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NEW DEVELOPMENTS AND APPLICATIONS OF INTENSE PULSED RADIATION SOURCES AT SANDIA NATIONAL LABORATORIES*

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ABSTRACT

In the past thirty-six months, tremendous strides have been made in x-ray production using high-current z-pinches. Today, the x-ray energy (1.9 MJ) and power (200 TW) output of the Z accelerator (formerly PBFA-II) is the largest available in the laboratory. These z-pinch x-ray sources are being developed for research into the physics of high energy density plasmas of interest in weapon behavior and in inertial confinement fusion. Beyond the Z accelerator current of 20 MA, an extrapolation to the X-1 accelerator level of 60 MA may have the potential to drive high-yield ICF reactions at affordable cost if several challenging technical problems can be overcome. New developments have also taken place at Sandia in the area of high current, mm-diameter electron beams for advanced hydrodynamic radiography. On SABRE, x-ray spot diameters were less than 2 mm, with a dose of 100R at 1 meter in a 40 ns pulse.

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.

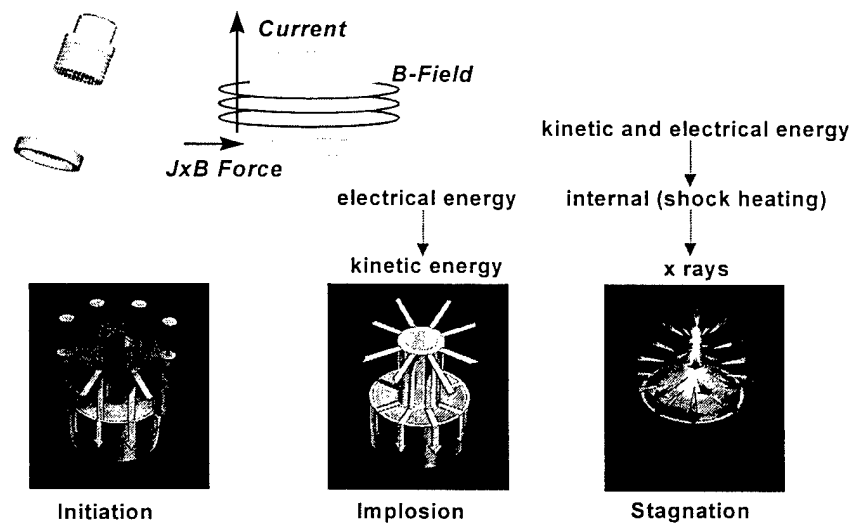


Figure 1. Z-Pinch configuration: stages of implosion and energy transfer

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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.

RECENT DEVELOPMENTS IN Z-PINCH X-RAY OUTPUT

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. The central region of Z, which consists of conically shaped magnetically insulated transmission lines leading to a double post-hole convolute near the wire array, is shown in Figure 2.

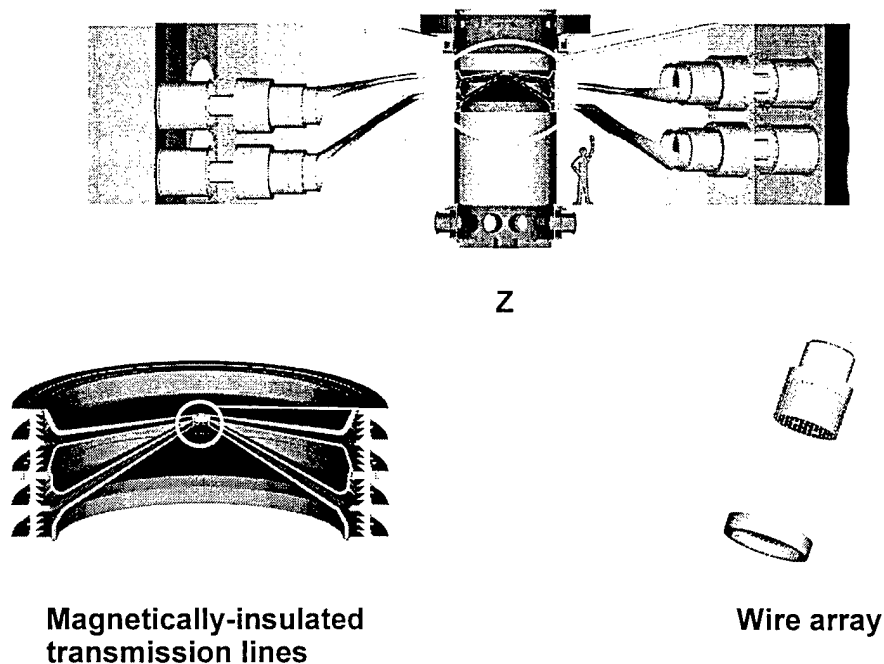


Figure 2. Central region of the Z accelerator

Near 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 accelerator, the x-ray power was increased to a level exceeding 160 TW, and a total x-ray energy level of 1.9 MJ. By May 1996, in experiments which reduced the height of the z-pinch from 2 cm to 1 cm, the x-ray power

achieved on the Z accelerator had increased to 200 TW. This dramatic increase of x-ray power on Saturn and Z is shown in Figure 3, which depicts x-ray power obtained as a function of year.

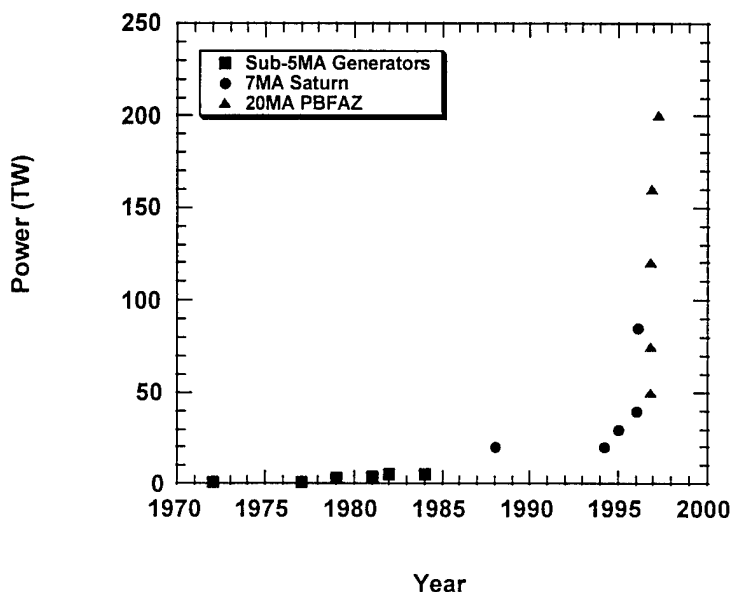


Figure 3. X-ray power generated by z-pinches as a function of year

We had anticipated 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. This dependence is referred to as “pressure” scaling since the hydrodynamic pressure is quadratic with magnetic field, or current. This scaling dependence of x-ray energy with z-pinch current is shown in Figure 4. We also anticipated that the power would be doubled from Saturn to Z, rather than quadrupled, for fixed temporal compression ratio (or power gain) from the z-pinch, since the Z accelerator uses a 100 ns current waveform to drive the z-pinch, while Saturn uses a 50 ns current waveform. Because the symmetry of the implosion has been improved from Saturn to Z, the power increase has more than doubled. 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 (1.9 MJ) exceeds 15%. This efficient compression of energy in the accelerator is depicted in Figure 5. Based upon the recent results, we now believe that it may be possible for a z-pinch x-ray source to drive a high-yield ICF reaction.

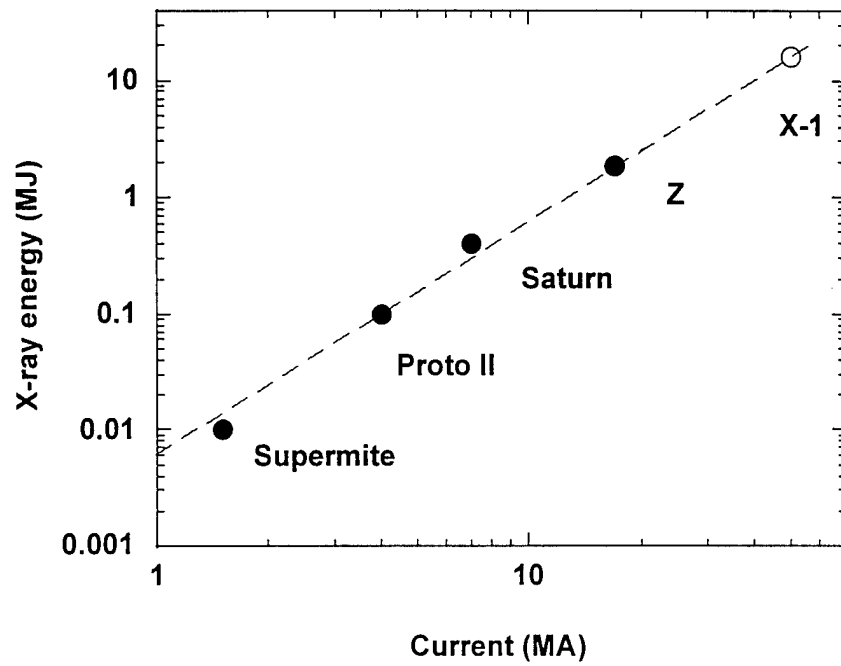


Figure 4. Scaling dependence of x-ray energy with z-pinch current

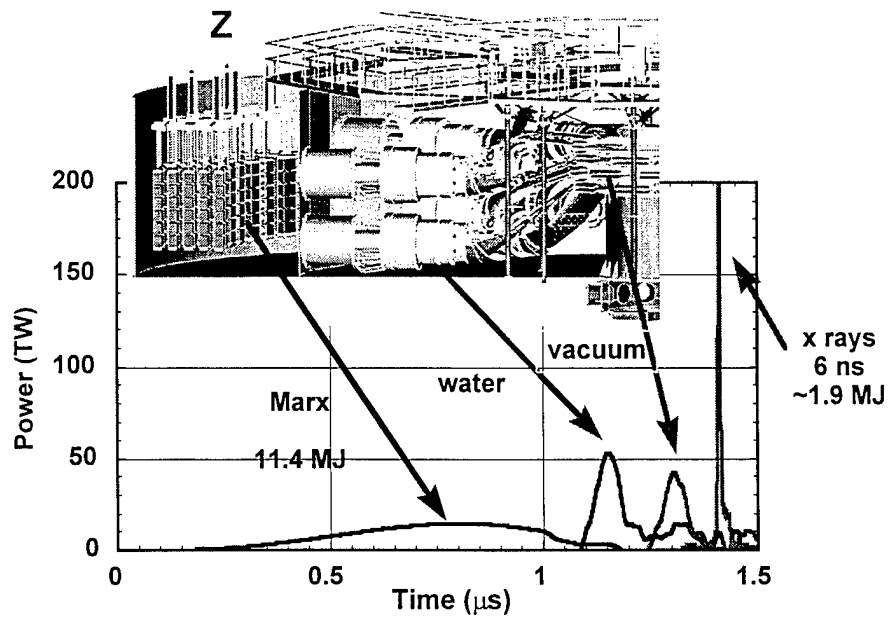


Figure 5. Efficient compression of energy in the Z accelerator

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, temperature greater than 250 eV, and radiation asymmetry smaller than a few percent, such 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, 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. The second approach places a capsule inside a density-tailored foam at the interior of a cylindrical, or quasi-spherical z-pinch. This latter approach is depicted in Figure 6.

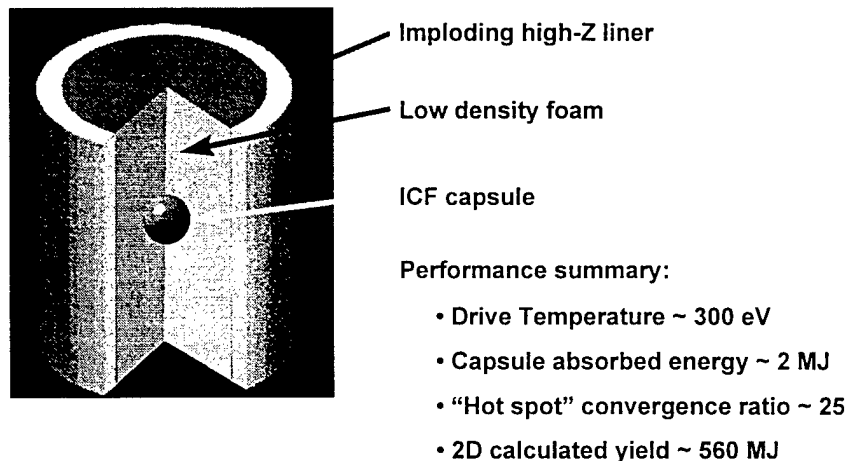


Figure 6. ICF capsule inside a dynamic hohlraum

NEED FOR HIGHER HOHLRAUM TEMPERATURES

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 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 up to 100 eV by a team led by John

Porter. By further reductions in hohlraum wall area made possible by reducing the height of the z-pinch, and further reductions in the vacuum power flow gaps, the temperature was pushed above 130 eV, its present value. Experiments are being planned with "dynamic" hohlraums, in which the hohlraum itself is imploded during the pulse to increase the temperature further, but there is substantial risk of hydrodynamic instabilities in this approach. Even the presently achieved temperature of 130 eV is very interesting, since it scales to a value of 225 eV on X-1. Since the radiative power should scale as the fourth power of temperature and as the square of current, then the temperature should scale as the square root of the driving current. At a current of 60 MA on X-1, three times the current of the Z-accelerator, the temperature multiplier is 1.73. If a temperature of 170 eV can be achieved on the Z accelerator, then the scaled temperature on X-1 would increase to 300 eV. This scaling dependence is shown in Figure 7.

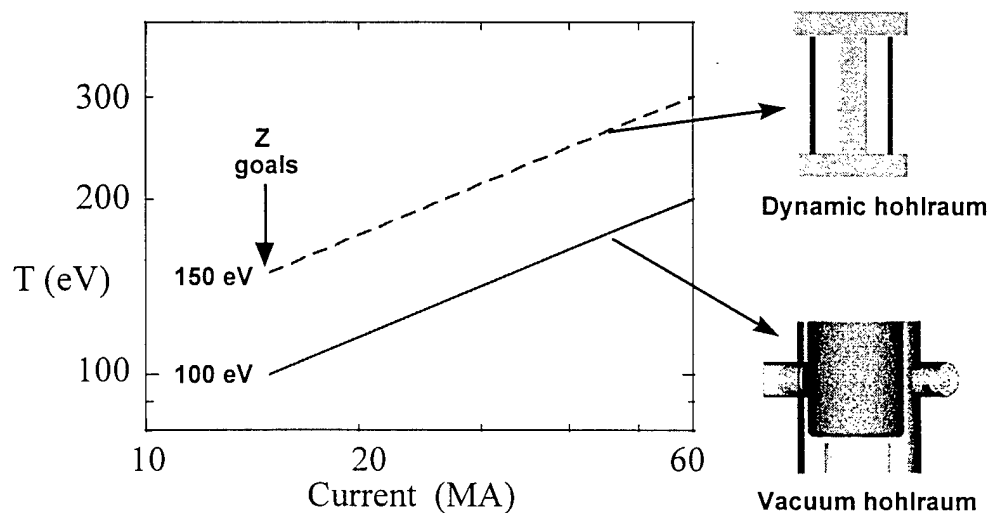


Figure 7. Scaling of hohlraum temperature as a function of z-pinch current

The technical issues involved in achieving small radiation asymmetry and a desirable radiation pulse shape are primarily related to hydrodynamic instability of the z-pinch, and the stagnation physics. Although there are several promising concepts, their evaluation will probably be paced by development of a three-dimensional MHD code with 3D multi-group radiation transport. The level of diagnostic sophistication needed to measure asymmetry and pulse shape with precision is also very demanding, and rapid progress in such diagnostics is being made on the Z-accelerator, with major contributions from LLNL and LANL.

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:

Milestones

X-ray energy: 1.5 MJ
X-ray power: 150 TW
Vacuum hohlraum temperature: 100 eV
Dynamic hohlraum temperature: 150 eV.

The presently demonstrated performance has exceeded the first three of these milestones. The dynamic hohlraum experiments will be done in late 1997 and early 1998.

Achievements

X-ray energy: 1.9 MJ
X-ray power: 200 TW
Vacuum hohlraum temperature: 130 eV
Dynamic hohlraum temperature: -----

Upon achievement of the fourth, and last, of these milestones, Sandia plans to make a formal request to the Department of Energy to approve the beginning of conceptual design of the X-1 accelerator.

ADVANCED HYDRODYNAMIC RADIOGRAPHY

Another new development and application of intense pulsed radiation sources involves the use of high current electron beams for radiography. By placing the 10-stage inductive voltage adder on the SABRE accelerator, shown in Figure 8, in negative polarity, a high current electron beam can be accelerated and extracted to a target region, where deposition in a high-Z material will produce bremsstrahlung x-rays for flash radiography. Because high current electron beams are susceptible to a number of instabilities, a strong pulsed solenoidal magnetic field is used to constrain the electron radial oscillations. The electron beam is produced at the end of a long vacuum magnetically insulated transmission line. The magnetic field, which has ranged from 20 T to 30 T in the experiments, has been able to constrain the electron beam spot size at the anode to a full-width-at-half-maximum intensity of 1.6 mm.⁵ The time-integrated x-ray spot achieved on SABRE is shown in Figure 9. This particular image is a high-brightness 2 mm FWHM x-ray spot on a graphite target.

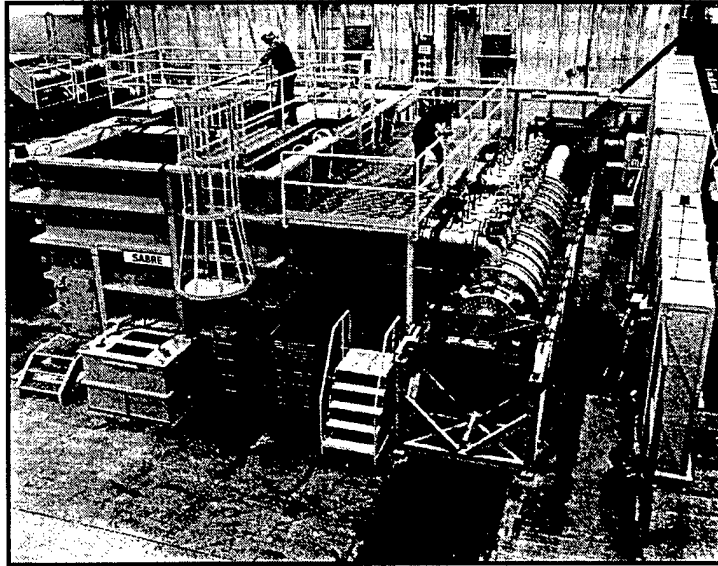


Figure 8. The SABRE accelerator in use as a radiographic test bed at Sandia

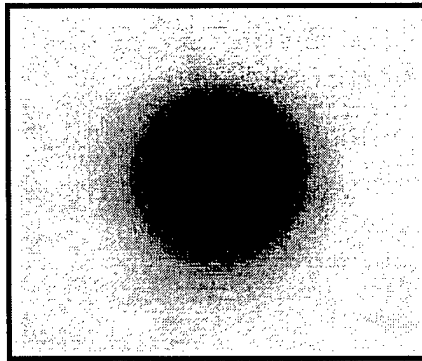


Figure 9. A high-brightness 2mm x-ray spot from a graphite target on SABRE

Initial difficulties with electron diode impedance collapse truncated the voltage pulse width, and reduced the x-ray dose available for radiography. Improvements to the vacuum system, diode cleaning, reduction of accelerator prepulse, and redesign of the beam absorber in the x-ray target resolved the problems, and a dose of 100 R at 1 meter was obtained. The power density of electron beams focused for radiographic applications can be exceed 20 TW/cm^2 . A stainless steel target with a 1 cm deep ablation crater from a single experiment on SABRE is shown in Figure 10.

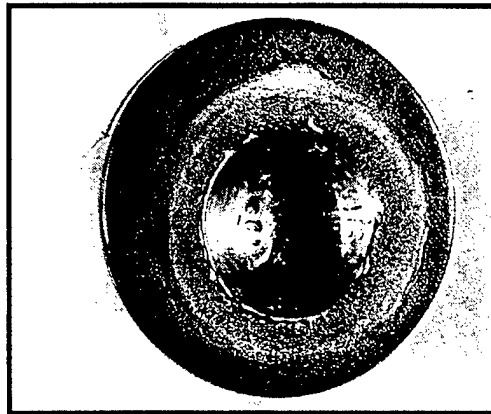


Figure 10. A 1 cm deep ablation crater in a stainless steel radiography target

Following the radiography “proof-of-principle” experiment on SABRE, the experiment was extended to the Hermes III accelerator⁶. The solenoidal magnetic field was increased to 50 T with a smaller bore. A photograph of one of the solenoidal magnetic field coils used on SABRE is shown in Figure 11.

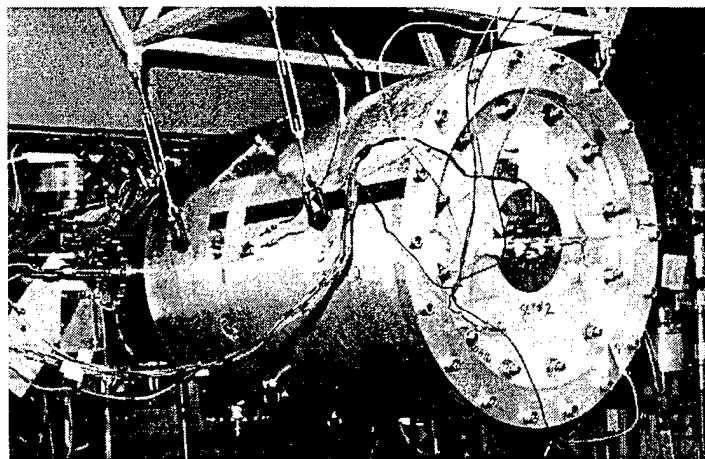


Figure 11. Immersed-field diode used in radiography experiments

INCREASING SOPHISTICATION OF INTENSE PULSED RADIATION SOURCES

Twenty years ago, pulsed-power-based radiation sources were developing rapidly in the level of energy output as accelerators around the US were being constructed for radiation effects experiments. Today, pulsed radiation sources are again developing rapidly, but with a level of required sophistication in experiment preparation, operational control, and diagnostic complexity which demands rather extraordinary subsystem performance and integration. The scientific understanding of pulsed power systems developed over two decades has enabled this to occur. Now, it is the demand for greater energy, power, temperature, and other output characteristics which is pushing this even further. Figure 12 shows a representative example of the kinds of elements which go into a typical experiment today. In order to conduct a shock physics experiment in the megabar range on the Z accelerator, and get data useful for improving computational models of the experiment, one must use multidimensional radiation-MHD codes. To actually acquire the data, one needs an extensive array of diagnostics with capability to precisely resolve the spatial, temporal, and spectral characteristics of the phenomena. Typically, the target fabrication must be precise as well, or the fabrication quality itself will limit the usefulness of the data. This complexity places a large requirement on integration of pulsed power technology, operations, target design, diagnostics, and materials technologies.

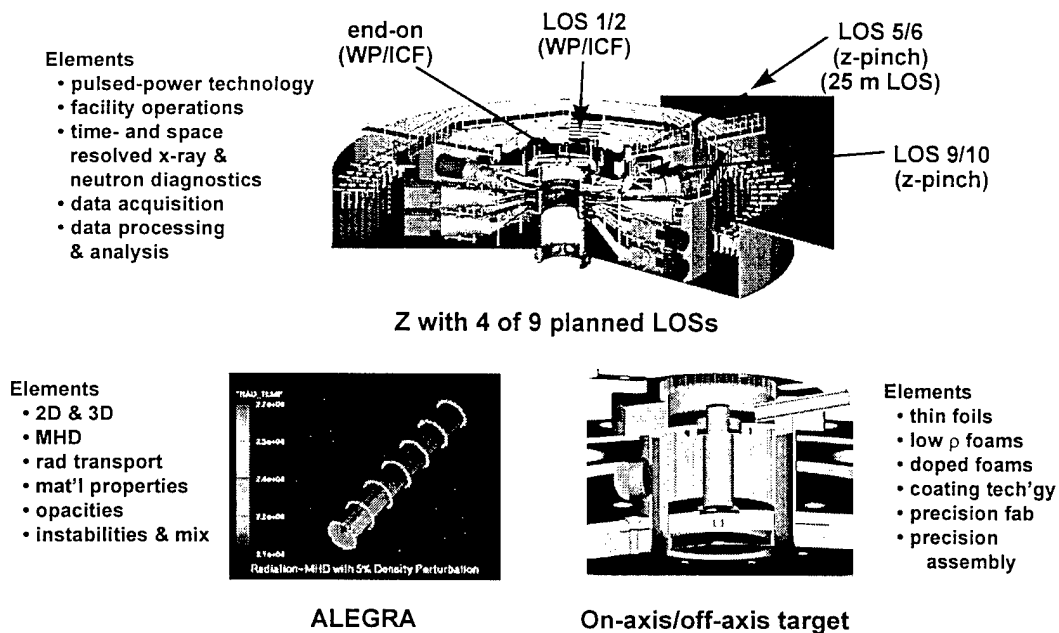


Figure 12. Complexity of precision experiments with modern radiation sources

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A partial bibliography of recent work at Sandia National Laboratories is included below as an aid to the reader.

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