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Pinch me – I'm fusing!

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(Fusion Power - what is it? What is a z pinch?
And why are z pinches a promising fusion power technology?)

The process of combining nuclei (the protons and neutrons inside an atomic nucleus) together with a release of kinetic energy is called fusion. This process powers the Sun, it contributes to the world stockpile of weapons of mass destruction and may one day generate safe, clean electrical power. Understanding the intricacies of fusion power, promised for 50 years, is sometimes difficult because there are a number of ways of doing it.

There is hot fusion, cold fusion and con-fusion. Hot fusion is what powers suns through the conversion of mass energy to kinetic energy. Cold fusion generates con-fusion and nobody really knows what it is. Honestly - this is true. There does seem to be something going on here; I just don't know what. Apparently some experimenters get energy out of a process many call 'cold fusion' but no one seems to know what it is, or how to do it reliably. It is not getting much attention from the mainline physics community.

Even so, no one is generating electrical power for you and me with either method. In this article I will point out some basic features of the mainstream approaches taken to hot fusion power, as well as describe why z pinches are worth pursuing as a driver for a power reactor and may one day generate electrical power for mankind.

What is fusion and why should we care?

Fusion of two or more nuclei can bring about an exchange of energy from one form to another. Einstein's famous formula $E=mc^2$ (E means energy, m is mass, and c the speed of light) represents the basis for nuclear power. It means that energy can be interchanged with mass. Fusion reactions, or collisions, allow nuclei to interact and come out of the collision changed. The mass energy can be reduced after a collision and the kinetic energy, that energy associated with the motion of the outgoing particles, is

increased by an amount equal to the reduction in mass. Once you convert nuclear mass to kinetic energy, the kinetic energy of the outgoing particles can be converted into thermal energy. This thermal energy is the randomly-oriented bouncing together of molecules we call heat. In this context it could be used to boil water and drive steam turbines for generating electrical power.

The concept of converting mass energy to kinetic energy is illustrated in the binding energy per nucleon curve shown in Fig. 1. Nuclei whose binding energy per nucleon is lower than iron may be reconfigured into more stable nuclei and the difference in binding energy of the whole system can be observed as thermal energy or heat.

The reactions that are typically considered for powering fusion reactors are those which involve deuterium ($_1H^2$, 1 proton and 1 neutron) and tritium ($_1H^3$, 1 proton and 2 neutrons). This is the reaction most frequently considered to be the basic fusion reaction for a reactor because the fusion cross section, or interaction probability, is highest for these two nuclei – by a lot. Fuel cycles other than the DT cycle are called 'advanced' fuel cycles and it is much harder to create the necessary plasma physics conditions. It is generally considered easier to create (called breeding) the necessary tritium than to create an advanced fuel cycle machine. The tritium can be bred by surrounding the fusioning material with a lot of lithium. This is because the neutrons leaving the fuel interact with lithium; the lithium then splits - creating tritium and helium as by-products.

What this means is that there must be a lot of lithium around the plasma to interact with the neutrons emitted during the fusion process. It is these neutrons which will cause the bulk of the material damage and long-lived (read as requiring long-term disposal) radioactivity.

The two methods most heavily funded for pursuing fusion are magnetic-confinement fusion energy (MFE) and inertial-confinement fusion energy (IFE). In MFE plasmas a magnetic bottle contains a high-temperature deuterium-tritium plasma at moderate particle densities for long times (>millisecond). IFE plasmas use a capsule filled with a deuterium-tritium mixture. This capsule is driven to implode by a radiation field. The fuel mixture inside the capsule is compressed in a short time (tens of nanoseconds) to very high densities and temperatures until it ignites. Ignition is the point at which energetic fusion fragments, also called reaction products, heat the fuel which generates additional fusion reactions faster than the fuel can expand and cool. In this way a burning wave can propagate through the fuel.

For both of these the physics is difficult. Incredible progress has been made in both methodologies but each has a long way to go and both methods are quite risky. The completion of a next-step machine for MFE or IFE may show the real capabilities of either method. Either method, MFE or IFE, could potentially result in a power reactor.

One reason to care about fusion power is that fusion power has the potential to provide energy without creating greenhouse gases and smog. In addition, as compared to nuclear fission plants, fusion reactors have the potential for much less radioactivity and improved safety. The reduced radioactivity is because there will be no fission products or heavy metals such as uranium. The reasons for the improved safety are that there will be much less decay heat after shutdown, there is no possibility of a runaway 'chain reaction' leading to meltdown, and there is no nuclear proliferation threat.

Sounds wonderful doesn't it? The problem is that it is hard to do.

What is a z pinch? Could pinches meet the requirements ?

A z pinch is a plasma created by an axially flowing current; this means current flowing in one direction at a given distance from the axis. The current flowing along a straight line creates a magnetic field. The magnetic field acts in such a way that an electron moving in the axial direction feels a force pushing toward the axis. This inward force by the self-induced magnetic field is what 'pinches' the plasma toward the axis.

There are a few ways fusion could be obtained in a pinch. I will only describe the Dynamic Hohlraum configuration. This type of z pinch inertial fusion target is shown schematically in Fig. 2. The parameters I list are those of the Z machine at Sandia National Laboratories in Albuquerque, New Mexico. The Z machine at Sandia National Laboratories is the world's largest z pinch driver today. [Please check out the web site http://www.sandia.gov/ACG/pinch.htm this site has a movie describing the z pinch and an animation of how a reactor chamber might work.] Of the nominally 10 megajoules (MJ) of stored electrical energy in its banks roughly 2 MJs of x-rays can be created. It can carry more than 20 mega-amperes (MA) of current and produce roughly 2 MJs of soft x-rays. What you have in a Dynamic Hohlraum itself, see Fig.

2, is a cylindrical wire array (hundreds of ~7 micron tungsten wires) inside of which is a small cylinder of low-density (>14 mg/cc) foam (CH). By passing current (>20 MA) through the wire array, a radially directed force is created that moves the wires inward or towards the axis. The wires heat as the current flows through them and becomes a plasma sheath (a fairly uniform "curtain" of tungsten). The bent arrow in the picture illustrates the path of the electrons through the target. The target is called a hohlraum, which means radiation case, because the tungsten wires act as an oven wall or radiation case for low energy x-rays. The target inside is this radiation case heated by x rays generated and confined inside the target. Because the tungsten plasma sheath is moving this configuration is called a Dynamic Hohlraum. This type of target is promising as an IFE target because it is of roughly the right size, and heated to the right temperature. There are some not so subtle effects such as the time history and spatial uniformity of the radiation field needed to be obtained before proving that IFE physics can be done in this type of pinch.

When this inward moving plasma sheath strikes the foam it generates a radiation wave and a pressure wave. Together they move to the axis with the radiation moving faster than the shock. This radiation pushes on a capsule containing fusion fuel in the center of the imploding plasma/foam structure. If the pressure on the fuel capsule has the appropriate characteristics then the fuel will burn and a net energy release will be obtained.

I'll next examine some significant engineering (not physics) differences of magnetic fusion energy (MFE) reactors and two Inertial Confinement Fusion (ICF) concepts (laser driven and z pinch-driven. (Disclaimer: what follows is my opinion – it is not Sandia's public stance or to be taken as the opinion of any one else.)

Let us assume that the appropriate physics conditions can be created in the target (the part we discussed above). The question then becomes - what is needed for a reactor?

Fusion power plants, MFE or IFE, will have a great deal in common. Land, electrical turbines, waste heat disposal, and tritium handling (an environmental and safety hazard) will be required in each case. Fuel will need to be handled and processed. Radioactive waste will be generated and need to be stored even though typical radioactivities, half-lives and volume of waste will potentially be vastly reduced from those of fission power plants. These issues will contribute significantly to the cost of any fusion plant but will not lead to a choice between concepts.

The fusion reactor components of these power plants also have some things in common. I have illustrated these schematically in Fig. 3. Each concept has a central plasma (this is what I am considering the physics part – described above) surrounded by a vacuum. There is a coolant which moderates (interacts with and slows down) the fusion neutrons, it is used to breed tritium and usually acts as the 'working fluid' to pull heat (the thermal reaction product) out of the reactor to feed it into the electricity generating part of the system. These reactors all have a driver (e.g. the equipment to create the fusing plasma).

The differences are legion. Let's work out from the center. The MFE plasma can be many cubic meters in volume and it needs to last a long time (milliseconds to steady-state). The ICF plasma is small, less than a cubic centimeter, and it only lasts a few nanoseconds. The MFE plasma requires excellent vacuum, meaning particle pressures less than 10^{-10} torr (760 torr=1 atm). This is a technical challenge in its own right. The pressure requirements are much less extreme for ICF reactors ($\sim 10^{-6}$ torr). In an MFE device the wall has many apertures to allow for heating and fueling the plasma. This wall must also survive the full neutron flux produced by the fusion reaction products and developing this wall is what I consider the hardest problem to solve for an MFE reactor. This poor wall must withstand enormous power densities and neutron irradiation without outgassing (evaporating material) significantly into the chamber. It must also survive for a long time.

In addition, MFE machines require lots of complicated high power equipment to maintain the plasma conditions. Keeping these high-power complicated mechanisms working reliably will be quite difficult. Because of the bulky plumbing (for power supplies to heat the plasma, fueling, field coils and moderator/coolant) it will be difficult to obtain adequate tritium breeding.

This wall may also be the saving grace of an ICF reactor. If you look in Fig. 3, the moderator sits inside the wall of an ICF design. The moderator in ICF reactor concepts absorbs much of the neutron energy. This material is normally a liquid and weakening of the structure is not an issue as it is for MFE. Recently at the Fusion Summer Study in Snowmass Colorado, my co-authors and I showed that the wall lifetime due to neutron damage may be long compared to the reactor lifetime of nominally 30 years for a z pinch driven power plant.

In our concept of a z-pinch-driven reactor, the moderator absorbs the shock of the explosion as well as breeds the tritium. The neutrons are substantially reduced in energy by the time they reach the wall so there is comparatively little neutron damage and activation. An important point here is that a low-Z moderator will have little activation compared with a high-Z wall. Our design also means that only the region between the electrodes needs to be pumped to 10^{-6} torr and the bulk of the chamber may need to be pumped down to only a few torr. This is a big deal, because pumping large volumes fast is hard to do.

In Fig. 4, we have a simple sketch of a z pinch-driven reactor chamber. There is a central containment chamber. At the beginning of a shot, meaning a single energy-producing event, a crane moves a prepumped target/electrode assembly into place on the machine. After this is loaded into the reactor chamber, the chamber is filled with bubbles of Li or FliBe (a ceramic made of fluorine, lithium and beryllium) as the moderator and working fluid. The working fluid, inside the chamber wall, is then pushed out of the chamber with a plunger. The fluid goes to heat exchangers while the tritium and other materials will be extracted for the next event. The mottled looking area outside the chamber is a confinement chamber. Power and energy are supplied by a large array of capacitor banks (not shown).

There are a number of technologies vying to be the motive power for ICF. These are lasers, ion beams, and now z pinches. I will only discuss lasers and pinches. Basically with a laser driver you fire many laser beams through the vacuum to a target. The chamber will need hundreds of apertures. Flowing liquid metal walls of lithium or FliBe, etc, are proposed as a means of breeding fuel and moderating the neutron flux. The laser optics will need to be protected somehow from the debris of the blast, the lasers must be transported to the target and the laser system must be capable of firing many shots per second. In addition, there must be a reliable way to rapidly load these targets and align them to tight tolerances so that the lasers can hit it. In addition, pumping out this many cubic-meter chamber 3-5 times per second so that the laser beams can be transported to the target will be a difficult problem.

Todays z pinch concept uses current supplied through solid electrodes. These are mechanically coupled to the fusion target. This simplifies target insertion and target alignment as compared to the competing ICF drivers. This is because they locate the targets as well as provide the power. The electrodes that transport current to the target are meant to be destroyed and recycled; Steve Slutz coined the term RTL, or recycleable transmission line. The RTLs may be made of the same material as the moderator. We believe they need only meet presently obtained tolerances.

For our z pinch concept we opt for a lower shot rate and higher energy yield per event than other concepts (every few seconds) rather than many times per second. Because the relative cost of the chamber and pulsed power driver is lower than other options, it may be feasible to have many chambers. This would lower the time between shots to tens of seconds in each chamber. From the perspective of having to move tons of material per shot and pumping speed, this simplifies the engineering. Multiple chambers also allow for periodic maintenance and improved overall reliability.

Regarding the per shot cost of these electrodes, the Advanced Manufacturing Group at Sandia National Laboratories obtained a crude estimate of the RTL cost that leads us to believe the costs may be economically acceptable. The cost assumes that all handling and manufacturing of these materials must be done robotically and in inert atmosphere. This is true for any hot fusion reactor concept.

There is negligible materials cost because the material is recycled and the capital costs were not included. There is one more big advantage to a z pinch. The pinch machines are a relatively low technology. Metal, plastic, oil, shock, dust, and debris are all part of the pinch environment and if you are going to build a big, earth shaking machine and move a lot of material, then this is the way to go. Screen rooms and high vacuum just seem like poor companions to large mass flows and floor-shaking environments.

This whole list of advantages may be enough to one day make a pinch driver reactor feasible. It is my opinion that the advantages described here mean that this program deserves a broad base of support and should be more adequately funded.

There are huge problems that need to be overcome for any potential fusion reactor concept. Neither MFE nor ICF plasma physics has been demonstrated in a laboratory even though the physics of ICF has been demonstrated in the performance of the H-bomb. At this point z pinches have not made thermonuclear neutrons from capsule implosions – a significant milestone. However, the only concept which has been seriously discussed, that I believe may be buildable with anything approaching near-term technology, is the pinch driven reactor. In fact, sometimes I could just pinch myself and see if I wake because this technology looks so promising.

For more information

Two new references on pinches are "**Physics of High-Density Z pinch Plasmas**" by M.A. Lieberman, et al., and D.D. Ryutov, M.S. Derzon and M.K. Matzen., "**The Physics of Fast Z Pinches**" in the *Reviews of Modern Physics*, Vol. 72, No.1, Jan. 2000. For those desiring more information on laser fusion refer to John Lindl's book "**Inertial Confinement Fusion**", New York: Springer-Verlag, 1998. Jeremy Chittenden has provided more depth in the physics of the z pinch target in a recent article in Physics World, May 2000, entitled "**The Z pinch Approach to Fusion**".

A version of this article can be found at URL: http://www.sandia.gov/ACG/pinch.htm. This version links to a movie of the Sandia Z machine and an animation of how the RTLs might work.

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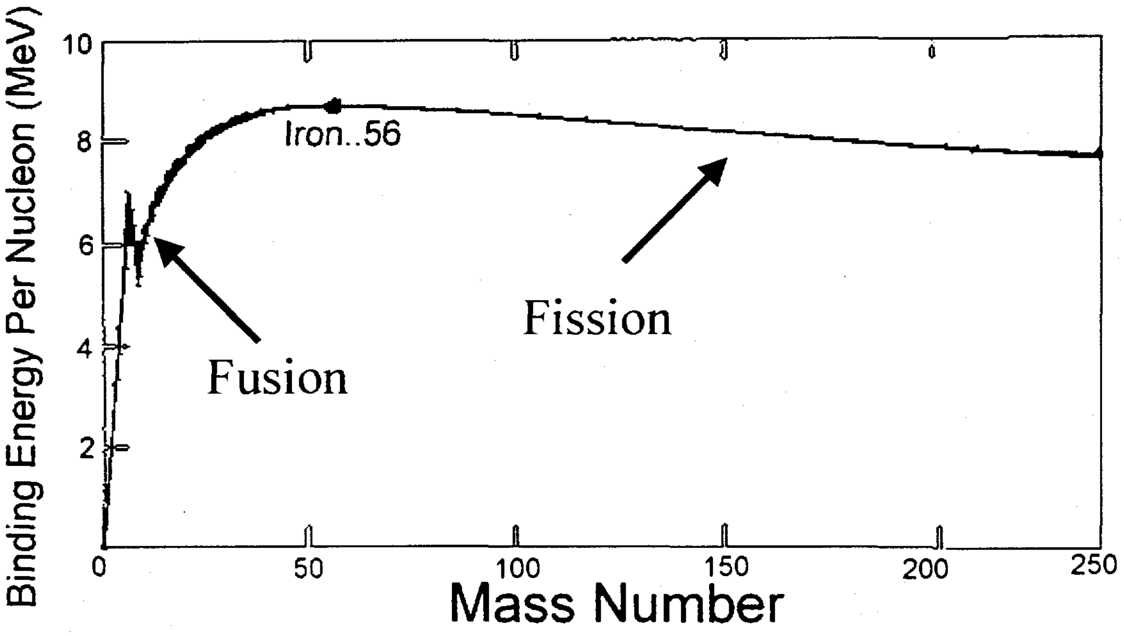
Fig.1.



* Adapted from *http://library.thinkquest.org/3471/noNetscape/mass_binding.html*

Fig.2.

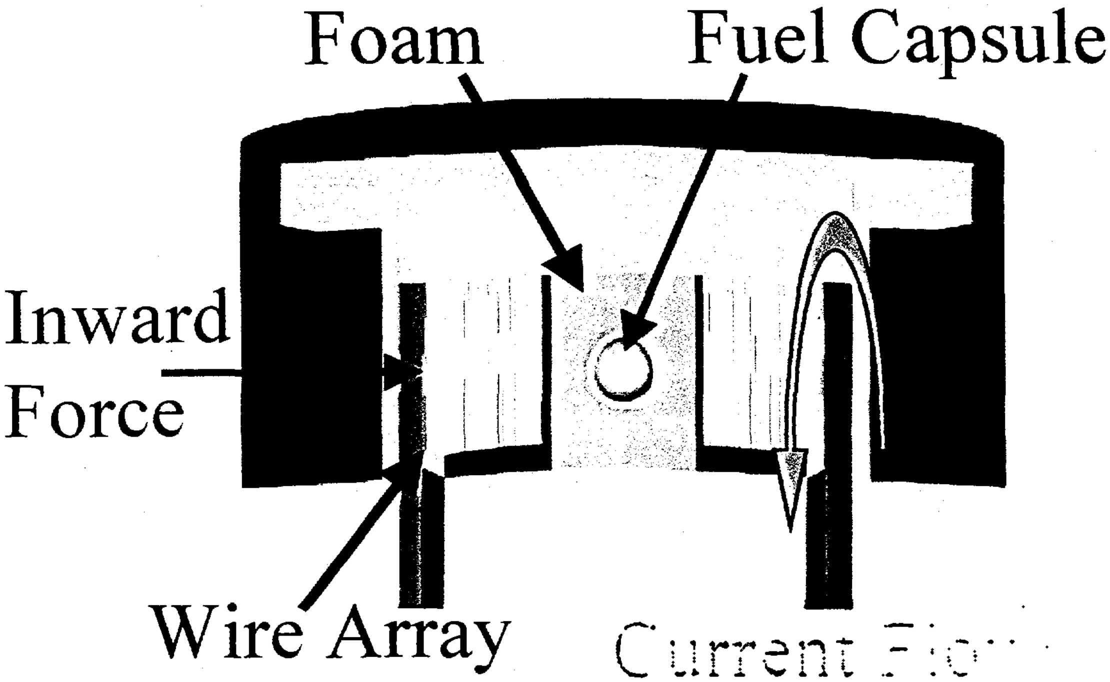


Fig.3

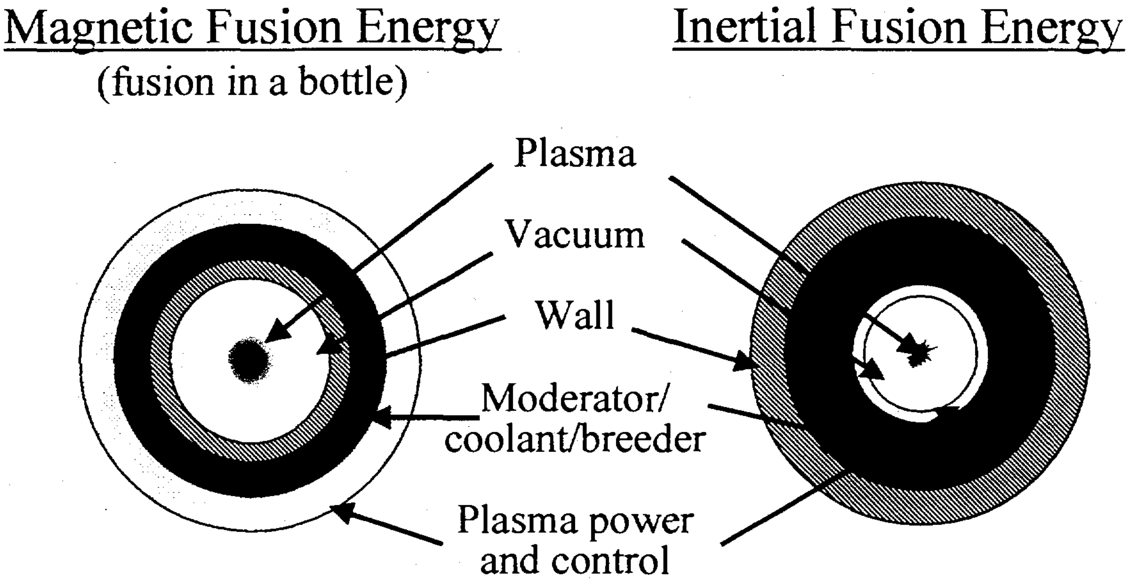

Magnetic Fusion Energy
(fusion in a bottle)
Inertial Fusion Energy
Plasma
Vacuum
Wall
Moderator/
coolant/breeder
Plasma power
and control

Fig.4.

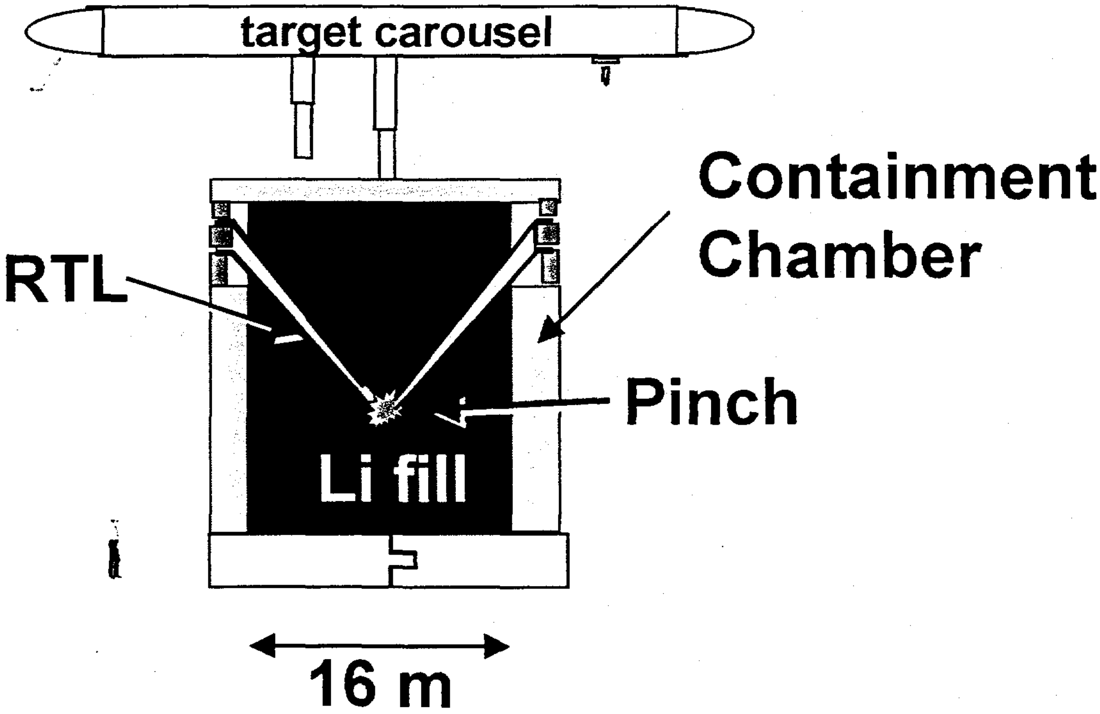


Figure captions.

Fig. 1. Binding Energy per nucleon. An interesting feature of a bound nucleus, the central core of an atom that is surrounded by an electron cloud, is that the average energy per nucleon (protons or neutrons) peaks at the configuration of the iron-56 (56-nucleons) nucleus. Massive nuclei (e.g. uranium) can be fissioned, or split, moving down the curve toward the stability peak. This is the process used in fission (what are normally called nuclear power) power plants. Fusion, or combining, of two or more nuclei happens on the low-mass-number portion of the curve.

Fig. 2. Dynamic Hohlraum configuration of a z pinch. Electrons move up through the outer electrode and down through the wire array. The force created by the magnetic fields they generate pushes the tungsten wires to the axis.

Fig. 3. Fusion reactor components.

Fig. 4. Sketch of a z pinch reactor chamber. An animation of this can be found at URL: http://www.sandia.gov/ACG/pinch.htm.