PROGRESS IN THE UPGRADE OF THE CERN PS BOOSTER RECOMBINATION

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Abstract

The CERN PS Booster recombination lines (BT) will be upgraded following the extraction energy increase foreseen for the long shutdown 2 (LS2) and meant to reduce the direct space-charge tune shift in the PS injection for the future HL-LHC beams. Henceforth the main line elements, recombination septa, quadrupoles and dipoles must be scaled up to this energy. An increase in the beam rigidity by a factor 1.3 requires the same factor in the field integral of the septa, $\int$ Bdl, in order to bend the same angle and preserve the present recombination geometry, which is one of the main upgrade constraints. This paper describes the new optics, in particular in the new and longer septa. In addition we consider the upgrade of the so called BTM line that brings the beam to the external dump and where emittance measurements are taken thanks to three pairs of grids. The new proposed optics has also the advantage to simplify the design of the new dipoles. Here we study this new optics and the issues related to the emittance measurement at the new higher energy.

INTRODUCTION TO THE RECOMBINATION LINES

The four transfer lines that extract protons from each ring of the PSB to the PS (BT1, BT2, BT3, BT4) are recombined in the BT line (Fig. 1).

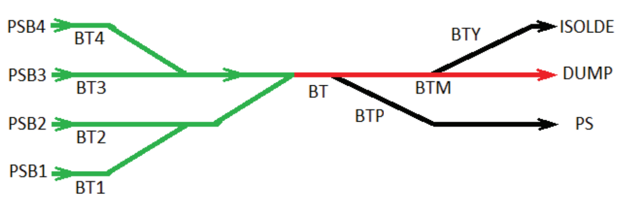

Figure 1: Scheme of the PSB ejection lines, not to scale

From the BT line, the beam can go to three different locations: to the PS (BTP line), to the ISOLDE facility (BTY) or to a dump (BTM). BT.BHZ10 is the switch magnet to the BTP line and BTY.BVT101 is the switch magnet to BTY (off when sending to the dump). Figure 2 represents the scheme of the BT-BTM magnets. A set of three couples of SEM grids lo-cated in the BTM line is used for the emittance measurement in the two planes. In this paper we describe the works on the recombination part (in green in Fig. 1) and the BT-BTM line (in red).

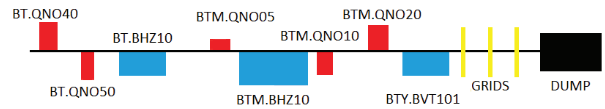

Figure 2: Scheme of the BT-BTM line. Quadrupoles are shown in red and dipoles in blue. It corresponds to the red line in Fig. 1.

UPGRADING

The LHC Injectors Upgrade (LIU) project [1] aims to an injection energy in the PS of 2 GeV, so that the present lines must work at that energy. In addition, the upgrade of the recombination lines must not hinder a possible upgrade of the ISOLDE faclity from 1.4 to 2.0 GeV. In particular, the energy upgrade translates into a 30% increase in beam rigidity, so that the same increase have to followed by the field integral $\int Bdl$ in all the bending elements: dipoles, septa and kickers. At the same time, a working energy of 1.4 GeV must be allowed in terms of element acceptances. The present 1.0-GeV working energy will be discarded after long shutdown 2 (LS2).

OPTICS

In order to deal with the different users of the extracted beams from the PSB, four different optics configurations for the BT-BTM line exist [2]:

1. Dump optics
2. ϵ_x (Horizontal emittance) measurement: large D_x
3. ϵ_x measurement: small D_x
4. ϵ_y (Vertical emittance) measurement

The first one is a common configuration to dump the beam and to send it to the ISOLDE facility, while the optics 2, 3 and 4 are used to measure the beam emittances. The reason for having two configurations for the ϵ_x-measurement is the large variety of beams that the PSB is supposed to deal with, which are summarized in Table 1.

Table 1: Expected Normalized rms Emittances and Momentum Spreads of the Different Beam Types in the PS Complex, after LS2

Beam	$\epsilon_{N,x}[\mu m]$	$\epsilon_{N,y}[\mu m]$	σ_δ
LHC (BCMS)	1.2	1.2	1.1×10^{-3}
LHC	1.6	1.6	1.5×10^{-3}
Fixed target	10	5	1.35×10^{-3}
ISOLDE	15	9	1.35×10^{-3}

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In the following, the half beam sizes are calculated as a function of the number of sigma (n_σ) as:

$$A_{x,y} = n_\sigma \sqrt{k_\beta \beta_{x,y} \frac{\epsilon_{N;x,y}}{\gamma_r \beta_r}} + \left| k_\beta D_{x,y} \sigma_\delta \right| + c.o. \sqrt{\frac{\beta_{x,y}}{\beta_{M;x,y}}}; \quad (1)$$

where k_β represents the uncertainty factor on the betatron (β) and dispersion (D) functions; while γ_r and β_r are the relativistic parameters. β_M represents the maximum value of the β-functions and $c.o.$ is the trajectory variation, 1.5 mm.

For the LHC beams, the first term in Eq. 1 is very small and in order to reduce the contribution of the second one, the small-D_x optics is used, On the other hand, this optics presents reduced horizontal acceptance due to larger values of β_x so that the large-D_x optics has to be kept for beams where the emittance contribution is significant, that is, for non-LHC beams.

Limitation of present optics

Studies have been performed to check possible bottlenecks of the present optics. Figures 3 and 4 show the two worst cases in aperture limitation. Beam sizes are represented (using the definition in Eq. 1 with n_σ=3, k_β = 1.2 and 1.4 GeV) and compared with the physical aperture of the line.

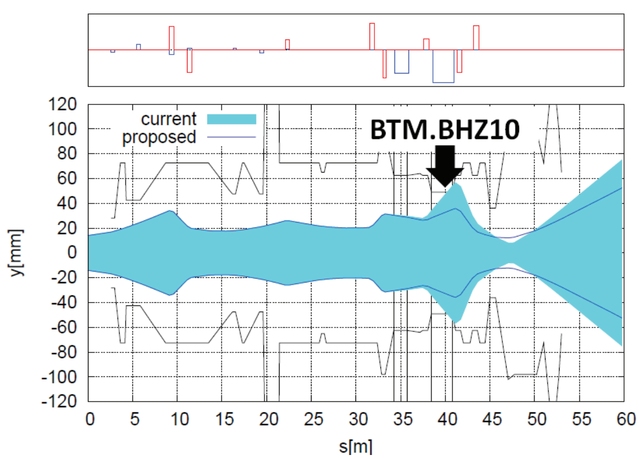

Figure 3: Aperture and beam envelope in the horizontal plane, for the dump optics and ISOLDE beam.

We can observe that the aperture is narrower than the 3-σ beam size at BTM.BHZ10 (horizontal plane) and BTM.QNO20 (vertical plane). The aperture bottleneck into the BTM.BHZ10 aperture may be the cause of an excess observed during a radiation survey performed in 2013 (Figure 5). A reduction of the beam size at these locations would reduce the beam losses and would ease the design of the new bending magnet for the 2-GeV upgrade at the position BTM.BHZ10 [3]. In fact its vertical gap can be reduced from the present value.

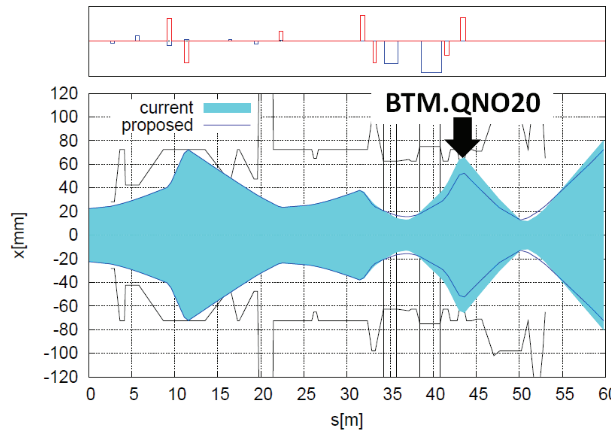

Figure 4: Aperture and beam envelope in the vertical plane, for the large-D_x emittance measurement optics and ISOLDE beam.

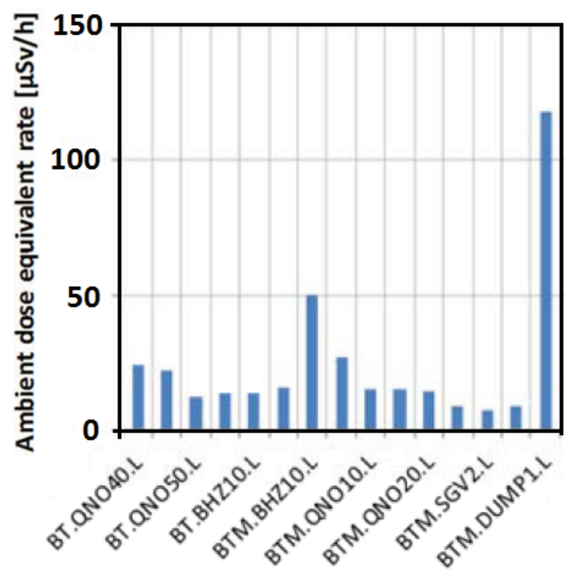

Figure 5: Radiation survey [4] for the BT-BTM line after recombination.

THE NEW OPTICS FOR THE BTM LINE

In order to reduce the beam size at locations BTM.QNO20 and specially BTM.BHZ10, a new full set of optics has been prepared, by rematching the quadrupoles BT.QNO40, BT.QNO50, BTM.QNO05, BTM.QNO10 and BTM.QNO20, while respecting the specification for the maximum energy desposition on the beam dump [5]. In addition, the following conditions of the optics in the grids must be fulfilled for either plane:

$$\alpha_2 = 0 \quad (2)$$

$$\Delta\mu_{1-2} = \Delta\mu_{2-3} = \pi/3 \quad (3)$$

$$min \left[\frac{D^2}{\beta} + \left(\alpha \frac{D}{\sqrt{\beta}} + \sqrt{\beta} D' \right)^2 \right] \quad (4)$$

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Here the subindex refers to the corresponding grid and the Twiss functions to those whose emittance is to be measured.

The comparison between the two optics is done in Fig. 6 for the dump configuration. We can appreciate how the β-function has been strongly reduced at BTM.BHZ10. Figure 7 compares the two optics for the large-D_x ϵ_x-measurement. Here the horizontal β-function is reduced at BTM.QNO20.

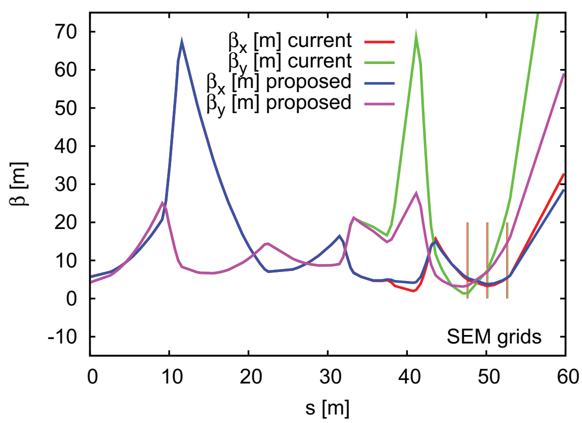

Figure 6: Comparison between the current and the proposed optics for the dump configuration.

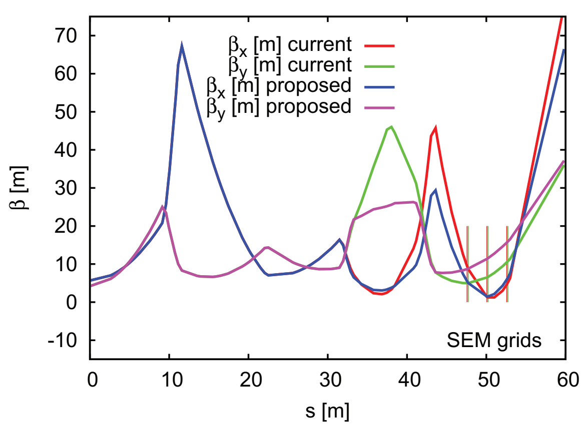

Figure 7: Comparison between the current and the proposed optics for the large-D_x ϵ_x-measurement configuration.

Figures 3 and 4 also compare the beam sizes with the present and with the new optics. It is evident the reduction on the beam at the two problematic locations.

Table 2 summarizes the maximum beam sizes for the present and for the proposed values of the ensemble of the four optics configurations. The maximum A_y in BTM.BHZ10 has been reduced by 19 mm and by the maximum A_x in BTM.QNO20 by 14 mm.

In order to ensure compatibility with possible upgrade of the ISOLDE facility to 2.0 GeV, the optics changes at the location of BTY.BVT101 have been kept to the minimum. This assures the optics matching to a future upgrade of this line and a reasonable beam acceptance at this location if this magnet is upgraded to a longer one.

Table 2: Maximum Beam Sizes for each of the Elements of the BT-BTM Line [mm].

	present		proposed	
	A_x	A_y	A_x	A_y
BT.QNO40	57	25	57	25
BT.QNO50	40	34	40	34
BT.BHZ10	35	42	34	36
BTM.QNO05	29	48	27	38
BTM.BHZ10	36	**56**	33	**37**
BTM.QNO10	45	59	35	37
BTM.QNO20	**67**	41	**53**	40
BTY.BVT101	49	29	38	29

With respect to the beam dump, the minimum value of beam size in the dump core is not reduced with respect to the specified value [6].

EMITTANCE MEASUREMENT WITH THE NEW OPTICS

The new optics would improve the emittance measurement, as the conditions in Eqs. 2, 3, 4 are met with more precision. However, at the upgraded energy of 2.0 GeV, the beam sizes become smaller due to the adiabatic damping. We need to evaluate if the present hardware will be capable to measure the emittance of the future beams. First of all, we have to consider the wire separation on the present grids. For the inner couple of SEM grids it has a value of 0.5 mm, while the outer ones feature 1 mm. In principle we consider that the beam profile can be well measured if the rms beam size is above the wire seperation [7].

The minimum rms beam size that the we can measure is given by:

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\frac{\epsilon_{N;x,y}}{\gamma_r \beta_r} + \left(D_{x,y}\sigma_\delta\right)^2}; \tag{5}$$

For the smallest future beam to be measured (LHC BCMS), the beam size in the central grid is $\sigma_y \sim 0.7$ mm and for the outer ones, ~ 1.6 mm. These values are above the wire separation, so in principle it will be possible to measure the emittance with the present systems. These studies will continue in order to account for the precise value of the error in the emittance measurement for all kind of beams.

APERTURE STUDY OF THE RECOMBINATION SEPTA

The recombination of the four beam lines is done by three septa and three kickers, as shown schematically in Fig. 8.

Septa and kickers are required to increase their field integral $\int Bdl$ by a 30% in order to deal with the higher energy, while bending the same angle and preserving the present recombination geometry. The new septa are longer, with their dimensions compared with the present ones shown in (Fig. 9). In addition, the deflection center is assumed to be moved downstream by 82 mm. The new septa have

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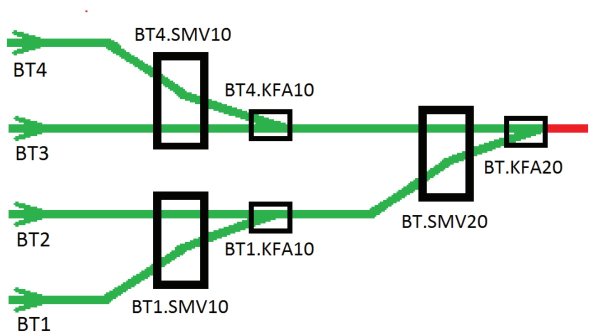

Figure 8: Scheme of the PSB recombination, showing the 3 septa (SMV) and the 3 kickers (KFA), not to scale.

been introduced in the model and the trajectories had been rematched. A study has been performed to evaluate the acceptance of the septa ($A_{x,y}$, Eq. 1) in terms of n_σ, comparing the case of the present with the upgraded septa and evaluating how to improve this acceptance.

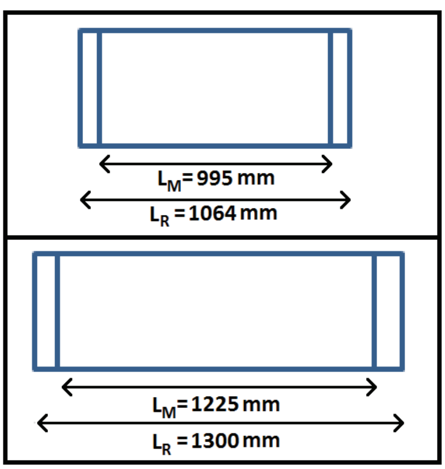

Figure 9: Comparison between the present (top) and new (bottom) septa, indicating the corresponding magnetic (L_M) and physical lengths (L_R) [8].

Figure 10 shows the septum that recombines the beams coming from ring 3 (undeflected) and ring 4 (deflected). The beam envelope corresponds to $n_\sigma = 2.6$ for the ISOLDE beam.

The first thing we observe is that this beam touches the septum blade at the exit while there is still some aperture margin at the entry face of the magnet. This situation is the same for the lengthened septa, as we can see in Fig. 11.

In the last case, we can observe a loss in the beam acceptance, ~ 0.1 n_σ. The case is simular for the other two recombinations (BT1.SMV10 and BT.SMV20), and also for the horizontal plane (see Figs. 12 and 13), with losses in acceptance while moving to larger septa in all cases below this quantity. In SMV20 the vertical acceptance is more reduced: $n_\sigma = 2.0$ for the present septum and 1.9 for the upgraded one.

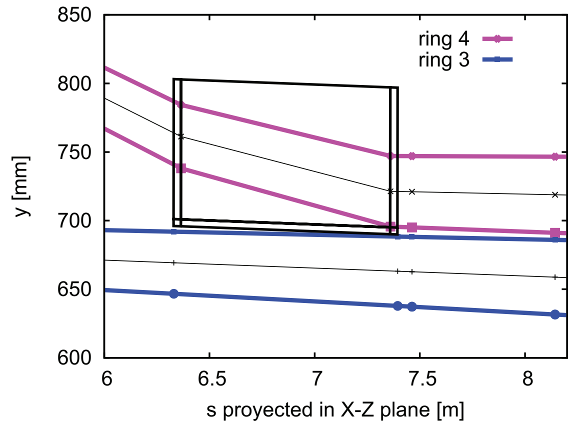

Figure 10: BT4.SMV10 vertical recombination with present septum ($n_\sigma = 2.6$).

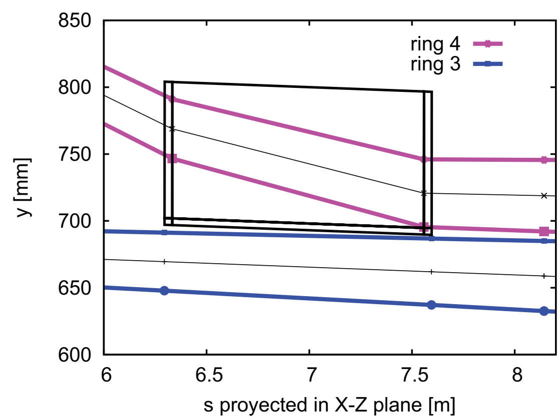

Figure 11: BT4.SMV10 vertical recombination with lengthened septum ($n_\sigma = 2.5$).

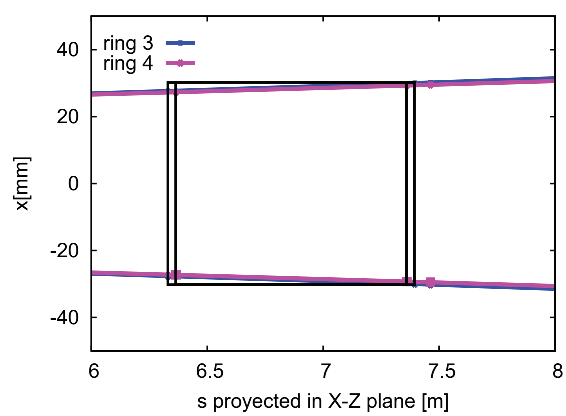

Figure 12: BT4.SMV10 horizontal recombination with present septum ($n_\sigma = 2.5$).

The fact that the limitation in acceptance is given by the vertical beam separation at the exit of the septum makes unnecessary to increase the transverse dimensions of the septa. This is not the case for magnets where the trajectories of the beam at the entry and the exit are symmetric, where a

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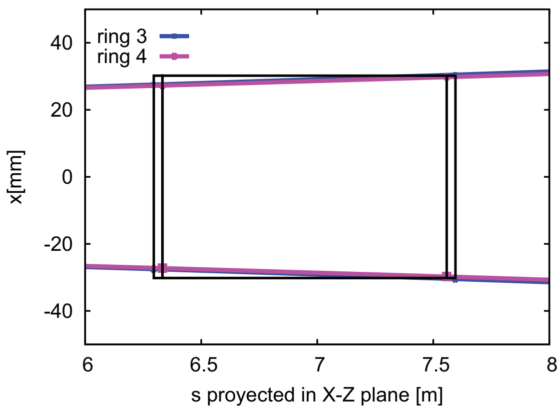

Figure 13: BT4.SMV10 horizontal recombination with lengthened septum ($n_\sigma = 2.5$).

longer magnet means a longer sagitta and the need to increse the gap.

In order to increase the acceptance of the septum, one could increase the separation of the orbit centers at the exit of the septum. However, one would need a increase in the angle of the recombination kickers (~8.5 mrad for KFA10 and ~5.4 mrad for KFA20). The KFAs will be upgraded to 2.0GeV; a further increase would be a major upgrade, that is the reason why the option of increasing the angle is discarded. There would be a solution to increase the beam separation at the septum exit without increasing the kicker angle, consisting on moving the quadrupoles between septa and kickers bringing them closer to the septa. But this option cannot be realized due to the lack of space in the line.

CONCLUSIONS

- For the present machine (1.4 GeV), the new optics is able to improve the transmission efficiency of the BT-BTM line, reducing potentially the beam losses and the radiation associated with these losses. It also offers improved conditions for the emittance measurements. It will be benchmarked with a machine development study (MD).

- For the upgrade of the PSB at 2 GeV, this new optics will ease the design of the bending magnet BTM.BHZ10, by reducing its gap height. It does not hinder, in principle, a future upgrade of the BTY line at 2GeV.

- The future beams will have a beam size in the SEM grids above the wire separation, so it seems possible to continue measuring the emittance at the same precision.

- The limitation on the septum acceptance is given by the orbit separation at the exit.

- The new longer septa can be built with the same vertical and horizontal gap with a negligible loss in acceptance.

- The work described here concerns the BT and BTM lines. For an update of the works on the BTP line and PS injection see [9].

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