Magnetized Target Fusion Using High Speed Pellets

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ABSTRACT

There is a way to perform inertial confinement fusion which avoids the usual need for either a sacrificial assembly of significant cost, or control of complex plasma behaviour.

Ultraspeed charged pellets have been fired at 100 km/s from modified particle accelerators for decades[1], and Winterberg suggested their use for inertial confinement fusion, also decades ago[2]. The show-stopper has been the impossibility of bringing charged pellets to a true focus using predetermined electric or magnetic fields, a consequence of Earnshaw's theorem. I have invented a technique for achieving such focusing, by measuring and adjusting the trajectories of individual pellets.[3] Precise focus can then be achieved at any range. A series of pellets fired at successively increasing speeds from a linear accelerator some distance from a target can catch up en route to arrive together. Thus an accelerator of relatively modest power can deliver an intense input to a compact volume.

Slutz et al. have shown that high gain magneto-inertial fusion can be performed using implosion speed as low as 130 km/s. They propose Z-pinch with a magnetized liner, plus a laser pulse to preheat a central portion of the fuel.[4,5,6,7] However disadvantages of this method include:

- Peak input power ~1 PW: high capital cost
- Sacrificial capsule with low impedance wires for ~60 MA input current pulse is difficult and costly to recycle: high 'kopeck' cost

Identical fusion conditions can be created using instead pellets fired in at high speed. This method has the advantages:

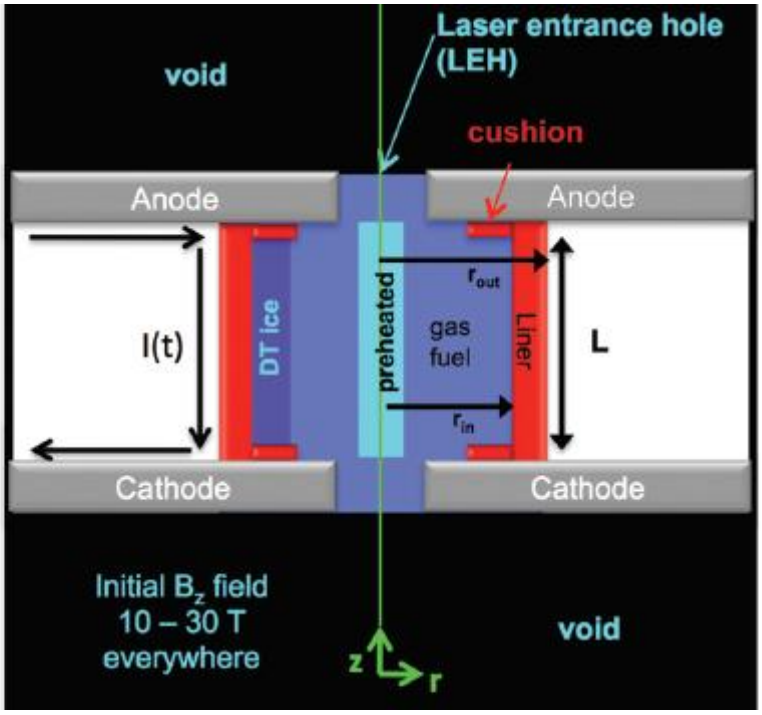
- Peak input power ~20 GW at a few MHz, provided by commercially available RF MOSFETs
- No central sacrificial capsule or wires needed; the pellets are cheap to make

This paper describes an appropriate design. The detonation can take place completely surrounded by lithium. Most of the energy produced can be directly converted to electricity by MHD.

Magnetized Target Fusion Using High Speed Pellets

We will perform fusion ignition and burn by providing conditions very similar to those described in[4,5,6,7], in which a tube of inert material surrounding DT fuel is imploded by Z-pinch. The general form of the Z-pinch design is shown in Figure 1. Slutz et al point out [6 p3, 7 p3] that the inert liner material can be Be, Li, Al or other choices, and that an outer portion of the cold DT gas can optionally be replaced by solid DT ice for larger fusion output as shown on the left side of Figure 1.

FIGURE 1 reproduced under Creative Commons license from [7 Figure 3]

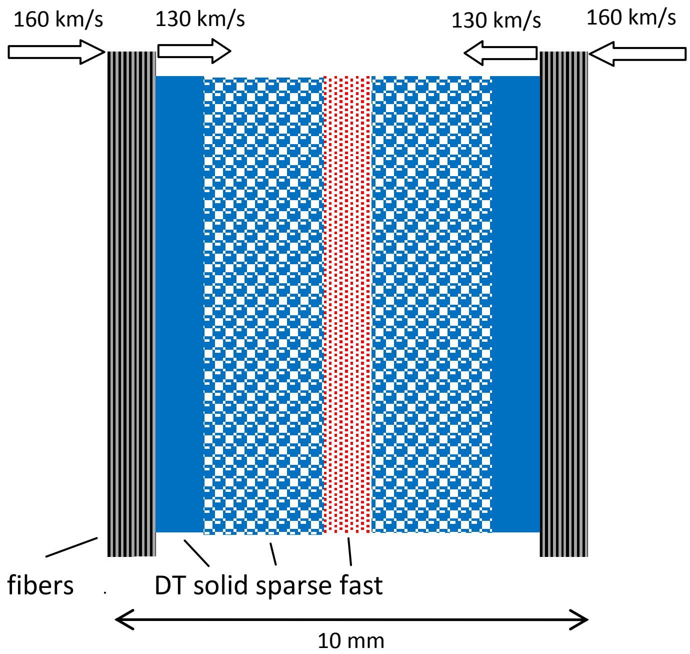


We will emulate the example described in [6, p9-10; figs 7d,7e,9c] using the Z800. Key parameters are:

- Liner Beryllium density 1.85 g/cc, tube 10 mm o/d x 0.83 mm wall thickness, mass 435 mg
- DT gas density within 18 mg/cc
- Energy input via liner 8.2 MJ
- Central 0.7 mm radius of DT gas preheated to 25 eV by axial laser
- Axial magnetic field 15-30 T

The operational sequence is shown in [6 Figure 9c]. An axial current of 60 MA is passed through the liner, which becomes plasma. The pressure of the circumferential magnetic field created by the axial current first compresses and accelerates the liner inward, then sustains a radial speed of 130 km/s against the outward pressure of increasingly compressed DT and axial magnetic field. Convergence ratio ~30 is achieved by stagnation, with axial field ~10 kT and temperature sufficiently high for ignition of the central DT gas followed by burn of surrounding DT.[5, Fig 16]

FIGURE 2



To create identical conditions by firing material inward from accelerators, no fuel capsule, Z-pinch current or laser are needed. The input materials, DT ice microspheres comprising the fuel and metal-coated fibers of S-2 glass comprising the liner, are fired inward toward a central axis from a surrounding ring of accelerators. The snapshot in Figure 2 is ~40 ns before stagnation and shows a situation very similar to that about halfway across [6 Figure 9c]. The fibers have just come into contact at natural solidity, the central fast DT pellets are colliding and heating, and the inner boundary of the liner is moving inward at 130 km/s. Note that the large slow DT pellets have been so aimed that there are gaps between them through which the fast DT pellets pass. An axial magnetic field of 15-30 T is provided by coils surrounding the entire detonation chamber.

All material is converging at speed sufficient that no additional energy input is needed. In the Z-pinch scheme, the liner has 3.7 MJ kinetic energy at its highest speed, 130 km/s: the remaining 4.5 MJ work is done by external magnetic field pressure, sustaining this speed against increasing central pressure. In our scheme, all input energy is kinetic: we use 780 mg of inert material whose initial speed ranges from 130 km/s at the inner side to 160 km/s at the outer, for 8.2 MJ kinetic energy as required.

The DT ice pellets to form the central ignition plasma are fired in radially at speed 72–88 km/s. As the pellets collide at the axis their own kinetic energy causes them to become 25 eV plasma: 280 µg fills a central cylinder of radius 0.7 mm to density 18 mg/cc.

A larger mass of DT pellets has previously been fired in to fill the surrounding volume to radius 4.2 mm with cold DT gas, also of density 18 mg/cc, with optionally an outermost layer of solid DT. These larger pellets are fired in at much lower speed, with initial gaps through which the fast pellets pass.

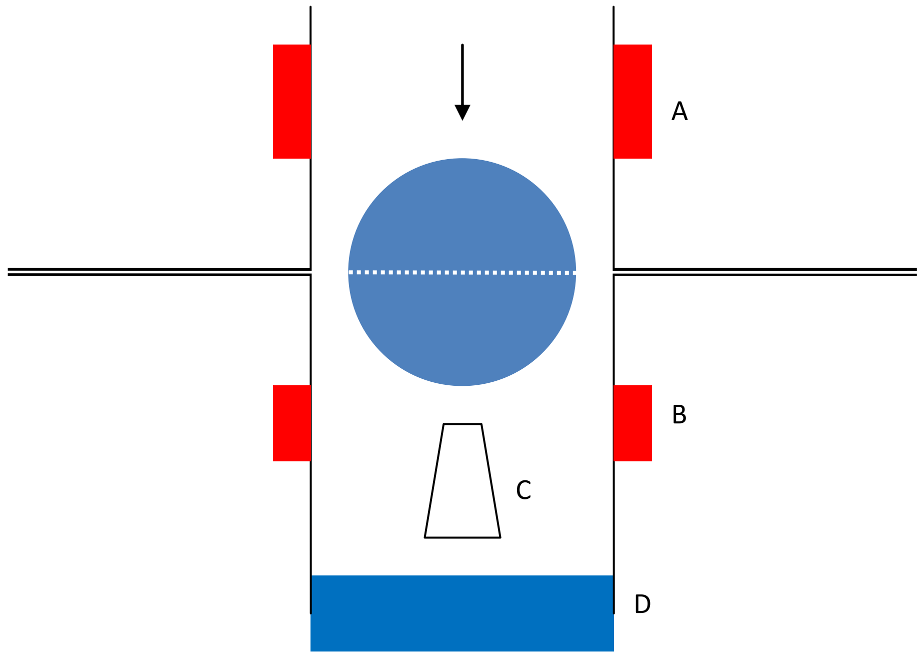
Lastly aluminium-coated glass fibers of total mass 780 mg are fired in at speeds ranging from 130 to 160 km/s to form the 'liner'. As soon as these fibers come into mutual contact, their rapid passage through the axial magnetic field lines causes current to flow through the aluminium, compressing the field within. Subsequent action heats the entire fiber mass to conducting plasma.

Subsequent to the snapshot of Figure 2, compression of the central fuel and the axial magnetic field in which it is embedded is very similar to the Z-pinch case, except that because there was no delay while the liner was accelerated inward from a standing start (left half of [6 Figure 9c]) there is less time for RT instabilities to grow. Note that exquisite fine-tuning of the energy delivery is possible: for example to match the exact inward movement shown in [6 Figure 9c], avoiding any shock discontinuity as the fibers impact solid DT, the initial speed of the fiber mass at its inner boundary could be reduced to equal that of the large DT pellets, with a larger total fiber mass and/or higher speed differential to the outer boundary so that total KE is as required.

There is room for up to several tens of mg of DT ice within the liner if desired. As pointed out in[5 p11], a high burn fraction can be expected with up to 10 GJ thermal energy release possible. For a 1 GW net electric output from one detonation per second, a little over 2 GJ thermal is required, equivalent to 30% burn of 20 mg DT, with 20% additional energy from fission in the surrounding ^{6}Li.

To extract this energy, the containment chamber sketched in Figure 3 is provided. Its key features include superconducting or pulsed coils **A, B** which provide an axial magnetic field of central strength 10–30 T, as in the Z-pinch cases but of sufficient volume to fill a cylindrical chamber of diameter ~1m, with a stronger field at the top to provide a magnetic mirror. Portions of solid lithium are dropped into the chamber so that at the moment of detonation, the detonation point is surrounded by an approximate sphere penetrated at its equator with radial holes to allow pellets to pass in from the surrounding ring of guns. Only ~0.01% of the fusion neutrons generated will escape by free paths through these holes. Additional narrow voids within the lithium minimize eddy current paths.

FIGURE 3

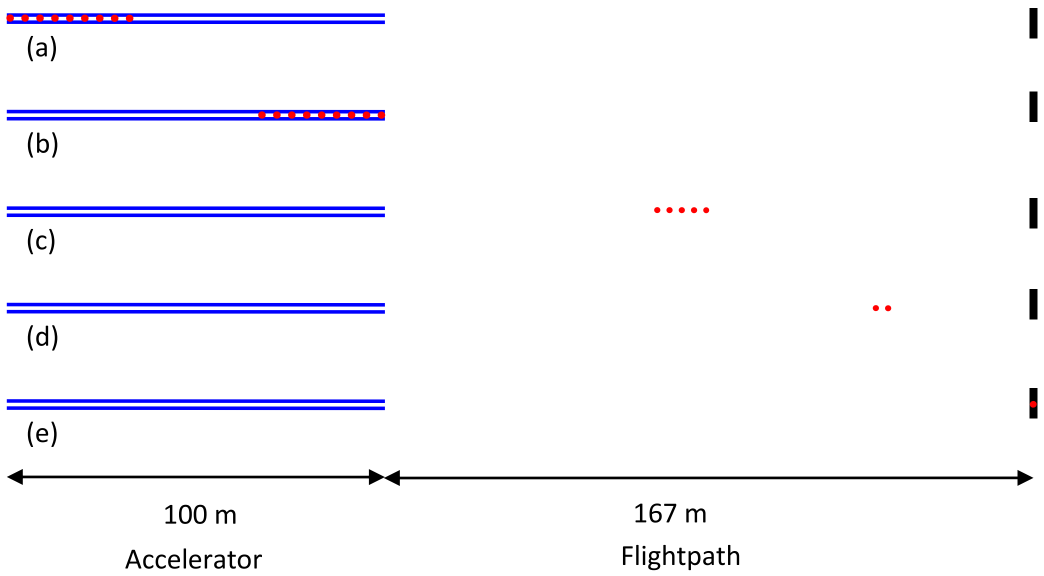


While neutrons from the fusion are not constrained by the magnetic field within the chamber, alpha particles and lithium ions are: the majority of the fusion energy, boosted 20% by induced fission of

^{6}Li, heats the central core of the lithium sphere to fully dissociated plasma which cannot expand laterally due to the magnetic field in which it is embedded. Due to the magnetic mirror above, this creates a downward-travelling plasma bullet which passes directly into magnetohydrodynamic generator **C**. The remaining lithium within the chamber is blown outward and falls downward into lithium pool **D**, as does the exhaust from **C**.

Lithium is pumped from this pool by an electromotive pump without moving parts, through a heat exchanger to heat water or carbon dioxide from which further useful energy can optionally be extracted by turbine. The lithium is subsequently poured into trays to cool further to form thin solid disks, which are stacked to form the sphere to surround a later detonation. A portion of the lithium flow is scavenged to remove hydrogen and helium gas, and nanoparticles of sand deriving from the fiber material.

FIGURE 4



The gun-to-target path is sketched in Figure 4. The general procedure is that the first one-third of the gun is loaded with pellets at regular intervals. The gun then operates at approximately constant acceleration: later pellets emerge travelling faster, as they have been accelerated over a greater distance, so that the first pellet is 10% faster, the last 10% slower, than the median speed. The pellets catch up together 1.67 gun lengths downstream. At any given moment, the pellet speed, hence drive frequency is the same at all points within the gun. Drive frequency increases approximately linearly with time, from a low initial value to a maximum as the last pellet reaches the end of the accelerator.

It is obviously desirable to minimize gun length, but there are three limitations:

1. Maximum charge/mass ratio of the pellets
2. Maximum voltage gradient of the accelerator without flashover
3. MOSFET cost: peak RF power required is inversely proportional to accelerator length

1. Pellets

For positively charged pellets, maximum charge is limited by physical breakup due to self-repulsion. As shown in Appendix 1, charge/mass ratio achievable is inversely proportional to pellet diameter.

We require a relatively small mass, 280 µg, of DT pellets to be fired in with r.m.s. speed 80 km/s to form a central cylinder of hot 25 eV gas which will reach ignition temperature after compression. (Note that collision is a vastly more efficient method of energy input than laser heating!) Solid DT microspheres can easily be made by allowing droplets of liquid DT to freeze while falling through cold helium gas. The density of solid DT is 0.225 g/cc, its tensile strength ~0.5 MPa at a few degrees K.[8, Fig 4 p582] Microspheres of diameter 30 µm, mass 3.2 ng can carry a charge/mass ratio of 2, allowing a 1.5 tensile safety factor. 87,000 microspheres are fired in at speeds increasing from 72 to 88 km/s. Total accelerator voltage 1.94 GV is required for the fastest microsphere, which is accelerated to 88 km/s over the full length of the accelerator.

The remainder of the DT fuel is fired in earlier at much lower speed, say *n* times slower. It can therefore be given a charge/mass ratio n^2 times lower, and be made up of much larger microspheres. For example if a total 20 mg of low-speed DT is needed, 90,000 microspheres of diameter 120 µm are appropriate, charge/mass ratio 0.5, speed <40 km/s.

Lastly and most demanding, 780 mg of fibers must be fired in at r.m.s. speed 145 km/s. Fibers are fired in radially and in the same plane as the preceding DT ice microspheres, with their axes parallel and vertical. A suitable choice for the fibers is S-2 glass coated with aluminium a few atoms thick. S-2 glass has tensile strength 8.3 GPa at cryogenic temperature[9]: the fiber can be cooled by passing it through liquid nitrogen shortly before insertion. A 1 cm long 24 micron diameter fiber masses 11 µg. A simple computer program referenced in Appendix 1 finds that such a fiber can carry a charge/mass ratio 6 with tensile safety factor 1.5. 70,000 fibers are fired in at speeds increasing from 130 to 160 km/s. Total accelerator voltage 2.13 GV is required for the fastest fiber, which is accelerated to 160 km/s over the full length of the accelerator.

(In principle, exotic forms of carbon could give much better charge/mass ratio. However cost is a significant factor: ~30 tonnes/year will be required for continuous operation. Ease of handling and excellent quality control is also vital. Glass fiber is cheap, and can be dispensed from reels and cut to length by laser: the technology to handle multiple fibers paid out at speed with extreme reliability was developed over 200 years ago. UHMWPE fibers could be a good alternative to glass, with the advantage that the hydrogen would provide useful neutron slowing when compressed to high areal density around the fusion site[5, Figure 16]. However the fiber needs radial strength at least 1/15 its longitudinal strength to avoid burst-apart when charged. Glass is isotropic, so has ample radial strength, and naturally forms a smooth surface. These could be issues for a polymer fiber.)

The same physical guns can be used to perform all three tasks consecutively: firing large low-speed DT pellets, followed by smaller high-speed DT pellets, followed by fibers.

2. Accelerator Gradient

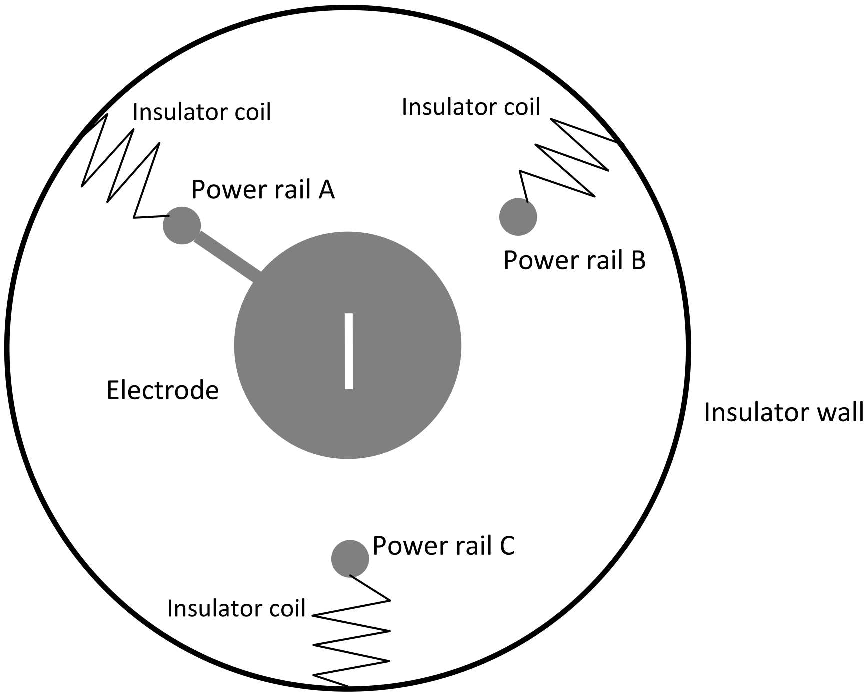
The pellet guns superficially resemble LINAC particle accelerators, but operate at a frequency orders of magnitude lower as pellet speed is <0.1% of lightspeed. Thus the electrodes do not form RF resonant cavities, and there are fewer constraints on their shape. A possible mounting of an electrode comprising a thin sheet of metal within a dielectric walled tube which resists flashover over the insulator surface is shown in Figure 5.

Three-phase electrodes set at 1 cm intervals are a suitable choice to provide acceleration in a field which each pellet experiences as approximately constant both spatially and temporally.

An RF gun has been successfully operated at field 190 MV/m in pulses of duration 0.7 μs with electrode separation 24 mm, even before advanced electrode conditioning[10]. A technical note to an industry standard electrical CAD program[11] gives scaling law $\mathbf{E_{max} \sim 1/V.\tau^{0.34}}$, where **V** is the voltage between conductors and **τ** is pulse length. This can be rewritten as, with conductor separation **L**: $\mathbf{E_{max} \sim L^{-0.5}.\tau^{-0.17}}$ (for **τ** up to 1 ms: thereafter $\mathbf{E_{max}}$ does not vary with **τ)**.

If dwell time within the accelerator tube is ~1 ms, the above formula implies that up to 36 MV/m could be used: we will select a comfortably lower value, 21 MV/m.

FIGURE 5



3. MOSFET cost

Cost of the guns will be dominated by the power required at high frequency to accelerate the fibers. We select as driver an RF power MOSFET amplifier which can deliver a pulse of 3 J at low duty cycle, e.g. 3 kW for 1 ms, and costs $100/unit[12,13]. If the guns are each 100m long, pulse duration is 1.25 ms, with work rate increasing from zero to 12.5 GW after 1.02 ms just as the first fiber exits each gun, then dropping to zero as the last fiber exits. If the guns contain 3-phase electrodes at 1 cm intervals, frequency peaks at 2.65 MHz, far below the chip's limit. With drive gradient 21 MV/m the maximum potential difference between electrodes is over 200 kV, whereas the chip's maximum output voltage is 250V, so the output passes through one or more stages of small open-core transformers en route to the electrodes. 10% power loss downstream of the MOSFETs is assumed:

to deliver 8.2 MJ kinetic energy 3 million MOSFETs are needed, total cost $300 million. Chip efficiency is just over 50%, so ~20 MJ of electrical energy must be supplied.

All pellets are initially charged to relatively low voltage, but rapidly become fully charged in the first instants of acceleration, by briefly switching the first electrodes they transit to appropriate positive voltage at the moment of closest approach. The surface curvature of both types of pellet is sufficient that electrons escape the surface easily when attracted by an external force.

Just as in a fundamental particle accelerator, mutual repulsion between nearest neighbour pellets will tend to defocus the beam. The most pathological situation is when consecutive pellets are displaced laterally in opposite directions. The critical parameter is the time constant, the approximate time it takes for a small displacement to double. If the pellets are set at the closest possible separation of 3 cm, equal to the wavelength of the travelling wave, the lateral doubling time is 35 ms for the fast DT pellets, which is an order of magnitude longer than their dwell time within the gun, so no in-gun steering is necessary. For the fibers however it is 60 µs, much shorter than the in-gun dwell time.

It is a well known consequence of Earnshaw's Theorem that it is impossible to provide true focusing using predetermined electric or magnetic fields: because the divergence of such a field in free space is zero, bringing about convergence in two directions causes divergence in the third. True focusing can be provided only by a system incorporating feedback. At multiple points within each gun, we therefore measure the position of each fiber end and apply a corrective impulse a small distance downstream. Displacement in a given direction can be measured optically by using a pulsed or constant LED and measuring the brightness a short distance away using a single-pixel sensor. Because the electric fields within the gun are large, the sensors are preferably mounted outside the gun within a Faraday cage, which is easily done using optical fibers. After each position measurement, a steering tweak is applied a short distance downstream, using rapidly switched electrodes which create an appropriate lateral field. To apply corrections to each fiber every 60 µs, ~100 equally spaced correction stations are needed within the first third of each gun, where the fibers are initially moving slowly, but only ~20 unequally spaced correction stations within the remaining gun length.

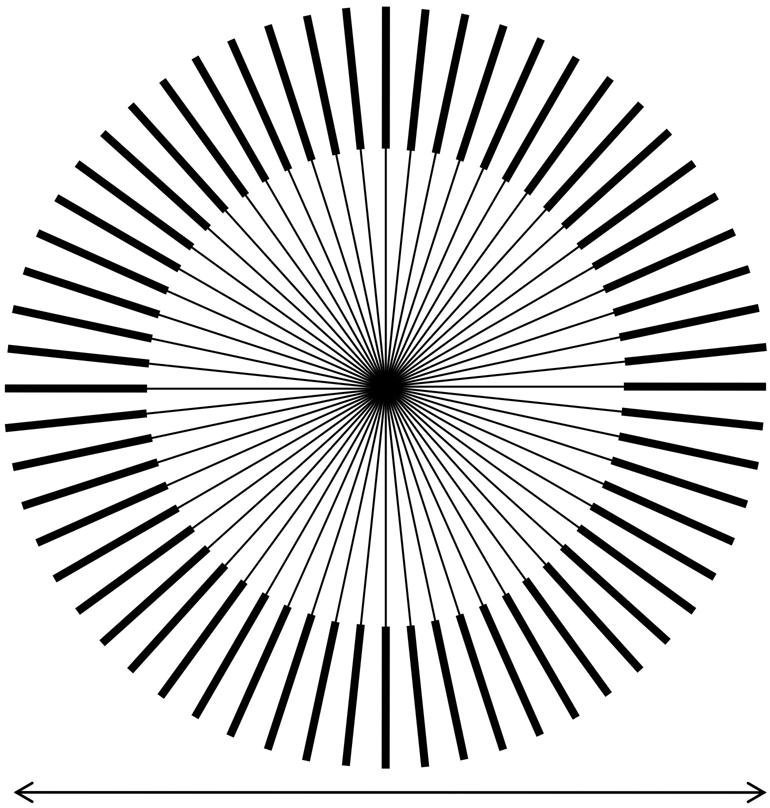
Individual pellet courses (and in the case of fibers, orientations) are refined after leaving each gun by a small number of course correction stations identical to those described above. Sampling and switching rates for individual sensors and steering electrodes range from a few MHz within the guns (where the vast majority of the stations are located) to a few tens of MHz at the final stations close to the central detonation point. Pellets of each type are partially discharged during free flight, to prevent inter-pellet repulsion becoming excessive as the pellets converge, while permitting ever-finer course corrections and also maintaining enough self-repulsion to keep the fibers taut and straight. The preferable discharge mechanism is dropping negatively charged ions, rather than electrons, onto the pellets, as electrons would arrive as low energy beta particles and would not stop immediately at the pellet surface.

Exquisite precision of pellet delivery is possible, limited only by optical accuracy: 0.1 µm spatial, 1 picosecond temporal. This can be applied to the whole of a fiber, not just its endpoints, if necessary. The fiber's configuration and vibrations are measured with high accuracy, e.g. using consecutive stereo pairs of cameras with CMOS chips capable of on-chip processing. It then passes through increasingly narrow vertical letterbox slots with arrays of electrodes along their sides which apply forces so as to first straighten the fiber, then reduce local lateral motion to zero everywhere.

The whole installation is sketched in plan in Figure 6: a ring of 60 100m long guns connect via 165m vacuum pipes to a central installation containing the detonation chamber and MHD generator. The guns are housed within long narrow buildings. The vacuum pipes connecting them to the central chamber can be in the open air: these pipes can tolerate side motion and vibration providing they have diameter sufficient that the pellet stream does not physically impact the walls.

It is the RF power supply, not the vacuum tube with electrodes, which is the expensive element of each gun: although a worst-case failure can release energy comparable to a hand grenade, individual gun tubes are wrapped in energy-absorbing material. A parallel 'hot backup' tube within each building can immediately be switched in ensure continuous operation after such an event.

FIGURE 6



Total cost of the accelerators, including buildings and ancillary equipment, will be ~$400 million. Cost of the central chamber and its equipment will be related to the power output required, but given that most or all of the electrical output is generated directly by MHD, total capital cost of a power station of 2 GW or greater electrical output is potentially lower than any other type. The cheapest fuel-burning station, based on large frame combustion turbines, costs ~$800 million/GW at 2013/2014 prices; a nuclear fission station ~$8,000 million/GW.[14]

Although the system occupies a site half a kilometre in diameter and 20 hectares in area, the total footprint of the buildings is ~2 hectares. The size of the central building depends on the desired power output, and whether it is thought necessary to scavenge energy not harvested by the MHD generator using a steam or CO_2 turbine system.

There is a highly attractive development path available, starting with construction of a single accelerator. As additional accelerators are added toward the configuration of Figure 6, there is very wide scope to tweak parameters in software alone. At this stage, of course, there is no need to provide a lithium surround or generate electricity: we are simply seeking optimal parameters for ignition followed by burn with reasonable energy gain. This may well be achievable with a smaller and less expensive configuration than that in Figure 6. The example in this paper has been selected to show that the most demanding parameters can be fulfilled if necessary. Later work on Z-pinch already indicates that for an 'ice burner' the optimum central gas density may be as low as 4.5 mg/cc with axial field 10 Tesla, which will be easier to achieve.[7 p7]

It will be possible to explore beyond the parameter space reachable with a Z-pinch design. Heating the central gas by collision rather than laser allows an arbitrarily low initial gas density: in principle, density <1 mg/cc lowers the implosion speed needed into the range 10–100 km/s.[4 p2] Convergence speeds can be chosen so that compression is uniform, hence RT instabilities cannot arise. Temperature and density do not have to reach ignition values everywhere along the central axis: ignition at a single point can create a burn which spreads axially as well as radially. Shape and density of the cold fuel can be tailored in ways impossible with Z-pinch. A 'hybrid' design, in which central low density hot gas is created by collision of DT ice pellets fired in along the axis, but the liner pinch is performed by other means, may also merit investigation.

APPENDIX Pellet charge/mass ratio

Maximum positive charge on a object is limited by burst-apart due to self-repulsion, and field evaporation from the surface. These are really two sides of the same coin: unless long periods at high temperature are involved, burst-apart is the limiting factor.

Spherical pellet

If the pellet is a sphere, charge will distribute itself evenly over the surface. The burst-apart force calculation is then mathematically identical to the well known case of the self-gravity of a thin spherical shell. A point mass **m** at a distance **R** from the centre of a spherical shell of mass **M** experiences a gravitational pull of $\mathbf{GmM/R^2}$ in the space outside the shell, and zero everywhere inside it. An average particle of the shell itself thus experiences $\mathbf{GmM/2R^2}$. The mass per unit area is $\mathbf{M/4\pi R^2}$, giving an inward surface pressure of $\mathbf{GM^2/8\pi R^4}$. The corresponding outward pressure on a spherical shell carrying charge **Q** is $\mathbf{kQ^2/8\pi R^4}$, where $\mathbf{k = 1/4\pi\varepsilon_0}$. This must not exceed the safely usable strength $\boldsymbol{\sigma}$ of the material, so maximum charge permissible is $\mathbf{5.3x10^{-5}\ R^2\surd\sigma}$. The mass of the sphere is $\mathbf{(4/3)\pi R^3\rho}$, so the maximum charge/mass ratio is

$$Q/M = \frac{1.26 \times 10^{-5}\sqrt{\sigma}}{R\rho}$$

Small diameter pellets can thus be given higher charge/mass ratio than large diameter ones.

Fiber pellet

The fiber case cannot be solved analytically, because longitudinal tension does not tend to a limit as length tends to infinity, although it increases very slowly (analytically, the sum of the harmonic series 1 + 1/2+ 1/3+ 1/4... is involved). The calculation must therefore be done by a finite element method. Approximate hand calculation is possible, e.g. treating the fiber as a uniformly spaced line of point charges at separation comparable to the fiber diameter. For better accuracy, I have written a simple computer program which allows charge to move longitudinally to approximate equilibrium before calculating the tension. This program is available free on request: it also calculates other relevant parameters, such as the radial tension, which is less than one-tenth the axial tension for length/diameter ratios likely to be used.

As with spheres, smaller diameter fibers can be given proportionately higher charge/mass ratio. Charge per unit length is nearly constant except very close to the ends, where it increases. In order that a fiber can be accelerated while remaining straight, minimizing vibration, charge/mass ratio should ideally be the same everywhere along its length. This can be achieved by varying the thickness of a metal coating.

Fibers perform better than spherical pellets of comparable mass due to increased average spacing between charges. Glass fiber is cheap and available in coils many kilometres long: it can be chopped into segments by laser as it is fed in. S-2 glass fiber has strength increasing from 5 GPa in a room environment to 8.3–11.6 GPa if cooled to cryogenic temperature.[9]

Polymer fiber would be a viable alternative if sufficient radial strength can be obtained. The hydrogen will help slow fusion neutrons, reducing the size of the lithium surround needed.

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