HARDWARE TRACKING RELATED TO COMPACT MEDICAL PULSE SYNCHROTRON*

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Abstract

A compact 200 MeV proton synchrotron for the radiotherapy is being developed. Dipole and quadrupole magnets were already manufactured and their field measurement is now going on under the pulse excitation. Preliminary field measurement was already done on the prototype dipole. Small RF cavity with a wide bandwidth (2~18 MHz) was successfully developed. Concerning to the simultaneous pulse operation of these components, there are some issues to be solved beforehand. These are the tracking between dipole field and the quadruple field gradient and the RF frequency generation sensing the dipole current (or field). These problems are being studied experimentally and numerically referring to the dipole current which plays an important role in the simultaneous operations of the synchrotron components.

INTRODUCTION

A very compact and cheap medical accelerator is demanded because the malignant tumor treatment based on the accelerator is expected to be an efficient remedy to keep QOL (Quality Of Life) in the country in which society is aging. The present work is playing a role to develop a compact proton synchrotron by reducing drastically its size by adopting the high power pulse technology. Benefits obtained by reducing its size are a low initial investment cost, a small space for installation and a low running cost. These factors will reduce the doctor's fee in which the machine construction and running costs are shared.

Essential items of the pulse synchrotron are the developments of the magnet and RF systems. The dipole and quadrupole magnets have been developed including their power supplies. The correction magnet system will be prepared in the near future. The RF system is almost completed except for the beam monitors which are used for the beam feedback control.

In this manuscript the hardware tracking characteristics of the quadrupole field gradient and accelerating frequency to the dipole field are treated experimentally and/or theoretically.

COMPACT PULSE SYNCHROTRON

A compact synchrotron under development is a small proton synchrotron based on the pulse technology to reduce the ring size drastically in order to use mainly for the radiation therapy. The circumference is less than 10 m by adopting the high field pulse dipole magnet which is excited to 3 T at maximum for 200 MeV proton. Its lattice configuration is simplified to DOB with 4 fold symmetry as shown in Fig.1. The dipole magnets are excited by the discharge current of the capacitor bank (6.5 kV, 10 mF) through the pulse transformer with the turn ratio of 11:1. The nominal current rise time is 5 ms and the fall time 5 ms corresponding to the half quasi-sinusoidal waveform by retrieving the residual energy in the dipole magnet.

The defocusing quadrupole magnet (QD) is excited with the 100 kHz switch-mode power supply of IGBT (Integrated Gate Bipolar Transistor) so as to track accurately to the dipole field. Moreover, the quadrupole field component in the dipole field must be compensated by adjusting the current of QD in addition to the fine tuning during acceleration [1]. An example of the fine tuning of QD is shown in Fig.2 in which the error quadrupole field component of the dipole magnet is considered according to the field measurement. All dipole and quadrupole magnets are already manufactured and their field measurement is underway.

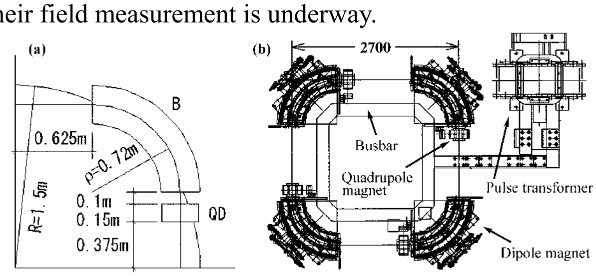

Figure 1: (a) DOB lattice and (b) the assembled image of the ring.

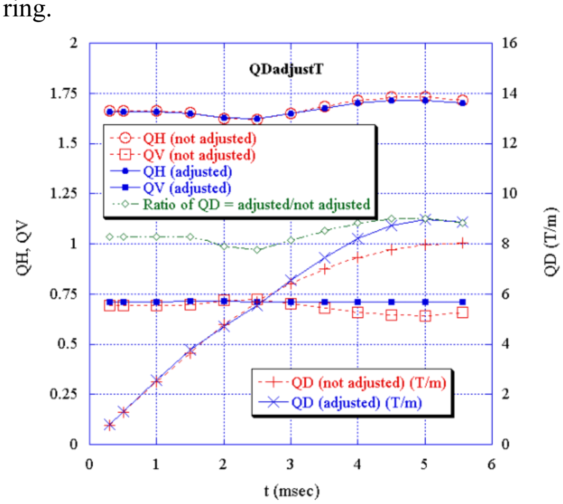

Figure 2: Example of the fine tuning for DOB lattice. In this case the current pattern of QD is controlled so that the vertical tune QV is constant during accerletion. The filled squares and circles are after the fine tuning and the corresponding QD excitation is marked with the symbol "x".

*Work supported by MEXT of Japan.

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The RF system has been almost completed. The required gap voltage of the cavity has been confirmed for whole frequency range in the high power test. The total cavity length is 40 cm which occupies half of one straight section. The observed maximum average acceleration voltage is 60 kV/m for 5~6 MHz around which the pre-amplifier has the maximum output gain and the cavity impedance has a peak value of 550 Ω. The acceleration frequency is generated by feeding the signal of the dipole current to the DDS (Digital Data Synthesizer). The continuous frequency generation has been successfully tested.

The main parameters of this compact proton synchrotron are given in Table 1.

Table 1: Parameters of the compact proton synchrotron.

Item	Value	Unit
Max. energy	200	MeV
Inj. energy	2	MeV
Av. Beam current	~20	nA
Acceleration time	5	ms
Circumference	9.5	m
Av. diameter	3	m
Max. dipole field	3	T
Max. Dipole current	200	kA
Max. field gradient	30	T/m
Max. quadrupole current	15	kAT
Orbit radius	0.72	m
Tune (hor/ver)	1.6 / 0.6	
Max. betatron function (hor/ver)	2.8 / 2.5	m
Max. dispersion function	0.8	m
Acc. frequency	2.0~17.8	MHz
Max. acc. voltage	10	kV
Repetition rate	<5	Hz

MAGNET AND POWER SUPPLIES

Power supplies for the dipole and quadrupole magnets have been manufactured. The dipole power supply consists of the main and auxiliary units. The former produces the main pulse current with a peak value of 200 kA corresponding to the dipole field of 3 T. The latter is used to produce the injection field (0.28 T at 11.6 kA) of which peak is flat within 10^{-4} during 10~20 μs for the multi-turn injection of the negative hydrogen ions [3]. Both currents are superposed but the former is triggered little after the latter is triggered. The delay time (~1.4 ms) is adjusted with the delay circuit to connect smoothly the injection field to the acceleration ramp-up field.

The quadrupole magnets are excited with the switch-mode power supply of which output current is regulated with the IGBT modules in 100 kHz. As each module is operated in 20 kHz, 10 modules are paralleled to operate at an interval of 5 μs but the PWM (Pulse Width Modulation) is applied to 5 pairs [4]. The current pattern is generated by referring to the dipole current. The real current is sensed with DCCT (DC Current Transformer) and digitized with the 2.5 MHz 16-bit DAC (Digital-to-Analogue Converter) to generate the quadrupole current waveform for the next cycle.

At the transition from injection to acceleration the current regulation becomes severe because of the transient quadrupole current. It is the reason why the 100 kHz switch-mode power supply is adopted. According to the circuit simulation the current is regulated to 10^{-3} by the 100 kHz switching. In Fig.3 simulations for the 20 and 100 kHz cases are compared.

RF ACCELERATION SYSTEM

A compact RF cavity fit to a short straight section has been developed by adopting 8 cores of the magnetic alloy (each having 397 mm in o.d., 158 mm in i.d., and 25 mm in thickness). It has two acceleration gaps with the separation of 20 cm. Its performance was reported already at the previous conferences [2, 5]. The high power test is being continued since 2003. The required accelerating gap voltage has been generated in the range of 2~18 MHz which is the fundamental frequency range for the harmonic number of h=1. The RF power is fed by the push-pull power amplifier of two tetrodes of 4CX35,000C which is drived by the bipolar 2 kW pre-amplifier.

At an early high power test the parasitic resonances were observed at 8.3 and 13.3 MHz with the anode reactor of 160 μH. It was expected by the circuit simulation that the reactor inductance couples with the stray capacitance to give rise to the parasitic resonance. If the inductance is reduced, it can be expelled out of the operational frequency range. Fig.4 shows the process how they are drove out by reducing the anode inductance.

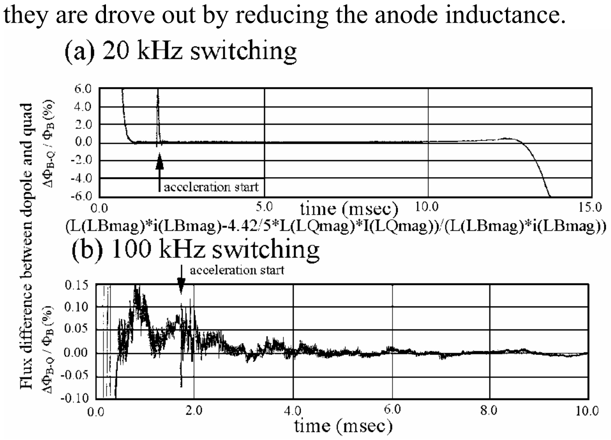

Figure 3: Quadrupole current regulation by the circuit simulation, (a) 20 kHz and (b) 100 kHz switching.

In Fig.4 the acceleration takes place in 5 ms during which the frequency is swept from 2 MHz to 18 MHz. The envelop gives the acceleration gap voltage which reflects both the cavity impedance and power amplifier characteristics. If the real-time voltage feedback is applied the envelope follows the programmed pattern as shown in Fig.5 [6]. The top trace is the dipole excitation current pattern with the short injection porch before the acceleration begins. This current pattern is supplied with the 16-bit arbitrary function generator which saves the

 0-7803-8859-3/05/$20.00

current data at every 2 μs in the text format. The DDS generates the RF frequency according to the dipole current.

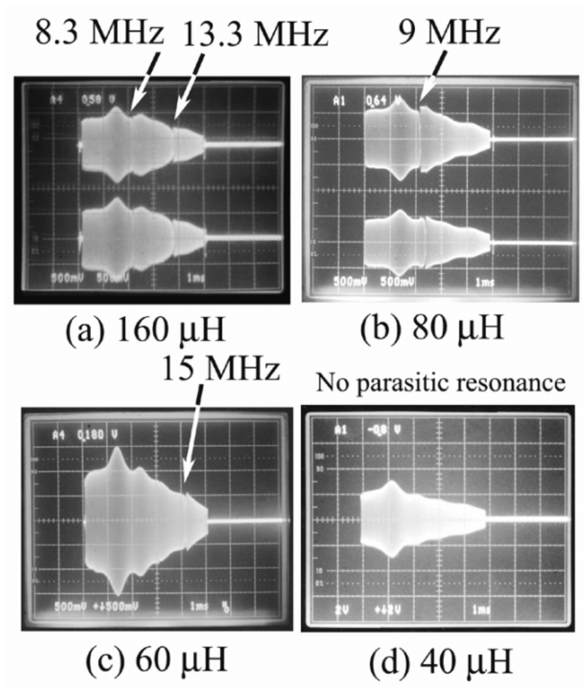

Figure 4: Dependence of the parasitic resonances on the anode inductance, (a) 160 μH, (b) 80 μH, (c) 60 μH and (d) 40 μH. Envelopes of two gap voltages are shown separately in (a) and (b), but their difference is given in (c) and (d). The horizontal axis is 1 ms/div.

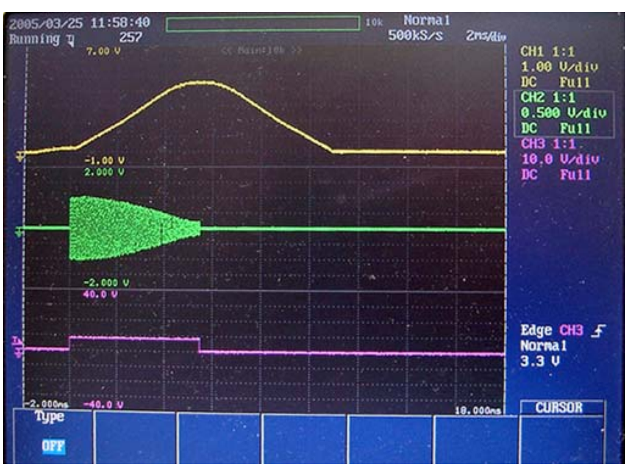

Figure 5: Performance of the real-time acceleration voltage feedback. Top: Dipole current waveform, Middle: Envelope of the programmed gap voltage, and Bottom: Gate signal to the RF amplifier.

FUTURE PLAN

In this fiscal year (2005) the correction magnet systems including its power supplies will be developed. The correction windings attached to the pole surfaces of the dipole magnets will serve to compensate locally the sextupole components at the low field. Their power supplies must combat with the induced voltage (~250 V/magnet) due to the time-dependent variation of the flux through the windings. At higher field the independent strong correction sextupole magnets are indispensable to stabilize the circulating proton beam. Both these magnets should be excited in phase with the dipole field.

Another component planned is the kicker magnet system for the vertical fast beam extraction adopting the Lambertson magnet. For an efficient extraction its rise time should be well less than the revolution period which is 56 ns at 200 MeV. The maximum kicker field will be 0.1 T with the length of 30 cm. It requires the high voltage power supply to establish the kicker field in 30 ns or so. Extracting in several turns as an alternative reduces the efficiency significantly [7, 8].

Authors are very grateful to Professor Y. Hirao for supporting the work to develop the pulse synchrotron and also to Dr. S. Yamada of NIRS for the beautiful management of several projects involved in the advanced compact accelerator development program.

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