Experimental Results for an Acoustic Driver for MTF

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Abstract General Fusion is planning to form an FRC or spheromak of 10^{17} cm^{-3}, 100 eV, 40 cm diameter by merging two spheromaks with reverse or co-helicity. This target will be further compressed in a 3 m diameter tank filled with liquid PbLi with the plasma in the center. The tank is surrounded with pneumatically powered impact pistons that will send a convergent shock wave in the liquid to compress the plasma to 10^{20} cm^{-3}, 10 keV, 4 cm diameter for 7 μs. General Fusion has built a 500 kJ, 80 μs, 6 GW pneumatic impact piston capable of developing 2 GPa (300 kpsi). In this paper we will present the performances achieved to date.

Keywords Magnetized target fusion · Spheromak · FRC · Shock wave

General Fusion MTF Concept

General Fusion proposes a new MTF compression system that offers many advantages. A near spherical vessel ~3 m in diameter is filled with liquid lithium–lead alloy (Li–Pb). This liquid is under consideration for fusion reactor blankets; it has a low melting point, low vapor pressure, re-breeds the tritium, and good nuclear characteristics. The liquid is spun in the vessel by pumps that inject the liquid tangentially near the equator and pump it out near the poles (Fig. 1). This creates a vertical vortex tube in the liquid metal. The vessel is surrounded by 200 steam actuated pistons. The steam accelerates the pistons to ~100 m/s. The pistons impact the spherical vessel and send a strong acoustic wave in the liquid metal. The pressure developed at the impact is: $P = \rho v c_s/2$ where ρ is the density, v the speed of impact and c_s is the sound speed in the impacting material. For steel $\rho = 8000$ kg/m^3 and $c_s = 5000$ m/s so the pressure developed is 2 GPa (300 kpsi). Good steel can handle up to 3 GPa (450 kpsi) of compression. The efficiency of the driver can be quite good. About 33% of the thermal energy goes into piston kinetic energy (the usual thermal to mechanical efficiency at realistic temperatures). For steel and liquid lead (specific gravity 10.8, $c_s = 2$ km/s), the acoustic impedance (density*speed of sound) match is good with 91% of the energy going into the liquid lead. The wave then focuses in the center, getting stronger. Just prior to the wave collapsing the center vortex, two spheromaks (a toroidal magnetized plasma configuration) of reverse helicity are injected from the top and bottom of the system. Tapered coaxial railguns accelerate and compress the injected spheromaks. They move rapidly to the center where they merge to produce a stationary FRC (Field Reverse Configuration). The advantages of this plasma target are that it can be rapidly sent in the center just prior to collapse and then stays there with low velocity while the vortex collapses and compresses it. If FRC stability is insufficient we can also inject spheromaks with co-helicity to form a spheromak target.

The target plasma parameters before compression are:

Diameter: 40 cm
Density: 10^{17} cm^{-3}
Temperature: 100 eV

And after a spherical adiabatic compression with 10:1 radial contraction the plasma will have the following parameters:

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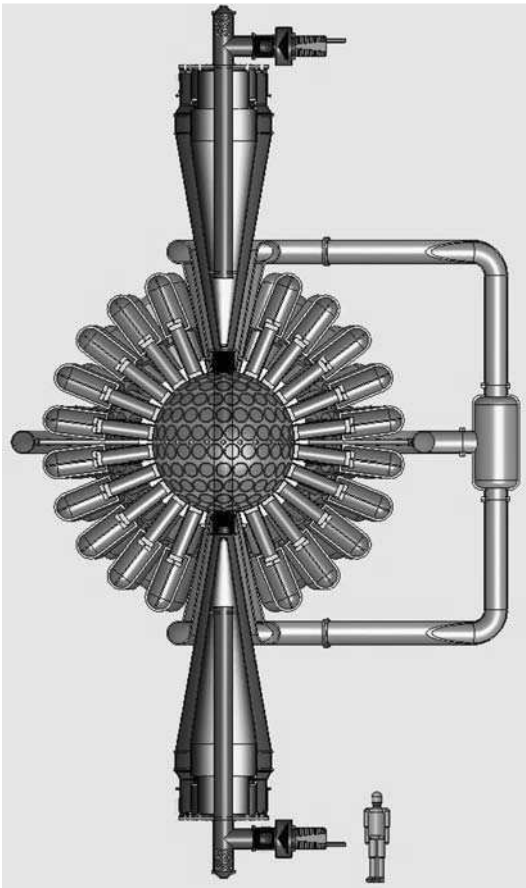

Fig. 1 Proposed MTF system

Diameter: 4 cm
Density: 10^{20} cm^{-3}
Temperature: 10 keV
Time at peak compression: 7 μs

After compression, the fusion energy is released in neutrons that heat the liquid metal. The cycle is repeated at ~1 Hz. The liquid metal goes in a heat exchanger to make steam. The steam is directly used to push on the pistons. Therefore the re-circulated power does not have to be converted in electricity, reducing the cost of the turbo-machinery and generator. Typical MTF systems use pulse power technology worth around $3/J. For typical fusion systems of order 100 MJ this is $300 million just for the pulse power system. 100 MJ of steam at 1300 psi in a 10 m^3 tank plus associated fast acting valves will cost of the order of $500 000; a considerable savings. Because of the high accuracy of the impact timing of the numerous pistons (~1 μs), an electric means of controlling the exact piston trajectory is required. But this system only needs to control a few percentage of the piston energy. In particular, the servo can rely on braking action alone and will not require any high power electrical components. The pistons are sent a few percent above the required velocity and a servo loop applies just the required braking to adjust the impact time and velocity. The spheromak injector will use a pulse power electrical system. But as only ~1% of the compression energy is required for the initial plasma, this should be only a ~1 MJ system worth ~3 M$. Most neutrons and all other radiations are stopped in the ~1.5 m radius of Pb–Li so the neutron flux at the wall is much reduced. This is extremely advantageous over many other fusion systems where neutron and radiation wall loading is a difficult and mostly unresolved technical issue. Many MTF systems under consideration also require the destruction and replacement of substantial amounts of hardware for each pulse; a costly and complex proposition. Our proposal does not require hardware replacement for each pulse.

Acoustic Drivers

This new proposal requires the development of precise pneumatic impact drivers.

We have built one such driver (Fig. 2) with the following specification:

Piston diameter: 30 cm
Piston length: 20 cm
Piston Material: S7 hardened tool steel with a compressive yield of 2 GPa (300 kpsi)
Piston mass: 100 kg
Stroke: 1 m
Displacement: 0.07 m^3
Pressurized tank volume: 0.21 m^3
Tank air pressure: 8.7 MPa (1300 psi)
Pressure force on the piston: 5×10^5 N (50 Tons)

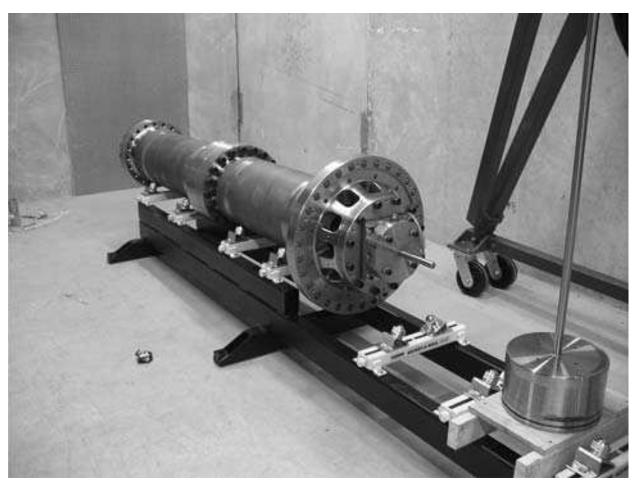

Fig. 2 Acoustic driver without pressure tank, piston with control rod on the right

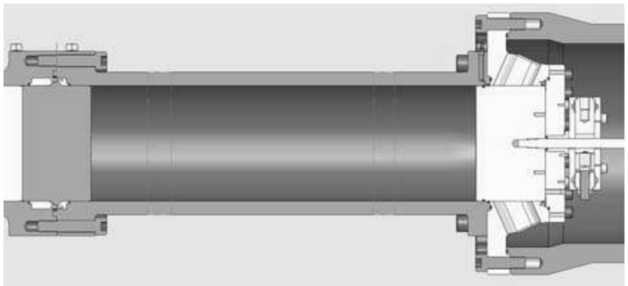

Fig. 3 Mechanical drawing of the acoustic driver

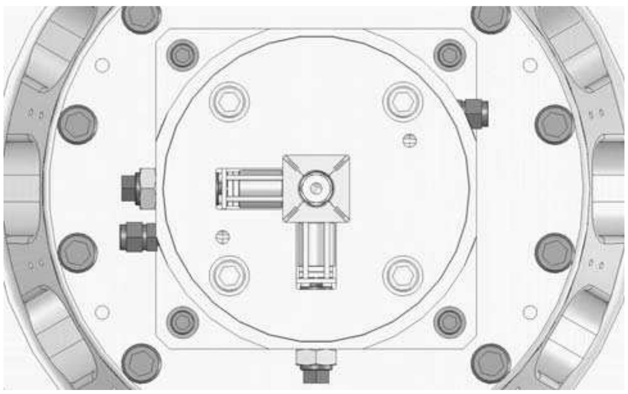

Fig. 4 Mechanical drawing of the piezo brake

Acceleration: 500 g
Final impact velocity: 100 m/s
Pressure developed at 100 m/s impact: 2 Gpa (300 kpsi)
Energy release at impact: 500 kJ
Duration of the acoustic pulse: 80 μs
Power in the acoustic pulse: 6 GW
Servo sensor: quadrature incremental optical encoder with 160 μm line spacing
Servo actuator: piezo electric friction brake with 10 μs response time
Maximum braking force: 10^4 N (1 Ton) 2% of air pressure force
DSP for digital servo control: Texas Instrument TMS320C6713B, clock 225 MHz

The compressed air is in a tank behind the piston (right on Fig. 3). Large ports can carry the air to the back of the piston during the stroke. At the reset position (shown on Fig. 3) the piston blocks these large ports and the front and back side of the piston is evacuated. The air pressure only acts on the diameter of the 25 mm (1 inch) diameter control rod that is attached behind the piston. That is a force of 5000 N (1000 pounds) and the piezo brake can retain the piston against that force. When the brake is released the piston slowly moves forwards until the large ports open and the pressure pushes on the full surface of the piston developing 5×10^5 N (50 Tons) of trust to accelerate the piston down the stroke. At the end of the stroke the piston hits the "anvil". The anvil is captivated both ways by a ridge running in a circular slot around it. There is 5 mm of axial play. On impact the anvil moves forward by 4 mm and sends the compression acoustic wave in the liquid lead on the left of it. Presently we use a third piston to absorb the impact energy and we run at room temperature. We will fill the tube with liquid lead later on, when nominal operation parameters are achieved. The piezo brake consists of two Physik Instrumente P-025.20 piezo stack of 25 mm diameter, 30 mm long, 30 μm expansion at 1000 V, 13000 N blocking force each, 32 kHz resonant frequency and 820 pF of capacitance. They are placed at 90° around a brass block that surrounds the control rod (Fig. 4). Flexures in that block allow for compressing the rod when voltage is applied to the piezo stack.

After release the optical encoder etched on the control rod is read by fiber optics and the position of the piston is measured to an accuracy of 20 μm. The control algorithm compares the measured position to the exact trajectory required to impact at the desired time and changes the braking force to keep the piston on that trajectory. Because the actuator delay (10 μs) is longer than the impact accuracy required (estimated to be about 1 μs) a predictive forward looking digital servo algorithm is required. The stretching and time delay of acoustic tension wave in the

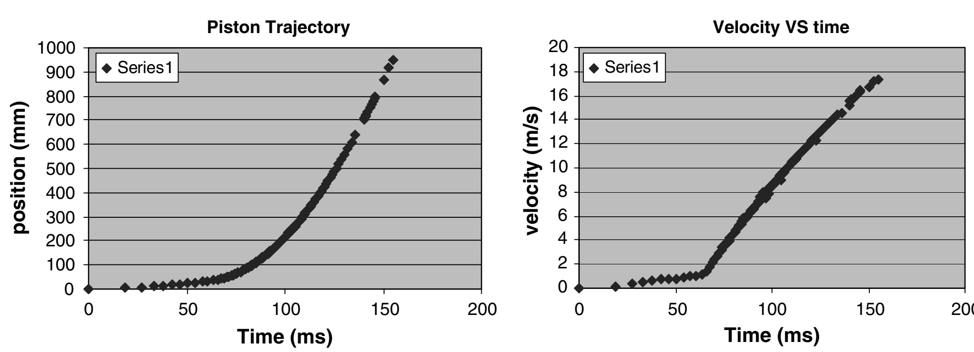

Fig. 5 Piston trajectory and velocity

rod must also be taken into account by the servo algorithm. At the terminal velocity of 100 m/s, a 1 μs timing accuracy corresponds to a distance accuracy of 100 μm, well within reach of the optical encoder precision.

We have so far achieved 17 m/s in open loop. The DSP can control the brake and read the encoder, but the control code is not operational as of today. The control rod broke at the piston connection. This is being re-designed with an oil filled shock absorber for the control rod. Figure 5 shows the position and velocity as a function of time for a 17 m/s shot. There is a slow acceleration until the ports open. The acceleration decreases slightly with time because the pressure in the tank drops as the piston moves down the stroke.

In the proposed MTF concept, 200 such drivers will surround the spherical vessel for a total energy of 100 MJ and a power of 1.2 TW.

Conclusion

General Fusion proposes a new MTF concept requiring precise pneumatic impact drivers. We have built one such driver and achieved so far an open loop impact velocity of 17 m/s. Impact velocity approaching 100 m/s with precise close loop control will be required.