9 Inertial confinement fusion: z-pinch

[C.L. Olson]

9.1 Introduction

The development of pulsed power over the last five decades has led to the present capability of producing large pulses of electrical energy (MJ) efficiently and relatively inexpensively, and delivering this electrical energy in short pulses (ns) at extremely high powers (hundreds of TW). Since fusion requires very large powers, it is natural to ask if pulsed power can be used directly for inertial fusion. Over the last three decades, pulsed power has been used to drive electron beams, ion beams, and z-pinches, each as a possible driver for fusion. The z-pinch approach has proved to be particularly successful [97Mat, 98Yon, 99Lie, 00Chi, 00Ryu1, 01Spi]. During the last decade, the Z accelerator at Sandia National Laboratories has routinely produced 1.8 MJ in soft X-rays using a fast z-pinch, and delivered this energy at powers as high as 230 TW in a pulse length of order 5 ns. In double-ended hohlraum inertial confinement fusion (ICF) target experiments on Z, capsule radial compression ratios up to 14…21 have been achieved [02Ben]. In dynamic hohlraum ICF target experiments on Z, DD neutron yields up to 8×10^{10} have been reported [04Bai1, 04Bai2]. These yields approach being a factor of 10 higher than that achieved by any other indirect-drive target experiments. Based on these and other outstanding recent results, and the development of a repetitive z-pinch power plant concept over the last four years [00Ols, 00Spi, 00Slu, 01Der, 02Ols, 02Roc, 03Slu1, 04Roc], z-pinches have become one of the three major driver candidates for inertial fusion energy (IFE).

To place z-pinch IFE in context, note that every IFE system requires a major driver, a target, and a chamber. The matrix of possible choices is shown in Fig. 9.1, and an IFE system includes one choice from each category. The three major driver candidates are lasers (KrF or DPSSL), heavy ions (induction linac or rf linac), and z-pinches. The mainline target candidates are direct-drive, indirect-drive, and fast ignition. Note that the fast ignition option requires a major driver and a petawatt laser. The chamber candidates are dry-wall, wetted-wall, thick-liquid wall, and solid/voids. Although the full matrix of possible IFE systems could be investigated, each major driver has developed a particular mainline approach. The mainline laser approach uses a KrF or DPSSL laser, a direct-drive target, and a dry-wall chamber. The mainline heavy ion approach uses an induction linac driver, an indirect-drive target, and a thick-liquid wall chamber. The mainline z-pinch approach uses a pulsed power driven z-pinch, an indirect-drive target, and a thick-liquid wall chamber. Note that z-pinches and heavy ions share a strong commonality, in that they both use indirect-drive targets and a thick-liquid wall chamber.

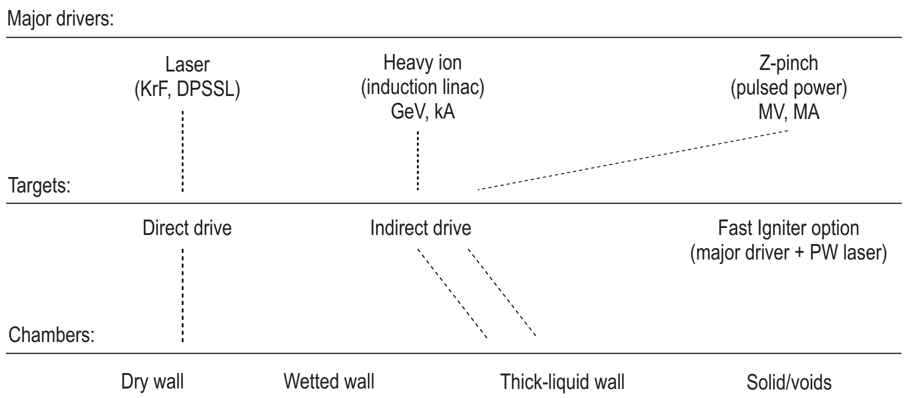

Fig. 9.1. IFE systems – matrix of choices. The mainline approaches are indicated by the dashed lines.

Since z-pinch IFE is the newest of the three possible approaches to IFE, one might ask "Why z-pinches?" *First*, z-pinch drivers are producing X-ray pulses at the 1.8 MJ level *now*, and they are routinely available for inertial fusion target experiments *now*. *Second*, z-pinches offer the lowest cost per joule of all IFE driver candidates. The demonstrated cost is about $30/J of X-rays delivered. Comparable estimates for lasers and heavy ions are at the $1000/J level. *Third*, z-pinches operate with extremely high efficiency. The demonstrated efficiency of Z from wall plug to X-rays out is 15 %, and it is believed that this efficiency can be optimized to 25 % or better. *Fourth*, fusion capsule compression experiments are being performed on Z *now* with targets that can be scaled to IFE high-yield levels. *Fifth*, repetitive pulsed power for IFE has three options, and one option is RHEPP (Repetitive High Energy Pulsed Power) that uses magnetic switching and has already demonstrated operation at 2.5 kJ/shot at 120 Hz for an average power of 300 kW. From these accomplishments and long-range advantages, it is clear that z-pinch IFE merits further investigation and development.

In regard to neutron effects on the first wall, the importance of the thick-liquid wall chamber concept for z-pinch IFE (and HIF IFE) cannot be over-emphasized (see, e.g., [02Gol]). For magnetic fusion energy (MFE), and for dry-wall laser IFE, the 14 MeV fusion neutrons must pass directly through the first wall, and then into a Li-containing blanket to absorb the neutron energy and breed tritium. Because the neutrons pass directly through the first wall, there is an inherent "first-wall problem" that requires the development of new neutron-damage resistant materials, and new neutron facilities to test these materials. For the thick-liquid wall chamber approach, the 14 MeV neutrons pass into a Li-containing thick-liquid wall, and then into a chamber structural wall. Most of the neutron energy is absorbed in the thick-liquid wall, the neutron energy spectrum is moderated down to about 5 MeV by the time the neutrons reach the structural wall, and any neutron materials testing for the structural wall could be done with existing fission reactor neutrons. Therefore, the thick-liquid wall approach appears to essentially eliminate the "first wall problem".

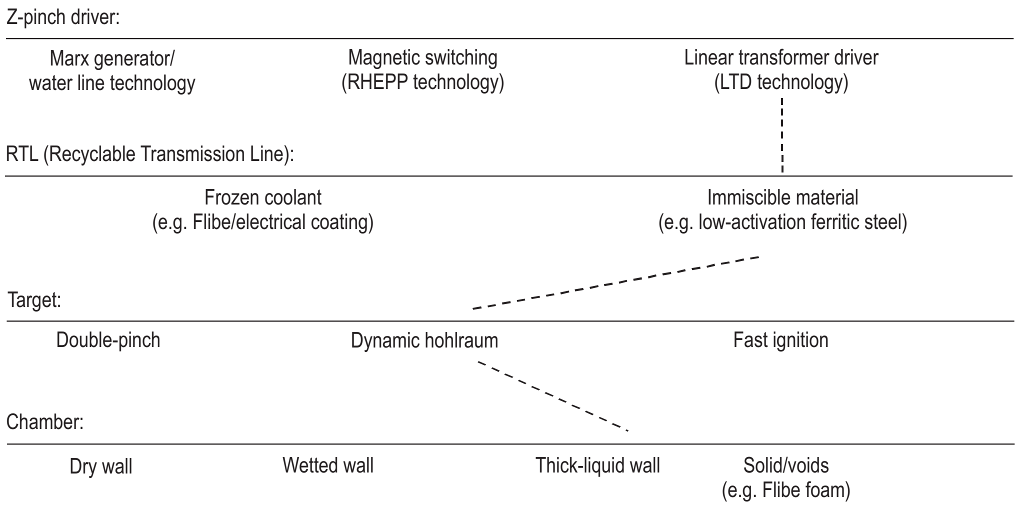

Fig. 9.2. Z-pinch IFE power plant – matrix of choices. The mainline approach is indicated by the dashed line.

A z-pinch IFE power plant consists of four main parts, as summarized in Fig. 9.2. These are (1) the z-pinch pulsed power driver, (2) the standoff method used to connect the driver to the target, (3) the z-pinch driven target, and (4) the z-pinch power plant chamber. There are three possible repetitive pulsed power driver technologies [fast Marx/water line technology; magnetic switching (i.e., RHEPP technology); and Linear Transformer Driver (LTD) technology)] that could be used for z-pinch IFE. The mainline standoff method is the Recyclable Transmission Line (RTL) that would connect the driver to the target [00Ols, 00Spi, 00Slu, 01Der, 02Roc, 02Ols, 03Slu1, 04Roc]. The RTL would be made out of frozen coolant or a material that is immiscible in the coolant. Z-pinch driven targets include double-pinch driven targets, dynamic hohlraum targets, fast ignition targets, and advanced targets. Chambers for z-pinch IFE include the options of thick-liquid walls, and, a new category – solids with voids (e.g., foam Flibe). The mainline z-pinch IFE approach today (as shown by the dashed line in Fig. 9.2) is to use LTD driver technology, an RTL of immiscible material, a dynamic hohlraum target, and a thick-liquid wall chamber. The next four sections will describe these four parts of a z-pinch IFE power plant in more detail.

The order of the following sections is as follows. Section 9.2 discusses z-pinch drivers; Section 9.3 discusses standoff and RTLs; Section 9.4 discusses z-pinch driven targets; and Section 9.5 discusses power plant concepts for z-pinch IFE. Section 9.6 summarizes testing of IFE chamber materials on pulsed power facilities. Section 9.7 discusses status and development plans for z-pinch IFE.

9.2 Pulsed power drivers for z-pinch IFE

For a z-pinch IFE power plant, it is convenient to divide the electrical circuitry into three parts – (1) the pulsed power driver, (2) the RTL (Recyclable Transmission Line), which is a magnetically-insulated transmission line (MITL), and (3) the load (the z-pinch target assembly). With these definitions, the pulsed power driver encompasses everything from the wall-plug to the RTL. The driver must deliver a high current (≈ 60…90 MA), high voltage (many MV), moderately short (≈ 100…150 ns), electromagnetic pulse to the RTL. The driver must do this with high electrical efficiency, high reproducibility, high reliability, and at a rep-rate of about 0.1 Hz – which is a pulse every 10 seconds. There are three different pulsed power technologies that may potentially be used for a repetitive driver for z-pinch IFE. These include (1) Marx generator/water line technology; (2) Repetitive High Energy Pulsed Power (RHEPP) technology with magnetic pulse compression and an inductive voltage adder; and (3) Linear Transformer Driver (LTD) technology with an inductive voltage adder. All three technologies are modular and have very high electrical efficiencies. Although each of these technologies will be thoroughly assessed for potential use as a z-pinch IFE driver, the LTD approach is currently the favored approach.

Here, a brief description of each of these three pulsed power technologies is given. This section concludes with a description of possible pulsed power driver approaches to be used for a single-shot high-yield driver (≈ 0.5 GJ yield), which is a major step on the path to repetitive z-pinch IFE.

9.2.1 Marx generator/water line pulsed power technology

This pulsed power technology has been used for decades [96Mar], and is the technology used on the Z machine at Sandia National Laboratories. The basic concept is to store electrical energy in capacitors over a relatively long charging time, then release the energy into subsequent storage/transmission stages on shorter and shorter time scales. Then, although the total energy lowers slightly due to losses, the instantaneous power increases dramatically. Using this technology, instantaneous powers exceeding 80 times all of the electrical power generating capabilities on earth have been achieved on Z.

A schematic of this technology is given in Fig. 9.3. This typically includes a Marx generator [25Mar], an intermediate energy store, water pulse forming lines, switches, vacuum transmission lines (magnetically insulated) and a load. Prime power (e.g., from the electric grid) supplies energy to the Marx generator on a relatively slow charging timescale (~ 100 s). A simplified schematic of a Marx generator is given in Fig. 9.4. In a Marx generator, a bank of N capacitors is charged in parallel up to a voltage V (e.g., 50…100 kV). Then the first of a series of switches is triggered, leading to over-volting and switching of the remaining switches. When so switched, the Marx is said to erect, the capacitors are instantaneously arranged in series, and a total voltage of NV results (e.g., several MV). The Marx generator output voltage then charges an intermediate water capacitor store, which in turn drives a water pulse forming line. The reason for using water as the dielectric is that the length of a transmission line for a desired pulse length T scales as $T(\varepsilon)^{-1/2}$, so that by using water (which has a high dielectric constant, $\varepsilon \approx 83$), the line can be relatively compact. The charged water pulse forming line at voltage V can be viewed as the sum of two waves traveling in opposite directions, each with amplitude $V/2$. Each wave reflects off the open end (high impedance) of the line. When a laser-triggered output switch is closed, the wave traveling towards the load begins to leave the line. The pulse now travels through the vacuum magnetically-insulated transmission line (see Sect. 9.3) to the load.

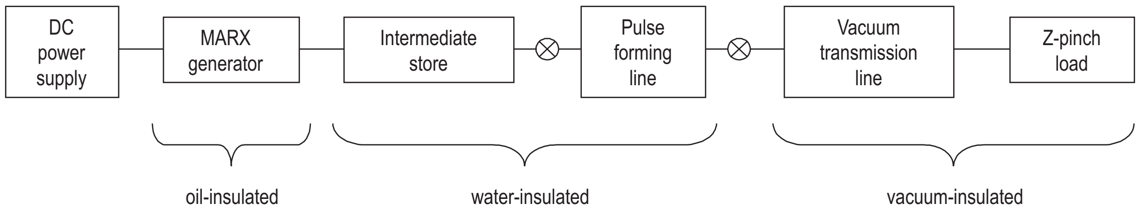

Fig. 9.3. Marx generator/water line pulsed power driver concept.

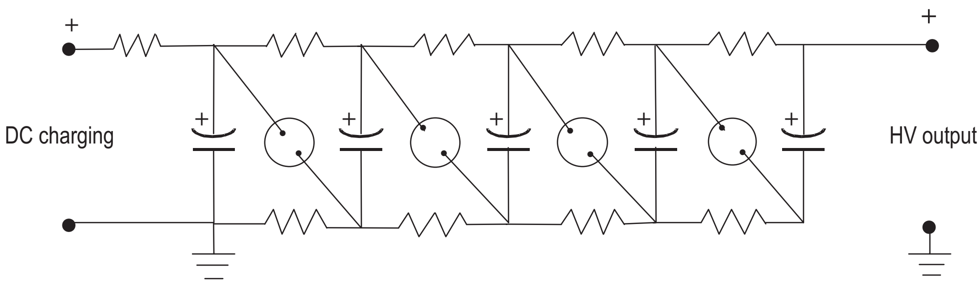

Fig. 9.4. Schematic of a Marx generator.

As an example of this technology, the Z machine [96Spi] is shown in Fig. 9.5. Z consists of a circular tank that is 108 feet in diameter and 12 feet tall. A series of 36 Marx generators lines the outer annular section which is insulated with transformer oil. The 36 Marx generators store 11.4 MJ, and when erected, transmit this energy on a time scale of about 1 µs. This energy is then transferred into the water section, which consists of intermediate storage capacitors, water pulse forming lines, and water transmission lines. Laser-triggered switches at the output of the intermediate storage capacitors command fire all 36 lines with low jitter. At the output of the water section, the pulse passes the insulator stack (which separates the water section from the vacuum transmission section) with about 3 MJ of energy and proceeds through the vacuum magnetically-insulated transmission line to the load. About 2 MJ is delivered to the load in a pulse of about 150 ns. The z-pinch load (discussed in Sect. 9.4) further compresses the pulse to produce an X-ray pulse of about 1.8 MJ of energy in a pulse length of about 5 ns. This X-ray pulse can have a power exceeding 200 TW.

Many pulsed power accelerators have been built over the past three decades using this Marx generator technology together with various forms of intermediate stores, pulse forming lines, and switching technology [96Mar, 99Lie, 00Ryu1]. These include Proto 1, Proto 2, Saturn, Z, and now ZR, at Sandia National Laboratories; Angara V at the Kurchatov Institute in Moscow; Gamble II at the Naval Research Laboratory; Magpie at Imperial College in London; and Zebra at the Nevada Terawatt Facility at the University of Nevada – Reno.

All of the above facilities are basically single-shot devices. The largest facility is Z, which does about 1 shot per day, which is a rep-rate of about 10^{-5} Hz. This low rep-rate is due to the time it presently takes to turn-around between shots; clean, refurbish, replace the front end of the magnetically-insulated transmission line; install the next target experiment; and pump down. For this section, we are concentrating on just the pulsed power (the recyclable transmission line and z-pinch target will be discussed in later sections). For z-pinch IFE, the pulsed power must be capable of firing every 10 s. In present operation of Z, the Marx charging time is about 120 s. This means that, if the remaining components (especially the switches) were easily rep-rated, Z pulsed power technology could, in principle, be fired every 120 s. The gap from 120 s down to 10 s is not unreasonable. To achieve operation every 10 s would require design of a "fast" Marx section with special care to minimizing inductances. In principle this could be done, but it will require an accurate assessment of this potential capability for this particular technology.

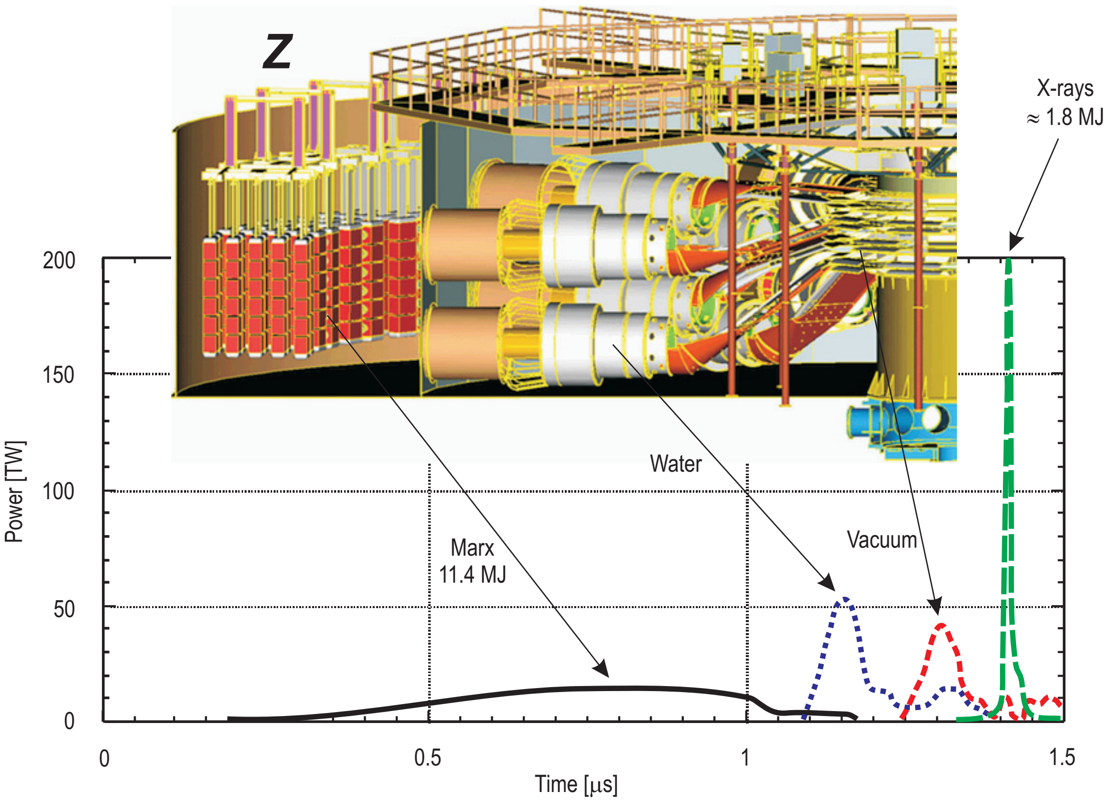

Fig. 9.5. The Z accelerator at SNL [96Spi].

Lastly, for repetitive operation for z-pinch IFE, long-lifetime repetitive switches will be required. The rate of 0.1 Hz corresponds to 3×10^6 shots/year. Therefore, to minimize switch change-out times for a z-pinch IFE power plant, it would be desirable to have switch lifetimes exceed 10^6 shots. At a minimum, switches are in the Marx generator, and in the output to the water pulse-forming lines. Present Marx pressurized-gas self-break switches are limited by surface erosion to a lifetime of about 4.5×10^3 shots. Laser-triggered switches, as used in Z, have characteristic lifetimes of about 0.5×10^3 shots. The extrapolation from 10^3 shots to the needed 10^6 shots is substantial, so it is clear that the development of long-lifetime pressurized-gas switches is an issue for the development of this type of pulsed power technology for z-pinch IFE.

9.2.2 RHEPP (magnetic switching, inductive voltage adder) technology

This technology is completely different than the Marx generator/water line technology discussed above. It uses magnetic pulse compression together with an inductive voltage adder (IVA) [99Sch]. The magnetic pulse compression concept is shown in Fig. 9.6. Power is fed directly into a step-up transformer to achieve voltages of the order of a few 100 kV. This high voltage is applied to a capacitor of capacitance C followed by a magnetic switch as shown. When the magnetic switch core saturates, current flows through the saturated core inductance, L_{sat}, to charge the next stage capacitor (also of capacitance C). This charging time is a fraction of the LC oscillation time that scales as $\tau \sim (L_{sat}C/2)^{1/2}$. In the next stage, L_{sat} is reduced by a factor F, and the charge time is reduced by the factor $F^{1/2}$. In this manner, each successive stage reduces the pulse length by a factor of $F^{1/2}$ (which might be a factor of 5). Any number of stages can be used, and final pulse lengths are of the order of 100 ns for many applications. One magnetic pulse compressor will have an output voltage of a few 100 kV. To achieve higher voltages (in the MV range), the outputs of several compressors are added in an “inductive voltage adder”. The inductive voltage adder concept [87Ram, 89Ram, 89Smi], as shown in Fig. 9.7 [91Cor], is similar to an inductive linear accelerator (e.g., as used in heavy ion fusion) in which pulses applied to inductively-isolated cavities add energy to a particle beam. However, in the inductive voltage adder, the voltages are added on a central metal electrode. Several stages may be used. As the voltage increases, the impedance increases, and the central electrode radius decreases. At the output end, the high voltage is applied to the desired load. The inductive voltage adder concept has been demonstrated at Sandia National Laboratories with the Hermes III accelerator (≈ 20 MV) [87Ram, 89Ram], and with the Sabre accelerator (≈ 5 MV) [91Cor].

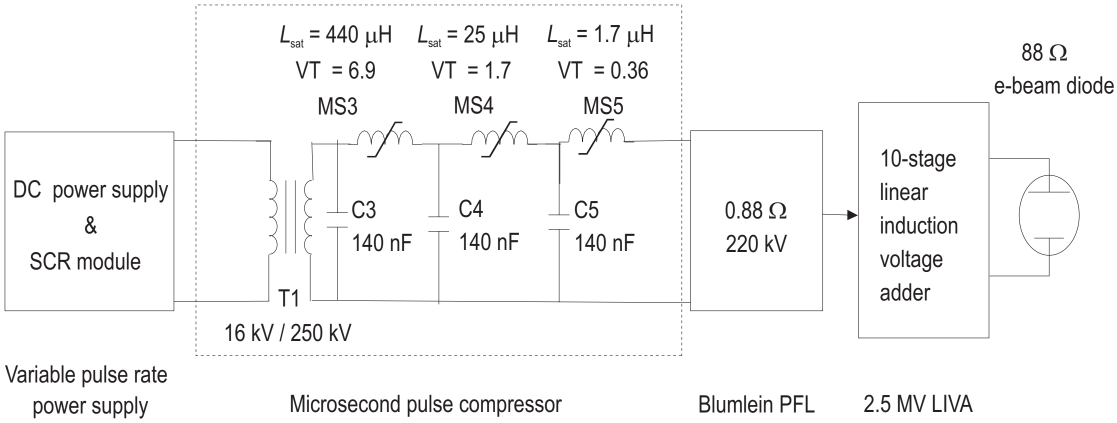

Fig. 9.6. Magnetic pulse compression concept, as used in RHEPP II [99Sch]. VT refers to the volt times second hold-off for the saturable magnetic core.

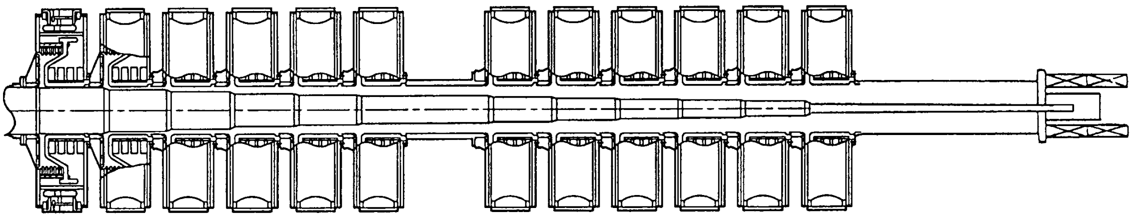

Fig. 9.7. Inductive Voltage Added (IVA) concept [91Cor].

As an example of this technology, the RHEPP II accelerator at Sandia National Laboratories is shown in Fig. 9.8. RHEPP stands for Repetitive High Energy Pulsed Power, and is a program that has been in existence for over two decades to develop repetitive pulsed power for many applications. In Fig. 9.8, the pulse forming lines (fed by the magnetic pulse compressors not shown) are on the right, and the 10-stage inductive voltage adder is on the left. The high voltage output goes through the floor to a load (diode) in the basement. RHEPP II has produced 2.2 MV, 25 kA, 2.5 kJ pulses at 120 Hz, for an average power of 300 kW [99Sch]. Repetitive magnetic switching and linear inductive voltage adders are well understood, robust, and cost effective.

Z-pinch IFE will need repetitive pulsed power at 0.1 Hz. RHEPP technology has already been routinely demonstrated at 120 Hz. Z-pinch IFE will need a low-impedance pulsed power driver (~ 0.1 Ω), whereas present RHEPP configurations are relatively high impedance (~ 100 Ω). However, RHEPP technology is modular, and could be configured in modules to attain lower impedances if desired. The present assessment is that RHEPP technology is “more than what is needed” for the application to z-pinch IFE.

Fig. 9.8. The RHEPP II Accelerator at SNL [99Sch].

For repetitive operation for z-pinch IFE, long-lifetime repetitive switches will be needed with lifetimes of the order of 10^6 shots. As part of the RHEPP program, magnetic switches have already been shown to be robust, and have long lifetimes. On a smaller RHEPP facility named Dos Lineas at Sandia National Laboratories, magnetic switches have been tested at 130 kV, 220 J, with up to 32×10^6 shots to date without significant failures [99Sch, 99Ree]. This suggests that magnetic switching might play a significant role in z-pinch IFE.

9.2.3 Linear Transformer Driver technology

This technology is very different than Marx generator/water line technology and the magnetic compressor portion of RHEPP technology. On the other hand, it uses the inductive voltage adder concept, as also used in RHEPP. The LTD concept [00Maz, 01Maz] is shown in Fig. 9.9. Marx generators and pulse forming lines are eliminated altogether. This means that there is no oil storage tank (since there is no oil-insulated Marx), there is no water storage tank (since there is no water pulse-forming section), and there is no insulator stack (to separate the water section from the vacuum section). In the LTD concept, a series of compact, low-inductance capacitors are charged directly in parallel, in a cylindrical formation, at a moderate voltage (~ 100 kV). A series of switches next to the capacitors, and in the same cylindrical formation, switches the charged capacitors directly to apply voltage to a single, inductively-isolated gap. By proper selection of compact, low-inductance capacitors, pulse lengths of the order of 100 ns can be achieved directly. An example of one module that can drive a gap at, e.g., 0.45 MA and 100 kV, is shown in Fig. 9.10. To reach higher voltages, a series of modules is stacked into an inductive voltage adder configuration. The LTD concept was pioneered at the Institute for High Current Electronics in Tomsk, Russia [04Maz].

Accelerators using the LTD concept with a wide range of pulse lengths and other parameters are being built now (USA, France, Russia). An example of an LTD design that could replace the Saturn accelerator (a nominally 10 MA machine) is shown in Fig. 9.11 [00Maz, 01Maz]. This system consists of 24 modules, each producing ~ 700 kA at 2.2 MV, for a total current of the order of 14 MA. Each module consists of 40 stages, each at 55 kV, in an inductive voltage adder configuration. Each stage is a circular array of 24 fast capacitors (capacitance 11 nF, inductance 25 nH, 30 kA maximum current). The switches would be either a ring switch being developed in Russia, or a photoconductive semiconductor (PCSS) switch being developed at SNL. The desired short pulse (~ 50 ns) is applied directly to the gap, magnetically insulated with Metglas^{TM}, without the need for any pulse compression or pulse forming lines. Because of the short pulse length, and modest parameters per stage, the dimensions of an air-core device would not be appreciably larger than the Metglas^{TM} design. The overall size of this LTD accelerator, with parameters exceeding the present Saturn, would be about 1/4 the size of the present Saturn.

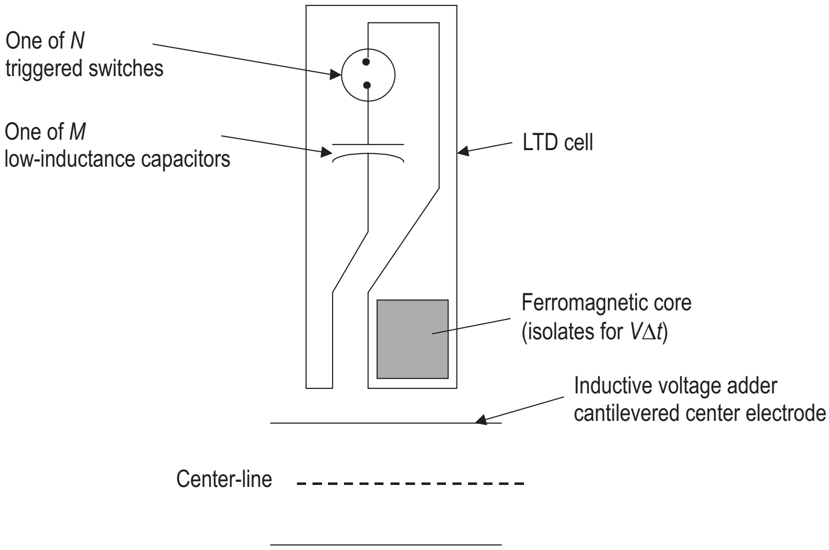

Fig. 9.9. The Linear Transformer Driver (LTD) concept.

Fig. 9.10. Example of LTD module (0.45 MA, 100 ns) developed at High Current Electronics Institute, Tomsk, Russia [04Maz]. The module radius is about 1 m, and the module thickness is about 20 cm.

The above examples of LTD accelerators are all single-shot devices. However, for z-pinch IFE, all that is needed is a slow rep-rate with about 10 seconds between shots. For this low rep-rate, a robust, DC power supply could be connected directly to the LTD accelerator. Switching operation at 0.1 Hz, electrode erosion effects, and heating effects due to the high average power, are concerns that would have to be investigated for z-pinch IFE. However, in comparison with the other pulsed power driver options for z-pinch IFE, the LTD approach appears to be very attractive.

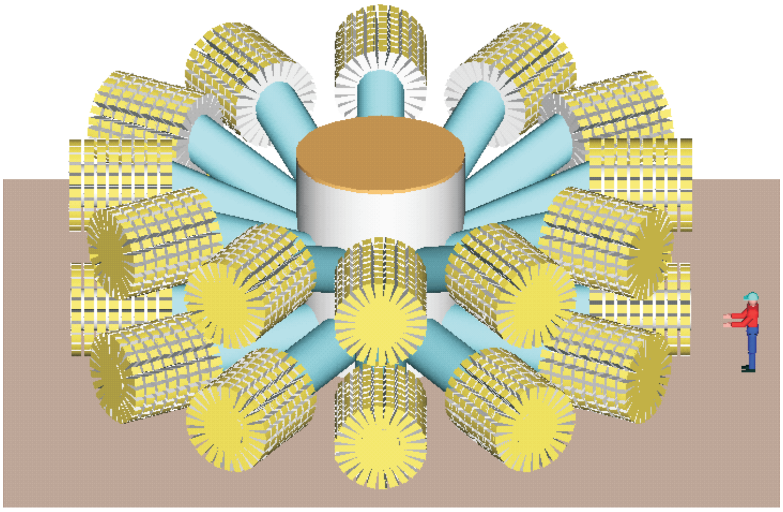

Fig. 9.11. LTD design for replacing the Saturn accelerator at SNL in 1/4 the volume with no oil and no water storage required [00Maz, 01Maz].

9.2.4 Z-pinch drivers for high-yield (~ 0.5 GJ) facilities

Several facilities that would achieve ignition and high yield (~ 0.5 GJ) using z-pinch driven fusion targets *on a single-shot basis* have been suggested. All would deliver currents of the order of 50…60 MA to a fusion target. These facilities include X-1 [99Coo] in the US, as well as Baikal [99Ale] and Emir [02Sel] in Russia. X-1 is based on the inductive voltage adder concept, and is indicated in Fig. 9.12 as the high-yield facility. Note that ZR, currently scheduled to be operational in 2006, will be within a factor of 2…3 in current (4…9 in energy) of a high-yield driver. Baikal is based on an inertial energy store and several stages of pulse compression, whereas Emir is based on explosive generators and a few stages of pulse compression. There is consensus that a driver with a current of 50…60 MA will be sufficient to drive a target to high yield (~ 0.5 GJ).

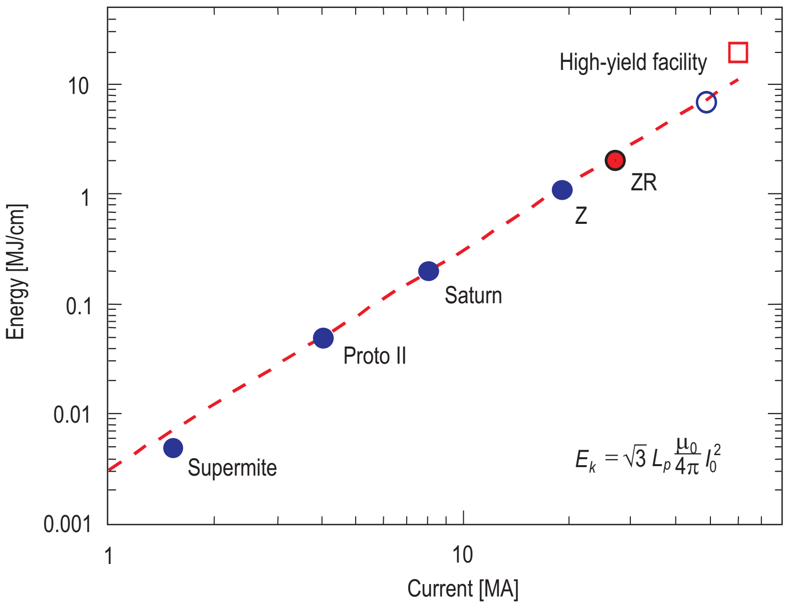

Fig. 9.12. Current scaling for z-pinch drivers showing that ZR will be within a factor of 2…3 (4…9 in energy) of a high-yield driver [99Coo].

9.3 Standoff: Recyclable Transmission Lines

On existing pulsed power drivers (which are all single-shot devices) the pulsed power driver is connected to the z-pinch load through a vacuum Magnetically-Insulated Transmission Line (MITL), which is a large, massive structure. For z-pinch IFE, the preferred method is to have the pulsed power driver connected to the target through a Recyclable Transmission Line (RTL). The RTL is a lightweight MITL made out of special materials that are easily recyclable. In this section, MITLs as used on present pulsed power machines are discussed first. Then RTLs are discussed, including the concept, recent research, and proposed research.

9.3.1 MITL (Magnetically-Insulated Transmission Line)

The concept of self-magnetic-field insulation of vacuum transmission lines was proposed in the 1970s [76Bar, 77Ber, 79Van], and has been widely used in pulsed power devices to deliver large currents at low impedances to a variety of loads. If a voltage pulse is applied to a two-electrode vacuum transmission line with a narrow gap, the strong electric field will cause electron field emission from the cathode side for fields exceeding roughly 250 kV/cm. The launched electron flow (up to the Child-Langmuir space-charge-limited value [11Chi, 13Lan, 29Lan]) will begin to cross the gap. However, as the current builds up, the self-magnetic field will start to turn the electrons back. When the magnetic field reaches the minimum insulating value of

$$B = \frac{1}{d}\left(\frac{2eV}{r_e}\right)^{1/2}\left(1+\frac{eV}{2m_e c^2}\right)^{1/2} \tag{9.1}$$

(where d is the gap width, V is the applied voltage, r_e is the classical radius of the electron, m_e and e are the mass and charge of the electron, and c is the speed of light), electrons will execute cycloid $\boldsymbol{E} \times \boldsymbol{B}$ trajectories and just graze the anode. As the minimum insulating value of the current is exceeded, the contained $\boldsymbol{E} \times \boldsymbol{B}$ electron flow will be confined to a thin layer next to the cathode surface as shown in Fig. 9.13. This magnetic insulation effect makes possible very efficient, large electrical power flow in small gaps at very low impedances without the gap shorting out. Of course, due to the high power levels, plasmas may form and start to cross the gap at velocities of the order of 1 cm/μs or more. Plasma closure can ultimately limit the performance of MITLs.

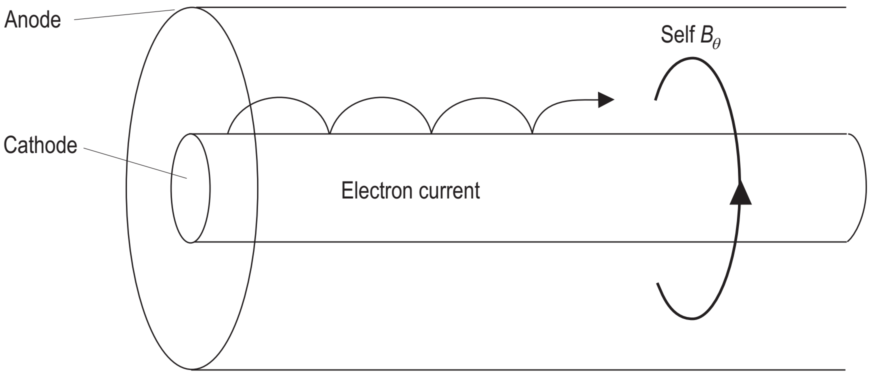

Fig. 9.13. Magnetically Insulated Transmission Line (MITL) concept.

The final vacuum magnetically-insulated transmission line (MITL) section on Z [97Sty] routinely permits currents of 18 MA to be delivered to a z-pinch load for pulse lengths of order 100 ns or more. The final vacuum magnetically-insulated transmission line assembly consists of a stack of six metal conical disks which form four stacked transmission lines, a “post/hole” convolute section that adds the four lines into one line, and a short final coax transmission line – the entire assembly is made out of aluminum and stainless steel and has a mass of 9000 kg (10 tons). This MITL section is shown in Fig. 9.14, which shows the insulator stack, the water-insulated section to the right, and the vacuum section to the left. The post/hole convolute is shown in the inset, together with the "inner MITL" (the final short MITL), and the connection to the load. Because the water lines are limited to a geometrically determined minimum impedance, four MITLs are required to carry the desired total current. In principle, the four MITLs could be added near the insulator stack and one final coax MITL could be used the rest of the way to the z-pinch load. The Z MITLs have worked at a peak electrical power of ≈ 50 TW, a peak current of ≈ 20 MA, and a peak voltage of ≈ 3 MV, on over a thousand shots on Z.

For z-pinch IFE, it is envisioned that a magnetically-insulated transmission line would be used to connect the pulsed power driver to the z-pinch load. The pulsed power driver technology could be any of the three types (or a hybrid thereof) discussed in Sect. 9.2. For any of these technologies, it is envisioned that the final transmission line would be a coax with a cross-sectional shape (e.g., disc, conical, or cylindrical) yet to be optimized for the selected pulsed power technology used. LTD technology is the currently preferred driver technology for z-pinch IFE, and this uses an Inductive Voltage adder that could be fed directly into a final coax MITL.

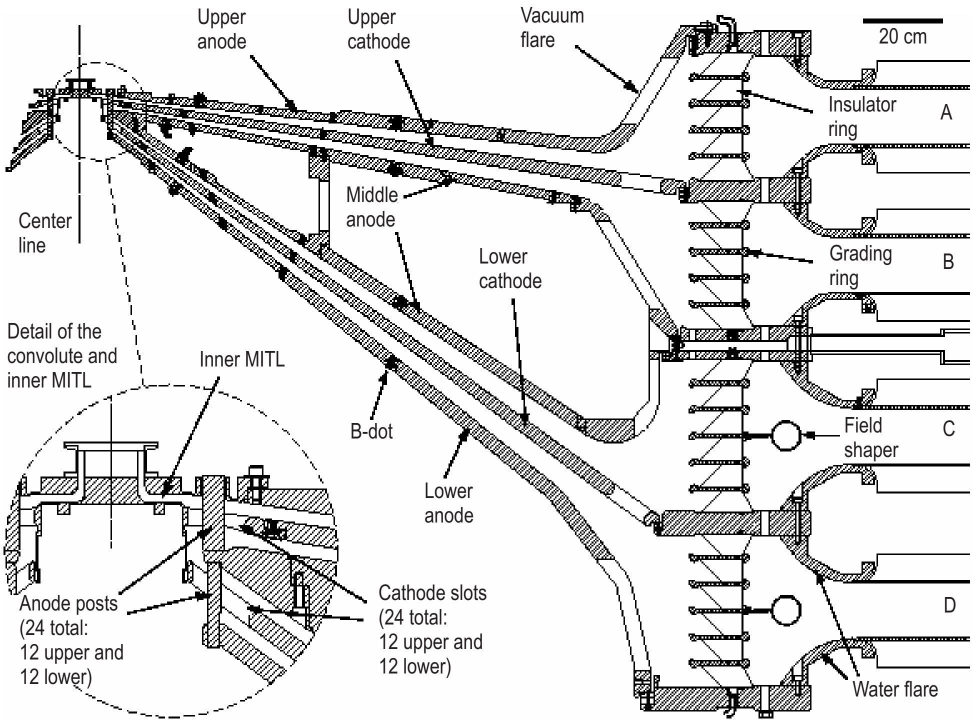

Fig. 9.14. The Z MITL section [97Sty].

9.3.2 RTL (Recyclable Transmission Line)

For repetitive z-pinch fusion high-yield shots for IFE, a means must be developed to repetitively connect the pulsed power driver to the target. Early suggestions to accomplish the repetitive connection included liquid metal electrodes, disposable electrodes, plasma electrodes, disposable inverse diodes fed by electron or ion beams, high-velocity projectiles to compress a magnetic field, or electrodes made from recyclable materials. From these possibilities, the most enduring approach to date is the RTL concept [00Ols, 00Spi, 00Slu, 02Roc, 01Der, 02Ols, 03Slu1, 04Roc]. In the simplest embodiment of this concept, the RTL is a lightweight coax vacuum MITL made out of frozen coolant or a material that is easily separable from the coolant. The power plant chamber coolant is the fluid material that absorbs the neutron energy, and is presently chosen to be Flibe – a binary salt mixture of beryllium fluoride and lithium fluoride. The RTL and the z-pinch target will be destroyed on each shot, but the RTL materials will be recycled, and a new RTL will be inserted on each new shot. (The full shot cycle is discussed in Sect. 9.5.) The present baseline parameters are to have 3 GJ yield shots every 10 s per chamber, i.e. a rep-rate of 0.1 Hz in any one chamber. The RTL is to be inserted into a power plant chamber through a single hole (of radius ~ 1 m) at the top of the chamber as shown in Fig. 9.15. Note that the RTL can be designed to bend around the entrance hole so that it is relatively easy to arrange for shielding to protect the permanent parts of the pulsed power feed from the driver. Already, it can be seen that there are several advantages to the RTL concept – it eliminates the problems of a final optic, pointing and tracking *N* beams (where *N* ~ 100), and high-speed target injection. In place of those problems, the scientific and economical viability of the RTL concept must be demonstrated.

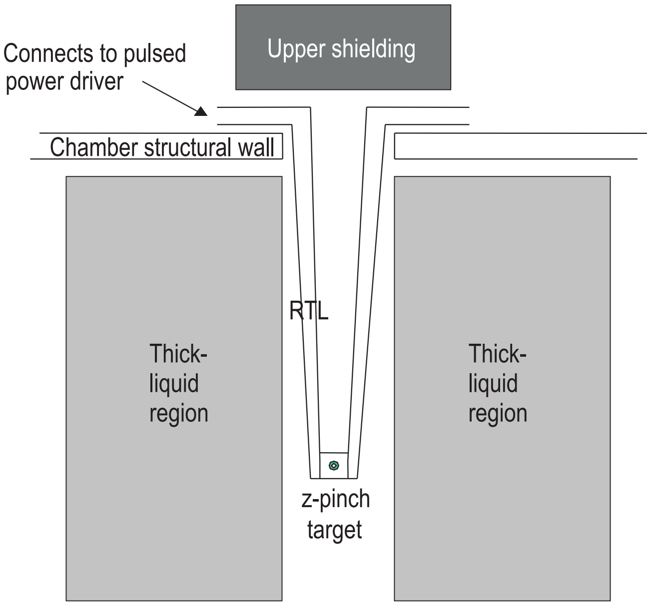

Fig. 9.15. The Recyclable Transmission Line (RTL) concept.

Since on Z the final MITL assembly has a mass of 9000 kg, it is reasonable to ask what the minimum mass of an RTL could be if the only constraint were that the electrodes do not separate more than a small portion (e.g., 10 %) of the original gap spacing due to the magnetic field pressure during the power pulse. Based on just this constraint, it has been shown analytically that the minimum mass for an RTL for a power plant would be less than 1 kg [03Slu1]. Other constraints (discussed in the following), such as sufficient electrical conductivity and adequate structural strength, raise the practical mass for an RTL for a power plant to about 50 kg.

Introducing an RTL into the power flow circuit will typically add inductance to the circuit, which means that the drive voltage from the pulsed power must be increased to compensate and achieve the same z-pinch load performance level [00Slu]. This is the key trade-off in designing the RTL and the pulsed power driver, and must always be considered in any full system design.

A list of issues that needs to be addressed for RTLs is given in Table 9.1. During the period 2000…2003, investigations of several of these issues were initiated. In the following, brief summaries of some of these investigations are given.

– *RTL movement:* Since the RTLs for a power plant are sizeable structures with dimensions of order of a meter by a few meters, and since other IFE approaches operate at ~ 10 Hz, a common concern is that it would be difficult to maneuver the RTLs into place as fast as needed. However, recall that the envisioned rep-rate for the RTLs is only 0.1 Hz, i.e., there is 10 s between shots. To move any mass a distance *L* in time *t* requires an acceleration *a* given by $L = (1/2)at^2$, so $a \sim 1/t^2$. Compared to other *IFE* approaches which have only 0.1 s between shots, *t* has increased by a factor of 100, and the required acceleration has decreased by a factor of 10^4. The consequences of this simple argument are summarized in Fig. 9.16, which shows a plot of *L* versus *t*, with lines of constant acceleration ranging from 0.1 g to 10^4 g. Major reactor studies (Sombrero and Osiris [92Sch], Prometheus H and Prometheus L [92McD]) are indicated for the other IFE approaches that require target accelerations up to 1000 g or more. In contrast, for RTLs for z-pinch IFE, the accelerations required to move the RTLs are less than 0.1 g. This is the equivalent of automobile assembly line technology, or elevator technology, and is therefore essentially not an issue.

- *RTL power flow uniformity:* One of the most important concerns for RTLs is the electrical turn-on uniformity. Once the power pulse voltage on the RTL gap rises above a certain level, electron field emission will occur on the cathode side, and a "launched electron flow" will occur. If the electrical turn-on is not azimuthally and radially symmetric, the power flow will be asymmetric and inefficient. Therefore, a series of RTL experiments was performed at the 10 MA level on the Saturn accelerator at SNL to investigate electrical "turn-on" [01Ols]. A cylindrical coaxial transmission line of radius 8 cm, height 30 cm, and gap 3 mm was connected to the Saturn power pulse output, and the load end was shorted. These parameters were chosen to provide a current density comparable to that for a full-scale RTL in a power plant. Several surface materials were tested – tin, aluminum, and stainless steel (these were candidate materials to be used to coat the RTL surfaces to insure good electrical conductivity). Three B-dots were placed at equally-spaced azimuthal locations, at the top, middle, and bottom of the RTL to measure the uniformity of the power flow. All materials tested showed excellent turn-on uniformity and no loss of current [01Ols]. It is believed that this occurred because the reactor-grade electrical parameters used had strong enough electric fields to induce prompt field emission.
- *RTL electrical conductivity:* The next most pressing question was to minimize the RTL mass, but with the constraint that the electrical conductivity be sufficient for efficient power flow. A new set of experiments was devised with a cylindrical coax composed of a solid inner conductor cathode, a thin test layer anode foil layer, and a final solid shunt current layer. If the conductivity of the test layer is not high enough, the magnetic field will diffuse through it and current will flow in the outer shunt layer. This RTL test structure was tested at the 10 MA level on Saturn for several test materials – 20 micron mylar, and 50, 100, and 150 micron ferritic steel [02Slu]. The conductivity of the test materials could be deduced from the experimental results. Using the conductivities from these results, the total mass and electrical efficiency for a 4 m radius *disc* coaxial RTL could be calculated. The results show that for a mass of 40 kg (80 kg), the electrical efficiency would be 70 % (90 %).
- *RTL structural properties:* Given that the electrical turn-on, low mass, and electrical conductivity appear to be reasonable, the next issue was the structural integrity of the RTL. Specifically, it was desired to know what a reasonable operating pressure would be for the power plant chamber. For a conical or cylindrical coax, vacuum is required only in the coax gap. For a finite chamber pressure, the inner RTL electrode is very strong because the hoop stress is outward – however, the outer RTL electrode is relatively weak, and will tend to collapse if the chamber pressure is too high. Analytic calculations predicted that for a 2 m long conical RTL made of 0.0025" steel would not buckle for pressures below about 60 torr, so that a safe operating regime would be about 10…20 torr. A finite-element model of a *conical* RTL was constructed in ANSYS, and a preliminary buckling analysis was performed [03Kam]. As shown in Fig. 9.17, the RTL is unaffected at 20 torr, but buckles at 78 torr. This computational tool will now be used to study and optimize other RTL geometries.
- *RTL shrapnel formation:* Following the fusion target explosion, the target and all materials near it (such as the end of the RTL) will be vaporized and become plasmas. Further up the RTL, it will become droplets, aerosols, liquid, dust, shrapnel, chunks, hot metal, etc. It is important to study and understand all of these phases, and assess their potential ability to cause damage to other parts of the system. Preliminary investigations using the Alegra code have led to a 1-D model of the effective source term for heating following a fusion target explosion [03Slu3]. Assuming normal incidence, this information has then been used to calculate the effective particle size of shrapnel at a specific distance from the explosion [03Gro]. This work will continue to develop an understanding of the shrapnel issue, and determine if the thick-liquid walls can effectively alleviate it.

Additional studies on RTLs in relation to vacuum/electrical connections, activation, mass handling, and manufacturing/cost are discussed in Sect. 9.5. The key physics issues for RTLs are on power flow limits, including the effects of ions and the potential problem of plasma formation and gap closure. It should be noted that the MITLs on Z work extremely well at 20 MA. For RTLs, the question is to validate operation at 20 MA, 60 MA (the envisioned level for a high-yield facility with 0.5 GJ yields), and at or less than 90 MA (the envisioned level for 3 GJ yields for a z-pinch IFE power plant). The other science issues involve the effects of post-shot EMP, plasma, droplets, and debris up the RTL. The remaining RTL issues are predominantly engineering/technology issues. A summary of RTL research areas is given in Table 9.2.

Table 9.1. Recyclable Transmission Line (RTL) issues.

RTL placement
RTL electrical turn-on
RTL low-mass limit
RTL electrical conductivity
RTL structural properties/chamber pressure
RTL mass handling
RTL shrapnel
RTL vacuum connections, electrical connection
RTL activation
RTL waste stream analysis
RTL shock to fluid walls
RTL manufacturing/cost
RTL optimum type (coax, triax, convolute)
RTL optimum configuration (shape, inductance, material, mass)
RTL power flow limits
Effects of post-shot EMP, plasma, droplets, debris up the RTL
Shielding of sensitive accelerator/power flow feed parts

Table 9.2. RTL research areas.

Power flow in the RTL
Power flow limits for currents exceeding 20 MA
Effects of ions and plasmas in magnetically-insulated gaps
Optimal RTL type (coax, triax, convolute)
RTL construction
RTL shape, inductance, material, mass
RTL electrical, vacuum, structural properties
RTL manufacturing, recycling, cost
RTL chamber/interface
RTL vacuum connections, electrical connections
Effects of post-shot EMP, plasma, droplets, debris up the RTL
Shielding of sensitive accelerator/power flow feed parts
RTL demonstration experiments
Design, build, pressure test PoP-scale RTLs
Design/cost/schedule an RTL demonstration on Z
Design RTL for a 60 MA driver for high yield

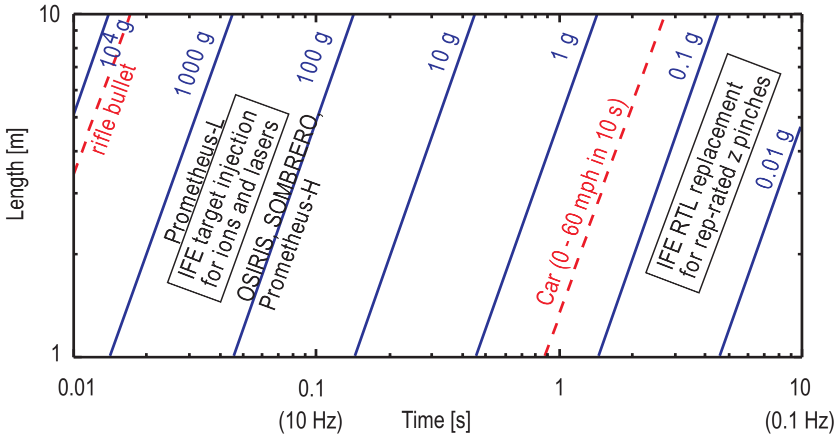

Fig. 9.16. RTL placement requirements for 0.1 Hz, showing that only very modest accelerations are needed.

Fig. 9.17. RTL structural properties buckling analysis [03Kam]. Designed for safe operation at 10…20 torr, this RTL is shown **(a)** unperturbed at 0 or 10…20 torr, and **(b)** buckling at 78 torr.

9.4 Z-pinch targets

The “target assembly” for z-pinch IFE uses some form of a fast z-pinch to produce intense X-ray radiation that is then used to drive a fusion capsule. In the first part of this section, the physics of a single multi-wire-array fast z-pinch is examined as an intense X-ray radiation source. In the second part of this section, the physics of several types of z-pinch indirect-drive target configurations are examined. For these targets, z-pinches supply X-ray radiation to a hohlraum, and a fusion capsule suspended in the hohlraum uniformly absorbs the radiation and implodes, resulting in fusion burn.

9.4.1 Fast z-pinches as intense soft X-ray radiation sources

A fast z-pinch consists initially of a cylindrical low-mass thin shell through which a fast pulse (~ 100 ns) of very large current (~ MA) flows. The radius of the shell is typically several cm, and the length of the cylinder is typically of the order a cm or more. The name "z" comes from the fact that the current flows in the "z" direction. The shell can be made of a gas puff, a foil, or an array of fine wires. For the latter case, when the current flows, each wire rapidly heats and becomes a plasma, the azimuthal magnetic field created by each wire (B_θ) causes the wires to be attracted to each other, and the cylindrical array starts to coalesce and decrease in radius. The collective magnetic field of the entire array (through the $\boldsymbol{J} \times \boldsymbol{B}$ force) continues to pinch the array to an ever smaller radius. The radial velocity of the converging array continues to increase as the array pinches. Finally, the array stagnates on axis (literally crashes in on itself), converting all of the array kinetic energy into intense thermal/radiative heat in the stagnated mass. This dense, hot, stagnated array is an intense X-ray radiation source. The process is shown in Fig. 9.18. Note that kinetic energy is supplied to the array over the "long" time scale of ~ 100 ns, whereas the stagnated pinch will radiate an intense X-ray burst over a much shorter time scale of about a few ns at a power level many times higher than the power level associated with the electrical current used to drive the pinch, i.e., the z-pinch acts as an energy converter (kinetic energy to X-rays) and as a power amplifier (X-ray power >> pulsed power drive).

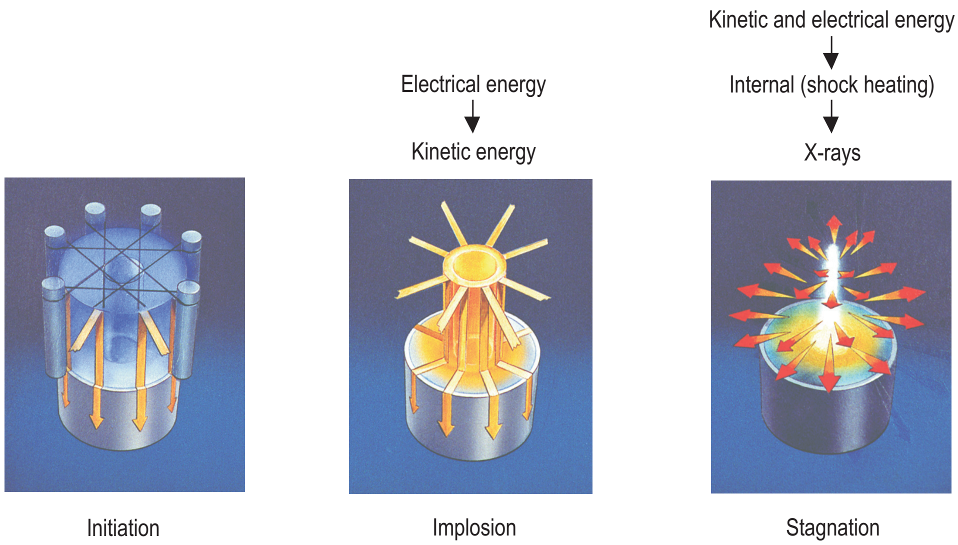

Fig. 9.18. Z-pinch wire array operation, from current initiation to generation of X-rays [99Coo].

Limiting our attention to wire arrays, we consider a simple model for an infinitely thin annular conducting shell undergoing pinch compression by acceleration by the $\boldsymbol{J} \times \boldsymbol{B}$ force due to a current $I(t)$ [80Hus, 99Lie]. The equation of motion for the shell of radius $R(t)$ is

$$\frac{M}{L}\frac{\mathrm{d}^2 R(t)}{\mathrm{d}t^2} = -\frac{I(t)^2}{R(t)\,\mathrm{c}^2} \quad , \tag{9.2}$$

where M is the mass of the shell, L is its length, $I(t)$ is the current, and c is the speed of light. For $I(t) = I_0$, $R(0) = R_0$, $\mathrm{d}R(0)/\mathrm{d}t = 0$, this equation is easily integrated to give:

$$\left(\frac{\mathrm{d}R(t)}{\mathrm{d}t}\right)^2 = 2\left(\frac{R_0}{\tau_0}\right)^2 \ln\left(R_0/R(t)\right) , \tag{9.3}$$

$$t/\tau_A = (\pi/2)^{1/2} \text{ erf } \ln\left(R_0/R(t)\right)^{1/2}, \tag{9.4}$$

where $\tau_A = c(R_0/I_0)(M/L)^{1/2}$ is the Alfven transit time, and "erf" is the error function. Due to instabilities, non-uniformities, and inductance increase, the pinch radius, $R(t)$, will not go to zero, and the final pinch radial compression ratio, $C_R = R_0/R_{MIN}$, will be limited to a finite value. Since C_R only enters logarithmically in the final results, typical values for dR/dt and τ at peak compression may be estimated by setting, e.g., $C_R = 10$, which yields

$$\frac{\mathrm{d}R}{\mathrm{d}t} \approx \frac{2R_0}{\tau_A} \quad \text{and} \quad \tau \approx (\pi/2)^{1/2}\tau_A\,, \tag{9.5}$$

at which time the kinetic energy of the imploding shell is

$$E = 2\,L\,I_0^{\,2}/c^2\,. \tag{9.6}$$

This is the kinetic energy that is available to transform into thermal/radiative energy, and it shows the simple scaling $E \sim I_0^2$.

Competing with this simple uniform fast pinch model is the fact that the pinch process is unstable since it is based on the acceleration of a heavy fluid (the plasma annulus) by a weightless fluid (the magnetic field). This is an example of the classic Rayleigh-Taylor instability [60Gre] for the surface of a liquid accelerated by gravity that has the growth rate

$$\gamma = |g\,k|^{1/2}, \tag{9.7}$$

where g is the acceleration and k is the wave number. Note that shorter wavelengths have higher growth rates. A substantial amount of work has been done on the Rayleigh-Taylor instability for fast pinches [99Lie, 00Ryu1] with calculations and simulations that include the effects of finite cylindrical geometry, plasma expansion, plasma conductivity, finite electron/ion cyclotron radius effects, magnetic field penetration into the plasma, and non-linear effects. An example of the Rayleigh-Taylor instability for a single pinch wire array z-pinch on its path to stagnation on axis is shown in Fig. 9.19 [00Dou]. Note that the instability leads to a series of "bubbles and spikes" that ultimately limit the minimum pinch radius achievable, the quality of stagnation on axis, and the brightness and uniformity of the resultant X-ray source.

Minimization of Rayleigh-Taylor instability effects can vastly improve the quality and X-ray output characteristics of the fast z-pinch. It is readily apparent that small non-uniformities in the original annular z-pinch will seed the Rayleigh-Taylor instability, and possibly other hydrodynamic instabilities such as the kink and sausage instabilities, so it is of utmost importance that the current flow in the z-pinch be as uniform as possible (both azimuthally and axially) from the outset. Concerns such as these led to the breakthrough discovery in 1995 [96San, 99San, 01San], which was continually extended thereafter [98Dee, 98Spi], that increasing the number of wires while keeping the mass constant leads to enormous increases in the X-ray power output. The original work was done on the Saturn accelerator at 6…8 MA, and used Al wire arrays [96San, 99San, 01San]. The total wire mass was fixed at 0.6…0.66 mg Al, the array radius was either 8.6 or 12 mm, the array height was 2 cm, the number of wires varied from 13 to 192, and the wire diameter varied from 38 μm down to 10 μm. The key results are summarized in Fig. 9.20, which shows the radiated total X-ray power as a function of the inter-wire spacing. For spacings larger than 2 mm, the wires behave as individual wires that are kink and sausage unstable, and a poor stagnation occurs that produces relatively low power (≤ 10 TW). For spacings smaller than 2 mm, the wires become plasmas that merge into a single converging annular cylinder, a very small radius stagnated pinch occurs, and the radiated X-ray power increases dramatically (to ≈ 50 TW). In subsequent experiments on Z at ≈ 18 MA with tungsten wire arrays, the number of wires was increased to beyond 300, and the X-ray power output was increased to beyond 200 TW [98Dee, 98Spi]. The importance of these discoveries is shown dramatically by the increase in X-ray power achieved versus year, as shown in Fig. 9.21 [04San].

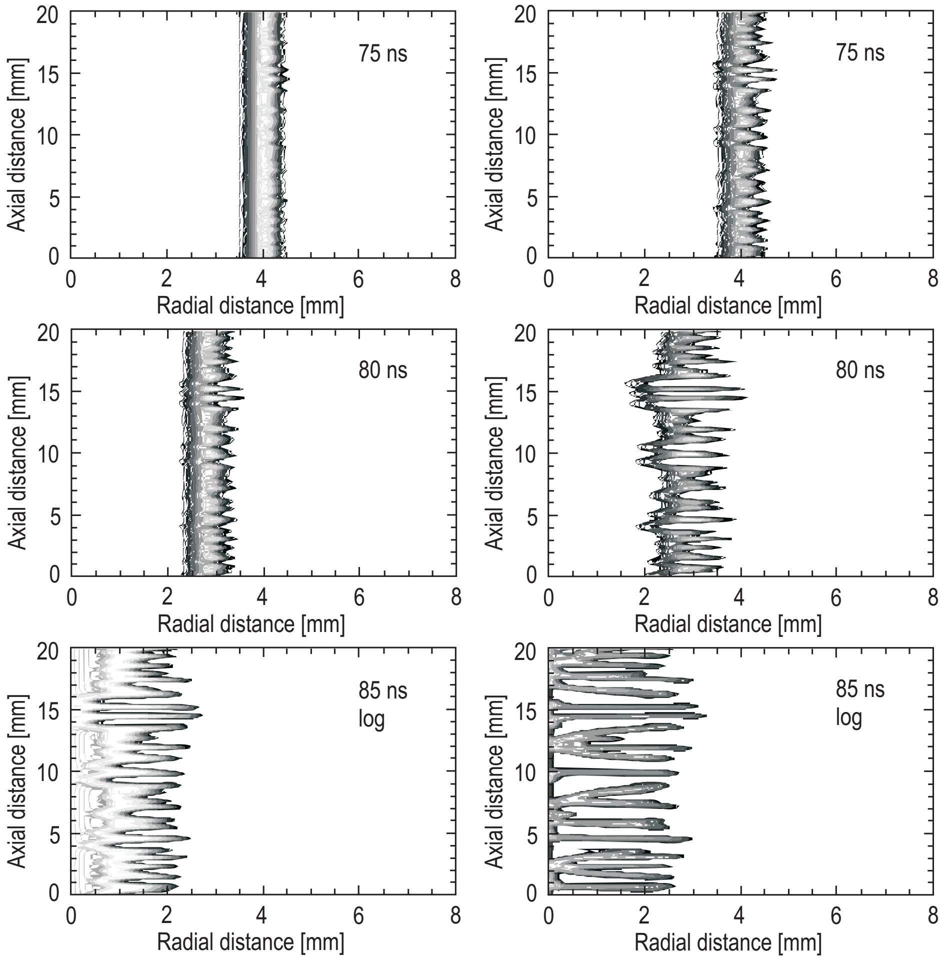

Fig. 9.19. Example of Rayleigh-Taylor instability of a z-pinch converging on axis [00Dou], for an initial 5 % random density perturbation (left three frames) and for an initial 20 % random density perturbation (right three frames). Note the bubble-spike structure which is indicative of nonlinear Rayleigh-Taylor development.

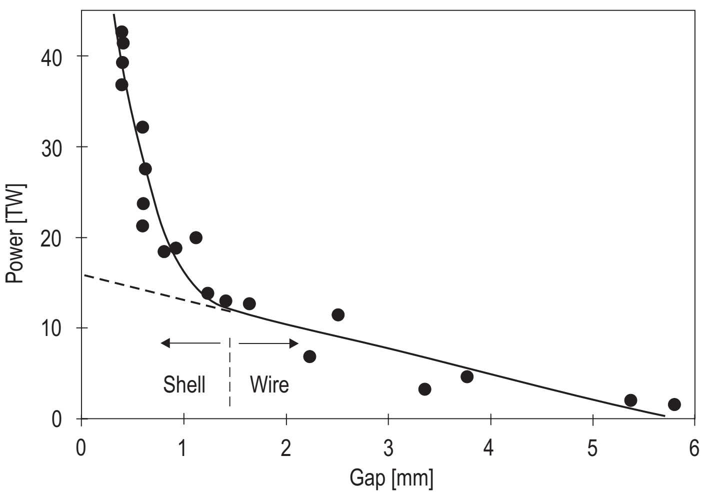

Fig. 9.20. Breakthrough in X-ray power production from wire arrays, showing the dramatic increase in X-ray power as the inter-wire spacing decreases below 2 mm (i.e., as the number of wires increases, while keeping the total wire mass constant) [96San, 99San, 01San].

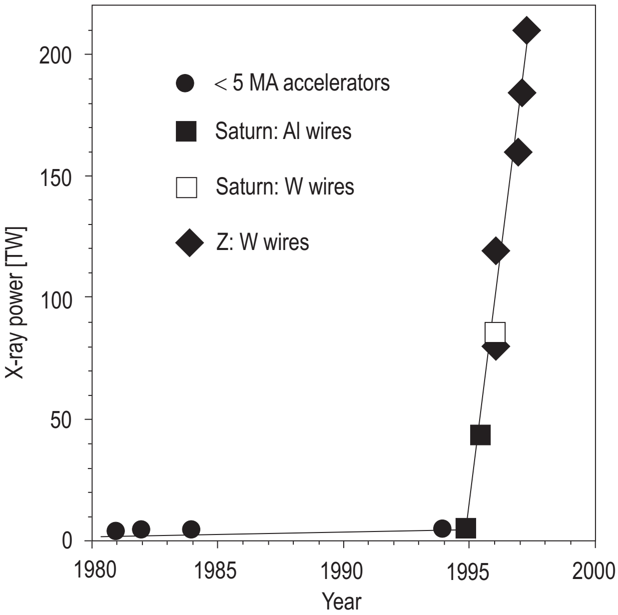

Fig. 9.21. Breakthrough in increase in X-ray output from wire array z-pinches versus year [04San].

Record X-ray power and energy levels continued to increase on Z for a variety of z-pinch configurations including single wire arrays, nested wire arrays, and wire arrays that implode on a foam core. As the peak total X-ray energies have increased, it is of interest to examine the scaling of the peak X-ray energy (and peak power) with the pinch current. In the above, the scaling $E \sim I^2$ was noted. Recently, scaling laws based on detailed z-pinch experiments on Z at 13 MA and 19 MA show the scaling $E \sim I^{1.73\pm0.18}$ and $P \sim I^{1.24\pm0.18}$ [04Sty]. However, it was also argued that if the power pulse length to the z-pinch is reduced as $\tau \sim I^{-1/3}$, then the scaling of $P \sim I^2$ is retrieved. The exact scaling laws are crucial for determining the accelerator parameters needed to reach the high yields required for IFE.

9.4.2 Z-pinch driven targets

The outstanding results achieved on Z as an X-ray source have led to several indirect-drive approaches for driving ICF capsules. Although there are many possible z-pinch driven target configuration, the most studied are the double pinch target, the dynamic hohlraum target, and the fast ignition target concepts. For each approach, experiments and theory have been done to study the energetics of radiation flow into a hohlraum, symmetry of the radiation, radiation absorption by a capsule, and time-dependent capsule compression. Results for each of the three types of targets are summarized in the following.

The *double pinch target* [99Ham] uses two z-pinches to drive a hohlraum placed between them as shown in Fig. 9.22. Each pinch stagnates on axis, and the X-ray radiation produced flows through a Be radial spoke and shine shield assembly to fill the central hohlraum. A baseline capsule design for a high-yield double pinch target [99Ham] is shown in Fig. 9.23. The capsule has an outer radius of 2.59 mm, and consists of a thin outer Be layer, a thin solid DT layer, and a DT gas fill as shown. This capsule requires a z-pinch driver energy of 2 × 16 MJ and has a capsule absorbed energy of 1.12 MJ, a peak drive temperature of 223 eV, a radial convergence ratio of 36, and a yield of 380 MJ. This approach of a double z-pinch drive is considered to be relatively conservative since the z-pinches act essentially as independent X-ray sources to feed an essentially fixed hohlraum.

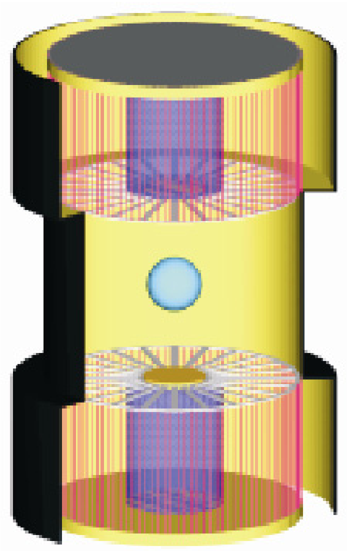

Fig. 9.22. The double-ended hohlraum target [99Ham].

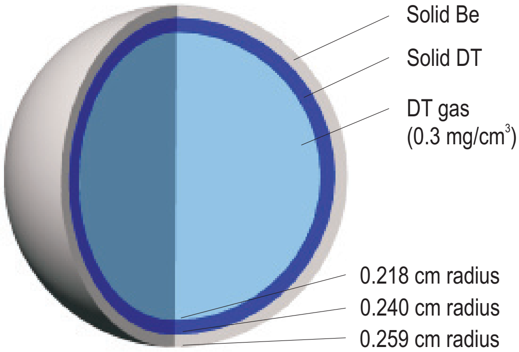

Fig. 9.23. The baseline capsule design for the double-ended hohlraum target [99Ham].

Experiments on Z have been performed to study hohlraum energetics [01Cun1, 01Cun2], symmetry measurements using foam ball radiation [02Han], double pinch operation with a single power feed [02Cun], symmetry control and pinch simultaneity [03Ves1, 03Ves2], and actual capsule compression experiments for the double pinch target [02Ben, 02Cun]. The Z Beamlet Laser [03Rug] with an Fe foil target acts as an intense point X-ray source at about 6.75 keV. The Z Beamlet Laser has been used for point projection imaging of capsules during X-ray absorption and capsule compression in double pinch targets. Capsule implosion experiments [02Ben] have been performed on Z using polymer plastic capsules of radius 2.15 mm, 59 μm wall thickness, and a 1 atm air gas fill. Z Beamlet Laser radiographs showing the implosion sequence are shown in Fig. 9.24. Radial compression ratios of 14…21 are reported [02Ben]. Also, precise experiments to study the effects of the separation spacing of the two pinches have shown systematic control with time-integrated symmetry of ≈ 3 %. This is within a factor of 2 of the symmetry requirements needed for scaling to high yield.

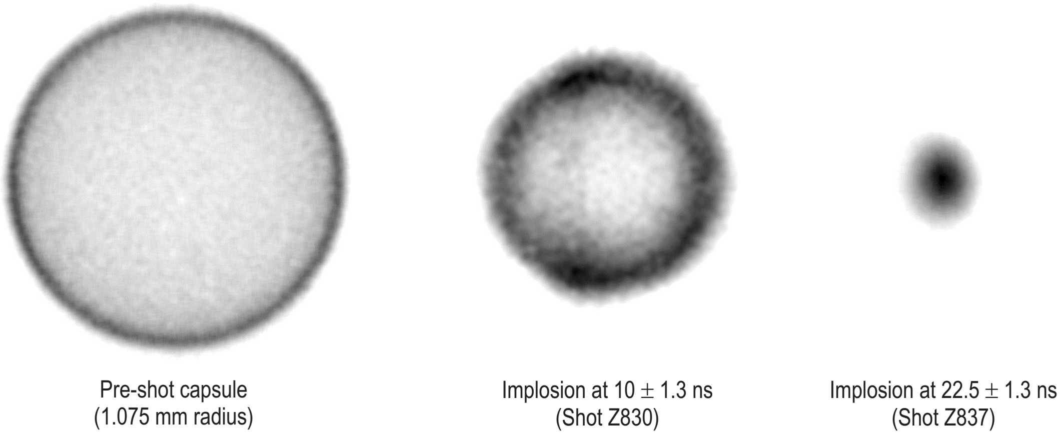

Fig. 9.24. Capsule implosion experiments [02Ben] with a double-ended hohlraum target on Z, using the Z Beamlet Laser as a backlighter. Radial convergence ratios of 14…21 are reported.

The *dynamic hohlraum target* [91Smi, 03Meh] uses a wire array that collapses onto a cylindrical foam with the capsule located at the center of the foam, as shown in Fig. 9.25. When the wire array strikes the foam, X-rays are emitted that drive the capsule contained within the hohlraum formed by the collapsing z-pinch (hence the name "dynamic" hohlraum). Since the hohlraum in this case will be considerably smaller than for the double pinch targets, it is expected that this target will be more efficient and require less driver energy to reach high yield. On the other hand, it is expected that attainment of adequate symmetry will be more difficult. A baseline capsule design for a dynamic hohlraum target [00Las] is shown in Fig. 9.26. The Be-coated capsule has an outer radius of 2.75 mm, and the target is layered as shown. This capsule requires a z-pinch driver energy of 12 MJ and has a capsule absorbed energy of 2.3 MJ, a peak drive temperature of 350 eV, a radial convergence ratio of 27, and a yield of 527 MJ. The increased performance is, of course, at the risk for obtaining the required symmetry.

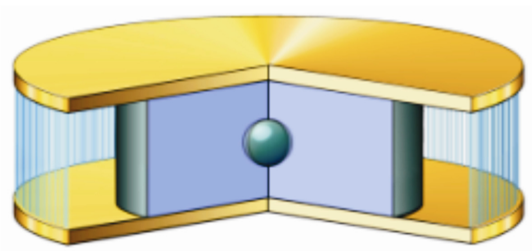

Fig. 9.25. The dynamic hohlraum target concept [00Las].

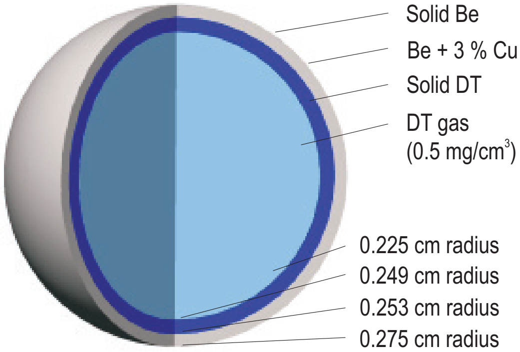

Fig. 9.26. The baseline capsule design for the dynamic hohlraum target [00Las].

Experiments on Z have been used to study the dynamic hohlraum concept, evaluate the energetics of the dynamic hohlraum geometry [99Lee, 02San], perform capsule implosion experiments [02Bai, 03Slu2], and measure neutron yields in DD capsule implosions [04Bai1, 04Bai2]. CH-walled capsules of 1.7…2.0 mm diameter filled with D_2 or CD_4 and doped with a small amount of Ar were used in dynamic hohlraum experiments on Z. The capsules absorbed about 20 kJ of X-ray energy from the radiation drive which peaked at about 200 eV, and core temperatures of about 1 keV were inferred from measurements of the Ar spectrum [04Bai1, 04Bai2]. DD-filled capsules produced thermonuclear fusion neutron yields with up to 8×10^{10} neutrons [04Bai1, 04Bai2]. This DD neutron yield is the largest achieved in the laboratory by any indirect-drive inertial confinement fusion driver to date.

Measurements of the dynamic hohlraum radiation temperature, T, versus driver current for experiments at 3.5 MA on Angara, at 7 MA on Saturn, and at 20 MA on Z show a scaling $T \sim I^{1/2}$ as shown in Fig. 9.27 [99Nas]. This shows that to achieve a radiation drive temperature of about 300 eV to produce a high yield of ~ 0.5 GJ will require a pulsed power driver current of about 60 MA.

The *fast ignition target* uses a hemispherical shell that is compressed by X-rays from a z-pinch source with a petawatt laser to ignite a spot in the compressed core. As shown in Fig. 9.28, initial experiments on Z have demonstrated a hemispherical radial compression factor of 3 [04Ves1]. When a petawatt laser capability becomes available at Z, further experiments relevant to fast ignition will be performed.

The mainline z-pinch targets – the double pinch target and the dynamic hohlraum target – 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 analytic scaling arguments [04Gro] and Lasnex code calculations for multi-GJ yields [04Ves2], 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 preliminary estimates show that, at this stage, both targets can be considered to be contenders for being a viable z-pinch IFE target.

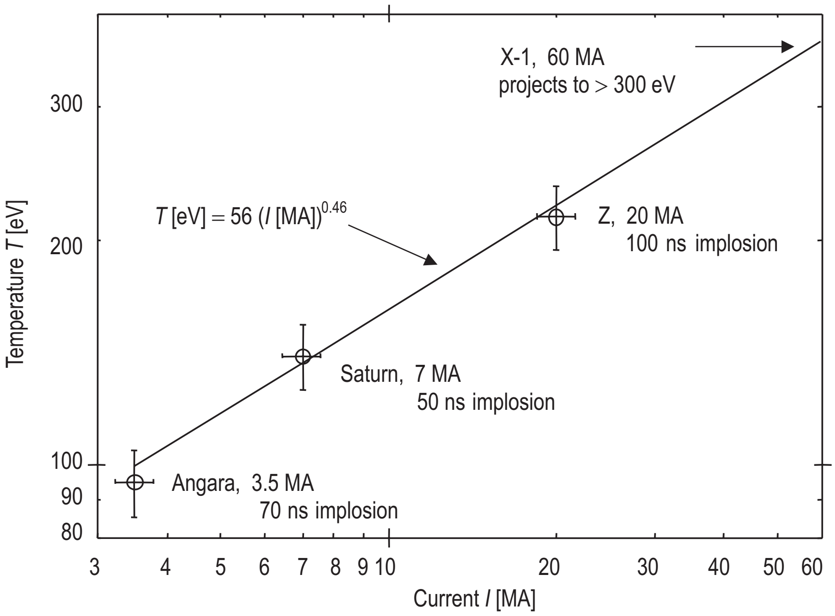

Fig. 9.27. Scaling of the dynamic hohlraum radiation temperature with driver current, showing that a pulsed power driver of about 60 MA is needed to achieve temperatures of 300 eV to drive a high-yield target (0.5 GJ) [99Nas].

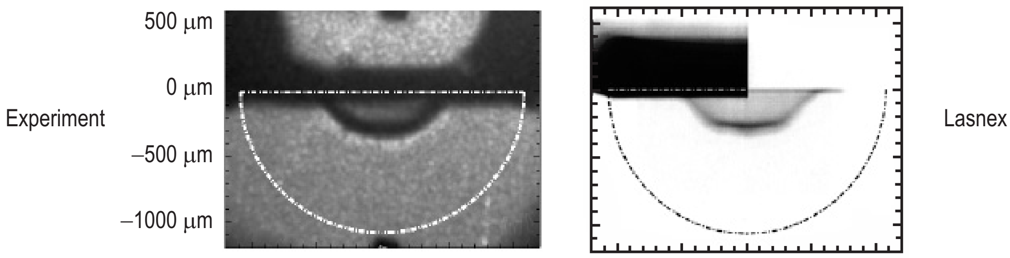

Fig. 9.28. Hemispherical target implosion experiment on Z, for z-pinch fast ignition concept [04Ves1]. Z experiment on left; Lasnex simulation on right. The dashed line shows the hemisphere initial shape.

9.5 Z-pinch power plant concept for IFE

For an IFE power plant, *single-shot* inertial confinement fusion with high yield must be performed on a *repetitive* basis with adequate “standoff” between the pulsed power driver and the high-yield target. Several power plant schemes have been proposed over the last 25 years that have addressed this standoff issue with various proposed solutions that include liquid metal electrodes, disposable electrodes, plasma electrodes, disposable final power conversion concepts (such as an inverse diode fed by electron or ion beams, or a high-velocity projectile to compress a magnetic field), and recyclable electrodes (see, e.g., [00Spi]). After briefly describing some of these concepts, we will focus our attention on the recyclable electrode concept, which is presently being developed as the mainline concept for z-pinch IFE.

Various methods for achieving standoff while essentially directly connecting an electrical driver to a fusion target (frequently of the fiber z-pinch variety) have been proposed as reactor schemes:

– A long, tapered, pulsed Li jet is used as the top electrode, together with a bottom electrode formed from a Li pool – the "electrodes" are connected to a z-pinch target in this concept proposed in 1977 [77Har].
– Plasma electrodes are connected to a pinch target assembly inside a hemispherical dome "dry-wall chamber" in this Russian concept proposed in 1978 [78Vel, 02Ned].
– Long, pointed, metal electrodes are used to drive a pinch, surrounded by a bubbled-water vortex flow containing breeding rods in this concept proposed in 1984 [84Rob]. Continuous feed of the electrodes is used to accommodate erosion, and a curtain of bubbles is used to absorb the shock. Small yields (4.4 MJ) are used at high rep-rate (120 Hz).
– A spinning Li fluid creates a free vortex surface around the area of high-voltage electrodes in this concept proposed in 1986 [86Bol].
– A wetted electrode concept is proposed in 1987 [87Hai].
– Two crossed Li jet "electrodes" are slightly separated to connect to a pinch in this concept proposed in 1989 [89Rob].
– A several meter long cone of frozen Flibe is used to guide a Compact Torus into an MTF-like target in this concept proposed in 1992 [92Moi].
– Several "inverse diode" concepts driven by ion or electron beams whose energy is converted in the inverse diode to a large power pulse to drive a z-pinch target are proposed in 1999 [00Coo].
– Schemes are proposed in which a high-velocity projectile is used to compress a magnetic field to power a z-pinch, in 1999 [00Ryu2].
– The RTL concept is proposed and developed in 1999…2004.

The mainline z-pinch power plant concept uses an RTL to provide the standoff between the pulsed power driver and the high-yield fusion target [00Ols, 00Spi, 00Slu, 01Der, 02Ols, 02Roc, 03Slu1, 04Roc]. An initial z-pinch power plant study named ZP3 was completed for the purpose of establishing one complete (but non-optimized) power plant description [02Roc, 04Roc]. This concept used multiple chambers, each being a thick-liquid wall chamber as shown in Fig. 9.29.This design is for a driver based on Marx/water line technology as used in Z, and at the top shows an insulator stack (similar to that in Z). For this example, a convolute adder would be used to drive a single final coax RTL. As shown, the coax conical RTL starts at the electrical/vacuum connections near the insulator stack, continues down into the chamber, and terminates in the connections to the z-pinch driven high-yield target. As noted earlier, only one opening at the top of the chamber is required for the RTL to enter. For a chamber radius of 5 m, and an RTL entrance hole of radius 1 m, the RTL entrance opening is only 1 % of the surface area of the chamber. This means that essentially 99 % of the blast will see thick-liquid walls, and the remaining 1 % will impact the RTL section. For the configuration shown, a shielding plug is used on top of the RTL. The pressure requirement inside the chamber is a modest 10…20 torr of an inert gas such as Ar. The RTL is designed to be structurally sound for those pressures. 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 s.

The Flibe liquid blanket absorbs the fusion neutron energy (which through conventional heat cycles drives electrical generators to produce electricity), breeds tritium to fuel the targets, shields the structural wall from neutron damage, and mitigates the shock to protect the structural wall. In initial neutronics studies with Flibe blankets, it was straight forward to achieve a tritium breeding ratio above 1 [01Der, 01Ols]. With a thick-liquid wall thickness of 40 cm or more of liquid Flibe, it was found that the resultant neutron fluence to the first (structural) wall was small enough to permit the wall lifetime to exceed the life of the power plant (30 years) [01Der, 01Ols]. Details of the RTL and how the entrance hole and pulsed power driver are shielded is an area of current innovative research. Shock mitigation in the thick-liquid wall remains as the key scientific chamber issue that needs further research and development.

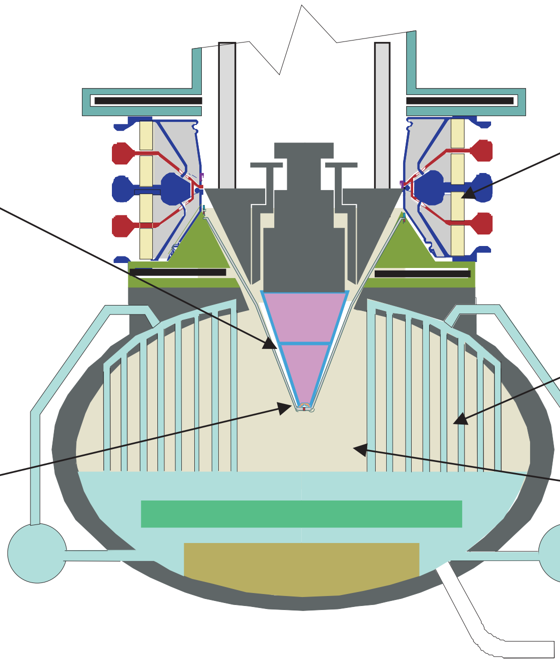

Fig. 9.29. Z-pinch IFE chamber concept [02Roc, 04Roc].

Vacuum is needed only inside the RTL and the region immediately next to the insulator stack in this design, whereas the chamber nominal pressure is 10…20 torr Ar. Once inside a region of 10…20 torr Ar, the RTLs can be prepumped to hard vacuum in the gap, and sealed with industrial-quality sliding O-ring seals. Similarly, the vacuum region near the stack can be prepumped and sealed with sliding O-ring seals. When the RTL is inserted in the chamber, an arrangement of sliding seals allows the vacuum region in the RTL to be joined to that near the stack [04Roc]. Following the shot, the plunger shears off the RTL remnant and seals off the vacuum region. The remnant is removed, while the sliding seals maintain the new vacuum in the vacuum region near the stack.

Activation issues are of utmost importance, due to the large amount of RTL mass that will be recycled. The two RTL materials considered to date are Flibe and low-activation ferritic steel. If Flibe is used for the RTLs, this just adds to the Flibe coolant inventory and there are no new activation issues. If the Flibe RTLs needed a metallic coating for electrical conduction, then the material should be a low-activation material. For the present mainline approach, low-activation ferritic steel is envisioned 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 coolant. Activated RTL Fe-based materials should be handled remotely, and satisfy design requirements for a recycling dose < 300 Sv/h and low level Class C waste (WDR < 1). Approximately a one-day RTL inventory supply seems reasonable for the proposed recycling approach – to allow for a short cooling-down time and for the remanufacture time [04Gue].

The sheer amount of RTL mass that must be handled could be a concern. A 1 GW (el) power plant using 50 kg RTLs at 3 GJ yield would require a one-day on-site storage of 5000 tons of RTLs. For comparison, the San Juan Generating Station in the Four Corners area of NM is a coal-fired power plant that produces 1.6 GW (el). This plant burns 7 million tons of coal per year and produces 1.5 million tons of waste per year. It has an on-site 30-day storage supply of coal that weighs 600000 tons. In one day, the plant burns 20000 tons of coal, and produces 5000 tons of waste (in the form of gypsum and flyash, that must be returned to the adjacent coal mine for disposal). This suggests that the one-day RTL supply of 5000 tons is about equal to one-day's waste from a coal-fired power plant, and should be manageable.

The manufacturing of RTLs and the cost per RTL are definitely a concern. First, it should be noted that it is often said that IFE targets must cost about $0.30 or less. This is true for yields of the order of a few hundred MJ, as are used in heavy ion and laser IFE scenarios at 5…10 Hz. The price of $0.30 per target is based on assuming the electricity produced sells for a reasonable price and that the target cost is a small fraction of that price. For z-pinch IFE, the yields are a few GJ, so by the same arguments, the price available for the RTL and target will be of the order of $3.00. Early cost estimates for casting Flibe RTLs by the SNL Advanced Manufacturing Group were $0.78 per RTL and, in a related study, $0.35 for a z-pinch wire array. Recent work has concentrated on low-activation ferritic 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 % [04Roc]. All of these results are very encouraging in that the costs per RTL are already in the acceptable range.

The first study of a complete z-pinch IFE power plant (ZP3) used multiple chambers (12, of which 10 would be operating at any one time), each with a 3 GJ yield at 0.1 Hz. As shown in Fig. 9.30, this concept is to have one central RTL/target factory to supply all of the chambers. Parameters for this power plant [02Roc, 04Roc] are shown in Table 9.3.

Fig. 9.30. The first complete (non-optimized) z-pinch power plant study (ZP3) for a 1 GW (el) power plant [02Roc, 04Roc].

Table 9.3. Parameters for the first z-pinch power plant study [02Roc, 04Roc].

Description	Baseline value	Unit
Nuclear energy release per shot	3×10^9	J
Energy recovery factor	80 %	
Thermal energy recovered	2.4×10^9	J
Shot frequency	0.1	Hz
Thermal power per unit	2.4×10^8	W
Power conversion efficiency	45 %	
Electrical power per unit	1.1×10^8	W
Number of units	12	
Availability	80 %	
Total power plant output	1×10^9	W
Annual power sales	9.1×10^9	kWh

9.6 IFE materials testing on pulsed power facilities

The "threat spectra" to the first wall in an IFE power plant consists of X-rays, ions, and neutrons [03Pet, 03Per]. The X-ray damage and debris ion damage to target chamber structures is an important issue on the path to the realization of IFE. For dry walls, 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 to measure the response of a variety of prototypical IFE materials samples to irradiation by (1) X-rays on the Z accelerator at SNL, and by (2) ions on the RHEPP/MAP ion facility at SNL is supported by the HAPL program to study candidate dry-wall materials for laser IFE [03Set]. The same type of tests will now be supported by the Z-Pinch IFE program to investigate the response of thick-liquid walls. Z produces up to 2 MJ, and fluences up to 3000 J/cm^2, of short-pulsed X-rays at ~ 1 keV in an environment that permits a variety of experiments at power-plant level X-ray fluences today. RHEPP/MAP produces ion fluences up to 10 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 can be performed as "add-on experiments" with existing Z-shots, and the experiments can 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 can use actual chamber materials (including the binary salt Flibe), so that the equation of state and chemical kinetics do not introduce experimental distortions. These experiments can be used to validate models for X-ray impulse loading for z-pinch IFE, heavy-ion IFE, and Magnetized Target Fusion. *Indirect-drive* IFE targets also release 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. *Indirect-drive* IFE targets release most of their energy in neutrons. For thick-liquid wall chambers for z-pinch IFE and heavy ion IFE, the neutrons will isochorically heat the coolant thick-liquid, and the first wall is essentially protected from neutron damage effects. While the neutron effects should be continually assessed, it is generally conceded that no new neutron test facilities will be required.

Direct-drive targets, currently expected to be used for laser fusion, will release 1…2 % of their yield directly in X-rays, with additional X-ray generation potentially occurring due to the interaction of target debris with chamber gas. IFE dry-wall materials are already being tested on Z. *Direct-drive targets* can release 15…16 % of their energy in debris ions and 13…14 % in burn-product ions [03Set]. Ion ablation and material blow-off experiments are being performed on the RHEPP/MAPP ion facility, and the effects of ablation and surface roughening are being studied. *Direct-drive* targets also release most of their energy in neutrons. For dry-wall IFE, the first-wall neutron damage problem remains to be solved, just as for MFE, and this will require new neutron test facilities.

A summary of the materials that can be tested both with X-rays from Z, and with ions from RHEPP/MAP, is given in Table 9.4. These materials have been selected from 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 (e.g., Flibe foam). In Table 9.4, a large X denotes a mainline approach, and a small x denotes a possible approach. For z-pinch IFE, most of the chamber (≈ 99 %) is protected by the thick-liquid walls. However, in the RTL region (representing ≈ 1 % of the chamber surface area), there is considerable room for innovation. One possibility is to have this region be a dry wall at a very large radius, and that is why a small x occurs in Table 9.4 under dry walls for z-pinch IFE.

Table 9.4. IFE materials for testing for X-rays and ions. A large X denotes a mainline approach, and a small x denotes a possible approach.

Material	IFE power plant type	KrF	DPSSL	HIF	Z-Pinch
Graphite	Dry wall	X	X	x	x
Tungsten	Dry wall	X	X	x	x
Tungsten/Rhenium	Dry wall	X	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

Present testing of IFE materials on Z and RHEPP has been to evaluate dry-wall materials for the HAPL laser IFE program [03Set]. The goal is to choose materials that will essentially show *no* growing damage effects. At high fluences, material ablation will occur; at lower fluences, materials appear to roughen; at sufficiently low fluences, there should be no net effect. These regimes of material responses to X-rays and ions are summarized in Fig. 9.31. Examples of materials tests of tungsten on Z are shown in Fig. 9.32 [04Tan], which shows the onset of roughening and ablation. Based on such testing, it has already been concluded that materials such as tungsten will survive the single-shot X-ray threat for laser dry-wall chambers for presently envisioned laser IFE parameters. The effects of the ion threat are more problematic, but progress is being made in solving this issue. The effects of long-time repetitive threats are still being assessed.

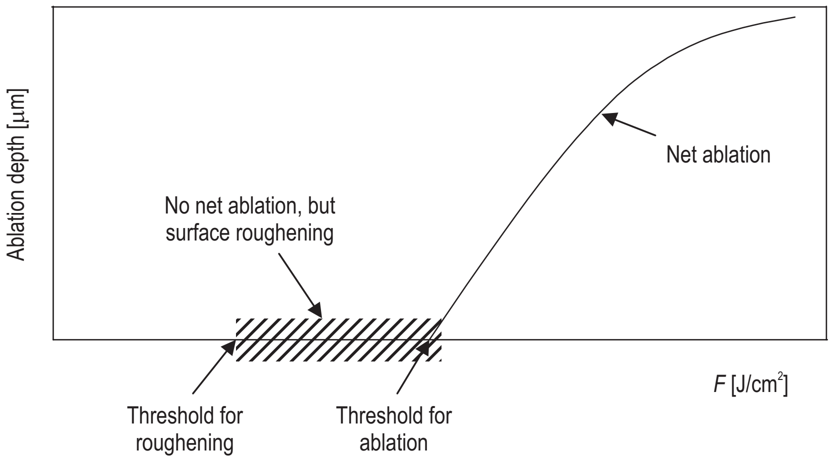

Fig. 9.31. Regimes of IFE materials response to X-rays and ions showing the ablation depth versus fluence, *F*.

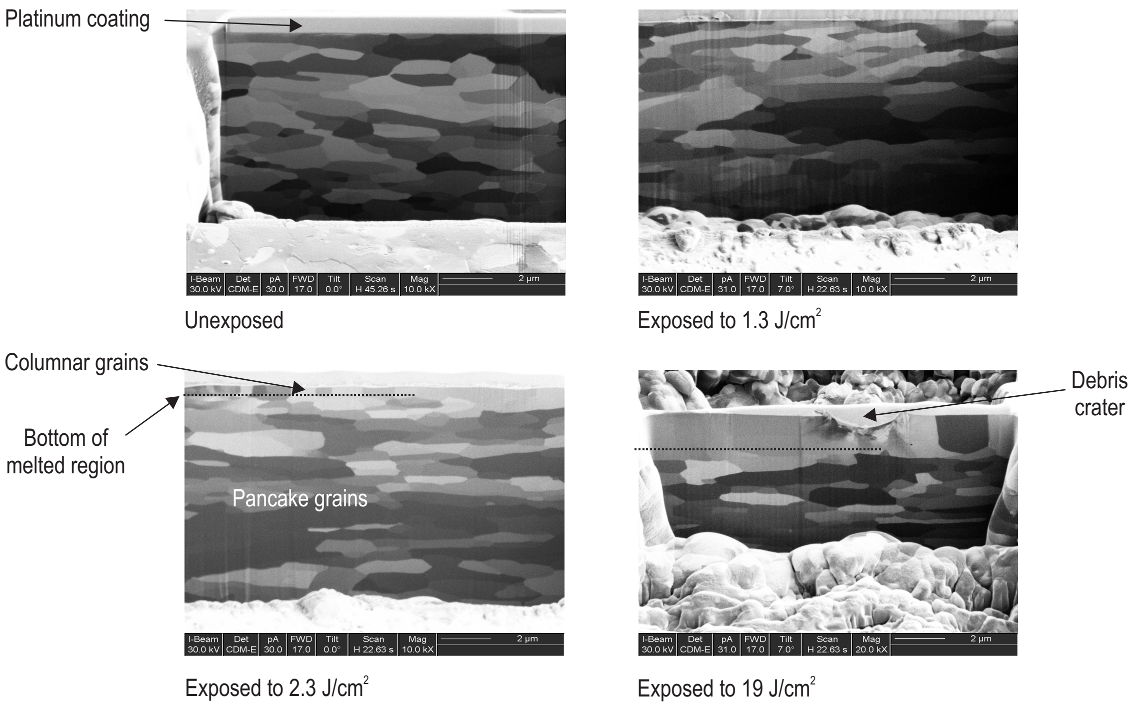

Fig. 9.32. Examples of tungsten response to X-rays on Z [04Tan].

9.7 Status and development plans for z-pinch IFE

A Road Map for the development of z-pinch IFE is given in Fig. 9.33 [02Ols]. This Map shows the development of single-shot *ICF* with the simultaneous and complementary development for repetitive-shot *IFE*. The five columns show progress in time from bottom to top, and the corresponding time line in calendar years is shown along the left side.

The first two columns show development of single-shot ICF, which refers to the science of demonstrating fusion capsule ignition and high yield on a single-shot basis. The development of the single-shot National Ignition Facility (NIF) is shown in the first column. NIF is a flashlamp-pumped glass laser facility designed to produce 1.8 MJ of laser light in the UV at 3 ω (0.3 micron light). When completed in the next several years, NIF will have 192 laser beams. Demonstration of indirect-drive ignition on NIF is scheduled to occur in 2013. This demonstration of indirect-drive ignition will be of utmost importance to both the z-pinch and heavy ion approaches to IFE, and the target physics learned will be invaluable to all approaches to IFE.

The development of z-pinch ICF, complementing NIF, is shown in the second column. The Z machine has been fully operational for several years, and nominally produces a current of 18 MA which yields up to 1.8 MJ in soft X-rays. A refurbished Z, named ZR for Z-Refurbishment, is under development and will be operational in 2006. ZR will produce a current of 26 MA, which will yield above 3 MJ of X-rays. During the same time period, a petawatt laser capability is being developed that will be used for investigating the fast ignition (FI) option for z-pinches. In the time frame of 2008…2010, the US DOE is expected to make a decision on the next large ICF facility it will construct. The desired facility for the z-pinch approach would be a high-yield (HY) facility at about the 60 MA level, that would rapidly show z-pinch driven capsule ignition, and then go on to demonstrate high yield with z-pinch driven capsules with yields up to ≈ 500 MJ (0.5 GJ). This z-pinch high-yield facility would be designed with three important features to allow it to be extended at a later time into an Engineering Test Facility (ETF) for IFE. The first feature is that the pulsed power would be designed so that it is easily converted to repetitive operation (this should be relatively easy with LTD technology). The second feature is that RTLs would be used to enable a higher shot rate, at a lower cost per shot. The third feature is that the containment chamber would be built so that is it easily convertible to a repetitive ETF chamber. For example, the chamber radius would be appropriately large, and a single-shot coolant waterfall (or foam Flibe) could be devised to help contain the single-shot high-yield capsule target output. Later, during the conversion to an ETF for IFE, the full coolant flow loops would be added. In this manner, the actual demonstration of single-shot z-pinch ignition and single-shot z-pinch driven high yield would occur first and be optimized on the HY facility. Then, knowing that the high-yield targets are fully operational, the HY facility would be upgraded to a full ETF with repetitive pulsed power and full coolant flow loops and additional equipment as needed for full-scale ETF operation.

The development of z-pinch IFE is shown in columns three to five. The names given to the steps of z-pinch IFE development in the third column are based on the stages of development suggested by the US DOE Fusion Energy Sciences Advisory Committee (FESAC). These stages are Concept Exploration (CE), Proof-of-Principle (PoP), Integrated Research Experiment (IRE), Engineering Test Facility (ETF), and DEMO (Demonstration power plant). Z-pinch IFE is presently at the CE stage, and has been supported by internal laboratory funds. Z-pinch IFE is ready for the PoP stage, which is planned to begin in 2004. Brief discussions of the PoP, IRE, ETF, and Demo stages follow after a brief discussion of the z-pinch driver machines needed for these stages of development.

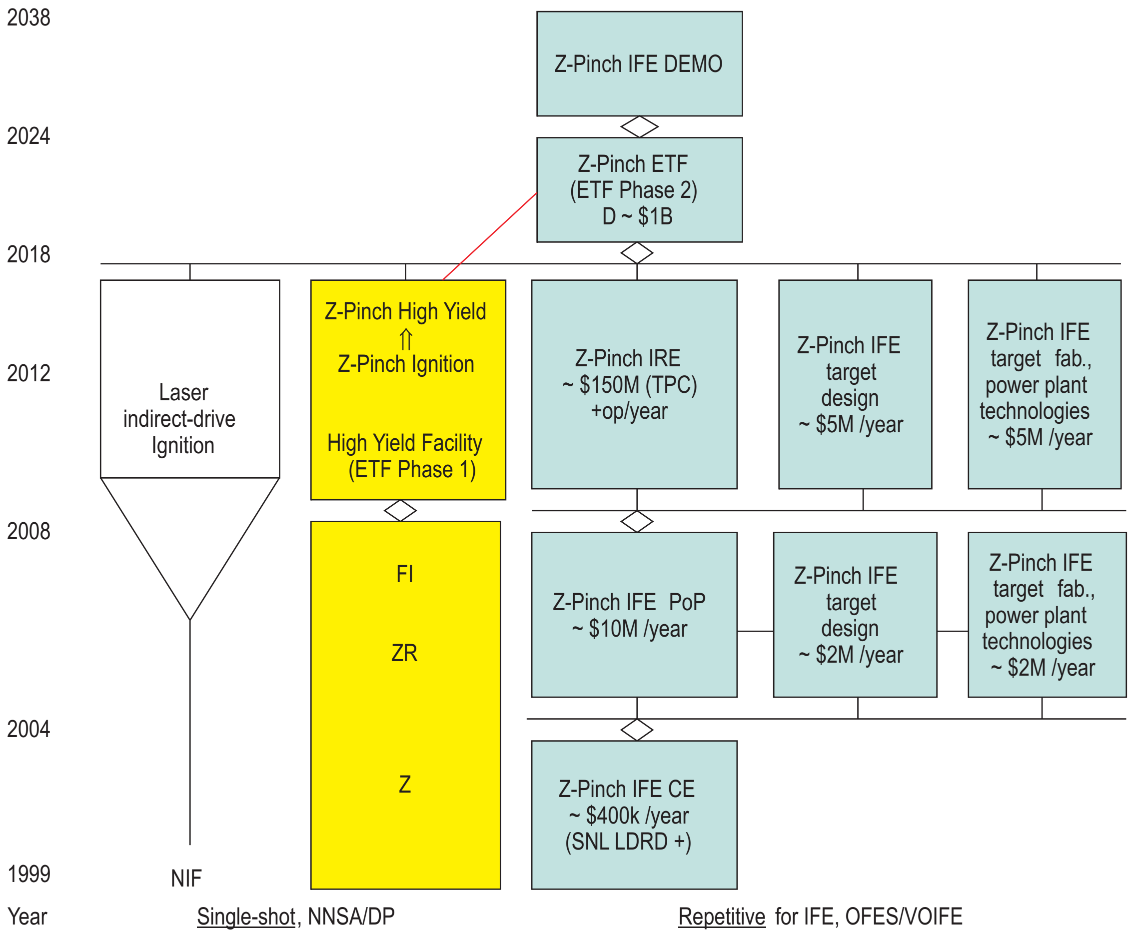

Fig. 9.33. Road Map for the development of z-pinch IFE.

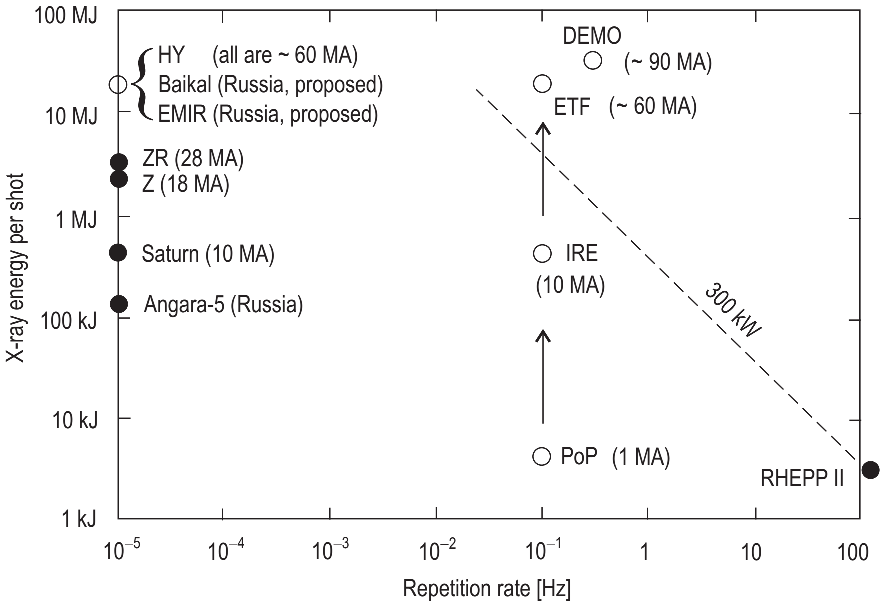

Fig. 9.34. Z-pinch drivers needed for the z-pinch IFE development path.

The z-pinch driver machines needed for the z-pinch IFE development path are shown in Fig. 9.34 [02Ols]. *For ICF*, the single-shot z-pinch machines needed are intended to be developed up to a high-yield driver at about 60 MA. Note that the HY facility, as well as Baikal and EMIR (two facilities proposed in Russia), would all be at the 50…60 MA level. *For IFE*, a series of three steps appears to be a reasonable approach for understanding repetitive operation and developing the necessary engineering technology for fusion energy. The three steps chosen are a 1 MA repetitive driver for the PoP level, a 10 MA driver for the IRE level, and a 60 MA driver for the ETF level. The final Demo driver will be a driver at about 90 MA. Fig. 9.34 is a plot of total X-ray energy per shot versus repetition rate (Hz). Single shot, or "one shot per day", corresponds to a repetition rate of 1×10^{-5} Hz. For z-pinch IFE, a repetition rate of about 0.1 Hz (10 s between shots) is envisioned for the development path for PoP, IRE, and ETF. For comparison, the RHEPP II demonstrated power level of 300 kW (2.5 kJ at 120 Hz) is shown as a dashed line.

The PoP phase consists of a set of four experiments, together with IFE target development and IFE power plant technology development. The four experimental areas are: (1) RTL experiments, (2) repetitive pulsed power driver experiment, (3) shock-mitigation scaled experiments , and (4) full RTL cycle at 0.1 Hz experiment. The *RTL experiments* would address RTL issues (RTL shape, inductance, mass, electrical characteristics, structural characteristics, manufacturing, cost, etc.), power flow issues (power flow limits, optimal power flow configuration, need and location of a convolute if used, etc.), and chamber/interface issues (vacuum/electrical connections, shrapnel/EMP up the RTL, debris removal, shielding, etc.). The culminating RTL experiment is to demonstrate an RTL on an actual shot on Z. The *repetitive pulsed power driver experiment* would first validate that the LTD approach is the preferred approach (by comparing MARX/water line technology, RHEPP magnetic switching technology, and LTD technology). Assuming the LTD is the preferred approach, a small, repetitive LTD driver (1 MA, 1 MV, 100 ns pulse, 0.1 Hz rep-rate) would be designed, constructed, and tested. LTD technology is modular, scalable, and easily rep-ratable. The *shock-mitigation scaled experiments* would address the effects of the large yields (≈ 3 GJ) that would be used with z-pinch IFE, as compared with the smaller yields (≈ 0.4…0.7 GJ) used in laser IFE and heavy ion IFE. However, for z-pinch IFE, coolant streams, or solid/voids, can be placed as close to the target as desired. Scaled shock experiments, using explosives and water hydraulic flows, would be used. The experimental results would be compared with code results to validate code capabilities for modeling the effects of full-scale driver yields. The *full RTL cycle* experiments would combine the above results and create a fully integrated experiment at the 1 MA level.

This would include the LTD driver, RTLs, and z-pinch loads, with the full system operating at 0.1 Hz for a designated amount of time. This would demonstrate RTL/z-pinch insertion, vacuum/electrical connections/firing of the z-pinch, removal of the remnant, and repeat of cycle. For this PoP level, the z-pinches would produce about 5 kJ of X-rays on each shot at 0.1 Hz. In addition to the four PoP experiments, PoP research and development would include z-pinch driven targets for IFE (theory, simulations, experiments on Z), and z-pinch power plant technology (chambers, coolant flow loops, target fabrication, RTL automation, waste stream analysis, cost of electricity, etc.).

The remaining development phases would increase the scale to higher power levels. *For the IRE*, repetitive operation would be demonstrated at the 10 MA level (comparable to the present Saturn machine at 10 MA, but repetitive). The IRE experiments would include a repetitive LTD driver (10 MA, 2 MV, 100 ns, 0.1 Hz) and full-cycle RTL experiments at 0.1 H, with z-pinch loads producing 0.5 MJ of X-rays on each pulse. Advanced engineering studies of RTL insertion techniques, vacuum/electrical connections, average power effects, and reliability/reproducibility would be performed. *For the ETF*, the z-pinch HY facility (nominally 60 MA with yields of 0.5 GJ) would be converted to a repetitive ETF, operating at 0.1 Hz for limited time periods, complete with coolant flow loops, and capabilities for some electricity generation. Note that the HY and ETF are really one large facility in two steps that span 16 years on the z-pinch IFE Road Map. Knowledge gained in the ETF phase could lead to decisions regarding the early phases of a Demo project as early as 2024.

Rough costs estimates for development of z-pinch IFE have been made [02Gol, 02Ols, 03Goo]. The PoP phase should cost about $14 M/year for 3…5 years, with $5 M to start the first year. The IRE nominal total project costs should be about $150 M. The ETF project cost to convert the HY facility to IFE operation should be about $1 B. (The HY facility itself should cost of the order of $1.2 B). Overall cost estimates for development up to the ETF have an integrated cost over 14 years of $0.44 B. The total estimated cost of the entire z-pinch IFE development plan through the ETF and Demo for an integrated 30-year time period is $5.7 B. All of these costs are in US FY 2003 dollars. By U.S. Congressional Initiative, $4 M for FY04 is being used to assess and begin development of z-pinch IFE.

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