Image: A scene from USPAS sessions in 2023.
Photo credit: Irina Novitski

APS DPB NEWS

APS Division of Physics of Beams Annual Newsletter ////////// **2023**

In this Issue:

Dear Readers,

Welcome to the 2023 APS-DPB newsletter! We are excited to introduce the 20th edition, which features updates from the Advanced Light Source, the ESS commissioning, the FCC feasibility study and the Argonne AWA facility. Furthermore, you will find great summaries on the newest developments of optical stochastic cooling, accelerator applications for space weather and RF technology development.

To keep you up to date with newest developments, we also included articles summarizing the CERN seminar series on future colliders, the GARD ABP Roadmap, recent in-person USPAS sessions, as well as the DOE accelerator traineeship program. We also include a highlight of the Ernest Courant traineeship (reports on the other three active programs can be found in previous issues of this newsletter).

We celebrate the international and collaborative nature of our field by featuring two articles on working together. These articles discuss scientific collaborations and how to engage with diversity while conducting research. In this spirit we also decided to keep the usage of American and British English of articles as they were submitted.

Moreover, we are delighted to honour the PRAB Courant Paper award with a summary of the winning article on 'Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature' and the winner of the 23' Faraday cup award with a summary of their submission titled 'Nonintrusive Diagnostics of Operational H- Beam Using Laser Wires'.

In addition to these featured articles, you will also find recurring articles such as a message from Chair Camille Ginsburg, a report on IPAC23 and the 2023 APS DPB Awards & Fellowship nominations, a discussion of the benefits of division activities for current and future members, our interview with the DPB Dissertation Award Recipient Chao Li and notice of some important dates for conferences and schools.

We would like to thank all of our authors for their valuable contributions and our 2023 APS DPB Executive Committee Members for their endless support.

As always, don't hesitate to get in touch with your ideas for the next issue.

Enjoy,

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From the Chair

Camille Ginsburg

Greetings dear Colleagues, dear APS/DPB Members!

Thank you very much for your membership and for keeping the Division of the Physics of Beams alive and well for recognition, advocacy and collegial interaction in the accelerator field. We need your help to advertise the benefits of APS/DPB membership to your colleagues and students, and to encourage them to initiate or maintain their membership.

Congratulations to the DPB members who received DPB travel grants to attend the U.S. Particle Accelerator School in January and June 2023. The award provides reimbursement up to $600 for travel to the school for approximately 10 students, and is awarded on a competitive basis.

Attendees at the APS April Meeting in Minneapolis were treated to a snowstorm (fun!) and an excellent program of accelerator talks. A highlight was the presentation of the paper which won the Courant Prize, a joint prize by APS/DPB and PRAB, by Mamdouh Nasr: M. Nasr et al., PRAB 24, 093201 (2021). Another highlight was a presentation by Chao Li (MIT), who won the DPB Ph.D. Thesis prize. Li also receives a lifetime APS/DPB membership thanks to a generous donation by David Yu.

Hearty congratulations to the 2023 APS Fellows from DPB: Bob Zwaska (Fermilab), Agostino Marinelli (Stanford University) and Chandrashekhara Bhat (Fermilab); and to the 2023 Wilson Prize winner Kaoru Yokoya (KEK). Their contributions to our field are as varied as they are significant.

Please note that the number of Fellows in each year depends on fraction of DPB membership within APS. It is a prestigious recognition for our colleagues made possible by your membership. Between 2021 and 2022, the number of DPB Fellows was reduced from four to three, due to falling membership.

If you would like to see someone win a DPB prize, please nominate them! Please consider nominating people who have not yet won a prize, perhaps an unsung hero who has had a critical impact on your accelerator topic. Make the case. Instructions are available on our websites, or feel free to contact me directly through the APS membership directory.

Thank you for your continued support.
Camille Ginsburg

Meet the 2023 Executive Committee

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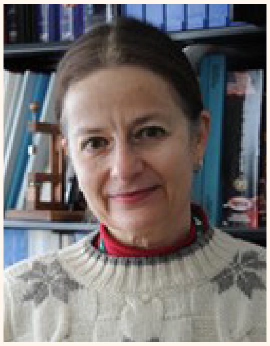

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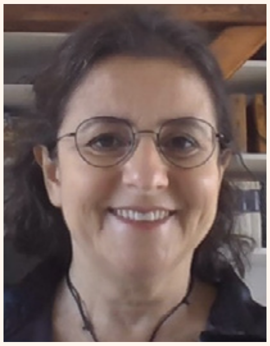

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The international accelerator community meets at IPAC23 in Venice with record attendance

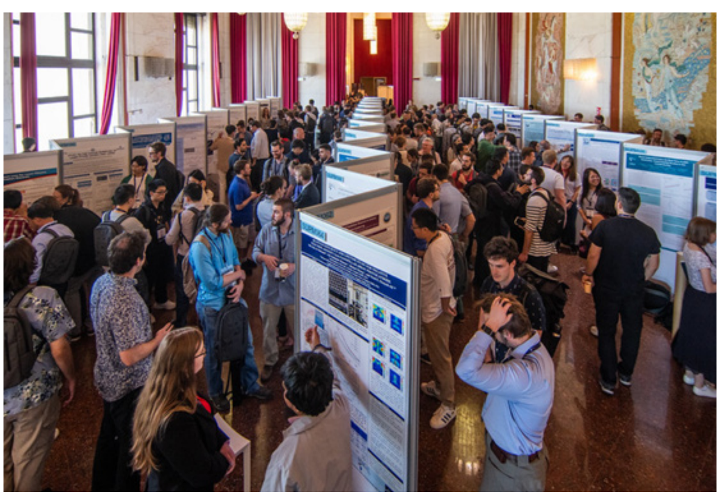
Ralph Assmann *(DESY), Chair Organizing Committee,* **Peter McIntosh** *(STFC), Chair Scientific Programme Committee,*
Alessandro Fabris *(Elettra)* **and Giovanni Bisoffi** *(INFN), Co-Chairs Local Organizing Committee*

The 14th International Particle Accelerator Conference (IPAC23) took place from May 7 to 12, 2023 in Venice, Italy. The fully in-person event had record attendance with 1,660 registered participants from 37 countries, illustrating the need for real-life interactions in the global accelerator landscape after the end of the COVID-19 pandemic.

The 273 students participating in IPAC got an opportunity to meet their peers and to build their professional networks. The IPAC is not only a scientific meeting but also works as global marketplace of accelerators, where science, technology and industry meet and discuss business. The 311 participants from 121 industrial companies assured that this crucial aspect for our field got impressively revived after the break due to COVID-19 measures.

The IPAC conference series is organized by the international accelerator community and its location rotates through the three regions 1) Europe, Middle East and Africa, 2) Americas and 3) Asia and Australasia. This year it was in Europe and was organized by the Accelerator Group in the European Physical Society (EPS-AG) and the local host organizations Elettra Sincrotrone Trieste and Istituto Nazionale di Fisica Nucleare (INFN).

The previous editions — IPAC20 in France and IPAC21 in Brazil — could only be held as remote conferences. Last year`s IPAC22 in Bangkok, Thailand, was held successfully in hybrid format, ongoing travel restrictions for certain countries affected attendance. Therefore, we decided that this year´s conference would be jointly opened by the four chairs of the Organizing Committees of the IPACs from 2020 to 2023. After the opening speech by Ralph Assmann, the OC Chairs Ralph Assmann (2023), Mike Seidel (2020), Lin Liu (2021) and Prapong Klysubun (2022) together swung the ceremonial hammer that opened IPAC23.



The poster sessions with more than 400 posters per day are the core of IPAC23.

The council member of the Venice Municipality for Economic Affairs Dr. Zuin welcomed the attendees on behalf of the Major of Venice Luigi Brugnaro. The Veneto Region President Luca Zaia and the Minister of Enterprises and Made in Italy, Senator Adolfo Urso, sent addresses that were read. Afterwards the presidents of INFN, Antonio Zoccoli, and of Elettra, Sincrotrone Trieste, Alfonso Franciosi, gave inspiring opening speeches, introducing the attendees to their organisations and to the important role of particle accelerators in Italy. Finally, the chairs of the local organizing committee, Alessandro Fabris and Giovanni Bisoffi, introduced the venue and practicalities for the conference.

The lively scientific program of IPAC23 had been prepared by an international committee led by Peter McIntosh. It included 87 talks and over 1,500 posters. The scope covered all particles (electrons, positrons, protons, ions, muons, neutrons…), all types of accelerators (storage rings, linacs, cyclotrons, plasma accelerators …), all use cases (particle physics, photon science, neutron science, medical and industrial applications, material physics, biological and chemical usages of accelerators …) and institutes in all the three regions. The extensive program offered such a wide perspective of excellence and ambition that the following highlights can just be a short subset of what was presented.

The scientific program started with a report by Malika Meddahi from CERN on the successful LHC Injector Upgrade (LIU) project. This project, with its predominantly female leadership team, was executed on budget and on schedule. It provides the LHC with beams of increased brightness as required by the ongoing luminosity upgrade program HiLumi, reported by Oliver Brüning. Emanuel Karantzoulis from Elettra presented the Elettra 2.0 project, the new ultra-low emittance light source under construction in Trieste, close to Venice, discussing the challenges and perspective in the design and construction of the new electron ring.

Axel Brachmann from SLAC showed the progress with LCLS-2 commissioning, the world's first CW free-electron laser (XFEL). While beam commissioning is somewhat delayed, the super-conducting RF accelerator structures perform beyond the performance specification and the facility is in excellent condition.

Dong Wang from the Shanghai Advanced Research Institute presented an impressive overview on the future of hard free-electron lasers, so called XFELs. The user demand for those facilities has led to an enormous investment into those devices, aiming now at high average power. He illustrated that high average power will be used to serve many more experimental lines as possible today, including experiments for highly non-linear QED.

Gianluca Geloni from European XFEL showed that user operation for the world's currently most powerful XFEL has been successfully enhanced with self-seeding. Massimo Ferrario from INFN showed the news and future promise for a novel, high-tech plasma-based FEL, as it is under construction in the European EuPRAXIA research facility, hosted by INFN and included in the ESFRI roadmap.

Jörg Blaurock from FAIR/GSI presented the status of the €3.3 billion FAIR project. Major obstacles have been overcome and the completed tunnel and many accelerator components are now being prepared for installation, starting in 2024. The European Spallation Source in Sweden is advancing well and the proton linac is approaching full beam commissioning, as presented by Ryoichi Miyamoto from ESS and Andrea Pisent from INFN.

Yuan He from China presented the chances in accelerator-driven nuclear power, both in safety and in reusing nuclear waste fuels. He impressed the participants with the news on a Chinese facility progressing well, also towards the goal of unprecedented up-time and reliability. This theme was also addressed by Ulrich Dorda from the Belgian Nuclear Research Centre who presented the status of the MYRRHA project.

Another impressive moment of the conference program was the talk by Andrey Zelinsky from the NSC in Ukraine, who presented the Ukraine Neutron Source facility at the National Science Center Kharkov Institute of Physics & Technology (NSC KIPT). Construction, system checks and integration tests for this new facility have been completed. Beam commissioning is being prepared by the Ukrainian colleagues in extremely difficult circumstances, as Russia attacks Ukraine, including the city of Kharkov.

Technological highlights included the report by Claire Antoine from CEA on the R&D in thin-film super-conducting RF cavities and their potential as game changers for sustainability. Sustainability was a major discussion topic at IPAC23 and was also covered by various other talks and many posters.

Several speakers presented the role of particle accelerators for the development of fusion reactors. The final talk of the conference was given by Beate Heinemann from DESY who discussed the role of accelerators for particle physics. She showed that without accelerators, much knowledge in particle physics would still be missing and she argued for new accelerator facilities at the energy frontier to allow further discoveries.

Common opening of IPAC23 by the OC Chairs from IPAC20 to IPAC23, to acknowledge the world-wide collaboration that makes IPAC possible. From left to right: R. Assmann (IPAC23), L. Liu (IPAC21), P. Klysubun (IPAC22) and M. Seidel (IPAC20).

The prize session was chaired by Mike Seidel (PSI) and awarded the EPS-AG accelerator prizes to Xingchen Xu, Mikhail Krasilnikov and Katsunobu Oide (reported before in the CERN Courier). In addition, the Bruno Touschek prize was rewarded to Matthew Signorelli from Cornell University. Two student poster prizes were awarded to Sunar Ezgi from Goethe Universität Frankfurt and to Christie Jonathan from the University of Liverpool .

IPAC23 included, for the first time in Europe, an Equal Opportunity session, featuring talks from Maria Masullo (INFN) and Louise Carvalho (CERN) on gender and STEM, pointing to the need to change the narrative and to move from talk to targets. The 300 participants in the session not only learned about ways to improve gender balance, but also about such important topics as neurodiversity. The very well attended industrial session of IPAC23 brought together projects and industry in a mixed presentation and round-table format.

For the organizers, the IPAC23 has been a remarkable and sometimes rocky five-year journey. But it has been a truly rewarding effort, seeing the many delegates, industry colleagues and students from all over the world coming together for a lively, peaceful and collaborative conference in Venice, Italy. The many outstanding posters and talks promise a bright future for the field of particle accelerators.

Upcoming Events

Conferences & Workshops

2024		
March 3–8	APS March Meeting 2024	Minneapolis, Minnesota & Virtual
March 5–8	4th ICFA Beam Dynamics Mini-Workshop on Machine Learning for Particle Accelerators	Gyeongju, South Korea
April 3–6	APS April Meeting 2024	Sacramento, California & Virtual
May 19–24	IPAC 2024 / International Particle Accelerator Conference	Nashville, Tennessee
July 21–26	AAC24 / Advanced Accelerator Concepts Workshop	Naperville, Illinois
August 19–23	FEL Conference	Warsaw, Poland
August 25–30	LINAC Conference	Chicago, Illinois
September 9–13	IBIC 2024 / International Beam Instrumentation Conference	Beijing, China
September 15–19	ECRIS (26th International Workshop on ECR Ion Sources)	Darmstadt, Germany
September 24–27	ERL (67th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs)	Tsukuba, Japan
October 7–11	66th Annual Meeting of the APS Division of Plasma Physics	Atlanta, Georgia

Accelerator Schools

2024		
January 22–February 2	US Particle Accelerator School, Winter	Hampton, Virginia
July 15–26	US Particle Accelerator School, Summer	Rohnert Park, California
March 11–15	CERN Accelerator School: Basics of Accelerator Physics and Technology	Ferney-Voltaire, France
June 2–15	CERN Accelerator School: Mechanical Materials Engineering	Sint-Michielsgestel, Netherlands

Announcement from USPAS:

In response to growing demand for a more basic introduction to the field of particle accelerator science & technology the USPAS will offer a certificate course, "Concepts of Accelerator Science and Technology" at their summer 2024 session. This new course will be taught at the entry, undergraduate-level and is geared towards familiarization of the field and operational aspects of accelerator facilities rather than research and development. The class will be one week in duration, will be graded pass/fail, and students passing will earn a USPAS Certificate of Achievement rather than university credit.

Details and more information will be available on the USPAS website soon.

Roadmap for Accelerator and Beam Physics

Jerry Blazey *(NIU)*, **Derun Li** *(OHEP)*, **and Vladimir Shiltsev** *(FNAL)*

Through the General Accelerator Research and Development (GARD) program, the Department of Energy Office of High Energy Physics (DOE OHEP) is a primary sponsor of the nation's accelerator science and technology R&D. Moreover, GARD provides support for several world-leading accelerator test facilities.

Accelerator and Beam Physics (ABP), one of five GARD emphases, is the science of the motion, generation, acceleration, manipulation, prediction, observation and use of charged particle beams. Particle accelerators can be used to better understand our universe and to aid in solving societal challenges. Beyond particle physics, current and future facilities in many disciplines rely on ABP methods, techniques, tools and expertise. ABP explores and develops the science of accelerators and beams to make future accelerators better, cost-effective, safer and more reliable.

GARD activities are guided by long-term roadmaps for each emphasis. The roadmaps have been developed from community consensus and input, in consideration of the U.S. HEP mission and recommendations from the High Energy Physics Advisory Panel (HEPAP) and P5 sub-committees. In April 2023, the *ABP Roadmap* was completed and published at:

https://science.osti.gov/hep/-/media/hep/pdf/2022/ABP_Roadmap_2023_final.pdf. This roadmap completes the road mapping exercise for the entire GARD program.

The ABP Roadmap development began with two community workshops held at Lawrence Berkeley National Laboratory (LBNL) in December 2019 and in Chicago in April-May 2020, respectively, and continued at the Snowmass "Accelerator Frontier" discussions in 2021-2022. In April 2022, DOE OHEP charged and sponsored the GARD Accelerator and Beam Physics Roadmap Workshop in Bethesda, MD to develop the ABP ten-year research roadmap (the photo below shows in-person participants).

The workshop was by invitation only and held in a hybrid mode. The workshop started with overviews from OHEP and the Office of Accelerator R&D and Production (ARDAP) followed by reports from two previous workshops and the most recent Snowmass 2021. Ample time was allocated for featured presentations and preliminary roadmap discussions of four interrelated Grand Challenges identified at the preliminary workshops and which taken together formed a framework for the workshop discussions:

1. Beam Intensity - How do we increase beam intensities by orders of magnitude?
2. Beam Quality - How do we increase the beam phase space density by orders of magnitude, towards the quantum-degeneracy limit?
3. Beam Control - How do we measure and control the beam distribution down to the individual particle level?
4. Beam Prediction - How do we develop predictive "virtual particle accelerators"?

ABP perspectives from international (CERN and Canada) and domestic agencies (NSF and NNSA) were also presented at the workshop. Considerable emphasis was placed on charting the roadmap and on community recommendations within the context of current and future facilities, integration of the individual roadmaps, organization of the ABP activities and integration with other programs. The requirements and challenges of specific

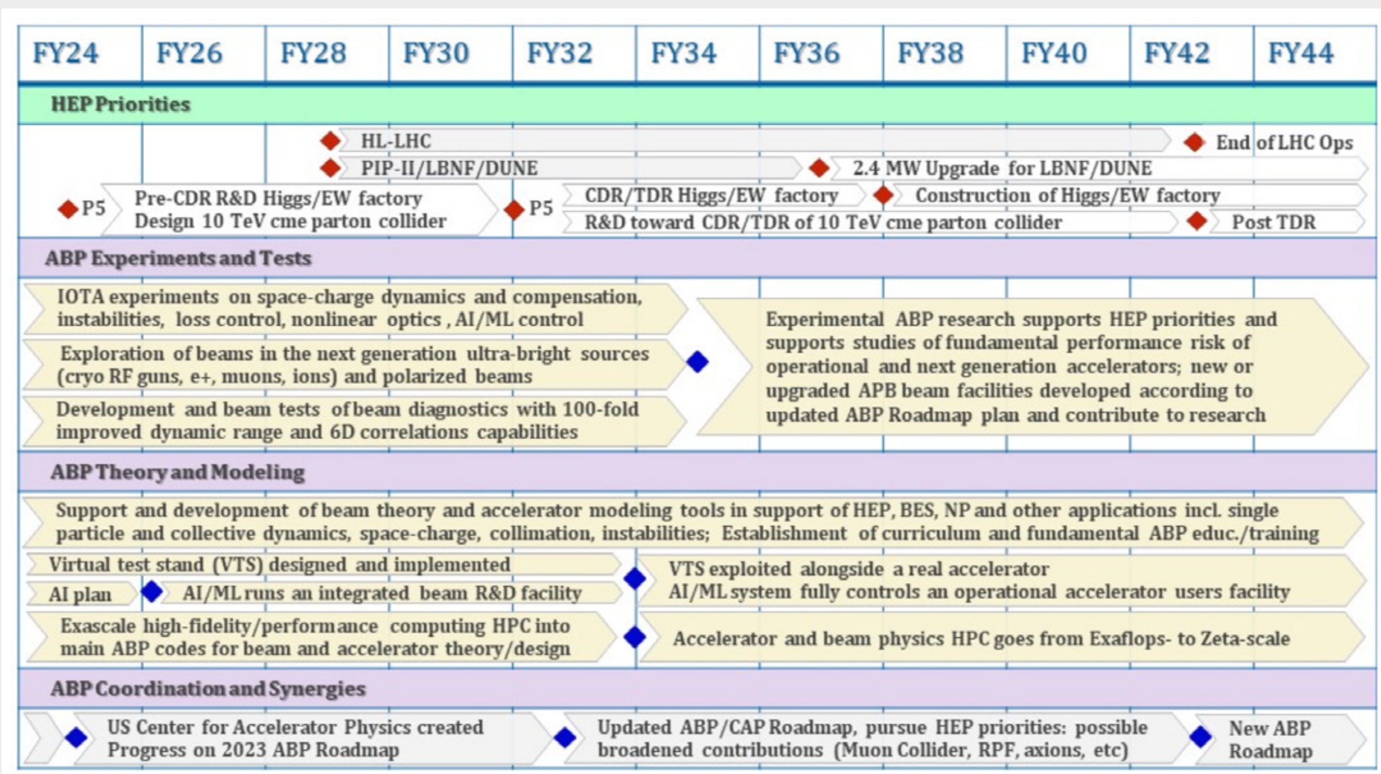
facilities provided important guidance for the ABP roadmap. For all future facilities, many interrelated research and development problems must be addressed. Their success requires a strong and robust ABP program.

The Grand Challenges must be considered in the context of the ABP goals as guided by the DOE HEP mission: i) advance the physics of accelerators and beams to enable future accelerators; ii) coordinate with other GARD thrusts to develop both the traditional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms; iii) guide and help to fully exploit science at the HEP GARD beam facilities and operational accelerators; and iv) educate and train the next generation of accelerator scientists and engineers.

The ABP Roadmap document provides a detailed R&D roadmap for each Grand Challenge, along with cross-cutting recommendations for ABP coordination, testing facilities and workforce development. The individual roadmaps provide strategic guidance, establishing chronological steps and major milestones to accomplish the ABP mission. Consult the report for the detailed roadmaps.

The figure below shows a notional 20-year overview of current and likely HEP facility priorities. It also provides a high-level overview of ABP experimentation and testing over the next two decades, including the development of FAST/IOTA and other test facilities, the exploration of ultra-bright sources and the development of advanced beam diagnostics. In terms of theory and modeling, this 20-year program supports the design and implementation of various applications, virtual testbeds and the development and integration of AI/ML and high-performance computing in ABP.

Three cross-cutting ABP themes emerged from the deliberations – coordination, test facility support and workforce development, which together form underlying recommendations to support the ABP roadmaps. The figure explicitly includes an important proposal for the establishment of an American Center for Accelerator Physics or a similar institution as a venue for coordinating ABP research and education across the country. Other key recommendations note that all efforts will require a sustainable support of testing facilities and workforce development is both a key requirement and a product of APB.



Engaging with Diversity in Research: A Journey at ORNL and Beyond

Andrea Delgado, *Oak Ridge National Laboratory*

The face of science is changing. As we advance into the 21st century, we are reminded that diversity is not just an aspiration but a necessity. At Oak Ridge National Laboratory (ORNL), this realization culminated in forming a coalition of efforts to increase the diversity of the next generation of high-energy physicists by actively engaging students and faculty from minority-serving institutions (MSIs). This move was more than symbolic; it was a practical step in acknowledging that the future of research is inextricably tied to our ability to involve a diverse group of minds and perspectives.

This intentional effort coincided with the introduction of Promoting Inclusive and Equitable Research (PIER) plans. These are now uniformly required for all new Office of Science grant proposals at the U.S. Department of Energy (DOE). This requirement was a watershed moment. On one hand, it highlighted the growing emphasis on diversity inclusion and inclusion in research. On the other hand, it revealed a stark reality: many in the research community were ill-prepared or hesitant to develop authentic and coherent diversity plans.

Why Diversity?

Before diving into the specifics of the coalition's formation and the broader implications of the PIER requirements, it is crucial to understand why diversity matters in the research realm. Science is a collective endeavor. Its strength is derived from its ability to aggregate different perspectives, backgrounds, and life experiences. When research teams are diverse, they reduce the chance of fostering an echo chamber of ideas and can enhance the opportunity for innovative breakthroughs.

ORNL's Coalition for Diversity

The DOE issued a new initiative called "Reaching a New Energy Sciences Workforce" (RENEW) and currently supports ORNL's initiative to engage MSIs to build a diverse talent pool to further the department's mission. The Collider, Artificial intelligence, Neutrinos, Dark matter, and heavy Ions for Diversity (CANDID) program was designed to overcome barriers associated with educational access and success for the nation's marginalized citizens by acknowledging the importance of MSIs in degree attainment for underrepresented minorities and leveraging the resources available at ORNL. CANDID combines mentor training, a series of career and personal development training for the mentees, and a rich research experience to guarantee the development of a physics research identity and enable students to succeed in graduate degrees in physics.

Another important aspect of the program is the focus on faculty engagement and building infrastructure for institutions not traditionally part of the DOE's portfolio. By reaching out to these institutions, CANDID is enabling the untapped potential within these educational hubs for future opportunities in physics. The engagement process was comprehensive, involving collaborative efforts, including internships and joint research projects. These interactions ensured that students and faculty from diverse backgrounds were not just passive participants but active contributors to DOE's mission, and particularly, to research focused on high energy physics (HEP).

In pursuing a diverse scientific ecosystem, the spotlight often remains on the successes. However, an essential story often goes untold: the challenges that institutions, especially minority-serving ones, face when aiming to bridge the gap between aspiration and realization.

The Roadblocks for MSIs:

MSIs have a significant amount of untapped potential. Nevertheless, their journey in participating in cutting-edge research has illuminated obstacles.

One of the primary challenges many MSIs face is adequate staffing. While national laboratories have specialized departments and personnel dedicated solely to the grant application process, many MSIs often work with a leaner team. This places an added burden on the faculty and can sometimes result in missed opportunities due to stretched resources.

For many MSIs, preparing application packages for large funding agencies is uncharted territory. The intricacies of such applications, the documentation, the benchmarks, and the adherence to nuanced requirements can be overwhelming. The process becomes even more daunting because many of these institutions might be applying for the first time or need more historical data to guide them. Furthermore, MSIs often lack dedicated workshops, training sessions, or mentorship programs that can guide them in aligning their expertise with submission expectations, which could boost their chances for success.

Bridging the Gap: The Role of Larger Institutions

Given these challenges, it is evident that if the goal is to have a more diverse and inclusive research environment, the responsibility does not solely lie with the MSIs. Larger institutions, research bodies, and even funding agencies need to play an active role in bridging these gaps.

For example, larger institutions, like ORNL, can initiate collaborative workshops dedicated to grant writing and application processes. These workshops can act as a knowledge-sharing platform, guiding MSIs on best practices, common pitfalls, and the specifics of preparing a winning proposal.

Funding agencies have started to recognize the challenges MSIs face and tailor specific calls for proposals designed for these institutions. This does not mean lowering the bar, but instead providing a clearer roadmap.

The PIER Mandate: A Necessary Disruption

Combined with the RENEW initiative, the PIER mandate by the DOE was a necessary disruption to the status quo. It forced research entities to introspect and reckon with the glaring gaps in their diversity and inclusion efforts. While some viewed it as a bureaucratic imposition, many others, especially those with a track record of engaging with diversity, saw it as an opportunity. The mandate did ruffle feathers, but it also opened the doors, prompting the research community to establish ties with institutions and communities they had previously overlooked.

Concluding Thoughts

My journey and my engagement with diverse institutions have reiterated one fact: diversity is not a checkbox activity. It is a commitment to broaden horizons, challenge our own biases, and recognize the future of research as vibrant, multifaceted, and inclusive.

For research institutions and communities looking forward, the message is clear. Embracing diversity is not just about compliance with mandates; it is about enriching the very fabric of scientific discovery. In this age, where global challenges necessitate global collaboration, diversity is not a mere virtue but a vital asset.

The journey towards a diverse research ecosystem is not a sprint but a marathon. It requires patience, collaboration, and an understanding of the challenges ahead. While the path might be fraught with obstacles, the destination —a vibrant, inclusive, and innovative scientific community —is undoubtedly worth the effort.

How Can We Scientists Engage In Building a Worthy Scientific World?

Christine Darve, *European Spallation Source, ERIC*

Although political challenges and wars will always perturb our international quality of life, we have to believe that international scientific collaborations shall prevail!

Inspired by wisdom and peace, the responsibility of scientists is to understand, teach and construct a sustainable universe. For that matter, schools, universities, individuals and physical societies around the globe are the actors of a latent transformation.

But we have to pause and ask: Will the rise of new technologies such as AI shape a flamboyant paradise or a hellish, dystopian future for our next generations?

On one hand, large-scale collaborations like CERN enlighten the scientific knowledge for high-energy physics and beyond. Established as a byproduct of World War II, this European research infrastructure represents a model of excellence, gathering beautiful and powerful minds [1]. Numerous other large-scale research infrastructures such as ITER, ILL, ESRF and ESS are shining a spotlight on the value of collaboration.

On the other hand, national laboratories and research infrastructures are also supporting national and international missions, pursuing goals that aren't always entirely peaceful. Los Alamos National Laboratory, constructed on the basis of the Manhattan Project, is an example of a scientific byproduct of conflict. The newly-released movie by Christopher Nolan has brought a lot of visibility on the development of the nuclear arsenal. Oppenheimer tells the story of the American theoretical physicist and director of the Manhattan Project's Los Alamos Laboratory during World War II. We should not forget Hiroshima, Nagasaki and the nuclear arms race — but we should also keep our eyes on the prizes that today's international science collaborations promise, and are making real. The Forum of Physics and Society (FPS) and the APS Forum on International Physics (FIP) have dedicated a Zoom session to this conundrum [2].

Modern physics and the search for a respectful nuclear archetype have opened the gates to the best and the worst possible worlds!

Scientific communication in a time of war is essential and should be upheld by those with both the knowledge and the skills to be both transparent and comprehensible. Hence, between the Cold War and the latest attack on Ukraine by Russia, one can always judge that the precarious balance between research openness and security drives another paradigm [3] [4].

Always remember that nuclear physics can produce our daily source of energy! The DBP and the FIP organized an engaging session during the 2023 APS April meeting to Accelerate Solving Energy Crisis: From Fission to Fusion. An impressive panel of worldwide experts have shared those insights [5].

In addition, a follow-up event was organized in the framework of the Physics Matters colloquia series: Accelerator Driven Systems — As a Solution To Multiple Problems of Society [6]. Organized by the FIP on August 31 2023, live from China, this colloquium portrayed the excellence of such ADS and how most large-scale RIs have inherited hardware and know-how from respectful international collaborations.

Another powerful platform is the International Union for Pure and Applied Physics (IUPAP). The IUPAP is gathering thematical groups of renowned individuals who together can inspire solutions to international problems. The FIP dedicated a whole session to the IUPAP's accomplishments over the last 100 years. Indeed, the first president of the IUPAP was William Henry Bragg, Nobel Prize winner in Physics in 1915. The famous Bragg peak is directly exploited by the scattering community, whose stringent hard work enriches our daily life with new discoveries, thanks to worldwide photon and neutron sources. Indeed, research issued from light sources has enabled the vaccines that have limited the proliferation of the Covid-19 SARS virus.

Therefore, beyond armed conflicts, science can stimulate priceless reasons worth fighting for. Here are some examples:

Science can be used as an incubator for peace, as with Andrei Sakharov, a Soviet physicist who was awarded the Nobel Peace Prize in 1975, while emphasizing human rights around the world. In March 2021 the APS celebrated in the 100th anniversary of Sakharov and his contribution to science and humanity [7], and had a follow-up event with the FPS during the 2022 APS April meeting [8].

A perfect example of a project in which science is used as an enabler for mutual understanding is the creation of the SESAME light source in Jordan, gathering multidisciplinary and international effort. The Forum on International Physics (FIP) is a strong supporter of this Middle Eastern messenger that enlightens and inspires. FIP shines a monthly spotlight on its achievements thanks to the Physics Matters colloquia series, Physics for Development

[9] [10][11].

Similar methods and ways-of-working can be applied in other contexts to solve issues and to raise similar goals in society like the quest for Equity, Inclusion and Diversity (EID).

As well, an ethical eco-system composed of research infrastructure, education and industry, can guide the human evolution in the context of particle accelerators [12].

No-one chooses where they are born! The local cultural heritage will shape this eco-system. One example of addressing this EID equation is in embracing the digital transformation to educate scientists in Africa [13] [14].

Although there are a few individuals willing to transform lofty ideas into action, to strengthen those positive bridges of knowledge, such proactive actions are greatly enhanced by multidisciplinary collaboration to reach a peaceful paradigm. Everyone shall engage with one complementary skill. Providing that those values are shared equally, any perturbation applied to this sensitive system should help converge to a more stable humanity.

As scientists, we have to keep working for and believing in positive outcomes! Sharing perspectives on continuing collaborations, joint publications between individuals, promoting scientific deontology and ethics and the freedom of an educated speech.

One can honor humanity by understanding its realm. Scientific activities driven by curiosity are the origin of positive evolution, transferring knowledge and wisdom as a leitmotif for peace!

References

[1] "International collaborations in large-scale scientific projects", by Christine Darve and Colin Carlile, p27-29, APS Forum on International Physics Fall 2013 Newsletter

[2 "Oppenheimer: Scientists, The Bomb, and the Implications for Today" , zoom session organized by APS/FPS, APS/FIP, and the APS/FHPP, July 31, 2023

[3] "The Precarious Balance Between Research Openness and Security" by E. William Colglazier (AAAS), Issues in Science and technology, Vol. XXXIX, No. 3, Spring 2023

[4] Session X00: Plenary III: Ukraine and Russia, APS April Meeting 2022, New York, 2022

[5] Session M06: Accelerate Solving Energy Crisis: From Fission to Fusion

APS April Meeting 2023, Minneapolis 2023

[6] "Accelerator driven systems – a solution to multiple problems of society", by Prof. Yuan He, August edition of APS/FIP Physics Matters Colloquia series, August 31, 2023

[7] Sakharov-100 Celebration" by Vladimir Shiltsev and Christine Darve, Forum on International Physics Newsletter, Summer 2021

[8] Session S29: Speaking Up for Human Rights of Scientists, Just as Important Now as in Andrei Sakharov's Time, APS March Meeting 2022, Chicago 2022

[9] Physics Matters Monthly colloquia series, APS/FIP

[10 Session C05: No Frontiers when Physics Matters

APS March Meeting 2023, Las Vegas, 2023

[11] "An epic journey across the quantum landscape to the APS March Meeting", by C. Darve - Societa Italiana di Fisica, SIF Prima Pagina, 4 April, 2023

[12] "Innovative Eco-System for Accelerator Science and Technology" (https://arxiv.org/abs/2106.00056) by C. Darve et al., IPAC2021

[13] "Physics and Humanity: the advancement of women in physics at universities" by Irvy Gledhill (Wits), Journal of Physics: Conference Series, 2020

[14] "Open science and Big Data in South Africa" by Tony Hey,

Frontiers in Research Metrics and Analytics, Nov. 2022

Radiofrequency Technology and Development for Particle Accelerators

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1 Introduction

Radiofrequency (RF) accelerators have a rich history that dates back to the early development of accelerators by D.H. Sloan, E.O. Lawrence and M. Stanley Livingston [1]. These early developments laid the groundwork for the development of modern RF accelerators for scientific applications (e.g., high-energy particle physics, nuclear physics and light sources) and subsequent spin-off technologies geared toward commercial, industrial, medical and security applications. A comprehensive review of the history of radiofrequency accelerators for particle accelerators is given in [2].

2 Radiofrequency accelerator technologies for linac and circular machines

Accelerating gradient and the cost of accelerators are the two main crucial parameters affecting the design, the choice of technology (normal conducting and/or superconducting), and the availability of the associated high-power RF sources and components. The choice of the operating frequency and operating mode (e.g., continuous wave, duty factor) imposes additional design constraints that could drive up the overall accelerator cost. The challenge is to develop reliable, efficient, and cost-effective high-gradient RF accelerators. Recent focused R&D on the development of RF structures and high-power RF sources have shown promising results to reach very high operating accelerating gradients with desired power efficiency. Advances in machining and production technologies of normal-conducting accelerating structures have made it possible to fabricate high-precision complex structures with strict dimensional accuracy [3]. Improved manufacturing technologies (high-precision forming, high precision electron beam welding) for superconducting accelerating structures [4] have resulted in better interior surface quality with less impurity contamination.

2.1 Normal-conducting RF accelerators

Many particle accelerators with the widest range of applications are based on normal-conducting technology utilizing oxygen-free high-conductivity copper as the material of choice for RF cavities (structures). Over the last decade, studies and investigations into the physics of RF breakdown at high gradients on normal-conducting radiofrequency structures demonstrated the feasibility of pushing the gradient above 50 MV/m to 100-150 MV/m. Improving manufacturing techniques to further reduce surface roughness below 0.001 micron and improving the brazing operations in inert atmospheres to eliminate surface contaminations are the necessary steps to better mitigate breakdown in sustained high accelerating gradient operation [5]. Significant progress, spearheaded by industries, has been made in the last decade to improve the manufacturing technology and augment the existing infrastructures, including high-precision milling, vacuum brazing and ultra-precision metrology. Adopting the procedures, chemistry and clean-room practices of superconducting radiofrequency structures (to the extent it is applicable) could be beneficial and should be considered.

Alternative techniques to brazing have been studied and tested [6]. These explore novel clamping for high-gradient RF structures using electron beam welding and tungsten inter-gas welding that would avoid high-temperature processing of RF structures to preserve superior high-gradient performance of hard copper alloys. Initial investigation on two braze-free 11.4-GHz structures with special cell-to-cell clamping and welded were demonstrated: one at an accelerating gradient of 90 MV/m (electron beam welding) and a breakdown rate of 103/pulse/meter with a 150-ns flat pulse, and one at an accelerating gradient of 150 MV/m (TIG welded) at the same breakdown rate and pulse length. Continued studies of the vacuum breakdown mechanism, including the effects of dislocation dynamics, geometry, dark current and RF pulse shaping are essential to a more robust breakdown model to push the limit of the accelerating gradient of the room-temperature radiofrequency structures, as the sustained operation in high-gradient applications is defined by a maximum breakdown rate that is a function of surface electric field and/or magnetic field (pulsed surface heating due to induced surface current) [7].

New concepts and approaches have recently been proposed to investigate the need for efficient and cost-effective high-gradient radiofrequency technologies (normal and superconducting) for future high-energy and high-intensity accelerators. An innovative technology employing C-band (5.7 GHz) cold copper cavities operating at liquid nitrogen temperature with distributed couplings is aimed at increased accelerator performance over room-temperature copper structures reaching substantially increased accelerating gradient power efficiency. A GeV-scale demonstration facility is proposed for the Cool Cooper Collider (C3) to test an RF design aiming for an accelerating gradient of about 155 MeV/m [8, 9]. Recently a UCLA collaboration has considered an RF design for an S-band cryogenic normal-conducting copper RF photoinjector that is designed to operate at 27K, reaching 250 MV/m with a sub-μs RF pulse and 50 MW peak power [10].

Following several years of development, optimization, and testing of X-band (12 GHz), room-temperature copper traveling-wave structures for the CERN Compact Linear Collider (CLIC), these have been experimentally validated and represent a key and important contribution to the accelerator community as well as a transfer of technology to industries. Accelerating-beam gradients up to 100-MV/m were achieved for the CLIC 12-GHz structures at the CERN test facility. Similarly, a short 11.4-GHz normal-conducting copper structure cooled to 77K at SLAC reached about 150 MV/m [11].

The main technical challenges were achieving micron-level machining tolerances as well as assembling waveguide power couplers and mode damping waveguide manifolds, which were the main cost drivers. The ability of CLIC to reach TeV energies in a compact and cost-effective way is one of its most important design features and is unique among the proposed concepts for future electron-positron colliders. Wider potential applications of X-band accelerating technology encompass compact Thomson scattering, inverse Compton scattering, wakefield and plasma accelerators and radiotherapy [12,13].

Amongst the beneficiaries of high-gradient radiofrequency accelerator development for ions is the use of carbon ions in radiotherapy oncology with the clear edge of their radio-biological effectiveness (RBE) in treating radio-resistant tumors. Although synchrotrons are the current workhorse for heavy ion therapy, ion cyclotrons and new ion linacs have been proposed. Recently, Argonne National Laboratory (ANL), in collaboration with RadiaBeam Technologies, developed a concept for a compact carbon ion linac—the Advanced Compact Ion Linac (ACCIL)—that is a total of 45 m long and incorporates a novel S-band (2856 MHz) high-gradient structure to produce ion beams of 450 MeV/u [14,15]. An MRI combined with CCIL could deliver a highly precise localized radiation dose to a tumor without affecting the healthy surrounding cells. Laser-driven ion accelerators for tumor therapy. although a possibility, have numerous technical challenges to overcome before they could be applied to tumor therapy [16].

2.2 Superconducting RF accelerators

The fundamental advantage of superconducting niobium cavities is the extremely low surface resistivity of roughly 10 nΩ at 2 deg Kelvin compared to a few mΩ in room-temperature copper cavities. Since the cavity quality factor, Q (stored energy capacity), is inversely proportional to the surface resistivity, high Q values on the order of 1010 can be achieved to obtain very low RF power dissipation on the cavity interior walls.

Over the past decades the radiofrequency performance of bulk niobium cavities has steadily improved with materials, refined fabrication techniques, and surface treatments (e.g., nitrogen infusion and low-temperature baking) at 2K of L-band cavities that have produced accelerating gradients of 54 MV/m with magnetic fields close to the DC superheating field of niobium (about 240 mT) at the cavity equator reaching the theoretical limit of accelerating gradient in niobium. Along with pushing the limit of Nb cavities operating accelerating gradient, investigations into improving the quality factor of the SRF cavities continue to reduce the cryogenic losses to optimize liquid helium cryogenic plants especially for continuous-wave (CW) mode operations.

The most recent investigations have focused on maintaining high accelerating gradients while improving the quality factor of SRF cavities. Efforts led by a FNAL group [17] utilizing nitrogen infusion cavity processing recipes resulted in improved unloaded Q value without the need for post-annealing chemical removal of materials from the inner surface. A combined buffered chemical polishing (BCP)/electropolishing (EP) post-nitrogen-infusion treatment suggests higher quality factor increasing with the accelerating gradient [18,19]

For nuclear physics applications, the need for high-performance reduced-beta (low or medium β, less than 1) superconducting cavities of different types ranging from multi-cell elliptical cavities (TM-class) and spoke, quarter-wave, half-wave cavities (TEM-class) structures, enhanced and improved BCP and EP surface processing techniques, along with tailored pre- and post-processing temperature treatments have increased the quality factors of both classes of cavities. Several current and new accelerator facilities worldwide have been the beneficiary of these latest developments, including FRIB, SNS(PPU) Fermilab (PIP-II) in USA and several other facilities in Europe and Asia.

2.3 Next-generation RF accelerators

Metallic radiofrequency structures (room temperature and superconducting) will continue to dominate the particle beam accelerator landscape in the foreseeable future. Alternative acceleration techniques, such as plasma wakefield, solid-state-based, dielectric wakefield, crystal channeling and several other exotic techniques, are envisioned as long-term options for future particle accelerators that would need fully dedicated and extensive R&D efforts to advance their novel concepts to prototyping and demonstration stages to validate the technology. These “non-direct” radiofrequency approaches aim at multi-GeV/m and multi-TeV/m field regimes. Even more exotic and futuristic approaches, such as using bandgap structures, nanostructures, carbon nanotubes and metamaterials, are being considered [20-22].

2.3.1 Normal-conducting technology

With the highest operational limit of the accelerating gradients of normal conducting “copper” radiofrequency structures reaching the predicted practical limit of about 100 MV/m set by the onset of surface breakdown, new investigations have been focused on alternative approaches to mitigate RF breakdown by using non-conventional geometries, improved theoretical breakdown models and sophisticated electrodynamics simulation suites with multi-objective algorithms. Theoretical and experimental investigations are ongoing to gain better insights into the mechanism of vacuum breakdown in radiofrequency accelerating structures aimed at enhancing the accelerating electric field while maintaining operation reliability [23].

Practical energy recovery should be a key consideration to reduce wall-plug power for future colliders. Ongoing studies are focused on the technical challenges in the core area of research to advance room-temperature radiofrequency accelerator technology for high-gradient operation. Initial investigations of copper for high-gradient applications show that, for example, room-temperature silver-matrix hard copper structures have superior accelerating gradient performance compered to soft and hard copper at a given breakdown probability [24]. Studies also indicate that operating copper structures at lower than room temperature (e.g., at 77K) could further push the accelerating gradient above 200 MV/m. Ongoing R&D on C3-related topics could directly benefit other accelerator areas including ultra-high-field electron cryogenic electron sources, linac injectors, compact x-ray free-electron lasers and industrial and medical accelerators. [25-27]

2.3.2 Superconducting technology (niobium and beyond)

The performance of superconducting niobium radiofrequency cavities over the years has been dramatically improved thanks to many innovations in design, fabrication and surface treatments [28]. Advances in niobium-based superconducting radiofrequency technology could allow accelerating gradients in the range of 50 to 90 MV/m. Use of niobium superconducting traveling-wave structures (SRF-TW) has been proposed for the Higgs-Energy LEptoN (HELEN) collider [29] and circular e+e using energy-recovery linac (CERC) [30]. In tandem with continuing investigation of niobium cavities performance enhancements, studies of new superconducting materials are underway using novel and advanced surface deposition techniques that could be used for practical accelerator applications. Initial investigations of high Tc materials, such as Nb3Sn, Mg2B, pnictides, etc., have shown promising results on test structures [31- 36]. Dedicated focused R&D efforts are essential to advance these concepts. Use of a thin film superconductor for accelerator applications could also play a key role in accelerator sustainability.

A renewed interest using deflecting/crabbing cavities for beam manipulations launched a number of R&D programs to design and fabricate a new class of TM110, TEM-type and TE11-like superconducting radiofrequency structures for colliders to help with increasing the luminosity of collisions and for light sources to generate short X-ray pulses for targeted time-resolved experiments [37,38]. In addition, deflecting cavities have been used for beam diagnostics in longitudinal phase space and emittance exchanges [39].

3 RF sources

The RF sources for next-generation radiofrequency accelerators must incorporate innovative technologies to make a sizable stride toward cost-effective, reliable and stable higher-power-efficiency RF sources that are aligned with sound environmental measures, i.e., initiatives toward more sustainable and greener energy accelerator facilities with targeted reduced carbon footprints [40]. These types of RF sources for accelerators include (but are not limited to) gridded tubes (triode, tetrode, pentode, and Diacrode), klystrons, inductive output tubes (IOT), magnetrons and solid-state amplifiers (SSAs) [41]. For the most part, commercial klystrons (operated in pulse or CW mode) have been reliable RF sources for particle accelerators worldwide for many decades with an efficiency below 60%. Investigation and exploration of new approaches and techniques, spearheaded by the CERN team, to boost existing commercial L-band klystrons efficiency beyond 70% using modern computer modeling and analysis tools is encouraging. Highly efficient RF sources are essential for any future large-scale high-gradient accelerators, such as ILC, FCC, Muon-Collider, CLIC, CEPC, C3 and HELEN, to be affordable. Developing low-cost RF sources will require serious, aggressive R&D for the next decade to meet the targeted performance figures that are cost effective. Recent research activities at CERN in collaboration with other accelerator facilities and the establishment of the High Efficiency International Klystron Activity (HEIKA) to explore and develop ideas to boost klystrons efficiencies via optimizing beam bunching techniques are underway [42].

Continuing investigation of high-efficiency inductive output tube (hybrid tetrode and klystron) linear vacuum devices in the 470-1500 MHz frequency range is essential towards low-cost RF source alternatives. Developing commercial multi-beam IOTs (MBIOTs) appears promising but requires additional R&D [43]

High-power magnetrons are commercially available and are used by the process heating industry. These devices offer 100 kW of power at 915 MHz. Although high-power magnetrons are inexpensive (~$0.10/Watt), the reported lifetimes are roughly 6,000 hours or less. Therefore, they have not been well suited for accelerator applications. With demonstrated high efficiency of ~90%, they appear suited for room-temperature radiofrequency accelerators with frequency and phase locking, but due to their unstable phase and amplitude, they could not be used for CW superconducting accelerator applications such as intensity frontier GeV-scale proton/ion superconducting linacs. Techniques using dynamic phase control, injection-locked mode allow stable operation with acceptable linearity and small phase errors [44].

Preliminary demonstration shows the feasibility of injection-locking cascaded magnetrons with adequate wideband dynamic phase and power control. Magnetron RF sources could be considered as a highly efficient, compact and affordable alternative to linear electron vacuum devices for future long-pulse and CW SRF accelerators.

A vast number of accelerator facilities worldwide are taking advantage of a laterally diffused metal-oxide-semiconductor (LDMOS) power transistor technology to transition from tube-based to SSA systems [45-46]. Current LDMOS RF power technology offers highly reliable and operationally stable devices of about 1 kW (CW) that are very attractive for RF accelerator applications up to about 1.5 GHz. Several companies now offer turn-key SSA systems for broadcasting, industrial, medical and accelerator applications, taking advantage of newer higher-power density LDMOS devices. At higher frequencies (above 1.3 GHz) and higher powers (above 1 kW) gallium nitride (GaN) technology is more operationally suited and offers several key advantages over LDMOS devices including: higher breakdown limit, higher power density and better efficiency and higher thermal conductivity that mitigates potential damages due to thermal stress [47]. For any future large accelerators (linear or circular) with MW-class RF power demand, vacuum electron tubes—such as high-power klystrons—remain viable. Ongoing R&D efforts to reach higher (DC to RF) efficiency greater than 75% is promising.

5 Closing remarks

Major game-changing breakthroughs in the development of radiofrequency accelerators have happened since the end of World War II, thanks to the groundbreaking work on RF power sources in megawatt (MW) ranges at frequencies of hundreds of megahertz (MHz). Collaboration and partnership between the particle accelerators community and the private sectors have allowed successful commercialization of turn-key accelerator systems through technology transfer that have benefitted the scientific needs as well as provided engineering solutions for a wide range of applications in communication and broadcasting, industry, medicine and security.

The next decade will be very challenging as we continue enhancing current radiofrequency accelerator technologies to be more efficient, cost-effective and environmentally friendly, while exploring new, novel and innovative ideas and developing new technologies to push the performance limits of future accelerators and RF sources. With eyes on the next "big" machine(s), a cohesive international collaboration, in partnership with the private sector and supported by comprehensive targeted R&D programs, is necessary to push radiofrequency technologies forward in a timely fashion consistent with the US-DOE, European and Asian strategies for the particle physics accelerator R&D roadmap.

Continuing the investigation of surface breakdown of room-temperature (copper) accelerating structures is essential to increase the nominal operating accelerating gradient by gaining more insights into RF breakdown mechanisms. Recent investigations by a SLAC team using cold copper cavities for collider applications (aka C3) is very encouraging. Exploring new high-Tc superconducting materials for superconducting radiofrequency applications is essential toward developing affordable and compact cryogen-free accelerators.

Working closely with the private sector on long-term needs for high-efficiency cost-effective RF sources should be seriously pursued. The immediate goal should be focused on performance optimization of klystron amplifiers with a realistic expectation of power efficiency improvement along with some degree of standardization that will make them affordable for scientific and commercial accelerators.

Improving and adapting new computational tools, such as Multi-Objective Bayesian Optimization (MOBO), to design, model and analyze RF sources in concert with advanced manufacturing techniques, prototyping and proof-of-concept demonstrations are the key elements to address the cost and efficiency of RF sources. R&D on alternative approaches, such as field-emitter arrays, plasma cathode and carbon nanotube sources, should be supported.

References

1 Lawrence, E. O. & Livingston M. S. Phys. Rev. 37, 1707 (1931).

2 Nassiri, A. et al. History and Technology Developments of Radio Frequency (RF) Systems for Particle Accelerators. IEEE Trans. Nuclear Sci. 63(2), 707 (2016).

3 Mirapeix, F. et al. High Precision Manufacturing for Linacs. To be published in Proc. LINAC 2024, Geneva, Switzerland.

4 Singer, W. SRF Cavity Fabrication and Materials, http://arxiv.org/abs/arXiv:1501.07142

5 Dolgashev, V. A. et al. High-gradient rf tests of welded X-band accelerating cavities. Phys. Rev. Accel. Beams 24, 081002 (2021).

6 Spataro, B. et al. A hard open X-band RF accelerating structure made by two halves, arXiv:2109.03954v1 (2021).

7 Simakov, E. et al. Advances in high gradient normal conducting accelerator structures. Nucl. Instrum. Methods A 907, 221 (2018).

8 Bai, M. at el., C3: A "Cool" Route to the Higgs Boson and Beyond, SLAC-PUB-17629 (2021).

9 Barklow, T. L. et al. C3: An Advanced Concept for a High Energy e+e- Linear Collider, Snowmass 2021 Letter of Interest (LOI). 10 Robles, R. R. et al. Versatile, high brightness, cryogenic photoinjector electron source, Phys Rev. Accel. Beams 24, 063401 (2021).

11 Dolgashev, V.A. et al., High-gradient rf tests of welded X-band accelerating cavities. Phys. Rev. Accel Beams 24, 2021.

12 Petrillo, V., at el., State of the Art of High-Flux Compton/Thomson X-rays Sources, Appl. Sci. 2023, 13(2), 752.

13 Muggli, P., White Paper: AWAKE, Plasma Wakefield Acceleration of

Electron Bunches for Near- and Long-Term Particle Physics, Max Planck Institute for Physics, Munich, Germany, 2022.

14 Mustapha, B., at el., Developments Towards a Compact Carbon Ion Linac for Cancer Therapy, 15th Conf. on Heavy Ion Acc. Technology _ HIAT 2022, Darmstadt, Germany (2022).

15 Kutsaev, S., at el., High Gradient Accelerating Structures for Carbon Therapy Linac, 28th Linear Accelerator Conference, 09/25/16- 09/30/16, East Lansing, MI, USA.

16 Ng, J., at el., MRI-LINADC: A transformative technology in radiation oncology, Front Oncol. 13, 2023. https://doi.org/10.3389%2Ffonc.2023.1117874.

17 Grassellino, A. et al. Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures. Supercond. Sci. Technol. 26, 102001 (2013).

18 Yang, L., at el., Investigation into surface composition of nitrogen-doped niobium for superconducting RF cavities, Nanotechnology, Vol. 32, No. 21 (2021).

19 Connella, D., at el., Nitrogen-doped 9-cell cavity performance in a test cryomodule for LCLS-II, J. of Appl Phys. 117 (2015).

20 Zhou, N., at el., RF design and simulation of a non-periodic lattice photonic bandgap accelerating structure, Proc. NAPAC2016, Chicago, IL, USA (2016).

21 Perera, A., at el., Towards ultra-high gradient particle acceleration in carbon nanotubes, JOP 1596 (2020).

22 Resta-Lopez, J., at el., Application of nanostructures and metamaterials in accelerator physics, Proc. IPAC2022, Bangkok, Thailand (2022).

23 Wuensch, W., High-gradient breakdown in normal-conducting RF cavities, Proc. of EPAC2002, Paris, France (2002).

24 Dal Forno, M., at el., High gradient tests of metallic mm-wave accelerating structures, SLAC-PUB-17104.

25 Solyak, N.A., Gradient Limits in Room Temperature and Superconducting Acceleration Structures, FERMILAB-CONF-08-435-TD.

26 Sjobaek, K.N., Avoiding vacuums arcs in high gradient normal conducting RF structures, PhD thesis, Dept. of Physics, Univ. of Oslo (2016).

27 Nanni, E., The Cool Copper Collider: An Advanced Concept for a Future Higgs Factory, Snowmass Meeting, SLAC (2022).

28 Padamsee, H., RF superconductivity: Science, technology, and applications, Weinheim, Germany: Wiley-VCH (2009).

29 Belomestnykh, S., at el., Highs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology, FERMILAB-FN-1155-AD-PPD-SQMS-TD (2022).

30 Litvinenko, V., at el., CERC – Circular e+e- Collider using Energy-Recovery Linac, https://arxiv.org/abs/2203.07358.

31 Posen, S., at el., Advances in Nb3Sn superconducting radiofrequency cavities toward first practical accelerator applications, https://arxiv.org/abs/2008.00599, (2020).

32 Nassiri, A., at el., Cryogen-free RF system studies using cryocooler-cooled Magnesium Diboride-coated copper cavities, Pro. Of SRF 2013, Paris, France (2013).

33 Tajima, T., at el., MgB2 Thin Film Studies, Proc. SRF2011, Chicago, IL, USA, (2011).

34 Withanage, W., Magnesium Diboride (MgB2) Thin Films on Copper and Silicon for Radiofrequency Cavity and Electronic Applications, PhD thesis, Phys. Dept, Temple University, (2018).

35 Porter, R. D., at el., Progress in Nb3Sn Cavities at Cornell University, NAPAC2019, Lancing, MI, USA, (2019).

36 Guo, X., at el., Fabrication and Radio Frequency Properties od 3-GHz SRF Cavities Coated with MgB2, Journal of Superconductivity and Novel Magnetism, Vol. 34 (2020).

37 Calaga, R., at el., First demonstration of the use of crab cavities on hadron beams, Phys. Rev. Accel and Beams 24 (2021).

38 Nassiri, A., at el., Status of the short-pulse X-ray (SPX_ project at the Advanced Photon Source (APS), Pro. of PAC 2011, New York, NY, USA (2011).

39 Shi, J., at el., A 3-cell deflecting RF cavity for emittance exchange experiment at ANL, NIM A, Vol. 598, Issue 2 (2009).

40 Jensen, E., Increased demand for high efficiency RF power sources, ARIES Workshop on Energy Efficient RF, June 18- June 20, 2019, Angstrom Laboratory, University of Uppsala, Uppsala, Sweden.

41 Ives, R.L., at el., High efficiency, low cost, RF sources for accelerators and colliders, Journal of Instrumentation, Vol. 18 (2023).

42Syratchev, I., Summary of the high-efficiency (HEIKA) day, CLIC Workshop, CERN (2016).

43 Bohlen, H., at el., Inductive Output Tubes for Particle Accelerators, Proc. of EPAC 2004, Lucerne, Switzerland (2004).

44 Nassiri, A., RF Sources for XFELS and ERLS, ICFA Workshop on Future Light Sources, TJNAF, Newport News, VA, USA (2012).

45 Jacob, J, New Developments on RF Power Sources, Proc. of EPAC 2006, Edinburgh, Scotland (2006).

46 Marchand, P., Review and Prospect of Solid-State Power Amplifiers for Particle Accelerators, Proc. of IPAC2017, Copenhagen, Denmark (2017).

47 Teo, K. H., at el., Emerging GaN technologies for power, RF, digital, and quantum computing applications: Recent advances and prospects, J. of Applied Physics 130 (2021).

Optical Stochastic Cooling at Fermilab's IOTA Storage Ring

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The tools and innovations of Accelerator Science and Technology (AST) shape the discovery potential of the accelerator-based science programs that we can envision and execute. Within AST, Accelerator and Beam Physics (ABP) considers both the fundamental and practical limitations of the particle beams that can be produced, maintained and measured. A broad program confronting the "grand challenges" of ABP ensures that existing accelerators are fully exploited, and that the next generation of accelerator designers, operators and scientific users will have a robust portfolio of tools for delivering on frontier science goals. These ABP grand challenges, as identified by DOE-sponsored community exercises [1], include:

- **Beam Intensity** – "How do we increase beam intensities by orders of magnitude?"
- **Beam Quality** – "How do we increase the beam phase-space density by orders of magnitude, towards the quantum-degeneracy limit?"
- **Beam Control** – "How do we measure and control the beam distribution down to the individual particle level?"
- **Beam Prediction** – "How do we develop predictive 'virtual particle accelerators'?"

Fermilab maintains broad R&D programs in AST and ABP using its unique, dedicated accelerator facilities and infrastructure. At the Fermilab Accelerator Science and Technology (FAST) facility, we are executing a variety of research programs that target transformational advances in these grand challenges. Here we describe our ongoing R&D program in Optical Stochastic Cooling (OSC), which addresses Beam Quality and Beam Control and which has recently established a new state of the art in particle-beam cooling while also demonstrating single-particle sensing and control [2]. We also briefly discuss the next phase of the OSC program, which is now underway. This effort seeks to demonstrate high-gain amplified OSC and develop an unprecedented tool for phase-space structuring of circulating particle beams to the ultimate benefit of scientific users in the accelerator-based sciences.

Beam cooling has been an essential element in the design, construction and operation of modern accelerator facilities. For example, one of the cornerstones of beam cooling, Stochastic Cooling (SC), was vital for the success of proton-antiproton colliders. First suggested by S. van der Meer in 1968, SC enabled an accumulation and cooling of the antiproton beams required for the discovery of the W and Z bosons at the CERN SPS in 1983 [3].

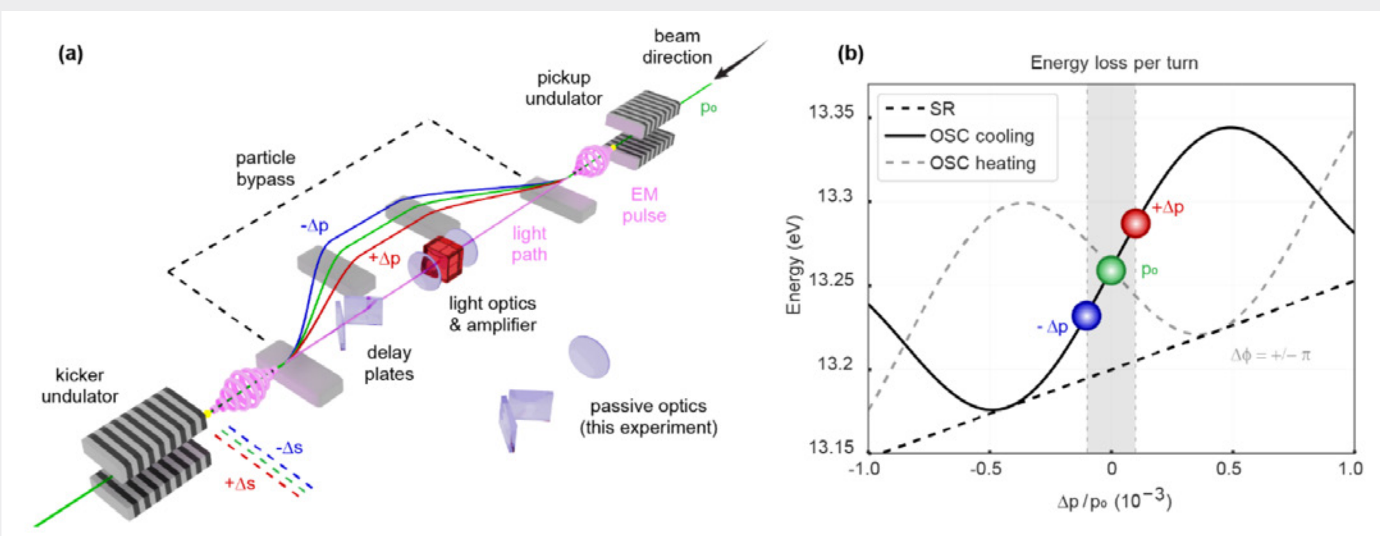

Figure 1. a) Conceptual schematic of a transit-time OSC system. Each particle produces an ultrafast optical pulse as it transits a pickup undulator. A precision magnetic bypass then encodes the particles' phase-space errors onto their arrival time at the kicker undulator. The light pulses are amplified (or not, in the "passive" case) and then focused into the kicker where they exchange energy with the particles that produced them. Precise tuning of the optical delay can produce either cooling (damping) or heating (antidamping) of the beam particles. b) In the passive OSC case, the system corrects each particle's energy loss at each turn based on the particle's phase-space error. The average energy loss is compensated by the storage ring's RF system. After many turns, this results in cooling of the particle beam. Reproduced from Reference [2]

The following year, van der Meer shared the Nobel Prize in Physics for his contribution to the discovery.

In a conventional SC system, circulating beam particles transit an electromagnetic pickup that operates in the microwave regime. The resulting time-varying signals carry information about the phase-space distribution of the beam particles. After proper amplification of this signal, it is used in conjunction with an electromagnetic kicker to make minute corrections to the transverse or longitudinal momenta of the particles. Remarkably, the system is effective in reducing single-particle amplitudes over many passes through the system, even though each particle's cooling signal is buried in the noise of potentially millions of neighboring particles.

The key to this capability is the sufficient randomization of the particle ensemble between passes through the system. In effect, SC comprises a random-sampling process in which, for proper setting of the system gain, the cooling force for an individual particle due to its own signal comes to dominate over the diffusive (heating) contributions of all other particles within the system's temporal response (bandwidth). SC thus bears resemblance to a Maxwell's demon that leverages not just information but also randomness.

F. Caspers and D. Möhl wrote that van der Meer himself initially resisted the entreaties of his CERN colleagues to publish this innovative and ultimately Nobel-Prize-winning concept as he considered the idea, in his words, "too far-fetched…to justify publication" [4]. As an AST innovation, SC has produced a step change in the performance and scientific reach of accelerators. It has been used for beam cooling at the collision energy of a collider, for the production of both stable and radioactive ion beams, for precision measurements in internal-target experiments, and even for the accumulation of antimatter for tests of CPT symmetry and gravity [5-9].

Next, we discuss an extension of the SC concept to optical frequencies and bandwidths. Optical bandwidths greatly reduce the response time of the SC system. The beam structure is then sensed with dramatically higher resolution resulting in a commensurate increase in the achievable cooling rates up to three to four orders of magnitude.

OSC, an extension of SC to the optical regime, was first described in 1993 [10], and one year later, an improved version known as transit-time OSC (henceforth simply OSC) was proposed (Figure 1a) [11]. While the underlying principles of SC remain the same, OSC replaces the microwave elements of SC with optical-regime analogs, such as undulator magnets and optical amplifiers. In OSC, each particle transits a pickup undulator and produces a free-space, ultrafast optical pulse. The beam and light are then separated by a precision magnetic bypass that encodes the phase-space error (e.g. momentum deviations) of each particle onto its arrival time at a downstream kicker undulator. The light pulses from the pickup are sent through a system of optical elements, which may or may not include an optical amplifier, and then refocused into the kicker undulator where they exchange energy with the beam particles. Depending on the exact tuning of the system's optical delay, this energy exchange can produce either cooling (damping) or heating (antidamping) of the beam particles. As shown in Figure 1b, OSC effectively modulates a particle's energy loss per turn based on its phase-space error, which leads to damping in the same manner as conventional synchrotron radiation (SR) damping. In general, even without amplification, the OSC effect can dominate other dynamics in the storage ring, such as SR damping or various scattering mechanisms.

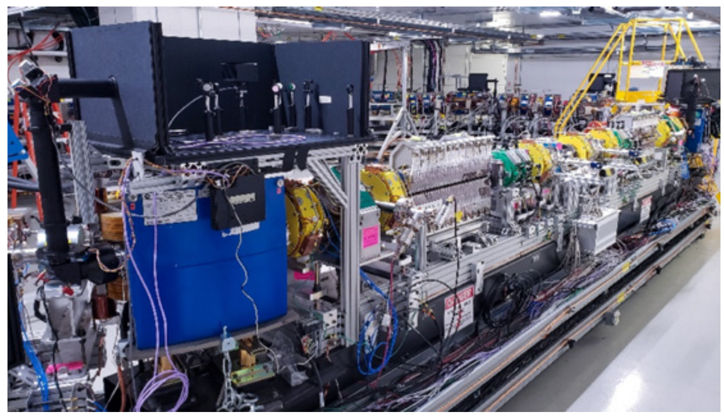

Figure 2. Phase-1 OSC apparatus installed in the IOTA ring at FAST.

The OSC R&D program has been conducted at FAST using the Integrable Optics Test Accelerator (IOTA). IOTA is a rapidly reconfigurable storage ring dedicated to frontier topics in ABP. The OSC program takes a two-stage approach: 1) an initial demonstration of the physics of OSC in a non-amplified configuration, 2) an OSC experiment that includes high-gain optical amplification and advanced beam-control activities.

After three years of planning and construction, and the completion of an extensive conceptual design report [12], the phase-1 experiment was executed in the spring and summer of 2021. Figure 2 shows the integrated experimental apparatus, which occupied the entire length of IOTA's six-meter experimental straight. Due to the short wavelength of the undulator radiation (~1 μm), the OSC systems demanded precise engineering and construction. For example, the integrated system required internal timing stability at the few-hundred-attosecond level, otherwise, the OSC force would be washed out by random fluctuations in the magnetic and optical systems.

On April 20, 2021, OSC was observed for the first time. This achievement marked the first realization of SC in the optical regime and demonstrated a system bandwidth of ~30 THz (FWHM),

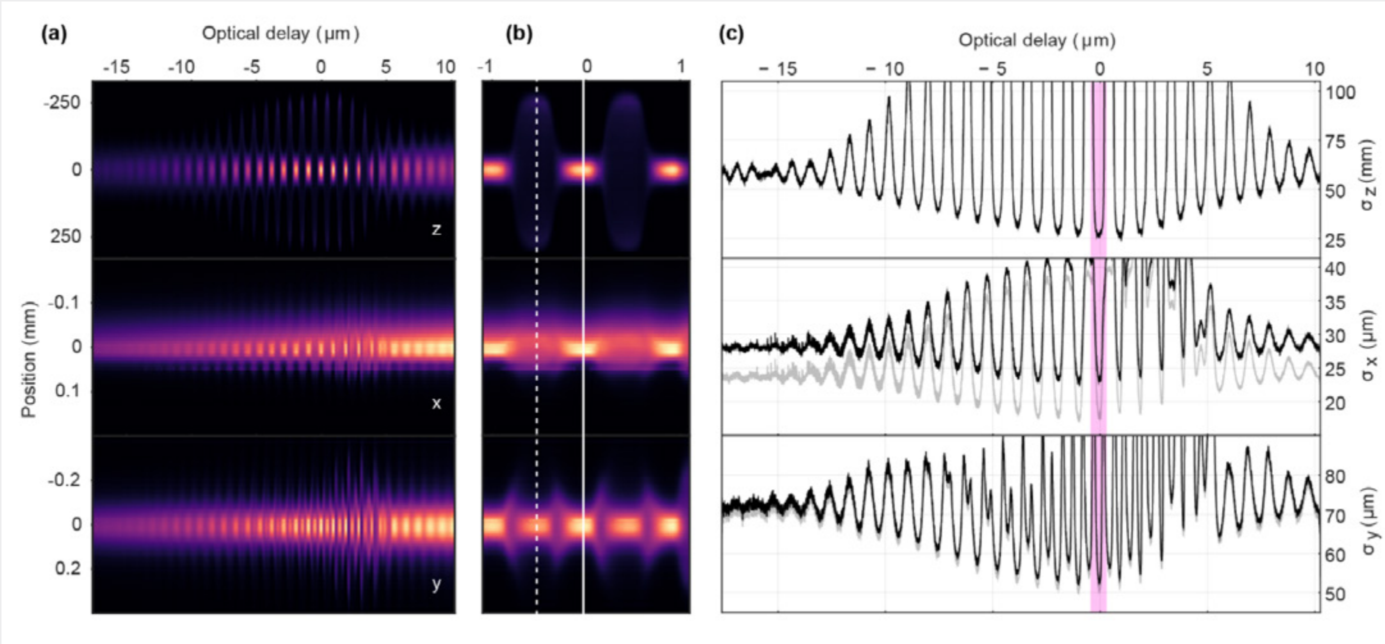

Figure 3. Response of the circulating beam to OSC during a scan of the optical-delay system. a) longitudinal (z), horizontal (x) and vertical (y) distributions of the beam during the scan. b) zoomed view of the strongest OSC zones, showing strong, simultaneous cooling (vertical solid line) in all degrees of freedom. The strongest heating zone is also shown (vertical dotted line). c) rms beam sizes during the scan with the strongest zone highlighted with pink shading. Reproduced from Reference [2].

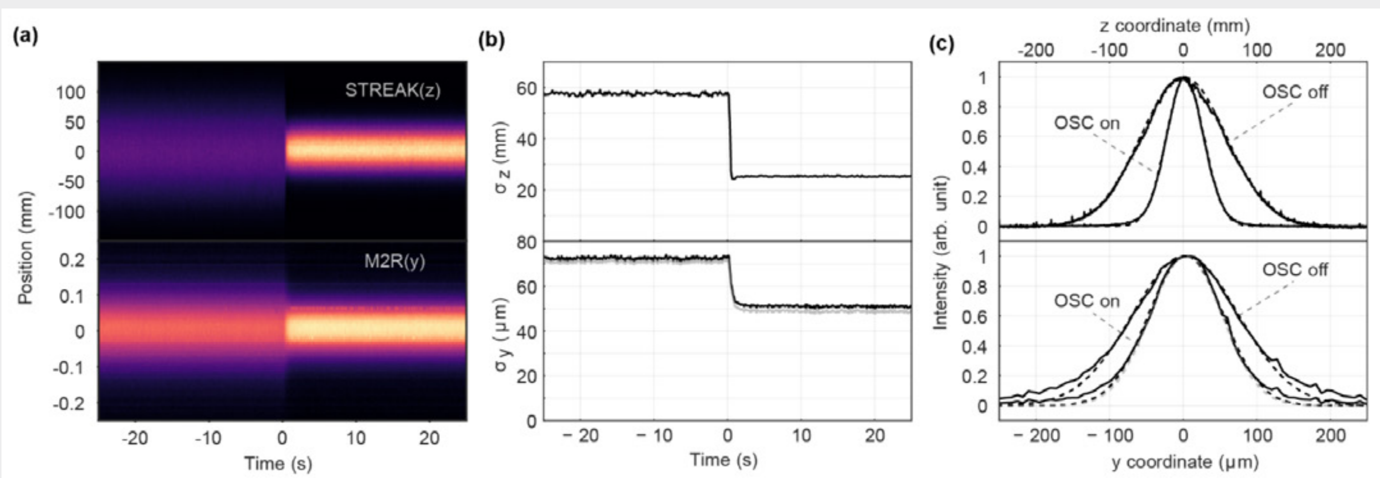

Figure 4. A fast toggle of the OSC system into the maximum-cooling configuration. a) projected beam distributions in the longitudinal and vertical planes during the toggle (t = 0 s); b) rms size of the distributions; c) normalized projected distributions in the OSC on/off cases. Reproduced from Reference [2].

more than 7000-times greater than state-of-the-art microwave SC systems. After tuning and optimization of the system, comprehensive scientific studies of the OSC physics were carried out through the end of August 2021, and the first report of the results appeared the following year in the scientific journal Nature [2].

The flexible design of the OSC system enabled cooling in one, two or three dimensions. Figure 3 presents experimental beam data from a scan of the optical delay system while configured for three-dimensional cooling. Alternating zones of cooling and heating are seen as the phase of the system is continuously swept. The strongest zones are shown in Figure 3b, and the cooling rate of the system can be extracted from the envelope modulation seen in Figure 3c. Figure 4 presents additional data where the OSC system is quickly toggled to its maximum-cooling configuration.

Figure 4a shows the longitudinal and vertical distributions of the circulating 100-MeV electron beam as the OSC system is switched on (t = 0 s). Initially the beam distribution is in its equilibrium state as determined by SR damping and diffusion. When OSC is switched on, the beam is additionally strongly cooled with corresponding decreases in its rms sizes, as shown in Figures 4b and 4c. Though not shown in Figure 4, one can also see the strong antidamping (heating) of the beam, as in Figure 3, when the delay is shifted by 180 degrees relative to the cooling phase(s).

Following the phase-1 experiments with beams, we performed a comprehensive set of OSC experiments with a single electron in both the 1-D and 2-D configurations. IOTA possesses a robust capability to store and characterize individual electrons as they circulate for tens of minutes or even hours at a time. The single electron served as a unique probe of the fundamental OSC physics and enabled observations that were not possible in the beam case. As a particle circulated in IOTA, we detected and timestamped individual photons emitted in IOTA's main dipoles and in the OSC undulators using single-photon detectors equipped with a picosecond event timers.

From this timing data alone, we reconstructed the longitudinal phase-space dynamics of the particle and then measured the evolution of its photon-emission probability (in the undulators), effectively reproducing the theoretical energy-loss curves of Figure 1b, which constitute the underlying mechanism of OSC. With control over the strength, phase and coupling of the OSC system, we were then able to control the photon-emission probability and thereby exert robust phase-space control over the single particle. Beyond any applied considerations, the achievement is very fundamental: an individual relativistic particle made to interact coherently, in a closed-loop fashion, with its own radiation field to affect precise control in phase space. These results are the subject of a forthcoming, dedicated publication.

There is good consistency between the full breadth of the phase-1 experimental data and our expectations from theory and simulations. This provides great confidence towards the design and execution of phase-2 of the program, the amplified OSC experiment. Specifically, this phase targets the development and demonstration of a high-gain (30-40 dB) amplified OSC system and its subsequent use for advanced beam control.

Currently under design, the new OSC system should achieve cooling rates more than an order of magnitude higher than the proof-of-principle system. Additionally, the amplifier system that is being developed will enable turn-by-turn modulation of the system gain. This and other flexibility in the system is being leveraged in a simulation campaign that will in turn serve as the basis for the training of a reinforcement-learning system for advanced beam manipulation. The new experiment will be executed in an upcoming run of the IOTA ring. If successful, the resulting concepts and technologies will set a dramatic new state of the art in the phase-space manipulation of stored particle beams, while also creating a powerful, general tool for accelerator designers and operators.

Summary

The recent demonstration of Optical Stochastic Cooling at Fermilab's IOTA ring constitutes the first realization of a stochastic cooling technology with optical bandwidth. In applicable regimes, it represents a multiple order-of-magnitude step change in the achievable performance for particle-beam cooling. Our experimental validation of the OSC physics, its good agreement with theory and simulations, and our development path towards operational high-gain OSC may enable systems for a wide range of applications, including proton/antiproton bunched-beam cooling in new energy regimes (0.25-4 TeV), and enhanced radiation damping for electron storage rings and ring-based electron coolers, as well as advanced phase-space manipulation.

References

[1] https://science.osti.gov/hep/-/media/hep/pdf/2022/ABP_Roadmap_2023_final.pdf

[2] Jarvis, J. et al., Nature 608, 287–292 (2022).

[3] Van der Meer, S., Science 230 4728, 900-906 (1985).

[4] Caspers, F., Möhl, D., EPJ H 36, 601–632 (2012).

[5] Blaskiewicz, M. & Brennan, J. M., Phys. Rev. ST Accel. Beams 10, 061001 (2007).

[6] Baird, S. et al., Nucl. Instrum. Meth. A 391, 210-215 (1997).

[7] Amoretti, M. et al. Nature 419, 456–459 (2002).

[8] Andreotti, M. et al., Phys. Lett. B 654, 74-79 (2007).

[9] Steck, M. & Litvinov, Y.A., Prog. Part. Nucl. Phys. 115 103811 (2020).

[10] Mikhailichkenko, A. A. & Zolotorev, M. S., Phys. Rev. Lett. 71, 4146 (1993).

[11] Zolotorev, M. S. & Zholents, A. A., Phys. Rev. E 50, 3087 (1994).

[12] Lebedev, V. et al., JINST 16, T05002 (2021).

Simulating Space Weather on Earth using Particle Accelerators

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Introduction

We are entering a new age where our greater presence in space will contribute significantly to the world's economic growth. However, to build such an economy we must understand how to survive in the space environment. Electronics are a critical part of this endeavor. We need communications systems, control systems, life-support systems and much more. Earth's magnetic field and atmosphere will not protect the things we put in space. On the moon, radiation levels are as much as 150 times higher than on Earth [1]. Fortunately, to prepare and understand the risks, we can use particle accelerators on Earth to simulate the conditions in space.

Occasionally, we see the impact of space weather here on Earth. The sun expels huge amounts of material in the form of coronal mass ejections, often called solar proton events (SPE). Such events can send billions of tons of material into space, as well as carry embedded magnetic fields that exceed the background solar wind and interplanetary magnetic field strengths [2]. When these huge clouds of high energy particles hit Earth they disrupt electrical systems and damage satellites and communications systems [3].

Solar protons can also become trapped in Earth's Van Allen Belts, where they can directly affect satellites. In addition, high-energy heavy ions stream into our solar system from many sources. These galactic cosmic rays (GCRs) are composed of the nuclei of atoms blasted into space from supernova remnants and other violent processes outside the solar system [4] (shown in Fig. 1). The combination of SPEs and GCRs can make the extraterrestrial environment very hazardous to anything we send out there.

Extreme space weather can also have significant impacts at sea level and aircraft altitudes — not just in space [6]. When cosmic-ray particles enter the earth's atmosphere, they interact with the elements in the air and produce secondary particles. The atmosphere absorbs most of the charged secondary particles. Neutrons, which carry no charge, penetrate the atmosphere, and can reach sea level. There they can interact with semiconductor devices, causing upsets and failures. Large data centers, supercomputers, communication hubs, autonomous cars and all equipment containing semiconductor devices are vulnerable. At aircraft flight altitudes, where the neutron intensity is 300 times greater than at sea level, the risks are even greater.

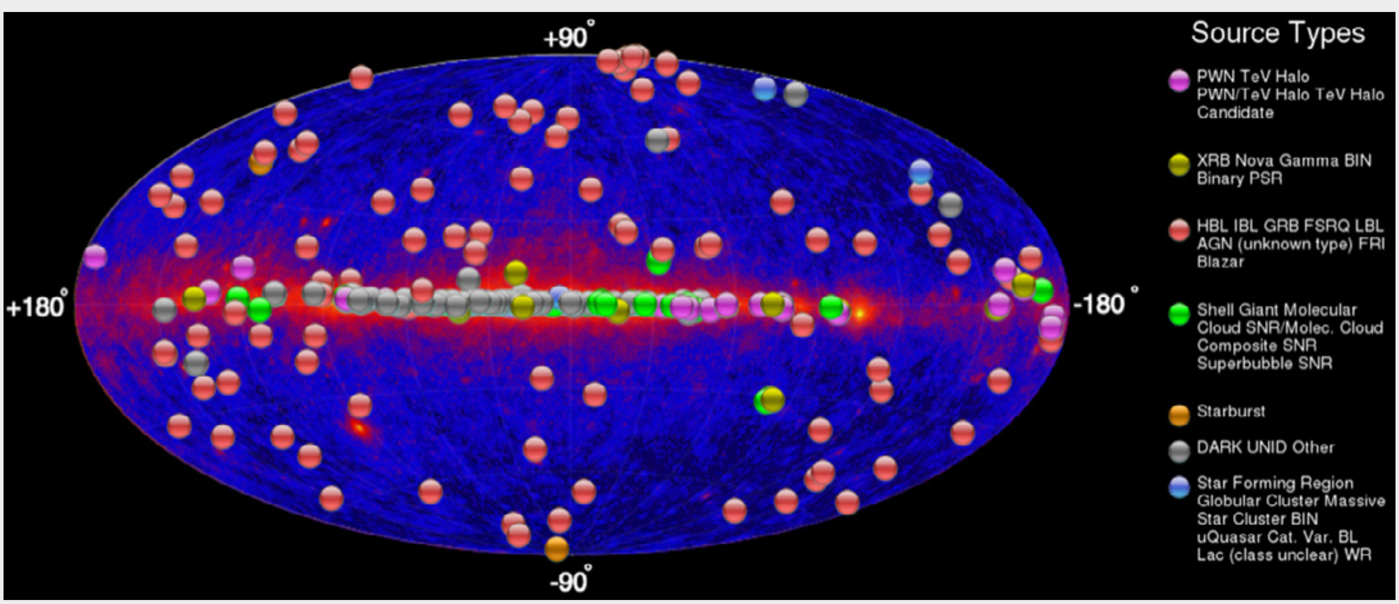

Figure 1: Skymap of high-energy gamma-rays. The dots are from Earth-based observatories. The red central region is from the EGRET skymap, and the blue areas are from the GLAST/Fermi Skymap. We used the TeVCat database to generate this figure [5]. This shows that GCRs are coming from all directions, even from outside our galaxy.

Understanding how these particles and other types of space radiation interact with our electronic systems can help us develop ways to mitigate or protect them from damage [7].

Existing Facilities

Researchers who test and design systems here on Earth have limited options. For a particle accelerator to simulate space weather, it must be capable of reproducing the particle interaction rates and energies that a device in space may experience. An SPE consists of protons with kinetic energies from 10 to 1000 MeV (see [8] for a description of energy scales). A 20 MeV proton penetrates more than 2 millimeters into silicon. Galactic cosmic rays have energies from tens of MeV to extremely high energies, even in the TeV range. The highest fluence is from protons and heavy ions such as iron in the range from 100 to 1000 MeV/nucleon. The peak in this distribution is broad, near 300 to 500 MeV/nucleon. A 100 MeV/nucleon iron ion, with 56 protons and neutrons in its nucleus, will have a total kinetic energy of 5600 MeV. The energy deposited by the ion will scale with Z2, where Z is the ion's charge. This ion will deposit 676 times more energy into the same cross-sectional area of silicon as a 100 MeV proton. A 20 MeV/nucleon iron ion will only penetrate less than 0.3 mm in silicon, or an order of magnitude less than a proton.

There are a handful of places where researchers can test electronics with ion beams at these energies in the United States. The highest-energy ions are available at the NASA Space Radiation Laboratory (NSRL) at the U.S. Department of Energy's Brookhaven National Laboratory. NSRL can deliver heavy ions with energies up to 1500 MeV/nucleon and protons up to 2500 MeV [9]. Researchers most often test at lower energies using beams at the Texas A&M University Cyclotron Institute [10], the Berkeley cyclotron [11] and at Michigan State University [12]. These facilities supply roughly 6,000 hours per year of testing time to a diverse collection of researchers, including from NASA, private companies such as SpaceX and Blue Origin, other U.S. government agencies, and many smaller companies.

The cosmic-ray-induced neutron spectrum ranges over one GeV in energy. To simulate the effects of these cosmic ray neutrons, researchers must use high-power, high-energy accelerators to send high intensity proton beams into spallation targets to produce a broad energy neutron spectrum. The linear accelerator at the Los Alamos Neutron Science Center produces a neutron spectrum designed to mimic the atmospheric neutron spectrum but is 100 times more intense than the sea level neutron flux [13]. Other accelerators at TRIUMF (Canada) and ISIS (England) also use neutrons for testing semiconductor devices.

As we expand our presence in space as well as use more sophisticated electronics in space-based systems, the need for higher energy beams and more facilities for testing will proportionally expand [14].

Requirements For Particle Accelerators

Simulating the space weather environment places strict demands on controlling beam quality (see Fig. 2) and beam delivery. An ideal accelerator would be capable of controlling the energy from below 50 MeV/nucleon to well above 1000 MeV/nucleon — and be able to deliver any ion in the periodic table. From an accelerator point of view, we need to change the energy and ion species very quickly. We also need well-calibrated detection systems to quantify exposure. Samples need to move in and out of the target room with high frequency. Testing in air is preferred, both to make test hardware accessible and to test without modifying the target sample (e.g., removing the lid). Often, experimenters want to test live, with complete systems running as they would in space.

Discussion

There are other ways a researcher can simulate the effects of space radiation on their electronics. They can use lasers to deposit large amounts of energy into a silicon chip. However, this usually requires de-lidding the chip to expose the silicon to the laser.

They can also use high-energy electrons. Using low-energy ion sources, such as the Tandem Van de Graaff accelerator at Brookhaven Lab, is a workable choice — especially if they can supply very high mass ions, such as bismuth or one of the actinides, which can increase the deposited energy density. But simulating with high-energy ions is the closest researchers can come to putting their equipment into the space environment. Full or more complete systems can only be tested when ions have enough energy to penetrate deep into the materials of the device.

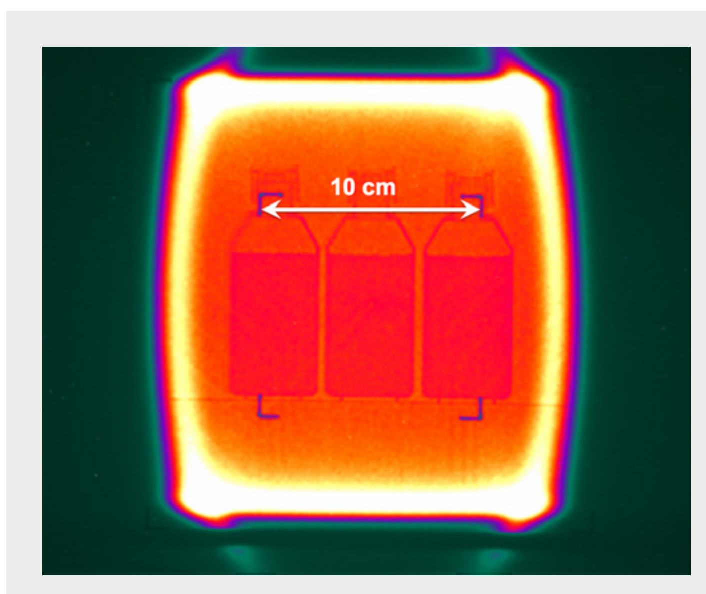

Figure 2. A large uniform beam produced at NSRL. To produce the uniform beam shape, achromatic beam optics include two octupoles that impose non-linear moments to the distribution of particles. Three bottles of water are visible in the image. High energy ions traverse the bottles and then pass through a phosphor screen imaged by a digital camera. The intensity of the radiation field within the exposure region is typically uniform to +/-3%.

Even with all these options, current projections for required testing time exceed availability by over a factor of two [15]. These are short term projections. Longer term needs are difficult to predict, as they depend on the rate of the economic growth in space. The supplies of ion beams for testing are already limited and supporting 20,000 or more hours per year of testing requires not just facilities but trained support staff, engineers and scientists. Building new facilities is the only way to meet the expected need. There are several proposals being developed to increase testing capacity, including a proposed new facility at BNL. These proposals will meet the short-term projected demand and help meet the need for innovation and workforce development that is critical to supporting the future space-based economy.

Acknowledgments

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1. M. Dixit, "How Space Radiation Threatens Lunar Exploration", Smithsonian Magazine, January 18, 2023, https://www.smithsonianmag.com/science-nature/how-space-radiation-threatens-lunar-exploration-180981415/

2. NOAA Space Weather Prediction Center, https://www.swpc.noaa.gov/phenomena/coronal-mass-ejections

3. Why renewed solar storms threaten to destroy more satellites after Elon Musk's Starlink, https://www.cnbc.com/2022/02/09/why-solar-geomagnetic-storms-destroy-satellites-like-spacex-starlink.html

4. European Space Agency, "What is Space Weather?," https://swe.ssa.esa.int/what-is-space-weather

5. This research has made use the TeVCat online source catalog (http://tevcat.uchicago.edu). Wakely, S. P. and Horan, D., "TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy,"International Cosmic Ray Conference, Vol. 3, 2008. https://ui.adsabs.harvard.edu/abs/2008ICRC....3.1341W/abstract

6. "Extreme Space Weather: impact on engineered systems and infrastructure" Royal Academy of engineering, https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf

7. K. LaBel, M. Gates, J. Barth, A. Johnston, P. Marshall, "Single Event Effect Criticality Analysis", Spon- sored by NASA Headquarters / Code QW, February 15, 1996, From NASA Radiation Effects & Analysis report found at, https://nepp.nasa.gov/DocUploads/6D728AF0-2817-4530-97555B6DCB26D083/seecai.pdf, • https://radhome.gsfc.nasa.gov/radhome/environ.htm

8. Wikipedia article, "Electron Volt," https://en.wikipedia.org/wiki/Electronvolt

9. K. Brown, et al., "The NASA Space Radiation Laboratory at Brookhaven National Laboratory: Preparation and delivery of ion beams for space radiation research", Nuclear Instruments and Methods in Physics Research A 618 (2010) 97–107, doi:10.1016/j.nima.2010.02.276, and https://www.bnl.gov/nsrl/

10. Texas A&M University Cyclotron Institute: Radiation Effects Facility, https://cyclotron.tamu.edu/ref/

11. Berkeley Accelerator Space Effects (BASE) facility, https://cyclotron.lbl.gov/base-rad-effects

12. Michigan State University Space Radiation Effects Facilities, https://msutoday.msu.edu/news/2023/msu-to-refurbish-worlds-first-superconducting-cyclotron-for-chip-testing • https://ece.msu.edu/news/new-space-electronics-center

13. Los Alamos Neutron Science Center, radiation effects testing. https://lansce.lanl.gov/facilities/Radiation%20Effects/index.php

14. National Academies of Sciences, Engineering and Medicine 2018. "Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure." Washington, DC: The National Academies Press. https://nap.nationalacademies.org/catalog/24993/testing-at-the-speed-of-light-the-state-of-us

15. Public report from the 2021 Strategic Radiation-Hardened (SRH) Electronics Council (SRHEC), Public Summary from Analysis of Alternatives (AoA) for Domestic Single- Event Effects (SEE) Test Facilities, https://nepp.nasa.gov/workshops/dhesee2021/talks/6a_SEE%20AoA%20summary%20Nov%202020%20approved%20for%20release.pdf

Future Colliders Seminar Series at CERN

Michelangelo Mangano, *CERN*

The discussion of future colliders has occupied the high-energy physics community ever since colliders existed. The main reason being that colliders are a critical and essential element in the progress of our field. Whatever machine is available today, we better start planning for the next ones, given the long time scales and the challenging technological developments required for their realization.

The 2012 discovery of the Higgs boson, by the ATLAS and CMS experiments at the LHC, and the apparent absence of phenomena beyond the Standard Model within the TeV energy range, have set concrete minimal performance targets for the next collider beyond the LHC. The detailed study of the properties of this 125 GeV particle, directly responsible for the observed breaking of the electroweak symmetry and the ensuing generation of a mass for the W and Z bosons and for all known charged fermions, is unanimously recognized as the top priority of the experimental programme, at the LHC and beyond.

The relative lightness of the Higgs has refocused the scope of long-established e+e– projects like the International Linear Collider (ILC) and the Compact Linear Collider (CLIC), and has opened the door to alternative, circular, collider options, like the Future Circular Collider (FCC) and the Circular Electron Positron Collider (CEPC). Innovations in the domain of cold copper acceleration cavities and of superconducting radiofrequency technology have introduced further e+e– linear collider options, the so-called Cold Copper Collider (C3) and the Higgs-Energy LEptoN (HELEN) collider, respectively. The lack of manifest new phenomena around the TeV scale has also shifted the interest in future exploratory machines from the (few-)TeV upgrades of ILC and CLIC, to the multi-TeV regime, only accessible to a future generation of hadron colliders in the 100 TeV domain, or to revolutionary muon-collider facilities in the 10 TeV range.

Each of those projects comes with its own immense technological, financial and sociological challenges. The community of accelerator and particle physicists is diluted among all these lines of research, at a time when just the ongoing running facilities and experiments are keeping everyone fully busy with the optimal exploitation of what is available today. Everyone's desire to stay informed about the progress of all future projects is frustrated by the variety, diversity and complexity of the ongoing developments. So, while the basic motivations for future colliders — and their physics potential — are usually well known, more detailed information about technological challenges and progress, achievements, timelines, etc., is typically confined to internal expert meetings.

To respond to the general interest, and following a similar initiative by DESY (see https://indico.desy.de/category/848/) , a new seminar series has recently begun at CERN, to help the broad community remain informed about progress in the definition of the future projects. The target audience includes personnel from all CERN departments, as well as users and visitors engaged in the ongoing CERN physics programme (LHC, fixed target, theory, etc.). The seminars, typically scheduled monthly, intend to share the exciting developments that are taking place within these projects with colleagues not actively involved in the studies for future colliders. The initial focus is on projects under active consideration at CERN, namely the FCC, CLIC and the muon collider, but attention will be given also to other directions like C3, HELEN and further ambitious technologies such as plasma wakefield acceleration.

Three seminars have taken place so far. The first one, on March 14, was given by Frank Zimmermann, Steinar Stapnes and Daniel Schulte, who presented a general introduction to the FCC, ILC/CLIC and muon collider projects. Over 600 people, in person and on Zoom, followed this successful inaugural event. An extensive discussion at the end touched upon several important aspects common to all projects, such as the long timelines, the optimal strategies and international collaborations or competitions. The second event, on May 5 by Andrzej Siemko and Bernhard Auchmann, offered a complete overview of the high-field magnet challenges present in the planning for future colliders, addressing the status, goals and prospects of the R&D activities ongoing world-wide.

The third seminar on June 20, by Patrizia Azzi and Mogens Dam, introduced the challenges posed to the design of detectors for future linear and circular e+e– colliders, presenting the performance targets set by the physics programme, the current design proposals and the opportunities offered by the rich ongoing technology R&D efforts. A further lecture, focused on detectors for a future muon collider and for the FCC-hh hadron collider, will occupy the fourth seminar, to be scheduled after the summer.

Future seminars in the series will address the environmental issues faced by the construction and operation of future colliders, the civil engineering challenges, the status of the geological exploration and of the studies to identify the ideal FCC accelerator layout in the light of the multiple constraints posed, on the surface, by the environmental, territorial and urbanistic impact. Regular updates on the development of the physics opportunities, the progress with the technological challenges for accelerator and detector designs, as well as reviews of the projects under discussion in other laboratories, will keep the seminar series active for a long time to come!

All seminars are held in person, with webcast and Zoom transmission. The slides and video recordings are available on Indico at the url https://indico.cern.ch/category/16478/. This material provides a unique resource to bring newcomers up to date with the latest developments. Information about forthcoming seminars is distributed through a dedicated mailing list, which everyone can subscribe to through the link https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=Future-Colliders-seminars. The seminar organizers (Martin Aleksa, Jenny List, Michelangelo Mangano, Daniel Schulte, Steinar Stapnes and Frank Zimmermann) will welcome your feedback on the seminars programme!

Future Circular Collider Feasibility Study—Midterm Review

Michael Benedikt and Frank Zimmermann, *CERN, Geneva, Switzerland*

The Future Circular Collider (FCC) Feasibility Study (FS) was launched by the CERN Council (see CERN/3566 [1] and CERN/3588 [2]), in response to the 2020 Update of the European Strategy for Particle Physics (ESPP) [3]. The FCC FS is expected to deliver a Feasibility Study Report (FSR) by the end of 2025. A "mid-term review" is scheduled for autumn 2023. The entire FCC governance structure (members of the Steering Committee, Collaboration Board, Scientific Advisory Committee and Coordination Group) was established by summer 2022.

In early 2023, a lowest-risk implementation baseline was finalized, with a circumference of 90.7 km. Meetings have already been held with the 41 municipalities concerned in France and Switzerland; see Fig. 1. Environmental studies and preparation of geological investigations (drillings and seismic investigations) are ongoing since February 2023.

Civil engineering has made significant advances, resulting in a complete 3D model for the underground structures, a full set of 2D drawings and preliminary representative designs for both the experimental and technical surface sites. Figure 2 shows example images of an FCC-ee technical surface site developed by Fermilab.

A CERN press release in February 2023, which had been prepared together with the Swiss and French authorities, informed about the Feasibility Study and its organization. This was followed, in April, by a press visit at CERN organized for local media. In total 11 journalists participated in this visit, which resulted in 90 press clippings, not only in the local area, but covering 31 countries.

An electrical powering concept for the FCC has been defined, together with the French high-voltage electricity grid operator RTE. Road accesses were identified and documented for all 8 surface sites. Four possible highway connections, which could be used for materials transport, were defined. The total length of new roads required at the departmental road level is less than 4 km.

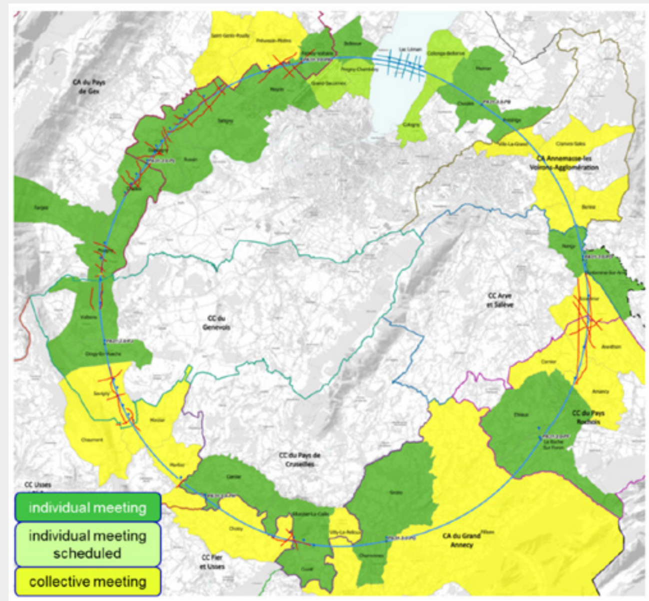

Figure 4. Meetings of the FCC study team with the municipalities concerned in France (31) and Switzerland (10).

The layout of the FCC-ee superconducting radiofrequency (RF) systems has been modified. The RF systems for collider and booster are now installed in the separate straight sections H (collider) and L (booster), also with fully separated technical infrastructure systems, such as cryogenics. The collider RF, with the highest power demand,

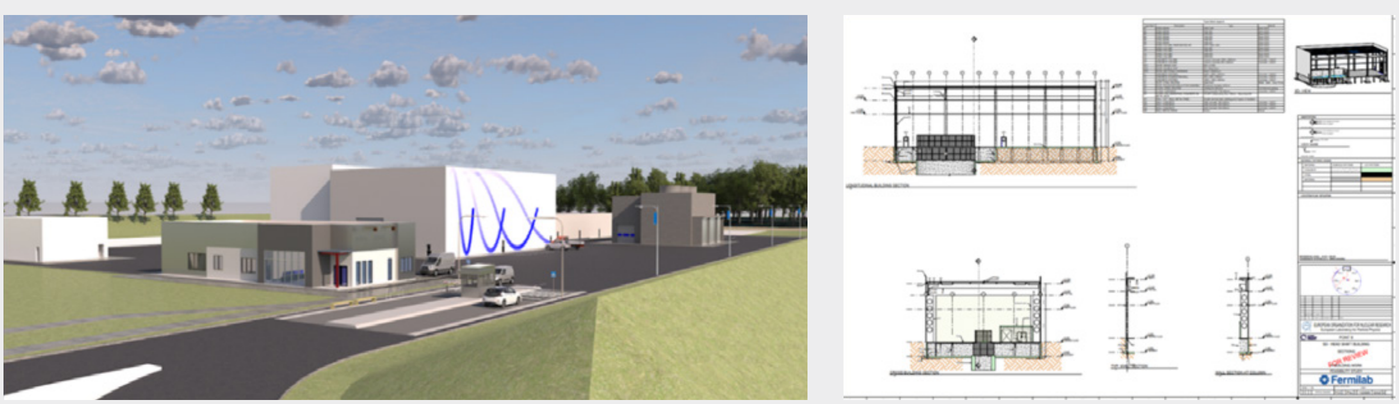

Figure 2. FCC-ee surface site developed by the Fermilab team.

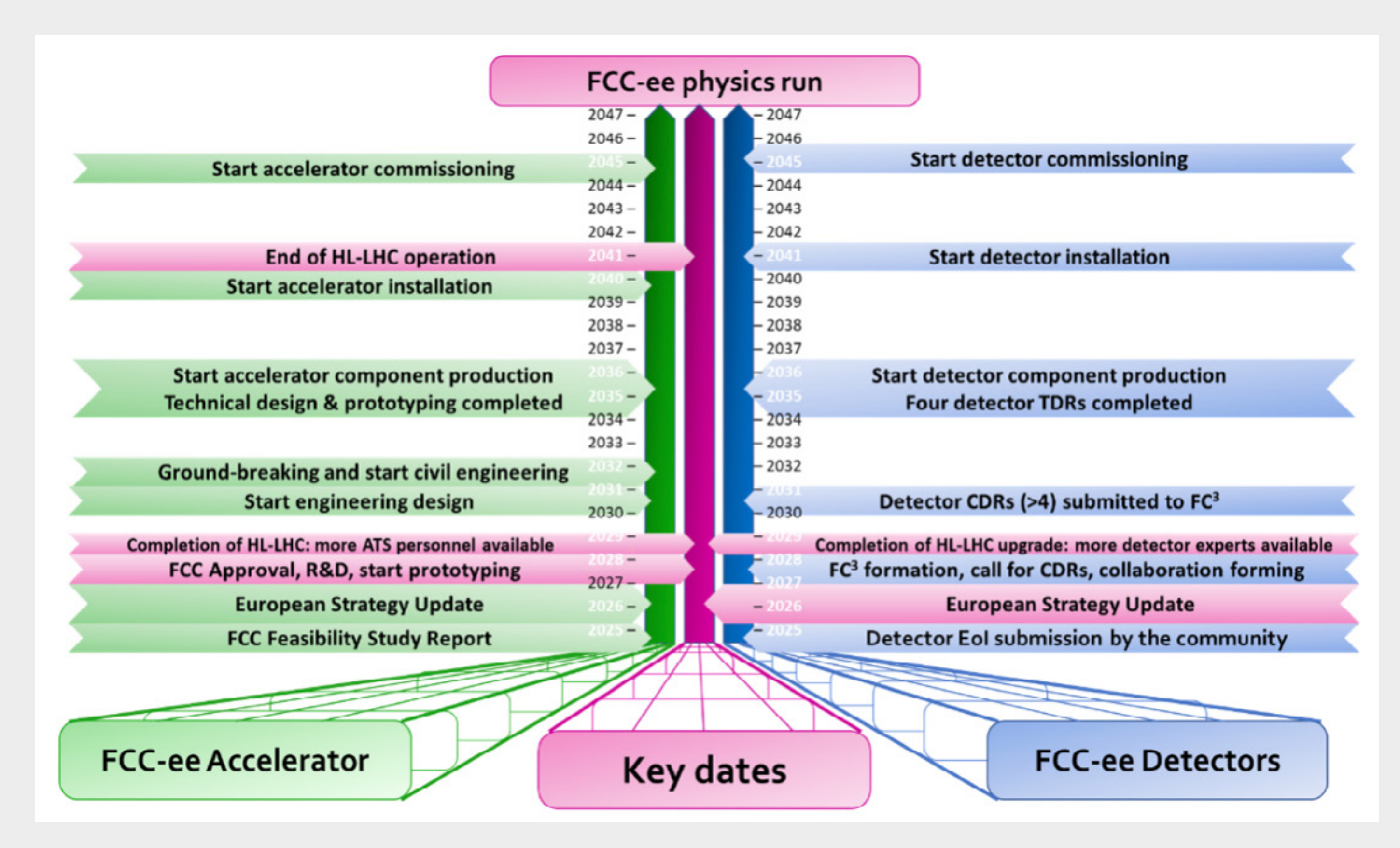

Figure 3: Tentative timeline from today to start of FCC-ee physics in the second half of the 2040s.

is now located in point H for an optimum connection to the existing 400 kV grid line and with a more suitable surface site.

Figure 3 presents a tentative timeline for the FCC project, FCC-ee accelerator and detectors, till start of physics operation.

In addition to the baseline operation sequence starting on the Z pole and, with increasing beam energy, followed by WW, ZH and ttbar, an alternative operation and RF staging sequence has been developed, which begins at the ZH production peak. Either sequence extends over a total of about 16 years, including 5 years of operation.

Collaboration with U.S. laboratories and universities is desired in all areas of the FCC Feasibility Study. This includes, for example, the development of superconducting radiofrequency cavities and cryomodules as a key technology for the FCC-ee, especially high-Q 5-cell bulk Nb cavities at 800 MHz, which could build on the unique U.S. experience with recent projects, such as LCLS-II and PIP-II.

Numerous synergies also have been identified with the EIC project, whose electron storage ring parameters are quasi-identical to — or even more challenging than — those of FCC-ee.

The FCC Week 2023 was held in early June. It attracted 473 expert participants, with a growing share of young scientists. London proved a highly appropriate place for many intriguing talks and discussions. This event significantly sharpened and cemented the case for the FCC, which became clear in the talks of the CERN DG Fabiola Gianotti, the CERN Council President Eliezer Rabinovici and the STFC Executive Chair Mark Thomson.

In conclusion, the first half of the FCC Feasibility Study will soon be completed with the mid-term review in the fall of 2023. Topics addressed in this midterm review include placement and territorial aspects; technical infrastructure; accelerator design for both FCC-ee and FCC-hh; physics, experiments, detectors; organization and financing; environmental impact; socio-economic impact; and a cost update.

Participation of US experts in all aspects of the Feasibility Study is increasing and highly welcome!

References

[1] Restricted Council, Organisational Structure of the FCC Feasibility Study, CERN/ 3566/Rev.2 (2021)

[2] Restricted Council, Main Deliverables and Timeline of the FCC Feasibility Study, CERN/3588 (2021)

[3] European Strategy Group, 2020 Update of the European Strategy for Particle Physics, CERN-ESU-013 (2020)

The Upgrade of Advanced Light Source Will Provide High-Brightness Soft X-Ray Beams to the Synchrotron User Community

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Light Source Facilities Serve Science Users

The Advanced Light Source (ALS) will soon undergo a major upgrade to provide fully coherent soft x-ray capabilities to the synchrotron user community, thirty years after it first saw light. The science user facility, operated by the U.S. Department of Energy and hosted at Lawrence Berkeley National Laboratory, currently boasts 40 beamlines operating in the soft x-ray regime (100 eV–2000 eV), serving over 2,000 users annually who seek to take advantage of the high resolution and elemental sensitivity of the x-ray beam. To meet the demands of exacting scientific experiments, light source facilities worldwide are undergoing diffraction-limited storage ring (DLSR) upgrades and entering the realm of the 4th-generation synchrotron light source.

Fourth-generation light sources

Fourth-generation light sources feature a very narrow (low emittance) electron beam that can produce nearly diffraction-limited synchrotron radiation, resulting in very bright, mostly coherent, x-ray light. This category includes synchrotrons with diffraction-limited storage rings, which produce an effectively continuous stream of coherent photons to a vast array of beamlines, and X-ray Free Electron Lasers (XFEL) that produce femtosecond x-ray pulses, such as LCLS-II at SLAC National Laboratory.

To reduce the beam emittance at the ALS to 70 pm.rad, two significant modifications of the original design have been implemented: the addition of an accumulator ring to enable on-axis injection of a diffraction-limited beam into the storage ring, and the use of multi-bend achromats in the storage ring, which guide the beam more gently and maintain a low emittance. The beam will consist of 100 ps bunches at 500 MHz with a storage ring energy of 2.0 GeV (up from the current 1.9 GeV), while maintaining a ring current of 500 mA. The upgrade also involves a seismic retrofit in anticipation of groundbreaking science emerging from the enhanced facility.

The ALS has commenced the upgrade, with the phased installation of the accumulator ring during maintenance periods. The storage ring will be replaced all at once over a year, starting in Summer 2026, during which the facility will be closed to users. During this downtime, four new insertion device beamlines, optimized to harness the increase in brightness, will be constructed and commissioned: COSMIC-U (Coherent Microscopy), MAESTRO-U (Angle-Resolved Photo-emission Spectroscopy with Nanometer Resolution), FLEXON (Fluctuation and Excitation at the Nanoscale), and Tender (coherent imaging and scattering in the Tender x-ray regime).

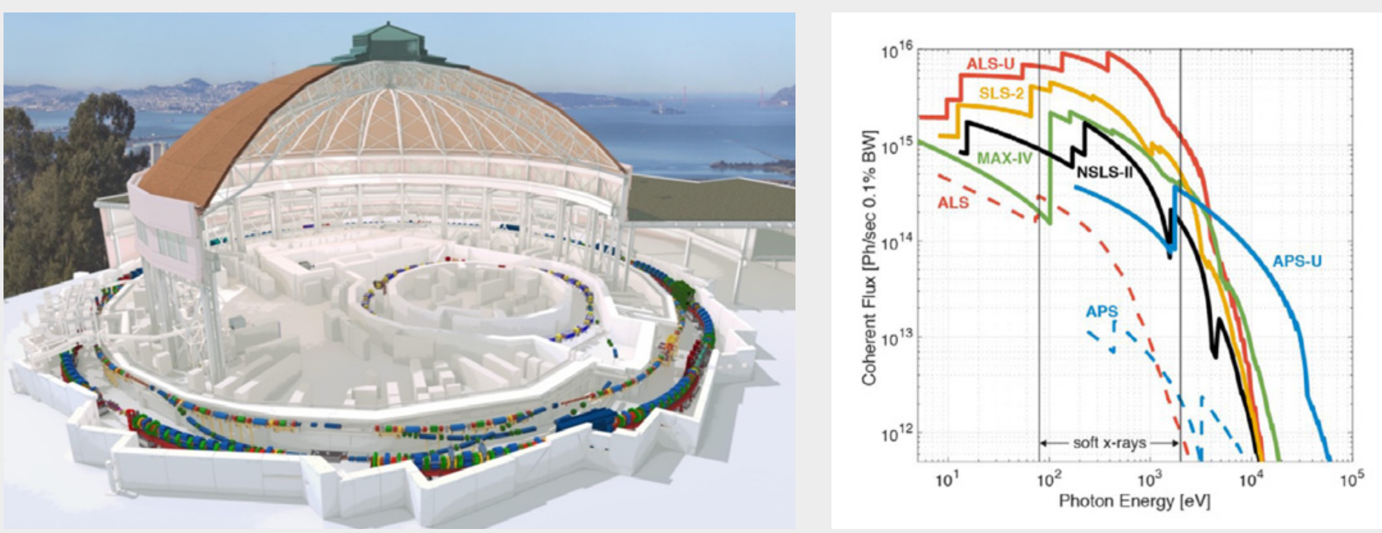

Figure 1. Advanced Light Source Upgrade. Cut-out (left) of the Advanced Light Source showing the accumulator ring and the storage (right) comparison of coherent flux between third- and fourth-generation facilities.

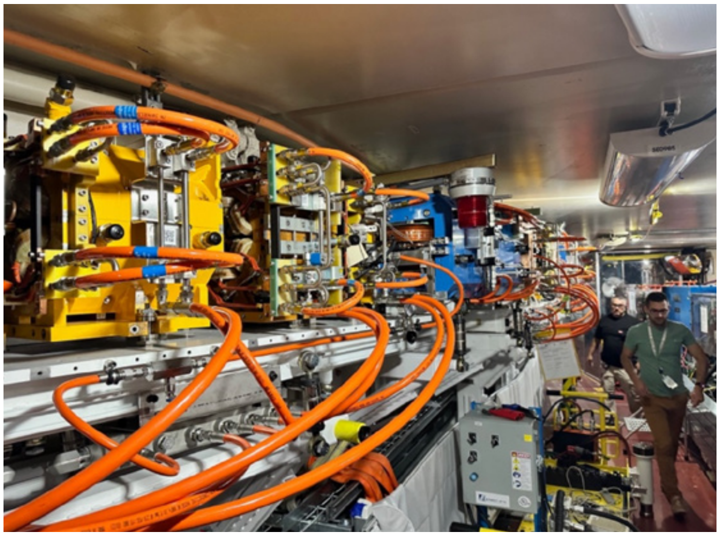

Figure 2. First full arc sector of the accumulator ring installed in the ALS tunnel (October 2023; Credit: Steve Rossi, ALS).

Coherent x-ray optics

After the upgrade, the electron beam in straight sections will be almost circular, with sizes of 12 um-rms x 6 urad-rms, both horizontally and vertically. This beam will then enter insertion devices (arrays of magnets), where the electron undergoes oscillations and produces x-ray light with adjustable photon energy. The intrinsic photon beam size for a 4-meter insertion device at 1 keV (1.25 nm wavelength) is 15 um-rms x 12 urad-rms, making it slightly larger than the originating electron beam. This dimension renders the photon beam almost fully coherent, nearing the maximum allowed by physical laws (>50% partial coherence below 1 keV).

To maintain beam quality, new technologies such as cryo-cooled mirrors and x-ray adaptive optics have been explored and adopted. All new beamlines will feature advanced x-ray wavefront sensors, deformable mirrors and the capability to use adaptive optics for aberration correction. Consistently achieving such performance levels during user operations necessitates the creation of automated alignment procedures. These build upon new instrument controls like Bluesky, developed collaboratively by various U.S. light-source facilities.

This augmented coherence will empower the most demanding imaging experiments to achieve resolutions better than 5 nm without photon loss. At present, coherence filters required to attain such resolutions reduce the flux by over 100 times. The heightened brightness will facilitate high-speed imaging and permit in-situ/in-operando experiments at the microsecond scale. These experiments, coupled with the elemental sensitivity of soft x-ray, will enhance our understanding of material chemistry. The ability to shape the light through wavefront engineering and reveal phase contrasts in sample for extreme sensitivity.

The facility will not only act as a more potent tool, allowing scientists to delve deeper into matter and develop innovative medications, such as treatments for COVID-19, but it may also pave the way for novel methods to manipulate matter. The ALS played a pivotal role in advancing extreme ultraviolet photolithography, a technique integral to crafting the most advanced microchips. It might further push the boundaries of Moore's Law towards the soft x-ray domain, and also help researchers to craft next-generation materials with bespoke properties.

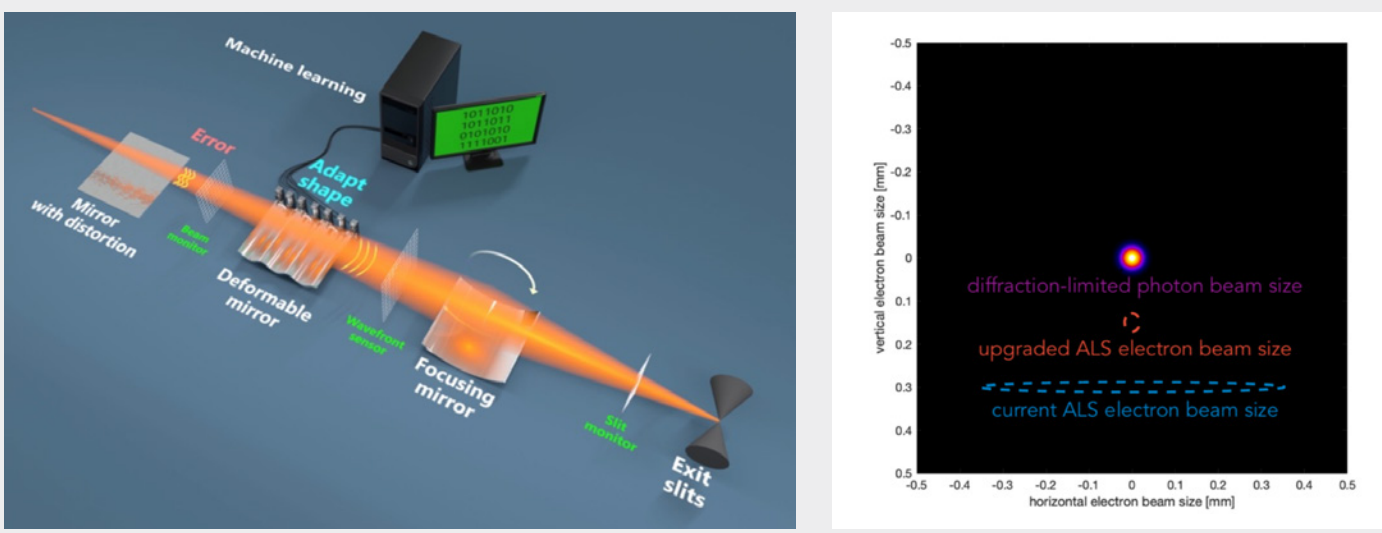

Figure 3. Comparison (left) of electron beam size for ALS and ALS-U, and natural photon beam size. Development (right) of x-ray adaptive optics and advanced controls to ensure optimal performance of the new beamlines.

The ESS Project and Linac Beam Commissioning

Mamad Eshraqi *for the ESS Project*

The ESS project

The European Spallation Source (ESS), undergoing concurrent installation, testing and beam commissioning in Lund, Sweden, will be the brightest source of cold neutrons once the driving proton linac reaches the intermediate energy of 800 MeV and a power of 2 MW.

The ESS has as the final goal to deliver a 2 GeV beam of protons with an average power of 5 MW to the target. The high brightness of the neutron source is achieved by optimization of the rotating tungsten target and the innovative butterfly neutron moderator. The high beam power of the linac demands high-quality beam production, efficient acceleration and near-lossless transport of a high current beam. All of these impose challenging requirements on the design and beam commissioning of this machine.

The linac is being commissioned in several steps. This paper will describe briefly the instrument types and their expected performance, how the neutrons are generated in the target and moderated, and eventually the high-power linear accelerator and some of the commissioning results.

Instrument suite

The European Spallation Source is a next-generation neutron source that will deliver neutron fluxes 10-100 times higher, than existing facilities to the different instruments. The instrument suite at ESS which is currently under construction for the user program is composed of 15 state-of-the-art instruments which can be broken down into four categories: Diffraction, Spectroscopy, Engineering and Industrial, and instruments tailored for Large-scale structures [1].

These will enable probing much smaller samples than what is achievable today in a reasonable duration. For example, the NMX instrument, a macromolecular diffractometer at ESS, is capable of collecting diffraction data from a crystal of 0.1 mm3 (~0.5x0.5x0.5 mm3) with a unit cell dimension of < 150 Å within a day with 2 Å resolution and >90% completeness.

The development of the instruments and their support infrastructure is a result of strong community involvement via in-kind contributions and collaboration, and their success is possible through long-term connection to the neutron science community,

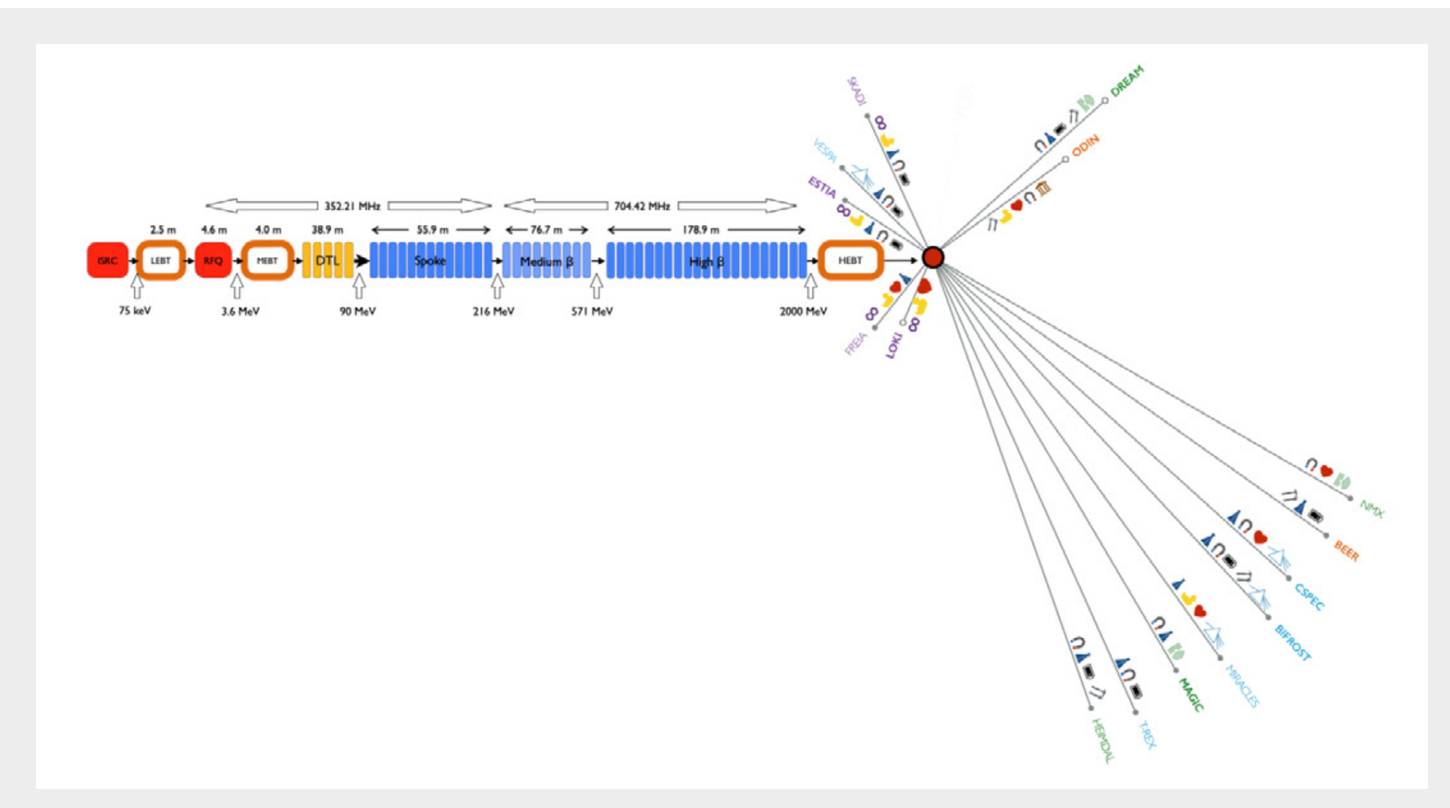

Figure 2: Block diagram of the ESS accelerator and instrument suite.

Figure 2. A view of the NMX neutron guide line (being installed) and other neutron guides, and the bunker (blue structure).

engagement with the users and the high brightness flux of cold and thermal neutrons from the target.

Target

ESS uses a rotating tungsten target. It has 36 sectors, and its rotation is synchronized with the incoming proton beam from the linac, i.e. each sector is exposed to a new pulse of protons coming at 14 Hz, resulting in a target rotation frequency of ~0.4 Hz. Around 7000 rectangular blocks of tungsten, each of them almost the size of two small matchboxes attached head-to-head, with a total mass of ~4 tons are used as the spallation material.

The target wheel itself is made of stainless steel, has a diameter of 2.5 m, and hangs from the rotation mechanism using a 7 m tall shaft. The shaft and the wheel also form the enclosure where the gaseous helium is circulated to cool the target during operation.

At the final energy of the linac, 2 GeV, each proton can release up to 50 fast neutrons. The design allows for one moderator-reflector system to be aligned above and one below the neutron production zone of the target. The ESS's butterfly moderator design is a low-profile moderator (height of 3 cm) made of aluminum enclosed within the beryllium reflector. The moderator being installed is shaped as a pair of triangles with round corners pointing at each other, separated by an "X" shaped volume, hence the name butterfly [2]. The next generation of the design has the two butterfly wings connected in the middle and has instead the water moderator separated in two.

The two triangles are filled with liquid hydrogen at 20 K with hydrogen molecules at their ground states (parahydrogen) and make the source of cold neutrons and the "X" shaped enclosure in the center is filled with water and is the source of thermal neutrons. The reflector has openings leading to neutron beam lines and each

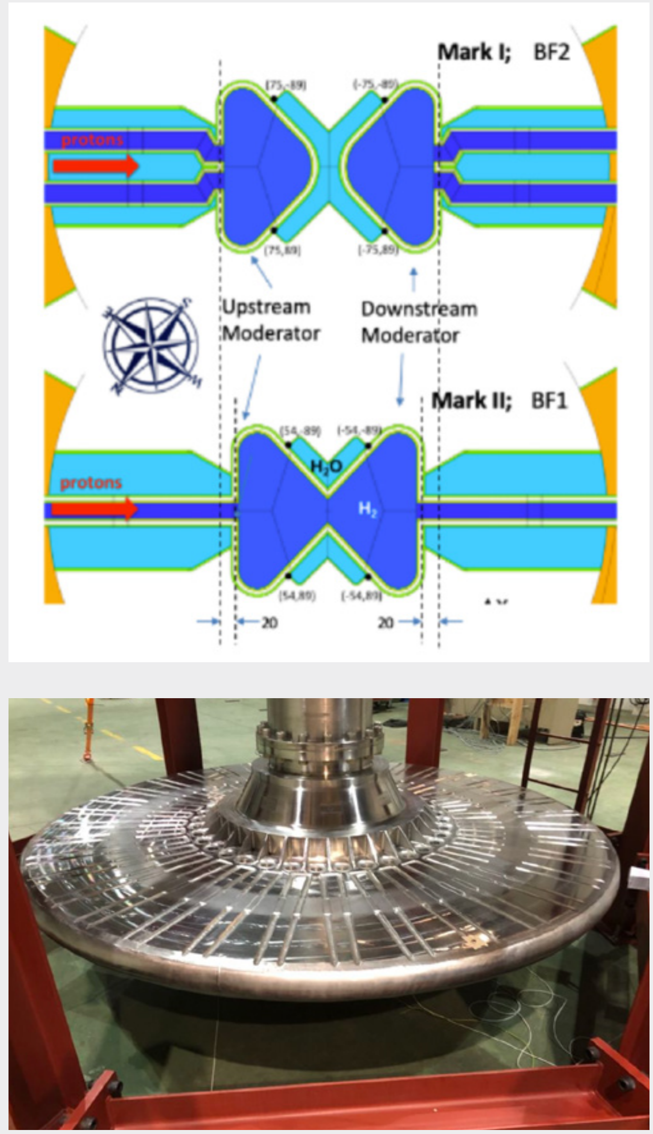

Figure 3. Neutron moderator design of the ESS (top) and the target wheel in the transport structure (bottom).

instrument can decide whether they are looking at the source of thermal or cold neutrons.

The target monolith encapsulates the target wheel, moderator and reflector plug, and several other systems including 6000 tons of steel shielding. The monolith keeps the target under a low vacuum; it has room for up to 42 double-decker neutron beam line penetrations and a penetration for the incoming high-current proton beam. The proton beam port is sealed with an actively cooled proton beam window that keeps the vacuum of the accelerator separated from that of the target.

Accelerator

The rotating tungsten target wheel is painted by a beam of protons of up to 62.5 mA in pulses of 2.86 ms long at 14 Hz, coming from the ESS linac [3]. The linac is composed of a normal conducting front end, which at 89 MeV injects the protons to the superconducting linac (SCL) that accelerates the protons further to 2 GeV.

The front end consists of the following systems:

- A microwave discharge ion source delivering pulses of +70 mA protons with a flattop of ~3 ms on a 75 kV platform, a low energy beam transport (LEBT). The ion source and LEBT are in-kind contributions (IKC) from INFN-LNS, Catania, Italy, and were commissioned initially in Catania [4] and in late 2018 in their final location at ESS [5].
- A four-vane radio frequency quadrupole (RFQ) with a frequency of 352.21 MHz and a final energy of 3.62 MeV. This is an IKC from CEA, Saclay, France. It was assembled, tuned and conditioned in the linac tunnel in 2020 and was commissioned with beam in late 2021 [6] with a transmission that exceeded 94% for a full current beam, similar to the expectations based on the simulation.
- A medium-energy beam transport (MEBT), that is composed of 3 bunching cavities, 11 quadrupoles with integrated corrector magnets. The MEBT is equipped with a chopper, collimating and diagnostic devices. It is an IKC from ESS-Bilbao, Bilbao, Spain. The MEBT, up to the Faraday Cup in the middle of it, was commissioned simultaneously with the RFQ.
- A five-tank drift tube linac (DTL), using permanent magnet quadrupoles in a FoDo lattice is an IKC from LNL-INFN, Legnaro, Italy. It was assembled and tuned at a dedicated workshop at ESS and later conditioned in situ. The beam commissioning of the DTL tanks is happening in three steps: the first step, where the beam was stopped at the end of tank 1 at ~21 MeV, was completed in the first half of 2022 [7], the second step, where the beam is accelerated in four out of five tanks, was completed in July 2023 [8], and the third step will be beam through all the DTLs during the SCL commissioning next year.

The SCL includes three families of superconducting cavities made of bulk niobium, cooled by helium which is fed to each cryomodule from a cryo-distribution line distributing helium at 4 K. This will be further cooled down to 2 K at the jumper connection (Spoke) or in the cryomodule (ellipticals), as IKCs from IJC-Lab, Orsay, France, and Wroclaw University of Technology, Poland:

- Thirteen cryomodules housing the 26 double-spoke cavities with a β_{opt} of 0.5 and an accelerating field of 9 MV/m will bring the energy up to 216 MeV. These are part of the IKC from IJC-Lab, Orsay, France. The spoke CMs are initially tested at Freia-lab, Uppsala, Sweden, and are now shipped to ESS ready to be installed following the successful pilot installation of the first spoke cryomodule in the tunnel.
- Nine medium beta elliptical cryomodules (IKC from CEA) will accommodate 36 six-cell elliptical cavities (IKC from INFN-LASA, Milan, Italy) with a β_{geo} of 0.67 and an accelerating field of 16.7 MV/m. There is a frequency jump to harmonic two starting at the elliptical cavities. A higher geometric beta helps in the overall energy gain and efficiency while keeping the phase advance variation smooth. These CMs are tested in a dedicated test stand at ESS; one has gone through successful pilot installation and the rest are waiting to be installed in the tunnel.
- Finally, 21 elliptical CMs, fitted with 5-cell high beta cavities with a β_{geo} of 0.86 and an accelerating field of 19.9 MV/m, will increase the beam energy from 571 MeV at the end of medium beta to 2 GeV. The cavities and cryomodules are IKCs from STFC, Daresbury, UK, and CEA, Saclay, France.
- A high energy beam transport, HEBT, is delivering this beam to the target or a line-of-sight dump, an IKC from ESS-Bilbao, Spain. The HEBT also contains a contingency area for future upgrades. The beam on the dump is only defocused and the beam on the target is both expanded and rasterized to generate a near-uniform rectangular footprint on the target, the rasterizing relies on 8 dipoles (4 horizontal and 4 vertical) powered by triangular waveforms with a main frequency of 40 kHz and up to the 5th harmonic (200 kHz).
- All the quadrupoles, correctors and dipoles downstream of the DTL are an IKC from Elettra, Trieste, Italy, and are assembled on the linac warm units at STFC. The raster magnets are an IKC from Aarhus University, Denmark.

All the power converters, RF equipment, controls, and electronics are located in a separate gallery (Klystron gallery) which is connected to the accelerator tunnel via 27 stubs, each with two 90° bends to attenuate the radiation from the prompt radiation caused by beam loss to less than 3 μSv/h in the Klystron gallery. Synchronization of events across the facility is performed using a global timing system that uses an event generator (linked to a GPS signal). A set of event receivers and fanout modules takes care of the distribution of trigger events, clock signals across the facility, timestamping of the events, actions and data, as well as broadcasting of beam-related parameters with deterministic latency.

Beam dynamics

The lattice design of the ESS linac has been developed through iterations to both fulfill the engineering limitations and meet the demanding high-level requirements, while not compromising beam quality. Optimizations were focused on maximizing the acceleration efficiency and thus minimizing the energy consumption, length and cost of the linac, while staying within the aforementioned constraints and maintaining beam quality and reliability of the entire machine. In this way, the lattice design is a balancing act among requirements, ideals of beam physics and engineering and financial constraints.

Figure 4. The Drift tube linac (top) and the Spoke cryomodules being installed (bottom).

The availability of the facility is one of the high-level requirements. This calls for, amongst others, scheduled and non-scheduled maintenance of the accelerator. Hands-on maintenance of a proton linac sets an upper limit of 1 W m−1 for the uncontrolled losses in the linac, i.e. in the order of 10−7 with respect to the total beam power.

This sets a tight requirement on the population of the particles in the beam halo. The main sources of halo generation are mismatches, high space charge and tune depression, nonlinear fields, as well as small longitudinal acceptance which results in particles falling off the accelerating bucket. To avoid generating beam halo, we set limits on the phase advance (strength of the focusing force), its continuity and smooth variation as well as the tune depression (ratio of phase advance with space charge to zero current phase advance).

The superconducting section of the ESS linac is designed to distribute the defocusing effect of space-charge forces equally among the three planes (i.e. equal tune-depression) in contrast to equalizing the product of emittance and phase advance (i.e. equipartition design) that would discriminate one or several planes in favor of the other ones if the emittances are not equal [9].

Beam commissioning

The linac was designed to allow staged beam commissioning using in-line beam diagnostics due to the ambitious project schedule aiming to expedite the start of the user program. Beam modes with upper limits on beam current, pulse length and repetition rate were defined to enable designing compact beam stops, cross-checking of beam parameters vs interceptive device limits using the Machine Protection System (MPS), and limiting the potential damage risks during early beam commissioning stages, e.g., first beam threading is done using a Probe beam (6 mA, 5 μA, 1 Hz).

The Production beam can only be sent to the targe and to the Faraday Cup in the LEBT. Simulations and measurements were benchmarked for several systems, including but not limited to Ion source high voltage, RF power and gas injection optimization, cavity tuning, transverse profile measurement and emittance reconstruction and initial Twiss parameters.

In parallel, the beam as the final integrator of the systems, has enabled integrated (vertical) testing of the systems, resulting in debugging, synchronization, cross-talk minimization and general improvements of the systems, paving the way for sending the beam to the target.

Energy and Sustainability

In the bid made by Sweden to host the facility, ESS committed to applying an Energy Management Strategy "in order to minimize costs, lower the environmental impact and factor out the variability in energy" (ESS Scandinavia Secretariat 2008). This commitment has led to several design choices, repercussions and implementations at ESS and its host city, Lund [10].

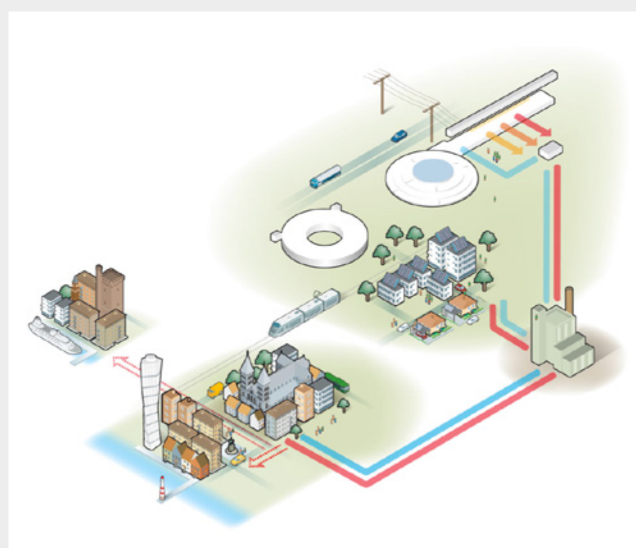

Figure 5. Schematics of the heat recovery.

Probably the main energy-saving measure is heat recycling, the excess heat at ESS is removed at low, medium and high temperatures (~8-16°C, ~25-31°C, and ~45-55°C respectively), depending on the cooling needs and operating temperature of the components. Using skids, heat pumps and heat exchangers, the excess heat from the primary circuit (not in touch with beam line components) is transferred to a circuit connected to the local district heating. The annual energy savings due to this single change at full power operation is 160 GWh, a significant value both environmentally and financially*. Some of the other measures are transition energies between different accelerator sections, the operating temperature of components, the choice of transition energy from normal conducting linac to superconducting linac and cooling of the helium to 2 K from 4 K just at the interface to the cryomodules, higher efficiency klystrons and magnetically levitated neutron choppers, to name a few.

*CO2e for electricity consumed is 433 metric tons CO2/GWh (source: EPA). The total CO2 saved over ESS's lifetime of +40 years is equivalent to the volume of solid CO2 almost twice that of the Empire State building.

References

[1] K. H. Andersen, et al, "The instrument suite of the European Spallation Source," NIM A, Volume 957, 2020 https://doi.org/10.1016/j.nima.2020.163402

[2] L. Zanini, et al, "Design of the cold and thermal neutron moderators for the European Spallation Source," NIM A, Volume 925, 2019

[3] R. Garoby et al, "The European Spallation Source Design,, Phys. Scr. 93 129501, 2018

[4] L. Celona, "Preliminary Commissioning Results of the Proton Source for ESS at INFN-LNS," in proceedings of IPAC2016, Busan, Korea

[5] R. Miyamoto et al., "Highlights from the first beam commissioning stage at ESS for its ion source and low energy beam transport," Journal of Instrumentation, vol. 15, July 2020

doi:10.1088/1748-0221/15/07/P07027

[6] R. Miyamoto et al., "Beam Commissioning of Normal Conducting Part and Status of ESS Project," in proceedings of Linac'22, Liverpool, UK,

[7] R. Miyamoto et al, "ESS Linac Overall Status and Normal-Conducting Linac Commissioning," Phys. Sci. Forum 2023, 8, 36. https://doi.org/10.3390/psf2023008036

[8] R. Miyamoto, "Status and Plan of the European Spallation Source proton linac beam commissioning", in proceedings of IPAC'23, Venezia. doi:10.18429/jacow-ipac2023-weogb1

[9] M. Eshraqi and J.M. Lagniel "Choice of Linac parameters to minimize the space-charge effects," JINST 15, P07024, 2020. DOI 10.1088/1748-0221/15/07/P07024

[10] T. Parker et al, "ESS Energy Design Report," ESS-0001761. https://europeanspallationsource.se/sites/default/files/files/document/2017-09/20130131_ess_edr.pdf

A Novel Approach to High Gradient Acceleration: Short-Pulse Two-Beam Acceleration at the Argonne Wakefield Accelerator Facility

John Power, *Argonne National Laboratory,* **Chunguang Jing,** *Argonne National Laboratory and Euclid Beamlabs*

Introduction

High-efficiency high-gradient acceleration for compact accelerators and bright-beam generation is an active research area [1-3], driven by the need for brighter, higher-energy electron beams in many scientific and societal applications. One promising approach to this is short-RF-pulse, two-beam acceleration (*short-pulse TBA*) [4], which is a variation of conventional TBA [5]. In TBA, a drive bunch travels through a slow-wave structure — the power extraction and transfer structure (PETS) — to generate RF power that is outcoupled and fed into an accelerating structure, which accelerates a main bunch produced in a different electron source. *Short-pulse TBA* differs from conventional TBA in its drive beam configuration, which has fewer bunches in a train but an ultrahigh charge per bunch. This results in an RF pulse length of around 10ns from the PETS.

In addition to supporting compact acceleration, *short-pulse TBA* can also be used to form bright electron bunches, given the scaling of the beam 4D brightness $B=Q/\varepsilon_t^2 \propto Q/MTE$ (where Q is the bunch charge, ε_t the transverse emittance, and MTE is the mean transverse energy associated with the photocathode) scales with the electric field applied on the cathode E as $B \propto E\alpha$, where $1 \le \alpha \le 2$ depends on the bunch aspect ratio [6]. This means that higher gradients can support brighter beams.

In this article, we discuss the potential of developing accelerator applications—based entirely on *short-pulse TBA* operating at accelerating fields of approximately 500 MV/m—that surpasses conventional klystron-driven accelerators in terms of both brightness and compactness.

Short-Pulse TBA: A path to suppressing RF breakdown.

The Compact Linear Collider (CLIC) pioneered the TBA approach. CLIC employed an X-band linac with an RF-pulse duration of 240 ns to support accelerating gradients E~100MV/m, ultimately limited by RF breakdown [7]. Although the theory of RF breakdown is still evolving, experimental studies suggest the RF breakdown rate (BDR) in normal-conducting RF cavities is correlated with the electric field and RF pulse width [8-14] according to the empirical scaling $BDR \propto E^{30}\tau^5$ [8]. Currently, normal-conducting high-gradient accelerator designs are limited to E~150 MV/m for pulse lengths in the range $200ns \le \tau \le 400ns$. Decreasing τ significantly below this range, towards the 10-ns scale, promises a significantly higher gradient.

RF overhead is a common concern in short-pulse operation. It is defined as the ratio of RF transient time (i.e., filling time in a traveling wave accelerator and rise/fall time of the RF pulse) to total RF pulse length. A small RF overhead enhances the RF-to-beam efficiency. To reduce RF overhead, the short-pulse TBA approach uses:

- PETS to avoid the slow RF rise time associated with klystrons.
- Broadband accelerating structures to reduce the filling time.
- Accelerating structure designs with large group velocity and short acceleration length to reduce the filling time.

Therefore, competitive RF-to-beam efficiency can be realized by designing accelerating structures with low RF overhead and, of course, optimal beam loading.

Within the last 5 years, ~10-ns RF pulses with peak power >500 MW were extracted from PETS, and accelerating fields >300 MV/m were demonstrated in X-band structures in several experiments at the Argonne Wakefield Accelerator (AWA) facility [15-19]. Exploration of the accelerating gradient limit in short-pulse TBA is one of the main research priorities at AWA.

The shortest RF pulse duration that a high-energy accelerator can use depends on several factors, including the requirements for: average beam current, efficiency, operating frequency and repetition rate. However, considering just the gradient, recent experiments carried out at the AWA facility with Tsinghua University has provided evidence that a new acceleration regime may occur for RF pulse duration at 10-ns level [19]. A new acceleration regime has been observed in which a breakdown event does not disrupt the accelerating field established by the RF pulse. This regime, we termed the "Breakdown Insensitive Acceleration Regime (BIAR)," has been reproducibly observed in different structures and resulted in gradients ~400 MV/m in both high-power RF tests and in a beam-generation experiment [20].

Discovery of BIAR [19]: In the original experiment, a 3-cell 11.7-GHz traveling-wave accelerating structure (see Fig. 1a) was powered with 10-ns 400-MW RF pulses and supported an accelerating field E ~313 MV/m (corresponding to a surface field

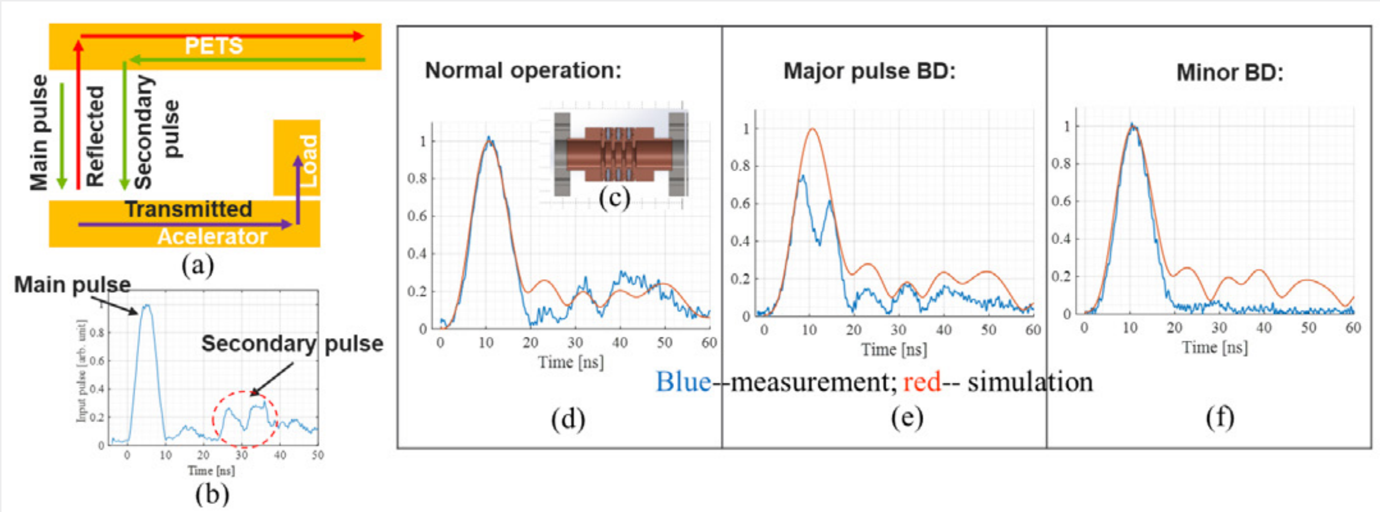

Figure 1. A high-gradient structure test carried out at the AWA facility in Oct. 2020, which reveals a new regime of acceleration that we have dubbed the BIAR (breakdown insensitive acceleration regime): a) the simplified testing diagram with arrows to represent the rf signal flow; b) the typical rf pulse measured at the output of the accelerator; c) a cut-away view of the accelerator; d~f) three different rf pulse shapes measured at the output of the accelerator, in which the major pulse breakdown indicates the accelerating fields inside the structure collapse but the secondary pulses remain; in comparison, only the secondary pulses disappear in the minor breakdown events.

of ~500 MV/m); see Fig. 1(c). The transmitted RF pulse, monitored at the output coupler of the accelerating structure, consists of the primary pulse followed by a secondary pulse; see Fig. 1(b). The simulation confirmed the existence of the secondary pulse; Fig. 1(d). Measuring transmitted power (blue curve) during high-power RF conditioning reveals two classes of breakdown events. The signature of the major breakdowns is associated with a collapse of the primary pulse so that the attainable accelerating field is limited but the secondary pulse remains; see Fig. 1(e).

In contrast, minor breakdown events do not disrupt the primary pulse, but only affect the secondary pulse; see Fig. 1(f). Therefore, in this BIAR regime, the short primary RF pulse is insensitive to the "minor" breakdown event, and thus it can still accelerate the beam.

Confirmation of BIAR [19]: In a beam-generation experiment, the BIAR was confirmed using an X-band (11.7-GHz) photocathode gun, shown in Fig. 2(c), operating at 390 MV/m and powered by 10-ns 300 MW RF pulses from PETS. Fig. 2(a) depicts the gun's first conditioning run: the *major breakdown regime* began at 150 MV/m, intensified until 250 MV/m, then began decreasing until, at 350 MV/m (limited by the available RF power), major breakdowns and dark current-related RF reflections conditioned away. This conditioning process was accomplished with 70,000 pulses, equivalent to 10 hours at AWA's 2-Hz repetition rate. The BIAR regime is observed when the gun was held at 350 MV/m. Finally, when the gradient was later reduced to 250 MV/m, no breakdown events were observed. In a subsequent round of conditioning, beam-generation experiments showed that a field strength of approximately 390 MV/m was achieved on the photocathode.

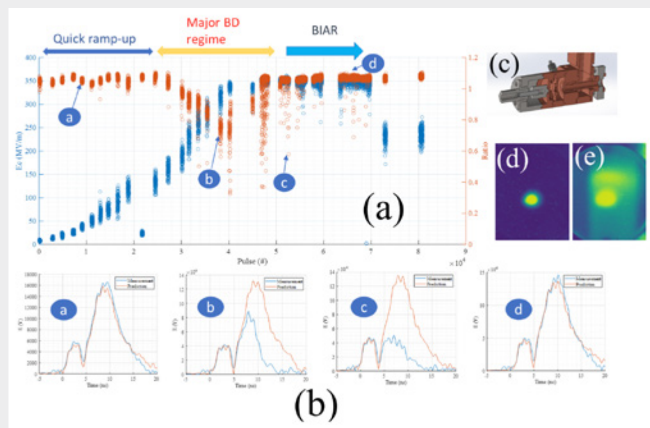

Figure 2. RF conditioning history of the short-pulse X-band photocathode gun (a) and typical RF pulse shapes of the reflected RF signal marked in the history plot (b). Note, this gun has a single port to feed RF, so the reflected signal was used to observe the breakdown events. Red is the simulated RF reflection signal and blue is the measurement. (c) Cut-away view of the gun. (d) photoelectron beam after RF conditioning. (e) A major breakdown event captured on the YAG screen. Major RF breakdowns occurred only a few times within the 3-week period of the beam generation experiment.

Current Research: Deploying *short-pulse TBA* to practical accelerators.

Pending further exploration of the BIAR regime, we envision an immediate application to high-efficiency compact FEL light sources. Regarding efficiency, many FEL facilities currently operate by accelerating a single microbunch, resulting in 99% of the RF pulse remaining unused. This significantly reduces the RF-to-beam efficiency. However, employing a 10-ns RF pulse ensures that a considerable portion of the RF pulse's energy is transferred to the beam, enhancing efficiency.

On the aspect of compactness, running the accelerating structures at approximately 500 MV/m can notably reduce the facility's footprint. Coupled with room-temperature operation, this promises cost savings. In terms of brightness, high-gradient X-band structures, due to their large aperture, are conducive to preserving beam brightness. Building on this understanding, AWA is currently in the process of designing and testing components. The goal is to achieve an integrated 100 MeV photoinjector that can produce a fully emittance compensated 100pC beam at 100nm, as depicted in Fig. 3 [21].

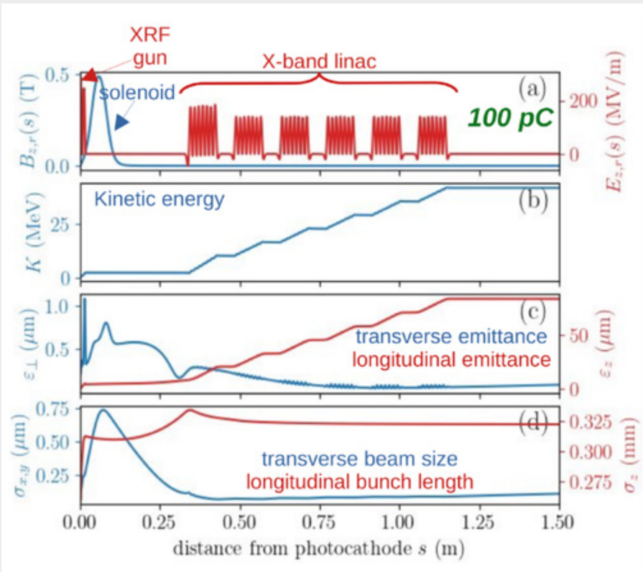

Figure 3. Evolution of kinetic energy (b), transverse and longitudinal emittances (c) and beam size (d) along an optimized photoinjector composed of the X-band photocathode gun and six X-band linac sections. Plot (a) describes the field experienced by a reference particle as it propagates along the photoinjector beamline.

To validate the scalability of the short-pulse TBA concept, the AWA group intends to construct a 0.5-GeV linac within an expanded AWA facility. The aim is to validate critical technology elements (CTE) for a potential TeV-class linear collider. A new, fast-filling, high-shunt impedance accelerator is required for this linac, with the Dielectric Disk Accelerator being a considered promising candidate due to recent positive results [22].

The 0.5-GeV demonstrator will serve both as a component of the short-pulse TBA framework and as a platform to utilize the X-band photoinjector previously discussed, potentially aiding in the development of a compact FEL. Figure 4 provides a layout for AWA, suggesting an accelerator composed of two stages, each containing two TBA structure modules. An RF delay waveguide is necessary to coordinate the timing between successive TBA structure modules. Parameters for this design are detailed in Table 1. These parameters are based on the use of a 26 GHz frequency for the TBA structure module, consistent with the conceptual SWFA 3-TeV collider design [23].

References

1. 2024 Advanced Accelerator Concepts Workshop (AAC2024) (https://indico.fnal.gov/event/59618/)

2. 2023 High Gradient Workshop (HG2023) (https://agenda.infn.it/event/34253/)

3. 2023 European Advanced Accelerator Concepts Workshop (EAAC2023) (https://agenda.infn.it/event/35577/)

4. W. Gai, J. Power, and C. Jing, Journal of Plasma Physics , 78 , Special Issue 4, (2012) 339- 345

5. D.B. Hopkins and A.M. Sessler and J.S. Wurtele, Nucl. Instr. Meth. A vol. 228, p. 15 (1984)

6. D. Filippetto et al., Phys. Rev.ST Accel. Beams, vol. 17, p. 024 201, 2 (2014)

7. CLIC collaboration, Updated baseline for a staged Compact Linear Collider, ArXiV 1608:07537 (2016).

Drive beam	Power extractor	Witness beam	Accelerator
Two 8-bunch trains, 150MeV, 40 nC/bunch, σz=1 mm	**-25 MeV/structure, -50 MeV total**	**Single bunch, 10 MeV, 100 pC/bunch**	**Energy gain: 125 MeV/structure, 500 MeV total**

Table 1. the proposed 0.5-gev short-pulse tba demonstration.

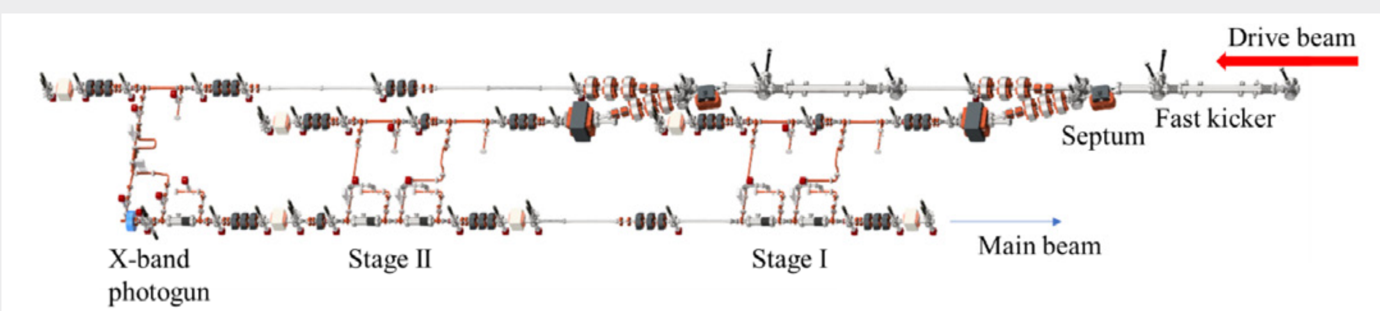

Figure 4. The proposed 0.5GeV demonstrator at AWA.

8. A. Grudiev et al., Phys. Rev. ST Accel. Beams, vol. 12, p. 102 001, 10 (2009)

9. V. Dolgashev et al., Appl. Phys. Lett. Vol. 97, 171501 (2010).

10. L. Laurent et al., Phys. Rev. ST Accel. Beams, vol. 14, p 041001 (2011).

11. F. Wang et al., Proc. Advanced Accelerator Concepts: 14th Workshop, 280-285, 2010.

12. W. Wuensch et al., Proc. PAC03, 495–497, 2003.

13. H. H. Braun et al., Proc. 2nd IEEE International Electronics Conference, 2001, 6–10.

14. W. Wuensch et al., Proc. 8th European Particle Accelerator Conference, 2002, 134–136.

15. J. H. Shao et al., Proc. IPAC'19, Melbourne, Australia, May 2019, pp. 734–737.

16. J. Shao et al., Phys. Rev. Accel. Beams, (2020) 011301.

17. X. Lu, et al., Appl. Phys. Lett. 116, (2020)264102.

18. J. Picard et al., Phys. Rev. Accel. Beams, (2022) 051301.

19. J. Shao, et al., Proc. IPAC 22, pp. 3134-3137.

20. W. H. Tan, et al., Phys. Rev. Accel. Beams 25, (2022) 083402.

21. P. Piot, et al., to appear in Nucl. Intr. Meth A (proceeding of the 2023 Channeling conference)

22. B. Freemire, et al., Phys. Rev. Accel. Beams 25, (2023) 041301

23. C. Jing, "Dielectric Wakefield Accelerators," Rev. of Accel. Sci. Tech., vol. 9, pp. 127-149, 2016.

Nonintrusive Diagnostics of Operational H-Beam Using Laser Wires

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Optical probes are among the most useful tools in modern scientific research. Thanks to advances in laser technology, photons can be packed in both space and time and coherently propagate to a remote location with high accuracy.

Since the 1980s, accelerator scientists have investigated the use of lasers as diagnostics for charged particle beams in accelerators [1-5]. One such diagnostic is laser wire, in which a focused laser beam mimics the carbon or metal wires in standard wire scanner beam profile monitors. Laser-wire-based H- beam diagnostics use a light-ion interaction process known as photo-detachment or photo-neutralization. As schematically shown in Figure 1, the irradiation of an ion beam with photons above a certain energy causes detachment of electrons from negative ions and the measurement of the resulting electron density leads to determination of the negative ion density.

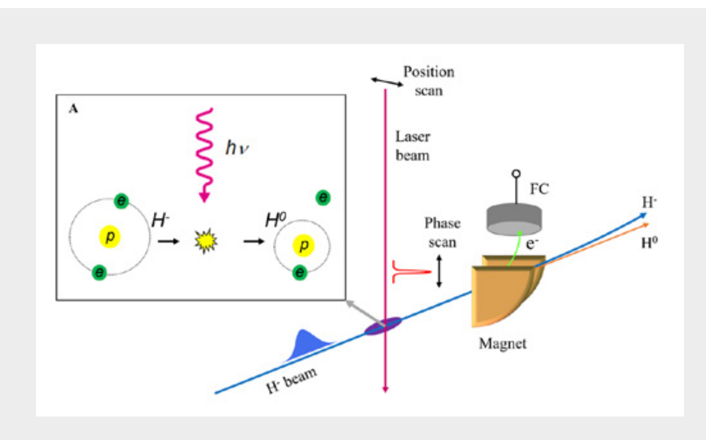

Figure 1. Schematic of laser wire-based H- beam diagnostics. Inset box A: photodetachment. FC: Faraday cup used for electron detection.

Compared to the conventional wire scanners, laser wire brought several notable advantages: 1) the measurement can be performed during normal operations, as opposed to the 50 μs, 1 Hz duty factor restriction needed to prevent damage to carbon wires; 2) there are no moving parts inside the vacuum system, thus reducing the possibility of a vacuum system failure; 3) a longitudinal beam scan can be performed using the same setup with a short pulsed light source; 4) a time-resolved measurement can reveal variations of the beam parameters within a very short time interval.

On the other hand, the laser wire also has inherent limitations: 1) since the laser is normally located outside the accelerator tunnel and the laser beams must travel tens or hundreds of meters to the measurement location, the position/power stability of the laser beam is not comparable to that of a moving wire installed at the beam line; 2) light reflection and scattering inside the measurement chamber contribute to the noise floor, decreasing the dynamic range of the measurement.

In this article, we give an overview of the laser wire technology used in the H- linac of the Spallation Neutron Source (SNS). Key components in the implementation and operation of this novel diagnostic technique, including laser source, detection scheme, control and data acquisition will be reviewed. Recent progress on the time-resolved measurement based on laser comb will be described.

Laser Wire Instrumentation at the SNS Superconducting Linac

A diagram of the SNS linac is shown in Figure 2(a). The superconducting linac (SCL) portion of the SNS linac is designed to have a capacity of 32 cryomodules. The first 23 cryomodules were commissioned in 2006 [6] and 7 new cryomodules are being added during the on-going proton power upgrade (PPU) project [7]. The first 11 cryomodules in the SCL contain 3 medium-beta RF cavities each and the remaining cryomodules contain 4 high-beta RF cavities each.

Measurement of the H- beam parameters in the SCL is important for the minimization of the beam loss. Due to the concern that broken wire fragments could cause a catastrophic damage on the superconducting cavity, a decision was made to replace the conventional carbon wire scanner with a laser profile measurement system. Therefore, a laser insertion port is designed in the warm section between each pair of adjacent cryomodules at the SCL. Nine laser wire measurement stations are installed and operating [8]. The first 4 stations are located after each of the first 4 cryomodules, the next 4 stations after the first 4 high-beta cryomodules, and the last laser wire station at the end of the SCL. In this way, the profiles of the H- beam at different energy levels (0.2 – 1.3 GeV) can be measured. Figure 2(b) illustrates primary components of a laser wire measurements station. The laser beam enters the vacuum chamber through a vacuum window (laser port) and interacts with the ion beam around the focal point of the laser beam. After the interaction, the laser beam is blocked by the beam dump installed behind the opposite vacuum window. The detached electrons are bent in the vertical direction by a magnetic field and collected by a Faraday cup (FC) and its output is processed by an electronic chassis and data acquisition (DAQ) unit located in the klystron gallery.

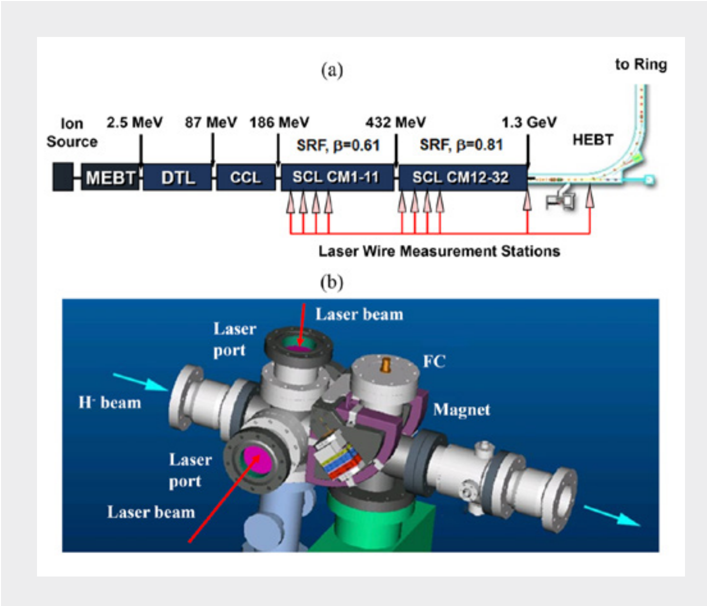

Figure 2. (a) Diagram of SNS linac. Laser wire stations were installed in the warm sections after SCL cryomodules 1, 2, 3, 4, 12, 13, 14, 15 and 32. (b) A typical laser wire measurement station. The correction magnet is not shown in the figure.

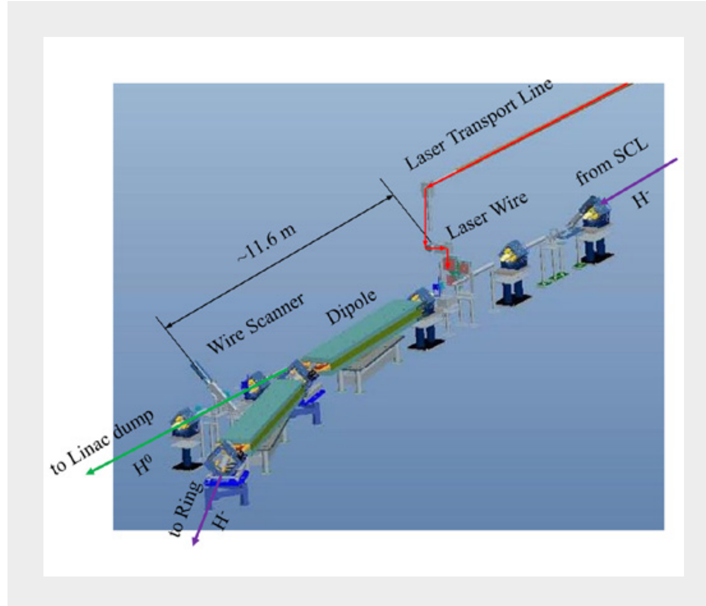

Figure 3. Laser wire-based transverse emittance measurement setup implemented at the HEBT of the SNS linac.

Transverse Emittance Scanner Using Laser Wire

In addition to the profile measurement, we have also implemented a laser wire-based transverse emittance measurement station at the high-energy beam transport (HEBT) of the SNS linac [9]. The measurement scheme is in principle a slit-detector-style emittance scanner, except the conventional mechanical slit is replaced by the laser wire. When the H- beam interacts with the laser light, some ions are neutralized and separated from the beam path. These hydrogen (H0) atoms preserve the angular distribution of the original H- beam. Therefore, the measurement of the divergence of the narrow H0 beam leads to the determination of the H- beam divergence. The measurement of the H0 beam angular distribution is conducted through the measurement of its transverse profile by a titanium wire scanner after its propagation over a certain distance. The titanium wires in the wire scanner detach the electrons from the H0 beam and the detached electrons are steered to a scintillator by a small magnet. Finally, photons emitted from the scintillator are detected by a photo-multiplier tube (PMT). Since the laser wire only interacts with a very tiny portion (~ 10-7) of the ion beam and the wire scanner is interacting with an off-line H0 beam, the entire measurement is effectively nonintrusive and can be conducted parasitically on a neutron production H- beam.

Key Components of the Laser Wire System

Light source

The first-generation light source used in the laser wire system was a commercial 1060-nm Q-switched Nd:YAG laser. The laser has a repetition rate of 30 Hz and a pulse width of 7-10 ns with a pulse energy of up to 1.5 J. Both the laser flashlamp and the Q-switching gate were externally triggered by the H- beam macropulse timing. Individual laser pulses typically covered several H- beam bunches, and there was no phase control of the laser pulse with respect to the ion beam bunch.

A customized laser was recently developed using a master oscillator power amplifier (MOPA) design with a fiber-based seed laser and diode-pumped Nd:YAG amplifiers [10,11]. The new laser system can produce laser pulses with different pulse durations varying from a few picoseconds to 100 ps. Furthermore, various macropulse structures can be generated for time-resolved measurement. The new laser has allowed several novel applications of the laser wire system. In addition, the diode-pumped amplifiers reduced the fast jitter of the laser beam and the 60 Hz operation improved the measurement speed.

Position instabilities

Variations in laser beam position can be a serious problem. The laser beam position instabilities consist of a shot-to-shot jitter stemming from the laser source and a slow drift (< 1 Hz) induced by the ambient temperature and humidity through the laser transport line. We have implemented an active position stabilization scheme to bring the laser beam pointing instability to less than 5 μrad which is mainly limited by the jitter of the laser source [12]. The effect of the laser beam position instabilities is further suppressed by two mechanisms: 1) the measurement takes place near the focal point of the laser beam, which reduces the position jitter by an order of magnitude; 2) since measurements are performed on a 60-Hz operational H- beam, the measured data is normally averaged over a consecutive 10 pulses and this process is quite effective on countering fast laser beam jitters. Currently, the accuracy of the transverse profiles is estimated to be about 0.1 mm and that of the longitudinal profiles is at sub-picosecond.

Stray light

Optical reflections from the opposite vacuum window and the wall of measurement chamber interact with the ion beam and cause unwanted background signal. For a Q-switched laser beam, such a background level can be as high as a few percent of the peak signal. Using a short-pulsed laser beam greatly reduces the background signal since the reflected light misses the ion bunch if the measurement chamber is carefully designed. The primary challenge is that the reflected light is diverging and therefore has a large size and the reflection or scattering can occur from uncontrollable surfaces such as the wall of the chamber, which made it very challenging to completely eliminate the stray light. Currently, the background noise is on the order of 10-3 of the peak signal.

How nonintrusive?

The photo-detached electrons are bent in the vertical direction by a dipole magnet and collected by a Faraday cup (FC). The magnet introduces a several millimeter vertical orbit distortion on the H- beam making it unacceptable for parasitic use during a normal production run. To mitigate the orbit distortion, a specially designed dipole correcting magnet with the same magnetic field but in the opposite polarity is installed in the proximity of the electron-collecting magnets to compensate the ion beam trajectory. The correcting magnet is powered in series with the collecting dipoles from the same power supply and thus provides an automatic compensation at all magnet currents.

While the photo-detached electrons are detected as the measurement signal, the remaining neutralized hydrogen atoms, H0, contribute to the beam loss. Although the loss is at 10-7 order and is negligible for operational beam, it can cause a momentary increase in one of the beam loss monitors (BLMs) in the downstream of the laser wire station. In some cases, especially for narrow beam bunches, such a beam loss increase can trip a BLM, which is the primary limiting factor for the laser power to be used in the measurement. Normally, a few milli-joules of laser pulse energy are used in measurements in the SCL.

Data acquisition

The laser wire DAQ system has five main components: (1) a hardware trigger which synchronizes the laser and DAQ components to the H- beam, (2) LabView software which controls the acquisition of data from multiple sources (photodiodes, PMTs, laser position sensors, phase shifter) from each laser wire stations, (3) a laser-light transport drift compensation system, (4) a laser power/position monitor and control, and (5) a laser personal protection and safety system. For a 60-Hz operational H- beam, typical profile measurements take about 1 minute for transverse profiles, 30 seconds for longitudinal profiles, and 15 minutes for emittances.

Time-Resolved Measurements using a Laser Comb

Another advantage of laser-based beam diagnostics is that the temporal structure of the laser beam can be designed such that the laser beam interacts with the particle beam at a specific location in the time domain. This feature can be used to measure time-resolved beam profiles and emittances with picosecond resolution. The key component in this measurement is the laser source, which produces laser pulses with a multilayer temporal structure — a laser comb. An example of the laser comb is illustrated in Figure 4 with the SNS H-beam waveforms as a reference. A typical laser comb contains 20–30 pulse packets (comb teeth) with a controllable comb span and comb teeth repetition rate. The laser comb is synchronized with the H-beam macropulse. Each comb tooth contains micro-pulses which are phase locked to the RF signal (402.5 MHz) of the H- beam bunches. The micro-pulse structure of the laser comb minimizes the required laser average power and enhances its capability of phase scan within the H- beam bunch.

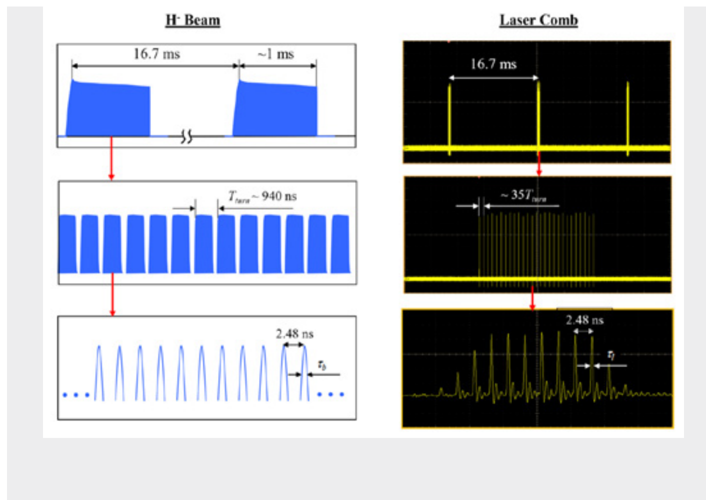

Figure 4. Temporal structures of H- beam of the SNS linac and laser comb used for time-resolved measurements. Tturn: turn period determined by the SNS accumulating ring; τb: bunch width, τl: laser micro-pulse width.

Using the laser comb, we have measured multiple emittances within one macropulse, one mini-pulse and even one micro-bunch of an operational H- beam [10]. Figure 5 shows an example of multiple emittance slices over the rising edge of a mini-pulse. Here, the laser comb tooth repetition rate is set to be 30.273 kHz which is 3 Hz lower than the 35th subharmonic of the H- beam turn frequency. As a result, each laser comb tooth interacts with the H- beam mini-pulse 3.3 ns later than its predecessor. Time-resolved measurements with sufficient temporal resolution can be useful for precise interpretation of the measured transverse emittance, meaningful comparison between measurement and simulation, or comparison between measurements at different locations.

We can also observe the variations of longitudinal profiles over different mini-pulses or within a single mini-pulse, which is not possible with conventional BSMs. Figure 6 shows the measured

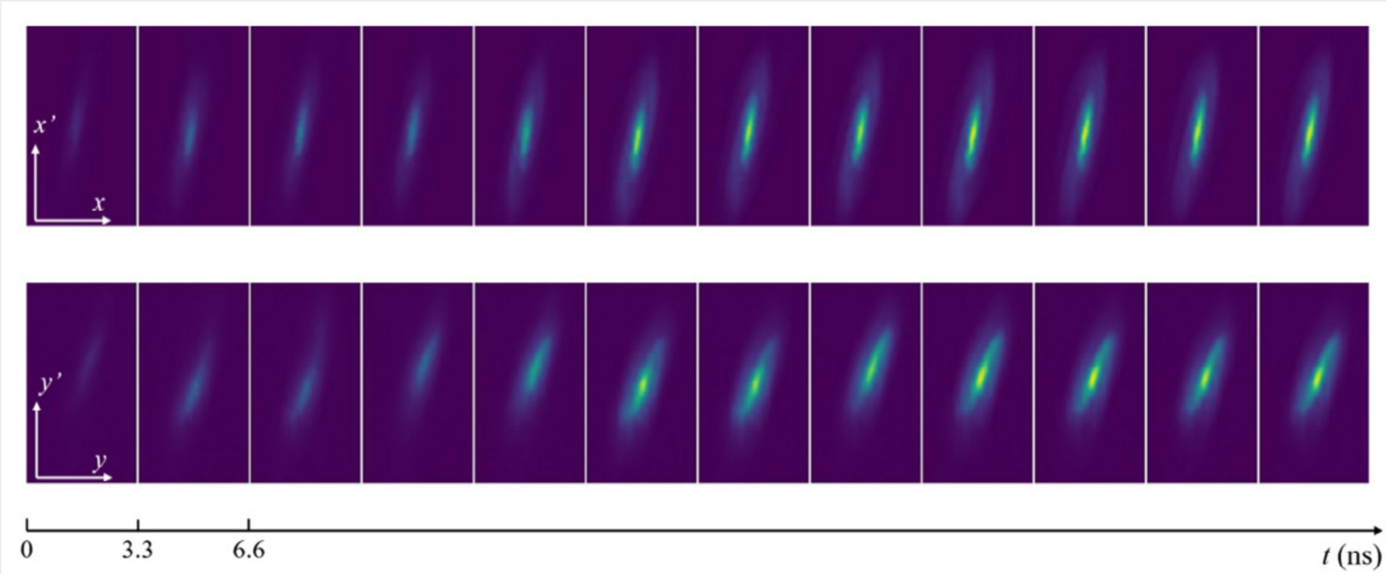

Figure 5. Multiple emittances within the same mini-pulse of the operational H- beam. The time difference between slices is about 3.3 ns. Top: horizontal emittance; bottom: vertical emittance.

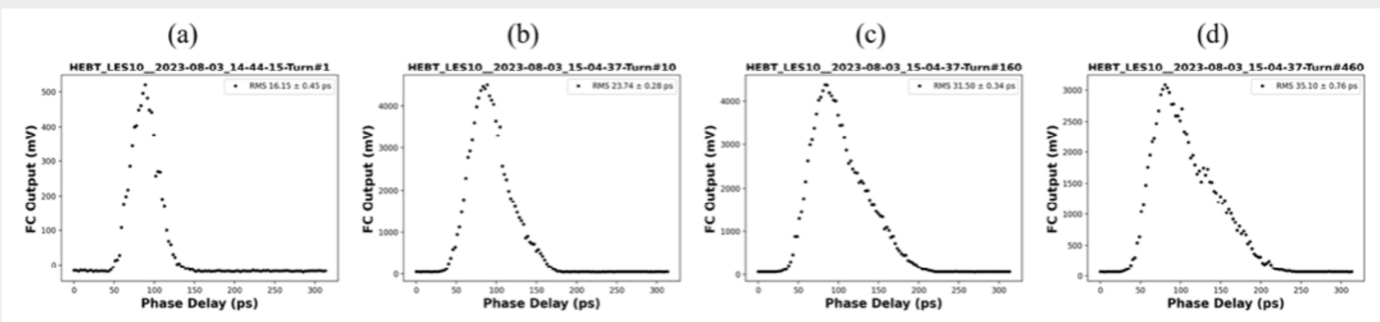

Figure 6. Longitudinal profiles measured at the HEBT. (a) Turn #1, (b) Turn #10, (c) Turn #160, and (d) Turn #460.

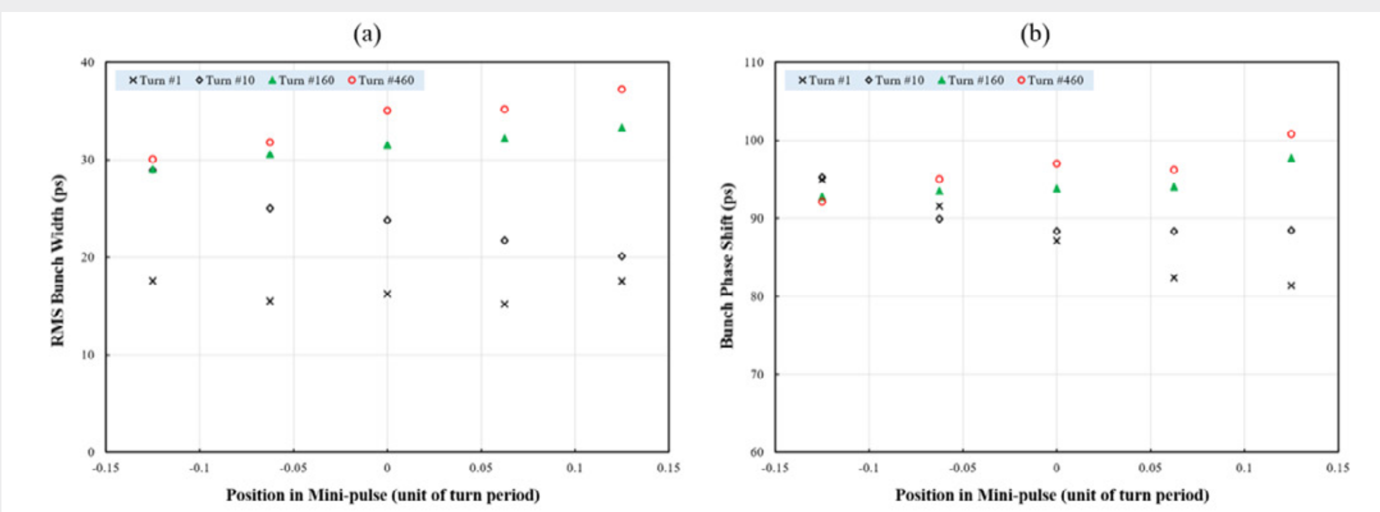

Figure 7. Bunch width and phase shift of micro-bunches at different locations within a turn (mini-pulse) of the 1.7-MW operational H- beam for 4 different turns.

longitudinal profiles in the 1st, 10th, 160th and 460th mini-pulse, which represent the very first mini-pulse, a mini-pulse during the transition edge of the macropulse, a mini-pulse after the transition edge of the macropulse and a mini-pulse in the middle of the macropulse, respectively. We observed a gradual build-up of the micro-bunch along the rising edge of the macropulse. The measurements have also revealed the non-trivial variations of the bunch width and center phase shift over a single mini-pulse and their dependence on the position of the mini-pulse in the macropulse. An example is given in Figure 7. Again, all measurements were conducted on a 1.7 MW neutron production beam.

Outlook

In summary, we have implemented the world's first operational laser wire-based beam instrumentation at the SNS linac. Ten laser wire stations have been operated at the SNS superconducting linac and High Energy Beam Transport. Those instruments provided measurements of beam parameters, i.e., transverse and longitudinal profiles and transverse emittances of operational H- beam. Laser wire diagnostics are not a simple replacement of traditional beam instrumentation such as wire scanners, emittance scanners or BSM; rather, the time-resolved data produced by laser wires reveal previously hidden beam properties.

Several future projects using the laser wire technology are being pursued. Similar to the transverse emittance measurement that uses a laser wire and a wire scanner, a longitudinal phase space measurement instrument can be conceived using a combination of a laser wire and a BSM. The design work has been completed and key components are being fabricated.

Using a laser beam with sufficient pulse energy and proper pulse width, it is possible to neutralize almost all ions in certain H- bunches [13]. This laser-based beam manipulation can be used to extract the neutralized high-energy (e.g., 1 GeV) H0 bunches from the linac. The extracted H0 beam can be further converted to the proton beam by using a stripping foil. In particular, since the temporal structure can be controlled by the laser beam, the obtained high-energy proton beam can be used to produce muons with the optimized temporal structure, e.g., 30ns/50kHz, for the muon spin relaxation/rotation/resonance (μSR) application that is frequently used in materials research [14].

References

[1] W. B. Cottingame, G. P. Boicourt, J. H. Cortez, W. W. Higgins, O. R. Sander, and D. P. Sandoval, IEEE Trans. Nucl. Sci. 32, 1871 (1985).

[2] R. C. Connolly, K. F. Johnson, D. P. Sandoval, and V. Yuan, Nucl. Instrum. Methods Phys. Res., Sect. A 312, 415 (1992).

[3] V. W. Yuan, R. C. Connolly, R. C. Garcia, K. F. Johnson, K. Saadatmand, O. R. Sander, D. P. Sandoval, and M. A. Shinas, Nucl. Instrum. Methods Phys. Res., Sect. A 329, 381 (1993).

[4] C. Gabor et al, "Design of nondestructive emittance measurement device for H- beams," Rev. Sci. Instrum. 73 (2002) 998.

[5] Y. Honda et al, Phys. Rev. ST Accel. Beams 6, (2003) 092802.

[6] S. Henderson et. al, Nucl. Instrum. Methods Phys. Res., Sect. A 763, 610-673 (2014).

[7] J. Galambos et. al., "Final design report – proton power upgrade project," ORNL/TM-2020/1570-R0 (2020).

[8] Y. Liu, A. Aleksandrov, S. Assadi, W. Blokland, C. Deibele, W. Grice, C. Long, T. Pelaia, and A. Webster, Nucl. Instrum. Methods Phys. Res., Sect. A 612, 241 (2010).

[9] Y. Liu, A. Aleksandrov, C. Long, A. Menshov, J. Pogge, A. Webster, and A. Zhukov, Nucl. Instrum. Methods Phys. Res., Sect. A 675, 97 (2012).

[10] Y. Liu, C. Long, A. Aleksandrov, Phys. Rev. ST Accel. Beams 23, 102806 (2020).

[11] Y. Liu, C. Long, A. Shishlo, A. Aleksandrov, and D. Brown, R. Thurman-Keup, and V. Scarpine, Phys. Rev. ST Accel. Beams 26, 042801 (2023).

[12] R. Hardin, Y. Liu, C. Long, A. Aleksandrov, Opt. Express 19 (2011) 2874-2885.

[13] D.E. Johnson, T.R. Johnson, C. Bhat, S. Chaurize, K. Duel, P. Karns, W. Pellico, B.A. Schupbach, K. Seiya, D. Slimmer, in Proc. HB'18, Daejeon, Korea, June 2018, p.416-421.

[14] Y. Liu. A. Rakhman, C. Long, Y. Liu, and T. Williams, Nucl. Instrum. Methods Phys. Res., Sect. A 962, 163706 (2020).

2023 Ernest Courant Outstanding Paper Recognition Recipients

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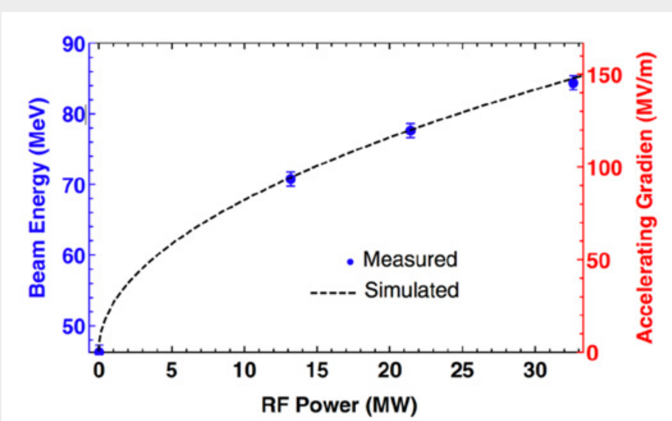
SLAC National Accelerator Laboratory

Particle accelerators have seen a new renaissance era over the span of more than three decades to pave the way for a future collider to explore the energy frontier of high-energy physics. These instruments are at the core of humanity's quest to understand the universe's smallest building blocks. To this end, we need linear accelerators (linacs) that can accelerate particles to higher energies in shorter distances, i.e., high-gradient linacs. However, the higher we push the boundaries, the more challenges we encounter.

A significant limiting factor in high-gradient acceleration has been the vacuum arcs causing rf breakdowns on the accelerator's surface. These breakdowns can disturb the particle acceleration, affecting the accuracy and efficiency of operation. In a quest to minimize these breakdowns, scientists have been working on building accelerator structures from harder materials and researching ways to reduce the surface's cyclic fatigue. Recent advances enabled the understanding of the underlying fundamental physics that governs the breakdown phenomena in high-field vacuum structures. With this new understanding, new linac topologies, engineered materials and new linac designs aimed at operating at low temperatures started to emerge.

The paper titled "Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature" presented the design and experimental data for a new linac topology that takes advantage of all the theoretical and experimental R&D that took place during the last three decades. It demonstrated the advantages of these new topologies and low operating temperatures to obtain record gradients. The work included in this paper has been honored with the 2023 Ernest Courant Outstanding Paper Recognition Award. The Courant Award annually recognizes one paper published in the journal Physical Review Accelerators and Beam (PRAB), primarily based on the potential impact on the field, innovation in the scientific or technical approach and clarity of the exposition. This recognition honors the late Ernest Courant's outstanding and long-lasting contributions to the field of accelerator science.

The paper, written by a team of scientists from SLAC National Accelerator Laboratory, demonstrated the first experimental high-gradient acceleration of an electron beam at the cryogenic temperature of 77 K. This low-temperature operation demonstration required extensive design efforts and experimental studies to reduce the surface resistance of copper at the microwave operating frequency of choice and to design the structure accordingly. The reduced surface resistance resulted in the reduction of the cyclic fatigue and, consequently, the breakdown rates compared to room-temperature operation. But the success doesn't stop there. This temperature reduction leads to many benefits, including an increase in rf-to-beam energy conversion efficiency and, hence, enhanced beam loading capabilities. The tested X-band, 11.424 GHz, 20 cells linear accelerator achieved an impressive gradient level of 150 MV/m and a shunt impedance of 349 MΩ/m—a 2.25-fold enhancement compared to its 300 K operation.



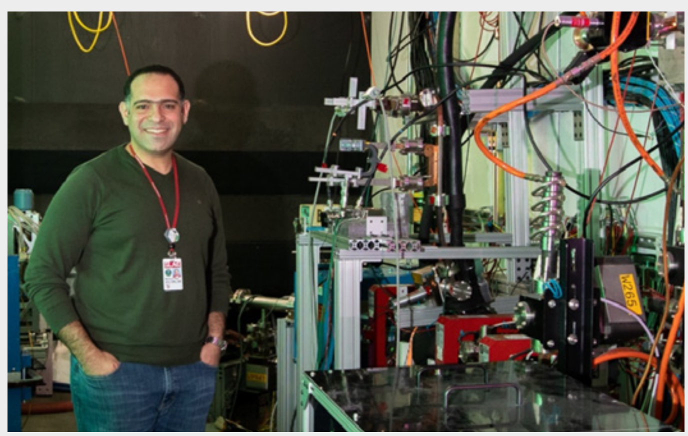


Figure 1. (left) The first electron beam acceleration measurements using a NC accelerating structure at 77k at different gradient levels, and (right) Mamdouh Nasr, the lead author of the awarded paper, with the cryogenic experiment at NLCTA facility at SLAC National Accelerator Laboratory.

The innovations presented in this study provide a cost-effective and practical approach to high-gradient acceleration using liquid nitrogen cooling, laying the groundwork for next-generation particle accelerators. With a 100-fold reduction in breakdown rates from 300 to 77 K, the door is now open for many more proposals for future discovery machines. Optimized for cost and performance, these new accelerators may well redefine our capacity to explore the unknown. Indeed, the future of particle acceleration looks bright, and the path to new discoveries is more accessible than ever before.

These advances also promise to revolutionize many other applications in the near future, including medical radiotherapy devices, cargo inspection systems and industrial sterilization of medical instruments and food products. From the point of view of medical applications, these new linacs may enable the so-called "flash treatment," a new modality that delivers the treatment dose at an exceptionally high rate. This high rate promises more discrimination between healthy cells and cancer cells. Higher dose rates also promise a much faster treatment time, which reduces the cost of treatment and hence makes it more readily available.

US Particle Accelerator School Successfully Returns to In-Person Sessions in 2023

Steve Lund, *MSU & USPAS* **and Susan Winchester,** *USPAS, Fermilab*

Pandemic-induced travel restrictions forced the U.S. Particle Accelerator School (USPAS) online for two years in 2021 and 2022. During this period, we held four Zoom-based intensive sessions patterned as closely to our traditional, in-person format.

Although this online transition provided continuity of training for the accelerator science and engineering community, the online sessions had issues including: student performance precipitously dropped due to the lesser remote support possible; dropouts and stress dramatically increased with struggles to balance class demands with work and home life; highly beneficial professional contacts proved much harder to foster; needed hands-on lab classes fit poorly; and there were acute difficulties in securing teaching teams due to the high load linked to online teaching.

We are pleased to report that the USPAS successfully restarted our in-person format in 2023 with two sessions, each of two weeks duration, which closely followed our traditional format and performed strongly. We anticipate no return to online instruction.

Our return to in-person started at our 2023 Winter Session (Jan. 23 – Feb. 3 in Houston, TX). Academic credit was provided by Northern Illinois University. The session functioned smoothly and was a strong success. Demand for classes was high, and enrollment priority was given to those seeking credit rather than audit. All class sizes were limited and spacing was enhanced to reduce remaining pandemic risks.

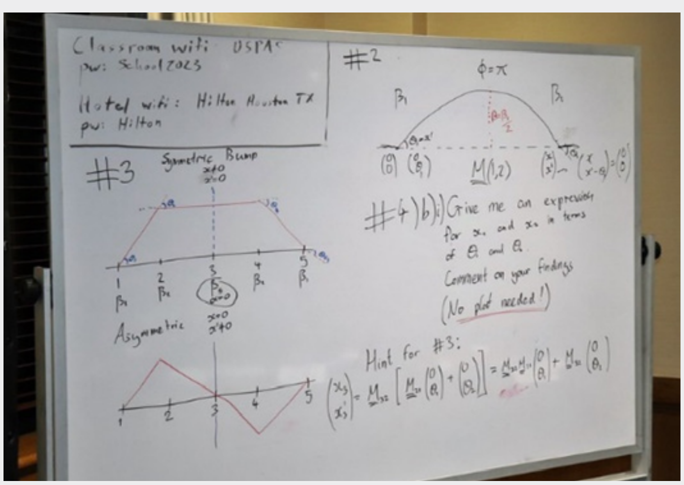
There were 11 classes: 5 two-week full-courses and 6 one-week half-courses. Full courses included undergrad-level Fundamentals and graduate Accelerator Physics (both typically offered every session), and a variety of full- and half-courses covering specialty topics in: RF Systems, RF Cavity & Magnet Design, Beam Diagnostics, Beam Dynamics and Cooling, and Radiation and Machine Protection.

The session had 131 students with 38% from universities (including 14 students in Department of Energy traineeships), 40% from U.S. national Labs, and 22% from industry, government and foreign Labs. Students attending were 84% linked to domestic U.S. institutions, 20% were women, and 11% were from underrepresented communities.

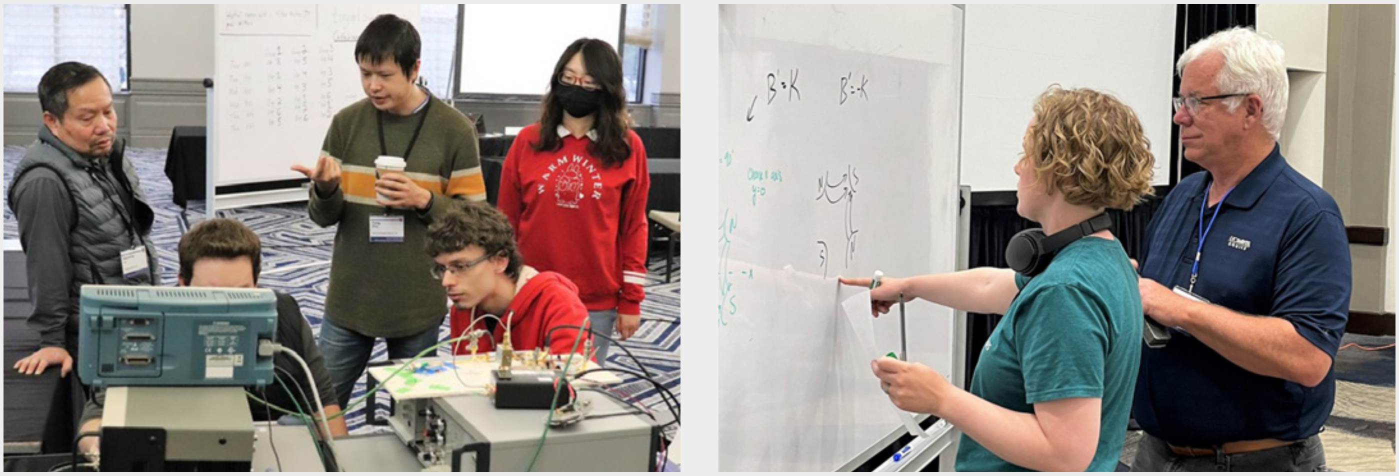
Student education levels were: 39% graduate students, 31% graduate-degreed, 27% B.S.-degreed, and 3% undergrad. There were 54 instructors, TAs and graders; of which 23 were teaching for the first time, and 5 were women. 40% of students received scholarships including: USPAS awards covering the course fees, meals and shared housing, DPB travel awards (11), and enhanced Sekazi K. Mtingwa Awards (4) designed to remove barriers to participation of underrepresented students.

Students and instructors were noticeably happy to be back to in-person and reconnecting with colleagues. For many, this was the first professional travel since pandemic restrictions were imposed. A higher than usual fraction (69%) of students took their classes for credit. Instructors expressed satisfaction with student effort and classroom performance.

Student feedback indicated high satisfaction with: 93% rating their classes as excellent, very good or good; and 97% rating their courses



Scenes from USPAS sessions in 2023. **Photo credit:** Irina Novitski



Scenes from USPAS sessions in 2023. **Photo credit:** Irina Novitski

as important or somewhat important to their careers. Classes employed flexible cloud computing, and instructor-maintained course web sites were encouraged. These changes continued positive aspects of changes that were necessary for online courses. In spite of the travel and long hours of close proximity in the session, there were no known Covid cases.

The Summer 2023 in-person session was held June 5-16 in Melville, NY (on Long Island), in proximity with Brookhaven National Lab and Stony Brook University. Academic credit was provided by Michigan State University. Again, the session ran smoothly, and had very high performance with 97% rating their classes strongly. The session included 4 full courses (Fundamentals, Accelerator Physics; Microwave Measurements; and RF Power Engineering) and 6 half-courses (Alignment; Vibrations; Laser Applications; Vacuum Science; Rings and Undulators for FELs and Light Sources; and Unifying Physics of Accelerators, Lasers and Plasma). There were 152 students: 34% from universities (including 12 students from DOE Traineeships), 52% from national labs, 14% from industry and foreign labs; 23% women; and 13% from underrepresented communities.

There were 42 instructors/TAs/Graders including 19 first-time instructors and 6 women. 28% of students were supported, including 11 with DPB travel awards, and 2 with Mtingwa awards. There was Saturday mid-session tour at BNL and Michiko Minty (BNL) received a USPAS Teaching Award in recognition of her exceptional teaching contributions over the years.

Community building activities linked to sessions have resumed with orientation talks, social functions, vendor outreach, tours, awards, etc. This effort includes session dinner presentations targeted to convince the high percentage of students who are not presently joining APS DPB to do so. Data is being gathered on reasons for students not joining DPB so future recruitment efforts can be better targeted. We are optimistic that this effort will help close the present shortfall to keep DPB above division threshold.

The high performance of both 2022 sessions gives the USPAS strong post-pandemic footing. Statistics support our perception that our restart is successfully reaching the community that we historically serve. Both demand for classes and student performance has been high and there has been no dilution of our rigorous academic format. Remaining issues include dealing with a robust business climate that has enhanced difficulty in securing necessary low-cost venue options for our sessions. In addition, our capacity for Fundamentals has outstripped demand (changes are in progress to address capacity).

We encourage the community to monitor session offerings at our USPAS web site https://uspas.fnal.gov/index.shtml. Please direct students and junior colleagues who will benefit from training provided and consider participation in teaching to deliver high quality training for our community.

DOE Traineeships in Accelerator Science and Engineering

Craig Burkhart, *OHEP*

The 2014 High Energy Physics Advisory Panel subcommittee on HEP Workforce Development Needs Report [1] identified a deficit in the accelerator science workforce as an area of special concern, both for its impact on the SC mission, and for its broader consequences.

In response, the Department of Energy crafted guidelines for a DOE traineeship program. In the following years, the Research & Technology Division of the Office of High Energy Physics has implemented traineeships in three program areas: accelerator science and engineering, instrumentation, and scientific computing.

"The HEP traineeship programs were created to address identified gaps in the scientific and technical workforce that impact the HEP research mission, and to provide additional opportunities for STEM training and career development for students working in these areas," said Division Director Glen Crawford. "These programs are focused on specialized technical skills that have broad applicability and aim to build the foundations for the next generation of physicists, engineers and computer scientists who will drive innovation in high energy physics, other scientific fields, and the larger STEM economy."

The traineeship program awards funding for up to five years to accredited U.S. universities/colleges offering graduate degrees in defined technical areas, to provide financial support (stipend, tuition & fees, travel and M&S) for graduate students for two academic years. The graduate students must be at least 18 years of age, a U.S. citizen or legal permanent resident, and working towards a master's or Ph.D. degree with a research thesis in an area of critical need (identified in the Funding Opportunity Announcement, FOA). Initially, the funding was limited to $55k per student annually, but in the most recent FOA this was increased to $70K to address DOE guidance on a living-wage stipend. Participating universities are expected to enroll 4 to 10 new trainees annually in their program to create a meaningful cohort of students. Total annual HEP funding for traineeships across the three technical areas has been $6M.

The first traineeships were awarded in Accelerator Science and Engineering (AS&E) in 2017. The traineeship scope (critical needs) was determined through community input in response to a 2015 Request For Information [2] on the status of academic training in accelerator science in the US.

These critical-need topics are:

- Physics of large accelerators and systems engineering
- Superconducting radiofrequency accelerator physics and engineering
- Radiofrequency power system engineering
- Cryogenic systems engineering (especially liquid helium systems)

Then Program Manager Eric Colby recalls, "We studied the NIH, DOD and NSF workforce development programs, picking the aspects of each that applied to DOE's needs. We realized a program 10 times the initial size of the AS&E traineeships would be needed to support the mentorship network, bridge programs and program evaluation efforts that make the comprehensive NIH approach successful. Nevertheless, we hoped colleges and universities would be creative with the funding available and make the most of the opportunity — and they did. The commitment and enthusiasm of the first awardees was critical to the successful start of the AS&E Traineeship program." That initial award was to Michigan State University [3], with subsequent awards to Stony Brook University [4] and Illinois Institute of Technology [5] in 2019, and Old Dominion University [3] in 2021.

As of July 2023, the accelerator traineeship has supported the graduate studies of 90 students at 6 universities (most of the awarded universities team with additional schools), graduating 17 students with a master's degree and another 11 with a Ph.D.; most impressive for an initiative that was launched less than 6 years ago.

Looking forward, all the awarded institutions have a rich pipeline of students working towards their degree in one of the targeted technical areas. A current priority for DOE and each of our awarded universities is to grow the program not only in terms of the total number of graduates, but also to attract trainees from historically underserved communities to increase the diversity, equity and inclusion of our workforce. Programs such as RENEW and FAIR provide opportunities to further strengthen and diversify this STEM student "pipeline." Just as at the inception of the traineeship program, our plans for its future are also challenging.

"The accelerator traineeship program is specifically designed to support workforce development in key accelerator technology areas where HEP GARD support is currently very limited," said Derun Li, current program manager. "These areas are critical to the design, construction and operation of existing and future accelerators. In order to meet the growing demand for future accelerator scientists and engineers, the program funding level must increase substantially."

A FOA was released this year to continue the program through another funding cycle. The high quality of both the new and renewal applications received (presently under review) ensures this program will continue to support the development of a vibrant AS&E workforce.

References

[1] https://science.osti.gov/-/media/hep/hepap/pdf/Reports/OHEP_Workforce_Letter_Report.pdf

[2] https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/AcadAccelSciRFI_CatalogOfResponses.pdf

[3] https://higherlogicdownload.s3.amazonaws.com/APS/9cf62627-7088-4bd3-bf97-6adfc913f623/UploadedImages/APS_DPB_Newsletter_2022-2-2.pdf

[4] https://vimeo.com/818731157/b27bad0273

[5] https://higherlogicdownload.s3.amazonaws.com/APS/9cf62627-7088-4bd3-bf97-6adfc913f623/UploadedImages/Newsletters/APS_DPB_Newsletter_2021_2022_RGB_FINAL_2.pdf

Stony Brook University Ernest Courant Traineeship in Accelerator Science and Engineering

Vladimir Litvinenko, Thomas Robertazzi, Avril Coakley, and Navid Vafaei-Najafabadi, *Stony Brook University*

Stony Brook University Ernest Courant Traineeship in Accelerator Science and Engineering

Stony Brook University (SBU), in collaboration with Brookhaven National Laboratory (BNL), Cornell University and the Fermi National Accelerator Laboratory, has established the Ernest Courant Traineeship (ECT) in Accelerator Science and Engineering. This program is named after the renowned accelerator physicist Ernest Courant, a long-serving physicist at Brookhaven National Laboratory, who laid the foundation of modern accelerator science. Courant also taught for twenty years as an adjunct professor at Stony Brook University.

The program is supported by a $2.9 million, five-year grant from the High-Energy Office at the U.S. Department of Energy (DOE). The traineeship is offered through the Center for Accelerator Science and Education (CASE), a joint venture between Brookhaven National Laboratory and Stony Brook University. CASE has three main goals: training scientists and engineers with the aim of advancing the field of accelerator science; developing a unique, advanced program that will provide access to research accelerators; and expanding interdisciplinary research and education programs utilizing accelerators.

The Ernest Courant traineeship focuses on four specific areas identified by the DOE as "mission critical" work force needs in accelerator science and engineering: (1) Physics of large accelerators and systems engineering (2) Superconducting radio frequency accelerator physics and engineering (3) Radio frequency power systems engineering and (4) Cryogenic systems engineering, especially liquid helium systems.

The Ernest Courant traineeship is available to all students. Participants who are U.S. citizens or U.S. permanent residents are eligible for funding provided by the DOE grant for stipend support and tuition. The expectation is that the traineeship can be completed in two years and students can pursue their research interests beyond the program. The graduate-level curriculum consists of courses and practical training at accelerators facilities of the participating institutions and project requirements. Each student has a supervisor guiding their training.

Students in the traineeship program who complete four courses of the core program – 12 or more credits in accelerator science and engineering with a B or higher in each – receive a certificate in accelerator science and engineering with specializations in the four technical areas listed above. This Stony Brook certificate was approved by the State University of New York and the New York

Figure 1. On the left: Proximity between SBU campus and BNL, hosting two major accelerator complexes, Relativistic Heavy Ion Collider (RHIC) and National Synchrotron Light Source II (NSLS II), provides ample opportunities for ECT students to get involved in ground-breaking research. On the right: one of the most popular hands-on Accelerator Lab ECT classes at BNL's Accelerator Test facility.

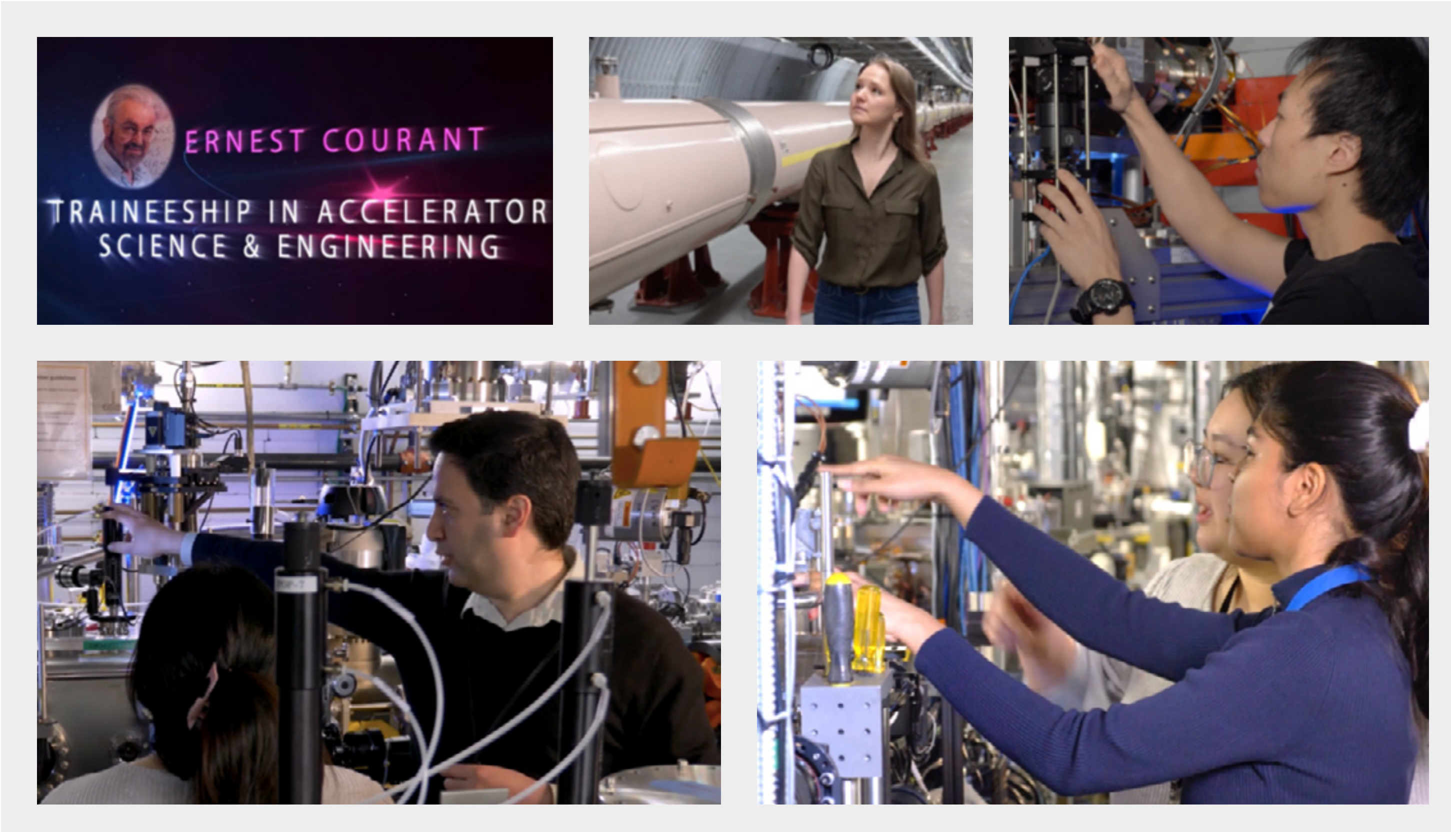


Figure 2. Snapshots from the ECT video [1], left to right, top to bottom: the opening with portrait of Dr. Ernest Courant, Res. Prof. Irina Petrushina inspects equipment in RHIC tunnel, and ECT PhD student, Kai Shih, adjusting equipment of the Coherent electron Cooling experiment at RHIC, Prof. Navid Vafaei-Najafabadi gives instructions of an ACT student, Two ECT students working on laser-driven plasma accelerator experiment. More details can be seen in the video [1].

State Department of Education in September of 2021. Since this program's inception forty students took ECT classes, 7 certificates in accelerator science have been awarded and six more students fulfilled the requirements and awaiting their certificates.

This Fall 2023 will mark the beginning of the fifth year of the Ernest Courant Traineeship Program. Currently, there are 7 Master's students and 3 Ph.D. students participating this Fall 2023 semester.

Reference

[1] https://vimeo.com/818731157/b27bad0273

APS DPB Awards & Fellowships

USPAS Student Travel Awards

Chuyu Liu

Since 2019, the DPB has provided a scholarship program for both domestic and international students attending the US Particle Accelerator School (USPAS). This travel grant is aimed at advancing the education of newcomers, and seasoned participants from other fields, in the broad spectrum of Beam Physics.

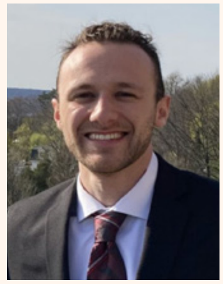
The APS DPB Executive Committee and the Education, Outreach, and Diversity Committee actively promote and implement this program. Notably, the number of recipients benefitting from the APS DPB travel grant is gradually increasing: 12 in the 2023 winter session, 13 in the 2023 summer session, and 13 in the 2024 winter session. These accomplished students represent a diverse array of backgrounds, contributing to the program's richness and inclusivity. For more details of the program, please refer to the link provided, https://uspas.fnal.gov/dpbscholarshipdetails.pdf.

Travel award recipients at the January USPAS session in Houston, TX (hosted by NIU).

Travel award recipiences at the June USPAS session in Melville, NY (hosted by MSU).

IPAC 2023 : Bruno Touschek Prize *(not sponsored by DPB)*

Presented at IPAC23 to Matthew Signorelli, for his significant contribution to the design of the Electron Storage Ring (ESR) which is part of the Electron-Ion Collider (EIC)



Matthew Signorelli, Cornell University (CLASSE)

Electron Polarization Preservation in the EIC

Matthew Signorelli (Cornell University (CLASSE)), Georg Hoffstaetter (Cornell University (CLASSE)), Vadim Ptitsyn (Brookhaven National Laboratory (BNL))

Abstract: Polarization levels in the Electron Storage Ring (ESR) of the Electron-Ion Collider (EIC) must be maintained for a sufficient time before depolarized bunches are replaced. The depolarizing effects of synchrotron radiation can be minimized with spin matching, however the optics requirements for the ring must still be satisfied. Furthermore, the robustness of the polarization in the presence of misalignments, beam-beam effects, and the eventual insertion of a vertical emittance creator – necessary to match the electron and ion beam sizes at the interaction point – must be ensured. In this work, the results of various polarization analyses of the ESR lattices are presented, and their implications discussed; the necessity for a longitudinal spin match in the 18 GeV case is investigated, and vertical emittance creation schemes with minimal effects on polarization are analyzed.

IPAC 2023: Student Poster Prize Winners

(not sponsored by DPB)

The Student Poster Prize was awarded to 2 students whose work, presented in the special session for students, was particularly meritorious.

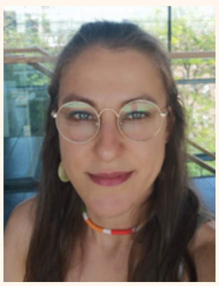
Jonathan Christie, The University of Liverpool

Developing a Two-Colour All-Fibre Balanced Optical Cross-Correlator for Sub-Femtosecond Synchronisation

Jonathan Christie (The University of Liverpool), Edward Snedden, James Henderson (Science and Technology Facilities Council), Laura Corner (Cockcroft Institute)

Abstract: In modern accelerator facilities, femtosecond synchronisation between an optical master oscillator (OMO) that provides facility-wide timing pulses and an external experiment

laser is needed to achieve the few-fs resolution required for experiments such as pump-probe spectroscopy. This can be achieved with a balanced optical cross-correlator (BOXC), which determines the timing delay between two laser pulses via the generation of sum-frequency radiation in a nonlinear crystal. In this paper, a design for a two-colour fibre-coupled BOXC using waveguided periodically-poled lithium niobate (PPLN) crystals is presented. An all-fibre two-colour BOXC is highly desirable as it would be more robust against environment fluctuations, easier to implement, and can achieve greater synchronisation performance compared to free-space coupled BOXCs that are currently used in accelerator facilities. This proposed design can theoretically achieve 5 - 10 times greater sensitivity to relative timing changes between laser pulses than current free-space two-colour BOXCs, which can make sub-fs synchronisation between an OMO and an external experiment laser of different wavelength achievable.



Ezgi Sunar,
Goethe Universität Frankfurt

The Double Drift Harmonic Buncher (DDHB) and Acceptance Investigations at LINAC and Cyclotron Injections

E. Sunar, U. Ratzinger, R. Tiede (Institute of Applied Physics, Goethe University, Frankfurt, Germany)

Abstract: Particle Accelerators demand high particle transmission and reduced longitudinal emittance; hence, effective bunching systems are requested. The concept based on an efficient, compact design called "Double Drift Harmonic Buncher - DDHB" fulfills these two requirements for a c.w. or pulsed beam injection into an RFQ, a DTL, or a cyclotron. The proposal is associated with two buncher cavities separated by a drift space and an additional drift at the end of the system for a longitudinal beam focus at the entrance of the next accelerator unit, whose candidates can be one of those mentioned above. The investigations are focused on exploring accurate acceptance rates. To obtain successful and understandable outputs from the DDHB concept, a new multi-particle tracking beam dynamics code called "Bunch Creation from a DC beam - BCDC" has been developed for detailed investigations of space charge effects. It allows to calculate the transformation of intense dc beams into particle bunches in detail with a selectable degree of space charge compensation at every location. This paper presents the results from various investigations with and without space charge effects.

IPAC23: Student Travel Grants

One of the roles of the APS-DPB is to promote student engagement within accelerator physics. One way the unit does this is through funding the IPAC Student Grant Program. The grants program for students in the Americas region is funded through a combination of APS funds and national lab support. This past year, a total of 19 students from the Americas region were funded to attend IPAC in Venice (12 of those were funded by APS). Students in the grant program were required to attend the student program on May 6-7, present at the student poster session on May 7, and serve in secretariat roles during the conference sessions.

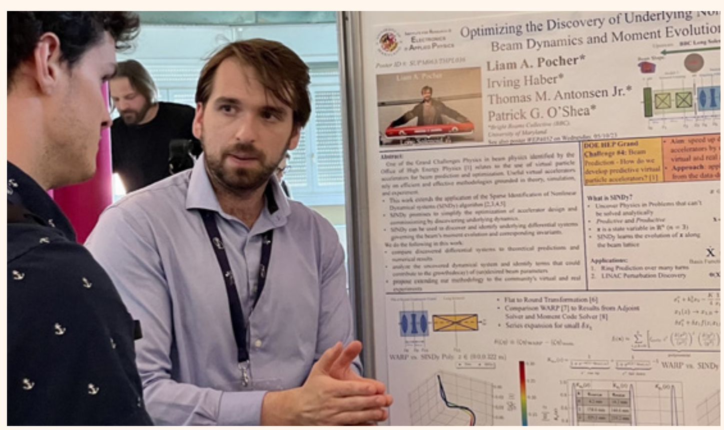
One of the funded students, Liam Pocher, shared his experience at IPAC23:

"What was the most interesting or rewarding aspect for you?"

For myself I considered the student poster session to be a good highlight. Many of the other sessions were very narrow, but the student poster session allowed presenters hours to practice and hone their talk over the breadth of beam physics. Having the session last four hours was initially disconcerting, but the time flew by and it gave time for students to mingle and see each other's posters, building community relationships.

"What was the non-scientific highlight of your trip?"

Having the opportunity to travel around Italy during and after the conference was amazing, especially because my girlfriend was able to join me. I would sit through many more lectures and volunteer much more to allow myself to do that again with a scholarship!



Liam Pocher presents during the Sunday student poster session at IPAC23.

2023 Ernest Courant Outstanding Paper Recognition

Mamdouh Nasr, Emilio Nanni, Martin Breidenbach, Stephen Weathersby, Marco Oriunno, and Sami Tantawi

For their paper on: "Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature."

Robert R. Wilson Prize for Achievement in the Physics of Particle Accelerators

Karou Yokoya, KEK

Citation: "For seminal contributions to the theory and control of beam polarization in electron storage rings, beam-beam interactions in linear colliders, crab-crossing and coherent beam-beam interactions in circular colliders, and bunched beam instabilities."

APS Fellows of the DPB in 2023

Agostino Marinelli, SLAC National Accelerator Laboratory

Citation: "For path-breaking contributions to the theoretical and experimental development of free-electron lasers and their application to ultra-fast science."

Chandrashekhara M Bhat, Fermi National Accelerator Laboratory

Citation: "For outstanding and sustained contributions to accelerator physics and technology that has enabled several significant discoveries in particle physics including the discoveries of single top quark production at the Tevatron and Higgs boson production at the Large Hadron Collider."

Robert Miles Zwaska, Fermi National Accelerator Laboratory

Citation: "For leadership and important contributions to the development of record beam power neutrino targets and high-intensity proton accelerators."

2023 Outstanding Doctoral Thesis Research in Beam Physics Award Recipient

Interview with Chao Li

Let's start with your thesis research: Can you give a brief description of the work, and its impact on the field?

My research focuses on the use of an array of thin silicon microchannels to generate highly collimated atomic beams. This process is augmented by enhanced brightness achieved through on-chip laser cooling. The goal is to create miniature or compact devices such as atomic beam clocks and atom interferometer gyroscopes. Throughout my research, the beam physics software Molflow+, originally developed at CERN, has been an indispensable tool. The contrast between the millimeter scale of my silicon collimator and CERN's kilometer-spanning infrastructure is stark. Nonetheless, the fundamental principles of beam physics remain consistent, even though the atomic beam physics I work with operates at a much lower energy scale.

The chip-scale atomic beam is a significant addition to the field of on-chip neutral-atom technologies. It complements existing innovations such as miniature Bose-Einstein condensates, magneto-optical traps and vapor cells. This technology offers a feasible path toward the miniaturization of traditionally large timekeeping and rotation-sensing instruments—like beam clocks and atom interferometer gyroscopes—to a chip scale. This advancement is particularly beneficial in scenarios requiring a compact size, a lightweight design and energy efficiency. Furthermore, this technology enables the accurate and targeted delivery of neutral atoms toward photonic cavities or nanostructures on-chip, thanks to its compatibility with cleanroom micro/nano-fabrication techniques.

The introduction of the chip-scale atomic beam platform could rekindle interest in employing century-old atomic and molecular beam technologies. This would be for the construction of fieldable miniature instruments for timekeeping, sensing and quantum information processing.

How did you become involved in beam physics research?

I never thought I would work on beam physics when I entered graduate school. At that time, I was fascinated by the overlap between quantum optics and cold atom physics. So, I joined my advisor's group, which was largely focused on a sodium BEC machine in 2017. This machine required an atomic beam for loading. Initially, I happily constructed a more compact atomic beam apparatus because I naively thought that what I was doing would be an upgrade to the existing "Big Mac." However, I continually miniaturized various components and developed beam techniques, never touching the existing BEC machine that had originally excited me. As a result, I became involved in beam physics research quite accidentally. My experience may inform future students: Ph.D. research can be unpredictable without a solid plan. Nevertheless, if I could turn back time to 2016 and know that my beam thesis would earn me an award to proudly display at home, I might still go with beams.

What did you find most challenging during your Ph.D., technical or otherwise?

The technical aspects of my Ph.D. were not particularly challenging for me. I was fortunate to work in a small group that allowed for regular interactions with my advisor, enabling us to collaboratively resolve problems in the early stages. As I became more independent, I grew adept at troubleshooting issues on a daily basis. Additionally, the presence of other graduate students in our lab and neighboring AMO labs, who were both kind and knowledgeable, fostered a supportive environment. Their input and positive feedback helped me stay on track and made the time fly by.

The real challenge lay in anticipating an exact timeline for collaborative, highly interdisciplinary research, especially when it spanned multiple institutions. My Ph.D. research relied heavily on fabrication processes, which were significantly affected by the COVID-19 pandemic. Collaborative efforts evolved over the last few years, with team members coming and going. The issue of authorship also proved challenging; in my field, alphabetic order is not the standard, and the current system often places too much value on the first and last authors. These administrative, though non-scientific, issues demanded a high level of cross-cultural communication skills. This was particularly challenging for a junior researcher like me, who is also not a native English speaker.

I hope my experience can offer some insights. Graduate programs might consider providing training sessions and resources aimed at well-informing and empowering students with less institutional influence. A deeper understanding of the mechanisms of academia, rather than solely focusing on research and knowledge acquisition, could significantly benefit students.

Life circumstances presented their own set of challenges. I am a first-generation college student, and all my family members are in China. Further complicating matters is the short validity of my F1 visa; each time I traveled outside the country, I had to spend about 1.5 months solely on the visa renewal process. These factors have at times significantly distracted me from my research. I hope that in the future, stipends for graduate students and postdocs will be adjusted to better reflect living costs, and that visa policies will evolve in a more accommodating direction.

What advice do you have for graduate students in the field of beam physics?

This may not be particularly useful for "beam physics graduate students," but I'd like to share some advice from senior graduate students I met during the early stages of grad school. Many of them told me that the actual time it will take to complete a task, initially estimated to take "t" amount of time, is likely to be "'pi times t." Therefore, it's essential to be both mentally and physically prepared for the unexpected. Another valuable lesson I learned from a postdoc was the importance of spending the majority of my time in the lab conducting actual experiments. This is in contrast to reading papers, purchasing equipment, taking classes or attending remote meetings—even while sitting in the office or standing in a lab. I believe this approach leads to creating knowledge rather than simply acquiring it. In my view, pursuing a Ph.D. is more about the former.

What are you working on now? Will you continue your earlier research, or start something new?

I am currently working in a quantum photonics research laboratory. My primary focus is on developing integrated photonic circuits tailored to control atoms or artificial atoms — such as color centers in diamond — in a scalable manner. This is completely different from my Ph.D. research, except for my understanding of two-level systems interacting with light fields and, of course, laser systems. Much of the fundamental physics still applies to my current work, even though it appears to be quite different. This is actually why I've loved physics for so many years, starting from junior high school—it is both universal and fundamental. There is the possibility of combining what I did during my Ph.D. with what I am currently working on, once I establish my own lab.

Tell us something interesting about yourself outside of work!

I used to be a soccer player and played almost every weekend as a graduate student. However, I stopped about six months before my graduation and haven't returned to the field since, even after becoming a postdoc. My schedule has become increasingly hectic, but I hope to resume exercising soon.

In Memoriam

We have collected the contributions for several of the accelerator and beam physics community members whom we have lost from the past few years. Here we present this information in their honor and to celebrate their contributions and lives.

Roger Bailey, CERN
1954 – 2023
Former head of the CERN operations group and a director of the Cern Accelerator School.

Obituary:
https://home.cern/news/obituary/cern/roger-bailey-1954-2023

Giorgio Brianti, CERN
1930 – 2023
An early champion and pioneer of the LHC, and technical director during construction of LEP.

Obituary:
https://cerncourier.com/a/giorgio-brianti-1930-2023/

Michel Martini, CERN
1945 - 2023
Well known for his refinement of the BM IBS theory, as well as teaching future physicists at the JUAS.

Vittorio Vaccaro, INFN
1941 - 2023
Father of the concept of accelerator impedance, and university teacher of many well-known accelerator physicists.

Obituary:
https://cerncourier.com/a/vittorio-giorgio-vaccaro-1941-2023/

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