SAND2000-1342C

Z-Pinch Driven Fusion Energy

S A. Slutz, C. L. Olson, G. E. Rochau, and M. S. Derzon
Sandia National Laboratories, USA

P. F. Peterson
University of California Berkeley

J. S. De Groot, N. Jensen, G. Miller
University of California Davis

Keywords: fusion, z-pinch, energy, inertial confinement

Abstract

The Z machine at Sandia National Laboratories (SNL) is the most powerful multi-module synchronized pulsed-power accelerator in the world. Rapid development of z-pinch loads on Z has led to outstanding progress in the last few years, resulting in radiative powers of up to 280 TW in 4 ns and a total radiated x-ray energy of 1.8 MJ. The present goal is to demonstrate single-shot, high-yield fusion capsules. Pulsed power is a robust and inexpensive technology, which should be well suited for Inertial Fusion Energy, but a rep- rated capability is needed. Recent developments have led to a viable conceptual approach for a rep-rated z-pinch power plant for IFE. This concept exploits the advantages of going to high yield (a few GJ) at low rep-rate (~ 0.1 Hz), and using a Recyclable Transmission Line (RTL) to provide the necessary standoff between the fusion target and the power plant chamber. In this approach, a portion of the transmission line near the capsule is replaced after each shot. The RTL should be constructed of materials that can easily be separated from the liquid coolant stream and refabricated for a subsequent shots. One possibility is that most of the RTL is formed by casting FLiBe, a salt composed of fluorine, lithium, and beryllium, which is an attractive choice for the reactor coolant, with chemically compatible lead or tin on the surface to provide conductivity. We estimate that fusion yields greater than 1 GJ will be required for efficient generation of electricity. Calculations indicate that the first wall will have an acceptable lifetime with these high yields if blast mitigation techniques are used. Furthermore, yields above 5 GJ may allow the use of a compact blanket direct conversion scheme.

I. Introduction

The efficient generation of high power thermal radiation[1] (> 200 TW) at high temperatures[2] (150-200 eV) has been demonstrated with z-pinch implosions, and this thermal radiation can be used to drive inertial fusion capsules. Lasnex computer calculations[3] indicate that a pulsed power machine delivering 55-60 MA could drive high yield (> 500 MJ) fusion explosions. This pulsed power based technology is efficient (>15% to x-rays) and much less expensive than other IFE driver technologies such as lasers or heavy ion beams, and the capability to operate reliably at high repetition rates has been demonstrated at small scale. However, a z-pinch driven fusion explosion will destroy a portion of the transmission line that delivers the electrical power to the z-pinch. These electrodes constructed from aluminium and stainless steel are expensive, and would be damaged if the z-pinch ignited a high yield inertial fusion capsule. This cost would outweigh the value of the energy created

by the fusion explosion. Thus, up until recently, it has been assumed that this technology is limited to single-shot experiments.

Various means of providing standoff for z-pinch have been suggested. One possible approach[4] is to use a high velocity projectile to compress a seed magnetic field. The compression of the field can generate the large current required to drive a z-pinch. This approach has difficulty generating short current pulses and will require either a large area projectile, an opening switch or a very large B » 1 Tesla seed field. The seed field could possibly be generated by an electron beam, but this results in a fairly complicated and probably expensive system. Another approach is to use an ion beam to deliver power to an inverse diode as proposed by one of the authors (SAS). The inverse diode is a magnetically insulated gap, which also serves as a transmission line to deliver current to the z-pinch. The cathode side would be constructed from a thin foil that allows the ions to pass through, delivering their current to the anode. This current then flows through the z-pinch wire assembly and back to the cathode foil. A potential problem in the inverse diode is that the large space-charge of the beam current is sufficient to generate a virtual-anode that could reflect the ion beam, unless electrons can effectively neutralize this space-charge. The effectiveness of the electron neutralization depends on electromagnetic fluctuations that allow them to cross magnetic field lines. Analytic theory[5] and numerical simulations[6] suggest this process is very effective. However, this process would have to be studied experimentally. Another potential problem is that the anode of the inverse diode will become a plasma and thus a source of ions. This will result in a loss of efficiency. The problem may be reduced by using a high-z material for the anode, but surface contamination will probably still be a problem. This approach has complex physics issues that must be resolved. Also the inverse diode will be destroyed on each shot. Since it is a moderately complicated piece of equipment this approach may not be cost effective.

The most promising concept is the Recyclable Transmission Line (RTL), which emerged at a workshop[7] at Sandia National Laboratories and was developed further at the Snowmass[8] workshop on Fusion Energy. This concept is much simpler than the two we have discussed previously. The idea is to construct the final portion of the transmission lines which deliver current to the z-pinch out of material that can be recycled inexpensively. We shall refer to this portion of the transmission line as the RTL (Recyclable Transmission Line) as shown in Fig. 1. The labelled RTL portion of the transmission line will be blown up with each detonation of the capsule located within the z-pinch. Then the entire assembly will be replaced with a new one for the next detonation. A coaxial feed is shown with a dynamic hohlraum[9] capsule. The use of doubled ended z-pinch driven hohlraum[3] would require the use of a triaxial feed. The connection between the recyclable and the permanent part of the transmission line is at the top of the reactor chamber. Only a small portion of the first wall at the top of the containment chamber is shown. Notice that the vacuum interface does not see the blast directly and could be a large distance from the opening in the reactor chamber (the schematic is not to scale). The RTL could be constructed from wires[10], sheets, or cast[11]. Wires have the advantage of easy alignment, but the anode side may form a source of ions when the wires explode. The use of thin sheets possibly strengthened by wires would not be as easy to align, but should not produce a source of ions on the anode side. The cost of constructing an RTL with these techniques should be approximately proportional to the total mass, e.g. stainless steel costs about $3/kg. However, one could construct a very low mass RTL with these two approaches. Calculations indicate that a total mass less than 1 kg results in an acceptable amount of electrode motion in response to magnetic pressure. The use of a casting technique could result in an even lower cost, which should be almost independent of the mass of the RTL. A particularly attractive option[11] is to use a lithium compound such as FLiBe, which would be in the reactor anyway to provide cooling and tritium breeding.

Note that the RTL has an advantage over all other existing approaches to inertial fusion, which is that the RTL does not have to go in a straight line. For example, as shown in Fig. 1, the RTL can have a right angle bend, which allows for shielding the x-rays and blast wave from the fusion explosion from the delicate parts of the accelerator (e.g. the convolute and vacuum interface) and the permanent connection hardware. In contrast, a laser or ion driver always has the problem of the last optic element.

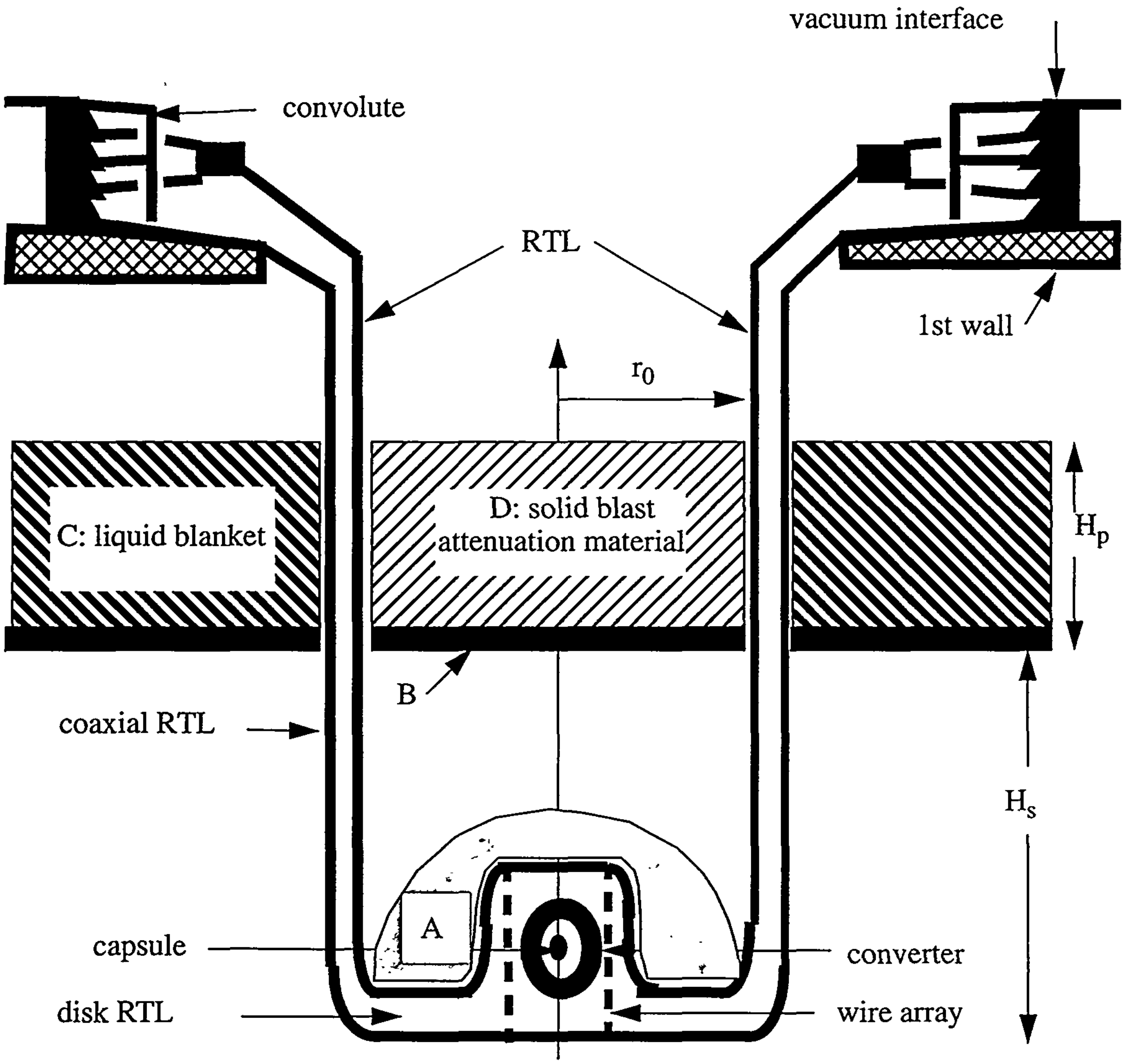

Figure 1. A schematic of a Recyclable Transmission Line

II. RTL materials

Studies indicate that the cost of replacing the damaged transmission line can be significantly below the value of the energy that is produced by the fusion explosion if a low mass transmission line is used (~ 1 kg) and the fusion explosion has a relatively high yield (~ few GJ) at low repetition rates (~ 0.1 hertz). Much larger RTL masses are possible if materials are used which can be separated from other materials within the fusion chamber and then refabricating another transmission line from this recovered material. A cost estimate of ($0.70/shot) has been made by the Advanced Manufacturing Group at Sandia National Laboratories, assuming that the parts could be fabricated robotically. The cost is essentially independent of the mass if a casting process can be used.

Studies have shown that the target chamber can be protected from each fusion blast by suitable liquid and/or solid materials. The use of lithium-bearing materials will also result in the breeding of tritium, which is needed for fuel. A material that can accomplish both of these functions is FLiBe, which is a salt composed of Fluorine, Lithium, and Beryllium. It may be possible to use FLiBe in its solid state as a portion of the RTL. However, FLiBe is an insulator, so it will need a coating of a conducting material. Materials such as lead, tin and aluminium can easily be separated from FLiBe and are reasonably good conductors. Alternatively, lithium metal or lithium metal alloys (LiPb, LiAl), could be used. In addition to the conductivity requirement, the cathode side of a transmission line must break down fairly uniformly to result in efficient power flow. For example, aluminum is a better conductor than stainless steel, but does not break down as uniformly as stainless steel. Therefore, we will need to test the power flow properties of the candidate conducting materials.

We expect to perform initial power flow experiments with some of these materials in the summer of 2000. In parallel with this effort, we will have determined if construction of RTLs with any of the candidate materials poses additional problems, e.g. insufficient physical strength, fabrication difficulties, etc. (For example, solid FLiBe will be tested for mechanical strength and we will determine if a suitable coating of tin or lead can be put onto the surface of FLiBe.)

III. Dimensions and driver voltage

The RTL must have the proper dimensions so that it operates as a self magnetically insulated transmission line. Efficient power flow has been demonstrated with a gap $d_0 = 2$ mm near the z-pinch. We shall assume a fixed gap in a disk transmission line out to a radius r_0 determined by magnetic insulation. To maintain magnetic insulation the gap voltage must be less than the critical voltage

$$V_c = B d_0 c = \frac{\mu_0 I_p \sqrt{F_L}}{2\pi r_0} d_0 c, \quad (1)$$

where I_p is the peak current and F_L is the fraction of the peak current that is needed before the RTL will be self magnetically insulated. The voltage across the disk RTL is approximately

$$V_d = \frac{\mu_0}{2\pi}\left(d_0 \ln\left(\frac{r_0}{r_i}\right) + h_p \ln\left(\frac{d_0 + r_i}{r_f}\right)\right)\frac{I_p}{t_r}, \quad (2)$$

where t_r is the current rise time, where r_i/r_f are the initial/final radius of the z-pinch. The result of solving eq. (1) and eq. (2) with the values I_p=60 MA, r_i=2 cm, r_f=3 mm, h_p=2 cm, F_L=.1, yields a value for r_0 of approximately 0.5 m. As shown in Fig. 1, the disk transmission line is attached to a coaxial (tri-axial for two pinches) line at r_0. The gap cannot be maintained at d_0, but must increase to maintain magnetic insulation. We set the voltage across the gap equal to the critical voltage and obtain the solution

$$d(z) = d_0 \exp(\beta z), \text{ where } \beta = \frac{1}{ct_r\sqrt{F_L}}. \quad (3)$$

The voltage at the beginning of the RTL (where it attaches to the permanent part of the transmission line) can then be found from the magnetic insulation condition, eq. (1). The results are plotted in Fig. 2 as a function of the length of the coaxial (or tri-axial) part of the RTL.

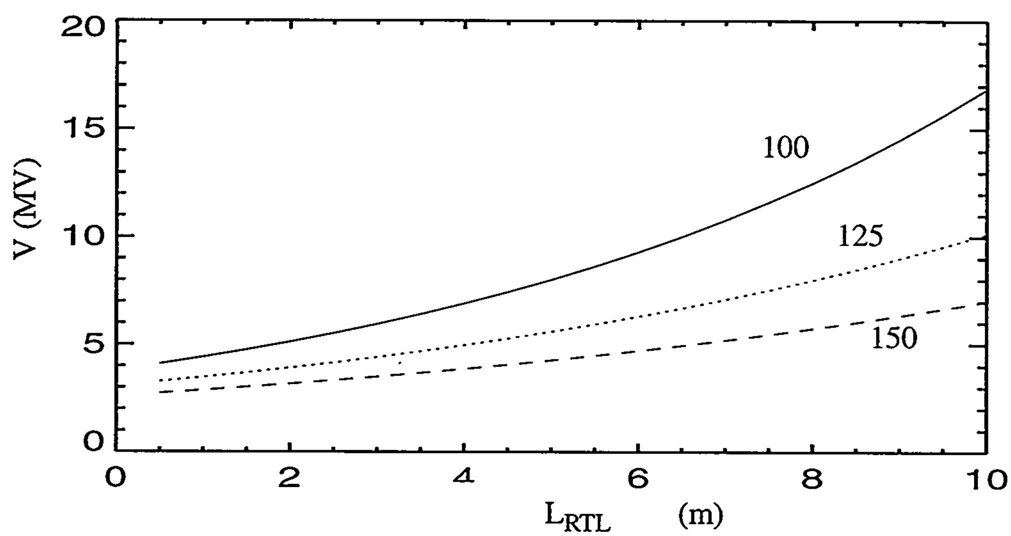

Figure 2. The RTL input voltage as a function of length for different rise times

The three curves are labelled by the pulse risetime in ns. This will be roughly the voltage at the stack for each of the permanent transmission lines that feeds the convolute. In this scenario, the convolute is assumed to be permanent.

IV. Minimum fusion yield

It is interesting to make an estimate of the minimum yield that allows a balance between the cost of recycling the transmission line and the price that the resulting electricity can be sold for. The minimum yield can be estimated from the formula

$$Y_{min} = \left(\frac{C_{TOT}}{C_E} + \frac{LI_{peak}^2}{2\varepsilon_{mach}}\right)\frac{1}{\varepsilon_G}, \quad (4)$$

where C_E is the price of electricity, and C_{TOT} is the cost of the RTL, the z-pinch and the capsule. The cost of casting an RTL has been estimated at C_{RTL} =\$0.70. Assuming \$.05/kW-hr, C_{TOT}=\$1.00 (assume the capsule assembly costs \$0.30), a machine efficiency, ε_{mach}, of 15%, and electrical generating efficiency, ε_G, of 30%, the minimum yield as calculated from eq. (4) is plotted in Figure 3. Estimates indicate that 3-4 m of standoff will be sufficient for a yield of several GJ if the blast is mitigated by appropriate materials[11].

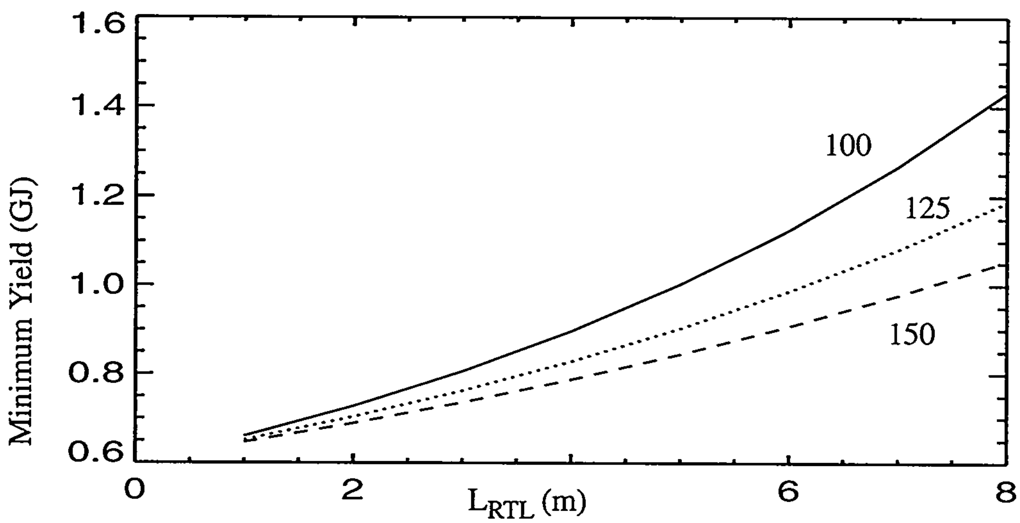

Figure 3. Minimum fusion yield as a function of the length of the RTL

The minimum yield is approximately 800 MJ for a transmission length of 4 m. Efficient generation of electricity (Low recirculating power) will require a yield at least four times larger, or about 3-4 GJ. Although this is larger than the yields expected for other inertial fusion energy approaches, it is not unreasonably large. For comparison the Pacer[12] concept would have used yields of roughly 4000 GJ. It should be noted that the higher yields allow a reduction in the repetition rate. A shot rate of 0.3 hertz would yield approximately 1 GW thermal. Lower shot rate allows more time to clear and/or pump out the reactor between shots.

V. Z-pinch driven fusion power plant issues

There are several power plant issues for z-pinch driven fusion that are somewhat different than expected for laser-driven or heavy-ion-driven power plants. Since the fusion yield and the mass of target material that is vaporized will be larger, a substantial blast is generated. The most effective method for mitigating the blast involves the use of thick, porous blankets to attenuate kinetic energy from impulse loads generated by the target, and the design of the target to minimize impulse loading in the direction of the permanent electrode hardware. The length of the electrode assembly, shown schematically in Fig. 1, should be made as small as possible to minimize the mass of electrode material, to reduce the maximum electrode voltage, and to improve the efficiency of pulsed power delivery to the target. Protection of the permanent electrode contacts and liquid injection nozzles from blast damage sets this minimum distance. Blast effects are determined by the geometry of the target, electrodes, liquid blanket and chamber structure; and by the target yield. We need to minimize the blast impulse to the permanent electrode junctions and injection nozzle assemblies, and transfer the blast impulse to these structures over a sufficiently long time period to avoid damage. A major advantage for pulsed power compared to other drivers is the ability of electricity to turn corners, which makes it simpler to interpose liquid between the target and the permanent chamber structures, and allows the driver energy to be delivered from one side of the target. Thus, as shown schematically in Fig. 1, the recyclable electrode assembly can be a relatively skinny cylinder inserted from the top of a target chamber. Here we assume that the chamber structures can be placed arbitrarily far away from the target in the radial (horizontal) and downward directions, and thus the primary goal is to minimize the upward momentum imparted toward the permanent electrode and nozzle assemblies that must be located as close as possible to the target. Energy from the target deposits in four primary regions.

Region A is a blanket of material surrounding the upper half of the target assembly. This blanket can stop most of the neutrons and hard x-rays generated by the exploding fusion capsule and direct most of the capsule kinetic energy downward. The residual neutron energy is deposited in region B. The target standoff distance, H_s, must be sufficiently large so that the energy deposition due to neutron heating remains below the cohesive energy of the liquid, so that vapor generation does not eject a substantial mass of liquid downward, imparting upward momentum to the remaining liquid. For a blanket composed of FLiBe located $H_s = 60$ cm from a 4-GJ target, the neutron energy deposition near the blanket surface will be around 1500 kJ/kg, which will raise the FLiBe temperature by 640°C. If the blanket material is initially liquid at 620°C, the final temperature 0f 1260°C is still below the boiling temperature 1435°C. The target debris emits x-ray energy that ablates the inner surface of the outer blanket (Region B). The typical ablation layer thickness is several tens of microns, and the impulse loading delivered to the bulk liquid depends on the details of the energy distribution in the ablated layer and the velocity with which the layer leaves the surface. This material is ejected primarily downward, colliding and mixing with target debris.

The fusion energy from alphas and some fraction of the neutron energy (25 to 50 percent of total energy) deposits in a relatively small mass of capsule and hohlraum debris, perhaps a few grams to tens of grams of material. This fraction can be increased if tritium-lean targets are used. Some of this energy is subsequently radiated as x-rays, and the remainder partitions between kinetic and internal energy in the debris. This very-high energy density material is directed toward the bottom of the reactor vessel. Although it carries a substantial fraction of the fusion energy, this small mass has relatively little momentum and thus results in relatively little upward impulse loading to the liquid blanket and structure. Region A is vaporized by fusion neutron heating and subsequently expands until it reaches the blankets C and D. Region C will be a liquid blanket generated by liquid coolant jets with voids to distribute the impulse uniformly and absorb kinetic energy. It will be more convenient to construct region D out of solid material (also with voids) so that it can be placed in the reactor vessel with the RTL. Accurate calculations of the upward impulse load delivered to regions C and D requires detailed two-dimensional gas dynamics simulations. We have made scaling estimates using a snowplow model of the impulsive loading of these materials with voids and assuming that the debris is ejected downward at the speed of sound after heating. We estimate that a fusion yield of 4 GJ will result in an average upward velocity of 4 m/s for $H_s = 2$ m, $H_p = 1.$ m and $H_t = 1$ m. The total impulse of $7.x10^4$ will be delivered to the first wall in approximately 40 ms. This would generate rather high pressures on a simple solid first wall. However, a "porous" first wall can be constructed using multiple arrays of tubes arranged in a manner similar to venetian blinds. Such a first wall would absorb the impulse over a longer time to reduce the effective pressure.

Since most of the kinetic energy is directed downward it can be converted directly into electricity by MHD in a manner similar to that described by Logan[13]. The large yield has the advantage that most of the 14 MeV neutrons can be stopped in a blanket that surrounds the capsule depositing enough energy to convert this material into a plasma. The residual energy can be recovered by a steam bottoming cycle to increase overall efficiency and to reduce thermal pollution which becomes an issue at large-scale deployment. Such a system could provide significantly higher efficiencies than the standard steam cycle, because of the high plasma temperatures. The key requirement is that the fusion yield is high enough to heat the compact blanket to working temperatures of 1 to 3 eV in the reactor chamber. Working temperatures this high are required so that the MHD converter operates efficiently. Another condition on the compact blanket is that the thickness must be several neutron energy mean-free paths thick to absorb most of the fusion energy. These two conditions place a lower limit on the fusion yield that can be used in this design. It was shown[14] that the lower limit is about 5GJ for FLiBe, lithium, and lead-lithium compact blankets, and 1GJ for lithium hydride. However, the separation of the tritium is more difficult for lithium hydride. Z-pinch IFE power reactors are well matched to this requirement, since they will operate with fusion yields in the range 1-20GJ.

We have begun to look at the power generation system that would incorporate the z-pinch technology. The Z-Pinch Power Plant would be sized to take best economic advantage of the manufacturing facility for RTLs, targets and wire-arrays. Our first estimate of a plant layout is shown in Figure 4. For this layout we have assumed a 12 unit plant with each unit generating 20 GJ of fusion energy. Assuming an 80% conversion efficiency of fusion energy to thermal energy and a 30% conversion of thermal energy to electrical energy, each unit would generate 5 GJ of electrical energy per shot. Assuming an average of 10 units (allowing for 2 units out of service) operating on a 10 second cycle, the plant would generate 5000 Megawatts to the electrical grid. This represents the same capacity as the largest nuclear power unit in the U.S., Palo Verde Nuclear Station in Tonapah, AZ, in roughly the same area.

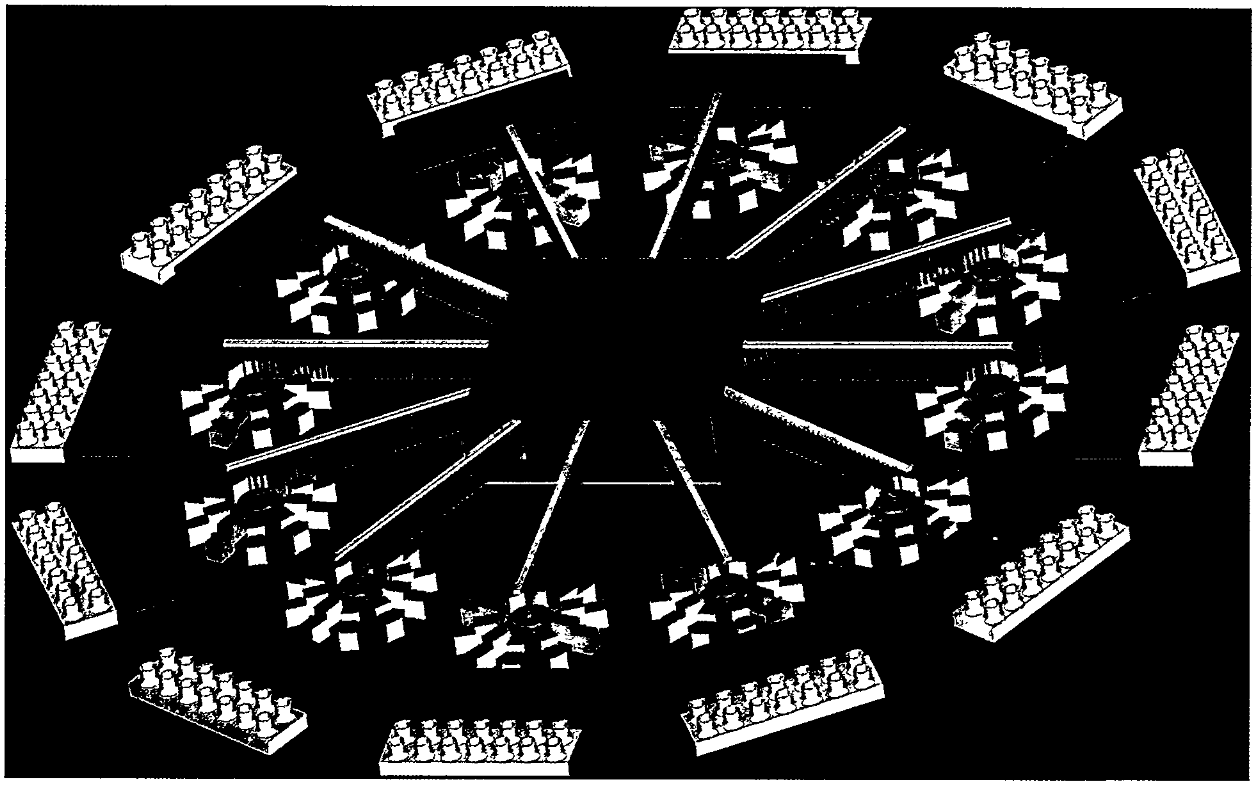

Figure 4. A schematic of a z-pinch driven fusion power plant

VI. Summary and Future Work

Several options that could provide standoff for z-pinch driven fusion energy have been reviewed. The most straightforward is the Recyclable Transmission Line (RTL). The RTL must be constructed from materials that can easily be separated from the reactor coolant (lithium, lithium-lead, or FLiBe). Several candidate materials have been identified. We have planned experiments to demonstrate efficient power flow in transmission lines constructed from these materials. The ratio $I_p/2\pi r$ will be approximately 2MA/cm, so that the magnetic pressure will be as large as expected in a reactor RTL.

We estimate that fusion yields greater than 1 GJ will be required for efficient generation of electricity. Calculations indicate that the first wall will have an acceptable lifetime with these high yields if blast mitigation techniques are used. Furthermore, yields above 5 GJ may allow the use of a compact blanket MHD conversion scheme.

We have done a preliminary conceptual study of the z-pinch driven reactor. We plan to initiate a detailed reactor design. Firmer estimates are needed of the cost of recycling materials from the transmission line, the capsule, and the z-pinch. The damage of the vacuum insulator under indirect exposure to the reactor materials and neutrons needs to be studied and the lifetime of the convolute needs to be determined.

acknowledgements

I wish to acknowledge J. Hammer, D. Ryutov, R. Spielman for helpful discussions.

References

1 Spielman, R. B. et. al. Phys. of Plasmas, 5, 2105, 1998.
2 Porter, J. L., Bull. Am. Phys. Soc. 42, 1948 (1998): Leeper, R. J., et. al. Nuclear Fusion, 39, 1283, 1999.
3 Hammer, J. H., Tabak, M., Wilks, S. C., Lindl, J. D., Bailey, D. S., Rambo, P. W., Toor, A., Zimmerman, G. B., Phys. Plasmas, 6, 2129, 1999.
4 D. Ryutov, and A. Toor "Stand-off Energy Sources for Z-Pinch Implosions" LLNL Report UCRL-ID-135082, July 20, 1999
5 Slutz, S. A., and Desjarlais, M. P., J. Appl. Phys., 67, 6705 (1990)
6 Slutz, S. A., Poukey, J. W., and Pointon, T. D., Phys. Plasmas, 1, 2072, (1994)
7 Z-Pinch IFE Workshop, Sandia National Laboratories, Albuquerque, NM, April 27-28, 1999
8 Snowmass Fusion Summer Stúdy, Snowmass CO, July 11-23, 1999.
9 J. H. Brownell, R. L. Bowers, Bull. Am Phys. Soc. 40, 1848 (1995)
10 Jim Hammer "Z-Pinch IFE Workshop", Sandia National Laboratories, April 27-28, 1999
11 Per Peterson "Z-Pinch IFE Workshop", Sandia National Laboratories, April 27-28, 1999: P. F. Peterson, C. Cole, A. Donelli, and D. R. Olander, "Application of Binary Metal/Salt Coolants for Electrodes for Pulsed-Power Fusion Plants" First International Conference on Inertial Fusion Sciences and Applications, University Bordeaux, France, Sept. 12-17, 1999.
12 R. P. Hammond, H.W. Hubbard and J. L. Dooley, Mech. Eng. p34 July 1982
13 B. G. Logan, "Low cost, High Yield IFE Reactors: Revisiting Velikhovs Vaporizing Blankets," Fusion Technology, 21, 1784 (1992).
14 B. G. Logan, "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD conversion," Fusion Engineering and Design 22, 151 (1993).

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.