Sustainability Aspects of Energy Recovery Linacs

Bettina Kuske, Helmholtz-Zentrum Berlin

April 10\textsuperscript{th}, 2022, APS April meeting, NY
Layout of the talk:

• Introduction to ERLS
  • The European ‘Accelerator R&D Roadmap process’
  • Some ERL history and achievements
• What is an ERL?
• Power needs in different accelerators
  • When are ERLs efficient?
• Normal conducting or superconducting linac?
• 2 proposals for high energy physics applications
• Needs for R&D and roadmap suggestions
• Summary
Since **2005** the CERN council mandates the
“**European Strategy for Particle Physics**” *

“… a broad consultation of the grass-roots particle physics community, actively soliciting the opinions of physicists from around the world, … in close coordination with similar processes in the US and Japan in order to ensure … optimal use of resources globally.”

2019/2020 update: CERN Council mandates the Laboratory Directors Group (LDG) to define and maintain a prioritised accelerator R&D roadmap** towards future large-scale facilities for particle physics.

LDG defined 5 areas of interest:
- High-field magnets
- High-gradient RF structures and systems Plasma
- High-gradient plasma and laser accelerators
- Bright muon beams and muon collider
- Energy-recovery linacs (chair: Max Klein, U-Liverpool),
  e+e- collider subpanel (chair: Andrew Hutton, JLab)

A broad yearlong effort, conducted in 2021, resulted in a document
“**European Strategy for Particle Physics**”

Executive summary (ERL)**: “The panel notes with much interest that the ERL technology is close to high-current and high energy application … with the stunning potential to revolutionise particle, nuclear and applied physics, as well as key industry areas.”


Extended ERL white paper - to be published
„**Sustainability Aspects of ERLs**, Bettina Kuske“
SOME ERL HISTORY AND ACHIEVEMENTS

1965 M. Tigner
“A possible apparatus for electron ch..."

1987 High Energy Physics Lab
Stanford University
SRF cavities, proof of principal experiment

1987 Los Alamos
SRF-operation, nc, coupled acc/dec cavities

2000 Jefferson Lab
“Front End Test”
SRF, first CW recovery

2002 Jefferson Lab
“IR-Demo”
SRF, 5mA, 48MeV, 2.1kW beam power IR

2002 JEARI, Japan
FEL, SRF, 700kW beam power

2003 CEBAF, 1 GeV, single turn

2004 BINP, Russia
FEL-operation normal conducting RF,
30 mA 2007: 4-passes

2005 Daresbury Lab, GB
“Alice”, SRF, 26MeV, versatile 10-year user program

2007 Upgrade:
9mA, 150MeV 1.1MW beam power with ~300kW RF power

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2004 BINP, Russia
FEL-operation normal conducting RF,
30 mA 2007: 4-passes

2013 KEK, Japan
“cERL”, prototype ERL light source

2020, Cornell
cbeta, FFAG-arc 4-pass ERL
(80mA injector, $\epsilon = 0.3\text{ mm mrad}$)

under construction:
MESA, Germany particle physics application
PERLE, France test facility (FCC-ee)
bERLinPro, Germany SRF/ERL technology test facility
Energy recovery is a concept in accelerator technology with many applications:

**APPLICATION OF ERLS**

- **FEL drivers**
  - Undulator in return arc
  - BINP, Jlab
- **Coherent electron Cooling**
  - 15MW electron beam power
  - CeC for EIC, BNL
- **High energy physics colliders**
  - Use ERL beam in collision
  - Proposals: eRHIC, FCC-ee, ERLC
- **Test facilities**
  - Test, develop, improve lacking technologies
  - PERLE, bERLinPro
- **Industrial applications**
  - FEL, irradiation lines
  - cERL, Japan, EUV lithography,
- **Light sources**
  - Use of recirculating arcs at different energies
  - CORNELL X-ray ERL, Russia, Japan, China

...
WHAT IS AN ERL? BASIC ACCELERATOR TYPES - LINAC

- RF installation
- beam transport
- source
- experiment / dump

- start-to-end, permanent injection
- bunch properties defined by the source
  => flexible bunch parameters and patterns
- single user, interaction point
- particle dump @max. E: waste of e⁻ and E

„Sustainability Aspects of ERLs“, Bettina Kuske

Linear Coherent Light Source, SLAC, Stanford University, US

https://lcls.slac.stanford.edu/overview
WHAT IS AN ERL? BASIC ACCELERATOR TYPES – RECIRCULATING LINAC

- RF installation
- Beam transport
- Source
- Experiment / Dump

Linac
Recirculating Linac

- Start-to-end, permanent injection
- Bunch properties defined by the source
  => Flexible bunch parameters and patterns
- Single user, interaction point
- Particle dump @max. E: waste of e⁻ and E

Mami-B: stage 3 of the 4 microtron cascade: 882 MeV, 100 μA cw
Final stage: 1.5GeV, 100 μA cw
Beam power: 150kW
WHAT IS AN ERL? BASIC ACCELERATOR TYPES – STORAGE RING

"Sustainability Aspects of ERLs ", Bettina Kuske

Max IV: 3 GeV, 400 mA

Linac

- start-to-end, permanent injection
  
  - extra injection system@full E, sparse injections, little charge

  - RF during operation: only to compensate SR

  - equilibrium bunch param. fixed by design

- bunch properties defined by the source
  
  - flexible bunch parameters and patterns

- single user, interaction point

  - multi-user facility / several interactions point

  - particle dump @max. E: waste of e⁻ and E

https://www.maxiv.lu.se/accelerators-beamlines/accelerators/accelerator-documentation/3-gev-storage-ring/
What is an ERL?

The best of two worlds

"Sustainability Aspects of ERLs", Bettina Kuske

Energy Recovery Linac – the hybrid solution
Recirculating Linac with pathlength modification $\Delta L = 1/2 \lambda_{RF}$

$\Delta L = 1/2 \lambda_{RF}$: electrons are decelerated in the linac and deposit their energy back into the RF cavities to accelerate further bunches.

ERL properties:
- start-to-end, permanent injection
- bunch properties defined by source
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Energy Recovery Linac – the hybrid solution

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ERL properties:
- start-to-end, permanent injection
- bunch properties defined by source
- flexible bunch parameters, bunch patterns
- multi-user / several interaction points / usage of arc(s)
- RF during operation only to compensate SR (+ losses)
WHAT IS AN ERL? THE BEST OF TWO WORLDS

Energy Recovery Linac – the hybrid solution
Recirculating Linac with pathlength modification $\Delta L = 1/2 \lambda_{RF}$

ERL properties:
- start-to-end, permanent injection
- bunch properties defined by source
- flexible bunch parameters, bunch patterns
- multi-user / several interaction points / usage of arc(s)
- RF during operation only to compensate SR (+ losses)
- dump beam at injection energy – less radiation hazard/higher current
- Still waste $e^-$, but save the energy

$\Delta L = 1/2 \lambda_{RF}$: electrons are decelerated in the linac and deposit their energy back into the RF cavities to accelerate further bunches.
bERLinPro* (SEALAB): ERL test-facility at HZB, Berlin 50 MeV, 100mA

Similar test facilities: Japan: KEK, cERL  France: IJClab Orsay, PERLE  US: BNL ...


"Sustainability Aspects of ERLs", Bettina Kuske
**MARS**: Proposal for a multi-turn ERL light source (2012)
5.6 GeV, 10mA

- cascaded injection
- two linacs for energy recovery
- multiple turns – 4 energy levels
- separated tracks for accelerated/decelerated beams

*Kulipanov, et al. MARS: FOURTH GENERATION X-RAY LIGHT SOURCE BASED ON MULTITURN ENERGY-RECOVERY LINAC, RUPAC2012, St. Petersburg, Russia*
Power (to beam) requirements for a generic beam:

$I = 100\, \text{mA}, \, E = 3\, \text{GeV}$ beam (typical light source)

$300\, \text{MW}$ beam power $\approx 70$ modern $160\, \text{m}$ windmills

<table>
<thead>
<tr>
<th></th>
<th>Linac</th>
<th>rec. linac 3 turns</th>
<th>ERL 1 turn</th>
<th>storage ring C=300m, $T_c=1, \mu\text{s}$, $\rho=5, \text{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{injection}}$</td>
<td>[MeV]</td>
<td>10</td>
<td>10</td>
<td>3000</td>
</tr>
<tr>
<td>acc. Current</td>
<td>[mA]</td>
<td>100</td>
<td>100</td>
<td>1e-7 mA·s</td>
</tr>
<tr>
<td>$P_{\text{injection}}$</td>
<td>[MW]</td>
<td>1</td>
<td>1</td>
<td>$P(\text{linac}) \cdot 10^{-6}\text{s}$</td>
</tr>
<tr>
<td>$P_{\text{RF (operation)}}$</td>
<td>[MW]</td>
<td>300</td>
<td>100</td>
<td>$P_{\text{SR}} + P_{\text{loss}}$</td>
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<td></td>
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<td>$P_{\text{SR}} \approx 150 \cdot 10^{-3}$</td>
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$P_{\text{SR}}$ = Synchrotron Radiation losses
$P_{\text{CAV}}$ = cavity losses
$P_{\text{ramp up}}$ = Power to establish fields in linac

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<td>10</td>
<td>3000</td>
</tr>
<tr>
<td>acc. Current [A]</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>$1e^{-7}\text{mA} \cdot \text{s}$</td>
</tr>
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ERL efficiency*: \[ \frac{P_b}{P_{RF}} = \frac{I_b E_{\text{f}}}{I_b E_{\text{inj}} + P_{\text{ramp up}}(+\text{losses})} \]

- \(P_b\) - beam current, power
- \(P_{RF}\) - RF power
- \(P_{\text{ramp up}}\) - power to build up field in cavities
- \(I_{\text{inj}}\), \(E_{\text{f}}\) - injection, final energy

ERLs efficient for:
- high energy
- high current
- low injection energy

*: Merminga et al., HIGH-CURRENT ENERGY-RECOVERING ELECTRON LINACS, doi: 10.1146/annurev.nucl.53.041002.110456

**Sustainability Aspects of ERLs**, Bettina Kuske

ERL efficiency parameter

- \(I = 1-300\text{mA, 3GeV}\)
- \(E = 1-7\text{GeV, 100mA}\)

- \(P_{\text{ramp up}} = 10\text{ kW}\)
- \(E_{\text{inj}} = 10\text{ MeV}\)

- \(P_{\text{ramp up}} = 10\text{ kW}\)
- \(E_{\text{final}} = 3\text{ GeV}\)
- \(I = 0.1\text{A}\)
Efficiency of the energy recovery process:
  Quality of the linac plays the dominant role

- principally, NC and SC linac feasible

Key quality parameters of a cavity:
- Low surface resistance $R_s$
- High quality factor $Q_0$
- High repetition rate

$$Q_0 = 2\pi \frac{\text{energy stored}}{\text{energy dissipated per cycle}} = 2\pi \ast \text{cycles to dissipate stored energy}$$

<table>
<thead>
<tr>
<th>cavity</th>
<th>$R_s$</th>
<th>$Q_0$</th>
<th>frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>1</td>
<td></td>
<td>&lt;500MHz</td>
</tr>
<tr>
<td>SC</td>
<td></td>
<td></td>
<td>~1 GHz</td>
</tr>
</tbody>
</table>

⇒ energy recovery becomes efficient in combination with SRF technology only

Drawback: SRF technology needs energy-intensive cooling
SRF-ERL: AC POWER CONSUMPTION INCLUDES THE CRYOPLANT LOAD

SC-ERL: Wall plug power includes the cryoplant power consumption
### ERL - LINAC WALL PLUG POWER* DURING OPERATION:

<table>
<thead>
<tr>
<th>RF loads</th>
<th>Dependencies</th>
<th>Rough estimates</th>
<th>Cryo loads</th>
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<tr>
<td><strong>RF losses and microphonics</strong></td>
<td>electric field gradient $V^2$, shunt impedance $R/Q$, quality factor $Q_0$, temperature $T$, no. of cells</td>
<td>RF: 20-50 W / cavity</td>
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<td>Microphonics: 10 kW @ 1.8K / cavity 70 kW @ 2K / cavity</td>
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<td><strong>HOM losses</strong></td>
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<td>Heat @4K, 80K, room temperature</td>
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<tr>
<td><strong>Synchrotron radiation losses</strong></td>
<td>energy $E^4$, current $I$, bending radius $\rho$</td>
<td>20% of heat dissipation ~10% (1-2W / coupler)</td>
<td><strong>Power coupler / Thermal shield</strong></td>
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<td></td>
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<td>15% of complete cryo power (0.75W / valve)</td>
<td><strong>Static losses</strong> Connections, cables, cryo boxes, absorber ~40%</td>
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<td>25% of complete cryo power 1W / 4W heat dissipation</td>
<td><strong>Utilities (supply of 1.8K He)</strong> Cooling towers, Compressors</td>
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* http://arxiv.org/abs/2201.07895, priv. communication
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- 1W RF power @ beam = 2W wall plug power
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"Sustainability Aspects of ERLs", Bettina Kuske
2020/2021: Two proposals of e+e- colliders using energy recovery:

**CERC (Circular Energy Recovery Collider)** - FCC-ee parameters
V. Litvinenko, T. Roser, M. Llatas
*Physics Letter B 804 (2020) 135394*
“*High-energy high-luminosity e+e- collider using energy-recovery linacs*”

**ERLC (Energy Recovery Linear Collider) – ILC parameters**
V. Telnov
“A *high luminosity superconducting twin e+e- linear collider with energy recovery*”

Both proposals raised much attention, led to formation of e+e- sub-Panel (-> report)
- Not complete, no fully coherent parameter set yet
- Problems identified & updates exist – no showstopper so far
- Numbers vary in different publications depending on different assumptions and effects included

[https://agenda.linearcollider.org/event/9312/contributions/48614/attachments/37188/58228/ERconceptForColliders-v3.pdf](https://agenda.linearcollider.org/event/9312/contributions/48614/attachments/37188/58228/ERconceptForColliders-v3.pdf)
**Storage Ring Solution**
*FCC-ee*
100km, 182.5 GeV/beam

- 6 GeV NC pre-injector linac
- 6-20 GeV pre-booster
- Main booster in collider tunnel 182.5 GeV (green)
- Storage ring, top-up operation

**ERL Solution**
*CERC*
100km, 182.5 GeV/beam

- 2 beam sources, 2 damping rings 2GeV
- 4 turns up, 4 turns down (16 beamlines in tunnel)
- 2 linacs (~23GeV)
- storage in damping rings, top-up
- reusage of particles and reusage of energy

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**: [https://doi.org/10.1016/j.physletb.2020.135394](https://doi.org/10.1016/j.physletb.2020.135394)
## Power Needs for Acceleration: FCC-ee and ERL Based e+e– Circular Collider

### Sustainability Aspects of ERLs

Bettina Kuske

### Storage Ring - FCC-ee* / ttbar Operation

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Luminosity $[10^{34} / \text{cm}^2 / \text{s}]$</td>
<td>1.55</td>
</tr>
<tr>
<td>Current [mA]</td>
<td>5.4</td>
</tr>
<tr>
<td>SR losses [MW]</td>
<td>100</td>
</tr>
<tr>
<td>RF power injector [MW]</td>
<td>10 pre injector, 8 Booster (RF &amp; Cryo)</td>
</tr>
<tr>
<td>RF power linac [MW]</td>
<td>123</td>
</tr>
<tr>
<td>50% RF efficiency</td>
<td>145</td>
</tr>
<tr>
<td>85% RF efficiency</td>
<td>145</td>
</tr>
<tr>
<td>Cryoplant [MW]</td>
<td>46</td>
</tr>
<tr>
<td>Utility power [MW] (cryo and RF)</td>
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### ERL – CERC**

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<td>Current [mA]</td>
<td>1.01</td>
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<td>SR losses [MW]</td>
<td>30</td>
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<td>RF power injector [MW]</td>
<td>8.1</td>
</tr>
<tr>
<td>RF power linac [MW]</td>
<td>41.9</td>
</tr>
<tr>
<td>50% RF efficiency</td>
<td>100</td>
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<td>153</td>
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<td>Utility power [MW] (cryo and RF)</td>
<td>63</td>
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### Notes

- ***: F Zimmermann, FCC Week 2019 Brussels, 24 June 2019
- ****: ERL: [https://doi.org/10.1016/j.physletb.2020.135394](https://doi.org/10.1016/j.physletb.2020.135394)

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**FCC Week 2019 Brussels, 24 June 2019**

**ERL**: [https://doi.org/10.1016/j.physletb.2020.135394](https://doi.org/10.1016/j.physletb.2020.135394)

**POWER NEEDS FOR ACCELERATION: FCC-ee AND ERL BASED e+e – CIRCULAR COLLIDER**

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<td>Luminosity (10^{34} / \text{cm}^2 / \text{s})</td>
<td>1.55</td>
<td>35</td>
</tr>
<tr>
<td>(no reuse of beam after collision, lower restriction for beam-beam tune shift)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current [mA]</td>
<td></td>
<td>1.01</td>
</tr>
<tr>
<td>SR losses [MW]</td>
<td>100 (\propto E^4) (collider rings)</td>
<td>30 (incl. DR)</td>
</tr>
<tr>
<td>RF power injector [MW]</td>
<td>10 pre injector</td>
<td>8.1 (damping rings) ***</td>
</tr>
<tr>
<td>8 Booster (RF &amp; Cryo)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF power linac [MW]</td>
<td>123</td>
<td>41.9 ***</td>
</tr>
<tr>
<td>(no HOM, no beam-beam losses)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% RF efficiency</td>
<td></td>
<td>100***</td>
</tr>
<tr>
<td>85% RF efficiency</td>
<td>145 (60% of total)</td>
<td></td>
</tr>
<tr>
<td>Cryoplant [MW]</td>
<td>46 Thin film Niobium on copper, 4.5 K, Q=3 (10^9)</td>
<td>153 ***</td>
</tr>
<tr>
<td>(56% of 85% RF eff. total)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2K, Q = 2 (10^{10}), BNL-ERL 5-cell cavity +20% thermal shield and power coupler cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utility power [MW] (cryo plant and RF)</td>
<td>37</td>
<td>63 ***</td>
</tr>
<tr>
<td>(total incl. magnets, data center, etc: 359MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>246MW</td>
<td></td>
<td>275MW @ 85% RF eff. (316MW *** @50%)</td>
</tr>
</tbody>
</table>

*: F Zimmermann, FCC Week 2019 Brussels, 24 June 2019

**: ERL: [https://doi.org/10.1016/j.physletb.2020.135394](https://doi.org/10.1016/j.physletb.2020.135394)

**Linear collider solution [*]**

**ILC**

125 GeV/beam

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**ERL Solution [**]** Twin-cavities

**ERLC—Valery TelNov**

125 GeV/beam

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****: V. I. Telnov, “A high-luminosity superconducting twin $e^+e^-$ linear collider with energy recovery”, 2021, DOI: 10.1088/1748-0221/16/12/P12025

„Sustainability Aspects of ERLs “, Bettina Kuske
### Power Needs for Acceleration: ILC and Proposal for ERL Based Linear Collider

<table>
<thead>
<tr>
<th></th>
<th>ILC – linear collider</th>
<th>ERLC – ERL based collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (10^{34} / \text{cm}^2 / \text{s})</td>
<td>1.35*</td>
<td>39* (current per pulse)</td>
</tr>
<tr>
<td>Bunch population (10^9)</td>
<td>20*</td>
<td>1.13*</td>
</tr>
<tr>
<td>Distance between bunches [m]</td>
<td>166*</td>
<td>0.23*</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>6560*</td>
<td>2.47+10^8*</td>
</tr>
<tr>
<td>Duty cycle</td>
<td></td>
<td>0.19* (to cope with RF heat load)</td>
</tr>
<tr>
<td>Average current [mA]</td>
<td>0.021</td>
<td>44.7</td>
</tr>
<tr>
<td>Beam generation [MW]</td>
<td>13**</td>
<td>2.5**</td>
</tr>
<tr>
<td>Damping rings [MW]</td>
<td>25**</td>
<td>15**</td>
</tr>
<tr>
<td>Linac RF + utilities [MW]</td>
<td>24.5**</td>
<td></td>
</tr>
<tr>
<td>SR losses (wigglers) [MW]</td>
<td></td>
<td>4.5 *</td>
</tr>
<tr>
<td>RF for HOM losses [MW] (50% efficiency)</td>
<td>0.66 **</td>
<td>5.5 *</td>
</tr>
<tr>
<td>Refrigeration ((1.8 \text{K}, Q_0 = 3 \times 10^{19})) [MW]</td>
<td>15.65**</td>
<td>110 * (80% of total)</td>
</tr>
<tr>
<td>Total [MW]</td>
<td>129*</td>
<td>137.5 ** (incl. 17.5MW DR+generation)</td>
</tr>
</tbody>
</table>

*: V. I. Telnov, DOI: [10.1088/1748-0221/16/12/P12025](https://doi.org/10.1088/1748-0221/16/12/P12025)

**: Yokoya, [https://agenda.linearcollider.org/event/9312/contributions/48614/attachments/37188/58228/ERconceptForColliders-v3.pdf](https://agenda.linearcollider.org/event/9312/contributions/48614/attachments/37188/58228/ERconceptForColliders-v3.pdf)
Selected ongoing R&D in SRF technology (sustainability centered):

- **Higher quality factors:** involves new cavity material (Nb₃Sn, NbN, NbTiN…)
- **4.4K operating temperature:** option to use cryo-coolers* (no cryogenic liquids)
- **Efficient HOM power absorbers** at the highest possible temperature
- **Fast reactive tuners****: (FRT): new technology to compensate transients and microphonics; (based on new ferroelectric material)

Selected ongoing R&D in general ERL technology:

**High current electron sources:**

- **Guns:** high cathode field & extremely high vacuum (DC, SRF, NCRF)
- **Photocathodes:** new cathode materials promise a longer lifetime, higher quantum efficiency
  - **Secure transport** of photocathodes (vacuum < 10⁻¹⁰)
- **Photo cathode laser pulses:** elliptical temporal profile for high charge, ultra-low emittance

**Diagnostics:** high beam power, non-Gaussian bunch profiles, multiple beams, high dynamic range

**Simulation:** Coherent Synchrotron Radiation, Beam Break Up, longitudinal matching, S2E calculations

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* : Ram C. Dhuley: “Cryocooler conduction-cooled SRF cavities for particle accelerators”, Cockcroft Institute Seminar, 08 September 2020

**: N. Chipman et al., “A Ferroelectric Fast Reactive Tuner for Superconducting Cavities”

19th International Conference on RF Superconductivity, Dresden, Germany, DOI: 10.18429/JACoW-SRF2019-WETEB7
European Accelerator R&D strategy:

“Progress should be based on several medium-scale projects underway around the world, with complementary goals in different aspects of the technologies involved.”

**High current** - 100mA (gun & load to SRF cavities)
- CeC-IEC@BNL, cERL@KEK, bERLinPro@HZB, BINP (NC, low f)

**Energy increase** to 10GeV in 5 passes (=> SR)
- ER@CEBAF, Jlab (&STFC Daresbury, U-Lancaster, U-Brussels)

**10MW beam power** in 3-pass configuration
- PERLE@IJCLab Orsay, broad int. collaboration

Test of **FRTs**:
- bERLinPro@HZB

**HOM damping**:
- BNL, bERLinPro@HZB, PERLE@IJCLab Orsay (always, if I > 1mA)

**Operational experience**:
- S-DALINAC (TU Darmstadt, Germany), MESA (U Mainz, Germany), CBETA (U Cornell and BNL, US), cERL (KEK, Japan), and the NC Recuperator facility (BINP Novosibirsk, Russia).
CONCLUSION

A detailed *European roadmap* – including timelines and costs – has been laid down for the further developments of ERLs towards the next generation of accelerators.

ERLs are a very active field with many emerging *technological novelties*.

The wide scope of technologies involved can only be met by intense *international cooperation*.

ERLs have a *high TRL* (technological readiness level).

To recover the energy of particles after their usage in experiments is mandatory to ensure further development in HEPs accelerators.

Thank you for your attention