MAGNET AND RF SYSTEMS OF SMALL PULSE SYNCHROTRON FOR RADIOTHERAPY

K. Endo*, K. Egawa, Z. Fang, S. Yamanaka, KEK, Tsukuba, Japan

Abstract

The pulse synchrotron aims to reduce the size of the accelerator by generating the high magnetic field in a short time which leads to a compact ring of high field magnets. Acceleration time is only 5 msec by using the discharge current of capacitor bank as large as 200 kA at peak, almost equivalent to half sinusoidal 50 Hz waveform. Part of the discharge current is branched to excite the quadrupole magnets to assure the tracking between the dipole and quadrupole fields. Pulsed power technique is also adopted to drive the RF power tubes. Both magnet and RF systems have been developed and being extensively studied. Technological sides of both systems will be treated in details as well as the theoretical beam parameters of this pulse synchrotron.

INTRODUCTION

To cure the malignant tumor it is desirable to equalize the treatment level to everybody anywhere he lives in. Proton and/or carbon-ion therapy are now considered as a powerful remedy as the radiation dose can be easily concentrated to the target volume by utilizing the Bragg's peak. If a small medical accelerator is developed at a reasonable cost, it has a big potential to promote the advanced medical treatment with the accelerator in every place.

The pulse synchrotron means that it has small ring circumference by adopting very high field dipole magnet to reduce the orbit radius well less than 1 m and its compacted magnet must be excited by a large peak current in very short time to avoid the excessive Joule heat in the magnet coil. By the half quasi-sinusoidal excitation with a peak current I_p [A], the pulse rate η [repetitions/sec] and the rise and fall time equivalent to the nominal frequency f =50 [Hz], the effective current is $I_{eff} = 0.5 I_p \sqrt{\eta / f}$ [A]. As the dipole already developed has the peak current of 200 kA for 3 T field at maximum, it is simply expressed as $I_{eff} = 14.1 I_p \sqrt{\eta}$ [kA] [1].

Four dipoles connected in serial are excited by the discharge current of the capacitor bank with 6.5 kV and 10 mF and the nominal acceleration time is 5 msec. A part of the discharge current is branched to excite the serially connected 4 defocusing quadrupole magnets.

To drive the 2 RF power tubes (4CX35,000C) in push-pull operation the relatively large capacitor with 10 kV rating is adopted which enables the repetition up to 10 Hz. Both magnet and RF systems have been already developed and being extensively studied. After the precise field measurements of magnets they will be ready to form a small ring by which the field tracking control between the dipole and quadrupole magnets and the accelerating frequency generation from the online dipole field sensing will be studied.

*kuninori.endo@kek.jp

MAGNET SYSTEM

Dipole Magnet

The original dipole coil is made of the paralleled 30 x 30 mm^2 strand cables having the cooling channel of 10 mm in diameter. However, it has been replaced with the hollow conductor of the same cross-section but the cooling channel of 12 mm in diameter because the heat conductivity of the former cable is insufficient for the operation more than 1 Hz. The anticipated problem associated with this replacement is the disturbance of the field distribution by an eddy current in the hollow conductor. Its effect is confirmed by the numerical field analysis by using the dynamic 3D code, JMAG. The cross-section of the dipole is shown in Fig.1 in which the 2 turn windings for the sextupole correction is given. By the half sinusoidal excitation to the peak current of 200 kA, the field distributions for the strand cable and the hollow conductor are given in Fig.2a and 2b, respectively.

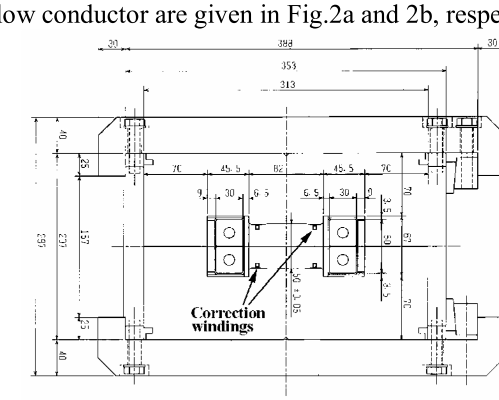

Figure 1: Dipole magnet with the correction windings.

The corresponding field distributions are also given in Fig.3 at 1, 3 and 5 msec [2]. The absolute field increases for the hollow conductor and the relative difference between them is very little as seen from the normalized field distributions. Thus the hollow conductor is adopted. The precise field measurement will be scheduled in this year.

The large sextupole component is inevitable to the compact dipole magnet. The measured field components for the dipole equipped with the strand cable are given in Fig.4. As the quadrupole component is not so large, its contribution to the tune is manageable and it is possible to correct by the fine adjustment of the excitation current waveform of the quadrupole magnet.

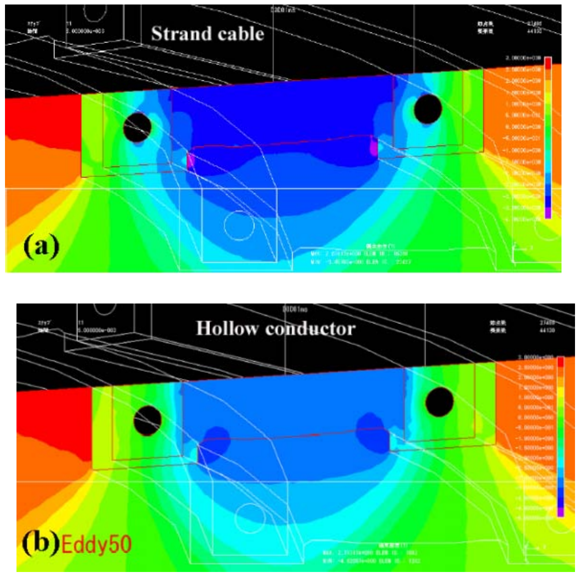

Figure 2: Field distributions at 200 kA excitation for (a) strand cable and (b) hollow conductor.

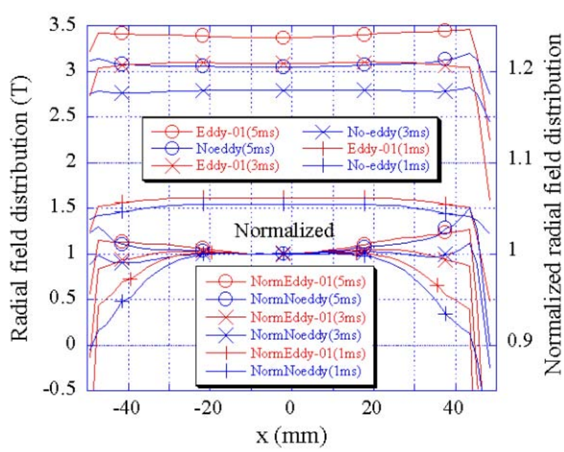

Figure 3: Normalized and absolute field distribution at 1, 3 and 5 msec.

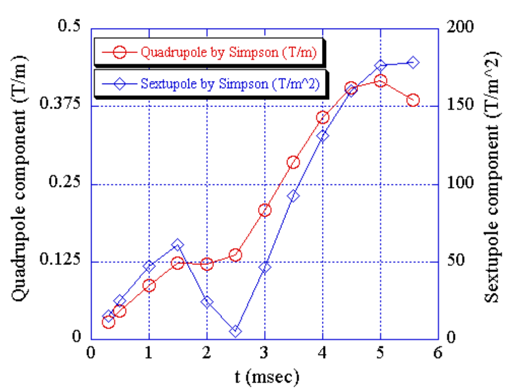

Figure 4: Measured error field components averaged over the dipole with the coil made of the strand cable.

As for the sextupole component, its contribution is so large that it must be corrected by using both the correction windings in the dipole and the sextupole correction magnets. Numerical estimation of the correction windings is obtained as shown in Fig.5. Its current must be supplied externally opposing to the current induced by the flux linkage from the main coil. Thus, the external loads, both inductor and resistor, to the correction windings will be connected so as to reduce the induced current. Without them it amounts to several thousand amperes.

The sextupole strength by the correction windings is limited by both the current supply and the saturation level of the dipole core. If the core is not saturated, it is possible to excite as far as the power supply allows. From Fig. 4 the core begins to saturate at around 1.5 msec and behaves non-monotonically up to 2.5 msec after when the sextupole component grows due to the gradual increase of the core saturation.

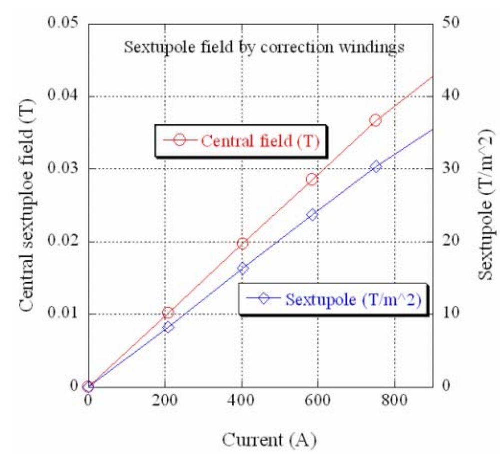

Figure 5: Estimated sextupole strength by the correction windings. The main dipole field is affected by the excitation of the correction windings and it is given as the central field.

Quadrupole Magnet

Four dipoles and four quadrupoles are already manufactured which form the compact synchrotron ring with the DOB lattice as shown in Fig.6. The quadrupole acts as a defocusing element (QD) and the maximum field gradient is 30 T/m at 4 kA to the bore diameter 70 mm and the coil of 5 turns/pole. With this configuration the orbit parameters are shown in Fig.7(a) and (b) at injection (2 MeV) and 200 MeV, respectively. The quadrupole field component of the dipole is reflected but the QD strength is given so as to be proportional to the proton momentum in this case.

RF SYSTEM

Adopting the magnet configuration of Fig.6 without the focusing quadrupole magnet, the RF parameters have changed from the previous lattice design in which the quadrupole triplet was employed [3].

The accelerating frequency range is 2~18 MHz corresponding between 2 MeV at injection and 200 MeV. The required maximum gap voltage is 10 kV for the phase angle of 40 deg. Very short cavity with the length of 0.4 m, in which there are 2 gaps separated by 0.2 m, could successfully generate the required gap voltage for this wide frequency range [4, 5].

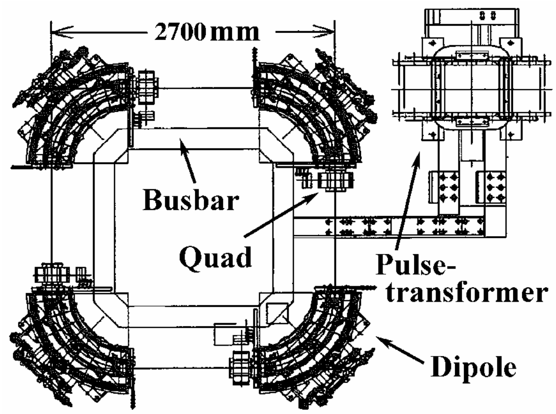

Figure 6: Layout of dipoles and quadrupoles.

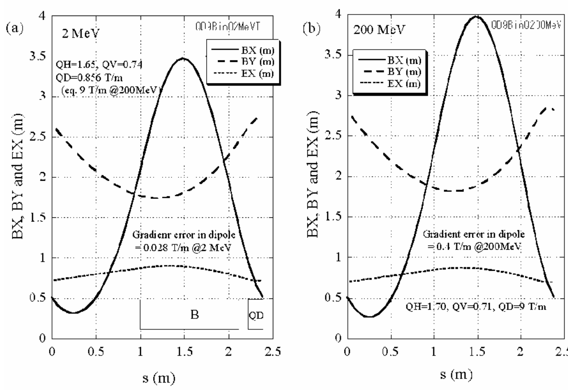

Figure 7: Orbit parameters considering the quadrupole field component of Fig.4 at (a) injection and (b) 200 MeV. The QD strength is assumed to be proportional to the proton momentum for this calculation.

Accuracy of the accelerating frequency is given in Fig.8 assuming the orbit deviation less than ±1 mm inside the dipole magnet and the peak dipole field of 3 T by 50 Hz half sinusoidal excitation with no saturation. Allowed accelerating frequency error is almost 0.05% and the corresponding maximum clock rate to change the frequency data through the DDS (Direct Digital Synthesizer) is about 3.5 MHz at around 0.5 msec before which the clock rate is not necessary larger than the accelerating frequency. The present low level control system could attain 2 MHz which corresponds to the orbit deviation of ±2 mm [6].

Similar tight relations are anticipated to the allowed errors for the cavity gap voltage and the phase angle adjustments. It means the very precise RF control is foreseen for the compact synchrotron operation.

In summary this compact proton synchrotron is almost ready to assemble small ring of 9.54m circumference with 4 superperiods of DOB structure for further studies of fine tunings, tracking controls, etc.

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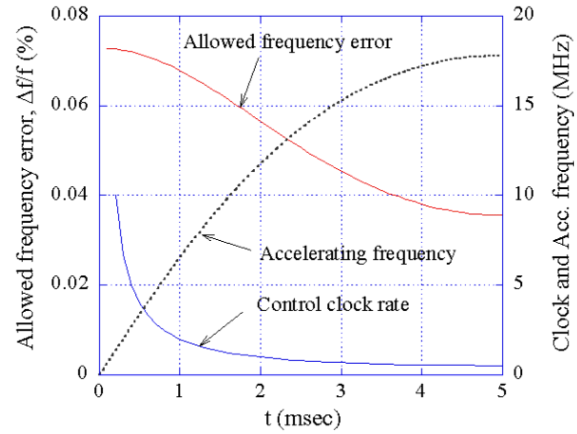

Figure 8: Accelerating frequency accuracy and the required clock rate to control the orbit deviation of ±1 mm inside the dipole.

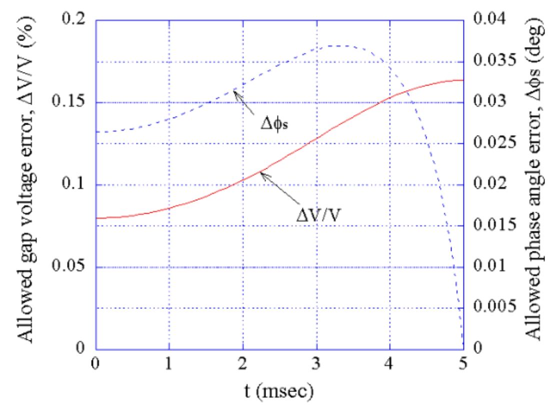

Figure 9: Allowed cavity gap voltage and phase angle errors for the same orbit deviation of Fig.8.

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