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BEAM EMITTANCE MEASUREMENTS WITH A DISPERSION-MATCHED MAGNETIC SPECTROGRAPH*

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Summary

The technique of dispersion-matching a beam to the split pole magnetic spectrograph at the MSU Cyclotron Laboratory was employed to eliminate the broadening of the beam spot size due to the coherent energy variations which come mainly from fluctuations of the amplitude of the cyclotron dee voltage. The incoherent emittance can therefore be measured directly.

This was accomplished by observing the spot size in the focal plane of the spectrograph with a high magnification television system and by measuring the beam divergence angle with a simple intercepting probe placed upstream. The emittance for proton beams was in agreement with previous indirect measurements. The luminosity of a proton beam was approximately equal to that inferred from previous d.c. test stand measurements. Measurements for $^3He^{2+}$ and $^{12}C^{4+}$ beams are also presented. The contribution to the divergence angle by the coherent energy spread was found to be negligible, in agreement with calculation. The correlation of observed line width with ion source slit width suggests that the complete optical system from ion source to the spectrograph is linear, and that an image of the ion source slit was observed in the spectograph focal plane.

Introduction

A television-scintillator beam detection system has been developed[1] for rapid tuning of the beam transport system to a "dispersion match" between the beam and the magnetic spectrograph. We adapted it to allow us to make direct measurements of the incoherent radial emittance of the accelerator beam. This quantity was inferred by Blosser[2] from standard emittance measurements on the dispersed beam by comparing them in detail with calculations giving the effect of dispersion on the beam distribution. The result for 40 MeV protons was 0.7 mm-mrad. A subsequent (unpublished) measurement with refined apparatus reduced the value to 0.3 mm-mrad. The present direct measurements have confirmed this more recent result. The method has also been applied to two other beams, 70 MeV $^3He^{2+}$ and 77 MeV $^{12}C^{4+}$.

Method

The direct beam was brought through the spectrograph to a focus on the scintillator in the focal plane. After passing through the scintillator it was stopped in a Faraday cup, which measures the beam current, as shown in Fig. 1. The beamline quadrupoles and the position of the plate holder, which supports the apparatus shown in the figure, were adjusted to give minimum line width, which is the condition for a focus and matched dispersion. The spot size Δx and the divergence angle $\Delta\theta$ were measured. The emittance area of the beam ellipse is $\pi/4\ \Delta x\ \Delta\theta$, where Δx and $\Delta\theta$ represent the full axis of the ellipse. The small wires in front of the scintillator were visible in the television picture. Their diameter and spacing served to calibrate the distance scale. An example of the television display, from which the line width was measured, is shown in Fig. 2. The full width of the beam spot was used. The precision is ±.005 mm for the high magnification used for the proton and He^3 measurements.

The angular divergence of the beam was measured with a transversely movable probe located 22 inches upstream from the focal point in the camera box of the magnetic spectrograph. The probe consisted of a tantalum plate with an attached .030" dia. tungsten wire that was clamped at one end in a bracket attached to the plate. As the probe was moved across the beam the current from it was measured. The wire signal gave a direct measure of the beam profile, but was subject to broadening from imperfect wire alignment. The occultation of the beam by the edge of the plate gave a more reliable measure of the beam width. The positions where 10% and 90% of the beam was transmitted were taken to define the divergence angle (includes 80% of the beam). The precision is estimated to be ±.7 mrad, partly due to beam intensity fluctuations. Simultaneous strip chart records of the probe current and the beam current transmitted past the focal plane to the Faraday cup are shown in Fig. 3.

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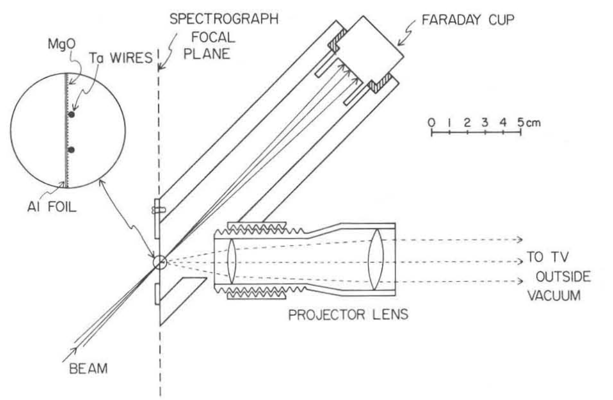

Fig. 1. Viewing apparatus positioned in the spectrograph focal plane. Light from the lens traverses a plastic window before entering the television camera lens. The two vertical wires in the insert, which are 25 μm in diameter and are separated by 2 mm, serve to calibrate the width and relative position of the beam image.

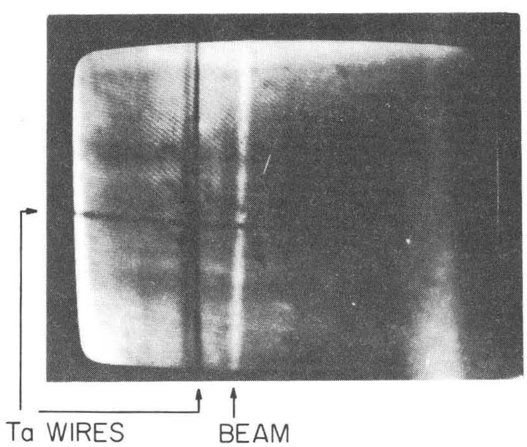

Fig. 2. Photograph of the television picture of the beam (white image) on the MgO scintillator. Only one of the two vertical wires is seen at this high magnification. Its shadow on the scintillator is also visible. The diameter of the wire is 25 μm. The tilt of the beam image is an indication of a small beam misalignment.

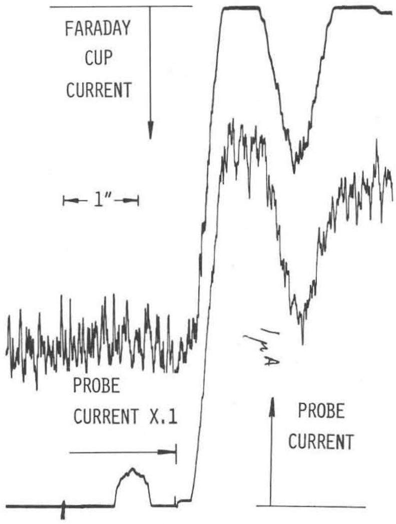

Fig. 3. Sample data for divergence angle measurement. Probe is scanned transverse to beam direction at constant speed (scale for one inch of probe motion is shown). Probe current (lower trace) increases upward; Faraday cup current (upper trace) increases downward. Beam intercepted by the probe disappears from the total Faraday cup current. Probe current amplifier sensitivity is increased by factor of 10 while wire portion of probe is in the beam, as shown in lower left corner of the figure. The large valley in both traces on the right side of the figure is a result of beam passing through some slots that were cut in the center of the probe plate for another experiment. The sloping parts of the traces near the center of the figure are used to measure the divergence angle.

Emittance Data

The measured emittance data are summarized in Table 1.

Table I. Incoherent Radial Emittance Data

E (MeV)	Ion	W_s (inches)	W_{fp} (mm)	Δx (mm)	$\Delta\theta$ (mrad)	$\pi/4\ \Delta x\ \Delta\theta$ (mm-mrad)		i (eµA)
35	protons	.008	.068	.048	23	1.1	(0.35π)	1.1
40	"	.008	.038	.027	--	--	-----	0.65
40	"	.008	.076	.054	21	.88	(0.28π)	0.24
41	"	.008	.088	.062	18	.88	(0.28π)	----
40	"	.008	.041	.030	15	.35	(0.11π)	0.83
70	$^3He^{2+}$	.019	.121	.086	20	1.4	(0.43π)	0.18
77	$^{12}C^{4+}$	.065	.25	.177	22	3.1	(0.97π)	0.09

The two columns at the right of the table give the emittance for each of the beams and the beam current. The ion source slit width W_s and the line width on the focal plane W_{fp} are given for reference. The beam is incident at 45° to the focal plane.

Evidence of an intermittent short circuit in the coil of the magnetic channel in the cyclotron was recently found, and the problem was corrected. The data in line 5 of the table were measured after that repair. The line width agrees with older data (given in lines 1 and 2), measured before the trouble occured, and also agrees within 20% with the narrowest line widths recorded on plates or other detectors in scattering experiments.[3]

Discussion

Optical Linearity

Since there is a unique optical path through the cyclotron and beam transport system to the focal plane and since coherent energy variations are cancelled, it is possible to make an image of the ion source slit on the focal plane of the spectrograph. Fig. 4 is a plot of line width *versus* the ion source slit width for the data in Table 1. The line through the data obtained when the magnetic channel may have been producing some extra broadening of the line does not extrapolate to zero image width at zero source width.

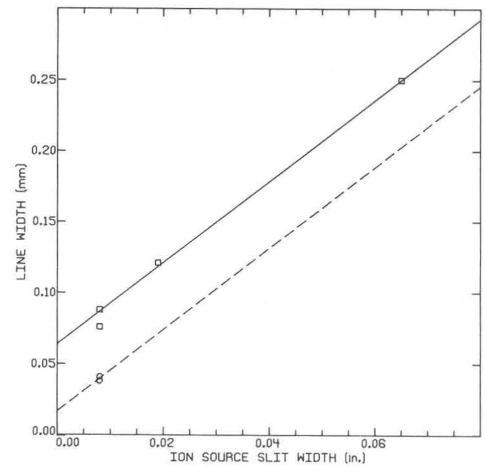

Fig. 4. Line width of image in spectrograph focal plane *vs.* ion source slit width. Dashed line is drawn with same slope as solid line. In the absence of aberrations and instrumental broadening effects, the line would pass through the origin if an image is formed.

If the line is translated downward to pass through the proton data under good conditions, the relation becomes more like the ideal one for a linear optical system. The intercept of the lower line represents an energy resolution of about 59000 (at zero beam intensity); the highest resolution achieved in elastic scattering test runs is 23000 with approximately 1µA beam current.

Divergence Angle Contributed by Beam Energy Spread

Dispersion matching cancels at the focal plane the line-broadening effect of beam energy variations, but the divergence angle may contain a coherent energy correlation. The deflection of an exit ray due to an energy shift has been calculated[4] from a model of the magnetic field distribution in the magnet.[5] The energy spread of the 40 MeV proton beam was measured by the beam analysis magnets[6] to be 26 keV or .07%. The corresponding calculated change in divergence angle ($.049 \frac{\Delta E}{E}$ rad) is .034 mrad, which is undetectably small. This is consistent with measurements of the divergence angle made with various amounts of beam energy spread, shown in Fig. 5. The energy spread was reduced by closing the exit slit for the analysis magnets.

Luminosity

The relationship between the density of the beam from an internal cyclotron source compared with the same source in a d.c. test stand is of great interest due to the relative simplicity of a d.c. source testing facility and its great utility in studying ion source performance. The luminosity characterizes the density of the beam and has been measured[7] for protons with a

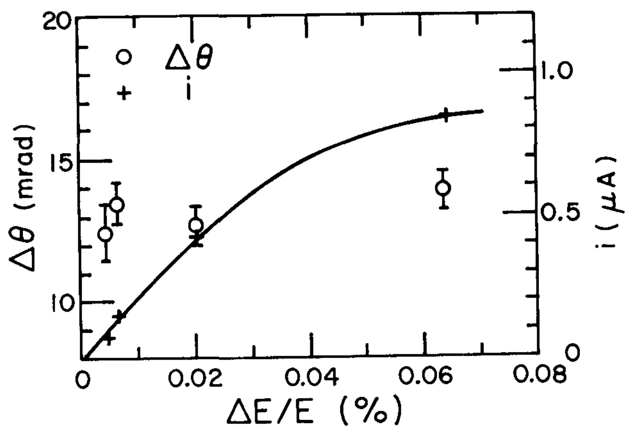

Fig. 5. Beam divergence angle (Δθ) and intensity (i) vs. energy spread, controlled by the width of the analyzing slit. The energy spread of the entire beam was about .07%. There is no detectable change in beam divergence as the energy spread is reduced by a factor of 10.

source similar to the one used in the present work, but having different slit dimensions. Since the luminosity is independent of the slit area to a first approximation, we compared luminosities.

The luminosity of the 40 MeV proton beam was estimated to be 130 A/cm^2 sr using a beam current of 1.9μA, radial emittance area .3 mm-mrad and axial emittance area 5 mm-mrad^2. Correcting this to an energy of 30 keV and for its duty cycle of 1% due to the rf phase acceptance of the cyclotron we obtain a predicted d.c. luminosity at 30 keV beam energy of 10 A/cm^2 sr, to be compared with 22 A/cm^2 sr measured from the test stand[7] with a comparable ion source arc current (1.5A for cyclotron measurement, 1A on test stand). This approximate agreement stands in contrast to some beam intensity comparisons done at Oak Ridge[8] on heavy ion PIG sources which showed a large beam intensity enhancement (allowing for duty cycle) when the source was operated in the cyclotron with rf beam extraction. There is, however, no comparison of luminosity available.

Conclusion

Making the beam spot in the focal plane visible greatly speeds up the process of tuning the beam transport system because a large amount of useful information is conveyed quickly to the operator. A tilt or distortion of the beam spot is instantly recognized and is not confused with an out-of-focus condition. If a similar display could be applied to the divergence angle it might be very helpful for discovering how the divergence is affected by various adjustments. The present moving probe is cumbersome to use for exploring such effects. Some variation in the measured divergence and in the beam profile does occur.

The luminosity of the proton source is in rough agreement with d.c. test stand measurements.

Acknowledgement

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References

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