A BEAM CHARACTERIZATION OF H⁻ PARTICLES*

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Abstract

A pinhole-scintillator diagnostics system has been developed to determine the characteristics of a 50-MeV H⁻ beam. The device consists of an aluminum plate (1.27 mm thick) with a series of pinholes (125 μm diameter) covered by a thin neutralizer foil and downstream scintillator plate and associated camera. The foil covered pinholes produce a series of H⁰ beamlets that are detected downstream by the scintillator plate. The use of H⁰ particles provides the ability to measure the beam parameters without changing the magnetic fields of downstream magnetic elements. Measurement of the intensities of the beamlets, the separations between beamlets, and the beamlet width allow determination of the beam parameters. The H⁺, produced by the plate, are sufficiently scattered by the plate, such that a sweep magnet is not required. The device has been used at the Argonne National Laboratory (ANL) Neutral Particle Beam Test Stand (NPBTS) to measure the parameters at the input of the beam expanding telescope.

Introduction

The 50 MeV H⁻ beam from the ANL linac is transported through roughly 50 meters of transport line into a beam expanding telescope [1]. By carefully collimating the beam at various locations, the emittance, in both the x and y planes, is reduced from 1.8 πmm-mr, at the linac output, to approximately 0.5 πmm-mr [2] at the telescope entrance.

The basic idea of characterizing the telescope input beam is to introduce into the beam a 1.27 mm thick aluminum pinhole plate approximately two meters upstream of the telescope eyepiece. The pinholes are covered by a thin neutralizer foil that neutralizes a portion of the incident H⁻ beam and thus produces a series of beamlets. These H⁰ beamlets are not affected by the eyepiece and are imaged on a scintillator screen located five meters downstream of the pinhole plate. The characteristics of the beam are then obtained by analyzing the spatial distribution of the H⁰ beamlets at the scintillator screen.

Theory of Measurement

In the first approximation, the distribution of the particles in phase space can be represented by a series of homothetic ellipses that are Gaussian in x and x' (also in y and y'). Figure 1 is a x-x' phase space plot showing the relationship between the pinholes and the beam ellipse. The slope of the "zero-emittance line" is given by $S = -\alpha/\beta$, where α and β are the Twiss parameters at the location of the pinhole plate. Furthermore, the divergence of the centroids of the beamlets at the spatial coordinate x_p is given by $x'_p = -(\alpha/\beta)x_p$. On traversing a drift space the transformation of the centroid of a beamlet located at x_p, coincides with the transformation of the "zero-emittance line," i.e., $x'_p = S\ x_p$. The new location of the "image" pinhole at the scintillator screen, x_s, is then given by
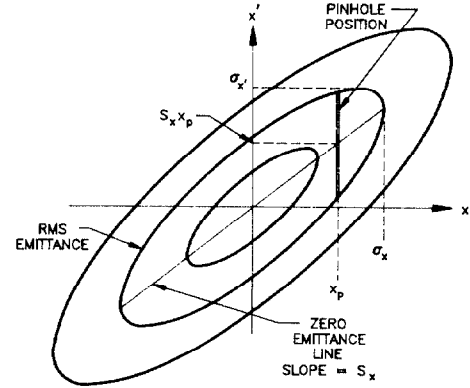
$$x_s = Lx'_p = LSx_p \tag{1}$$

Figure 1:   Phase space diagram showing the relationship of the pinholes to the phase-space ellipse. The centroids of the beamlets defined by the pinholes coincide with the "zero emittance line" of the slope, $S_x = -\alpha/\beta$.

where L is the distance from the pinhole plate to the scintillator screen. By measuring the image position, x_s, and the pinhole position, x_p, the divergence of a beamlet, x'_p, is calculated as

$$x'_p = \frac{(x_s - x_{sc}) - (x_p - x_{pc})}{L} \tag{2}$$

where x_{sc} and x_{pc} are the centroids of the beam at the plate and scintillator, respectively. By plotting x'_p versus x_p, one can then determine the slope of the "zero emittance line."

The amount of beam passing through a pinhole is obtained by integrating the light output of the scintillator around the image of the equivalent pinhole. The RMS beam profile (σ_{xs} and σ_{ys}) at the scintillator is found by fitting the integrated beamlet intensities at the scintillator screen to that of a two-dimensional Gaussian distribution. The RMS beam sizes at the pinhole plate (σ_{xp} and σ_{yp}) are found by transforming σ_{xs} and σ_{ys} back to the pinhole plate.

In terms of the emittance, the RMS beam size (dropping the subscripts s and p), σ_x can be written as

$$\sigma_x^2 = \epsilon_x \beta_x \tag{3}$$

where ϵ_x is the RMS emittance of the beam. Assuming that the pinhole diameter is negligible when compared to L, the beamlet images on the scintillator screen, W_x, can be written as

$$W_x^2 = L^2 \epsilon_x/\beta_x \tag{4}$$

From equations (2), (3), and (4), α_x, β_x, and ϵ_x can be determined from the measured quantities: σ_x, S_x, and W_x.

Equation (4) is derived assuming a zero size pinhole. Since the pinholes were of finite size, the width of the image at the scintillator screen, W_x, is not an accurate method to determine the first order parameters of the beam. In terms of the emittance, the Twiss parameters are given as:

$$\beta_x = \sigma_x^2/\epsilon_x \tag{5}$$

$$\alpha_x = -S_x\beta_x \tag{6}$$

Hence, if the emittance of the beam is known a priori, then the first order beam characteristics of the input beam can be obtained by measuring the RMS beam size at the pinhole plate and the slope of the "zero emittance line." The emittance is measured at a location upstream of the pinhole plate [4].

The telescope is operated such that, in both the x and y planes, the incident H⁻ beam goes through a waist in the vicinity of the pinhole plate. The magnification parameter, M_x, is defined as:

$$M_x = \frac{\Delta x_{image}}{\Delta x_{plate}} \tag{7}$$

$$= 1 - L\alpha_p/\beta_p \tag{8}$$

where Δx_{image} and Δx_{plate} are the distances between adjacent pinholes at the scintillator screen and the pinhole plate, respectively. α_p and β_p are the Twiss parameters at the pinhole plate. A magnification of 1.0 ($L\alpha_p/\beta_p = 0$) implies that $\Delta x_{image} = \Delta x_{plate}$. If $M_x = 0$, then $\Delta x_{image} = 0$; the case in which all the pinhole images overlap at the scintillator screen. A negative magnification implies that the H⁰ beamlets cross over which indicates the occurrence of a waist between the pinhole plate and the scintillator screen. In order to detect any crossing over of the beamlets, a keyhole was drilled into the pinhole pattern.

The Effect of the Aluminum Plate

The H⁺, H⁻, and H⁰ particles are equally produced by the neutralizer foil. Moreover, almost all of the H⁻ impinging on the aluminum plate are converted to H⁺. The 1.27 mm thick aluminum plate increases the RMS divergence of the H⁺ by about 11 mrad. This leads to an RMS H⁺ beam size of about 2.2 cm at the entrance to the permanent magnet eyepiece. Since the half aperture of the eyepiece is 2 cm, a significant portion of the H⁺ are lost at the eyepiece. Furthermore, the high gradient of the eyepiece (~25 T/m) diverges the H⁺ and H⁻. Consequently, it is safe to assume that the majority of the particles hitting the scintillator are H⁰.

System Description

The beam characterization system consisted of a pinhole plate, a scintillator-camera system, and subsequent computer hardware and software interface (see Figure 2). The pinholes were each 125 μm in diameter and were separated by 1 mm. The pinhole plate was mounted on a horizontal drive located 0.5 m downstream of the Q716 quadrupole.

The H⁰ beamlets produced by the pinholes are imaged using a 4 × 4 cm² scintillator screen oriented at 90° to the beam axis. A pellicle, inclined at 45° in front of the scintillator reflects the images of the pinholes onto a camera that is located directly above the scintillator. On command from the experimenter, the 640 × 480 image array from the camera is acquired by a frame-grabber system. The data were then processed using peak search and analysis routines to derive the first-order beam parameters.

The routine to determine pinhole location was implemented using a spatial filter and peak search
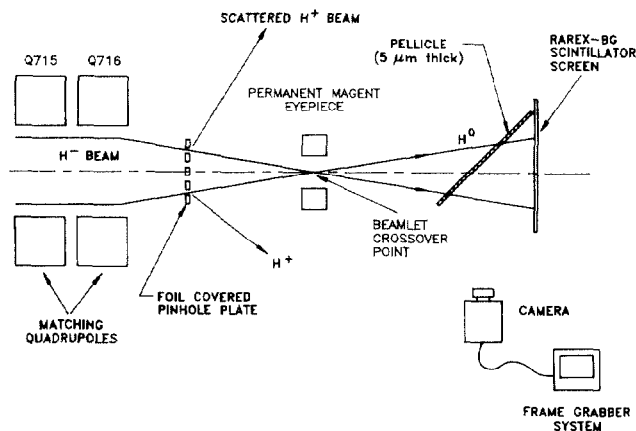

Figure 2: Layout of the pinhole-scintillator diagnostic system. A cross-over of the H⁰ beamlets is shown. The H⁻ and H⁺ are scattered by the eyepiece and the aluminum pinhole plate.

algorithm. The spatial filter consisted of compressing the 640 × 480 picture array from the camera down to 124 × 124 array, performing a two-dimensional Fast Fourier Transform (FFT) method, zeroing out all frequencies above an arbitrary threshold and finally performing an inverse two-dimensional FFT. A lower limit was picked at 25 percent of the highest initial peak to avoid "finding" false peaks introduced by the inverse FFT process. Using a microvax, the peak search routine required about three minutes of CPU time to complete. A more detailed description is given in Reference 3.

Once the beamlet locations had been determined, the next step was to fit a two-dimensional Gaussian distribution to the intensity of the pinhole images. In doing so, the centroids and RMS sizes of the full beam were calculated both at the plate and at the scintillator. Next the divergence of each pinhole, x'_p, was calculated using equation (2). S_x and S_y were then determined by linearly fitting the plot of x_p versus x'_p.

Data Measurement and Analysis

The optimum tune for the telescope operation produced a focused image in the x plane and a well-separated image in the y plane (see Figure 3). The inability to resolve the beamlets in the x plane direction meant that an indirect method was required

Figure 3: An image of the pinholes at the scintillator screen for the optimum telescope tune. The optimum tune is at a current of 20.5 A. The y axis (vertical) is in the horizontal direction.

to determine the beam parameters. The indirect method consisted of varying the gradient of the quadrupole immediately upstream of the pinhole plate (quadrupole Q716), so that the optimum tune could be interpolated. This was achieved by increasing the current from 13 A to 24 A. The optimum tune occurred when the Q716 current was at 20.5 A. Figures 4 and 5 show the pinhole images at i = 13A and i = =24A, respectively.
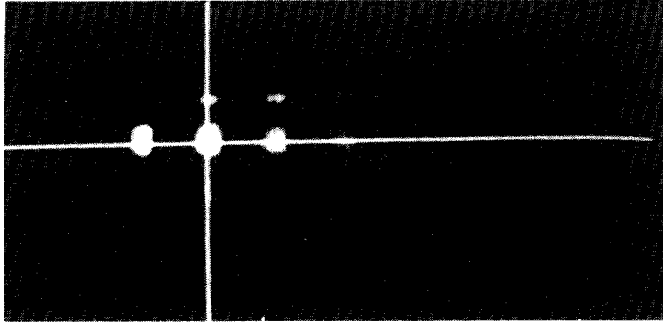

Figure 4: Pinhole image at the scintillator screen with Q716 current set at 13 A. The y axis is in the horizontal direction. Q716 current was varied from 13A to 24A.
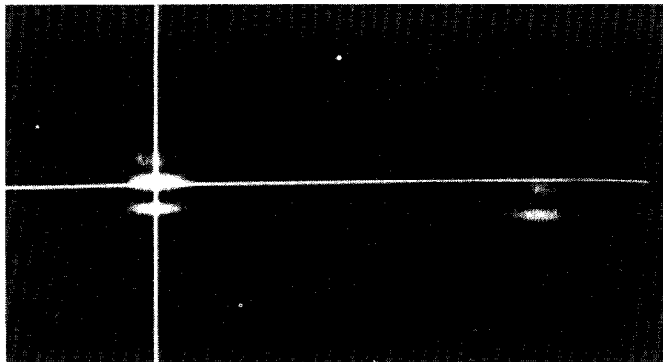

Figure 5: Pinhole image at the scintillator screen with Q716 set at 24A. The y axis in the horizontal direction.

By identifying the location of the keyhole on the scintillator screen with respect to the pinhole plate, one determined the sign of S_x and S_y. Figure 6 shows the plots of σ_x and σ_x, and S_y and S_y as a function of the quadrupole current. Fitting these data linearly, σ_x and σ_y can be written as

$$\sigma_x = 0.035i + 0.159 \tag{9}$$

$$\sigma_y = -0.100i + 2.82 \tag{10}$$

where i is the Q716 quadrupole current. The RMS beam size at the optimum tune of the telescope (i = 20.5 A) was then found to be 0.89 mm for σ_x and 0.81 mm for σ_y. S_x and S_y were fitted to a quadratic function of the form

$$S_x = 2.64 - 0.138i + 0.493 \times 10^{-5} i^2 \tag{11}$$

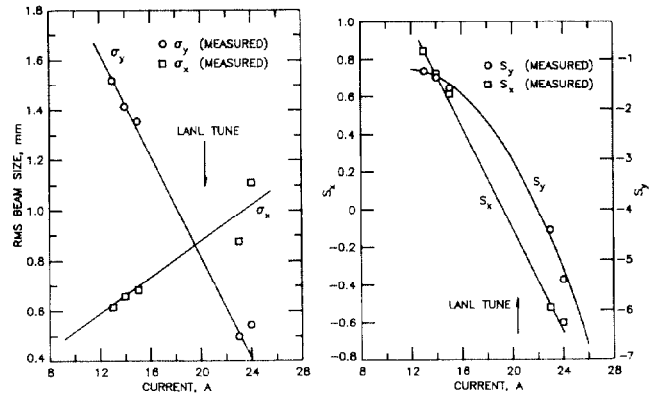$$S_y = -5.68 + 0.715i - 2.90 \times 10^{-2} i^2 \tag{12}$$

Figure 6: Plots showing the RMS beam sizes (σ_x and σ_y) and the slope of the "zero emittance line." S_x and S_y are a function of the Q716 current. The optimum time is at current i = 20.5 A.

At the optimum tune, S_x and S_y were found to be -0.128 and -3.07, respectively. The emittance was measured approximately 7 meter upstream of the pinhole plate by using a scanning slit and recording the beam profile with a Segmented Faraday Cup (SFC) [4]. There was insignificant emittance reduction between the SFC and the pinhole plate because the beam current measured at the two locations differed by less than 5 percent.

For the optimum tune of the telescope, the emittance of the input beam was found to be 0.53 πmm-mr and 0.47 πmm-mr for the x and y planes, respectively. Using these values, the optimum tune input beam Twiss parameters, α_x, β_x, α_y, and β_y, were found to be 0.184, 1.49 m, 4.27, and 1.39 m, respectively.

Current Status

When the emittance of the beam is known, the pinhole-scintillator diagnostic system is a relatively convenient technique to dynamically measure the characteristics of the H⁻ beam. The technique of converting the H⁻ particles into H⁰ particles can be used to measure the beam characteristics at any point along the beam line provided that there are magnetic elements or drift space downstream of the pinholes to sufficiently disperse the charged particles. This technique can also be used to measure the operating characteristics of magnetic elements.

At present, work is in progress to extract additional information from the widths of the pinhole images. This will provide information about the full four-dimensional phase space, including higher order optical aberrations.

References

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[2] C. Hummer, "Two Dimensional Emittance," Argonne National Laboratory Internal Report ANL/NPBTS-RPT-011 (1987).

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[4] M. G. Rosing, et al., "Measurement of the Twiss Parameters by using SFCs," to be presented at the IEEE Particle Accelerator Conference, Chicago, 1989.