

# INDUCTIVE VOLTAGE ADDER DRIVEN X-RAY SOURCES FOR HYDRODYNAMIC RADIOGRAPHY\*

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## Abstract

Inductive Voltage Adder (IVA) accelerators were developed to provide high-current (100s of kA) power pulses at high voltage (up to 20 MV) using robust modular components. This architecture simultaneously resolves problems found in conventional pulsed and linear induction accelerators. A variety of high-brightness pulsed x-ray radiographic sources are needed from sub-megavolt to 16-MeV endpoints with greater source brightness (dose/spot<sup>2</sup>) than presently available. We are applying IVA systems to produce very intense (up to 75 TW/cm<sup>2</sup>) electron beams for these flash radiographic applications.

The accelerator electromagnetic pulse is converted to a directed electron beam at the end of a self-magnetically insulated vacuum transmission line. The cantilevered cathode threading the accelerator cavities terminates in a small (1-mm diameter) needle, producing the electron beam which is transported to a grounded bremsstrahlung converter within a strong (~50-T) axial magnetic field. These systems produce mm-sized stable electron beams, yielding very intense x-ray sources.

Detailed simulations of the electron beam generation, transport, and target interaction are presented along with scaling laws for the radiation production and x-ray spot size. Experimental studies confirm these simulations and show this reliable, compact, and inexpensive technology scales to 1000-R doses a meter from a mm-diameter source in 50 ns.

## I. INDUCTIVE VOLTAGE ADDER

The Inductive Voltage Adder architecture was first demonstrated on the Helia [1] accelerator in 1985, and subsequently has been used in HERMES [2], Sabre [3], Reiden-IV [4], RHEPP [5], the DARHT injector [6], and Kalif-Helia [7]. Most recently we have used this approach in the Radiographic Integrated Test Stand (RITS) [8]. The IVA architecture allows power pulse

shaping and switching at the well understood and reliable few million volt and few ohm levels, with subsequent voltage addition through ferromagnetic-isolated stages to the terminal voltage.

Figure 1 shows the RITS architecture. A fast Marx charges two water dielectric transfer capacitors to 3 MV in a  $\mu$ s. Laser triggered gas switches couple each capacitor to three, 7.8-ohm, 60-ns water pulse forming lines (PFLs) which drive, through self-closing switches, matched impedance and length output transmission lines (Fig. 2). A second water peaking switch then transfers the pulse into a third matched

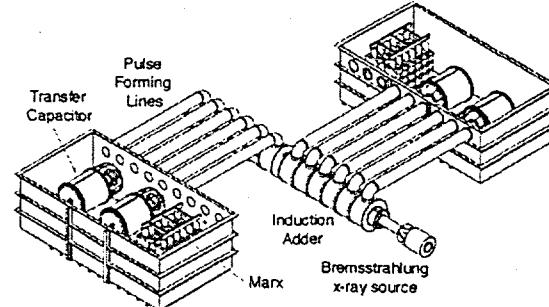


Figure 1. Radiographic Integrated Test Stand Inductive Voltage Adder accelerator. The 16-MV configuration shown is designed to provide 1000 rads a meter from a 1-mm radiographic source

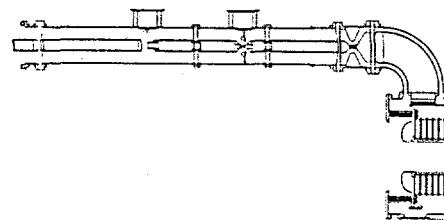


Figure 2. RITS pulse forming line, output lines, and induction cavity. The system is designed for wave shape control and stability with fast rise-times and minimal pre-pulse.

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water transmission line which, through an oil switch, drives an induction cavity. The sequential PFLs assure accurate pulse shape control and pre-pulse minimization for 95% of all shots, as shown in Fig. 3.

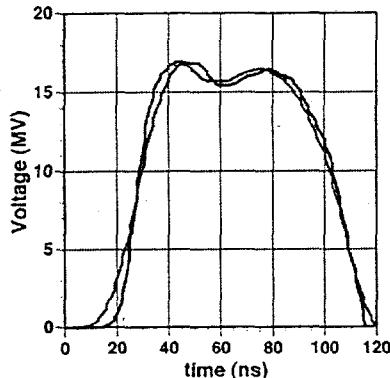


Figure 3. RITS output pulse variation. Statistical analysis shows that 95% of all shots will lie between blue (nominal) and green curves. The principal difference is an increase in rise time from 13 to 21 ns.

The induction cavities incorporate a unique tapered azimuthal transmission line to uniformly load the vacuum insulators and provide a symmetric radial wave to the adder. These series cavities are threaded by a grounded cathode stalk, forming a coaxial vacuum transmission line whose impedance grows through the adder to match the injected wave impedance. The output transmission line dimensions are chosen to operate in a magnetically inhibited flow, where a fraction of the current is carried in an  $E \times B$  drifting cathode sheath [9].

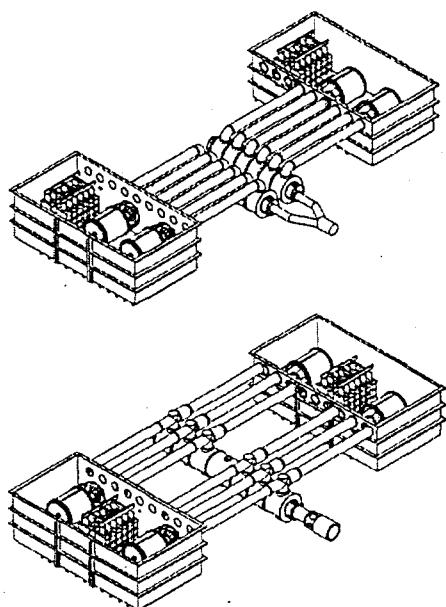


Figure 4. Two pulse 8 MV RITS configurations: top: independent accelerators driving sequential-adjacent-pulse sources within the same diode; bottom: independent accelerators coupled through induction cavities multi-pulsing a single x-ray source.

RITS will be assembled in two identical 6-cavity modules, each capable of providing a single 50-ns (full width at 90% maximum), 8-MV, 50-ohm pulse. These modules are designed to be operated in a variety of configurations: in series (16 MV, 1000 rads a meter from a 1-mm source spot as shown in Fig. 1); separately, driving close proximity radiographic sources (few mm spacing in a sequential-adjacent-pulse mode); or in parallel (multi-pulsing a single MITL) (Fig. 4). Thus RITS will support the entire suite of single- and double-pulse pulsed-power driven flash radiographic technology demonstrations.

## II. MAGNETICALLY IMMERSED ELECTRON DIODE

High-brightness flash radiography requires coupling the coldest possible, highest intensity electron beam into the smallest area of a high-atomic number anode at a voltage appropriate to radiograph the object under investigation. Pinched beam and paraxial diodes have historically been used on a spectrum of pulsed power drivers coupling up to 30 kA into 3-mm diameter spots [10]. Magnetically immersed diodes have also been extensively studied [11], and are now being applied to this problem with the goal of coupling 50 kA into a 1-mm diameter spot [12].

Figure 5 shows the magnetically immersed electron beam diode geometry. The IVA cathode cantilever extends beyond the final cavity to the experimental test area, tapering to a 0.5-mm diameter. The surrounding coaxial vacuum enclosure terminates in a pulsed solenoid magnet. MITL sheath electrons unable to enter the solenoid loss cone are shunted to the wall, while a cold high intensity beam is drawn from the boundary current in the cathode needle and is transported in the axial

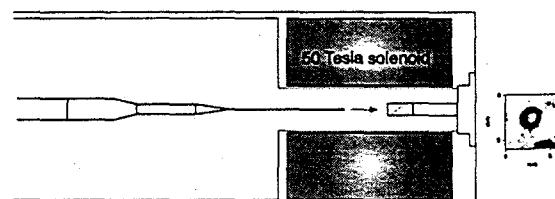


Figure 5. Magnetically immersed diode. MITL sheath electrons are diverted at the magnet entrance while a cold high intensity beam is drawn from the boundary current in the cathode needle. Inset: the measured HERMES x-ray spot from this diode.

magnetic field to the bremsstrahlung converter target. Extensive analytic and numerical modeling [13] suggests the electron current can be simply described by the space charge limit

$$I_{beam} = \frac{17kA \left( 1 + \frac{V}{511kV} \right)}{\left( 1 - \frac{Zn_i}{n_e} \right) \left( 1 + 2 \ln \left( \frac{R_{wall}}{r_{beam}} \right) \right)} \quad (1)$$

and the x-ray source size is just the needle size added in quadrature to the electron gyro-orbit in the applied magnetic field (Figs. 6, 7):

$$spot = 2.6 \sqrt{r_c^2 + \left( \frac{0.17 \text{ Tesla}}{B_z} \sqrt{2\gamma l / 17kA} \right)^2} \quad (2)$$

The particle in cell simulations shown in Fig. 7 predict electron and ion motion during the pulse and are used to optimize the transition and immersed diode regions (Fig. 7). It is found that balancing the electric and magnetic profiles in the presence of the evolving beam and wall particle flows is critical to designing a highly focused radiographic source (Fig. 8).

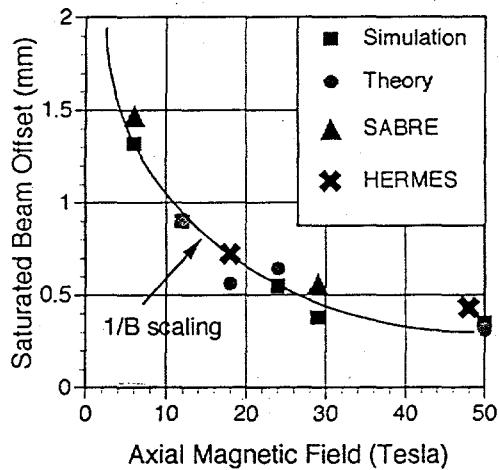


Figure 6. Beam spot size scaling. The simple analytic model agrees well with both PIC simulations and experimental data from two accelerators.

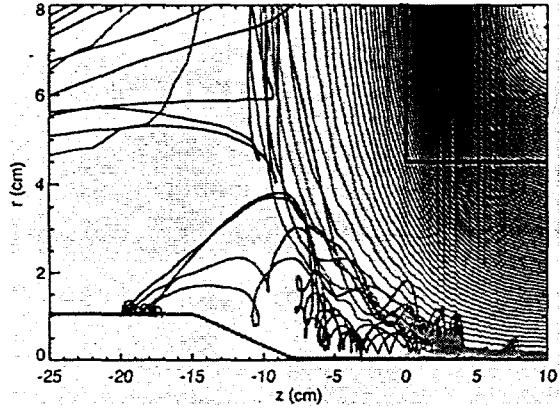


Figure 7. 2D and 3D PIC simulations enable optimized transition and diode designs. The electron trajectories show paths from different emission locations in the applied magnetic field and can be tallied to differentiate spot and halo sources.

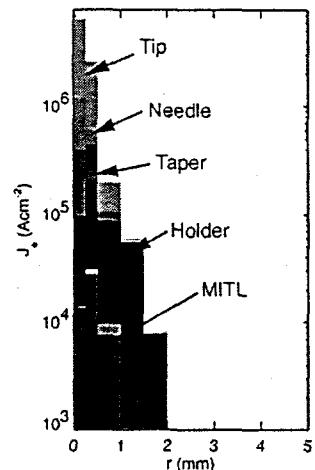


Figure 8. Calculated electron distribution on target, tallied by emission site.

### III. RADIOGRAPHIC SOURCE

Monte Carlo calculations have been used to model the x-ray production from these intense electron beam sources interacting with high atomic number (typically Tungsten or Tantalum) anodes. The PIC electron trajectories discussed in the previous section were used as the source distribution into the Integrated Tiger Series [14] Monte Carlo model of the experimental geometry, and the results compared to experimental data. Since x-ray source spatial distribution and dose production are the experimental measurable, it is important to relate them to the incident (PIC) electron distribution. Figure 9 displays this comparison, showing that the measured x-ray spot size can be directly linked to the electron source distribution for this class of diodes. This correlation has been used to display the experimental data in Fig. 6.

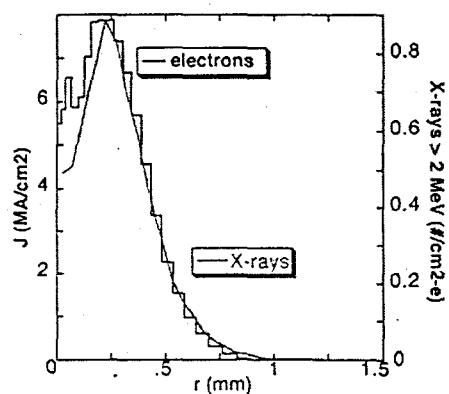


Figure 9. Correlation between electron source and x-ray profiles. The x-ray spot can be used as indicative of the electron beam distribution at the target.

Figure 10 shows the results for a suite of such calculations above 6 MV, where the circles represent HERMES experimental data [15]. The shaded region

represents the parameter space capable of producing > 1000 rads a meter from the x-ray source for the tested diode. All the experimental data lie on this surface, confirming an x-ray production scaling of:

$$dose = 340 QV^{3.2} \exp\left(-\frac{(V + 0.5)\beta_{\perp}}{1.1\pi}\right) \text{ rads} \quad (3)$$

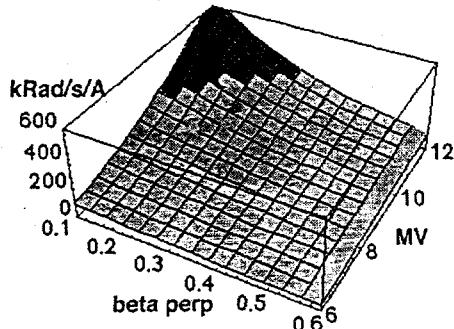


Figure 10. Monte Carlo x-ray production predictions for the HERMES magnetically immersed diode. Experimental data shown confirms the model shape and the generation of a cold focused electron beam.

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## IV. FUTURE PLANS

Having demonstrated the concept of IVA accelerators powering magnetically immersed electron diodes as radiographic x-ray sources on the Sabre and HERMES facilities, we are scaling this source to both higher and lower voltages with the construction of RITS and TriMeV [16]. RITS will be the first IVA driver optimized for this specific application, and will test a number of pulsed power technologies and approaches needed for the future as well as provide the basis for confidence in high-brightness multi-pulse pulsed power radiographic technology. While RITS is under construction, TriMeV is being utilized in Nevada to develop further understanding of the different possible radiographic sources (pinched beam, paraxial, rod pinch, and immersed diodes) to provide a basis for application specific technology decisions.

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