

SUPERCONDUCTING CYCLOTRON FACILITY FOR NEUTRON THERAPY

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Abstract

This paper describes a neutron therapy system in which a superconducting, 50 MeV, deuteron cyclotron is mounted directly on an isocentric gantry. Neutrons from an internal beryllium target pass through the collimating system and irradiate tumor regions in a patient lying on an adjustable table at the isocenter axis. Compared to conventional room temperature neutron therapy systems, the superconducting system is much simpler since no beam extraction is involved and also no beam transport and no beam swinging system. The system is also very much more compact, since the treatment room and cyclotron room coalesce, and is also expected to be much less costly. Construction of a first unit based on this design is expected to begin soon as a collaborative project between MSU and Harper-Grace Hospitals.

Introduction

The greatly reduced weight of a superconducting cyclotron immediately leads to the idea that the need in neutron therapy for an isocentric irradiation system might be effectively met by mounting such a cyclotron directly on a support gantry. A possible conceptual layout of such a system was presented by Hepburn, Bigham and Schneider in 1977.¹⁾ More detailed consideration of the characteristics of such a system brings up several problems viz. how to feed cryogenics to a system which desirably rotates thru 360deg., how to keep liquid Helium from being pushed out of a liquid bath container when the container is inverted, how to support the rather large weight of the cyclotron and collimator (realistically in the range of 10-20 tons) while providing adequate access for physicians and medical technicians, etc. In this paper we describe a cyclotron configuration which deals with all these problems and which constitutes a realistic solution to the requirements of the neutron therapy application. The cyclotron is sizeably less expensive and easier to operate than the room temperature cyclotron systems presently used for neutron therapy.

Choice of Projectile and Energy

The cyclotron has been designed to accelerate deuterons to 50 MeV, the detailed magnet design being based on studies presented in another paper at this conference.²⁾ The selection of deuterons over protons involves several considerations, namely:

1. The rf frequency for the "in-phase" acceleration mode matches the standard fm band

so that the amplifier system can be selected from a wide variety of commercially available units.

2. The yield of neutrons per deuteron is an order of magnitude higher than the yield from a proton of comparable energy. Beam current for a given dose rate is then correspondingly lower, and targets and probes are much easier to design. Because of the higher yield, a relatively large target to isocenter distance can be used giving an improved depth dose characteristic. Target radioactivity is also greatly reduced relative to the target systems often used for protons, which absorb the low energy component of the beam in normal metals.

3. The stronger forward collimation of the neutrons from deuteron bombardment leads to reduced secondary activation of the cyclotron components, per unit flux in the treatment direction.

4. The spectrum of neutrons from 50 MeV deuterons is strongly peaked near 25 MeV, and the reduced low energy component relative to protons may well have a significant therapeutic advantage. At the least all available evidence indicates deuterons to be at least as good as protons on all therapy characteristics.

5. The reason customarily cited for picking a proton beam rather than a deuteron beam, namely that a cyclotron of given size will produce protons of twice the energy does not hold for a superconducting cyclotron as the previously referenced study²⁾ on magnet designs establishes. This follows from the fact that a high field cyclotron in this mass-energy range is focusing limited³⁾ and the energy per nucleon of the proton is twice that of a deuteron of the same total energy. A lower magnetic field must be used for the protons and, since the magnetic flux in a cyclotron scales as 1/B for fixed maximum rigidity, the magnet becomes comparably massive to the deuteron system. (When aperture and focusing strength are equal the deuteron magnet is 50% heavier than the proton magnet--20 tons vs. 13 tons--in the high field case which compares with 100% heavier which would be expected at low fields--when the proton magnetic field is reduced to give an rf frequency matching standard FM transmitters, the weight of the proton magnet increases to 80% of the deuteron magnet weight.)

Carefully weighing the above factors, we concluded that, the deuteron system has significant advantage overall and our design of a superconducting neutron therapy cyclotron has then been based on use of deuterons as the accelerated projectile.

Cyclotron Design Details

Details of the cyclotron proper are shown in Figs. 1 and 2, which are respectively a vertical section through the axis and a horizontal section through the median plane of the cyclotron. The basic form of the cyclotron is patterned after the MSU K500,⁴⁾ i.e. an iron core magnet with three hills and three valleys and with an accelerating dee in each valley. The three dees operate on the third harmonic of the orbital frequency and are connected at the center so that the dees are forced to oscillate in the "in-phase" mode. The charged particle beam stops in an internal beryllium target which comes in through a vacuum lock (at the left in Fig. 2) and the beam of neutrons passes through collimating apertures in the magnet yoke and dose monitoring devices.

The superconducting coil is housed in an annular cryostat with an independent vacuum jacket so that the main cyclotron vacuum can be opened without disturbing the insulating vacuum of the coil. Various penetrations and flats on the side of the yoke provide for mounting the collimating system, the feedlines for cryogenics, the electric leads, the folded columns⁵⁾ to support the low temperature vessel (the latter as shown in detail in Fig. 2a), etc. The yoke arrangement is such that all magnetic materials have exact three sector symmetry.

The system for containing liquid helium in the coil vessel while the vessel is being turned thru 360 degrees is illustrated schematically in Fig. 3. The key idea of the system is to subcool the liquid bath in which the coil resides below its normal boiling point so that the liquid can absorb energy without the formation of bubbles. The subcooling is accomplished by pressurizing the helium in the main bath to 1.8 atmospheres and heat exchanging this helium against a 1.3 atmosphere, two-phase loop which threads through the outer part of the liquid vessel just outside the coil. The pressure drop from 1.8 to 1.3 atmospheres is accomplished internally in the coil vessel by means of an appropriate constricted annulus. Other details in the figure illustrate a similar subcooling loop in the main liquid helium storage dewar and the use of boil off gas to vapor cool the leads and to cool upper and lower radiation shields (appropriately tailoring temperature and pressure drops in a series of chambers labelled 1- 4).

Support System

The support system for the cyclotron is illustrated in Figs. 4 and 5, which are a vertical section view through the rotation axis and a top view, respectively, of the system. The cyclotron and an opposing counterweight are mounted on a pair of large rings (which also show clearly in Fig. 8). These rings in turn rotate on four small support rollers, two under each ring. Cryogenics are fed into the system through flexible cryogenic lines which are mounted on a six turn helical spring, this spring expanding or contracting as illustrated in Fig. 6 as the whole assembly rotates, to add or subtract one turn. Support for the spring is provided by a line of rollers as illustrated in Fig. 7 and Fig. 7a.

Access to the patient for checking alignment of the system is provided by a flexible moving floor arrangement which runs on a track matching the innerdiameter of the support rings, except for a flat sided area corresponding to the normal floor height. The angular drive for the floor comes from the cyclotron support ring system thru sliding, radially oriented linear bearings at each end of the cyclotron. Comfortable physician access for positioning the patient is provided as illustrated in Fig. 9. The patient table is fully independent of the moving floor, the table mounting as shown in Fig. 4, in a cantilevered fashion from a support pillar which attaches to the main concrete floor of the building.

An alternate mounting system for the cyclotron is shown in Figs. 10 and 11 in which the cyclotron and counterweight hang on a "bicycle crank" style support system, the cyclotron location corresponding to one of the pedals of the bicycle crank and the counterweight corresponding to the location of the other pedal. With this arrangement an intelligent moving floor system is needed as illustrated in Fig. 12; a floor system of this type is commercially available.⁶⁾

Technical specifications for the complete cyclotron system are given in Table I. The specifications indicate that the overall system will be an exceedingly effective therapy configuration. Plans for installing such a system in a new addition to the Radiation Oncology Center of Harper-Grace Hospital are well advanced and construction is expected to begin in the summer of 1984 and beam testing of the cyclotron should occur early in 1986.

Conclusions

The design for a neutron therapy cyclotron system, which we have described in this paper, provides technically sound solutions to the various engineering problems which arise when one considers such a system in detail. The overall therapy systems should be less costly to construct, simpler to operate, and easier to maintain than room temperature systems which are presently used for this purpose as a consequence of eliminating some of the most intricate parts of conventional systems, namely, those which are required to take the internal beam from the cyclotron to the target. We expect to present a report describing actual operating experience with such a cyclotron system at the next conference.

References

†Consultants.

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3. H. Blosser and D. Johnson, *Nuc. Inst. & Meth.* 121(1974)301.
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TABLE I: SYSTEM SPECIFICATIONS

CYCLOTRON

Magnetic Field: center 4.6 tesla, hill 5.4 tesla
 rf System: frequency 105 Mhz, dee voltage ± 40 kV peak, rf power 25 kw
 Vacuum: source gas off 5×10^{-6} torr, source gas on 1.5×10^{-5} torr.
 Beam Energy: $\pm 50 \pm 0.3$ MeV deuterons
 Maximum Beam Current: Pop-in target 50 microamperes, Be target 20 microamperes
 Beam current reproducibility: for beam current greater than 5 microamps the beam current setting will reproduce to within 5% of the previous value when the cyclotron is turned on after an off period of up to 30 minutes (without adjustment of ion source parameters).

SUPPORT SYSTEM

Rotation Range: $+180^\circ$ to -175° (355° total travel)
 Mechanical Rigidity: the extended central axis of the neutron collimator will intersect with a single sphere of 3 mm dia irrespective of the gantry rotation angle
 Rotation Speeds: fast $90^\circ/\text{min}$, slow $22 \frac{1}{2}^\circ/\text{min}$.
 Angular Accuracy: The readout of the gantry angle will be accurate to 0.5° .

NEUTRON FLUX

Spatial Reproducibility: the dose distribution at the isocenter will reproduce on five successive days within a total variation of 6%, as observed in a test performed with neutron collimator set for a 10×10 cm field at the isocenter and using a 17 member array of detectors, (one detector at the isocenter and four lines of four detectors extending from the central detector on lines perpendicular to the collimator axis at 1 cm spacing).
 Angular Stability: The neutron flux as measured at the isocenter will be constant to within 5% as the cyclotron is successively moved in 30° steps through its full angular range.

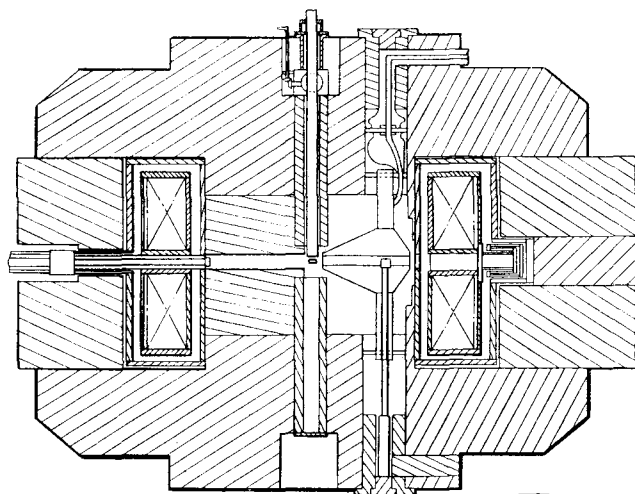
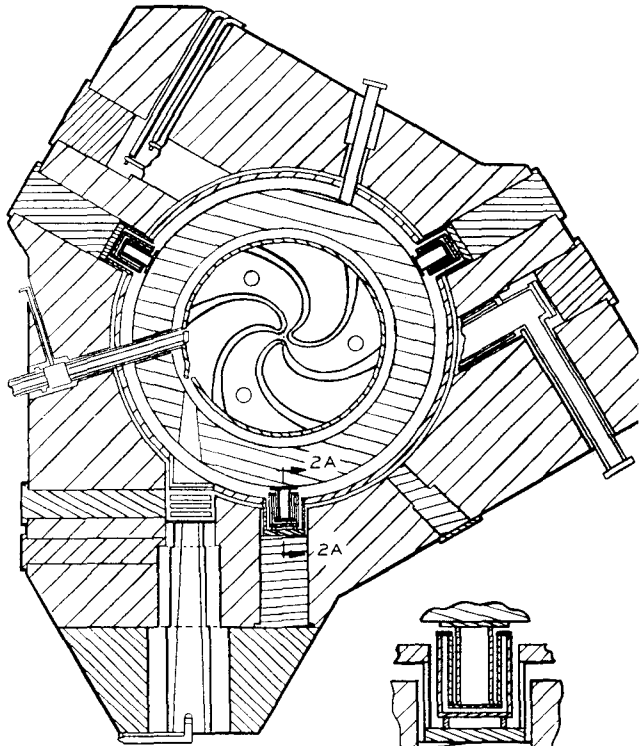


FIG 1

Fig. 1. Section view through the cyclotron axis showing the target inserted from the left into the hill region and one of the three accelerating electrode structures in the valley at the right of the axis.

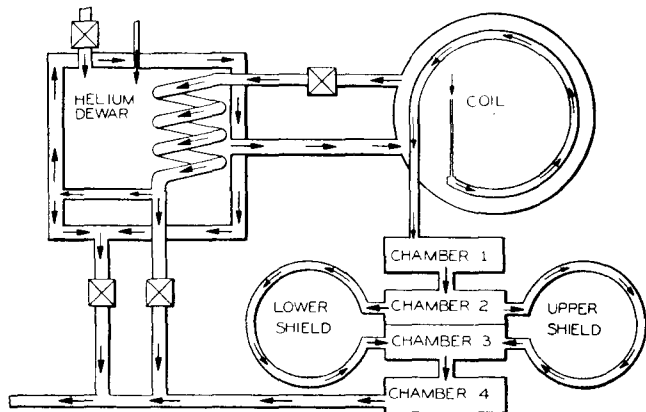
—FIG. 2



—FIG. 2A

Fig. 2. Median plane section view of the medical cyclotron showing the three spiral hills and accelerating electrodes. Collimators will be of polyethylene concrete mounted in a nonmagnetic collimator snout at the lower left.

Fig. 2a. Section view of the folded column helium vessel support.



—FIG. 3

Fig. 3. Schematic diagram showing features of the subcooled liquid Helium system for cooling the main coil.

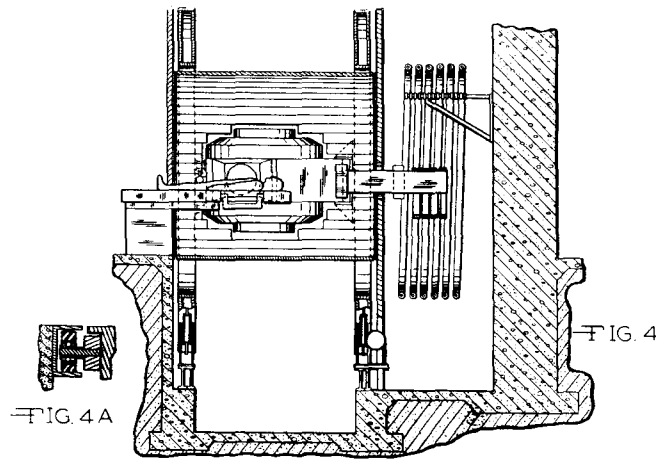
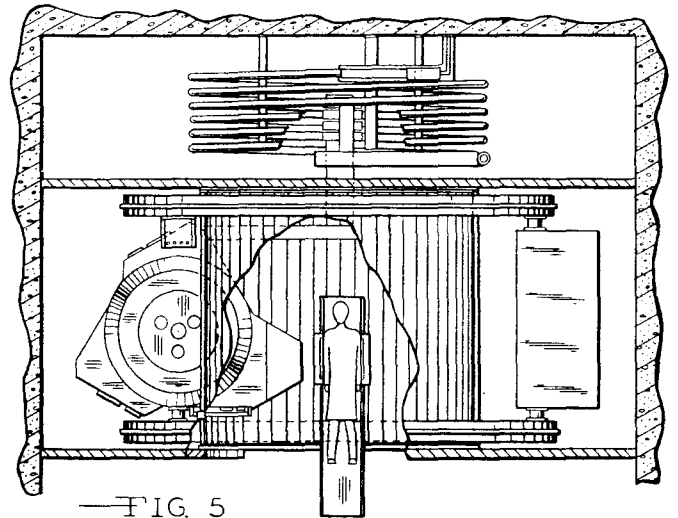
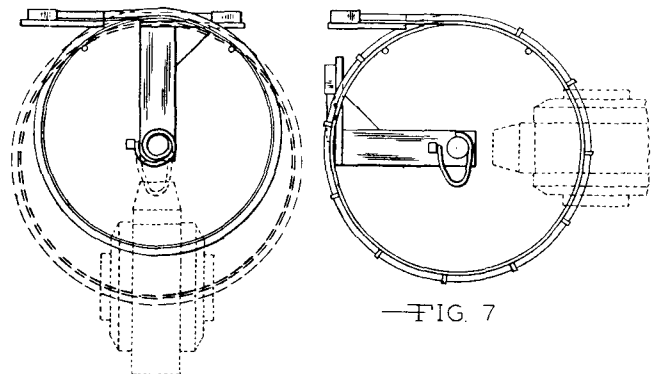


Fig. 4. Vertical section view of the support system. The cyclotron is behind the patient who is positioned on a movable table cantilevered from the fixed floor at left. The patient table extends into an "oval", hinged slat type, moving floor in the region between the support rings. The Helical feed hose system for cryogenics is on the right.



—FIG. 5

Fig. 5. Horizontal section view with the cyclotron in the same position as in Fig. 4 and showing at the right the counterweight assembly mounted diametrically opposite the neutron collimator.

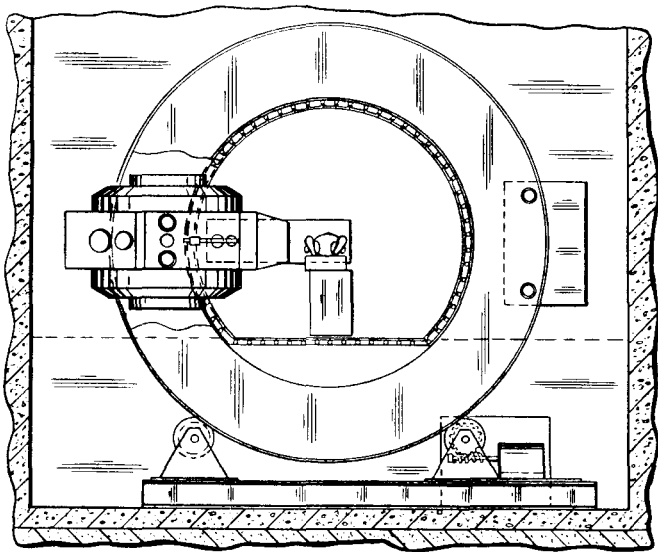


—FIG. 6

Fig. 6. End view of the cryogen feed hose structure showing the hose arrangement at +180° and in dashed outline at -180°.

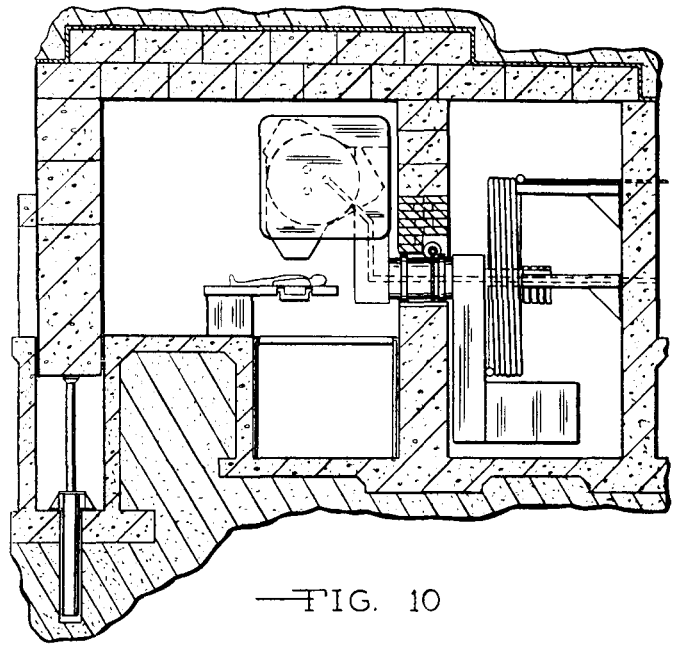
Fig. 7. Similar to Fig. 6 except with cyclotron and feed hose at the +90° position.

—FIG. 7



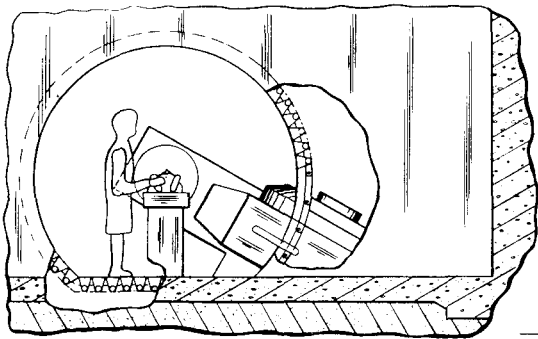
—FIG. 8

Fig. 8. Section view showing the mounting rollers and drive system for the cyclotron support rings and floor.



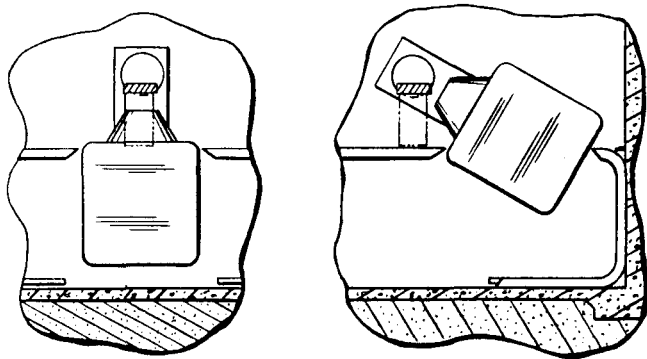
—FIG. 10

Fig. 10. Vertical section view illustrating an alternate "bicycle crank" type mounting system for cyclotron and counterweight. The cyclotron corresponds to one pedal of the bicycle crank and the counterweight to the other. A computer controlled moving floor opens to allow the cyclotron to move to positions below the normal floor level. Primary support for the bicycle crank system comes from a main bearing assembly mounted in a central shielding wall.



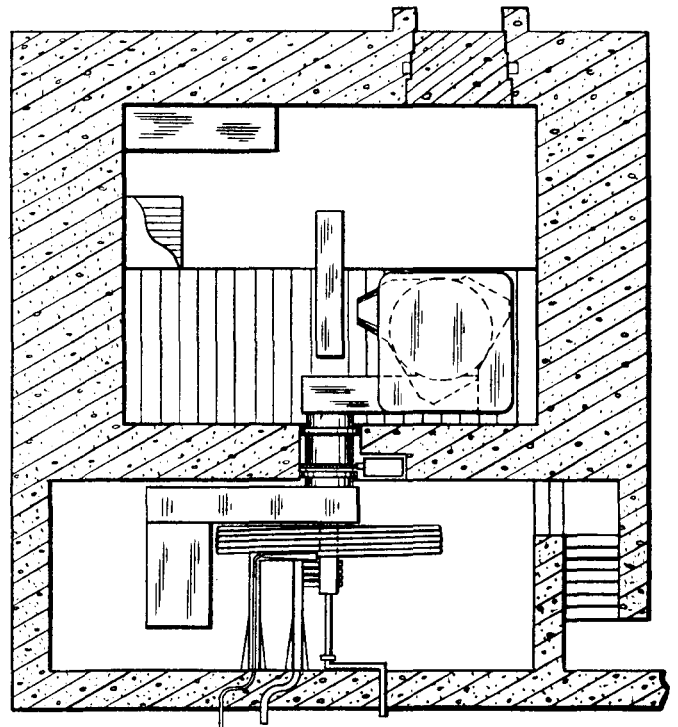
—FIG 9

Fig. 9. A typical radiation configuration with the cyclotron at -120° illustrating physician access.



—FIG. 12

Fig. 12. End view of the cyclotron movable floor system with the cyclotron in the 180° position at the left and in the -120° position at the right, illustrating motions of the movable floor.



—FIG. 11

Fig. 11. Horizontal section view of the bicycle crank type system with the cyclotron in the $+90^\circ$ position.