CONCEPTIONAL DESIGN CONSIDERATIONS FOR A 1.3 TeV SUPERCONDUCTING SPS (scSPS)

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Abstract

The Future Circular Collider for hadrons (FCC-hh) envisaged at CERN will require a High Energy Booster as injector. One option being studied is to reuse the 6.9 km circumference tunnel of the SPS to house a fast-ramping superconducting machine. This paper presents the conceptual design considerations for this superconducting single aperture accelerator (designated scSPS) which can be used to accelerate protons to an extraction energy of 1.3 TeV, both for FCC and for fixed target beam operation in CERN's North Area. As FCC injector this accelerator has to be used in a fast cycling mode to fulfil 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 inclusion of a fixed target capacity also has significant implications for the lattice and layout. The cell design, magnet parameters, overall layout, design of the different insertion and performance estimates for specific applications will be presented and discussed.

MOTIVATION FOR A 1.3 T*e*V scSPS

Requirements as FCC Injector

The FCC injector chain design should be such that it can fill roughly 80 % of FCC with protons, corresponding to 10600 bunches, 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, the HEB designs should take into account a range of possible top energies in the overall optimization [3].

One of the three options being studied is to reuse the 6.9 km circumference tunnel of the SPS to house a fast-ramping single-aperture, low-complexity 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 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.

Using an upgraded SPS would reduce the operational costs compared to LHC as HEB, and could reduce the complexity of the FCC injector chain. Instead of 5 pre-accelerators (LINAC4, Booster, PS, SPS, LHC-HEB) only 4 pre-accelerators for FCC (LINAC4, Booster, PS, scSPS) could be needed. Another advantage of using scSPS as injector for FCC would be that the transfer lines to FCC may 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 [4]. An upgraded SPS and a higher injection energy into HE-LHC would reduce the energy swing and be beneficial for impedance.

Requirements for Fixed-Target Beams at 1.3 TeV

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

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 of 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.

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.

Fast extracted beams are of interest for some physics experiments and materials test beams. A test-area like HiRadMat would be feasible, with a larger range of beam energies and intensity.

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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. 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 systems 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 Fig. 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 sections is in progress in close collaboration with the responsible hardware groups.

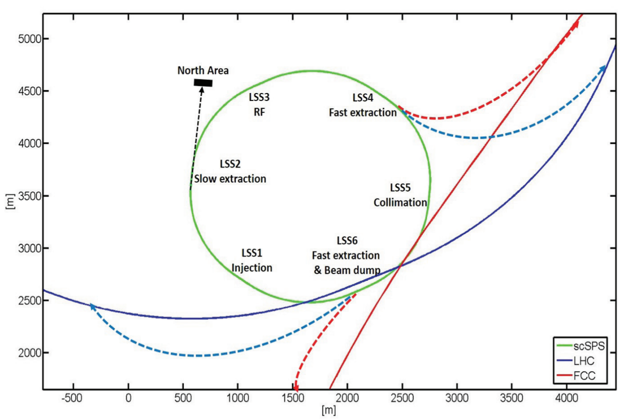

Figure 1: Layout of scSPS with the different systems in the straight sections, the transfer lines to FCC and LHC are schematically shown. Injection in LSS1, slow extraction towards North Area in LSS2, RF in LSS3, extraction towards FCC point B in LSS4, collimation system in LSS5, beam dump and extraction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

Main Parameters

The main parameters can be found in Table 1. These values are based on the magnet parameters of a 12 m long, superconducting dipole magnet with a maximum field of 6 T. The interconnects between two neighbouring magnets were assumed to have a length of 1.25 m. 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. The minimum operable dipole field is 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 and an energy swing of a factor 50 are feasible.

To stay in the limit of ~30 - 40 min FCC filling time, the average ramp rate should be 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 combination of a superconducting environment and ~33 MJ stored beam energy requires a reliable active and passive machine protection system.

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
Dipole magnet length	m	12.12
Cold bore inner diameter	mm	80
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

Optics Assumptions and Arc 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 a half-cell with 2 instead of 4 dipole magnets. There will be 372 dipoles in total, each with a bend angle of 16.89 mrad The dispersion suppression is assumed to be performed as in the present SPS with a missing dipole scheme. 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 ° phase advance per cell. A plot of beta function and dispersion in the arc and the straight section is shown in Fig. 2.

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 normalized emittance for the fixed target beam was assumed to be the same as the FCC beam (2.2 μm).

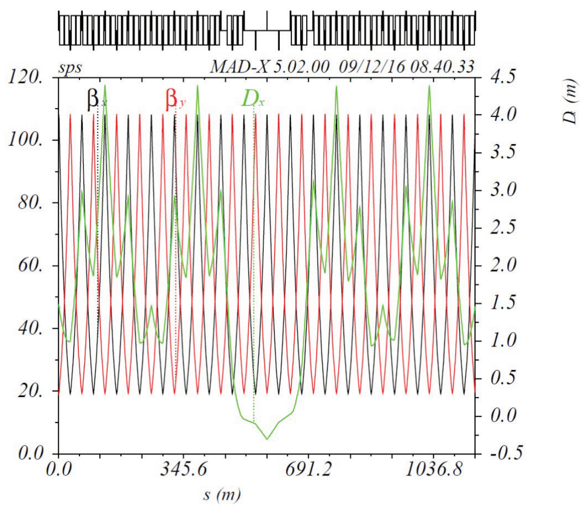

Figure 2: Straight section, dispersion suppressor and arc lattice.

To calculate the aperture a minimum beam-stay-clear (full aperture A) was then calculated by using $\pm 10\ \sigma$ (at injection), an offset of $O_{x,y} = \pm 2.5$ mm for 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 was used.
The following expression was used to calculate the radius of the aperture:
$A_{x,y}/2 = |O_{x,y}| + |I_{x,y}| + 10\sqrt{1.21\beta_{x,y}\epsilon_{x,y}} + 1.1|D_{x,y}|\delta p/p$.
An additional 2 mm thickness is assumed for the vacuum chamber and its support inside the cold-bore. Finally the inner diameter of the circular cold-bore at 26 GeV is 80 mm. The magnets are assumed to be built curved, therefore no extra aperture is assigned for sagitta, which is larger than 25 mm for the 12 m dipole. 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.

It should be noted that no extra aperture for slow extraction separatrices has been considered.

LONG STRAIGHT SECTION DESIGN

The design of the different straight sections is ongoing. The parameters for the injection hardware (fast pulsing kickers and septa) are defined and feasible. As starting point for the slow extraction design, a crystal-based extraction with low losses is assumed [7], 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. 3. 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.

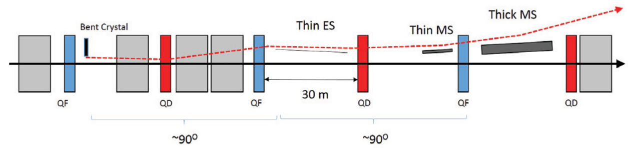

Figure 3: Schematic of the slow extraction equipment. The crystal is located at the missing bend location in the dispersion suppressor, followed by the septa in the straight.

The extraction parameters for the fast extraction towards FCC have been studied. Together with the necessary drift space to reach the clearance for septum blade and cryostat the extraction of a 1.3 TeV proton beam in a straight section is feasible [8]. 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 has to point downwards) and be used as beam dump line. The stored beam energy is enough to drill a hole in a graphite beam dump block, therefore a dilution kicker system, analogous to the LHC, is needed [9]. The extracted beam from the scSPS will be sent directly onto the beam dump, if the beam quality is sufficient and FCC injection is ready to take beam an additional kicker magnet system in the dump line will deflect the beam into the transfer line to FCC.

DISCUSSION AND CONCLUSIONS

This paper 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 and minimum field level for 6 T, 12 m dipoles;
- field quality required for injected beam;
- attainable orbit and mechanical tolerances for vacuum chambers in 12 m curved dipoles;
- design of slow extraction system at 1.3 TeV;
- design of collimation system, with constraints from slow extraction and limited space.

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