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PROGRESS TOWARD A DYNAMIC EXTRACTION BUMP FOR SLOW EXTRACTION IN THE CERN SPS

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Abstract

The possibility of reducing the angular spread of slow extracted particles with a time-dependent extraction bump at the CERN Super Proton Synchrotron (SPS) is under investigation. In order to create this so-called dynamic bump, two orthogonal knobs were designed to enable independent movements of the beam in position and angle at the upstream end of the electrostatic extraction septum (ES). With the present slow extraction scheme, simulations show that the use of a dynamic bump can reduce the angular spread at the ES by roughly a factor two and reduce beam loss on the ES. A reduction in the angular spread is also a prerequisite to exploit the full potential of other loss reduction techniques being considered for implementation at the SPS [1], like the active or passive diffusers [2, 3] planned for installation upstream of the ES in 2018. In this paper, the simulated loss reduction with a dynamic bump alone or in combination with other loss reduction techniques will be assessed, the first beam-based tests of the dynamic bump presented, the details of its implementation examined and its potential for future operation at the SPS discussed.

PURPOSE AND DESIGN

It is well known that, in a slow extraction using an electrostatic septum (ES), the angular spread of the extracted separatrix can lead to losses higher than those expected based on the septum thickness alone [4]. This is due to the fact that incident particles do not only hit the upstream end of the septum head on, but may hit downstream due to their angular mismatch with the alignment of the septum.

In the SPS, the instantaneous angular spread of the beam at the ES (induced mainly by the small range of momenta extracted inside the stop-band width) remains almost constant throughout the spill. However, in the presence of large chromaticity, the changing optics as the tune is swept during the spill causes a coherent, time-dependent rotation of beam that effectively increases the angular spread at the ES. The time dependent component of the angular spread can be reduced by using a time dependent extraction bump. The dynamic bump could furthermore be used to maintain the relative alignment of the beam and ES even in the presence of slow drift of the closed-orbit throughout the run. A similar method is already employed at the J-PARC main ring and has been shown to reduce the losses per spill and to keep good alignment over the course of several months [5].

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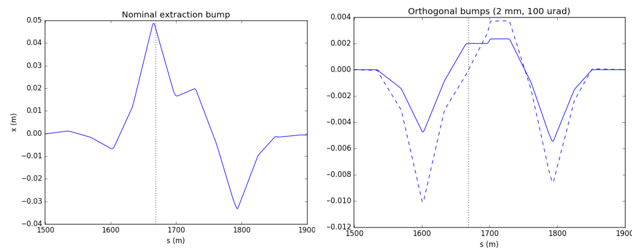

Figure 1: The three closed-orbit bumps combined to construct the dynamic bump: the nominal bump (left), and the orthogonal bumps in position (right, solid) and angle (right, dashed). The dotted black line indicates the entrance of the ES.

The SPS dynamic bump will use the same bumper magnets as are already in use for the extraction bump. Two orthogonal knobs using these magnets have been designed and can be superimposed with the nominal bump in order to move the beam center exclusively in position or angle, at the entrance of the ES. The shape of these bumps, as calculated in MAD-X, is shown in Fig. 1. The positional bump changes the position at the ES without changing the angle, while the opposite holds for the angular bump.

SIMULATIONS

In order to find the optimal bump settings and to assess the reduction in extraction losses, tracking simulations were carried out using MAD-X coupled with the `pycollimate` [6] scattering routine to simulate the interaction of the beam with the wires of the ES. The presentation of the separatrix arm at the ES with and without dynamic bump for the nominal extraction parameters is shown in Fig. 2, without the scattering routine. In reality, the optimal settings in the machine may differ due to feeddown from the non-zero closed orbit and the exact momentum spread, but the dynamics at the simulated optimum are expected to be representative of the machine. As shown in Fig. 3, the angular spread of particles near the ES wire is reduced by more than a factor two, from 22 to 9 μrad (rms).

Simulated ES

The alignment, mechanical and material properties of the ES are crucial to simulating the efficiency of the slow extraction. In reality, the SPS ES consists of five separate tanks on a common girder, the first two of which have 60 μm wires and the latter three have 100 μm wires. The five septa tanks are then aligned in a beam-based procedure where the

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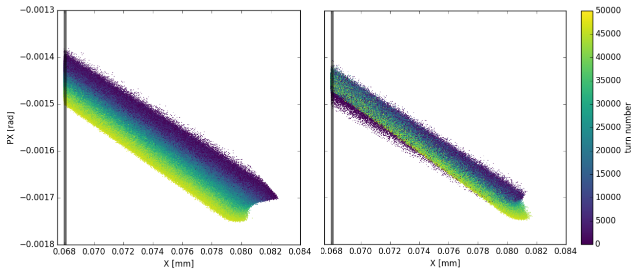

Figure 2: Extracted beam in phase space, with the ES wires indicated in grey, for the case without (left) and with (right) dynamic bump. Particles are colored by the turn number in the simulation at wich they are extracted.

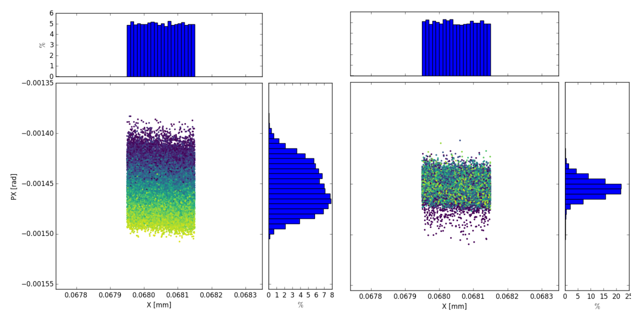

Figure 3: Section of the separatrix hitting the simulated 200 µm ES wires head on, for the case without (left) and with (right) dynamic bump.

position of the upstream end of the first tank's wire array is kept fixed and the downstream end of the girder, as well as the up and downstream ends of the other tanks' wire arrays (together with the respective cathode) are varied and set to minimise the signal on the beam loss monitors (BLMs). For more details of this alignment procedure see [7].

The anode wires of the five ES tanks were simulated as a single continuous rectangle to save computation time by avoiding additional calls to the `pycollimate` routine. A width of 200 µm was used for the anode, in order to mimic the expected effective thickness due to deformation and misalignment, with a scaled effective density to account for the correct amount of material. The upstream position of the ES was kept fixed, while the downstream position was scanned and the corresponding extraction efficiency simulated. The position of the girder leading to the minimal simulated loss was defined as nominal.

Expected Loss Reduction

The expected loss reduction depends strongly on the effective ES thickness, as shown in Fig. 4. With the estimated 200 µm thickness, the loss reduction is only about 5 %, much less than the reduction in angular spread. The reason for this is discussed in [7]. In short, one has to distinguish between head on losses, which are determined by the ES width, and losses from particles impacting on the sides of the wire array, which are linked to the angular spread of the beam. With a larger effective thickness the beam losses are

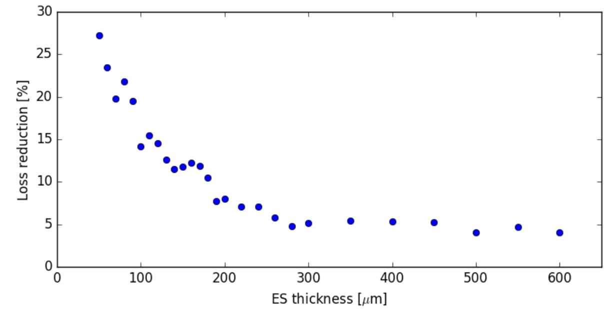

Figure 4: The simulated loss reduction obtained with using the dynamic bump, for various values of the effective ES thickness.

dominated by particles impacting head on, whereas with a smaller thickness the fraction of particles impacting from the sides is more significant. Therefore, the dynamic bump has a larger impact on total loss reduction when the effective ES thickness is small.

Combination with Diffuser

As part of ongoing efforts to reduce the activation of the ES per extracted proton, the use of a thin passive scatterer (diffuser) was also studied [2]. A prototype was installed in the SPS this year and first tests with beam are underway. Simulations show a greatly improved loss reduction factor when the diffuser and dynamic bump are combined. The small (3.7°) phase advance between diffuser and ES allows the dynamic bump to improve beam conditions in both locations.

A diffuser consisting of 20 tungsten-rhenium wires with a 300 µm diameter, equally spaced over 40 mm was simulated. The losses were reduced by 14 % with the diffuser alone, and by 37 % with the diffuser in combination with the dynamic bump. The predicted loss reduction obtained by combining the diffuser and dynamic bump is very promising, and could have a significant impact on the future operation of SPS if shown to work reliably in practice.

Similarly, the loss reduction obtained with a bent crystal, as proposed in [3], is expected to be much greater in combination with the dynamic bump, since a reduced angular spread at the crystal will lead to a higher channeling efficiency.

FIRST TESTS

First Machine Development studies (MDs) using the orthogonal knobs in the SPS were carried out at the end of 2017. The first MDs have shown that both bumps at their maximum amplitudes are closed to better than ±0.5 mm around the circumference of the SPS, with a corresponding rms closed orbit of 0.3 mm. The non-closure is almost an order of magnitude lower than the nominal 2.3 mm rms closed orbit of the SPS. Nevertheless,the small non-closure induces a tune dependence on the amplitude of the bump applied, thought to be due to feed-down in the sextupoles.

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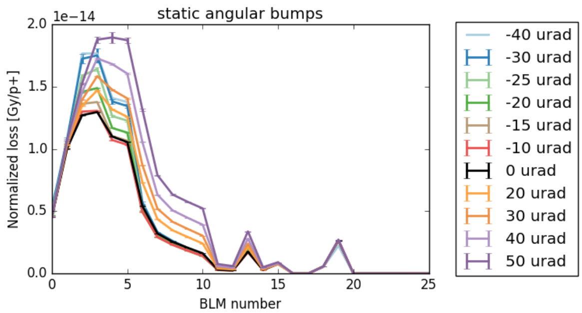


Figure 5: Loss profile in the extraction region, starting with the 5 ES tanks, for different static values of the angular bump.

The fact that the orthogonal bumps influence the tune is an unfortunate complication. It was however shown that for both bumps the tune change is linear with the bump amplitude, and the slope of this linear relation remains constant for at least a few weeks. Hence, a corrective algorithm can still be envisaged.

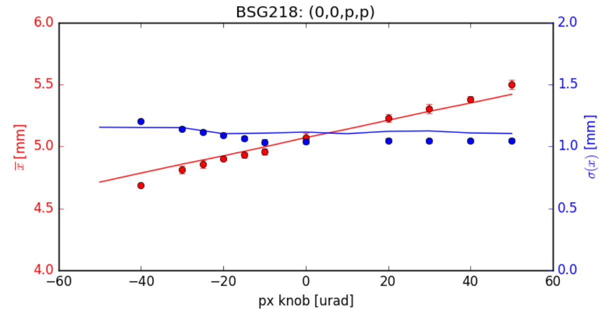
The behaviour of the BLM loss map for different static angular knob settings was compared to data from an earlier MD in which the angle between the ES and the beam was varied by mechanically moving the girder of the ES. Figure 5 shows the measured loss maps. The behaviour is similar to that observed in the earlier MD: when the girder is moved toward the circulating beam, or the beam angle is changed toward the extraction aperture, losses increase most on the downstream end of the ES, and when the girder is moved toward the extracted beam, or the beam angled more toward the machine centre, losses increase most on the upstream end of the ES.

During the systematic scans of the angular bump, profile measurements of the beam were also made, at a grid at 90 degrees phase advance downstream of the ES. A good agreement between simulation and measurement was found, as shown in Fig. 6a, which verifies the behaviour of the bump. The positional bump was validated in the same way, as shown in Fig. 6b.

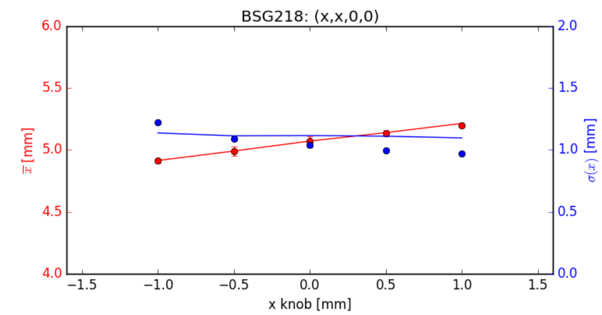
First results with dynamic orthogonal bumps, i.e. bump amplitudes changing in time during the spill, were also obtained during the 2017 MDs. The extraction losses could clearly be affected with the dynamic bump, but no improvement was found. However, the simulated optimum bump function (position: 1 to −1 mm, angle: -64 to 64 μrad) could not be tested yet due to software interlock problems on the day of the MD.

In order to set up the dynamic bump in the SPS like in simulations, the bump amplitude would have to scale as a function of time with the resonant momentum, which is known to have the same time dependence as the programmed tune sweep.

To simply the first MDs a linear time dependence of the bumps was applied, whilst the tune sweep had a more complex time dependence to guarantee a uniform spill rate. In future MD's, the dynamic bump functions will either be programmed to follow the time-dependence of the tune sweep, or, even more simply, a linear tune sweep will be programmed. It is hoped this will allow us to observe the 5 % expected loss reduction.



(a) Angular bump.



(b) Positional bump.

Figure 6: Beam position (red) and rms size (blue) 90° downstream of the ES for various static bump settings. Comparing measurement (dots) to simulation (lines).

OUTLOOK

MDs for the dynamic bump are expected to continue in 2018. The loss improvement predicted by simulation is expected to be observed once the bump amplitudes track the resonant momentum more closely. Furthermore, the expected larger loss reduction in combination with a diffuser, now installed in the SPS, should make tuning the bump settings easier.

Recently, the source of the time-dependent change of the beam angle at the ES has been shown in simulation to stem from the edge-focusing of the main dipoles, which do not sweep along with the quadrupoles during the spill. As a result, the optics of the machine is perturbed throughout the spill. As discussed in [8], the majority of the angular time-dependence can be eliminated simply by scaling the main dipoles along with the main quadrupoles, which is expected to be far simpler to set-up and operate than a dynamic bump. MDs will be carried out this year to test this new concept.

A dynamic bump, albeit far weaker than attempted in MDs last year, may still serve a purpose in the future to compensate for the small but non-zero dispersion at the ES.

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