OPTICAL REQUIREMENTS FOR THE MAGNETIC LATTICE OF THE LHC HIGH ENERGY INJECTORS

G. Arduini, CERN - AB Department, Geneva, Switzerland

Abstract

The basic requirements for the magnetic lattice of the LHC high energy injectors will be given taken into account, wherever possible, the constraints imposed by high energy injection, fast and slow extraction, beam cleaning and dumping, acceleration. Possible solutions, based on presently available technology, will be sketched and potential limitations or difficulties indicated. The paper will focus on the case of a Super-SPS sharing the same tunnel with the present CERN SPS.

BEAM PARAMETERS FOR A SUPER-SPS IN THE SPS TUNNEL

The beam parameters assumed for the estimation of the basic parameters of the main hardware systems of the Super-SPS (SSPS) are listed in Table 1.

Table 1: Basic beam parameters for the SSPS.

Injection momentum [GeV/c]	100
Extraction momentum [GeV/c]	1000
ε^*_H [μm] (1 σ)	7 (LHC)/12 (FT)
ε^*_V [μm] (1 σ)	7 (LHC)/7 (FT)
Δp/p [eV s] (2 σ)	0.002 (LHC)/0.002 (FT)

Both the beam parameters for the LHC proton beam and a fixed target high intensity beam are given. It has been assumed that the LHC beam for the upgrade has a transverse emittance twice the nominal. This implies that the beam size at extraction will be approximately the same as the present because of the higher (approximately double) extraction momentum (1000 GeV/c instead of 450 GeV/c).

CONSTRAINTS FOR A SUPER-SPS IN THE SPS TUNNEL

The SPS tunnel has a circumference of 6911.5 m. It has a six-fold symmetry with six long straight sections (LSS), each approximately 130 m long.

Additional constraints are imposed by the cohabitation with the existing SPS machine. This implies the installation of the SSPS at approximately 2 m from the tunnel floor. The radial position of the SSPS must lie approximately 1 m inside in the long straight sections in order to avoid mechanical interference with the existing SPS hardware (e.g. the RF wave-guides and loads in LSS3). Furthermore SPS extraction, SSPS injection and SPS to SSPS transfer must be located in the same long straight section.

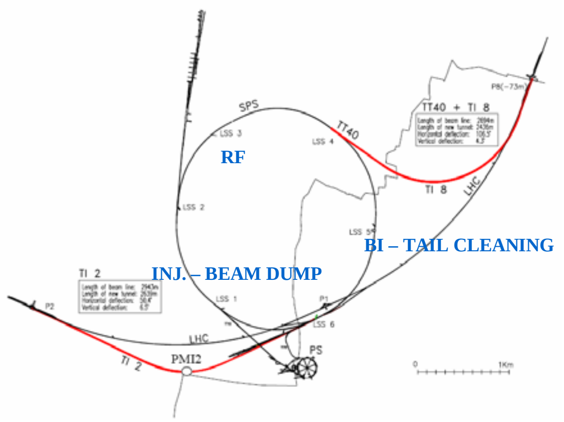

Figure 1. Schematic layout of the SPS.

Figure 1 shows the SPS layout. The functionalities of the six SPS long straight sections (LSS) are listed below:

- LSS1: Injection and beam abort;
- LSS2: Slow extraction to the transfer line TT20 to the North Experimental area;
- LSS3: Acceleration system;
- LSS4: Fast extraction to the LHC (anti-clockwise beam);
- LSS5: Beam instrumentation and tail cleaning;
- LSS6: Fast extraction to the LHC (clockwise beam).

The required functionalities for a SSPS are listed below:

1. Injection;
2. Acceleration;
3. Fast extraction 1 to LHC (LSS4-in order to use the TI8 tunnel);
4. Fast extraction 2 to LHC (LSS6-in order to use the TI2 tunnel);
5. Slow resonant extraction (LSS2-in order to use the TT20 tunnel to North area);
6. Beam dump;
7. Betatron collimation;
8. Momentum collimation.

Betatron and momentum collimation are mandatory in order to minimize losses in the superconducting magnets of the machine.

Only six straight sections are available to host eight different functionalities therefore two long straight sections will have to accommodate two different functionalities.

ARC APERTURE CONSIDERATIONS

The present SPS lattice has a regular FODO structure with 6-fold symmetry with a phase advance per cell of approximately 90 degrees and 18 cells per sextant. In most of the operating conditions the focussing quadrupoles are powered in series. The same applies for the defocusing quadrupoles. Each half-cell contains 4 dipoles each 6.26 m long and providing a bending angle of 8.45 mrad. The beam sagitta in each bending magnet is 6.6 mm, that is 1.1 mm per unit magnet length. Approximate dispersion suppression in the long straight sections is obtained by means of a missing dipole scheme although at the expense of a significant beating of the dispersion in the arcs. The horizontal beta function and dispersion along one sextant are shown in Figure 2. Transition occurs at γ=23.23.

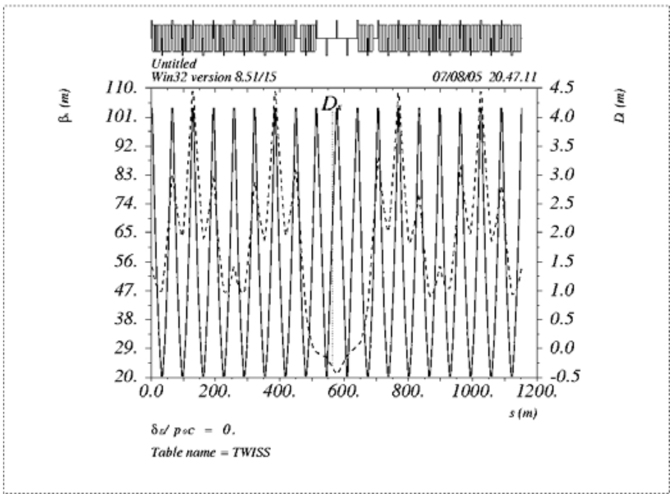

Figure 2. Horizontal beta function and dispersion of the SPS lattice.

Assuming the same lattice for the SSPS the required half-aperture $A_{H,V}$ in the arcs can be estimated:

$$A_{H,V} = \left(m_{halo}\,\mathrm{Max}\left(n\sqrt{\frac{\varepsilon^*_{H,V}\beta_{H,Vmax}}{\beta\gamma}}, A_{sep.max} \right) + D_{H,Vmax}\delta_p \right) k_\beta + \Delta_{COpkH,V} + t_r + sag$$

where:

- n=6 is the number of sigma delimited by the primary collimators;
- m_{halo}=1.2 is an additional margin for the secondary halo;
- $\beta_{H,V\ max}$=104 m is the maximum value of the horizontal and vertical beta functions;
- $\beta\gamma$=106.6 is the product of the β and γ relativistic factors at injection (p=100 GeV/c);
- $A_{sep\ max}$=47 mm is the maximum amplitude of the separatrix for the slow-extraction based of the SPS configuration (third-integer). The estimated maximum amplitude of the separatrix in the arcs is based on the assumption that the spiral step at the electrostatic septum (ES) is approximately 16 mm to keep losses at the level of few percents.

$$A_{sep.\,max} \div \sqrt{\frac{\beta_{H\,max}}{\beta_{H\,ES}}} \qquad (1)$$

where $\beta_{H\ ES}$ is the horizontal beta function at the electrostatic septum (ZS).

- $D_{H,V\ max}$=4.5/0 m is maximum of the absolute values of the dispersion in the horizontal and vertical planes, respectively;
- $\delta_p=3\times10^{-3}$ is the maximum relative momentum offset including radial errors;
- k_β=1.1 is a correction factor taking into account of β-beating;
- $\Delta_{CO\ pk\ H,V}$=4 mm is the peak amplitude of the closed orbit distortion;
- t_r=2 mm is the tolerance for mechanical and alignment errors;
- sag=3.3 mm is half the beam sagitta in the dipoles assuming that the dipoles are straight and have the same length of the SPS dipoles.

The resulting required arc half-aperture is:

- 51 (H) × 27 (V) mm^2 if no slow-extraction capabilities are included;
- 86 (H) × 27 (V) mm^2 if slow-extraction capabilities are included.

The requirements for the horizontal aperture are dominated by the size of the separatrix for the slow-extracted beam. From (1) it follows that the impact of the implementation of the slow-extraction in the SSPS can be mitigated by increasing locally the horizontal beta function at the electrostatic septum. This requires a dedicated insertion design for the slow-extraction straight section. For example, an increase of the horizontal beta function from about 100 m to 400 m would reduce the required horizontal arc half-aperture from 86 to 57 mm.

A reduction of the required horizontal arc half-aperture can be obtained by a proper matching of the arc dispersion to the vanishing dispersion in the straight section by independently powered quadrupoles in the straight section. A possible solution is presented in Fig. 3.

The peak dispersion in the arcs can be reduced from 4.5 m to about 3 m and the required arc half-aperture can be reduced to:

- 46 (H) × 27 (V) mm^2 if no slow-extraction capabilities are included;
- 82 (H) × 27 (V) mm^2 if slow-extraction capabilities are included.

This design of the insertion guarantees a significant gain (approximately 10%) in horizontal aperture only if implemented together with an increase of the horizontal beta function at the electrostatic septa.

A symmetric (with respect to the centre of the straight section) solution with symmetric pairs of quadrupoles powered in series can be obtained by extending the number of independently-powered quadrupoles to include the first arc cell in order to obtain a number of degrees of freedom corresponding to the number of constraints (at least six parameters, α_H, β_H, α_V, β_V, D_H, $D`_H$, assuming that the variation of the phase advance in the straight section with respect to the phase advance/cell for the FODO solution can be compensated by an opposite variation in the arcs to obtain the required value of the tune).

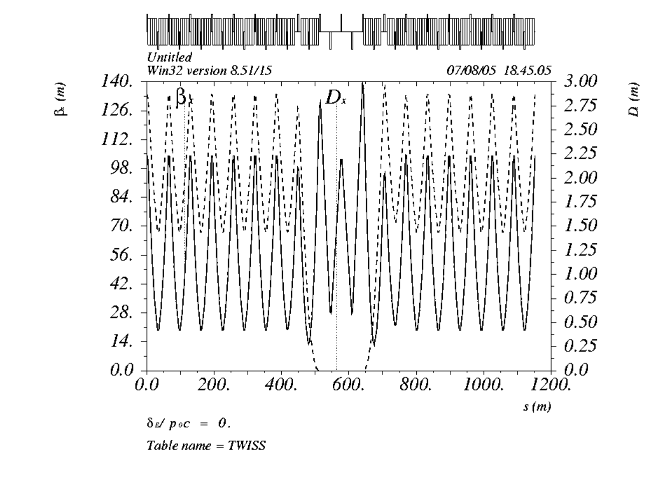

Figure 3. Horizontal beta function and dispersion for a lattice with independently powered quadrupoles in the straight section allowing proper matching of the dispersion.

An additional reduction of the aperture requirements in the arcs can be achieved by reducing the cell length while keeping the same phase advance per cell and the same radius of curvature in the dipoles. In that case the tune will increase proportionally to the number of cells and:

$$\beta \sim \frac{R}{Q} \quad D \sim \frac{R}{Q^2}$$

As an example a reduction of the cell length by a factor 2 will imply an increase in the tune from 27 to 51 and the gamma transition will increase from 23 to 45. The corresponding horizontal beta function and dispersion are represented in Figure 4.

The corresponding required arc half-aperture is:

- 31 (H) × 21 (V) mm^2 if no slow-extraction capabilities are included;
- 56 (H) × 21 (V) mm^2 if slow-extraction capabilities are included. Once more this reduction in the required half-aperture can be combined with the dedicated insertion design of the slow extraction section to further optimise the aperture requirements.

The option of reducing the cell length has the beneficial effect of reducing the beam sagitta in the dipoles (if the number of magnets is kept constant) and the requirements on the aperture. On the other hand a larger number of magnets (if the dipole length is kept constant) and stronger quadrupoles are required. Furthermore the dipole filling factor will be smaller (because of the larger number of quadrupoles) and the space available for auxiliary elements (instrumentation, correctors, kickers) will be smaller.

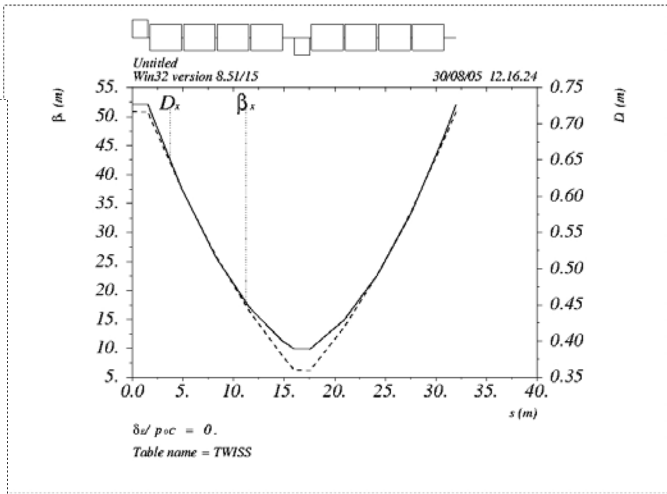

Figure 4. Horizontal beta function and dispersion for a lattice with a cell length half that of the SPS.

CONSIDERATIONS ON THE INSERTION DESIGN

SPS to SSPS transfer

Cohabitation with the SPS in the SPS tunnel will imply hosting the SPS fast extraction to the SSPS and the injection in the SSPS in the same straight section

In order to gain space it might be necessary to install the SPS fast extraction kickers in the missing dipole section providing a horizontal kick towards a vertically bending Lambertson septum magnet in the dispersion free section downstream.

The Injection in the SSPS could be “symmetric” to the SPS extraction. This solution might be incompatible with a reduction of the cell length.

The above solution is probably feasible taking into account the aperture of the existing SPS kickers for the fast extraction to LHC and CNGS and the favourable energy scaling laws (assuming similar β functions):

$$\sigma \sim \frac{1}{\sqrt{p}} \quad \theta \sim \frac{1}{p}$$

where σ is the beam size (defining, together with the septum thickness, the kick strength θ to be provided by the kickers).

The expected length of the transfer line from SPS to SSPS would be 50-60 m. The matching section required to transfer the beam without blow-up between the two machines in both planes must fit in the above space.

Protection elements (like injection stoppers) must also find place in this section. This might be particularly difficult given the higher energies implied as compared to the SPS.

Slow extraction

The electrostatic septa used to cut the separatrix produced by the third integer resonance are one of the critical elements in the design of the slow extraction system. From the present SPS experience reliable operation of these devices can only occur at electric fields not higher than 110 kV/cm. Using in the SSPS the SPS extraction layout is not possible because the separation of the extracted and circulating beams at the magnetic septa located just downstream of the electrostatic septa will be less than half that presently achieved in the SPS as a consequence of the higher extraction momentum and would result in unacceptably high losses.

Increasing the number of extraction electrostatic and magnetic septa while keeping the simple FODO structure in the long straight section allows increasing the separation between the extracted and circulating beams at the magnetic septa although at the expense of an inefficient use of the hardware because of the reduced lever arm between the most downstream electrostatic septa and the first magnetic septum.

This "brute force" solution is schematically showed in Fig. 5. 10 electrostatic septa (ES - 5 in the present SPS layout) are followed by 5 magnetic septa with 4 mm thick septum (MST - 3 in the present SPS layout) and 7 magnetic septa with 17 mm thick septum (MSE - 5 in the present SPS layout). In the estimation of the extracted beam trajectory the characteristics of the present SPS extraction hardware have been assumed.

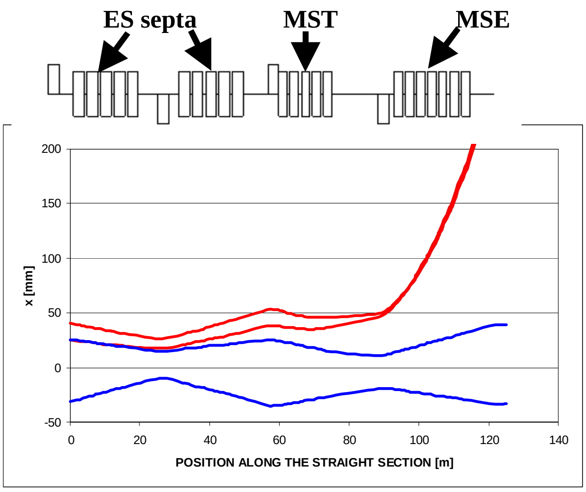

Figure 5. Possible layout for the resonant extraction based on existing SPS hardware and assuming a FODO structure for the long straight section. The trajectory of the extracted beam (red) and that of the circulating beam (blue) are shown. The extraction bump is not shown.

In spite of the larger number of elements the clearances at the MST and MSE magnetic septa are 13 mm and 39 mm to be compared with 17 mm and 41 mm, respectively, for the present SPS resonant extraction. The requirements for the extraction bumpers have not been assessed in the schematic layout presented above.

A dedicated insertion seems therefore necessary in order to increase the clearance at the magnetic septa and to make a more efficient use of the hardware. The optics of the slow-extraction insertion should satisfy the following requirements:

- The dispersion function must vanish at the electrostatic septa to minimize the thickness of the separatrix and to reduce the size of the extracted and circulating beams to enhance the clearance.
- The horizontal beta function at the electrostatic septa should be larger than the maximum value in the arcs in order to minimize the aperture requirements in the arcs while keeping the losses small (i.e. a spiral step comparable with the present SPS extraction) as discussed above.
- The strength for the defocusing quadrupole downstream of the electrostatic septum and the distance between the electrostatic and magnetic septa should be optimised (possibly increased) to enhance the kick provided by the electrostatic septum.
- Magnets with larger aperture might be required in the dispersion suppressor in order to accommodate the circulating and extracted beams.

Adequate protection elements will have to be designed and implemented in the extraction layout in order to provide adequate protection of the superconducting magnets downstream of the extraction elements from the extraction losses.

Fast extraction

The design of the insertion for the fast extraction from SSPS to LHC poses problems similar to the design of the slow extraction. Figure 6 shows the schematic layout and trajectories of the circulating and fast-extracted beams for a FODO lattice.

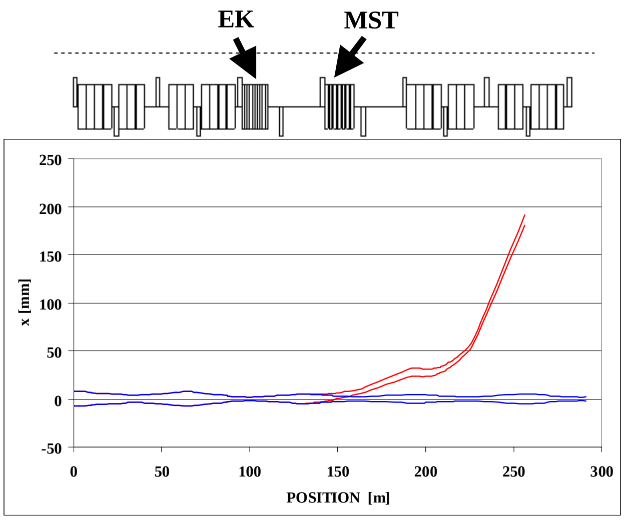

Figure 6. Possible layout for the fast-extraction based on existing SPS hardware and assuming a FODO structure for the long straight section. The trajectory of the

extracted beam (red) and that of the circulating beam (blue) are shown. The extraction bump is not shown.

In the proposed layout 10 fast extraction kickers (EK) are followed by 7 magnetic septa (MST). The clearance at the entrance of the first MST is 19 mm, which might be acceptable from the point of view of beam losses. Pulsed magnetic septa could provide larger deflection angles for comparable septum thickness [1].

Again, magnets with larger aperture might be required in the dispersion suppressor in order to accommodate the circulating and the extracted beam.

Protection elements for the magnetic septa and for the downstream superconducting magnets should be designed and inserted in the layout.

Other issues to be addressed

Given the high intensity and high energy of the beams circulating in the SSPS a beam abort system with an external beam dump absorber are necessary. A dedicated insertion is therefore required and could be based on the design of the LHC beam dump insertion in IR6 [2].

The issues related to betatron and momentum collimation have been treated elsewhere [3].

The cohabitation of eight distinct functionalities in six straight sections need to be addressed and will require a careful layout study.

SUMMARY AND CONCLUSIONS

Some basic requirements for the optics of a Super-SPS accelerating high brightness proton beams up to 1 TeV/c and sharing the tunnel with SPS have been sketched.

The constraints dictated by the existing tunnel (and in particular by the length of the long straight sections) together with the SSPS higher energy, as compared to that of the SPS, impose to design dedicated insertions for the slow and fast extraction, beam dump and for betatron and momentum collimation. That is also necessary in order to minimize the aperture requirements in the arcs.

Cohabitation of different functionalities in the same straight section is needed at least in two cases and the corresponding implications need to be studied.

ACKOWLEDGEMENTS

I would like to thank F. Ruggiero, W. Scandale, E. Shaposhnikova and J. Tückmantel for the interesting discussions during the preparation of the talk and at the workshop.

REFERENCES

[1] G. H. Schröder et al., ‘A Novel Eddy Current Septum Magnet for SPS Extraction towards LHC and CNGS’, Proceedings of the 7th European Particle Accelerator Conference (EPAC2000), 26-30 June 2000, Vienna, Austria, pp. 2370-2372.

[2] A. Verdier, The LHC IR6 optics, LHC Project Note 146.

[3] N. Catalan-Lasheras, these proceedings.