OPERATING EXPERIENCE WITH THE BERKELEY 88-INCH CYCLOTRON ELECTROSTATIC DEFLECTOR (*)

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(Presented by H.A. Grunder)

Introduction

The 88-inch cyclotron deflector is an electrostatic channel which extends 108° azimuthally. The ground electrode is pivoted 72° downstream from the channel entrance. The high-voltage electrode, negatively charged, is in two parts which form the entrance and exit channels (see Fig. 1 of paper I-2, p. 8). The voltage is supplied by two rectified RF power supplies. Detailed information about the deflector and its power supplies is given in ref. 1, 2 and 3.

The channel entrance is located near the beginning of a hill; therefore, the deflector has to be adjusted to the orbit shape, which changes with the flutter (Fig. 1). The practical consequence of this adjustment to the orbit shape is that at half energy only the entrance channel is effective. No voltage is usually applied to the exit channel at this energy. At full energy, however, both channels will be needed for deflection. We have chosen a septum shape that matches the particle orbits at full magnetic field, believing that the deflection at lower magnetic field levels is sufficiently easier to justify this choice. For particles with a charge-to-mass ratio of 1/2 or smaller there is no problem with deflection at lower field levels. Protons of 60 MeV have the same stiffness ($B\rho$) as alphas of the same total energy, yet they have only one charge. Hence, twice the gradient is required for comparable deflection. Computer calculations with the CYBOUT code[1], however, indicate that protons of 60 MeV are not more difficult to extract than full-energy alphas (130 MeV). The observed gradients and deflection efficiencies are in good agreement with predicted behavior of the beam as far as we can check (Table I).

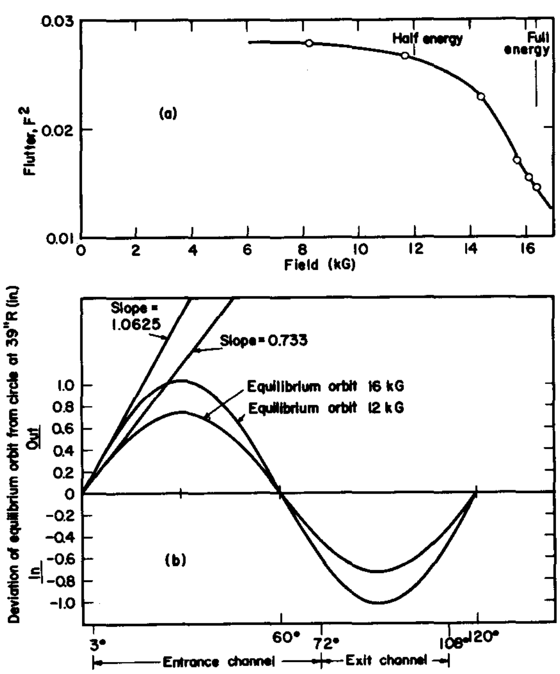

Fig. 1 (a) Flutter (F^2) versus magnetic field.
(b) Deviation of equilibrium orbit at 39 in. from a circle for full- and half-energy field.

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Table I

Comparison between calculated and actual deflection properties of 88-inch cyclotron

Energy at full radius and type of particle	Assumed Radial amplitude	Assumed Dee Voltage	Calculated Max. gradient	Calculated Channel transparency	Observed Dee Voltage	Observed max. gradient	Observed Channel transparency
	inch	kV	kV/cm	%	kV	kV/cm	%
65 MeV α (33 MeV d, 33MeV H_2^+)	0.13	36	93	64	50	80-100	50-60
130 MeV α (65 MeV d, 65 MeV H_2^+)	0.13	70	153	56	-	-	-
50 MeV p	0.13	70	153	30	65	170	5*

* With test-deflector, high-voltage electrode not adjustable. With the same deflector the 65 MeV α channel transparency was 10%.

The Deflector and Septum

The deflector is made of Inconel, which has a good resistance to sparking, with a typical cross section as shown in Fig. 2. The entrance and exit high-voltage sections are each supported by movable arms which allow changes in channel shape[2]. Operating experience and the tests[4] show that the large surface presented by these structures are a hindrance to voltage-holding capability. It has also been found that 80% of the beam at the channel entrance is contained within a 1/8 in. height. Consequently a revised design is planned, which will reduce the channel height and minimize the high-voltage surfaces.

The best septum shape we have used so far is a tapered slot having the cross section shown in Fig. 3. The initial tapered part is provided to distribute and absorb the power of the vertically blown up beam; whereas the small slot distributes the power of the extractable beam. Obviously a good alignment is essential. We achieved a closely uniform heat distribution along the slot observed with the telescope.

For the selection of material for the septum, there are several criteria : (a) ability to hold voltage with the beam impinging upon it, (b) ability to dissipate heat without excessive erosion and (c) low residual activity. Three materials have been tried : graphite, tantalum, and tungsten.

Graphite is good in regard to heat dissipation. For very short times, up to 15 kW was dissipated in a simple slotted graphite septum of 0.03 in. thickness (Fig. 3).

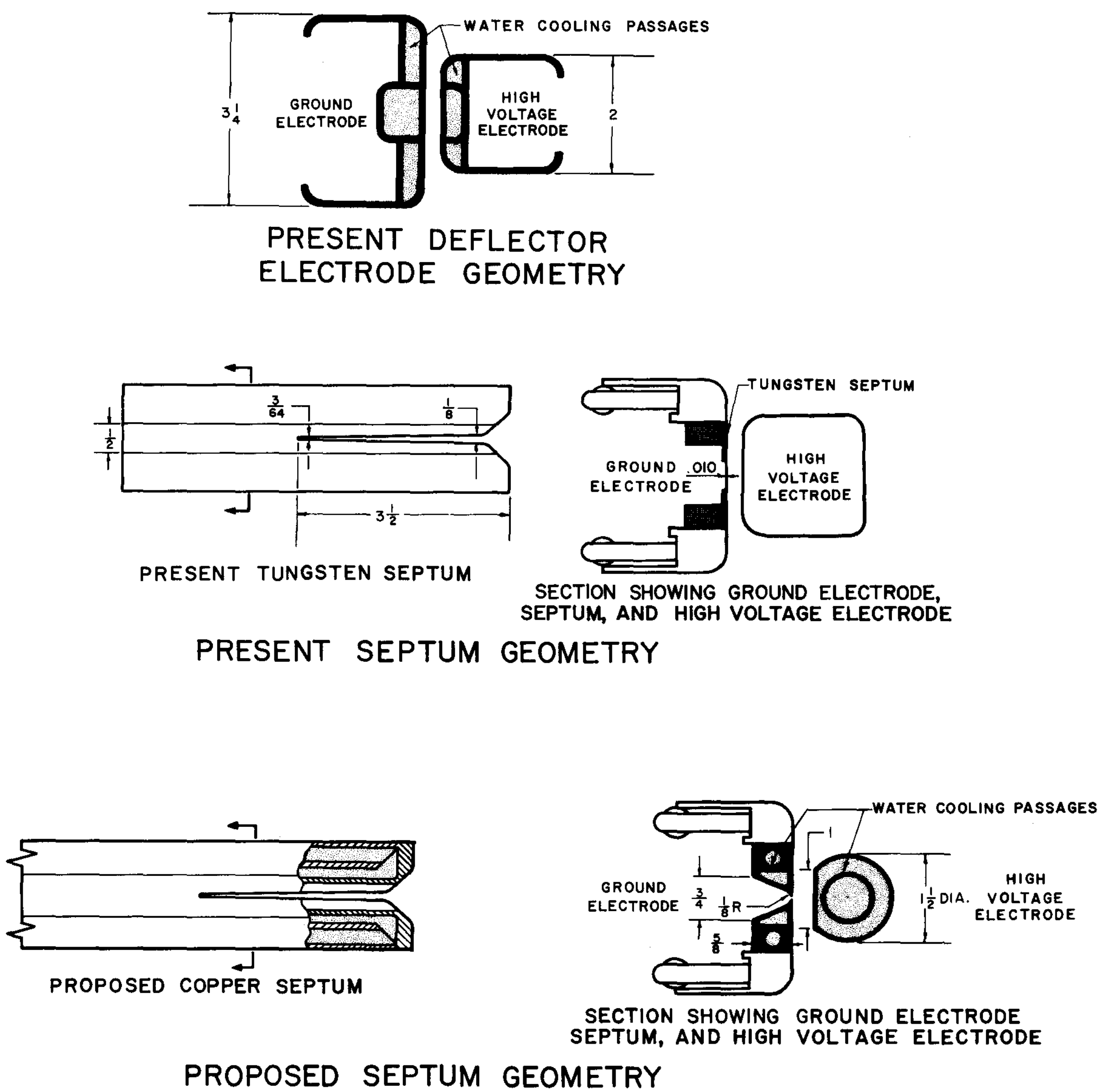


Fig. 2 Deflector cross sections and septum shapes of the 88-inch cyclotron.

We hope eventually to have a septum that will stand 30 kW. Graphite is also very good from the standpoint of residual activity. However, it is very poor in regard to holding voltage. Apparently, when the beam strikes the septum, the graphite evaporates and contaminates the high-voltage electrode. A beam power of less than 1 kW reduces the voltage the deflector can hold to 60% of that attainable with no beam.

Tantalum works moderately well at low beam levels. The beam slowly cuts a slot in the septum. This could be tolerated if the droplets formed did not prevent the deflector from holding suffciently high voltage.

From the overall standpoint, tungsten is the best material tried so far. It is poor in regard to residual activity and, because of this, septa of tungsten will require special handling devices.

Practical Deflection

In order to deflect a beam, we choose a radius for the leading edge of the septum (point 1 in Fig. 1 of paper I-2, p. 8). This radius is usually arrived at by computer calculations. For instance, for 65 MeV α, 39.3 in. is our preferred radius. At this radius, the 65 MeV α beam ahs the following properties.

Radial betatron frequency :	ν_r = 0.88 (calculated)
Vertical betatron frequency :	ν_z = 0.60 (calculated)
Incoherent radial amplitude :	A_r = 0.25 ± 0.15 in. (estimated)
Coherent radial amplitude :	B_r = 0.3 ± 0.2 in. (estimated)
Turn separation for 50 kV on dee :	ΔR_{50} = 0.07 in. (calculated)
Phase width :	$\Delta\Phi$ = 80 ± 10 deg (measured).

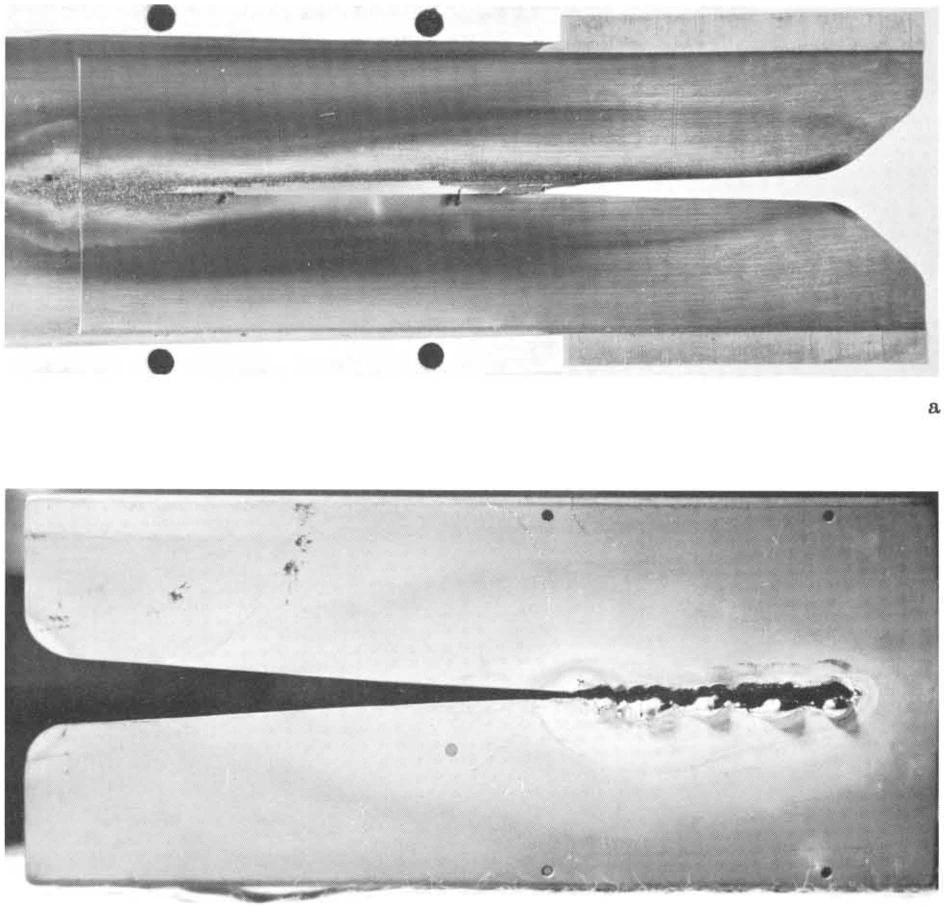
The next step is to move point 3 of the deflector radially in or out until the beam hits the septum tangentially. The glow of the beam along the septum is observed with a telescope. The high-voltage electrode is then positioned to ensure a large gradient. With the exit deflector wide open, point 4 is moved until a small amount of deflected beam is detected with the target probe. As soon as the first measurable beam is obtained, the deflection becomes easy.

The beam is maximized by readjusting points 2, 3 and 4, the deflector voltage, the first-harmonic coils, the dee voltage and frequency. For the measurement of the external beam we use the so-called five-finger probe (Fig. 1 of paper I-2, p. 8). The five vertical fingers are insulated, and give a fair impression of the beam width and its intensity distribution.

The principal object in working with the extracted beam ahs been to make the extraction efficiency ar large as possible. To make this concept precise, we define extraction efficiency as the ratio of the extracted-beam intensity, measured externally to the cyclotron, to the internal beam intensity measured at 30 in. radius. In working with a beam of 65 MeV α particles, a reproducible extraction efficiency of about 40% has been achieved. However, the channel transparency, which is the ratio of beam leaving the deflector to beam reaching the deflector, is about 50%. These figures represent what the machine can deliver during several hours of operation, with only the normal attention of an operator. For a short period, with careful tunings, a maximum efficiency of 53% has been recorded, with a channel transparency of 63%.

The particles that are not extracted can be grouped into three categories : (a) those which acquire vertical amplitudes large enough to strike the inside of the dee, (b) those which lag or lead in phase enough to be decelerated, and (c) those which strike the deflector. With the 65 MeV α beam, about 20% of the intensity is lost by the first two mechanisms.

Defining slits are provided in the center region of the 88-inch cyclotron[5)]. They clip the beam at the second or third turn. At the time when we had a large loss close



a

b

Fig. 3 Erosion on (a) graphite and (b) tantalum septa.

to full radius due to phase loss and vertical blowup, the defining slites increased the deflection efficiency by clipping that part of the particles, which would otherwise be lost. We have now learned to avoid most of the phase loss at nearly full radius by using first-harmonic coils; hence, the defining slits mainly reduce the internal beam.

In the beginning we deflected the beam without using first-harmonic coils. The best beam quality should be expected with a well-centered beam; therefore, we tried to center the beam by changing the center region parameters. These center region parameters are : (a) ion source radial position, (b) ion source azimuthal position, (c) ion source rotation, (d) puller position north-south, and (e) puller position east-west. If there are negligible magnetic-field distortions it should be possible to center the beam by varying these center region parameters and the dee voltage and frequency.

By measuring the deflected beam versus dee voltage, we observed distinct peaks of external beam (Fig. 4). We suspect that these peaks are connected with the precession of radial betatron oscillations. Whether the beam is centered or merely has a favorable angle for deflection at the peaks has not been shown. However, there are indications that coherent oscillations ease the deflection, and it seems likely that the peaks correspond to a favorable amount of coherent oscillations.

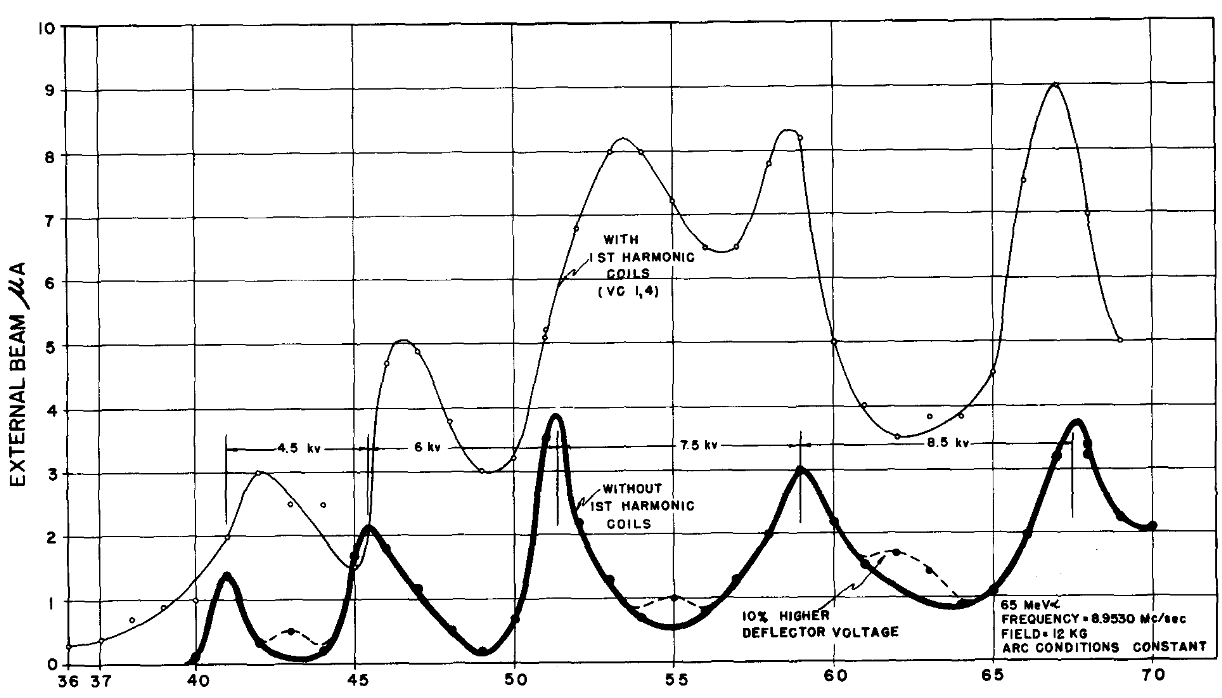


Fig. 4 External beam versus dee voltage with and without use of first-harmonic coils.

The number of precessions P required to achieve full radius is given by

$$P = \frac{E}{\epsilon} (< \nu_r > - 1), \qquad (1)$$

where E is the particle energy, ϵ the average energy gain per turn, and $< \nu_r >$ the average radial betatron frequency. Since ϵ is proportional to dee voltage V, the change in dee voltage ΔV required to increase P by one is seen to be approximately

$$\Delta V \approx - \frac{V\epsilon}{E(< \nu_r > - 1)} \cdot \qquad (2)$$

The intervals between the peaks of Fig. 5 are in good agreement with Eq. (2). The machine was initially tuned for 51.5 kV, which means the external beam had been maximized with center region parameters and frequency for this dee voltage.

Measurement of only the external beam current is somewhat misleading, because with increasing dee voltage, the internal beam increases for the same center region geometry. Therefore we studied the deflection efficiency as a function of center region geometry[5] and dee voltage.

We chose five different source positions with five corresponding puller positions. The source moved only radially and the puller was moved only north-south. By experimenting we convinced ourselves that the deflection efficiency was rather insensitive with respect to the east-west motion of the puller, and therefore made no attempt to correct the east-west position of the puller as the ion source was moved radially.

The defining slits were not used in this study, and the deflector position remained unchanged, optimized for ion source position 0.9 in. (Fig. 5). With respect to dee voltage, frequency, and deflector voltage, small tuning changes were made to compensate for the drift of machine parameters. In all these tests, the frequency was not adjusted more than 1 part in 10^4, and the deflector voltage not more than 1 part in 10^2.

The deflection efficiency drops off remarkably fast as the ion source is displaced. For 52 kV dee voltage, a radial motion of 0.15 in. is enough to reduce the deflection efficiency by a factor of 2. It seems likely that one could regain part of the lost efficiency by changing the deflector position. We have not been able to demonstrate this point so far.

That the peak of the deflection efficiency with increasing voltage shifts to increased radial position of the source reflects the energy gain in the first turn and hence the centering of the beam.

The next attempt was to add the influence of first-harmonic coils (valley coils) to maximize the deflection efficiency (Fig. 6). Again the channel position remained unchanged. Naturally the skill of the operator enters into such an experiment to a large extent. There are five valley coils with steps of 10° in azimuth and a continuous variation in current up to 200 A[6].

Two conclusions could be obtained. The majority of points indicate higher

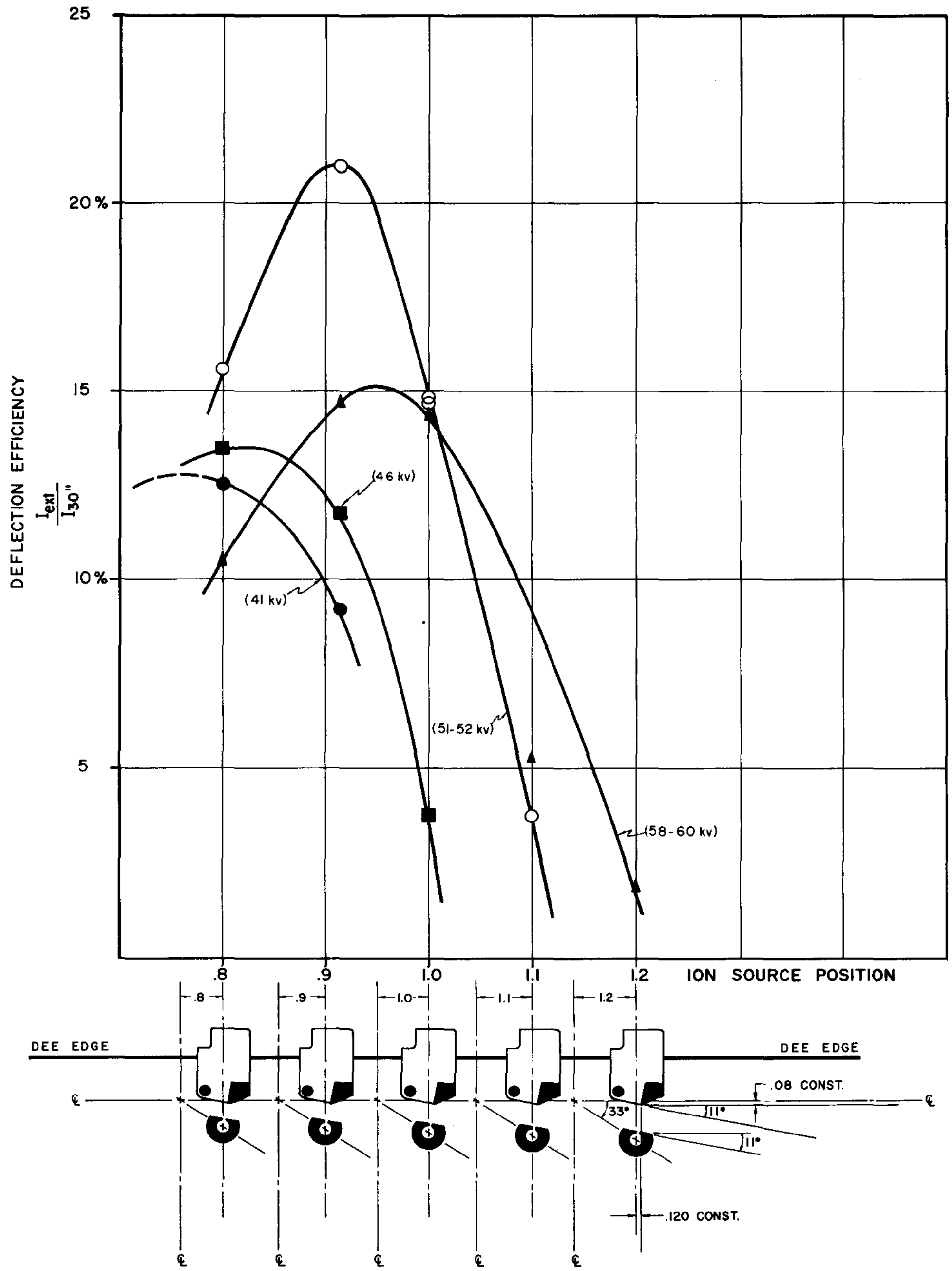


Fig. 5 Deflection efficiency versus ion source position in inches without use of first-harmonic coils.

deflection efficiencies with valley coils thant without. In addition, the ion source position 1.0 in. gave rather promising deflection efficiencies. Therefore we decided to use this ion source position with about 52 kV on the dee, and by further experimenting we reached the quoted deflection efficiencies.

If valley coils are used as in the 65 MeV α case[7]), the beam centering is essentially unaffected. In fact the beam reaches larger radii on all three diagnostic probes with the valley coils on than with the valley coils off. The reduction in beam

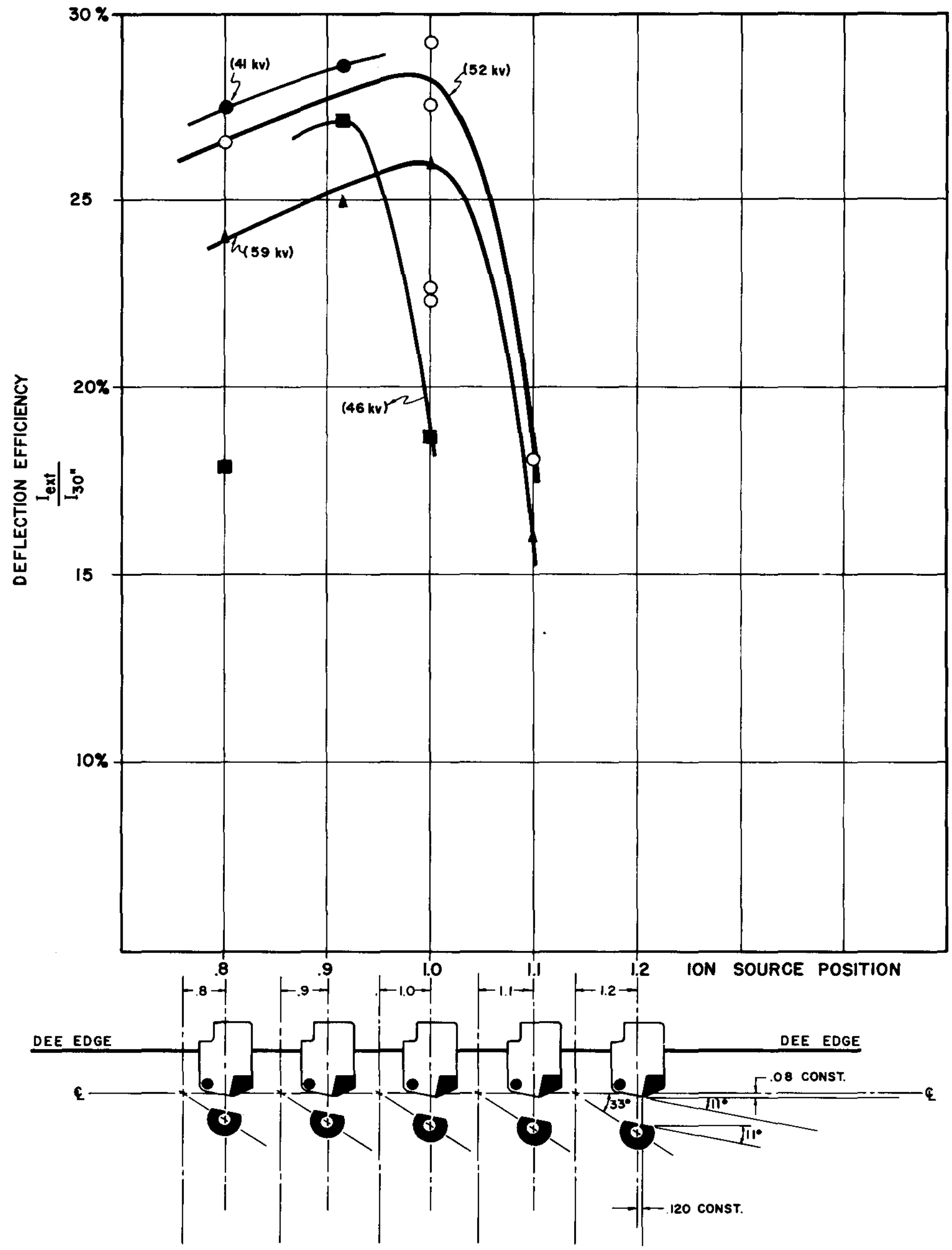


Fig. 6 Deflection efficiency versus ion source position in inches with use of first-harmonic coils.

loss is very distinct prior to the extraction. Therefore we believe that we brought more extractable beam to the septum without appreciably increasing the channel transparency.

Emittance and Effective Sources

The emittance of the 88-inch cyclotron for 65 MeV α's has been measured, radially as well as vertically, for beam currents between 2 and 20 μA continuous beam, and in one case (vertically) for a pulsed beam with a current during the pulse of 450 μA internal and 70 μA external. The emittance remained constant radially and vertically.

We measured the radial emittance (Fig. 7(a)) of 90% of the beam current to 50 mm mrad, and a comparable vertical emittance (Fig. 7(b)) of 90 mm mrad. The accuracy of the measurement is about ± 20%. This is in good agreement with theoretical calculations made by Garren, for the emittance immediately after the deflector channel of 30 mm mrad radially and 60 mm mrad vertically. The measurements ignore any interaction between vertical and radial phase space. They also give only the average phase space density, which is probably appreciably lower thant that for the most dense spot.

The apparatus for measuring the emittance (Fig.8) is a slotted graphite plate, S1, positioned in the beam pipe. This plate has 12 slots of 0.01 in. width. An appropriate distance ℓ downstream, the probe P1 with a narrow pickup finger (0.01 in.) can be moved across the beam radially or vertically. Our setup accepts for radial measurements a maximum diverg-ence of ± 18 mrad.

The same measurements yield the virtual source position and source width. Quite consistently we have measured the virtual radial source to be 2 mm wide and pos-tioned 75 in. upstream of the physical pole edge of the first quadrupole.

Since the vertical source is consider-ably more extended, and the maximum divergence smaller than in the radial plane, the apparatus had to be modified as shown in Fig. 8. Quadrupole 1 was excited to 2 kG/in. for the vertical measurements. The error was increased by about a factor of 2. Fortunately this error can be tolerated because the vertical emittance is about twice as large as the radial. The vertical source position and width can be calculated from these measurements (Fig. 7(b)).

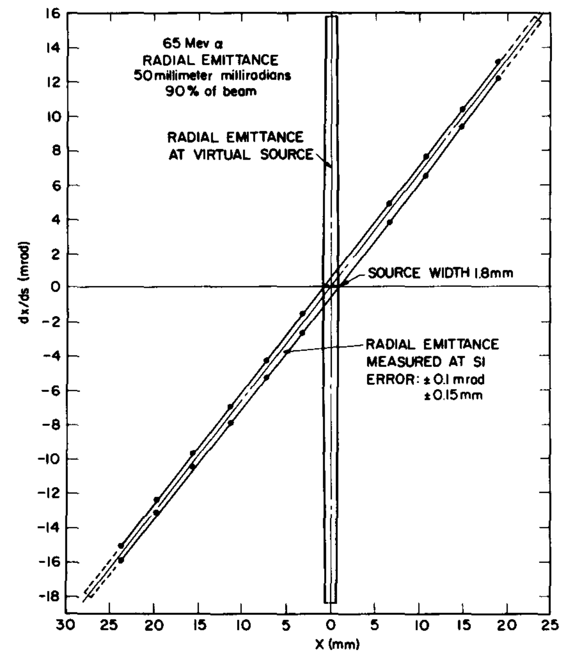


Fig. 7a Radial emittance for 90% of 65 MeV alpha beam.

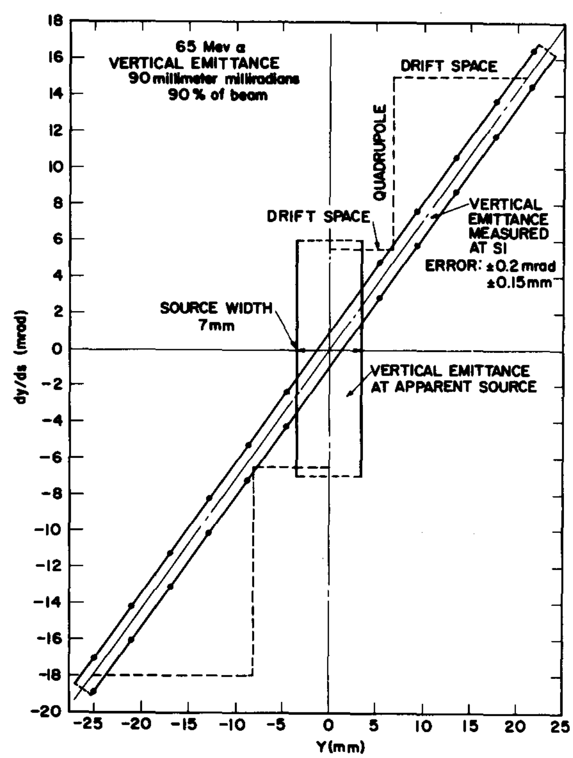


Fig. 7b Vertical emittance for 90% of 65 MeV alpha beam.

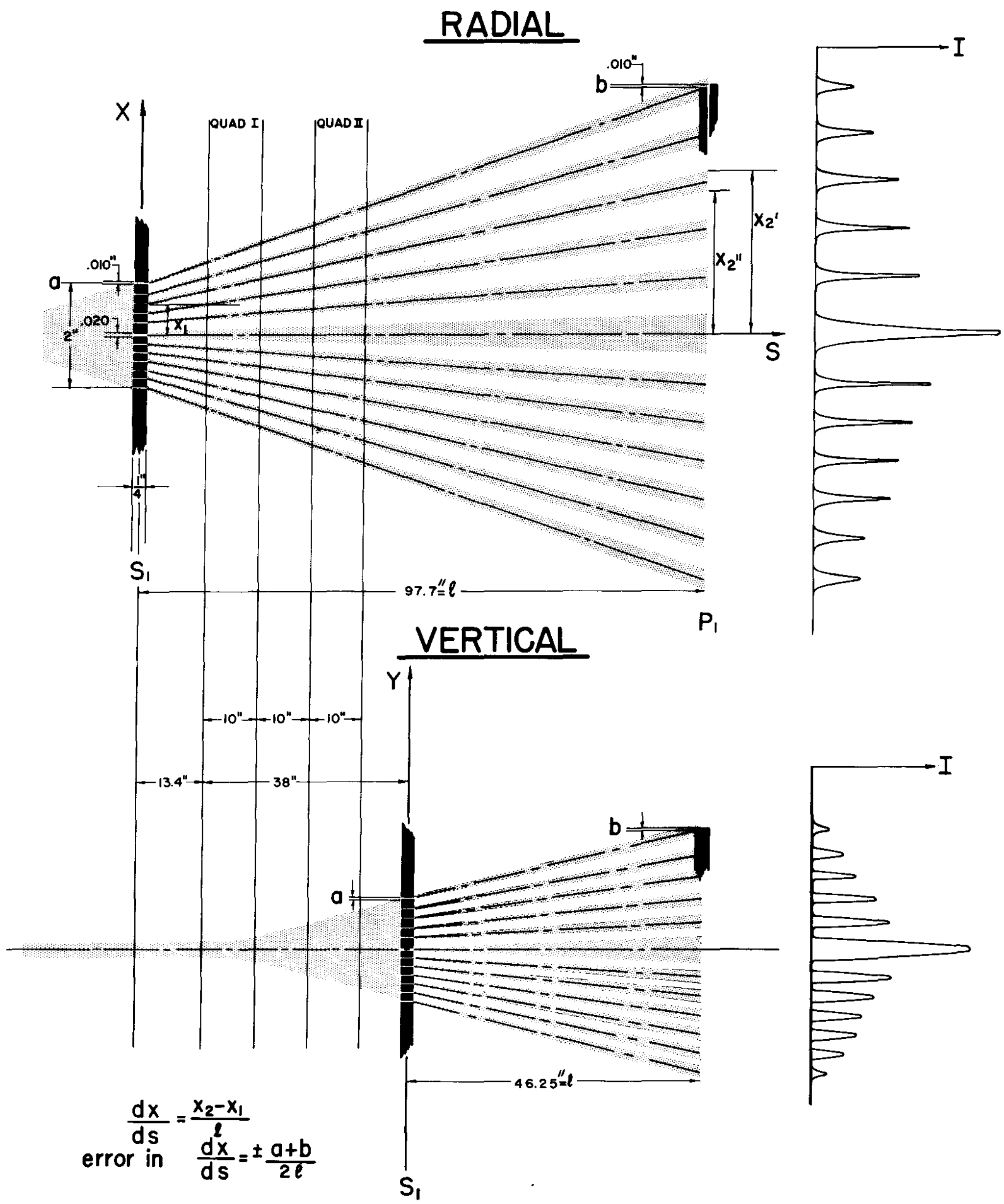


Fig. 8 Schematic view of emittance-measurement apparatus.

The effective source width was estimated to be 7 mm and its position approximately 50 in. upstream of the physical pole edge of the first quadrupole. These measurements also agree quite well with the theoretical predictions.

Influence of Deflector Voltage Regulation on Optical Beam Quality

The 88-inch deflector has two RF power supplies[3]. The voltage is regulated to 2 parts in 10^3. We studied the deflection efficiency and the emittance as a function of deflector voltage regulation. The deflector voltage was modulated with an external signal.

Three cases were studied :

(a) Unmodulated voltage ± 0.1% voltage regulation,

(b) Modulated with ± 0.5% voltage ripple of 100 c/s,

(c) Modulated with ± 2% voltage ripple of 100 c/s.

Since our setup to measure the radial emittance accepts beam of a maximum radial divergence of ± 18 mrad only, the relevant number will be the fraction of the total beam included in these emittance measurements.

The deflected beam at the target probe is very nearly the same in all three cases. However, the beam width for the ± 2% ripple is considerably larger (Fig. 9).

Since the radial emittance for different beam currents in all three measurements is essentially the same, the primary effect has been to reduce the density in phase space. The radial virtual source width and the channel transparency are less influenced by poorly regulated deflector voltage.

DEFLECTOR VOLTAGE REGULATION

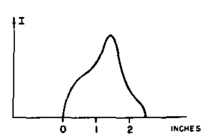
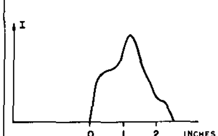
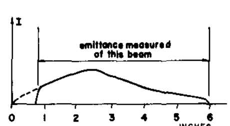
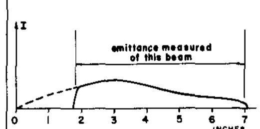
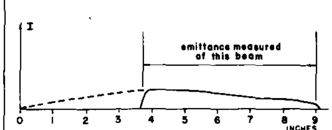
VOLTAGE REGULATION	± .1%	± .5% (100 cps)	± 2.0% (100 cps)
BEAM WIDTH AT TARGET PROBE* (beam direction into paper) *see fig. I			
BEAM WIDTH AT P1* *see fig. I			
DEFLECTED BEAM THROUGH DEFLECTOR MEASURED AT DEFLECTOR EXIT (absolute and in % of beam at $\frac{3}{4}$ radius)	13 μA 40 %	12.8 μA 40 %	12.3 μA 38 %
BEAM IN BEAMPIPE (absolute and in % of beam at $\frac{3}{4}$ radius)	13 μA 40 %	12.8 μA 40 %	10.8 μA 27.2 %
BEAM AVAILABLE FOR EMITTANCE MEASUREMENT (P1) (absolute and in % of deflected beam)	12 μA 93 %	10 μA 77 %	8 μA 65 %
RADIAL EMITTANCE	60 mm (milliradians)	60 mm (milliradians)	60 mm (milliradians)

Fig. 9 Radial beam quality versus deflector voltage regulation.

Beam Handling

A general description of the beam-handling system has been given elsewhere[8]. A Layout of the present setup is shown in Fig. 10. The deflected beam is focused by a quadrupole doublet Q_1 and is directed into a switching magnet M_S which bends the beam into any of several experiment caves. To reach the high-level cave (provided for high-intensity bombardments), the beam has to be bent through an angle of 104°. This is accomplished by means of the switching magnet M_S and a 47° sector magnet M_B. This system has been arranged in such a way that the radial size of the beam at the target is practically independent of the momentum dispersion caused by the bending magnets, provided proper focusing conditions are used.

The beam entering cave 1 is analyzed at the slit S. In this case the focusing is such that an intermediate radial image is formed between Q_1 and M_S. The dispersion caused by M_S adds to the dispersion of the cyclotron fringe field if the virtual source moves inward with energy, as discussed elsewhere[1,8]. A first-order calculation of the momentum resolution obtained under these circumstances has been reported previously in Ref. 8.

Cave 3 can be considered as a typical setup using nonanalyzed beam. The cave has two experimental stations connected to the same beam pipe. The focusing conditions

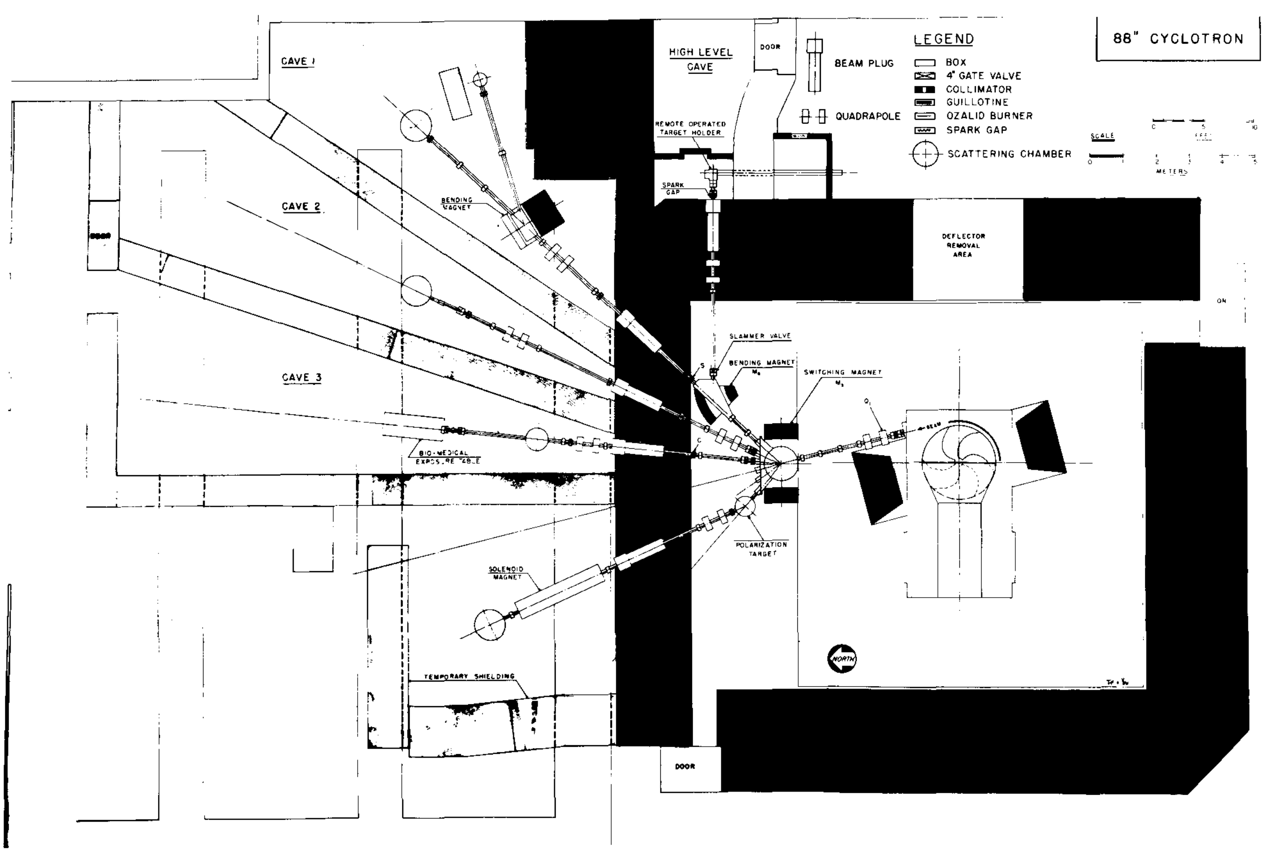


Fig. 10 Layout of cyclotron vault and experiment areas.

used will depend upon the radial and vertical magnifications desired at these stations. If the beam downstream from M_S is made parallel both radially and vertically, the calculated magnifications at station 2 are 3.4 radially and 0.97 vertically. If the beam is focused to produce an intermediate image at C (in both planes) the magnifications in the radial and vertical planes are increased to about 7.8 and 1.1 times, respectively. The first-mentioned case, therefore, is to be preferred if a radially small beam spot is more important than a small convergence. At C an X-Y collimator can be used to collimate the beam both radially and vertically.

Acknowledgments

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4. B.H. Smith and H.A. Grunder, See paper VI-11.
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7. H.A. Grunder and F.B. Selph, See paper I-2.
8. H. Atterling, Nucl. Instr. Methods 18, 19, 589 (1962).

DISCUSSION

BROBECK : I understood Lind to say that he ran with 90 kV on the deflector with 5 mm clearance, which is 180 kV per cm, whereas you were not able to reach 150 kV/cm. Can you explain the difference?

GRUNDER : The deflector voltage follows the VE = k law. The gradient increases at smaller apertures so what we really should compare is 90 x 90/0.5 kV^2/cm and, in our case, 75 x 75/0.55 kV^2/cm. Our problem is high capacity and high voltage surface.

ALLEN : We regularly operate at 100 kV with a gap of 3-4 mm; 100 kV is the limit of our power supply. I am sure we could go to 25% higher. The secret is that you must have graphite liners above and below your deflector assembly. We were never able to obtain this without the graphite. We would never use a tungsten septum as your people use, but one of graphite. I might suggest the use of pyro-graphite for the septum. As you know it has the conductivity of copper in one direction.

TICKLE : Where is the septum located with respect to the $\nu_r = 1$ resonance, and the coupling resonance?

GRUNDER : It is about 1/2 in. outside $\nu_r = 1$ and the coupling resonance.

WIDEROE : Can you tell us a little bit more about valley coils? Do they extend over the whole radius or only over a part of it? Are you shaping your field in the valley, or are you simply erasing it?

GRUNDER : I must refer you to the magnetic field measurement data which were reported at last year's conference.

BLOSSER : Do you see any change or any coupling effects between vertical and radial directions? Does the vertical extent change for instance as you go to different positions in the radial plane?

GRUNDER : I have not observed any coupling effects but I am sure they are there. I think that my measurements are still too crude. One should probably measure the emittance not in a two-dimensional but in a four-dimensional phase space to see these effects.