RADLAC II/SMILE PERFORMANCE WITH A MAGNETICALLY INSULATED VOLTAGE ADDER*

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Abstract

A 12.5-m long Self Magnetically Insulated Transmission LinE (SMILE) that sums the voltages of 8, 2-MV pulse forming lines was installed in the RADLAC-II linear induction accelerator. The magnetic insulation criteria was calculated using parapotential flow theory and found to agree with MAGIC simulations. High quality annular beams with $\beta_\perp \leq 0.1$ and a radius $r_b < 2$ cm were measured for currents of 50-100-kA extracted from a magnetic immersed foilless diode. These parameters were achieved with 11 to 15-MV accelerating voltages and 6 to 16-kG diode magnetic field. The experimental results exceeded our design expectations and are in good agreement with code simulations.

INTRODUCTION

The linear induction accelerator, RADLAC II, was originally designed with eight 2 MV electrically-graded vacuum insulator stacks or envelopes. A magnetically insulated transmission line (MITL) coaxial cathode stalk was passed through the first two envelopes and used to generate a 4-MeV, 20 to 40-kA annular electron beam in a foilless diode.[1] The remaining six envelopes contained specially contoured accelerating gaps of 2 MV each that were designed to minimize radial oscillations of the beam envelope.[2] A pulsed longitudinal magnetic field, B_z, of 20 kG was used throughout the accelerator to generate and transport the annular beam through the accelerating gaps. The final beam voltage was 16 MV. The pulsed magnets proved to be unreliable with numerous mechanical failures and alignment of the magnets was extremely difficult.

To reduce the number of magnets the MITL was extended through the first four envelopes. The four-feed, 8-MV injector successfully produced a 7 to 8-MeV, 40 to 50-kA annular beam. Failures in the remaining solenoidal magnets still caused a reliability problem. We replaced the 8-MV MITL with SMILE, which added the voltages of all eight feeds to a single foilless diode. This modification eliminated all of the unreliable magnets except for one small coil, used for the foilless diode, that was located external to the accelerator. This modification provided very reliable accelerator operation and routinely produced 10 to 13-MeV, 40 to 110-kA, annular electron beams.

SMILE

The design of SMILE is similar to that of the HERMES III and HELIA accelerators.[3, 4] The criteria for the self magnetic insulation was derived from Creedon's theory.[5] The radius of the accelerator insulators and interconnecting piping was fixed at R = 21.5 cm. The cathode radius needed to be $r_c = 1$ cm. The final design was for 110 kA and assumed 2 MV applied to each of the eight insulating stacks. Given these parameters we calculated the shank radii r_i, and operating impedances at each envelope section using Creedon's formula for the minimum current I_ℓ required to establish self-limited magnetic insulation. The current, I_ℓ is given by:

$$I_\ell = 8500\, g\gamma_\ell^3\, \ell n\left[\gamma_\ell + (\gamma_\ell^2 - 1)^{1/2}\right],$$
$$\gamma_o = \gamma_\ell + (\gamma_\ell^2 - 1)^{3/2}\, \ell n\left[\gamma_\ell + (\gamma_\ell^2 - 1)^{1/2}\right], \qquad (1)$$
$$g = [\ln R/r_i]^{-1} \text{ and } \gamma_o = V[MV]/mc^2 + 1 = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

The relativistic Lorentz factor, γ_ℓ, is for electrons at the boundary of the electron sheath in the minimum current case. The main criteria was to keep $I_\ell \geq 110$ kA in order to maintain magnetic

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insulation. The final design of the 12.5-m long cathode stalk started at a radius of 10 cm and utilized seven conical steps to reduce the radius to 1 cm. The dimensions are summarized in Table I.

The design was simulated with the PIC MAGIC code.[6] Figure 1 shows an electron map of the SMILE configuration and verifies that magnetic insulation does occur. The losses near the cathode tip are due to the radial component B_r of the applied magnetic field of the foilless diode and occur when the self field B_θ is $\leq B_r$.

TABLE I.
SMILE Self-Limited Minimum Current MITL Design

MITL Segment	Optimum Segment Voltage V [MV]	Actual Cathode Radius r_c [cm]	Cathode Radius r [cm]	Vacuum Impedance Z [Ω]	Operating Impedance Z [Ω]
1	2.0	13.33	10.2	45.3	30
2	4.0	8.05	7.6	55	40
3	6.0	6.30	5.7	80	61
4	8.0	3.86	3.5	96	80
5	10.0	2.69	2.5	121	97
6	12.0	1.90	1.6	149	122
7	14.0	1.35	1.3	162	135
8	16.0	.952	1.0	180	151

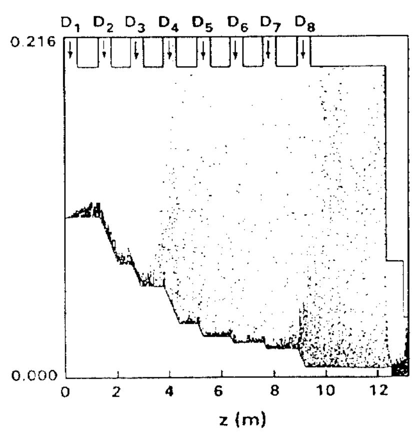


Fig. 1: **Electron map simulation for SMILE showing magnetic insulation.**

The 12.5-m MITL adder was cantilevered from one end of the accelerator. The adder was preloaded while it was out of the machine to compensate for gravitational droop. A diagram of SMILE is shown in Fig. 2.

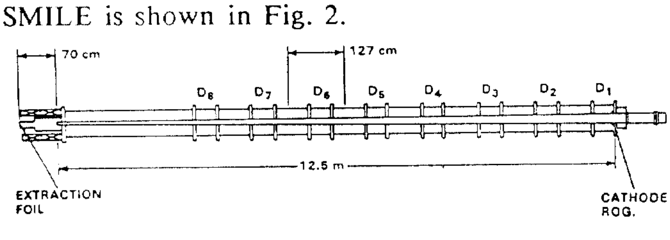


Fig. 2: **SMILE configuration for RADLAC.**

HIGH CURRENT BEAM GENERATION

With the SMILE modification the annular beam was still generated in a magnetic foilless diode with a small, reliable, pulsed magnet, located outside of the accelerator tank. This greatly simplifies the operation. A diagram of the foilless diode and associated beam diagnostics is shown in Fig. 3. The PIC MAGIC simulations have shown that the output current is a function of the beam loss at the divergence of the applied magnetic field at the cathode, the value of the applied field, and the anode-cathode spacing. A typical diode simulation is shown in Fig. 4. We were able to use these variables to generate high quality annular beams over a wide range, 50 to 113 kA. The voltages were 11-15 MV. Figure 5 shows voltage and current waveforms.

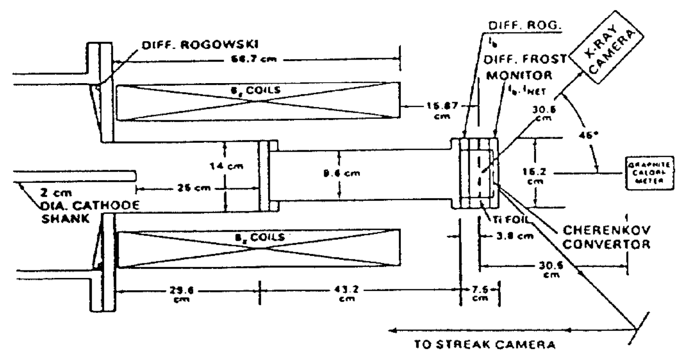


Fig. 3: **Schematic diagram of the immersed foilless diode with associated diagnostics.**

To determine the beam kinetic energy the voltage applied to each of the eight feeds was measured and added with appropriate time shifts to correct for electron transit time along the stack. The sum was then corrected for pulse distortion due to the MITL operation. The pulse was broadened and reduced in amplitude due to the finite inductance of the system. In addition the erosion associated with the establishment of the magnetic insulation led to a steepening of the front of the pulse. The correction typically reduced the measured peak voltage by 1-2 MV and resulted in beams with kinetic energies of 10-13 MeV.

The beam quality was measured using witness foils and time integrated x-ray and Cherenkov photos. A few shots were fired with the extraction foil and targets located in the uniform magnetic field to measure the beam radius; however, at the high current density in the

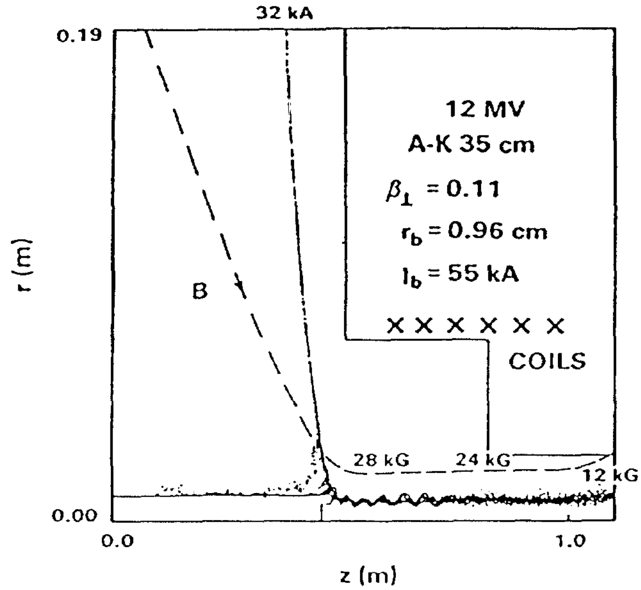


Fig. 4: PIC MAGIC simulation of typical SMILE foilless diode.

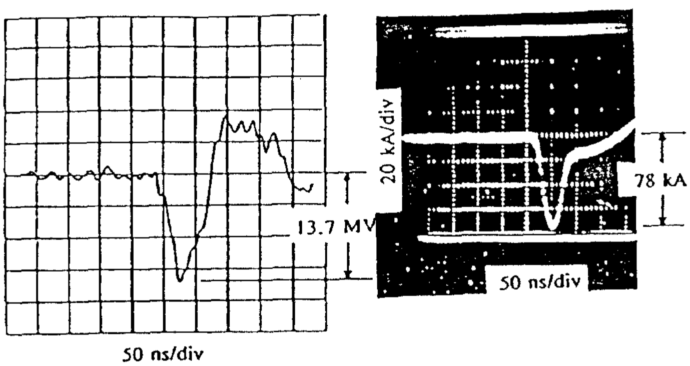
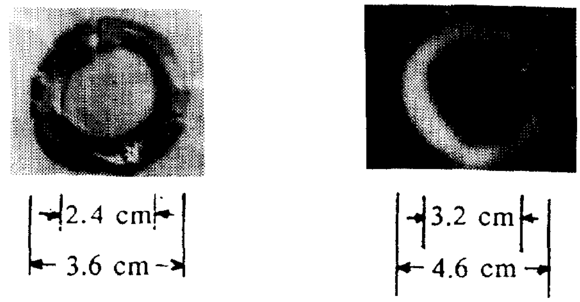


Fig. 5: Sum of voltages applied to MITL adder and extracted beam current.

annular beam the extraction foil would rupture bringing the accelerator up to air. Most of the shots were fired with the foils located in the diverging field of the magnet. This allowed the beam to adiabatically expand and reduce the current density, allowing the foils to survive.

The perpendicular thermal velocity, $v_\perp = \beta_\perp c$ is determined by measuring the spreading of the annular beam from finite Larmor radius effects. The annulus width of an x-ray pinhole camera image is a function of the width of the cathode annulus (3 mm for SMILE), the applied B_z, the beam energy, and $\beta_\perp$. Representative witness foils and x-ray pinhole photographs are shown in Fig. 6. Typical values for $\beta_\perp$ were ≤ 0.1 indicating very low emittance beams in good agreement with simulations.



(a) (b)

Fig. 6: (a) Witness foil of a 13 MeV, 78 kA beam that was adiabatically expanded to reduce the current density, $\beta_\perp = 0.05$. (b) X-ray pinhole photograph of a 10 MeV, 80 kA beam generated with a 2.1 cm radius cathode, $\beta_\perp = 0.07$.

CONCLUSION

The SMILE modification has resulted in a reliable and reproducible high current accelerator. Beam currents were easily varied by parameter changes predicted by MAGIC simulations. The resulting beams were of very high quality with a small transverse velocity.

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