A HIGH RESOLUTION HIGHLY SENSITIVE NONINTERCEPTING BEAM PROFILE MONITOR FOR THE LOS ALAMOS MESON FACILITY (LAMPF)*

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ABSTRACT

A high resolution, highly sensitive, nonintercepting beam profile monitor is described. Calculations show that profiles of 1 mm and 1 cm diameter beams may be measured with less than 0.05 mm and 0.1 mm error respectively. Signal is derived from primary beam ionization of the residual gas molecules in a vacuum. Parallel, homogeneous electric and magnetic fields are utilized in guiding the liberated electrons to image the beam cross section precisely on a detector. A slit defines the resolution and the beam profile is acquired by mechanically moving the slit and detector across the image. Alternatively, the image may be moved across a stationary slit by simply shifting the magnetic field. The high sensitivity necessary for the LAMPF H^- beam, is achieved with a detector consisting of a phosphor on a photomultiplier tube. The lower level of beam current for which a profile is measurable is determined by the rate at which the profile is scanned and the statistics required.

Introduction

The cross sectional distribution of charged particle beams can be determined by collecting the products of residual gas ionization occurring when the beam passes through a partial pressure gas.[1] The ions can be collected with little disturbance to the beam so that the technique is virtually nondestructive. DeLuca[2] gives a good survey of detection schemes using residual gas ionization.

Of early concern was the effect of the initial ion velocity on the accuracy of the beam profile measurement[2,3,4]. Observations and measurements tended to show that electrons are created predominately with initial energies less than ten electron volts.[2] Indeed, some measurements make it appear that the electrons may be created predominately with energies less than one electron volt.[5] These observations are in agreement with a statement by Bethe and Ashkin[6] in which they say that in the primary

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collision by an ionizing particle, the most probable of the ionizing collisions are those in which a relatively slow secondary electron is ejected with kinetic energy smaller than the ionization potential. The small percentage of delta rays which can have high energies are of little concern here as their contribution to the signal should not be significant.

The requirements at some newer accelerators such as LAMPF and the NAL machines are more demanding than the applications in the references cited above since beams of ~ 1 mm in diameter must be measured; further, the beam current in a linear accelerator and in external lines is but a small fraction of the apparent beam current in a circular machine so that high sensitivity is required as well as high resolution. This requirement is particularly true for the LAMPF H^- beam line. The development of such a measuring device is the purpose of this report.

Collection Considerations

The residual gas ionization products can be collected by using only small sweeping fields (~ several volts/cm). The collection time for electrons being several orders of magnitude less than for the ions (~ nanoseconds compared to microseconds for typical geometries). However, since the products are created with finite initial velocities, the collecting technique and sweeping field become important in determining the spatial distribution of the beam.

For the simple case where a homogeneous y directed, static electric field is used to collect the ions liberated by a z directed beam, the well known parabolic trajectory results from an ion created with initial velocity in the x direction as indicated in Figure 1.

When the distance to the detector is 5 cm and an electric field of $2.5\ (10)^4$ volts/m is used (both realistic values), the resultant error at the detector exceeds 1 mm for an ion with an initial x directed velocity corresponding to an energy of 1 eV. A more sophisticated collection scheme for high resolution is required. Indeed, Johnson and Thorndal[4] have attacked the problem with crossed electromagnetic fields. The approach here is somewhat different.

A High Resolution Beam Scanner

In spite of the initial velocity, high resolution beam profiles are attainable if a small magnetic field is used in combination with a relatively strong parallel electric collecting field. Consider an incident z directed proton beam with a homogeneous magnetic field B_y parallel to an electric field ξ_y as depicted in Figure 2. In general the electrons created in the ionization process will have a distribution of velocities in the x, y, and z direction. Consider first only the electrons with

initial velocities v_{ox} in the x direction. Recall that projected on to the xz plane the paths of these electrons will be circles with radii determined by the following relationship:

$$R = \frac{(10)^4 v_{ox}}{e/mB_y} \tag{1}$$

where R is the radius in meters, B_y is the magnetic field in gauss in the y direction, and m is the mass of the electron in Kg.

The period of the revolution (Larmor period), T_L, for a nonrelativistic electron is as follows:

$$T_L = \frac{3.57(10)^{-7}}{B_y} \text{ s.} \tag{2}$$

That T_L is independent of initial velocity makes it possible to image at the detector all electrons independent of their initial x velocities. The trick is in choosing the combination of electric and magnetic field values such that the collecting time is precisely equal to the Larmor period, i.e., exactly one spiral is completed as indicated in Figure 2. In reality, electrons will be created with velocities in the y direction making the collection time a function of this velocity; in addition, the proton beam will always have a finite y dimension so that not all electrons are created at $y_o = 0$. Therefore, the collection scheme must be reasonably achromatic to image electrons with initial y velocities and must have a depth of field to image electrons over the range of interest with $y_o \neq 0$. A closer look at the geometry is necessary to quantitatively evaluate the aberration produced from the above effects.

Aberrations

Consider a reference electron created at $y = 0 = v_{oy} = v_{oz}$ but with $v_{ox} \neq 0$ (the ideal situation discussed above). The trajectory with the xz plane is illustrated in Figure 3 where $\Delta\theta = 0$ for the reference electron. In general however, $v_{oy} \neq 0$ and the initial $y \neq 0$ so that $\Delta\theta \neq 0$ and then

$$x_e \simeq -2\pi R\frac{\Delta t}{T_r} = 2\pi R\frac{\Delta\theta}{\theta} \tag{3}$$

where T_r is the Larmor period of the reference particle and $\Delta t = T_g - T_r$ where T_g is the time for a general particle having $y_o \neq 0 \neq v_{oy}$. The transit time T_r of the reference particle is as follows:

$$T_r = \left(\frac{2y_d}{\frac{e}{m}\xi}\right)^{\frac{1}{2}} \tag{4}$$

where y_d is the distance to the detector. The transit time must equal

the Larmor period determined by the magnetic field as defined in equation (2), so that the reference electron is imaged at the detector precisely at the projection of the origin of the electron. The transit time T_g for the general particle is as follows:

$$T_g = \frac{-v_{oy} + \left[v^2_{oy} + 2\frac{e}{m}\xi\,(y_d - y_o)\right]^{\frac{1}{2}}}{\frac{e}{m}\xi} \tag{5}$$

accordingly,

$$\frac{\Delta t}{T_r} = \frac{T_g - T_r}{T_r} = \frac{\left[v^2_{oy} + 2\frac{e}{m}\xi\,(y_d - y_o)\right]^{\frac{1}{2}} - v_{oy} - \left(2\frac{e}{m}\xi y_d\right)^{\frac{1}{2}}}{(2\frac{e}{m}\xi y_d)^{\frac{1}{2}}}. \tag{6}$$

Evaluation of this expression will show that minimum depth of field and minimum chromatic aberrations require a large collection distance and a large ξy_d product (collecting voltage) respectively. Practical considerations will limit the voltage to several kV and the distance to several cm. Table I illustrates the resolution expected in a configuration, depicted in Figure 4, for which the following values apply:

$$y_d = 10 \text{ cm}, \tag{7}$$

$$\xi = \frac{12 \text{ kV}}{12 \text{ cm}} = 1 \text{ kV/cm}, \tag{8}$$

so that $$T_r = 3.37(10)^{-9}\text{s}, \tag{9}$$

requiring $$B = \frac{3.57(10)^{-7}}{T_r} = 106 \text{ gauss}. \tag{10}$$

Assume in all cases that $v_{ox} = 8.5(10)^5$ m/sec corresponding to 2 eV initial energy, then R = 0.45 mm.

y_o (mm)	v_{oy} (10^5 m/sec)	$\frac{\Delta T}{T_r}$	x_e (mm)
0	$\pm$8.49	$\mp$0.014	$\mp$0.04
$\pm$1	0	$\mp$0.005	$\mp$0.003
$\pm$10	0	$\mp$0.05	$\mp$0.14

Table I

Chromatic ($v_{oy} \neq 0$) and Depth of Field ($y_o \neq 0$) Errors for Electrons Collected with Configuration of Figure 4.

Table I indicates that both the absolute and the relative spatial resolution are greatly improved over the simple method of collection. Clearly, profiles of beams 1 mm in diameter can be measured with precision if the initial energies of the electrons are as small as evidence indicates.

Detector Scheme

To be useful, the above collection system must be combined with a detector capable of collecting electrons to give the resolution available. Furthermore, as previously stated, not only is high spatial resolution required but high sensitivity as well.

The signal available will now be determined. Using the Sternheimer range energy relationships and assuming that 90 eV is required to produce an ion pair, one calculates that a 1 ma minimum ionizing incident proton beam in a gas pressure of 10^{-6} mmHg provides an available ionization current I_c of 0.035 na per cm of incident beam path. In equation form the relationship is as follows:

$$I_c = \frac{0.035 \text{ na ions}}{(\text{ma proton beam})\ (\text{cm})\ (10^{-6} \text{ mmHg})} \tag{11}$$

For example, if a detector 10 cm long were used in a gas pressure of 10^{-4} mmHg to collect ions created by a 10 ma incident proton beam, then the total instantaneous available signal would be as follows:

$$I_c = \frac{0.035 \text{ na}}{(\text{ma protons})\ (\text{cm})\ (10^{-6} \text{ mmHg})}\ (10 \text{ cm})\ (10 \text{ ma protons})\ (10^{-4} \text{ mmHg})$$

$$= 350 \text{ na} \tag{12}$$

In the collection method described above, the electrons arrive at the detector with significant energy. This energy can be converted to useful signal by an electron to photon to electron conversion process in the form of a phosphor on a photocathode. For example, consider a sandwich consisting of a P-31 phosphor on an S-11 photocathode. Assume the phosphor is aluminized for the usual reasons, i.e., to reflect back scattered light, to form a conductive surface and to protect the phosphor. Applied in this manner, the phosphor conversion efficiency is approximately 800 photons per 10 keV electron. These photons are predominately 2.39 eV (5200A°). The quantum efficiency of an S-11 photocathode to these photons is approximately 15, i.e., 0.15 electrons/photon. The spectral matching factor[7] for P-31 phosphor and an S-11 photocathode is approximately 0.7; accordingly, an approximate sandwich gain of (0.15) (800) (0.7) = 84 is realized.

A variable width slit in front of the phosphor may be used to define the spatial resolution of the detector. Once the width is selected, a profile can be obtained by moving the slit and detector assembly across the image at the detector. Alternately, it may be possible to move the image across a stationary slit by shifting the magnetic field B_y with a horizontal component B_x much like a magnetically scanned image dissector tube[8].

The sensitivity of the detector may be further increased if a high gain photomultiplier tube is used with the photocathode at the detector. A gain of ~ 10^6 should be possible. The total signal, i_s, of the composite detector with the above gain is then as follows:

$$i_s = \frac{0.03 \text{ na} \cdot 84\ (10)^6}{\text{cm (ma proton beam) } 10^{-6} \text{ mmHg}} \simeq \frac{2.5 \text{ ma}}{\text{cm (ma proton beam) } 10^{-6} \text{ mmHg}}. \quad (13)$$

For measuring profiles, the slit width would be some fraction of the beam width depending on the spatial resolution desired so that the actual signal will depend upon the resolution and the portion of the profile being measured. If a fast responding scintillator replaced the phosphor, then measurements could conceivably be made at beam current levels where the rate of ionization in the residual gas is within the counting capability of the photomultiplier tube and the electronics. Accordingly, the lowest level of measurable beam current would be dictated by the scan rate and the statistics required for the desired resolution. Figure 5 is a schematic of a detector assembly.

Conclusion

The technique described here is capable of measuring beam profiles with the precision necessary for contemporary accelerators. With the low noise photomultiplier tube used in the detector, beam currents in the low microampere and possibly into the nanoampere range could be measured.

The use of a mechanical device to move the slit and the detector permits accurate absolute resolution. The use of a magnetic scanning technique is complicated by the magnetic shielding necessary for a photomultiplier tube and by the lack of a calibrating method; however, the simplicity and economy of this type scanning makes it worthy of serious consideration, at least for relative profile measurements.

A prototype mechanical scanner is being constructed for test on the electron prototype accelerator (EPA) at the Los Alamos Scientific Laboratory. A laboratory test model of a magnetic scanner is also being constructed to study its optical and scanning properties.

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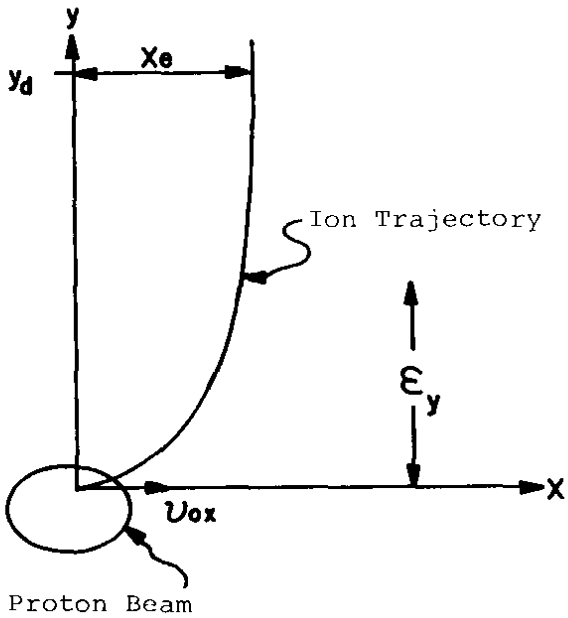

Figure 1
Simple Ion Collection Scheme
Showing Position Error x_e Resulting
From Initial Ion Velocity v_{ox}

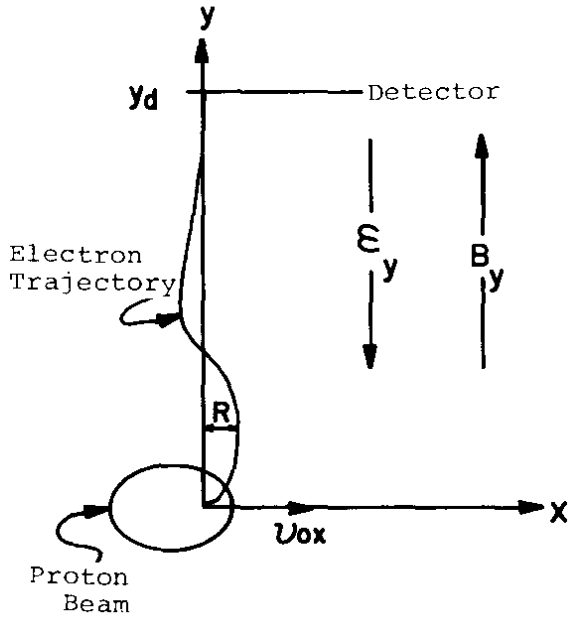

Figure 2
Collection Scheme Utilizing
Homogeneous Parallel Electric
and Magnetic Fields

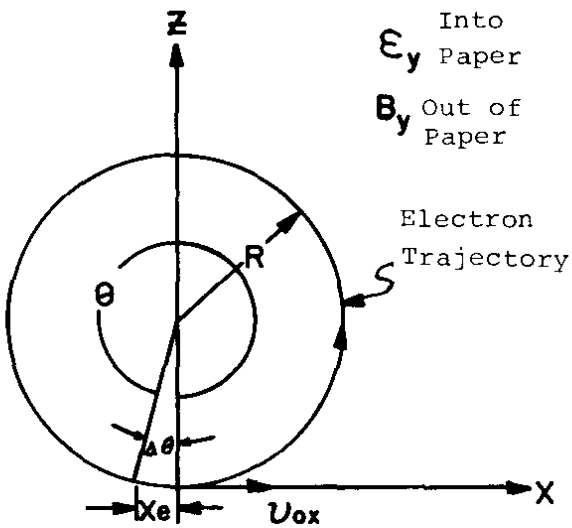

Figure 3
Projection of Electron Trajectory
on xz Plane for Homogeneous y
Directed Magnetic and Electric Fields

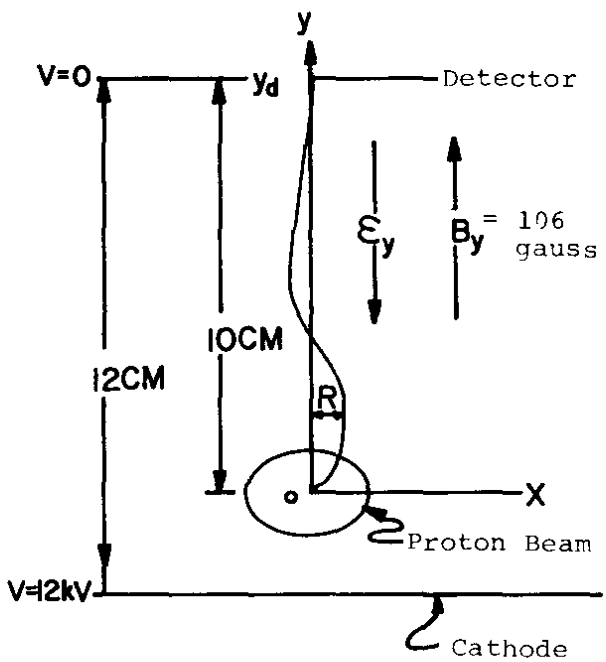

Figure 4
Detector Configuration and
Field Values Used in Calculations
for Table I

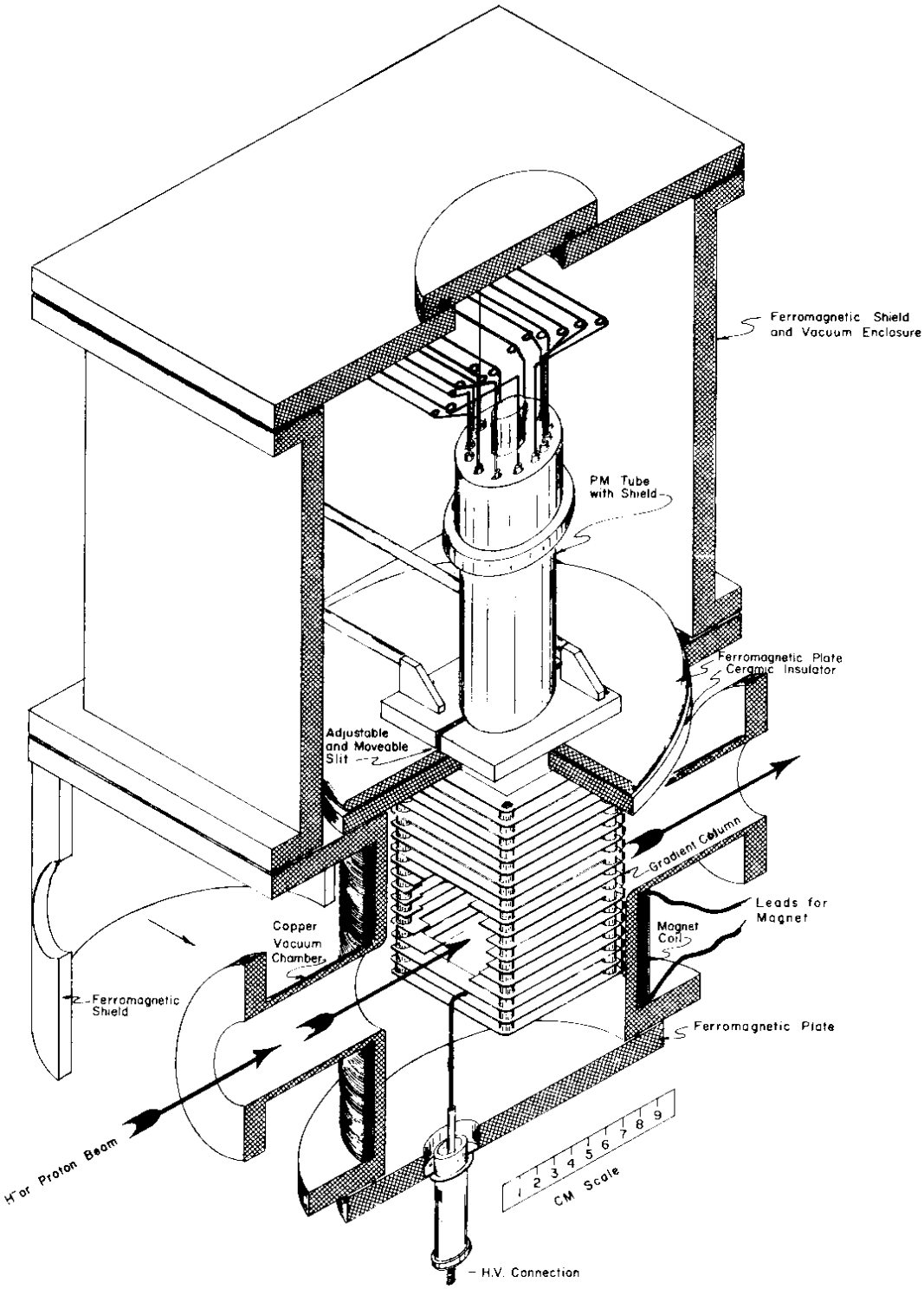

Figure 5
Complete Detector Assembly

DISCUSSION

R. H. Miller (SLAC): Are you acquainted with the crossed-field residual gas profile monitor that CERN has, and would you comment on the relative advantages and disadvantages?

F. Hornstra (NAL): The crossed e-m field, the one that Johnson and Thornbell have worked on at CERN, pulls the electrons out of the beam using a magnetic field in the direction of the beam and an electric field across the beam such that the electrons do a hypercycloid coming out. They arrive at the detector with low energy, first of all, so that there is no inherent gain in the collection process, which in their case is not important because they have a circulating beam in the machine with much higher apparent current. Second, it uses a velocity-selection principle, and some of the electrons would be rejected. In our case, all electrons are used, so we would find a further increase in sensitivity. Furthermore, in this process, if you want to check the motion of the beam through the magnetic field, the magnetic field can be reversed and you can note any dispersion or position shift of the beam. In their case reversing the magnetic field turns the beam around, and you are not allowed to use that technique as a diagnostic tool.

J. Claus (BNL): Have you any idea about the sensitivity to radiation damage of this instrument?

F. Hornstra: We have used devices like this, with a 1/4-inch layer of phosphor on glass, elsewhere inside an accelerator, and they have lasted for many weeks, indeed months, without significant detraction of the signal due to radiation damage. That is one of the reasons why one wants to use the photomultiplier tube with the phosphor on it, because the amount of material subjected to radiation damage is at an absolute minimum.

J. Claus: Are the multiplier cathodes themselves subject to radiation damage?

F. Hornstra: I don't know to what extent these are subject to radiation damage. We don't propose to use this near heavy targets.

D. W. Mueller (LASL): How many primary particles per mm in cross section of the beam per second do you expect? Is there any statistical problem or will it take a long time to make a measurement?

F. Hornstra: For the H^- beam, one may have to use synchronous detection to increase the noise rejection of the system; however, for beams on the order of 1 mA, I do not anticipate any problem with that. The statistics of it are as follows: for the case here, the probability of a molecule being ionized in this gas pressure is approximately 2.5×10^{-8}, so one can take the primary current and multiply by that to get the specific signal and then add the multiplication one has to that to get the total signal.

R. L. Martin (ANL): If both proton and H^- beams are present, do you anticipate that you can pick out each one?

F. Hornstra: No, I don't. I don't think our time resolution would be that good, unless we replace the phosphor with a fast-responding scintillator. We have not considered that.

R. L. Martin: If you deal just with the H^- beam in which the process can release rather energetic electrons, do you anticipate any problems?

F. Hornstra: No. I suspect that these electrons will have an orbit which will not be within our acceptance. One can put in a center aperture to stop the high-energy electrons from entering the system.

R. H. Helm (SLAC): People interested in superconducting machines are interested in a nondestructive profile monitor. I wonder what the problems are of running such a machine in a cryogenic vacuum if you don't have any ions. How could this be adapted to these conditions?

F. Hornstra: The calculations are pretty straightforward: you know what the gas pressure is and you know what the specific ionization is and obviously the signal level will be quite low. However, one can cheat a little by introducing a small high-pressure area in the vicinity of this to increase the specific ionization and hence the signal.

R. H. Miller: I wonder if the problem with radiation there isn't more of a problem with background rather than damage to the monitor?

F. Hornstra: We have used one of these without the photomultiplier tube next to the septum magnet when the beam was being extracted, and there was no problem with selecting signal. However, if there is a problem, one can turn off the accelerating voltage and find out exactly what the excitation of the phosphor is without collecting ions. Then one has some kind of background on which to measure again. I hope that isn't very high.