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NEVIS SYNCHROCYCLOTRON BEAM STATUS REPORT

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I. Introduction

In January 1975, the first full energy (570 MeV) beam was obtained at the Nevis Synchrocyclotron. Measurements of beam current at small radius indicate a beam current of 12 μA for 300 pulse/s operation. We have measured the vertical properties of the beam and have some information on the radial width. This paper will begin with a brief review of the design features of the Nevis Synchrocyclotron with emphasis on the unusual ones. In the remainder of the paper, we will describe the beam studies and the current status of the accelerator.

II. Outline of Accelerator Design

The details of the accelerator design have been presented previously.[1-3] Figure 1 illustrates the main features of the accelerator. The magnetic field has 3-fold azimuthal symmetry. The south sector iron is supported on five Al_2O_3 insulators, since it is inside the dee. Figure 2 indicates some of these insulators schematically.

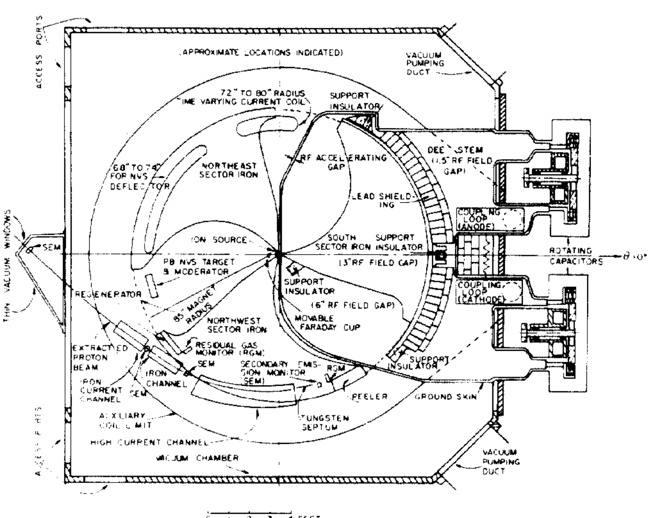

Fig. 1. Diagram of the Nevis Synchrocyclotron showing the dee, capacitors, sector iron, ion source, NVS target and deflector, and the extraction system.

The magnetic field, averaged azimuthally, increases by about 10% from R = 0 to R = 77 in. The field has been carefully designed and shimmed to keep ν_z and ν_r away from major resonances.[1] We have recently remeasured the field and shimmed out a small first harmonic that was found between 60 and 80 in. Now the first harmonic amplitude is less than 5 g from 21 to 75 in.

The RF system is tuned by the two rotating capacitors from 28 to 18.8 MHz. It is operated at 300 pulses/s, with the actual acceleration taking 1.4 ms. The peak RF voltage on the dee is nominally 30 kV. We have actually operated 10 to 15% above that value.

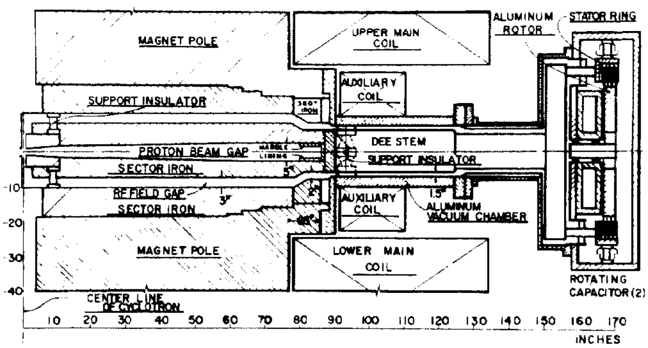

Fig. 2. Side view diagram of the coils, RF sector iron, dee-dummy dee, capacitor, and support insulators.

The ion source is a cold cathode Penning type, as shown in Fig. 3. It extends through the median plane, and the ions are extracted through the side. The two cathodes are connected by a wire running externally. The entire source is pulsed to +30 kV, and the ions are extracted by an electrode at ground potential, which is about 1 mm away from the slit. The actual arc voltage is 5 kV to initiate the arc, which draws 8 to 15 amperes.

The extraction system[2] (see Fig. 1) is of the regenerative type. The beam is accelerated to 77 in. radius, where the RF is turned off slowly, compressing the beam energy spread and completely spreading out its azimuthal extent. During this time, the field in the time-varying-bump coil (TVB) holds the parked beam away from the peeler and regenerator. This TVB field is then lowered and finally reversed, pushing the beam into the peeler and regenerator. These elements induce exponentially increasing radial oscillations. Orbits eventually jump the tungsten septum and particles pass out of the accelerator through the three element extraction channel. Since the acceleration takes 1.4 ms of the 3.3 ms cycle, the extracted beam will have better than 50% macro-duty factor. There should be no RF micro structure in the beam.

The main unusual features of this accelerator are related to its conception as an AVF Synchrocyclotron. The central region is very small, having the sector tips at 0.25 in. radius. The vertical space between the sectors is 0.75 in. Thus, the ions injected at 0.6 in. radius already are subject to strong vertical focusing. This scheme enables the injected current at the space charge limit to be much higher than in an ordinary synchrocyclotron. The requirement of such a small central region forces one to put one sector inside the dee.

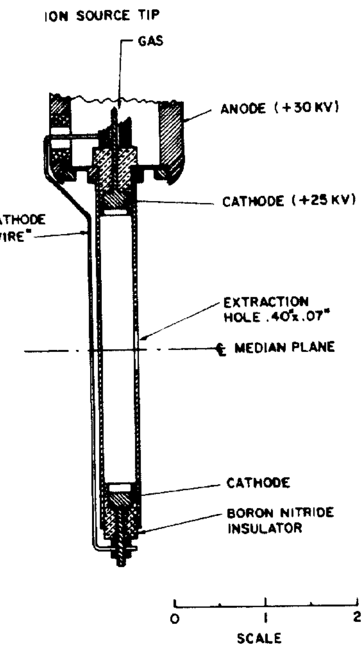

Fig. 3. Cross section view of the Penning ion source. The gas is introduced around the top cathode. The top and bottom cathodes are connected electrically by the stiff stainless steel wire outside the source. Ions are extracted by a grounded electrode near the extraction hole, which extends through the median plane.

III. Operation

During the last year, we have operated the accelerator enough to discover a few weak points and improve them. Other components have operated satisfactorily as originally designed. The RF system has been run extensively at half power (by pulsing 150 s^{-1}). In addition, several hours of steady running at 80% power have been logged. Early in the year, we had trouble with the center support insulators. Due to a poorly designed RF contact, they were being overheated. This contact was revised, and we have since had no trouble with the insulators.

The rotating capacitors have the shafts sealed by ferrofluidic[4] seals. We had trouble with these seals failing during the first half of the year. The failures were probably due to alignment problems and/or RF voltage appearing on the shaft during capacitor sparks. The alignment has been corrected. We have built spark detection circuitry which turns off the modulator as soon as an incipient spark is detected. We have had no seal failures in the last 6 months. A recent bearing failure is attributed to a defective bearing cage, as the other bearings show no signs of damage or wear.

IV. Beam Tests

On January 24, 1975, we obtained the first full energy beam. Prior to that date, we had accelerated the beam to 55 in. radius, where it was lost due to a lowering of the orbit plane. Increasing the current in the lower coil of the magnet corrected the orbit plane, and after some other difficulties, we were able to accelerate the beam to full radius. We have measured the current in the beam at about 20 MeV simply by stopping it in a plate and measuring the current. Then we have measured the beam losses during acceleration by correlating signals in a scintillation counter with the RF. The current measurement, performed with a 10 pulse/s repetition rate, gave 0.4 μA. This projects to 12 μA for the 300 pulse/s operation. (In all cases, we are operating with 3.3 ms pulses.)

The beam lost during acceleration is mainly lost from the phase bucket, but some beam is also lost due to orbit instabilities. Particles lost by this second means will make a radiation pulse as they are lost. However, particles lost from the phase bucket will coast in the machine, and will be slightly accelerated or decelerated during subsequent RF pulses. Their oscillation amplitudes will gradually build up, due to collisions, until they are lost. They tend to be lost at specific frequencies in the RF cycle - presumably because those frequencies correspond to regions of the magnetic field where the stable phase space volume is at a minimum.

It is possible to differentiate between the radiation pulses produced by these two loss mechanisms. If there are no particles coasting in the machine and a single pulse is accelerated, the radiation occurring during that pulse will result from orbit instabilities. After a number of pulses, an equilibrium will build up, where the number of particles lost from the phase bucket during each pulse will equal the number that have been coasting in the machine for a while and hit the structures of the dee or sectors. Thus, by looking at the scintillator output after a number of pulses have been accelerated, the total losses can be determined. By then pulsing the RF once without firing the ion source, the losses of coasting particles can be determined. Figure 4 illustrates all three types of observations. From Fig. 4, we conclude that approximately 25% of the beam accelerated beyond the first phase oscillation is lost during the remaining acceleration. Furthermore, about 5% of the beam is lost directly, and the remaining 20% is lost from the phase bucket. When we place a target to interrupt the beam before it is accelerated through the dip in the RF voltage near the end of the pulse, we observe that the losses from the phase bucket are much less than 20%. Thus, we conclude that most of these losses occur in that voltage dip, as one expects.

Measurements using two targets indicate that the beam is distributed vertically such that 50% of the beam lies inside of a 0.25 in. vertical band. Measurements of the radial oscillations are difficult to make. To date, we have measured a combined width due to

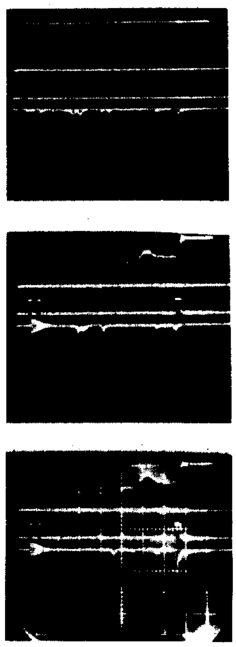

Fig. 4. Oscilloscope traces of the RF envelope and radiation bursts from lost beam. The top trace is the RF envelope, and the bottom trace is the output of a scintillation counter viewing the radiation. The time scale is 0.2 ms/division. The vertical scale for the scintillator is highly amplified. The final pulse at the end of the acceleration, when the beam hits the target at 78 in., would be 18 divisions in the top or bottom picture. In the middle picture, the entire final pulse is visible. The top picture was taken after steady operation at 10 pulses/s. The middle picture was taken when the source was not pulsed, but previously the machine had been operated steadily at 10 pulses/s. The bottom picture was taken of a single acceleration pulse that took place when no coasting particles had been left in the machine. Thus, the top picture shows radiation from all lost beam, the middle picture shows radiations from particles lost from the phase bucket, and the bottom picture shows beam lost due to orbit instabilities. Comparisons of the various pulses of radiation with the final pulse made by the beam hitting the target indicate about 20% beam lost from the phase bucket and 5% lost due to orbit instabilities.

betatron and synchrotron oscillations, which is consistent with the expected dominance of synchrotron oscillations.

The measurement of vertical beam width also gives the vertical position of the beam centroid. This measurement first clarified the problem of beam loss at 55 in. We have found that, in order to optimize the transmission of the beam during acceleration, we must position the orbit plane a little below the midplane of the cyclotron (by unbalancing the main magnet current). The orbit plane is then 0.6 in. below the mid-plane from orbit average radii of 52 to 72 in. It then drops to 0.7 in. at R = 73 in. and rises smoothly to 0.1 in. below the mid-plane at 78 in. radius.

V. Summary and Implications

The full energy beam with vertical width 0.25 in. and projected intensity 12 μA is a major step toward fulfilling the design goals (20 μA) of the accelerator. We anticipate that an increase in intensity by a factor of 2 will be obtained by extending our injection time from 10 μs (at present) to 25 μs. By varying the timing of the source trigger, we have verified that this time window is indeed available for injection. This injection time extension will require modifying the ion source pulser. We also expect to be able to extract higher ion currents by modifying the source tip to bring the plasma closer to the extraction hole. Calculations on the operation of the extraction system indicate that we should be able to exceed 75% extraction efficiency with the vertical and radial widths measured. The adiabatic turn-off of the RF voltage, with concurrent compression of energy spread, has not yet been tested, but we expect that it will improve the extraction efficiency. We are presently installing the extraction system, and anticipate extracting beam in April 1975.

References

[1] J. Rainwater, Proceedings of the Sixth International Cyclotron Conference, Vancouver (1972).

[2] IEEE Trans. NS-18, #3 (1971), J. Rainwater, p. 263; R. Schneider et al, p. 303, R. Cohen et al, p. 326; M.M. Holland et al, p. 787.

[3] R. Cohen et al, IEEE Trans. NS-16, #3 (1969), p. 421, 434.

[4] Ferrofluidic Co., Burlington, Mass.