COMPACT EMITTANCE SCANNERS FOR MeV PARTICLE BEAMS*

P.G. O'Shea, T.J. Zaugg, L.D. Hansborough
Los Alamos National Laboratory
Los Alamos, NM 87545

Compact electric sweep emittance scanners have been previously described for low energy ion beams. New scanners have recently been developed to operate in the MeV range without a significant increase in physical size. These scanners are suitable for the analysis of electron and ion beams. The scanners have excellent angular resolution despite their compact dimensions. Electrical and mechanical design and scaling parameters are presented. Operational experience with a 1 MeV, 25 mA, 50 µs H^- beam is discussed.

INTRODUCTION

Emittance scanners involving electrostatic deflection of beam particles have previously been described by Billen,[1] Ames,[2] Allison *et al.*[3] and by other authors.[4] These devices were designed for ion beams with energies less than 100 keV, and long pulse lengths (> 500 µs).

The principle of operation of these devices is that the angle a particle makes with the axis of the accelerator may be determined by the voltage required to deflect the particle for passage through collimating slits as in Figure 1.

The scanners described here are very similar to the Allison scanners, however they are capable of operating at much higher beam energies (> 1 MeV), and much higher scan voltages (± 3000V) than before with ramp times ≈ 40 µs. The mechanical configuration has been modified to produce a light-weight device that is easily aligned and has simple wiring.

The brief analysis presented below has been extended to the relativistic case suitable for electrons. The non-relativistic situation has been discussed by Allison.[3]

If a particle of charge q and kinetic energy γ (in units of the rest-mass mc²), makes an angle x′ with the z axis, and V is the voltage required for deflection through the slits, then the relationship between angle and sweep voltage is:

$$x' = \frac{qV(D-2\delta)\gamma}{2gmc^2(\gamma^2-1)} \tag{1}$$

The maximum angle that can be analyzed is limited by geometry, i.e., x'_m occurs when a particle strikes the deflecting plate, and:

$$x'_m = \frac{2g}{D+2\delta} \tag{2}$$

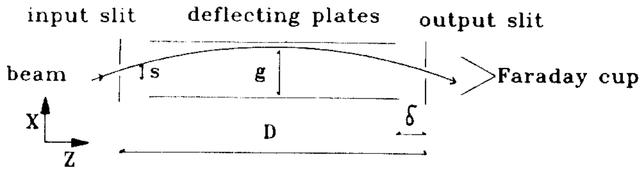

Figure 1. Particle trajectory between input and output slits.

The voltage required to analyze x'_m is:

$$V_m = \frac{mc^2}{q}\left(\frac{\gamma^2-1}{\gamma}\right)\left(\frac{D+2\delta}{D-2\delta}\right)(x'_m)^2 \tag{3}$$

Under most practical situations δ << D, and this allows us to write some simple scaling laws:

$$V_m = K(x'_m)^2 \tag{4}$$

$$\text{where } K = \begin{cases} \dfrac{mc^2}{q}\left(\dfrac{\gamma^2-1}{\gamma}\right) & \textit{relativistic} \\ 2T & \textit{nonrelativistic} \end{cases}$$

with T = kinetic energy in eV

and

$$x'_2 = \frac{2g}{D} \tag{5}$$

The angular resolution of the scanners is limited by mechanical and electronic constraints. The mechanical resolution coefficient $\Re_m$, which corresponds to the fractional angular resolution at $x' = x'_m$, is given approximately by:

$$\Re_m = \frac{\Delta x'}{x'_m} \approx \frac{s}{2g} \tag{6}$$

Typically a mechanical resolution coefficent of 1% is adequate.

An electronic resolution coefficent $\Re_e$ may also be determined. For pulsed beams the ramp time, τ, is usually less than the beam pulse length. For a linear ramp we can write:

$$\frac{dV}{dt} = \frac{2V_m}{\tau} = \frac{2K(x'_m)^2}{\tau}$$

$$\text{also } \frac{dx'}{dV} = \frac{D}{2gK} = \frac{1}{x'_m K}$$

$$\text{Then } \frac{dx'}{dt} = \frac{2x'_m}{\tau}$$

$$\text{and } \Re_e = \frac{\Delta x'}{x'_m} = \frac{2\Delta t}{\tau} \tag{7}$$

If we consider dt to be the minimum increment of time that can be resolved with an amplifier of bandwidth F then we can approximate Δt ≈ 1/2F and write $\Re_e$ as:

$$\Re_e = \frac{1}{\tau F} \tag{8}$$

---

* Work performed under the auspices of DOE for SDIO.

CH2669-0/89/0000-1553$01.00©1989 IEEE

Then the total resolution coefficent is :

$$\Re = \frac{s}{2g} + \frac{1}{\tau F} \tag{9}$$

Typically we choose $\Re_m \approx \Re_e$ so that

$$\Re \approx \frac{s}{g} \approx \frac{2}{(\tau F)} \tag{10}$$

For a given current, I, and emittance, ε, the current detected, ΔI, at the Faraday cup is approximately:

$$\Delta I \sim \frac{I \Delta x \Delta x'}{\pi \varepsilon} = \frac{I (\Re x'_m)^2 D}{\pi \varepsilon} \tag{11}$$

This results in a signal voltage :

$$V_s = \Delta I r G \tag{12}$$

where r is the output resistance of the scanner and G is the gain of the amplifier used. Then:

$$V_s = \frac{I r G (\Re x'_m)^2 D}{\pi \varepsilon} \tag{13}$$

In practice the product rG is limited by capacitance and available bandwidth. The output resistance of the Faraday cup is limited by the requirement of an small rC time constant, i.e., rC << 1/F. A further constraint is provided by the limited gain-bandwidth product of available amplifiers, i.e., GF ≤ L. Then rG << L/F²C. Substituting for F in terms of the resolution coefficent $\Re$ from eqn. 10 gives:

$$rG \ll \frac{L \Re^2 \tau^2}{4C} \tag{14}$$

Finally we can develop an expression which bounds the output voltage of the amplifier from eqns. 13 and 15:

$$V_s \ll \frac{I \Re^4 (x'_m)^2 L D \tau^2}{4 \pi C \varepsilon} = M \tag{15}$$

"M" in eqn. 15 may be considered to be a figure of merit indicating the practicality of a scanner design. Usually it is desirable to have V_s in the 1-5 volt range. Therefore for a realistic design we require M >> 5 volts. If this condition is not satisfied the scanner is likely to have poor signal to noise ratio and poor angular resolution.

CONSTRUCTION AND OPERATION

The present scanner is designed to operate with a 1 MeV, 25 mA, 50 µs, 5 Hz, H^- beam.[5] Because of the low duty factor there is no need for cooling. A cut away view of the Scanner body is shown in Figure 2. Figure 3 shows two emittance scanners and their actuators mounted in a vacuum beam-box. The maximum angle to be measured is 40 mrad. This resulted in a maximum scan voltage of ± 3200 V , and g/D = 0.02. A choice of g = 2 mm and D = 100 mm was made. A mechanical angular resolution coefficent of 0.01 is achieved with s = 50 µm. Making slits narrower than this is not considered practical. For low beam current situations a slit width of 100 µm ($\Re_m$ = 0.02) was used. The voltage ramp was 40 µs long and an amplifier with a bandwidth of 1 Mhz was chosen to give an electronic angular resolution coefficent of 0.02. The typical gain required is 200-1000 with a 50 Ω output resistance on the scanner Faraday cup. The amplifier of choice is a Tektronix AM 502 differential amplifier. The variable gain and bandwidth of this device made it very flexible for use for a variety of beam conditions. From eqn. 13 we obtain an output voltage of approximately 3 V with a gain of 1000. The capacitance of the Faraday cup in the present scanner is ≈30 pF, and the value of M in eqn. 15 is ≈1000 volts, which indicates that the design is quite practical.

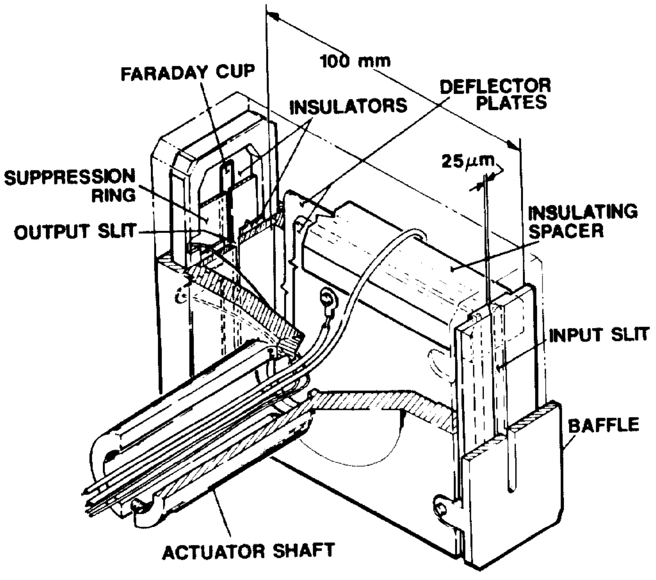

Figure 2. Emittance scanner body.

In order to obtain the high sweep voltage each deflector plate is driven by a separate high voltage pulser as indicated in Figure 4. Driving the plates with the ramp waveforms shown results in a zero electric field across the plates except during the ramp time. This allows high ramp voltages with reduced likelihood of arcing between the plates. The ramp voltage is not quite linear because of the inability of the voltage controlled amplifiers to charge the cable capacitance at high voltage. Compensation for ramp nonlinearities is built into the data analysis program. Severe nonlinearities must be avoided as they lead to a time dependant angular resolution.

The main body of the scanners is made of 6061 aluminum, and is machined from a solid block. This provides a high precision base to which the deflector plates and collimating slits are attached and aligned. The collimating slits were made of OFHC copper with a diamond finish. In front of the input slit is a copper baffle which carried 90% of the beam energy to the body of the scanner and reduced the possibility of thermal distortion of the slits. For high power beams this baffle could be modified to include cooling tubes. Between the output slit and Faraday cup there is an electrostatic secondary emission suppression ring. The scanner is moved by a stepper-motor and gear drive with a resolution of 50 µ m.

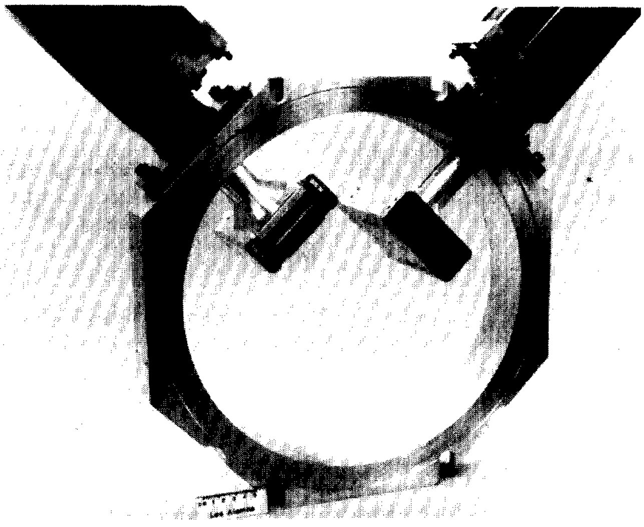

Figure 3. Two scanners with actuator and vacuum beam box.

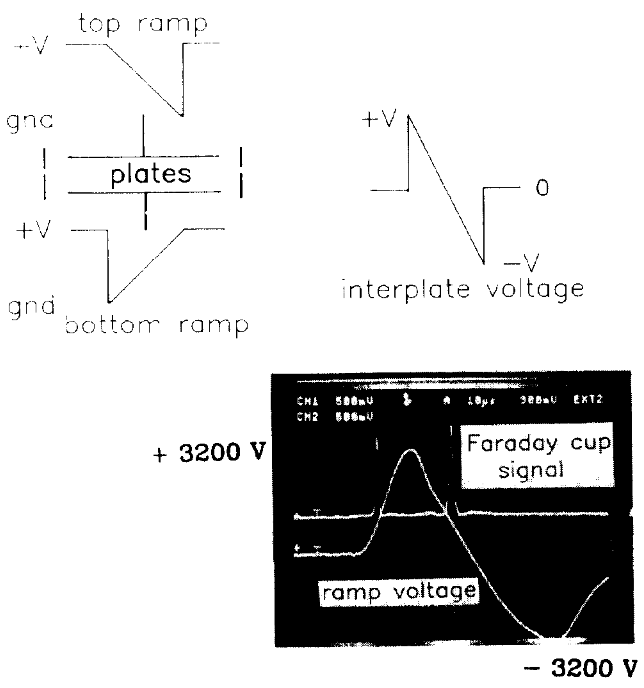

Figure 4. Idealized and actual ramp voltage waveforms, and scanner Faraday cup signal.

In designing this scanner it was critical that any noise reduction techniques be such that they not be bandwidth limiting. In a typical scanner configuration, two scanners were used, one of which scanned the beam while the other remained out of the beam. Common mode noise rejection is achieved by feeding the signals from both scanners into a differential amplifier. Also a 1 μm Ni foil is placed between the output slit and Faraday cup to stop any low energy particles (< 200 keV) which could cause confusion in the emittance measurements.

As the data is collected the signal $\Delta I(x, x')$ is stored in an array of angular and spatial bins (x, x') for later analysis. The emittance analysis and graphics were done using a Los Alamos National Laboratory code called REANE. Sample emittance plots are shown in Figure 5. These are for a 25 mA 1 MeV H^- beam. One is for the beam from the BEAR RFQ[5], which has a diverging beam at its output. The other is for the same beam after collimation to an rms divergence of less than 1 mrad. Both runs were taken with the same scanner. The typical scan time is 5 minutes for 40 scanner steps while averaging over 3 beam pulses at each step.

OTHER APPLICATIONS

The use of these devices is not limited to ion beams. They will also work well with electron beams. For example a 1 MeV e^- beam with $\gamma = 3$ will only require a ramp voltage of ± 530 volts to analyse ± 60 mrad with g/D= 0.02 as in the present scanner. From equation 15 we see that reasonable signal voltages would be difficult to achieve for very short pulse, low current beams, when high resolution is required. However, high current beams will not need the amplifier stage and the bandwidth limitations can be overcome by the design of an appropriate low capacitance Faraday cup. Such scanners are impractical for beams with unknown or large energy spread. However if the beam energy is known as a function of time, then this information can be enfolded into the analysis program so that the angular measurements are not compromised. If the total current is not constant during the scan time, then this also needs to be taken in to account.

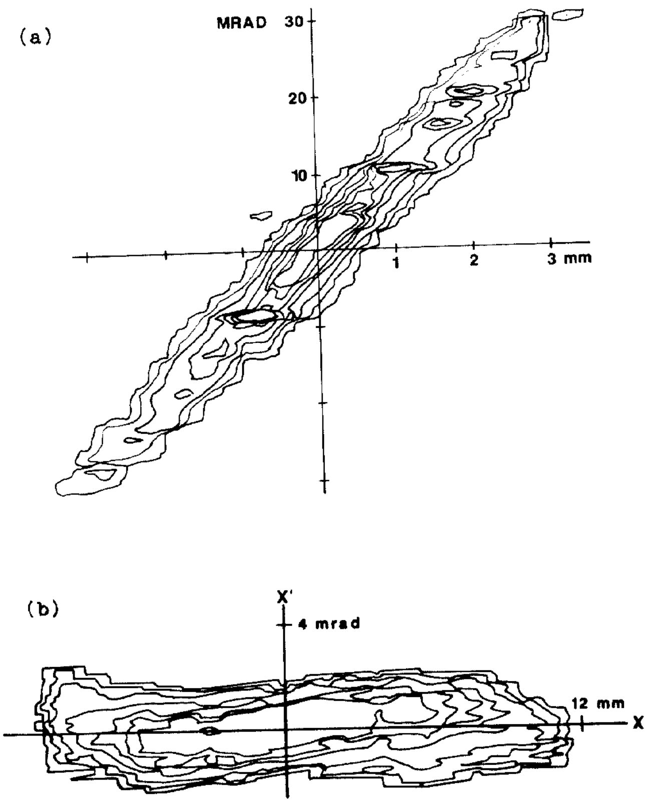

Figure 5. Emittance plots for a 25 mA, 1 MeV, 50 μs H^- beam:
a) RFQ output at 120 mm downstream;
b) after collimation.

ACKNOWLEDGEMENTS

We would like to thank J. Martinez for mechanical design assistance, P. Schafstall for scanner assembly and alignment, and M. Crawford for assistance with the electronics.

REFERENCES

1. J.H. Billen, *Rev. Sci. Instr.*, **46**, 33, 1975.
2. L.L. Ames, *Nucl. Instr. Meth.*, **151**, 363, 1978.
3. P.W. Allison, J.D. Sherman, and D.B. Holtkamp, IEEE Trans. **NS-30**, 2204, 1983.
4. C. Lejune and J. Aubert, in "Applied Charged Particle Optics", ed. A. Septier, Academic Press, New York, 1980, p. 159.
5. P.G. O'Shea, T.A. Butler, L.D. Hansborough, M.T. Lynch, K.F. McKenna, D.L. Schrage, M.R. Shubaly, J.E. Stovall, T.J. Zaugg, "The BEAR Accelerator," Proc. 1989 IEEE Particle Accelerator Conf., Chicago IL, March 1989.