Developing Acoustic Magnetized Target Fusion
An Overview of the Science and Development Program at General Fusion

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Abstract

Magnetized Target Fusion (MTF) is an alternative approach to fusion which proposes to meet Lawson's criterion for net gain by the rapid compression of a compact toroid plasma using a conductive metal wall. This paper provides an overview of the science behind MTF and General Fusion's systematic development program to design, test, and demonstrate the ability to produce energy using its acoustic MTF technology.

1. Background

Magnetized Target Fusion was first proposed in the 1970's and the US Naval Research Lab did significant work on MTF through the LINUS program [1]. Working in an intermediate regime of plasma density and confinement, MTF is recognized for its low cost potential. LINUS in particular, with its use of compressed gas for compression and thick liquid metal liner provided an elegant solution to traditional fusion challenges of heat extraction, tritium breeding, and neutron flux on structural components [2],[3]. Unfortunately the short lifetime of compact toroid plasmas and slow compression times did not allow the LINUS concept to be constructed using the technology of the day.

General Fusion is pursuing acoustically driven magnetized target fusion technology that it developed following reviews of the literature on the promise of MTF, starting from the LINUS concept. Using modern servo control systems, General Fusion is making use of impact to create an acoustic wave in a thick liquid metal liner and speed up compression a thousand fold compared to LINUS, to less than 80 μs. When combined with modern compact toroid plasma technology allowing the creation of plasmas with lifetimes over 100 μs, an MTF reactor with the potential to achieve net gain can be developed today.

2. System concept

In designing an appropriate development program, careful consideration was given to the scale of experiments that would verify MTF for the lowest risk and cost. General Fusion is a private company, and it was determined that demonstrating net energy gain would be necessary to allow the company to secure the resources for a follow-on commercialization program. We rejected pursuing smaller scale MTF research because cost savings were minimal and a multi-step timeline would take longer. Finally, net gain equivalent tests are required to address the largest technical risks and we determined it was best to undertake those tests as quickly as possible.

General Fusion's prototype system was designed to achieve net gain and demonstrate economic viability, assuming worst case scenarios for plasma heat loss (General Fusion has assumed

Bohm losses, an assumption external reviewers have suggested is overly pessimistic). In General Fusion's MTF concept a small, low temperature, and relatively low density magnetized plasma (40 cm, 100 eV, beta 10%, 10^{17} particles/cm^3) is created in a metallic enclosure and compressed in <100 μs to 4 cm in size, 10 keV, 10^{20} particles/cm^3. Peak compression is maintained for a few microseconds, satisfying Lawson's criterion [4]. Achieving these parameters requires compression energy levels of up to 100 MJ.

The lowest cost option, by an order of magnitude, was a low repetition rate, compressed air-driven piston system. Current MTF research at Los Alamos National Labs and the Air Force Research Labs takes advantage of the Shiva Star capacitor bank [5], however in General Fusion's case electrical drivers were rejected because the cost of large capacitor based pulse power supplies - at \$2 to \$5 per joule - resulted in an estimated cost of over \$200 million. To prove the physics and achieve net gain on a single-shot basis, General Fusion aims to construct a piston-driven system capable of only 1,000 cycles at an estimated total cost of \$35 million.

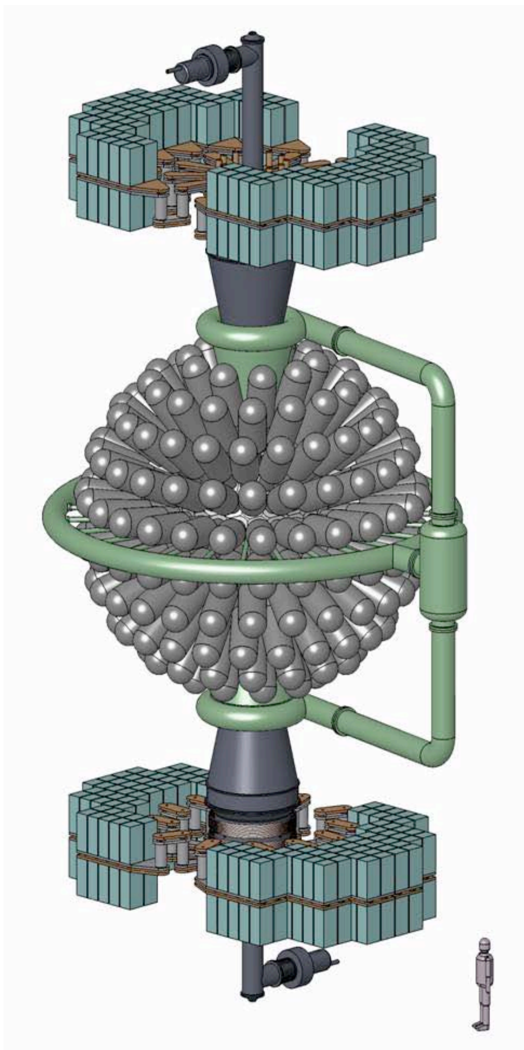

Figure 1: General Fusion's Acoustic MTF Reactor Concept

The pneumatically driven system is General Fusion's principal innovation. It creates a focused shock wave for compressing the plasma with a blanket of liquid lead-lithium. The major advancement over other thick liner systems is the use of servo controlled impact to increase the compression power 1,000 fold (each piston is accelerated in 80 ms and at impact transfers its energy in 80 μs) [6]. Based on computer simulations, this will require synchronization of piston impacts to within 20 μs.

For a future power plant, economics, neutronics, tritium supply, and overall reactor energy density do need to be considered.

The integral liquid lead-lithium liner provides a number of key benefits. As an atomic liquid, nothing is destroyed by the fusion reaction avoiding the "kopeck" problem (to be economically viable, pulsed systems, including both MTF and IFE, must generate significantly more revenue with each pulse than the cost of any hardware consumed). The eutectic absorbs the bulk of the fusion products through elastic scattering and provides a straightforward means of extracting the energy. The thick blanket significantly shields the wall by reducing the neutron flux on the structure and by lowering the neutron energy spectrum [7]. The 4 pi coverage provides an enhanced tritium breeding ratio (TBR) of 1.6 to 1.8 [8]. The neutron multiplication factor results from the Pb(n,2n) reaction and also from the $^{7}Li + n \rightarrow {}^{4}He + {}^{3}H + n$ reaction as diagramed by Moyer [9]. The challenge with a thick Pb-17Li liner is likely to be too much tritium production.

General Fusion is proposing a system with a core power density of 40 MW/m^3. This would be similar to reactors such as Westinghouse's AP1000 with a power density of 23 MW/m^3. Other proposed designs are much higher: the Russian SVBR-100 lead-cooled reactor has a design spec of 160 MW/m^3, and proposed fusion power plants such as HYLIFE-II indicate densities of 50 MW/m^3 to 100 MW/m^3 [10],[11].

3. Principal risks

The biggest risks to the project are plasma cooling due to plasma instability during compression and plasma/wall interaction leading to plasma contamination by high Z materials. Heat loss via plasma instability/turbulence has been experimentally derived and scaling laws formulated. Unfortunately, the scaling laws for compact toroid plasmas have only been verified to plasma densities of ~10^{17} particles/cm^3; they are extrapolated for higher densities. Further experimentation at fusion relevant densities is required to verify plasma behaviour.

Regarding plasma/wall interaction, it can be calculated that contamination levels of 10% for Li and 0.01% for Pb can be tolerated for the expected compression timescales in a General Fusion system. Indications are that if Bohm-like diffusion is present then a protective layer of Li will have to be implemented; for gyroBohm diffusion it is likely that mixing will be acceptable even for Pb [12]. General Fusion is undertaking a full simulation of plasma compression including plasma/wall mixing in partnership with the All Russian Research Institute for Experimental Physics (VNIIEF).

Both the plasma stability and plasma/wall interaction risks have been thoroughly discussed with all of General Fusion's external advisors. The consensus is that neither issue is expected to prevent the system from working however experimental verification is required to be certain. General Fusion is focusing on mitigating these risks with our (i) development and experimentation program, (ii) simulation work in collaboration with VNIIEF and others, and (iii) cooperative research and development agreement (CRADA) for ongoing MTF research at Los Alamos National Labs (LANL). Plasma experiments at LANL will use electrically driven implosion of an aluminum liner, and the results will be used to verify plasma scaling laws at densities from 10^{16} and up to 10^{19} particles/cm^3 [13],[14],[15],[16].

4. Development program

General Fusion is pursuing a methodical project plan, first scaling up and constructing major components, then verifying component performance, and finishing with full system construction. In parallel, design and experimentation will be matched and calibrated against computer simulation work internally and in partnership with other institutions. The entire program is expected to take at least four years to complete.

Our primary objectives for the first two years are:

- Construct a full scale plasma injector, producing a spheromak of 10^{17} particles/cm^3 and 100 eV [17].
- Construct 14 full scale pistons assembled onto a scale version of the liquid lead vortex chamber to produce a symmetrical driven and partially spherical implosion in liquid Pb-Li.
- Magneto-hydrodynamic (MHD) plasma simulations, calibrated to our plasma injectors.
- Hydrodynamic simulations of acoustic driven implosions in two and three dimensions, calibrated to piston experiments.

Furthermore, General Fusion is undertaking low cost chemically driven experiments to rapidly compress a magnetized plasma target. The literature discusses such tests; however, we have found no experimental results in open publications [18],[19]. With the support of NRC-IRAP, field trials to verify plasma compression at small scale (10 keV, 10^{17} particles/cm^3) are expected to be completed by July, 2011. Larger scale verification tests (10 keV, 10^{20} particles/cm^3) would follow towards the end of 2011.

Construction of the full scale piston-driven system will only proceed once the above work is complete and calibrated computer simulations show that the full scale system will achieve net gain.

5. Program status

General Fusion began its development program in September, 2009 after securing a significant venture capital investment. Per the program, the first plasma injector was constructed and began operation in May, 2010. Testing on this injector has continued with power gradually increased to the full design power of 2.4 MJ.

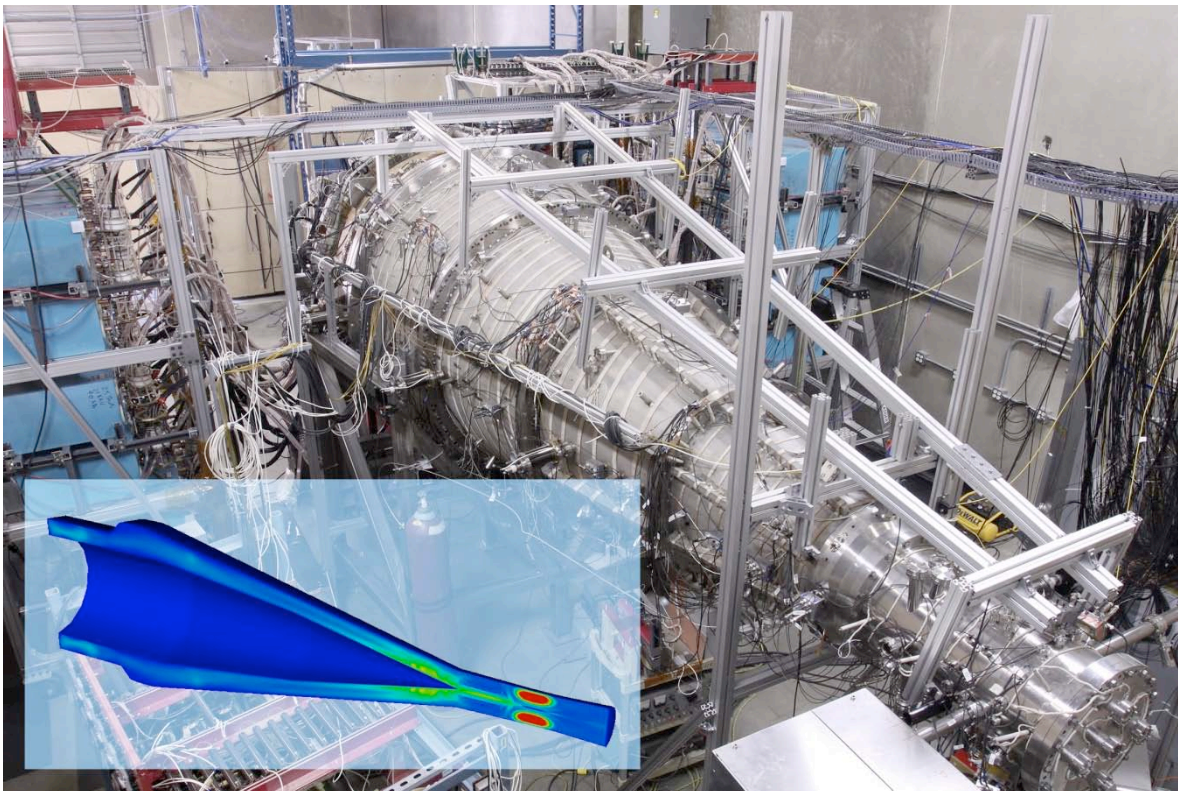

Figure 2

General Fusion's plasma injector including; 2.4MJ (100 GW) pulse power supply (22kV formation, 44kV acceleration), programmable pulse shaping control, 1 MW DC stuffing flux power supply, and diagnostics (Thomson scattering, X-ray photo diodes, triple Langmuir probe, 5 interferometer chords, >12 Rogowski coils, >50 B-dot probes with in-situ integration, high resolution time resolved spectroscopy).

The device continues a long tradition of Canadian plasma injector innovation and experimentation. The first non-disruptive CT injection demonstrated on TdeV at the CCFM using the CTF, designed and constructed under a contract with the Canadian Fusion Fuels Technology Project [20],[21],[22]. A smaller compact torus injector built with funding from NSERC was installed on STOR-M in 1995 [23],[24],[25]. Compact toroid fueling designs proposed for ITER by Canadian scientists [26],[27].

Inset: NIMROD simulation of CT formation and acceleration in a plasma injector.

General Fusion has also constructed two full scale acoustic driver systems. The first is used for servo control development and uses and air damping system to absorb the impact energy. This system has demonstrated successful servo control of impact timing to within ±8 µs. The second system (shown below) incorporates a liquid metal system and has been used to verify impact of pistons on liquid lead. Simulations and measured results of acoustic wave propagation through the lead in this system agree to within 10-20% of absolute values.

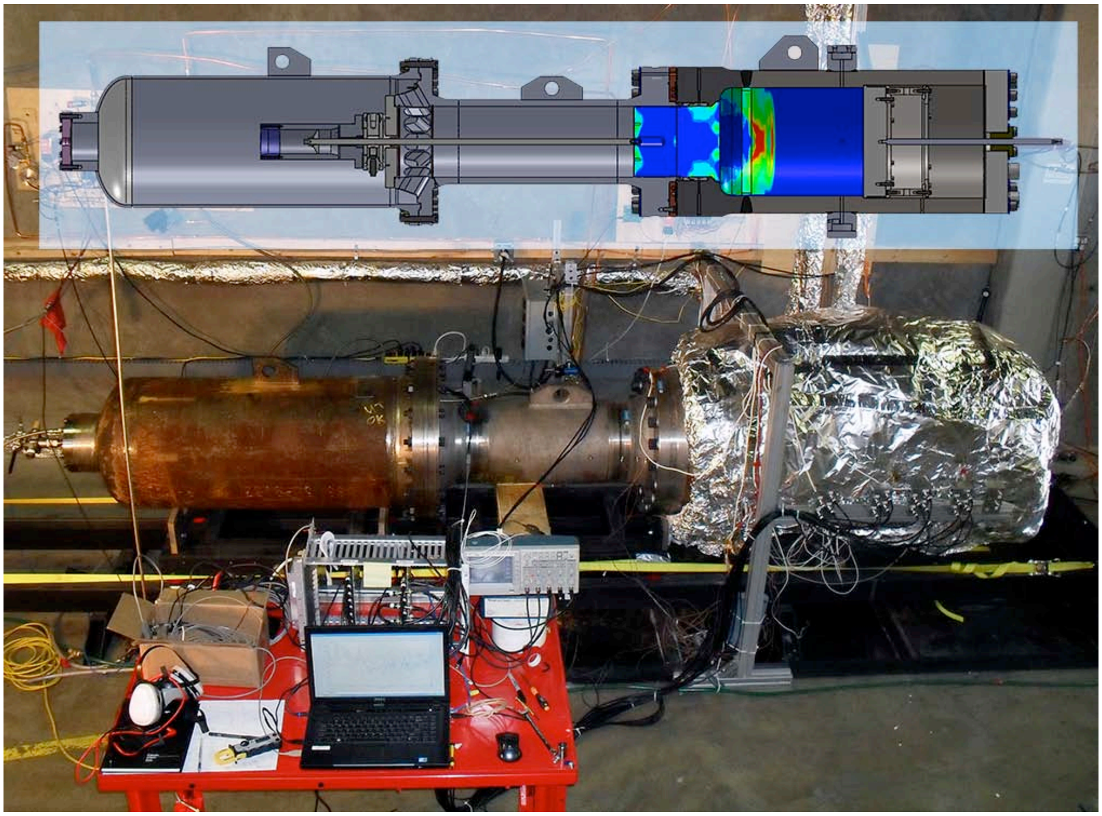

Figure 3

Single 500 kJ (5 GW) acoustic driver including: molten metal (400 ˚C) target chamber, Pb/Li mixing station, molten metal storage pot, and pumping system.

Inset: Mechanical drawing superimposed with LS-Dina simulation of acoustic wave impact through molten lead.

General Fusion is currently designing a 14 piston assembly to test the synchronized impact and collapse of a vortex in liquid lead-lithium. This system will be completed in 2011. Results from this “ring” system will be used in combination with simulation to design the full scale prototype reactor.

Understanding vortex dynamics and stability will also be important for the design of a full scale prototype reactor. Through its project with the University of Victoria, General Fusion has constructed a 1/3 scale acrylic sphere water vortex apparatus. Vortex simulations and behaviour is being studied (images below).

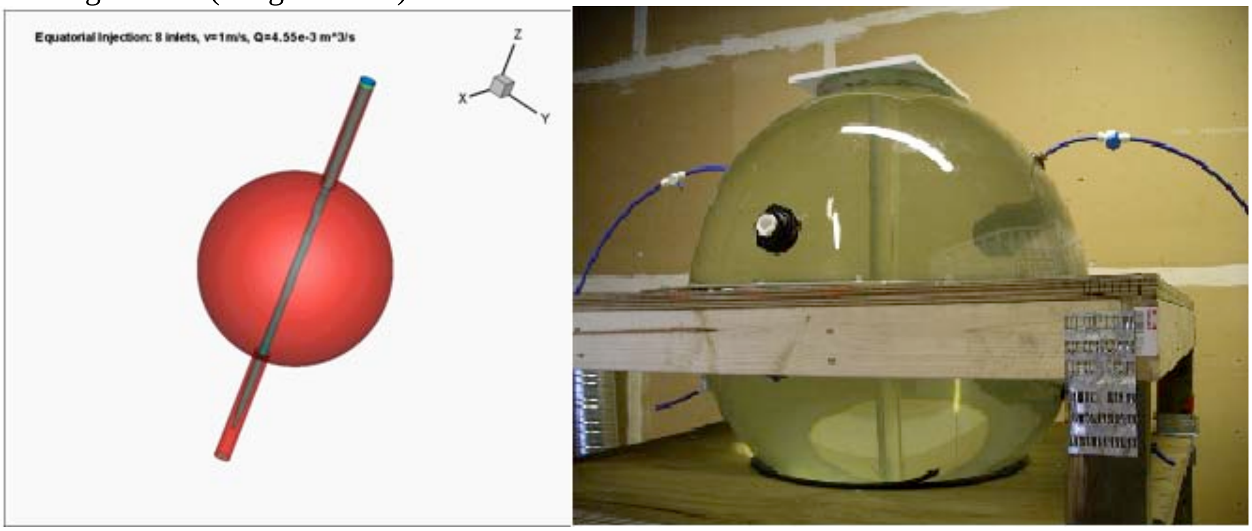

Figure 4

Vortex simulation and 1/3 scale model with water vortex

6. Acknowledgements

Our team, our investors, NRC-IRAP, and SDTC have no illusions about the difficulty of this challenge. The bulk of our funding is from experienced private technology investors. Funding is staged and contingent on validation by external experts for each of our key milestones. This investment is going directly into Canadian jobs and Canadian technology. General Fusion would like to thank them all for their support.

The due diligence by all our investors and funding sources has included external reviews from leading fusion researchers in the US, Europe, and Canada, including scientists from Lawrence Livermore National Labs, LANL, VNIIEF, the FOM Institute for Plasma Physics, UC Berkeley, University of Washington, the US Air Force Research Laboratory, and UC Davis. In all cases, peer reviews following detailed analysis and meetings have reached the same conclusion: the physics underlying General Fusion's approach is sound. Furthermore, our engineering systems were reviewed in detail by the Phantom Works division of the Boeing Company. They concluded that the engineering, project, and schedule were feasible. The consensus from all detailed reviews is that the physics is solid, the engineering is challenging but achievable, and the technology is worth pursuing. These reviewers and advisors continue to be important contributors to the project.

General Fusion is proud to have formal research and development agreements with LANL and VNIIEF. With the support of NSERC and MITACS, General Fusion is funding research at Queen's University and the École Polytechnique of Montreal. We would also like to acknowledge past collaborations with researchers at UBC, the University of Victoria, and the Department of Defence Research Groups in Valcartier and Suffield.

The progress to date represents the work of a dedicated team that now includes over thirty-five engineers and scientists, including ten Ph.D.s in physics. General Fusion continues to build our team and is actively recruiting plasma physicists and magneto-hydrodynamic simulation researchers in Canada and abroad.

General Fusion firmly believes that there are areas where Canadian researchers and industry have expertise that could assist our efforts. From the beginning, General Fusion has been open with the scientific community and we invite interested scientists to contact us, to share ideas, to debate, and to pursue good science with the hopes of advancing the prospects of fusion power to the benefit of all Canadians.

7. References

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