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ORIGINAL PAPER

An Acoustically Driven Magnetized Target Fusion Reactor

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Abstract We propose a new acoustic compression scheme for a MTF power plant. A strong acoustic wave is produced by piston impacts. The wave focuses in liquid PbLi to compress a pre-formed FRC plasma. Simulations indicate the possibility of building an economical 60 MWe power plant. A proof-of-principle experiment produces a small D-D fusion yield of 2000 neutrons per shot.

Keywords Fusion power plant · Magnetized target fusion · Acoustic compression

Introduction

Magnetic target fusion (MTF) is a new fusion regime presently being studied by many researchers. Magnetic fusion operates at a plasma density of around 10^{14} cm^{-3} and needs a confinement time of ~1 s to achieve energy gain. This turned out to be difficult because of anomalous transport. The inertial confinement approach seeks a density of 10^{25} cm^{-3} and requires a confinement time of 1 ns. Researchers are facing difficulties with the stability of the implosion and the extreme power requirement of the driver. MTF is an intermediate concept requiring a density of ~10^{20} cm^{-3} and a confinement time of 1 µs. Because the pressure of a plasma of this density at a thermonuclear relevant temperature is ~1 Mbar, only a pulsed machine can generate these pressures.

The MTF approach consists of producing a cold, low density plasma and rapidly compressing it to thermonuclear conditions. Because of the much reduced confinement time requirement compared to magnetic fusion, the reduced plasma lifetime due to plasma instabilities is now acceptable. Also, the energy required to compress the plasma is delivered in a much longer time than the inertial approach, reducing the power and complexity of the driver.

The most studied MTF approach is to inject the cold plasma in a metallic tube. A large current from a capacitor bank passes in the tube and makes it collapse at high speed (~5 km/s). The tube and the cables leading to it must be replaced after each shot. The reaction chamber must be protected from debris and fusion products. These issues make such a scheme quite complex and likely expensive.

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Acoustically Driven MTF

We propose a new compression system that offers many advantages. A near spherical vessel ~2 m in diameter is filled with liquid lead-lithium alloy (PbLi). This liquid is under consideration for fusion reactor blankets; it has low a 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. This creates a vertical vortex tube in the liquid metal. The vessel is surrounded by many steam actuated pistons. (Fig. 1). High pressure 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 ρ = 8000 kg/m and c_s = 5000 m/s so the pressure developed is 2 GPa. Good steel can handle up to 3 GPa of compression. The duration of the acoustic pulse is twice the thickness of the piston, divided by the

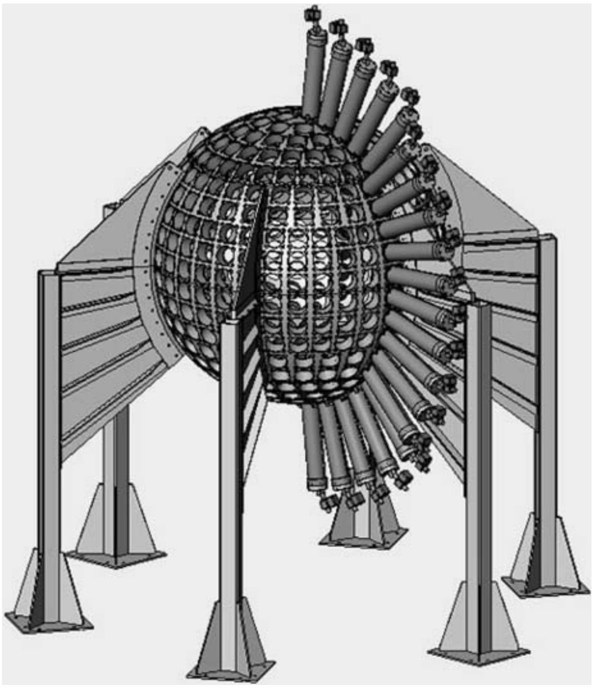

Fig. 1 Reactor tank with some of the cylinders installed

steel speed of sound. For a typical piston of 10 cm thickness, this is a pulse duration of 40 μs. The power injected in the fluid is 0.2 TW/m^2. For a sphere of 2 m diameter the total power is 2.5 TW, an MTF relevant power level. The efficiency of the driver can be quite good. About 33% of the steam thermal energy goes into piston kinetic energy (the usual thermal to mechanical efficiency of a steam cycle at a realistic temperature). For steel and liquid lead (density 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. 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 stay there with low velocity while the vortex collapses and compresses it. The toroidal magnetic field is canceled and its energy goes in thermal energy heating up the plasma just prior to compression. Also, it has been observed that when merging, the resulting plasma has higher ion temperature than electron temperature. As radiation losses increase with electron temperature but fusion goes with ion temperature, this may somewhat improve the operation. 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 turbomachinery 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 1500 psi in a 10 m^3 tank plus associated fast acting valves will cost of the order of $500 000; a considerable saving. Because of the high accuracy of the impact timing of the numerous pistons (~1 μs), an electric means of controlling the exact piston trajectory is required. But this system can control only a few % of the piston energy. In particular, it can be a braking only system not requiring any high electrical power components. The pistons are sent a few percent above the required velocity and a servo loop applies just the required braking to adjust the impact time and velocity. The spheromak generator will use a pulse power electrical system. But as only ~1% of the compression energy is required for the initial plasma, this should be only a 1 MJ system worth ~3 M$. Most neutrons and all other radiations are stopped in the ~1 m radius of PbLi 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. Radio isotopes produced by neutron activation of the structure is also a problem, especially for maintenance, in most proposed fusion machines. Expensive robotic maintenance is the usual answer to this problem. It is much less of an issue for our proposed machine. 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. Finally, the PbLi re-breeds the tritium. The full solid angle coverage offers very good breeding ratio. The solubility of tritium in PbLi is very low so there is less than 1 g of tritium inventory in the liquid metal, an important safety advantage.

Simulation

Optimizing the parameters for the smallest possible power plant (to reduce cost of development), a simple 1 D hydrocode predicts the following parameters.

	Initial pre-formed plasma	Compressed plasma
Density	1.2×10^{17} cm^{-3}	1.2×10^{20} cm^{-3}
Temperature	100 eV	25 keV
Diameter	40 cm	4 cm

	Initial pre-formed plasma	Compressed plasma
Magnetic field	7 T	666 T
Kinetic energy of pistons	120 MJ	
Radial compression	9.76	
Energy transferred to plasma	14 MJ (12%)	
Fusion yield	704 MJ	
Energy gain	5.9	
Maximum liner velocity	2.6 km/s	
Peak plasma pressure	4.7 Mbar	
FWHM of peak density: substantial alpha particles heating	6.9 μs	

A power plant with 30% thermal to mechanical efficiency and 0.5 Hz would generate 64 MWe.

Experiment

Although we intend to use the impact of pistons to generate the shock in future machines, we decided to use a simpler shock generator for this small experiment.

The energy to produce the shock comes from 30 2 μF 40 kV capacitors storing 50 kJ. Each capacitor is connected to a 50 μm thick aluminum foil spiral laminated on a 1.5 cm thick polycarbonate tile. The 30 tiles are arranged to cover the inside of a 9.5 cm inside radius 316 stainless steel spherical tank filled with ordinary water. The inside surface of the tiles is machined to a spherical figure to better than 20 μm.

A spark gap switch discharges all the capacitors simultaneously. The fast discharge vaporizes the aluminum spirals immersed in the water and launches a 22 kJ spherical shock wave toward the center of the tank. The ringing time of the capacitor, cable and aluminum spiral system is 11 μs. The width of the aluminum trace is adjusted to tune the load to the capacitor so all the energy is transferred in half a ringing cycle (5.5 μs).

The aluminum spirals are computer cut to good precision ensuring uniform shock all around the sphere. The aluminum spirals are laminated on an adhesive backed carrier, and are manually put on the polycarbonate tiles (like some stickers). They must of course be changed after each shot. The center of the aluminum spiral is connected to a central electrode connected to the high voltage cable. The outside of the spiral is grounded to the sphere with a small metal clip running between the tiles (Fig. 2).

A 3 cm diameter, 0.75 mm wall thickness lithium tube coated with a thin plastic layer (for chemical protection from the water) is installed vertically in the center of the

Fig. 3 Lithium tube in the center of a half tank

Fig. 2 Aluminum foils and tungsten electrodes

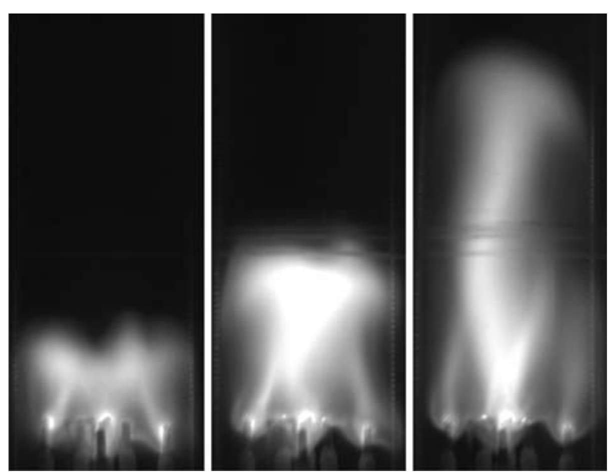

Fig. 4 Plasma expending above the electrodes at t = 5, 20 and 40 μs

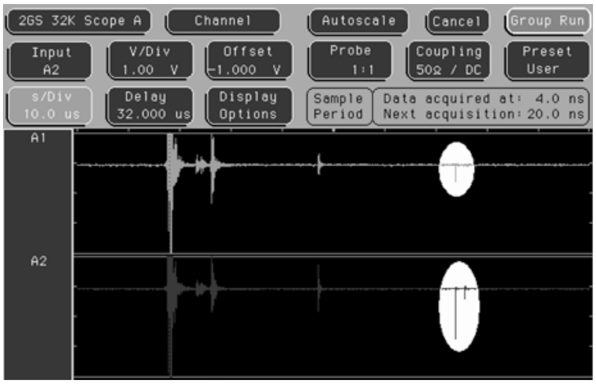

Fig. 5 Signal from the two scintillators. The noise bursts are from the capacitor discharges. The fusion signal is highlighted

tank (Fig. 3). Lithium is chosen for its electrical conductivity (to compress the magnetic field), low density (less than water to prevent R-T instability) and softness (to prevent buckling).

The plasma is formed by discharging a small capacitor bank between two concentric rings of eight tungsten electrodes at the base of the tube. The tube is filled with 10 torr of deuterium (or hydrogen for comparison shots). The plasma expands in the tube (Fig. 4) and is compressed when the tube collapses. The tube collapse was investigated with an array of electrical pins and determined to collapse at a terminal velocity of 4 km/s, 53 µs after shock initiation. The timing between the shock and the plasma is adjusted so the plasma has time to expand to fill the tube but still has ~½ of the maximum current (23 kA) flowing in it when the tube starts collapsing. The top and bottom of the tube collapse first, pinching the current from the bottom electrodes and forming a small self contained plasma toroid that is then further compressed to higher density and temperature.

We detect nuclear emission in two ~1 l scintillation counters just outside the tank when using deuterium (Fig. 5). The fusion signal arrives 53 µs after shock initiation (the time of maximum compression). There is no signal in hydrogen. The noise bursts are from the various capacitor discharges. This corresponds to a small fusion yield of 2000 neutrons per shot.

Conclusion

We propose a new acoustic compression method that could lead to a more practical, lower cost MTF power plant. A small experiment to demonstrate the principle achieved low level fusion reactions.