STATUS AND RESULTS FROM THE TR30 CYCLOTRON CENTRE REGION MODEL

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Abstract

A full scale model for the centre region of the compact 30 MeV, 350 μA H^- cyclotron (TR30) has been constructed, to test the design of critical components and to study beam properties and space charge effects out to the 5th turn (1 MeV). The ion source and injection line system duplicates that used in the TR30. The centre region can be accessed with diagnostic probes at four different angles. The normalized circulating emittances as estimated from beam profile measurements are 1.7π mm-mrad (radially) and 1.8π mm-mrad (vertically). The radial centering error of the beam is less than 1.5 mm. After initial tests the maximum intensity achieved at the 5th turn is 650 μA. This corresponds with a transmission efficiency of 12.5% for a continuous (non-bunched) input beam. No significant space charge effects are observed up to 650 μA.

For the TR30 bunching is not a must because of the high current available from the source. Nevertheless, it was considered useful to study beam bunching for the Centre Region Cyclotron (CRC). Some of these results are described.

1. Introduction

During the past two years TRIUMF has been cooperating with Ebco Industries Ltd. in designing and constructing the H^- isotope production cyclotron TR30 [1]. The basic requirements for this machine are i) an accelerated beam intensity of at least 350 μA, ii) two external beam lines each capable of currents up to 200 μA and iii) energy variation from 15 to 30 MeV. The contract requires that the cyclotron be constructed and commissioned within a time period of not more than 18 months. In order to be able to test in an early stage the design of critical components like the spiral inflector and the dee-configuration in the centre, a full scale model of the TR30 centre region was built. This Centre Region Cyclotron (CRC) can be also used to study beam properties, space charge effects and as a tool in achieving as high as possible currents. This paper describes the experimental arrangement and the results obtained so far. Because of the high currents available from the ion source, the beam injected into the TR30 is not bunched. However, with the existing set up of the CRC, not much additional effort was required to install and test a simple buncher.

2. Experimental Arrangement

A schematic overview of the experimental set up is given in Fig. 1. The main parts are the ion source, the injection line and the Centre Region Cyclotron.

The ion source used, makes feasible accelerated beam currents in the TR30 of 500 μA or more. It is the high brightness dc multicusp source developed at TRIUMF, from which an H^- current of 7 mA has been extracted within a normalized emittance of 0.35π mm-mrad at an arc power of 3.5 kW. The emittance scanner, contained in the diagnostic box can be employed to study the influence of source modifications on the quality of the beam. Two sets of steering magnets are mounted directly after the source extraction system to correct any displacement of the beam. A detailed description of the source has been given in Ref. 2.

An important feature of the injection line is the space charge neutralization of the 25 keV H^- beam. The main advantages of this are that the injection line settings become intensity independent and that emittance growth due to non-linear space charge forces is avoided. The basic elements in the injection line are the two quadrupoles and the solenoid. The two quadrupoles can be rotated around the optical axis. The measured beam transmission into the cyclotron varies approximately 30% for quadrupole rotations over the full range of ±90 degrees. The aperture radii of the solenoid (5 cm) and the quadrupoles (2.5 cm) has been chosen such that the emittance growth due to abberations is less than 2% [3]. The position of the source with respect to the cyclotron was optimized in order to obtain high beam transmission through the injection line. Typically, for an ion source current of 5 mA we loose approximately 700 μA on the beam line collimator and 100 μA on the inflector collimator. A tilted spiral inflector with an electric bending radius of 25 mm is used to bend the beam into the median plane. A total voltage of $\approx$ 14.5 kV across the 8 mm entrance aperture is needed for optimum transmission. No significant beam spill ($\leq$ 100 μA) is observed on the electrodes. The optical properties of the inflector were studied extensively [4-7].

The CRC accelerates the first five turns to an energy of 1 MeV, corresponding with a radius of $\approx$ 12 cm. The pole radius is 16 cm.

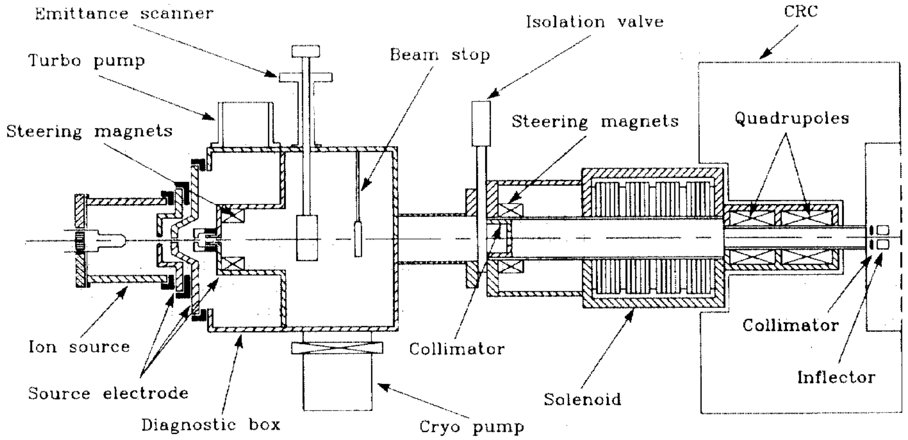

Fig. 1. Lay-out of the experimental arrangement showing the ion-source, injection line and Centre Region Cyclotron.

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The magnetic field was measured with a Hall probe mounted on a computerized X-Y mapping machine. The maximum phase slip calculated from the field map is less than 12° rf, which was considered tolerable. Unlike the TR30, the rf of the CRC runs in a self-excited mode. The dee-voltage was determined by X-ray end point measurements using a Ge semiconductor detector. For 50 kV operation an rf-power of ≈ 6.5 kW is required. Dee-voltages at different rf power levels were also determined from energy gain per turn data obtained from the measured turn spacings. The energy gain as a function of radius was found to vary $\approx 10\%$ due to rf phase slip. The results agreed well with the X-ray callibrations however. The CRC can be accessed with diagnostic probes at four different angles (two in opposite valleys and two in opposite hills). Different probe heads have been made such as radial differential and wire probes to determine radial beam profiles and vertical centering probes and a 5-finger probe to determine vertical beam profiles. The probe heads are driven by computer controlled stepping motors.

3. Results

In the beginning of October 1989 the first beam was achieved with an intensity of 100 μA. Figure 2 shows the intensity distribution of this beam as a function of radius, measured in the middle of a valley with a radial differential probe. Since the input beam is dc, the major part of it will be lost in the centre of the cyclotron. As can be seen from Fig. 2, a significant part of the beam is accelerated up to the first half turn (two gap crossings) but then is lost between turn 0.5 and 1.5. In the next full turn, another 20% of the beam is lost vertically due to the defocussing action of the accelerating electric field for large negative rf phases. No further losses are observed beyond the second turn.

The measured 100 μA beam intensity accounted for 11% of the input beam at the inflector entrance, corresponding to an rf phase acceptance of 40 degrees. The maximum intensity at the 5th turn obtained so far is 650 μA for a source current of 6 mA. For this case we were able to raise the transmission to 12.5% by increasing the dee-voltage from ≈ 50 kV to ≈ 55 kV. Figure 3 shows the measured beam transmission from the entrance of the inflector to the 5th turn as a function of dee-voltage. This measurement was done using a smaller version of the TR30 source which produces 1 mA H$^-$ in a normalized emittance of 0.12π mm-mrad. For this emittance the transverse beam losses in the first few turns are smaller then for the TR30 source, leading to an rf phase acceptance as high as 54 degrees. The drop in transmission for high dee voltages is caused by excessive energy gain in the first turn resulting in the beam hitting a vertical post at the third gap crossing. No loss of transmission with increasing beam intensity indicates space charge forces are not significant at least up to 650 μA. Moreover, the injection line settings are found to be almost intensity independent, indicating good space charge neutralization of the beam.

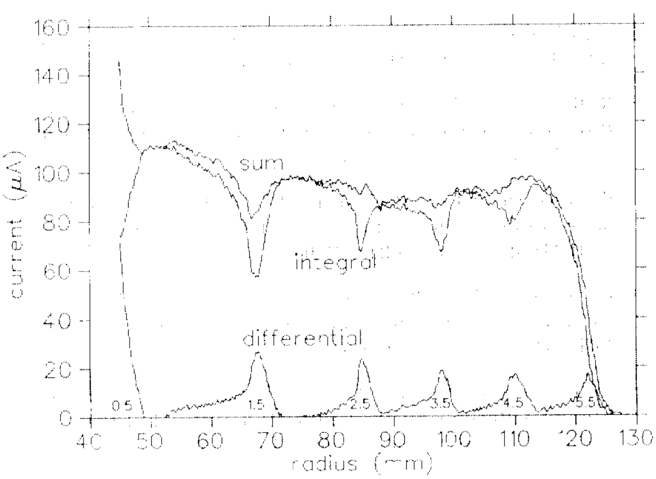

Fig. 2. Differential probe scan in the valley of the CRC.

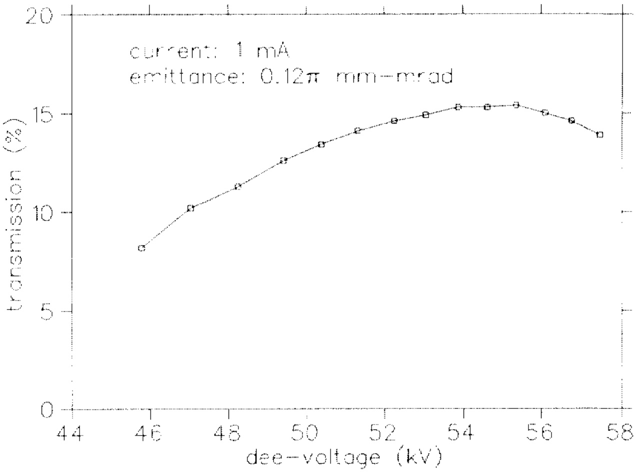

Fig. 3. Transmission of the beam from the entrance of the inflector to the 5th turn as function of the dee-voltage. The measurement was done for a smaller version of the TR30 source having an emittance of 0.12π mm-mrad.

The vertical beam profile was measured with a 5-finger probe. The maximum half beam size was found to be 2.5 mm (rms) corresponding with a circulating normalized emittance of $\approx 1.8\pi$ mm-mrad (with a calculated value for ν_z of 0.4). A rough estimate of the radial emittance can be obtained from the differential probe scans such as given in Fig. 2. Since the maximum in each of the peaks corresponds with the centroid of the phase space distribution, the broadening of the turns at the right hand side of the peaks is solely due to radial emittance. The maximum width (rms) of this edge for different turns and different azimuths is found to be ≈ 1.5 mm. This corresponds to a circulating normalized emittance of $\approx 1.7\pi$ mm-mrad. The emittance growth factors (5.1 vertically and 4.9 radially) are in reasonable agreement with the factors 4.9 (vertically) and 4.7 (radially) found from matching calculations done with the computer code TRANSOPTR[8,9].

Figure 4 shows the measured orbit centre displacement of the beam as a function of turn number for four dee-voltages. This result was obtained from differential probe scans in two opposite valleys, using the formula $y_c = (P_1 + 3P_3 - 3P_2 - P_4)/8$, where P_1 and P_3 are the radial positions of the turns in one valley, P_2 and P_4 their

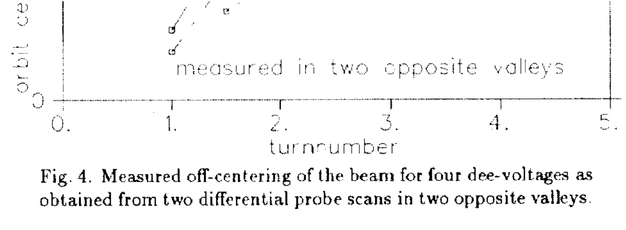

Fig. 4. Measured off-centering of the beam for four dee-voltages as obtained from two differential probe scans in two opposite valleys.

positions in the opposite valley and y_c the projection of the orbit centre on the mid-valley line. This formula is accurate up to 2nd order in the energy gain per turn. For the design dee-voltage (50 kV) the beam centering error is less than 1.3 mm. Similar measurements were done in the hill gap. The projected orbit centre displacement on this azimuth is smaller than 0.5 mm. A radial emittance growth factor of 2.6 may be expected[10] from the measured off-centering of 1.3 mm. Also investigated was the influence of asymmetric inflector settings on the orbit centre displacement. Since fringe field effects will be different, one might expect a different radial kick at the inflector exit. The measurements show however that the horizontal steering by this mechanism is minimal (less than 0.5 mm orbit centre shift for an asymmetry in inflector voltage of 2 kV).

All of the foregoing measurements were done with a dc input beam. To determine what improvement would be possible with a buncher, a single 2-gap first harmonic buncher was installed in the only space available along the injection line, between the diagnostic box and the isolation valve (see Fig. 1). The transverse beam size at this location is approximately equal to $\beta\lambda$, i.e. the distance travelled by the beam in one full rf period ($\approx$ 3cm). Transit time effects are therefore important. Particles at the edge of the beam have a transit time factor which is considerably larger than on axis, resulting in a transverse longitudinal coupling that reduces the bunching efficiency. Moreover, the non-linear behaviour of the radial defocussing at the buncher gaps becomes also more important. A semi-analytical model was developed to study these effects as a function of beam and buncher parameters[11].

In Fig. 5 we give the calculated emittance growth due to rf phase mixing in the radial phase space as a function of the beam envelope (buncher aperture radius is 2.0 cm). The solid line illustrates the result for a linear approximation of the transverse optics, whereas the dashed line corresponds with the actual non-linear optics. For the CRC beam ($r_e \approx 1.5$ cm, $\epsilon_{init} = 50\pi$ mm-mrad (0.35π mm-mrad normalized)), an emittance growth of 11π mm-mrad (0.08π mm-mrad normalized) is predicted.

The measured bunching efficiency as function of the accelerated unbunched beam current is shown in Fig. 6. At low intensities there is a factor of 2.5 increase in current. This is in reasonable agreement with the factor of 2.8 predicted by the semi-analytical model. At higher currents the efficiency drops due to longitudinal space charge. However, at 200 μA there is still a gain of almost a factor of 2. Moreover, a substantial improvement would be possible by reducing the beam size in the buncher aperture.

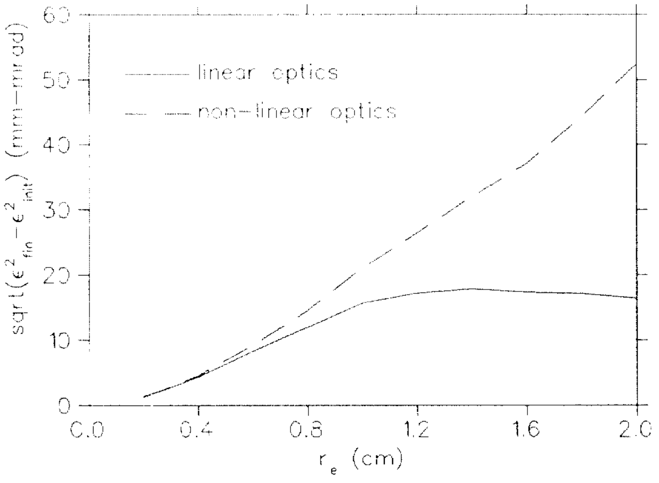

Fig. 5. Calculated emittance growth in the 2-gap first harmonic buncher due to rf phase mixing. The solid line assumes a linear approximation of the optics. The dashed line corresponds with the actual non-linear optics.

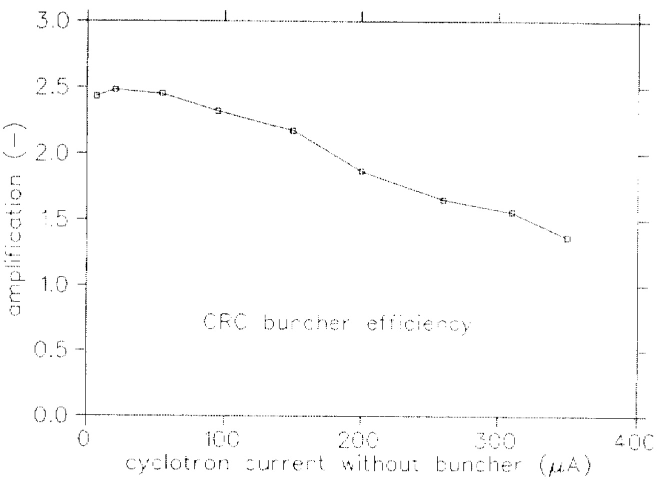

Fig. 6. Measured bunching efficiency as function of the accelerated unbunched beam current.

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