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ION FOCUSED TRANSPORT EXPERIMENTS*

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Abstract

We have developed a new technique for generating ionized channels for electrostatically guiding high current relativistic electron beams with ion focused transport (IFT). In IFT, beam electrons are electrostatically focused by a positive ion core left after the plasma electrons are ejected by the beam charge. The new method for channel formation allows beam transport over curved paths for applications in circular accelerators such as Sandia's recirculating linac, and also avoids the need for a UV laser. Our technique uses a low-energy electron beam to ionize a guiding channel in a low pressure gas. A weak longitudinal magnetic field is applied to confine and guide the low-energy beam, enabling one to precisely define the ionization channel. The steady state channel produced by this technique has been diagnosed using Langmuir probes. Channel density and radius were then optimized for beam guiding. Using this method we have efficiently guided relativistic beams with currents exceeding 20 kA over several meters and through a 90° bend. In these experiments with high ν/γ beams, we observed erosion and instabilities which can be important for accelerator applications. PIC simulations of IFT were performed and show stable propagation for high current beams passing through accelerating gaps.

Introduction

Laser-generated ion focused transport (IFT)[1] is a new technique that uses a laser ionized channel in a very low pressure background gas to guide a high current relativistic electron beam by electrostatic attraction to an ion core which is formed when the beam space charge ejects plasma electrons from the channel. The rod of ions focuses the beam leading to the term ion focused transport. IFT is similar to wire guiding[2] in that it can prevent the growth of coherent beam motion by phase mix damping in the anharmonic channel potential. For high current beams, the electrostatic attraction to the ion core is very powerful, and guiding strengths equivalent to a 100-kG solenoidal field can be obtained. Most recently, laser-generated IFT has been used to transport the 10-kA beam through the ATA with good results.[3]

This technology could revolutionize high current accelerator design. However, to fully utilize the IFT technique, a method is needed to steer the beam so that machines with multiple passes through the same accelerating gap are possible. If a way could be found to bend the ionized channel into a closed path or to interconnect multiple straight sections so as to form a closed path, then betatrons, cyclotrons, and other conventional accelerator designs could be extended to the high current regime using the powerful electrostatic forces to prevent beam self-expansion and damp transverse oscillations.

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A particular accelerator application is the recirculating linac[4] which is based on an inductively isolated accelerating gap. (See Figure 1.) Sandia's test-bed facility will use a 2.5 MV isolated Blumlein injector with four passes through the 1.5 MV accelerating gap that is energized with a bipolar waveform from a mismatched transmission line driver (ET-2).[5] This scheme requires four passes around a 30-m delay path. These beam transport requirements can be met with conventional solenoidal beam transport using high applied magnetic guide fields. The magnetic field energy, however, is quite large, and the use of IFT would have a significant advantage. For scaling to higher energies, the advantage would increase. Since laser-generated IFT has already been shown to work well through accelerating gaps, the additional feature needed to make this concept work is beam turning.

One method for turning IFT beams which we have developed uses a dipole magnet to deflect beam particles from one laser ionized guide channel to another intersecting channel. This method is especially useful for high current beam switchyard applications to direct beams to multiple experimental areas or to steer high current e-beams to multiple targets. This technique has been demonstrated by steering a 1 MV, 2 kA beam through a 45° bend.[6] It can, however, lead to a small, but cumulative, emittance growth which is a disadvantage for a recirculating linac where many passes are required. This emittance growth is due to the sharp change in direction at the turn. A smoothly curved channel would lead to a much smaller emittance growth. A method for producing just such a channel has been developed and will be described. This method has the additional benefit of avoiding the need for a UV laser.

New Method for Channel Generation

For IFT, sufficient channel ionization must be provided to overcome beam space charge expansion. This requires $f_e > 1/\gamma^2$, where f_e is the ratio of channel to beam linear charge density. Additional ionization $f_e > \langle\beta_\perp\rangle^2\gamma/\nu$, is required to overcome the finite beam emittance.[7] On the other hand, if $f_e >$ 1, excess plasma electrons will remain in the channel to form a destabilizing return current. We have previously reported laser guiding experiments where both of these limits were clearly observed.[8] In particular, $f_e > 1$ was seen to lead to violent instability and rapid ejection of the beam from the channel. If the gas pressure is not sufficiently low, beam-induced ionization will cause f_e to grow during the beam pulse. To prevent f_e from growing to exceed 1, a very low gas pressure (~ 0.1 mTorr) is required and large UV lasers are needed to ionize this tenuous gas to $f_e > 1/\gamma^2 + \langle\beta_\perp\rangle^2\gamma/\nu$.

Electron impact ionization using low-energy electrons presents an attractive alternative to laser photoionization because cross sections for this process are typically many orders of magnitude larger than two-photon ionization cross sections. Furthermore, the long recombination lifetime of monatomic gases allows the ionization to build up over a long time with a very low-current, low-energy beam. A simple calculation shows that a 1-A, 300-V, 1-cm electron beam will ionize a 0.3-mTorr argon background to an equilibrium density, $n_e = 10^{12}$ in about 10^{-4} sec. Such a low-current, ionizing beam can be guided and confined by a weak solenoidal magnetic guide field, which can easily be provided in either a straight or curved geometry by low current dc energized magnets.

Figure 2 is a simplified schematic of the experimental apparatus. A low-energy, 100-1000-eV, electron beam was generated in an electron gun consisting of a hot tungsten filament and an annular anode plate immersed in a magnetic field. The ionizing beam was extracted through a hole in the anode plate and confined by a 100-Gauss solenoidal field. The field transported the 0.5-cm radius beam down the 3-m length of the 5-cm radius drift tube and formed a luminous ionized channel in various low-pressure (0.1-1 mTorr) noble gases. The channel extended to the graphite cathode of the electron beam accelerator. This allowed the extraction of a high-current beam directly into the channel from the cathode without the used of a foil.[9]

The channel-generation technique was later improved (for experiments on RADLAC II[10]) and a 16-m channel was generated. The anode plate was removed increasing the radial electric field and causing the electrons to spiral down flux tubes with large pitch angles. This greatly shortened the axial mean free path and increased the ionization efficiency. This was further enhanced by installing negatively biased reflector foils at both ends of the channel. The reflectors cause large reflex currents which yield about 50% ionization of the low pressure (~ .05 mTorr) argon gas. Since the electron energy of 200-1000 V is higher than the 100 eV peak of the impact ionization cross section, one electron causes multiple ionization. Also the electron current can greatly exceed the space charge limit due to plasma neutralization.

Because this method produced a steady-state channel, it was simple to measure the plasma column parameters with Langmuir probes. The electron temperature and plasma density were obtained from full current-voltage characteristics of platinum wire probes, measured at several radial positions. A typical IV curve is shown in Figure 3.

Beam Transport Results

The IFT resulting from injection of a 1.5-MeV, 10-kA electron beam into an ionized channel with $f_e = 0.5$ was simulated with a fully electromagnetic axisymmetric PIC code[7] which shows stable propagation. The self-consistent results include motion of plasma electrons and allow motion of the ions which was seen to occur. For runs with a cold beam injected, the beam heated rapidly to equilibrium with $\beta_\perp = (f\ \nu/\gamma)^{1/2}$. Little further heating occurred thereafter. Hall currents, which are observed as current enhancement, are seen for high-current IFR transport. Figure 4 shows particle trajectories for a simulation early in the pulse as plasma electrons are being expelled. The plasma electrons are completely expelled in about 1 nsec leaving an ion core which focuses the beam. This type of propagation should be suitable for application in a high-current accelerator. Indeed, Figure 5 displays a simulation of the passage of a 6-MV, 10-kA beam through an accelerating gap. The beam propagates stably through the gap and picks up the full 2 MV accelerating potential with little emittance gain.

An experiment was performed to test the beam transport properties of the ion channel using the apparatus shown previously in Figure 2. After optimization of background gas pressure, composition, and channel ionization, 1.2-MeV, 40-ns beams with currents greater than 20 kA were transported. The beam properties were monitored by fast current and centroid monitors along the beam line. IFT of such high ν/γ beams implies a very powerful guiding force. Figure 6 shows a typical current waveform as measured by an apertured ($r = 1.5$ cm) current monitor 3 m from the cathode. This optimum transport was obtained with a 0.6-A, 800-V, 0.5-cm-radius electron beam ionizing a 0.3-mTorr argon background.

Transport over this distance was severely degraded when the working gas was changed from argon to helium. With helium at an equivalent ionization level, less than 5 kA was transported over 3 m and the pulse was shortened by erosion of the tail. This may be due to increased instabilities with the lighter ion.

Inductive erosion is predicted to scale with f_e and ν/γ. For the case of large f_e with high ν/γ, we observed very fast risetimes with about 10 nsec of beam front erosion occurring in 1.5 m of propagation. The erosion rate decreased as the beam propagated, implying that some of this loss is due to the slow rise in kinetic energy of the injected beam causing low γ and large emittance on the early portions of the beam pulse. It is also possible that plasma return currents caused radial expansion of the low current portion where $f_e > 1$.

To demonstrate beam steering, the drift tube and surrounding solenoid were bent into a 90° sector with 1.3 m radius. A small transverse field was applied to correct for curvature drift. With these simple modifications, a 25 kA beam was steered through the bend and with > 90% current transport efficiency. The radius expansion and erosion were not measurably different from those which occurred in the straight section.

Summary

A new technique, using a low energy electron beam, has been developed for generating an ionized channel in low-pressure gas for IFT. The new technique should find application to high-current accelerators because it will allow transport around circular paths. This technique has been applied to the experimental investigation of IFT of beams. Preliminary results include observation of inductive erosion for high f_e and increased stability for heavier ions. The new method should lead to improved understanding of IFT because it will allow experiments where high f_e is obtained at very low gas pressures. In addition, since any noble gas can be used, the effects of ion mass on the growth of instabilities can be studied. We have also applied this technique to a 16-m transport section for RADLAC-II beams.

References

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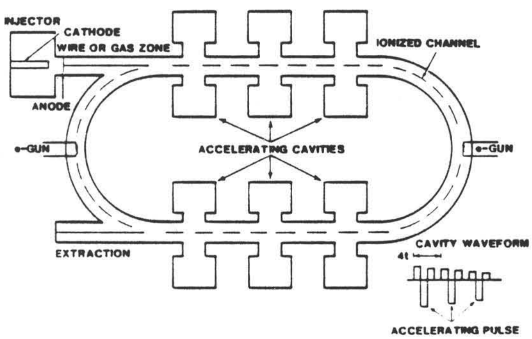

Figure 1. Conceptual design for recirculating linac with IFT.

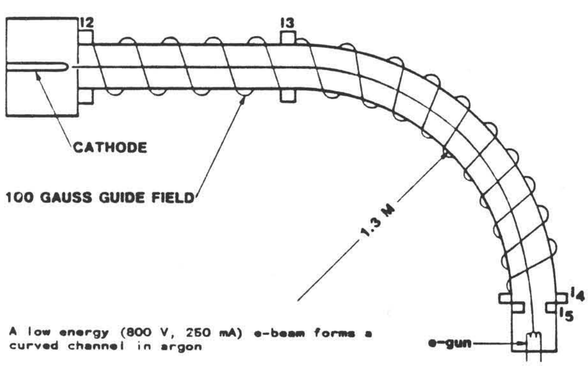

Figure 2. Electron impact channel ionization schematic.

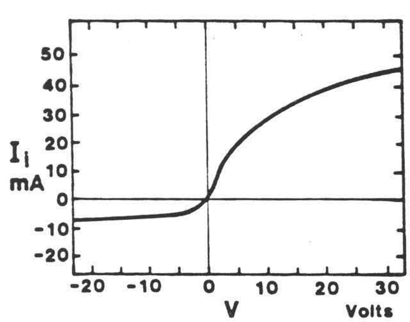

Figure 3. Langmuir probe I versus V curve.

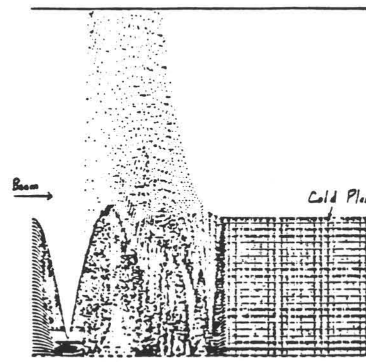

Figure 4. MAGIC simulation of 1.5-MeV, 10-kA, cold beam injected into IFR channel with $f_e \sim 0.8$.

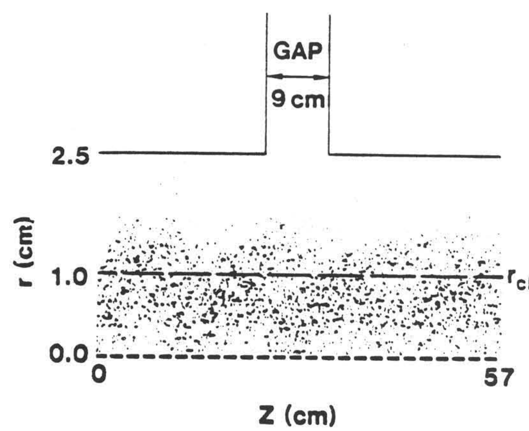

Figure 5. IFT through a 2-MV accelerating gap.

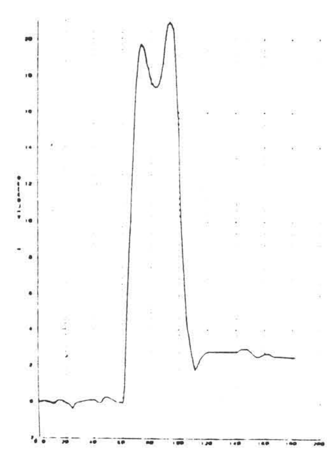

Figure 6. Beam current waveform at Z = 3 m.