Doublet Dudes: Shaping the Future of Fusion

By: Ryan Chaban, August 2017

Fusion, in the grand tradition of American and international physics is a relatively small group of scientists pursuing a goal with the reluctant understanding that it will most likely not be achieved during their lifetimes. This is less true today than it was 60 years ago; however, the progress towards fusion owes a debt to the determined pioneers of the General Atomics (GA) fusion program who persevered through politics, budget cuts, and others' disinterest in their research. Among those pioneers are Dr. Tihiro Ohkawa (1928-2014), a lauded leader, innovator, and risk-taking scientist; and Torkil Jensen (1932-2004), a man whose name is always spoken with a soft undertone of awe inside the gates of GA and is seldom heard outside the campus save for the innovation award that bears his name. Ohkawa was a powerful visionary with drive to build; Jensen was a kindhearted mentor and innovator.[i] As a pair, the impact they left on the fusion program at GA and the world is rich and lasting.

As the inaugural VP of the Fusion program, Ohkawa's name is the first to appear on many public histories and publications from the company. Ohkawa visualized the future machines he wanted to build and pursued them single-mindedly inside GA and unreservedly to the public when seeking funding. He was an accomplished scientist when he arrived at GA, and his team complemented him well; none more so than Jensen with his softer friendly style and critical intuition that exposed and patched any shortcomings in Ohkawa's experiments[ii]. Together, the pair operated by proposing unusual ideas, defending them vehemently until the attempt, then once proven correct, repeating the process. Jensen and Ohkawa's careers and contributions to fusion science span an immense range of topics such as shaping and control theory, the foundational ideas and theory behind shaped plasmas, preventing Resistive Wall Modes (RWM) and locking modes, and the induction motor model of plasma rotation. Their research was not only relevant during their lives, but survives today in the designs and approaches of international fusion programs and in the minds of the students they mentored who are now some of the leaders in physics within and outside of fusion.

The duo's work is closely tied to the independent fusion program at GA. From 1957 until 1965 fusion at GA (then General Dynamics) was supported by the Texas Atomic Energy Research Foundation (TAERF)[iii]. In 1960 both Ohkawa and Jensen arrived, the former from the University of Tokyo and the latter from an electrical engineering research assistantship in his native Denmark. Ohkawa initially worked under Donald Kerst (1911-1993) until the latter left GA in 1962 and Ohkawa assumed the role of primary experimentalist for fusion research. Jensen began at GA familiarizing himself with basic plasma research through a smaller effort on Landau damping. In 1965 the contract with TAERF ended and the GA fusion program, because of budget and disillusionment, dwindled to 14 scientists who needed to come up with something notable to survive.[iv] The difficulty troubling Princeton Plasma Physics Laboratory (PPPL) scientists at the time was the Model-C stellerator losing confinement on the timescale of Bohm diffusion[1]. Ohkawa managed to secure funding from the Atomic Energy Commission (AEC) to build the DC Octopole that, while did not confine the plasma past the Bohm time, did show diffusion several hundred times lower than the Bohm value, showed Bohm loss was avoidable when pursuing toroidal confinement, and brought enough renown to GA to secure more funding.[v]

In 1968 the Russian T3 tokamak’s impressive progress in confinement time and temperature was confirmed by the British using the new Thompson scattering diagnostic technique and steered the direction of fusion research worldwide towards the tokamak, including at GA with an important twist.[vi] Instead or a traditional circular tokamak, Ohkawa put forward the radical idea of the “plasma-current multipole” or doublet. The doublet was a strongly shaped plasma based on principles of MHD stability and focused on using an elongated plasma with two separate currents to create a “figure 8” (see Figure 1) in the magnetic equilibria.[vii] Doublet-I (DI) was a small-scale (8cm major radius) proof-of-concept model built with thick, shaped copper walls to allow better inductive control and was so successful it only operated for three months before Ohkawa secured funding for the much larger Doublet-II (DII). Jensen would go on to prove theoretically—subsequently backed by experiment—why the doublet and elongated plasmas in general were better than the tokamak to achieve high plasma pressure. Not only did he prove its merits, but Jensen also showed the doublet’s weaknesses and discovered why the doublet shaped plasma kept decomposing into two separate plasmas or one large plasma known as the “droplet-ellipse mode”.

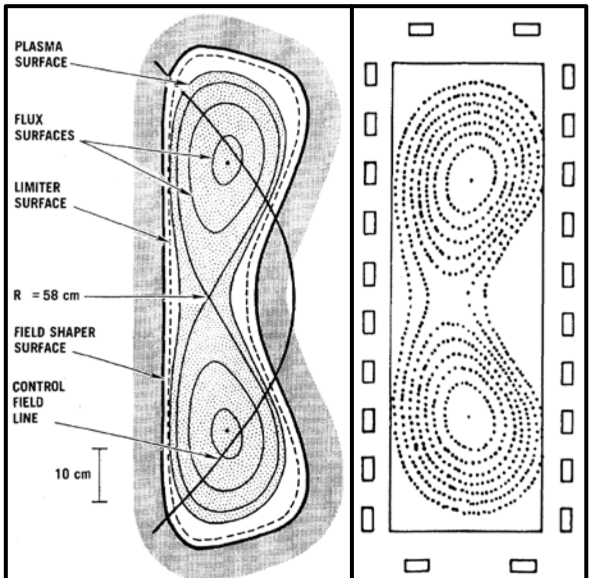


Figure 1: a) [left] An image of the magnetic field equilibria with relevant surfaces and field lines labeled for Doublet II. The shaded grey represents the thick copper wall to control the plasma. b) [right] An image of DIIA's magnetic equilibria and the location of the shaping coils around the thinner vacuum vessel wall.

DII was successfully built, ran for two years, and demonstrated longer confinements times with a higher "β” [2] than comparable tokamaks[viii]. Because Ohkawa had earned his name on the DC Octopole and mos of his staff were working on it, Jensen was placed in charge of many of the operations for DII and made some of his most important contributions to MHD theory, such as higher β of elongated plasmas, while working on that machine. Eagerly pressing onward, Ohkawa

[1] Bohm diffusion is the transport of plasma across magnetic field lines and occurs on a much faster timescale than the required confinement times for a fusion device. It was discovered that Bohm diffusion increased with plasma temperature which it was thought would make a fusion device impossible. See R. Post, “Scientific Problems of Fusion, Solved and to Be Solved”, EPRI Executive Seminar on Fusion, October 11-13, 1977.

[2] “β" is defined as the “plasma pressure” divided by the “magnetic pressure. Because it is dimensionless, β is used to compare performance across different sized tokamaks and doublets. Lower β is often associated with more expensive machines because of the requirement for larger magnets to create higher magnetic pressures.

proposed and built Doublet IIA (DIIA) hoping to show that the large conducting wall, which facilitated eddy currents to correct changes in plasma shape, could be replaced by external shaping coils around a thinner vacuum vessel wall (see Figure 1b). Designed by Dr. Teuro Tamano (b. 1937) and troubleshot by Jensen, the shaping coils were a significant step forward in active control of plasma;[ix] they forced GA's scientists to develop advanced control techniques which would become the basis of the modern-day Plasma Control System (PCS)[x]. During DIIA's experimental run which also confirmed the comparable abilities of doublets against similar tokamaks[xi], Jensen discovered that the 3-D helical state of the plasma in the doublet device could have a lower energy than the axisymmetric state, essentially solving why the droplet-ellipse mode occurred and where the plasma parameters needed to remain to maintain stability[xii].

As DIIA met its objectives, Ohkawa with the aid of his team of theorists, proposed the significantly larger Doublet III (DIII) in 1974 and construction was completed in 1978. Because DIII was designed as a doublet, it possessed a much larger number of shaping coils and exhibited greater flexibility of design than other tokamaks of the time. DIII was a machine with impressive capabilities, but to continue to make progress, it would need more heating power as the limit of Ohmic heating (1keV) had been established and reached[xiii]. After Neutral Beam Injectors (NBI) were installed on DIII, the doublet machine's last great achievement was to create a High-confinement mode (H-mode) plasma which was discovered in 1982 on ASDEX (a limiter[3] tokamak in Germany with a circular cross section). In 1983 the DIII machine under the supervision of John Gilleland was upgraded to a D-shaped vessel (nicknamed "Big Dee" by the scientists) to achieve even higher β. The modern DIII-D was christened and doublet research at GA officially ended.

During this period, the heyday of doublet research (1968-1984), not only were several machines built, but the foundations for a long-lasting energy program were laid with the training of a new generation of plasma physicists. For example, spurred by the oil crunch of 1973, the US recognized its lack of a comprehensive energy policy and the AEC transformed from 1975 through 1977 into the Department of Energy (DoE)[xiv]. Driven by fear from of dependence on foreign oil imports, the DoE sought to establish a reputation for funding research that would draw the US to a diversity in energy assets such as solar and wind moving towards eventual energy independence. Because of the tremendous amount of capital required to build energy research sites, and seeking to establish itself quickly, Ohkawa saw an opportunity and appealed to the DoE for the funding of continued research studies on DIII-D, with the implied promise carried out by Jensen that they would train a new generation of plasma physicists. Jensen operated as a universal sounding board for ideas from his peers, and during his entire time at GA he always had a mentee.[4] The impact of Jensen's emphasis on mentorship can be seen in GA's modern culture and active attempts to not only pull in funding for their researchers to study DIII-D, but also to secure money to expose graduate students who may be uncertain of plasma into fusion research.

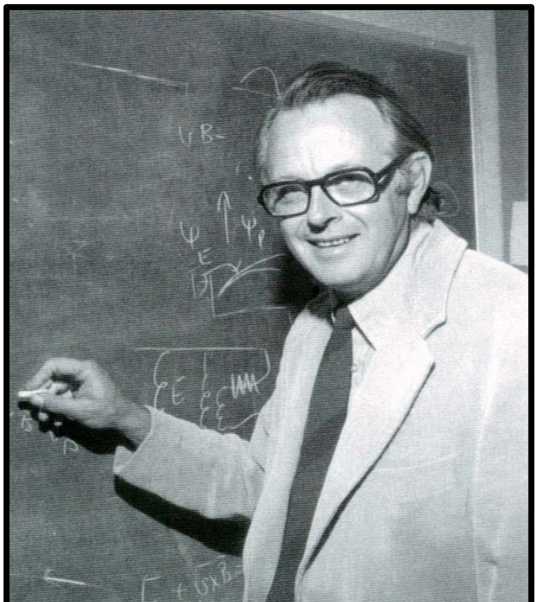
---

[3] A "limiter" tokamak uses only closed flux surfaces and has no separatrix (crossed or "pointy" field lines) or diverter.

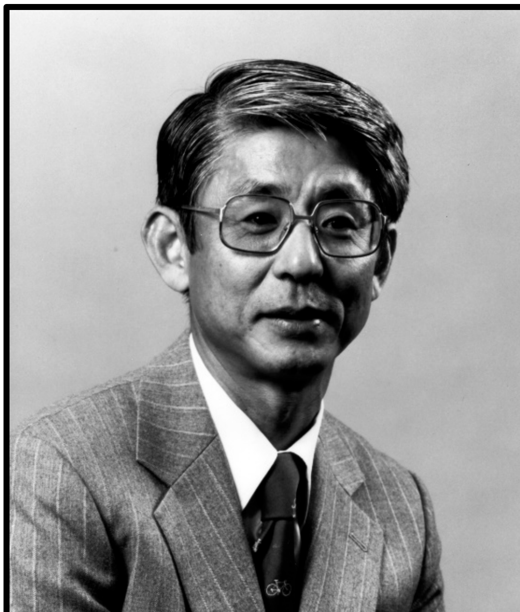
[4] Notable students of Jensen include Dr. Omar Hurricane, current director of NIF at LLNL, and Andrea Garofalo.

Later in their tenure as scientists at GA, while Ohkawa climbed the ranks to VP of Fusion, Jensen ever remained the Senior Technical Advisor, always lending his aid and ideas on new approaches to research and training his mentees. His accomplishments are extraordinary and the influence of his training on the doublet is evident in his understanding of the Resistive Wall Mode (RWM) and its control due in large part to his time learning to control doublet plasmas. Jensen continued to work and publish papers at GA even after his official retirement in 1994. His influential engineering ideas laid the foundation for Dr. Lang Lao's EFIT code (cited over 1100 times and used ubiquitously in fusion research), "almost" ideal MHD, and helped create the inductor motor model of plasma rotation which is still used as an easy explanation for how a tokamak starts and how the rotation is affected by currents and fields[xv].

DIII-D to this day remains one of the most capable tokamaks for the investigation of the effects of shaping on confinement. Its success has led to advancements in plasma control through GA's development of the nearly universal PCS, Resonant Magnetic Perturbations to suppress plasma bursts (known as Edge Localized Modes or ELMs), and probing the limits of MHD stability through shapes that lead to disruptions. DIII-D's success has affected the design of other programs that have come after it and currently serves as America's premier tokamak devoted to establishing the scientific basis for ITER[5]. If fusion were likened to a river, it would be almost entirely composed of the blue of tokamak research. However, because of the determination of the "doublet dudes", the red flow of doublet and shaped plasmas persisted for long enough that even though it is now a tributary of the greater water, the river of fusion will always carry the purple tint of their research in the prevalence of shaped plasmas and the generation of excellent researchers who once called GA home.



Torkil H. Jensen



Dr. Tihiro Ohkawa

[5] The largest scientific undertaking since the LHC, ITER is a reactor-scale tokamak currently being built in Marseilles, France with a budget of $14 billion.

[i] Ryan Chaban interview with Dr. Andrea Garofalo, July 12, 2017; paraphrase.
[ii] Ryan Chaban interview with Dr. Teruo Tamano, July 20, 2017.
[iii] M. W. Maisel, "Celebrating 50 Years of Fusion at General Atomics", Internally distributed, 2007.
[iv] Ryan Chaban interview Dr. Rob La Haye, July 11, 2017; Lisa Bromberg, "Fusion: Science Politics, and the Invention of a New Energy Source", Book, MIT Press, Cambridge, 1982; Tamano interview.
[v] Tamano interview; Bromberg pp. 148-149.
[vi] Bromberg, p 151; Tamano interview.
[vii] La Haye interview.
[viii] T. H. Jensen et al., "Confinement of Plasma in the Doublet-II Device", Physical Review Letters, Volume 34 No. 5. February 3, 1975.
[ix] Tamano interview.
[x] La Haye interview.
[xi] R. K. Fisher et al., "Studies of Doublet Plasmas in Doublet IIA", Physical Review Letters, Volume 39 No. 10, September 5, 1977.
[xii] T. H. Jensen vs. W. B. Thompson, "Low frequency response of a resistive plasma to axially independent or axisymmetric perturbations, Journal of Plasma Physics, Volume 19 part 2 pp 227-235, 1978; Tamano interview
[xiii] Ryan Chaban interview Dr. Ming Chu, July
[xiv] Chu interview; Bromberg pp. 237-243.
[xv] Ryan Chaban interview Alan Turnbull, July 11, 2017; Garofalo interview.