CONCEPTUAL DESIGN AND ORBIT DYNAMICS IN A 250 MeV SUPERCONDUCTING SYNCHROCYCLOTRON

by

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ABSTRACT

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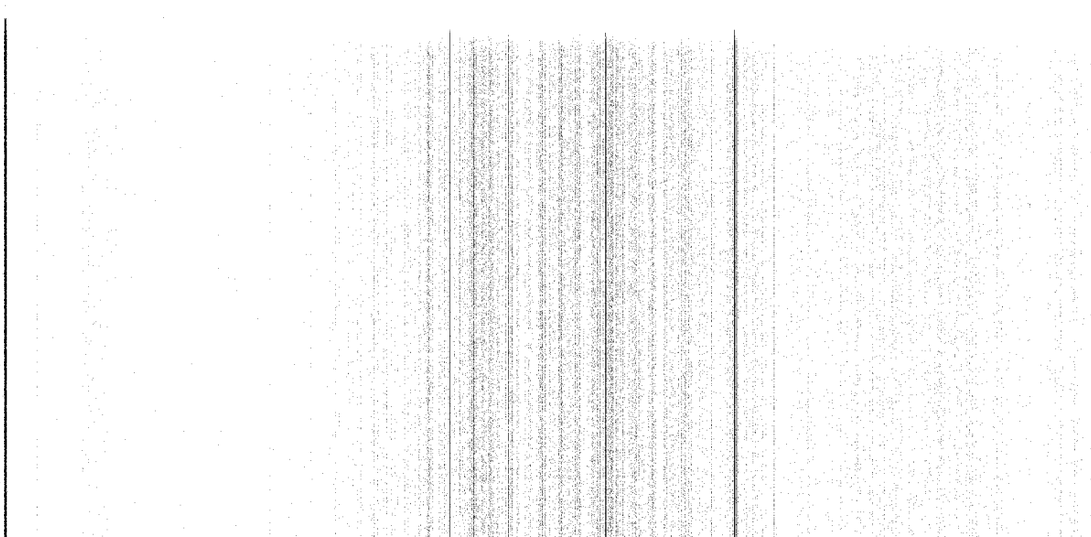
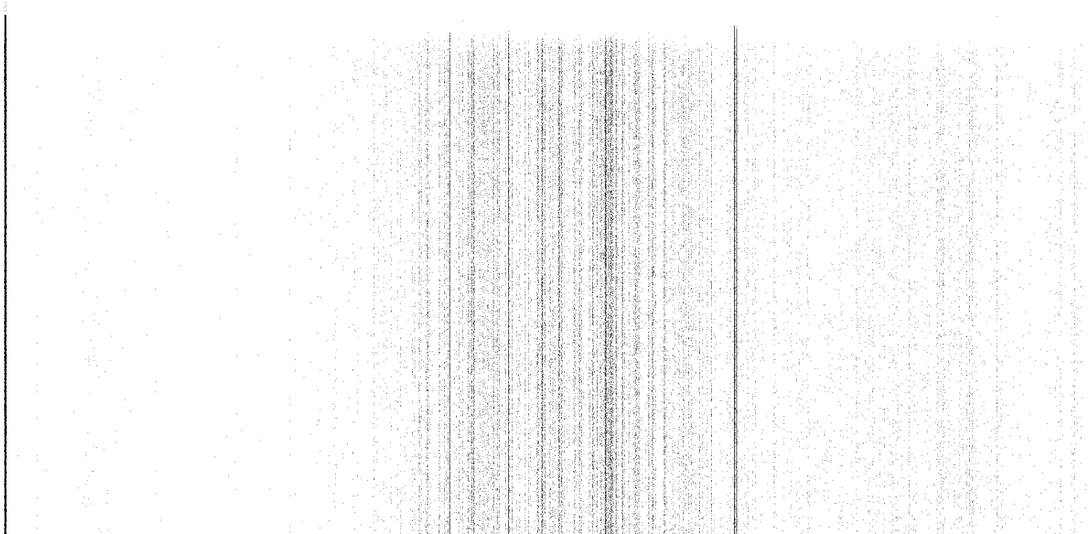
A feasibility study has been carried out on a 250 MeV superconducting synchrocyclotron specifically designed for use in cancer therapy. A superconducting magnet has been designed with a pole radius of 53 cm and a strong central magnetic field of 55.3 kG. The extraction system is based on a regenerator followed by a passive magnetic channel which contains a series of deflecting and focusing elements, and the properties of this system are described. The extraction efficiency for different initial conditions and the resultant properties of the extracted beam have been calculated using the Z^4 Orbit Code which treats nonlinear effects realistically. A central region electrode configuration with a closed ion source plus puller has been designed and orbit calculations have been performed to determine the orbit behavior in the central region. An ion

source experiment has been carried out to determine whether sufficient ion current can be produced with this type of central region geometry. A transfer matrix program has been developed and used to perform the capture time calculations, and to determine conditions for optimizing the capture efficiency. Possible RF frequency programs have also been studied that would avoid a loss of particles by maintaining a constant bucket area.



To my wife

JingLing Wang



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Chapter 1

Introduction

1.1 Background

Cancer therapy using protons was first proposed by Robert Wilson [1] in 1946 and the first work on the biological and medical application of proton beams was done by J. H. Lawrence and C. A. Tobias [2] at Berkeley in 1948. As reported by B. Gottschalk [3], the advantages of using protons in cancer therapy rest on two physical characteristics. First, the dose delivered by a proton penetrating tissue rises as the proton slows down, reaching about three to four times the entrance dose near the stopping point (Bragg Peak), and is zero beyond the stopping point. Protons in a monoenergetic beam have very nearly the same range and therefore deliver maximum dose at the same depth. The high localizability of protons in a monoenergetic beam means that side effects are smaller than with neutrons. Secondly, being heavy, protons do not deviate very much from a straight line as they penetrate into the tissue and come to rest. Their physical peak-plateau dose ratio is also higher than that of any other beam.

There have been many years of successful clinical applications of proton beams in cancer therapy at different institutions around the world and different kinds of accelerators have been used to provide the proton beams for cancer therapy, such as cyclotrons, synchrocyclotrons and synchrotrons.

Initial clinical work at Berkeley in 1954 used 340 MeV protons and from 1957 to 1988 work at the 184" cyclotron has made use of 910 MeV helium ions. (The biological effects of helium ions are similar to those of protons and the physical dose distribution is even sharper than for protons [3].) Many patients have received treatment with success. Another early work in this field was done starting in 1955 by the Uppsala group under B. Larsson and L. Leksell [4] using the 185 MeV synchrocyclotron of the Gustav Werner Institute. Since 1959, a 160 MeV synchrocyclotron has been used at the Harvard University Cyclotron Laboratory [5, 6] for cancer therapy and some 3400 patients have been treated to date. There is also an extensive program in the USSR using a synchrotron and synchrocyclotrons to provide the proton beam for cancer therapy at three centers: a 1000 MeV proton beam from the synchrocyclotron in Gatchina, a 200 MeV proton beam from the Dubna 680 MeV synchrocyclotron and a proton beam of 70 - 200 MeV, in 5 MeV steps, from the 7.2 GeV synchrotron ring at the ITEP [3, 7] in Moscow.

In the United States, considerable attention has been recently directed toward the development of accelerator systems optimized for radiation therapy with protons. The most recent development is a cancer therapy facility at Loma Linda University Medical Center [8, 9]. A 250 MeV proton synchrotron has been used to provide 70 - 250 MeV protons with a beam intensity goal of 1.2×10^{11} protons per pulse in a two second cycle time. The current beam intensity achieved is about 4.0×10^{10} protons per pulse in a four second cycle time. There are a total of four quadrants around the accelerator circumference, each composed of a 90° bending and a straight section, and the central orbit is approximately 19 feet in diameter. The beam is injected with an energy of 2.0 MeV and then accelerated to the desired energy by a radiofrequency system. After acceleration, the beam is extracted and then transported through a beam switchyard to different treatment rooms.

Of all the accelerators used in proton cancer therapy facilities, the synchrocyclotron is the least demanding machine. It uses an internal ion source to provide a proton beam directly to the accelerator; no injector is needed. A RF system with frequency modulation is used to avoid the resonance limitation due to a fixed frequency and to allow acceleration to higher energies. A simple symmetric weak

focusing magnetic field is used to contain the protons in circular orbits and provide adequate radial and vertical focusing force. Cyclotrons can accelerate many more particles than synchrocyclotrons per unit time, but the beam intensity from a synchrocyclotron is entirely adequate for cancer therapy.

All the synchrocyclotrons used in present proton therapy programs are older, massive room temperature machines which are located in physics laboratories and are overall poorly matched to a hospital environment. H. Blosser has asserted [10] that such a machine would be inordinately costly to reproduce in present conditions. If the synchrocyclotron is redesigned as a superconducting high magnetic field device, the mass and cost are greatly reduced and an overall system with many appealing features results. The advantages of adapting the superconducting cyclotron to medical use have been demonstrated by the construction and completion of the first superconducting cyclotron for neutron therapy - Harper Cyclotron by H. Blosser [11,12,29,43,44] at MSU from 1984 to 1990. A 250 MeV superconducting synchrocyclotron has been proposed at the National Superconducting Cyclotron Laboratory. The conceptual design of the magnet, extraction system and central region and the orbit dynamics in this machine are described in this thesis.

1.2 Features of the Design

As reported by H. Blosser, et. al. [11], design studies of the 250 MeV superconducting synchrocyclotron magnet have been carried out at MSU based on the pillbox magnet concepts used in earlier MSU isochronous cyclotrons [12]. The magnet of such a cyclotron weighs about 60 tons, and it is still compatible with direct gantry mounting. A possible system arrangement is shown schematically in Fig. 1-1. Figures 1-2 and 1-3, respectively, show the plan view and the vertical cross section view of the proposed 250 MeV superconducting synchrocyclotron.

The proton energy of 250 MeV is chosen because of the range of protons in tissue. It is sufficient for irradiation of even obese patients from many directions and corresponds to the range in tissue of 37 cm. The beam current is closely related to the treatment time desired for patients. A few nanoamps are marginally adequate and tens of nanoamps are comfortable for even the largest tumors. The performance and design parameters of the 250 MeV superconducting synchrocyclotron are:

Particle	Protons
Energy	250 MeV
Beam current	20 - 100 nA
Central Magnetic Field	55.3 kG
Magnet Pole Radius	21.0 in.