2.16.7 Acknowledgements

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2.16.8 References

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2.17 Update on the SPPC design

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2.17.1 1 Introduction

With a recent change on the tunnel circumference from 50-60 km to 100 km, we have an updated design on the CEPC-SPPC project [1-2]. As the second phase of the project, with CEPC being electron-positron collider to exploit Higgs physics, SPPC (Super Proton-Proton Collider) is envisioned to be an extremely powerful proton-proton collider, and both colliders share a 100-km circumference tunnel. The primary design goal of SPPC is to have a center of mass energy 75 TeV, a nominal luminosity of 1.0 x 10^{35} $cm^{-2}s^{-1}$ per IP, and an integrated luminosity of 30 ab^{-1} assuming 2 interaction points and ten years of running. A later upgrade to even higher luminosities is also possible. It is true that luminosity has a more modest effect on energy reach, in comparison with higher beam energy [3], but raising the luminosity will likely be much cheaper than increasing the energy. The ultimate upgrading phase for SPPC is to explore physics at the center of mass energy of 125-150 TeV by using higher-field magnets. Some key parameters are shown in Table 1.

Table 1: Key parameters of the SPPC baseline design

Parameter	***Value***		***Unit***
	Phase-I	Ultimate	
Center of mass energy	75	125-150	TeV
Nominal luminosity	1.0×10^{35}	-	$cm^{-2}s^{-1}$
Number of IPs	2	2	
Circumference	100	100	Km
Injection energy	2.1	4.2	TeV
Overall cycle time	9-14	-	Hours
Dipole field	12	20-24	T

SPPC is a complex accelerator facility and will be able to support research in different fields of physics, similar to the multi-use accelerator complex at CERN. Besides the energy frontier physics program in the collider, the beams from each of the four accelerators in the injector chain can also support their own physics programs. The four stages, shown in Figure 1 and with more details in Table 3, are a proton linac (p-Linac), a rapid cycling synchrotron (p-RCS), a medium-stage synchrotron (MSS) and the final stage super synchrotron (SS). This research can occur during periods when beam is not required by the next-stage accelerator.

The option of heavy ion collisions also expands the SPPC program into a deeper level of nuclear matter studies. There would also be the possibility of electron-proton and electron ion interactions.

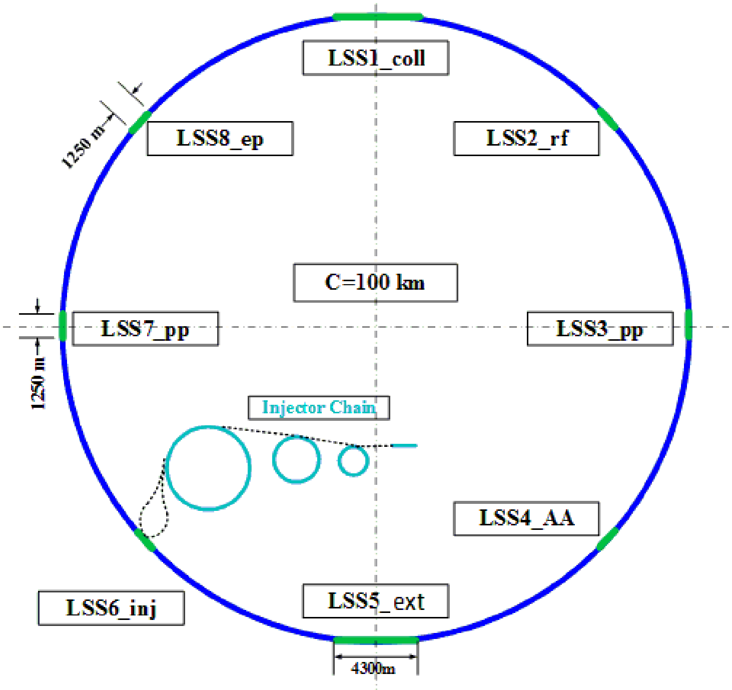

Figure 1: Schematic for the SPPC accelerator complex

2.17.2 **Lattice**

Different lattice schemes have been studied. The solution with eight arcs and eight long straight sections has been accepted by both CEPC and SPPC. To comply with the two colliders in the same tunnel, a LHC-like lattice was chosen for the arcs for its good flexibility to match the different cell lengths of the two colliders. The arc sections should be designed to be as compact as possible to provide necessary long straight sections. Traditional FODO focusing is everywhere, except at the IPs where triplets are used to produce the very small β*. The arcs represent most of the circumference, and the arc filling factor is taken as 0.78, similar to LHC [4]. Long straight sections are crucial to host interaction sections with large detectors, beam injection and extraction systems, collimation systems and RF stations. Figure 2 shows the lattice functions at one of the IP regions. The some main parameters are listed in Table 2.

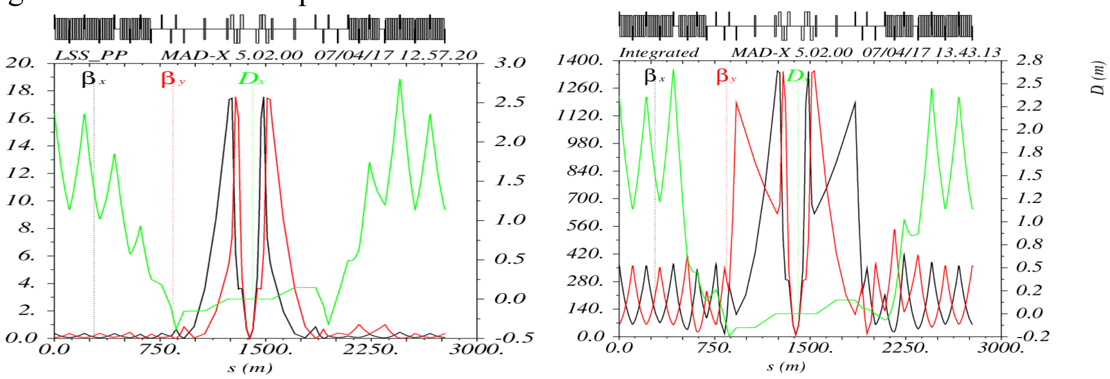

Figure 2: Lattice at one of the two main IRs. Left: at collision energy; Right: at injection energy.

Table 2: Some main SPPC parameters

Parameter	***Value***	***Unit***
Circumference	100	km
Beam energy	37.5	TeV
Dipole field	12	T
Arc filling factor	0.78	
Total dipole magnet length	65.442	km
Number of long straight sections	8	
Total straight section length	16.1	km
Injection energy	2.1	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Nominal luminosity per IP	1.0×10^{35}	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	0.70	A
Nominal beam-beam tune shift limit per IP	0.0075	
Bunch separation	25	ns
Number of bunches	10080	
Bunch population	1.5×10^{11}	
Normalized rms transverse emittance	2.4	μm
Beam life time due to burn-off	14.2	hours
Full crossing angle	110	μrad
rms bunch length	75.5	mm
Stored energy per beam	9.1	GJ
SR power per beam	1.1	MW
SR heat load at arc per aperture	12.8	W/m
Energy loss per turn	1.48	MeV

2.17.3 **Luminosity and leveling**

Although the initial luminosity (or nominal luminosity) of 1.0×10^{35} $cm^{-2}s^{-1}$ is modest for a next-generation proton-proton collider. It is comparable to FCC-hh [5-6] and lower than in the HL-LHC [7]. This design also allows future luminosity upgrading.

Besides the synchrotron radiation power limits the circulation current and luminosity, the number of interactions per bunch crossing is also a limit to the luminosity. It is believed that ongoing R&D efforts on detectors and general technical evolution will be able to solve the data pile-up problem. On the other hand, it is important is to increase the average, and thus integrated luminosity while maintaining the maximum instantaneous luminosity [8]. Thus one kind of luminosity leveling scheme should be applied. By taking into account the loss of stored protons from collisions, cycle turnaround time, shrinking of the transverse emittance due to synchrotron radiation, and beam-beam shift, one can design different leveling schemes, as shown in Figure 3. An emittance blow-up system is needed to control the emittance shrinkage. Another method to increase the luminosity is to adjust β^* during the collisions by taking advantage of emittance shrinking while keeping the beam-beam tune shift constant.

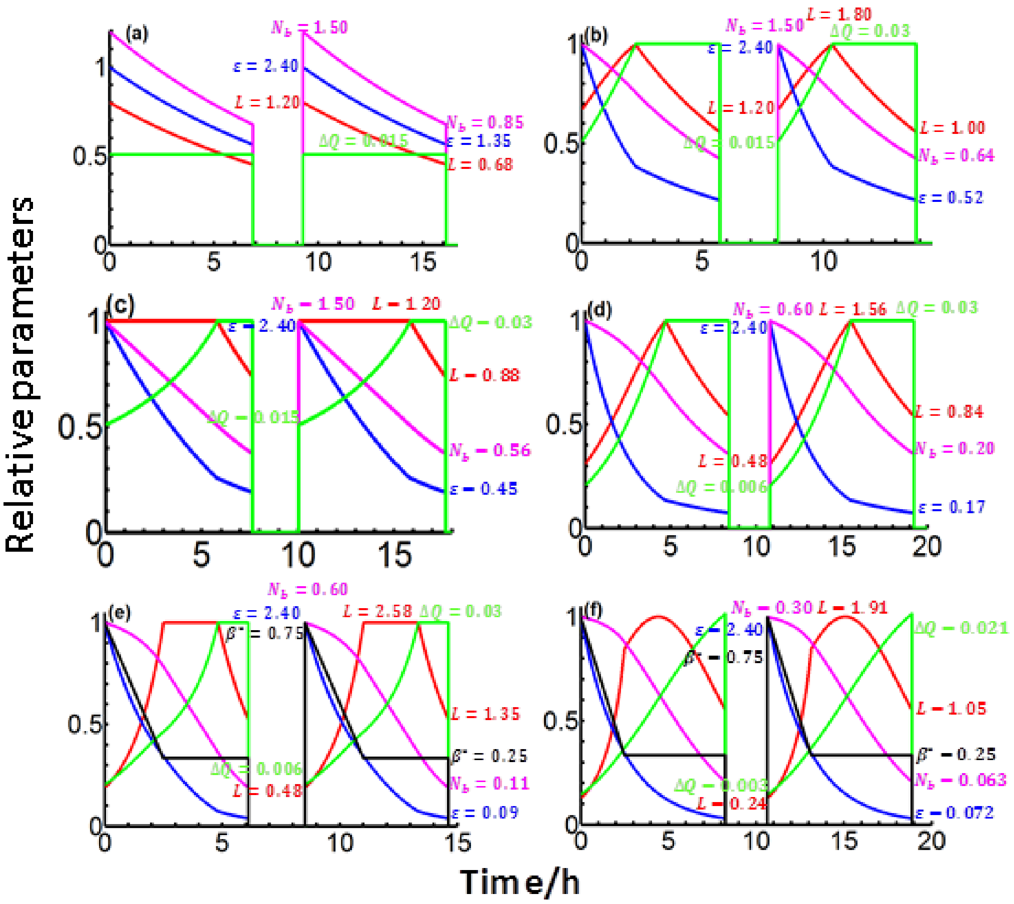

Figure 3: Evolution of parameters vs time with a turnaround time of 2.4 hours and bunch spacing of 25 ns. Red: luminosity, magenta: number of protons per bunch, blue: transverse emittance, green: beam-beam tune shift, black: beta* at the IP. (a) with fixed tune shift; (b) allowing the tune shift to rise to 0.03; (c) as in (b) but with the luminosity "leveled" at its initial value; (d) as in (c) but bunch spacing of 10 ns; (e) as for (d) but reducing beta* in proportion to emittance down to 25 cm; (f) as for (e) but with bunch spacing of 5 ns. In plots a), b), c) and d), beta* is kept constant at the nominal 0.75 m.

2.17.4 **Collimation**

Beam losses will be extremely important for safe operation in a machine like SPPC where the stored beam energy will be 9.1 GJ per beam. The radiation from the lost particles will trigger quenching of the superconducting magnets, generate unacceptable background in detectors, damage radiation-sensitive devices, and cause residual radioactivity that prevents hands-on maintenance. These problems can be addressed by sophisticated multi-stage collimation systems. At SPPC, extremely high collimation efficiency is required to deal with the huge stored energy. In addition, it is very difficult to collimate very high energy protons efficiently and the material for the collimators becomes a problem due to impedance and radiation resistance issues.

A five-stage collimation system has been studied for the betatron collimation to reach the required cleaning inefficiency of only 3.0×10^{-6} [9]. To avoid the critical SD (Single Diffractive) scattering [10-12] which becomes very important at tens TeV energy, we developed a novel concept by combining the betatron collimation and momentum collimation in a same long straight section, see Figure 4. In this way, the particles from the SD effect at the betatron primary collimators can be cleaned by the momentum collimation system, and we can avoid warm collimators in the downstream arc sections. One of the two very long straight sections of about 4.3 km is used to host the collimation system. Low-field superconducting magnets with protection in the betatron collimation section are found very much helpful in reducing the collimation inefficiency, as shown in Figure 5.

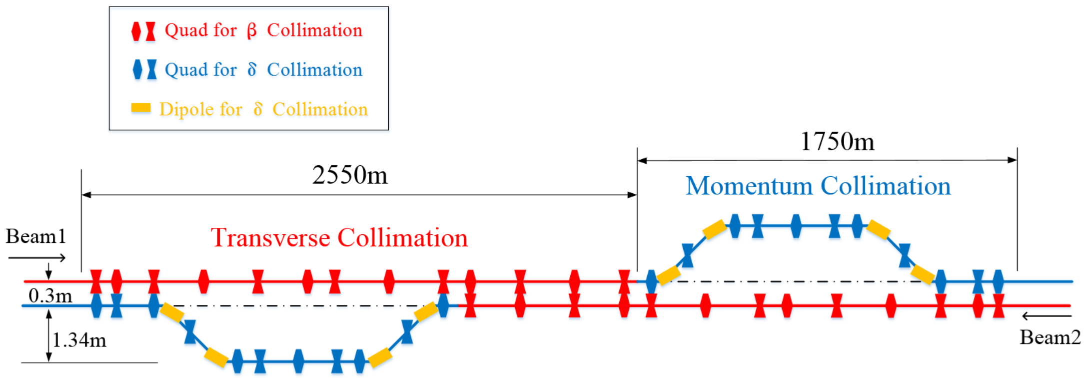

Figure 4: Combined transverse and momentum collimation scheme for SPPC

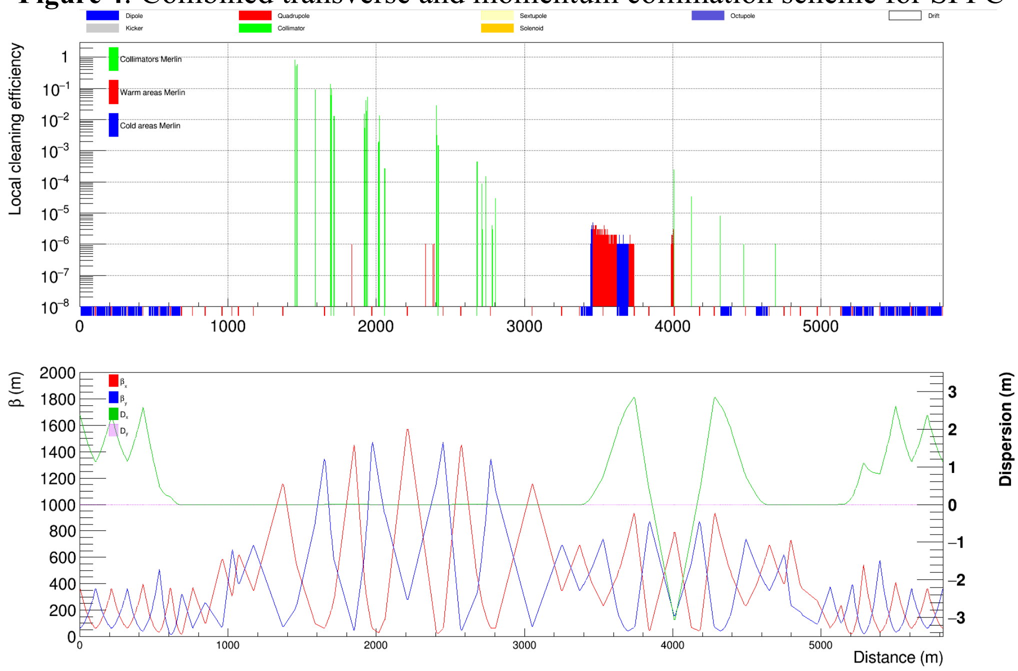

Figure 5: Loss distribution in the collimation section and lattice functions, protected superconductor magnets are used in the section

2.17.5 **High-field superconducting magnets**

With a circumference of 100 km, a modest dipole field of 12 T is required to reach the design goal for the 75-TeV center of mass energy, which is not far from the state-of-art magnet technology using Nb_3Sn superconductors [13]. However, Iron-based HTS technology has a bright expectation to be available and much cheaper in 10-15 years, and to generate a field higher than 20 T in far future. Thus Fe-HTS magnet technology is chosen for SPPC [14]. The nominal aperture for the arc magnets is 50 mm. A field uniformity of 10^{-4} should be attained up to 2/3 of the aperture radius. The magnets are designed to have two beam apertures of opposite magnetic polarity within the same yoke (2-in-1) to save space and cost. The currently assumed distance between the two apertures in the main dipoles is about 300 mm, but this could be changed based on detailed design optimization to control cross-talk effect between the two apertures, and with consideration of overall magnet size. The current magnet design is focused on a common-coil type which is still under developing. Figure 6 shows such a design.

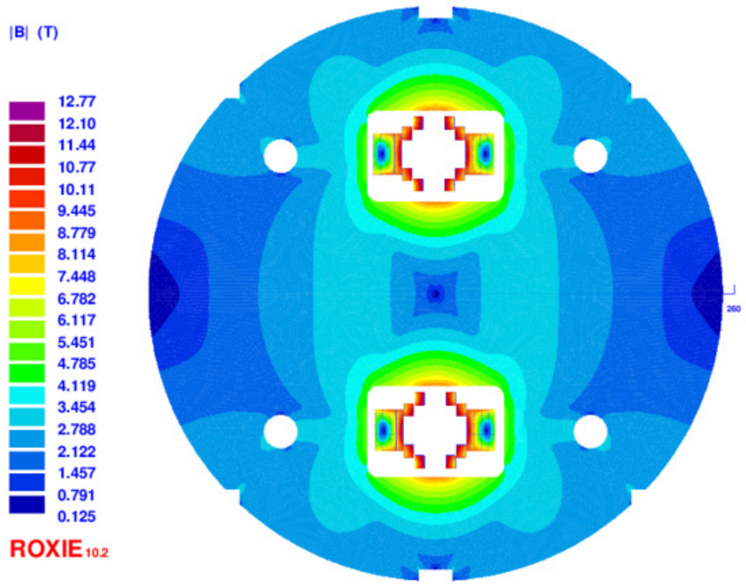

Figure 6: Dipole magnet in common coil type is under design

2.17.6 **Vacuum and beam screen**

SPPC has three vacuum systems: Insulation vacuum for the cryogenic system; beam vacuum for the low-temperature sections; and beam vacuum for the chambers in the room-temperature sections. The critical part is the cryogenic vacuum. The main problem comes from synchrotron radiation. It produces huge heat load to the cryogenic system, and critical electron cloud which risks important beam instabilities. Following the successful application at LHC, a beam screen between the beam and cold bore working at a higher temperature is being studied. However, due to much higher synchrotron radiation power, the beam screen at SPPC becomes much more challenging. A beam screen scheme is shown at Figure 7, which is somewhat similar to the one proposed by FCC [15]. A special layer with a slit which allows entering of synchrotron rays but avoid exiting of secondary electrons is considered to solve the electron cloud problem. The operating temperature of the screen must be high enough to avoid excessive wall power needed to remove the heat, but not too high to avoid excessive resistivity, e.g. 50-70K. High-temperature superconducting material (e.g. YBCO) coating on its inside surfaces to reduce the impedance is also under investigation.

The temperature for the cold bore is also under investigation, 1.9 K or about 4 K, which is mainly related to the hydrogen pumping issue.

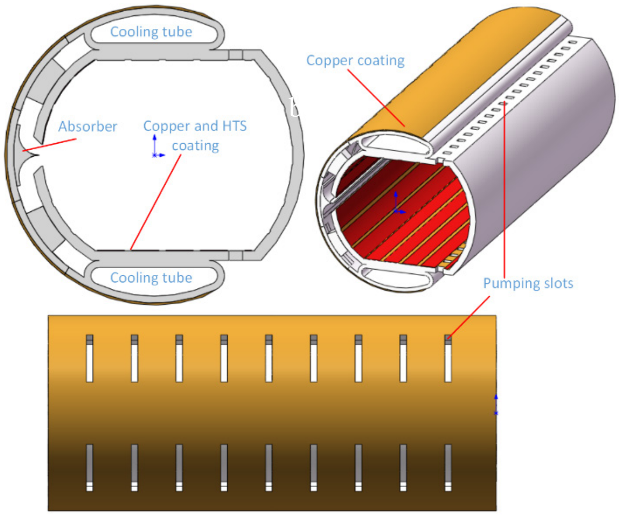

Figure 7: Schematic for the beam screens with inner HTS coating

2.17.7 Injector chain

The injector chain by itself is an extremely large accelerator complex. To reach the beam energy of 2.1 TeV required for the injection into the SPPC, we require a four-stage acceleration system, with energy gains per stage between 8 and 18. It not only accelerates the beam to the energy for injection into the SPPC, but also prepares the beam with the required properties such as the bunch current, bunch structure, and emittance, as well as the beam fill period. Some key parameters are given in Table 3. The preliminary physics design work for all the four stages is also under going.

Table 3: Main parameters for the injector chain at SPPC

	Energy	***Average current***	***Length/ Circum.***	***Repetition Rate***	***Max. beam power or energy***	***Dipole field***	***Duty factor for next stage***
	GeV	mA	km	Hz	MW/MJ	T	%
p-Linac	1.2	1.4	~0.3	50	1.6/	-	50
p-RCS	10	0.34	0.97	25	3.4/	1.0	6
MSS	180	0.02	3.5	0.5	3.7/	1.7	13.3
SS	2100	-	7.2	1/30	/34	8.3	1.3

2.17.8 Summary

The report presents the recent design update of the SPPC accelerators. In particular, the tunnel circumference is increased from the previous 50-60 km in the Pre-CDR to 100 km, and Iron-based HTS magnets of 12 T are used to reach a center-of-mass energy of 75 TeV. Future energy upgrade with higher-field magnets is reserved.

2.17.9 Acknowledgements

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2.17.10 **References:**

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