SPS energy upgrade considerations

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Abstract

A new SPS with significantly higher extraction energy than the present 450 GeV is of interest for several CERN projects presently under study. Firstly, for the Future Circular Collider for hadrons (FCC-hh) the tunnels of SPS, LHC and the 100 km collider will be available to house a High Energy Booster (HEB). Replacing the SPS by a superconducting single aperture, low complexity accelerator (scSPS), accelerating the beams up to 1.3 TeV, would have several advantages compared to the other HEB designs. Secondly, for an eventual High-Energy-LHC (HE-LHC) in the LHC tunnel, a higher injection energy could be mandatory for field quality, aperture and impedance reasons. And finally, for future Fixed Target programmes, the possibility of slow extracted beams at energies above 1 TeV could open new physics and detector test beam possibilities. This note presents the conceptual design considerations for a superconducting single aperture accelerator (designated scSPS) in the SPS tunnel which can be used to accelerate protons to an extraction energy of 1.3 TeV for FCC and for interleaved fixed target beam operation in CERN's North Area. The additional specific use-case as injector for HE-LHC is also described. The preliminary cell design, magnet parameters, overall layout, design of the different insertion and performance estimates for specific applications will be presented and discussed in detail.

I. Motivation for a 1.3 TeV scSPS

A. Requirements as FCC injector

The FCC injector chain design should be such that it can fill roughly 80 % of FCC, corresponding to 10600 bunches, with protons in around 30 minutes, reusing as much as possible the existing LHC injector chain [1]. The different machine options for the High Energy Booster (HEB) to inject into FCC-hh cover a large technology range [2], from an iron-dominated machine in the 100 km tunnel, through the reuse of LHC, to a new superconducting machine in the SPS tunnel. Even though the present baseline injection energy for FCC-hh at CERN is 3.3 TeV [3], the HEB designs should take into account a range of possible top energies in the overall optimization.

One of the three options being studied is to reuse the 6.9 km circumference tunnel of the SPS to house a fast-ramping superconducting machine. As FCC injector this accelerator has to be used in a fast-cycling mode to fulfill the FCC-hh requirements concerning filling time, which impacts directly the choice of magnet technology. The reliability and availability will also play important roles in the design, and the machine should have a high degree of flexibility in terms of stability and insensitivity to configuration changes, as it will be called upon to serve multiple users.

Replacing the SPS by a superconducting single aperture, low complexity accelerator (scSPS), accelerating the beams up to 1.3 TeV, would have several advantages compared to the other HEB designs. Using an upgraded SPS would reduce the operational costs compared to LHC as HEB, and could reduce the complexity of the FCC injector chain, since provided the scSPS energy swing is large enough, instead of 5 pre-accelerators (LINAC4, Booster, PS, SPS, LHC-HEB or FCC-HEB) only 4 pre-accelerators for FCC (LINAC4, Booster, PS, scSPS) are needed. Another advantage of using scSPS as injector for FCC would be that the transfer lines to FCC can be designed with normal-conducting magnets The lower energy also means that a higher number of bunches can be transferred safely, reducing the complexity of the machine protection systems associated with this beam transfer.

Another important potential user is as HE-LHC injector. HE-LHC is a study for reaching 13 - 16.5 TeV in the LHC tunnel, by applying the main dipole technology developed for FCC. The requested bunch intensity is 2.2E11 protons per bunch. An upgraded SPS and a higher injection energy into HE-LHC would reduce the energy swing and be beneficial for impedance. The filling time per ring for HE-LHC should be of the order of 10 minutes, as at present [4].

B. Requirements for Fixed-Target beams at 1.3 TeV

During the time the scSPS is not used for FCC or HE-LHC fillins, it will provide a unique capability for high energy, high intensity Fixed Target beams.

Fast extracted beams are of interest for some physics experiments and materials test beams. This type of extraction and beamline does not pose any serious technical challenges, since a beamline can be provide with a simple slow magnetic dipole switch element from the extraction already essential for the transfer of beams to the high energy collider. A test-area like HiRadMat would be feasible, with a larger range of beam energies and intensity.

A slow extraction over the milli-second to several seconds range is needed to guarantee high integrated proton rates for most Fixed Target experiments and experimental test beams. This poses a lot more challenges for the scSPS design, in the extraction elements, the radiation dose, the uncontrolled beam loss and the integration with the collimation system. If a slow extraction system can be designed for scSPS to work together with a collimation system at 1.3 TeV, Fixed Target beam operation in the North Area could continue with a much higher beam energy [5]. Innovative solutions for slow beam extraction will need to be developed, to avoid increasing the machine aperture dramatically. The interplay with the collimation system will be a first-order design consideration, and the insertion design will need to be tightly coupled with the protection of the superconducing aperture from beam losses. The inclusion of a Fixed Target capacity with slow extraction has significant implications for the lattice and potentially for the magnet aperture, depending on the solutions which can be developed.

For the slow extraction, the design goals are tentatively identified as the capacity to provide around 10^{19} PoT per year for a Fixed Target experiment, with an extraction flat-top of up to several seconds. With a beam intensity of around 5×10^{13} protons per cycle, and a cycle time of 90 seconds, the machine could deliver around 1×10^{19} PoT per year, with reasonable assumptions on availability and operational days per year. At these intensities, the beamloss control at the slow extraction of the 25 MJ beam will be the limiting performance factor - with a 1 minute cycle the power on the target is around 400 kW (the instantaneous power during the spill is, of course, much higher).

C. Energy and cost saving compared to present SPS

II. Basic design considerations for scSPS

For the basic design of the layout the present tunnel geometry was maintained and locations for existing long straight section (LSS) functionalities kept, as far as possible. The injection was kept in LSS1 with the beam circulating in a clockwise direction, this would allow to keep the slow extraction and transfer lines to the North Area in LSS2. The RF system should be kept in LSS3 if possible. The fast extractions towards FCC points B and L will be located in LSS4 and LSS6, which would be also compatible to a beam transfer to HE-LHC. With the higher beam energy and superconducting main magnet system a new collimation system and an external beam dump are required to guarantee safe beam operation. These system will be placed in LSS5 and LSS6, respectively, with the beam dump needing to co-exist with a fast extraction system. An overview of the layout is shown in Figure 1.

To reduce the number of kicker systems and magnets in the ring and therefore also reduce the beam impedance a non-local extraction from LSS4 to LSS6 might be considered [6]. The detailed design study of the different straight section is currently starting in close collaboration with the responsible hardware groups.

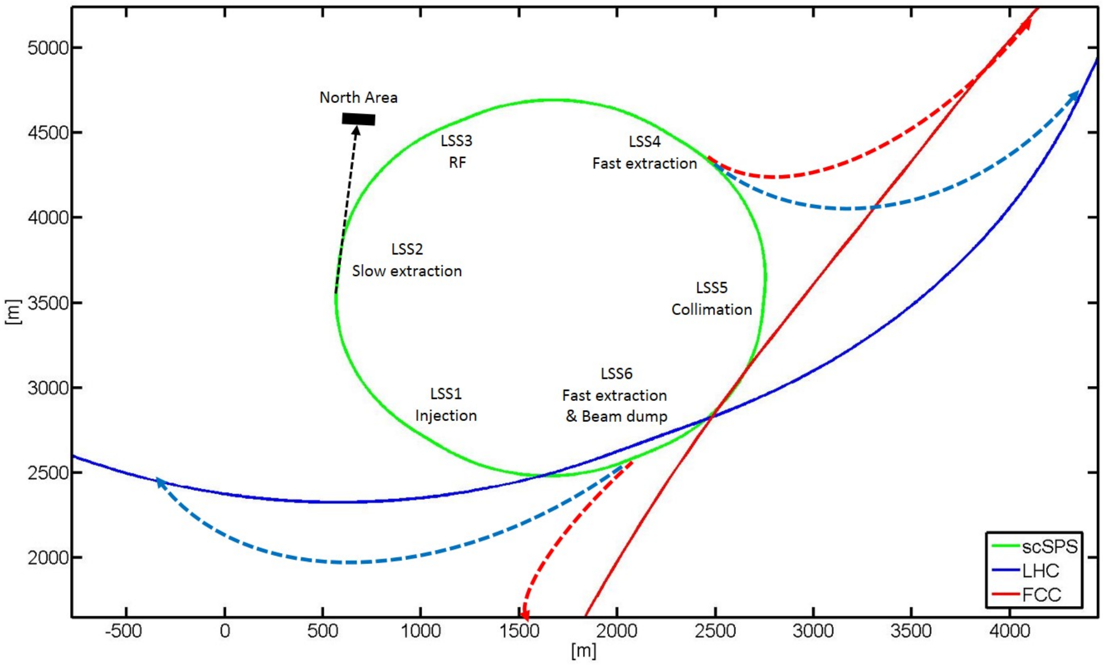

Figure 1: Layout of scSPS with the different systems in the straight sections and the transfer lines to FCC and LHC are schematically shown. Injection in LSS1, slow extraction towards North Area in LSS2, RF in LSS3, extraction towards FCC point B in LSS4, collimation system in LSS5, beam dump and extraction towards FCC point L will be combined in LSS6.

A. Main parameters

The main parameters can be found in Table 1. These values are based on the magnet parameters described in chapter 3, assuming a 12 m long, superconducting dipole magnet with a maximum field of 6 T. For use as HE-LHC injector identical parameters are assumed.

Assuming the present PS as pre-injector, the scSPS injection energy would be 26 GeV. In case the resulting energy swing (in this case 50) for the magnets is too big, the injection energy would need to be increased, for instance to $\sim$50 GeV assuming an upgraded PS or a new PS2 [8]. In this case the energy swing would then be reduced to 26, compared to 32 for the present SPS Fixed Target beams and 15 in LHC. The minimum operable dipole field is really a key project parameter and initial conceptual studies of the magnet system are needed to address the question of whether 120 mT imposed by 26 GeV injection from the PS is feasible.

For the configuration, in the scSPS the initial assumption is that two SPS dipole magnets will be replaced by one new superconducting magnet with the same cell length of 64 m. These parameters can be optimized in future with a detailed study of the trade-off between dipole, quadrupole and cell length and strengths of the magnets.

The number of protons transferred per scSPS extraction is defined by the damage limit of the FCC injection protection absorber, which is presently assumed to be $\sim$320 nominal FCC bunches. If scSPS is almost full, with 8 injections from the PS, it will accelerate 640 bunches per cycle and extract 320 bunches per beam transfer to FCC [7].

To reach a cycle length of $\sim$ 1 min the average ramp rate should be in the order of 0.5 T/s. To fill FCC with 10800 bunches 34 cycles of scSPS are needed which will fulfil the FCC filling time requirements.

The combination of a superconducting environment and $\sim$10-20 MJ stored beam energy requires a reliable active and passive machine protection system. A collimation system will be needed, and straight section LSS5 has been earmarked for this system. The beam dump will need to be combined with another machine system, as there are only 6 LSS for 7 systems, and a co-existence with the fast extraction system in LSS6 will have to be studied.

Table 1: Main parameters of scSPS.

Parameter	Unit	Value
Injection energy	GeV	26
Extraction energy	GeV	1300
Maximum dipole field	T	6
Dipole field at injection	T	0.12
Number of dipoles		372
Number of quadrupoles		216
Ramp rate	T/s	0.35 - 0.5
Cycle length	min	1
Number of bunches per cycle		640
Number of injections into scSPS		8 (80b)
Number of protons per bunches		$\leq 2.5\times10^{11}$
Number of extraction per cycle		2 (2x320 b)
Number of cycles per FCC filling		34
FCC filling time	min	34 - 40
Max stored beam energy	MJ	33

III. Optics, aperture and magnets

A. Optics assumptions and cell design

The optics in the scSPS are very similar to the present SPS. The current SPS cell design with a half-cell length of 32 m with one quadrupole magnet, 4 dipole magnets, correctors and beam instrumentation will be replaced by set-up with 2 instead of 4 dipole magnets. There will be 372 dipoles in total, each with a bend angle of 16.890 mrad The dispersion suppression is assumed to be performed as in the present SPS with a missing dipole scheme, which avoids the need for different main dipole strengths. Alternative cell lengths and an optimization of layout and optics will be investigated at a later stage. Peak β values are 107 m in the centres of the quadrupoles, and peak dispersion functions 4.3 m, for an integer tune of 26 in both planes and 89.96 $^\circ$ phase advance per cell.

B. Aperture requirements

For the scSPS two different beam types were considered, for comparison purposes. First is the dedicated FCC (and HE-LHC) beam, the second one is a fixed target (FT) beam. The emittance for the fixed target beam was assumed to be the same as the FCC beam (2.2 μm).
The minimum beam-stay-clear (full aperture A) was then calculated by using $\pm 10\ \sigma$ (at injection), $O_{x,y} = \pm 2.5$ mm combined orbit and alignment tolerance in both planes, $I_{x,y} = \pm 1.5$ mm for injection oscillations, with linear addition of the betatron and dispersion terms and a factor of 1.21 allowed for optics imperfections.
The expression used was $A_{x,y}/2 = |O_{x,y}| + |I_{x,y}| + 10\sqrt{1.21\beta_{x,y}\epsilon_{x,y}} + 1.1|D_{x,y}|\delta p/p$. If an additional 2 mm thickness is assumed for the vacuum chamber and its support inside the cold-bore, then at 26 GeV the inner diameter of the circular cold-bore is 80 mm.
No extra aperture is assigned for sagitta, which is larger than 25 mm for the 12 m dipole, as the magnets are assumed to be built curved.
The vertical aperture required is slightly smaller, as the vertical dispersion is taken as zero, and the injection oscillations can be assumed only in the horizontal plane.

Table 2 lists the assumed parameters, the inner diameter of the cold bore and the minimum horizontal and vertical apertures required, comparing 26 and 50 GeV injection energies. It should be noted that no extra aperture for slow extraction separatrices has been considered, as discussed in section B.

Table 2: Beam parameters for the proton beam for an injection energy of 26 GeV.

Parameter	Unit	Value
Max. beta $\beta_{x,y}$	m	107
Max. dispersion D_x	m	4.3
Orbit + alignment tolerance $O_{x,y}$	mm	2.5
Max inj. oscillation	mm	1.5
Emittance $\epsilon_{x,y}$ (1 σ, norm.)	m	2.2×10^{-6}
$\delta p/p$		5×10^{-4}
A_x/A_y 26 GeV	mm	76/69
Coldbore diameter 26 GeV	mm	80

C. Discussion of beam parameters for slow extraction

For the slow extraction the proton beam characteristics of the LHC injector complex after the LIU upgrade was used. The scSPS can be filled with the 2.2 μm emittance beam from the pre-injectors, with up to 2.5e11 protons per bunch [9]. Assuming 8 injections of 80 bunches this will result in 1.6e14 protons per cycle and spill. The feasibility concerning survival of the collimation and slow extraction systems and RF parameters needs a detailed study.

To note that, in the 80 mm coldbore diameter, no extra allowance is made for the slow extraction separatrices at high energy. Typically these will reach about $\pm$20 mm in the horizontal plane and a detailed study is needed to investigate the implications for the overall aperture and for the extraction region where the intercepting devices should be outside the aperture at injection. Alternatives to resonance exicitation such as transverse noise driven extraction will also need to be investigated.

This filling mode for FT beams will require 6 additional injections from the PS, which is an overhead of 19.2 s per cycle concerning the proton throughput. Assuming an average period between FT extractions of 90 s this effect is at the 20 % level, which can easily be compensated by just assuming 20 % more protons per spill.

Assuming 2e5 spills per year (200 days), and 5e13 p per spill, 1e19 protons per year can be extracted, which is comparable to what is presently delivered to the NA.

D. Tentative dipole magnet parameters

To minimise complexity and cost the dipole magnets should have a reasonably low maximum field, assumed after initial discussions to be 6 T on the beam axis. This value together with the present tunnel geometry and a dipole filling factor of 0.75 leads to a maximum extraction energy of 1.3 TeV. After optimizing the half cell in terms of available free space and B.dl an optimal magnetic length of the dipole magnets was found to be 12.12 m.

The sagitta for such a magnet would be over 25 mm. To avoid an aperture increase due to this very big sagitta it is assumed that the dipoles are built with a curved aperture. The attainment of $\pm$2.5 mm absolute tolerance on the position of the installed vacuum chamber plus beam orbit is certainly also an aggressive challenge, which needs separate study. As input for the initial magnet feasibility study one coldbore aperture is quoted at 80 mm corresponding to a 26 GeV injection with FCC type emittance (2.2 μm).

The interconnects between two neighbouring magnets were assumed to have a length of 1.25 m. To stay in the limit of $\sim$30 - 40 min FCC filling time, the average ramp rate should be in the order of 0.35 - 0.5 T/s, assuming 34 ramps to fill both rings of FCC. The maximum ramp rate will need to be slightly higher than this, to allow for some round-off at the start and end of the ramp. The parameters for the dipole magnets are summarized in Table 3, including the free space per half-cell which will need to be used for correctors, chromaticity sextupoles, instrumentation and special magnets like extraction bumpers and multipoles.

E. Quadrupole magnet parameters

For the quadrupole magnets a peak pole tip field below 6 T was assumed. The parameters for length and quadrupole pole tip field can be found in Table 4.

Table 3: Preliminary design parameters of scSPS dipole magnets for an extraction energy of 1.3 TeV.

Parameter	Unit	Value
Max. field	T	6
Magnetic length	m	12.12
Ramp rate	T/s	0.35 - 0.5
Cold bore inner diameter (FCC/FT beam)	mm	80
Free space per half cell	m	2.65

Table 4: Preliminary design parameters for quadrupole magnets in the scSPS with an extraction energy of 1.3 TeV.

Parameter	Unit	Value
Magnetic length	m	1.35
Coil inner diameter (FCC/FT beam)	mm	80
Pole tip field	T	5.85

F. Magnet transport

The present SPS access shafts are limited to elements with a maximum length of 6.9 m. This option would require bigger access shafts to the SPS tunnel level. The transport in the tunnel is feasible as the SPS tunnel has a bigger diameter than the LHC tunnel, where 15 m long dipoles are used.

IV. Layout

V. Arc and LSS lattice

As starting point for the SPS energy upgrade studies, the current SPS lattice was used. For this lattice, two dipole magnets were replaced by one superconducting dipole. A plot of beta function and dispersion in the arc and the straight section is shown in Figure 2 and 3. A detailed optimization will start when the magnet parameters are confirmed.

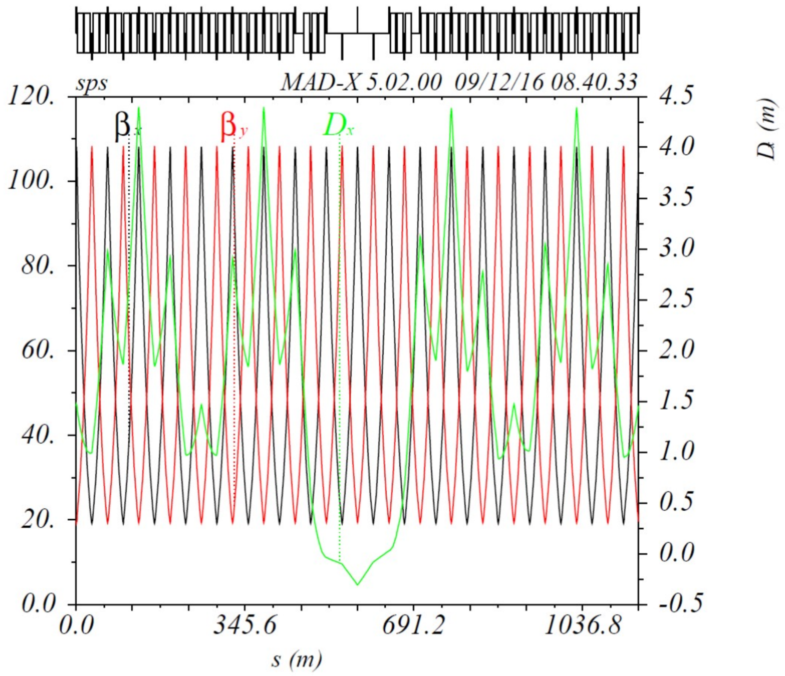

Figure 2: Straight section, dispersion suppressor and arc lattice.

A. Injection insertion

The injection equipment will be located in LSS1, compatible with an injection from the TT10 transfer line. The injection direction is clockwise to allow for a slow extraction in LSS2 to deliver fixed target beams to the North Area. A schematic of the injection equipment in the straight section is shown in Figure 5. The drift distance between two neighboring quadrupoles is 30 m. The main constraint of this insertion is the 90 degree phase advance requirement between injection kicker and internal dump to protect the further downstream machine in case of injection failures. The main hardware parameters for an injection of a 26 GeV proton beam can be found in Table 5 (injection kicker) and 6 (injection septa). The total length required for the injection system is $\sim$60 m, including drift space. The main parameters are feasible, but the details of the apertures, failure cases and equipment conceptual design need further studies.

B. Slow extraction insertion

A slow extraction towards North Area in LSS2 in a superconducting environment will require significant changes to the present extraction paradigm. As starting point a crystal-based

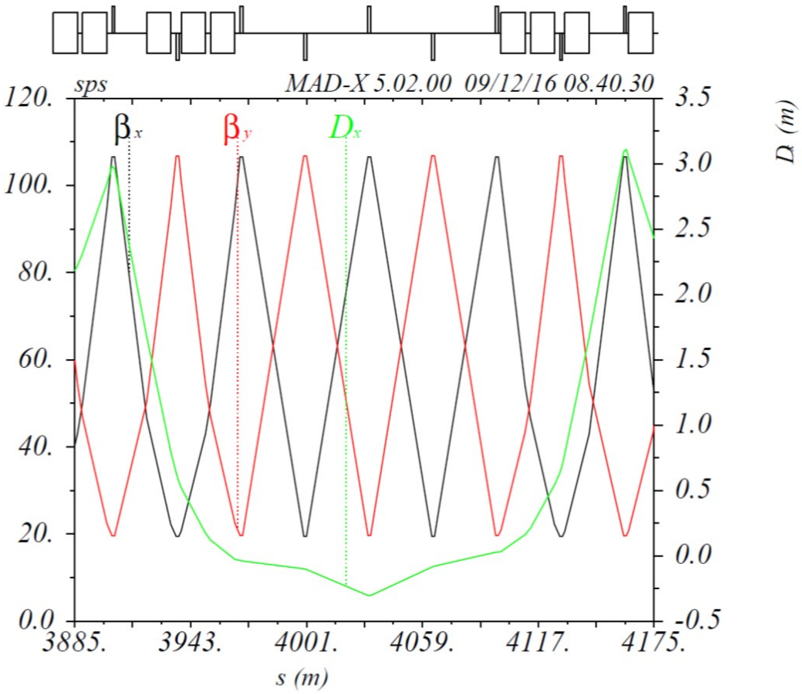

Figure 3: Straight section and dispersion suppressor lattice. Dispersion suppressor design as in the current SPS with missing bends scheme.

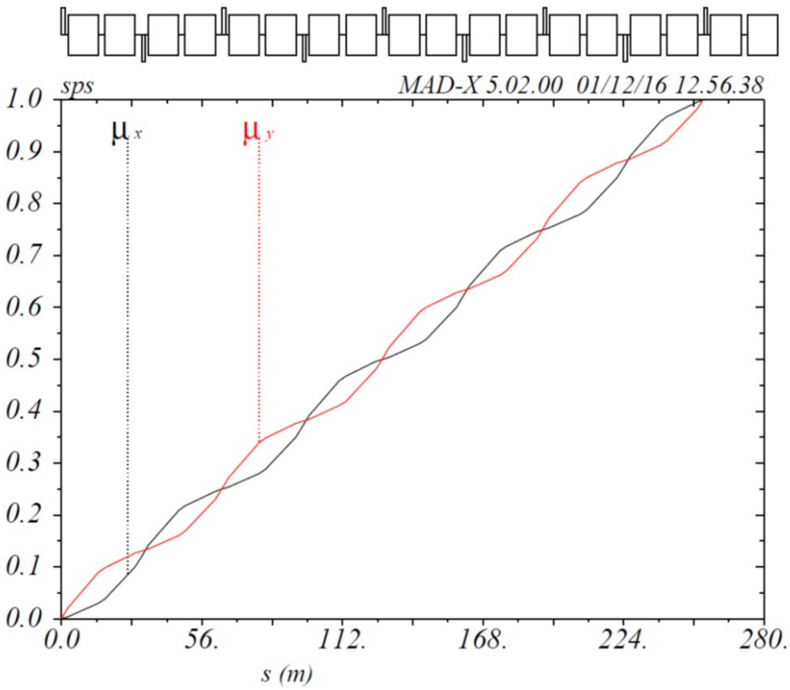

Figure 4: Phase advance in the arc.

extraction with low losses is assumed [10], possibly with non-resonant transverse excitation of the beam to avoid large excursions caused by the resonant separatrices. A schematic of a possible extraction straight layout is shown in Fig. 6. Other extraction methods (e.g. resonant

Figure 5: Schematic of the injection equipment in the straight section, the hardware would fit between two neighboring quadrupoles. The 90 degree phase advance is necessary to protect the SC aperture in case of injection failures.

Table 5: Injection kicker parameters for an injection of 26 GeV protons

	26 GeV
Bdl [Tm]	0.25
Kick angle [mrad]	3
Rise time [ns]	200-250
HW length [m]	10

Table 6: Injection septa parameters for an injection of 26 GeV protons.

	26 GeV
Bdl [Tm]	1.8
Kick angle [mrad]	22
Blade thickness [mm]	7
HW length [m]	10

extraction) could eventually need a bigger horizontal aperture in the magnet. For any slow extraction method, some level of beam loss is inevitable, and the impact of high loss levels and additional protection elements in addition to the system interplay with the scSPS collimation system need to be studied.

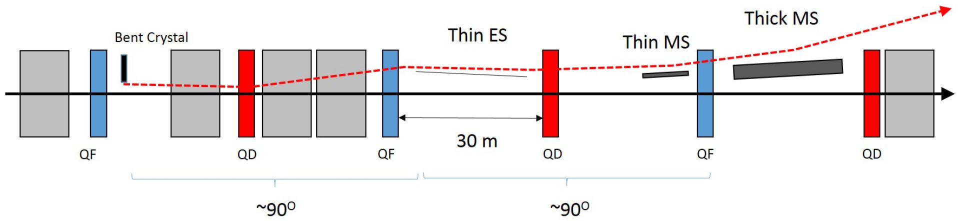

Figure 6: Schematic of the slow extraction equipment. The crystal is located at the missing bend location in the dispersion suppressor, followed by the septa in the straight.

C. Fast extraction insertions

The extraction parameters for the fast extraction towards FCC are listed in Table 7 (for extraction kicker) and 8 (for extraction septa). This would allow to place the extraction hardware in the space between two quadrupoles. Together with the necessary drift space to reach the clearance for septum blade and cryostat and extraction of a 1.3 TeV proton beam in a straight section is feasible.

The required length for the extraction is ~ 120 m. Detailed studies on lattice design and failure cases are ongoing.

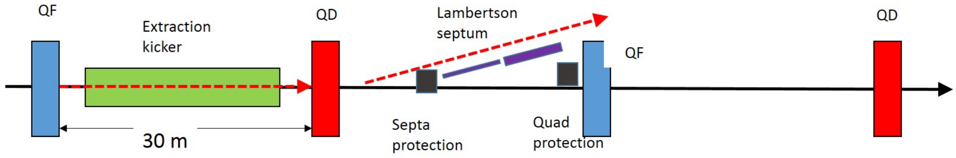

Figure 7: Schematic of a possible extraction equipment layout in the straight section, the hardware would fit between two neighboring quadrupoles.

Table 7: Extraction kicker parameters.

Bdl [Tm]	0.8
Kick angle [mrad]	3.4
Rise time [ns]	tbd
HW length [m]	20

Table 8: Extraction septa parameters.

Bdl [Tm]	20
Kick angle [mrad]	4.6
Blade thickness [mm]	7
HW length [m]	20

D. Collimation insertion

Studies for a (multi-stage) collimation system to be placed in the free space of a straight section need to be started. The main limitations are the possible need for normal conducting quadrupoles and the limited space and phase advance per straight section. The presence of strong beamloss locations at high energy at the slow-extraction elements will constrain the collimation system design, possibly requiring a local cleaning system to be incorporated with or immediately downstream of the extraction elements.
First discussions with the collimation team showed that an aperture of 10 sigma at injection would lead to an aperture of 70 sigma at flat top. A staged collimation system with a set of primary and secondary collimators can maybe squeezed into a straight section. Studies are ongoing in the collimation team.

E. RF insertion

First estimates show that the installation of a superconducting RF system can be placed within one straight section. A detailed study of the optimum frequency (or frequencies) and parameters (also to debunch the beam for slow extraction) is needed.

F. Beam dump

The beam dump has to be combined with an high energy extraction due to the limited amount of straight sections. TT61 (presently used for HiRadMat) might be modified (dumped beam as to point downwards) and be used as beam dump line. The stored beam energy is enough to drill holes in a graphite beam dump block therefore a dilution kicker system, analogous to the LHC, is needed. In combination with the radiation concerns an external beam dump line is necessary to house the beam dump block and dilution kicker equipment. The extracted beam will be send directly to the beam dump, if the beam quality is sufficient and FCC injection is ready to take beam, kicker magnets will deflect the beam into the transfer line to FCC. A schematic is shown in Fig. 8

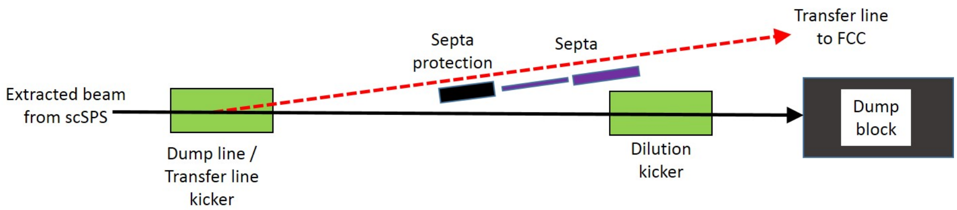

Figure 8: Schematic of a beam dump line and beam transfer to FCC layout. The beam will be send onto the beam dump block, if the conditions are correct, fast kicker magnets will deflect the beam into the transfer line to FCC.

G. Transfer lines to FCC

A schematic of the position of scSPS, LHC, FCC and transfer lines (in blue) are shown in Figure 1. Detailed studies are needed for the transfer line design and system parameters. With the current FCC position (v4) [11] partially superconducting transfer lines are feasible from LSS4 and LSS6.
An alternative extraction from LSS3 and LSS5 is currently under study. This option would increase the length of the transfer lines but it would allow for a fully normalconduncting transfer line.

VI. Heat load and beam dynamics

First estimates and a comparison to LHC show that the heat load expected for scSPS is reasonable. The ramp losses can be defined with the final magnet parameters.The parameters are listed in Table 9. The synchrotron radiation losses are negligible, the heat load coming from electron cloud can be reduced with an efficient vacuum chamber coating [14]

A. Electron cloud

By using a coating the heat load contribution from electron cloud is negligible [12]. It has to be evaluated by VSC-SSC and the magnet group if the cold-bore can be coated directly or if a laser treatment of the surface is possible.

B. Vacuum requirements

The vacuum pressure should be comparable to present SPS (10^{-9} mbar) and LHC (10^{-10} mbar). Transfer lines can be higher - present SPS to LHC transfer lines with 10^{-8} mbar.

VII. Discussion and conclusions

This note describes the initial assumptions concerning layout, lattice parameters, cell and LSS design and magnets for an energy upgrade of the SPS (scSPS) to 1.3 TeV. This should serve as the basis for subsequent detailed studies. This study is of major interest as scSPS can be used as fast and reliable FCC-hh and HE-LHC injector. In addition, it will increase the energy range for fixed target beam operation in the North Area. Several key feasibility studies are needed to allow a conceptual design to be finalized, these are:

- achievable ramp rate for 6 T, 12 m dipoles;
- minimum field level for 6 T dipoles;

VIII. Discussion and conclusions

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  – achievable ramp rate for 6 T, 12 m dipoles;
  – minimum field level for 6 T dipoles;
  – field quality required for injected beam;
  – attainable orbit and mechanical tolerances for vacuum chambers in 12 m curved dipoles;
  – design of LSS containing both beam dump and fast extraction system;
  – design of slow extraction system at 1.3 TeV;
  – design of collimation system, with constraints from slow extraction and limited space;

The detailed studies for magnets and the different insertions has started, and it is planned to address and document the resulting subsystem concepts in separate notes.

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Table 9: First estimates of the heat load calculations.

	LHC	scSPS
beam current [A]	0.582	1.09
particle / bunch [10^{11}]	1.15	2.5
rms bunch length [cm]	7.55	10?
dipole bending radius [km]	2.8	0.7
beam energy [TeV]	7	1.3
critical photon energy [eV]	43	1.7
radial aperture [cm]	2	4
heat loads [mW/m]	at 5-20 K	at 1.9 K
synchrotron radiation	220	2
Ohmic losses	110	30 (at same conductivity)
pumping slots	10	0
welds	10	?
electron cloud [W/m]	2000 (max)	low with coating
beam losses	50 (at 1.9 K)	10 (with same cleaning efficiency as LHC)
ramp losses - AC and ohmic	-	tbd

IX. Acknowledgment

Many fruitful discussions with different colleagues have helped shaped this report; in particular Jan Borburgh, Thomas Kramer, Giovanni Iadarola, Stefano Redaelli, Daniel Schulte, Elena Shaposhnikova and Linda Stoel are thanked for their contributions.

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