RECIRCULATION ACCELERATION OF HIGH CURRENT RELATIVISTIC ELECTRON BEAMS - A FEASIBILITY STUDY*

Mark A. D. Wilson**

Introduction

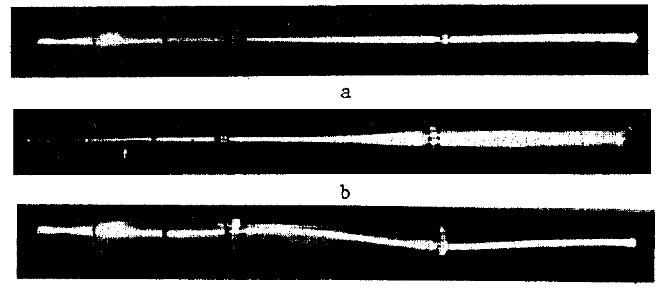
One of the advanced accelerator concepts under study at NBS involves multiplying the energy gained by a long pulse, high current relativistic electron beam by directing the beam several times through the same induction accelerator during the time of one voltage pulse. Should this concept of the recirculation acceleration of intense electron beams be proven feasible, the savings in cost, size and weight of a high current accelerator would be considerable. Energy gain by recirculation acceleration through a small-scale proof-of principle facility has been demonstrated at NBS. The study employs a 750A, 750keV electron beam pulse, 2μsec long, generated by a linear induction accelerator of unique design which was also developed at NBS.[1] Self-focusing beam transport through a charge-neutralizing low pressure gas is employed in the demonstration recirculator for simplicity. Success with gas-focus beam transport has been limited, due to beam-plasma instabilities and emittance limitations with the relatively low energy high current electron beam available at NBS. An alternate beam transport method for future high current recirculating accelerators is also presented.

Beam Propagation in Charge-Neutral Gas

Equations of motion have been derived for the behavior of the radial envelope of a relativistic electron beam under the influence of magnetic and electric self-forces.[2] Ionization of any background gas by the beam electrons will tend to reduce the repulsive forces of the beam charge. In helium gas (chosen for low beam scatter) at a pressure of a few Torr, a 750 keV electron beam will be fully charge-neutralized in a few nanoseconds. The beam is then confined, in the absence of external focusing fields, by the magnetic self-fields. For a given beam emittance, an equilibrium radius can be found.

Figure 1a shows the gas glow from the NBS electron beam propagating through 4.5 meters of helium at 5 Torr. The gas was confined to a 16.5 cm I.D. clear plastic pipe covered with copper screen for return currents. A 0.0076 mm polyamide foil separates the gas from the accelerator vacuum at the left of the picture. After 4.5 meters in gas, the beam radius is about 1.5 cm and the measured radial beam current profile has developed wings due to gas scattering, in agreement with the theory by E. P. Lee[3] of beam profile evolution in gas. If the beam is introduced into gas at a sufficiently small radius, any asymmetry in the beam self-forces will lead to beam disruption in a short distance due to a transverse beam-plasma instability often referred to as hose instability.[4] Figure 1b shows the beam blow-up resulting when the NBS beam is magnetically focused into gas at a radius under 0.5 cm. At a larger beam radius (Figure 1a and 1c) the self-forces are sufficiently reduced so that the growth of the hose instability is slowed to the point that stable beam propagation in charge-neutral gas is possible over extended distances.

In figure 1(c), the beam was deliberately steered toward the pipe wall with an external field near the entrance to the gas-filled pipe. Image current forces[5] then reflected the beam toward the axis. The effects of image currents on the NBS beam have been calculated from relationships between beam current, energy and wall radius given in reference 5 and agree quite well with measured beam excursions. These results show that smooth conducting walls provide for more stable transport of intense, charge-neutral beams with no current neutralization.



a

b

c

Fig 1 Beam glow in 5 Torr helium

360° Circulation

To establish the feasibility of intense beam recirculation, the gas-focused electron beam was deflected through a 360° spiral consisting of four 90° bending magnets with a 50 cm central radius. This configuration is shown in figure 2. Over 70% of the entering current emerged from the loop in a straight, stable, well-focused beam. Since most of the beam current losses were in the first 90° bend of the 7.5 cm diameter vacuum pipe, the losses appear to be due primarily to aperture limits on the wings of the radial beam current distribution.

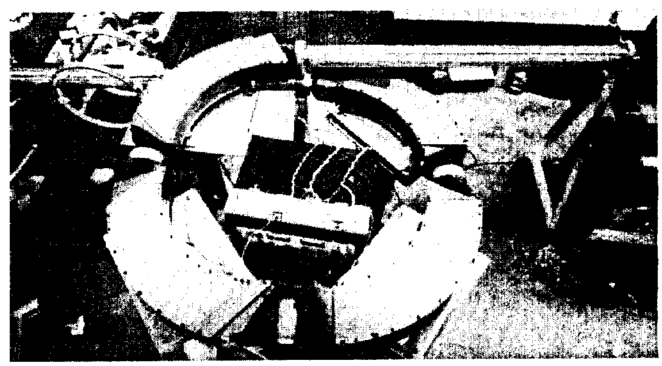


Fig 2 Top View 360° loop

Recirculation Acceleration

Iron core induction linacs are inherently low impedance devices with a large accelerator aperture capability. Therefore, many separated high current beam paths may be supported simultaneously within one accelerating structure. With one long beam current pulse making several separated wraps during one slightly longer voltage pulse, the energy gained by the beam electrons is increased by the number of passes through the accelerator. This results in a smaller, lighter, less costly accelerator with a higher power efficiency. The limit to the number of passes is governed by the impedance of the voltage source and by the transit time of the beam during the recirculation process. To provide energy gain over the full length of the current pulse, the voltage must be maintained for the added time required for the beam head and tail to circulate through the accelerator. A practical configuration providing an energy gain of 40 MeV in 5 passes through a double-sided induction accelerator for a 2 μsec beam pulse is shown in Figure 3.

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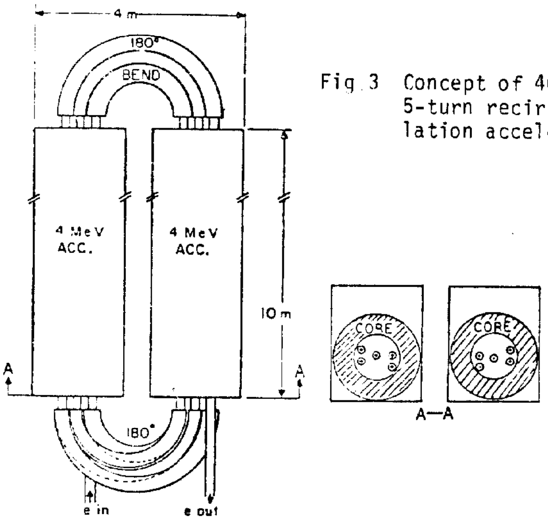

Fig 3 Concept of 40 MeV 5-turn recirculation accelerator

The NBS Proof of Principle Experiments

A two-pass test facility, delivering 20 keV per pass, was built by inserting an over/under pair of accelerating electrodes (driven by a single induction core) at the cross-over of the spiral path used earlier to study circulation. A top view of the lay-out is shown schematically in Figure 4. A side view photo of the completed facility is shown in Figure 5. Since the accelerator electrodes require high vacuum for voltage hold-off, foils were installed at each end of the accelerator housing (Figure 4), while the remaining portions of the loop were filled with about 5 Torr of helium. Focus coils to match the beam from vacuum to gas are also shown in Figure 4.

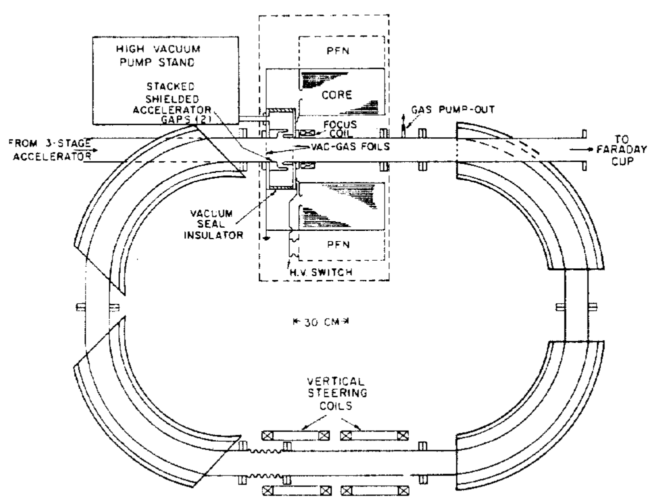

FIG. 4 SCHEMATIC TOP VIEW OF RECIRCULATING INDUCTION ACCELERATOR TEST FACILITY

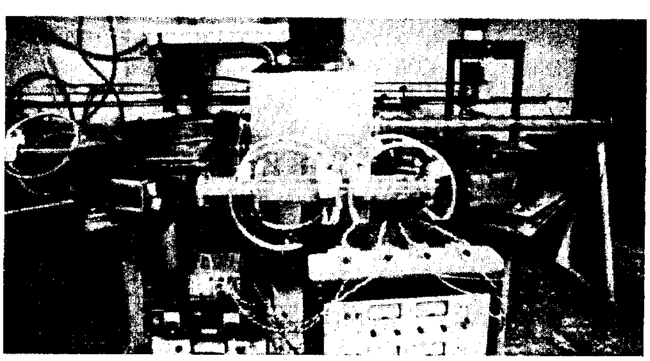

Fig 5 Recirculation test accelerator

Single-pass studies showed that steering effects, due to the asymmetry of multiple independent beam paths, can be overcome by proper design of R.F. shielding and magnet shielding for the accelerator gaps and focus elements. The expected energy gain was demonstrated. Close scrutiny of the gas glow after one pass showed pulsations on the beam envelope. These pulsations, produced by force mismatch in the high vacuum region of the accelerating gaps, were reduced, but not eliminated, by the focus solenoids after the accelerating sections.

After two passes through the accelerating section, the gas glow filled the 8.0 cm I.D. exit beam tube, suggesting a significant increase in beam radius and loss of beam to the plastic tube walls. The beam current transmitted through two passes was less than 35% of the entrance current.

In recent theoretical work, Lee and Yu[6] have developed a semi-empirical theory which shows that beam pulsations cause the beam emittance to grow until a larger equilibrium radius is achieved. At NBS, the radial envelope equation[2] was solved numerically, including the coupling between emittance growth and radial oscillations developed by Lee and Yu. The results of these simulations, using the NBS experimental parameters, is shown in Figure 6. Large envelope oscillations (followed by damping to a larger envelope size) after passage through the vacuum gap are evident. The effect of solenoid focusing in reducing the oscillations is also clear. The large envelope growth suggests considerable beam loss to the walls, along with a loss in beam quality.

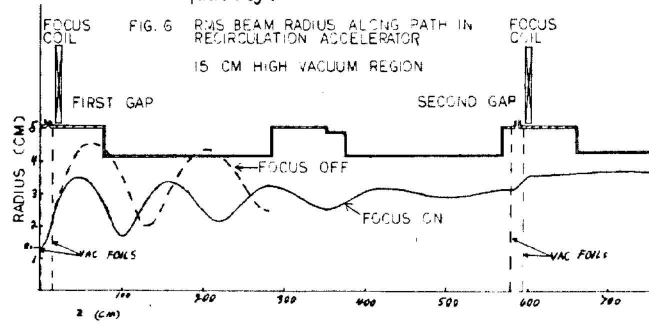

Fig 6 Straight-line schematic of beam line and computed beam envelope through two-pass recirculator with original vacuum gaps. Note z-axis compressed.

These calculations led to the design of accelerating electrodes which reduced the length of the vacuum gap by placing a foil window near the tip of one electrode (Figure 7). The calculated effect of the reduced high vacuum path is shown as a dramatic reduction in the envelope oscillations (Figure 8).

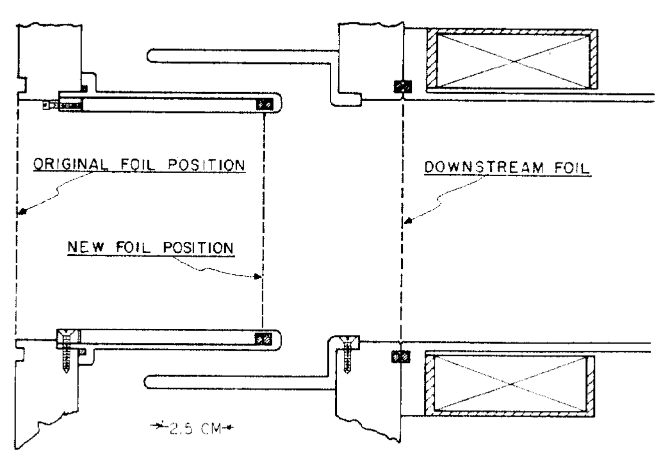

Fig 7 Modified gap assembly, recirculation test acceleration

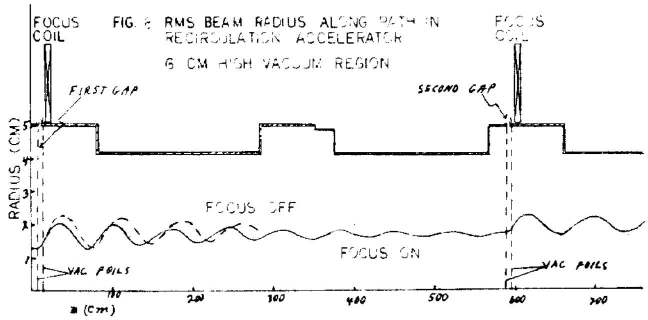

Fig 8 Straight-line schematic of beam line and computed beam envelope through two-pass recirculator with short vacuum region. Note z-axis compressed.

Preliminary beam current measurements with the reduced gap showed an increase in transmission to 45-50%. However, along with improved beam transmission, severe hose instabilities were also encountered. This prevented further study with the recirculation test accelerator using gas-focus beam transport.

Although the narrower gaps reduced mismatch effects, the residual pulsations evident in Figure 8 would lead to considerable beam envelope growth for a beam passing through several gaps, as would be required for meaningful energy gain. Figure 9 shows the best calculated attempt at matching with a focus coil on either side of a 6 cm vacuum gap for the present energy of 0.75 MeV. A 10% envelope oscillation is still present. With the current and emittance of the NBS beam, a smooth match would only be achieved by increasing the beam energy to 1 MeV, as shown by the calculated envelope in Figure 10. For wider gaps (15 cm is more likely for gap voltages over 100 kV) with beams of comparable radius, the minimum beam energy for matching would increase accordingly. Any increase in beam current or emittance would also require higher beam energy for smooth matching.

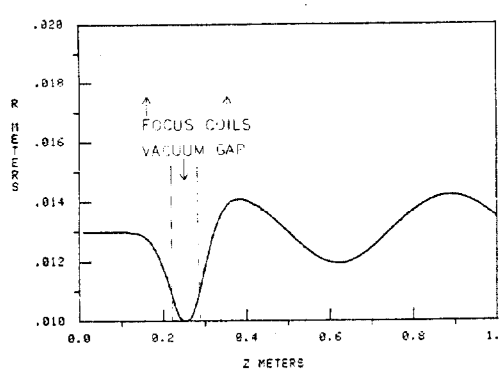

Fig 9 Computed RMS beam radius at E_b = 0.75 MeV

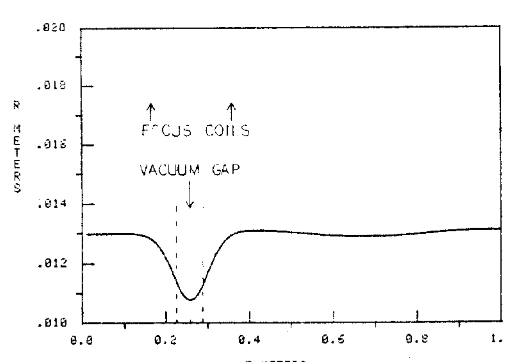

Fig 10 Computed RMS beam radius at E_b = 1.0 MeV

Conclusions

High current beam transport through charge-neutralizing gas is convenient, simple, and inexpensive. However, scattering in the many foil windows and in the extensive path in gas required for a multiple pass high energy gain system would degrade the beam quality considerably. Furthermore, it appears inevitable that, for a long pulse high current electron beam, the hose instability would grow to intolerable amplitudes over any such extensive path in gas.

Vacuum transport is an alternative. Solenoidal focusing at low energy and quadrupole focusing at high energy would be applied in the straight sections between accelerating gaps. The solution to confining a high current beam through the 180° bends lies in matching double-focus, n = 1/2, 90° bending magnets to the ends of the straight focus system. This concept is shown schematically in Figure 11. Focusing forces for these magnets are derived by Livingood.[7] Approximate analytic expressions for the envelope behavior of a high current beam indicate that such a system of focusing elements appears practical up to electron energies of several hundred MeV. It is recommended that a vacuum transport system based upon such elements be used in the next generation of intense beam recirculation acceleration studies.

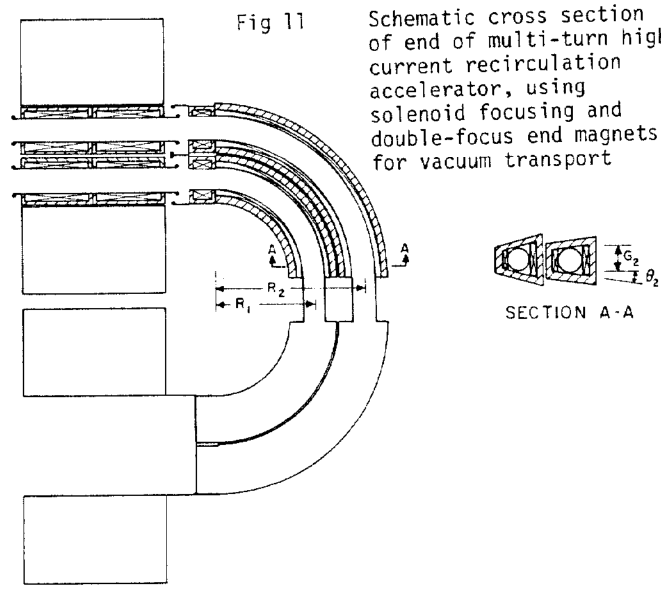

Fig 11 Schematic cross section of end of multi-turn high current recirculation accelerator, using solenoid focusing and double-focus end magnets for vacuum transport

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