DESIGN OF A SYNCHROTRON FOR PROTON THERAPY

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Abstract: A dedicated proton synchrotron for cancer therapy is designed. It consists of a multicusp H⁻ ion source, a tandem electrostatic accelerator as an injector, a slow-cycling synchrotron and beam lines to two treatment rooms. The synchrotron accelerates 5 MeV protons up to 230 MeV. The design goal of its intensity is 10 nA for 0.5 Hz and 20 nA for 1 Hz repetition rate. Beam loss caused by Coulomb scattering in the ring and transmission in the tandem accelerator are estimated.

Introduction

Since 1983, clinical trial of proton therapy has been made at Particle Radiation Medical Center (PARMS), the University of Tsukuba using 500 MeV proton beams delivered by the KEK booster of the 12 GeV proton synchrotron. Its results are so promising that a dedicated proton accelerator is designed to use proton beams much more freely and appropriately for therapy. It will be built in the University Hospital. Either a cyclotron or a synchrotron can be considered as a candidate. Although a linac can deliver such a beam, it is probably more expensive than the accelerators above mentioned. The synchrotron has advantage of variable energy capability of the accelerated beam. However, it requires a separate accelerator as an injector. Its another issue is a complicated RF accelerating system. Recently, the injector is commercially available and a simple RF accelerating system has been developed. Thus the synchrotron will be operated and maintained by technical staff members of the medical group without difficulty.

Design Parameters

Main parameters are listed in Table 1. Three different energies are to be available, 120 MeV, 180 MeV and 230 MeV. Operating conditions of the accelerator are much different from a high energy accelerator. It should start in the morning and stop in the evening Monday through Friday. It should be tuned in 1 hour every day. A shutdown for maintenance and improvement is limited in a week, and it is at most twice a year. This is mostly due to the treatment planning of fractionating irradiation. Both fast and slow extraction systems are supposed. The pulsed beam has been used at PARMS and ultrasonic signal produced by the pulsed protons might be utilized to detect their range in tissue during irradiation in the future. Slow extracted beams are prepared for development of advanced beam delivery system. Quick change of beam course and energy is other important consideration.

Synchrotron

Layout of components is shown in Fig. 1. Circumference of the ring is determined primarily by the currently feasible rise time of the kicker magnets for fast extraction.

When the normalized emittance of the injection beam is 1.5 π mm.mrad and emittance dilution of factor two is assumed in horizontal plane, the horizontal and vertical emittances are 30 π mm.mrad and 1.5 π mm.mrad respectively. If the injection energy is 5 MeV, the space-charge limited current for tune shift of - 0.15 is 1.3×10^{11} ppp or 20 nA for 1 Hz operation.

For the injection energy of 5 MeV, it is feasible to use a commercially available tandem electrostatic accelerator as the injector.

Table 1 Main parameters of 230 MeV proton synchrotron for cancer therapy

Lattice			
Circumference		34.939	m
Average Diameter		11.121	m
Superperiod		6	
Structure		DOFB	
Straight Section		3.0	m
Bending Radius		1.55	m
Bending Magnet Length		1.623	m
Magnetic Field			
Bending Magnet			
Injection	(5 MeV)	0.2087	T
Extraction	(120 MeV)	1.0534	T
	(230 MeV)	1.498	T
Ramp		2.6	T/sec
Deflection Angle		60	deg
Gap		6.5	cm
Width		28	cm
Edge Angle		30	deg
Quadrupole Magnet			
Aperture		11.6	cm
Length		20	cm
Field Gradient	(Focusing)	5.9483	T/m
	(Defocusing)	1.1416	T/m
Orbit			
Tune	(Horizontal)	1.8	
	(Vertical)	1.85	
Beta Function	(Horizontal)	1.836--6.439	
	(Vertical)	1.684--6.955	
Maximum Dispersion		2.6	
Gamma at Transition		1.5606	
Horizontal Maximum Beam Width			
Betatron Oscillation		± 4.3	cm
Dispersion		± 0.8	cm
COD		± 3.0	cm
Total		± 8.1	cm
Vertical Maximum Beam Width			
Betatron Oscillation		± 1.0	cm
COD		± 1.7	cm
Total		± 2.7	cm
Radiofrequency Acceleration		(5--230 MeV)	
Frequency Range		0.8823--5.1123	MHz
Stable Phase		20--30	deg
Voltage		450--300	V
Repetition Rate		0.5--1	Hz
Injector		Tandem Van de Graaff	
Input Energy		70	keV
Output Energy		5	MeV
Normalized Emittance		1.5	πmm.mrad
No. of Multiturn Injection		20	

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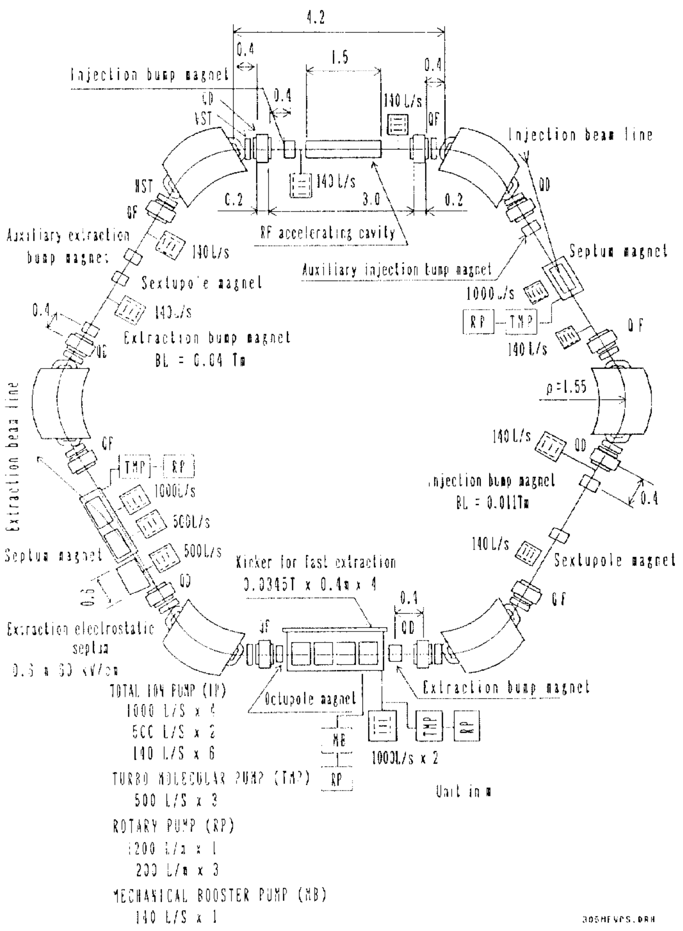

Fig. 1 230 MeV proton synchrotron.

Lattice

Lattice parameters are already reported with fast and slow extraction [1]. To simplify bending magnet production, their entrance and exit planes are parallel. Two quadrupole magnets in a cell ensure to avoid dangerous resonance in vertical plane when the horizontal tune moves from 1.8 to 1.5 for slow extraction.

RF Accelerating Cavity

RF acceleration parameters are shown in Figure 2. Because of low RF accelerating voltage, an untuned cavity loaded with ferrite can be used with a commercially available solid state power amplifier [2]. Bias current and its sophisticated tuning system are eliminated. The RF accelerating system becomes simple and adequate to a medical machine. For further development of the system, a quarter-wavelength coaxial model cavity is made and tested with two types of Ni-Zn ferrite, one is the type which is used in the 12 GeV proton synchrotron at KEK and the other is specially made for the untuned cavity. When the former is loaded, the cavity shows a high-Q resonance as expected and it needs bias current to control the resonant frequency. On the other hand, the latter has a higher μ' than the former up to about 1 MHz and μ' decreases in the operating frequency range according the Snoek's limit with large loss or big μ". The resonance becomes broad and its Q is around 1 with the 20 ferrite rings, 50 cm outer diameter, 28 cm inner diameter and 1.27 cm thick. The impedance is 900 ohm at the resonance of 3 MHz, so that its impedance and phase are very flat over the operating frequency range with an external 50 ohm resister [3]. With a transmission-line transformer and an external 200 ohm resister, the driving power might be reduced from 2 kW to 500 W. The ferrite rings will be cooled by forced air in full power operation

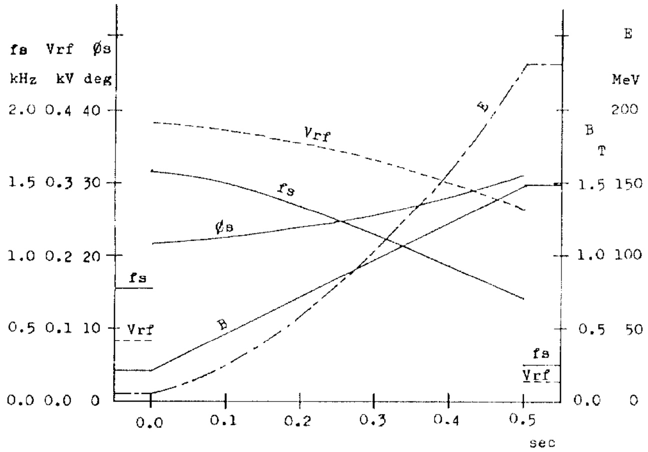

Fig. 2 RF acceleration parameters.

Vacuum

For a slow cycling, low energy proton synchrotron, Coulomb scattering by residual gas atoms is serious during acceleration in the ring. Beam losses during acceleration are estimated by successively applying life time calculation for a storage ring.

$$I(t+\Delta t) = I(t)\exp(-\Delta t/\tau)$$

The life time of protons in a storage ring with elliptical vacuum chamber is approximately given by [4]

$$\tau = \tau_{sq} \{ 0.58 + 0.42 (A_H + A_V) / (\sqrt{A_H} + \sqrt{A_V})^2 \}$$

where

$$\tau_{sq} = 2.16\ \beta^3\gamma^2 / \lambda P \{1 / (A_H/\pi) + 1 / (A_V/\pi)\}.$$

λ = R/Q, or the average radius of the ring divided by the tune, β and γ are the relativistic velocity and normalized total energy. Instead of adiabatic damping of the beam size, the acceptances are increased by $\beta\gamma/\beta_{inj}\gamma_{inj}$ as $A_H = (\pi a^2/\lambda)(\beta\gamma/\beta_{inj}\gamma_{inj})$ and $A_V = (\pi b^2/\lambda)(\beta\gamma/\beta_{inj}\gamma_{inj})$ where a and b are the horizontal and vertical semi-apertures of the vacuum chamber. Figure 2 shows beam intensities for different pressures in the ring. The injection energy is 5 MeV, and acceleration starts 1 msec later. The protons are accelerated to 230 MeV in 0.5 sec. Beam loss of less than 5% can be attained under the pressure of less than 3×10^{-7} Torr, which will be achieved without baking.

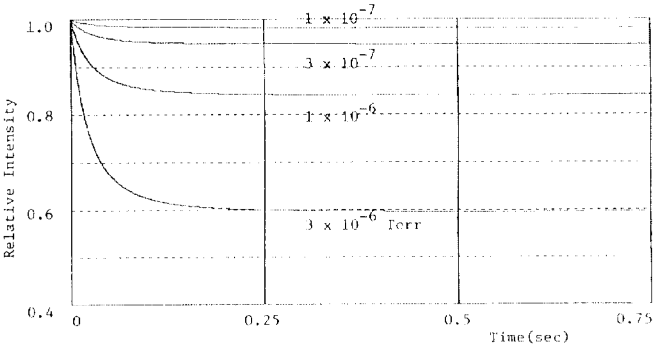

Fig. 3 Beam loss during acceleration in 0.5 sec from 5 MeV to 230 MeV for different pressures in the ring.

Injector

There are two options for the injector. One is a DT linear accelerator, which is now widely used for the proton and heavy ion synchrotron injector, and the other is a Van de Graaff accelerator. Although both are established technically, the most favorable injector system is a combination of a 10 MeV DT linac and H^- charge-exchange injection scheme. The charge-exchange injection was supposed to be effective for high energy H^- ions of more than 50 MeV, but it worked well for 20 MeV H^- with a specially prepared carbon stripping foil at KEK in 1985. It can be applied for 10 MeV H^- ions [5]. This injector system simplifies the vacuum system, increases the beam intensity or reduces the synchrotron magnet aperture. Residual activity produced by beam loss at injection is little. However, installation and operation costs of the system are expensive so far.

Tandem Van de Graaff Accelerator

It was used as an injector in the early days of the proton synchrotron. Combined with a modern high intensity H^- ion source, a Tandem Van de Graaff accelerator can be used as the injector. In addition to the huge electrostatic accelerators, a number of small tandem machines are distributed world-wide.

There are two methods of generating high DC terminal voltage, mechanically with a charging belt or pellet chain or electrically with rectifiers and capacitors. Since the needed average beam current is very low, a Van de Graaff accelerator is chosen and estimations of the beams are made for NEC 9SD-2 Pelletron. Its rating terminal voltage is 3 MV.

The Tandem Van de Graaff accelerator is primarily designed for a low intensity (≈μA) steady beam and not for a high intensity (≈mA) pulsed beam. No Sparking occurred for high intensity pulsed heavy ions such as Si and Cu accelerated by NEC 12UD Pelletron at Tandem Accelerator Center of the University of Tsukuba with a terminal voltage of 10 MeV [6]. It might be conservative to operate 9SD-2 Pelletron with a terminal voltage of 2.5 MV to get 5 MeV protons.

The beam emittance increases with its intensity. The normalized emittance of 20 mA H^- beam is typically 2 π mm.mrad at 750 keV in routine operation at KEK, and it is larger than the normalized acceptance 1 π mm.mrad of 9SD-2 [7]. If Gaussian distribution of the beam is assumed, a half of the injected beam can reach the terminal. A 5 $\mu g/cm^2$ carbon stripping foil changes almost completely H^- ions into protons. Because of mechanical strength, multiple scattering by a 10 $\mu g/cm^2$ foil is treated and 85 % of the 2.5 MeV protons are estimated to be 5 MeV.

The beam pulse duration is 24 μsec for 20 turn injection to the ring. If a 5 mA beam passes through the terminal, the total charge to the terminal is 240 nano-Coulomb. When the capacity of the terminal is 70 pF [7], its voltage drop by the beam loading is - 3.4 kV. The change of the accelerated protons is twice of the voltage drop and - 6.8 keV or 0.14 % of their energy. This corresponds to $\Delta p/p = \pm 0.07$ % and is much smaller than ± 0.3 % for the RF design.

Beam Intensity

For following efficiencies;

injector transmission	0.4
beam transport from injector to ring	0.9
multi-turn injection	0.5
RF capture	0.5

and for 1.3×10^{11} ppp in the ring, the injector beam should be more than 4 mA. A beam more than 10 mA of 70 keV should be injected into the injector.

High Energy Beam Line

There are two treatment rooms. The accelerated protons are transported to the targets by high energy beam lines as shown in Figure 4. Each room has two vertical beams, one from upper and the other from lower. One room has a horizontal beam additionally.

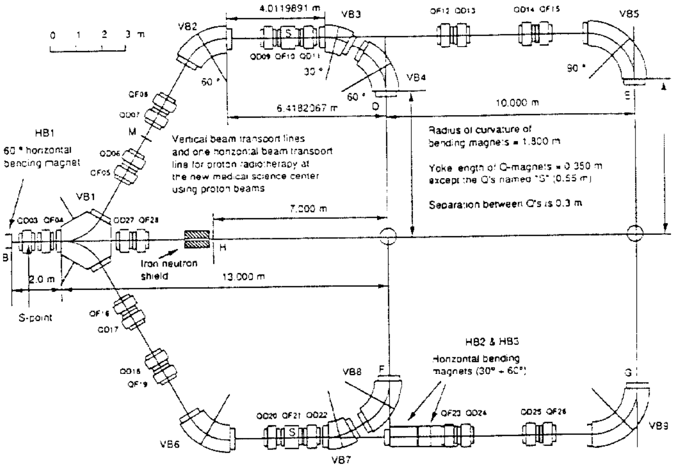

Fig. 4 High energy beam lines for two treatment rooms.

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