DEVELOPMENT PATH FOR Z-PINCH IFE*

C. Olson[1], G. Rochau[1], S. Slutz[1], C. Morrow[1], R. Olson[1], M. Cuneo[1], D. Hanson[1], G. Bennett[1], T. Sanford[1], J. Bailey[1], W. Stygar[1], R. Vesey[1], T. Mehlhorn[1], K. Struve[1], M. Mazarakis[1], M. Savage[1], T. Pointon[1], M. Kiefer[1], S. Rosenthal[1], K. Cochrane[1], L. Schneider[1], S. Glover[1], K. Reed[1], D. Schroen[1], C. Farnum[1], M. Modesto[1], D. Oscar[1], L. Chhabildas[1], J. Boyes[1], V. Vigil[1], R. Keith[1], M. Turgeon[1], B. Cipiti[1], E. Lindgren[1], V. Dandini[1], H. Tran[1], D. Smith[1], D. McDaniel[1]), J. Quintenz[1], M. K. Matzen[1], J. P. VanDevender[1], W. Gauster[1], L. Shephard[1], M. Walck[1], T. Renk[1], T. Tanaka[1], M. Ulrickson[1], W. Meier[2], J. Latkowski[2], R. Moir[2], R. Schmitt[2], S. Reyes[2], R. Abbott[2], R. Peterson[3], G. Pollock[3], P. Ottinger[4], J. Schumer[4], P. Peterson[5], D. Kammer[6], G. Kulcinski[6], L. El-Guebaly[6], G. Moses[6], I. Sviatoslavsky[6], M. Sawan[6], M. Anderson[6], R. Bonazza[6], J. Oakley[6], P. Meekunasombat[6], J. De Groot[7], N. Jensen[7], M. Abdou[8], A. Ying[8], P. Calderoni[8], N. Morley[8], S. Abdel-Khalik[9], C. Dillon[9], C. Lascar[9], D. Sadowski[9], R. Curry[10], K. McDonald[10], M. Barkey[11], W. Szaroletta[12], R. Gallix[13], N. Alexander[13], W. Rickman[13], C. Charman[13], H. Shatoff[13], D. Welch[14], D. Rose[14], P. Panchuk[15], D. Louie[16], S. Dean[17], A. Kim[18], S. Nedoseev[19], E. Grabovsky[19], A. Kingsep[19], V. Smirnov[19]

[1] Sandia National Laboratories, Albuquerque, NM 87107 USA
[2]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
[3] Los Alamos National Laboratories, Los Alamos, NM 87545, USA
[4] Naval Research Laboratory, Washington, DC 20375, USA
[5] University of California, Berkeley, CA 94720, USA
[6] University of Wisconsin, Madison, WI 53706, USA
[7] University of California, Davis, Davis, CA 95616, USA
[8]University of California, Los Angeles, Los Angeles, CA 90095, USA
[9]Georgia Institute of Technology, Atlanta, Georgia 30332, USA
[10]University of Missouri-Columbia, Columbia, MO 65211, USA
[11]University of Alabama, Tuscaloosa, AL 35487, USA
[12]University of New Mexico, Albuquerque, NM 87106, USA
[13]General Atomics, San Diego, CA 92121, USA
[14]ATK Mission Research, Albuquerque, NM 87110, USA
[15]EG&G, Albuquerque, NM 87107, USA
[16]Omicron, Albuquerque, NM 87110, USA
[17]Fusion Power Associates, Gaithersburg, MD 20879, USA
[18]Institute of High Current Electronics, Tomsk, Russia
[19]Kurchatov Institute, Moscow, Russia

Sandia National Laboratories, Albuquerque, NM 87185-1190 clolson@sandia.gov

The long-range goal of the Z-Pinch IFE program is to produce an economically-attractive power plant using high-yield z-pinch-driven targets (~3GJ) with low rep-rate per chamber (~0.1 Hz). The present mainline choice for a Z-Pinch IFE power plant uses an LTD (Linear Transformer Driver) repetitive pulsed power driver, a Recyclable Transmission Line (RTL), a dynamic hohlraum z-pinch-driven target, and a thick-liquid wall chamber. The RTL connects the pulsed power driver directly to the z-pinch-driven target, and is made from frozen coolant or a material that is easily separable from the coolant (such as carbon steel). The RTL is destroyed by the fusion explosion, but the RTL materials are recycled, and a new RTL is inserted on each shot.

A development path for Z-Pinch IFE has been created that complements and leverages the NNSA DP ICF program. Funding by a U.S. Congressional initiative of $4M for FY04 through NNSA DP is supporting assessment and initial research on (1) RTLs, (2) repetitive pulsed power drivers, (3) shock mitigation [because of the high yield targets], (4) planning for a proof-of-principle full RTL cycle demonstration [with a 1 MA, 1 MV, 100 ns,

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0.1 Hz driver], (5) IFE target studies for multi-GJ yield targets, and (6) z-pinch IFE power plant engineering and technology development. Initial results from all areas of this research are discussed.

1. INTRODUCTION

The goal of z-pinch IFE is to extend the recent single-shot z-pinch ICF results on Z to a repetitive-shot z-pinch power plant concept for the economical production of electricity [1-9]. Z-Pinch IFE is relatively new, and has become part of the IFE community over the last five years. Z-Pinch IFE has been part of the 1999 Snowmass Fusion Summer Study [10], the IAEA Cooperative Research Project on IFE Power Plants (2001), the 2002 Snowmass Fusion Summer Study, the FESAC 35-year Plan Panel Report (2003) [11], and the FESAC IFE Panel Report (2004) [12].

Over the last few years, several outstanding results have been achieved with z-pinch ICF targets on the Z accelerator at Sandia National Laboratories. On Z, the high magnetic field pressures associated with 20-MA load currents implode a z-pinch wire array, generating up to 1.8 MJ of x-rays at powers as high as 230 TW. Using a *double-pinch hohlraum target*, capsule implosions in the ~70 eV hohlraum [13] have been radiographed by 6.7 keV x-rays produced by the Z-Beamlet Laser (ZBL). These experiments demonstrated capsule implosion convergence ratios between 14 and 21 from a radiation drive symmetry that is within 1.6 to 4 times the symmetry required for scaling to high yield [14]. Using a *dynamic hohlraum target*, a 2.1-mm-diameter deuterium-filled CH capsules absorbs up to 35 kJ of x-ray energy from the ~ 220 eV dynamic hohlraum [15]. The capsule convergence ratio is 5-10 and the thermonuclear DD neutron yield measured with activation detectors is up to 8×10^{10}. These yields approach being a factor of 10 higher than that achieved by any other indirect-drive target experiments. Computer simulations of the symmetry, electron temperature, electron density, and convergence agree reasonably well with the measurements in both target configurations [16]. Hemispherical capsule implosions have also been radiographed on Z in preparation for future experiments with *fast ignition targets.*

Based on (1) these demonstrated z-pinch driven target results, (2) the high demonstrated electrical conversion efficiency (~ 15%) on Z from wall-plug to x-rays, and (3) the lowest cost in $/Joule for all IFE drivers, it appears that z-pinches are particularly attractive for IFE provided a suitable method for rep-rated standoff (separation of driver and target) can be devised. Although several concepts for repetitively replacing the final magnetically insulated transmission line that connects the driver to the target have been proposed, the simplest and most robust is the Recyclable Transmission Line (RTL) concept [1-9]. In this concept, an RTL is made from a solid coolant (e.g., Flibe) or a material that is easily separable from the coolant (e.g., carbon steel). The RTL/target assembly is inserted through a single opening at the top of the thick liquid wall power plant chamber. The shot is fired, portions of the RTL are vaporized and end up mixed with the coolant to be recycled, the upper remnant of the RTL is removed, and the cycle is repeated. The present strategy for Z-Pinch IFE is to use high-yield targets (~3 GJ/shot) and low repetition rate per chamber (~0.1 Hz).

The RTL concept eliminates the problems of a final optic, high-speed target injection, and pointing and tracking N beams (N ~ 100). Instead, the RTL concept must be shown to be feasible and economically attractive. Z-Pinch IFE studies over the last three years have included RTL experiments at the 10 MA level on Saturn, RTL structural studies, RTL manufacturing/cost studies, RTL activation analysis, power plant studies, high-yield IFE target studies, etc. Recent funding by a U.S. Congressional initiative of $4M for FY04 is supporting research on (1) RTLs, (2) repetitive pulsed power drivers, (3) shock mitigation [because of the high-yield targets], (4) planning for a proof-of-principle full RTL cycle demonstration [with a 1 MA, 1 MV, 100 ns, 0.1 Hz driver], (5) IFE target studies for multi-GJ yield targets, and (6) z-pinch IFE power plant engineering and technology development.

To place Z-Pinch IFE in context, note that every IFE system requires a major driver, a target, and a chamber. There are three major drivers (lasers, heavy ions, and z-pinches), and the matrix of possible choices for an IFE system is shown in Fig. 1. Note that Z-Pinch IFE and heavy ion IFE share a strong commonality in that they both use indirect-drive targets and a thick-liquid wall chamber.

In the following, the Z-Pinch IFE concept is presented, recent research results are given, and a Road Map for Z-Pinch IFE is discussed.

II. Z-PINCH IFE CONCEPT

While many schemes for Z-pinch IFE have been proposed, the most enduring appears to use the Recyclable Transmission Line (RTL) concept [1-9]. In this scheme, an RTL connects the repetitive driver directly to the target, and the fusion explosions are contained in a thick-liquid wall chamber as shown schematically in Fig. 2. The RTL can be made out of frozen coolant (e.g., Flibe) or a material that is immiscible in the coolant (e.g., carbon steel). The later is the present preferred choice for z-pinch IFE. The RTL would enter the chamber through a single hole at the top of the

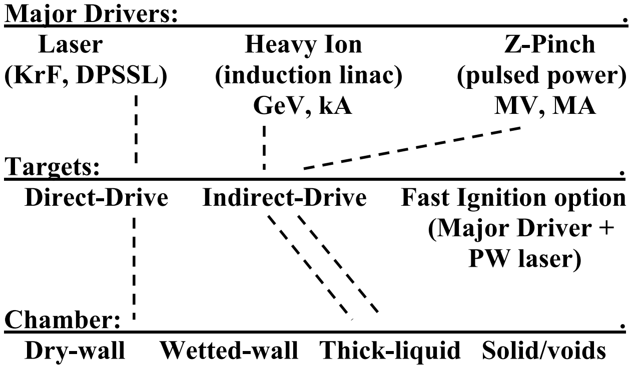

Fig. 1. IFE systems – matrix of choices. The dashed lines show the mainline choices.

chamber (~1 meter radius), and extend into the chamber a distance of two or more meters. The RTL would bend at the top of the chamber, and upper shielding would be placed above it. Note that this bend alleviates the usual problem of a final optic. For a spherical chamber of radius 5 meters, and an RTL entrance hole at the top of the chamber of radius 1 meter, the entrance hole represents only 1 % of the chamber surface area. Therefore, in principle, 99 % of the chamber can be shielded by the thick liquid walls. The 1% of the chamber surface area associated with the entrance hole then becomes, of course, the key issue for shielding. Issues associated with the RTL include movement (but the required accelerations are very low, since there is 10 seconds between shots); RTL electrical current initiation; RTL low-mass limit and electrical conductivity; structural properties; mass handling; shrapnel; vacuum/electrical connections; activation; waste stream analysis; shock disruption to liquid walls; manufacturing/cost; optimum configuration (inductance, shape, etc.); power flow limits for magnetic insulation; effects of post-shot EMP, debris, and shrapnel up the RTL; and shielding of sensitive accelerator parts. Initial experiments at the 10 MA level on Saturn have been successfully used to study the electrical current initiation in the RTL, the RTL low-mass limit, and the RTL electrical conductivity [5,7,8].

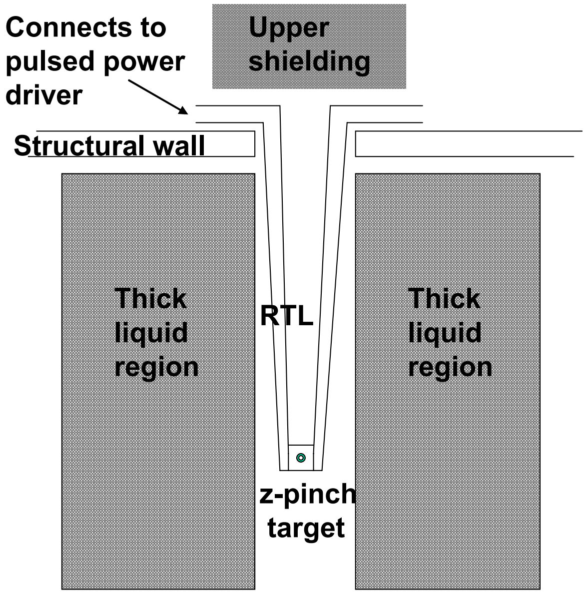

Fig. 2.The RTL (Recyclable Transmission Line) concept.

The matrix of choices available for a Z-Pinch IFE power plant is summarized in Fig. 3. Note that several options are available for each part of the power plant – the driver, the RTL, the target, and the chamber type.

III. RECENT RESULTS ON Z-PINCH IFE

The development of Z-Pinch IFE has been organized into six research areas. Some recent research results in each of these areas are as follows:

RTL: The present approach is to use a carbon steel, coaxial, conical RTL, with a total mass of about 50 kg. The RTL radius at the chamber entrance would typically be about 1 meter and the RTL length would be 2 meters or more. The structural properties of the RTL set the pressure limit. ANSYS computer code studies [17,18] predict the outer RTL electrode would buckle at about 80 Torr, so a conservative approach is to require a chamber pressure of 10-20 Torr of an inert gas. Prototype RTLs with a length of 2 meters have been fabricated and are undergoing pressure testing [19] to compare with the code results. Hard vacuum is required only in the gap between the two RTL electrodes, and schemes have already been proposed that would have the gap pre-pumped before the RTL is inserted into the chamber [6,9].

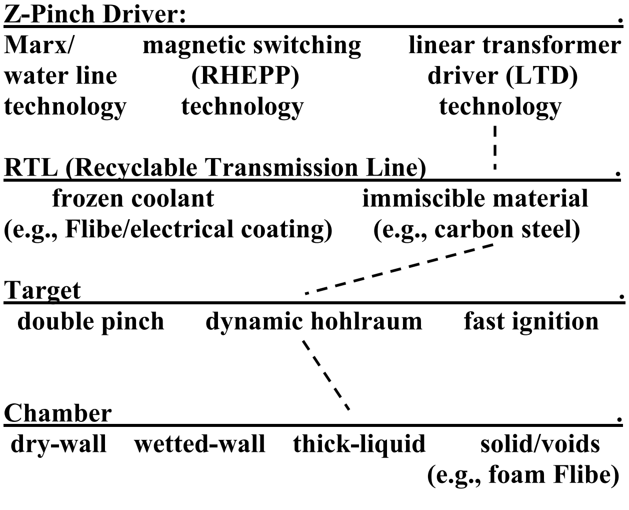

Fig. 3. Z-Pinch IFE Power Plant – matrix of choices. The dashed line shows the preferred choices.

The key physics issues for the RTL concern power flow, especially near the target where the "surface" current densities become very large. The major issues are electrode heating, the formation of surface plasmas, accurate determination of the electrical conductivity, magnetic field diffusion into the electrode material, and motion of the electrode material during the power pulse. As the drive current in the RTL approaches the target, the "surface" current density $J_s = (I)/(2\pi R)$ [where I is the total current and R is the radial distance from the axis of the target] becomes very large. With solid metal transmission lines on Z, J_s routinely approaches 1.6 MA/cm near the z-pinch wire array. With a low-mass RTL for z-pinch IFE, J_s may approach values as high as 5 MA/cm near the z-pinch. Initial ALEGRA computer simulations [20] for RTL-like electrodes indicate that substantial electrode deformation does not occur until J_s approaches 20 MA/cm. Initial LSP computer simulations [21] indicate that plasma formation, magnetic field diffusion, and plasma motion should not be a significant issue for $J_s \sim 5$ MA/cm. These results are extremely encouraging, and suggest that favorable power flow properties should occur for RTL z-pinch IFE parameters.

The RTL adds inductance (over that of a flat disc coax transmission line), and this is the key trade-off feature of the RTL that must be optimized in a full circuit model that includes the driver, the RTL, and the target. As the RTL inductance increases, the drive voltage must be increased to compensate [3,5]. Initial computer code circuit modeling [22] indicates that reasonable increases in the drive voltage should be adequate to compensate for the inductance of several meter long RTLs.

Repetitive pulsed power drivers: Although other potential repetitive pulsed power technologies are being assessed, the present preferred approach is to use a Linear Transformer Driver (LTD) voltage adder accelerator. In the LTD concept, a series of compact, low inductance, capacitors are charged directly in parallel, in cylindrical formation. A series of switches next to the capacitors, and in the same cylindrical formation, switches the charged capacitors to directly apply voltage to a single, inductively-isolated gap. Several such cells are combined in a voltage-adder formation to reach high voltage. (The HERMES III accelerator at Sandia National Laboratories is a 20 MV voltage adder accelerator.) LTD technology requires no water tanks or oil storage tanks, is about ¼ the volume of comparable Marx generator/water line technology, and should be easily rep-rateable at 0.1 Hz. LTD technology was pioneered in Russia [23]. Fig. 4 shows a scaled drawing of a 10 MA LTD accelerator [24] that is about ¼ the volume of the 10 MA Saturn accelerator at Sandia National Laboratories.

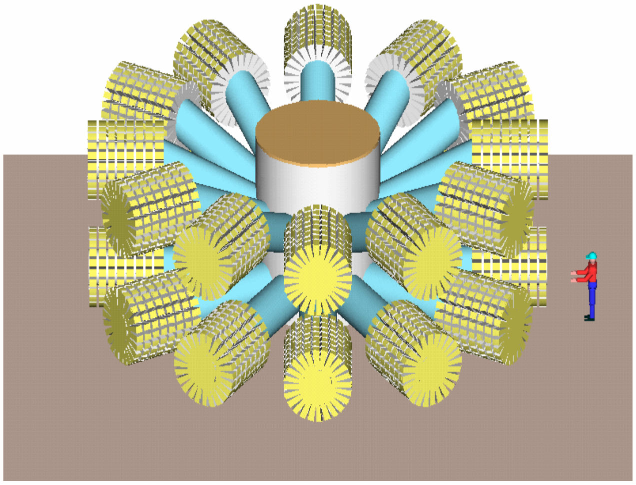

Fig. 4. LTD accelerator design (10 MA) [24].

Repetitive switches are required for the LTD approach, with parameters of ~25 kA, 200 kV, 0.1 Hz, 50-100 ns risetime, low cost, and a lifetime of the order of $\sim 3 \times 10^6$ shots (one year at 0.1 Hz). Several categories of switches (magnetic switches, photo-triggered semiconductor switches, electrically-triggered gas switches, high-pressure fluid switches, and laser-triggered water switches) are being assessed [25,26].

Progress is being made on an LTD PoP (Proof-of-Principle) accelerator for Z-pinch IFE, that will ultimately have parameters of 1 MA, 1 MV, 100 ns, 0.1 Hz. One LTD cell at the 100 kV, 1 MA, 100 ns level has been designed, constructed, and tested – the cell has performed well in initial tests [23,24]. Two more cells are being constructed, and a total of ten cells will be needed for the full LTD PoP accelerator.

Shock mitigation: The envisioned fusion yields for Z-Pinch IFE are large (~3GJ) compared to the other IFE approaches that typically use yields ≤ 0.4 GJ. Therefore, shock mitigation (in the thick liquid walls) to protect the structural chamber walls is an issue that must be addressed. This is being modeled in scaled experiments with a shock tube and water layers [27], and with explosives and water jets [28]. Water jets with entrained bubbles have been created with various void fractions to study enhanced shock mitigation in thick liquid walls [29].

Code calculations [30-32] are being performed with the goal of validating the codes with the experiments, and then using the codes to predict effects for a full-scale Z-Pinch IFE power plant. Metallic foams are also being studied as a possible means of shock mitigation. Metallic foams have been fabricated, and are being tested [27], and are being modeled with the ALEGRA code [30].

PoP Experiment Planning: The Z-Pinch IFE Proof-of-Principle (PoP) experiment, named Z-PoP, is in the planning stages. It is based on a 1 MA, 1 MV, 100 ns, 0.1 Hz LTD accelerator, as mentioned above, that is under development. Z-PoP would use this driver, together with an RTL, and a z-pinch load (~5 kJ), and would be automated to run at 0.1 Hz. The procedure would be to insert an RTL and a z-pinch load, pump down, fire, remove the remnant, reload, and repeat the process every 10 seconds.

Robotic systems are being investigated to perform these functions for Z-PoP. Commercial off-the-shelf robotics can operate with payloads up to 60 kg, placement accuracy to 0.04 mm, a workspace of ~1.5 x 1.5 x 1 m^3, and movements of ~ 1.5 m in < 2 seconds [33]. These parameters are already close to what is needed for full-scale z-pinch IFE.

Targets for Z-Pinch IFE: As shown in Fig. 5, the mainline z-pinch ICF targets are the double pinch target [34] and the dynamic hohlraum target [35]. Both targets are being developed for ICF with the goal of yields of ~ 0.5 GJ. For z-pinch IFE, yields of ~ 3 GJ are envisioned. Based on Lasnex code calculations for multi-GJ yields [36], and on analytic scaling arguments [37], the general requirements for a high-yield driver for z-pinch IFE have been estimated. For the double pinch target, 36 MJ of x-rays (from two drivers, each at 66 MA) should produce a yield of 3 GJ, giving a target gain of 83. For the dynamic hohlraum target, 30 MJ of x-rays (from a single driver at 86 MA) should produce a yield of 3 GJ, giving a target gain of 100. These estimates show that both targets can be considered contenders for being a viable z-pinch IFE target. In addition, a recent independent theoretical study [38] based on scaled experimental results from z-pinch experiments on Z and laser experiments on Nova show that z-pinch driven high-yield targets with gains near 100 should indeed be feasible.

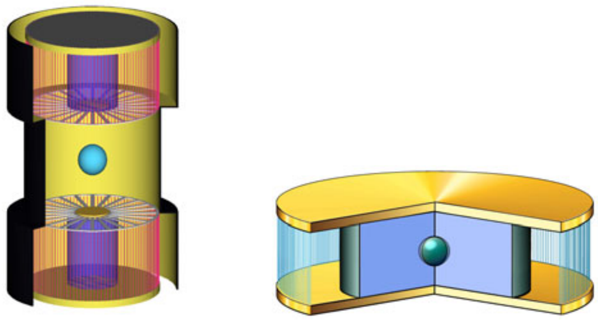

Fig. 5. Z-pinch fusion targets. The double-pinch target [32] is shown on the left, and the dynamic hohlraum target [33] is shown on the right.

A target gain G of 100, coupled with a driver efficiency (η) that is already 15% (and might be optimized to 25% or more in the future), gives an ηG ~ 15 or more. This high value of ηG ensures a favorable power plant operating scenario.

Z-Pinch power plant technologies: An initial Z-Pinch power plant study named ZP3 was performed to establish one complete (but non-optimized) 1000 MWe power plant scenario [6,9]. This concept used multiple chambers, each being a thick-liquid wall chamber as shown in Fig. 6. This concept assumed Marx generator/ water line technology for the pulsed power driver, an RTL to connect the driver to the target, a dynamic hohlraum target, and a thick-liquid wall chamber. The chamber pressure requirement is 10-20 Torr of an inert gas such as Ar. The sequence of events is that an RTL/target assembly is inserted into the chamber; the shot is fired; a plunger shears off the top remnant of the RTL and seals the vacuum opening; the RTL plug is removed; another RTL/target assembly is inserted into the chamber; and the process repeats every 10 seconds.

The Flibe liquid blanket absorbs the fusion neutron energy, breeds tritium to fuel the targets, shields the structural wall from neutron damage, and mitigates the shock to protect the structural wall. With a thick-liquid wall thickness of typically 40 cm or more of liquid Flibe, it has been found that the resultant neutron fluence to the first (structural wall) is small enough to permit the wall lifetime to exceed the life of the power plant (30-40 years) [39,40]. An adequate tritium breeding ratio (TBR ~ 1.1) can be achieved with about 65 cm of Flibe [39].

Activation for the RTLs is potentially a concern, because of the large amount of RTL mass that will be recycled. For the present mainline approach, carbon steel would be used for the RTLs because it has very low long-lived activation, and because it is immiscible in Flibe so it should be relatively easy to recover it from the Flibe. Recent studies show the RTL recycling dose peaks at 160 Sv/hr at shutdown, and drops to ~1 Sv/hr after 1 day [41]. Therefore, the RTL meets the 3000 Sv/hr remote handling limit for advanced recycling equipment with wide margin even in the absence of a cooling period and without removal of the transmutation products [41]. While carbon steel is the mainline RTL material, analysis shows that many other materials could also be possible [42].

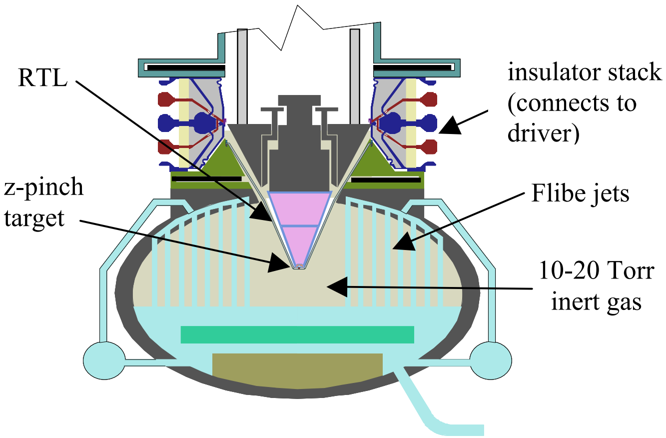

Fig. 6. Z-Pinch IFE chamber concept used in the ZP3 study [6,9].

Waste management of the RTL material has also been analyzed. The RTL carbon steel will be slightly activated, containing traces of radioactive elements after recycling for the entire plant life without the removal of the transmutation products. The RTL waste management options include disposal in repositories as Class A low-level waste after plant decommissioning or, preferably, release to the nuclear industry after an interim storage period of 35 years [41]. A separate, independent study gives similar results [40].

Approximately a 1-1.5 day inventory supply seems reasonable for the proposed recycling approach – to allow for a short cooling down time and for the re-manufacture time [41]. If each RTL is ~50 kg, then a one-day supply is 5,000 tons. This is the inventory needed for the power plant, and it would be recycled constantly. (For comparison, the one-day *waste* from a coal-fired power plant is about 5,000 tons.)

The manufacturing of RTLs and targets, and the cost per RTL/target are definitely a concern. For yields of a few hundred MJ (as used in laser IFE and heavy ion IFE at 5-10 Hz), the targets must cost about $0.30 or less. For yields of 3 GJ (as used in Z-pinch IFE), the price available for the RTL and target will be about $3.00.

For the RTL, recent work has concentrated on steel RTLs that would use standard industrial process equipment (e.g., an electric arc furnace, rolling mill, stamping plant, etc.). These studies predict a cost of $3.58 per RTL, at a confidence level of 90 % [9].

For the target, recent work has concentrated on manufacturing and costing of a tungsten wire array plus a cryogenic dynamic hohlraum target. These studies predict a cost of $2.12 - $2.86 per shot for the wire array/target assembly [43]. Also, it should be noted that for the high yields envisioned (~ 3 GJ), the wire array may possibly be replaced by a simpler structure such as a foil.

Combining these results shows that the present estimates (unoptimized) for the total cost of an RTL plus wire array/target assembly would be in the range of $6.00 (about a factor of two higher than desired). However, these results are encouraging in that they are already in the correct range. Futher refinement and optimization should lower the costs even more.

Further Z-pinch IFE power plant studies that are also underway include Flibe condensation and clearing studies [44], alternate chamber concepts such as carbon composite walls [40], and systems studies that suggest even higher yields (~20 GJ) may by useful [40].

IV. THE Z-PINCH IFE ROAD MAP

The Z-Pinch IFE Road Map is shown in Fig. 7. The left two columns indicate single-shot ICF research on DOE NNSA DP facilities. The National Ignition Facility (NIF) is shown coming up over the next several years, and NIF will be used to demonstrate laser-driven indirect-drive ignition. Complementing NIF is the development of z- pinch ICF with Z and ZR (to be operational in 2006). A decision point in 2008-2010 is envisioned for a next large facility – in this case, a z-pinch high-yield facility. Such a facility would be used to demonstrate and optimize high yield z-pinch-driven targets. It could be built using RTLs, the single-shot equivalent of a thick-liquid wall, and compact LTD technology - as such, this would be ETF Phase I as shown in Fig. 7. The right three columns in Fig. 7 show the development of repetitive z-pinch IFE. With a Congressional Initiative of $4M for FY04, the PoP (Proof-of-Principle) phase is just starting. The PoP phase is envisioned to cost ~ $14M for 3-5 years. It would be followed by an Integrated Research Experiment (IRE) phase, and then an Engineering Test Facility (ETF phase II). The ETF would be a conversion of the single-shot high-yield facility to a repetitive ETF, and would produce electricity for short periods of time.

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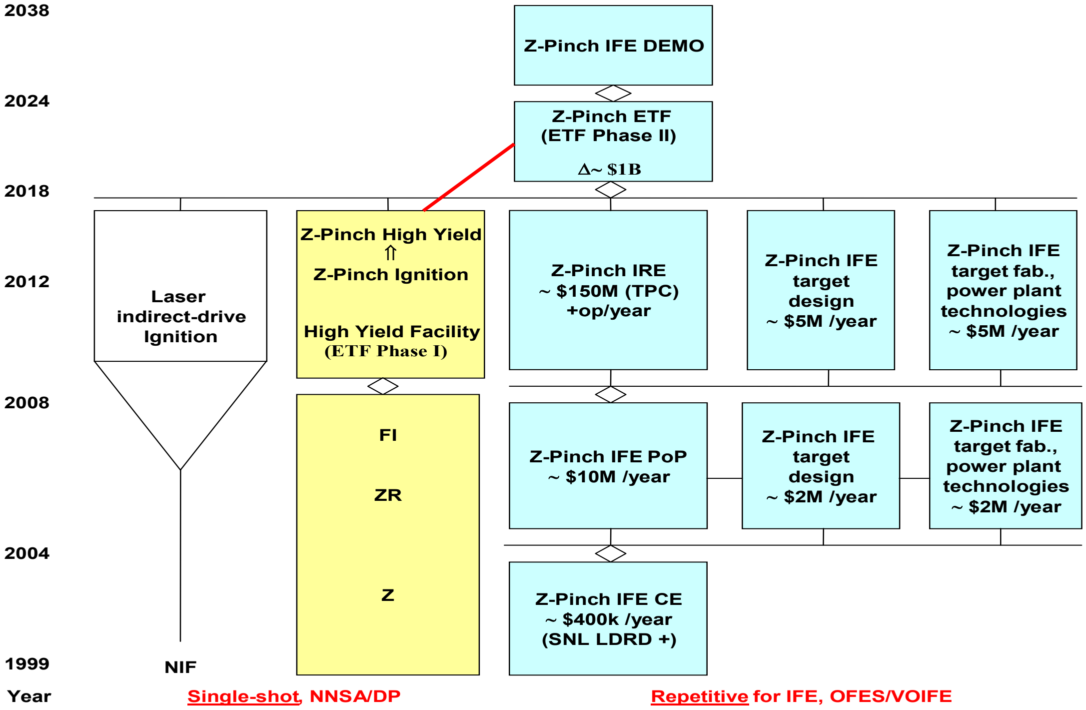

Fig. 7. The Z-Pinch IFE Road Map.

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