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FUSION WITH Z-PINCHES

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In the past thirty-six months, great progress has been made in x-ray production using high-current z-pinches. Today, the x-ray energy and power output of the Z accelerator (formerly PBFA-II) is the largest available in the laboratory. These z-pinch x-ray sources have the potential to drive high-yield ICF reactions at affordable cost if several challenging technical problems can be overcome. In this paper, the recent technical progress with Z-pinches will be described, and a technical strategy for achieving high-yield ICF with z-pinches will be presented.

A z-pinch is a plasma configuration in which a high current is passed through some conducting matter arrayed in a cylinder. The current, which runs axially through the plasma in the "z" direction, creates a strong azimuthal magnetic field which "pinches" the plasma assembly, accelerating it radially inward. If the current is pulsed, and if it is sufficiently strong, the plasma acceleration will be large. When the plasma finally stagnates, either upon itself, or upon a central mass, the kinetic energy is converted to thermal energy, and a burst of x-rays is produced. Until 1995, the largest x-ray power available from a z-pinch was 20 TW, on the Saturn accelerator at Sandia National Laboratories. Because the duration of the pulse was approximately 20 ns, the x-ray output was about 400 kJ.

A series of experiments conducted by Tom Sanford, Chris Deeney, Rick Spielman, and their colleagues¹⁻³, increased the record x-ray output power to 80 TW in 1996 by improving the symmetry of the z-pinch implosion. The improved symmetry, achieved by increasing the number of fine wires used to carry the current, resulted in a decreased

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pulse width at implosion stagnation, and consequently, an increased power for the same total x-ray energy. This progress on Saturn, as well as the succeeding progress made in generation of high x-ray powers using high-current z-pinchs is shown in Figure 1, which displays the level of z-pinch x-ray power output as a function of year.

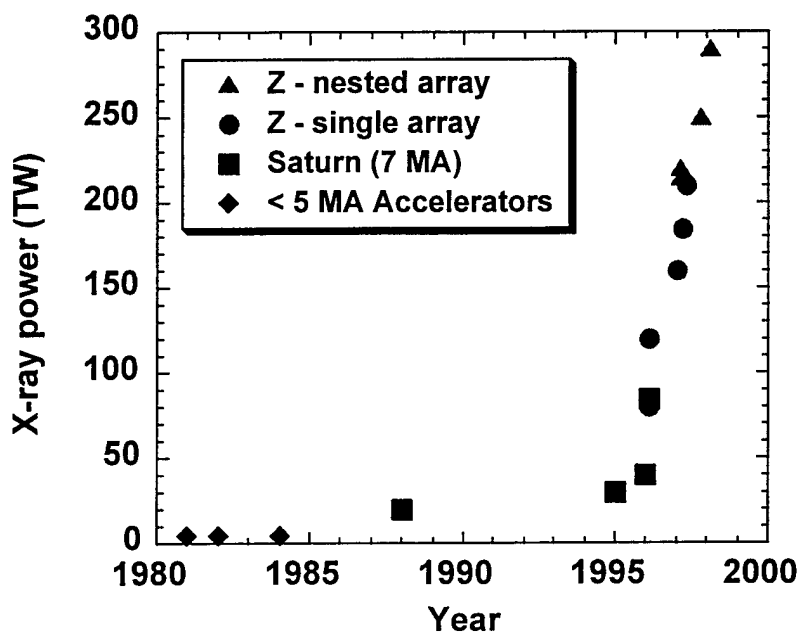


Figure 1: X-ray output power produced by z-pinchs as a function of year.

At the end of 1996, when the experiments were moved from the 7-10 MA level of Saturn to the 17-20 MA level of the Z accelerator⁴, the x-ray power was increased to a level exceeding 160 TW, and a total x-ray energy level of 1.8 MJ. We expected that the x-ray energy would quadruple from the Saturn accelerator to the Z accelerator, scaling as the square of the current, and this has been confirmed. We refer to this dependence as “pressure” scaling since the hydrodynamic pressure is quadratic with magnetic field, or current. In addition, we expected that the x-ray power would be doubled from Saturn to Z, rather than quadrupled, since the Z accelerator uses a 100 ns current waveform to drive the z-pinch, while Saturn uses a 50 ns current waveform, and the temporal compression ratio (or power gain) from the z-pinch was held constant, determined by the symmetry of

the implosion. It is a remarkable result that the overall efficiency of the Z accelerator, from energy stored in capacitors (11.4 MJ) to x-ray energy out (1.8 MJ) exceeds 15%. Based upon the recent results, we believe that it is possible to conceive of a z-pinch x-ray source driving a high-yield ICF reaction.

The basic requirements for high yield come from multi-dimensional target calculations. With an x-ray energy greater than 10 MJ, x-ray power greater than 1000 TW, temperature greater than 250 eV, and radiation asymmetry smaller than a few percent, calculations give yields in the range of 200-1000 MJ. The X-1 accelerator facility, which is being explored at the pre-conceptual level now, will be designed to produce 16 MJ and 1000 TW of x-rays, and a temperature of 300 eV. Radiation symmetry can be provided in at least two ways: the first has a z-pinch x-ray source on each end of a cylindrical hohlraum, much like existing heavy-ion-driven ICF target designs. The second approach places a capsule inside a density-tailored foam at the interior of a cylindrical, or quasi-spherical z-pinch.

With the large values of x-ray energy and power achieved on the Z accelerator in 1996 and 1997, the next technical step to be taken was that of increasing the hohlraum temperature. By designing a hohlraum with small spatial gaps (3 mm) for allowing the current inside to power the z-pinch, and by suitable choice of materials on the inside of the hohlraum, the temperature was pushed from 70 to 100 eV. Experiments by Spielman, Deeney, and colleagues⁵ in 1997 showed that the same electrical energy which could be coupled to a 2-cm-tall z-pinch could also be coupled to a 1-cm-tall z-pinch. This achievement made possible further reductions in hohlraum wall area at comparable z-pinch power, and the hohlraum temperature was increased to 130 eV. By reducing the vacuum power flow gap even further, to 1.5 mm, the temperature was increased to 140 eV. In late 1997, experiments by Rick Spielman, Chris Deeney, and Melissa Douglas, showed that multiple ("nested") cylindrical arrays of fine wires could push the x-ray

power even higher, up to 280 TW. The largest power achieved with a single array of wires was about 200 TW. The increased power made possible with the nested wire arrays is believed to result from improved stabilization of the hydromagnetic Rayleigh-Taylor instability, the instability of principal concern in z-pinch. The increased stability is thought to be a result of mass accumulation at the collision of the outer wire array with the inner one. Two-dimensional simulations of nested wire arrays by Douglas⁶ which showed this effect were the principal motivation for undertaking the experiments. In Figure 2, a nested wire array is shown along side a single wire array for comparison.

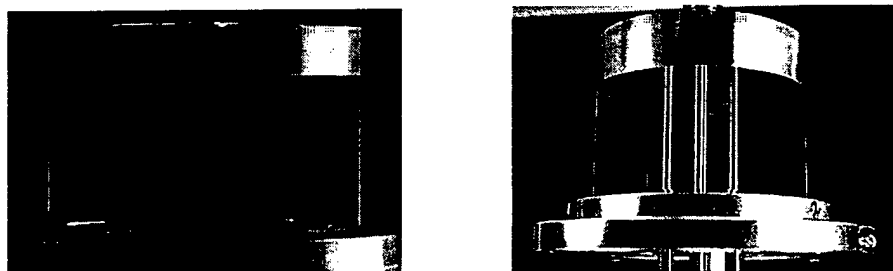


Figure 2. A single (left side) and nested (right side) z-pinch wire array.

Inclusion of the higher power produced by a nested wire array in a 23-mm-diameter vacuum hohlraum, with power flow gaps of 1.5 mm, and a z-pinch with a total height of 0.75 cm, has now produced a hohlraum temperature of 155 eV⁷.

In principle, it is possible to increase the hohlraum temperature by reducing the wall area of the hohlraum even further. One method of accomplishing this puts a cylindrical hohlraum inside the z-pinch wire array. When the rapidly imploding wire plasmas, which have merged into a cylinder, strike the hohlraum, the interior of the hohlraum is filled with radiation. Experiments using these "dynamic" hohlraums, have produced temperatures in excess of 155 eV⁸. The presently achieved temperature of 155 eV is very interesting, since it scales to a value of 270 eV on X-1⁹, an accelerator proposed to extend the results of high-current z-pinch implosions up to the level capable of driving an ICF

capsule to high yield (high fusion output energy). Since the radiative power in the hohlraum will scale as the fourth power of temperature (σT^4) and the z-pinch power will scale as the square of the driving current (I^2), then the temperature should scale as the square root of the driving current. At a current of 60 MA on X-1, a value which is three times the current of the Z-accelerator, the temperature multiplier is 1.73. If a temperature of 175 eV can be achieved on the Z accelerator, then the scaled temperature on X-1 would increase to over 300 eV.

The technical issues involved in achieving small radiation asymmetry and a desirable radiation pulse shape for driving an ICF capsule are primarily related to hydrodynamic instability of the z-pinch, and the stagnation physics. Figure 3 shows three approaches to the target configuration for high yield. In the first (3a), two z-pinches stagnate on axis, providing x-rays on either end of a hohlraum containing a capsule. In the second approach (3b), the z-pinches strike a central cylinder which is filled with a low-Z gas or foam, producing a high-temperature temporally shaped source of x-rays to drive the capsule. In the third approach (3c), a single z-pinch strikes a cylinder containing the capsule. In going from left to right in Figure 3, the temperature increases as the wall area which must be heated by the z-pinches is reduced, but the hydrodynamic risk also increases. Experiments on the Z accelerator over the next 1-2 years will determine the optimum configuration which can be achieved in the laboratory.

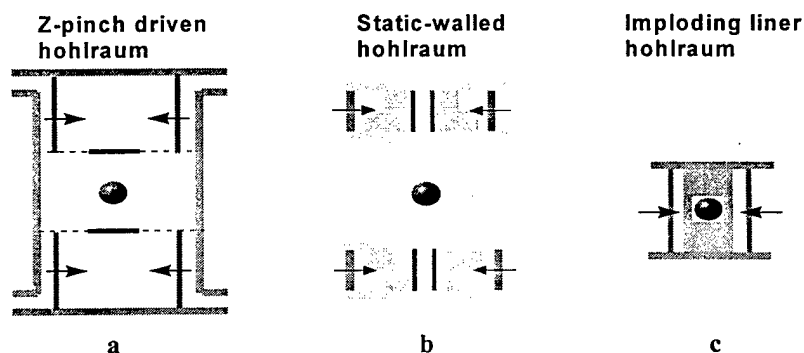


Figure 3. Three approaches to driving a high-yield ICF target using a z-pinch.

CONCLUSIONS

The very rapid development of powerful sources of x-ray energy and power using high-current z-pinchs on the Saturn and Z accelerators at Sandia in the last three years has opened up the possibility of achieving high fusion yield from an ICF capsule driven by an accelerator with three times the current of that available on the Z accelerator. The X-1 accelerator is intended to operate at 60 MA, and produce a fusion output energy exceeding 200 MJ somewhere around 2007. In the next 2-3 years, critically important experiments will be conducted on the Z accelerator to determine achievable levels of x-ray pulse shaping and x-ray symmetry in various target hohlraum configurations. If successful, results from these experiments will provide a design basis for X-1, which will constitute a major step on the path to fusion power.

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