Title
150 MEV PROTON MEDICAL CYCLOTRON DESIGN STUDY

Author
Burleigh, R.J.

Publication Date
1975-08-01

To be presented at the 7th International Conference on Cyclotrons and Their Applications, Zürich, Switzerland, August 19 - 22, 1975

150 MEV PROTON MEDICAL CYCLOTRON DESIGN STUDY

R. J. Burleigh, D. J. Clark, and W. S. Flood

August 1975

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

DISCLAIMER

150 MEV PROTON MEDICAL CYCLOTRON DESIGN STUDY*

R. J. Burleigh, D. J. Clark, W. S. Flood
Lawrence Berkeley Laboratory, University of California
Berkeley, California, 94720, U.S.A.

Abstract

A brief design study has been done for a 150 MeV proton sector cyclotron. The object was to minimize cost but maintain good reliability and easy maintenance. The use of the proton beam would be for therapy, radiography and isotope production.

Introduction

During the past several years the medical community has shown interest in using protons and heavier ions for radiation therapy and radiography.[1)2)3)] Protons have the advantage over x-rays and neutrons of having a fixed range and a high rate of energy loss near the end of the range. This makes possible the radiation of small internal tumors with low dosage to the surface tissue. Heavier ions and π^- mesons also have fixed ranges and advantage over protons of a low OER (oxygen enhancement ratio) which reduces damage to normal tissue, but they require considerably larger accelerators to produce beams with enough range to penetrate the human body. So we present this preliminary design study in the hope that there is an area of therapy which can utilize the high definition of protons at a cost which is much less than for heavier ions or π^- mesons. The goal is to design a cyclotron at minimum cost but with high reliability and easy maintenance. This paper is a summary of an LBL internal engineering note.[5)]

General Design

For a 150 MeV proton cyclotron for the modest current of .1 μA external beam we have a choice between a sector-focused and a synchro-cyclotron. Some[2)] may like the synchro-cyclotron for its simplicity of magnetic field design and loose tolerance on dee voltage regulation. We prefer the sector-focused design because there is no rotating capacitor and high currents of 100 μA are easily available for optional isotope production. The magnetic field design is similar to many such cyclotrons and the magnetic field, frequency and dee voltage stabilization are routine engineering design jobs now.

A new design option has arisen in the past several years: normal conducting vs. superconducting main coil. As described elsewhere at this conference there are superconducting cyclotron magnets under construction at Michigan State and Chalk River, and some studies have been done at Berkeley with average fields of 4-5 T. These are for machines in the range of K = 400 (about 400 MeV protons). Brief estimates were made to compare the cost of a superconducting magnet at 5 T and a normal conducting one at 2 T. Although the superconducting design has a pole diameter about 40% that of the normal design, the higher cost of the superconducting technology makes the overall costs about the same, for this size. At larger K values the superconducting design becomes cheaper than the normal one. Because some development still is necessary for the superconducting design such as deflection, and because a medical environment requires high reliability and proven design, we decided on a normal coil magnet.

Another design choice is that of the dee configuration. The dee or dees can extend over both hill and valleys, as in most of the sector cyclotrons. Or two dees can lie in two opposite valleys of a 4-sector magnet as in the UCLA design.[5)] In the first case (dee-over-hill) the magnet gap is determined by the dee-ground clearance over the hills. In the second case (dee-in-valley) it is determined by the dee-ground clearance in the valleys, and the magnet gap can be considerably smaller. A comparison was made of these two options in an LBL engineering note by R. Burleigh.[6)] It was found that if other factors are left constant (such as average field, current density, dee-ground clearance, etc.) the dee-in-valley design requires only 60% of the copper, 60% of the magnet power, and 80% of the steel, compared to the dee-over-hill design. So the dee-in-valley design was chosen for this study.

The parameters chosen are shown in Table I.

Table I. Specifications

Proton Energy......................	150	MeV
Beam Current (External)............	0.10	μA
Beam Current (Internal,max.).......	100.0	μA
Average Field......................	2.0	T
Hill Field.........................	2.4	T
Valley Field.......................	1.6	T
Field in Return Path...............	1.7	T
Hill Gap...........................	5	cm
Valley Gap.........................	12	cm
Orbit Radius at Output Energy......	91	cm
Pole Diameter......................	198	cm
Weight of Steel....................	1.44×10^5	kg
Weight of Copper in Main Coils.....	2.6×10^3	kg
Main Coil Power....................	120	kw
Trim Coil Power....................	20	kw
No. of Dees........................	2	
Dee-to-Ground Clearance............	2.5	cm
Design Dee Voltage.................	60	kv
RF Power...........................	70	kw
RF Frequency.......................	30	MHz

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

The high field level of 2.0 T average are based on similar values used at UCLA.[5] For a fixed energy design such as this the steel can be run into saturation in the gap region, but 1.7 T is used in the return yoke to conserve coil power. These values were not optimized. The small average gap allows the outer orbit to come close to the pole edge for easier extraction, and also requires only a small main coil power. The dee voltage of 60 kV across a 2.5 cm gap is consistent with previous cyclotron experience.

Mechanical Design

The layout of the magnet and dees is shown in Fig. 1. The design looks much like that of the

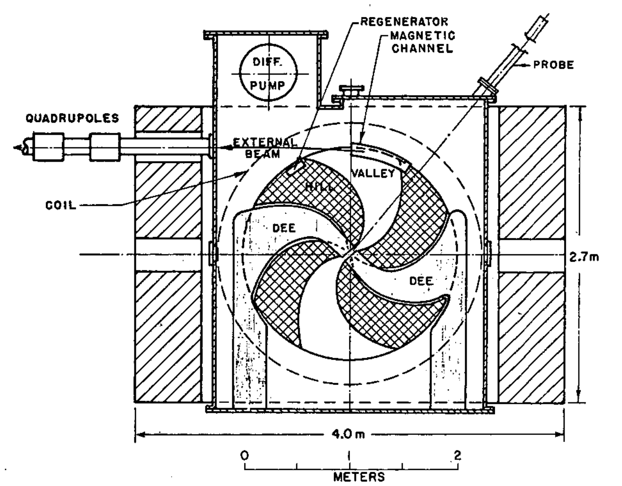


Fig. 1. Plan view of magnet and RF system at median plane.

50 MeV proton UCLA cyclotron[5] except that this machine is bigger and has an extraction system to bring out the positive protons. The side return legs of the magnet are quite close to the dee tank and are wider than the pole diameter to reduce cost at the expense of accessibility. The larger size makes the 1/4 wave dee stems end at the tank wall, giving a unit RF structure which can be rolled away from the magnet for maintenance. The ion source is inserted axially through the pole and is not shown in this figure. Alternatively it could come in radially on the deflector side, if space above the roof were not available. One probe for beam measurements is shown. This could be specially cooled for isotope production. Modern computer programs are so accurate that a centered orbit geometry can be designed in advance, so other probes should not be necessary. Extraction is shown using a regenerator. Fig. 2 shows an elevation view of the magnet. The gap geometry along a dee edge is shown in Fig. 3. The hill gap is left wide enough to remove the dees without raising the upper magnet yoke. Low power trim coils in the valleys provide some radial field trimming and harmonic control for centering and extraction.

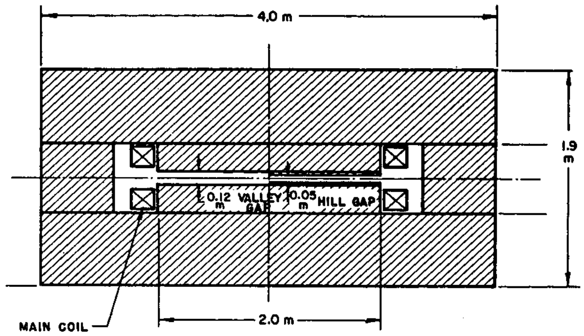
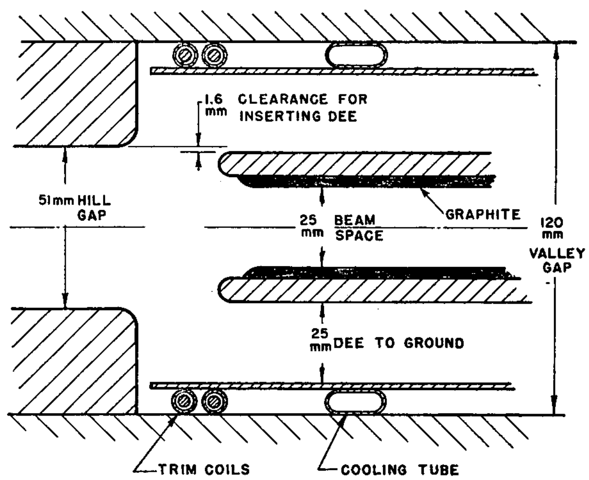


Fig. 2. Elevation view of magnet cross-section through a valley and a hill.



GAP GEOMETRY

Fig. 3. Elevation view of dee and hill cross-section at sector edge. Dee is on right side.

RF Design

Dee support structure is simplified and rf power minimized by using separate grounded dee stems. The total rf power to dees, stems and liners is 70 kW at 60 kV dee voltage, 30 MHz. This requirement is well within ratings of a single forced-air cooled power tube (4CX35000).

For single frequency operation the simplest and most economical oscillator circuit is one tube driving a half-wave anode line connected between the dee stems as shown in Fig. 4. Oscillator feedback will be taken from one of the dee stems through a half wave line foreshortened by the tube input capacitance. The dee resonators will be separately tuned by motor-driven trimmers covering about 5% frequency range to accommodate construction tolerance and

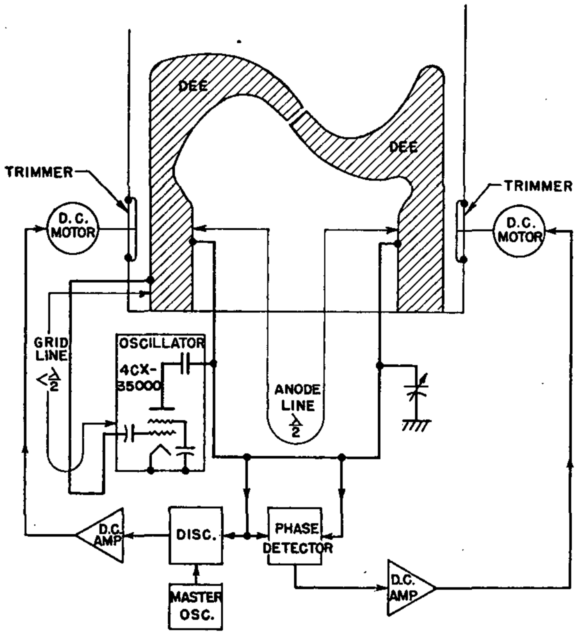


Fig. 4. RF electronics block diagram and dee system.

variations due to temperature changes. Both trimmers will be servo controlled, one by a frequency control servo referred to a master oscillator, and the second by a phase-sensitive servo referred to the standing wave minimum on the half wave anode line, maintaining proper dee to tube voltage ratio. Within the narrow operating range of the trimmers appreciable dee voltage can be produced only with dees oscillating 180° out of phase, and only when they are tuned close to the same resonant frequency. The phase servo will be cycled through a simple program to start the oscillator. During this tune-up sequence the oscillator will pass through an overdriven condition with the tube working into a negligible plate load. The tube can be protected in this region by a regulator in the screen power supply which limits the screen current to the full power operating value (approx. 0.5A). The dee voltages rise slowly in this sequence and it is assumed that the dee tank vacuum will be good enough so that multipactoring will not be a problem.

Although the configuration of separate dees with an external anode line and tetrode oscillator will complicate the problem of high order mode suppression, for single frequency operation this problem is assumed to be tractable.

The oscillator power supply will be controlled by a hard-tube modulator employing the same 4CX35000 tube type as the oscillator. This will provide on-off switching, including fast fault protection of the oscillator tube, and will regulate the oscillator plate voltage to within 1% of a fixed value of 13 to 14 kV against rectifier ripple and line voltage variations.

Beam Dynamics

No detailed beam dynamics calculations have been done on this design. The inner section out to 50 MeV is very similar to the UCLA cyclotron as far as center region, magnetic field level and flutter, and dee system are concerned.[5] The spiral angle necessary to obtain vertical focussing out to 150 MeV was calculated using the approximate formula: $\nu_z^2 = 1 - \gamma^2 + F(1 + 2\tan^2\alpha)$, where ν_z^2 is the square of the vertical frequency, $\gamma = m/m_0$, F is the magnetic field flutter and α is the spiral angle (angle between hill edge and a radial line). This formula gave good agreement with more accurate computer calculations at UCLA. It was used to calculate the sector shape shown in Fig. 1. Computer calculations will be necessary near full radius because of the rapid change of radial field and flutter in that region. The deflector shown in Fig. 1 is just schematic. Orbit calculations need to be made on deflection when the details of the field at full radius are known.

Vault

The layout of the cyclotron in a vault is shown in Fig. 5. This is a minimum cost configuration, using earth shielding around concrete walls. Space is provided in the vault to remove the RF system for maintenance. One or more patient treatment rooms can be provided in the building. An elevation view of the vault is shown in Fig. 6. It is assumed that space for the vault is available at ground level next to the building where treatments take place. This makes installation inexpensive. Also any serious repair on the cyclotron which requires taking apart the magnet can be done easily by removing the roof blocks with a commercial crane. The details of the beam transport to the treatment room are not covered in this paper. A possible method of providing multiple beam paths through the required region of the body by rotating a bending magnet system is described in an LBL internal engineering note.[7]

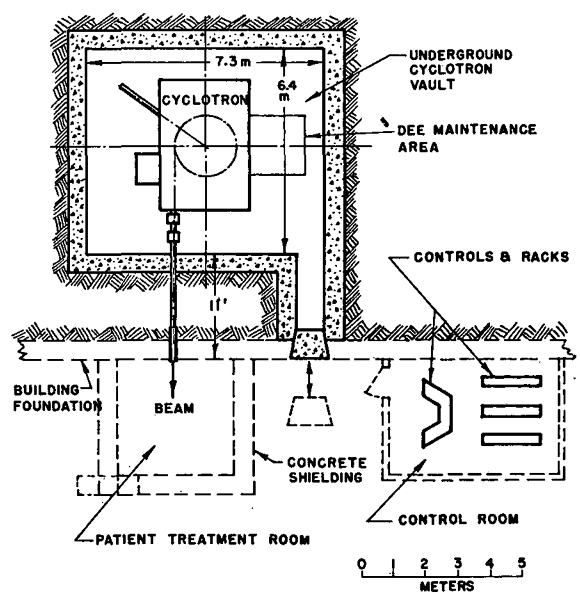


Fig. 5. Plan view of vault, control room and one treatment room.

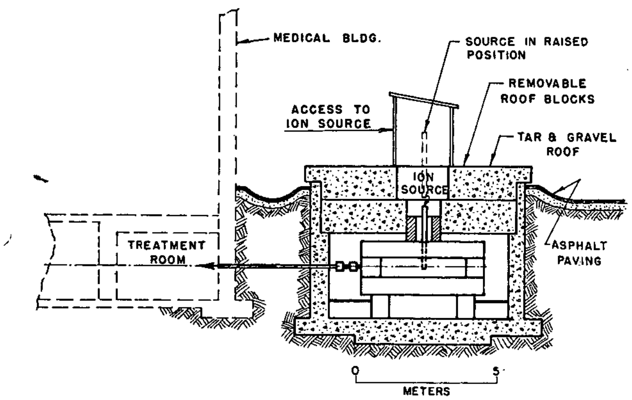


Fig. 6. Elevation view of underground vault and earth shielding.

Costs, Bugs and Operation

In the original 1973 note about this design[4] a detailed cost estimate was made, based on experience in the construction of the LBL 88-Inch Cyclotron.[8] Since then costs have increased significantly, so that today the cost of construction of the cyclotron would be between $1.5-2.0 M U.S., including design and controls but not vault, site preparation, utility installation, control room or treatment room. This would provide an initial external beam. However, experience with the 88-Inch Cyclotron and other accelerators has shown that any new machine which is not a copy of an older one will have a period of debugging which may last from .5 - 5 years, depending on the number of new features, the experience of the designers and the competence of the debuggers. So one should plan a period of commissioning of 6 mo. - 1 year on the first model of a cyclotron like this, under the direction of experienced people. This is not included in the cost estimate.

An operating crew should consist of one operator and one electronic maintenance man per shift. A desirable type of operation is two shifts per day with perhaps 5 operator/maintenance people to provide adequate depth for sickness and vacations.

Acknowledgements

The authors wish to thank Dr. B. Harvey for encouragement in applying cyclotron lore to the medical field. Dr. D. Judd provided many valuable suggestions on this work. W. Brobeck gave us some good practical advice.

References

1. R. Wilson, Proc. 6th Intl. Cyclotron Conf. (Amer. Inst. Phys., New York, 1972) p. 578.
2. A. M. Koehler, Proc. 6th Intl. Cyclotron Conf. (Amer. Inst. Phys., New York, 1972) p. 586.
3. R. S. Heusinkveld and M. L. M. Boone, IEEE Trans. Nucl. Sci. NS-22, 3 (1975) p. 1211.
4. R. Burleigh et al., LBL Engr. Note M4581, Feb. 1973.
5. D. J. Clark et al., Proc. Intl. Conf. on Sector-Focused Cyclotrons (North-Holland, Amsterdam, 1962) p. 1
6. R. Burleigh, LBL Engr. Note M4581, Feb. 1973
7. F. Selph and J. Gunn, LBL Engr. Note M4634, Jul. 1973.
8. R. J. Burleigh, Proc. Intl. Conf. on Sector-Focused Cyclotrons (North-Holland, Amsterdam, 1962) p. 634.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720