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RECENT PROGRESS OF THE ADVANCED TEST ACCELERATOR*

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The Advanced Test Accelerator (ATA) of Lawrence Livermore National Laboratory is a linear induction accelerator whose electron beam parameters are 10 kA, 50 MeV, and 70 ns. This accelerator structure basically is a 2.5 MeV injector followed by 190 identical induction accelerator cores each of which incrementally adds 250 kV to the electron beam as it threads the center of the core. Shown in Fig. 1 is one induction accelerator core; the primary components include the input power feed from the blumleins, the oil to vacuum insulator, the ferrite which increases the inductance of the shorted turn input power feed, the ferrite reflector which damp modes in the vacuum cavity, and finally the acceleration gap across which the inductive accelerating electric field appears. With this surprisingly simple structure, high current electron beams can efficiently be accelerated; however, beam transport through a linear induction accelerator where there are many such accelerating cores is a very formidable challenge, primarily because of the difficulties presented by the discontinuity of the accelerating gap itself. In a smooth pipe, the self-radial electric and azimuthal magnetic field of the electron beam are terminated by the pipe wall, a condition invalidated under the accelerating gap. Thus, an electron beam ever so slightly off axis while under the accelerating gap has its dipole magnetic fields excite the accelerating gap and cavity. This results in non-symmetric cavity modes feeding back onto the beam and imparting a slight transverse impulse. Between adjacent

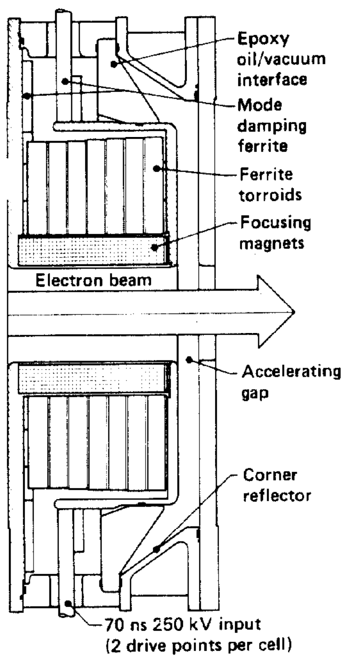

Fig. 1. Cutaway view of the components inside one accelerating case.

accelerator cores, this transverse impulse grows to a slight transverse displacement which then more strongly excites the next cavity. The very rapid growth of the beam's transverse displacement makes this instability, termed Beam Break-Up (BBU), the most virulent of instabilities plaguing induction accelerators. In this asymptotic limit, it is predicted[1] that an initial small displacement, ξ_0, will grow to a value ξ after passage through N_c accelerator cores, where ξ is given by

$$\xi = \xi_0 \exp\left[K \frac{\omega I_B N_c (z_\perp/Q)Q}{B_z}\right] \qquad (1)$$

Here, ω is the frequency of the most strongly excited asymmetric cavity mode, I_b is the electron beam current, $z_\perp/Q$ is the transverse shunt impedance, Q is the typical cavity parameter, B_z is the axial magnetic field used to focus the beam and K reflects gap physical parameters. For ATA, $K = 1.2 \times 10^{-13}$, $N_c = 190$, w = 800 MHz, Q = 4, $z_\perp/Q = 6.9$, $I_b = 10$ kA, and $B_z = 3$ kg which results in approximately 11 e-folds of growth. Figures 2a and 2b show how this severe growth manifests itself in degraded beam performance. Along the length of ATA are small magnetic induction loops which sense the time changing B_θ field. In Fig. 2a, we show the signal output from magnetic induction loops as one progresses down the length of the accelerator. The loop located nearest the injector shows the inductive field associated with only the rise and fall of the electron beam pulse. As one progresses down the accelerator this beginning and end of the induction signal becomes distorted due to difficulties in smoothly transporting a time varying current, but of more interest is the rapid growth of the 800 MHz oscillations characterizing BBU growth of transverse beam motion. So severe is this growth that the beam actually is intercepting the side walls of the accelerator (7 cm radius) causing disruption of the current pulse. This disruption is shown in Fig. 2b where beam current monitors along the accelerator length show an increasing truncation of the transported current pulse duration. Clearly, a means to suppress this instability is required to enable the beam to exit the accelerator with a full current and pulse duration. But also the instability should be early stabilized to minimize any growth of transverse motion which, for most applcations of high intensity electron beams, must be damped out thereby increasing beam emittance and equilibrium beam size.

What is required is a continuous, very strong focusing system which not only tightly constrains the electron beam to the accelerator centerline, but also phase mix damps any coherent transverse beam momentum into an overall increase in beam emittance. Higher order magnetic systems can accomplish these ends but are limited in versatility and difficult, if not expensive, to get strong field gradients near the accelerator centerline. An alternative choice is a continuous electrostatic system whereby one establishes a positive line of charge the entire length of the accelerator and to inject the electron

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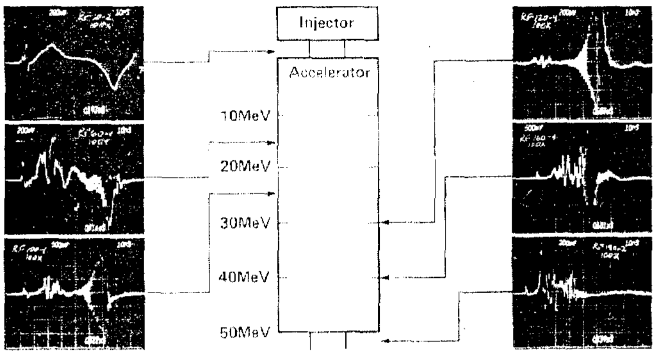


Fig. 2a. Magnetic induction signals indicating growth of BBU transverse motion as the beam transports through the ATA when using customary magnetic transport.

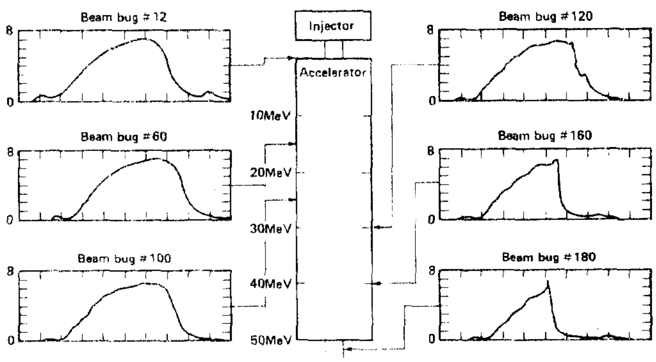


Fig. 2b. Current monitors showing pulse disruption due to BBU growth when using customary magnetic transport.

beam onto this axis. The positive line charge has a symmetric radial electric field that attracts and strongly focuses the electron beam onto the centerline axis. In addition, the radial electric field of the line charge forms an anharmonic potential well within which the restoring force is inversely proportional to the radial distance from the centerline axis. Thus, the beam electrons confined within the anharmonic potential well oscillate at different frequencies depending on their radial displacement. This spread in oscillating frequencies will cause electrons that initially form a displaced portion of the beam to be spatially randomized during transport in the anharmonic potential well, i.e., orbital phase mixing. Previous experiments at LLNL using the ETA demonstrated the effectiveness of a short (1.5 m) positive line of charge in stabilizing transverse beam motion.[2] In these highly successful experiments, the positive line charge was created by using the high-intensity electron beam to induce positive charges on a resistive graphite thread that was supported along the axis of the accelerator. This technique, effective though it is, is not feasible for creating a positive line charge the full length of a 100-m accelerator like the ATA.

Instead, the following technique, laser-guiding, is used. A vacuum base pressure of 10^{-4} Pa is achieved throughout the length of the accelerator. Benzene gas (C_6H_6) is then carefully bled into the accelerator in such a way that an axially uniform elevated pressure of 10^{-2} Pa is created. Since the injector (the electron-beam source) of the ATA is co-linear with the entire accelerator structure, we can direct a low-energy, small-diameter KrF laser beam through the injector and down the length of the accelerator. (The KrF laser parameters were 0.4-J energy, 28-ns pulse length, and 50-μrad divergence). We selected the 249-nm-wavelength KrF laser and the benzene gas on the basis of a survey of photo-ionization cross sections which indicated that, through a two-photon ionization process, the fraction of ionized benzene could approach 20%.

The laser is fired about 100 ns before the injector launches the electron beam into the accelerator. The laser pulse partially ionizes the benzene and forms a continuous, narrow, straight plasma channel of benzene ions and free electrons. The low energy of the KrF laser used in the ATA limits the ionization fraction of the benzene to 1%. In the brief 100-ns interval after passage of the laser pulse but before injection of the electrons, the plasma, with its heavy benzene ions, experiences almost no recombination or spatial diffusion.

To form the positive line charge (that is, a column containing only benzene ions), the high-intensity electron beam is injected onto the preformed plasma column (see Fig. 3). The free benzene electrons are ejected by the strong radial electric field at the head of the electron beam. To avoid accumulation of these free electrons and to ensure that their ejection from the ion channel is complete, the axial magnetic field for the entire length of the accelerator is turned off. Once the secondary electrons are ejected, the dominant force acting on the beam electrons is the focusing electric field of the ion column since the electron beams self fields cancel to order $1/\gamma^2$.

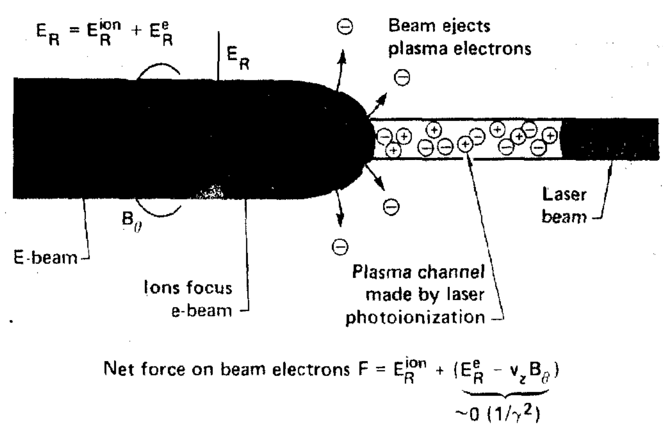


Fig. 3. The essence of laser guiding is that a laser preionizes a small diameter plasma column and that when the relativistic beam is injected onto this column the secondary electrons are expelled having a strongly focusing, positive ion column.

The impact of laser-guiding transport through the accelerator is shown in Fig. 4, which is to be compared to the data shown in Figs. 2a and 2b. We see that there is virtually no apparent growth of the BBU instability and full beam current and pulse duration is preserved. Clearly the laser guiding technology gives a tremendous improvement in accelerator performance as well as simplifies accelerator operation and future construction (i.e., no longer needed are transport solenoid or steering magnets). But what are the limits of the laser-guiding beam transport technique?

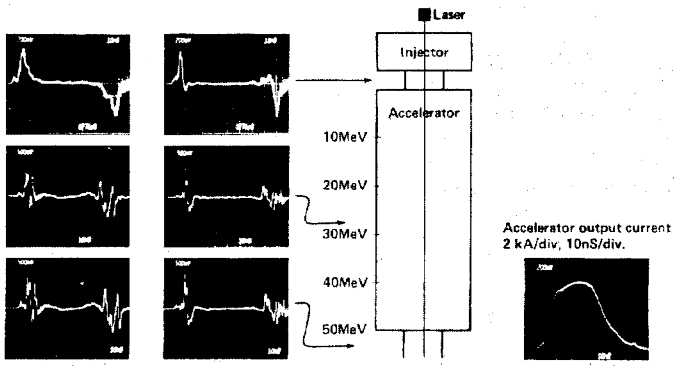


Fig. 4. With laser guiding transport of the beam through the accelerator, there is minimal BBU growth and pulse disruption.

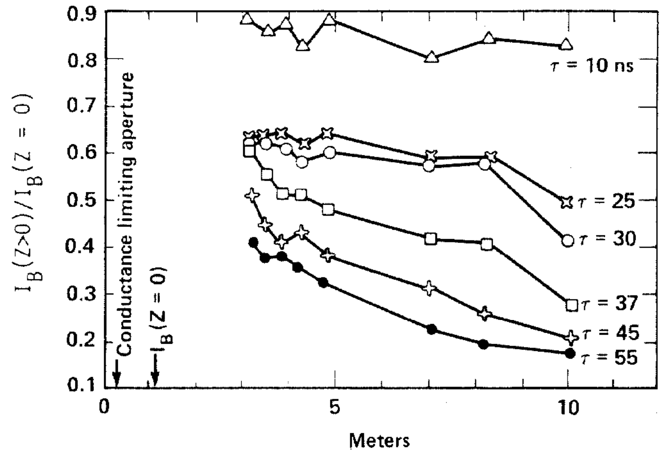
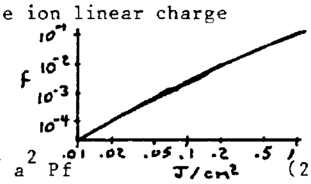


Fig. 5. Vacuum expansion of the electron beam as it exits the ion column and free transports into a six inch diameter pipe indicates that beam angles increase during the pulse, an observation consistent with intrapulse ionization of the benzene.

The strength of laser-guiding transport is initially determined by the ion linear charge density,[3] λ_i,



$$\lambda_i\left(\frac{esu}{cm}\right) = 5.34 \times 10^4\ a^2\ Pf \qquad (2)$$

where a is the ion channel radius in cm, P is the benzene pressure in microns and f is the laser ionization fraction which is predicted by multilevel rate equations to have the dependence upon laser fluence shown in the sketch. From this information, it is apparent that modest increases in laser fluence can quickly pay off in substantial gains in ionization fraction and approach the saturated level of ∿20%. Increased laser fluence would also allow lower operating pressure of the benzene pressure and proportionally reduce the linear growth of primary beam ionization of benzene (cross-section for electron beam ionization of C_6H_6 is ∿5.8×10^{-18}). Of greater concern is the likely exponential growth of ionization due to benzene molecular ions or fractured molecular component ions on the remaining benzene gas. Cross-sections for these processes are less well known but the benzene ions are sloshing around in potential wells that are close to 1 MV.

There is supportive evidence that intrabeam pulse ionization, at rates greater than linear electron beam ionization, does occur. At the end of ATA, benzene gas limiting apertures were installed so that with sufficient pumping capacity the benzene pressure profile truncated abruptly. Laser guiding transported the beam through the accelerator but terminated at this aperture where the benzene pressure went to essentially zero. No magnets were used after this aperture so that the beam was allowed to freely expand into the remaining beam transport section. Current monitors measured the transmitted current as a fraction of axial distance from the aperture as the beam propagated down the 7.25 cm radius vacuum pipe; the results are shown in Fig. 5. We presently have no information on the beam profile, thus time variation in the axial dependence of the fraction of transmitted current ($I_B(z > 0)/I_B\ (z = 0)$ is an imcomplete data set but does suggest a time variation in beam angle, $\theta(t)$. Such $\theta(t)$ could result either from emittance increase intrapulse or intrapulse beam radius decrease due to increasing focusing resultant from ion line density increase.

Further hints of the important role of intrapulse ionization follows from consideration of ion hose instability. For rigid electron beams and rigid ion channels, the ions sloshing in the potential well couple to the electron beam and initiate a connective instability. The strength of coupling depends on the ion slosh time, T_i, being much shorter than the electron beam pulse duration, T_p; i.e.,

$$T_p >> T_i = \left[\frac{a_B^2}{c^2}\ \frac{m_i}{m_e}\ \frac{17(kA)}{I_B(kA)}\right]^{1/2} \qquad (3)$$

where a_B is the electron beam radius through which the ions oscillate, m_i is the ion mass and I_B is the beam current in kA. On ATA, experiments have been performed[4] where the electron beam was perturbed and deflected from the ion column in attempts to excite ion hose. For these experiments T_p/T_i has been as great as 12, yet there has been no observed ion hose growth. Analytic work backed with particle simulations[3] have shown that a very powerful means of making the ion channel electron beam system strongly resistant to ion hose is for an ionization rate to be comparable or greater than the ion density convection. This implies that on one hand intrapulse ionization is possibly beneficial for stabilizing ion hose which would otherwise disrupt beam transport. But on the other hand, the time variation in beam angle caused by changes in the focusing field (ion line density) is potentially limiting for smooth extraction off a laser guiding column. If these constraints hold, then there may be an intrinsic limit to the pulse duration, and perhaps beam charge that can be transported within the present-day limits of laser guiding.

A final note on additional phenomena that accompany laser guided transport through the accelerator should serve to illustrate the complexity of this seemingly straightforward technology. For good beam transport with no pulse distortion, the matching of the electron beam onto the laser channel is a critical process. Careful adjustment of the benzene pressure profile, the magnetic transport up to the benzene profile, the electron beam size and the electron beam head centroid stability all are tuned by the accelerator operators to accomplish an optimum beam transport through the accelerator.[5] These controls, although perhaps not yet all quantitatively understood, are qualitatively explainable since the beam must be matched from a magnetic to an electrostatic transport, and done so in a manner that allows ejection of secondary electrons from the laser designated plasma column. However, laser timing relative to the electron beam is also a critical parameter, that primarily controls the electron beam current rise time, and laser/e-beam timing relative to the accelerator core voltage governs a process of current accumulation through the accelerator (which implies beam electrons with a γ spread). This latter process results from incomplete secondary electron ejection, particularly those initiating under an accelerating gap.[5] These processes are currently under study since they seriously impact how laser guiding transport affects electron beam parameters.

At ATA, progress has also been made on beam emittance and brightness. Actually, ATA's initial concern on beam emittance did not reflect FEL goals, but rather was motivated again by beam transport issues. Before laser guiding was in place, and even prior to addressing the difficulties of the BBU instability, magnetic solenoidal transport of the beam through ATA was characterized by a continual loss of current. In Fig. 6, we show a collection of data that illustrate the problem. The experimental arrangement was that the injector, at this time equipped with a plasma surface discharge cathode, produced a beam that was accelerated up to 6.5 MeV.

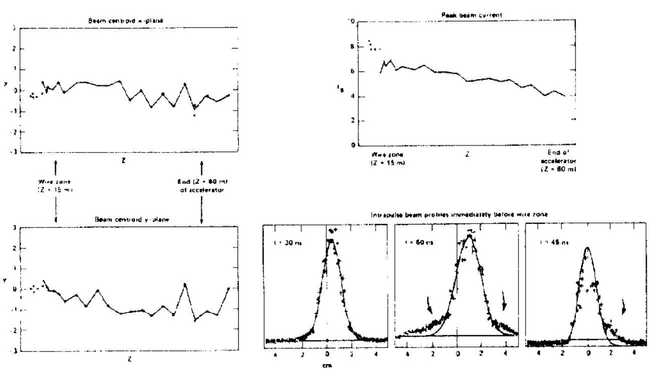


Fig. 6. Data on beam magnetic transport after a wire zone shows the centroid to be localized near axis, but still current loss down the accelerator. The key is in the beam profiles before the wire zone which show significant asymmetric wings (particles greatly expanding phase space) coming from the injection.

At this point a "wire zone" was located co-linear to the accelerator axis and with proper entrance and exit matching magnets. The wire zone damped out beam motion and centered the beam.[2] This beam then was re-injected into the remaining part of the accelerator. As the data shows, during transport through the remaining accelerator, the centroid of the beam was confined to $\sim$1 cm excursions from axis, but still there was a gradual current loss. Before the wire-zone, measurements of the beam's radial profile at various time intervals during the pulse show that there are time varying asymmetric wings. The transport properties of the wire zone[2] are such that it only damps transverse motion at the expense of increasing emittance, and that it centers the beam to axis--it is not an emittance limiter. Particles populating these asymmetric wings, after being phase mixed by the wire zone, still do execute sufficiently large radial excursions during transport to be carried to regions of poor magnetic field and eventually lost. Since small current test beams do not show anomalies in the accelerator magnetic transport or in the pulse power systems, we concluded that the far off axis particles represented characteristics of the beam as it emerged from the cathode/injector.

A collimator, even if immersed in an axial B_z field, is a simple means of positively limiting the area in phase space populated by beam particles.[3] The collimator length must be longer than the cyclotron wavelength, λ_c, and it is simpler to interpret, although not necessary, if the beam has sufficient energy to be emittance dominated. For a B_z-immersed collimator, the equilibrium ($d^2/dz^2 \equiv 0$) beam envelope solution is

$$\frac{2 I_p}{\gamma^2 I_A R_p} + \frac{E_p^2}{R_p^3} = 1/4\, k_c^2 R_p \quad (4)$$

where the subscripts "p" refer to pipe quantities and $I_A = 17{,}000\ \gamma$ and $k_c = eB/\gamma m_o c^2$. Assuming incident beam current and output collimator current are related as

$$\frac{I_p}{I_B} = \alpha \frac{E_p^2}{E^2} \quad (5)$$

where the weighting factor α adjust for beam distribution in phase space and E_p refers to the phase space area (i.e., emittance) delineated by the collimator and E is the full beam emittance (normalized emittance $E_n = \gamma E$). From this we find

$$I_p = \frac{0.727\ \gamma\ R_p^2\ B_{kg}^2}{1 + \frac{E_n^2}{2\alpha R_p^2}\frac{I_A}{I_B}}\ , \text{ if emittance dominated is proportional to } R_p^4 B_z^2\ . \quad (6)$$

Because these are all "hard-edge" quantities, for a given collimator and B_z field it is straightforward to determine, at least relatively, how much phase space is occupied by beams produced from different cathodes and injector configuratons. In Fig. 7, we summarize some of the results.[6] For the collimator located 2 m from the injector output but always with its B_z field at $\sim$1000 gauss, we experimented with different cathode configurations. The surface plasma discharge cathode was 25 cm diameter and was filled with 5000 independently power surface breakdown sites. This cathode was also operated with a control grid spaced 3 cm from the cathode surface. The discrete site field emission cathode was 6.7 cm radius and filled with carbon tufts on 0.2 cm spacing. Units like this with variable field emission site spacings were tested, and as expected, the more dense the filling factor the better the beam emittance. The vacuum electric field stress on this cathode as well as for the uniform planar "velvet" field emission surface was $\sim$220 kv/cm; both these field emission units had field shaping electrodes added to the cathode and anode and were operated without a control grid. Work on our development laboratory[7] and supported by outside research[7] indicates that after sufficient filling factor is achieved to insure smooth E-field termination, that further increasing site concentration of emission whiskers is beneficial but only by increasing surface area for occluded gases to form, and this is what gives the beneficial increase in plasma density. As the data of Fig. 7a shows, there is an exponential like increase in beam through the collimator, for these various cathodes. We mention that for each of these cathodes, the magnetic transport within the injector and to the collimator was adjusted for maximum current transmission with no loss. In all cases $\sim$8 kA was incident on the collimator and the injector was always operating at 2.5 MeV.

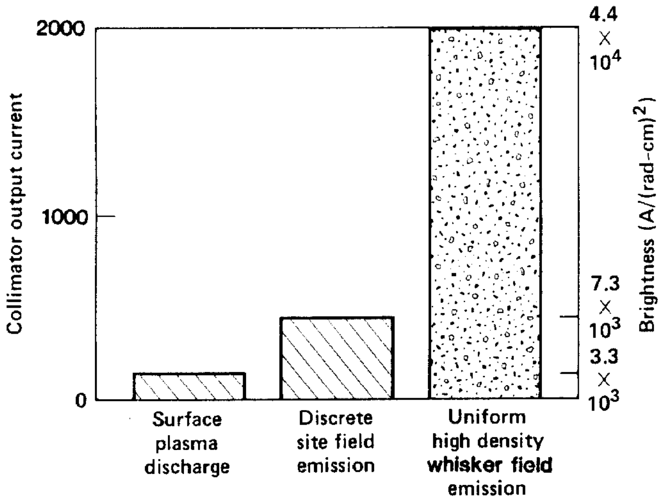


Fig. 7a. For various cathode surfaces that have been tested, the current through a B_z immersed collimator indicates the emittance and brightness.

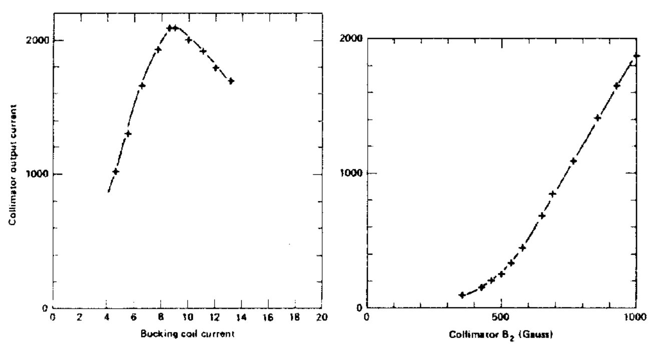


Fig. 7b. (Left) Varying the magnetic flux on the cathode surface by using a Bucking Coil changes the effective total beam emittance by canceling beam angular momentum. Figure 7c. (Right) Varying the B_z field over the solenoid/ collimator controls the output current in a manner that suggest non-uniform phase space distributions (nonlinear α).

For completeness, in Fig. 7b, we show how, for a given setting of the injector magnetic transport, the collimator output current varies as the "Bucking Coil" current is varied. This Bucking Coil is a solenoid located behind the cathode and arranged to cancel the magnetic flux threading the cathode surface. This is done to zero any angular momentum contribution to the total emittance. The peak of the collimator output current versus Bucking Coil current has been verified to correspond to complete flux cancellation on the cathode surface. Finally, in Fig. 7c we show the collimator output current dependence on the B_z^2 field. The departure from a B_z^2 fit indicates both space charge effects and that the beam does not have a uniform distribution in phase space (non-linearity in α).

Attempts to further improve the beam brightness from field emission cathodes are currently centered on the issue of how beam optics and phase mixing within the injector transport tend to "average down" the beam brightness. Particle simulation work indicates that beam brightness can be significantly improved by simply reducing the injector transport magnetic field and losing peak transport current, i.e., only transporting that high brightness portion of the total current. The simulation results shown in Fig. 8 suggest that beam brightness can be increased perhaps a factor of 5 or more simply by "tuning for brightness" rather than tuning for peak transported current. If this can indeed be experimentally realized and the resulting beam matched onto accelerator transport (magnetic and/or laser guided) without emittance degradation then simple field emission cathodes would, at least in the immediately near term, satisfy the needs for 10 micron FEL experiments.

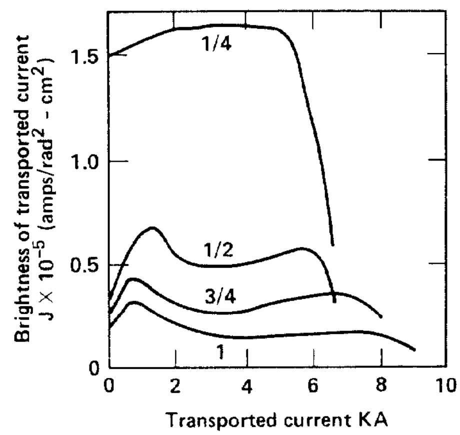


Fig. 8. Computer simulations on how beam brightness is improved, at the cost of transported beam current, by lowering the magnetic field that is used for total peak current transport.

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