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FOR THE ELECTRON LASER FACILITY

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MASTER

A VARIABLE-EMITTANCE FILTER FOR THE ELECTRON LASER FACILITY

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ABSTRACT

We describe a variable-emittance filter designed for the Electron Laser Facility (ELF). The filter attenuates the 4.5-MeV, 6-kA Experimental Test Accelerator (ETA) beam, permitting electrons only which fall within a given region of phase space (r , dr/dz) to pass. Initial experimental results are presented.

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INTRODUCTION

The strong dependence of FEL performance on emittance necessitates careful selection of emittance from ETA. Beam position and angular jitter can simultaneously be improved by choosing only the central portion of the ETA beam phase space as input to the ELF experiment. The first element of the ELF beamline at the ETA facility is such an emittance current selector, figure 1. The 3-5 MeV 6 kilo-ampere beam from ETA impinges on the filter from the left of the figure. The beam is larger than the pipe radius of the filter. Typically the beam is 5 or so cm in radius at this location. This filter serves as the effective source to the ELF experiment tuneable from 100 to 1000 Amperes.

THEORY OF OPERATION

A simple double slit system separated by a large distance, ℓ , in a field free region will have a phase space acceptance defined as the enclosed area of the polygon cut by the projection of the slits in phase space. Consider figure 2. At the center of the system, Z_c , slit S_1 of half aperture s , is defined by two parallel lines in phase space given by

$$x_c' = \left(\frac{x_c - s}{s} \right) x_0' \quad (1a)$$

$$x_c' = \left(\frac{x_c + s}{s} \right) x_0' \quad (1b)$$

where $x_0' = 2s/\ell$ is the limiting divergence of the system. Slit S_2 of identical half aperture s is defined as

$$x_c' = - \left(\frac{x_c - s}{s} \right) x_0' \quad (2a)$$

$$x_c' = - \left(\frac{x_c + s}{s} \right) x_0' \quad (2b)$$

If the double slits are replaced by a continuous pipe, the acceptance is unaltered as shown in figure 2B. The beam emerging from this system will occupy the polygon. The bounding (circumscribed) ellipse characterizing the motion in any subsequent focusing system will give an apparent phase space dilution to the beam.

This problem can be circumvented by running the slit system inside a continuous focusing field such that each point of the continuous slit (pipe) which traces out the same eigen-ellipse, figure 3. The system must be at least a cyclotron wavelength in length. For a solenoid, this is given by

$$Z_{\lambda} = 2\pi \left(\frac{E_0}{ec} \right) \frac{\beta_Y}{B_Z} \quad (3)$$

where B_Z is the solenoid field, E_0 the rest energy and β_Y the usual relativistic factor.

The required pipe radius r , for a desired acceptance is found from the solution of the beam envelope equation for a given beam energy and magnetic field.

$$r'' + \left(\frac{eB_Z c}{2E_0 \beta_Y} \right)^2 r = \frac{\epsilon_0^2}{r^3 (\beta_Y)^2} + \frac{2i}{i_A} \frac{1}{(\beta_Y)^3} \frac{1}{r} \quad (4)$$

ϵ_0 is the normalized beam emittance, i the beam current in kA, and $i_A = 17$ kA for electrons. We require the beam passing through the emittance filter to be matched to the solenoid field. Assume for the ETA parameters of interest that the beam is emittance dominated. Then the beam envelope equation reduces to

$$\left(\frac{ec B_Z}{2E_0} \right)^2 r^4 = \epsilon_0^2, \quad (5)$$

giving the required pipe radius.

Nominal ETA operating parameters are $\beta\gamma = 9$, $I = 6$ kA, and $\epsilon_0 = 1$ cm-radians. The numerical constant (E_0/ec) is 1.703 for B_z in kG and ϵ , r , z , in cm. As a numerical example, (table 1) consider the pipe radius required to carve out a beam emittance of 0.01, 0.02 and 0.03 cm-radian in a field of 0.5 and 1.0 kG. The required filter system length, Z_λ , is also given in the table.

The current transmitted by this system, i , can be calculated under the assumption of uniform phase space density which is valid for a parabolic density profile (a calculation for another profile is presented later).

$$i = I \left(\frac{\epsilon}{\epsilon_i} \right)^2 \quad (6)$$

Here ϵ_i is the emittance of the beam of current I arriving at the filter. Table 2 gives the beam current passed for the conditions assumed in table 1. A check of the validity of the assumption of emittance dominance can now be made from η , the ratio of the emittance to space charge term in the beam envelope equation (4).

$$\eta = \frac{1}{2} i_A (\beta\gamma)^3 \left(\frac{\epsilon}{r} \right)^2 \frac{1}{I} \quad (7)$$

Table 3 gives this ratio which should be much larger than unity for emittance dominance.

By proper selection of the magnetic field and pipe size radius, a beam of desired emittance can be selected for the experiment. As the current is determined by the phase space density and area, it is not a free choice. The matching condition to the emittance filter should make the passed beam as insensitive as possible to incident positional and angular jitter.

This determines the focus condition, i.e., beam radius incident on the filter, figure 3B.

The current passing through the emittance selector is a function of the phase space density as previously mentioned. To explore this dependence a particle code was used to simulate the experiment. Typical output is shown in Figs. 4a and 4b. Particles were loaded in two different ways. First a parabolic radial density profile was used which corresponds to a uniform phase space density. Results matched equations (5) and (6) very closely.

However, when another beam radial density profile was used results varied significantly. A truncated Bennett distribution was used with density

$$J(r) = \frac{I \left[1 + r_c^2/a^2 \right]}{\pi r_c^2 \left(1 + \frac{r^2}{a^2} \right)^2} \quad (8)$$

where a is the "Bennett" radius and r_c is the radius of the edge of the distribution. For equal incident emittances much more current passed through the emittance selector in the case of the Bennett distribution than in the parabolic case. Moreover the scaling of output current with solenoid current was the same for both distributions over the range investigated.

EXPERIMENTAL OPERATION

A series of runs were made during the course of the ELF experiment using a pipe of 1 inch diameter in the emittance selector. Table 4 gives the calculated acceptance of the filter based on the solenoid field which spans the range of 0.018 to 0.051 cm-rads. From equation (6) and the normalized ETA emittance of 1.1 cm-radians at 6 kA we can calculate the current passed by the filter, table 5. This current compares favorably with the measured current i_3 .

The current measured just before the selector is I_2 .

Figure 1

ELF beam line configuration showing the major components of the beamline.

Figure 2

Phase space carved out by two slits separated by λ . The phase space midway between the two slits is a parallelogram. If the two slits are replaced by an infinite number of slits (C), the parallelogram is unaltered (D) determined by the extreme entrance and exit slits.

Figure 3

Emittance filter consisting of a pipe forming a beam scraping aperture immersed in a continuous solenoidal magnetic field, a) The phase space acceptance of the pipe is an upright ellipse, b) The emittance passed by this acceptance is independent of the initial beam match provided there is adequate beam centering and that the beam radius is larger than the pipe radius and the beam angular divergence is larger than the pipe angular acceptance.

Figure 4a

Particle code output plot showing output current as a function of position through the input matching solenoids and emittance filter. Output shown is for a parabolic density profile at $Z = 0$ with an RMS emittance of .081 rad-cm and an emittance selector solenoid current of 400 Amps.

Figure 4b

Output for the same conditions as for Figure 4a but using a truncated Bennett density profile at $Z = 0$ with an RMS emittance of .081 rad-cm.

Figure 5

Ratio of output current to input current as a function of solenoid current squared for two different types of beam profile: parabolic (corresponding to uniform phase space density) with RMS emittance of .040 rad-cm (+ symbols), and truncated Bennett with RMS emittance of .081 rad-cm (squares).

Table 1

Emittance filter pipe radius in cm.

ϵ (cm-radians)

<u>B(kG)</u>	<u>0.01</u>	<u>0.02</u>	<u>0.03</u>	<u>Z_{λ}</u>
0.5	0.78	1.1	1.35	193
1.0	0.55	0.78	0.96	96

Table 2

Beam current in kAmps passed by the filter.

ϵ (cm-radians)

<u>B(kG)</u>	<u>0.01</u>	<u>0.02</u>	<u>0.03</u>
0.5	0.1	0.4	0.9
1.0	0.1	0.4	0.9

Table 3

Ratio of emittance to space charge term in the beam envelope equation.

ϵ (cm-radians)

<u>B(kG)</u>	<u>0.01</u>	<u>0.02</u>	<u>0.03</u>
0.5	10.2	5.12	3.40
1.0	20.5	10.2	6.73

Table 4

<u>Case</u>	<u>Solenoid I₆₅(Amps)</u>	<u>B(gauss)</u>	<u>ε(cm-rad)</u>
1	551	854	.0506
2	502	775	.046
3	450	627	.041
4	401	621	.037
5	350	542	.037
6	300	465	.028
7	251	389	.073
8	201	311	.018

Table 5

<u>Case</u>	<u>I₂(Amps)</u>	<u>Calculated i(Amps)</u>	<u>Measured i₃(Amps)</u>
1	5000 ± 200	952	900 ± 20
2	5000 ± 200	676	580 ± 20
3	6000 ± 200	601	600 ± 20
4	6000 ± 200	434	400 ± 20
5	5500 ± 200	364	240 ± 20
6	5500 ± 200	292	200 ± 20
7	5500 ± 200	187	100 ± 20
8	5800 ± 200	130	60 ± 20

Figure 1

Figure 2

Figure 3

Figure 4a

Figure 4b

Figure 5