Z, ZX, and X-1: A REALISTIC PATH TO HIGH FUSION YIELD*

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Abstract

Z-pinchs now constitute the most energetic and powerful sources of x-rays available by a large margin. The Z accelerator at Sandia National Laboratories has produced 1.8 MJ of x-ray energy, 280 TW of power, and hohlraum temperatures of 200 eV. These advances are being applied to inertial confinement fusion (ICF) experiments on Z. The requirements for high fusion yield are exemplified in the target to be driven by the X-1 accelerator. X-1 will drive two z-pinchs, each producing 7 MJ of x-ray energy and about 1000 TW of x-ray power. Together, these radiation sources will heat a hohlraum containing the 4-mm diameter ICF capsule to a temperature exceeding 225 eV for about 10 ns, with the pulse shape required to drive the capsule to high fusion yield, in the range of 200 – 1000 MJ. Since X-1 consists of two identical accelerators, it is possible to mitigate the technical risk of high yield by constructing one accelerator. This accelerator, ZX, will bridge the gap from Z to X-1 by driving an integrated target experiment with a very efficient energy source. ZX will also provide experimental confirmation that the full specifications of the X-1 accelerator for high yield are achievable, and that a realistic path to high fusion yield exists.

I. INTRODUCTION

In a high current z-pinch, an axially directed current produces a strong magnetic force, resulting in very large inwardly directed plasma acceleration. 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. The general configuration of a z-pinch is shown in Figure 1.

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Figure 1. Z-Pinch configuration: stages of implosion and energy transfer

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Until 1995, the largest x-ray power available from a z-pinch was 20 TW, a level produced 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 in large part by increasing the number of fine wires used to carry the current, while keeping the total mass of the wire array constant, resulted in a decreased pulse width at implosion stagnation, and consequently, an increased power for the same total x-ray energy. During 1996, a modification to the PBFA II accelerator was made by a team led by Rick Spielman to enable the accelerator (now called Z) to drive up to 20 MA into a z-pinch⁴.

II. SCALING OF Z-PINCH X-RAY OUTPUT

The Z accelerator at Sandia National Laboratories now produces an x-ray output energy of 1.8 MJ and an x-ray output power of 280 TW. Optimization of z-pinch behavior on the Z accelerator and three prior generations of accelerators (Saturn at 10 MA, Proto II at 5 MA, and SuperMite at 1.5 MA) has shown that the x-ray energy output from high-current z-pinchs scales quadratically with z-pinch current. This scaling, shown in Figure 2, is in agreement with simple zero-dimensional analytic theory. For fixed output pulse width, the x-ray power also scales quadratically with current. When the z-pinch is used to drive a hohlraum, the hohlraum radiation (σT^4) is proportional to the z-pinch source radiation (I^2), and the hohlraum temperature is proportional to the square root of the z-pinch current. These basic relationships, demonstrated conclusively on the Z accelerator, indicate that a single accelerator (X-1) with about three times the current of Z (or about 60 MA), or two accelerators (ZX), each having about twice the current of Z (or about 40 MA), should be sufficient to drive a fusion capsule to high fusion yield.

Figure 2. Scaling dependence of x-ray energy with z-pinch current

It is a remarkable result that the energy conversion efficiency, from electrical energy stored in the Marx generator to x-ray energy produced in a short pulse by a fast z-pinch, exceeds 15% on the Z accelerator. This energy compression in time is shown in Figure 3. The implications of this result are that sufficient x-ray energy can be produced at modest cost in X-1 to drive an ICF capsule to high yield.

Figure 3. Efficient compression of energy in the Z accelerator

III. REQUIREMENTS FOR FUSION

The basic requirements for high fusion yield come from multi-dimensional target calculations. With an x-ray energy greater than 10 MJ, x-ray power greater than 1000 TW, hohlraum temperature greater than 225 eV, radiation asymmetry smaller than 1-2%, and a temporal pressure profile at the capsule ablation surface appropriate for nearly isentropic compression of cryogenic fusion fuel, calculations give yields in the range of 200 - 1200 MJ. The X-1 accelerator facility, which is being explored at the pre-conceptual level now, is being designed to produce an energy level of 16 MJ of x-rays, a peak power level of 1000 TW of x-rays, and a hohlraum 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. This approach, termed the Z-Pinch Driven Hohlraum⁵ is shown in Figure 4. The second approach, termed the Dynamic Hohlraum, places a capsule inside a density-tailored foam at the interior of a cylindrical, or quasi-spherical z-pinch, as shown in Figure 5. In each case, the magnitude of the hohlraum temperature, the spatial symmetry of the radiation, and the temporal shaped of the radiation pulse must be carefully controlled.

Figure 4. Z-Pinch Driven Hohlraum

Figure5. ICF capsule inside a dynamic hohlraum

IV. STATUS OF PROGRESS AGAINST TECHNICAL MILESTONES

As a means of benchmarking progress in understanding of z-pinch behavior prior to committing to construction of the larger X-1 accelerator required for future experiments, four difficult technical milestones were established for performance on the Z accelerator at the 20 MA level. These included the following, all of which have been exceeded:

Pulsed power milestones	Milestone value	Achieved value	Date achieved
X-ray energy	1.5 MJ	1.9 MJ	Nov. 1996, 1.6 MJ Mar. 1997, 1.8 MJ Sep. 1998, 1.9 MJ
X-ray power	150 TW	280 TW	Nov. 1996, 150 TW Mar. 1997, 190 TW Jan. 1998, 280 TW
Hohlraum temperature for driving weapons physics experiments	100 eV	230 eV	Apr. 1997, 100 eV Oct. 1997, 140 eV Apr. 1998, 150 eV Aug. 1998, 230 eV
Hohlraum temperature for driving capsule compression	150 eV	180 eV	Sep. 1997, 140 eV Mar. 1998, 155 eV Aug. 1998, 180 eV

IV. PROJECTIONS

The temperature achieved to date on the Z accelerator in these two configurations ranges from 150-180 eV in a volume sufficient to contain a 1mm-diameter capsule. These temperatures are very interesting, since they scale to a value of 250-300 eV on X-1, higher than the value of 225 eV required for high fusion yield. The principal questions remaining to be answered, then, are (1) can adequate radiation symmetry be achieved in one or more of the hohlraum configurations, and (2) can a radiation pulse shape adequate for keeping the fusion fuel on a low adiabat be achieved? It appears that these questions could be answered on an accelerator with current intermediate between Z and X-1 (thus termed ZX) with a driving current of 40-50 MA. Coincidentally, this is also the level of current required for one side of the system shown in Figure 4 for a high-yield configuration. As a result, construction of a ZX accelerator offers a unique combination of results – the capability to conduct an integrated target experiment with the required pulse shape and the required radiation symmetry to demonstrate conclusively that the target risk is acceptably low to proceed with construction of a driver for high yield, and also an experimental demonstration that the driver for high yield on X-1 can perform satisfactorily at full scale. The extension from ZX to X-1 then becomes a replication of the driver at ZX scale (not a daunting task), and development and construction of a target chamber to contain the explosive yield and activation of a high fusion yield at the level of 200 – 1000 MJ (definitely a daunting task).

V. CONCLUSION

The breakthroughs in Z-pinch x-ray output made since 1994, the continuing high rate of technical advances, and the strategy to constrain and manage technical risk through the series of increasingly powerful z-pinch drivers from Z to ZX to X-1 provide a realistic path to High Fusion Yield.

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VII. REFERENCES

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