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

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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 206.8kA 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 compensate 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.

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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 (E₁) charges the capacitor bank C₁ (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 (S₁) of C₁. The current of the magnets attains a peak at the injection time. The capacities of C₁ are selected according to a cost (less capacity), accuracy (less than 10⁻⁴) of the magnetic field (current) at injection period (10⁻²⁻⁻µs) and a temperature coefficient of a capacitor. As for the pulse power supply, the IGBT DC power supply (E₀) charges capacitor bank C₀ (10mF) to +/-6.5 kV alternately. The dipole magnets are excited by the discharge current through SCR (S₀) of C₀ at the acceleration beginning time. SCR (S₁) turns off at this time when the voltage of C₀ becomes a commutation voltage of S₀. 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 S₀ and by recharging C₀ 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 S₀, 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 SCR₀. 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.

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
output peak values are 500V and 2.3kA.

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 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 $10^{-3}$) 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


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

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

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