INTERNAL CURRENT MEASUREMENT ERRORS IN HIGH ENERGY PROTON CYCLOTRONS - SIMULATION, CORRECTION, DESIGN AND MEASUREMENT

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Abstract

The charge collection efficiency of a probe traversing a compact spiraled 235 MeV cyclotron at a constant azimuth is calculated from .2 R extract to R extract, taking into account the varying angle of incidence of the beam, the energy dependant stopping range, beam straggling in the probe, nuclear stopping due to inelastic collisions, and probe geometry, as well as beam offcentering effects. This is verified with experiment, and used to design a probe with less sensitivity to centering effects near extraction. This probe improves the consistency and accuracy of internal transmission, and extraction efficiency measurements.

1 OVERVIEW

High energy, light ion cyclotrons present unique challenges towards the design of beam measuring devices. A charge collection device, such as an integral probe, needs to be able to collect the charge of particles that stop quickly at inner radii, and yet still be able to collect the charges of particles that have a significant range in matter near extraction. Spiralled, azimuthally varying fields result in orbits which, at a set azimuth, vary the angle of incidence on the probe as a function of radius. These varying angles of incidence are perturbed, or broadened, by beam oscillations. Spirals have even prevented radial probes from reaching all the way in near the machine center[1]. Gains in radius per turn can get very small near the outer edge of the machine. This has the effect of significantly reducing the effective volume of the probe. Coupled with larger ranges, this further enhances the need to accommodate the varying angles of incidence. Limited space, especially in compact cyclotrons, will complicate things further, by severely limiting the size of possible probes.

Marti summarises many ingenious devices designed to overcome these obstacles, including a probe train that spirals in to the center. This probe “removes” the effects of the spiral by spiralling with the beam. While these ingenious devices have continued to be implemented and improved, Marti goes on to point out that simpler designs can be sufficient in tuning and operating cyclotrons[1,2]

2 IBA C235 BEAM DIAGNOSTICS

The C235 is a compact, spiralled cyclotron designed by Ion Beam Applications (IBA) in collaboration with Sumitomo Heavy Industries (SHI), for the purpose of providing 235 MeV proton beams to be used in Proton Therapy Systems[3,4,5]. It is a 4 sector machine with 2 spiraled dees occupying two of the valleys. A third valley is taken up by the electrostatic deflector. The hills, in vertical cross sections, have elliptical profiles with very narrow gaps at the outer edge. This precludes using the hills to mount a probe. The C235 has one radial probe, mounted in the remaining valley.

The C235 radial probe has interchangeable heads and bodies, with a present collection of a viewer probe with two heads, two differential probes, and an integral probe which has had three different heads. Most of these probes run from the last turn before extraction in to about 20 cm radius. The viewer and differential probes have heads that allow penetration into the narrower axial gaps of the central region. They can go in to about 7 cm in radius.

The face of the first integral probe head was cut at 2 degrees off of the tangent. Throughout most of the machine, the point with the acute angle was the first to intercept beam. The copper head itself is 56 mm wide (the approximate range of 235 MeV protons in copper). The front face has overhanging electron collecting lips, top and bottom, extending 4 mm past the probe face. The sides though have convex curvature, allowing the probe head to pass through the circular vacuum feedthrough, without damaging the quad o-rings. As the probe was pulled out to a radius of about 1m, the beam would be parallel to the probe, maximising the probe collection efficiency. From that radius on out, the obtuse angle first intercepts the beam, and the efficiency declines.

Commissioning a cyclotron is handicapped by having a probe with decreasing efficiency near extraction. It always looks like beam is being lost. The 2 degree probe head was replaced by a 4.5 degree head, which is the angle expected at extraction for 235 MeV protons. To avoid axial beam losses near outermost radii, the Northeast Proton Therapy Center (NPTC) has been commissioned with beam extracted at 230.5 MeV. (Progress is now being made towards achieving the full 235 MeV extracted beam.) Thus use of the 4.5 degree

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probe head always had efficiency rapidly increasing, but never reaching a maximum, near extraction. Again, the increase in efficiency dominates many possible mechanisms of beam loss. Also, it was found that the "apparent extraction efficiency", a comparison of the amount of beam just before extraction to extracted beam, varied wildly from day to day. A good tune of the cyclotron could range from 70% to 150% apparent extraction efficiency. These results have led to further studies of probe design in order to obtain benchmarks for cyclotron tuning.

3 INTEGRAL PROBE CHARGE COLLECTION EFFICIENCY STUDY

Protons that strike the probe scatter as they pass through and/or stop in the metal. In this study, Janni tables were used to interpolate the mean range, longitudinal, and lateral straggling, based on the energy as determined by the radius of the probe[6]. These values were used to randomly determine each proton's stopping position. Using this, in conjunction with the probe geometry and the starting position and angle of the proton on the probe, each simulated proton is flagged as having passed through or scattered out, or as having stopped in the probe. If it stops in the probe, it is assumed that the charge is collected, otherwise the charge is assumed lost.

The angle of the beam striking the probe was determined by orbit calculations[7]. This is displayed in Figure 1, as a function of probe radius. 0 degrees is tangent to a circle about machine center, and positive angles scallop inwards.

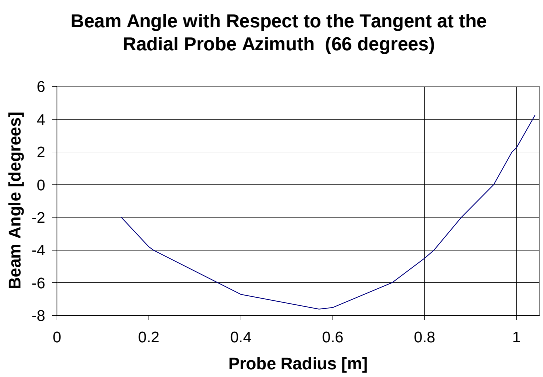
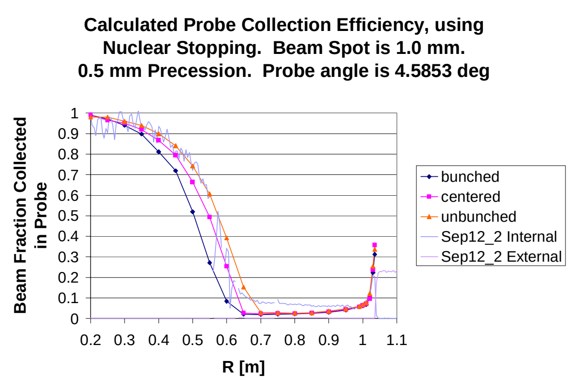


Figure 1: Angle of the C235 proton beam as a function of probe radius, at the azimuth of the probe, expressed relative to the tangent at that radius. Positive angles are scalloping inwards.

The radius gain per turn was calculated at each radius, and this was used as a baseline from which to add precessional effects from off-centered beams. As off-centered beams precess, successive turns cycle through bunching and debunching. This is simulated in this study by respectively decreasing or increasing the possible radius gain per turn. The effects of small angle changes will make very small changes in proton range, and are omitted from this study. The starting position of each proton striking the probe, is randomly located uniformly within the resulting total radius gain per turn. This is translated into a position along the probe face, based upon the beam angle and the probe geometry. Care is taken to correctly simulate the proper starting location as the beam moves from the forward face to the leading side of the probe.

The resulting calculation showed 0 collection efficiency for the 4.5 degree probe between 80cm and 95cm. In practice, this region has about a 8-10% efficiency. It was pointed out, that at these energies, many of the protons undergo at least one inelastic nuclear scattering event[8]. The Janni tables included this information, so this was added to the simulation[6]. Each proton is randomly checked to see if it underwent some such reaction before stopping or exiting the probe. The charge from these protons is counted. The remaining protons are checked to see if they stop in the probe. Even with such a favorable interpretation, the calculations do not make up the difference in this region. Since these protons pass out the trailing convex edge, without any electron catchers, it is assumed that beam measured in this area is actually a measurement of electron loss. Such a loss will take place over a much larger region, which should be taken account of if further improvements of this study are needed.

Figure 2: Comparison of calculated and measured radial



probe traces with the 4.5 degree probe head.

The final results are depicted in Figures 2, & 3. In Figure 2 , it can be seen that there is good agreement between calculation and measurement at 4.5 degrees. Most of the effects are dominated by geometry, probe shape and beam angle. The fluctuations in beam measured with partial charge collection efficiency correspond nicely with the calculated variations in efficiency from beam off-centering. This is not proof, but it does make beam off-centering a likely cause of much of this "apparent noise." A 2 degree probe head calculation, did show that the beam dropped off quite rapidly near the end. But, in it, and in a 3 degree probe head calculation, both compared with the 4.5 degree probe head calculation in Figure 3, the probe head was less sensitive to the effects of beam off-centering after the peak as compared to before the peak

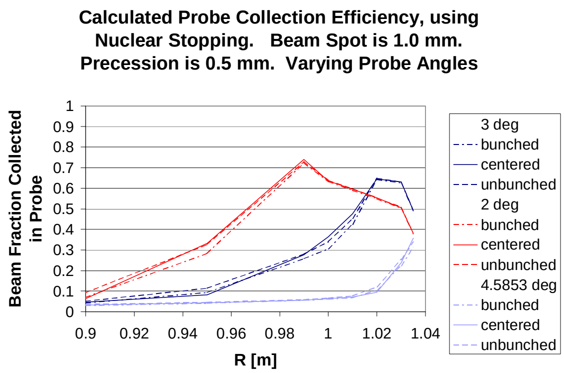


Figure 3: Comparison of calculations with 2.0, 3.0, and 4.5 degree probe heads. The calculations show a greater variation of efficiency at radii lower than the peak, compared with radii greater than the peak.

4 CONCLUSIONS

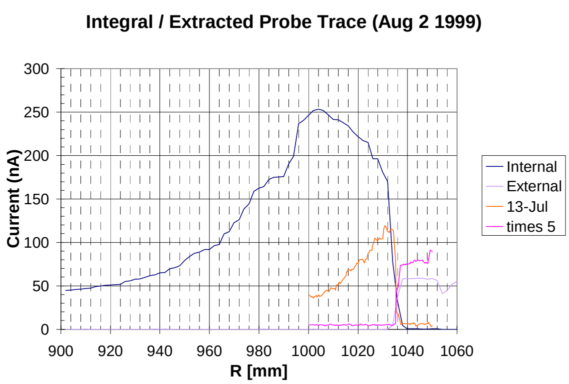


Figure 4: Comparison of a radial probe trace taken with the new 3.0 degree probe head, compared to one taken with the old 4.5 degree probe head.

In the study, the peak efficiency is seen as a good referent. A position chosen shortly after the peak will be relatively stable, and can be used for comparisons with R<40cm for internal transmission, and with extracted beam for extraction study. The 4.5 degree probe head was replaced with a 3 degree probe head. Figure 4 shows a comparison of measurements with the two probes. The location of the peak will vary by up to 2mm, and its relative efficiency will range from 40-50%. This probe head is presently used for routine cyclotron measurements. The comparisons for extraction efficiency are more stable, but we usually look at total transmission from 35 cm to the extraction beam stop.

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