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Bigham et al.

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[54] **SUPERCONDUCTING CYCLOTRON**

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June 19, 1973 Canada 174422

[52] **U.S. Cl.** **313/62,** 328/234, 335/216
[51] **Int. Cl.** **H05h 13/00**
[58] **Field of Search** 313/62; 328/234; 335/216

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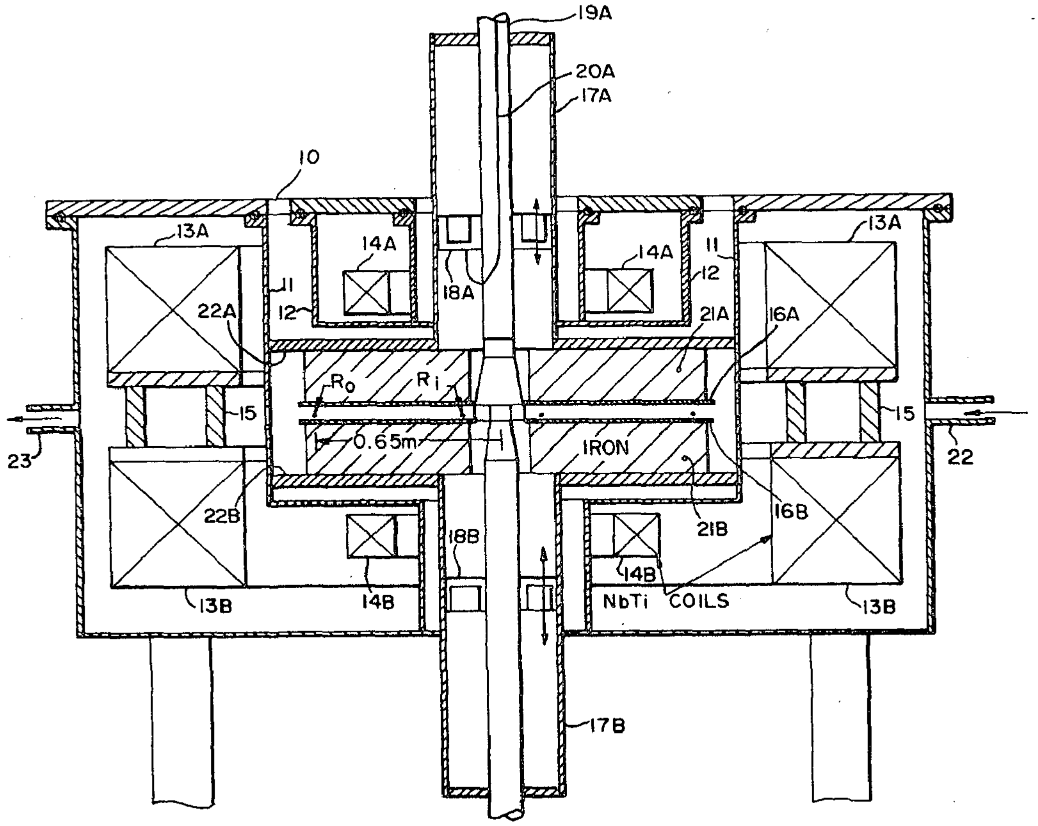
Attorney, Agent, or Firm—James R. Hughes

[57] **ABSTRACT**

Isochronous cyclotron using an air core superconducting magnet to provide high intensity magnetic fields. To provide an axial focussing field, iron sectors with spiral edges acting as flutter poles positioned in the magnetic field such that saturation of the iron in the sectors gives an increased field between the sectors and a slightly decreased field outside.

7 Claims, 8 Drawing Figures



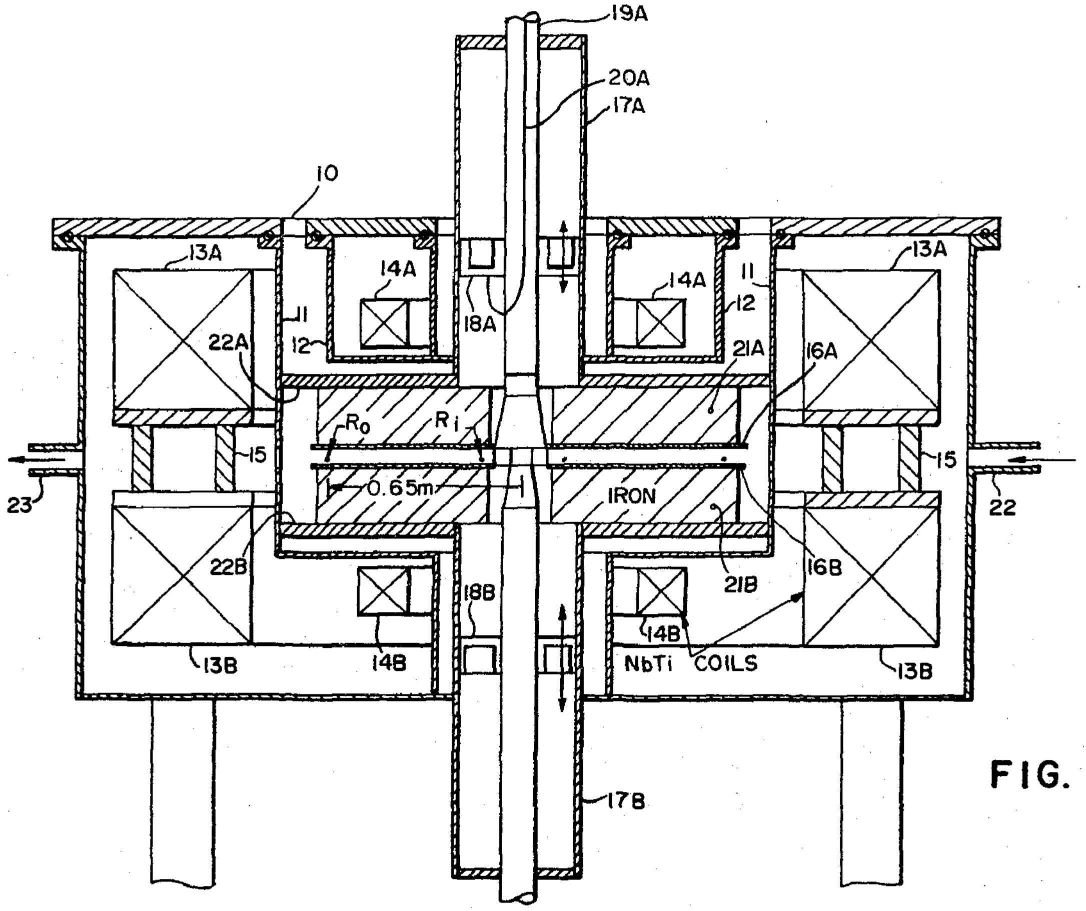

19A
20A
17A
10
13A
14A
14A
13A
11
12
11
12
18A
22A
21A
16A
R_o
R_i
15
15
23
0.65m
IRON
22
22B
21B
16B
18B
14B
14B
NbTi
COILS
13B
13B
17B

FIG. 1

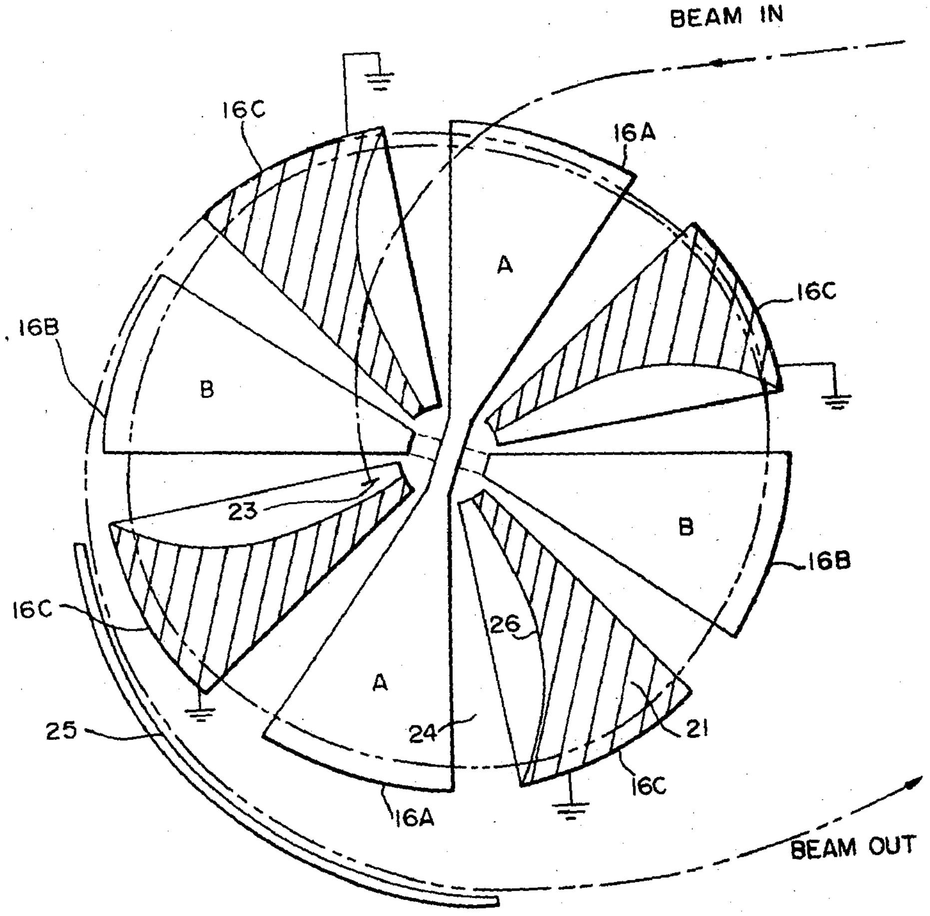

BEAM IN
16C
16A
A
16C
16B
B
23
B
16B
16C
26
A
25
24
21
16C
16A
BEAM OUT

FIG. 2

O OR π - MODE ACCELERATION

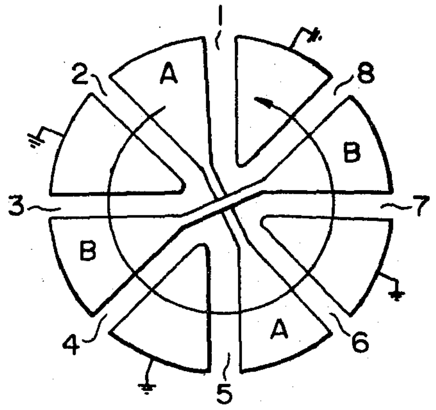


FIG. 3A

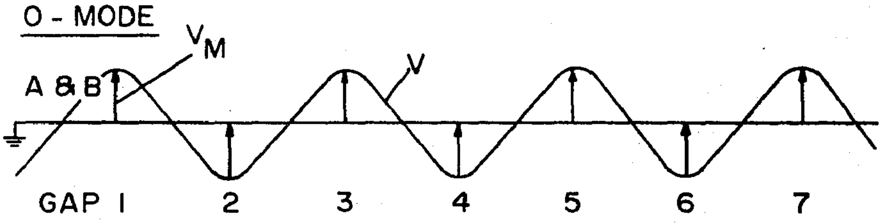


FIG. 3B

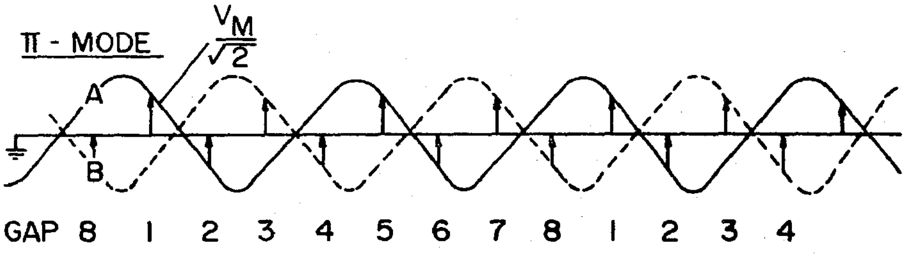


FIG. 3C

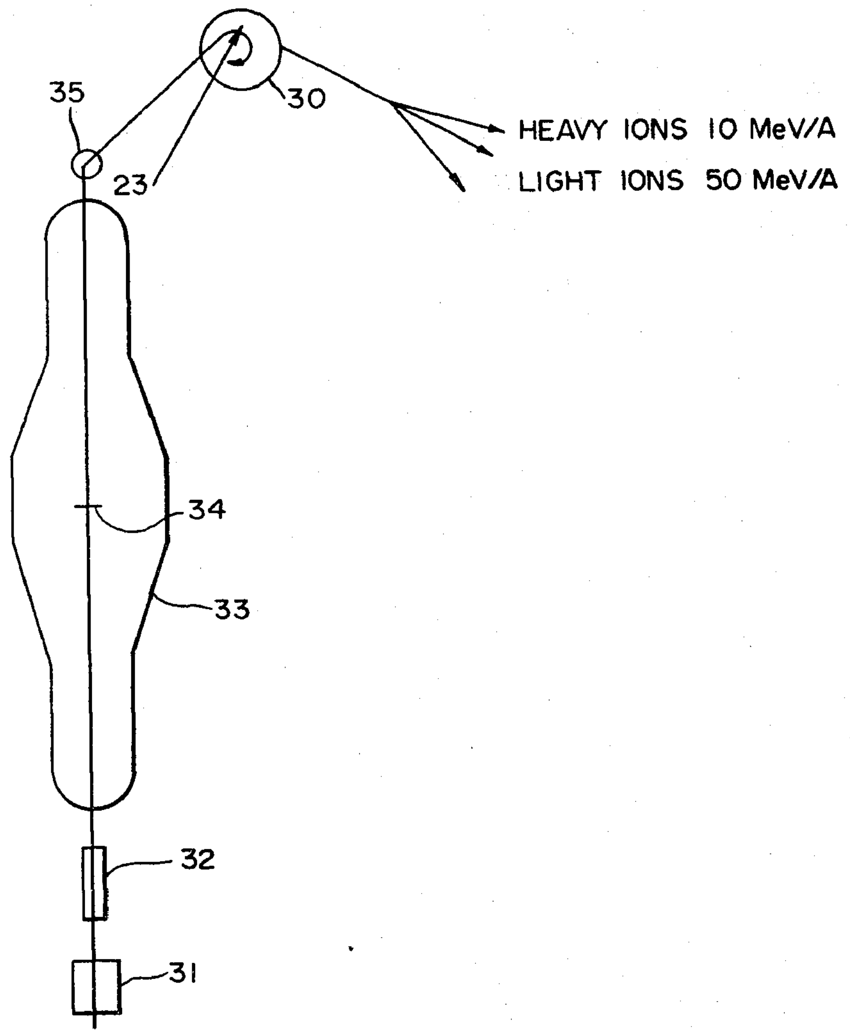


FIG. 4

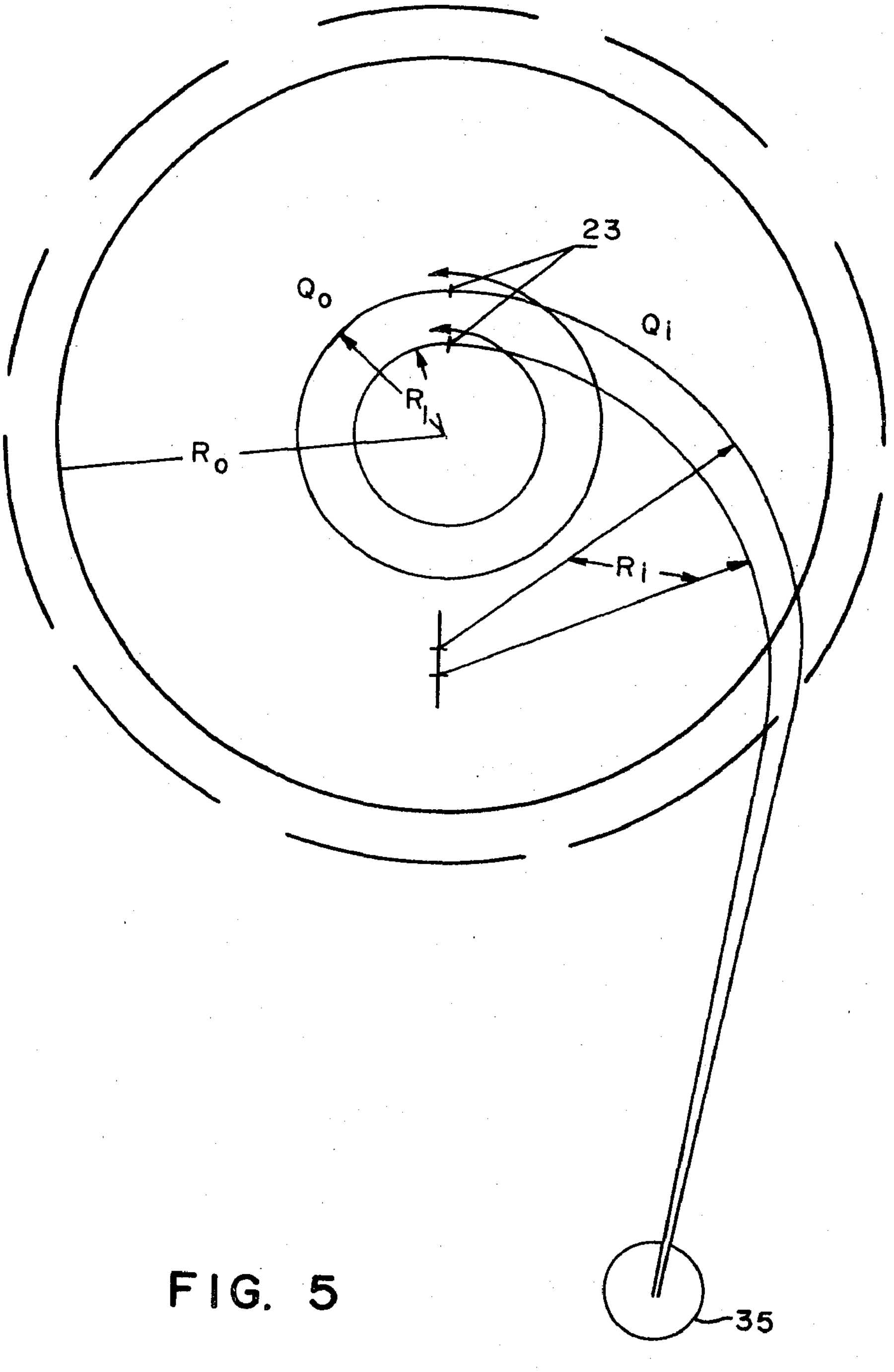


FIG. 5

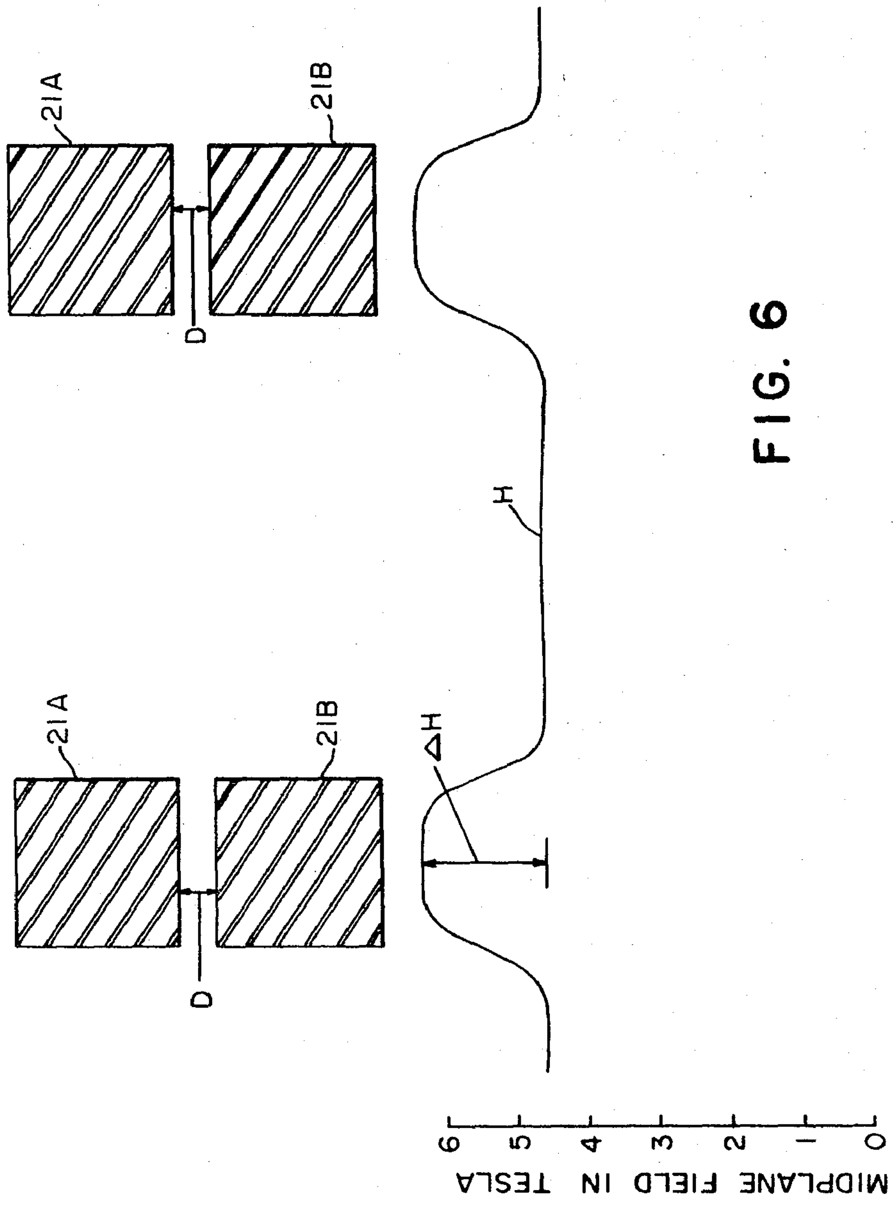


FIG. 6

SUPERCONDUCTING CYCLOTRON

This invention relates to an isochronous cyclotron and more particularly to a cyclotron for producing beams of heavy or light ions in which the magnetic field for orbiting the ions is produced by superconducting coils.

One of the disadvantages of the cyclotron has been the great size and weight of the large radius iron pole pieces required to produce high energy ions with the magnetic field strength limited to less than the 2.2 Tesla saturation value for iron. Another complication arises when the ion velocities approach the speed of light, and relativistic effects become important. Then the ion velocity is no longer constant and ion arrival at the accelerating gaps would not be at the proper phase. This can be corrected for by making the magnetic induction nonuniform in the radial direction but at the expense of introducing axial defocussing forces. These are overcome in present isochronous cyclotron designs with axial focussing provided by shaped sectors (hill and dale structures) built on or forming part of the magnetic pole faces such that axial flutter focussing is achieved.

It is an object of the present invention to provide an isochronous heavy and light ion cyclotron of small size but giving high energies.

This and other objects of the invention are achieved by a cyclotron using an air core superconducting magnet system to provide high intensity magnetic fields. To provide an axial focussing field, iron sectors with spiral edges acting as flutter poles positioned in the magnetic field such that saturation of the iron in the sectors gives an increased field between the sectors and a slightly decreased field outside.

In drawings which illustrate an embodiment of the invention,

FIG. 1 is a cross-section of a cyclotron structure with superconducting coils,

FIG. 2 is a plan view of the sectors,

FIGS. 3A, 3B, 3C illustrate modes of operation of the rf accelerating structure.

FIG. 4 is a schematic of the proposed cyclotron and a tandem accelerator supply,

FIG. 5 is a schematic of an injection system, and

FIG. 6 is a graphical representation of the magnetic field.

Referring to FIG. **1**, a superconducting cyclotron is contained in a vacuum tight enclosure **10** containing cryostat tanks **11** and **12** which contain superconducting main coils **13***a*, **13***b*, and **14***a*, **14***b*. Because of the large magnetic attraction between them, the large coils **13***a* and **13***b* require a fairly strong separating structure **15** positioned between them. The design of these coils which is well within the scope of present superconducting magnet technology provides a magnetic field about three times that of an iron core structure of comparable size. This results in a much smaller overall size and reductions in space and containment requirement. The accelerating structure is made up of eight upper and lower conducting sectors (shown in plan view in FIG. 2) and shown in cross-section as **16***a*, **16***b*. These are positioned centrally in the air core region and define the orbital gap between them with R_i being the inner ion orbit radius and R_o being the outer. There are four "hot" sectors and four grounded sectors. The hot sectors are connected alternately to quarter wave resonators **17***a*, **17***b* containing movable tuning shorts **18***a*, **18***b*. Energy is provided via a coaxial line **19***a* having a center conductor **20***a* which is connected to the tuning shorts. The RF power supply (not shown) is generally conventional and in a typical design would provide 60 kw at 22–45 MHz. The four upper and lower grounded sectors **16***c* (see FIG. **2**) contain iron flutter pole pieces shown in cross section as **21***a* and **21***b* in FIG. **1**.

To maintain a constant orbital angular velocity for the ions during acceleration (isochronism) a magnetic field which increases with radius according to the relation,

$$<B(R)> = \gamma\ (R)B_c$$

is required.

$<B(R)>$ is the average midplane field at radius R

$\gamma(R)$ is the relativistic factor related to the ion kinetic energy T and rest energy E_o by,

$$\gamma(R) = 1\ [T(R)/E_o]$$

B_c is constant.

A magnetic field with a maximum azimuthally average value of $5T$ (50,000 G) and a shape matching $B(R)$ to within ± 0.1% is generated by the superconducting coils. Normal trim coils **22***a*, **22***b* provide the necessary adjustment for isochronism. The cyclotron is connected to an input ion beam source at **22** and provision is made at **23** for extraction of the accelerated beam.

Referring more particularly to FIG. **2**, the input beam is introduced tangentially and on the midplane to orbit inwardly to strike stripper foil **23** suitably mounted on a moveable carriage (not shown) for positioning purposes. The ion energy and charge state on injection are chosen so that the most probable charge state after stripping is approximately four times the initial charge state. With suitable positioning of the stripper foil and adjustment of the source accelerator (tandem Van de Graaf generator) voltage, ions from Li^1 to U^8 can be injected into the cyclotron. After passing the stripper foil the ions orbit outwardly (approximately 100 turns) from an inner orbit R_i to an outer orbit R_o being accelerated in the eight accelerating gaps **24** between the sector pairs. The beam is extracted by electrostatic deflectors **25** positioned at the orbit periphery. The four flutter pole sector pairs **21** are conveniently mounted in the grounded sectors **16**c and are completely encased in conducting metal to shield the magnetic material (iron) from the *RF*. The sectors have spiral edges **26** as shown to obtain sufficient focussing.

Referring to FIGS. **3**A, **3**B, and **3**C it will be seen that the device described in FIGS. **1** and **2** has two resonances and can be used in two modes, i.e., a **0**-mode where the upper and lower resonator plates or sectors in each pair (A and B) are in phase and a π-mode when the upper and lower plates are out of phase or in "push-pull." In the π-mode the ion velocity at extraction is twice that in the **0**-mode as seen from FIGS. **3**B and **3**C. In the π-mode, the accelerating voltage at the gaps is $V_m/\ \sqrt{2}$ compared to V_m for the **0**-mode because of the operation mode and therefore about twice the *RF* power is required.

FIG. **4** shows a typical arrangement with the cyclotron **30** being supplied from a negative ion source **31**, a double drift harmonic buncher **32** for bunching the DC beam to a narrow phase width and a tandem accelerator **33** (with gas or foil stripper **34**) for pre-accelerating the beam. An analyzing magnet **35** directs the ion beam with desired charge state to the foil stripper **23** in the cyclotron. The output of the cyclotron is a heavy ion beam up to 10MeV/A or a light ion beam up to 50MeV/A. FIG. **5** shows the mid-plane injection geometry in more detail. Stripper foil **23** has to be correctly positioned for each particular type of ion used.

Radial focussing of the beam results from the radially increasing field required for isochronism while vertical (or axial) focussing is achieved with an azimuthally varying field. The latter is produced by the iron sectors (flutter poles) mounted above and below the mid-plane. The radial and axial frequencies expressed as fractions of the cyclotron frequency are measures of the focussing forces, and are given by the following approximate relations

$$\nu_x{}^2 = 1 + k$$

$$\nu_z{}^2 = -k + (N^2/N^2-1\cdot)\, f(1+2\tan^2\epsilon)$$

k is the average field index,

$$k = (d<B>/<B>)/(dR/R)$$

N is the number of sectors

F is the flutter factor, $F = (<B^2>/<B>^2) - 1$

and

ϵ is the flutter pole spiral angle.

In the magnetic fields considered, i.e., $\gtrsim$ 2 Tesla, the iron flutter poles will except for small edge effects, be uniformly magnetized with a magnetization equal to the saturation value M_s ($M_s \cong (2/4\pi) \times 10^7$ Ampere turns/m for iron.)

As seen in FIG. **6**, the magnetic field of the magnetized iron poles **21***a*, **21***b* is superimposd on the coil field H, resulting in an increased field ΔH between the poles and a slightly decreased field outside. The magnitude of the increase depends on the gap d between the poles. In the limit of a very small gap the field increase is equal to M_s. For a reasonable gap size such as that illustrated in FIG. **1**, the increase in approximately 0.75 M_s or 1.5 T in the case of iron. For the four sector geometry shown in FIG. **2**, F ranges from ≈ 0.015 at $<B> = 5T$ to ≈ 0.06 at $<B> = 3T$. Axial focussing should be adequate if $\nu_z > 0.1$, with a pole shape similar to that shown in FIG. **2**, this is the case for ion energies up to 10 MeV/A at $<B> = 5T$ and up to 50 MeV/A at $<B> = 3T$.

A typical design for the main superconducting magnet would be as follows. The superconducting coils are constructed of **76** pancake windings each with 130 turns of 1,000 A conductor. The superconducting NbTi is in the form of fine filaments embedded in copper and twisted for stabilization against eddy currents. Sufficient copper conductor and cooling surface is allowed for complete cryostatic stabilization. This means that the coil could recover from any possible thermal transient. A stainless steel ribbon is wound in with the conductor to keep the hoop stress below the yield point. The axial force is substantial so that a strong support is required between the coils. The field in the coil is well below the critical value for NbTi. The current density is in the range that has been used in some existing large magnets.

The following are representation mechanical and electrical design parameters:

MECHANICAL	
Inside diameter	1.84 metres
Cross Section (Square)	0.46 metres
Spacing	0.325 metres
Turns (both)	9880
Weight (both)	17.25 tonnes (1 tonne = 1000 Kg)
Average Hoop Stress	7250 psi
Axial force	3400 tonnes
ELECTRICAL	
Maximum Midplane Field	5 Tesla
Maximum field at conductor	6.2 Tesla
Conductor Current	1000 A
Overall Current Density	2360/cm²
Charging Time at 10 Volts (0-5T)	3.5 hours
Stored Energy	64 M Joules

The cyclotron specifically described above is illustrated only; various changes and reaarangements could be made, e.g., the cyclotron could accomodate an ion source located internally. This might require a change in the design and construction of the RF structure but this should present no great difficulty. Extraction of the beam is achieved by initial deflections with electrostatic deflectors in adjacent grounded sectors. These deflections bring the beam out over the edge of the magnetic field where the orbit radius increases and the beam spirals out. Other extraction methods are possible.

We claim:

1. An isochronous cyclotron for heavy or light ions comprising:

a. a superconducting coil system for producing a strong magnetic field in the air core centrally of the coils,

b. an even number of pairs, at least four in number, of generally flat sectoral conducting plates, alternate pairs of which are at low or ground potential and the other pairs are connected to an RF voltage supply, mounted on tunable quarter wavelength resonator structures and defining an annular orbital region between the plates in the pairs and ion accelerating gaps between the edges of the pairs of plates and positioned in and generally orthogonal to the magnetic field in the central air core region,

c. means for energizing said plates with an RF voltage such that orbiting ions will be accelerated between the gaps,

d. means for injecting the ions to be accelerated into an inner position in the orbital region,

e. means for extracting the accelerated ions at an orbit location adjacent the periphery of the orbital region, and

f. means for varying the magnetic field in the radial direction to provide radial focussing of the orbiting ion beam.

2. An isochronous cyclotron for heavy or light ions comprising:

a. a superconducting coil system for producing a strong magnetic field in the air core centrally of the coils,

b. an even number of pairs, at least four in number, of generally flat sectoral conducting plates, alternate pair of which are at low or ground potential and the other pairs are connected to an RF voltage supply, defining an annular orbital region between the plates in the pairs and ion accelerating gaps between the edges of the pairs of plates and positioned in and generally orthogonal to the magnetic field in the central air core region, wherein the pairs of sectoral plates at ground or low voltage have associated and mounted adjacent to them pairs of shaped ferrous material structures, said pairs of structures being positioned in the magnetic field and as opposing pairs on each side of the orbital region such as to become saturated in the magnetic field and increase the magnetic field between them and thus providing a flutter pole axial focussing effect to the orbiting ions,

c. means for energizing said plates with an RF voltage such that orbiting ions will be accelerated between the gaps,

d. means for injecting the ions to be accelerated into an inner position in the orbital region,

e. means for extracting the accelerated ions at an orbit location adjacent the periphery of the orbital region, and

f. means for varying the magnetic field in the radial direction to provide radial focussing of the orbiting ion beam.

3. An isochronous cyclotron for heavy or light ions comprising:

a. a superconducting coil system for producing a strong magnetic field in the air core centrally of the coils,

b. eight pairs of generally flat sectoral conducting plates defining an annular ion orbital region between the opposing plates in the pairs and ions accelerating gaps between the edges of the pairs of plates and position in a ring and generally orthogonal to the magnetic field in the central air core region,

c. means for energizing said plates with an RF voltage such that orbiting ions will be accelerated between the gaps,

d. means for injecting the ions to be accelerated into an inner position in the orbital region,

e. means for extracting the accelerated ions at an orbit location adjacent the periphery of the orbital region,

f. trim coils mounted above and below the beam orbiting region to adjust the magnetic field shape in the air core region and provide an accurately isochronous radial profile, and

g. four pairs of shaped ferrous material structures positioned in the magnetic field in the air core region and as a ring of opposing pairs on each side of the orbital region such as to become saturated in the magnetic field and increase the magnetic field between structures in the pairs and thus providing an axial focussing effect to the orbiting ions.

4. An isochronous cyclotron as in claim **3** wherein the coil arrangement is made up of a first pair of superconducting coil firmly mounted in spaced axial relation and a second pair of superconducting coils of smaller cross-section and diameter mounted radially inward of the first pair.

5. An isochronous cyclotron as in claim **3** wherein the ferrous material is an iron containing metal.

6. An isochronous cyclotron as in claim **3** wherein four alternate pairs of the sectoral plates are connected

via tunable quarter-wave resonators to the RF supply and the interleaved remaining four pairs of plates are connected to ground or low potential and have the four pairs of shaped ferrous material structures positioned adjacent to their surfaces away from the orbital region.

7. An isochronous cyclotron for heavy or light ions comprising:

a. a first pair of superconducting coils firmly mounted in spaced axial relation,

b. a second pair of superconducting coils of smaller cross-section and diameter mounted radially inward of the first pair, said first and second pairs of coils capable of producing a strong unidirectional magnetic field in the air core region centrally of the coils,

c. eight pairs of generally flat sectoral conducting plates defining an annular ion orbital region between the opposing plates in the pairs and ion accelerating gaps between adjacent edges of the pairs of plates and positioned in a ring in and generally orthogonal to the magnetic field in the central air core region,

d. two tunable quarter-wave resonators electrically connected to an RF power supply and to four alternate pairs of said plates such that orbiting ions between the plates will be accelerated between the gaps, said resonators being turned to either the **0**-mode or π-mode resonance either in phase of 180° out of phase to provide two accelerating modes of operation,

e. means for injecting the ions to be accelerated into an inner position in the orbital region, said means including a stripper foil for changing the charge state on incoming ions,

f. means for extracting accelerated ions at an orbit location adjacent the periphery of the orbital region, said means including capacitor plates carrying a potential such as to deflect the ion beam outwardly from the orbit region,

g. trim coils mounted above and below the beam space to adjust the magnetic field in the radial sense to provide an accurately isochronous radial field variation,

h. four pairs of shaped ferrous material structures positioned in the magnetic field in the air core region and as a ring of opposing pairs on each side of the orbital region such as to be magnetically saturable in the magnetic field and provide a fixed increase in the magnetic field between structures in the pairs and thus an axial focussing effect to the orbiting ions,

i. each of said structures being positioned adjacent to each plate of the remaining alternate pairs of said sectoral plates, said plates being connected to ground or low potential,

j. each of said structures being enclosed in conducting material to shield them from RF effects and having at least one spiral shaped edge, said spiral shape being predetermined for optimum axial focussing.

* * * * *