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CEPC SRF SYSTEM DESIGN AND CHALLENGES*

J.Y. Zhai†, Y. Chi, J. Dai, J. Gao, R. Ge, D. Gong, R. Han, T. Huang, S. Jin, Z. Li, B. Liu, Z. Liu
Q. Ma, F. Meng, Z. Mi, G. Pei, Q. Qin, P. Sha, Q. Wang, T. Zhao, H. Zheng, IHEP, Beijing, China
Carlo Pagani, University of Milan and INFN-LASA, Milan, Italy

Abstract

CEPC is a 100 km circular electron positron collider operating at 90-240 GeV center-of-mass energy of Z, W and Higgs bosons. CEPC and its successor SPPC, a 100 TeV center-of-mass super proton-proton collider, will ensure the elementary particle physics a vibrant field for decades to come. The conceptual design report (CDR) of CEPC will be completed in the end of 2017 as an important step to move the project forward. In this contribution, CEPC SRF system CDR design and challenges will be introduced, including the system layout and parameter choices, configuration at different operation energies, transient beam loading and its compensation, cavity fundamental mode (FM) and higher order mode (HOM) induced coupled bunch instabilities (CBI) and the beam feedback requirement, etc. The SRF technology R&D plan and progress as well as the SRF infrastructure and industrialization plan are discussed at last.

INTRODUCTION

The discovery of the low mass Higgs boson in 2012 triggered renewed interest in a large circular e+e- collider served as a Higgs factory. The ring must have a large circumference in order to combat the synchrotron radiation from the high energy electron and positron beams. If such a large size ring were to exist, the tunnel would be ideal for housing a pp collider with an energy much higher than that of the LHC. In this context, the CEPC-SPPC project - a 240 GeV centre-of-mass energy Circular Electron Positron Collider (CEPC) and its successor in the same tunnel a 100 TeV centre-of-mass energy Super Proton Proton Collider (SPPC) - was proposed in October 2012 and officially given the name in June 2013 by the Chinese high energy physics (HEP) community. The CEPC experiment at the Higgs resonance is planned to start in 2030. Experiments at the Z-pole and the WW production threshold will be also conducted. The luminosity goal for Higgs is 2×10^{34} cm^{-2}s^{-1} and higher than 1×10^{34} cm^{-2}s^{-1} for Z-pole.

The CEPC-SPPC preliminary conceptual design (Pre-CDR) (white book) was published in March 2015 [1]. At that time, a 54 km single ring with pretzel scheme was chosen as the baseline for a low project cost. However, due to the difficulty of the pretzel scheme and low luminosity of Z-pole, a partial double ring (PDR) with crab-waist scheme was proposed instead in May 2015. The advantages of PDR are: 1) PDR can avoid pretzel separation by collision with two bunch trains (1+1). 2) PDR in the two collision regions allow the use of the crab-waist scheme to enhance the luminosity and reduce the RF voltage due to longer bunch length. 3) More bunches can be accommodated in the long bunch trains to have higher luminosity for Z-pole. While the disadvantages are also obvious mainly due to transient beam loading of the large bunch gaps and the saw-tooth effect. In order to alleviate the problems, the scheme of advanced partial double ring (APDR) was proposed in May 2016. Eight partial double rings with 4+4 short bunch trains can reduce the RF transient. But the dynamic aperture as well as the saw-tooth effect of such a scheme is still problematic and needs further investigation. Finally, in November 2016, the 100 km double ring (Fig. 1) was chosen as the baseline scheme for the CEPC conceptual design report (CDR), which is to be published in the end of 2017. The APDR scheme is the alternative design for CDR. As the intermediate step towards CDR, a CEPC-SPPC progress report (yellow book) [2] was published in April 2017 to summarize the latest design and R&D progress since 2015.

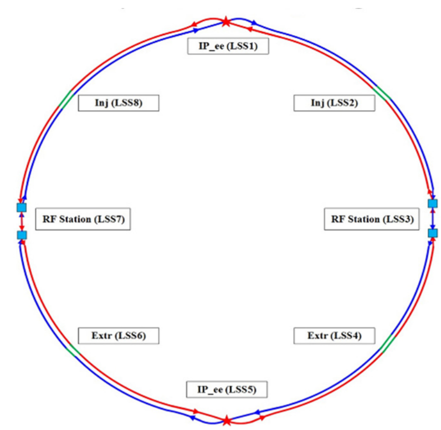

Figure 1: CEPC Main Ring layout.

As a result of the continuous evolution of the collision scheme, ring type and circumference and other machine top parameters in these four years, the design of the CEPC superconducting RF (SRF) system also changed a lot. The main differences of the SRF system between CEPC Pre-CDR and CDR are: 1) Ring circumference changed from 54 km to 100 km, thus lower RF voltage; 2) Ring type from single ring to double ring, thus more bunches, lower bunch charge and HOM power; 3) W and Z mode design included. In this paper, we will only focus on the latest design especially the double ring scheme, while the Pre-CDR design was described in detail in reference [3].

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†zhaijy@ihep.ac.cn

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CEPC SRF SYSTEM LAYOUT AND PARAMETERS

CEPC Main Ring parameters and lattice design are described in reference [4]. The RF system accelerates the electron and positron beams, compensates for synchrotron radiation loss and provides sufficient RF voltage for energy acceptance and the required bunch length in the CEPC booster and collider ring.

Layout

CEPC will use 650 MHz cavities for the Main Ring (collider) and 1.3 GHz cavities for the Booster. The baseline design of the Main Ring is a double-ring with Higgs cavities shared between two rings [5] (Fig. 2).

Each of the two RF sections locates at LSS3 and LSS7 respectively (Fig.1). An RF section contains two RF stations. The Higgs electron or positron beams will go through the two RF stations in each RF section. Half of the ring buckets will be filled to avoid collision in the RF section. The W and Z-pole will use part of the Higgs cavities in each RF station, and the electron or positron beams will go through only one of the two RF stations of an RF section. The W and Z-pole bunches will be (quasi)uniformly distributed in the two rings. This configuration enables half of the cavities for H, half of the current seen by the W & Z cavity, and half of the cavity impedance for W and Z. Enough RF straight section length should be remained for future upgrade.

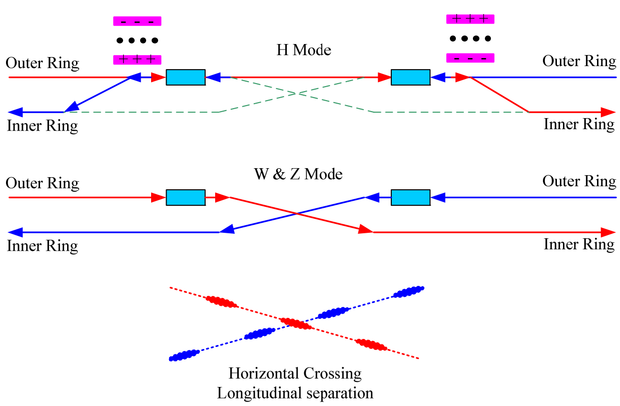

Figure 2: One RF section of CEPC Main Ring [5].

The Main Ring cavities operate in CW. The Booster cavities operate in quasi-CW mode with the following time sequence for the Higgs mode: first, stay at 1 MV/m for one second of electron injection from the Linac, followed then by a ramp up to about 14 MV/m in four seconds, followed by one-second extraction to the Main Ring and then the RF is turned off. After a four-second magnet ramp down, the same ten-second cycle begins for positrons. The RF and cryogenic duty factor of the Booster, with respect to a purely CW operating mode, is about 20 % for continuous alternative injection and extraction of electrons and positrons.

An RF station consists of 14 Main Ring cryomodules and 5 Booster cryomodules. The Main Ring module will be mounted on the tunnel floor and the Booster module hung from the ceiling in series with the Main Ring module string at a different beamline height. Each of the 10 m-long Main Ring cryomodule contains six 650 MHz 2-cell cavities, and each of the 12 m-long Booster cryomodule contains eight 1.3 GHz 9-cell cavities. The Booster cryomodules will be similar to LCLS-II but without superconducting magnets inside. The Main Ring cryomodule will have one beamline HOM ferrite damper on each side at room temperature.

Parameters

The baseline SRF parameters for the CEPC Main Ring (Table 1) are designed to meet the luminosity requirement for each operation energy, with possible higher luminosity reach (for example the high luminosity mode Z-HL).

The total cavity number (input power limited), cell number per cavity (gradient and HOM power limited) and klystron number are determined with margin to run in high luminosity or high voltage mode for Higgs, W and Z. The SRF system is optimized for Higgs mode of 32 MW SR power per beam, with margin for 50 MW per beam. The cavity gradient for Higgs mode has margin for higher voltage and RF trip.

It is assumed to use part of the Higgs cavities for W and Z, i.e. the same cryomodules for all the operation energy and modes and the same RF power source and distribution, for the first phase of CEPC. The unused cavities should be detuned and kept at 2 K to extract HOM power.

For the Z-pole operation, cavity impedance of the high current and small damping is the most concern. Smallest number of cavities are preferred to provide high power to the beam, which results in very high input coupler power. If the higher luminosity Z-pole is further limited by HOM power and CBI, high current (e.g. KEKB/BEPCII type) cavity and cryomodule will be used with separate cavities for the two rings.

The large HOM power handling in multi-cavity cryomodule is also challenging. The LEP2 and LHC HOM coupler experience is the important reference.

For possible energy upgrade, high RF voltage (both Main Ring and Booster) requires both high gradient and high Q, which should be realized by pushing SRF technology frontier to control the capital and operational cost.

High efficiency 800 kW CW klystron is being developed for CEPC with the initial target efficiency of 65 % and higher than 80 % as the final goal [6]. Due to RF mismatch of different operating energy and current, the input coupler should have variable coupling to avoid extra power so that not to destroy the effective overall power efficiency at any power level.

Table 2 gives the Booster SRF parameters for Higgs mode and high luminosity Z mode. The beam and cavity parameters are similar to LCLS-II. The major challenge is the narrow bandwidth operation with microphonics control and voltage ramp in a short time.

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Table 1: CEPC Main Ring SRF System Parameters

Parameter	Unit	H	W	Z	Z-HL
Circumference	km	100	100	100	100
Beam energy	GeV	120	80	45.5	45.5
Luminosity / IP	10^{34} cm^{-2}s^{-1}	2	5	1	12
Energy loss per turn	GeV	1.67	0.33	0.034	0.034
SR power / beam	MW	32	32	1.9	16
Bunch charge	nC	15.5	5.8	3.5	7.3
Bunch length	mm	2.9	3.4	4	4
Bunch number / beam		412	5534	5100	21300
Beam current / beam	mA	19.2	97.1	54	466
RF frequency f_{RF}	MHz	650	650	650	650
RF voltage V_{RF}	GV	2.1	0.41	0.049	0.14
Cell number / cavity		2	2	2	2
Number of cavity in use		336	192	24	96
Cavity voltage V_c	MV	6.3	4.3	4.1	2.9
Cavity gradient E_{acc}	MV/m	13.6	9.3	8.9	6.3
Input power / cavity	kW	190	333	158	335
Cavity number / klystron		2	2	2	2
Klystron power	kW	800	800	800	800
Klystron number in use		168	96	12	48
HOM power / cavity	kW	0.4	0.3	0.1	1.8
Cavity number / cryomodule		6	6	6	6
Cryomodule number in use		56	32	4	16
Q_0 at operating gradient @ 2 K		1E10	1E10	1E10	1E10
Total wall loss @ 2 K	kW	6.2	0.8	0.1	0.2
Optimal Q_L		9.6E5	2.6E5	4.9E5	1.2E5
Extra power (if fixed optimal coupling for H)	%	0	50	12	155
Cavity bandwidth	kHz	0.7	2.5	1.3	5.5
Optimal detuning	kHz	0.3	0.9	0.7	10.9
Cavity time constant	µs	471	126	242	58
Cavity stored energy	J	45	21	19	10
Max relative voltage drop for 1 % beam gap	%	0.9	3.3	1.9	23.2
Max phase shift for 1 % beam gap	deg	0.8	3.2	1.5	13.7

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Table 2: CEPC Booster SRF System Parameters

Parameters [Unit]	H	Z-HL
Injection beam energy [GeV]	10	10
Extraction beam energy [GeV]	120	45.5
Bunch charge [nC]	0.77	0.3
Beam current [mA]	0.37	0.96
Extraction RF voltage [GV]	2.8	0.4
Extraction bunch length [mm]	4.7	1
Cavity number in use (1.3 GHz TESLA 9-cell)	160	32
Gradient [MV/m]	16.9	12.0
Q_L	2E+07	2E+07
Cavity bandwidth [Hz]	65	65
Input power per cavity [kW] (remained detuning 10 Hz)	5.8	2.5
SSA power [kW] (one cavity per SSA)	10	10
HOM power per cavity [W]	0.4	1.6
Cryomodule number in use (8 cavities per module)	20	4
Q_0 @ 2 K at operating gradient (long term)	2E10	2E10
Duty Factor	~ 20 %	~ 50 %

TRANSIENT BEAM LOADING

Transient beam loading is the most concern of a large ring with long abortion gap or in bunch train operation. A bunch extracts cavity stored energy when passing through, and the power source will recover the cavity voltage when the next bunch comes. When the bunch spacing is much smaller in the case of bunch train operation, cavity stored energy and voltage will drop continuously due to lack of power. The latter bunch will move towards voltage peak by auto-phasing, resulting in bunch phase shift, less longitudinal focusing, smaller energy acceptance, and possible lifetime (especially when Beamstrahlung dominated) and luminosity degradation or other dynamical problem. Due to symmetry, the phase shift will be the same for an electron and positron colliding bunch pair, thus the interaction point will not move.

Small phase shift can be estimated by analytical calculation [7] or transfer function simulation [8]. For CEPC double ring scheme, even 1 % beam gap to mitigate ion-trapping and fast beam ion instability (FBII) will have large bunch phase shift of the Z-HL mode (Table 1). It is proposed to change the fill pattern from one long gap to many small gaps and short bunch trains [9, 10]. The phase shift is even more serious for the APDR scheme.

There are several methods of transient beam loading compensation. Reduction methods include: 1) increase cavity stored energy. 2) change fill pattern and RF distribution (spread as uniformly as possible). 3) increase synchrotron phase (change beam parameters). Correction methods include: 1) Global correction: provide via the RF generator an additional current to fully cancel out beam current variations in each cavity. But this method needs special RF source with high peak power and high repetition rate. Special techniques are needed to reduce the filling power and average power due to low RF-to-beam power efficiency [11]. 2) Local correction: travelling wave cavity or beat cavity [12].

CEPC APDR may use beat cavity to compensate the transient beam loading [13]. The concept of beat cavity compensation is to tune the frequency of some RF sources and cavities slightly different from the normal RF sources (650 MHz) and cavities (optimal detuning), and then use the linear part of the beat wave to compensate voltage and phase variation due to transient beam loading. The non-linearity will increase with bunch train length. Higher order beats are more effective but have more non-linearity.

INSTABILITY

CEPC Main Ring cavity HOM CBI growth rates of the dangerous modes have been calculated with the assumption that the external Q of all the modes equals 1E4 taking into account the HOM frequency spreads among the cavities, which is not hard to achieve by the HOM couplers on the cavity beam pipe. The beam current thus the luminosity target can't be achieved for the W and Z mode. Beam feedback system with feedback time of 3.3 ms (10 turns) will raise the luminosity beyond the SR power limit of 50 MW per beam. CEPC Booster cavity HOM CBI growth rate of the dangerous modes have been calculated with the measured external Q of the TESLA cavity. With the feedback time of 3.3 ms, all the modes are safe with enough margin.

Fundamental mode CBI of CEPC high luminosity Z-pole mode will happen due to large circumference (small revolution frequency), low RF voltage and high current (large cavity bandwidth and detuning). Direct loop and comb filter loop feedback will be used to lower the effective cavity impedance thus the instability growth rate (as PEP-II, LHC), and then bunch-by-bunch feedback will work to cure the fundamental mode instability. Detailed growth rate calculation of the CEPC Z-HL mode can be found in reference [10].

Robinson stability analysis of the Z-HL mode was done using a Mathcad code [14]. Fast direct feedback with group delay of 2 μs and loop gain of 22 is used. About 10 % more power is needed to have Robinson stable operation of high current Z-pole.

R&D PROGRAM AND PROGRESS

CEPC SRF R&D plan of 2016-2020 has been made and the key component design and R&D have started in 2016. Two small test cryomodules (650 MHz 2 x 2-cell, 1.3 GHz 2 x 9-cell) and two full scale prototype cryomodules

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(650 MHz 6 x 2-cell, 1.3 GHz 8 x 9-cell) are planned (Fig. 3) and partially funded.

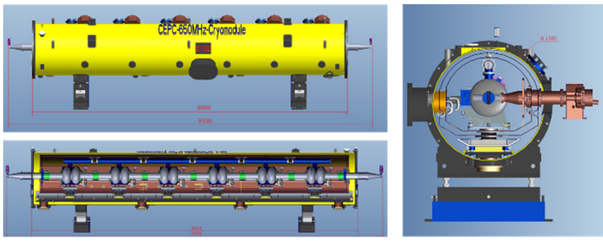

Figure 3: CEPC Main Ring cryomodule concept.

RF and mechanical design of the 650 MHz 2-cell cavity with coaxial HOM couplers [15, 16] and 5-cell cavity with waveguide HOM couplers [17] have been completed and the fabrication will be done this year. Nitrogen-doping for high Q 650 MHz and 1.3 GHz cavities are under investigation [15]. The Main Ring 650 MHz variable coupler of 300 kW CW power and capable of assembly with cavity in Class 10 clean room is under design [18]. The compromise between coupler heat load and cryomodule diameter size will be necessary. The cold coaxial HOM coupler of 1 kW power capacity [19] and the warm HOM absorber of 5 kW power capacity and wide frequency range [20] are also challenging. A cryomodule capable of fast-cool-down and low magnetic field and a reliable tuner etc. are also import design aspects.

SRF INFRASTRUCTURE AND INDUSTRIALIZATION

IHEP will build a 4500 m^2 SRF lab in Huairou Science City in the north of Beijing [21]. The SRF facility is aimed at processing and testing of several hundreds of SRF cavities and couplers, and assembly and testing of about 20 cryomodules per year for different users including CEPC.

Several large projects based on SRF accelerators will be built in China, such as HIAF, CIADS and SCLF (Shanghai Coherent Light Facility). More than 1000 cavities will be needed in the coming five years. The industrialization of the CEPC SRF technology will have synergy with these domestic projects as well as the ILC.

SUMMARY

CEPC SRF system will be one of the largest and most powerful SRF accelerator installations in the world. The CDR design is nearly completed. R&D program has been launched for the key components and test cryomodules.

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