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BEAM QUALITY OF THE ATA INJECTOR

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Abstract

The beam quality of the ATA injector has been experimentally measured using a magnetic collimator. These measurements have been performed for a variety of magnetic field profiles, including field strengths where the collimator is shorter than a cyclotron wavelength. The experimental currents transmitted through the collimator have been predicted numerically. The numerical predictions and experimental data are in good agreement.

Introduction

The beam quality or brightness of the <u>A</u>dvanced <u>Test A</u>ccelerator (ATA) injector has been experimentally measured using a magnetic collimator. Brightness is determined by measuring the current transmitted through the collimator with a particular magnetic field. The experimentally transmitted current has also been accurately predicted using numerical models, which have been successful in predicting the experimentally measured brightness. The selection of ATA injector configurations has been guided by injector performance trends, indicated by numerical model parameter surveys. The performance of the ATA injector has been evaluated taking into account the issues of emission area size, field stress levels, and acceleration gradient.

Injector Design Issues

The emission area size influences the degree to which nonlinearities impact the beam dynamics. Nonlinearities caused by external magnetic fields, self-, or applied electric fields can contribute to beam emittance. The beam brightness \mathcal{J} is defined to be,

$$I = \frac{\pi^2 I}{(\gamma \beta)^2 V_4}.$$
 (1)

where I is current, V_4 is the transverse phase space volume, $\gamma = 1/\sqrt{1-\beta^2}$ and $\vec{\beta} = \vec{v}/\epsilon$, with velocity \vec{v} . For uniformly filled phase space, $V_4 = 0.5(\pi\epsilon)^2$. where ϵ is emittance so \mathcal{J} scales inversely as emittance squared and thus any contribution to emittance degrades beam brightness. In general, the electric and magnetic fields can be written as an expansion about the axis or more specifically the r coordinate in cylindrical coordinates. The exact field can be approximated at small **r** by a linear term and higher order nonlinear terms that are smaller in size. A small emission area reduces the effect of the nonlinear terms and thus tends to minimize the emittance contribution. Two limits restrict how small the emitting surface can become. If a particular amount of total current is desired, reducing the emitting area causes the current density to rise. Usually ATA operates at 50- to 100-A/cm² current density so at a fixed current this sets the minimum size. Furthermore, for laser-guided transport [1] the ATA injector usually operates with a hole in the cathode so clearly the total area must be several times the area of the hole

When the current density is restricted, more current can be obtained by going to a large emission area. In this mode of operation, the effect of nonlinearities is increased. Because the strength of the nonlinearity is increased with larger radius, it is sometimes possible to draw more current than needed and then scrape the outer edge of the beam. In this way, it may be possible to climinate the undesirable portion of the beam. In the experiments under discussion, the anode has been shaped to allow the beam to expand, and the magnetic field strength has been set at a high enough level to inhibit beam contact with the wall. The field stress is mainly determined by the shape of structures and the voltage level. For these experiments, ATA was operated as a fieldemitting diode and thus the acceleration gradient is controlled by the applied voltage and A-K gap. When the gap is reduced at a fixed voltage, the field stress increases, and thus these two parameters are related. The normalized emittance scales like the product of energy and transverse velocity. Thus, emittance is affected by nonlinearities in the radial force. The self-field contribution to the radial force is a balance of the defocusing radial electric field and the focusing azimuthal magnetic field. The two contributions cancel to order γ^{-2} so any nonlinear self-field contribution to the emittance is reduced as the energy is raised. Thus, it is advantageous to increase energy rapidly, and beam quality is aided by high stress. The ultimate stress limit is set by the allowed breakdown voltage.

The ATA beam quality has been measured for large and small emission area cathodes, with and without cathode holes. By setting injector solencids, we define a magnetic field profile for transport of the beam up to the collimator. The size of the magnetic field over the collimator determines how much current is transmitted; the brightness can be related to the transmitted current. Simulations of this process have been made with two computer codes.

Numerical Models

The Darwin Particle Code (DPC) [2] calculates space-charge-limited emission and subsequent particle trajectories past all injector electrodes, including the anode. DPC is a particle-in-cell code that computes trajectories by solving the relativistic force equation. The fields are obtained from the Darwin [3] approximation of Maxwell's equations. DPC is an axisymmetric code that includes capabilities for external magnetic field coils, finite electrode voltage rise times, and "stair-case" shaping of electrodes for modeling geometric effects. The geometry is two-dimensional mainly for the purpose of realistically modeling the low-energy acceleration and the longitudinal influence of electrodes. After the beam passes into the ATA anode, the geometry is essentially that of a pipe and the energy is at the 2- or 3-MV level. In this situation, the dynamics are decoupled longitudinally to order γ^{-2} . At this stage of the transport, in steady state, it is sufficient to follow only the motion of a slice of the beam.

The phase space that exits the DPC code is used as an initial condition for the <u>Slice Transport</u> (ST) computer code. ST transports a slice of the beam at a fixed distance from the beam head. Because ST assumes longitudinal decoupling of particle dynamics, it is necessary only to solve for motion in the transverse plane. The equation for u_x and u_y is,

$$m\frac{d\vec{u}}{dz} = q(\gamma \vec{E} + \vec{u} \times \vec{B})/(u_z c).$$
(2)

where $\vec{u} = \gamma \vec{\beta}$, *m* is mass, *q* is charge, $\vec{E} = -\nabla \phi$ is the electric field, \vec{B} is the magnetic field, and *c* is the speed of light. The particle energy is used to obtain $u_z = (\gamma^2 - 1 - u_x^2 - u_y^2)^{1/2}$ with γ given in terms of the potential, $\gamma = 1 - q\phi/(mc^2)$. Only the radial electric field is needed; $E_r = -d\phi/dr$ and ϕ is calculated from a reduced Poisson equation.

$$\frac{1}{r}\frac{d}{dr}r\frac{d\phi}{dr} = -4\pi\rho + \lambda. \tag{3}$$

In Eq. (3), λ is a source modification that provides a first-order correction for longitudinal charge variation and satisfies,

$$\frac{1}{r}\frac{d}{dr}r\frac{d\lambda}{dr} = 4\pi\frac{d^2\rho}{dz^2}.$$
(4)

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The ST magnetic field consists of the sum of external prescribed fields and the beam self-magnetic field. The self-magnetic field satisfies the timeindependent Ampere's law,

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{J}.$$
 (5)

The self-theta component, B_{θ} , is obtained from a radial integral of the z component of Eq. (5).

$$B_{\theta} = \frac{4\pi}{rc} \int_{0}^{r} J_{\varepsilon} r \, dr. \tag{6}$$

The z component of the self-magnetic field, B_z , is obtained by integrating the theta component of Eq. (5),

$$B_z = B_{axis} - \frac{4\pi}{c} \int_0^r J_\theta \, dr. \tag{7}$$

The axis value B_{axis} is determined by requiring zero longitudinal magnetic flux at the radial wall position.

Experimental Description

The ATA injector experiments were run in a diode configuration. The basic geometry is then a single gap followed by an anode cone and 6.7cm-radius beam pipe. The anode cone has seven focusing solenoids $(f_1 \text{ to } f_7)$, and the beam pipe has an additional three solenoids (f10a to f10c). The magnetic collimator is a 106-cm-long, 2-cm-diameter pipe with four axisymmetric solenoids (f10d to f10g). In order to cmit a beam with zero canonical angular momentum, \mathcal{P}_{θ} , there is also a bucking coil behind the cathode.

Two electrode sets were run, with and without cathode holes. The first configuration designated "standard" is illustrated in Fig. 1.



Fig. 1. Standard injector configuration

The f_1 magnet is indicated by a rectangle with an "x" located in the anode stalk. The cathode is pictured as solid; for some experiments, however a 1.2-cm-radius hole is present.

The second electrode configuration referred to as ATA-MOD-D1, is sketched in Fig. 2.

The main differences between the two configurations are in the cathode radius, A-K gap, and operating voltage. The parameters of each configuration are summarized in Table 1.



Fig. 2. ATA-MOD-D1 injector configuration

$\operatorname{Standard}$	ATA-MOD-DI
3.0	2.0
20.0	20.0
13.0	10.8
6.8	3.4
	Standard 3.0 20.0 13.0 6.8

Originally ATA-MOD-D1 was designed for operation at 3 MV; however, experimentally it was found that breakdown and arcing occurred at a voltage of 2.5 MV. Most experiments were consequently run at 2 MV to eliminate this behavior. Computer calculations showed only a minor performance

Beam Quality Measurements

The beam quality or brightness is obtained by measuring the current transmitted through the magnetic collimator. As reported in other work [4], the brightness, \mathcal{J} , is expressed in terms of field *B*, collimator radius r_p ,

$$\mathcal{J} = \frac{6I(amp)}{(k_{\rm c}^2 - 4k^2) r_{\rm p}^4},\tag{8}$$

and current *I*, where $k_c = (qB/mc^2)/\sqrt{\gamma^2 - 1}$ and with *I* expressed in amps $k^2 = 2I/(17050(\gamma^2 - 1)^{3/2})$. The formula in Eq. (8) is appropriate when the magnetic field is constant and of large enough magnitude so that the collimator is longer than a cyclotron wavelength.

<u>Standard</u>

change at the reduced voltage.

The standard configuration has been run with and without a hole in the cathode; here we concentrate on the experiments that do have a hole in the cathode. The hole causes an aberration in the field near the emission surface that manifests itself as an increase in emittance. For moderate magnetic field settings over the collimator, not all of the beam current transmits. The most interesting question is whether or not the current transmitted through the collimator is purged of electrons that have suffered cathode hole aberrations. If the purging process takes place, there is an increase in the beam quality of the transmitted beam compared to the beam incident on the collimator.

The experimental results and code predictions of brightness for two cases are given in Table 2. The first case has such a low field over the collimator that the length is shorter than λ_c . The experimental current can still be used with Eq.(8) to calculate brightness since most current loss occurs for distances less than $\lambda_c/2$.

Case	Expt	Code	$\lambda_c/106$	Itrans(kA)
1	2.65×10^{5}	4.00×10^{5}	1.74	0.6
2	1.30×10^{5}	2.00×10^{5}	0.86	1.8
	Table 2	. Standard conf	Iguration	_

The code and experiment show that the brightness is larger at lower transmitted current where $l_{trans} = 0.6$. The current incident on the collimator for both cases is 9 kA. The case 1 phase space calculated by the code before and after the collimator is plotted in Figs. 3 and 4.



Fig. 3. Phase space before the collimator, z = 268 cm



Fig. 4. Phase space after the collimator, z = 379 cm

The phase space at z = 268 cm in Fig. 3 shows electrons near x = 0 scattered out from the bulk velocity. At this z position, the code calculates a brightness *including* these particles of 5×10^4 . This is almost an order of magnitude lower than the brightness of 4×10^5 at z = 379 cm, which corresponds to Fig. 4 where these particles have been lost from the beam in passing through the collimator.

ATA-MOD-D1

The ATA-MOD-D1 configuration has been run experimentally to explore the issue of reduced emission area. As shown in Table 1, the cathode radius is half that of the standard configuration. A smaller radius is beneficial for the aberration problem as discussed earlier. Unfortunately, the

operational voltage had to be lowered to 2 MV to avoid breakdown, and this lowers the applied stress and the rate of voltage increase. The results for two different magnetic profiles are given in Table 3.

Case	Expt	Code	$\lambda_c/106$	Itrans(kA)		
1	2.60×10^4	3.70×10^4	0.58	0.62		
2	[]	7.00×10^{5}	0.72	0.57		
Table 3. ATA-MOD-D1 configuration.						

Both of these cases were run with a hole in the cathode. The first case has reasonable agreement with the code, but the brightness is 10 times lower than the standard configuration results in Table 2. The magnetic profiles for cases 1 and 2 are plotted in Fig. 5(a) and 5(b), respectively. The field over the collimator for case 2 is slightly larger than that for case 1.



Fig. 5. (a) Magnetic field profile for case 1



Fig. 5. (b) Magnetic field profile for case 2

There are no analyzed experimental data for case 2; however, the code result indicates that the case 2 magnetic profile yields a much brighter beam.

<u>Summary</u>

The injector issues relevant to experiments conducted on ATA have been discussed. The experimental results and code comparisons for the standard and ATA-MOD-D1 injector configurations have been presented. Good agreement is obtained between experimental beam quality results and computer calculations. More experiments are needed to resolve whether or not smaller cathode radius is beneficial.

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