IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

A SIMPLE METHOD FOR DAMPING TRANSVERSE MOTION OF A HIGH INTENSITY ELECTRON BEAM

Daniel Steve Prono, G. J. Caporaso, J. C. Clark, E. J. Lauer and K. W. Struve
Lawrence Livermore National Laboratory*
Post Office Box 808/L-436
Livermore, California

Abstract

We describe a simple electrostatic focusing method which efficiently damps transverse motion of a high intensity (both high current and high particle energy) electron beam. The principle is to create an electrostatic central force anharmonic potential field which phase mix damps transverse beam motion into increased beam emittance. The non-linear electrostatic field is created by a very resistive wire (L/R time ~2 ns) strung axially down the accelerator vacuum pipe. Positive image charge equal to ~1/2 the negative beam charge is induced onto the wire. Since the beam self fields cancel to within $1/\gamma^2$, the resultant wire electric field dominates. Experimental results showing the guiding, focusing and damping of transverse motion will be presented.

Introduction

Accelerators that produce high current and high particle energy electron beams are often plagued with difficulties in guiding the beams, and more importantly, in damping out unwanted beam motion. For example, in linear induction accelerators where numerous accelerating cavities are used, a cavity mode-beam interaction, the Beam Break-up instability (BBU),[1] impresses transverse oscillations on the beam. For many applications, transverse motion of the beam is an undesirable phenomenon that adversely affects beam propagation. This paper summarizes experimental results of a simple electrostatic focusing technique that damps transverse motion. Analytic models and simulations of this technique are presented in a companion paper (S-16, Caporaso and Cole[2]). The concept involves creating a positive line charge that is centered on and extends axially down a circular beam vacuum transport pipe. In practice, the positive line charge is created by suspending a highly resistive graphite wire within a beam vacuum pipe. An electron beam injected into this zone induces significant positive charge on the wire; the high resistivity of the wire limits the L/R time to ≅ 2 ns so that transient currents die out quickly leaving a positive electrostatic line charge. The highly anharmonic potential of the line charge causes beam electrons far off axis to oscillate slower than electrons near the axis i.e., the orbital frequencies of the particles depend on their distances from the wire. As the beam particles orbit in an anharmonic potential there occurs a dissipationless process known as phase mix damping.[3] That is, any coherent motion of the beam will eventually damp out since the individual beam particles will fall out of phase with one another. As this damping occurs, the area occupied by the beam in its transverse phase space increases. The emittance of the beam is a measure of this area.

* Performed jointly under the auspices of the U.S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA Order No. 4395, monitored by NSWC.

Experimental Results

Results from two experimental configurations are now presented. Configuration I tested survivability of the graphite wire and tested the focusing/guiding effects of the system. This configuration, shown in Fig. 1, consisted of an experimental tank connected to the ETA vacuum beamline. The experimental tank was 1 meter long, 15 cm diameter and was evacuated to $<10^{-5}$ torr base pressure. The entrance to the tank was a 6 cm diameter aperture covered by a 0.001" thick Titanium foil. The wire passed through a small (1 mm dia) supporting graphite craddle at the center of the entrance foil. This end of the wire was firmly anchored to the outer periphery of the foil, the other end was kept in tension by passing it through a second foil and then attaching it to a weight. The wire diameter is $\lesssim$ 1 mm, and consists of many individual long graphite fibers giving a continuous and smooth surface, and a line resistance of ~1000 Ω/m. Such a configuration survives several days without failure (the accelerator is the ETA[4] which produces a beam of 8 kA, 30 ns, 4.5 MeV, 0.75 cm radius, beam emittance ≅0.15 rad-cm, with a 1 pps pulse rate continously operating for up to 8 hours/day). Note that the wire was drawn through a second 6 cm diameter aperature (without foil) located 75 cm downstream; this tested the focusing capability of the system. Diagnostics which monitored the time variation of beam current and displacement of the beam centroid in two orthogonal planes were located immediately preceding the entrance foil to the tank, at 40 cm and finally at 80 cm immediately after the last aperature.[5] A TV was also used to view beam induced light from the entrance foil and to estimate beam radius upon injection.

Three test cases were run with Configuration I and the results are shown in Fig. 1. Test A was with a 1.5 cm diameter beam delivered on axis to the entrance foil but with no wire installed. The current monitors recorded a decrease in transported current; the rate of decrease is consistent with emittance dominated beam expansion. Test B was with the same beam incident upon the entrance foil but with the wire installed. Nearly total current transmission occurred (>90%) and the beam centroid was held to the axis. The current monitors which are over the wire zone showed a slightly different time response than the injected current due to the transient currents carried by the resistive wire. Test C was to deliver the same 1.5 cm diameter beam to the entrance foil with the wire still axially suspended, but now the beam centroid was displaced by a full beam diameter. Slightly less transport efficiency (~85%) was observed but the beam was returned to the axis.

The experimental arrangement for Configuration II is schematically shown in Fig. 2; this setup is that modeled by the simulations presented in the companion paper by Caporaso and Cole.[2] Here the electrostatic wire zone is located within a continuous beam transport system. This allowed study of the dynamics of matching a beam into the zone and then transporting the beam after it left the zone. Diagnostics consisted of current monitors before and after the zone (total current and centroid movement), a TV to determine entrance beam size, and pairs of

0018-9499/83/0800-2510$01.00© 1983 IEEE

B_θ probes (before and after the zone) which sense the magnitude of the BBU high frequency (800 MHz) spatial oscillations. The supporting foils are 0.003" thick graphite and are separated by 1.4 m. For the experimental results shown, the exit foil was apertured with a 4 cm diameter, thick graphite annulus. The effects of intercepting the weakly electrostatically focused slow rising current and the fact that the low current "wings" are not matched to the transport (hence lost to the walls) cause the sharpening of current rise time as measured by the current monitors. As the data shows, an input beam monitored upstream of the wire zone's matching-focus magnets has an ~8 ns risetime and significant spatial oscillations of the beam centroid (especially of the beam head and tail). The current monitor located downstream of the wire zone and half-way through the output matching-focus magnets measures 90% current transmission with a risetime sharpened to ~3 ns, the beam centered throughout its pulse length and amplitude of centroid displacement decreased by factors of 5 to 10. The oscilloscope traces of the B_θ probes located before and after the wire zone also record the sharpened risetime, but more importantly show the 800 MHz BBU oscillations have also decreased by a factor of 5 to 10.

As indicated in Fig. 2, there is good current transport to a position ~1 meter downstream of the wire zone. However, deficiencies in the magnetic transport system prevented the beam to be properly focused further downstream. Previously with 8 kA exciting the wire zone only 4 kA could be injected into a propagation tank 2.4 mts from the wire zone; this propagation tank has an entrance aperture of 6 cm diameter. By improving the transport after the wire zone we have recently been able to inject >6 kA into the propagation tank.

The difficulty in beam transport after the wire zone arises from two sources. The first is caused by the very rapid expansion of the beam after the wire zone. Throughout the wire zone the beam is strongly pinched. As the beam exits the wire, it rapidly expands and within 16 cm hits the wall, unless it is caught by the strong B_z field of a focusing magnet. The practical difficulty here is that the magnet must have a focal length which is no longer than 16 cm. If the focal length is too long, the magnet no longer acts as a simple lens. Although the beam can be caught before it hits the wall, it then re-pinches and re-expands.

The second difficulty with the beam transport is that the B_z field of any focusing solenoid must be uniform over the radius of the beam pipe. If it is not, then particles at different radii do not have the same focal lengths. Further transport is then complicated because it is not possible to focus the bulk of the beam without over or under focusing the remainder.

The 6" lens magnet, the first magnet after the wire zone, was found to have a field strength that varied significantly across the radius. It was therefore replaced with a 16" (inside diameter) solenoid which has a longer focal length, but is more uniform across the radius. With this change, we can tune for 6 kA into the propagation cell - an increase of 50%. We can now predict computationally the beam current transport given the experimental tune. A comparison of the computed versus the experimentally obtained beam transport is seen in Fig. 3. These computations show that the remaining current loss is due to the longer focal length of the 16" magnet. Efforts are now underway to design a new magnet with a shorter focal length.

Conclusion

In summary, a new and simple method for beam transport and control has been discussed. Experimental results are in qualitative agreement with simulations which show effective focusing and damping of a transversely displaced electron beam. The technique promises to be of significant benefit in reducing the amplitudes of various accelerator instabilities and undesirable transverse beam offsets.

References

1. V. K. Neil, L. S. Hall and R. K. Cooper, Part. Accel. 9, p. 213, (1979).
2. G. J. Caporaso and A. G. Cole, Proc. of the 1983 Part. Accel. Conf., Paper S-16, to be published in IEEE Trans. on Nuc. Sci. (June, 1983).
3. E. P. Lee, Phys. Fluids 21, p. 1327 (1978).
4. T. J. Fessenden, et al., Proc. of the 4th Int. Topical Conf. on High Power Electron and Ion-Beam Research and Technology, p. 813 (1981).
5. T. J. Fessenden, B. W. Stallard and G. G. Berg, Rev. Sci. Instr. 43, p. 1789 (1972).

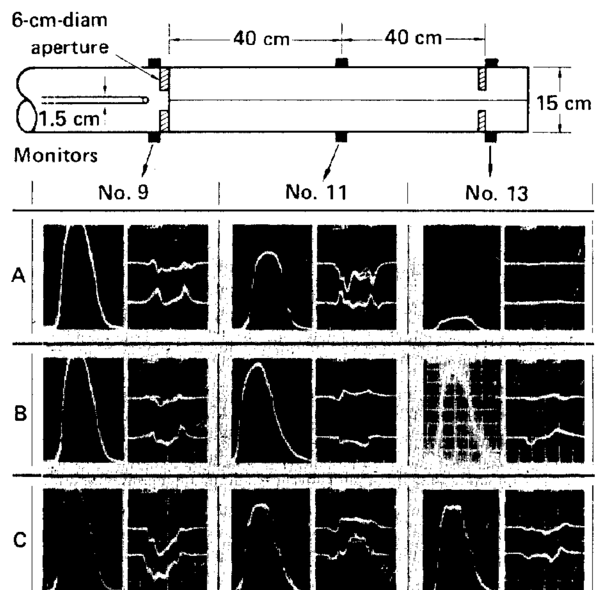
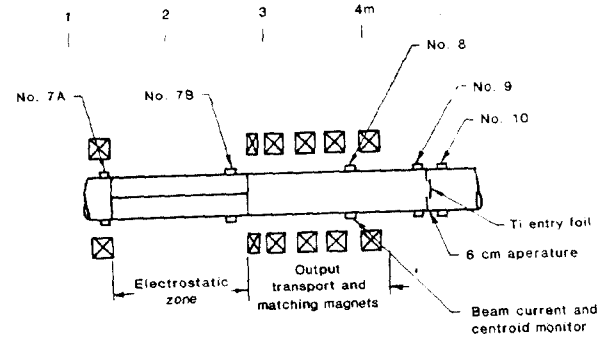
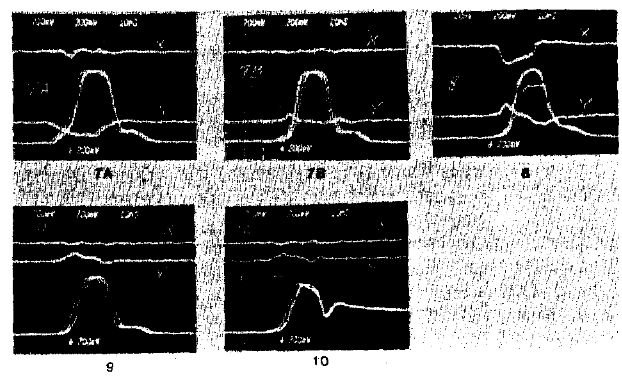


FIGURE 1

The schematic indicates the experimental arrangement of Config. I. Shown are measurements in three axial locations (Z = 0, 40 and 80 cm) of beam current (1 kA/div, 10 ns/div) and current weighted beam centroid displacement from axis in the X and Y plane (at peak current 1/2 cm/div, 10 ns). The three data sets correspond to the experiments described in the text.



(b)



(c)

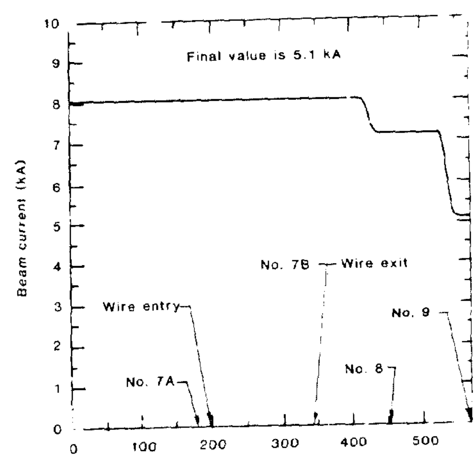


FIGURE 3

Improved transport of beam current through the wire zone to the gas entry foil. The locations of beam current monitors and magnets are shown in (a). The beam currents and X and Y offsets are shown in (b) at 2 kA/div and 10 ns/div. The computed beam current is shown in (c), based on B_Z field time used experimentally.

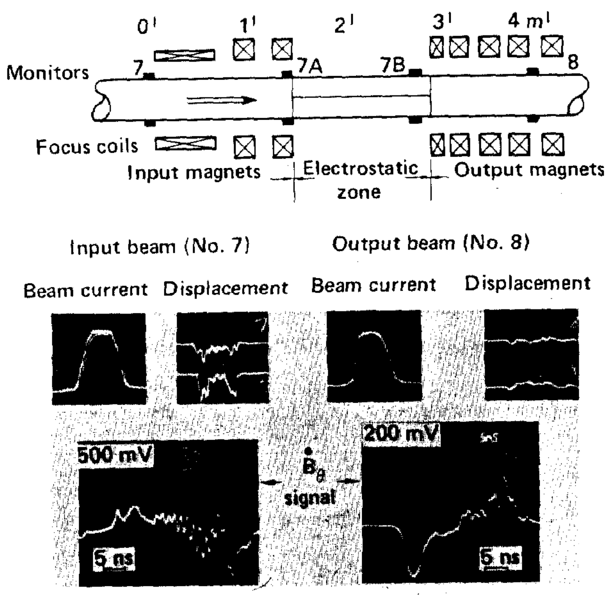


FIGURE 2

The schematic indicates the experimental arrangement of Config. II. The data shows beam current (2 kA/div, 10 ns/div) current weighted beam centroid displacement (at peak current 1 cm/div, 10 ns/div) and $\dot{B}_\theta$ signals (5 ns/div) before and after the electrostatic zone. The $\dot{B}_\theta$ signal is proportional to d/dt (I/r) where r is distance from beam to probe. Four probes, each 90° apart were actually used at each axial location to insure that geometric correction factors were accounted for. The downstream $\dot{B}_\theta$ scale is 2.5 times more sensitive than the upstream scale.