INVESTIGATION OF THE REMANENT FIELD OF THE SPS MAIN DIPOLES AND POSSIBLE SOLUTIONS FOR MACHINE OPERATION

F. M. Velotti, H. Bartosik, J. Bauche, M. Buzio, K. Cornelis, M. A. Fraser, V. Kain
CERN, Geneva, Switzerland

Abstract

The CERN Super Proton Synchrotron (SPS) provides different types of beams at different extraction energies. The main magnets of the SPS are regulated with a current loop, but it has turned out that hysteresis effects from the main dipoles have a significant impact on reproducibility and hence efficiency and availability. Beam and machine parameters were found to depend on the programmed sequence of magnetic cycles - the so-called super cycle - representing the production of the different beams. The scientific program of the SPS requires frequent changes of the super-cycle composition and the effect of the main magnet hysteresis has to be understood, modelled and used in accelerator control system. This paper summarises the first main field measurements carried out with the currently available systems during operational conditions as well as measurements of vital machine and beam parameters as a function of the super cycle composition. Finally, ideas will be presented to provide reproducibility by automatically correcting different parameters taking the magnetic history of the main magnets into account.

INTRODUCTION

The SPS is the last machine of the Large Hadron Collider (LHC) injector chain and it is the second largest CERN accelerator (7 km circumference). It also provides beam to the North Area (NA) Fixed Target (FT) experiments, AWAKE [1] and HiRadMad experimental area. To deliver beam to all users, the SPS is a cycling machine, meaning that the production cycles of the different beams are organized in a so-called Super Cycle (SC) and are played one after the other. Two examples of typical SC are shown in Fig. 1. They include two of the main SPS cycles: the SFTPRO (FT proton beam) and the LHC cycle. The FT beam is injected at 14 GeV and accelerated up to 400 GeV, instead the LHC beam is injected at 26 GeV and accelerated up to 450 GeV.

The change of the SPS SC translates in a change of the remanent field in the main dipoles. Due to the lack of an absolute magnetic field measurement, such effect is not compensated and translates in differences between cycles, mainly visible on the spill of the FT beam and on the beam closed orbit.

Using these observables, a first campaign of measurements was carried out. In this paper, the analysis of the results are presented and correlations of these parameters discussed.

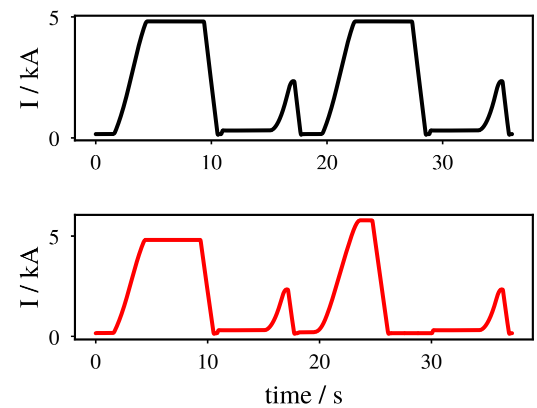

Figure 1: Typical SPS SC used during normal operation. (Top) Typical cycle during nights for FT physics. It is a combination of FT cycle (highest current) and machine development cycles, mainly there for hysteresis compensation. (Bottom) Typical cycle for parallel operation of FT physics and low intensity LHC. Here, both FT and LHC cycles (highest current) are played together in the same SC.

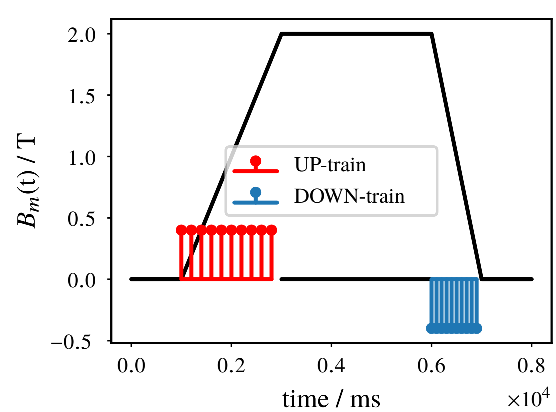

Figure 2: Example of magnetic cycle and B-train signal. The measurement of change of magnetic field is represented by trains of pulses of the same amplitude called UP-train and DOWN-train [2].

SPS B-TRAIN

At the SPS, the only available system to evaluate the magnetic field is via the measurement of the magnetic filed variation $\dot{B} \equiv \frac{dB}{dt}$ with time. This is obtained with the so-called B-train [2], which is a real-time measurement of the inte-

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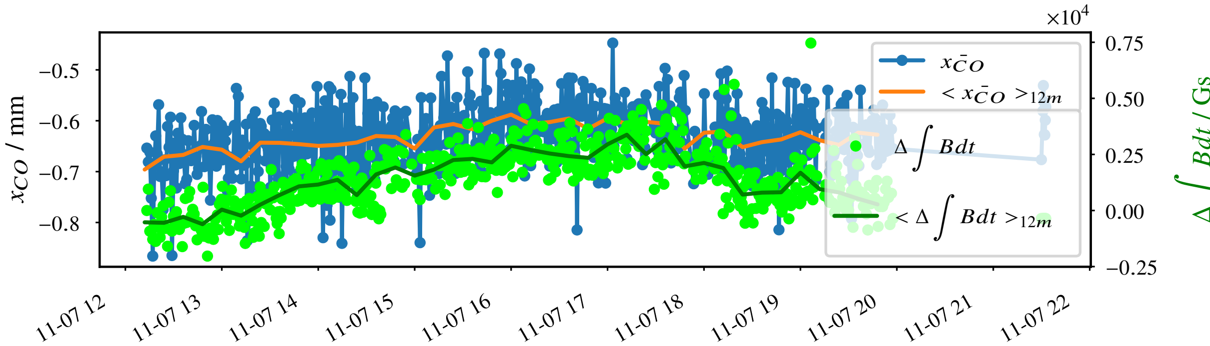

Figure 3: Time evolution of FT beam mean closed orbit (blue) and time integral of the measured magnetic field (green). The solid lines (orange and dark green) represents the averages over 12 minutes of the corresponding quantities.

grated field in two reference magnets of the SPS. Such a measurement system is currently used, for example, by the RF system to regulate the beam energy according to the main field variation along the cycle. As a way to improve the machine reproducibility, and hence the beam quality, the B-train can be used to adjust the main beam parameters according to the measured field using a software based slow feed-forward system [2].

At the SPS, the B-train system is composed of two integral pick-up coils placed inside the gaps of two reference magnets (one of each two different types), which are powered in series with the main SPS dipoles. Each coil measures the rate of change of the linked magnetic flux and the system provides an average field defined as:

$$B_m(t) = B_0 + \frac{1}{2L^* w_e} \int_0^t \dot{B} dt, \qquad L^* \equiv \frac{2\pi R}{744} \quad (1)$$

where w_e is the effective coil width, R is the nominal closed-orbit radius, L^* is the nominal magnetic length of one dipole (assuming equal bending radii in MBA and MBB types). The integration restarts at the beginning of each cycle $t = 0$, and B_0 represents the integration constant. In the B-train systems of other injectors such as the PSB and PS this constant is measured by a dedicated sensor ("field marker"), currently unavailable in the SPS where B_0 is given by a pre-set value [2]. The resolution of the field measurement distributed is 0.02 G and 0.10 G on the two available parallel output channels respectively.

DATA ANALYSIS

A campaign of measurements of some of the main FT cycle parameters was carried out in 2016, in order to evaluate the effect of the remanent field on the beam. The main observables compared here are the horizontal average closed orbit at flat top, the effective spill length [3] and a quantity correlated to the magnetic field of the main dipoles. The purpose is to evaluate the available observables in order to compensate the remanent field in a slow feed-forward way.

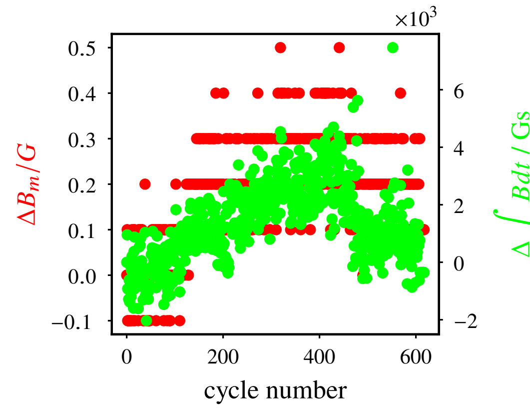

Figure 4: In red the evolution over time of the measured magnetic field (integral of $\dot{B}$) at $t = 4461$ ms as difference with the first observation. In green the evolution over time of the time integral of the measured magnetic field as difference with the first observation.

A first observable is the beam horizontal average position along the SPS. This was recorded after reaching the extraction energy of 400 GeV and just before the RF gymnastic [4]. In the SPS, the closed orbit at high energy cannot be corrected due to lack in corrector strengths, hence any variation of the field will be seen in the orbit, if no RF frequency adjustment is done.

As discussed in the introduction, another of the main observables of remanent field in the main SPS magnets (dipoles and quadrupoles) is the slow extraction spill quality. As presented in [3], a simple and effective way to characterise the spill quality is the *effective spill length*.

As mentioned before, the B-train measurement system is not an absolute field measurement. A way to infer the magnitude of the difference in field, cycle to cycle, in the main dipoles is to compare the measured field $B_m(t)$ at two instants of time where the current is the same. Excluding the ramp up and ramp down, the only two times where the

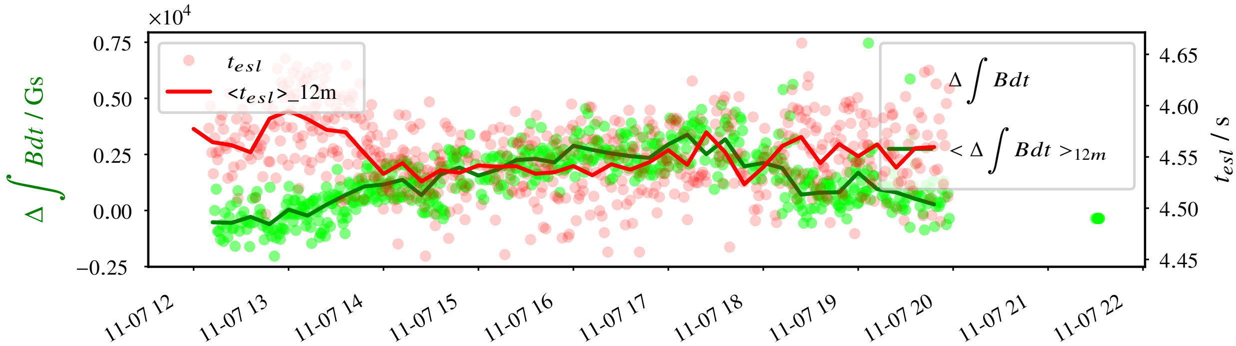

Figure 5: Time evolution of FT beam effective spill length (red) and time integral of the measured magnetic field (green). The solid lines (red and dark green) represents the averages over 12 minutes of the corresponding quantities.

current in the main power supplies is the same is at the beginning and at the end of the cycle. This is essentially equal to the field at the end of the cycle, as $B_m(t = 0) = 0$ due to the absence of a field marker. Equivalently then, instead of taking the field at the end of the cycle, a possibility is to use the B_m at the instant when the orbit was recorded, i.e. $t = 4461$ ms. It will be shown that this choice increases the correlation between closed orbit average and field variation.

Due to the way $B_m(t)$ is calculated from the B-train measurements, the difference is significantly discretised (due to the 0.1 G resolution), as shown in Fig. 4 (red dots). A way to smooth the difference cycle to cycle of $B_m(t)$, and to include information regarding the change in field all over the cycle, is to take the integral over the whole magnetic cycle (Fig. 4). This results in the variation of the time integral of $B_m(t)$:

$$\Delta \int B_m dt \equiv \Delta \int \int \dot{B} dt^2. \qquad (2)$$

Doing so, a quantity correlated to the remanent field of the main dipoles is obtained.

In Fig. 3, the evolution of the average horizontal closed orbit, together with the time integral of the measured magnetic field, is shown. In Fig. 5 instead, the variation of the magnetic field is compared with the evolution of the effective spill length. In both cases, correlation between the different observables is observed.

The correlation of the closed orbit variation and time integral of the magnetic field is shown in Fig. 6. This plot shows the evolution of these parameters correlation as a function of the time interval used for averaging. This curve shows a maximum starting from 12 minutes, which then saturates (for the correlation with respect to the field measured $t = 4461$ ms) at $\rho_{X,Y} = 0.72$.

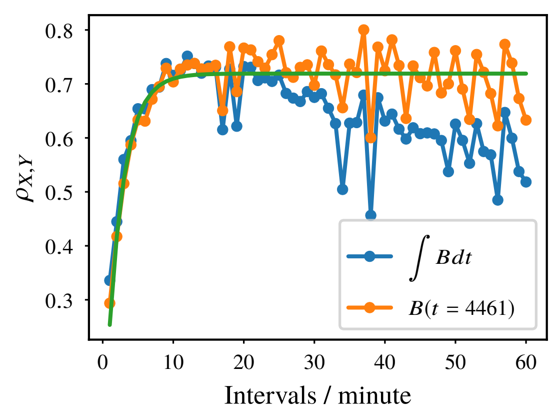

Figure 6: Plot of the dependence of the correlation factor between mean closed orbit and time integral of the measured magnetic field (blue) or the measured magnetic field at $t = 4461$ ms.

CONCLUSION

Variations in the SPS SC composition impact significantly the machine reproducibility.

A campaign of measurements was carried out to observe the evolution in time of relevant machine parameters such as mean horizontal orbit and effective spill length of the slow extracted spill for the North Area experiments. The available B-train measurement system was used to infer the main field evolution at the same time. Changes of the effective spill length as well as average closed orbit are correlated with changes of the time integral of the measured magnetic field. Maximum correlation is reached when the observables are averaged over a period of at least 12 minutes. Simulations will be used in the near future to investigate whether these results can be used to build a feed-forward beam energy correction algorithm to compensate for the remnant field.

The implementation of a filed marker will significantly improve the usability of the B-train, as well as the present resolution of the B-train should be improved to match the beam-based measurements available.

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