Compact Synchrotron for Radiotherapy Based on Pulse Technology

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Abstract To realize the small proton and carbon ion medical accelerator, a compact proton synchrotron is now under development by using the pulse power technology. Planned proton energy is 200 MeV at maximum by adopting the practical high dipole field of 3 T to get the small orbit radius. Through the past works on the detailed dipole field measurement and the pulsed power supply the problems related to the beam optics became clearer. They are treated here in relation to the revised lattice which is missing the focusing quadrupole magnet.

1. Introduction

Proton and/or carbon ion radiotherapy is now considered as an effective treatment to cure the malignant tumors. Its superiorities are not only in the localization of radiation to the affected volume but also in the non-invasiveness. The latter is very important factor in the countries where society is aging. Nevertheless, its adoption is limited by the expensive installation cost of the accelerator. This work is motivated to make a breakthrough in the accelerator technologies on which the present medical accelerators rely. For the treatment proton and carbon ion must have a sufficient range in the human tissue to cure the deep seated tumors. Usually their maximum accelerated beam energy is 250 MeV for proton and 400 MeV/u or higher for carbon ion. To make the accelerator compact in size so as to install at a reasonable cost in as many hospitals as possible, the maximum beam energy should be reduced to the level which can be applicable to the majority but not all. This attitude can lead to adopt the high field magnet to reduce the accelerator size. The small size and high field are inconsistent in the accelerator magnet. This difficulty leads to adopt the pulse power technology [1,2,3,4].

The main magnet system has manufactured except for the focusing quadrupole magnet and is waiting for the field measurement. A compact accelerating cavity and its RF power supply have almost completed. Its high power test is underway and the designed gap voltage was recognized already. Details of the RF system will be given in the companion paper to this symposium [5].

2. Compact Synchrotron Lattice

Every magnet used in the compact synchrotron is excited by the respective large pulse current. The dipole magnet attains 3 T at peak current of 200 kA and the defocusing quadrupole magnet is designed up to 30 T/m at 20 kA. These magnets have a nominal rise time of 5 msec during which the proton beam attains 200 MeV. Magnets are excited by a half sinusoidal current (equivalent to 50 Hz) with the repetition of 1 Hz or more depending on the heat dissipation of the coil. As for the carbon ion the required peak current to attain 300 MeV/u is estimated as 270 kA for 4 T dipole field [6].

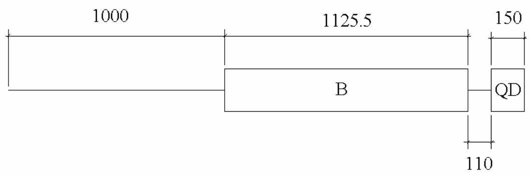

Figure 1: Superperiod of the proton synchrotron lattice for the missing QF version (unit: mm).

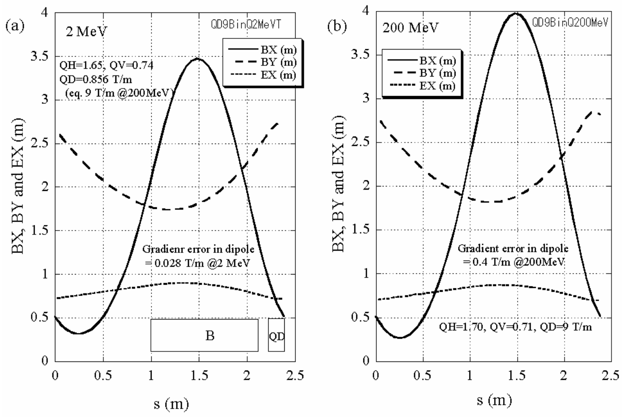

Figure 2: Beam parameters for the missing QF version. (a) QD=0.856 T/m at 2 MeV, (b) QD=9 T/m at 200 MeV.

The synchrotron lattice for the present magnet system is shown in Fig.1 for a superperiod which is the latest version of the missing QF and its beam parameters affected by the gradient error field in the dipole magnet are given in Fig.2 at injection (Fig2a) and at 200 MeV (Fig.2b). Small modifications are given to the short straight section to avoid the interference of coil ends of adjacent magnets. The ring consists of 4 superperiods to get 4 long straight sections to accommodate RF cavity, injection and extraction devices. Small sextupole and steering magnets are also installed after the main elements are placed.

The horizontal and vertical tune variations, shown as QH and QV respectively, by the excitation of the defocusing quadrupole magnet QD is given in Fig.3 when the gradient error in the dipole magnet is not considered. If the gradient error of Fig.4 is considered, it has a large contribution to the tunes as shown in Fig.5. As the gradient error in the dipole magnet is slightly focusing, it contributes to separate the horizontal and vertical tunes and helps to choose easily the operational tunes avoiding dangerous resonance but it requires the precise control of the excitation current of QD because the gradient error depends on the saturation degree of the dipole magnet. Fig.5 is obtained numerically at injection field. Similar calculations are required at each excitation level.

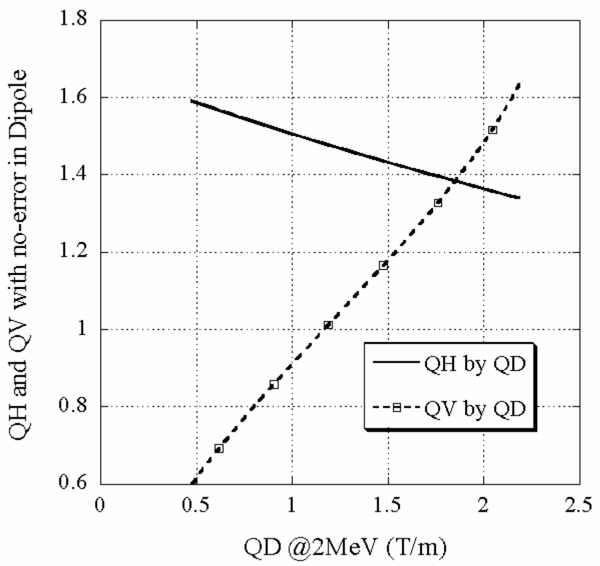

Figure 3: Tune variation by the defocusing quadrupole magnet QD at injection (2 MeV).

3. Sextupole Error Field Correction

In addition to the gradient error, the dipole magnet has a large sextupole component which must be compensated [7]. Fig.6 gives the sextupole component measured during the excitation. The dipole magnet begins to saturate around 2 msec and has a complicated behavior which requires a sophisticated correction. The sextupole strength averaged over the whole dipole magnet length is 15.4 T/m^2 at 2 MeV injection and 180 T/m^2 at 200 MeV. At injection protons with momentum -1%<Δp<1% should be saved by correcting the sextupole error field with both correction coils place in the dipole gaps and the independent sextupole magnets. The allowed sextupole magnet strength is limited less than 4 T/m^2 at injection according to the beam simulations shown in Fig.7. The correction coils are already equipped with the dipole magnets as shown in Fig.8.

At higher energy the correction coil is no more useful. The sextupole magnets are excited with the pulse power supply. Beam simulations show that protons with -0.3%<Δp<0.3% are stable by exciting 4 sextupole magnets (each 15 cm in length and 1350 T/m^2). Fig.9 gives the simulation result for 50,000 revolutions at 200 MeV.

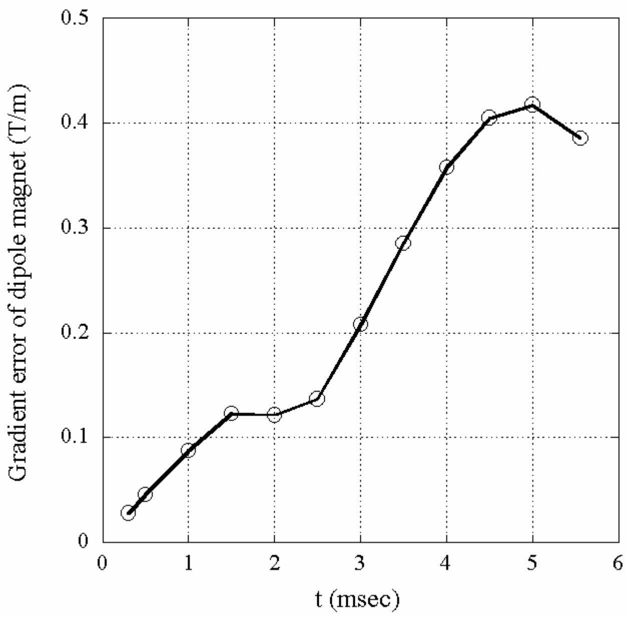

Figure 4: Measured gradient error averaged over the whole length of the dipole magnet.

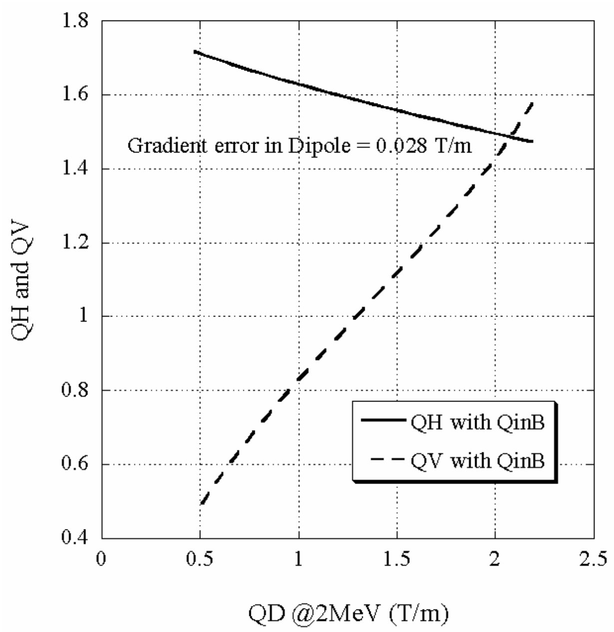

Figure 5: Tune variation by the field gradient of QD at injection when the gradient error of Fig.4 is considered.

4. Problems related to RF control

Due to the small circumference of the ring the RF system also has large effects on its control properties. From injection (2 MeV) to the maximum energy (200

MeV), proton is nominally accelerated in 5 msec. The revolution time changes from 493 nsec to 56 nsec, corresponding to the acceleration frequency of 2 MHz to 17.8 MHz. At higher frequency side the required acceleration voltage can be managed to generate, however, it is desirable to have a margin. The acceleration voltage is reducing because of the sinusoidal excitation of the dipole magnet. Therefore, the gap voltage is reduced as in Fig.10b instead of constant voltage of Fig.10a, while the acceleration voltage remains same in both cases by changing the RF phase. By this modification the momentum spread reduces remarkably to 0.35% benefiting to the correction of sextupole component of the dipole magnet.

The orbit excursion should be limited to minimal in the aperture of the dipole magnet. Effect of the deviation of the acceleration frequency Δf_a to the orbit radius ρ is given by

$$\Delta\rho = \left[\frac{1}{\rho\{1+(c\rho B/E_0)^2\}} - \frac{1}{R}\right]^{-1} \frac{\Delta f_a}{f_a},$$

where R is the average ring radius, B the dipole field and E_0 the proton rest mass. Assuming $\Delta\rho = \pm 1$mm at the dipole magnet, an accuracy of RF parameters can be estimated.

As the dipole field is generated by the discharge of the capacity bank, its current waveform and peak current is determined by the circuit time constant and the charging voltage. Its precise waveform control is difficult, so other devices must be controlled after the dipole field which is here treated as half sinusoidal magnetic field for the sake of convenience.

Fig.11 shows an accuracy of the acceleration frequency to attain the orbit stability less than 1 mm in the dipole magnet. As shown in Fig.12 the RF control clock rate is vary large at the lower frequency side but does not

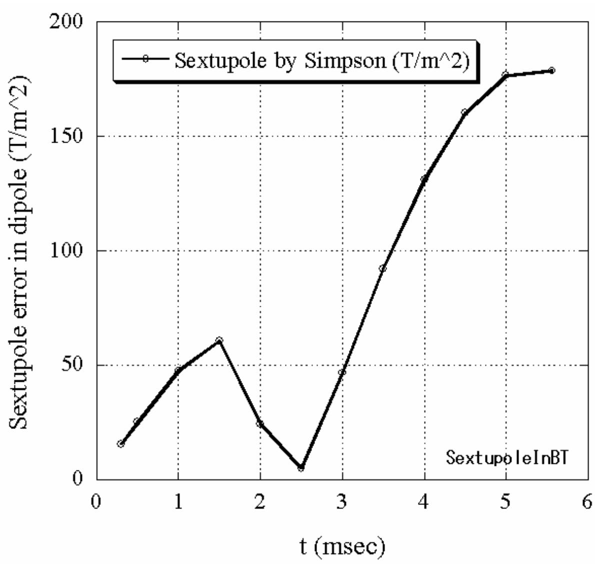

Figure 6: Sextupole field component in the dipole magnet.

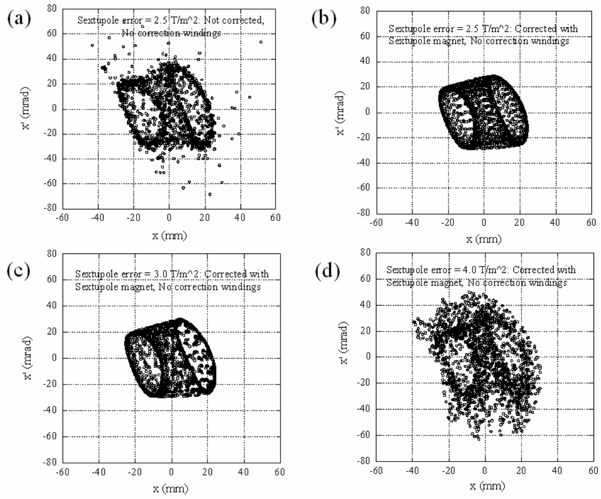

Figure 7: Proton behavior in the error sextupole field of the dipole magnet, (a) not corrected for 2.5 T/m^2, (b-d) corrected for 2.5, 3.0 and 4.0 T/m^2, respectively.

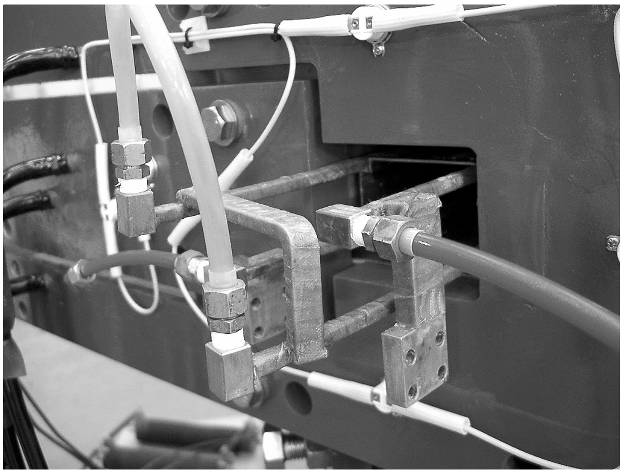

Figure 8: Correction coil in the dipole magnet gap.

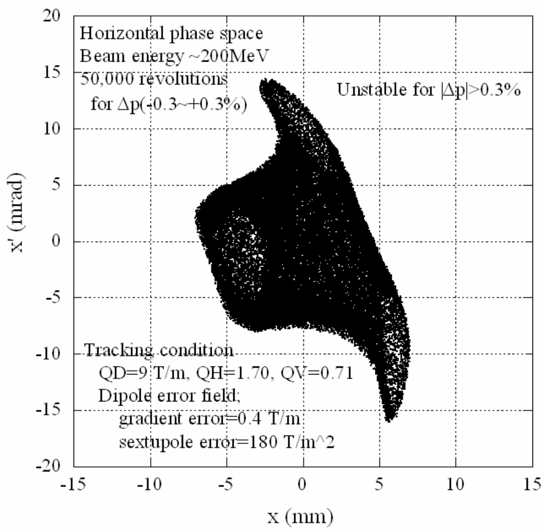

Figure 9: Sextupole error field of the dipole magnet is corrected with 4 sextupole magnets for proton with momentum of -0.3%<Δp<0.3% at 200 MeV.

need to be larger than the revolution frequency (harmonic number h=1 for this case). However, just after injection the RF control becomes severe when few MHz clock rate is required. Despite that the present low level control has attained 2 MHz clock, it requires more frequent control.

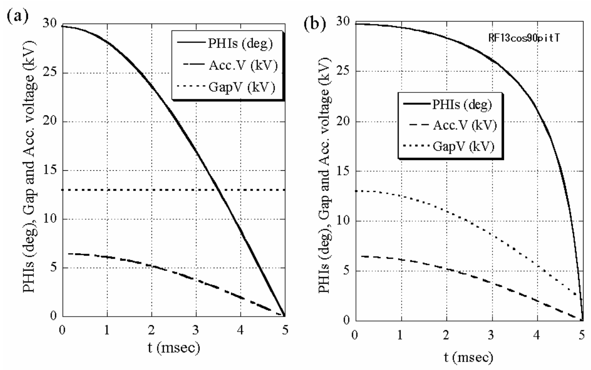

Figure 10: Required RF phase for the gap voltage: (a) 13 kV constant, (b) reduced according to 13cos(90πt) kV.

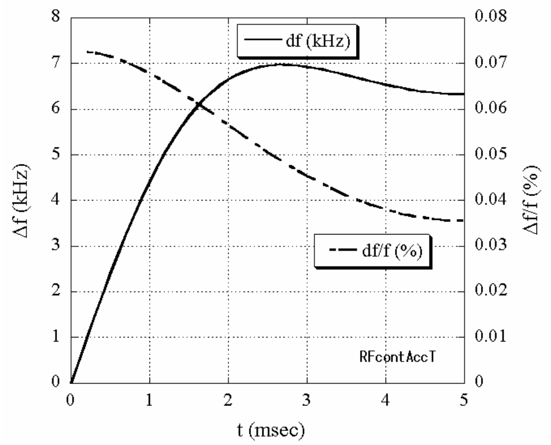

Figure 11: Accuracy of the acceleration frequency to attain the orbit error less than 1 mm in the dipole magnet.

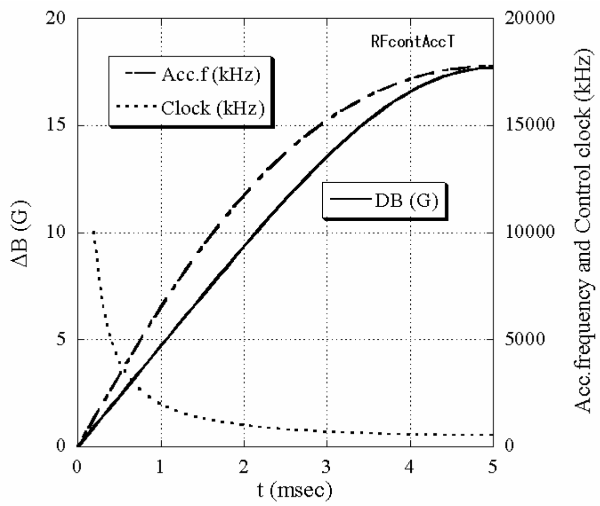

Figure 12: Control clock rate to attain the frequency error of 0.05%. ΔB corresponds to the 0.05% frequency step at each time.

As for the gap voltage and the RF phase control, the required accuracy is given in Fig.13 for the orbit deviation of 1 mm. Every RF parameter becomes very severe compared to the former ring which has both QF and QD quadrupole magnets [6]. In the old version the dispersion function is very small everywhere in the ring by a factor of 6 which makes the matter easy. For the compact synchrotron the dispersion function should be made as small as possible from the view point of the RF control.

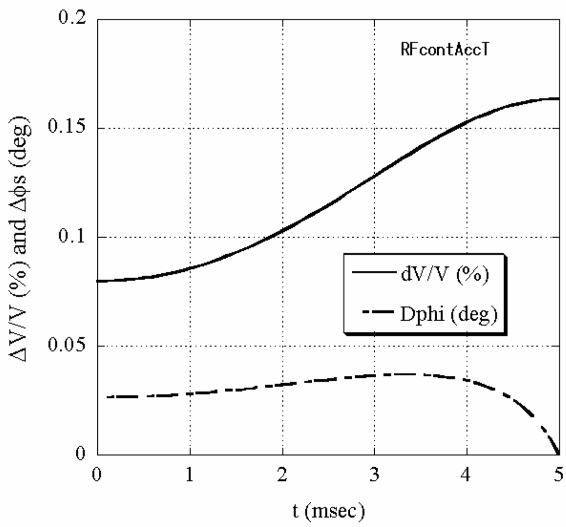

Figure 13: Accuracy of the gap voltage and phase control.

5. References

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