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Injector MD Procedure – SPS

IMPLEMENTATION OF A DYNAMIC EXTRACTION BUMP IN LSS2

Abstract

This note summarises the Machine Development (MD) studies proposed to test the implementation of a dynamic extraction bump in LSS2. The objective is to demonstrate a reduction of losses during extraction on the SFTPRO user at the electrostatic septum (ZS) by superimposing two small additional orthogonal corrections, in position and/or angle, to correct for the movement of the separatrix arm during the spill. The dynamic bump concept is introduced and the damage limits of the ZS wires are outlined before the proposed steps of the MD programme are described, along with the necessary modifications to the machine protection systems.

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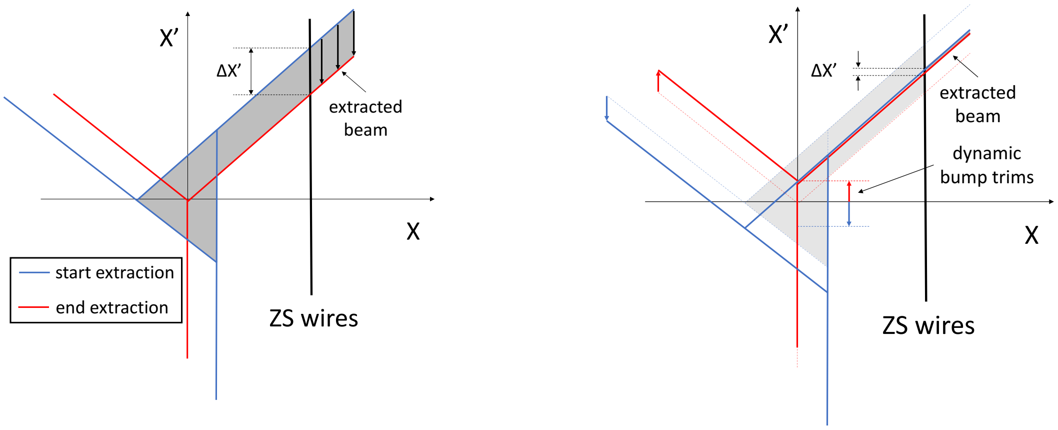
1. INTRODUCTION

In view of tightening restrictions on dose-to-personnel for the necessary hands-on maintenance of accelerator equipment, and ever increasing experimental requests for higher slow-extracted proton flux to the North Area, the SPS Losses and Activation Working Group (SLAWG) [1] has been established to investigate, implement and follow-up various methods to reduce the induced radioactivity in LSS2, and the SPS in general.

A dynamic extraction bump is a key pre-requisite for many of the proposed slow extraction loss reduction techniques by reducing the angular spread of the beam's separatrix arm throughout the spill as seen by the wires of the ZS. It is proposed to superimpose small, closed and time-dependent orthogonal bumps (position and angle) onto the nominal extraction bump to trim the phase space presentation of the beam at the ZS during the spill. The principle is most easily described for an amplitude (zero chromaticity) based extraction, as shown schematically in Figure 1.

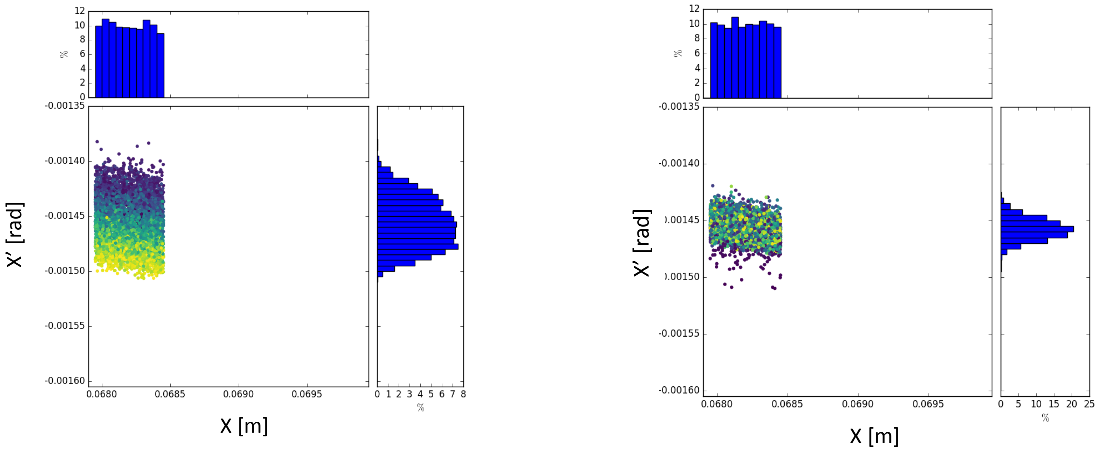


(a) without dynamic bump (b) with dynamic bump

Figure 1 – A schematic representation of the dynamic bump for an amplitude-based slow extraction typically lasting 1 – 5 seconds, over 50 – 200,000 turns of the SPS. In this case only a trim in angle need be applied.

Other effects may drive movement of the separatrix at the ZS including feed-down effects of the non-zero closed orbit as the tune of the machine is swept and, in the case of momentum extraction, non-linear chromaticity deforming the presentation of the separatrix. All of these effects can be compensated with a dynamic bump. The expected improvement in the angular presentation of the beam for a momentum-based extraction is shown as simulated in Figure 2 where orthogonal trims of $\Delta x = \pm 1.1$ mm and $\Delta x' = \pm 64$ μm are applied.

The ZS is composed of 5 tanks, each about 3 m long, extending over 15 m on the beam line in LSS2 with wires of diameters ranging from 60 – 100 μm, which are graded thicker in the downstream tanks. The tanks are aligned for operation with a beam-based technique and the total prompt beam loss minimised in a time-consuming and iterative alignment procedure. The expected improvement in extraction losses with the dynamic bump depends strongly on the effective thickness that the wires present to the beam. Simulations have shown that one could expect a loss reduction at the ZS of 6% for an effective septum thickness of 200 μm.



Without dynamic bump: $\sigma_{x'}$ = 22.7 mrad

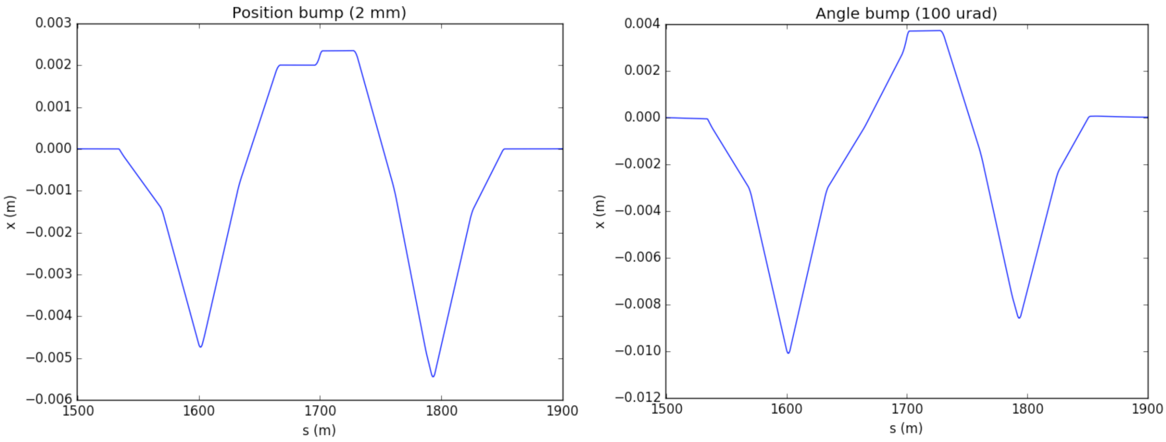
With dynamic bump: $\sigma_{x'}$ = 9.6 mrad

Orthogonal bump variation:

$\Delta x = \pm 1.1$ mm, $\Delta x' = \pm 64$ µm

Figure 2 – Presentation of the extracted beam in phase space across a width of 500 µm in the vicinity of ZS septum wires.

The shapes of the two closed orthogonal bumps are shown below in Figure 3. The worst-case summation of the two orthogonal knobs for on-momentum circulating beam, is shown enveloped in Figure 4 for a maximum amplitude of 2 mm and 100 µrad.



(a) X bump (X_{ZS} = 2 mm)

(b) PX bump (PX_{ZS} = 100 µrad)

Figure 3 – Orthogonal bump shapes in LSS2

The orthogonal bumps will vary in time during the extraction (~ 1 to 5 seconds) with an arbitrary trim function, which will, in principle, follow the tune sweep function. The dynamic beam position at the ZS will move very slowly, at a rate below a maximum of 4 mm/s during the MD for the X bump. The successful demonstration of loss reduction could lead to the deployment of a dynamic extraction bump on the operational SFTPRO beam in the future.

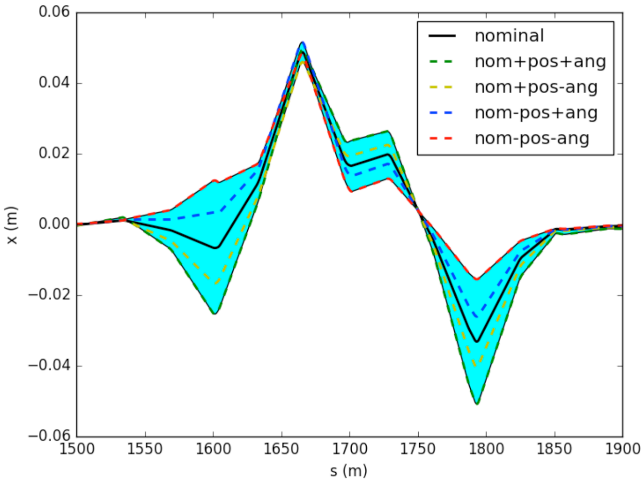


Figure 4 – Summation of all combinations of the two orthogonal knobs, with the worst-case excursion for on-momentum circulating beam.

The beam envelope stays within the aperture, although the very conservative tolerances used show the beam may approach the aperture QF220 and in the MBA's upstream of the ZS. This is not unusual with this definition of aperture and the low intensities foreseen during the MD will allow potential aperture limitation to be probed in a safe way.

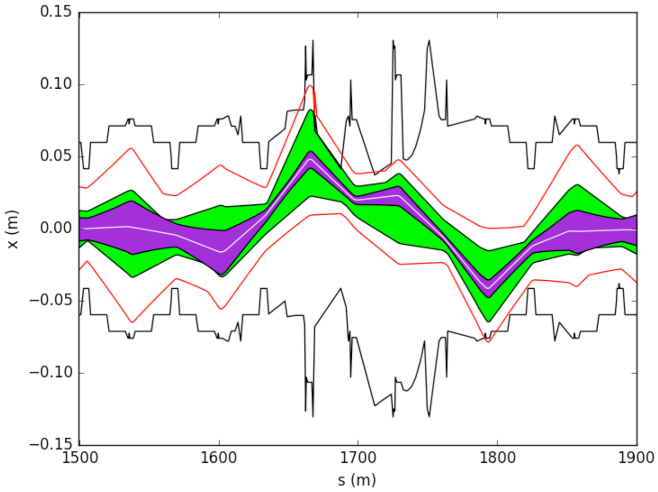


Figure 5 – Beam envelope on nominal extraction bump summed with maximum angular bump of 100 urad: Purple: 3 sigma non-resonant beam (emittance + dispersion), Green: 3 turn maximum spiral arms, Red: $x_{bump}+(DX*\delta_p+m_{halo}*\max\{6\sqrt{(\beta^x\varepsilon_x)},\Delta x_{3turn}\})*k_\beta+CO_{max}+M_{max}$ where δ_p=3E-3, $m_{halo}=1.2$, $k_\beta=1.1$, $\varepsilon_x=12$ mm·mrad $CO_{max}=4$ mm, $M_{max}=2$ mm.

The MD goals are therefore as follows:

- Check closure of the new orthogonal bumps before demonstrating loss reduction during slow extraction with low intensity.

2. ZS DAMAGE LIMITS

Owing to the strength of the extraction bumpers it is possible to produce a bump of over twice the nominal amplitude at 400 GeV/c. An incident in 2007 [2] involving damage to the ZS and flying wire MD’s in the 1990’s [3] give indications for the damage limits of the device.

2.1 SUMMARY OF 2007 INCIDENT DAMAGING ZS1

At the end of the 2007 physics run, a 90 mm bump was erroneously applied during the ramp, bumping two consecutive cycles containing a circulating beam of 9E12 protons over the ZS wires in a few ms breaking wires in the first tank (ø = 60 μm). The incident occurred as a result of superimposing two bumps of nominal amplitude. The bump speed was 0.3 mm/ms. The beam was swept over the wires in about 9 ms, for $\pm 4\sigma$. The beam was dumped on losses but the reaction time of the TT20.BLM.210222 was too slow sampling at 20 ms. Since this event TT20.BLM.210222 was connected to the fast BLD system, with μs reaction time, the status of the extraction bumper (ON/OFF) are surveyed in SIS and limits placed on the extraction bump amplitude in LSA (120% of their nominal value).

2.2 FLYING WIRE MD’S

ZS (W26Re) wires were flown through circulating proton beams in the SPS at speeds varying from 0.6 to 6 m/s in the horizontal plane. First tests were carried out at injection energy using a set-up of 4 wires (2x 60 μm and 2x 110 μm). Several attempts were made to break the wires with even a 2.3E12 SFTPRO beam failing to break the wires at the slowest scan speed; beam was quickly scattered out of the SPS because of the number of wires. Some modification to the surface of the wires was observed in electron microscopy but the wires remained intact.

Tests with a single 110 μm wire and circulating LHC bunches at 450 GeV/c broke near the middle of its passage with 7.3E12 protons, i.e. a single batch of 72 bunches, at 0.7 m/s. The **damage limit was therefore estimated at 1.9E12 circulating protons for a 60 μm wire at 0.7 m/s**. The beta-function used at the wire-scanner is 3 times smaller than at the first ZS tank, giving some margin in this number. The wires that were broken were shown to have melted due to beam induced heating. These results showed reasonable agreement with simulations and were extrapolated for single-pass damage limits for the design of LHC fast extraction regions, put at about a factor 10 higher.

It should be pointed out that reference [3] implies a single-bunch with 7.3E12 protons was circulating, although this, most obviously, appears to be a typo. We infer that this intensity refers to a train of 72 circulating bunches of close to 1.0E11 ppb.

3. DETAILED STEPS TO BE TAKEN BEFORE, DURING AND AFTER THE MD

3.1 STEPS TO BE TAKEN BEFORE THE MD

The MD would be best timed for the end of the proton run when the ZS girder can be moved without requiring accurate re-alignment.

3.1.1 BEAM INTENSITY REDUCTION

A low intensity version of MTE shall be prepared in the injectors of a few E11 ppp, to help mitigate any risk. The beam intensity typically used for alignment and setting-up of the SFTPRO cycle is 1 – 2E12 protons, which is at the estimated damage limit for the 60 μm diameter wires in the first ZS tanks. Recent tests have shown that an intensity of 3E11 protons is feasible if the MD is dedicated and no other high intensity beams are in the SPS super-cycle (to protect the LLRF electronics when attenuators are removed for the very low intensity MTE beam).

3.1.2 IMPLEMENTATION OF ORTHOGONAL BUMP KNOBS

The orthogonal bumps will be loaded into LSA and limits assigned to their maximum and minimum trim amplitude.

3.1.3 IMPLEMENTATION OF FAST BLM INTERLOCK

The fast BLMs in LSS2 are connected to the interlock system, as well as the BLM identified as sensitive by the 2007 incident. The interlock thresholds should be reduced according to the reduced intensity factor, i.e. roughly a factor 100 lower than for the normal operational beam to be consistent with the beam intensity used during this first MD: ~3E11 for very low intensity MTE vs. ~3E13 operational MTE).

The reaction time of the LSS2 BLMs has been tested and shown to be faster than 800 μs. Further invesitgations will be made to confirm exact reaction time before the MD.

The BLM thresholds will be set and tested during the MD, before the orthogonal knobs are applied.

3.2 PREPARATION OF THE MD

Number of MD's	2
Time required per MD [h]	8
Beam required	SFTPRO3 (7.2 s SHiP MD cycle)
Beam energy [GeV]	400
Bunch intensity [#p]	**MD1 (no extraction) = MTE at <=2E12 ppp** **MD2 (extraction) = MTE at <=3E11 ppp**
Extracted spill length [s]	< 1.2
Number of batches	1 batch from PS
Transv. emittance [m rad]	< 8
Orbit change [yes/no]	Yes: local, closed orbit in LSS2 will be moved during flat-top
RF system change [yes/no]	RF turned ON/OFF from CCC, might need tuning by RF expert for very low intensity MTE
What else will be changed?	Chromaticity and QF tune function may be trimmed.
Extraction configuration	TT20 TED IN

Table 1: SPS machine parameters during the MD

3.3 STEPS TO BE TAKEN DURING THE MD

The MD will be split into two parts with the first verifying the correct workings and functioning of the dynamic bump without the resonant extraction and with the beam dumped internally, and with the ZS safely retracted.

The first MD was already completed on 4th October and the procedure below is included for completeness. In a second MD the ZS will be inserted and extraction carried out with the dynamic bump.

The individual k and I limits on the LSS2 extraction bumpers need removing by the INCA team before the MD.

The current comparator for the PS internal dump interlock is set correctly to limit intensity extracted from PS. TT20 TED inserted IN beam.

3.3.1 MD1: VERIFICATION OF DYNAMIC BUMPS (INTENSTY = 2E12 PPP)

1. Retract ZS girder to parking position at 98 mm (ZS girder upstream)
2. Without beam, check bumper current functions follow the reference reliably (validated)
3. Set-up cycle with extraction sextuples OFF and with RF ON, dumping internally at end of the flat-top, i.e. beam bunched on flat-top to allow BPM acquisition.
4. Ensure nominal LSS2 extraction bump OFF and set tight LSA interlock of a few mm.
5. Without beam, check and validate interlock limits on orthogonal bumps:
    a. 2 mm and 100 urad (interlocks worked as expected and correct closure of bumps was validated on 4th October)
6. Apply orthogonal knobs one at a time:
    a. Check both bumps are closed throughout the flat-top as a function cycle time and knob amplitude (closure as function of cycle time validated)
    b. Measure the tune as function of cycle time and knob amplitude (tune variation quantified as a function of bump amplitude)
    c. Apply a time-dependence (linear ramp) to the knobs to check for closure and tune perturbation throughout movement and flat-top (tune variation as a function of cycle time amplitude and closure validated)
7. Repeat above for orthogonal knobs and LSS2 extraction bump (at 50%) applied together (validated)

3.3.2 MD2: RESONANT EXTRACTION WITH DYNAMIC BUMP (INTENSITY = 3E11 PPP)

1. ZS retracted at 98 mm
2. Without beam, set and validate nominal extraction and orthogonal knob interlocks
3. With beam, set-up cycle with extraction sextuples OFF and with RF ON, dumping internally at end of the flat-top.
4. Repeat BPM and tune measurements as function of cycle time and orthogonal knob amplitude applied together with the nominal LSS2 extraction bump ON (i.e. at 100% amplitude):
    a. Orthogonal bump knobs applied independently
    b. Orthogonal bump knobs applied together
5. With orthogonal bumps OFF and ZS inserted to nominal operational position, set-up nominal slow-extraction, extraction sextuples ON and with RF OFF:
    a. Choose between amplitude or momentum based extraction by trimming the chromaticity and QF tune function.
6. Once nominal slow-extraction is achieved, reduce and test fast LSS2 BLM interlock thresholds.
7. Orthogonal knobs can now be applied.
8. Record the BLM loss distribution and beam size on grids (BSGHs) as a function of the start and end values of the orthogonal bump function, applying a linear ramp in time:
    a. Work within the defined orthogonal bump limits
    b. Start with angular orthogonal bumps.
    c. Repeat with position bump orthogonal

3.4 STEPS TO BE TAKEN AFTER THE MD

After the MD double-check that all orthogonal bump trims are turned OFF. Restore nominal extraction bumper interlocks with INCA team. Revert fast BLM interlock levels to their nominal values. Insert ZS to nominal position, turn extraction elements ON and check ZS alignment with LSS2 loss profile at low intensity. Realign ZS girder, if necessary.

4. CHANGES OF MACHINE PROTECTION SETTINGS DURING MD

4.1 CHANGES TO BEAM INTENSITY LIMITS

The intensity sent from the PS can be interlocked by setting correctly the current comparator and the PS internal dump.

4.2 CHANGES TO SOFTWARE INTERLOCKS

Software interlocks will be placed on the individual knobs controlling the LSS2 extraction bumpers, to ensure the bump amplitude is never too high.

4.3 CHANGES TO BLM INTERLOCKS

The LSS2 BLM fast interlock threshold will be tightened to envelope the lower intensity of 3E11 ppp.

5. CONCLUSIONS

A procedure to investigate the slow extraction loss reduction potential of a dynamic LSS2 extraction bump has been prepared. The correct functioning of the new orthogonal bumps in LSS2 has already been tested in a first MD without extraction and with the ZS retracted. A very low intensity MTE beam of <= 3E11 ppp has been prepared and tested to further mitigate the risk of damaging the ZS when extracting with the dynamic bump. The fast BLM interlock reaction times have been validated. The BLM threshold will be reduced and tested before the MD, along with the software interlocks on the nominal extraction and orthogonal knob amplitudes.

6. REFERENCES

[1] M.A Fraser and B. Goddard, SPS Losses and Activation Working Group (SLAWG) meeting series, https://indico.cern.ch/category/7887/

[2] J. Wenninger, "SPS Machine Protection and Incidents in 2007", CERN-AB-Note-2008-003, CERN, Geneva, Switzerland, 2008.

[3] G. Ferioli et al., "Energy Deposition in a Septum Wire", CERN SL-Note-01-029 MD, CERN, Geneva, Switzerland, July 2001.