Design of a Synchrotron Control System with DPO Series for Advanced Therapy Operations

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Abstract

Therapeutical use of heavy ion synchrotrons is characterized by a frequent change of energy (range) and intensity (dose) to perform irradiation for individual cases. Reducing the switching time is more important in case of three dimensional irradiation, where a successive switch of energy is necessary during few-minutes treatment times.

The DPO series, that is developed to meet the above-mentioned requirement, is a group of VME modules with a powerful microprocessor unit and dual port memory (DPRAM). It has several functions such as multiple paged memory, calculation algorithms and regulation synchronous to other modules. (A synchrotron control system adopting the DPO series is designed as an upgrade version of present control system.)

This paper reports a system design by utilizing DPO series and a method of control for variable energy operations.

1 Introduction

The HIMAC (Heavy Ion Medical Accelerator in Chiba) accelerator at NIRS, that has been in operation since 1993, is used for clinical treatment of several kinds of tumor. At the HIMAC energy change is carried out within 15 or 20 minutes, which includes the initializing excitation of the main magnets. Reducing the energy switching time for individual patients is necessary to increase the number of patients. The dynamic pattern output module (DPO), that was specified with increased pattern memory to solve these problems, has been developed by collaboration with NIRS and Hitachizosen[1].

The irradiation synchronous to breathing has been successfully carried out since February 1996, which covers a tumor moving along with the breathing of a patient[2]. In this scheme, the precise concentration of the dose to tumor is possible. A series of experiments of three dimensional irradiation by utilizing a range-shifter is tried to shape the depth dose distribution[3].

Another method, to shape the depth dose distribution is by switching the energy of synchrotron operation. An energy shift is effective to prevent fragmentation produced in the range-shifter material. This method is realized to increase or decrease the flat-top (FT) on the excitation of the main magnets and the acceleration frequency of the rf cavity at spill by spill simultaneously. It is essential to synchronize all devices during the repetitive operation. The energy change per patient is presently carried out by switching two memories on the pattern memory board, however, it is impossible to be successively synchronous at spill by spill; it is necessary to increase the memory. A pattern memory board development is required for the method of variable energy operation.

In the heavy ion medical accelerator project, by Hyogo Prefectural Government, it is also planned to use 3-d irradiation by extraction energy switching[4].

2 Specifics of the DPO series

2.1 Firmware

The firmware of the DPO series is loaded in a flush ROM on the board. A DPO operation is carried out according to the command from the software and the external control code. The software control code is shown in table 1, which is simply coded to the function. To send a command to the DPO series, the software control code sets the ID number to the command port in DPRAM. DPO application software can be developed without driver software.

When the DPO power on starts, the boot program checks the DRAM, SRAM and the look up tables (LUT). The firmware is duplicated to the SRAM area for the sake of handling speed of the program. The pattern data is tagged by an ID number because of managing a pattern memory area in DRAM. Therefore, the pattern is switched by selecting an ID number only. The pattern memories of the DPO provide 128k counts (128k long words) and 128 pages at maximum within the DRAM volume, of which 32 pages are selected to switch by the external control code.

Arithmetic functions of the DPO include the digital filter, the spline fit, the linear fit, the four rules in arithmetics and the Boolean operation. These can be real-time calculations and off-line modes. Real-time mode is carried out within the data sampling cycle. Another mode calculates the pattern off-line, which helps pattern edition.

The spill by spill energy switch necessitates that the host CPU understands the DPO status exactly. It is informed by an interrupt request from the external control code. Thus the host CPU is able to manage the real-time handling by using interrupt services of the VME architecture.

The firmware procedure is executed by interrupt to the command handling. When the DPO is not receiving a command, the firmware runs a RAS and status watching task. The part of subroutine is carried out by utilizing a direct memory access controller (DMAC) due to handling speed.

2.2 Performance

The DPO series uses the high performance RISC micro-processor, SH-2 (SH-7604). The operating frequency and calculation capability are 28.7MHz and 25MIPS. The SH

series, in which fast calculation is possible under low power operation, is adopted widely in home game machines. The SH-2 microprocessor is characterized as follows :
(1) Versatile mnemonics helps increase the handling speed of the calculation. In particular, integral multiplication and sum mnemonic, as used in DSP, enables real-time operation of the filtering and feed-back operations.
(2) Interrupt priority is precisely set. The priority has 15 levels. The interrupt is assigned for the external control code, clock and software control code.
(3) The microprocessor is accompanied with peripheral devices, such as watch dog timer, direct memory access controller, clocks and bus arbitrator.

The DPO's microprocessor was tested for handling performance. The result of output data synchronizing T-clock is shown in fig. 1. The test result was compared with the calculated execution time of a microprocessor instruction; it is about 3μs. The difference of both times is caused by the handling time in the field programmable gate array circuit (FPGA). The result of the test is satisfactory for the performance of DPO's external clock (T-clock), of which the frequency is higher than 50kHz.

Table 1 Software control code (excerpt).

Code	Function
128 (H80)	(Non-Reserved)
129 (H81)	START
130 (H82)	STOP
131 (H83)	PAUSE
132 (H84)	RERUN
133 (H85)	SELECT
134 (H86)	BIT-MASK
135 (H87)	BIT-UNMASK
143 (H8F)	RESET
144 (H90)	PATTERN - COPY
145 (H91)	PATTERN - INCREMENT
146 (H92)	FILTERING - START
147 (H93)	FILTERING - STOP
148 (H94)	STRAIGHT FIT - START
149 (H95)	STRAIGHT FIT - STOP
150 (H96)	CALCULATION - START
151 (H97)	CALCULATION - STOP
152 (H98)	CONTROL - ENABLE
153 (H99)	CONTROL - DISABLE
154 (H9A)	T to B to T - ENABLE
155 (H9B)	T to B to T - DISABLE

2.3 DPI to DPO loop control

At HIMAC, the tracking control of the main magnetic field was realized by utilizing an iterative control[4].

The iterative control algorithm is given by the equation:

$$V_{set(n+1,m)} = V_{set(n,m)} + G_{(m)}\Sigma(W_{(k)}\Delta I_{(K-k)})$$

where, n : pattern number;
m: sample number;
G : control gain;
W : control weight;
ΔI : differential current;
K : filter tap number.

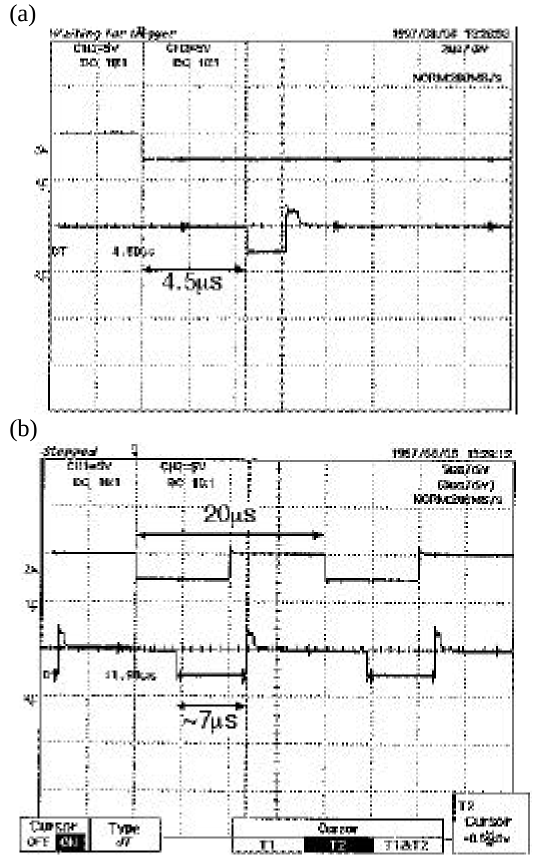

Fig. 1 Test result of DPO performance. (a) Turned on and off LED of signal by triggered T-clock. LED is turned on 4.5μs later. (b) Output data by triggered 50kHz T-clock. Data pulse width is about 7μs in 50kHz T-clock case.

The renewal voltage setting pattern is given to minor-AVR in the power supply of main magnets. After the optimized voltage setting pattern is reproduced and stored into idle memory by the algorithm, the iterative control switches pattern in the power supply controller (PC).

The control system by the DPO series can perform the iterative control within the DPI-DPO loop. The data exchange between DPO and DPI is independently done through the VSB bus, which reduces any disturbance of handling on the VME bus. Thus the DPI-DPO loop can carry out the iterative control algorithm in real-time within a sampling cycle of 833μs.

Such feed back control is of advantage to reduce the iterative time. At present, the iterative control is carried out which 10 ~ 15 minutes. This time almost corresponds to the time spent in the data swapping between the pattern memory and the host CPU. At last, the optimized voltage setting pattern utilized by the iterative real-time control is saved to the database. Only optimized pattern controls are loaded to the power supply without the iterative control.

2.4 Dynamic event timing output (DTO)

The DTO is adopted as a component module of the present Timing System (TS) at HIMAC. The DTO uses 20 bits pattern data as 20 items event trigger. DTO hardware was planned in common with the DPO. In order to regulate synchronized DPO series, DTO generates, as a master controller, the external control codes and clock signals (T-clock, B-clock). These are shown in fig. 2. The functions are achieved by a new design of FPGA. These functions are : (1) the master signal (MST), which controls the repetitive operation of the synchrotron, is generated from a U-phase upper zero crossing timing pulse of the 50 Hz power line; (2) timing setting event is set to notch for 1 μs; (3) each timing setting event is interpolated during the pulse to pulse of $24f_0$(1200Hz), which can be delayed by synchronizing the $24f_0$ pulse with a digital counter circuit; (4) a pulse width of the timing event can be variably set on the contiguous address of the same channel in the timing memory (on DRAM).

DTO's functions are carried out by the commands of the software control code from the host CPU.

3 System design

3.1 Reducing of energy switch time

The energy change is accompanied by the initializing excitation of the main magnets. In the presently running system at HIMAC, the main computer (CS) transfers an initializing excitation pattern, in addition to the next current setting pattern to the PC. In order to reduce the energy change time, it is necessary to reduce the initializing time, because this time is dominant.

The system of DPO series is able to store the initializing excitation pattern data with each DPO. The initializing excitation pattern is transferred from CS to PC within the energy change time. When the system starts, DPO series stores itself with the initialized excitation pattern, in addition to operational parameters (e. g. the initializing times, the upper and lower limit to load and the deviation value for warning).

Initializing of all magnets is carried out by setting a pre-selected pattern ID by the TS.

3.2 Spill by spill operations

The spill by spill energy switch is carried out by the external control code from TS (with master DTO). TS sends the code to the DPO of PC when beam stopping signal comes from the irradiation system for dose control. The action of PC synchronizes the MST. The spill by spill energy switch triggering is controlled by TS. Fig. 3. Shows the beam control schematically. When the beam stopping signal is received during spill extraction, the signal is directly sent to the extraction device without TS, since the quick stopping is necessary, is shown in Fig. 3. Then, TS switchs the energy pattern to synchronizing next MST. Shaping the depth dose distribution in 3-d irradiation, the stopping time is shorter than 1ms[6]. RF-KO extraction technique satisfies this requirement[7].

3.3 beam adjusting and pattern edition.

The spill by spill energy change is prepared for beam adjusting from $E_{shallow}$ to E_{deep}.(these pattern are P_0, P_1, P_2,..,P_N) of each energy pattern. The beam adjusting by the DPO function is described in three cases as follows : (1) pattern is shifted by addition or subtraction of the very small changing quantities (ΔE) to a basic pattern (P_0) produced by CS; (2) pattern is shifted by ΔE multiplied by P_0; (3) all patterns of P_0 to P_N are prepared in DPO. These are synchronously switched by the TS.

Pattern editing for beam adjustment is enhanced to help with synchrotron operation. Two ways of (1) and (2) are considered to attain a simple adjustment because the setting pattern data in the DPO are enlarged by the information of ΔE. The present control system provides the energy pattern by CS editing. The operation on the CS is adjusting FT (move up or down). To reproduce the energy pattern and for the real-time calculation by the DPO series, it is necessary to reduce any disturbance of the network and CS handling time.

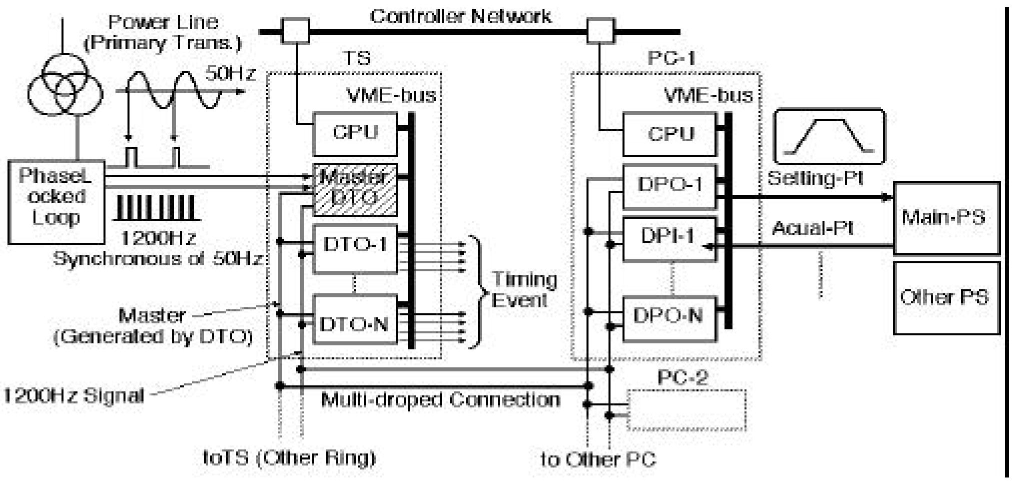

Fig 2 Schematic diagram of DTO to DPI/DPO control system.

4 Summary

In order to shape depth dose distribution without degrader, the summary of energy patterns are enough. Each energy pattern produced by operator is expected to increase the adjusting and energy change time for individual patient's case. DPO system will reduce these transactions by taking over the function from CS and utilizing real-time iterative control. The HIMAC synchrotron control system will be upgraded to meet increased requirement of energy change operation of a pattern number and treatment time.

Acknowledgment

The authors would like to thank Dr. K. Kawachi and the members of the Division of Accelerator Physics and Engineering at NIRS for helpful discussions. The authors would like to thank Mr. Y. Hibi of Cosmotec Corp. for helpful firmware development.

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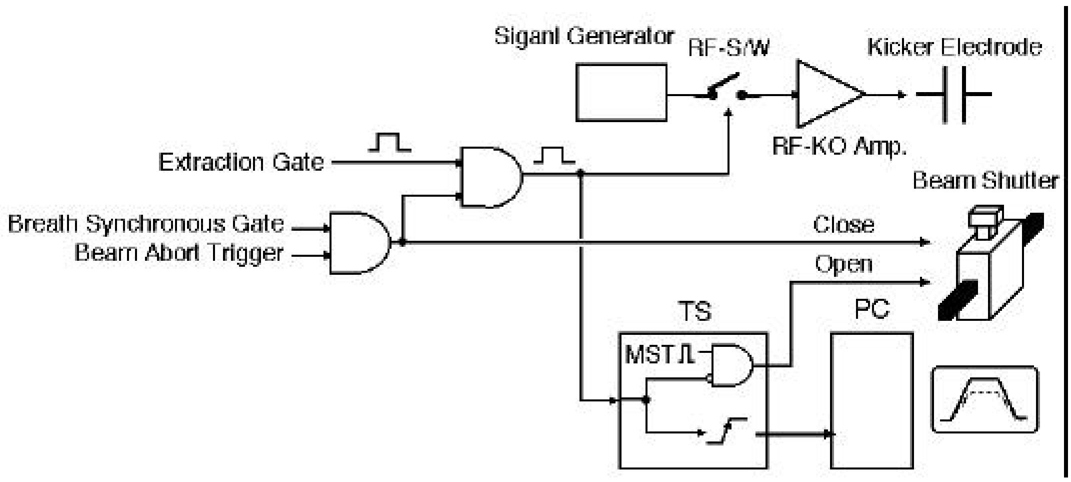

Fig. 3 Schematic diagram of beam stopping and energy change control.