PROPOSED HIGH INTENSITY, HIGH ENERGY CYCLOTRON FOR LIGHT AND HEAVY IONS

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Summary

Since ions with small charge are produced more copiously from ion sources than are highly charged particles, it is proposed to construct a sector-focused cyclotron of large diameter to obtain heavy ions in much greater number and at higher energies than are available from existing cyclotrons or linacs. In addition, the machine will produce protons at 120 MeV and other light ions in excess of 120 MeV.

To obtain large currents of heavy ions at higher (and variable) energies than are now available, it is proposed to employ ions of low charge state in a cyclotron of large diameter, since low charge ions can be produced much more copiously than highly charged particles. A magnet of 170" diameter with B_{max} = 16.7 kg and ancillary components are well within the bounds of practical construction.

The Laboratory also desires protons of 120 MeV from the same machine. This requirement establishes the maximum frequency of the dee, and since a 3-to-1 frequency span is a practical limit, third harmonic acceleration is required for low energy heavy ions.

Projectile Output

An estimate of the accelerator's potential output has been established by the use of ANL ion source data,[1] and transport efficiencies that have been obtained in practice. It is our opinion that the following values are reasonable and form an adequate basis for the prediction of the accelerator's output.

The source data from the test bench was obtained by the use of an internal type source operated with d.c. power, an extraction dee at 10 kV, 8 kgauss magnetic field, and 180° spectrometer analysis. Using the d.c. ion yield data, it is assumed that the R.F. capture efficiency is 8% (~ 30°) to obtain the approximate number of ions available for acceleration. In the region between the source and extraction from the cyclotron, an average acceleration efficiency of 20% is assumed; as is discussed later, in connection with charge exchange, this is very conservative. Extraction efficiency has been taken to be 50%. The over-all transport efficiency from source to an outside target is thus 8% x 20% x 50% = 0.8%.

In general, for heavy ion beams, this accelerator will be primarily operated on the third harmonic mode. No additional losses are assumed for this operation because the required precision in magnetic field and R. F. stability appear to be attainable. Ions with a z/A ratio ranging from 1 to 0.075 can be accelerated and extracted.

Figure 1 sets forth the capabilities of this accelerator in regard to both the quantity and energies of most of the projectiles for a wide range of z/A ratio. The number of certain ions, i.e., H, D, He and N^{2+} has been arbitrarily limited to give 12 kW of heat dissipation in the deflector for an extraction efficiency of 50%. This is based upon ANL experience with its 60" cyclotron where 12 kW of power are successfully dissipated on a water-cooled and slotted copper septum. The external yield of heavier ions is limited (at this date) by the capability of the ion source, rather than by the heat dissipating characteristics of the septum.

The potential of this machine can best be realized if one considers an accelerator a factor of two smaller in pole diameter, such as the largest class of sector-focused cyclotrons existing or being constructed. Since for the same magnetic field the projectile energy varies directly with the z^2 of the ion, and the R^2 of the accelerator, an ion of z = 2 accelerated by the ANL 170" machine will be of the same energy as a z = 4 ion in the smaller device. Hence, the ANL cyclotron can employ particles of lesser charge with consequent greater output currents. This is seen by referring to Figures 2 and 3 which are comparisons, between the two machines, of current vs. energy for nitrogen and for argon projectiles, assuming equal ion source outputs, beam transport and extraction efficiencies for both accelerators. For nitrogen, at 5 MeV/nucleon the Argonne accelerator has an advantage factor in current of 2; this factor is 21 at 9.5 MeV/nucleon, and is 430 at 15 MeV/nucleon (the upper energy limit of the smaller accelerator). In addition, the ANL machine has the capability of attaining 21 MeV/nucleon with Z = 3 ions of N, 35 MeV/nucleon with Z = 4 and 42 MeV/nucleon with Z = 5. For argon, the ANL advantage factor in current is 23 at 2.5 MeV/nucleon, 250 at 5 MeV/nucleon (the upper energy limit of the smaller accelerator), with the ANL machine capable of providing intense currents up to 18 MeV/nucleon. From these examples, one sees the value of working with a larger magnet (greater $\bar{B}R$ product) and a lower Z for the ion. These are typical cases illustrating the capabilities of the accelerator and are representative of the other heavy ions.

Figure 4 displays the energy characteristics of the accelerator in respect to $\bar{B}R$, frequency, and the z/A ratio of the projectile. The minimum energy of a projectile is determined by the lowest frequency of the dee (4.2 Mc/s on the first harmonic or the equivalent of 1.41 Mc/s on the third) or by the minimum usable magnetic field, whichever is first applicable. It seems probable that fields as low as 3.3 kG (250 kG inches) may be attained without encountering difficulties from remanence, and that value has been assumed in our estimates.

The upper energy limit is established by either the maximum $\bar{B}R$ of the magnet (1250 kG-inches at 75" radius) or by a minimum acceptable separation of the last two equilibrium orbits. This limit is indicated in Figure 4 by the dashed line.

Centering of Orbits

To keep radial betatron oscillation amplitudes at a minimum, the orbits of all type particles at all energies should be centered on the machine's axis. There are two ways to accomplish this:

(1) Employ constant dee voltage and a movable ion source and pullers. This is fraught with engineering difficulties.

(2) Keep the ion source and pullers fixed in position and adjust the dee voltage, for each ion and at every energy, so as to obtain almost identical orbits. When the desired final energy is very low (as may occur with third harmonic operation), with consequent low dee voltage, it will be desirable to raise the dee potential and to move the ion source to a second set of fixed pullers. Since this second set must not block the ions when the first pullers are in use, a fixed ratio of dee voltages (approximately 3) is required when changing from the first to the second pullers.

No matter which system is used, the minimum separation between final equilibrium orbits will be about 0.1 inch, as determined by the maximum dee voltage of 150 kV, and the assumption that extraction will occur when $\nu_x = 1$.

Charge Exchange Effects

Because of the low velocity of heavy ions, charge exchange at collisions with residual gas molecules may be expected to throw the ions out of resonance and so reduce the percent transmission during acceleration. This has been studied for several gases using the cross section data for capture and loss of electrons given by Nikolaev, et al.[2] and by Dimitriev, et al.[3] and by a method of analysis akin to that of Clark.[4] The following example indicates that the losses are not prohibitive, for pressures which are attainable, even in the worst case where fixed pullers are used and the dee voltage varies in proportion to the projectile energy. Thus, for N^{3+} at 315 MeV with V_{dee} = 150 kV, the transmission is T = 61% at 1 x 10^{-6} Torr. On lowering the energy to 105 MeV and the dee voltage to 50 kV, T drops to 44%. If the source is now repositioned opposite the second set of pullers, 105 MeV may again be attained with V_{dee} = 150 kV and T rises to 75%; as the dee voltage is lowered a second time to 50 kV, the energy falls to 35 MeV and T drops to 61%. If the pressure is halved (to 5 x 10^{-7} Torr), the transmission figures for the situations given above become 80, 70, 87, and 80 percent. It will be noted that these transmission numbers are considerably in excess of the 20% figure assumed as a general average when quoting the over-all expected yields shown in Figure 1. Scattering effects have been investigated and were considered to be negligible.[5]

By scaling from the known surfaces and gasket areas and the projectile gas input for the 60-inch cyclotron at ANL, it is estimated that two 48-inch diffusion pumps will produce 5 x 10^{-7} Torr in the 170-inch machine. More precise calculations will soon be made on the basis of pressure gradients to be measured in the 60-inch device.

It is apparent that if the mechanical problems associated with continually movable pullers can be solved, so that 150 kV is applied to the dee for all projectiles at all energies, then the transmission will always rise as the energy is lowered.

Deflection

For an electrostatic deflector of angular extent θ and electric field E, the increase in radial coordinate during its traversal is approximately

$$\Delta r = \frac{AM_o\gamma B_c^2(1-\cos\theta)E}{Ze\left(\frac{B}{B_c}\right)^2}$$

where A is the mass number, M_o the nucleon rest mass, γ is the total energy in units of M_oc^2, B_c is the field at the cyclotron's center and B is the field averaged along the path in the deflector. The angle between the orbit as it leaves the deflector and a circle about the machine center is approximately given by

$$\alpha = \frac{AM_o\gamma B_c^2E\sin\theta}{Ze\left(\frac{B}{B_c}\right)^2 r}$$

where r is the average radius of curvature in the deflector. It is evident that both Δr and α may be kept constant for all projectiles at all energies by suitable change of E (thus assuring proper entry of the ions into the beam transport system), provided B/B_c remains constant. This condition can be approached by rounding the hill sector edges so that the pole face is approximately an equipotential on which the flux density is approximately constant. In this way, the change in the fringing field configuration, mainly due to saturation, is minimized. Local variations of B/B_c along the deflector channel can be minimized by making the deflector in sections with individual control of the field E in each. To increase the extraction efficiency for the lightest, high energy ions, it is probable that resonance methods will be used to increase the separation of final turns.

R.F. System

The design of the tuning system must necessarily compromise between large power and large physical size. The practicality of third harmonic operation (although at the expense of increased precision of magnetic field control) is a fortunate factor in keeping the tuner volume to reasonable dimensions. Panel tuning eliminates the difficulties of sliding contacts. A one-fifth scale model oscillates over the required 3 to 1 range and shows no signs of undesired modes. At full scale, the distance from dee tip to short circuit is 20 ft, the tuner section being 9.6 ft long, 15.3 ft wide and 9.2 ft high. Computed copper losses at 12.7 Mc/s are 675 kW including 10% for strays. Hinge currents are in conformity with known capabilities. With 1 mA of circulating beam and an amplifier efficiency of 60%, the D.C. power requirements will be about 1.4 megawatts.

The final stage of the amplifier will be two RCA 6949 shielded grid triodes in parallel in a single-ended Class C amplifier, driven by an Eimac 4CW 10,000 preceded by a variable frequency oscillator. Two Machlett 7560 triodes will serve as a vernier voltage control and ripple suppressor.

Magnet

Present plans, subject to modification after studies with a one-sixth scale model magnet are completed, call for a 3-sector magnet with 60° maximum spiral angle, 15.1" hill gap and 25.3" valley gap. The range of ν_z is from 0.2 for 120 MeV protons to 0.4 for very slow heavy ions, the flutter changing from 0.30 to 0.207. The general magnet parameters are: length, 387 inches; width, 182 inches; height, 247 inches; pole diameter, 170 inches; total weight, about 2000 tons. Hill coils consume 340 kW, valley coils 270 kW, trim coils 275 kW, main coil 430 kW, for a total of about 1300 kW.

Buildings

Five separately shielded target rooms are planned, four receiving the beam energy-analyzed to 0.02 percent by a pair of 120 degree magnets. Long out-of-doors flight paths are possible. Three large target-instrumentation rooms are provided, plus offices, laboratories, with two small caves, for users and cyclotron staff.

General Parameters

Magnet

Pole Diameter	170 in.
No. of Sectors	3
Max. Spiral Angle	60°
Hill Gap	15.1 in.
Valley Gap	25.3 in.
Max. Orbit Radius	75 in.
$\bar{B}_{max}$	16.7 kGauss
$\bar{B}_{min}$	3.3 kGauss
Iron Weight	2000 Tons
Copper Weight	127 Tons

R.F.

Single Dee	180°
Internal Height	2.5 in.
Clearance to Ground	3.0 in.
Max. Dee Voltage	150 kV
Panel Tuner Frequency Range	4.2-12.7 Mc/s
D.C. Power	1.4 MW

References

[1] Mavrogenes, G. S., Ramler, W. J., and Turner, C. B. Paper H-3, Particle Accelerator Conference, Washington, D.C., March 10-12, 1965.

[2] Nikolaev, et al., JETP 13, 695 (1961).

[3] Dimitriev, et al., JETP 15, 11 (1962).

[4] Clark, D. J., Rutherford Laboratory, CDN-500-30-060, August 27, 1963.

[5] Friedman, A. M. (Private communication).

Projectile	T MeV	External Microamperes	External Power kW	External Projectiles/sec
$_1H^+$	18-120(+)	100	12	6×10^{14}
$_2D^+$	10-120	100	12	6×10^{14}
$_3He^+$	7-130	90	12	6×10^{14}
$_3He^{2+}$	25-240	100	12	3
$_4He^+$	6-120	100	12	6×10^{14}
$_4He^{2+}$	20-240	100	12	6
$_{14}N^{2+}$	21-130	165	11	5×10^{14}
$_{14}N^{3+}$	21-290	120		3
$_{14}N^{4+}$	21-520	15		0.2
$_{14}N^{5+}$	34-615	0.5		0.006
$_{16}O^{2+}$	24-115	120	7	4×10^{14}
$_{16}O^{3+}$	24-255	65		1
$_{16}O^{4+}$	24-450	10		0.1
$_{16}O^{5+}$	29-625	0.2		0.002
$_{12}C^{2+}$	18-155	90	7	3×10^{14}
$_{12}C^{3+}$	18-335	50		1.0
$_{12}C^{4+}$	25-500	4		0.06
CO_2 gas was used to obtain the C ion.				
$_{20}Ne^{2+}$	30-95	100	5	3×10^{14}
$_{20}Ne^{3+}$	30-200	50		1
$_{20}Ne^{4+}$	30-370	5		0.1
$_{20}Ne^{5+}$	30-560	0.2		0.002
A^{3+}	60-110	135	7	3×10^{14}
A^{4+}	60-190	65		1
A^{5+}	60-285	10		0.1
A^{6+}	60-420	3		0.03
A^{7+}	60-560	2		0.02
A^{8+}	60-720	0.5		0.004

Fig. 1. Projectiles, Energy Ranges and Particle Yields.

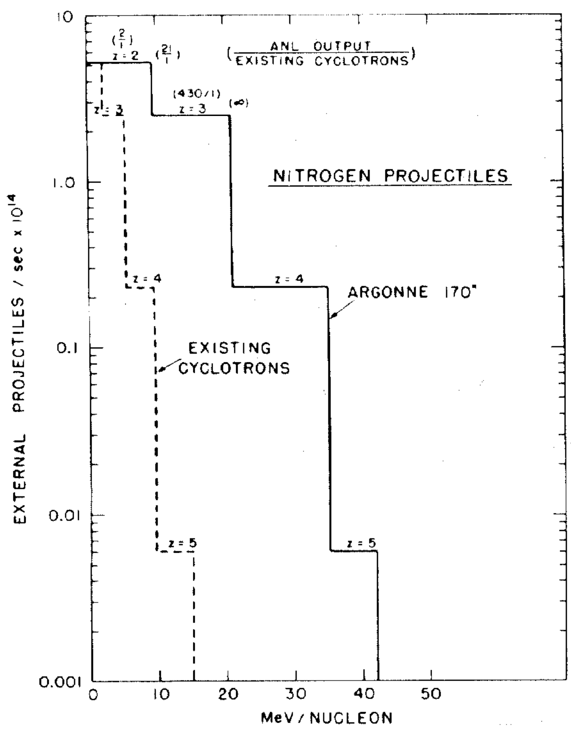

Fig. 2. Comparison of Proposed and Existing Cyclotrons - Nitrogen.

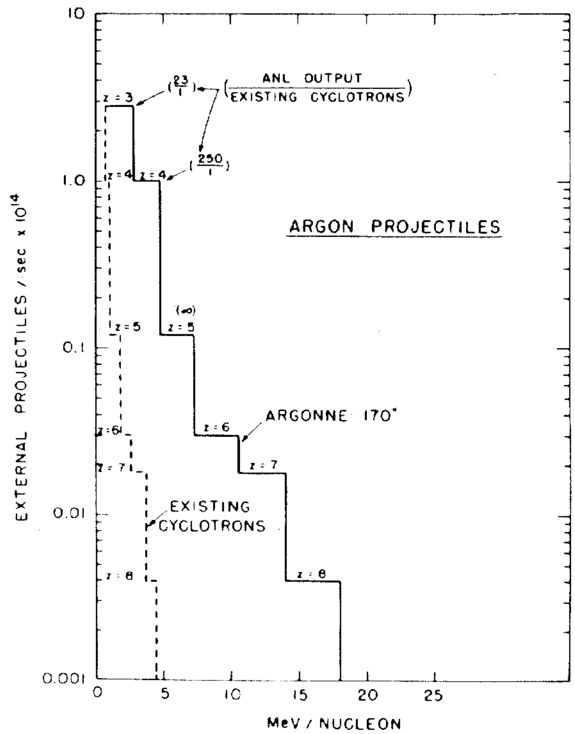

Fig. 3. Comparison of Proposed and Existing Cyclotrons - Argon.

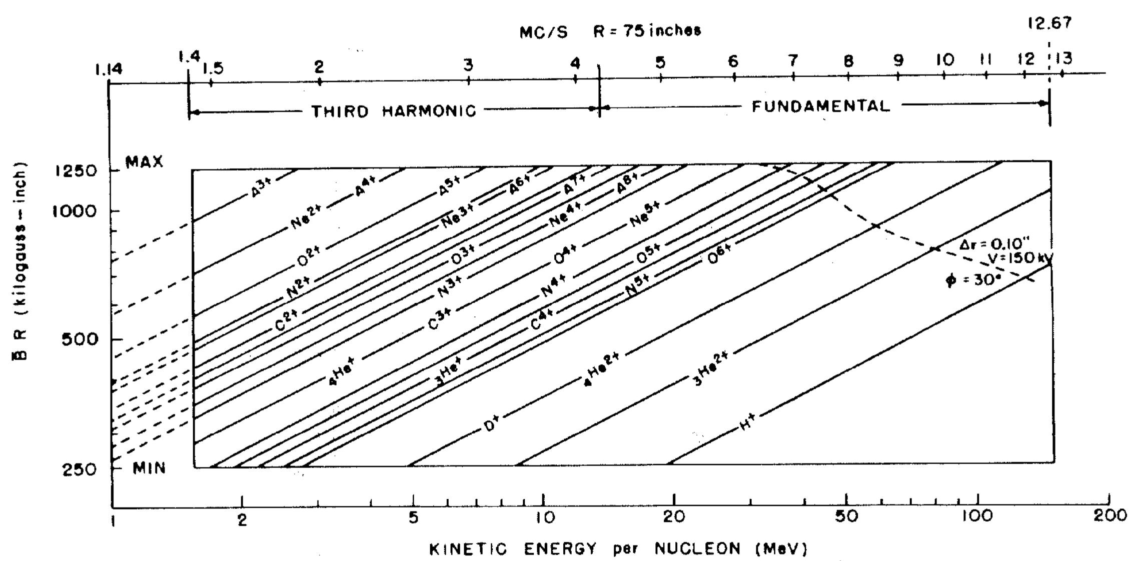

Fig. 4. Projectiles, Energies, BR and Dee Frequency.