Outline of the
5 MeV Electron Cooling Test Beam Project

August 21, 1995

Purpose

The purpose of the 5 MeV test beam project is to generate a quasi-DC electron beam which can be use to simulate the electron cooling system envisioned for the Recycler ring. It would allow tests of latice designs, magnet prototypes, and beam diagnostic concepts well in advance of commissioning of the electron cooling system itself. In fact, most of the instruments and magnets used in this test are anticipated to be installed in the Recycler cooling system.

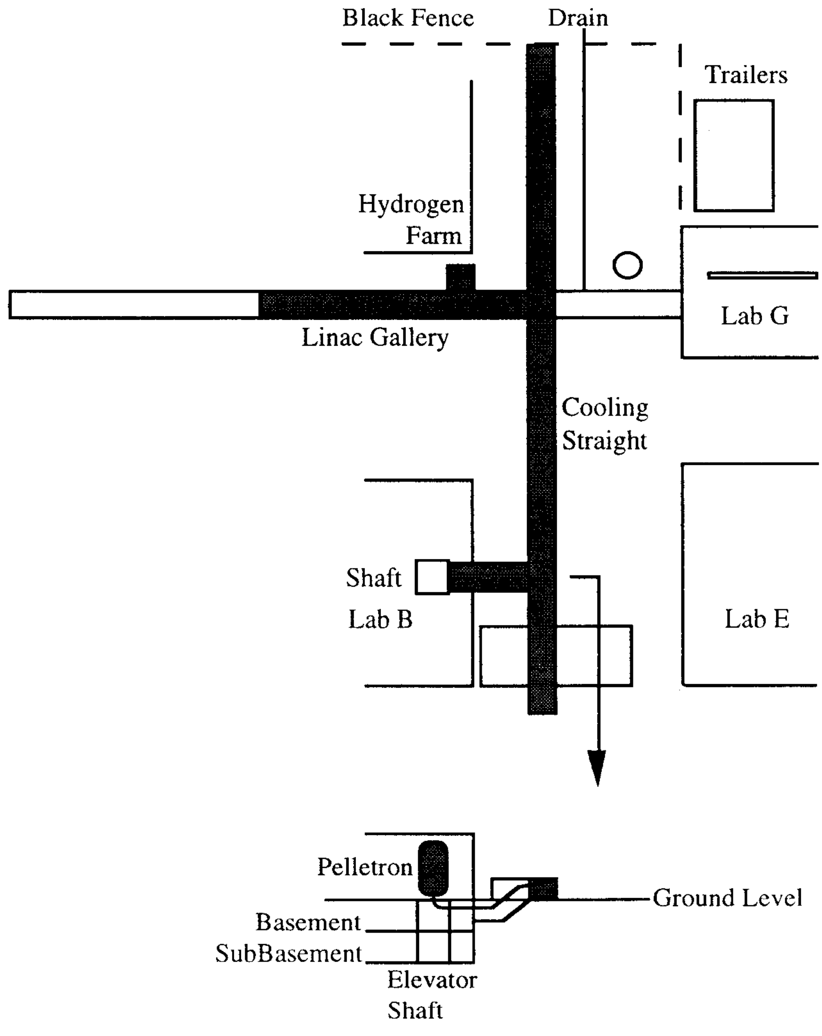


Figure 1: Sketch of the basic construction envisioned of the full capability 5 MeV electron test beam facility. The shaded portions represent the location of the proposed facility. The linac is assumed to deliver 1 ms pulses of DC beam at a 1 Hz repetition. The Pelletron (if installed) will allow a full test of electron cooling beam operations.

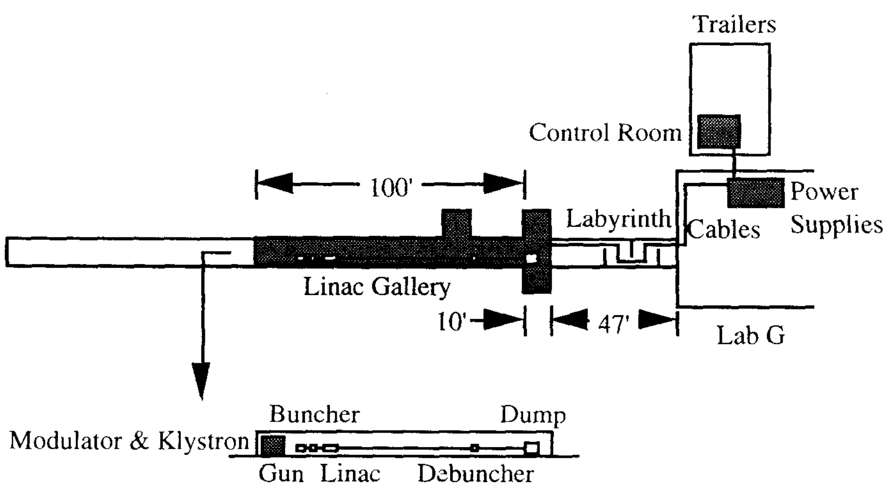
Short Description

Because the purchase of a Pelletron is prohibitively expensive and the delivery time is so far into the future, an RF based source for 5 MeV electrons is envisioned for the first phases of the project. To keep the average power reasonable, a duty factor of 0.1% is anticipated by delivering 1 ms of DC beam at a repetition rate of 1 Hz. A pulse length of 1 ms is long enough to simulate DC beam for the diagnostic systems which will be developed with this facility. The location of this facility is between Lab G and Lab B in the fixed target area of Fermilab. Figure 1 contains a sketch of the ultimate layout showing both the linac gallery and the Pelletron (if installed).

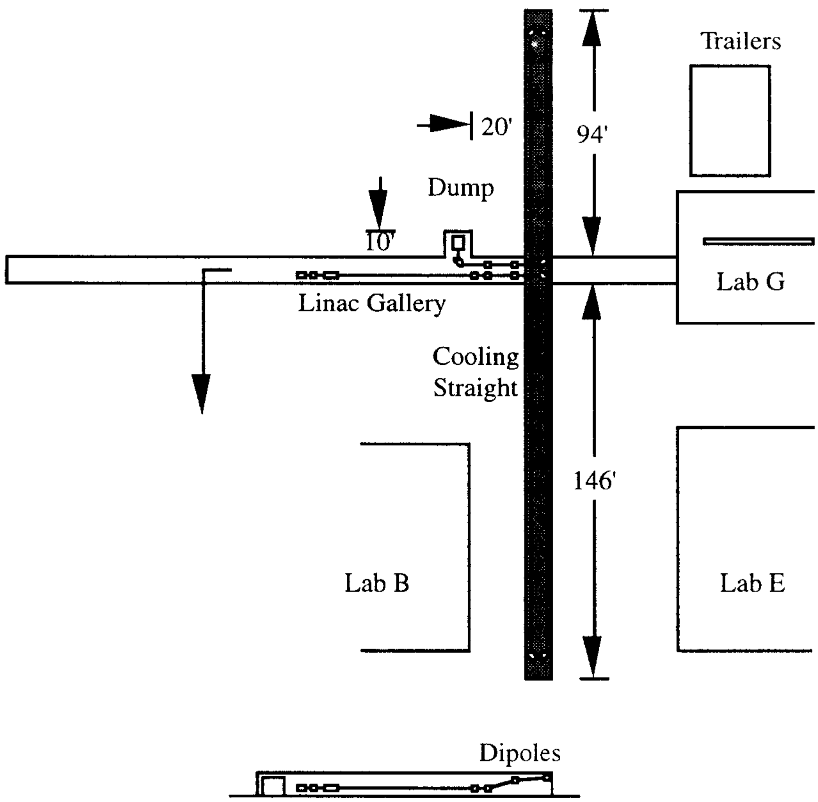
The phases anticipated in the evolution of this project are dictated by the construction and commissioning of beam line elements and the radiation enclosure. The anticipated phases are:

1) **Optical Design Verification with Protons.** Using the existing NEF enclosure behind Lab G, an existing duoplasmatron proton source can be used to check the space charge dominated optical design. The portion of NEF to be used is already weather-proof, and has cable trays, LCW water, and power distribution. Given the lack of radiation hazard, no remote control system is needed for this phase.

2) **Linac Installation and Commissioning.** Most of concrete block enclosure already exists, but in an effort to weather-proof the enclosure it is desirable to create the beginnings of the new cooling straight enclosure and the stub around the eventual position of the electron beam dump. Though the control room space is already available, the area behind the existing shield wall within Lab G needs to be cleaned out to make room for the required power supplies. Maintaining the radiation door between Lab G and the existing enclosure and adding a layrinth for personnel and cable tray access, the electron source aimed directly into the dump can be installed and commissioned.



3) Cooling Straight Installation and Commissioning. The cooling straight enclosure is needed for this phase. The inside enclosure width of 10' is shown in all figures. In order to make room for the entire length of this enclosure, the trailer next to Lab B needs to be moved. Using permanent magnets for the 90° bends, the general beam path is determined. Installation of all magnets and beam diagnostics is anticipated before commissioning begins. Commissioning is expected to occur at a maximum current of approximtely 10 mA.



4) High Current Commissioning. In this phase no major hardware installation is required, but diagnostic and beam control software will be developed. The goal is to increase the peak DC beam current from 10 mA to 2 A. The minimum acceptable ultimate current is 200 mA, the design current for run II.

5) Pelletron Installation and Commissioning. This phase exists as a contingency in case the Recycler project is substantially delatyed. As shown in figure 1, the Pelletron would be installed over the elevator shaft in Lab B. This would allow the output and recirculation beam lines to run along the basement ceiling before exiting the basement wall. An 8' deep and 10' wide tunnel is required to mate the Pelletron into the cooling straight enclosure.

6) **Electron Cooling Optics Commissioning.** Given that the final beam line is the exact geometry of the final cooling system geometry in the Recycler, this phase would represent a complete dress rehearsal of electron cooling beam control and diagnosis. Actual cooling of a proton or antiproton beam is the only feature of the final system which cannot be tested.

Project Schedule

The electron cooling system in the Recycler must be ready for commissioning in late 1998 or early 1999. Given the desire to run the 5 MeV test beam for a couple of years before this date, it is necessary to complete the construction and commissioning of the test beam in a year or less. In this discussion it is assumed that the test beam construction starts on August 1, 1995.

There is a great deal of work necessary to commission the 5 MeV electron test beam facility. Below is a list of some of the required tasks:

- August - Clear electronics out of the shielded area in Lab G. (Phase 1)
- August - Start installing the vacuum system, the proton source, and dedicated proton diagnostics. (Phase 1)
- September - Set up control room and decide on the type of control system. (Phase 2)
- September - Design the thermionic gun, the RF systems, and the major magnets. At the same time, a search for an existing compact 5 MeV electron source should be carried out. A search for available magnets should also be initiated. The 90° bends may end up being permanent magnets (radius = 0.5 m, momentum = 4.8 MeV/c, field = 160 G). (Phase 2 & 3)
- September - Design the basic beam instrumentation like beam position and intensity monitors. (Phase 2 & 3)
- September - Start installing the control system. Control crates, cables, and power supplies can also be installed. (Phase 1)
- September - Order or start building the thermionic gun and the RF system. (Phase 1)
- September - Start construction of basic electron beam instrumentation. (Phase 1)
- November - Thermionic gun is complete and commissioning starts. (Phase 1)
- December - RF systems are complete and installed. Commission low current 5 MeV beam up to the first 90° bend (which is used as a spectrometer). (Phase 1)

- February - Entire facility is commissioned up to a peak current of 10 mA. Start pushing up the beam current, with an ultimate peak current of 2 A. (Phase 2 & 3)

- March - Facility is operational! Start studying space charge dominated beam propagation, precision beam control issues, and advance beam diagnostics. Sublet beam time to Antiproton Source department for Schottky pickup R&D. (Phase 3)

Personnel

In order to meet the above schedule, names need to be attached to the above specified tasks. Below are some suggestions:

- Hurh/Research Division Personnel - Clear out Lab G and oversee radiation enclosure construction.

- Chuck Schmidt - Help set up proton gun and acceleration optics.

- Jackson - Set up layout of the control room in Lab G trailers. Specify the required basic beam instrumentation. Design the vacuum system.

- Barsotti Jr. - Oversee design, construction, and installation of basic beam instrumentation.

- Controls Group - Decide on type of control system (ACNET in a box). Put system together and install in Lab G trailers.

- Kroc - Design the build and thermionic gun. Oversee the construction, installation, and commissioning. Perform the same functions for the electron dump.

- Morretti - Design the RF structure and high level driver for the linac.

- Foster/May - Design and construction of the permanent 90° bends.

- Pruss - Develope a list of available magnets and power supplies for tuning and optics. Confirm the availability of sufficient power and cooling water services at Lab G. Take care of magnetic shielding.

- MacLachlan - Design the beam line optics for both the low beam current and space charge dominated (2 A) cases. Specify the performance requirements of the electrostatic quadrupoles.

- Curtis Crawford - Design and oversee construction of the electrostatic quadrupoles.

- Colestock - Design and oversee fabrication of the advanced beam diagnostics for precision alignment and beam size measurements.

- Assadi - Based on Ralph Pasquinelli's Linac Upgrade implementation, design and oversee construction of the low level RF system and beam loading compensation feedback for the linac.

5 MeV Electron Cooling Test Beam Facility

Phase 1:
12 keV Proton Beam Transport

Overview

The goal of the electron cooling system in the Recycler ring is to cool 8 GeV kinetic energy protons and antiprotons. In order to cool, the electrons must have a relativistic velocity exactly matched to that of the antiprotons, which is 0.994475. Electrons with this velocity have a kinetic energy of 4.330 MeV, and a momentum of 4.814 MeV/c. Because this electron kinetic energy is not a trivial accomplishment at a beam current of 200 mA, a short term alternative is desired which allows study of the optics and propagation of space charge dominated beams. Following a suggestion by Jim Simpson of Argonne, a proton beam with the same momentum as the electrons would fullfil this need. It turns out that the kinetic energy of this proton beam is 12.351 keV.

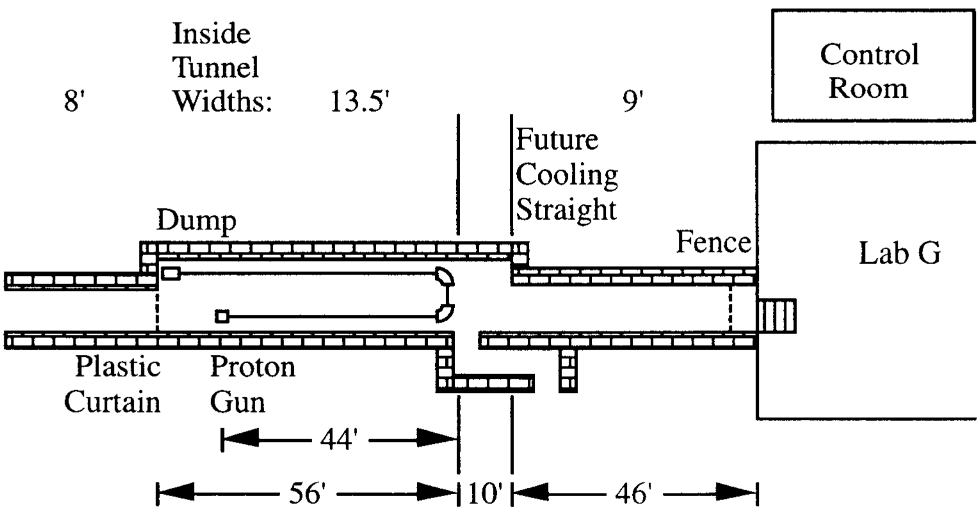


Figure 1: Sketch of the existing concrete enclosure NEG behind Lab G with the phase 1 accelerator configuration superimposed. In addition, the location of the future cooling straight section enclosure is also displayed.

Kinematics

The differential equation describing the propagation of a space charge dominated beam is called the envelope equation. For an axisymmetric beam with a rms width of r_m (using the convention in the book "Theory and Design of Charged Particle Beams" by Martin Reiser), the general envelope equation can be written as

$$r_m'' + \frac{\gamma' r_m'}{\beta^2\gamma} + \frac{\gamma'' r_m}{2\beta^2\gamma} + \left(\frac{qB}{2mc\beta\gamma}\right)^2 r_m - \left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{r_m^3} - \left(\frac{\varepsilon_n}{\beta\gamma}\right)^2 \frac{1}{r_m^3} - \frac{K}{r_m} = 0 \quad , \qquad (1)$$

where

$$K = \frac{I}{I_o} \frac{2}{\beta^3 \gamma^3} \qquad I_o = \frac{4\pi\varepsilon_o mc^3}{q} \qquad . \qquad (2)$$

The characteristic beam current I_o has the value of 17 kA for electrons and 31 MA for protons. Keeping the beam size constant, the space charge term is equal for protons and electrons are equal when the proton beam current I_p and the electron beam current I_e have the relationship

$$I_p = I_e \frac{m_p}{m_e} \left(\frac{\beta_p \gamma_p}{\beta_e \gamma_e} \right)^3 \qquad . \qquad (3)$$

Similarly, in the relationship between the proton invariant rms emittance ε_{np} and the electron invariant rms emittance ε_{ne} is

$$\varepsilon_{np} = \varepsilon_{ne} \left(\frac{\beta_p \gamma_p}{\beta_e \gamma_e} \right) \qquad . \qquad (4)$$

The values of the kinematic quantities and the resultant beam parameter values for the antiprotons in the Recycler, the cooling system electrons, and the momentum equivalent protons are listed in tables 1,2, and 3 respectively. The quantity which was held the same between the antiprotons and electrons is the relavistic velocity. The kinematic parameter held the same between the electrons and protons is the momentum, so that the optics design is identical for the two beams.

Table 1: Values of kinematic parameters for the antiproton beam in the Recycler.

Parameter	Value
Kinetic Energy (MeV)	8000
Rest Mass (MeV)	938.28
Total Energy (MeV)	8938
Momentum (MeV/c)	8889
Relativistic Energy (E/m)	9.474
Relativistic Velocity (v/c = P/E)	0.9945
Relativistic Momentum (P/m)	9.421

Table 2: Values of kinematic and beam parameters for the electron cooling beam.

Parameter	Value
Relativistic Velocity	0.9945
Relativistic Energy	9.474
Relativistic Momentum	9.421
Rest Mass (MeV)	0.511003
Total Energy (MeV)	4.841
Kinetic Energy (MeV)	4.330
Momentum (MeV/c)	4.814
Beam Current (A)	0.2-2
Normalized rms Emittance (π mmmr)	0.8

Table 3: Values of kinematic and beam parameters for the proton beam to be used in phase 1 to simulate the electron cooling beam.

Parameter	Value
Momentum (MeV/c)	4.814
Total Energy (MeV/c)	938.29
Kinetic Energy (keV)	12.351
Relativistic Energy	1.000013
Relativistic Velocity	0.005131
Relativistic Momentum	0.005131
Space Charge Equiv. Beam Current (nA)	60-600
Space Charge Equiv. Emittance (π mmmr)	0.000436

Bending Magnets

The equation relating the magnetic field B inside a dipole of radius of curvature ρ to the particle momentum P is

$$B[kG] = 33.356 \frac{P[GeV/c]}{\rho[m]} \quad . \qquad (5)$$

Therefore, for the momentum of 4.814 MeV/c a radius of curvature of 0.5 m requires a magnetic field of 0.321 kG.

The aperture of the bending magnets is determined by the beam size. The worst case beam size is that of the antiproton beam, which has an rms width of 8.4 mm. Assuming an admittance of at least ±5 sigma, the smallest standard beam pipe size would have a diamter of 4". Due to vacuum and other optical considerations, the beam pipe diameter will be 6".

Proton Source

The required kinetic energy of 12.351 keV can be supplied by biasing the proton gun at electrostatic potential with respect to the beam pipe. The beam current of 600 nA or less is much lower than the maximum peak current standard proton guns can achieve. In this case we plan to use a duoplasmatron, which can reach currents of 1 A. A beam power of 7.4 mW is required to sustain a DC beam of 600 nA.

The emittance of the beam is also quite small. For a emitting surface with uniform current density of radius r_s, the effective normalized emittance is given by

$$\varepsilon_n = 2r_s\sqrt{\frac{k_bT}{mc^2}} \quad . \qquad (6)$$

The value of the Boltzmann constant k_b is 8.61735×10^{-5} eV/°K. Assuming a source at room temperature 300°K, a normalized emittance of 0.000436 π mmmr is achieved using a source radius of 41.5 μm. The rms transverse velocity σ_v from the source in the absence of a magnetic field is related to the emittance by

$$\varepsilon_n = 2r_s\frac{\sigma_v}{c} \quad . \qquad (7)$$

The rms width r_m of the beam is related to the source radius by the relationship

$$r_m = \frac{r_s}{2} \quad . \tag{8}$$

In the case of this example, the values of the rms beam size and divergence from such a source have been calculated and are summarized in table 4.

Table 4: Values of kinematic and beam parameters for the proton gun.

Parameter	Value
Kinetic Energy (keV)	12.351
Beam Current (nA)	60-600
Normalized RMS Emittance (π mmmr)	0.000436
Plasma Temperature (°K)	300
Source Effective Radius (μm)	41.5
RMS Transverse Velocity Spread (m/s)	1575
RMS Transverse Beam Size (μm)	20.75

Optics

Now that the proton source has been determined, it is time to apply the envelope equation (1) to calculate the rms beam size as a function of distance down the beam line. This calculation will determine the number and strength of required focussing lenses.

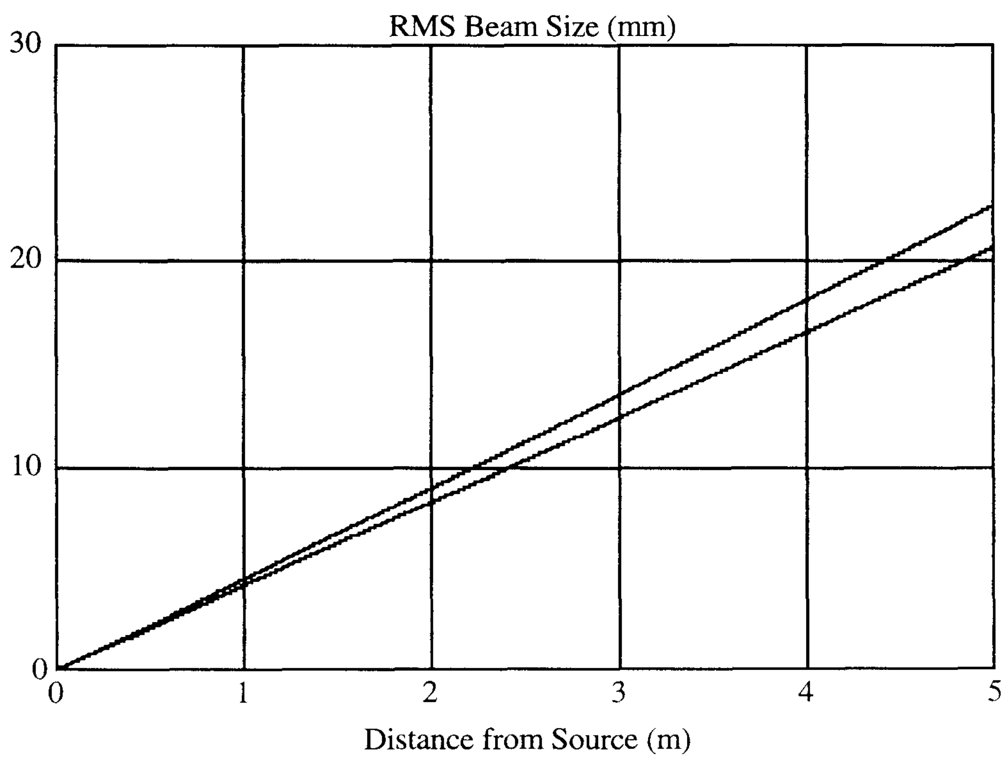


Figure 2: Calculation of the zero current (lower curve) and 600 nA proton beam (upper curve) rms beam size vs. distance from the source.

A dedicated computer program was written to evaluate the envelope equation. As a check, this program also calculated Twiss parameters and propagated the zero current beam size evolution. The first result of this program appears in figure 2. Using the starting values in table 4 for emittance and initial rms beam radius, a 600 nA proton beam is compared with the expected evolution of a zero current beam. The curve for the 60 nA proton beam is virtually identical to the zero current case.

When the beam reaches a rms radius of 2 cm, assume that an infinitesimally narrow focussing solenoid is used to focuss the protons into a parallel beam. The computer program was then asked to simulated the evolution of the beam size with distance. The result is shown in figure 3 for a 600 nA beam current. As before, the zero current expectation is also plotted. As in the case of beam size evolution away from the source, the curve for the case of a 60 nA beam current is indistiguishable from the zero current situation.

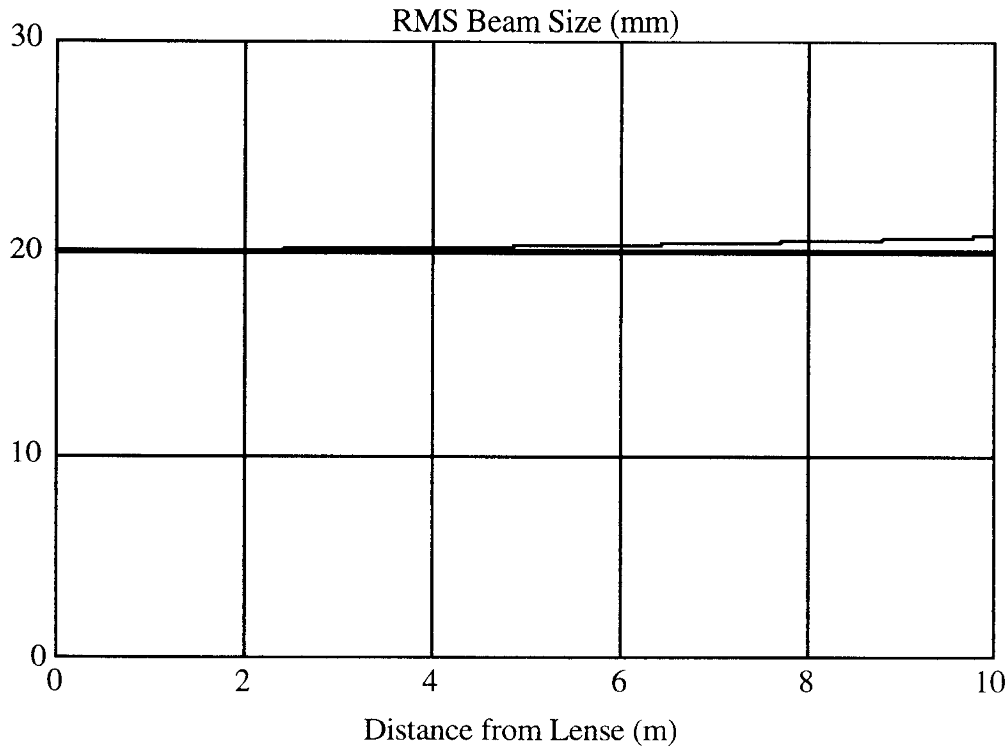


Figure 3: Calculation of the zero current (lower curve) and 600 nA proton beam (upper curve) rms beam size vs. distance from a lense for which the exiting protons are focussed into a parallel beam.

Instrumentation

The mission of phase 1 is to confirm calculations of beam size evolution through the optical system. Therefore, a monitor capable of measuring the beam profile is required. Because of the low energy of the protons, a Faraday-based profile monitor will be constructed. To allow measurement of the evolution of the beam size with distance down the pipe, the profile monitor will be designed to travel up and down the vacuum chamber, which is envisioned to be 6" O.D. electropolished stainless steel tubing. Shown in figures 4 and 5, this monitor has three outputs. The first two are the currents on the horizontal and vertical wires. The third is the current on the Faraday plate which terminates the beam. There are 3 degrees of freedom on this roving mechanism. The first two are the motion of the forks which move the sensor wires. The third is the motion of the detector up and down the vacuum chamber.

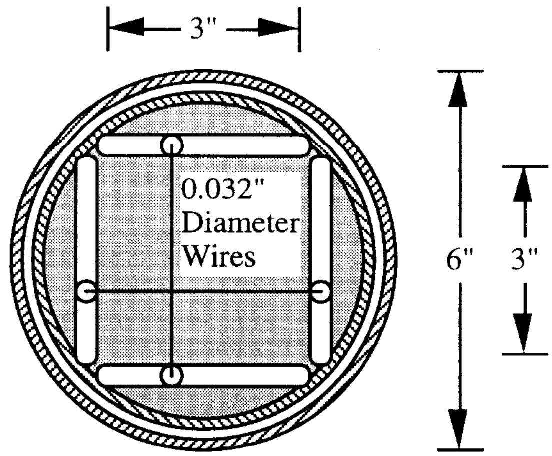


Figure 4: Beam eye view of the roving profile monitor. The horizontal and vertical wire are mounted on rotating fork arms which rotate across a 3" chord.

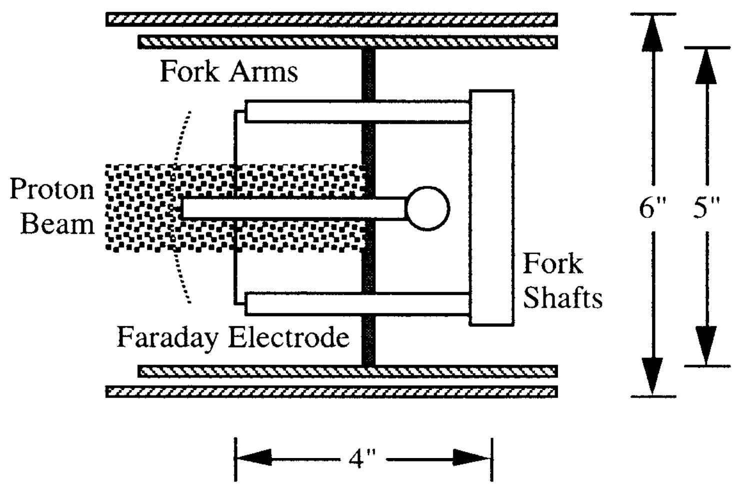


Figure 5: Side view of the roving profile monitor. The beam is terminated on a Faraday plate which, along with the two wires, simultaneously give the horizontal profile, vertical profile, and the beam current.

If the beam current I_b is 600 nA and the rms beam radius σ_b is 2 cm, a wire of diameter d_w approximately equal to 1 mm will sense a peak current I_w of

$$I_w = \frac{d_w}{\sqrt{2\pi}\,\sigma_b} I_b \qquad , \qquad (9)$$

or 12 nA. If a dynamic range of 100:1 is desired to fully describe the density distribution, a current resolution of 120 fA is required. There are circuits which can easily handle such currents.

Sub-Phases

In order to attain the goals outlined for phase 1, a number of intermediate goals or configurations or sub-phases can be identified.

Phase 1.1: Proton gun delivering beam into a 6 m long drift. The drift is terminated by the roving Faraday-based profile monitor. If all goes well, first beam should be measured in mid-September 1995.

Phase 1.2: Focussing the protons into a parallel beam with a short solenoid lens. The protons are again intercepted by the roving profile monitor. This sub-phase should begin in early October 1995.

Phase 1.3: Bending the protons twice by 90°. The protons are again intercepted by the roving profile monitor. The schedule calls for this sub-phase starting in mid-October 1995.