PRESENT STATUS OF COMPACT MEDICAL PROTON SYNCHROTRON DEVELOPMENT

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Abstract

Compact medical accelerator is being discussed to promote the advanced cancer treatment which has no regional dependency, because it can be installed at any hospital without special facilities at cheaper cost than ever. As one of candidates for this purpose the proton pulse synchrotron by adopting high field magnets is under development. The heavy ion synchrotron will be easily realized by applying the same technologies which have been developed in the compact proton synchrotron. Main magnet and RF systems were already manufactured and their performances are being studied.

INTRODUCTION

In general the maximum proton energy required for the radiotherapy is 230 MeV of which range is ~33 cm in tissue. However, every medical accelerator is not always necessary to attain the highest energy if the medical accelerators are classified into several categories in the attainable energy. The regional medical center should be equipped with the machine of the highest energy and others located not far from this center with the modest energy which can treat most of the deep seated cancers. According to the screening by the radiation oncologist the patients could be treated at the most suitable medical facility. The present pulse synchrotron aims 200 MeV corresponding to the maximum range of ~26 cm in tissue. It adopts the high field dipole magnet to reduce the bending radius which is 0.72 m for 3 T and the ring circumference is reduced to 9.4 m. Therefore, the ring itself can be installed in the small room of 5 x 5 m^2, but power supplies will occupy additional 100 m^2 or so.

As the most important synchrotron components, the compact magnet and acceleration systems were manufactured with their power supplies and their performances are being studied.

PULSE SYNCHROTRON

Main features of the 200 MeV proton pulse synchrotron are given in Table 1. Ring has the lattice structure of DOB in 4 fold symmetry [1]. The previous lattice had adopted both focusing (QF) and defocusing (QD) quadrupole to have better tunability [2], however, in new lattice QF is omitted to save the space because both horizontal and vertical tunes can be managed barely only by the defocusing element as shown in Fig.1.

Four straight sections, each having 1 m, are used for injection, RF cavity and fast extraction. The fast extraction system will occupy 2 straight sections for the kicker and septum magnets.

In every straight section the correction sextupole magnets are installed to correct the large sextupole field component contained in the dipole field. They are indispensable to stabilize the beam orbit [3].

Table 1: Parameters of the proton pulse synchrotron.

Lattice	DOB	FODOFB
Max. energy (MeV)	200	
Inj. Energy (MeV)	2	
Av. Beam current (nA)	~20	
Acc. time (ms)	5	
Max. dipole field (T)	3	
Dipole gap height (mm)	50	
Max. dipole current (kA)	200	
Orbit radius (m)	0.72	
Max. quad gradient (T/m)	30	
Max. quad current (kAT)	15	
Quad length (m)	0.14	0.18
No. of quads	4	12
Superperiod	4	
Circumference (m)	9.4	11.9
Long straight section	1.0 m x 4	0.6 m x 8
Tune (QH/QV)	1.6 / 0.6	2.25 / 1.25
Acc. frequency (MHz)	2.04-17.2	1.6-14.3
Peak RF voltage (kV)	10	13
No. of RF cavity	1	1
Repetition rate (Hz)	<5	<5

MAGNET AND POWER SUPPLY SYSTEM

Magnets

Main dipole and quadrupole magnets were already manufactured and their performances were measured under the pulse excitation. The coil conductor of the dipoles has been altered to the hollow conductor with the same outer dimensions instead of the previous strand cable. A slight increase of the sextupole component is expected for the dipole with the hollow conductor coil by the 3D dynamical field simulation [1]. Field measurement gave the expected results as shown in Fig.2.

Power supplies

The pulse current to excite the dipole magnets is the discharge current of the capacitor bank of which total capacity is 10 mF and its maximum voltage is 6.5 kV. The matching transformer placed between the dipole magnet and the discharge circuit serves to amplify the secondary current according to the winding turn ratio of 11:1. Thus the peak current is 200 kA which generates the maximum bending field of 3 T. After attaining the maximum field, the residual energy in the dipole magnets is recovered to recharge the capacitor bank and the consumed energy is compensated from the primary line with the charging circuit. At present this power supply is able to operate at 1 Hz repetition rate [4].

Quadrupole magnets were measured with long twin coils up to 3 kA corresponding to the field gradient of 30 T/m. Fig.3 shows the normalized integrated gradient distribution by measurements. Slight sextupole field component is observed.

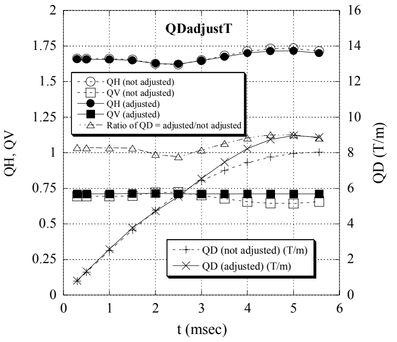

Figure 1: Horizontal and vertical tune variation by changing the QD gradient. When the vertical tune QV shown by filled squares is kept constant, the horizontal tune QH varies as shown by filled circles.

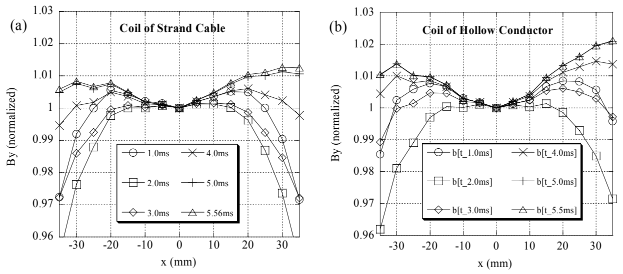

Figure 2: Dipole field distributions by measurement, (a) strand cable, (b) hollow conductor.

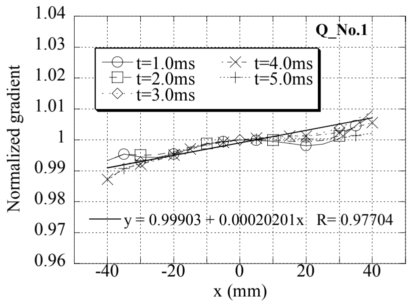

Figure 3: Radial distribution of the integrated gradient of the quadrupole magnet.

A short uniform injection field of 10-20 μs duration for the multi-turn beam injection should be attached at the beginning of the half sinusoidal dipole field by superposing small pulse current which is generated by the discharge of small capacitor bank. For this purpose an auxiliary power supply has been connected to the primary winding of the matching transformer in parallel with above pulse power supply as shown in Fig.4 [5, 6]. The pulse power supply is triggered with a short delay time after the auxiliary power supply is operated so that the injection field is smoothly connected to the acceleration phase [7, 8].

As the dipole current increases suddenly when the acceleration begins, the QD current must be controlled precisely by PWM (Pulse Width Modulation) of the stabilized DC source with IGBT (Integrated Gate Bipolar Transistor) in order to track the dipole current (or field) accurately. The current is regulated at 100 kHz with 10 IPM's (Intelligent Power Module) in parallel. Each IPM is controlled at 20 kHz, but two IPM's are provided with the same PWM at 5 μs interval. Accuracy of the tracking to the dipole current is confirmed by the circuit simulations with Micro-Cap as shown in Fig.5. The QD current is well regulated to ±0.1% by 100 kHz PWM at transition from injection to acceleration. Tracking error is given by the magnetic flux difference in both magnet for the sake of convenience [9]. The QD current pattern can be corrected in every short interval between the successive operations according to the dipole current immediately before the present operation cycle.

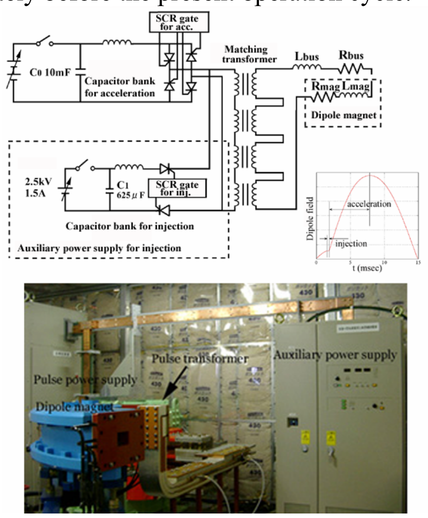

Figure 4: Auxiliary power supply has been connected to the pulse power supply in parallel at the primary winding of the matching transformer.

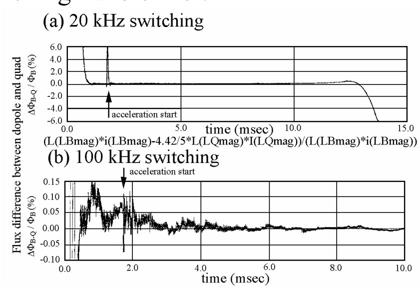

Figure 5: Current tracking accuracy by the circuit simulation for (a) 20 kHz and (b) 100 kHz PWM control.

RF SYSTEM

A compact RF cavity with two acceleration gaps (0.4 m in total length) fit to the half of one straight section is developed successfully. Its maximum field gradient is 60 kV/m at 5~6 MHz where the pre-amplifier gain and the cavity frequency response are large [10, 11]. The cavity performance of the high power test is shown in Fig.6. The measured cavity voltage exceeds the value required by the fundamental acceleration frequency which spans from 2 MHz to 18 MHz with no parasitic resonance.

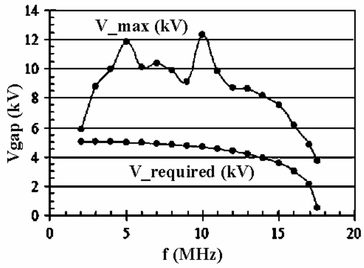

Figure 6: Measured maximum cavity voltage (V_max) of each gap exceeding the required voltage (V_required) for whole range of the fundamental acceleration frequency.

The acceleration frequency is obtained from the data table stored in ROM (Read Only Memory) when the real dipole current (or field) signal is fed to the low level controller in which DDS (Digital Data Synthesizer) generates the RF frequency at 2 MHz clock rate as shown in Fig.7. In this low level test the measured dipole current is fed by an arbitrary function generator in which the current data of the text format are stored at every 2 µs. In Fig.7 the smooth programmed voltage envelope is obtained, as the RF voltage feedback control is applied [12].

The stable acceleration phase is a function of the acceleration frequency and should be also programmed. Its feedback control test is scheduled for the final test of the RF system shortly. The preliminary test was performed at several fixed frequencies as given in Fig.8 which shows the linear response for the wide angle range. Total RF high power system developed so far is shown in Fig.9.

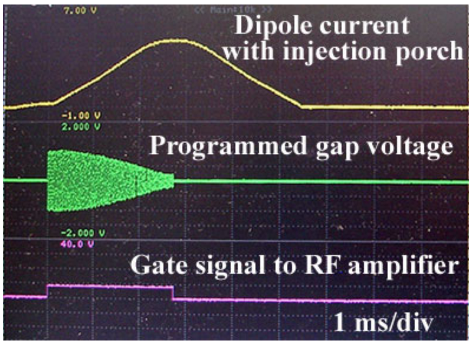

Figure 7: RF frequency generation (2 MHz at 2 MeV and 18 MHz at 200 MeV) sensing the dipole current (top trace) which is fed by an arbitrary function generator.

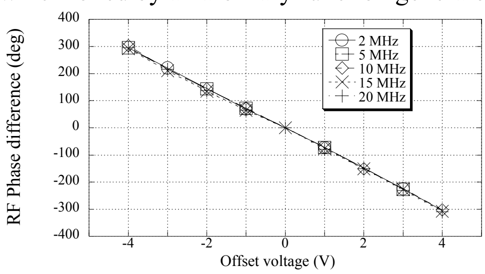

Figure 8: Preliminary phase feedback test on its linearity.

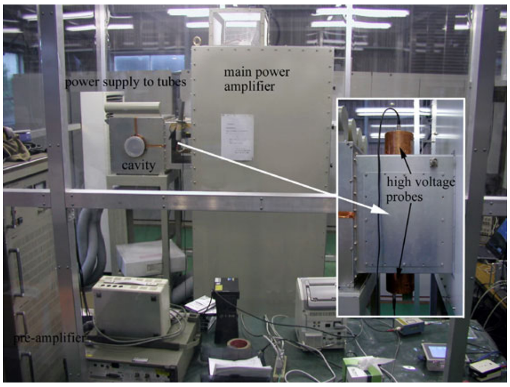

Figure 9: Developed RF high power system. Compact cavity is connected to the power amplifier in the middle. Pre-amplifier is at the left bottom corner and DC power supply to the main amplifier is in the rear.

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