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AN EMITTANCE SCANNER FOR INTENSE LOW-ENERGY ION BEAMS*

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Summary

An emittance scanner has been developed for use with low-energy H$^-$ ion beams to satisfy the following requirements: (1) angular resolution of ±1/2 mrad, (2) small errors from beam space charge, and (3) compact and simple design. The scanner consists of a 10-cm-long analyzer containing two slits and a pair of electric deflection plates driven by a ±500-V linear ramp generator. As the analyzer is mechanically driven across the beam, the front slit passes a thin ribbon of beam through the plates. The ion transit time is short compared with the ramp speed; therefore, the initial angle of the ions that pass through the rear slit is proportional to the instantaneous ramp voltage. The current through the rear slit then is proportional to the phase-space density $d^2i/dxdx'$. The data are computer-analyzed to give, for example, rms emittance and phase-space density contours. Comparison of measured data with those calculated from a prepared (collimated) phase space is in good agreement.

Introduction

As beams of increasing intensity and brightness are used in accelerators, the details of the transverse phase-space distribution (the emittance) become more important. The electric-sweep scanner (ESS) described here measures a two-dimensional emittance and was designed to overcome some intensity and angular resolution limitations for low beam energy in the slit and collector type scanner used at many accelerators.[1] Because of the relative simplicity of the ESS, it can be used to produce emittance contours on a storage oscilloscope without a computer;[2] however, the present version is computer interfaced and controlled to provide the most flexible operation and data analysis.

Theory of Operation

The ESS is schematically depicted in Fig. 1. A beam of current i impinges on the narrow front slit of the scanner pod. The emerging beamlet passes between a pair of electric deflection plates driven by a linear ramp generator. The ramp voltage changes slowly compared to the ion transit time; thus, for ions passing through the rear slit, there is a simple relationship between the initial angle x' and the instantaneous ramp voltage. The scanner current as a function of time during the ramp then is proportional to the phase-space density $d^2i/dxdx'$ as a function of x'. The scanner pod is stepped across the beam to complete the measurement as a function of x,x'.

We assume that the ions have uniform energy $e\phi$ and that the velocity of ions does not change significantly in passing through the plates. We also assume that the deflecting field is uniform and confined to the geometric length of the plates $D - 2\delta$, where D is the distance between slits and δ is the gap between the plates and the slits (Fig. 1). A more accurate calculation shows a negligible error due to this assumption of hard-edged electric field.

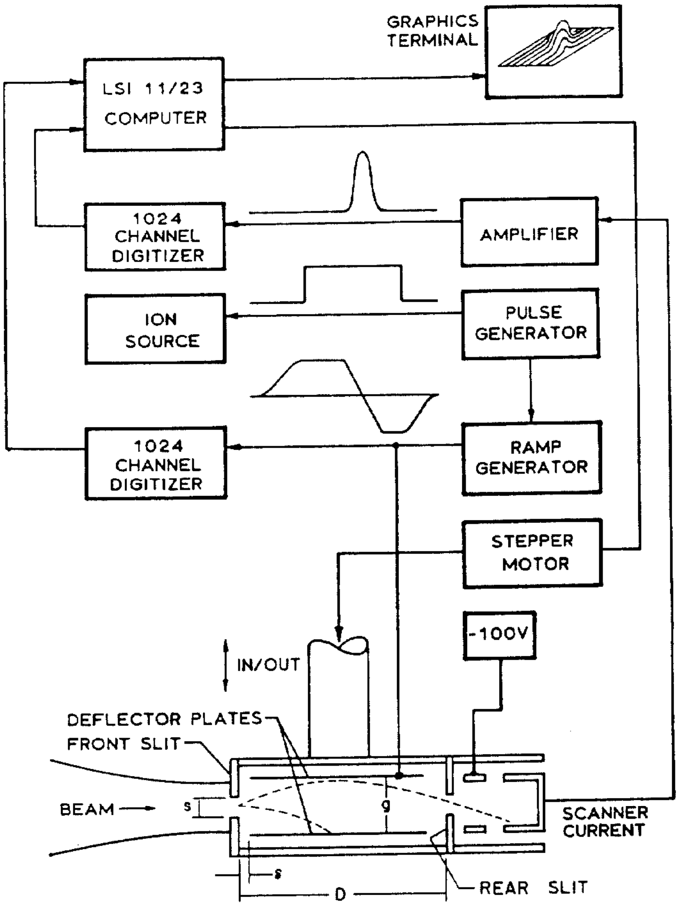

Fig. 1. Schematic of electric-sweep emittance scanner.

Using the paraxial ray approximation, we find for ions passing through the rear slit with deflection voltage V applied across the gap g between the plates that

$$x' = \frac{V}{\phi}\,\frac{(D - 2\delta)}{4g} \quad .$$

The maximum analyzable angle x'_m, limited by ions striking the deflecting plates is

$$x'_m = \frac{\pm 2g}{(D + 2\delta)} \quad ,$$

corresponding to a maximum voltage V_m required:

$$V_m = \frac{\pm 8g^2\phi}{D^2 - 4\delta^2}$$

$$= \pm 2(x'_m)^2\,\phi\,\frac{D + 2\delta}{D - 2\delta} \quad .$$

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The full mechanical angular resolution ΔΘ is

$$\Delta\Theta = \frac{\pm s}{D} \quad ,$$

and the rms value (for a parallel beam uniformly illuminating the front slit) is

$$\Theta_{rms} = \frac{s}{\sqrt{6}\,D} \quad ,$$

where we have chosen the front and rear slit widths s to be equal to maximize the scanner current for a given angular resolution. The approximate scanner current δi is obtained from the ratio of scanner acceptance to the unnormalized phase-space area ($\pi\varepsilon/\beta$):

$$\delta i \sim \frac{is^2}{D(\pi\varepsilon/\beta)} \quad .$$

We calculate that the rms angle from finite bandwidth f of the scanner amplifier is

$$\Theta_{rms} = \sqrt{2}\,\frac{x'_m}{\pi T f} \quad ,$$

where T is the ramp time to analyze angles $\pm x'_m$. We obtain a bandwidth criterion by equating this to Θ_{rms} of the mechanical resolution:

$$f = \sqrt{12}\,\frac{x'_m D}{\pi s T} \quad .$$

To assess the effect of space-charge forces, we assume a uniform density beam of elliptical shape with radii R_x and R_y. The electric field E_x at the surface $x = s/2$ of the ribbon beamlet is $E_x = si/2\pi\varepsilon_o R_x R_y v$, where v is the beam velocity. After a drift of distance D this force expands the beam by an additional amount h: $h = \pm eisD^2/4\pi\varepsilon_o R_x R_y mv^3$, where m is the ion mass. If we require h to be less than s/2, then space-charge forces require that

$$D^2 < \frac{2\pi\varepsilon_o R_x R_y mv^3}{ei}$$

if resolution is to be determined solely by ΔΘ.

Design and Performance

Electric-sweep scanners were built for measurements in both planes on 20- and 100-keV H^- beams operating at 5 Hz with a 1-ms pulse width. The four scanners are identical except that the deflecting plate gap g was smaller for the 100-keV models because the required scan angle x'_m was smaller. With this choice, the required ramp voltages are nearly identical, so that a single transistor ramp generator can be used. The ESS, shown in Fig. 2, can scan a beam of radius ±5 cm. Most of the beam power is dumped on a cooled plate shadowing the front slit, and the heating due to current passing through the scanner is negligible. The scanner cup bias ensures that there is little or no response to neutral particles or secondary electrons. A list of pertinent specifications is given in Table I. From the space-charge consideration D should be less than ∿7 cm for a 0.1-A, 20-keV round beam of 1-cm radius; therefore, in this case the angular resolution will be degraded from the mechanical limit.

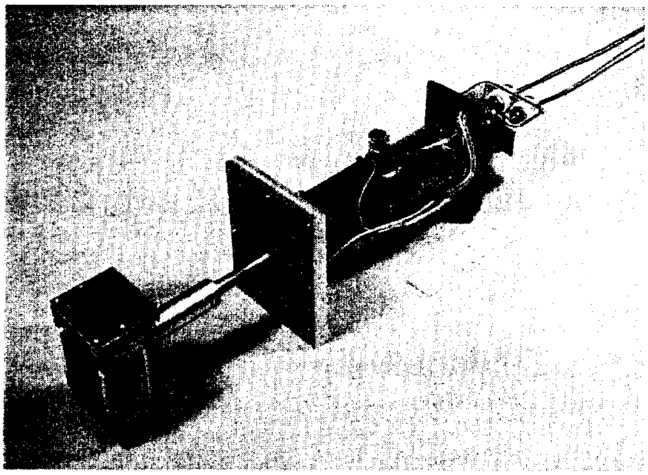

Fig. 2. Photograph of emittance scanner, showing scanner pod (left) and linear actuator (right).

TABLE I

EMITTANCE SCANNER DESIGN PARAMETERS

Parameter	20-keV Unit	100-keV Unit
s(cm)	0.005	0.005
D(cm)	10	10
δ(cm)	0.48	0.48
g(cm)	0.5	0.25
ΔΘ(mrad)	±0.5	±0.5
x'_m(mrad)	±91	±46
V_m(V)	±400	±510

The ramp generator drives a single plate from $+V_m$ to $-V_m$ at the desired time in the pulse, with a typical 200-µs ramp time. A typical scan covers ±2 cm, with both the mechanical step size and the angular scan width selectable. Typical scanner current, ramp voltage, and beam-gate pulses are shown in Fig. 3. The bandwidth of the scanner-current amplifier is 1 MHz, hence the ramp time must be >200 µs for the 20-keV unit to avoid limiting the angular resolution. Digitizers record the scanner-current and ramp-voltage waveforms, and the data are reduced in the computer to a format of 48 bins in angle by 50 bins in position. Plotting the data in isometric form on the graphics terminal limits the measurement rate to ∿0.4/min. At our pulse rate, 10 s would be required even if stepper motors and data reduction were very fast. The computer program can calculate and display phase-space contours, rms emittance, emittance versus beam fraction, and Courant-Snyder beam-envelope parameters.

The calibration of the 100-keV scanner was tested by analyzing a beam from a phase-space collimator, consisting of two 4-mm apertures spaced 25.4-cm apart. After a final drift of 4.4 cm from the end of the collimator, the allowable phase space is as shown in Fig. 4. This calculated outline is superposed on the phase space measured at the lowest possible contour level and is in good agreement with the measurement. The 2-mm displacement is due to the collimator mount.

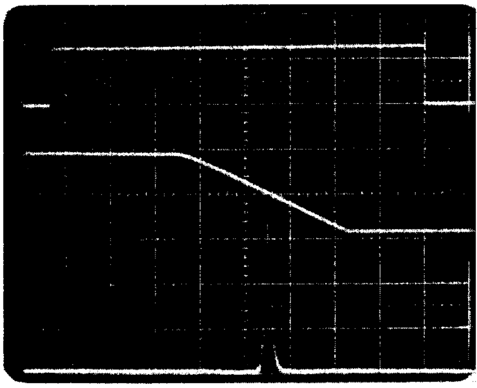

Fig. 3. Emittance scanner signal waveforms. Top, beam-gate pulse; middle, deflector plate voltage; bottom, scanner current at a 100-μs/division sweep speed.

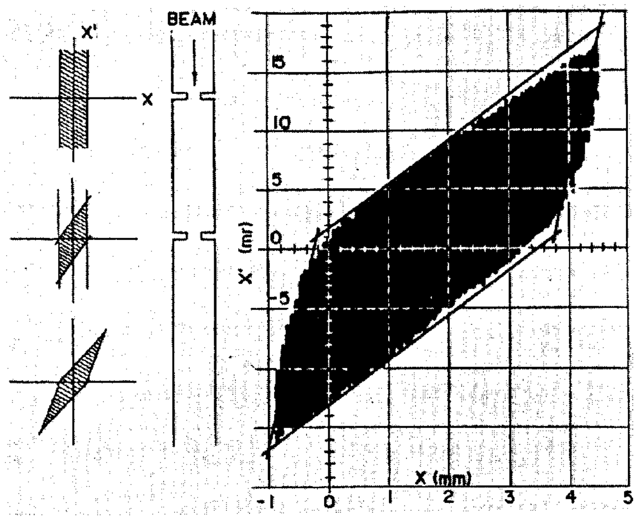

Fig. 4. Left, preparation of collimated phase space; right, comparison of calculated and measured phase-space contours.

Discussion

The ESS is most useful at low energy and probably would be impractical beyond a few million electron volts because of excessive scan voltage required. The length of the scanner is determined primarily by the required angular resolution and the precision with which the small slit width s can be maintained. This slit must be thin enough to pass ions with angles $\pm x'_m$ without collimation. Construction of a 5-cm-long scanner with resolution ±1 mrad seems practical. Emittance is sampled over 50 beam pulses and over the time of the ramp voltage, thus the measurement gives neither an average nor a snapshot. One might expect that beam pulses are identical but that there is time variation during the pulse. We limit the bandwidth of our scanner-current amplifier to 1 MHz to reduce extraneous noise pickup but with our scanner currents of 1 to 10 μA, it should be possible with improved shielding to reach a 10-MHz bandwidth, so that the ramp time could be reduced to 20 μs.

References

1. Robert W. Goodwin, Edward R. Gray, Glenn M. Lee, and Michael F. Shea, "Beam Diagnostics For the NAL 200-MeV Linac", Proc. 1970 Proton Linear Accel. Conf., Batavia, Illinois, September 28-October 2, 1970, National Accelerator Laboratory report LCO-058, p. 107 (1970).

2. P. W. Allison, "Experiments with a Dudnikov-Type H^- Ion Source," Proc. Symp. on the Production and Neutralization of Negative Hydrogen Ions and Beams," Upton, New York, Brookhaven National Laboratory report BNL-50727, p. 119 (1977).