STATUS OF BEAM TRANSPORT WITH THE ETA AND ATA ACCELERATORS*

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Introduction

Efforts are now underway to improve both the production of electron beams and their transport through the Experimental Test Accelerator (ETA) and the Advanced Test Accelerator (ATA). These efforts are focused on lowering the emittance and reducing the transverse motion of these beams. There are many possible sources and solutions to these problems. In this paper we discuss a limited subset of these: namely, (1) phase-mixed damping of transverse motions with a wire zone, (2) efforts to find and correct possible magnetic focusing misalignments or errors, (3) azimuthal drift of the beam caused by the image displacement effect in the accelerator gaps, and (4) growth of the beam breakup[1] instability through the accelerators. These problems are common to both machines. However, because of its much longer length, they become more apparent with the ATA. Therefore, much of the discussion will be on ATA results, even though the problems and solutions apply equally well to the ETA.

Description of the Experiments

The ETA accelerator is described in detail elsewhere.[2] The ATA is described in a companion paper.[3] Both machines are of similar design; the main difference is that the ETA has eight accelerator cavities, and the ATA one hundred and seventy. Both have 2.5 MeV, 10 kA injectors which use spark-board surface flash-over cathodes.[4] The diagnostics in the ETA and ATA consist mainly of rf B_θ loops, and resistive wall current monitors, which are also called "beam bugs." In the ETA both are located throughout the machine,[5] and in the ATA between each cell block, as shown in Fig. 1. The rf loops produce a signal proportional to d/dt (I/r), where I is the beam current and r the distance from the probe to the beam center. Near the peak of the beam pulse, where dI/dt is small, the signal is proportional to the frequency and amplitude of the transverse motion of the beam. The beam bugs are used to determine x and y positions. For the ATA experiments, average x and y positions have been plotted. Additional rf loops, beam bugs, and an energy and emittance analyzer are located at the end of the ATA. Beam intercepting diagnostics for measuring beam size are also placed throughout the accelerator.

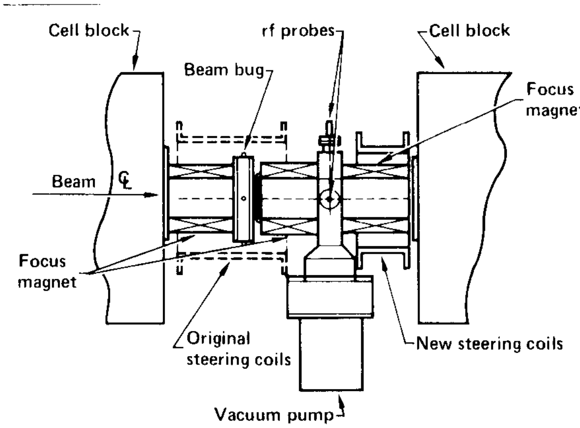

Fig. 1. Typical ATA Intercell Section.

Wire Zone Damping

Transverse motions of the beam due to energy variations in the head and tail of the pulse, or due to the beam breakup oscillations have been significantly attenuated using a wire damping zone.[6] The wire, which is a resistive carbon filament, electrostatically focuses the beam and provides an anharmonic potential through which coherent motions of the beam are phase-mixed damped. As this damping occurs the area in phase space that the beam occupies, which is its emittance, is increased. ETA wire zone damping has reduced transverse head and tail motions and beam breakup oscillations by nearly a factor of ten. In doing this, beam rms normalized emittance has increased from 0.6 rad-cm to about 1.5 rad-cm. The ATA has also deployed a wire zone at the 10 MeV level and seen similar results.

A difficulty in using this damping technique is that of catching and transporting the beam at the end of the zone. Throughout the wire zone the beam is strongly pinched. As it exits the wire, it rapidly expands and hits the wall within a very short distance unless caught by a focusing solenoid with a short enough focal length. Presently on ETA, there is an approximate 10 percent loss of current after the wire zone because a magnet with a sufficiently short focal length has not been available. A new solenoid with a shorter focal length and with a uniform field across the beamline has been built and is being installed.

Error Field Measurements

For investigating possible magnetic alignment errors in the solenoidal focusing of the ATA a low current probe beam was used. By using low current, it was possible to study particle motion in the applied fields without the complications associated with the self-forces of high currents. With the steering magnets off, the transverse drift of the probe beam was measured. The probe beam was then used to optimize the current in the steering magnets to compensate for the drift.

For these runs, the wire zone was in place between accelerator cells 20 and 25 to center and desweep the beam. A 100 Amp probe beam was produced with a 0.6 cm diameter aperture at the variable attenuator just upstream of cell 25. A uniform 2800 Gauss focusing field was was used starting with cell 25, and no steering was applied. The beam was observed to drift off center, as shown in Fig. 2. (The beam bugs are numbered consistently with the accelerator cells. For example, beam bug 180 is the monitor just after cell 180.) The beam center drifted east about one cm in the first cell blocks, then drifted more slowly for the next few cell blocks and finally drifted another cm east in the downstream region. There is also a small upward drift.

The beam can be modeled as having a center of mass which undergoes cyclotron motion about a guiding center with the guiding center following a magnetic flux line. The flux line drift is given by

$$\frac{B_x}{B_z} = \frac{x}{N\,L} \qquad (1)$$

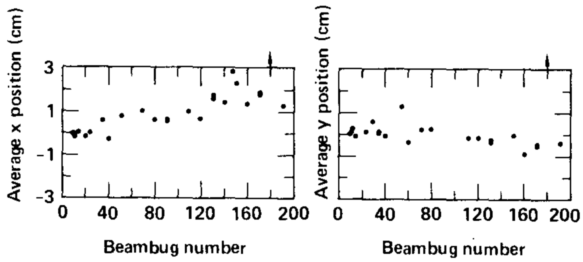

Fig. 2 Probe beam drift with no steering applied.

where B_z is the axial field, B_x is the horizontal component of error field, x is the horizontal displacement of the flux line, L is the length per beam bug space and N is the number of spaces. There is also a similar equation for y. Solving Eq. (1) for B_x, noting that the horizontal displacement is approximately 1 cm and that L is about 370 cm, gives an average error field of about 1.3 Gauss. A localized error field could be much larger. Tests are now underway to find the source of the error field.

It was originally thought that the transverse drift might be associated with an asymmetrical drive from the accelerator cells. The cells were turned off and no difference was seen, indicating that the pulsed power was not the cause. All ferrous materials are being removed from the vicinity of the beamline. A magnetic probe is now being developed that can traverse an ATA cell block and pump station, using a three-axis Hall effect probe. The largest problem is one of alignment. The average distributed error field is about 1 Gauss, but the nominal axial field is 3 kilogauss. This requires an alignment accuracy of 0.3 mrad. Initial measurements using a laser for the probe alignment indicate that there are no localized error fields of order 10 gauss or larger within one ten-cell accelerator block. Efforts are continuing to extend the measurements into the intercell pump station area, and to other cell blocks.

The probe beam experiments were also done with steering fields applied to center the beam. The beam still exhibited a small drift. In comparing the measured beam offset with that which was expected it was found that the effective magnetic field generated by the steering coils was 50 Gauss-cm/ amp, which is only 60 percent of the designed field for these coils. The field plots of this region showed that the low value and a bad field distortion was caused by the ferrite rings in the beam bugs, which were mounted under the steering coils. The distortion was also found to be more severe near the wall, causing the steering to depend on both the offset and the diameter of the beam. New steering coils are being built and will be placed away from the beam bugs.

Azimuthal Drift of the Beam Center

Higher current beams (>3 kA) follow a much different trajectory than low current beams. Beam bug data from both ETA and ATA suggest a spiraling of the beam centroid about the centerline. One of us (Lauer) has suggested that this motion is due to the image displacement force in the accelerator gaps. The rotation can be calculated as a guiding center $\vec{E} \times \vec{B}$ drift. In esu units, the electric field at the gap is

$$E_r = -\frac{2\ I/c}{\beta\ (r'-r)} \quad . \qquad (2)$$

The distances r and r' are to the beam and its image. Since there are many accelerating gaps per cyclotron period, the E-field is averaged to L_g/L times that of eq. 2, where L_g is the gap length and L is the distance between gaps. Also, the image distance is $r' = a^2/r$, where a is the beamline radius. A first principles calculation of the wavelength of the azimuthal drift gives

$$\lambda_{drift} \cong \frac{\pi c a^2 L\ B_z}{I\ L_g} \quad . \qquad (3)$$

For an ATA test at 3.3 kA, B_z = 2800 gauss, $L_g/L \cong .1$ and a = 6.7 cm λ_{drift} is 122 meters compared to 90 meters as determined from the data. Also, the calculated orbital phase of the beam centroid is in agreement with the data. This motion can be overcome by adjusting the steering to compensate for the error fields.

Growth of the Beam Breakup Instability

With initial operation of the ETA at 8 to 10 kA, beam breakup oscillations at 800 MHz associated with the TM_{130} resonant mode of the cavities become severe. Growth at other modes was not seen. The Q of this mode was reduced from 41 to 7 in the ETA by ferrite damping of the cavities. Similar damping in the ATA cavity has reduced its Q to 4. With these changes beam breakup oscillations are barely detectable on ETA below 8 kA. Even with 10 kA operation it is not severe enough to disrupt beam transport. With operation of the ATA with a field emission brush cathode it has been possible to observe the beam breakup instability without complications of large perturbations. Beam transport was now seen to be now affected by this instability, especially as the current and current rise time are increased. For a slow rising, 5 kA pulse, as seen in Fig. 3, it was possible to transport the entire 5 kA beam through the accelerator without loss of charge. With a slow rising 7 kA pulse, as shown in Fig. 4, the tail end of the pulse was lost by the time it reached the end of the accelerator. Less charge was transported to the end of the machine than with the 5 kA beam. When a faster rise time is used, even less charge is transported to the end of the accelerator. In both 7 kA tunes the tail of the pulse is lost to beam breakup oscillations. This effect is shown by the B_θ loop signals in Fig. 5. Large 800 MHz beam breakup oscillations appear near the peak of the pulse at the end of the accelerator.

Growth of the beam breakup oscillations through the ATA was measured for the 5 kA beam. A plot of rf amplitude of the 800 MHz oscillations versus cell number is seen in Fig. 6. The growth rate is very close to the predicted value. Preliminary analysis of the data shown in the figure indicates that the $Z_\perp$, the product of $Z_\perp/Q$ and Q, for the ATA cavities is 33 $\pm$ 4 Ohms. This compares favorably with the best

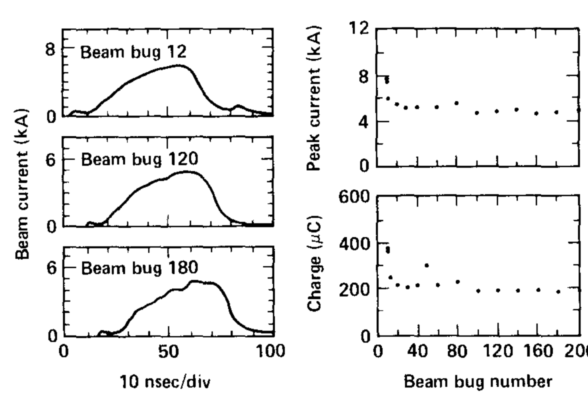

Fig. 3. Beam transport with a small dI/dt, 5 kA brush cathode.

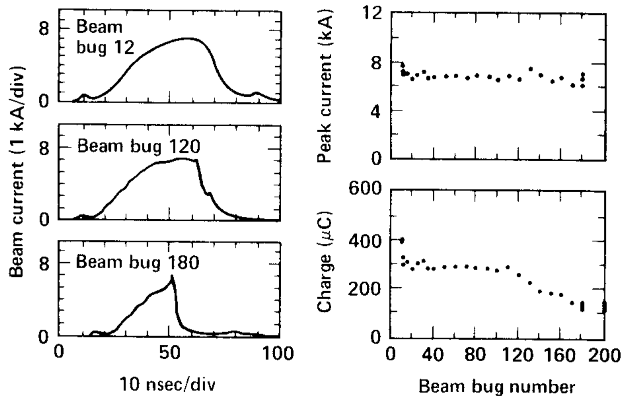

Fig. 4. Beam transport with a small dI/dt, 7 kA brush cathode.

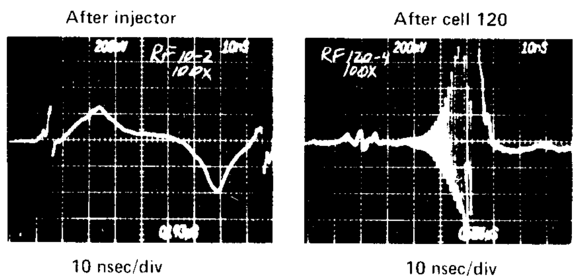

Fig. 5. B_θ loop signals showing growth of beam breakup oscillations for a 7 kA tune.

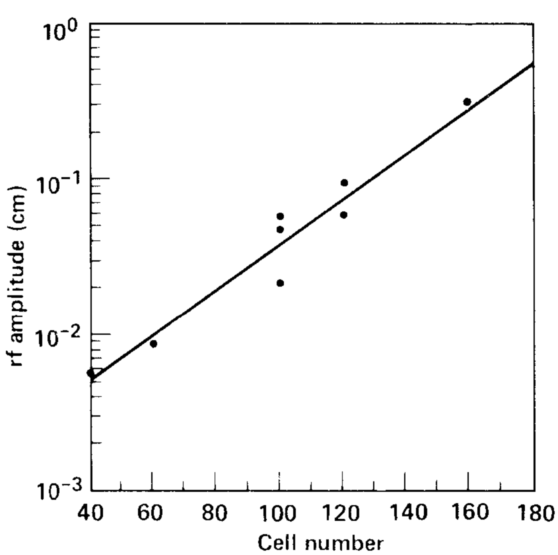

Fig. 6. Amplitude of the 800 MHz oscillations versus beam bug number.

estimate of $Z_\perp$ based on ETA measurements of $Z_\perp/Q$ which implied that $Z_\perp$ is in the range of 28 to 32 Ohms.[5] The final amplitude, however, is approximately a factor of ten higher than that predicted based on noise levels of the ETA using the flashbord cathode. This is due to larger than expected excitation levels, perhaps from the helical motion of the beam, or from cathode effects.

Conclusions

Phase-mixed damping of transverse beam motions using a resistive wire has been seen on both ETA and ATA and has reduced these motions by roughly a factor of ten. An average 1 gauss transverse error field in ATA has been found but that error is not considered severe. Investigations are continuing, however, to find its source and to eliminate it. Indications are that the error fields combined with the image displacement effect have caused an azimuthal drift of the beam. Beam breakup growth rates in the ATA were as predicted. Efforts will continue to reduce the initial noise amplitudes to further limit its effect on beam transport.

References

1. V. K. Neil, L. S. Hall, R. K. Cooper, Particle Accelerators 9, 213 (1979).

2. R. E. Hester et al., IEEE Trans. Nucl. Sci. NS-26, 4180 (1979); and T. J. Fessenden, et al., IEEE Trans. Nucl. Sci. NS-28, 3401 (1981).

3. R. J. Briggs, "High Current Electron Linacs (Advanced Test Acceleratory/Experimental Test Accelerator)," to be presented at LINAC '84 Conference in Darmstadt, West Germany June 7 - 11, 1984; Lawrence Livermore National Laboratory, Livermore, California UCRL-90395.

4. G. J. Caporaso, D. L. Birx, Lawrence Livermore National Laboratory, Report UCRL 85613 (1980).

5. G. J. Caporaso, A. G. Cole, and K. W. Struve, IEEE Trans. Nucl. Sci. NS-30, 2507 (1983).

6. D. S. Prono, G. J. Caporaso, J. C. Clark, E. J. Lauer, and K. W. Struve, IEEE Trans. Nucl. Sci. NS-30, 2510 (1983).

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