Time-dependent Degradation of an Ion-Focused ATA Beam*

W.M. Fawley, J.K. Boyd, G.J. Caporaso, F.W. Chambers, Y.P. Chong, J.S. Hildum, P. Lee,† T.J. Orzechowski, D.R. Rogers, K.W. Struve, and J.T. Weir

Beam Research Program

Lawrence Livermore National Laboratory

Abstract

We have made detailed measurements of the time-dependent beam quality of an ATA pulse transported on a KrF laser-photoionized benzene channel. We have found that the tail portion ($\tau \geq$ 20-30 ns) of the pulse becomes severely degraded both at high currents (I > 3 kA) and at long transport distances. Non-axisymmetric channel ion motion is suspected as the predominant source of the problem. We discuss various experiments which varied laser properties (timing, fluence, profiles), background ion pressure, and electron beam current in order to study the physics behind this degradation.

Introduction

The Advanced Test Accelerator (ATA) is a high power (2-10 kA, 50 MeV), induction linac currently supporting both free-electron laser and endoatmospheric charged particle beam experiments. Although ATA was initially operated with continuous solenoidal focusing, beam-breakup instability (BBU) growth limited to ~5 kA the maximum amount of current that could be accelerated to full energy. Furthermore, transverse field errors within the solenoids, when coupled with a small amount of temporal energy sweep, induced a corkscrew mode [1] that itself could excite BBU growth and/or emittance degradation.

Following successful experiments on the 4.5 MeV ETA [2], a new form of focusing - "laser-guiding" - was adapted to the ATA [3] in late 1984. This type of transport uses a low power KrF laser to photoionize very low pressure (0.1-0.2 mT) benzene; the resulting ion channel then electrostatically guides the high current ATA electron beam. Both the high strength (equivalent to $\geq$ 5 kG solenoidal equivalent) and anharmonicity of the ion focusing permit transport up to 12 kA of beam current without noticeable BBU degradation.

However, as we obtained additional experience with laser-guiding on the ATA, a number of disturbing features were uncovered. First, if the short ($\tau \approx$ 27 ns) KrF laser pulse was timed well in front ($\geq 4\ \mu$s) of the injector pulse, large amounts (exceeding 20 kA) of "laser current" - that is, free electrons from the ionized benzene - would be accelerated in the gaps just before the cathode pulse arrived. We minimized this problem by moving the laser timing to just before or on top of the injector pulse. A second, more serious problem became apparent after a number of both high current ($\geq$ 5 kA) beam propagation and moderate current ($\sim$ 2 kA) FEL experiments: measurements of the electron beam emittance after the last accelerating cell block showed a monotonic increase with time in the pulse body.

We conducted a series of experiments in the spring of 1988 to investigate the physics of emittance degradation on laser-guided transport. In particular, we wanted to examine the roles played by: 1. electron beam current; 2. laser timing, fluence, and profile; 3. solenoidal/ion focusing match point conditions.

Diagnostic Ensemble

Three spatially distinct diagnostic stations were established along ATA. The first two, located just beyond cell 15 (4.25 MeV) and cell 90 (22.5 MeV) respectively, included both x-ray bow probes and insertable Cerenkov foils. A third location, approximately five meters downstream of cell 200 (by which point the beam has made a transition from ion guiding to magnetic quadrupole transport), included both a Cerenkov foil and a triple-slit emittance selector (TSES). The bow probes are thick tungsten-powder filled carbon crucible rods which are scanned transversely through the electron beam. The Cerenkov foils are thin (10-30 mil) quartz sheets (see conference paper by Chong et al. for a more complete discussion). The TSES consisted of three apertures, each drilled into a range-thick, 10 cm piece of POCO graphite, separated from each other by $\sim$ 2 m. Resistive current monitors were located downstream of each aperture. The TSES provided an accurate measure of the core brightness of the e-beam in the range 5×10^6 to 2×10^8 A/(m − rad)^2. In addition to these specialized diagnostics, we had the normal complement of ATA resistive current monitors and RF loops located at 5 and 10-cell block intervals.

Observational Results

Current Dependence

The first parameter we varied was the beam current. This was done by changing the solenoidal field and thus the acceptance of the "matching" collimator just beyond the 2.5 MeV injector. This collimator is a 1-m long, narrow (2-cm inner diameter) copper pipe which serves as a transition zone from solenoidal to ion-focused transport. The narrowness ensures (in theory at least) that the e-beam matches onto the harmonic part of the 2-cm wide ion channel, thus minimizing emittance growth, and also provides a linear ramp in benzene pressure. We concentrated on three current values: 1, 3, and 6 kA.

Measurements of high-current beams showed severe time-dependent emittance degradation as early as the cell-15 diagnostic station. As illustrated in Fig. 1, the beam radius could

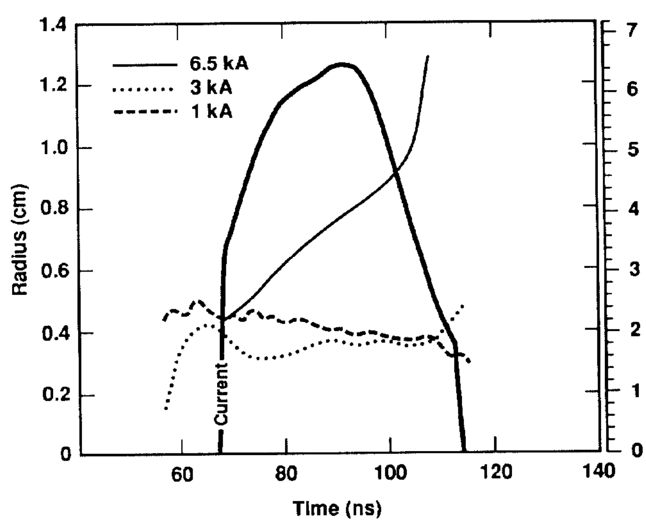

Figure 1. X-ray bow probe scans at cell 15 of three different current ATA beams. The data were fit with gaussian profiles.

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† GA Technologies, Inc.

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grow by as much as factors of 2.5 over 20 ns of pulse. Gated Cerenkov foil light measurements at the same location confirmed the degradation. By cell 90, the pulse remained large ($R_b \geq 7$ mm); presuming constant ion channel strength, the beam radius should have decreased 35% relative to the cell-15 value if the normalized emittance had remained constant (*i.e.*, $R_b \propto \varepsilon_N^{+1/2}\gamma^{-1/4}$).

At moderate currents (I $\sim$ 3 kA), the cell-15 diagnostics generally showed constant radii over the main body of the pulse with mild tail flaring apparent only on some occasions. However, by cell 90, the beam body and tail were degraded, with beam radii growing in time from $\sim$ 2.5 to 6 mm.

At very low currents, measurements at both the cell-15 and cell-90 diagnostic stations indicated temporally flat beams, with beam sizes generally at the resolution limit of the bow probe.

Despite the current sensitivity at cell 15 & 90, the TSES diagnostic beyond cell 200 exhibited similar core brightnesses and temporal dependence for all three current levels. In Fig. 2, we plot the temporal current profiles before and after each of the three apertures. Despite a reasonably wide pulse before the apertures, only 10-15 ns passed through the second and third slits. In all cases, the bright portion of the beam was at the front end with the third slit typically passing about 100 A corresponding to $J \sim 3.5 \times 10^7$ A/(rad $-$ m)^2. The brightness degradation of the beam tail was so extreme that we were unable to find a set of quadrupole magnet strengths that maximized tail rather than front transmission through the TSES.

Dependence on Laser Properties

During the course of the experiment, we purposely varied many of the KrF laser properties: relative timing, intensity, profile, and total pulse energy. We also could use two separate KrF lasers simultaneously, each with its own individual timing circuit..

One of the most interesting phenomena was the "movement" of the bright portion of the electron beam pulse in conjunction with the laser timing. We varied the timing of the laser pulse to that of the injector by as much as 50 ns and studied the beam properties at our various diagnostic stations. Without fail, we found that the bright spike transmitted by the TSES moved in lockstep with the laser timing (see Fig. 2). Often but not always, "late" laser timing led to a brighter current spike through the third aperture (monitored by BB2200). Similar observations were made with the streak camera at cell 15; as the laser timing moved into the e-beam pulse, the flare on the main body would move later in absolute timing. These results suggest that the cathode was not responsible for the temporal emittance degradation and that another phenomenon, such as channel ion motion, was the agent.

In order to examine the effects (such as increased anharmonic mixing) of a more "wire-like" channel, we used telescope optics to reduce the laser profile from a 1 $\times$ 2 cm rectangular spot size to one approximately half as large (500 mJ $\rightarrow$ 250 mJ). The laser energy on the channel also decreased by a factor of two, so the net fluence increased by two (at these fluence levels, benzene photoionization increases linearly, not quadratically with laser fluence). Nonetheless, measurements at all three beam current levels showed only moderate sensitivity to the laser profile changes. As before, a 6-kA beam showed radius blowup by cell 15, a 2.5-kA beam by cell 90, and all currents just a 10-15 ns spike of high brightness through the TSES. However, at the higher fluence levels, emittance degradation appeared by cell 15 for a 2.5-kA beam and, at 6 kA, beam sweep at the $\sim$5-mm level became evident just beyond the collimator. When the laser energy was reduced by another factor of two (thus returning the fluence to the nominal value used on the fatter channels), both the cell-15 and cell-90 diagnostics showed temporally flat radii for moderate current

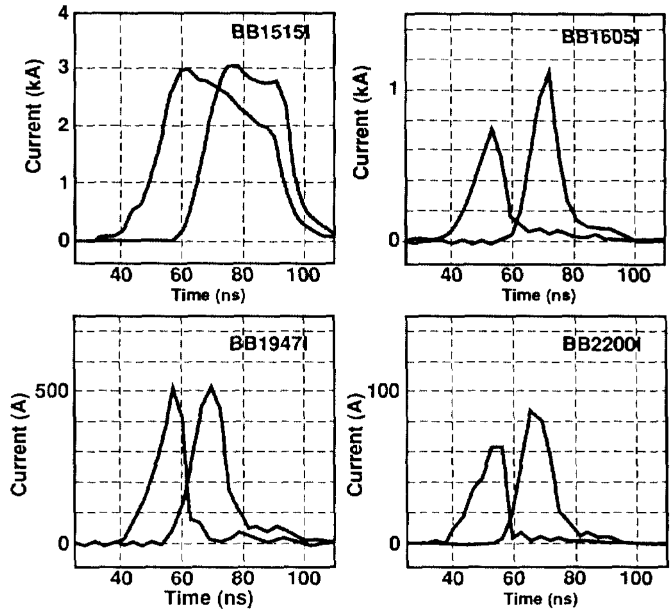

Figure 2. Resistive current monitor readings upstream (BB1515) and downstream of each of the TSES apertures. The left trace on each plot represents laser timing just before and the right trace laser timing $\sim$ 25 ns later than that of the injector. As explained in the text, the maximum core brightness (*i.e.*, BB1947 and BB2200) moves temporally with the laser timing.

beams, although there was essentially no change in the TSES measurements of the downstream beam brightness. When the telescope optics were removed, the e-beam brightness increased by $\sim$ 75%. Another test involved a change from a rectangular to circular profile. Apart from fractionally greater current transmission through the collimator, there was little change in the TSES measurements.

Although the laser beam has a rectangular pattern in the near-field, in the far-field beyond cell 100 there is extensive filamentation, with three or more major spots developing. We alternated use of the two lasers on various occasions, but detected little sensitivity in the current transmitted through the TSES to the individual filamentation patterns. More interesting results appeared when we staggered the firing times of the two lasers, thus extending the duration of ion creation. Although the TSES data remained insensitive to the relative timing, streak camera data at cell 15 showed a significant delay of the radius "flaring" when laser #1 was timed with the injector pulse and #2 was fired 30 ns later. When we purposely misaligned the two lasers in angle so that their downstream central positions were approximately 1 cm apart, the TSES currents dropped substantially, indicating that each channel captured some portion of the electron beam, thus increasing the phase space volume occupied.

Dependence upon collimator match conditions

Once we discovered the spatially-rapid degradation of high current beams, we studied the degradation sensitivity to the match condition from magnetic to ion-focused transport just beyond the injector. Apart from the aforementioned laser parameter variations, we also at different times changed the benzene pressure, the collimator radius, and the "bucking coil" current which zeroes the solenoidal field immersing the cathode.

Experimental variation of the benzene pressure indicated that while the maximum brightness measurements at the TSES correlated with low pressures ($\leq$ 0.1 mT) and late laser timing, the cell-15 bow probe and Cerenkov light data were insensitive to the variation, apart from a slight tightening of the early part of the beam pulse at the lowest pressures. High current transport, however, generally required larger benzene pressures ($\geq$ 0.15 mT) to match the beam onto the ion channel (in general, if the beam was well-matched just beyond the collimator, RF loop measurements indicated no noticeable BBU activity growth down the accelerator).

We also took data with a larger (4 cm diameter) collimator. Here we were interested in determining whether the increased ion collapse time from the collimator walls would lead to a noticeable effects on the emittance degradation time scale. We had difficulty, however, in matching the beam onto the ion channel and found it necessary to reduce strongly the solenoidal magnetic field over the collimator to avoid passing the entire 9+ kA injector current. With this caveat, neither the cell-15 diagnostics nor the TSES indicated any change in time scale of the degradation or in peak brightness of the front part of a high current beam pulse.

With the larger collimator, we also examined the sensitivity of the emittance degradation to the bucking coil strength. In particular, we noticed that at higher currents, much larger transverse beam sweep than usual appeared just beyond the collimator and that this sweep could be reduced by adjusting the bucking coil current up or down from its nominal value. Threading the 12.5 cm diameter cathode with 15 gauss of field increased the duration of the well-pinched portion of the pulse head at cell 15 from 15 ns in the nominal (zero field) case to nearly 35 ns. However, the current transmitted through the collimator decreased from 5.3 kA to 3.8 kA and the pulse radius in the beam head increased from 5 to 6 mm.

Analysis

During the course of the experiment, no one phenomenon appeared to be solely responsible for the emittance degradation of an ion-focused ATA electron beam. We were able to rule out a number of agents: time-dependent injector emittance (from the laser timing variations), BBU instability (from the laser fluence, profile, and benzene pressure variations and from the RF loop measurements), and downstream laser filamentation (from the laser profile variations and degradation appearing as early as cell 15).

The data set considered as a whole does show some intriguing patterns. First, the stronger the ion channel at the match point, be it due to increased laser fluence or collimator pressure, the stronger the emittance degradation. Second, the bright portions of the electron beam tend to occur simultaneously with ion creation and the duration of the bright portion of the beam can be extended by delayed firing of a second laser. Third, the greater the beam potential, the more rapid (in z) the degradation. Fourth, there is no direct correlation between the degradation and enhanced beam transverse motion. Fifth, the addition of azimuthal canonical momentum to the e-beam appears to lengthen the time scale and reduce the magnitude of the degradation.

From these patterns, we conclude that there are probably two related phenomena occurring simultaneously: 1) following the collapse of a non-axisymmetric channel, there is a match-point discontinuity between the solenoidal and ion focusing which degrades the emittance at late times for high current beams; 2) beyond $\sim$ cell 100 at all current levels, there is extensive beam "hopping" between channel filaments in the far-field of the laser.

In support of the first assertion, we note that independent *axisymmetric* particle simulations (including both channel electrons, ions and beam electrons) done at LLNL by one of the authors (J.B) and at NRL (R. Hubbard) have not been able to replicate the magnitude of the observed emittance degradation at cell 15. In contrast, *dipole* mode simulations done both at Mission Research Corp. (B. Godfrey) and at SAIC (C. Yee and L. Feinstein) have shown that a virulent ion hose instability [4] should significantly heat the tail portions of the ATA beam by cell 15. However, the general absence of beam sweep between the collimator and the cell-15 diagnostic station under a variety of beam and channel conditions make us consider "classic" ion hose a secondary possibility. Instead, we currently support an explanation that depends both upon the non-uniformity of the laser pattern (*i.e.*, hot spots) and its rectangular shape in the near-field. As this pattern collapses on a time scale of $\sim$ 10 ns, the non-uniformity worsens and the strong, non-axisymmetric anharmonic potential can lead both to the formation of an extensive beam halo and to degradation of the central core brightness without large ($\geq$2 mm) beam sweep developing. The addition of canonical momentum to the e-beam would make it stiffer to collapse on the shrinking ion column and would also have an "averaging" effect over azimuthal non-uniformities. Similarly, the creation of new channel ions by delayed firing of a second laser would also have an averaging effect. The weaker potential of lower current beams will be less effective in compressing the rectangular ion channel. However, the time scale only increases as $R_b/\sqrt{I_b}$ and we are not completely comfortable with this explanation for the absence of observable degradation at cell 15 for 3-4 kA beams. We hope to do more extensive non-axisymmetric simulations, including quadrupole and higher order modes, in the near future to examine this point more fully.

Regarding the second assertion, the laser filamentation beyond cell 100 must cause some degree of emittance degradation; moving filaments would make this degradation time dependent. Following acceleration to $\geq$ 25 MeV, low current (2 kA) ATA beams become very small ($\leq 2-3$ mm), and benzene ion slosh times decrease to $\sim$ 10 ns, leading to the hypothesized filament movement and possible beam "hopping". When the laser timing is "late", there is a temporal smearing out of the filament motion and consequently less brightness degradation. Similarly, lower benzene pressures would increase the e-beam radius and thus the slosh time. Possible future experiments with a "cleaned-up" laser beam can explore these issues more fully.

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