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INTERMEDIATE ENERGY ELECTRON COOLING FOR ANTIPROTON SOURCES USING A PELLETRON ACCELERATOR

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1. Introduction

It has been shown at FNAL that electron cooling of protons is a very efficient way to reach high luminosity in a proton beam.[1] The emittance of the 120 KeV electron beam used at Fermilab corresponds to a cathode temperature of 0.1 eV. In order to apply cooling techniques to GeV proton beams, MeV electron energies are required. In this experiment, the emittance of a 3-MV Pelletron electron accelerator was measured to determine that its emittance scaled to a value appropriate for electron cooling. The machine tested was jointly owned and operated by the University of California-Santa Barbara and National Electrostatics Corporation for research into free-electron lasers, which also require low emittance beams for operation.

2. Thermal Emittance Estimate

The thermal emittance ε of the beam will be defined to be the area in phase space in which 90% of the beam trajectories lie. The only contribution to the perpendicular velocity of the particles is assumed to be the perpendicular thermal velocity of the electrons as they are emitted from the cathode. The area of the phase space ellipse is then

$$\varepsilon = \pi x_{max}\Theta_{90}. \tag{1}$$

In evaluating ε, it is assumed that the cathode emits electrons uniformily over its surface. Thus x_{max} is the radius of the cathode. In this case $x_{max} = 7.6\times10^{-3}$m. The quantity Θ_{90} is defined to be the angle with respect to the beam axis that contains 90% of the electron trajectory angles.

$$\Theta_{90} = P_\perp/P_{11} = MV_{\perp 90}/\gamma MC\beta \tag{2}$$

We evaluate $V_{\perp 90}$ by assuming a one-dimensional Maxwell distribution with the cathode temperature KT = 0.1eV. This yields $\varepsilon = 1.8\pi$mm-mrad for $\gamma = 5$ and $\varepsilon = 1.5\pi$mm-mrad for $\gamma = 6$ as the estimates of thermal emittance.

3. The Emittance-Measurement Method

A. Theory

The radius of a beam of emittance area $\pi\varepsilon$ is $r = \sqrt{\beta_L\varepsilon}$ where β_L is one of the Twiss parameters[2] α_L, β_L and γ_L which satisfy the equations

$$\gamma_L + \alpha_L' = K\beta_L,\ \beta_L' = -2\alpha_L,\ \gamma_L = (1+\alpha_L^2)/\beta_L. \tag{3}$$

$K = B'/B\rho$ is determined by the transverse gradient of the magnetic field and the prime denotes differentiation with respect to distance in the beam direction. Space charge adds defocusing in both transverse directions and can be represented for a circular uniform beam by an additional term $K_{S.C.} = 2I/I_0(\beta\gamma)^3\beta_L\varepsilon$ with $I_0 = MC^3/e = 17000$A. The equations for the Twiss parameters can now be numerically integrated to give the beam radius as a function of distance, given the initial values of α_L, β_L and ε. This treatment then includes both the effects of space charge and thermal velocities (emittance). Measurements of beam radius at several positions, including a waist, gives a unique value for the emittance. Calculations indicated that measurements downstream from the waist yielded the initial values α_L, β_L and that given these initial values ε varied linearly with the radius of the waist.

B. Beam-Size Measurements

Current flowing from the terminal of the Pelletron causes the terminal voltage to decrease, which in turn causes the particle energy to decrease during the pulse. In the constant magnetic field of the dipole, this decrease in energy causes the beam to sweep upward during the current pulse. This sweep acts as though it is swept from a single pivot point.

We can determine an effective length L for the distance from the exit edge of the dipole to the pivot point for the sweep. The equation of motion in the bending plane for a particle of momentum p+Δp in a dipole of bending radius ρ is

$$x'' + w^2x = \rho(\delta p/p). \tag{4}$$

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A solution for this differential equation, with $x' = x = 0$ at $\Theta = 0$, is

$$x = \frac{\rho}{w^2}\frac{\Delta p}{p}(1-\cos w\Theta). \qquad (5)$$

Hence $x' = dx/ds = dx/d(\rho\Theta) = (\Delta p/pw)\sin w\Theta$. Therefore, since $x' = x/L$, $L = x'/x = \frac{\rho}{w}\frac{(1-\cos w\Theta)}{\sin w\Theta}$. For our dipole $\rho = 24.1$cm, $w = \sqrt{1-0.44}$, $\Theta = \pi/2$, so $L = 21.5$cm.

Multiple wires located parallel to each other were installed at several locations downstream from the dipole. (Figure 1 shows a diagram of the wire chamber installed). The electrical signals picked up as the beam crossed the wires were observed on an oscilloscope and photographed.

The beam was successively focused on each set of wires by adjusting a quadrupole in the beamline. This produced sharp signals from which a sweep rate could be calculated. The effective distances from the pivot point to the three wire sets are $r_1 = 39.5$cm, $r_2 = 79.5$cm and $r_3 = 109.5$cm. (See Fig. 1). The distance between the two wires at r_2 is 3.0cm, while the distance between the wire at r_3 and its support frame is 4.5cm. (The beam hitting this support frame also generated an electrical signal.) Thus the angle the beam sweeps out between the two wires at r_2 is $\Delta\Theta_1 = 3.77\times10^{-2}$rad. Similarly the angular sweep made at r_3 is $\Delta\Theta_2 = 4.11\times10^{-2}$rad. Sweep rates are obtained by dividing the appropriate angular separation by the time between pulses ΔT.

To measure beam blow up from a waist, the quadrupole was set near zero so that a waist was formed at r_1. (The expected temperature rise of the 25μ carbon filament was ~400C.) The quadrupole was then left at this setting for measurements at r_1, r_2 and r_3. The "angular size" of the beam is $\Psi = \Delta\tau\cdot\overline{\Delta\Theta/\Delta T}$ where $\Delta\tau$ is the time duration of the beam hitting the wire and $\overline{\Delta\Theta/\Delta T}$ is the average measured sweep rate. The beam radius is then $R(r_i) = \frac{1}{2}r_i\Psi_i$ where r_i is the distance from the pivot point to the i^{th} wire set. $(i = 1,2,3)$.

Table I

Experimental Results of Sweep Rates at $\gamma=5$

	ΔT(μsec)	ΔΘ/ΔT(rad/μsec)
r_2	19	1.98×10^{-3}
r_3	21.5	1.91×10^{-3}

These data yield an average sweep rate of $\overline{\Delta\Theta/\Delta T} = 1.95\times10^{-3}$rad/μsec.

Table II

Experimental Results on Beam Size at $\gamma = 5$

	Δτ(μsec)	R(mm)
r_1	0.7	0.27
r_2	10	7.75
r_3	13	13.9

These data can be fitted by an optics calculation using an emittance value of $\varepsilon = 1.7\pi$mm-mrad.

Table III

Experimental Results of Sweep Rates at $\gamma = 6$

	ΔT(μsec)	ΔΘ/ΔT(rad /μsec)
r_2	12.5*	3.01×10^{-3}
r_3	14	2.94×10^{-3}

These data indicate an average sweep rate of $\overline{\Delta\Theta/\Delta T} = 2.97\times10^{-3}$rad/μsec.

* The scope trace used to obtain this value is shown in Fig. 2.

Table IV

Experimental Results on Beam Size at $\gamma = 6$

	Δτ(μsec)	R(mm)
r_1	0.5*	0.29
r_2	5	5.9
r_3	6	9.8

An optics calculation that gives a close fit to these data uses an emittance value of $\varepsilon = 1.25\pi$mm-mrad.

*The scope trace used to obtain this value is shown in Fig. 3.

C. Error Analysis

The major source of error in the data analysis is in reading the scope traces. Scope traces are readable to about 1/2 of one division. There is thus a relative error in scope trace readings of about half of a division divided by 15 divisions for the sweep rates or a 3.5% error in this value and a relative error in the wire pulse readings of about 25% (0.5/2) for the waist pulse readings. Thus the relative error is about 30% for the waist size. Since the beam emittance used in calculations is linearly dependent on the waist radius, the relative error in the emittance measurement is estimated at 30%.

Conclusion

The emittance of the beam at 2.0MeV is 1.7±0.6mm-mrad and at 2.5MeV is 1.25±0.3mm-mrad. This implies no emittance growth between cathode and measurement. The beam quality is adequate for electron cooling.

[1] W. Kells, AIP Conference Proceedings No. 87, pp. 656, American Institute of Physics, New York 1982.

[2] E.D. Courant and H.S. Snyder, Annals of Physics: 3, 1, 1958.

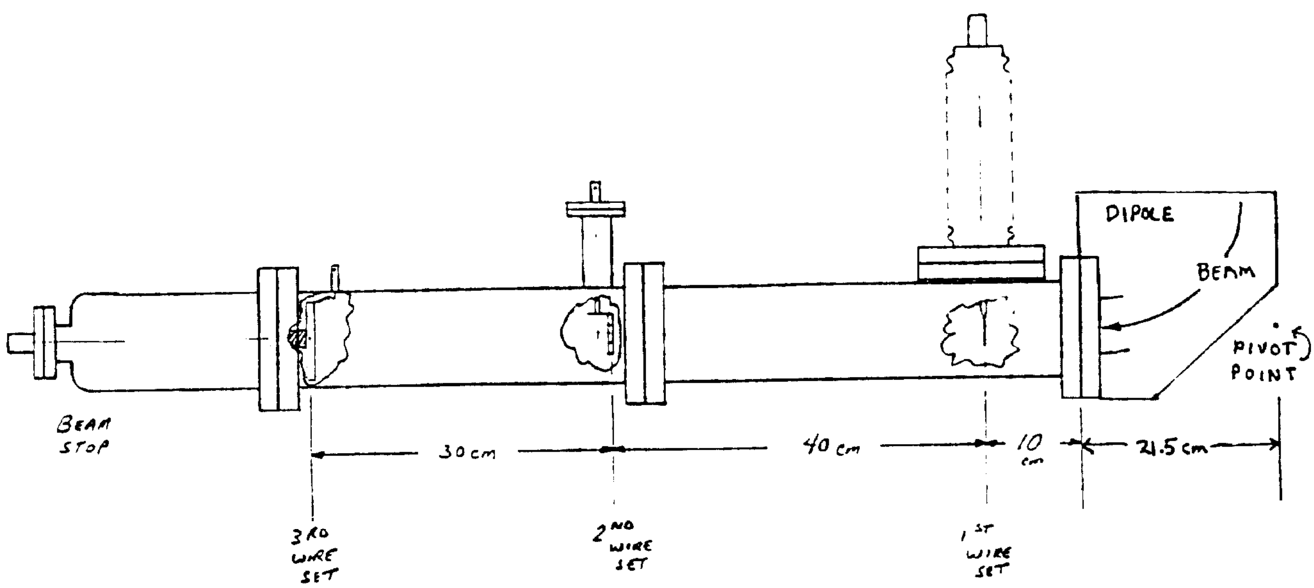

Figure 1. Diagram of the wire chamber installed. Shown are the distances between wire sets, the distance from the first wire set to the edge of the dipole, and the distance from the edge of the dipole to the pivot point.

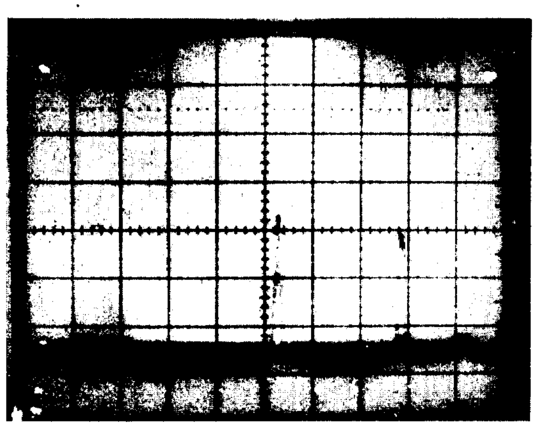

Figure 2. Scope trace used to evaluate sweep rate at r_3 for γ=6.

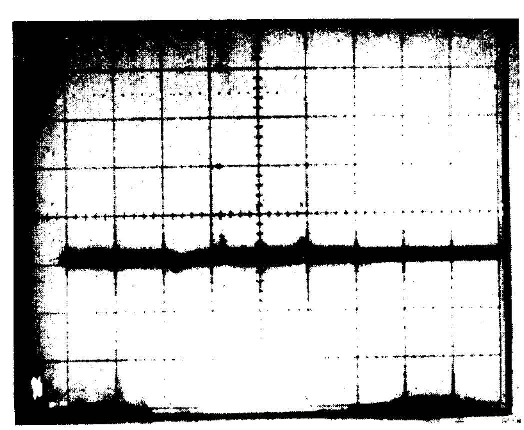

Figure 3. Scope trace used to obtain wasit pulse size at γ=6.