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BTRAIN CALIBRATION WITH RF-MASTER METHOD

E. Bressi, L. Falbo, C. Priano, M. Pezzetta on behalf of CNAO accelerator division, CNAO, Pavia, Italy

Abstract

CNAO is the only Italian hadrontherapy facility able to treat tumors with beams of protons and carbon ions. It is based on a synchrotron with a 77 m ring equipped with 16 normal conducting dipoles characterised by a long delay in the field stabilisation. B-Train system is a fundamental device of the whole machine; it is used in feedback to the dipole power supply in order to regulate the magnetic field, eliminating the natural stabilization times that would cause long treatments. Furthermore, it allows to measure B field starting from B-field changes: it works as an integrator and it needs a system to reset the counts compensating the electronic and numerical drift of the system cycle per cycle. An innovative method has been implemented at CNAO to reset B-Train counts exploiting beam measurement after the RF cavity trapping. This method has the advantage to avoid external and additional element like NMR probes and so on. The paper shows the use of B-train system at CNAO and its calibration with this application, called "RF-master method".

CNAO SYNCHROTRON

CNAO is the unique Italian facility treating cancer patients using high-energy protons and carbon ions. In this section some general informations on the machine will be given in order to better understand the paper main topics.

The facility is based on the PIMMS design [1] and it is made up of two ECR sources, one 7 MeV/u linear accelerator, a synchrotron and 3 treatment rooms (2 rooms are equipped with a horizontal line while the third one is equipped with a horizontal and a vertical line). Extraction Energy ranges from 60 MeV/u to 250 MeV/u for protons and from 120 MeV/u to 400 MeV/u for carbon ions. The synchrotron has a circumference of 77.641 m and it contains 16 main bending dipoles connected in series with a 17th identical magnet placed outside the ring and altogether fed by a single power supply. The bending magnets are rectangular dipoles with laminated iron core with the following characteristics: magnetic length of 1677.2 mm, maximum magnetic field of 1.5 T (@ I=3000 A), maximum ramp rate of 3 T/sec, integrated field quality $\frac{\Delta BL}{BL} = \pm 3 * 10^{-4}$, bending radius ρ=4.253 m at low currents and ρ=4.228 m at the maximum current. The synchrotron is equipped with 11 horizontal and 9 vertical capacitive pick-ups able to detect beam position in the vacuum chamber when beam is bunched by the RF cavity. The machine cycle can be divided into two parts: the “extraction” and the “interspill”. The interspill can be subdivided into three moments: injection, acceleration, and washing. During injection all the synchrotron magnets go to the value corresponding to the beam injector energy; beam is injected in the ring with a multi-turn mechanism, this is an unbunched beam. After 1 msec the RF cavity is switched on with an adiabatic voltage ramp to trap and bunch the beam.

During acceleration beam reaches the extraction energy and all the synchrotron magnets increase their current from the injection value to the extraction value: the current ramp of the dipoles is the reference for the ramp of the other magnets. The RF cavity changes frequency to accelerate the beam according to the dipole ramp but also using the frequency corrections of a radial and a phase loop that fix the beam position in a dispersive pick-up.

During extraction, beam is extracted from the ring to the patient and the synchrotron magnets are fed to a fixed current (“flat-top current”). During washing, the synchrotron magnets follow a “standardization cycle”: they ramp up to a standardization current (higher than the current for the highest beam energy) and then go to the minimum current. This is mandatory to guarantee the repeatability of the magnetic field cycle per cycle avoiding hysteresis problems. As it will be explained in the following section, using the B-Train during washing cycle the dipole current goes directly to the minimum values [2]: since the dipole ramp are the slowest ramps of the whole synchrotron, it is possible to dedicate smaller times for the washing cycle resulting in faster treatments. The extraction lasts for 100 microsec-4 sec depending on the size of the tumor to be irradiated while the interspill lasts for 1.8-2.2 sec for both particle types.

B-TRAIN SYSTEM

When dipoles were commissioned an important bad behaviour became apparent: the higher the flat-top current the higher the time the field takes to settle to its nominal value (there is a delay between dipole feed current and magnetic field due to eddy currents). When accelerating carbon beams this delay is large compared to the time scale of the machine cycle. Figure 1 shows the decay of the magnetic field error versus time after the dipole power supply has reached the current needed to accelerate the carbon ions beam at maximum energy (about 2990 A). About 3 seconds are needed to have a stable magnetic field (Magnetic error < 1 Gauss).

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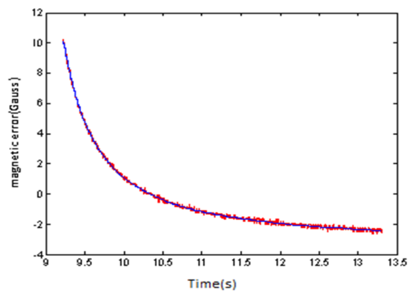

Figure 1: Trend of the magnetic field error after the dipole has reached 2990 A without B-Train feedback.

In order to solve this problem a B-Train system has been developed. Usually the name B-Train system is referred to a system that measures the main dipoles magnetic field of a ring and distributes this measurement to other systems (like RF cavity and beam diagnostics) to maintain the synchronism among all the ring devices. At CNAO the B-Train system is not only a measurement system but it has another important functionality: it uses the magnetic field measurements to correct the field itself, generating a feedback on the dipoles power supply.

The architecture of the system is the following: an induction coil is inserted in the 17th dipole gap; the voltage induced on the ends of the coil is proportional to the magnetic field variations, then the magnetic field is given by:

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

where N = 106 is the number of windings of the coil, A = 0.008 m is the coil's width, L_{magn} is the mean value of magnetic length of the dipole, V(t) is the induced voltage, and B_0 is an absolute measurement of the magnetic field when the power supply is at its minimum current.

The voltage induced in the induction coil is filtered, converted in an 18-bit word by an ADC (AD7643) at a sampling frequency of 1.25 MHz and integrated. The reconstructed field is compared to a desired value and generates a current correction that is sent to the dipole power supply. The B-TRAIN electronics system is made up of three PXI chassis that host National Instruments FPGAs programmed to control the whole system. The three PXI chassis are installed in three different rooms and connected by optical links and Ethernet connection. The general layout is presented in [3]. The system is also equipped with a Hall gauss-meter and a NMR magnetometer that is used to calibrate the system by absolute measurements of magnetic field. Considering beam quality for the treatments and the operations, the field reconstructed from the induction coil must have a precision of about 0.1 G. The integrator system is affected by drift that creates problems in maintaining the precision: tests made with a fixed voltage on the ADC [4] showed that the error on the reconstructed magnetic field increases quite linearly with time (about 0.05 G/sec) with a statistic noise overlapped and then it stays below 0.1 G just within the first three seconds of acquisition: a way must be found to reset the integrator after this time. The feedback parameters are varied depending on the part of the cycle that is being performed, in order to have the best compromise between the residual error and the oscillations induced on the field by the feedback itself [5].

RF-MASTER METHOD

As explained in the previous section, to have a good precision in the magnetic field measurements it is not possible to integrate the field variations for long time intervals using Eq. (1). At least once per cycle, it is mandatory to reset the integral on the field variations and measure the magnetic field in order to have a precise value of the term B_o in Eq. (1). Tests have been performed using NMR probes and tHall probes to reach this goal, but the precision and the stability of the system was not sufficient to obtain 0.1 G precision; this problem led us to elaborate the so called RF-master calibration method.

When a bunched beam circulates in a synchrotron trapped by an RF cavity, the position in a dispersive pick-up is related to the cavity RF frequency by:

$$x = \frac{D}{\eta} \cdot \frac{F_{RF} - F_B}{F_B} + x_c \qquad (2)$$

Where x is the position measured by the pick-up; D is the dispersion; F_{RF} is the RF cavity frequency, x_c is the closed orbit error, F_B is the frequency of the synchronous particle circulating along the vacuum chamber centre and η is the slippage factor given by

$$\eta = \cdot \frac{1}{\gamma^2} - \alpha_c \qquad (3)$$

(γ is the relativistic factor and α_c is the machine momentum compaction). Using the relativistic kinematics formulas, F_B is related to the dipole magnetic field by

$$B = \frac{mA}{cZ\rho} \cdot \frac{F_B L / c}{\sqrt{1 - F_B{}^2 (L/c)^2}}$$

where m is the mass per nucleon, A is mass number, Z is the atomic number, ρ is the bending radius, L is the machine nominal circumference and c is the speed of light. Considering that the RF cavity frequency is always the same and it is constant when injecting and trapping beam, a displacement in a dispersive pick-up can be caused only by an erroneous magnetic field in the dipoles. Therefore, using the position after trapping and before the beginning of the acceleration, it is possible to calculate the error on the B-Train magnetic field measurement due to drift of calibration of the B-train electronics itself. As shown in Fig 2, during injection the B field oscillations due to dipole power supply ripple cause oscillations in the

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beam position. To obtain a precise value, it is needed to average the position and the Bfield over about 20 msec.

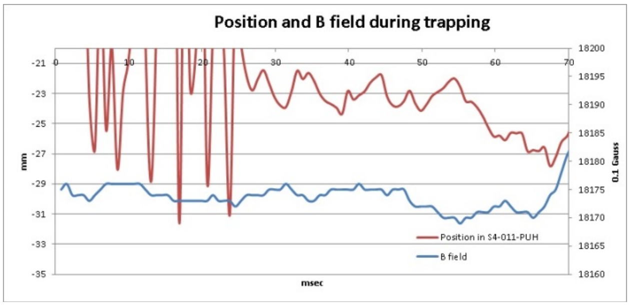

Figure 2: Position in a dispersive pick-up and magnetic field during the injection: 0 msec is when beam is injected in the ring, 20 msec is the start of the RF adiabatic voltage ramp; 60 msec is the beginning of the acceleration.

The Low Level RF (LLRF) processor is the natural device to calculate the B field error with this algorithm. Indeed, the LLRF generates the RF signal so it knows precisely the RF cavity frequency; it acquires a dispersive pickup for the radial loop and it receives the B-Train field measurement: inserting the machine parameters (dispersion, slippage factor, machine length and so on) it has all the elements to calculate the real B field and to send it to the B-train system for the cycle per cycle calibration. This calibration method gives to the LLRF electronics a fundamental role in the correct working of the B-Train system: this explains the meaning of the name “RF-master method”. An obvious advantage with this strategy is that no additional hardware is needed for the calibration because it is obtained just implementing an additional functionality in the firmware of the processor used for beam acceleration. Such method works only if beam is injected, because its position is the fundamental parameter of the algorithm, so it is important that at the first cycle with injected beam the magnetic field is correct. To solve this problem, before each treatment a magnetic calibration procedure allows to reset the B-Train integrator to a value that suitable for injection. The procedure is the following: the dipole power supply ramps from the minimum to the maximum current and again to the minimum following a precise current reference with the B-Train feedback off. Since this reference current is always the same, the magnetic field at the end of the ramp is always the same and it is possible to set correctly the constant B0 in the magnetic field formula. This allows the first injection and for each next cycle, the RF master method corrects any B-Train drifts. Figure 3 shows the corrections sent from RF to B-Train system cycle per cycle during a treatment.

This method has another important advantage: if the machine parameters used to calculate the B field error are not correct, the magnetic field will be not correct too, but anyway it will be reproducible cycle per cycle. In other words it is possible to change the magnetic field at injection by changing the parameters that were used to calculate the B field error.

For example if one wants to change the position at injection it is possible to change one of the parameters involved in the calculus (for example the dispersion) to obtain cycle per cycle the correct position.

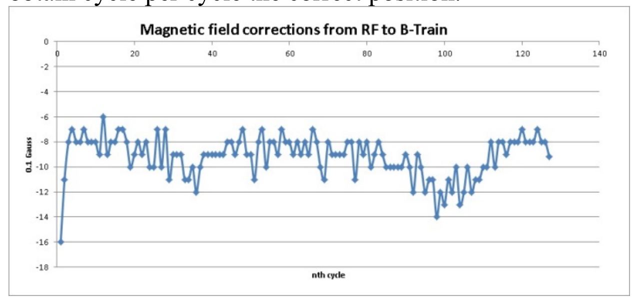

Figure 3: Corrections sent to the B-train cycle per cycle during a treatment from the minimum to the maximum carbon beam energy.

In Figure 4 the position at the dispersive pick-up S4-011-PUH is shown in two different cases: in Case 1 the Dispersion used in the calculus has been changed at each cycle in order to obtain a linear trend of the position while in Case 2 the dispersion has been set as a constant in order to obtain a fixed position at injection.

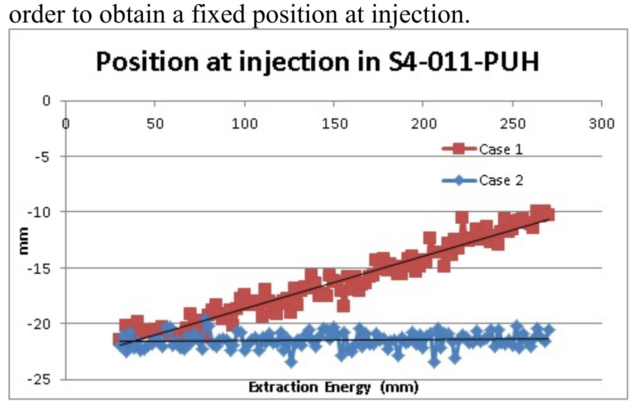

Figure 4: Comparison of the position at injection when the B field corrections are calculated by a dispersion that depends or does not depend on the extraction energy.

CONCLUSION

B-Train system has a fundamental importance in CNAO machine since it allows to reduce the length of the treatments. The system needs a cycle per cycle calibration: an original and efficient way has been elaborated and implemented at CNAO by an upgrade of the LLRF firmware.

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