EXPERIMENTAL FACILITIES AND RESOLUTION CAPABILITY OF THE MSU CYCLOTRON (*)

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Cyclotron Characteristics

The MSU 64" Cyclotron is designed for variable-energy acceleration of a variety of particles, as can be seen in Fig. 1. In addition to broad flexibility in particle and energy, the cyclotron has been designed to maximize beam precision in accord with the presently indicated needs of medium-energy nuclear physics; essentially all design decisions reflect this emphasis on precision. Estimates of performance for the cyclotron, based on detailed orbit computations and experimental data on the source output, have previously been reported¹⁾. These estimates indicate unusually high external-beam precision and intensity.

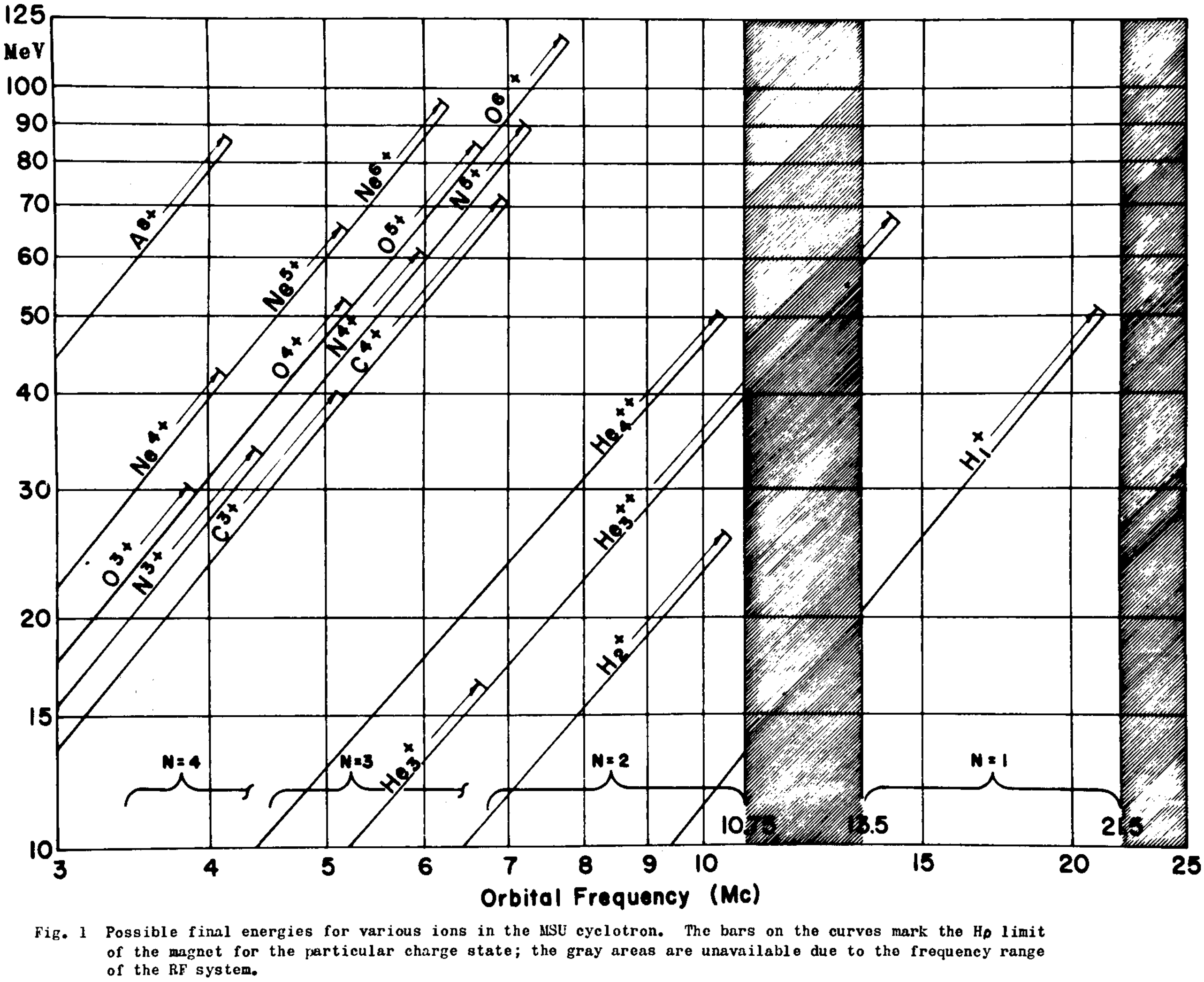

Fig. 1 Possible final energies for various ions in the MSU cyclotron. The bars on the curves mark the Hρ limit of the magnet for the particular charge state; the gray areas are unavailable due to the frequency range of the RF system.

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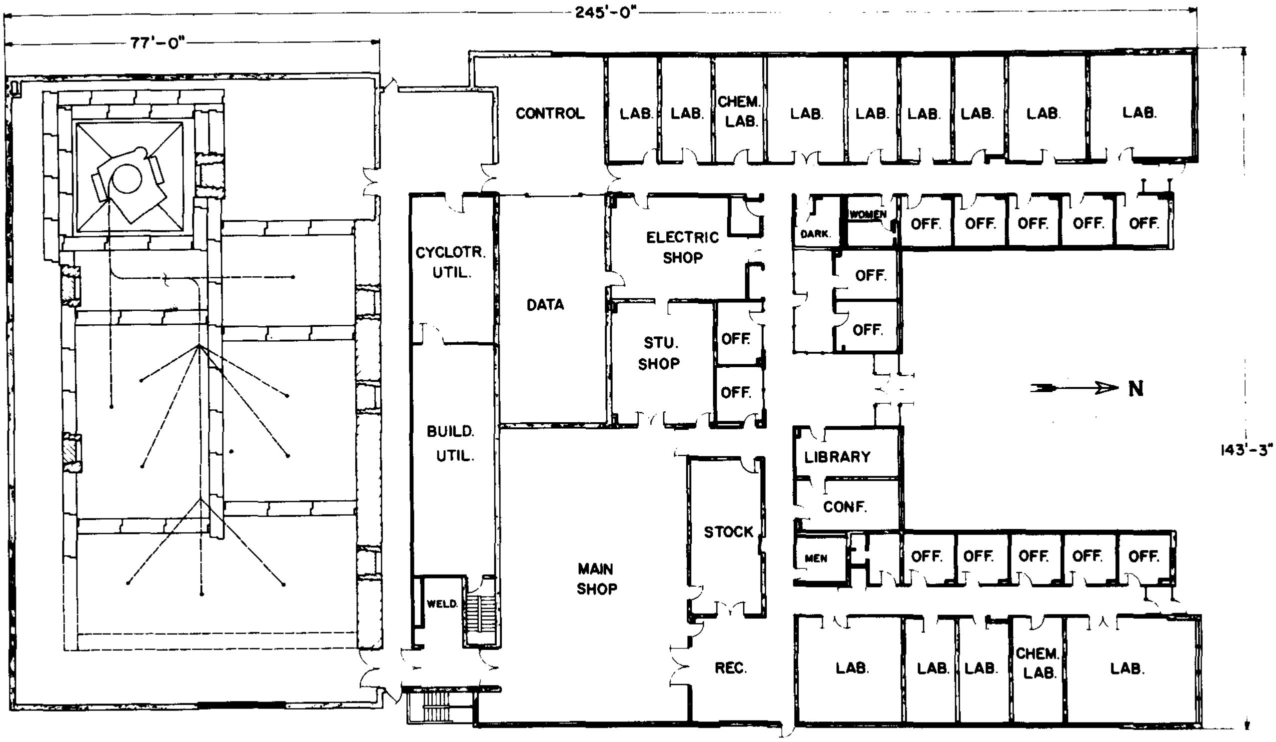

Fig. 2 Floor plan of the cyclotron building. On the north a U-shaped group of offices face onto an open courtyard; general purpose laboratory rooms are located across the halls from the offices. Personnel traffic to the cyclotron and experimental areas at the south of the building is deliberately required to pass through the control room to provide a good radiation safety situation. (The door from the main shop to the experimental areas will normally be kept locked). A poured-in-place shield wall separates the experimental areas from the remainder of the building - otherwise shielding is of stacked-block construction.

Building Arrangements

To effectively utilize such a cyclotron it was considered essential to arrange the building in a manner which would (a) provide a large number of target positions, (b) permit set-up work at a number of positions simultaneously with experimental operation at others, and (c) provide substantial laboratory areas away from the beams for use in assembly and testing of equipment and for radioisotope studies. Following these general guidelines, the floor plan shown in Fig. 2 was developed. Fig. 3 is a perspective sketch of the experimental area showing the arrangement of stacked block shielding. The gross floor area of the building is 34,500 square feet and the cost, including architects' fees, is $1,008,057. Completion is scheduled for the summer of 1963.

Beam Analyzing System

Momentum analysis of the beam from the cyclotron is accomplished by a pair of 90^{0}, $n = \frac{1}{2}$ magnets as can be seen in Fig. 2 and 3. Downstream from the analyzing magnets a pair of steering magnets will be provided to shift the beam to various target positions, along with a series of quadrupole magnets to accomplish necessary focusing. Beam-optical studies have been performed on a steering system in which single-stage, vertically-focusing quadrupoles are placed before and after a flat-field steering

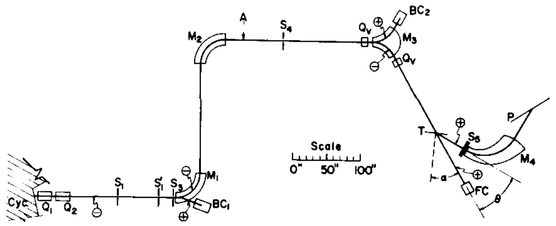

Fig. 4 Plan view of a portion of the beam analyzing and steering system. M_1 and M_2 are $N = 1/2$ bending magnets, M_3 and M_4 flat field magnets, $BC_{1,2}$ beam catchers, $Q_{1,2}$ standard quadrupoles, the Q_V vertically focusing quadrupoles, $S_{1,...,5}$ various slits, T is the target, ϑ the scattering angle, α the target angle, P a photographic plate detector, and FC a Faraday cup and beam catcher. The + and - symbols denote beam polarity for a negative ion reaction experiment. The assumed radius of curvature is 36" in M_1, M_2, and M_3 and 50" in M_4.

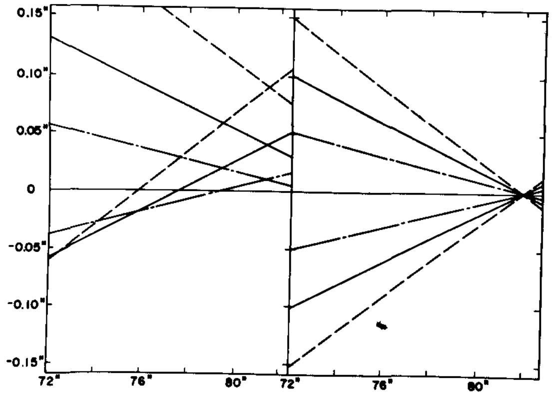

Fig. 5 Left - an expanded median-plane view of the focusing of pairs of rays of varying divergence by a 90°, $n = 1/2$ magnet. The three pairs of rays started on the optic axis with divergence angles of ±5, ± 10, and ±15 milli-radians. Right - similar view for a magnet with a field given by $B(r) = B(r_0)\ [1 - 0.5x + 0.425x^2]$, where $x = (r - r_0)/r_0$. Median-plane aberrations are seen to be essentially eliminated by this field.

magnet. The results show that such a steering system behaves essentially like a double-focusing $n = \frac{1}{2}$ magnet, which is highly desirable in steering a well-focused beam to the target.

The pair of 90^0, $n = \frac{1}{2}$ magnets have the attractive feature of allowing a broad variation in the resolving power merely by changing the position of the initial object with respect to the first magnet$^{2)}$. Referring to Fig. 4: when the object is at S_1', which is the focal point of magnet M_1, all energies focus with unit magnification and zero dispersion at point A. Hence the system in this condition functions essentially as a perfect achromat. Transmission is limited only by the finite aperture of magnet M_2 and by nonlinearites. Essentially all particles should be transmitted. If the object is shifted away from the first magnet by one focal length, to position S_1, the dispersions of the two magnets add, yielding a momentum resolution, $\Delta p/p$, of 27 parts in 100,000 full width at half maximum, when slits S_1 and S_4 are set to 2 mm aperture.

To determine the extent of aberrations in the magnet system the orbit-tracking codes, which were used in the design of the cyclotron, have been employed for ray tracing. The technique has the advantage of giving the exact median plane solution at once, thereby avoiding the laborious term-by-term computation of the usual series expansion. Fig. 5 shows the results of two sets of median-plane ray-tracing experiments, one in a pure $n = \frac{1}{2}$ field, and one in an $n = \frac{1}{2}$ field with an additional term in x^2 of empirically optimized magnitude. For axial motion studies, orbit programmes such as the MURA Ill-Tempered-Five routine$^{3)}$ can include axial motion accurate to essentially any order desired. Fig. 6 shows results of a series of axial motion runs with Ill-Tempered-Five to determine the extent of coupling of the axial into the radial motion. The radial displacement increases with increasing z amplitude. Hence a given radial resolution results in a maximum allowable axial amplitude.

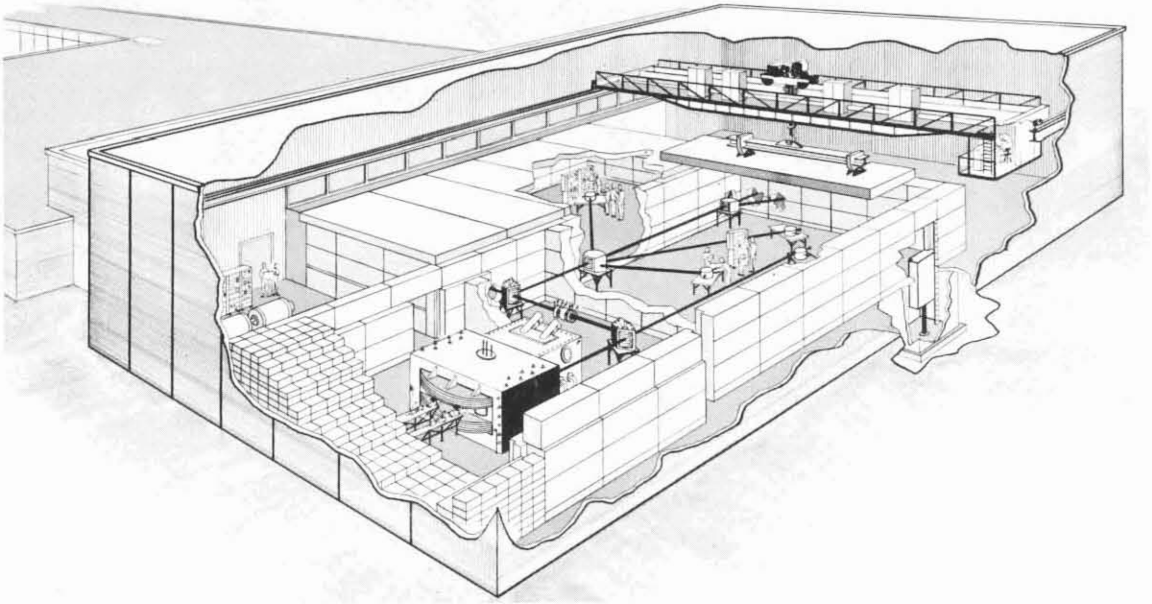

Fig. 3 Perspective cut-a-way sketch of the high bay area showing the arrangement of stacked-block shielding. The overhead crane has 40 ton capacity. One of the hydraulically actuated shield doors is visible in the cut-a-way at the right; the doors rise from below-the-floor pits on standard elevator rams.

The results shown in Fig. 5 and 6 are for sharp-edged magnets, i.e. the field is azimuthally uniform within the magnet and zero outside. Median-plane studies have been performed also for a field with realistic edges. If the edge is properly placed there will be no appreciable difference from the sharp-edge results.

From these preliminary studies it appears that aberrations in the magnet system can be made quite small provided that sufficient care is exercised. It is planned to measure the field of each analyzing magnet, compute orbit properties, and correct the field on the basis of the computations. It is hoped that this method will lead to better results than the usually employed hot-wire technique.

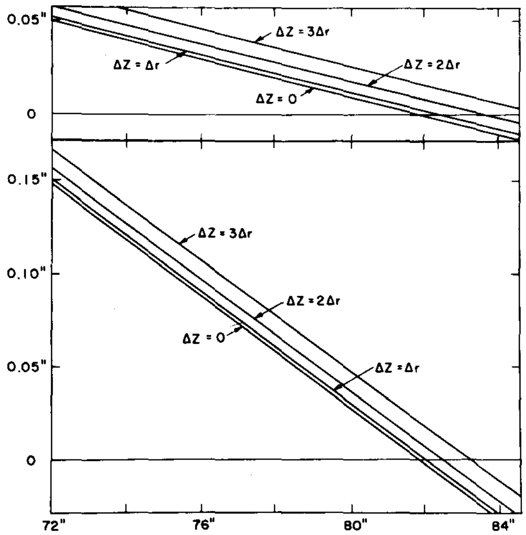

Fig. 6 Median plane projections of rays with various z amplitudes in the x^2 corrected, n = 1/2 field. The Δz's and Δr's refer to displacements at the center of the analyzing magnet. The rays Δz = 0 are the +5 and +15 milli-radian rays from the right of Fig. 5.

Negative Ion Reaction Experiment

At the Los Angeles Conference an interesting speculation was raised by the Colorado group4) concerning the acceleration of H^- ions, with extraction by conventional means and thin foils employed downstream as slits for the analyzing system. The thin foils effectively eliminate slit scattering, and the slit aperture can therefore in principle be as small as desired, giving beams of very high resolution. Since detailed estimates of the properties of the external beam of the MSU cyclotron are available from the previous performance study1), an interesting speculative estimate of the parameters of a typical reaction experiment easily follows by applying the techniques of a resolution study by Cohen5) to the situation posed by the Colorado group.

The efficiency of negative ion sources gives rise, of course, to considerable uncertainty in the estimates. For purposes of computation the phase-space density of the H^- ion beam from the source was arbitrarily assumed to be 1/10 of that measured for H^+ beams. With this assumption the properties of the external beam can be calculated from the known orbit dynamics of the cyclotron and extractor using the same techniques as previously. An external current of 250 μA of 50 MeV H^- ions is predicted with an energy spread of 60 keV, a radial spot-size-divergence of 0.004 radian-cm, and an axial spot-size-divergence of 0.02 radian-cm; all quantities being full widths.

Fig. 4 depicts a typical reaction experiment using the negative beams. The initial object size and divergence are defined by the foils S_1 and S_3 - particles penetrating either foil become positive and are deflected into the beam catcher BC_1. The momentum spread is defined by S_4 - particles penetrating S_4 are deflected into BC_2 by M_3, while the negative particles passing through the aperture of S_4 are focused on the target. In the target all particles become positive and a thick slit S_5 must be provided in front of the reaction products analyzer M_4 to define the scattering angle. This slit can fortunately be rather large even for an ordinary flat-field reaction products magnet, so that scattering from this slit is of small effect. Since all other stopping beam is guided into heavily-shielded beam catchers, the experimental situation should be extremely clean.

Sources of error in such an analyzing system and reaction experiment have been tabulated by Cohen[5]). These include: (a) direct momentum error due to the size of S_1 and S_4, (b) kinematic errors due to variation in center-of-mass scattering angle allowed by S_3 and S_5, (c) target-thickness errors due to variation in depth within the target at which scattering occurs and to fluctuations in energy loss, and (d) errors analogous to (a) and (b) due to finite axial size of the slits.

With the situation shown in Fig. 4, the methods of Cohen predict a counting rate of 100/hour at a resolution of ± 2 keV when 30 MeV protons are inelastically scattered to a level of 10 MeV excitation, assuming S_1 to have an aperture of 0.005" radially by 0.750" vertically, S_3 to be 1.000" by 0.900", S_4 to be 0.100" by 1.000", S_5 to be 0.600" by 0.900", the target to be of mass 170 and thickness 0.15 mg/cm^2 oriented at an angle α of 20°, the scattering angle ϑ to be 30°, and the cross-section for scattering from the particular level to be 0.1 mb/steradian. The resulting counting rate is approximately 2.5 times the minimum level considered workable by Cohen.

Conclusions

The large building and flexible experimental areas are expected to allow effective, multi-purpose use of the cyclotron for an extensive period of years. The proposed analysis system is highly flexible in resolution and can apparently be constructed with minimal aberrations. The speculation regarding negative-ion reaction experiments indicates a strong probability that ultra-precision reaction studies can be speedily accomplished with a relatively simple analysis system.

References

1. H.G. Blosser and M.M. Gordon, Nuc. Inst. and Meth., 13 (1961), 101.
2. The system is a slightly modified version of one proposed by High Voltage Engineering Corp. for the National Bureau of Standards.
3. E.Z. Chapman, MURA 457 (1959), unpublished.
4. M.E. Rickey and R. Smythe, Nuc. Inst. and Meth., 18-19 (1962), 66.
5. B.L. Cohen, Rev. Sci. Inst. 33 (1962), 85.

DISCUSSION

RICHARDSON : I would like to comment that one should not take too seriously the present big performance at UCLA. In my view I think that the ratio between positive and negative ions is about 200 at the moment. On the other hand Kelly at Berkeley has observed 5 mA of negative ions out of an ion source. However, this requires a large through-put of gas. If your pumping speed is very poor, such as it is at present at UCLA, you cannot do this, and you cannot take advantage of the negative ions the way you should.

BLOSSER : Actually in making these estimates we were trying to take a little into account the fact that the acceleration of negative ions is a rapidly improving science, and tried to extrapolate to what it might be when we start running.

I might add a remark relative to the comment on what floors it takes to hold our shielding walls. According to our architect ten inches of concrete with double reinforcing is all that is required. The floor is laid on undisturbed earth.