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Characterization of the Self Magnetic Pinch Diode at High Voltages for Flash Radiography

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Abstract

The Sandia Laboratories Advanced Radiographic Technologies Department., in collaboration with the United Kingdom Atomic Weapons Establishment , has been conducting research into the development of the Self-Magnetic-Pinched diode as an x-ray source suitable for flash radiographic experiments. We have demonstrated that this source is capable of meeting and exceeding the initial requirements of 250 rads (measured at one meter) with a 2.75 mm source spot-size [1]. Recent experiments conducted on the RITS-6 accelerator have demonstrated the ability of this diode to meet intermediate requirements with a sub 3 mm source spot size and a dose in excess of 400 rads at one meter..

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I. Introduction

In collaboration with members of the Atomic Weapons Establishment (AWE), the Advanced Radiographic Technologies Dept. 1645 is conducting research on the development of X-ray sources for flash radiography. The source development is conducted on the Radiographic Integrated Test Stand (RITS-6)[2,3].

RITS-6 is an Inductive Voltage Adder (IVA) accelerator developed at Sandia National Laboratories for driving high brightness flash x-ray radiographic sources. In its present configuration six induction cells are each driven by an 8Ω parallel water dielectric pulse forming line. The individual induction cells are joined in series by a vacuum coaxial Magnetically Insulated Transmission Line (MITL) which delivers power from the cells to a diode region, where the electron beam is created. The geometry of the accelerator and diode region is shown in Fig. 1a. RITS-6 is capable of delivering greater than 10-MV, 125-kA, 60-ns pulses to high impedance ($> 200\ \Omega$) electron beam diodes. Flexibility in the architecture via changes to the MITL operating point and or geometry also allows for the ability to deliver ~ 7.5 -MV, 180-kA, 60-ns pulses to lower impedance ($\sim 50\ \Omega$) diodes.

A field shaping “knob” is attached (Fig. 1b) at the end of the MITL, just upstream of the diode anode-cathode (A-K) gap. The knob serves to shed excess flow current from the MITL, controls the electric field profile in the region of the diode and shield accelerator components from debris generated by the diode. In the diode region, the electron beam is generated at the cathode, accelerated across the A-K gap and impinges the anode. The anode is usually a $1/3$ electron-range thick high atomic number (Z) target (e.g. Tantalum). Stopping of the e-beam in the anode/target generates bremsstrahlung radiation. The radiation is extracted in the forward direction and used for imaging dense material via point projection x-ray radiography.

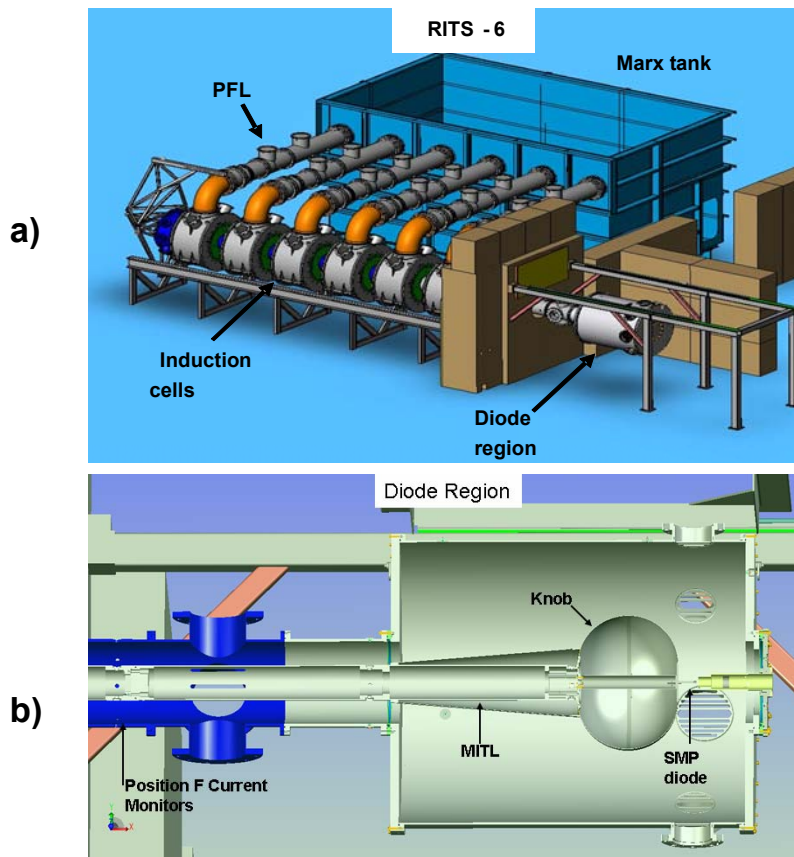


Figure 1. Illustration of a) the RITS-6 accelerator and b) a cutaway of the MITL and diode region.

Minimization of the radiographic spot size and maximization of the radiation dose is a long-range goal for development of electron beam driven X-ray radiographic sources. As part of a collaborative effort with the Atomic Weapons Establishment, Sandia National Labs is developing the Self-Magnetic-Pinched (SMP) diode [4] as a possible source to meet flash radiographic requirements. The SMP diode (Figure 2) consists of an anode and hollow cathode separated by a small A-K gap typically on the order of 1 cm. The anode is comprised of a thin Aluminum foil and a converter made of Ta. The foil and Ta converter are typically separated by a small vacuum gap. Electrons emitted from the cathode are accelerated across the A-K gap and impinge the anode within a diameter that is larger than the cathode diameter. As the current in the diode increases, the electrons heat the anode foil and eventually cause ions to emit from the anode surface (typically within $\sim 5\text{-}10$ ns after the beginning of electron emission). The ions are accelerated across the A-K gap and provide nearly complete charge neutralization of the electron beam. This results in both an increased diode current (due to enhanced space-charge limited emission of the electrons from the cathode and a contribution due to the ion current) and a pinching of the electron beam by the self-magnetic field generated in the diode. Because of the cylindrical

geometry, the magnetic field is expected to be azimuthally symmetric and can thus efficiently compress the beam by a factor of nearly 5 upon traversing the A-K gap. This results in e-beam diameters on target that are significantly smaller than the cathode diameter and of order 2-3 mm. The near term radiographic source requirements of 250 rads (measured at one meter) with a 2.75 mm source spot-size has been met previously with this diode fielded on RITS-6 [1] .

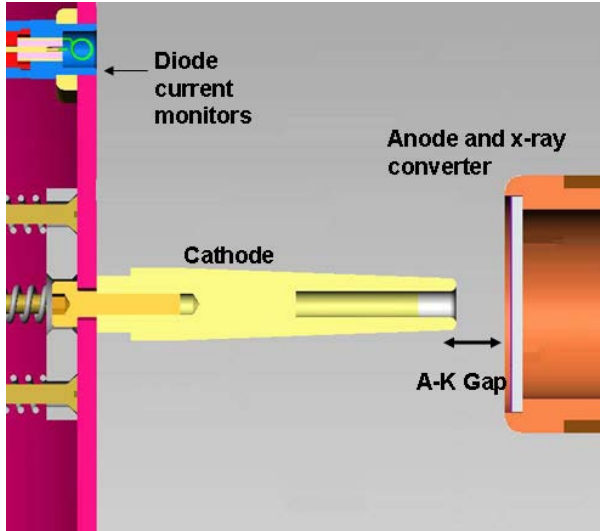


Figure 2. Illustration of the SMP diode

The results presented here demonstrate the potential of the SMP diode as a future high brightness source by meeting and exceeding the medium term radiographic requirements established by AWE. The experiments were conducted on RITS-6 configured with a low-impedance ($\sim 40 \Omega$) MITL and a charge voltage of 86 kV. This charge voltage stresses the induction cavities close to their design limit but the extra 10% increase in diode voltage allowed for a $\sim 33\%$ increase in radiation output. Geometric changes to the diode allowed for the increased radiation power output without sacrificing spot size.

II. Experimental Configuration

A. Low Impedance – High Charge Voltage Configuration for RITS-6

The nominal configuration for RITS-6 is a high impedance mode capable of delivering a 10-MV, 120-kA forward going wave to the diode region. In this mode, the induction cores are threaded by a MITL with a characteristic operating impedance of about 80Ω , which is optimal for driving high impedance ($\sim 200 \Omega$) diodes such as the Paraxial diode [5] and the Immersed-Bz diode [6]. On previous studies the SMP diode was characterized using RITS-6 in the high impedance configuration. In this and other related studies it was determined that the diode has characteristic impedance that begins around

60-50 Ω and falls to $\sim 30 \Omega$ during the pulse [1]. Because of this, the SMP diode is not well-matched to the high-impedance RITS-6 configuration.

Numerical studies of the operating characteristics of RITS [7,8] demonstrate the possibility of operating the accelerator in a low impedance mode by under-matching the MITL to the accelerator induction cells. For particular MITL geometries, this can be accomplished without significantly degrading the forward power to the diode region. This has been demonstrated experimentally [1] on the initial RITS-6 SMP study. For the experiments reported here we have threaded the RITS-6 cavities with a low-impedance (40- Ω) MITL and used an 86 keV charging voltage which provides a 70-ns full-width-half-maximum (FWHM), 200-kA, 8.0-MV forward going electrical pulse to the diode.

B. Electrical diagnostics

The accelerator and diode currents are measured with magnetic induction (B-dot) current monitors at the locations shown in Fig. 1b and 2. The inner (cathode) current, I_c , and outer (anode) currents, I_a , measured at Position F are averaged from 4 discreet B-dot monitors located at 90 degree increments in azimuth. The difference between I_a and I_c is the free electron sheath current flowing along the MITL. Based on the theory of Mendel [9], the MITL voltage can be calculated as a function of the anode and cathode currents:

$$V = Z_0 * (I_a^2 - I_c^2)^{1/2} - .511 * \left[\left(\frac{I_a}{I_c} \right) - 1 \right] * \left[\left[2 \left(\frac{I_a}{I_c} + 1 \right) \right]^{1/2} - 1 \right] \quad (1)$$

where V (MV) is the MITL voltage in MV, $Z_0=51.3 \Omega$ is the vacuum impedance of the MITL in Ohms, and I_a and I_c are expressed in MA. The diode currents are averaged from two B-dot monitors located at the radial position shown in Fig. 2 and separated azimuthally by 90 degrees. Representative accelerator currents at position F, the diode current and calculated voltage at F (based on Eq. 1) for a typical SMP diode shot are shown in Fig. 3. In the low-impedance configuration, the accelerator delivers a forward-going wave with a peak voltage of ~ 8.0 MV and a peak total (anode) current of ~ 200 kA with a pulse width of ~ 70 ns.

The measured diode current rises rapidly to ~ 100 kA and then continues to increase at fairly steady rate to a peak current of ~ 160 kA, suggesting a decreasing diode impedance. This is evidenced by a small current retrapping wave propagating up the stalk late in time and discernable by a slight increase in cathode current I_c from 60 kA to 80 kA, at the position F.. The retrapping wave is generated when the diode impedance falls below the characteristic operating impedance of the MITL.

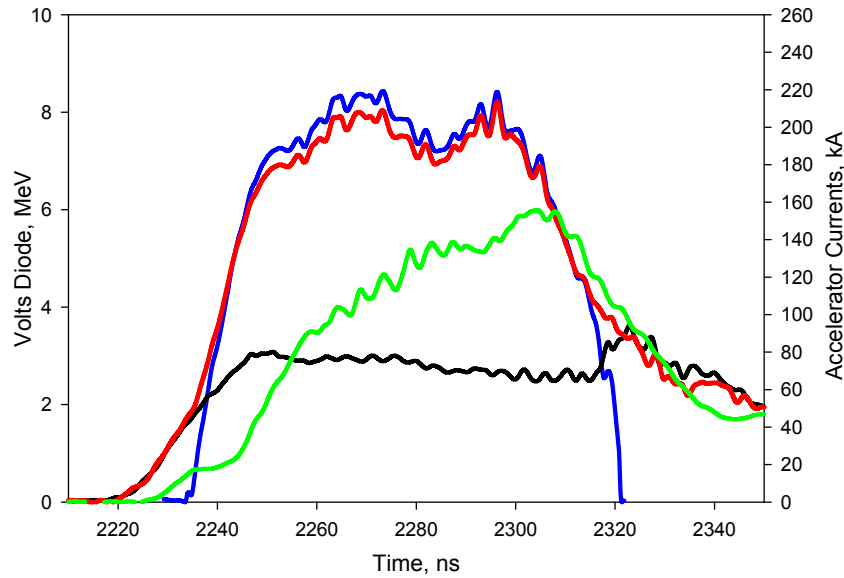


Figure 3. Electrical signals for a high charge voltage (86kV) SMP shot on RITS-6. The cathode current is in black and anode current in red. The Mendel derived voltage is in blue and the diode current in green.

C. Dosimetry and spot-size diagnostics

Figure 4 shows a layout of the RITS-6 experimental test cell region and the location of the dosimetry and spot-size diagnostics. The dosimetry diagnostics are located both inside and outside the test cell (at the end of the radiographic aperture shown in Fig. 4). Time-integrated dosimetry measurements are made with equilibrated CaF_2 thermoluminescent dosimeters (TLDs). Dose rate measurements are made using Silicon PIN diodes. The time integratal of the PIN signals are calibrated to co-located TLDs to yield an absolute measurement of the time resolved dose rate. Although dosimetry is located at various distances from the source, all the dosimetry data (both time-integrated and time-resolved) presented are normalized to the dose equivalent at 1 m, assuming an inverse distance squared scaling. There is the equivalent of 16 mm of aluminum filtering/attenuation between the source and the dose diagnostics.

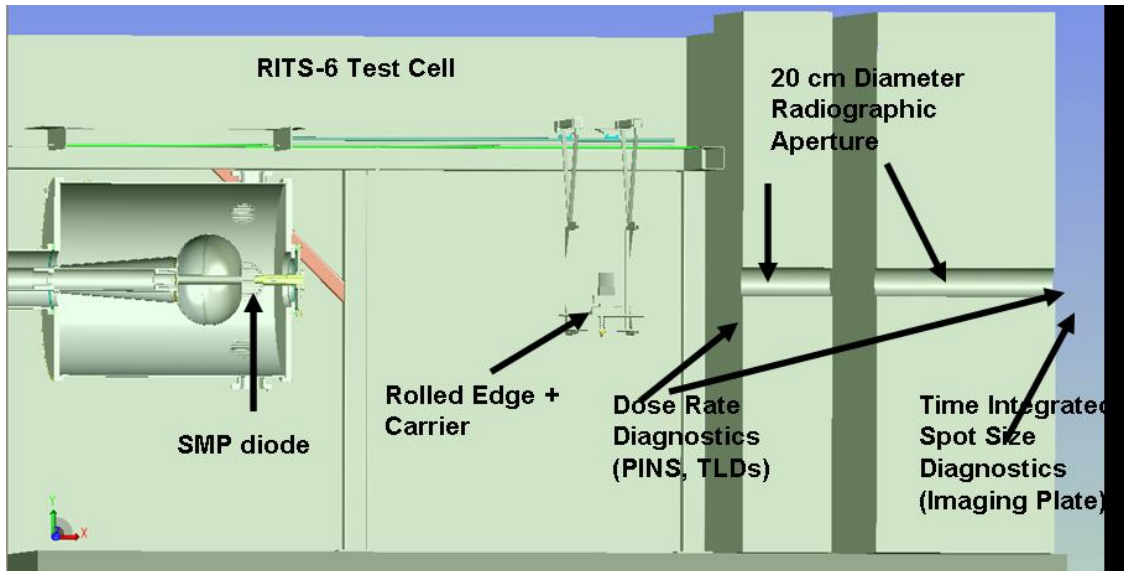


Figure 4. Cross section of the RITS-6 test cell, showing location of the rolled edge and radiation and spot diagnostics.

Spot size measurements of the x-ray source are taken with a dual sided Tungsten “Rolled Edge”, which is opaque to the incoming radiation and is placed orthogonal to the source (Figure 4 and Figure 5). The dual sided rolled edge allows one to obtain 2-d radiographic spot information. The resulting penumbra is captured on a radiographic Imaging-Plate (IP) detector. The rolled edge and imaging plate were located at the positions shown in Fig. 4. The imaging plate is placed parallel to the rolled edge in a geometry that minimizes blur from the detector as shown in Fig. 5. The resulting penumbral measurement yields the Edge Spread Function (ESF) (see Fig. 5) and by analyzing this transition the spot size can be calculated using various methods. One of the methods we use is the AWE method for determining spot-size[10]. The AWE method of calculating the spot takes the distance between the 25% and 75% points on the normalized ESF, divided by the magnification, and multiplied by 2.5. This definition yields the equivalent diameter of a uniformly illuminated disk. The derivative of the ESF yields the Line Spread Function (LSF). The LSF can also be used to calculate the source spot size. Our method of calculating the spot from the LSF is based on a variant of a Lawrence Livermore (LLNL) method. We define the spot as 1.4 times the FWHM of the LSF. In this case, if the source distribution were Gaussian, the value determined by the AWE definition and the LLNL definition would be equivalent.

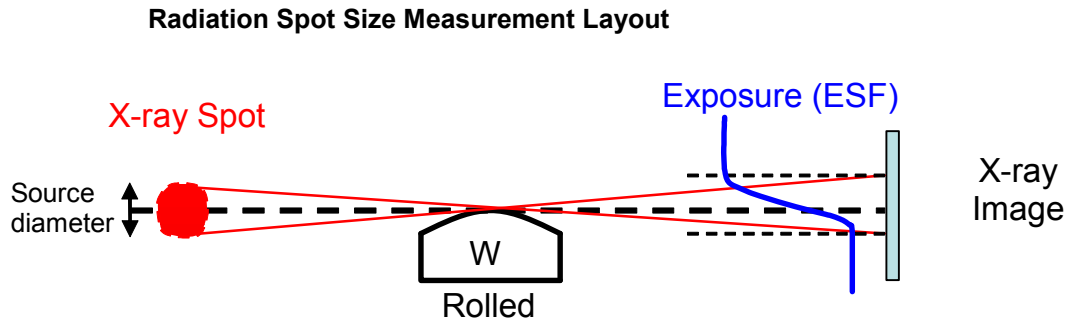


Figure 5 Penumbra measurement technique for measuring spot size.

By having a co-planar 2-dimensional rolled edge it is possible to use the corner where the two edges meet to derive the spot distribution following the method of Barnea [11,12]. We have implemented a modified version of Barnea's methodology for a single corner and present results of spot size measurements in comparison with the standard penumbra-edge technique.

III. Results

Figure 6 shows the electrical characteristics for an SMP diode shot 427 overlaid with the absolute dose rate measurement from a PIN detector. The radiation pulse width (FWHM) is approximately 50 ns with a peak dose rate of 9 rads/ns at the peak of the diode current. Lack of electron flow equilibrium in the diode region makes it difficult to accurately calculate a diode voltage and since at present there exists no direct diagnostic with which to experimentally measure the actual voltage, we have employed a voltage calculation method based on the inversion of a dose rate radiographer's equation. A radiographer's equation (or dose rate model) which gives the relationship between beam current, diode voltage and the radiation output has been developed by Crotch [13] for the SMP diode and is given by the expression:

$$\frac{dD}{dt} = I_e * [-2.952 * V + 2.349 * V^2 - 0.06934 * V^3] \quad (2)$$

where dD/dt (rads/ns) is the dose rate, I_e is the electron beam current impinging on the target in MA, and V is the time-dependent diode voltage in MV. This equation assumes that the electron beam impinging the anode can be well represented by a 40 degree fully filled cone. This agrees well with the electron trajectories calculated from simulations with the hybrid Particle-In-Cell (PIC) code, LSP[16]. A radiation transport code is used to propagate the electrons through the target material as well as creating and propagating the resultant bremsstrahlung radiation onto a plane where the energy deposition is measured. This method of using a dose rate equation to calculate voltage has been validated by comparing to calculated voltages from PIC simulations and to transmission line corrected voltages from position F [1]. Because the measured diode current includes both electrons and ions, an estimate of the ion current is subtracted from the measured current before using Eq. (2) to solve for the voltage. Based on PIC simulations of the

diode, the ion current accounts for $\sim 11\%$ of the total current, which is subtracted from the total current to obtain I_e .

Using the measured dose rate and electron beam current ($I_e = 0.89I_{\text{diode}}$), the time dependent diode voltage can be calculated by inverting Eq. (2). The result from such a calculation is shown in Fig. 6 (blue line) and labeled V_{diode} . The diode impedance (black line) shows that initially there is a fast decaying impedance that stabilizes ~ 10 ns into the pulse at $\sim 60 \Omega$. Once this stable period is over the impedance begins a gradual decrease until the end of the radiation pulse to a value of approximately 30Ω . A hard Bremsstrahlung endpoint is given by the diode voltage at a peak of 7.6 MeV. The dose rate has a 50 ns FWHM with a peak of ~ 9.8 rads/ns, and a net dose of 460 rads @ 1 meter. The low impedance MITL configuration of RITS-6 and the 86 keV charge voltage led to a 10% increase in the voltage compared to 78 keV experiments and a concomitant 33% increase in dose.

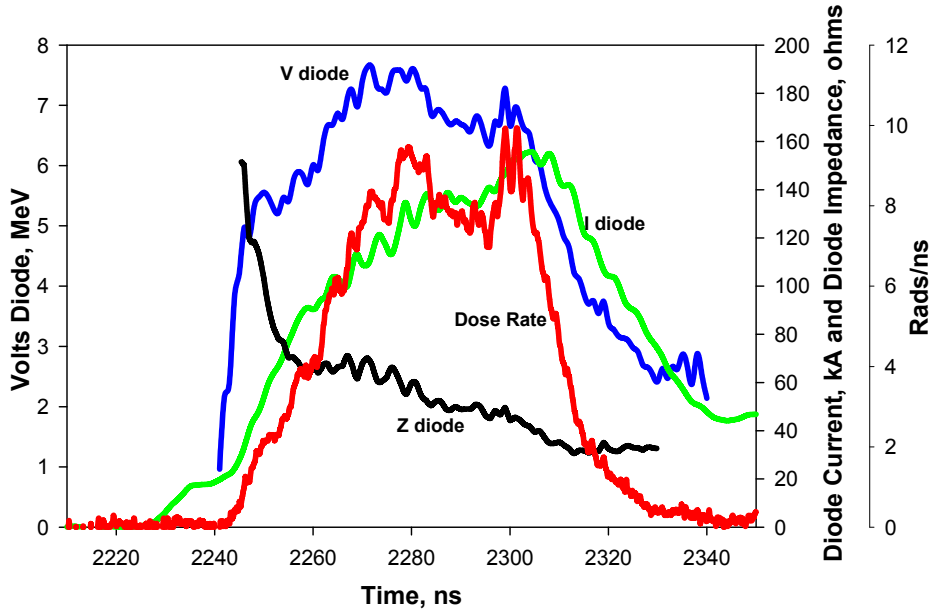


Figure 6. The diode voltage (blue), diode current (green) and impedance (black) of the SMP diode on a low Z MITL configuration and 86 keV capacitor charge. Dose rate (red) is normalized to TLD dose at a meter.

Figure 7 shows the experimentally measured and normalized Edge Spread Function (ESF) for the 86 keV charge experiments, this is given by the blue dots. For presentation purposes the numbers of points in the raw ESF have been decreased by a factor of ten. The raw ESF is reasonably fit by a Bennett function, shown by the solid red line. Analysis of the ESF yields an AWE spot-size definition [10] of 2.7 mm. For every shot,

the spot-sizes determined from the horizontal edge and vertical edge are averaged using the quadratic mean.

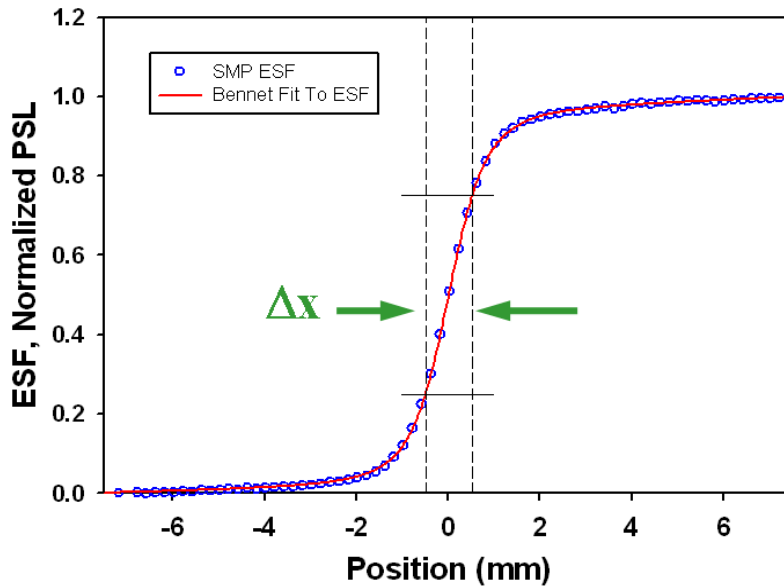


Figure 7. Raw ESF (blue dots) and Bennett fit (solid red line). Arrows indicate measurement region for calculating AWE defined spot size.

The Line Spread Function (LSF) is obtained by taking the derivative of the Bennett fit to the normalized Raw ESF. The LSF yields another method for measuring the spatial distribution of the radiation. This is given in figure 8. The LSF with a FWHM of 1.4 is given by the dashed blue line. As explained in section II c) this FWHM can be multiplied by 1.44 to give an LSF spot of 2.0 mm. The spatial distribution given by a fully filled disk of radius 0.6 mm is given by the red line. This is equivalent to a ‘hot’ core in the LSF which contains approximately 60% of the dose. This hot core suggests that the resolving power of the SMP diode in this configuration are greater than given by the standard ESF measurement.

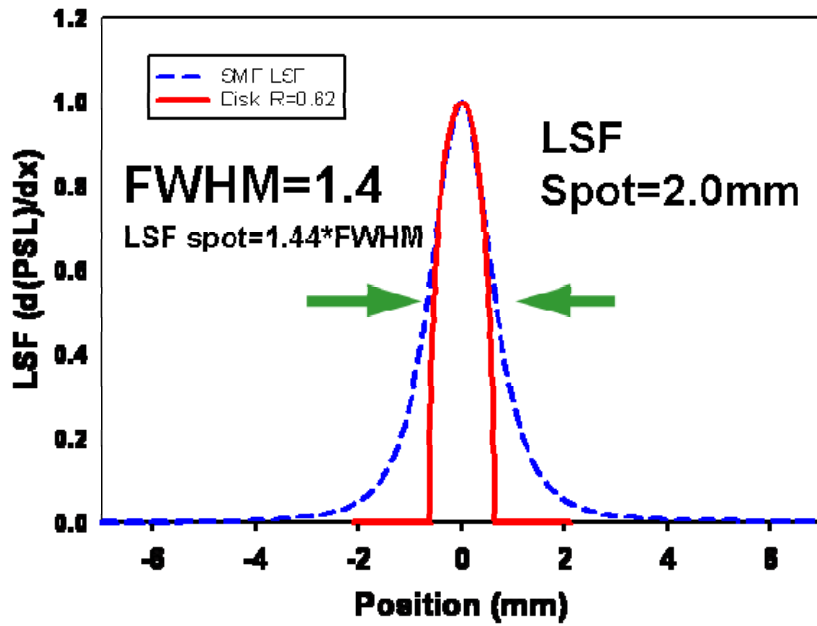


Figure 8. LSF of 86 keV charge SMP diode is shown in blue. Arrows indicate FWHM region used in calculating the LSD defined spot size. Approximately 60% of the energy lies within the 0.6mm radius uniformly filled circle.

The symmetry of the source can be measured by reconstructing a 2-d beam image of the source using the method of Barnea [11,12]. This reconstruction is shown in Fig. 9. The hot core is evident as is the relative good symmetry.

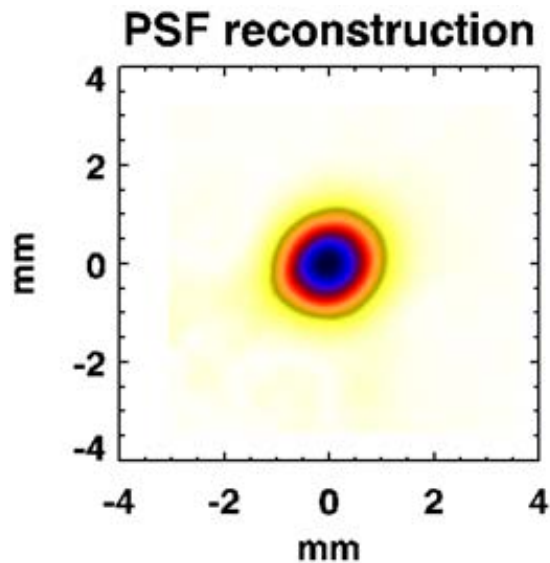


Figure 9. Reconstruction of the beam profile for an 86 keV charge SMP diode shot.

The relevance of this comparison between spot definitions with regard to radiographic utility are two fold. First, the AWE definition based on the ESF has a large contribution associated with the wings of the source distribution, whereas the LSF definition does not. Second, the two definitions would be identical if the source distribution were in fact Gaussian. The fact that the AWE definition value is always larger than the LSF value suggests a more strongly peaked distribution on axis than that of a Gaussian profile.

Results from this experimental campaign have demonstrated the performance of the SMP diode at higher voltage which provided a dose at 1 meter in excess of 450 rads with sub 3mm spots. Results which demonstrated optimal x-ray performance are summarized in Fig. 10.. The dose (rads@m) and spot-size (mm) are plotted for a number of shots conducted during the experiment and are compared to earlier data from shots conducted at 78 keV charge. The doses are indicated by the red circles in Fig. 12 and represent the average of two TLD readings at the position where the spot information is recorded.

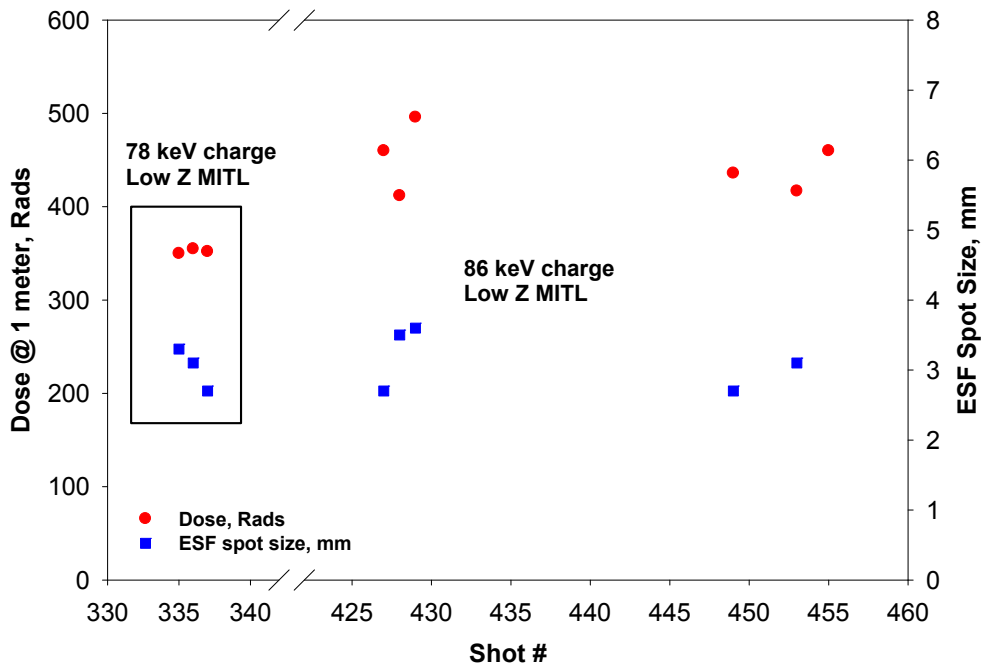


Figure 10. Spot size and dose @ 1 meter for the high charge voltage SMP shots on the low Z MITL configuration fielded on RITS-6

IV. Conclusions

Experiments conducted on the RITS-6 accelerator with a low impedance (40 Ω) MITL, high (86 keV) charge voltage and the Self-Magnetic Pinch diode have demonstrated the capability to create 7.5 MeV endpoint energy bremsstrahlung X-rays with radiation output in excess of 450 rads @ meter and spot sizes in the range of 2.5-3 mm. This specification meets a mid term requirement for flash radiography and provides the U.S. with the brightest Pulsed Power driven X-ray source developed to date. The results involved both an optimization of the source geometry and the accelerator to drive the source. An analysis of the source distribution suggests a peaked profile which should yield a greater resolving power than would be inferred from the simple spot size measurement.

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