POWER SUPPLY FOR MAGNET OF COMPACT PROTON AND/OR HEAVY ION SYNCHROTRON FOR RADIOTHERAPY*

S. Yamanaka#, NIRS, Chiba, Japan
K. Endo, Z. Fang, K. Egawa, KEK, Tsukuba, Japan

Abstract

A resonant type pulse power supply, for an application to a compact proton and/or heavy ion synchrotron with a several Hz repetition rate, is attractive from the view point of attaining an average beam current that is enough for the radiation therapy. Maximum ampere-turn of the dipole magnets is as large as 200 kAT corresponding to dipole field of 3T to make the bending radius as small as possible. Pulse current is generated by discharging the stored energy of a capacitor bank through a pulse transformer. Moreover, the auxiliary power supply for the dipole magnets which adds the flat magnetic field (10-20μs) for the multi-turn beam-injection is being developed. The power supply for the quadrupole magnets is the high frequency (20 kHz × 5) switch-mode power supply which enables the fine tuning and the accurate tracking between the quadrupole and dipole fields. Detailed analysis on these pulse power supplies will be presented.

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 like the compact synchrotron under development is constructed at a reasonable cost, it has a big potential to promote the advanced medical treatment with the accelerator in every place [1-3].

It is the pulse type 200MeV proton synchrotron with 5ms acceleration period in 1Hz repetition rate. The pulse synchrotron means that it has small ring circumference by adopting very high field dipole magnets to reduce the orbit radius well less than 1 m and its compacted magnets must be excited by a large peak current in very short time to avoid the excessive Joule heat in the magnet coil. Fig. 1 shows a picture of the dipole magnet and Fig. 2 shows the magnet excitation curve. The dipole magnet already developed has the peak current of 200 kA for 3 T field at the maximum. Pulse current is generated through a pulse transformer by discharging the energy stored in a capacitor bank [2].

REQUIREMENTS OF POWER SUPPLIES

This magnetic field pattern is a half-sinusoidal waveform as shown in Fig. 2. In this case only a few turns of beams could be injected because the magnetic field increases rapidly around the injection field (0.28T for 11.6kA). Then, the auxiliary power supply for the dipole magnets which adds the flat magnetic field (10-20μs) for the multi-turn charge exchange injection is being developed [4].

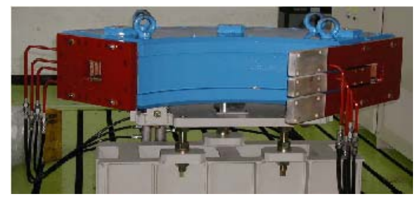

Figure 1: Dipole magnet (inductance is 2.9μH at low field, 1.5μH at high field (3T)).

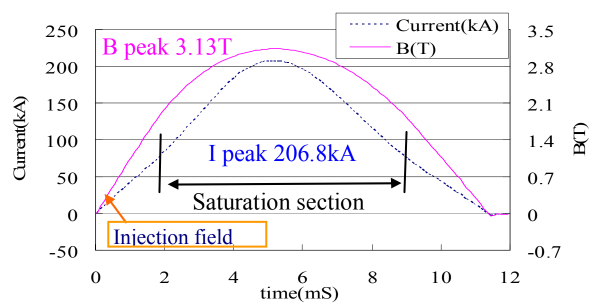

Figure 2: Measured time-dependent excitation curve.

Four dipoles and four quadrupoles are already manufactured which form the compact synchrotron ring with the DOB lattice as shown in Fig. 3. The quadrupole shown in Fig. 4 acts as a defocusing element (QD) and the maximum field gradient is 30 T/m at 3 kA to the bore diameter of 70 mm and the coil of 5 turns/ pole [1].

The high frequency (20 kHz × 5) switch-mode power supply has been chosen to excite the quadrupole magnets because it requires the precise control of a load current for two roles. The first role is the tracking between the quadrupole and the dipole fields to make up for the heavy saturation of the dipole magnet during acceleration. The second role is the fine tuning to compensete the gradient error in the dipole field which is slightly focusing and it depends on the saturation of the dipole magnet, 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 [1]. The switch-mode power supply is used for the first time as a power supply for a rapid acceleration as short as 5ms.

* Work supported by MEXT of Japan
# yamanaka@post.kek.jp

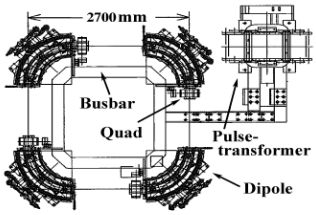

Figure 3: Layout of dipoles and quadrupoles. Tune is Qx/Qy=1.6/0.6.

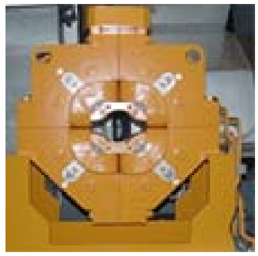

Figure 4: Picture of QD.

PULSE POWER SUPPLY FOR DIPOLE MAGNETS

The circuits of the pulse power supply and the auxiliary power supply for the dipole magnets are shown in Fig. 5. The principle of operation is detailed in Fig. 6. To the auxiliary power supply, the IGBT DC power supply (E_1) charges the capacitor bank C_1 (0.652mF) to 2.1 kV repeatedly. The dipole magnets connected in series are excited by the discharge current through a pulse transformer and SCR (S_1) of C_1. The current of the magnets attains a peak at the injection time. The capacities of C_1 are selected according to a cost (less capacity), accuracy (less than 10^{-4}) of the magnetic field (current) at injection period (10-20µs) and a temperature coefficient of a capacitor. As for the pulse power supply, the IGBT DC power supply (E_0) charges capacitor bank C_0 (10mF) to +/-6.5 kV alternately. The dipole magnets are excited by the discharge current through SCR (S_0) of C_0 at the acceleration beginning time. SCR (S_1) turns off at this time when the voltage of C_0 becomes a commutation voltage of S_0. The magnetic field (current) of the magnets became a peak at the extraction time. Immediately after finishing the acceleration the residual energy in the secondary circuit is recovered to increase the repetition rate of the synchrotron. The secondary cycle is excited by the commutating S_0 and by recharging C_0 to the specified voltage of the negative side. By forced switching of the power switching elements from the discharge to the recovery mode, most of the energy initially stored in the capacitor can be restored except for the resistive loss.

The problem of this circuit is a noise generated by a surge voltage of $S_{0,\ 1}$ and a reverse current at the switch time from an injection to acceleration. The solutions for this noise problem are given by the snubber circuits across $SCR_{0,\ 1}$. Accurate control (less than 10^{-4}) of this noise is studied through the numerical simulations.

The dipole magnet current waveform is shown in Fig. 7 from an injection to acceleration when both the pulse power supply and the auxiliary power supply are excited. The accuracy less than 10^{-4} at the flat injection field is maintained for 15µs before acceleration. The required accurate flat-porch of the dipole magnetic field for the multi-turn injection is observed when the pulse power supply is triggered with an appropriate time delay after the auxiliary power supply is operated.

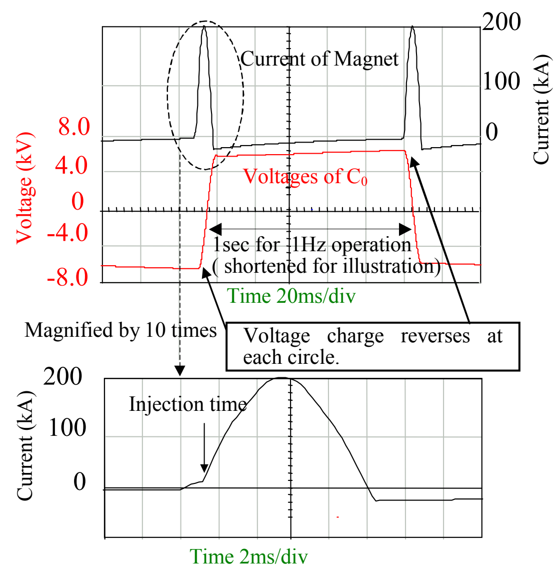

Figure 6: Operation of power supply.

SWITCH-MODE POWER SUPPLY FOR QD MAGNETS

The circuit of the high frequency switch-mode power supply for QD is given in Fig. 8. Its current is regulated by five phases of ten modules of 20 kHz IPM (Intelligent Power Module) which corresponds to 100 kHz switching. This power supply can afford an accurate tracking between the QD and dipole fields less than 10^{-3}. The

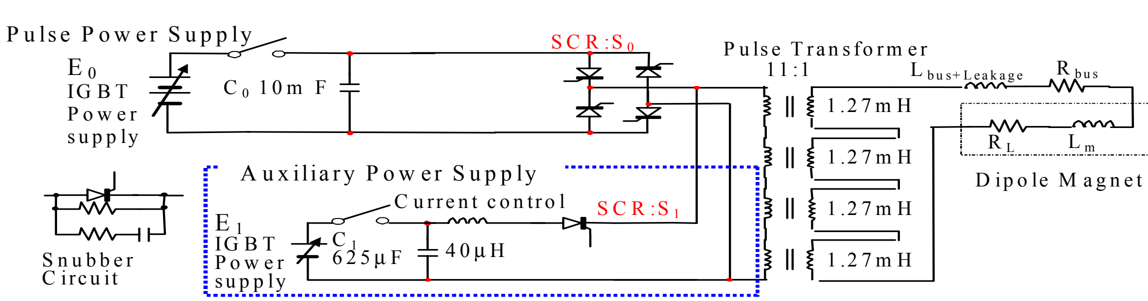

Figure 5: Pulse power supply for the acceleration and auxiliary power supply for injection. Lm 2.9µH–1.5µH/magnet R_L 27µΩ/magnet.

output peak values are 500V and 2.3kA.

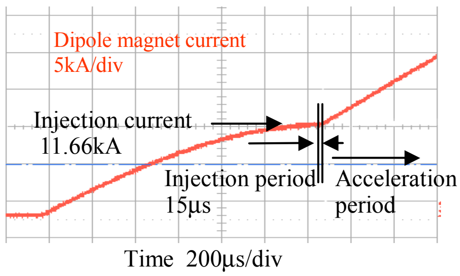

Figure 7: Measured time-dependent excitation curve of the dipole magnet for injection and acceleration.

The current pattern of the dipole magnet is used to control the current of QD and to generate the acceleration frequency of the RF system. Fig. 9 shows the control of the QD power supply. The digital current data of the dipole magnets is converted to the QD magnetic field in which the tuning and tracking are taken into the QD current as the first step of the control. PWM (Pulse Width Modulation) signal is made from the voltage of power

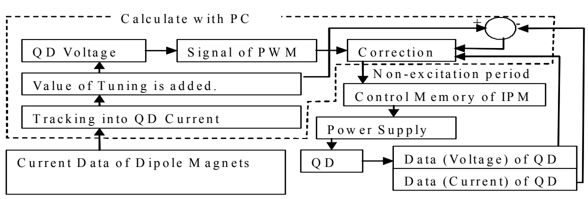

Figure 9: Control system of the switch-mode power supply.

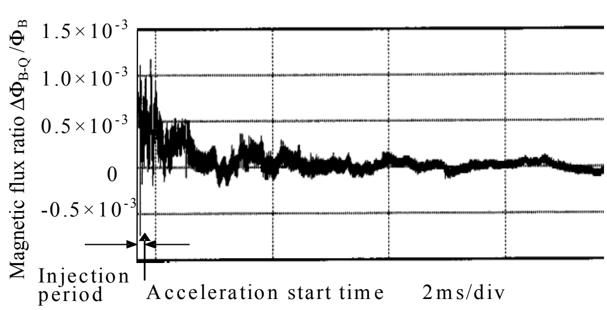

Figure 10: Simulation result for the tracking between the QD and dipole fields.

supply based on the QD current at the next step. However, it is not enough to track to the dipole magnetic field increase at the switch time from injection to acceleration by a usual PWM signal. Accuracy less than 10^{-3} against it is achieved by putting appropriate weight on PWM signal and by correcting data saved in the memory of the control circuit of IPM by comparing this data with a QD current in PC (Personal Computer).

Accurate control (less than 10^{-3}) of the tracking is studied through the numerical simulations. The simulation result for the tracking between the QD and dipole fields is shown in Fig. 10 when both the pulse and auxiliary power supply and the switch-mode power supply are excited simultaneously. The operation of the switch-mode power supply is expected in the near future.

SUMMARY

The power supplies for magnets of the compact proton synchrotron have been developed. One for the dipole magnets is a power supply which has a capacity to produce 200kA at peak and a flat magnetic field for 15μs at injection. One for the quadrupole magnets is a power supply which has a capacity to allow the accurate the tuning and tracking between the dipole magnets and the quadrupole magnets [5].

If the switch-mode power supply works as recognized by simulations, the main power supply system for the ring magnets will assure the realization of the compact synchrotron based on the pulse power technology.

REFERENCES

[1] K.Endo et al, “Magnet and RF Systems of Small Synchroteon for Radiotherapy”, EPAC’04, Lucerne, p.26561-3.

[2] K. Endo et al, “Development of High Field Dipole and High Current Pulse Power Supply for Compact Proton Synchrotron,” PAC’03, Portland, p.1074-6.

[3] K. Endo et al, “Resonant Pulse Power Supply for Compact Proton and/or Heavy Ion Synchrotron”, APAC’01, Beijing, p.636-8.

[4] S. Yamanaka et al, “Excitation current waveform ornamentation of a synchrotron pulse power supply”, JPAC01, Narashino, p.456-8.

[5] K. Endo et al, “Hardware Tracking Related to Compact Medical Pulse Synchrotron ”, This conference (RPAP032).

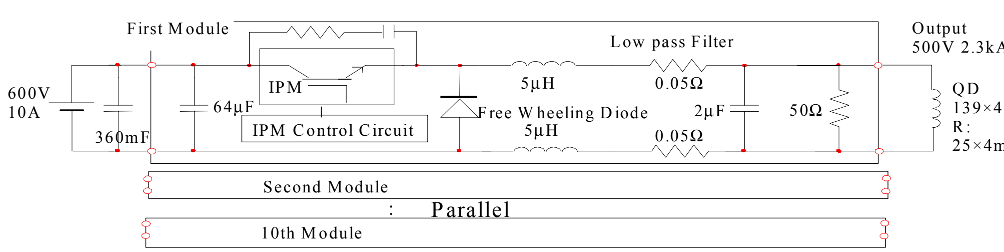

Figure 8: Circuit of the high frequency switch-mode power supply.

0-7803-8859-3/05/$20.00 ©2005 IEEE