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Intense Electron Beams for Radiography

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Abstract - High intensity pulsed electron beams generate bright bremsstrahlung x-ray sources for flash radiographic interrogation of dynamic experiments. Typical industrial sources operate between 10 and 200 GW/cm^2 intensities, while experimental requirements can demand 10 to 100 TW/cm^2. Recent studies of Pulsed Power-driven high intensity electron beam systems have significantly increased these operating regimes, demonstrating 10-20 TW/cm^2, and computations predict successful extrapolation to 100 TW/cm^2. Detailed studies of electron beam configurations, both theoretical and experimental, will be presented, and the prognosis for each to increase to the required levels will be discussed.

1. Introduction

Pulsed power driven flash radiography, where high intensity pulsed electron beams are stopped in a high-atomic-number bremsstrahlung converter anode, has been used for decades to interrogate the interior mass distributions of dynamic experiments. The utility of the approach is limited by the x-ray source intensity, the radiographic contrast, and the detector resolution and efficiency, all of which must be optimized together to maximize the radiographic information content for a specific experimental geometry and observable. This paper discusses recent studies to investigate and improve the radiographic source brightness using a variety of electron beam approaches.

Figure 1 depicts a typical point-projection radiographic configuration. A small, bright source of x-rays is generated by an electron beam focused onto a bremsstrahlung-converter, producing a dose

$$\frac{\text{rads}}{\text{Coulomb}} = 1290 V^{2.8} \exp\left[-\frac{(V+0.5)\beta_\perp}{0.67\pi}\right]$$

where V is the applied voltage in megavolts and $\beta_\perp$ is the electron beam relativistic velocity component transverse to the radiographic axis.

The x-rays expand as a cone through the object, attenuated by $\int \exp(-\mu x)dx$, and are recorded on a detector plane. The radiographic information metric has been extensively discussed by Watson [1] and includes electron kinetic energy, which determines penetration power and contrast; dose

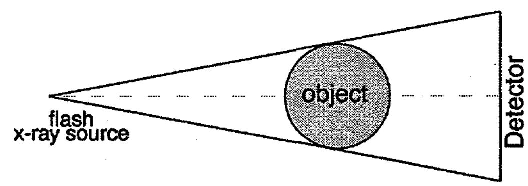

Figure 1. Radiographic point-projection geometry

which, with detector sensitivity and dynamic range defines measurement statistics; and spot size, detector blur and pulse duration which determine spatial resolution through a dynamic object. There are a wide variety of dynamic radiographic objects that require a suite of radiographic source and detection capabilities, as no single radiographic system can be optimized for all experiments. Typically experimenters desire a smaller source spot, more dose at the voltage which optimizes radiographic contrast, and multiple pulses to record a dynamic evolution in a compact, inexpensive, reliable system which can be easily reconfigured to address varied applications, all close coupled to a severe explosion environment. This paper addresses only the fundamental physics and engineering issues of generating a high brightness pulsed power-driven electron beam for radiographic applications. The next sections discuss different electron beam diode approaches, leading to a description of a proposed flash radiographic source which should operate at unprecedented 100 TW/cm^2 intensities.

2. Industrial radiographic x-ray source

Industrial radiographic sources are typically positive polarity conical anodes which are irradiated

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by an annular electron beam drawn from a surrounding grounded cathode ring (Figure 2). The

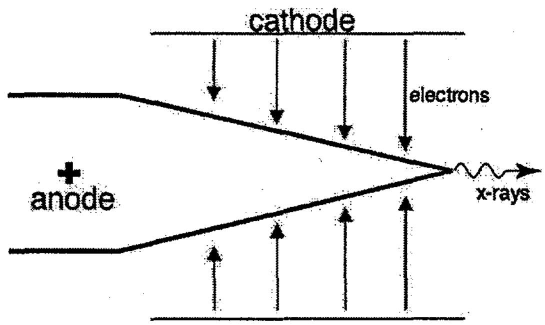

Figure 2. Industrial Radiographic diode

electrons spread across the anode surface producing a diffuse bremsstrahlung x-ray source. The maximum (non-relativistic) electron current is [2]

$$I_{SCL}\,(kA) = 14.7\,(L/k^2R_a)\,V^{3/2}$$

(where L is the cathode emission length, R_a is the anode radius, and k is a geometric term), corresponding to a few kiloamperes. The low intensity nature of this geometry produces minimal anode damage, allowing multiple shot operation without maintenance. It is simple and easy to operate, can be adequately designed using electrostatic orbits. These industrial diodes typically operate from 1 to 300 GW/cm^2.

3. Pinched Beam x-ray source

A significant increase in electron beam intensity can be obtained by operating above the critical current

$$I_{crit}\,(kA) = 8.5\,(\gamma^2 - 1)^{1/2}\,(R_c/d)$$

where R_c is the cathode radius and d is an axial vacuum gap spacing (Figure 3). The current

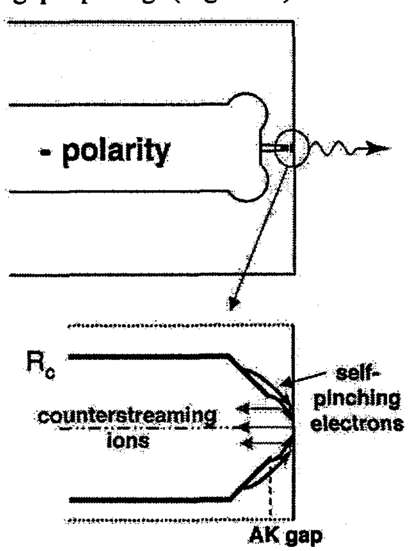

Figure 3. Pinched Beam x-ray source

produces a strong azimuthal magnetic field behind the electron flow. Near the planar conducting boundary this azimuthal field bends the electrons inward. Formation of a counter-streaming ion flow further neutralizes the electron space charge, enabling a high intensity focus [3].

In negative polarity, electrons sweep onto an axial focal spot and emit x-rays in the forward direction, with typically a 30° mean incidence angle. As with all high power diodes, the intent is to operate at very high electron beam intensities to create extremely bright radiographic sources. The deposited energy per gram of the anode converter therefore exceeds melt and often vaporization thresholds, limiting these sources to single shot operation between maintenance. The small vacuum gap makes pinched beam diodes sensitive to prepulse, and the requirement for counter streaming ions limits the impedance lifetime as the anode plasma evolves during the pulse. The sweeping electron beam produces a radiographic halo during the pinch phase, and the core typically wanders, making post-diode x-ray collimation difficult. These diodes can reasonably couple 35 kA onto about a 2-mm diameter focal spot, operating at about 1 TW/cm^2 intensities.

4. Paraxial Diode x-ray source

A more robust high focal intensity alternative can be accomplished by launching a large area electron beam, such that the energy deposition on the anode is insufficient to form a plasma, through a thin foil and compressing the electron beam in a gas transport cell before irradiating the bremsstrahlung converter (Figure 4). Gas ionization occurs within

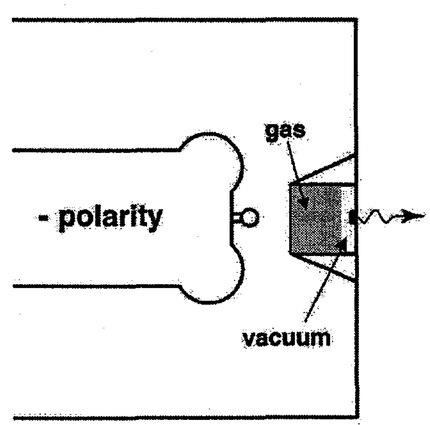

Figure 4. Paraxial x-ray source

a few nanoseconds and fractionally neutralizes the electron beam space charge. Depending on the plasma magnetic decay time, the electron beam either slowly sweeps through a focus at the converter or rapidly collapses into fixed Betatron oscillations (Figure 5).

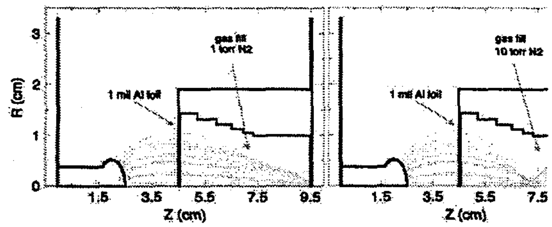

Figure 5. Paraxial diode orbits
left: Ballistic, right: Betatron

The larger vacuum gap and lower initial beam intensity result in a more stable impedance history compared to the pinched beam diode, though this system is also sensitive to prepulse (foil turn-on) and pulse risetime (gas breakdown). Radiation produced while the beam is pinching similarly produces a radiographic halo and spot wander precludes tight collimation. These paraxial diodes are very reliable radiographic sources which operate from 5 to 10 MV, coupling 35 kA into foil scattering limited spot diameters of at least 3-mm at about 1 TW/cm^2 [4].

5. Magnetically Immersed x-ray source

In contrast to the large-source area paraxial approach, the magnetically immersed diode utilizes a very small cathode emitter and augments the self-magnetic field with a solenoidal applied magnetic field to contain the electron orbits to a tight spot (Figure 6). This diode is designed to operate on

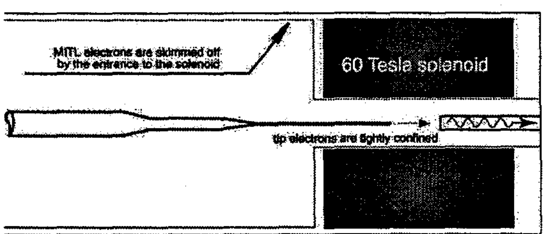

Figure 6 Magnetically Immersed x-ray source

either a vacuum-insulated transmission line drive (where the cathode electric field is below field emission) or on a magnetically insulated vacuum transmission line [5] where the load self-magnetic field insulates the power flow upstream. In this case a fraction of the total current is transported as free electrons **ExB** drifting along the transmission line. The magnetically immersed diode strips these higher temperature sheath electrons and draws a cold, small diameter radiographic source electron beam from the cathode tip within the solenoid.

$$I_{beam} = \frac{17\ \text{kA}\left[\left(1+\frac{V}{511\ \text{kV}}\right)\right]}{\left(1-\frac{Zn_i}{n_e}\right)\left(1+2\ln\left(R_w/r_b\right)\right)}$$

The magnetically immersed diode has demonstrated mm-diameter radiographic spots from 3 to 9 MV, operating at 10 to 20 TW/cm^2, hence promptly producing energetic anode plasmas which drive an ion hose instability. This instability saturates when the beam offset equals the electron gyro-radius, and the spot size can be expressed as

$$\text{spot} = 1.3\sqrt{\text{offset}^2 + \text{needle}^2}$$

$$\text{offset} = \sqrt{\frac{2\gamma I}{17\ \text{kA}}}\ \frac{0.17\ \text{Tesla}}{B_z}\ \text{cm}$$

Experiments [6] have shown this diode is capable of providing either a benign ion hose instability limited spot size described above or in a deleterious enhanced instability mode, where the spot grows abruptly to many times the analytic prediction. Numerical simulations indicate that this enhanced mode is caused by multi-species ions orbiting into the beam from both the walls and axially from the bremsstrahlung target (Figure 7), which may be

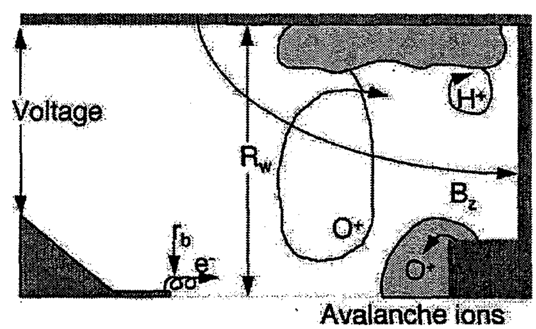

Figure 7 Physics issues in the magnetically insulated diode.

controlled by surface preparation, adequate magnetic insulation of the wall ions, and magnetic mirroring of target ions.

6. Rod Pinch x-ray source

The final radiographic diode we will discuss is the Rod Pinch [7], Figure 8. This diode combines the

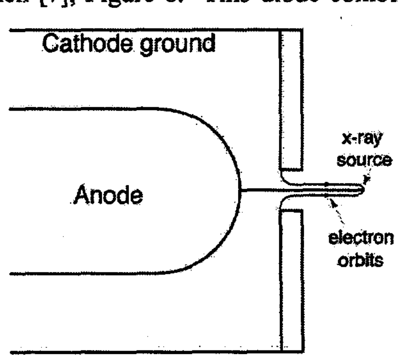

Figure 8 Rod Pinch x-ray source

geometry of the industrial source with self-field pinched beam focusing, operating above critical current in positive polarity.

$$I \sim 2 * I_{crit} = 17 (\gamma^2 - 1)^{1/2} / \ln(R_c/R_a) \text{ kA}$$

Preliminary Particle in Cell (PIC) simulations suggested this diode could rapidly transition from Langmuir-Blodgett radial flow (industrial case above) into magnetic pinching, and then stably operate with electrons impinging only the tip of the rod which extends through the cathode. Experiments around 2 MV with a 0.5 to 2-mm diameter anode rod support this prediction with electron beam intensities from 10 to 20 TW/cm^2. Radiation measurements suggest the electron beam strikes the rod radially, producing less dose in the desired forward cone than the other x-ray sources discussed above. As the most recent configuration studied, there remain many unanswered physics questions such as the limits of reliable operation in spot size, diode voltage and impedance.

The spot size is governed by the rod diameter, so prediction of performance and alignment of the radiographic axis is straightforward. Experimental investigations [8] show this diode to be insensitive to pre-pulse, pulse shape, or misalignment, operating reliably in modest vacuums (<50 mPa) with a falling diode impedance which appears to scale with plasma closure velocities in the above equation. The high electric fields and electron beam intensities should promptly produce diode plasmas, consistent with the observed behavior. As the rod diameter decreases or the diode voltage increases, the electron range becomes greater than the converter thickness, leading to electrons which re-enter the diode to reflex. Their passage through the rod converts kinetic energy into bremsstrahlung and the orbits scatter, which should lead to a significant modification of the electron phase space. This physics has recently been been modeled

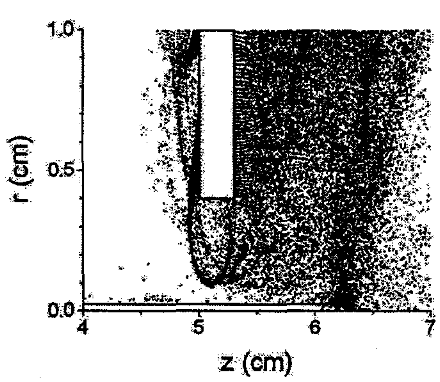

Figure 9. Hybrid Particle in Cell/Monte Carlo simulation of the Rod Pinch diode

(Figure 9) by treating PIC electrons which enter the rod with Monte Carlo techniques, then re-initializing the slowed and scattered electrons (and secondaries) as they exit the rod back into the PIC simulation. These simulations show the anticipated electron phase space modification and suggest the Rod Pinch diode should provide a reliable, high intensity radiographic x-ray source at 2 to 3 MV from 20 to 40 ohms. Experiments are underway to verify this performance and to study three dimensional and scaling limits.

5. Radiographic source summary

The radiographic diodes discussed above can be summarized in terms of their electron beam intensity as a function of operating voltage, as shown in Figure 10. Shown here are industrial radiographic sources from a variety of manufacturers, all operating below 300 GW/cm^2 and typically below 2 MV. The Pinched Beam and Paraxial diodes developed at AWE in the United Kingdom operate at about 1 TW/cm^2 on a wide variety of drivers from 1 to 10 MV. The Magnetically Immersed and Rod Pinch diodes have been shown to operate from 10 to 20 TW/cm^2 from 1 to 9 MV (Magnetic) and around 2 MV (Rod).

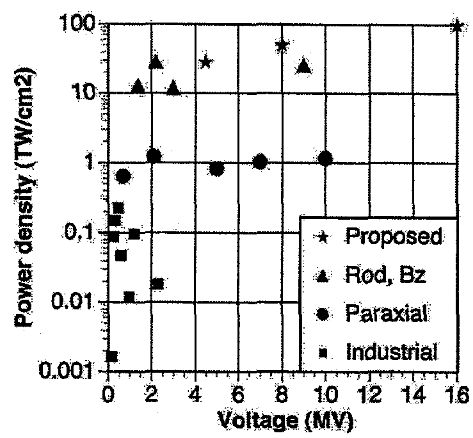

Figure 10 Radiographic diode comparison

6. Next generation radiographic drivers and sources

Our program goal is to develop pulsed power-driven advanced radiographic technologies. We are assembling the first module of an Inductive Voltage Adder Radiographic Integrated Test Stand (RITS) accelerator which will provide a 4 MV, 24 ohm, 50-ns (full width at 90%) drive pulse into a magnetically insulated vacuum transmission line using three IVA cavities (Figure 11). This accelerator architecture will be continued to an 8-MV, then a 16-MV single or an 8-MV double pulse capability. Alternate pulsed power approaches will be pursued when applicable prototypes are demonstrated.

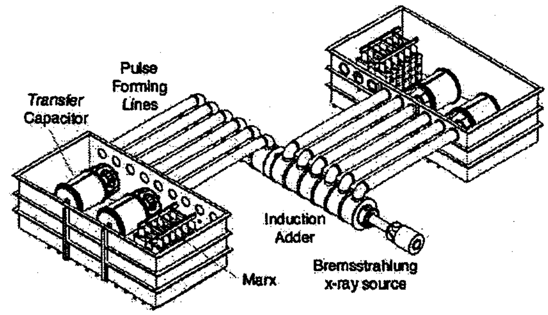

Figure 11. Radiographic Integrated Test Stand

The RITS accelerator family will enable studies of intense radiographic sources at a variety of voltages. Based on the experience to date, the rod pinch appears to be the simplest and highest brightness x-ray source for < 3MV voltages. At higher voltages, ion loss current and the increasingly transverse bremsstrahlung radiation cone from the Rod Pinch will reduce its utility and probably make the magnetically immersed diode the preferable radiographic x-ray source to scale to 100 TW/cm^2.

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