The Fork in the Road to Electric Power From Fusion

US Navy compact fusion reactors

Peter Lobner, 1 February 2021

1. Background

For at least the past 40 years, the US Navy has been funding fusion power research and development in considerable secrecy. In this article, we'll take a brief look at the following US Navy fusion programs, focusing on the two most recent programs.

- LINUS - pulsed stabilized liquid liner compressor (SLC)
- Low Energy Nuclear Reactions (LENR, aka cold fusion)
- Polywell fusion - inertial electrostatic confinement (IEC)
- NIKE & Electra krypton fluoride direct-drive laser inertial confinement fusion (ICF)
- Plasma compression fusion device (2019)
- Argon fluoride direct-drive laser ICF (2020)

2. LINUS - pulsed stabilized liquid liner compressor (SLC)

In the 1970s, this Naval Research Laboratory (NRL)-sponsored project developed and tested several pulsed stabilized liquid liner compressor (SLC) machines: LINUS-0, SUZY-II and HELIUS. A plasma is injected into a void space in a flowing molten lead-lithium liner. The liquid liner is then imploded mechanically, using high-pressure helium-driven pistons. The imploding liner compresses and adiabatically heats the plasma to fusion conditions.

While the SLC concept was abandoned by the US Navy in the 1970s, it was revived in the 2000s as the basis for the small fusion reactor designs being developed by Compact Fusion Systems (US) and General Fusion (Canada).

3. Low Energy Nuclear Reactions (LENR, aka cold fusion)

From the mid 1990s to at least the mid-2000s the US Navy sponsored research into cold fusion. You'll find a list of cold fusion papers by Navy researchers from NRL, China Lake Naval Weapons

Laboratory, and Space and Naval Warfare Systems Center (SPAWAR) here: https://lenr-canr.org/wordpress/?page_id=952

4. Polywell fusion – inertial electrostatic confinement (IEC)

From 1995 to 2014, the firm EMC2 received about $21 million in funding from the US Navy for research into Polywell fusion, with $12 million of that funding awarded between 2008 – 2014. During that time, EMC2 tested 19 different prototypes of their Polywell fusion machine, leading to a performance breakthrough reported in Physical Review in 2015, just after the Navy's funding had ended.

WB-6 Polywell device. Source: EMC2

EMC2 continued operating until 2019. It did not receive any DOE funding. See my separate article on EMC2 for more details.

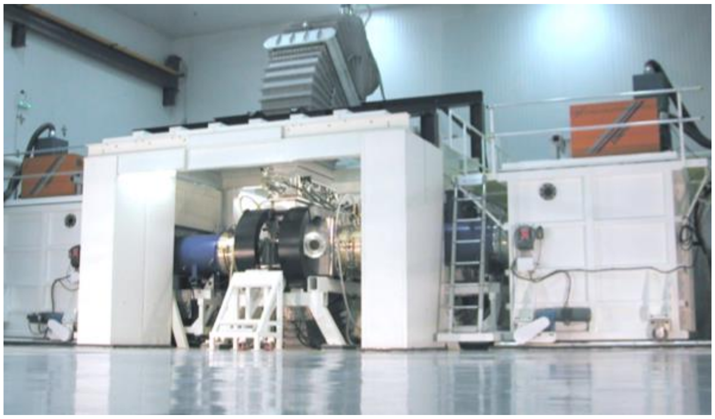
5. NIKE & Electra krypton fluoride (KrF) direct drive laser ICF machines

NIKE was a large direct-drive laser inertial confinement fusion (ICF) machine in which numerous laser beams are used to implode and compress a small deuterium-tritium (D-T) target to achieve fusion conditions. NIKE has a 56 beam, 4-5 kJ per pulse, electron beam pumped, krypton fluoride excimer laser that operated at the ultraviolet wavelength of 248 nm with a pulse width of a few nanoseconds. It was completed in 1995 at NRL in Washington, DC and has been used for investigations into inertial confinement fusion, laser-matter interactions, and high energy density physics.

- NIKE provided very uniform illumination of directly driven targets and provided the capability to ‘zoom’ the focal profile down to follow an imploding target and thereby maintain high absorption efficiency throughout a direct-drive implosion.
- Nike accelerated targets to 1,000 km/sec to explore impact ignition.
- Predicted power plant class gains with modest lasers:
  - “Conventional” direct drive: Gain: 160 @ 2.4 MJ laser
  - “Shock ignition” direct drive: Gain: 300 @ 2.0 MJ laser

NIKE reaction chamber.
Source: NRL

Electra was a pulsed 300 to 700 Joule electron beam pumped KrF laser. It demonstrated long-duration high-energy operation, with 11.5 million shots continuous, at a pulse rate of 10 Hz.



Electra.
Source: NRL

6. Plasma Compression Fusion Device

US Department of Navy filed patent application US2019/0295733A1, “Plasma Compression Fusion Device,” on 22 March 2018 and it was published 26 September 2019. Salvatore Pais was listed as the inventor and the assignee is the US Department of Navy. As of January 2021, the patent application status is “pending.”

The device is illustrated in patent Figure 1.

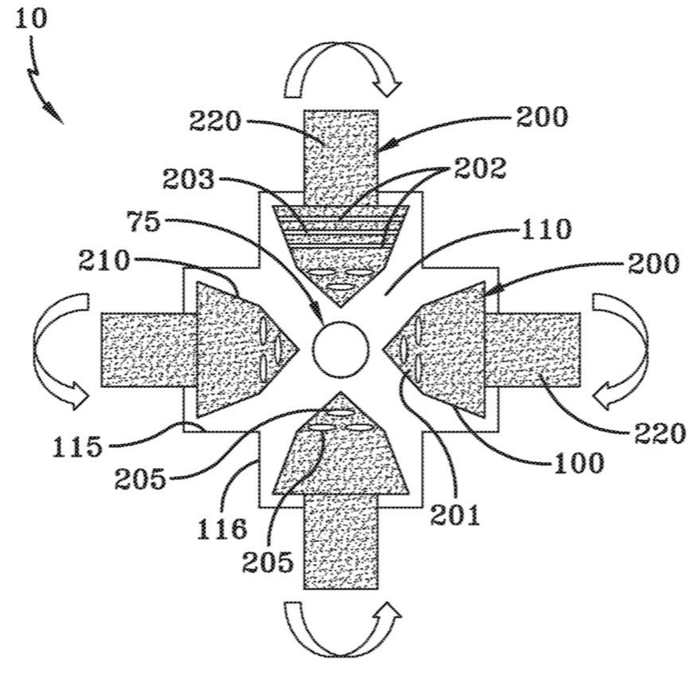


FIG-1

Legend:

10: plasma compression fusion device
75: plasma core
100: hollow, cruciform cross-duct in which all of the fusors (item 200) are located (in the diagram, the leader line from “100” should not be touching item “200.”)
110: vacuum chamber within the cross-duct
115: cross-duct inner surface
116: cross-duct outer surface (this can be the interface with a conformal heat exchanger to transfer heat to a cooling & power generation system)
200: counter-spinning conical structures, which act as dynamic fusors
201: smoothly curved apex section of the fusor
202: assemblies of electrified grids on the fusor
203: toroidal magnetic coil on the fusor
205: orifice on the fusor
210: electrically charged outer surface of the fusor
220: hollow rotating shaft of the fusor

The patent application provides the following high-level descriptions of the device.

> “The present invention is directed to a plasma compression fusion device which includes a hollow duct and at least one pair of opposing counter-spinning dynamic fusors. The hollow duct includes a vacuum chamber disposed within the hollow duct. Each dynamic fusor has a plurality of orifices and an outer surface, which is electrically charged. In combination, the pair(s) of dynamic fusors create a concentrated magnetic energy flux and electromagnetic radiation within the vacuum chamber, whereby the concentrated magnetic energy flux compresses a mixture of gases that are injected through the orifices to the vacuum chamber such that a plasma core is created, and the electromagnetic radiation heats the plasma core, while produced magnetic fields confine the plasma core between the dynamic fusors, such that when an additional mixture of gases is introduced into the plasma core through the orifices, an energy gain is created.”
>
> “In general, the invention uses controlled motion of electrically charged matter via accelerated vibration and/or accelerated spin subjected to smooth yet rapid acceleration transients, in order to generate extremely high energy/high intensity electromagnetic fields, which not only confine the plasma but also greatly compress it is so as to produce a high power density plasma burn, leading to ignition and energy gain.”

Features identified in the patent include:

- The fusion device is a small, compact package, ranging from 0.3 to 2 meters (1 to 6.6 feet) in diameter.
- Fusion fuel can be neutronic (D-T, D-D or D-Xe) or aneutronic (D-He3, p-B11), which requires much higher fusion temperatures. The uncommon deuterium – xenon fusion reaction produces Xenon-129 and two fast neutrons.
- Can produce power in the gigawatt to terawatt range (and higher), with input power in the kilowatt to megawatt range.

- Can be used for any type of application that requires the use of energy generation.
- The dynamic fusors can be used in a linear-duct configuration, a cross-duct configuration (as in the above figure), or any type of duct configuration practicable.
    - A “linear duct” configuration has just two opposing fusors.
    - A flat cross-duct configuration is shown in patent Figure 1, has four fusors in a cruciform cross-duct.
    - Other configurations are possible, such as a 3-dimensional cross-duct with six fusors.
- The key to fusion rests with the achievement of extremely high magnetic fields (B-fields), possibly exceeding 30 Tesla.
- Extremely high B-fields can be generated by controlled motion of electrically charged matter, via accelerated spin and/or accelerated vibration, subjected to rapid acceleration transients.
    - Fusors will spin at about 108 radians/sec (1,031 rpm). B_{MAX} will be on the order of 10^6 Tesla.
    - Vibration can be achieved by passing an electrical current through piezoelectric films such as lead zirconate titanate (PZT) imbedded in the plasma compression fusion device, particularly in the inner surface. PZT is the same material described in a separate Salvatore Pais patent application for a room-temperature superconductor.
- Power from neutronic fusion (D-T, D-D, D-Xe) can be extracted as heat via conformal heat exchangers (not shown in the above figure) on the duct outer surfaces. The cooling fluid carries the heat to a power conversion system that generates electricity.
- Power from aneutronic fusion (D-He3, p-B11) can be extracted via direct energy conversion.

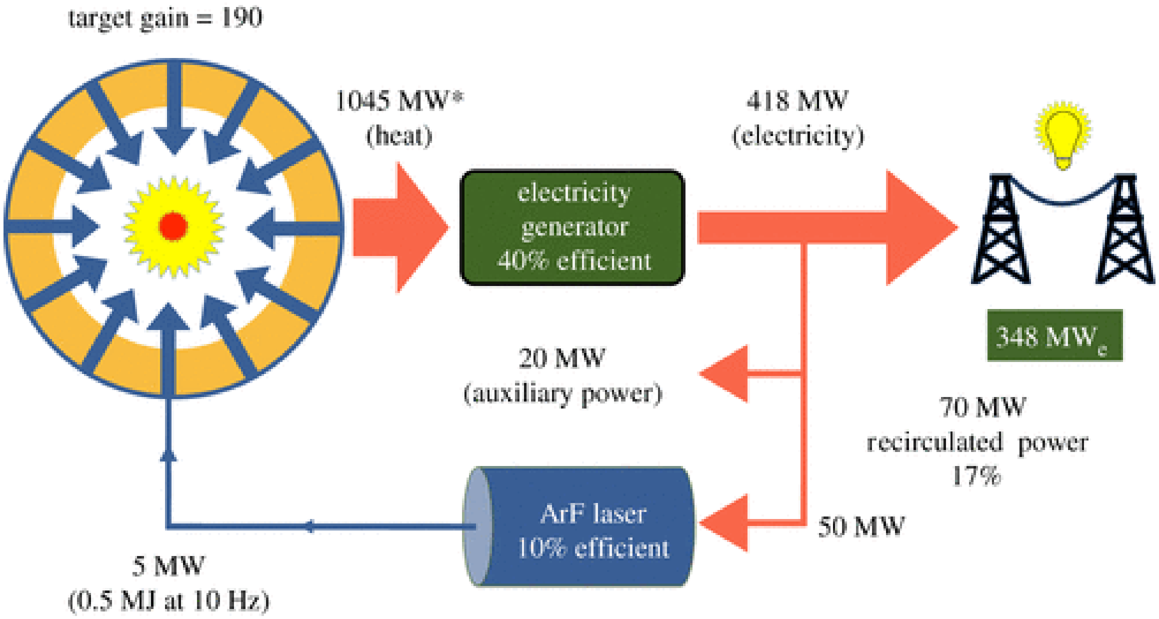
You’ll find a more detailed description in the patent application, which you can read here: https://patents.google.com/patent/US20190295733A1/en?oq=us20190295733

With no further information released by the inventor or the Navy, there has been a lot of speculation about how (or if) this device really works. It will be very exciting news if a working prototype device gets developed.

7. Argon fluoride (ArF) direct drive laser ICF machine

In October 2020, NRL announced the following milestone for their 193 nm argon fluoride (ArF) direct drive laser ICF experiment: “It delivered a laser beam capable of applying more force to implode a laser fusion target than any other laser technology.” This was accomplished with a hybrid machine that adapted parts from NRL’s older NIKE and Electra machines. This interim facility does not produce the energy required to achieve fusion.

Reporting in October 2020 on work performed at NRL, authors S. P. Obenschain, et al. described a small laser inertial fusion power plant design concept using argon fluoride (ArF) laser drivers, which currently have the shortest wavelength that can credibly scale to the energy and power required for high gain laser inertial fusion. In contrast to earlier concepts for large laser inertial fusion power plants, technical performance advantages of ArF lasers could enable the development of modest size and lower cost fusion power plant modules that operate at laser energies well below 1.0 MJ. The energy throughput for such a power plant is shown in the following diagram.



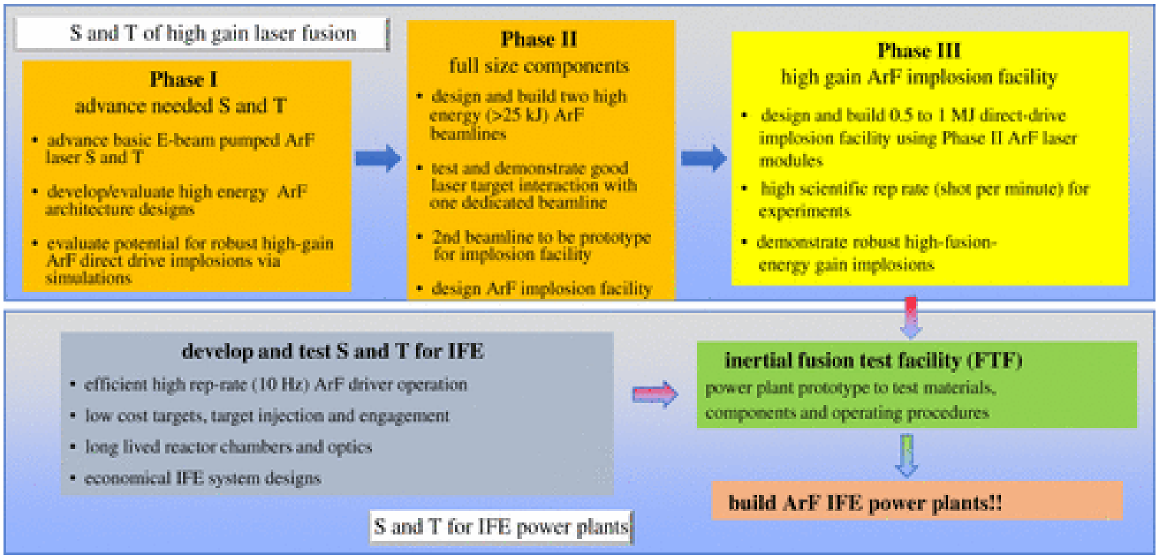
*Note: nuclear reactions in chamber ‘blanket’ enhance target gain by 1.1×

Source: Obenschain, et al. (October 2020)

The authors explain the above process diagram:

> "Here a 0.5 MJ ArF driver provides a gain of 190 by means of a shock-ignited implosion….. With a 10 pulse-per-second repetition rate the system generates 950 MW fusion power, which is amplified to 1,045 MW thermal power by nuclear reactions in the lithium-containing blanket. For the parameters shown, 418 MW of electrical power is produced with 70 MW needed to power the ArF laser and other auxiliary systems, leaving 348 MWe available to the grid."

NRL has not yet built a dedicated argon fluoride direct drive laser ICF machine. The following graphic outlines an integrated plan to advance current science and technologies to the level needed to construct an argon fluoride laser ICF test facility and power plant.



Source: Obenschain, et al. (October 2020)

Among the challenges facing a power plant application of laser inertial fusion is the need to greatly extend the period of operation between maintenance on the electron beam diode, pulsed power and optical components. For research applications, these items are maintained after thousands of shots. In contrast, the laser system for a power plant will make over 300 million shots per year if operated continuously at 10 pulses per second.

8. Conclusions

The Navy has been engaged in fusion research for a very long time. The recently published patent US2019/0295733A1 for a "plasma compression fusion device" has raised a lot of discussions, but no hard facts have emerged on the state of developing an experimental machine based on the patent.

The recent success with NRL's hybrid argon fluoride direct drive laser ICF machine suggests that a modest size direct drive laser ICF power plant is possible. Building NRL's proposed argon fluoride direct drive laser ICF test facility could give the US one of its first viable fusion reactor prototypes.

9. For more information

Stabilized liquid compressor (SLC)

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- A.E. Robson, "A Conceptual Design of an Imploding-Liner Fusion Reactor (Linus)," NRL Memorandum Report 3861, Office of Naval Research, Naval Research Laboratory, September 1978: https://apps.dtic.mil/dtic/tr/fulltext/u2/a060588.pdf

Low Energy Nuclear Reactions (LENR aka cold fusion)

- "U.S. Navy Cold Fusion Research," a library of papers about cold fusion, LENR-CANR.ORG: https://lenr-canr.org/wordpress/?page_id=952
- S. Szpak & P.A. Mosier-Boss (editors), ""Thermal and Nuclear Aspects of the Pd/D2O System," Volume 1, "A Decade of Research at Navy Laboratories," SPAWAR, February 2002: https://www.lenr-canr.org/acrobat/MosierBossthermaland.pdf

Polywell

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NIKE and Electra krypton fluoride direct drive laser ICF

- Nicholas Cunningham, “NIKE krypton fluoride direct drive laser inertial fusion,” American Security Project, 21 May 2013: https://www.americansecurityproject.org/nrl-nike-laser-focuses-on-nuclear-fusion/
- S. P. Obenschain, et al., “High-energy krypton fluoride lasers for inertial fusion,” Applied Optics, Vol. 54, No. 31, 1 November 2015: https://www.osapublishing.org/DirectPDFAccess/36C22D74-BD17-4BA2-8437B2C4C7898386_324139/ao-54-31-F103.pdf?da=1&id=324139&seq=0&mobile=no

Argon fluoride direct drive laser ICF

- “NRL-built Argon Fluoride Laser marks breakthrough, sets new energy record,” CISION PR Newswire, 18 September 2020: https://www.prnewswire.com/news-releases/nrl-built-argon-fluoride-laser-marks-breakthrough-sets-new-energy-record-301134182.html
- S. P. Obenschain, et al., “Direct drive with the argon fluoride laser as a path to high fusion gain with sub-megajoule laser energy,” The Royal Society Publishing, 12 October 2020: https://royalsocietypublishing.org/doi/full/10.1098/rsta.2020.0031

Plasma Compression Fusion Device (2019 Patent)

- US2019/0295733A1, “Plasma Compression Fusion Device,” inventor: Salvatore Pais, filed 22 March 2018 by US Department of Navy, published 26 September 2019, assigned to United States of America as represented by the Secretary of the Navy: https://patents.google.com/patent/US20190295733A1/en?oq=us20190295733
- Brett Tingley & Tyler Rogoway, “Scientist Behind The Navy's ‘UFO Patents’ Has Now Filed One For A Compact Fusion Reactor,” The Drive / The War Zone, 9 October 2019: https://www.thedrive.com/the-war-zone/30256/scientist-behind-the-navys-ufo-patents-has-now-filed-one-for-a-compact-fusion-reactor

- Ariel Cohen, “A Breakthrough In American Energy Dominance? U.S. Navy Patents Compact Fusion Reactor,” Forbes, 30 October 2019: https://www.forbes.com/sites/arielcohen/2019/10/30/a-breakthrough-in-american-energy-dominance-us-navy-patents-compact-fusion-reactor/?sh=1a8b0a210701
- Jennifer Leman, “The Navy's Patent for a Compact Nuclear Fusion Reactor Is Wild,” Popular Mechanics, 10 October 2019: https://www.popularmechanics.com/science/energy/a29427713/navy-compact-fusion-reactor/