FINAL DESIGN AND FEATURES OF THE B-TRAIN SYSTEM OF CNAO

G. Franzini, O. Coiro, D. Pellegrini, M. Serio, A. Stella, LNF-INFN, Frascati, Italy
M. Pezzetta, M. Pullia, CNAO Foundation, Pavia, Italy

Abstract

CNAO, the Italian Centre of Oncological Hadrontherapy located in Pavia, is under commissioning and will be soon fully operational. It is based on a synchrotron that can accelerate carbon ions up to 400 MeV/u and protons up to 250 MeV for the treatment of patients. In this paper we present the subsystem, called B-Train, which has the purpose of measuring the magnetic field in a dedicated dipole connected in series with the sixteen dipoles of the synchrotron and to provide instantaneous values of the synchrotron field to the dipole power supply, to the RF, diagnostics and dump bumpers control systems, via optical lines, using a custom communication protocol. In order to measure the magnetic field with the specified precision (0.1 G over 1.5 T @ 3 T/s), a different approach has been taken with respect to previous versions of the system. The field is obtained by digitizing the voltage induced on a pick-up coil inserted in the gap of the dedicated dipole through an 18 bit, 1.25 Msamples/s ADC and integrating it by numerical methods. This paper describes the final design and features of the B-Train system, as well as the results obtained on the magnetic field readings precision.

INTRODUCTION

CNAO, the Italian Centre of Oncological Hadrontherapy, is presently under commissioning [1]. The hadrontherapy involves the use of hadron beams, as an alternative to X-Rays, to ionize DNA molecules and kill targeted cells. Its main goal is to treat patients affected by cancer with proton (up to 250 MeV) and carbon ion beams (up to 400 MeV/u). The proton and carbon ion beam's energy release curve through the matter is characterized by Bragg peak, resulting in the possibility of concentrate ionizing power in a small volume (1 mm^3), by using beams with the appropriate width. Thus, it is possible to kill tumor cells while preserving healthy cells located in the surroundings of the treatment volume.

In the CNAO accelerator, protons and carbon ions are collected from the sources and accelerated through a LINAC up to 7 MeV/u. They are injected in a synchrotron of about 25 m of diameter, in which they are stored and further accelerated and then directed to the extraction lines. Four extraction lines head to three treatment rooms, which allow parallelizing treatments.

The typical magnetic cycle of CNAO synchrotron lasts few seconds and consists of an injection plateau, an acceleration ramp, an extraction plateau and a final stage of "standardization" in which the magnets are cycled for the next treatment cycle. The sixteen magnetic dipoles of the CNAO synchrotron (Tab.1) are connected in series to a single power supply [2].

During the acceleration ramp, the particle speed increases, thus it is very important that the magnetic field of the dipoles and the frequency of the RF system are synchronized. For this reason a dedicated system, similar to the control system of PS at CERN and called B-TRAIN has been developed [3]. At present, most of the B-TRAIN sub-systems are installed and are under testing, keeping pace with the commissioning of the synchrotron.

Table 1: Dipoles Specifications

Parameter	**Value**
Maximum magnetic field	1.6 T
Maximum dipole current	3000 A
Magnetic Length	1677.2 mm
Slew Rate	3 T/sec

THE B-TRAIN SYSTEM

The B-TRAIN is a high precision, Analog/Digital measurement system for the magnetic field of the bending dipoles. The RF, Dump Bumpers and Diagnostics systems use the real-time B-field measurements to track the beam energy. In addition, the measurements of the magnetic field are used to generate a feedback correction signal for the dipoles Power Supply (PS) to compensate for the transient response of the magnetic field.

The magnetic measurements are obtained by summing a measurement of the magnetic field (B_0) at the begin of each cycle and a real-time measurement of the B-field variations ($\Delta B(t)$), during the cycle. $\Delta B(t)$ is measured by using an induction coil inserted in the gap of a spare 17th dipole, connected in series with the 16 synchrotron dipoles.

By Lenz's law, the B-field variations are proportional to the time integral of the induced voltage. Thus, the magnetic field is given by:

$$\mathrm{B}(t) = -\frac{1}{NAL_{magn}} \cdot \int_0^t V(\tau)d\tau + B_o \qquad (1)$$

where N = 106 is the number of coils, A = 0.008 m is the coil's width and L_{magn} = 1.6772 m the magnetic length of the dipole.

The voltage induced in the pickup coil is filtered, converted in an 18-bit word at a sampling frequency of 1.25 Msample/s and integrated.

The system is equipped with a Hall magnetometer (Lakeshore model 475) that is used to obtain the digital B reference (B_0) at the beginning of every magnetic cycle. A

NMR magnetometer (Metrolab PT 2025) is used for offline calibrations and measurements.

Two digital single bits signal, *B_up* and *B_down* correspond to an increment and a decrement of 0.1 G. These two signals are sent via two dedicated lines with a maximum frequency of 300 kHz to the RF, Dump Bumpers and Diagnostics systems. Two other lines, *B_enable* and *B_preset*, are used respectively to validate the data sent by the system and to set the magnetic measurements to an established value.

The B-TRAIN system also converts the magnetic field into a current equivalent by using the static B vs. I curve. This current value is then used to close the feedback on the dipoles power supply. More specifically, a ΔI_{corr} is computed and summed to the I_{ref} sent to the power supply controller.

The B-TRAIN system is based on NI PXI architecture. It uses a total of three PXI chassis (NI PXI-1031 with embedded controller PXI-8196), in which are installed NI Reconfigurable I/O cards with Virtex-II FPGA (7813R), programmed with LabVIEW. The control firmware runs on these FPGA's, which manage all the operations of the system.

The general layout is shown in fig. 1. The three PXI chassis are installed in the synchrotron hall, in the CNAO electronics room and in the power supply room, which are several dozen meters far from each other. Optical links are used to transport digital signals between the three PXI systems.

Synchrotron Hall

All the B-TRAIN devices directly related to the magnetic measurement system are installed in the synchrotron hall, near the 17^{th} dipole, just few meters away from the synchrotron. The ADC used to digitize the voltage of the pickup coil (AD7643, mounted on an EVAL-AD76XXCBZ) is installed in a rack near the dipole. It is an 18-bit, 1.25 MSPS, charge redistribution SAR, fully differential analog-to-digital converter. A front-end circuit developed in LNF acts as a buffer for the signal coming from the coil and can also be used to calibrate the ADC, as it offers two fixed and stable reference voltages that can be sent to the ADC by means of relay switches. The front-end circuit and the EVAL-AD76XXCBZ are enclosed in a µ-metal box (about 30x20x10 cm), which shields the electronics from low frequency magnetic interferences. A power supply board, fed by two linear power supply Agilent E3631A, uses high precision voltage regulators to generate stable supply voltages for the ADC and the front end circuit.

The 7813R manages the digital output and the control signals of AD7643. It collects data from the ADC and with a serial-parallel communication protocol sends them to the system core, which is located in the electronics room. Two TTL-Optical converter cards are used to transmit and receive data.

The NMR and Hall magnetometers are both installed near the 17^{th} dipole and are controlled via GPIB interface by the 7813R-FPGA. Their digital outputs are sent to the core system through Ethernet.

Electronic Hall

The core of the B-TRAIN system is represented by a 7813R-FPGA installed in a PXI chassis in the electronics room of CNAO. In the same rack, a VME crate is installed and used as a fan-out and an electro-optical converter for all the B-TRAIN I/O digital signals. A timing unit [4] communicates the synchrotron events to the FPGA, so that the various phases (injection, acceleration, extraction) of the synchrotron are identified.

The 7813R-FPGA transmits and receives data through two TX/RX cards inserted in the PXI chassis and connected to the VME crate. This FPGA labelled as CORE, manages the main operations of the system. It collects measurement data coming from the synchrotron hall, elaborates them in order to obtain a digital representation of the magnetic field, at a refresh rate of 1.25 MHz. It generates the B-TRAIN output signals (*B_up*, *B_down*, *B_preset*, *B_enable*) for the RF, Dump Bumpers and Diagnostic systems, which are installed in the same room. It calculates the ΔI_{corr} by comparing the B-field measured with the B-field reference provided by a Digital Function Generator card (GFD) [5]. It also manages the Hall magnetometer measurements (B_0) and the procedure to calibrate the main parameters of the system.

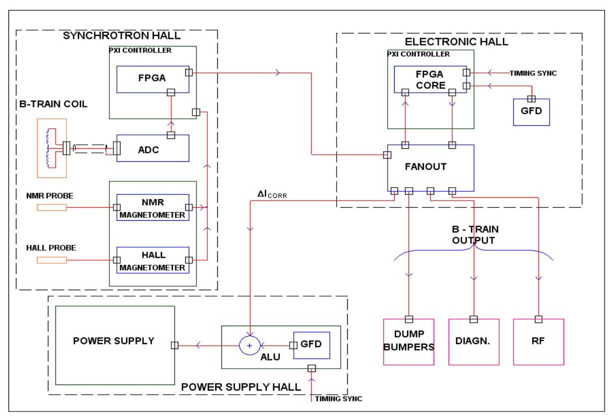

Figure 1: Layout of the B-TRAIN system.

Power Supply Hall

The third PXI-chassis is installed in the proximity of the power supply of the dipoles. The 7813R-FPGA installed here acts like an ALU, summing up the ΔI_{cor} (provided by the system core, through a Serial peripheral Interface communication protocol via optical links) with the digital current reference provided by a GFD cards. The resulting digital signal is sent to the PS at a rate of 20 Ksample/sec.

MEASUREMENTS

The main goal of the B-TRAIN is to measure the magnetic field of the dipoles with a precision of 0.1 G (about 10 ppm over 1.5 T) with a maximum update frequency of 300 kHz (at 3 T/s slope). Many efforts have been spent to achieve this precision.

As already mentioned, at the beginning of each cycle, the B-TRAIN system uses the readings of a Hall Magnetometer (Lakeshore model 475) in order to establish the starting value of the magnetic field (B_0). Thus, by digitizing and integrating the voltage of the pickup coil, it offers a real-time measurement of B ($B_0 + \Delta B(t)$).

In order to characterize the precision of the $\Delta B(t)$ component, we have digitized and integrated a fixed voltage ($V_{ref}/2$ of the AD7643) for several hours. Then we have compared subsequent 20-seconds long records to measure the repeatability of the system.

The standard deviation calculated on these measurements shows that the system is affected by drifts and that the error increases with time, degrading the precision of the system. From fig. 2 we see that the standard deviation stays below 0.1 G within the first three seconds of acquisition.

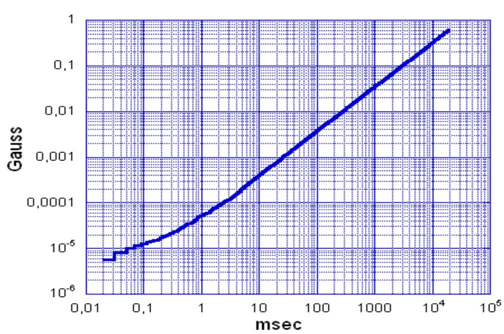

Figure 2: Standard deviation vs. time calculated with repeatability measurements.

Thus, to reset the error caused by the drifts, it is important to acquire a new B_0 from the Hall magnetometer at the beginning of each cycle. The latter (Lakeshore model 475) is currently under test. It provides triggered measurements with a precision within 0.1 G.

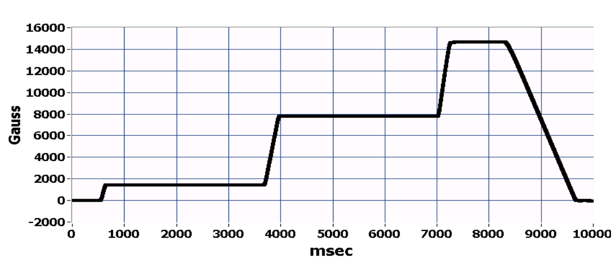

Figure 3: Magnetic cycle measured at CNAO through the pickup coil (B_0=0).

We are studying the possibility to obtain a second measurement with the Hall magnetometer during the cycle. Thus, it would be possible to calibrate gain and offset of the measurement system at every cycle, reducing calibration errors.

We have performed a number of tests at CNAO using the final setup that have confirmed the results shown. Figure 3 shows an example of a 10 seconds magnetic cycle measured by our system.

In fig. 4 we have plotted the differences between one cycle and the five subsequent ones during the injection plateau only.

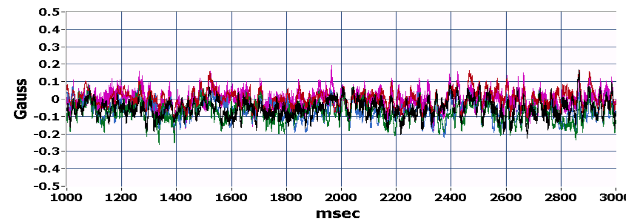

Figure 4: Differences of one magnetic cycle and the five subsequent ones during the injection plateau.

CONCLUSION

The B-TRAIN system communicates real-time magnetic field measurements of the CNAO main dipoles to the radio-frequency, dump bumpers and diagnostics systems, by sending single bit signals associated with 0.1 G increment (or decrement), at a maximum frequency of 300 kHz. At present, most of the B-TRAIN sub-systems are installed and are under testing, keeping pace with the commissioning of the synchrotron. Many efforts have been spent to match the 0.1 G precision requirement. The system is capable of measure magnetic field variations, $\Delta B(t)$, with the given precision within a single CNAO magnetic cycle, which lasts few seconds. At the begin of each cycle a new magnetic reference, B_0, provided by a Hall magnetometer, is needed to reset drifts and to possibly calibrate system parameters.

The first measurements of typical magnetic cycles have confirmed the B-Train system functionality and that it matches the required specifications.

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