NOTES ON THE HARWELL VARIABLE ENERGY CYCLOTRON

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1. USES.

(a) Radiation Chemistry (Chemical effects of radiation)

(b) Radio Chemistry (Chemistry of radioactive materials:

(i) Study of fission reactions
(ii) Preparation of special isotopes)

(c) Radiation damage (p, d, α simulate fast neutrons; heavy ions simulate fission fragments; effects can be observed more quickly than in a reactor, better control of energy and direction of particles, more room for better instrumentation and better control of specimen temperature; no restriction on use of neutron-absorbing materials.

Measure electrical resistivity, Hall coefficient, Young's modulus, brittleness.)

(d) Solid state physics

2. PARTICLES AND ENERGIES

Particles	Energy	Internal Beam Current	External Beam Current
Protons	1.25 MeV - 50 MeV	0-1 mA	0-100 µA
Deuterons	2.5 MeV - 25 MeV	0-1 mA	0-100 µA
Alphas	5 MeV - 50 MeV	0-1 mA	0-100 µA
Heavy Ions	Up to 10 MeV per nucleon	Up to several uA depending upon ion	

The magnetic fields and frequencies required for different ions at different energies are given in Memo. P.E.1. Briefly, using C.G.S. units,

$$\frac{mv^2}{r} = Bqv \qquad (1)$$

where m = mass of ion in grams
v = velocity of ion in cms/sec
r = radius of orbit in cms.
B = magnetic field in gauss
q = charge of ion in e.m.u.

Whence K.E. $= \frac{q^2}{2m} . B^2 . r^2$ (2)

$B = 2\pi f . \frac{m}{q}$ (3)

$\frac{K.E.}{m} = 2\pi^2 \; r^2 . f^2$ (4)

(K.E. per nucleon)

Although the beam energy and current are to be variable over wide ranges the width of the energy spectrum and the fluctuations in the beam current (at frequencies below 1 Kc/s) are to be a minimum.

3. ORBIT THEORY

(a) Phase Condition

From (1) $W_p = \frac{Bq}{m}$ where W_p = Angular frequency of particle

For correct phase $W_D = W_p = \frac{Bq}{m}$ (5)

where W_D = angular frequency of dee voltage

(b) Radial Stability

Field Index, n, is defined as

$$n = -\frac{dB}{B} \bigg/ \frac{dr}{r} = - \frac{r}{B} . \frac{dB}{dr} \quad (6)$$

Equation of radial oscillations:

$$\frac{d^2r}{dt^2} + (1-n)\, w_p^2\, r = 0 \quad (7)$$

∴ Radial oscillation angular frequency, $W_r = (1-n)^{\frac{1}{2}} W_p$

Q_r is defined as $\frac{W_r}{W_p}$.

$$∴ \; Qr = \frac{Wr}{Wp} = (1-n)^{\frac{1}{2}} \quad (8)$$

For stability (S.H.M.) $1-n > 0$ (9)

∴ $n < 1$

(c) Vertical Stability with flat polepieces

Equation of vertical oscillations:

$$\frac{d^2z}{dt^2} + n . W^2p . z = 0 \quad (10)$$

∴ Vertical oscillation angular frequency, $Wz = n^{\frac{1}{2}} Wp$ (11)

Q_z is defined as $\frac{W_z}{W_p}$

$$\therefore Q_z = \frac{W_z}{W_p} = n^{\frac{1}{2}} \qquad (11)$$

For stability (S.H.M.), $n > 0$ (12)

i.e. from (6) the average field decreases with radius, but this is contrary to the correct phase condition (5) when m increases relativistically.

Combining (9) and (12) $0 < n < 1$ (13)

(d) Vertical stability with radial ridges

Vertical focusing is due to the interaction of the radial component of the particle velocity with the tangential component of the magnetic field (Thomas force). Focussing occurs at both edges of the ridges.

The flutter, f, is defined as $\left(B_{max.} - B_{mean}\right)/B_{mean}$ (14)

Equation of vertical oscillations:

$$\frac{d^2 z}{dt^2} + (n + \tfrac{1}{2} f^2) W_p^2 z = 0 \qquad (15)$$

$$Q_z = \frac{W_z}{W_p} = (n + \tfrac{1}{2} f^2)^{\frac{1}{2}} \qquad (16)$$

For stability (S.H.M.), $n + \frac{1}{2} f^2 > 0$

$$\therefore -\tfrac{1}{2} f^2 < n \qquad (17)$$

i.e. n can be negative and average field can increase with radius.

(e) Vertical stability with spiral ridges

Vertical focussing is due to the interaction of the radial component of the magnetic field with the tangential component of the particle velocity (Kerst force). Focussing occurs at one edge of each ridge and defocussing at the other edge; the overall effect is, however, always focussing since the particles are further from the median plane at the focussing edge than at the defocussing edge. In addition there is an equal net focussing force (Laslett force), which doubles the effect, since the non-circular shape of the orbit causes the particles to spend a longer time in the focussing field than in the defocussing field.

The spiral ridge angle γ is defined as the angle between the tangent to the ridge boundary and a radial line.

Equation of vertical oscillations:

$$\frac{d^2z}{dt^2} + \left[n + \tfrac{1}{2} f^2 (1 + 2 \tan^2\gamma)\right] W^2 p z = 0 \qquad (18)$$

$$Qz = \frac{Wz}{W_p} = \left[n + \tfrac{1}{2} f^2 (1 + 2 \tan^2\gamma)\right]^{\frac{1}{2}} \qquad (19)$$

For stability $-\tfrac{1}{2} f^2 (1 + 2 \tan^2\gamma) < n$ (20)

i.e. n can be even more negative and magnetic field can increase with radius even more. Typically $\gamma = 45^\circ$ and the vertical focussing with spiral ridges is three times that with radial ridges for the same flutter.

4. MAGNET

Max. field	:	17 kilogauss (approx.)
Pole diameter	:	70 inches
Pole gap	:	17 inches
Number of ridges	:	3
Thickness of ridges	:	4.75 inches
Gap between ridges	:	7.5 inches
Total weight	:	200 tons (approx.)

Power in Main Coils	:	300 kW (77 volt M.G. Set, Stability 1 in 10^4)
No. of Orbit Coils	:	12 pairs
Total pwer in Orbit Coils	:	460 kW (12 415 volt rectifier sets, stability ± 3 Amps)
No. of Valley Coils	:	3 per valley.
Total pwer in Valley Coils	:	25 kW (9 415 volts rectifier sets, stability ± 1 Amp).

5. RADIOFREQUENCY EQUIPMENT

(a) Dee

Internal diameter	=	67 inches
Internal depth	=	2 inches
Heat dissipated at 22 M/cs.	=	20 kW
Peak working voltage	=	100 kV

(b) Transition Section

Heat dissipated at 22 Mc/s = 54 kW

(c) Coaxial Line

Frequency range	=	7.2 Mc/s - 23.5 Mc/s
Heat dissipated at 22 Mc/s	=	14 kW
Length of travel of "short"	=	12ft. 6 ins.
Positional accuracy	=	± 50 thou.

(d) Transmitter

Frequency range	:	6-26 Mc/s
Frequency stability	:	1 in 10^7
Power output	:	250 kW

6. ION SOURCE No.1.(P.I.G. TYPE)

Gases	:	H_2, He, N_2, O_2, Ne.
Flow rate	:	10 cc/min. max.
Radial position	:	0-2.75 ins.
Angular position	:	0° to 30°
Filament	:	400 Amps at 10 volts
Arc	:	20 Amps at 2 kV.

7. EXTRACTOR

Extraction radius	:	29.6 ins - 32.6 ins.
Length of first channel	:	48°
Length of second "	:	56°
Max. voltage on either channel	:	-100 kV.
Stability of power supply	:	1 in 10^3

8. PROBES

See Cyclotron Parameter Note 500/47/018.

Angle to Centre Line	Probe	Radial Movement	Clearance to Vault Wall
63°	Beam Probe No. 2.	0-30 ins.	5ft.4 ins.
176.5°	Defining Post	0- 6 ins.	5ft.0 ins.
180°	Puller	± 2 ins.	6ft.9 ins.
183.5°	Beam Probe No.1.	0-30 ins.	
303°	Beam Probe No.3. or Phase Probe	0-30 ins.	5ft.6 ins.
315°	Users Probe		6ft. 6 ins.

The puller has an additional lateral movement of 3 ins. The beam probes can dissipate up to 5 kW. The trackways for beam probes Nos. 2 and 3 are designed to enable the outer portion of the track to hinge upwards into the vertical position after inserting the probe in the machine. This gives the maximum clearance round the machine. The probes can be moved radially 0-30 ins. with the hinged portions in the vertical position. The hinged portions are only required to be lowered to withdraw the probes from the machine.

9. BEAM HANDLING EQUIPMENT

(a) Bending Magnet

Angle of bend	:	75°
Mean field	:	14 kilogauss
Power dissipated	:	50 kW
Temperature rise	:	17° C
Power supply	:	500 Amps. at 100 volts (M.G.Set)
Stability of power supply	:	1 in 10^{4}
Total weight	:	20 tons. approx.

(b) Switching Magnet

Angle of Bend	:	$0 \pm 19\frac{1}{2}^{\circ}, \pm 53\frac{1}{2}^{\circ} \pm 73^{\circ}$
Max. field	:	14 kilogauss
Max. power dissipated	:	50 kW
Max. temperature rise	:	17° C.
Power Supply	:	0-500 Amps. @ 100 volts (M.G.Set)
Stability of power supply	:	1 in 10^{4}
Total weight	:	20 tons approx.

10. VACUUM EQUIPMENT

(a) Cyclotron Tank The layout is shown in Drawing DR 50030-001.
Ultimate pressure = 10^{-6} torr.
Two Leybold pumps on tank each with a pumping speed, when baffled, of 20,000 litres/sec. One 24 inch Edwards pump on R.F. line with a pumping speed, when baffled, of 5,000 litres/sec. All baffles cooled with chilled water ($0^{\circ}C - 5^{\circ}C$).

(b) Beam Handling Equipment
Ultimate pressure varies as follows:

Cyclotron Tank	10^{-6} torr
Bending Magnet	1.1×10^{-5} torr.
Switching Magnet	0.9×10^{-5} torr.
Shielding Plug	3×10^{-5} torr.

One Edwards 9 inch pump with a chilled water baffle is connected to the switching magnet manifold through a channel with a minimum conductance of 800 litres/sec.

11. WATER CIRCUITS

The layout is shown in drawing ER 50073-001. Demineralised water is used throughout.

(a) Primary Circuits

From the 2 Megawatt cooling tower there are five primary circuits.

(i) Heat exchanger for machine

(ii) HEat exchanger for R.F. resonator in vault (temperature $85^{\circ}F \pm 5^{\circ}F$)

(iii) Heat exchanger for Users' Hot Laboratory

(iv) Vacuum pumps (diffusion and Kinney), RF plant room, electrical plant room. (On account of activity from the diffusion pumps in the vault this water is returned to the pond.)

(v) Air-conditioning condenser.

(b) Secondary Circuits

Entrained air removed by header tank. Dissolved oxygen removed by nitrogen blanket over header tank. Filters to remove particles greater than 3 thou.

(i) Pressure 300 p.s.i. Metallic ions removed by ion exchanger column in deflector cooling circuit which requires lowest conductivity.

Provision is made for flow as follows:-

Item	Power (kW)	Flow (g.p.m.)
Magnet		
Main Coils	300	52
Orbit Coils	300	20
Valley Coils	25	2
Ion Source	150	24
Deflector	50	12
Magnetic Channel	200	32
Probes	50	30
Beam Handling		
Bending Magnet	50	11
Switching Magnet	50	11
Squeeze Coil	10	2
Quadrupoles and beam measuring equipment	90	20

(ii) Pressure 60 p.s.i. R.F. resonator, 200 kW, 150 g.p.m.

12. BUILDING LAYOUT

This is shown in Drawing No. DR 50000-025

13th January, 1964.