Design and performance of a compact multi-particle cyclotron

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ABSTRACT

Two compact cyclotrons have been constructed and are now being used for routine production of short-lived isotopes at medical research centres. A third of these cyclotrons, as well as two slightly larger ones, are currently being manufactured in Berkeley, California. The measured external beam of the CS–15 and CS–22 cyclotrons are shown in the following table:

	CS–15	*CS–22*
Energy		
Proton	15·0 MeV	22·3 MeV
Deuteron	8·0 MeV	12·3 MeV
^{3}He	21·0 MeV	33·0 MeV
Intensity:		
Proton	100 μA	70 μA
Deuteron	200 μA	90 μA
^{3}He	95 μA	80 μA
Resolution:	$\Delta E/E = 0{\cdot}0025$	$\Delta E/E = 0{\cdot}0025$
Emittance:		
Horizontal	20 mm mrad	30 mm mrad
Vertical	15 mm mrad	20 mm mrad

Both the CS–15 and CS–22 use two-dee fundamental acceleration with three-fold magnet symmetry. A small spiral angle is used. Unique design features include a folded rf system to conserve space, copper-plated pole tips and hill iron to eliminate the rf liner, a small cold cathode P.I.G. ion source capable of generating intense ion beams, dee voltage regulation, rf stabilisation, and a focusing magnetic channel, which provides a small spot size at the beam exit port. The design parameters and performance of these cyclotrons are discussed in this paper.

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1. INTRODUCTION

The increasing use of cyclotrons to produce isotopes and fast neutrons in activation analysis and for physics research has led to the design and manufacture of both a 15 MeV and 22 MeV proton isochronous cyclotron. These cyclotrons, which also accelerate deuterons and ^{3}He and ^{4}He particles, can be maintained and operated by one or two technicians. The first of these machines has been routinely producing radioisotopes at Sloan-Kettering Institute for Cancer Research in New York City since October 1967.

The major design considerations for our compact cyclotron were low cost, ease of operation and maintenance, and high external beam currents for isotope and neutron production. A two-dee, three-sector, isochronous cyclotron operating in the fundamental mode appeared to best satisfy these requirements. This design allows relatively high energy gain per turn with reasonable dee voltages, and the fundamental operation also permits acceleration farther into the fringe field without excessive phase loss, which facilitated the design and

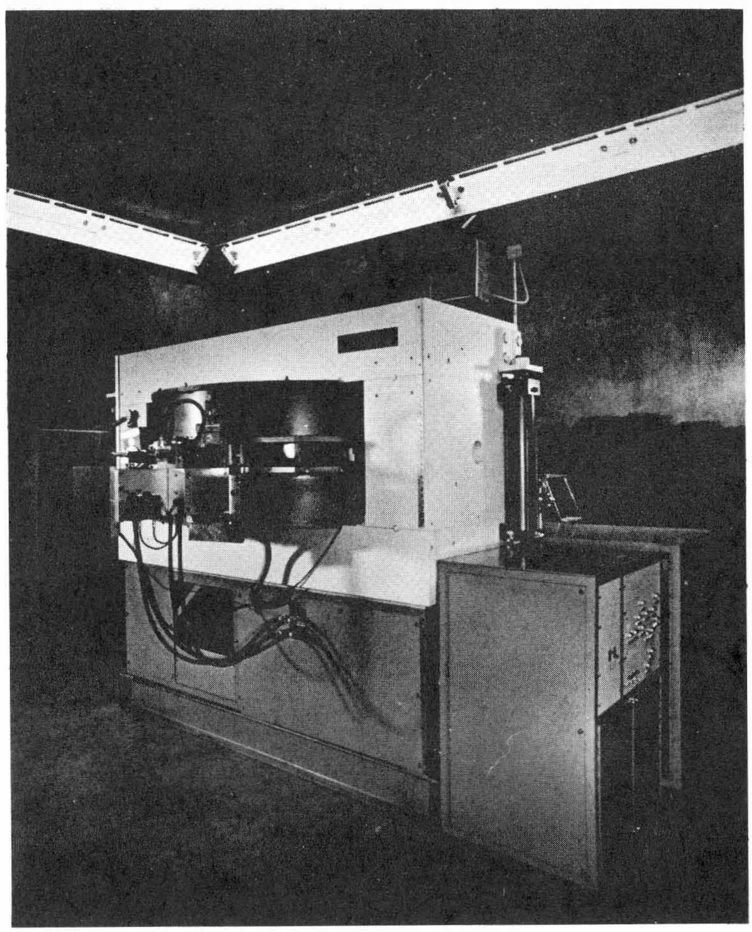

Fig. 1. CS-15 cyclotron

adjustment of the precessional extraction system. The three-sector geometry provides early vertical focusing and, in our case, has simplified the extractor design. The resulting cyclotron has proved to be rugged, easy to operate, and reliable in producing external beams in excess of 50 μA. The extraction efficiency is well over 50% for all particles.

The following is a discussion of the major features of our CS-22 cyclotron. Our smaller Model CS-15 which is shown in Fig. 1 is very similar.

2. MAGNET

The CS-22 magnet parameters are summarised in Table 1. The magnet, with the exception of the pole tips and hills, is fabricated from hot rolled plate. The pole

Table 1. CS-22 MAGNET PARAMETERS

Pole diam.	38·0 in
Return yoke area/pole area	1·0
Outside hill diam.	36·0 in
Valley gap	4·0 in
Hill gap (min)	2·0 in
Flutter squared (max)	0·042
Spiral angle (max)	36°
Vertical tune (ν_z) (min)	0·13
Turnover point of $B_{ave.}$	15·5 in

tip plates and hills are made of upset forgings. Both the flare and the thickness of the three spiral hills are cut to provide the profile required for 22 MeV protons and suitable profiles for deuterons and ^{3}He are obtained by increasing the magnet excitation. There has been no difficulty in accelerating protons, deuterons, and ^{3}He to maximum energy without the aid of radial profile coils.

Magnetic measurements are made on each cyclotron in order to check the radial profile and harmonic content of the magnetic field. These measurements are made on a polar grid and are processed by a series of computer programs based on the Oak Ridge orbit code.[1] We also use a simple program based on the Smith-Garren[2] equations for most of our magnetic field design. This saves considerable computer time.

The magnet is excited by four strip-wound coils, each coil having 250 turns of 0·040 in by 2·5 in copper. Mylar insulation is included between each turn and the coils are edge cooled. The temperature rise of the copper, determined by relative resistance measurements, is ~22°C for 180 A excitation current. The coils are insulated from a water cooling manifold by a thin layer of glass cloth cast in epoxy.

About 150 000 A turns are required to produce a central field of 16·4 kG. This corresponds to a magnet efficiency of 70%. The efficiency varies slightly from magnet to magnet, a fact which is not completely understood at this time.

3. RF SYSTEM

The principal rf system parameters are summarised in Table 2. The resonant structure is a simple half wave line terminated at either end by the dees.[3] The dee

Table 2. RF SYSTEM PARAMETERS

Dee voltage–Maximum	40 kV
Operating	25–30 kV
Dee angle–CS-22	90°
CS-15	120°
Maximum frequency	26 MHz
Minimum frequency	12 MHz
Minimum clearance to ground	0·5 in
Minimum beam aperture	0·8 in
Oscillator tube–CS-22 (40 kW)	6426
CS-15 (20 kW)	6424
Total d.c. power available–CS-22	75 kW
CS-15	40 kW
Oscillator efficiency	≈70%

stems pass out of the vacuum through vacuum-tight support insulators. The frequency is adjusted by varying the length and impedance of a link external to the vacuum tank which connects the dee stems. The entire dee structure is biased about 1000 volts negative to prevent multipacting.[4] This bias is introduced at the external voltage node on the resonant structure.

The hills and the pole tip plate are copper plated and serve as an rf liner. This allows maximum gap under the portion of the dees over a valley, which minimises dee capacity. The angular rotation of the hills is determined by the requirement that there be equal capacity for each dee.

The oscillator is a grounded grid triode which has both the anode and the cathode circuit coupled directly to the main resonant system.[5] This circuit, which was suggested by K. R. Mackenzie, has proved quite stable and easy to adjust. The anode and cathode coupling is controlled by variable vacuum capacitors which terminate both the anode and cathode coupling lines.

The dees are fabricated by the Roll Bond process by which water cooling passages are formed in the dees. This technique allows good water cooling for the dee surface with a minimum of space consumed for the dee skin.

The anode power supply incorporates a 12-phase rectifier followed by a series pass tube which serves as a voltage control device and as a fast crowbar. The rf dee voltage is fed back, compared to a reference, and the difference used to drive the pass tube, which thus regulates the dee voltage. Short-term regulation of 0·1% peak to peak has been achieved. The series pass tube is the same tube type as that used by the oscillator.

4. ION SOURCE

A radial cold cathode ion source[6] is used which produces protons, deuterons, doubly ionised ^{3}He and ^{4}He particles. The proton and deuteron beams obtainable from the cyclotron are not ion source limited. The internal ^{3}He and ^{4}He beams are ion source limited to about 250 μA. The ion source has two modes of operation—the cold cathode mode, which is typified by high arc voltage and low arc current; and the thermionic mode in which the cathodes are heated to the point of thermionic emission. The high arc current in the thermionic mode greatly increases ion production, which makes this mode useful for producing intense beams of doubly ionised ^{3}He and ^{4}He. Physically, the ion source anode is about half an inch in diameter and about one inch high. The cathode supports are water cooled as well as the anode support structure. The whole assembly is quite compact, which makes possible a compact central region.

The ion source position is remotely adjustable in the horizontal plane, a feature which has been quite useful in tune-up.

5. BEAM OPTICS

5.1. *Central region*

The central region, which was suggested by Martin Reiser,[7] consists of an angled off-centre puller, electrostatic shields and a central magnetic 'cone' of about 150 G. Electrolytic tank model measurements and detailed central region calculations were not performed. The central region was adjusted to obtain a minimum incoherent radial amplitude in the cyclotron. The incoherent radial amplitude, as determined by shadow probe measurements, is about 1 mm, peak to peak, at the optimum dee voltage and is within 1·5 mm, peak to peak, over a ±10% dee voltage adjustment. Central region slits are not normally used.

5.2. *Acceleration*

The magnetic guide field is isochronous from about 4·5 in to 15·5 in in the CS-22 cyclotron. Over this region, the minimum value of the vertical tune, ν_z, is 0·13. The energy gain per turn is about 100 keV for protons. The magnet is operated slightly above resonance so that the ions lead the rf by as much as 45° at 15·5 in where they start to lose phase. This phase advance was measured using the Garren and Smith[8] technique and agreed quite well with calculations.

5.3. *Extraction*

Precessional extraction is used with the centre of the electric channel placed at $\nu_r = 0{\cdot}8$. The ions are lagging the rf about 45° at this point. The amplitude and phase of the coherent first harmonic on the beam is controlled by a set of

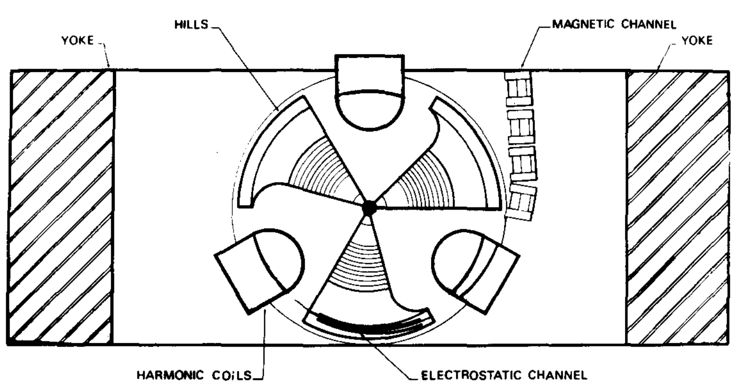

Fig. 2(a). Extraction system plan

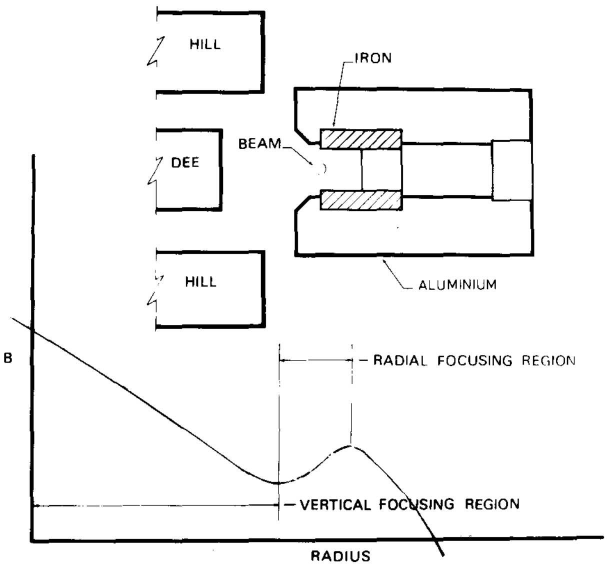

Fig. 2(b). Magnetic channel cross-section

Table 3. SUMMARY OF CS-22 PERFORMANCE

		Rated	*Best observed*
Proton			
Energy		22·0 MeV	22·3 MeV
Intensity	– Internal	1000·0 μA	N.M.
	External	50·0 μA	70·0 μA
Emittance	– Horizontal (100%)	50·0 mm mrad	30·0 mm mrad
	Vertical (100%)	50·0 mm mrad	20·0 mm mrad
$\Delta E/E$		1%	N.M.
$^{3}He + 2$			
Energy		30·0 MeV	33·0 MeV
Intensity	– Internal	100·0 μA	220·0 μA
	External	50·0 μA	80·0 μA
Emittance	– Horizontal	50·0 mm mrad	N.M.
	Vertical	50·0 mm mrad	N.M.
$\Delta E/E$		1%	0·3%
Deuteron			
Energy		11·5 MeV	12·3 MeV
Intensity	– Internal	1000·0 μA	N.M.
	External	50·0 μA	90·0 μA
Emittance	– Horizontal	50·0 mm mrad	N.M.
	Vertical	50·0 mm mrad	N.M.
$\Delta E/E$		1%	0·3%

harmonic coils located at $\nu_r = 1$. The electric extraction channel is a single section 15 in long and the deflector-to-septum spacing is 0·150 in. After leaving the extractor, the beam drifts through a dee and enters the focusing magnetic channel shown in Fig. 2, which reverses the gradient of the fringe field, thus producing radial focusing.[9] The beam obtained at the exit port of the cyclotron is about 1 cm diam. and within 30 mm mrad in both planes.

6. PERFORMANCE

The performance of the CS-22 is summarised in Table 3. Rated performance is that which is easily obtained on a routine basis. The best observed performance is that which was obtained under optimum conditions in our facilities. External beam intensity measurements are made at the end of a 20 ft beam extension which includes a single 2 in quadrupole doublet centred 5 ft from the cyclotron. Emittance measurements were made at the cyclotron exit port with a set of graphite slits followed by a drift space and a glass slide to record the slit pattern. Energy and energy resolution measurements were made at the cyclotron exit port using a cooled silicon detector and a gold scattering foil.

7. CONCLUSION

At the present time, three CS-15 cyclotrons and one CS-22 cyclotron have been completed and two additional CS-22 cyclotrons are under construction. In addition, two negative ion injector cyclotrons have been completed.[10] The negative ion injector cyclotrons (CNI-15) are based on the design outlined above and are used as negative ion injectors to tandem electrostatic accelerators. Below is a list of the cyclotrons we have completed or have under construction:

Model	*Institution*	*Operational since*
CS-15	Sloan-Kettering Institute for Cancer Research New York, N.Y.	8/67
CS-15	Argonne Cancer Research Hospital Chicago, Illinois	8/69
CNI-15	Nuclear Structure Laboratory Duke University Durham, North Carolina	8/68
CNI-15	Lawrence Radiation Laboratory Livermore, California	5/69
CS-15	The Cyclotron Corporation Berkeley, California	8/69

Model	*Institution*	*Operational since*
CS-22	New England Nuclear Corporation Boston, Massachusetts	8/69
CS-22	Mt. Sinai Hospital Miami Beach, Florida	Under Construction
CS-22	The Cyclotron Corporation Berkeley, California	Under Construction

DISCUSSION

Speaker addressed: G. O. Hendry (Cyclotron Corporation)

Question by M A. Chaudhri (MRC, Hammersmith Hospital): The energy resolution figures which you quote in the abstract seem fantastically high so can you please let us know whether this was obtained with the full extracted beam or was it for an analysed beam?
Answer: The beam energy was not measured at high intensity. The figures quoted were for an external beam of 100 nA and were obtained using a gold scattering foil and solid state detector. They represent the energy spread of the total beam, there was no beam analysis.

Question by H. Liesem (A.E.G.): What is the orbit separation for 22 MeV protons at extraction radius when using precessional extraction?
Answer: This is not a separated turn machine. A particular proton gains 0·040 in per turn due to the rf accelerating voltage but this can be increased by precession.

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