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EFFECT OF THE EXTRACTION KICKERS ON THE BEAM STABILITY IN THE CERN SPS

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Abstract

Longitudinal beam instability in the CERN SPS is a major limitation in the ability to achieve the bunch intensities required for the goals of the High-Luminosity LHC project (HL-LHC). One of the major drivers in limiting the intensity of the machine is the broadband contribution to the beam-coupling impedance due to the kicker magnets.

The extraction kickers (MKE) discussed in this paper are known to give a significant contribution to the overall longitudinal beam-coupling impedance.

We present the results of bench measurements of the MKE's impedance to determine the accuracy of electromagnetic simulation models from which the impedance model—used for beam dynamics simulations—is constructed. In addition, we discuss the feasibility and implementation of beam measurements that can indicate the contribution of the MKE magnets to the longitudinal beam-coupling impedance of the SPS.

INTRODUCTION

Instabilities during the acceleration cycle in the Super Proton Synchrotron (SPS) are a major limitation in achieving the goal of providing nominal bunch intensities of 2.3×10^{11} protons per bunch (ppb) to the High-Luminosity LHC (HL-LHC). In order to achieve this level of beam intensity a major upgrade of the injector chain in the form of the LHC Injectors Upgrade (LIU) project has been undertaken [1].

In terms of the upgrades to the SPS this includes; upgrading of the existing RF systems, upgrading of the existing slow extraction system, and impedance reduction through the shielding of vacuum flanges, all of which is designed to enable the production of stable HL-LHC type beams in the SPS. In addition to this, the identification of existing impedance and minimisation of the impedance of newly installed equipment play a key roll in developing a detailed understanding of what limits the performance of the SPS in terms of beam instability.

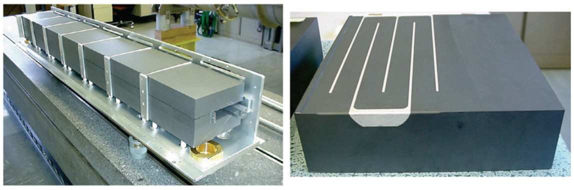
Many sources of impedance in the SPS have been identified and characterised. These sources of impedance have then been used to identify in particle tracking simulations which particular sources are limiting. These simulations have been extensively compared with beam measurements and indicate that the impedance model is on the whole a fair representation of the machine—or at least of the components which currently dominate the behaviour of the SPS beam. This paper focuses on the longitudinal plane.

In the year 2016, a detailed study of the properties of the reactive (imaginary) components of the SPS impedance was carried out through the measurement of the quadrupole frequency shift [2]. Comparisons to the impedance model using the beam tracking code BLonD [3] showed a significant difference which could be attributed to a low frequency (350 MHz) resonance with an R/Q of order 3 kΩ. The ultimate aim of this measurement is to identify the source of this missing impedance.

One possibility could be an underestimated contribution attributed to the kicker magnets. The most significant contributors to those are the injection kickers (MKP) and the extraction kickers (MKE) which are discussed in detail here.

IMPEDANCE OF THE EXTRACTION KICKERS

In the SPS the extraction systems utilise a combination of septa and kicker magnets. In the current layout, there are seven MKE kickers; four in sextant four and three in sextant six. Prior to the introduction of impedance reducing measures, the MKE was the dominant contribution to the machine impedance (neglecting the 200 MHz RF cavities) and was a cause of single bunch instability through the loss of Landau damping. In 2007, the MKE magnets were modified to reduce the beam coupling impedance through the use of serigraphy (conducting strips that allow a reduced impedance path for the image currents) to help reduce the impedance as well as the beam induced heating [4]. Details of this can be found in Ref. [5] and images of the ferrite core of the magnets are shown in Fig. 1 where the painted serigraphy pattern is clearly visible.



(a) Full kicker (b) Serigraphy pattern

Figure 1: Pictures of the MKE ferrite core showing the core assembly and serigraphy pattern [5].

Simulations

The MKE kicker was remodelled in CST [6] making several changes to the original model developed in 2013 [7]. These changes include:

- The addition of the ground bar.
- Correction to the layout of the serigraphy.

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- Serigraphy modelling using the thin panel material in CST MWS.

These relatively small changes have a significant impact on the impedance found when performing wakefield simulations using the wakefield solver in CST MWS. The large difference between the two models is shown in Fig. 2.

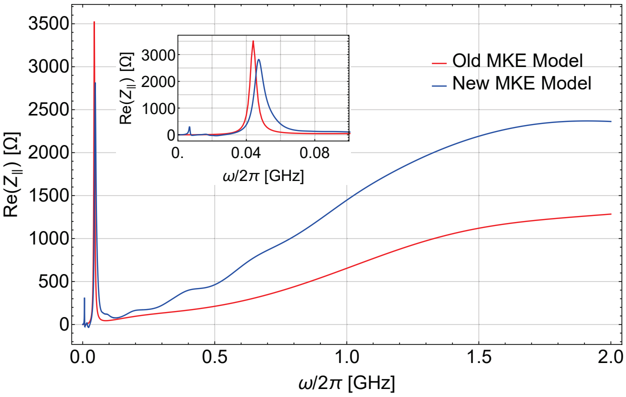

Figure 2: Simulated real part of longitudinal impedance of the MKE kicker as a function of frequency.

The key differences in the impedance are the frequency and width of the serigraphy peak (at around 50 MHz) and the general increase of the broadband impedance by a factor of approximately two. Considering that the MKE is one of the most dominant sources of resistive impedance in the SPS (behind only the 200 MHz cavities and the MKP kickers), this difference becomes concerning. One issue with the new model is that it is unable to reproduce the heating of the kicker ferrites, which has been observed during operation in the SPS.

The heating is highly dependent on the frequency of the serigraphy's resonant peak as an overlap of the resistive impedance with beam spectrum peaks produces heating. The resonant frequency is highly dependent on the ferrite properties, especially on the relative permittivity ϵ_r. The value for high frequencies is constant and around 12. For lower frequencies however, it is probably growing as found in Ref. [5]. Investigations of the correct values are ongoing and simulations here use a constant ϵ_r of 12. In order to determine the contribution of the MKE kicker to the broadband impedance measurements with the coaxial wire method described in Ref. [8] were undertaken.

In Figs. 3 and 4 the good general agreement between the new MKE model and the measured results up to a frequency of 1.5 GHz can be seen. This frequency range is the main area of interest for beam dynamics and heating as this is the region which overlaps with the beam spectrum during normal operation of the SPS. The disagreement at higher frequencies—in particular the clear resonance—is an artifact of the measurement setup introduced by flanging the structure off to enable it to be measured. In addition, the new model accurately reproduces the frequency and peak impedance of the serigraphy peak which is expected to be the dominant contributor to heating of the serigraphed MKE.

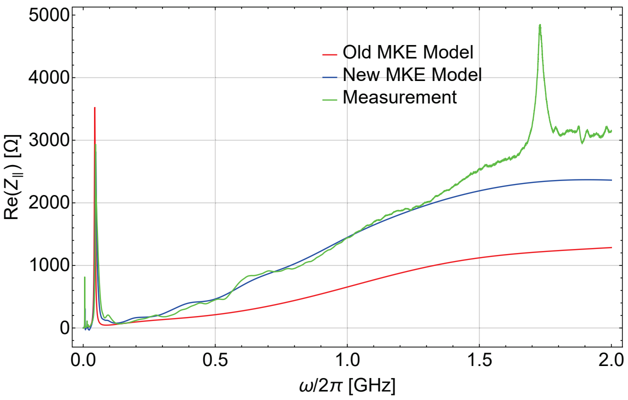

Figure 3: Comparing the simulated longitudinal impedance to the measured impedance. (The measured impedance is calculated using the log formula [8]).

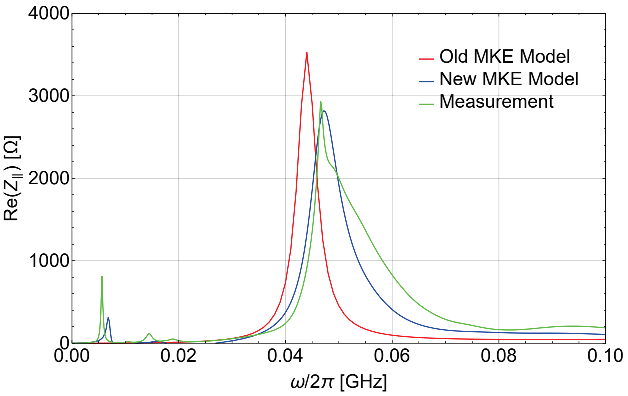

Figure 4: Detailed look at the serigraphy resonance peak shown in Fig. 3.

But as wakefield simulations are compared to wire measurements, the simulated resonance is expected to be lower because the wire introduced for the measurement influences the resonance frequency.

The effect of the significant increase in the contribution of the kickers to the broadband component of the impedance model has to be investigated with respect to the impact on the expected performance in the post-LIU era and the ability to reach the required 2.3×10^{11} ppb with the currently planned improvements.

IMPACT ON THE INSTABILITY THRESHOLD

To predict future intensity threshold and to study devices suspected of lowering the stability in the SPS, the knowledge of the machine longitudinal impedance is crucial. The full post-LIU impedance model [1,9–12] contains various broad- and narrow-band resonances with frequencies up to 4 GHz, including the resistive wall impedance.

Due to its many individual contributors, the model is complex. However, three main categories can be drawn. First, the biggest contribution to the impedance are the travelling-wave RF cavities at 200 MHz with the accelerating and

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HOM bands. The beam-coupling impedance in the accelerating band will be reduced by 26 dB after the upgrade of the one-turn delay feedback. A factor three reduction of the impedance of the HOM band at 630 MHz is assumed to be obtained. The second contributor are the vacuum flanges and more generally all vacuum elements which contribute mainly to higher frequencies (>1 GHz). The LIU impedance model assumes shielded QF type vacuum flanges between beam position monitors and magnets and also in the short straight sections. The model contains 29 sector valves of type A (VVSA) and 38 sector valves of type B (VVSB). In addition 25 unshielded pumping ports remain in the model as well. The third and last main contributor are the kicker magnets with seven MKE, 16 MKP and seven other kickers used for tune measurements and dumping of the beam present in the SPS. Their impedance is broad-band and can have a major impact on the single-bunch behaviour and necessarily on the stability of the beam. With the SPS being pushed already to its limits [13], every contribution to the impedance can have a significant impact on the stability. Single resonances contributing to an instability are sometimes difficult to extract.

As stated before, the impedance of the MKE has been re-evaluated and found with a larger broadband impedance. The impact of this additional impedance is studied by means of particle tracking simulations using the code BLonD, developed in the RF group at CERN. Simulations are done for trains of 48 bunches spaced by 25 ns matched with the RF bucket including intensity effects. The LHC proton beams in operation contain 72 bunches but similar stability limits were obtained in simulation with a batch of 48 bunches, which allows the simulation time to be reduced. The beam distribution is chosen in agreement with measurements. Beam-loading with HL-LHC intensity limits the maximum voltage in the 200 MHz RF cavities, V_{200}, to 10 MV; this value is used as a voltage limit in the simulations for all intensities. The 800 MHz RF voltage is fixed to $V_{800} = 0.1 \times V_{200}$ in bunch-shortening mode since it provides increased stability at SPS flat top [1, 14, 15]. The oscillations of the bunch length averaged over the entire batch are used to separate a stable beam from an unstable one.

Figure 5 shows the intensity threshold for the updated and previous model of the MKE impedance. A significant reduction of the threshold is observed for the newly found impedance decreasing the beam stability margin gained by the impedance reduction campaign. This reduction is significant enough that the already proposed impedance reductions may require expanding to encompass more machine elements. To regain margin, it could become necessary to enlarge the scope of the impedance reduction campaign to known contributors to the instability threshold which include the MKP kickers, the VVSA/B sector valves and unshielded/nonconforming pumping ports.

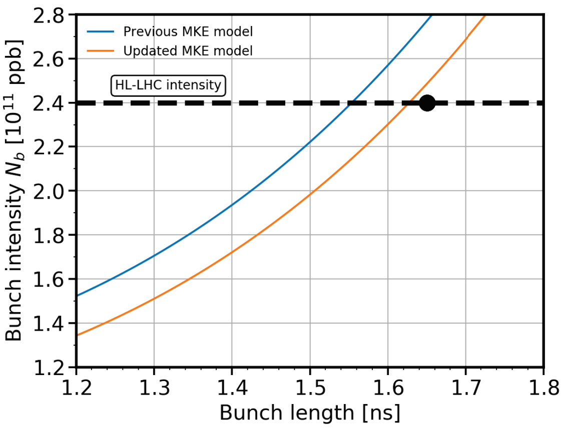

Figure 5: Stability threshold at SPS flat top for a batch of 48 bunches spaced by 25 ns with the previous and updated impedance models of MKE. A significant reduction on intensity threshold is witnessed using the latest MKE impedance model.

BEAM MEASUREMENTS

It is currently not possible to directly measure the intensity threshold in the SPS with beams meeting the HL-LHC requirements and hence infer the impact of the kickers by comparison to predictions. A method that theoretically can determine the kicker impedance with beam is proposed as an alternative.

We propose to measure the resistive component of the impedance through the measurement of the synchronous phase shift similar to what was done in 2004 [16]. In these measurements the RF system was used to define the phase shift. In the proposed measurement two bunches; one of low intensity (reference bunch) and one of high intensity (test bunch) would be used and the relative phase difference between the two will be used to define the synchronous phase shift.

In a single RF system without acceleration, feedback or feedforward, the synchronous phase, ϕ_s is defined by

$$\sin\phi_s = \frac{U}{eV}, \tag{1}$$

where U is the energy lost per turn per particle and V is the amplitude of the RF voltage. By measuring the synchronous phase it is possible to obtain the total energy lost per turn by a bunch. The energy lost by a bunch per turn is directly related to the bunch properties and the impedance of the machine. It can be calculated analytically by

$$U_b = -e^2 N k = -e^2 N \sum_n k_n(\sigma). \tag{2}$$

k_n is the loss factor [17] which for a Gaussian bunch and longitudinal impedance $Z_n(\omega)$ is

$$k_n(\sigma) = \frac{\omega_0}{\pi} \sum_{p=0}^{\infty} \Re[Z_n(p\omega_0)] \exp[-(p\omega_0\sigma)^2]. \tag{3}$$

N is the number of particles per bunch, σ is the RMS bunch length and ω_0 the revolution frequency of the beam. Equations (1) and (2) link the resistive component of the impedance to the synchronous phase shift, theoretically allowing the contribution of the MKE kicker to be determined. These measurements are complementary to those probing the reactive component of the impedance [2].

BLonD Simulations

To test the feasibility of this measurement, the BLonD code was used. In these simulations the bunches are modelled with a binomial bunch distribution with an exponent of 1.5 and the full SPS impedance model is used. The bunch length σ and number of protons per bunch have been varied from 3–4.5 ns (4σ) and 0.8×10^{11} to 2.8×10^{11} respectively. The final parameter is the voltage in the 200 MHz RF cavities. Lower voltages allow for larger synchronous phase shifts, see Eq. (1), but reducing the bucket area ultimately limits the achievable intensities. In the case of using lower voltages the optics chosen also play a role in defining the bucket area as it depends on the transition energy.

By computing the expected synchronous phase shift and only varying the contribution from the MKE kickers, the dependence on the broadband impedance is obvious. Figure 6 shows the difference in the expected synchronous phase shift from the two MKE models for a bunch length of 3 ns. At high intensity with short bunch lengths and low RF voltage there is a significant difference in the expected phase shits. Also, this shift is relatively small and in measurement with beam it may not be possible to distinguish the difference.

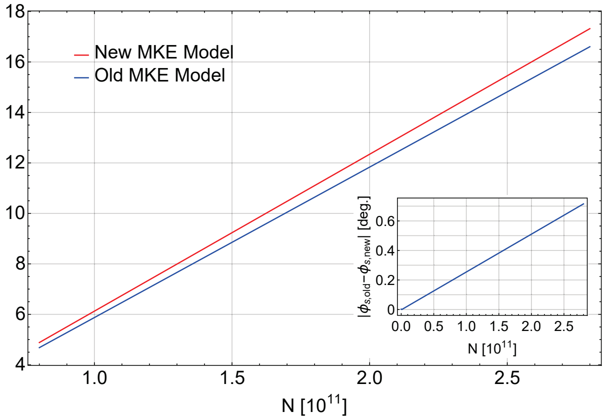

Figure 6: Synchronous phase shift as a function of intensity at $4\sigma = 3.0$ ns with $V_{200} = 2$ MV from BLonD with Q20 optics. The full SPS impedance model is included, only changing the MKE model used.

Preliminary Beam Measurements

To perform the beam measurement, a method of referencing the synchronous phase shift is required. Here two bunches of equal bunch length—one at low intensity (reference bunch) and one at high intensity (test bunch) are used. By doing so, a linear dependency of the relative phase shift between the two bunches is ensured and the absolute phase shift can be extrapolated.

In order to perform this measurement, it must be ensured that the bunches are far enough apart not to be influenced by the longitudinal long range wakefields. To achieve this, the bunches are maximally spaced in the sub-cycle of the Proton Synchrotron (PS), about one tenth of the SPS length which is more than adequate for the purposes of the measurement.

The profiles of the two bunches are then recorded simultaneously on a single frame of a 25 ps sampling oscilloscope. At each acquisition 250 frames are taken at intervals of every 360 SPS turns and for each frame the bunch length and position is calculated and the relative phase (at 200.22 MHz) is then determined.

The measurements have been performed with a reference bunch intensity of 0.5–0.6×10^{11} ppb and test bunch intensities in the range of 0.8–2.5×10^{11} ppb. Two bunch lengths have been investigated; 3.2 ns and 3.6 ns with a 200 MHz cavity voltage of 2.5 MV.

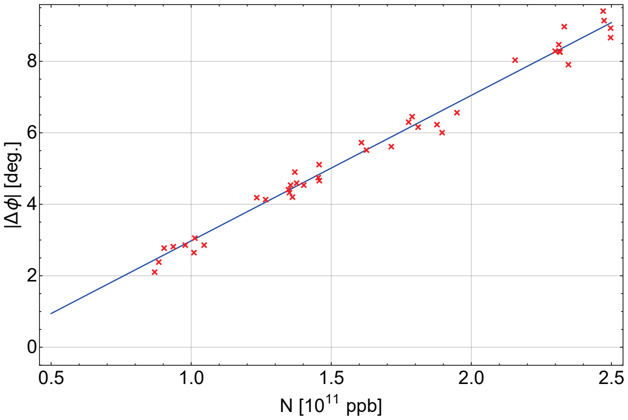

Figure 7: Relative phase shift between the reference and test bunches in the SPS using $V_{200} = 2.5$ MV and $4\sigma = 3.6$ ns.

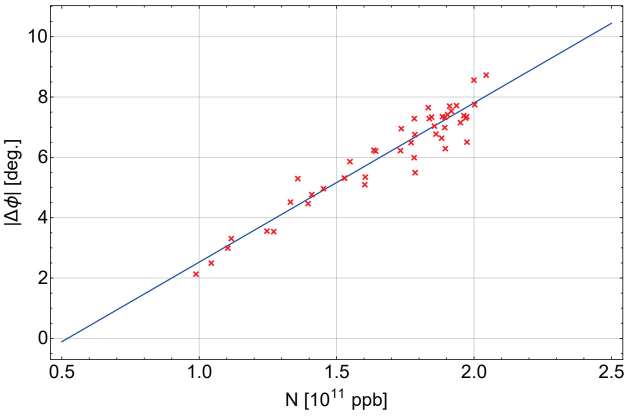

Figure 8: Relative phase shift between the reference and test bunches in the SPS using $V_{200} = 2.5$ MV and $4\sigma = 3.2$ ns.

The data shown in Figs. 7 and 8 clearly indicate the linear dependence of the synchronous phase shift on bunch intensity. The phase shift gradients found are 0.41 and

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0.52 deg./10^{10} corresponding to an energy loss per turn of 17.9 and 22.7 keV/10^{10}, respectively. The data for the longer bunch length have less variation due to a more consistent bunch length produced earlier in the accelerator chain. The relatively high intensities used in the 3.2 ns measurements result in a large bunch-by-bunch variation in bunch length. In addition it was not possible to exceed 2.0×10^{11} ppb due to limitations in the injectors. The measured data are compared with BLonD simulations in Fig. 9.

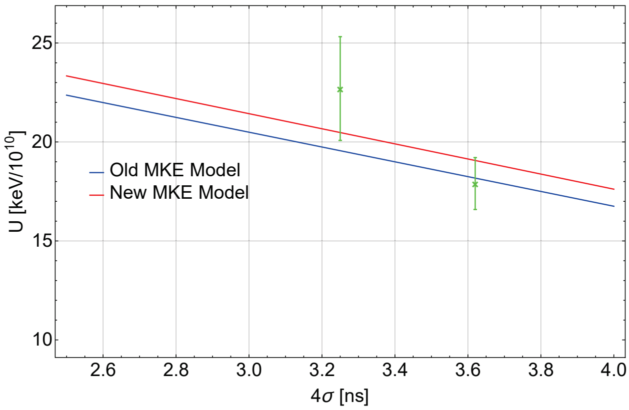

Figure 9: A comparison of the energy loss measured with beam and the results from the BLonD code. The error bars on the measurements represent the 95% confidence level on the fit without weighting factors applied to the data. The full SPS impedance model is included only changing the MKE model used.

In order to obtain a complete picture, further studies with a wider range of bunch intensities, bunch lengths and RF accelerating voltages are required. Due to the significant variation in the bunch length produced earlier in the accelerator chain bunch length corrections have to be applied. The region in which the measurements are most sensitivity to the impedance of the MKE kicker are found at low cavity voltage with short bunch lengths and high intensity. These conditions are difficult to reach and therefore probing the kicker impedance through beam measurements may prove challenging.

SUMMARY

The model of the longitudinal impedance of the extraction kickers in the SPS at CERN has been updated, leading to an increase in the broadband impedance, with values per MKE being roughly double that of the previous model. The larger impedance has been confirmed by coaxial-wire measurements of the kicker. The impact of this significantly higher impedance on the intensity threshold of the post-LIU SPS has been investigated in simulations. The threshold expected is potentially 10% lower than originally anticipated leading to the probable requirement of further impedance reduction in the SPS. Furthermore, a way of measuring the impedance contribution of the kicker has been introduced. Preliminary measurements delivered promising results for benchmarking of the SPS impedance model.

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