Design features of the Princeton A.V.F. cyclotron facility*

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ABSTRACT

Recent operating performance is reported and several features in the design of the accelerator, beam line and laboratory of the Princeton A.V.F. Cyclotron are described. Although begun as a close copy of the 56 MeV cyclotron at Michigan State University, a number of modifications were made to the machine, and a somewhat different approach to the laboratory layout and beam transport design was adopted. An rf amplifier, outside the vault shielding, drives the dees through tunable half wave transmission lines. Mode separation is obtained with a simple transmission line coupler. The tuning range was extended by a modification of the dee stem inductance. A magnetic channel in the beam extraction system uses coils and laminated iron foil stacks which avoid saturation while reducing the power demand relative to an air core design. The channel is designed for minimum first harmonic perturbation at the critical radius for the $\nu_R = 1$ resonance and for reduction of the first and second radial derivations of the field on the extraction trajectory. Beam energy analysis is achieved with a 90°, 183 cm radius, flat field magnet made double focusing with discrete quadrupoles. Rotating slits and localised shielding in the beam line will permit external bombardments at the full intensity available from the cyclotron. A high resolution, 15 millisteradian spectrograph is under construction.

1. BACKGROUND AND RECENT PERFORMANCE

The Princeton A.V.F. Cyclotron closely follows the design of the highly successful Michigan State University (M.S.U) Cyclotron of H. G. Blosser and colleagues, except for certain features described below. Construction began after funds for the cyclotron and laboratory were made available by Princeton University in the autumn of 1965. Beam transport hardware and portable shielding were acquired after funding by the U.S.A.E.C. in January 1967. The

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first internal beam was produced in December 1968 and the experimental programme began in February 1969 with an energy resolved external beam produced by stripping extraction of 35 MeV H^- ions. Since that time, experimenters have recorded external beams of 1·5 μA, a measured energy resolution of 0·2% *FWHM* and 0·3 μA with a resolution of 0·05% using single turn stripping extraction. During a shutdown in late spring and early summer the positive ion extraction elements were installed. Since then proton beams have been extracted at 21, 27·5, and 35 MeV. Extraction efficiencies of 60 to 80% have been observed. With careful attention to centring and phase selection the 35 MeV beam was extracted with 94% efficiency and an energy spread of 0·08% *FWHM* before magnetic analysis. Beam currents have been deliberately held below 2 μA during the early operation. Acceleration of deuterons on $N = 2$ mode is scheduled for the week following the conference.

2. DEVIATIONS FROM THE M.S.U. DESIGN

2.1. *Magnetic field*

The magnetic field reproduces the M.S.U. field with sufficient accuracy that acceleration to full radius using M.S.U. computer predicted profile coil settings has been demonstrated. Isochronism is improved if the fields are corrected for a 0·7 mm difference in the effective radial placement of pole tips which was observed in the field mapping. The Princeton yoke legs have been thickened to reduce the magnet power and fringe field at low energies while offering the prospect of reaching a deuteron energy of 30 MeV with 800 ampere excitation. The Princeton version incorporates two sets of harmonic coils at the $\nu_r = 1$ radii in the valleys.

2.2. *Rf designs*

The frequency range of the Princeton cyclotron is 13·4 to 24·5 MHz. The high frequency limit was extended by reducing dee stem inductance through closer liner spacing in the region between the tuning panels and the magnet gap. This change substantially reduces the forbidden energy range for protons (17–21 MeV) and He^3 (50–62 MeV). The rf final amplifier is located outside the shielding at the end of halfwave transmission lines. The effective line length is varied by lumped elements at either end. The two dees are driven symmetrically by strong coupling to the dee stems from two identical amplifiers. Mode separation is accomplished by coupling the transmission lines by a coaxial cable at the lower transmission line boxes. At lower powers this coupling allows driving both dees from either amplifier if necessary.

2.3. *Extraction elements*

The electrostatic deflector is mechanically similar to the M.S.U. design inside the vacuum chamber. The septum tip is quickly replaceable. The oil-filled high voltage bushing at the end of a coaxial cable accepts 100 kV from a Cockroft-Walton supply above the shielding. These components are scaled down from a 400 kV design for a beam separator at the Princeton-Pennsylvania 3 GeV accelerator. Voltage of 98 kV across the 6 mm gap has been reached with less than one hour of conditioning. The magnetic channel was designed by K. Wakefield of the Princeton Plasma Physics Laboratory. The design uses iron foil stacks laminated perpendicular to the field lines with inert foils to obtain a known permeability free from saturation effects over the entire field range. Two simple coils provide independent control of beam direction and first harmonic cancellation at the outer $\nu_r = 1$ radius. The design compensates partially for first and second radial derivatives of the cyclotron field on the extracted orbit. The success of the extractor design is evidenced by the clean turn patterns prior to extraction and the demonstrated high extraction efficiency.

2.4. *Beam defining and measuring apparatus*

In addition to the half-turn and 3/2 turn slits, the radial differential probe for turn patterns, and the external fast scintillation counter for time width measurements in common with M.S.U., the Princeton cyclotron probe assembly incorporates fixed aperture phase selection slits at 180° azimuth which are adjustable in radius about the 18th and 24th turns, a stop at 17 in radius and two high power stops at full radius for measurement of current before and after extraction in high intensity operation. The radial probe may be rotated through 90° about its axis to function as a two finger probe for study of axial oscillations.

3. BEAM TRANSPORT SYSTEM

Three independently shielded scattering rooms are reached by the beam after passing through a 180 cm, flat field, 90° analysis magnet. Double focusing is provided by a symmetric pair of horizontally defocusing quadrupole singlets which give vertical cross-over in the 90° magnet. On each high resolution line, an intermediate image with cleanup slits following the switching magnet and a slit-free final leg is employed. After careful mapping, the analysis magnet fringe field clamps were modified to reduce the (x, θ^2) aberration to zero. Based on the accuracy of the mapping procedure, the analyser magnet should give an energy resolution better than 0·02% for horizontal emittance up to 15 mm mrad with an absolute energy scale established to 0·05%.

In addition to the scattering rooms after the analysis system, the unresolved beam may be conducted to a bombardment cave for isotope production at high intensity. Rotating slits, cooled target geometry and localised shielding will permit operation up to 50 μA.

Beam areas are protected by shielding, neutron shutters, radiation alarms and interlocks to permit occupancy of all rooms not selected for beam.

4. EXPERIMENTAL EQUIPMENT

Scattering chambers of 50 cm and 150 cm diam. from the old Princeton F. M. cyclotron are positioned in two of the scattering rooms. An atomic beam apparatus for spin and moment determinations on radioisotopes and a bombardment facility based on that of the Berkeley 88 in cyclotron are in use in the high level cave. A single gap, multiple element spectrograph magnet of 15 millisteradian solid angle and dispersion along the focal plane of approximately 0·2 keV/mm/MeV is under construction. The design permits remote magnetic adjustment of aberrations and the focal plane position to correct for shifts caused by reaction kinematics. Electrostatic vertical deflection to select a single charge to mass ratio is also incorporated into the design. Calculations of the aberrations through fourth order show that energy resolution of 0·02% over most of the focal plane with the full solid angle in use may be attained. This spectrograph promises to be a uniquely useful instrument for reactions of very low cross-section and for particle correlation experiments as well as for spectroscopy with high resolution.

5. ACKNOWLEDGEMENT

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