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CHARACTERISATION OF SPS SLOW EXTRACTION SPILL QUALITY DEGRADATION

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Abstract

The main physics users of the Super Proton Synchrotron (SPS) are the experiments installed in the North Area (NA). They are supplied with slowly extracted protons or heavy ions, exploiting a third integer slow extraction to provide a 4.8 s spill. High duty cycle and constant particle flux are the main requirements. Frequent super cycle changes induce variation of the spill macro structure which directly deteriorates the final spill quality. In this paper, the source of this effect is investigated. Results of both beam based measurements and direct magnetic measurements on the SPS reference magnets are presented. Finally, a possible strategy to counteract this effect is discussed in order to remove the spill variations caused by super cycle changes.

INTRODUCTION

The biggest fraction of protons accelerated in the SPS goes to the North Area (NA) fixed target experiments. As the SPS is operating as a cycling machine, many other users can and do populate the SPS Super Cycle (a super cycle is a series of different magnetic cycles). In order to reduce the idle time and guarantee high duty cycle for all users, super cycles are optimised. Only cycles where beam is requested at the very moment are played. This translates however in frequent SC composition changes. The so-called physics production SC is the main SC in the SPS. It consists of one SFTPRO (cycle to deliver beam to the NA) followed by one Machine Development (MD) cycle (Fig. 1-top). In this configuration, the duty cycle to the NA is maximised. The second most common SC, instead, is the SC for the Large Hadron Collider (LHC) filling consisting of one SFTPRO, one MD, one LHC cycle and another MD cycle, see Fig. 1-bottom. The integer part of the tune for LHC beams in the SPS is 20 instead of the canonical 26 as used for the SFTPRO beam. This translates into 12 % lower field in the quadrupoles in an LHC cycle in spite of the higher energy of (450 GeV for LHC beams compared to 400 GeV for SFTPRO). The swap between the two super cycles as discussed before occurs several times per day during normal operation.

The fixed target and LHC cycles in the SPS are different in many ways: extraction energy, optics, duration, ramp speed, etc. As the magnetic behaviour of the SPS main dipoles and quadrupoles is different, not only extraction energy and optics have an effect on variations of machine properties when the super cycle changes [1,2]. The effect on the slow extracted spill quality is non-negligible and needs to be corrected each time.

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In this paper, the results of a field measurement campaign carried out on a spare SPS quadrupole in the laboratory is presented. The magnetic behaviour of the SPS quadrupoles following a SC change is then compared to beam-based measurements and expectations from beam simulations.

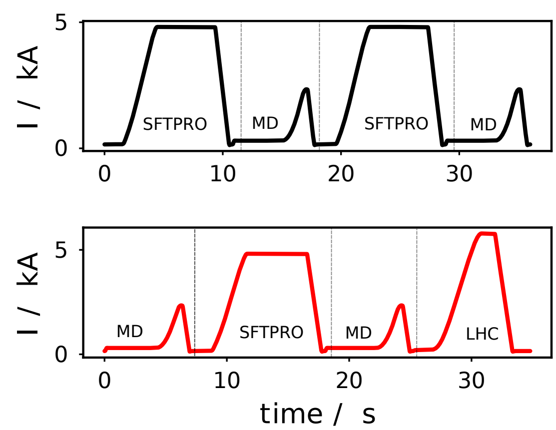

Figure 1: Two super cycles in the SPS plotted as current in the main dipoles as a function of time. Top: physics production SC with two SFTPRO or fixed target cycles at 400 GeV followed by 200 GeV MD cycles. Bottom: LHC filling SC with the 450 GeV cycle at the end and a fixed target cycle. 2 MD cycles are used as buffers.

MAGNETIC MEASUREMENTS ON SPS SPARE QUADRUPOLE

Magnetic measurements of SPS quadrupoles are not available online and difficult to organise in the tunnel. As spares are available, an ad-hoc test bed to evaluate the effect of SC changes on the integrated quadrupole field was prepared. The SC used for the measurements corresponds to a LHC filling SC with the LHC and MD cycles swapped, which was supposed to make hysteresis effects more apparent. The measurements are performed using a pick-up coil, which permits to measure the flux change in a given time interval (V s). The integrated field can then be calculated by integrating the voltage induced in the coil after an offset correction applied knowing that at constant current the output of the coil should be 0 V. The integrated field in T is obtained by dividing the flux by the effective coil area, which is estimated to be 0.79 m^2. Although absolute measurement accuracy is poor with this technique, relative field variations, which are of interest for the discussion here, can still be measured with high resolution.

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EVALUATION OF THE FIELD VARIATION AT FLAT TOP OF THE FIXED TARGET CYCLE

Figure 2 shows the measured relative field change for the first three SFTPRO cycles after changing from the production SC to an LHC filling SC. The relative change is calculated as: $\frac{Gdl-Gdl_0}{Gdl_0} \equiv \frac{\Delta Gdl}{Gdl_0}$, where Gdl_0 is the quadrupole integrated field recorded after 7 repetitions of a production SC. The LHC cycle quadrupole field is lower than for SFTPRO due to the lower tune and hence there is a positive change at injection energy and a negative one at flat top. In other words, the field of an SFTPRO cycle is higher at flat bottom and lower at flat top after the SC change.

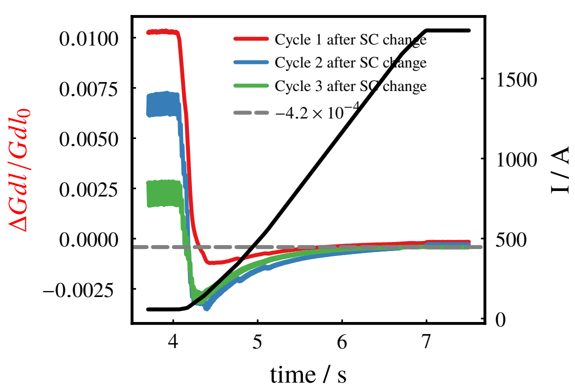

Figure 2: Measured relative integrated field variation for an SFTPRO cycle following a SC change. The reference field is referring to an SFTPRO cycle in a production SC after 6 repetitions. (Note the expected variation of the field at flat bottom for the correct SC configuration where the MD cycle precedes the SFTPRO in the LHC filling SC is to be expected lower than what showed in this plot.)

In order to compare the obtained results later on with beam-based measurements, the variation of the field when arriving at flattop is recorded. The reference point in time is illustrated in Fig. 3 as a blue dot. Figure 4 shows the trend of the flat top field evolution while playing one super cycle after the other including a super cycle change. Note also that while playing the production super cycle the field decreases for some time. It stabilises after the 7th repetition of the fixed target cycle. After a super cycle change to an LHC filling super cycle, the field starts dropping again reaching the final value of -4.2×10^{-4} after roughly 5 cycles.

COMPARISON WITH BEAM-BASED MEASUREMENTS AND SIMULATIONS

Due to transition crossing on the fixed target cycle, the radial loop is used to control the RF frequency during the ramp. When a SC change takes place, the radial loop will counteract the effect of hysteresis in the main dipoles. The resulting tune variation from the field changes in the main

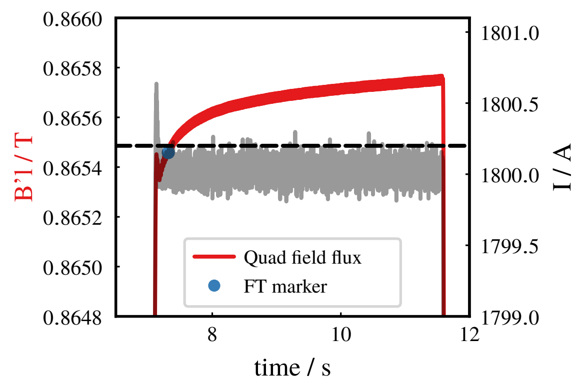

Figure 3: Integrated field (red) and currents in the test quadrupole used for the magnetic measurements presented. The blue dot represent the reference chosen as indication of the field at flat top.

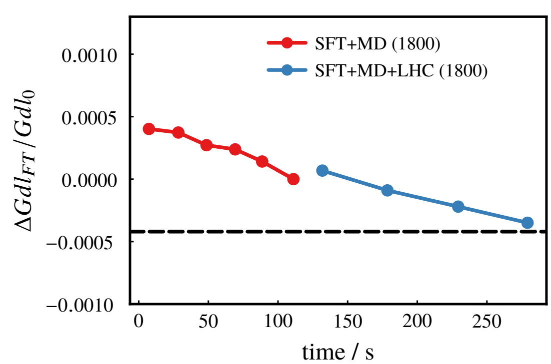

Figure 4: Evolution of the flat top field in SFTPRO cycle as consequence of SC change. The first point of the blue curve (LHC filling SC) is still part of the previous SC due to the choice of the order of the cycles in the SC.

quadrupoles together with field changes in the main bends will result in a degradation of the spill quality.

The relative main dipole field changes can be derived from the so-called BTRAIN [3] measurement. The BTRAIN measurements are not calibrated, but are adequate for measurements of beam energy change [1]. An example of these measurements is shown in Fig. 5, together with the effective spill length [4] variation. An average of about 2×10^{-4} variation in the main dipole field, and hence the beam energy, was measured.

Using the measured quadrupole and dipole field changes after a super cycle change, the tune change at the fixed target flat top can now be evaluated. This was done both analytically and with MADX [5]. The parametric results are shown in Fig. 6. The expected tune variation is 0.007 (black dashed lines in Fig. 6) for both horizontal and vertical tune given the measured quadrupole and dipole field changes.

Figure 7 finally shows beam-based measurements [2] together with the predictions from the magnetic measurements. The predictions agree remarkably well with the beam mea-

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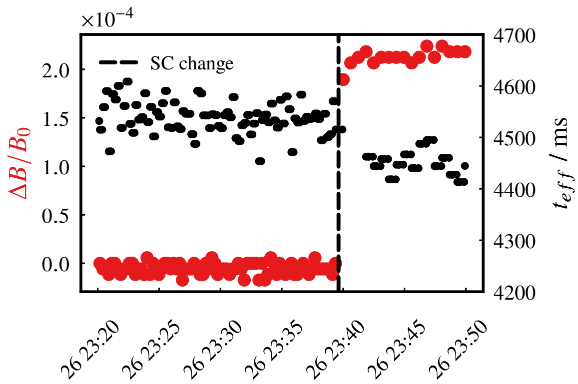

Figure 5: Relative field variation measured in the main SPS dipoles using the SPS BTRAIN. The dashed vertical line represent the instant when the SC was changed. The black dots are the time evolution of the effective spill quality.

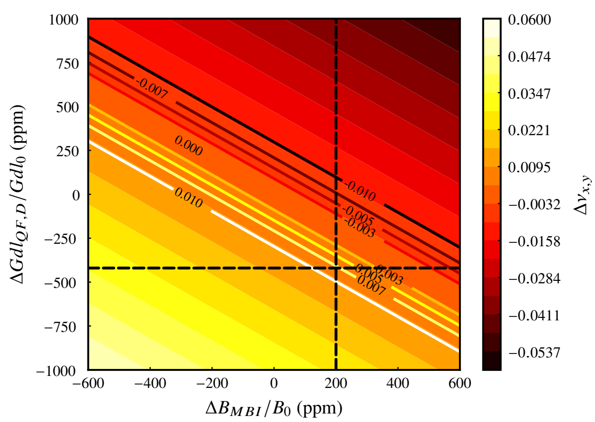

Figure 6: Simulations of the tune variation (both horizontal and vertical) in the SPS as a function of relative field variation in both quadrupoles and dipoles. The variation in the quadrupoles has been assumed to be the same for both the focusing and the defocusing ones.

surements, despite the poor current reproducibility of the power supply used for the quadrupole magnetic measurements of only 280 ppm (this is typically in the range of variation significant for spill quality). We therefore conclude that the hysteresis effects of the main dipoles together with the main quadrupoles explain the tune variations and thus spill degradation experienced with slow extraction after super cycle changes.

CONCLUSIONS

An extensive magnetic field measurement campaign was carried out to understand the source of beam parameter changes after SPS super cycle modifications. As a continuation from the work started in [2], magnetic measurements of the main SPS quadrupoles were performed.

The relative field variation observed at flat top for a fixed target cycle undergone a SC change was estimated to be -4.2×10^{-4}. Combining it with the measured main dipoles

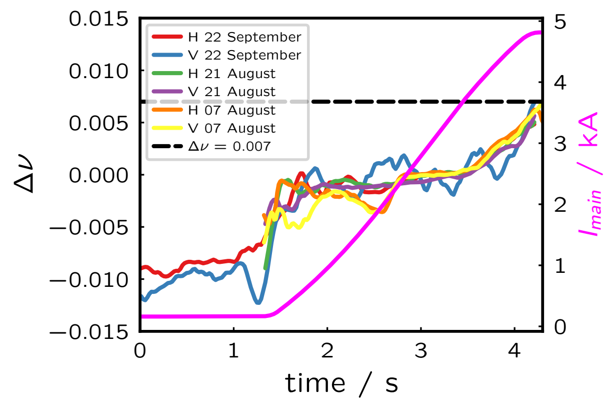

Figure 7: Measured tune variation following a SC change [2]. The horizontal dashed line is the expected change from simulations, as shown in Fig. 6.

field variation, 2×10^{-4}, the theoretical tune calculated corresponds to 0.007 for both horizontal and vertical tune. This is in very good agreement with the tune change measured with beam on a fixed target cycle as a result of a super cycle change.

Due to the difference in the exact super cycle composition used during the measurement campaign for the LHC filling super cycle, another series of tests has been proposed to evaluate possible differences to the results so far presented. No significant effects for the flat top field measurements are however expected.

Finally, the development of a synthetic model of the SPS quadrupoles could be investigated using advanced algorithms, e.g. machine learning, with the aim to predict the field at each cycle and correct the tune accordingly. If the quality of the prediction will not be adequate, the option to reintroduce feedback control based on real-time measurements of a reference quadrupole, already implemented in the early days of SPS, should be considered.

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