

Pinch me – I'm fusing!

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

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The process of combining nuclei (the protons and neutrons inside an atomic nucleus) together with 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.¹

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 pinchs are worth pursuing as a driver for a power reactor and how it may one day generate electrical power for mankind.

What is fusion and why do I 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 is the speed of light in this equation) 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 at the end of a collision and the kinetic energy 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 can be converted into thermal energy. This thermal energy is typically used to boil water and drive steam turbines.

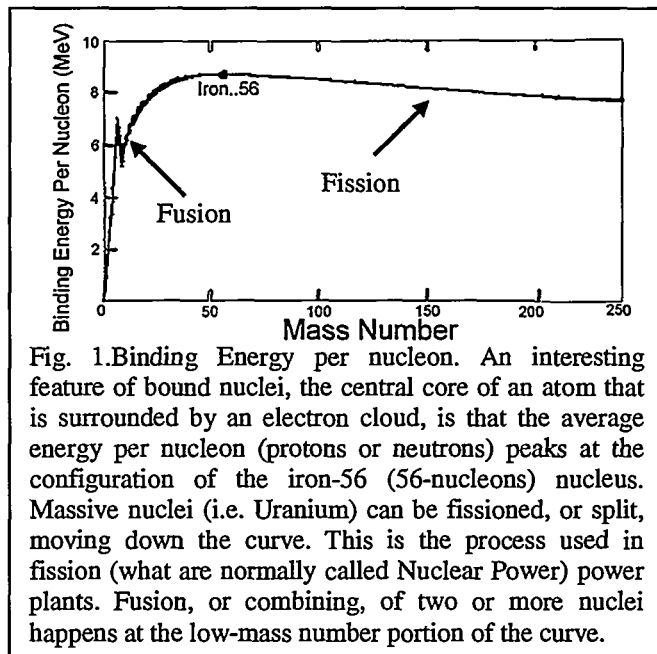


Fig. 1. Binding Energy per nucleon. An interesting feature of bound nuclei, the central core of an atom that is surrounded by an electron cloud, is that the average energy per nucleon (protons or neutrons) peaks at the configuration of the iron-56 (56-nucleons) nucleus. Massive nuclei (i.e. Uranium)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

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 (${}^2_1\text{D}$, 1-proton and 1-neutron) and tritium (${}^3_1\text{T}$, 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 generally called ‘advanced’ fuel cycles and it is much harder to create the necessary plasma physics

¹ Honestly - this is true. I did a literature search a few years ago on Cold Fusion and I found about 5000 papers and lots of books. There does seem to be something going on here, I just don't know what. I don't think anyone else does either. 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.

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conditions. It is generally considered easier to breed the necessary tritium in a blanket around the plasma than to create an advanced fuel cycle machine. The tritium can be bred by surrounding the fusing material with a lot of lithium. The term breed means that the neutrons leaving the fuel are made to interact with lithium and lithium interactions create tritium, more fuel, as a bi-product.

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 ($>ms$). 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 until it ignites. Ignition is the point at which the energetic fusion fragments heat the fuel fast enough that fuel around the initial hot-spot is heated to the point it will also fuse. In this way a burning wave can propagate through the fuel.

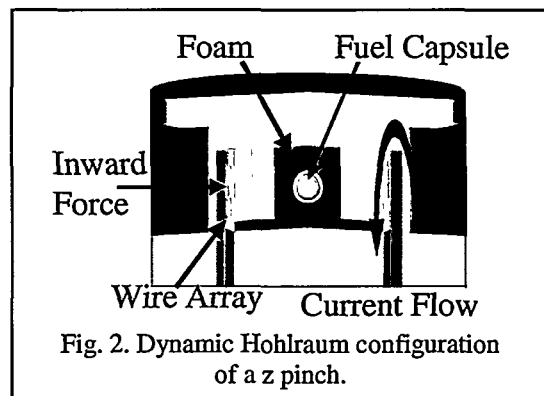
For both of these the physics is difficult. Incredible progress has been made in both methodologies but each has a long way to go and both methods are quite risky. The completion of a next step machine for MFE or ICF (Inertial Confinement Fusion) may show the real capabilities of either method. Either method MFE or ICF 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. 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 and 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 ? and why might z pinches be well suited to driving a fusion reactor?

A z pinch is a plasma created by an axial current; this means current flowing in one direction at a given distance from the axis. A type of pinch is shown schematically in Fig. 2. Physically, what you have 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 Mega-Amperes) 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).



There are a few ways fusion could be obtained in a pinch. I will only describe the one called a Dynamic Hohlraum. When this inward moving plasma sheath strikes the foam it generates a radiation wave and a shock. 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.

The Z machine at Sandia National Laboratories is the worlds largest z pinch driver today. Of the nominally 10 MJ of stored electrical energy in its banks roughly 2 MJ of x-rays can be created. It can carry more than 20 MA of current and produce roughly 2 MJ of soft x-rays.

What I'll do next is compare some significant engineering differences, not physics, of magnetic fusion energy (MFE) reactors and two Inertial Confinement Fusion (ICF) concepts (laser driven, and z pinch driven). One disclaimer is that this 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 plasma (the part where the fusion happens). 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 over that 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 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 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. Lets work out from the center. The MFE plasma can be many cubic meters in volume and it needs to last a long time (ms 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 the plasma and fueling it, this wall must also survive the full neutron flux produced by the fusion reaction products. This 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.

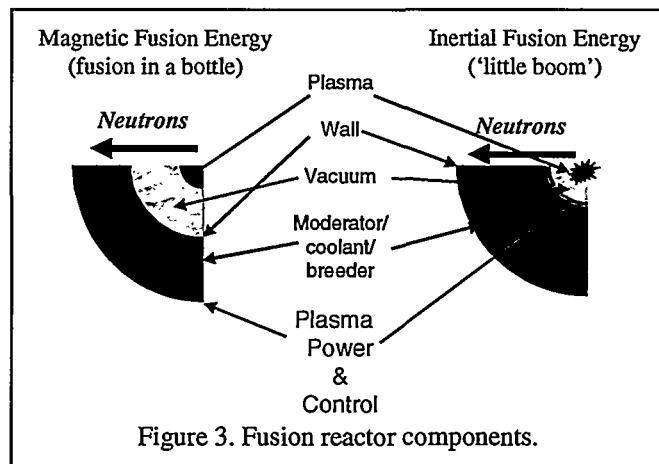


Figure 3. Fusion reactor components.

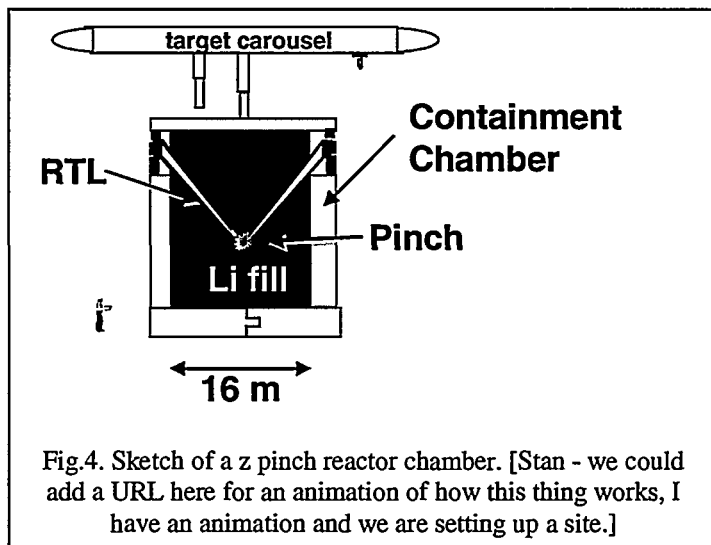
This wall may also be the saving grace of an ICF reactor. If you look in Fig. 3, the moderator sits inside the wall of an ICF design. The moderator in ICF reactor concepts absorbs much of the neutron energy. This material is normally a liquid and weakening of the structure is not an issue like it is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

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, field coils and moderator) it will be difficult to obtain adequate tritium breeding.

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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 a 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 z pinch driven reactor chamber. There is a central containment chamber. At the beginning of a shot, a single energy producing event, a crane moves a prepumped target/electrode assembly (pink) 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 and the tritium 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 100's of apertures. Flowing liquid metal walls of lithium or FLiBe (Fluorine, Lithium, Beryllium walls), 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.

Today's 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 this 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 10's 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 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 and I don't know how to quantify it. 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 a poor companion 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.

Don't get me wrong - 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. 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 good.

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, et al., "The Physics of Fast Z Pinches" to be published in the Jan. 2000 volume of *Reviews of Modern Physics* (SAND98-1632). For those desiring more information on laser fusion I refer you to John Lindl's book 'Inertial Confinement Fusion', New York: Springer-Verlag, 1998. Spielman has recently completed a compendium of talks and background information on z pinch fusion in SAND99-3155, "Z-Pinch Fusion for Energy Applications".

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