B-TRAIN PERFORMANCES AT CNAO

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Abstract

The commissioning of CNAO, the Italian Centre of Oncological Hadrontherapy, with proton beams is completed. The real-time measurement of the synchrotron dipole field with the so-called B-train, together with its electronic systems and related software and firmware are here described. An additional magnet, powered in series with the synchrotron dipoles, is equipped with a special coil that measures the field integral variation along the beam nominal path. The voltage induced in the coil is digitized with a fast ADC and numerically integrated by an FPGA. The field integral is then distributed to the users every time that the equivalent field changes by 0.1 G. The measured B field ranges from 0 to 1.6 T with maximum ramps of 3 T/s.

The B-train system will be used to provide feedback in field to the dipole power supply. It will handle the limited bandwidth of the active filter, the B-field lag in the magnets and will avoid current jumps.

INTRODUCTION

CNAO, the Italian Centre of Oncological Hadrontherapy [1], will cure oncological patients using beams of protons accelerated in the range from 60 MeV to 250 MeV and beams of carbon ions accelerated in the range from 120 MeV/u up to 400 MeV/u.

The accelerator complex consists of 2 ions sources, a 7MeV/u injector, a 78 m long synchrotron and 4 extraction lines. The magnetic bending in the synchrotron is realized by 16 dipoles whose specifications are given in Table 1.

The typical magnetic cycle of CNAO synchrotron lasts few seconds and changes depending on the medical spill length requirement that is in the range from 250 msec to 10 sec. The cycle consists of an injection plateau, an acceleration ramp, an extraction plateau and a final stage of "standardization" in which the magnets are cycled to the same maximum current value. R&D is devoted to maintain all the parts of the cycle (except the extraction) as short as possible to reduce the time of the treatment and increase patients duty cycle.

The injection plateau has two different values for proton (0.0915 T) and carbon ions (0.18 T) while the energy range needed for both the ions species corresponds to a range of magnetic extraction plateau from 0.27 T (60 MeV protons) to 1.496 T (400 MeV/u carbons).

The different magnetic field values for the flat top and the different cycle lengths result in different magnetic paths for the dipoles cycle by cycle. This fact can alter the correspondence between current and magnetic field. Most of this problem is solved by means of the standardization part of the cycle. However, at high field values, a non negligible fraction of the magnetic field shows a large rise time. Waiting till the completion of the transient, especially when the considered field lag refers to the extraction flat top, would lengthen the cycles in an unacceptable way.

Because of this, it has been decided to insert the magnetic field measured by the B-train in an "external" control loop of the power supply.

Table 1: Dipoles Characteristics

Maximum magnetic field	1.6 T
Maximum dipole current	3000 A
Magnetic Length	1677.2 mm
Maximum slew rate	3 T/sec

HARDWARE DESCRIPTION

The 16 dipoles of the synchrotron are connected in series with a 17th identical magnet and they are altogether fed by a single Power Supply (PS). Such power supply follows a reference current ramp I_{ref} generated by a Digital Function Generator (GFD). To obtain the desired control in B, the B-train system measures the B-field, compares it with the desired field ramp stored in an additional GFD (BT GFD) and computes a correction ΔI_{corr} that is added to the ramp I_{ref} inside the current control loop. Special care has to be taken in order to avoid current steps larger than the (small) value that the power part of the PS can handle.

The field value is obtained by summing a measurement of the magnetic field (B_0) at the beginning of each cycle and a real-time integral of the B-field variations ($\Delta B(t)$), along the cycle. $\Delta B(t)$ is obtained by measuring the voltage induced on a mesurement coil inserted in the gap of the 17th dipole.

In other words, the magnetic field is given by:

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

where N = 106 is the number of windings of the coil, A = 0.008 m is the coil's width, L_{magn} = 1.6772 m is the mean value of the magnetic length of the dipole and V(t) is the voltage across the coil.

The voltage is filtered, converted in an 18-bit word at a sampling frequency of 1.25 MHz and integrated numerically.

B_0 is obtained by a NMR magnetometer (Metrolab PT 2025): the instrument is configured to detect the crossing of the nuclear resonance at a given magnetic field identified by the frequency of an internal VCO.

In this way the field is reconstructed with a precision of 0.1 G that corresponds to about 6 ppm of the maximum value.

In order to reset the integrator, B_0 has to be measured at every cycle; if the integrator is not reset, slowly varying errors would add up, spoiling the precision of the field reconstruction. Typical values of such a drift, are of the order of 0.05 G/sec.

The B-train electronics system [2] is based on NI PXI architecture. It is composed of three PXI chassis (NI PXI-1031 with embedded controller PXI-8196), that host NI Reconfigurable I/O cards (7813R, 7833R, 7831R cards) based on Virtex-II FPGA and programmed in LabVIEW. The control firmware runs on these FPGAs which manage all the operations of the system. The three PXI chassis are installed in three different rooms: the synchrotron room, the electronics room and the power supply room. Optical links and an ethernet connection are used to transport signals among the three PXI systems.

In addition to the feedback on the power supply, the B-train system distributes the magnetic field value to other systems, whose behaviour is strongly dependent on dipole field: RF cavity, dump bumper, synchrotron DCT. The information is sent under the form of four digital signals: B_{up} and B_{down}, that correspond respectively to an increment and a decrement of 0.1 Gauss, B_{enable} indicating that the B train system is working properly, and B_{preset} indicating that the magnetic field is equal to B_0. These signals are sent via dedicated lines to the users at a maximum frequency of 300 kHz (related to the maximum slew rate of 3 T/sec). The general layout is shown in Figure 1.

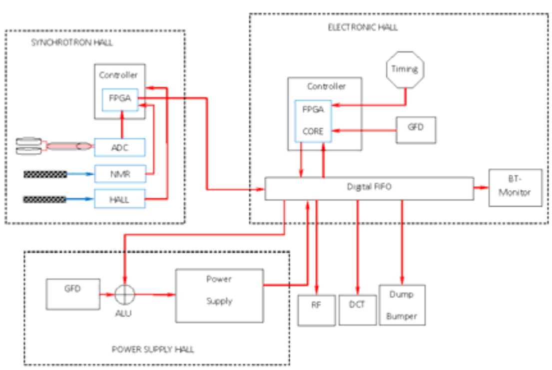

Figure 1: Layout of the B-TRAIN system.

Synchrotron Hall

As shown in Figure 1, all the B-TRAIN devices directly related to the magnetic measurement system are installed in the synchrotron hall. The ADC used to digitize the voltage of the induction coil (AD7643, mounted on an EVAL-AD76XXCBZ) is an 18-bit, 1.25 MHz, fully differential SAR-ADC based on charge redistribution. A front-end circuit, developed at LNF, acts as a buffer for the coil signal 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. A power supply board, fed by two linear power supplies Agilent E3631A, uses high precision voltage regulators to generate stable supply voltages for the ADC and the front end circuit.

A 7831R FPGA manages the digital output and the control signals of AD7643. It collects data from the ADC, serializes and sends them optically to the system core, which is located in the electronics room.

The NMR and Hall gauss-meters are managed via GPIB interface by the 78XXR-FPGA and their digital outputs are sent to the electronics room via ethernet.

Electronics Room

The core of the B-TRAIN system is a 7813R-FPGA installed in a PXI chassis in the CNAO electronics room.

This FPGA, manages the main operations of the system:

- It collects the measurement data coming from all the magnetic probes installed in the synchrotron room, elaborates them in order to obtain the digital representation of the magnetic field, at a sample frequency of 1.25 MHz.
- It generates the signals for RF, dump bumper and DCT, whose electronics are installed in the same room;
- It calculates the ΔI_{corr}.

In the same rack, a VME crate is installed and used as an electro-optical converter and a fan-out for all the B-train I/O digital signals. A timing card communicates the events of the machine cycle to the FPGA.

Power Supply Room

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, adding the correction ΔI_{cor} to the digital reference current provided by the PS GFD. The resulting digital signal is sent to the PS at 20 kHz.

BTRAIN COMMISSIONING

The choice of the B-Train feedback controller has been the most challenging issue. In fact, because of the tight ripple and ramp tracking specifications (both about 10 ppm of the full output current), the power supply includes a parallel active filter which is limited in current but very reactive to fast variations of the reference because of a strong feedforward path in its controller: in order to avoid fault conditions the current reference must meet severe limitations on the first and second order derivatives and no jumps (or only very small ones) are allowed when the current reference is flat. This makes the proportional action unpractical if applied without precautions. The integral action alone creates problems too: the high gains, required to compensate the error during the ramps, cause an oscillation (which is much higher than the normal ripple) to appear at the resonance frequency of the power supply output filter (about 70 Hz) during the flat tops.

The final architecture of the feedback, overcoming these difficulties, is composed by:

- a variable feedback frequency, depending on the part of the machine cycle
- a smooth and discrete correction in the range 0-3 current LSB (1 LSB= 0.011A) depending on the error: below a threshold the correction is zero, in a range it is 1 LSB and so on.

Such a feedback has been first commissioned without beam, by minimizing the field error, optimising the system time response and avoiding deterioration of the field ripple that has been kept below 0.7 Gauss peak-peak at each plateau.

Figure 2 and Figure 3 show the error between the desired magnetic field and its measurement respectively without and with feedback. The cycle illustrated is the one used to accelerate Carbon ions at 400 MeV/u; this is the one in which the delay of the field is maximum (the cycle is for a 4 seconds extraction).

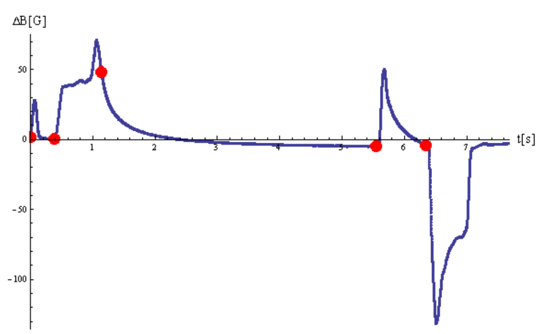

Figure 2: Error without B-train feedback.

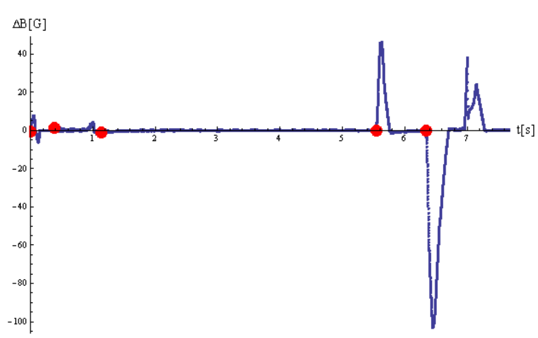

Figure 3: Error with B-train feedback.

The red points indicate different significant points in the cycle: the third point represents the nominal end of the acceleration and the fourth the beginning of the standardization cycle. We can note that the only part in which the feedback does not work is during the standardization cycle, during which there is no beam in the ring. CNAO commissioning with protons has been completed without the use of the B-train: the field delay is not too large at the flat-top currents for protons, and during acceleration the error in the magnetic field is compensated by the RF beam loops.

Recently the first runs with carbon ions at 400 MeV/u have shown that even if the RF loops permit to accelerate the beam also without B-train, extraction would not be convenient without it. Waiting for the transient to finish, would lengthen the cycles to an unacceptable level.

This effect is shown in Figure 4 in which the beam position is represented during a 3 seconds flat top. To show the effect, RF loops are switched off but RF cavity is kept on during the flat top to keep the beam bunched; during extraction the RF is normally switched off because otherwise the betatron acceleration would be thwarted by the RF.

Figure 4 demonstrates that switching off the RF loops at the nominal end of the acceleration, the beam position changes significantly with the lagging field increase. Without B-train a 1.5 seconds delay is necessary, which is unreasonable for a 3 seconds cycle. On the contrary when B-train feedback is on, the position is stable along the whole flat top.

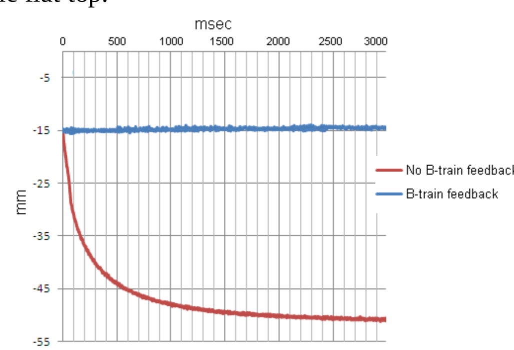

Figure 4: 400 MeV/u Carbon beam positions with and without B train feedback.

CONCLUSIONS

A B-train system has been designed and commissioned at CNAO both to provide the field information to the standard users and to compensate the field lag in the main synchrotron dipoles. B-train commissioning with carbon beams has demonstrated its functionality.

The system works very well, but some minor aspects need further development. In particular, tests with proton beams have shown that the B_0 field measurement with NMR is not stable and cycle by cycle it oscillates by up to 1.3 G.

REFERENCES

[1] S. Rossi, Eur. Phys. J. Plus (2011) 126: 78.
[2] G. Franzini et al, “Final design and features of the B-Train system of CNAO”, IPAC’10, Kyoto.