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Z-Pinch Power Plant Design and IFE Materials Program on Z and RHEPP at SNL*

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1. Introduction

There are presently four driver technologies that are being developed for IFE Power Plants: these are HIF (Heavy Ion Fusion), KrF (Krypton Fluoride laser), DPSSL (Diode-Pumped Solid-State Laser), and Z-Pinches. All four types were included in the discussions at the Snowmass Fusion Summer Study in 1999 [1]. The purpose of this paper is to discuss (1) the z-pinch power plant concept, and (2) the IFE chamber materials program on Z and RHEPP at SNL. The z-pinch power plant concept offers several advantages for a robust IFE power plant. The IFE chamber materials program will be used to study IFE chamber materials response for all IFE power plant scenarios at power plant level fluences now.

2. Z-Pinch Power Plant Concept

The Z machine at Sandia National Laboratories (SNL) is the most powerful multi-module synchronized pulsed-power accelerator in the world, and it routinely delivers up to 20 MA to a z-pinch load. 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 of the Inertial Confinement Fusion (ICF) program for Z is to demonstrate single-shot, high-yield fusion capsules. Lasnex computer calculations indicate that a pulsed power machine delivering 55-60 MA could drive high yield (> 0.5 GJ) fusion explosions. Pulsed power is a robust and inexpensive technology, which should be well suited for Inertial Fusion Energy (IFE), but a rep-rated capability is needed. 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 pulsed power 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. On Z, these electrodes are constructed from stainless steel, and are expensive, and would be damaged. The cost for the transmission line 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.

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However, 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 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 electrical conductivity. We estimate that fusion yields greater than 1 GJ will be required for efficient generation of electricity. (For comparison, IFE power plant studies using heavy ions or lasers typically use yields of 0.4 - 0.7 GJ.) 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 direct energy conversion.

The Recyclable Transmission Line (RTL) concept 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 labeled 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 capsule. The use of doubled ended z-pinch driven hohlraum 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, sheets, or cast. 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 is to use a lithium compound such as Flibe with a chemically compatible metal conductor, since Flibe would be in the reactor anyway to provide cooling and tritium breeding.

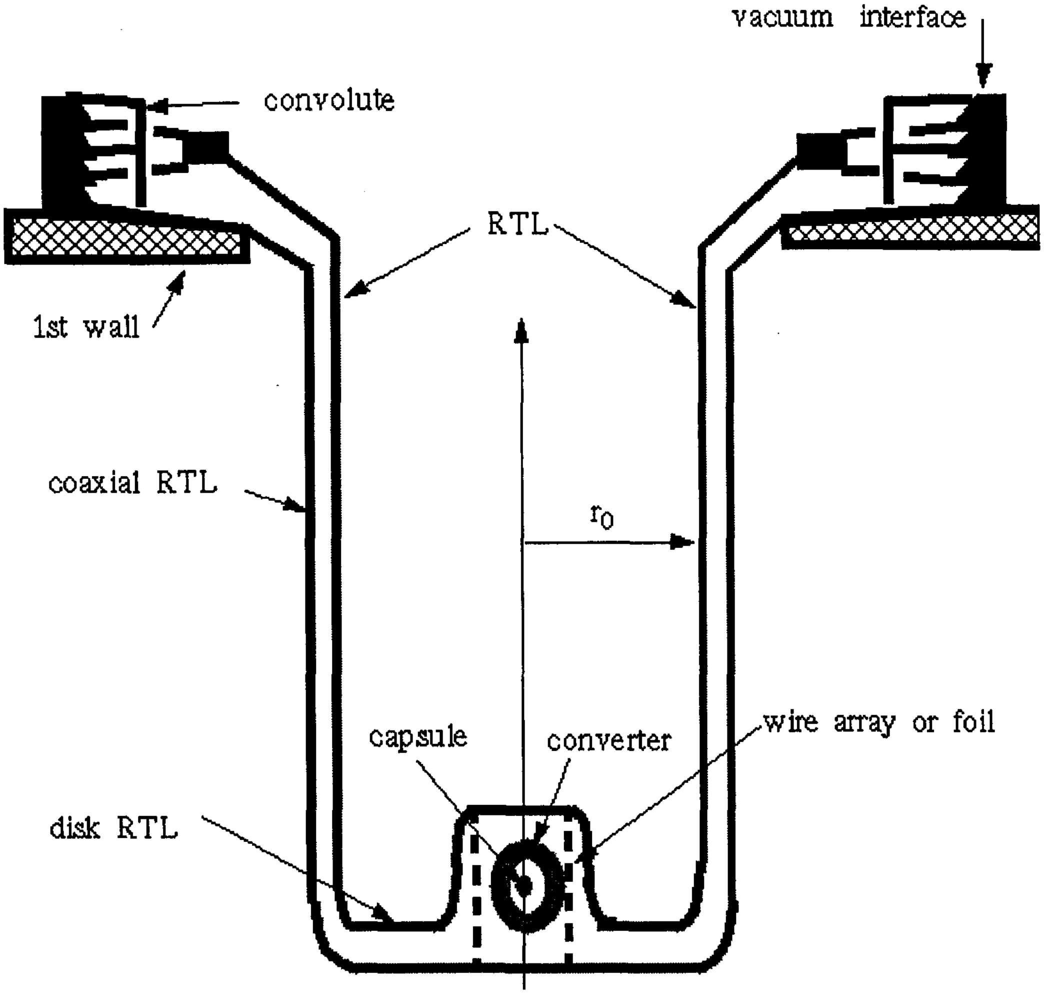

Figure 1. A schematic of a Recyclable Transmission Line (RTL).

Note that the RTL has an advantage over all other existing approaches to ICF and IFE, 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.

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). Much larger RTL masses are possible if materials are used which can be separated from other materials within the fusion chamber, and then this recovered material is refabricated into another transmission line. 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 a lithium-bearing coolant blanket of sufficient thickness will result in (1) absorption of the fusion neutron energy (the primary function for a power plant), (2) breeding of tritium (which is needed for fuel), and (3) protection of the first wall from neutron damage. A material that can accomplish all of these functions is Flibe. 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.

The key advantages of the RTL z-pinch power plant concept are that (1) the z-pinch is essentially hard-wired to the accelerator, essentially guaranteeing that it will work, (2) the problem of a final optic is essentially eliminated, (3) the problem of accurately pointing and tracking N beams to accurately hit the target is eliminated,(4) the problem of high speed target injection is eliminated, and (5) the concept is simple, robust, and works in an industrial environment. The main issues to be addressed are to (1) find a suitable RTL material, (2) investigate the use of tailored-density gradients to mitigate the shock to the first wall, (3) develop a suitable rep-rated pulsed-power concept to drive the z-pinches, and (4) refine the overall RTL power plant concept.

Preliminary experiments on the Saturn accelerator (10 MA) at SNL to test RTL materials have been performed successfully. A coaxial transmission line (height 30 cm and diameter 8 cm) made of various test materials was used. Previous experiments had indicated that aluminum electrodes break down non-uniformly, and could lead to power flow losses. No current loss or non-uniform power flow was observed for stainless-steel, aluminum, or tin-coated RTLs.

A program is now being developed to study the z-pinch power plant concept in detail.

3. IFE Chamber Materials Response Program on Z and RHEPP

X-ray damage and debris ion damage to target chamber structures is an important issue on the path to the realization of inertial fusion energy (IFE). For dry walls, which have the potential to maintain high cleanliness levels desirable for laser IFE, a key issue is the energy deposition profile and the resulting thermal and mechanical responses. For liquid walls, which offer the promise of effective neutron shielding of chamber structures, a key issue is the rapid vaporization of the liquid surface, with a potentially large recoil impulse transmitted to the remaining portion of the liquid. A program is being developed to perform a series of experiments to measure the response of a variety of prototypical IFE materials samples irradiated by (1) x-rays on the Z accelerator at Sandia National Laboratories, and by (2) ions on the RHEPP/MAP ion facility at Sandia National Laboratories. Z produces up to 2 MJ, and fluences up to 3000 J/cm^2, of short-pulsed x rays in an environment that permits a variety of experiments at power-plant level x-ray fluences, today. RHEPP/MAP produces ion fluences up to 15 J/cm^2 in an environment that permits a variety of experiments at power-plant level ion fluences today.

Indirect-drive IFE targets, currently expected to be used for heavy ion fusion and z-pinch fusion, will release about 25% of their yield in x-rays. Indirect-drive targets are compatible with target chambers protected by thick liquid walls or wetted walls, where the protective liquid is partially vaporized by the x-rays and a large recoil impulse is transmitted to the remaining liquid. X-ray ablation experiments will be performed as "add-on experiments" with existing Z-shots, and the experiments will use the extensive existing suite of Z diagnostics to measure time-resolved pressure loading and debris blow-off density and velocity. Most importantly, these Z shots will use actual chamber materials (including the salt Flibe), so that the equation of state and chemical kinetics do not introduce experimental distortions. These experiments will be extremely valuable in validating models for x-ray impulse loading for heavy-ion, MTF and z-pinch chambers. The experiments include the capture of ablation debris onto simple collection coupons, which will also provide data for validation of multidimensional gas dynamics and condensation models.

Direct-drive targets, currently expected to be used for laser fusion, will release a few percent of their yield directly in x-rays, with additional x-ray generation potentially occurring due to the interaction of target debris with chamber gas. Dry-wall materials that are resistant to damage from x-rays would significantly improve the prospects for laser IFE. Planned experiments will test candidate dry-wall materials, including graphite and special engineered carbon materials.

Direct-drive targets can release over 16% of their energy in debris ions and 12% in burn-product ions, whereas indirect-drive targets release only several percent of their energy in debris ions and burn-product ions. Ion ablation and material blow-off experiments can be performed on the RHEPP/MAPP ion facility, and a variety of diagnostics can be used to assess the effects.

A summary of the materials to be tested both with x-rays from Z, and with ions from RHEPP/MAP, is given in Table 1. These materials have been selected from all of the major IFE power plant studies to date. Note that there are four types of IFE power plants, as characterized by their chamber walls - dry wall, wetted wall, thick-liquid wall, and solid wall/density gradient. Also note that there are four main technologies that are being developed that could lead to an IFE power plant - KrF lasers, DPSSL lasers, heavy ion drivers, and z-pinch drivers. In Table 1, a large (X) denotes a mainline approach, and a small (x) denotes a possible approach. Several materials (e.g., carbon composites and graphite) really represent a class of materials, of which several examples would be tested. A material that is listed in () means that that material is not presently in vogue, but should be tested for completeness. Lastly, note that two materials would be tested as reference materials.

Table 1. Materials to be tested (tentative list)

Material	IFE Power Plant Type	KrF	DPSSL	HIF	Z-Pinch
Carbon composite	Dry wall	X	X	x	
Graphite	Dry wall	X	X	x	
(SiC)	Dry wall	X	X	x	
LiPb	Wetted wall	x	x	X	x
SnLi	Wetted wall	x	x	X	x
Flibe	Wetted wall	x	x	X	x
Flibe	Thick liquid			X	X
(Li)	Thick liquid			X	X
Flibe	Solid/density gradient				X
(Li)	Solid/density gradient				X
Tungsten	Reference material				
Al	Reference material				

4. Conclusions

The z-pinch power plant concept, and the IFE chamber materials program, have been discussed briefly. Of the four driver technologies being developed (HIF, KrF, DPSSL, Z-Pinch) for IFE, the z-pinch approach offers simplification and several advantages for a robust IFE power plant. For the IFE materials response program, x-rays from Z, and ions from RHEPP/MAP will be used to study IFE materials response for all IFE power plant scenarios at power plant level fluences now.

References

[1] C.L. Olson, Comments on Modern Physics **2,** 113 (2000).