MEASUREMENTS OF BEAM EMITTANCE, ACCELERATED RF PHASE BAND, AND CENTRING IN A 1 MeV TEST CYCLOTRON

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Differential probe measurements of radial and axial circulating beam intensity in the EBCO/TRIUMF 1 MeV H^- Test Cyclotron have been made. Intensity profile simulations from an analytical model compare well with the measured beam intensity data, and yield important beam related quantities such as the emittance, the accelerated RF phase band and the beam centring. The experimental hardware details, comparisons of measured and computed data, and a description of the analytical model are reported.

1 Introduction

The EBCO/TRIUMF 1 MeV cyclotron known as the CRM [1] is outfitted with a test bed for evaluating ion sources and injection systems, and with diagnostic devices for evaluating beam properties in the centre region. This paper describes a simple technique for obtaining the beam emittance, the size of the accelerated RF phase band, and the beam centring from measured beam intensity profiles in the centre region.

2 Experimental Set-Up:

The CRM has four diagnostic probes for beam measurements in the centre region. One probe is simply a beamstop, whereas the remaining three are used to quantitatively measure the radial and/or axial beam intensity profiles.

The four probes are shown in Figure 1. Probes #3, #5 and #6 are computer controlled, and can be programmed to move radially through keyboard commands. The probes have radial ranges of 75 mm, 84 mm and 88 mm, respectively. The radial position readbacks for these probes are output to a computer terminal. The readback systematic error is ±0.3 mm, and the random error is ±0.05 mm. The axial centring of these probes is within ±0.2 mm of the median plane. The axial widths of the probes are 15.0 mm except for probe #5 whose axial design is as shown in Figure 1. Probe #3 was not used in these experiments. The integral parts of probes #5 and #6 are biased at 300 V, and the differential parts are biased at 45 V.

The ion source and injection line set-up is as described in [2,3,4,5]. A relatively low H^- beam current was accelerated (69 μA @ 1.125 MeV beamstop) because the differential probes #5 and #6 are indirectly cooled through boron nitride insulators and are not capable of dissipating a large heat load. The ion source emittances are not minimized for low current runs, and in this case the normalized emittances are 0.49 π·mm·mrad. The system tune is given in Table 1.

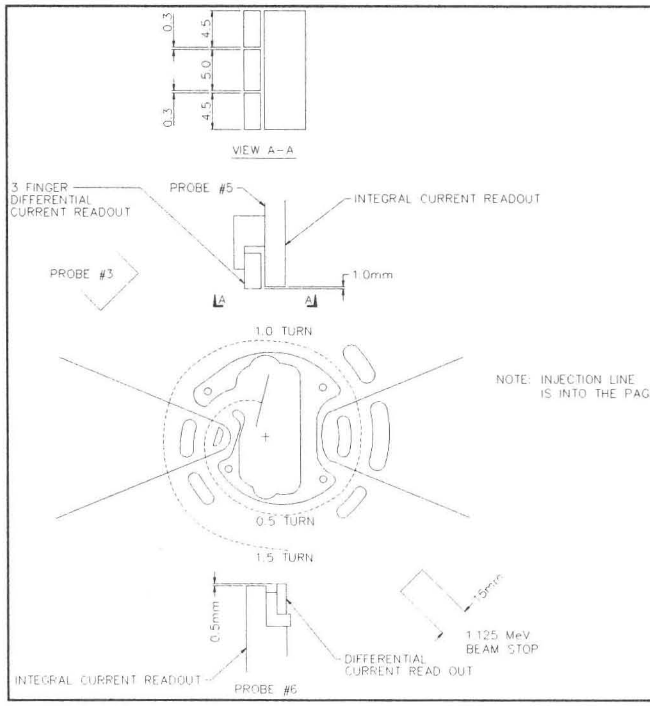

Figure 1: CRM centre region including diagnostic probes is shown.

Table 1: Injection system setpoints.

Parameter	Value
Multicusp source arc current (A)	2.6
Hydrogen flow rate (cc/min)	4.6
Plasma electrode current (A)	1.8
Plasma electrode voltage (V)	2.8
Extractor electrode current (mA)	9
Extractor electrode voltage (kV)	1.73
Source bias voltage (kV)	25.0
Steering magnet [x, y] (A)	[0.61, 0.68]
Quadrupole Magnet 0 (A)	2.11
Quadrupole Magnet 1 (A)	4.1
Quadrupole Magnet 2 (A)	4.4
Quadrupole Magnet 3 (A)	3.92
Main Magnet (A)	446
Inflector electrodes (kV)	±7.6
Cyclotron vacuum (Torr)	1.8×10^{-6}
RF (kW)	7.5
1.125 MeV Beamstop current (μA)	69

3 Radial Measurements

Figures 2 and 3 show the differential probe scans obtained using probes #5 and #6. The beam intensities (dI/dR) are given in arbitrary units (a.u.). Turn overlap is clearly occurring in the centre region, which corroborates well with the large RF phase band that TR cyclotrons are known to accelerate [6,7]. The beam transmission rate for this particular run is 14%. This corresponds to a fully populated accelerated RF phase band of ±25°, or a slightly larger accelerated phase band if axial collimation is occurring on axially defocused outer phases.

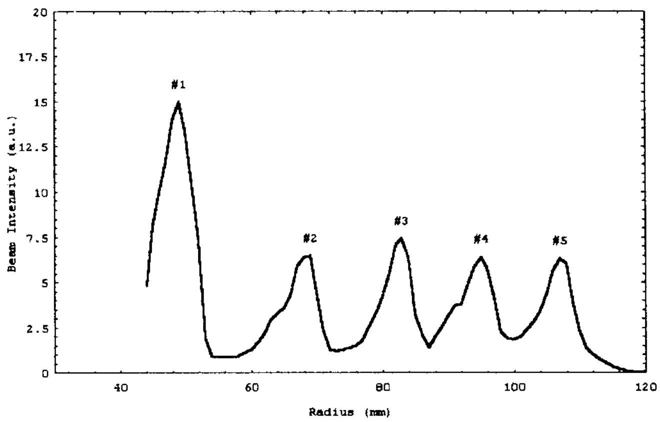

Figure 2: A radial beam intensity scan with differential probe #5 is shown. The three probe fingers were connected together for this measurement.

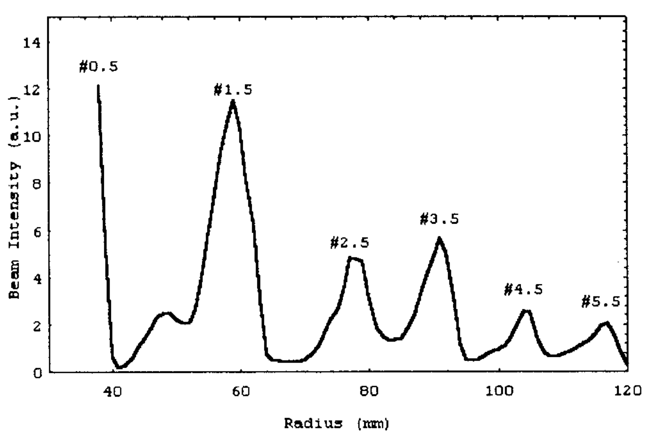

Figure 3: A radial beam intensity scan with differential probe #6 is shown.

Figures 2 and 3 do not directly reveal important beam related quantities such as the accelerated RF phase band, the circulating radial emittance, or the beam centre for beam accelerated in the 0° RF phase band. Estimates of these quantities can be made by using the following prescription:

- assume a total width for the beam's RF phase band of $\pm\theta$, and divide this band into individual phases (φ) separated by 2° each.
- assume each of the beam's phases has an identical gaussian intensity distribution in the radial direction characterized by a beam width of a standard deviation (σ).
- choose the radial location of the beam's central phase intensity distribution $R_{0°}$.
- sample the intensity distribution of each of the beam's phase slices using radial increments of 0.1 mm over a range of $\pm 3\sigma$, and centre the distributions of each phase slice φ at the location $R_{0°} - (p_{0°} - p_{\varphi})/qB$ where p is the momentum of each phase slice, q is the charge on the beam particles and B is the average magnetic field in the region of interest.
- sum the intensity distributions for each phase over the entire phase band $\pm\theta$, and plot the resulting curve.
- adjust θ, σ, and $R_{0°}$ until the curve representing the sum over the intensity distributions of each phase approximates the measured beam intensity profile reasonably well.

Mathematica [8] was used to model the turn #5.5 intensity profile from Figure 3 using the above prescription, and the result is shown in Figure 4. The parameters used to achieve this fit are $\theta = \pm 32°$, $\sigma = 1.4$ mm, and $R_{0°} = 117.8$ mm. As can be seen the model simulates the measured intensity distribution very well.

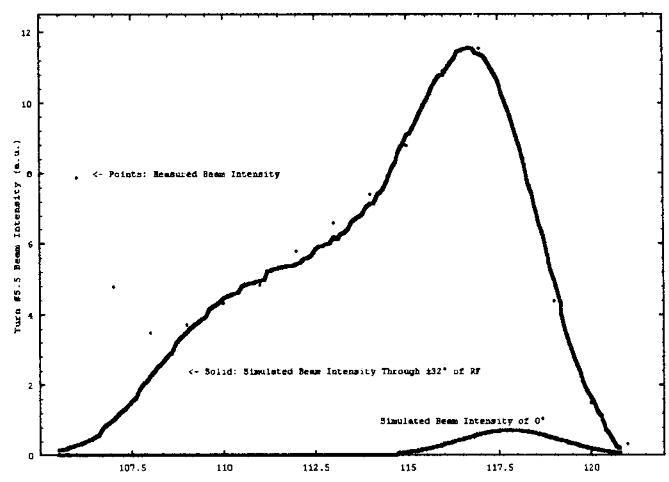

Figure 4: Measured and simulated beam intensity profile at turn #5.5.

The magnitude of σ can be used to directly estimate the circulating emittance of the beam. Since a single gaussian distribution was used to represent each phase slice with a good result, this distribution is acting as an average distribution across all phase slices. Assuming an upright radial phase ellipse, one can use the relationship given in (1) to calculate the normalized radial emittance

$$\varepsilon_{cnx} = \frac{\beta\gamma(\nu_x x_{max}^2)}{R_{cyc}}. \qquad (1)$$

A 2σ beam half-width is a good approximation to the x_{max} dimension of a 4rms ellipse ($x_{max} = 2\sigma = 2.8$ mm). The radial tune υ_x is equal to 1.03 [5]. The cyclotron radius for the average magnetic field of 12 kG and a beam kinetic energy of 1.125 MeV is 127.7 mm. The value of $\beta\gamma$ is 0.049. This results in a circulating normalized radial emittance of $\varepsilon_{cnx} = 3$ πmm·mrad. The measured 4rms emittance for the injected low current beam is 0.49 πmm·mrad. This gives a value for the emittance growth in the radial phase space of 3/0.49 ≈ 6, which is comparable to the factor of 5 measured in [1].

The value of $R_{0°}$ = 117.8 mm is within 0.5 mm of the value calculated using CYCLONE [9,5]. The accelerated phase band θ = ±32° is larger than was anticipated, but is not out of step with the large transmission rates seen in TR cyclotrons [6].

4 Axial Measurements

Figure 5 illustrates the axial and radial intensity distribution of the beam. The data for the plot was obtained using probe #5 in the three-finger configuration. With only three data points in the axial direction, the data was too sparse to be directly converted to a contour plot. The program TRANSFORM [10] was used to fill in and smooth the data according to a statistical process known as kriging. Kriging replaces each missing data value with a weighted calculation that minimizes the variance of the whole data array. The weighting function assigns weights to those intensities neighbouring the missing intensity value. The weighting function used for the data displayed in Figure 5 was $1/R^2$.

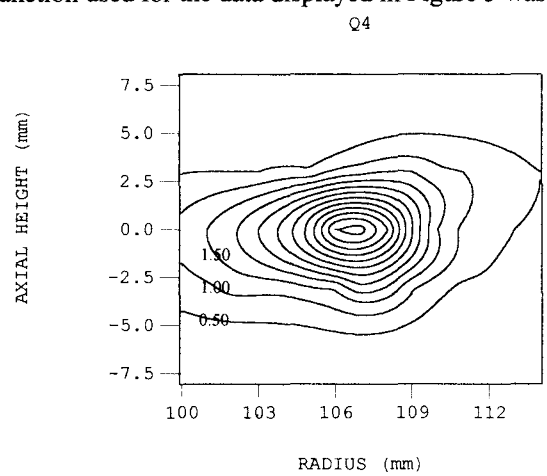

Figure 5: Turn #5 beam intensity profile.

An estimate of the effective axial circulating emittance can be made using equation (1), if the radial parameters are replaced with axial parameters. Since the axial width oscillates over the first turns, the overall effective circulating emittance can be estimated by using the largest axial beam size attained between turns #2 and #5. The largest axial width ($2 \cdot y_{max}$) was measured at turn #3 and is 10 mm. Thus, y_{max} is equal to 5 mm. With an axial tune υ_y equal to 0.333 [5], a cyclotron radius, for the average magnetic field of 12 kG and beam kinetic energy of 0.625 MeV, of 95 mm, and a value of βγ equal to 0.037, an estimate of the axial circulating emittance ε_{cny} = 3 πmm·mrad is obtained. This again corresponds to an emittance growth of approximately 6, which compares well with the value 5 obtained in [1].

5 Conclusions

This paper describes a simple technique for modeling the radial beam intensity profiles in a cyclotron centre region using three parameters: the width of the accelerated RF phase band, an average standard deviation width for each of the beam's RF phase slices, and the radial position of the beam's central phase. The simulated beam intensity profile compares well with the measured data.

Although useful the technique has limitations in that it assumes the cyclotron is isochronous at the measurement radius, that a gaussian distribution is appropriate for an individual phase slice, that all phases are identical, and that no partly filled phases exist.

Circulating emittance calculations were made for the low current case under investigation. Since the TR ion sources are optimized for high current operation, the emittances were found to be rather large in the low current regime. However, the emittance growth factors were found to be comparable to those obtained in earlier studies.

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