PRELIMINARY CONCEPTUAL DESIGN OF THE CEPC SRF SYSTEM

J.Y. Zhai#, J. Gao, T.M. Huang, Z.C. Liu, Z.H. Mi, P. Sha, Y. Sun, H.J. Zheng, IHEP, China
Carlo Pagani, University of Milano and INFN-LASA, Italy
Sergey Belomestnykh, BNL and Stony Brook University, USA

Abstract

CEPC is a circular electron positron collider operating at 240 GeV center-of-mass energy as a Higgs factory, recently proposed by the Chinese high energy physics community. The CEPC study group, together with the FCC and ILC community, will contribute to the development of future high energy colliders and experiments which will ensure that the elementary particle physics remain a vibrant and exciting field of fundamental investigation for decades to come. Superconducting RF (SRF) system is one of the most important technical systems of CEPC and is a key to achieving its design energy and luminosity. It will dominate, with the associated RF power source and cryogenic system, the overall machine cost, efficiency and performance. The CEPC SRF system will be one of the largest and most powerful SRF accelerator installations in the world. The preliminary conceptual design of the CEPC SRF system is summarized in this paper, including the machine layout, key parameter choices and some critical issues such as HOM damping, emphasizing the new technology requirement and R&D focuses.

INTRODUCTION

CEPC-SPPC is the most ambitious accelerator project ever proposed in China and even in the world. It will be housed in a 54 km circular tunnel (current baseline; 100 km as alternative). The first phase is an electron-positron Higgs factory at a centre-of-mass energy of 240 GeV (CEPC) for precise measurements of the newly discovered Higgs boson. The experiment is planned to start in 2028 and run though the 2030's. Experiments at the Z pole and the WW production threshold will be also possible. Then the tunnel will be filled by a proton-proton collider with a 70 TeV centre-of-mass energy (SPPC) with next-generation superconducting magnets, to explore the energy frontier [1].

Figure 1 is a layout of the CEPC. The circumference is about 54.4 km. There are 8 arcs and 8 straight sections. Four straight sections, 944 m each, are for the interaction regions and RF; another four, also 944 m each, are for the RF, injection, beam dump, etc. Among the four IPs, IP1 and IP3 will be used for e+e– collisions, whereas IP2 and IP4 are reserved for pp collisions. Both the electron and positron beams will circulate in the same beam pipe with an energy of 120 GeV each. The peak luminosity goal of CEPC is $2\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$ at each interaction point. The total synchrotron radiation loss is limited to ~100 MW.

The CEPC tunnel will accommodate two ring accelerators: the collider and a full energy Booster. While the two colliders will be mounted on the floor, the Booster will hang from the ceiling.

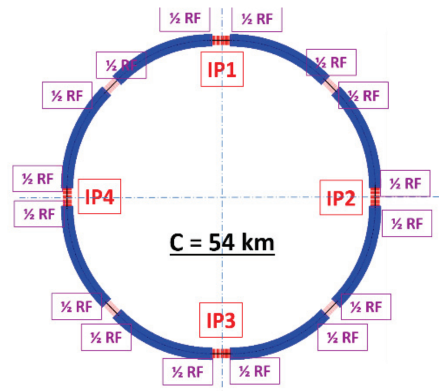

Figure 1: CEPC layout.

Superconducting RF (SRF) system is the most demanding technical system of CEPC. Because the Booster beam current is relatively low (0.8 mA), it is decided to use a 1.3 GHz SRF system, a mature technology that has been used in the ILC, XFEL and LCLS-II. The collider beam current is very high (33 mA) and both beams use the same RF cavity; the average RF power is bigger than in any exiting SRF system, and a large power coupler is required. Even more difficult is the HOM damper, which must extract most of the HOM power from the cavity. Therefore, it is decided to use a 650 MHz SRF system, which is used in the China ADS project and PIP-II at Fermilab.

CEPC SRF SYSTEM LAYOUT

Eight RF stations are placed in eight straight sections of the tunnel, and each of them split into two half stations. The total RF station length is approximately 1.4 km with 12 GeV of RF voltage. Table 1 shows the main parameters of the CEPC SRF system.

CEPC will use 384 five-cell 650 MHz cavities for the collider (main ring) and 256 nine-cell 1.3 GHz cavities for the Booster. The collider cavities operate in CW. The Booster cavities operate in quasi-CW mode. The collider module will be mounted on the tunnel floor and the Booster module hangs from the ceiling in series with the collider module string at a different beamline height.

During the conceptual design phase, significant effort is needed to identify high-risk challenges that require R&D. The highest priority items are efficient and economical damping of the huge HOM power with minimum dynamic cryogenic heat load, achieving the cavity gradient with high quality factor in the vertical test and real accelerator environment, robust 300 kW high power

#zhaijy@ihep.ac.cn

ISBN 978-3-95450-178-6

input couplers that are design compatible with the cavity clean assembly and low heat load.

Table 1: CEPC SRF System Parameters

Parameter	Unit	Main Ring	Booster (120 GeV)
Circumference	km	54.4	54.4
Beam energy	GeV	120	120
Energy loss per turn	GeV	3.11	2.81
SR power	MW	103.42	2.46
Bunch charge	nC	60.64	3.2
Bunch length	mm	2.65	2.66
Total bunch number	-	100	50
Total beam current I	mA	33.2	0.87
RF frequency f_{RF}	MHz	650	1300
RF voltage V_{RF}	GV	6.87	5.12
Number of cavity	-	384	256
Cavity voltage V_c	MV	17.9	20
Cavity gradient E_{acc}	MV/m	15.5	19.3
Operating temperature	K	2	2
Q_0 at operating gradient	-	4E10	2E10
Q_{ext} of input coupler	-	2.2E6	1E7
Cavity bandwidth	Hz	295	130
RF power / cavity	kW	280	20
Cavities per module	-	4	8
Cryomodule length	m	10	12
Number of cryomodule	-	96	32
Modules per RF section	-	12	4
RF section length	m	120	48
Total RF length	m	960	384
Energy acceptance (RF)	%	6	2.1

In parallel with design and key R&D, extensive development of SRF personnel, infrastructure and industrialization is essential for the successful realization of CEPC. Industry should participate in the R&D and pre-production work as early as possible.

CAVITY

To realize high Q_0 operation of the cavities, new nitrogen-doping [2] and flux expulsion [3] technology should be used. Thin film technology (such as Nb3Sn [4]) will be studied as an alternative. To avoid field emission, very clean cavity surface processing and string assembly is required.

Given the total synchrotron radiation power, parasitic loss and RF voltage, the main ring cavity numbers and voltages are mainly determined by the input coupler power handling capability, taking into account that the acceleration should be divided equally between the eight straight sections and other details such as cryomodule size optimization. The main ring input coupler operating power has been chosen to be 280 kW. This is a balance between SRF system capital cost, coupler operational risk, and cavity gradient and impedance.

The cavity gradient is determined by the cell numbers when the cavity RF voltage and frequency are fixed. More cell is better for low gradient, but will increase the cavity HOM power and impedance and lower the coupling of the HOMs. We chose 5-cell and 15.5 MV/m for the collider cavity. 4-cell (19.4 MV/m) is also an option. Because of the low current and duty cycle of the Booster, the TESLA 9-cell cavity at 19.3 MV/m is chosen.

HOM DAMPING

HOM power damping of 3.5 kW for each 650 MHz 5-cell cavity and 21 kW for each cryomodule is required for the CEPC main ring (Table 2). About 80 % of the HOM power is above the cut-off frequency of the cavity beam pipe and will propagate through the cavities and finally be absorbed by the two HOM absorbers at room temperature outside the cryomodule. A LEP/LHC-type HOM coupler will be used for kW level power handling capability. Waveguides at the cavity beam pipes are also suitable for the main ring cavity HOM power extraction, but with large size waveguides, more complicated structure and interfaces of the cryomodule, and large heat load.

Table 2: Cavity HOM Power and Heat Load

	Main Ring	Booster
HOM power / cavity	3.5 kW	5.3 W
HOM power / module	21 kW	56 W
HOM 2K heat load / module	13 W	5.9 W
HOM 5K heat load / module	39 W	3 W
HOM 80K heat load / module	390 W	43.8 W
Percent of total cryogenic load	22 %	11 %

HOM power dissipation in the main ring cryomodule is the main concern. Table 2 gives the preliminary upper limit estimate, which is also the design goal for the HOM heat load.

The main ring cryomodule will use RF shielded bellows (copper plated) and gate valves, and flanged connections with gap-free gaskets to reduce the HOM power generation and dissipation. Assume 10 kW HOM power propagating through the beam tubes and bellows

ISBN 978-3-95450-178-6

(thin copper film RRR=30, in the abnormal skin effect regime), the power dissipation is less than 2 W/m. The heat load at 5 K and in the 80 K region is dominated by HOM coupler cable heating. We will make careful calculation and engineering design to reduce the power dissipation.

The beam instability calculation gives the upper limit of the external quality factor of the HOMs with high R/Q of the main ring 650 MHz cavity. They are in the order of 10^6~10^7, which is easy to reach with the LEP/LHC HOM coupler for the modes below cut-off frequency or with the beam pipes for the modes above cut-off. Large HOM frequency spread from cavity to cavity also relaxes the Q_{ext} requirement. Although the beam current is 1/40 of the main ring, the Booster has much weaker radiation damping especially during the low energy part of the ramp. The instability growth times are much shorter than the radiation damping time in the low energy region of the Booster. Both transverse and longitudinal feedback systems will be needed to mitigate the multi-bunch instabilities. Another concern of the HOMs is that some modes far above cut-off frequency may become trapped among cavities in the cryomodule due to the large frequency spread [5].

Further design optimization of HOM properties of the main ring cavity is needed. For example, enlarge the iris diameter to decrease loss factors while keeping relatively high R/Q and low surface field of the fundamental mode, identifying trapped modes within the cavity and cryomodule, and reducing the cavity cell number or design asymmetry end cells to avoid trapped modes.

SOM DAMPING

The other four pass-band modes of the operating mode of the multi-cell cavity (hereby we call them the Same Order Modes, SOMs) may also drive instabilities or extract significant RF power from the beam. SOM parameters of the Collider 650 MHz 5-cell cavity are given in [1], including the Q limit of the coupled bunch instability.

Since the SOMs are so close in frequency to the operating mode, they can't be damped in the same way as HOMs using HOM couplers or beam tubes. The SOMs' external Q of the HOM coupler is estimated to be around 1E10, similar with the cavity Q_0. While the input coupler can be used as the SOM coupler, and the calculated external Q are enough to damp the beam instability.

The SOM frequencies are nearly fixed and have very small spread between cavities when the operating mode is tuned to near 650 MHz during operation. The total SOM power is quite small when we consider the real cavity passband modes frequencies and the bunch time spacing of the collider. Even assuming resonant excitation (beam spectral lines coincide with all the SOM frequencies), the total SOM power is about 1 kW and with the input coupler damping, the power dissipated on the cavity wall is negligible (~ 0.1 W).

POWER COUPLER

For CEPC, one of the key technologies is the very high power handling capability of the input power coupler for the main ring SRF cavity. Both the Q_0 and the accelerating gradient for CEPC SRF cavities are high, which requires that the coupler can be assembled with the cavity in a Class 10 cleanroom. In addition, considering the large number of couplers, heat load (both dynamic and static) is another important issue to be solved. The main challenges of the input power couplers are as follows: very high power handling capability (CW 300 kW), two windows for vacuum safety and cavity clean assembly, very small heat load, simple structure for cost saving, high yield and high reliability.

Considering the excellent performance, close frequency and IHEP experiences, BEPCII 500 MHz SCC coupler design is taken as the baseline. Several modifications are considered for the CEPC main ring SRF cavity: reduce the distance between the window and the coupling port, putting the window into the cryostat profile and thus having the window and cavity assembled in a Class 10 cleanroom, add one waveguide or cylindrical type warm window for vacuum safety, redesign the mechanical structure for higher power capacity and lower heat load.

SUMMARY AND OUTLOOK

CEPC superconducting RF (SRF) system will be one of the largest and most powerful SRF accelerator installations in the world. The major challenges are: HOM damping design and heat load, high Q_0 cavity and high CW power input coupler operation. The preliminary CDR design is the baseline for further study. R&D works towards publication of the CEPC-SPPC CDR in end 2016 are ongoing.

If Z and W high luminosity run is considered in the future, the beam current will be much higher than the Higgs run by increasing bunch numbers using either bunch train scheme (partial double ring) or double rings [1]. The CEPC SRF system design will need to be re-baselined accordingly and will face the same big challenges and possible staging scenarios as FCC-ee [6].

REFERENCES

[1] CEPC-SppC Preliminary Conceptual Design Report, http://cepc.ihep.ac.cn/preCDR/volume.html
[2] A. Grassellino, et al., "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures," Supercond. Sci. Technol. 26 102001 (2013).
[3] A. Romanenko, et al., "Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around Tc," J. Appl. Phys. 115, 184903 (2014).

[4] S. Posen, et al., “Recent progress in Nb3Sn SRF cavity development at Cornell,” Proceedings of IPAC2014, Dresden, Germany.
[5] J. Sekutowicz. “Multicell superconducting structures for high energy e+e- colliders and free electron laser linacs,” EuCARD Editorial Series on Accelerator Science and Technology, Vol.01 (2007).
[6] E. Jensen, “FCC RF Overview”, FCC Week 2015, Washington DC, 23-27 March 2015

ISBN 978-3-95450-178-6