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LINEAR INDUCTIVE VOLTAGE ADDERS (IVA) FOR ADVANCED HYDRODYNAMIC RADIOGRAPHY*

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Abstract

The electron beam which drifts through the multiple cavities of conventional induction linacs (LIA) is replaced in an IVA by a cylindrical metal conductor which extends along the entire length of the device and effectuates the addition of the accelerator cavity voltages. In our approach to radiography, the linear inductive voltage adder drives a magnetically immersed electron diode with a millimeter diameter cathode electrode and a planar anode/bremmstrahlung converter. Both anode and cathode electrodes are immersed in a strong (15-50 T) solenoidal magnetic field. The electron beam cross section is approximately of the same size as the cathode needle and generates a similar size, very intense x-ray beam when it strikes the anode converter. An IVA driven diode can produce electron beams of equal size and energy as a LIA but with much higher currents (40-50 kA versus 4-5 kA), simpler hardware and thus lower cost. We present here first experimental validations of our technology utilizing HERMES III and SABRE IVA accelerators. The electron beam voltage and current were respectively of the order of 10 MV and 40 kA. X-ray doses of up to 1 kR @ 1 m and spot sizes as small as 1.7 mm (at 200 R doses) were measured.

1 INTRODUCTION

Up to the cessation of the nuclear tests, radiography of an imploding primary (with surrogate material) was utilized to supplement the information gathered from these tests. However, this is now the only means available to probe and characterize such a device.

To radiograph very thick objects, a high-energy, high-flux, and very small spot x-ray source is required. The small spot (~ 1 mm in diameter) will provide the necessary spatial resolution while the high-energy photon flux is required to penetrate the thick object and produce a clear image of its interior. To generate those penetrating x-rays an electron accelerator is being used. The electron beam strikes a tantalum x-ray converter plate. The forward x-ray beam illuminates the surrogate primary and produces a photograph on a package of films or imaging detectors located on axis downstream from the radiographed object, similar to medical or industrial radiography.

Presently, two types of accelerators are being utilized for x-ray radiography: first, linear RF (PHERMEX) or induction accelerator (FXR); and second, single gap pulsed power devices using a high-voltage Blumlein pulse forming line (AWE). The first can produce high-energy, small-diameter (2-3 mm) electron beams relatively easily, but the current is limited to 1-2 kA yielding low photon fluences. The Blumlein pulsed power devices can produce much higher beam currents (50-100 kA), but the beam spot diameter is relatively large (~ 6 mm) and the beam energy is limited to 8-10 MV.

Our linear inductive voltage adder accelerator (IVA) coupled to a magnetically immersed foilless diode can successfully bridge the gap between the two devices. It can produce small spots (~ 1 mm), high voltages (15-20 MV), and high currents (40-50 kA) at a fraction of their cost.

In the next sections, we present first experimental validations of our technology utilizing available Sandia National Laboratories IVA accelerators.

2 SABRE EXPERIMENTS

For these experiments, SABRE was modified to increase the output voltage and proportionally reduce the current, delivering the same energy. It was, therefore, operated at 9-12 MV and 100-120 kA. The design of the MITL voltage adder and the foilless diode (Fig. 1) were validated with a large number of particle-in-cell simulations.

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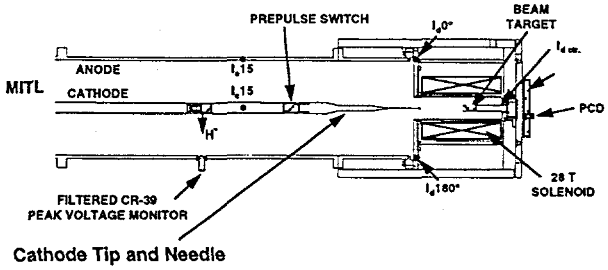

Figure 1 Schematic diagram of diode design utilized in both SABRE and HERMES-III experiments.

The intense electron beam produced by the SABRE foilless diode quickly produces an ion-emitting anode plasma. The ions are accelerated toward the cathode. The electrostatic attraction between the two beams is considerable and an ion-hose two-stream instability is excited. If left uncontrolled, this instability can cause large deflections and heating of the beam which would substantially increase the beam spot size. A strong axial magnetic field (B_z) controls this behavior. The beam offset (ε) grows until it reaches the gyrodius value. A simple model matches the simulations:

$$\varepsilon = (2\gamma \ \ I/17 \ \ kA)^{1/2} \times (0.17 \ \ Tesla/B_z) \ \ cm$$

$$r_b(FWHM) = \sqrt{\varepsilon^2 + r_k^2} \ ,$$

where I is the beam current and r_b and r_k are respectively the beam and cathode needle radius. According to this model and IPROP simulations, a 30-T magnetic field should control the ion-hose instability and produce a 0.75-mm radius beam. The experimental results (Fig. 2) are in very good agreement with theory and simulations [1].

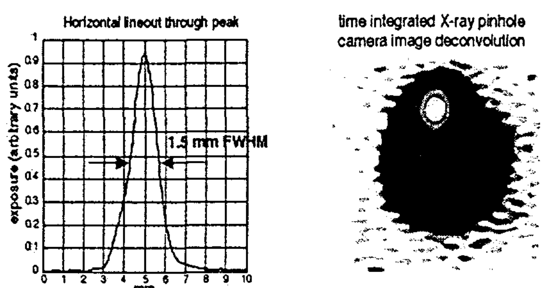

Figure 2. Time integrated x-ray image of the beam for B_z = 29 T, SABRE results. Beam size agrees with theory and simulations.

3 HERMES-III EXPERIMENTS

HERMES III is larger than SABRE, having twenty 1-MV inductively insulated cavities. It routinely produces 18-20 MV, 700-kA electron beam in normal operation, but in the present experiments, we operate it at lower voltage (12 MV), reduced current (150 kA), and longer pulse (~ 70 ns FWHM).

The outer cylinder of the extension MITL has conical sections to reduce the radius down to SABRE size. Thus, the same magnetically immersed diode (Fig. 1) assemblies are utilized with HERMES III. In addition, a smaller, 50-Tesla, cryogenic diode was designed and constructed (Fig. 3) for these experiments.

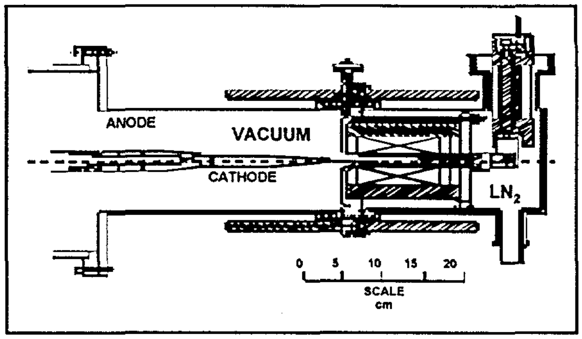

Figure 3. The 50-Tesla cryogenic diode design utilized only with HERMES-III.

During SABRE experimentation we observed a severe decrease in the diode impedance near the peak of the voltage pulse. It was attributed to a 100-kV prepulse arriving 200 ns before the main pulse. A flashover prepulse suppression switch solved the problem. The impedance remained constant during the entire duration of the voltage pulse (30-ns FWHM). In HERMES III, we installed two flashover switches in series and we made sure that no appreciable prepulse was making it into the diode. In addition, special care was taken to improve the diode vacuum to 1-3 10^{-7} torr levels. Despite all this the diode impedance still exhibited a collapse at about 10-30 ns into the voltage pulse (Fig. 4). The onset of this abnormal impedance decrease was delayed by opening the AK gap (Fig 5). While the diode impedance remained normal (~ 300 Ω) the beam spot size was small and in good agreement with numerical simulations (Fig. 6). As soon as the impedance started plummeting, the beam spot size increased and the x-ray intensity decreased. All the above are characteristic of diode shorting.

Figure 4 shows typical behavior of the diode current. At the beginning it is consistent with a monopolar flow of electrons from the cathode to the anode. About 20 ns into the pulse the expected bipolar flow sets up with a 30% increase of the total current. Finally ~ 33 ns later the current breaks away from the voltage trace and keeps increasing to 150-180 kA until the end of the voltage pulse. Analytical calculations and numerical simulation [2,3] explain the late time current behavior as due to counterstreaming heavy ions emitted from the cylindrical anode walls and the converter target. Very high-intensity heavy-ion (carbon, nitrogen, oxygen, etc.) beams, while in transit toward the cathode, suffer many electron stripping ion-ion collisions and increase their charge. When this increased ion charge density reaches the cathode, it bootstraps currents into an abnormal impedance collapse. Forty-five degree slant targets and larger anode cylindrical walls appear to delay impedance collapse for the same AK gap (Fig. 5).

A number of impedance collapse mitigation methods have been extensively studied [4] and will be implemented in future experiments. Among them, an increase in magnetic insulation will prevent ions from the diode cylindrical walls reaching the axis. The ions emitted from the target can be reduced by utilizing a small 1-mm diameter target. Finally, the counterstreaming ions following the magnetic field lines can be prevented from striking the needle if a less-immersed cathode tip is utilized. A new 60-T diode is being designed that will offer those capabilities which, we believe, will enable us to achieve the advanced hydrodynamic radiography goals of 0.8-mm (FWHM) x-ray spot, 1-kRad dose @ 1 meter from a 12-14 MeV electron beam.

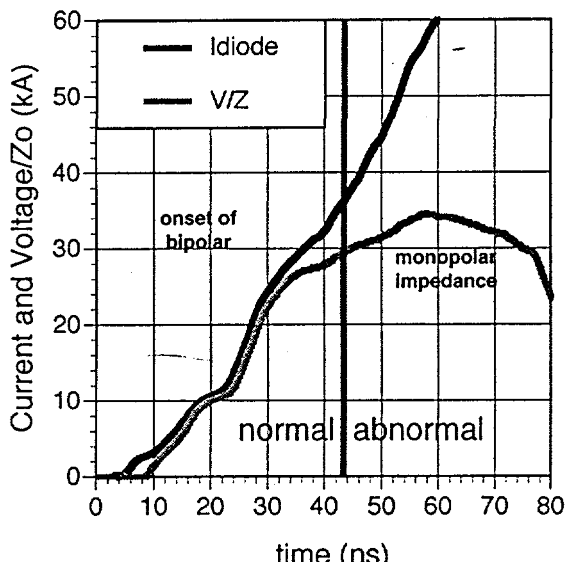

Figure 4. HERMES-III immersed diode current and voltage time behavior for a 22-cm AK gap.

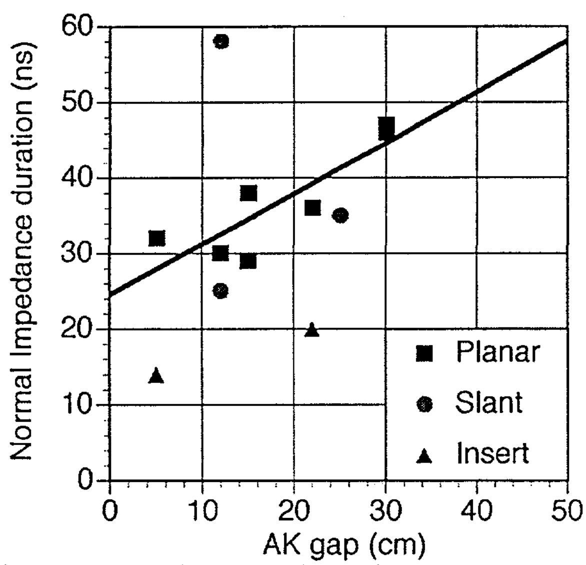

Figure 5. The time duration of the normal diode operation increases with the AK gap spacing and orientation of the converter front surface.

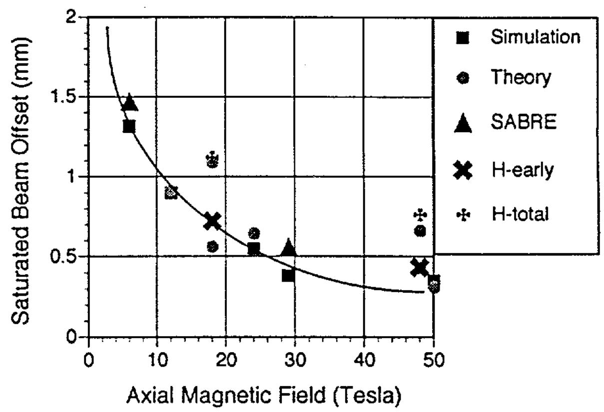

Figure 6. Measured beam offsets (ε) in SABRE and HERMES III are in very good agreement with theory and numerical simulation.

4 SUMMARY

SABRE and HERMES III experiments demonstrated that IVA/immersed diode technology can produce millimeter size x-ray sources capable of penetrating very dense objects. The observed ion hose instabilities can be controlled to acceptable levels with 50-60-T confining magnetic fields. The abnormal diode impedance behavior is well understood and mitigating diode designs are under construction for future IVA experiments. SABRE and HERMES-III results (normal diode operation) are in full agreement with theory and numerical simulations.

5 REFERENCES

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