PRELIMINARY DESIGN OF CEPC RF SUPERCONDUCTING SYSTEM

H. J. Zheng#, J. Y. Zhai, S. Jin, Z. C. Liu, J. Gao, T. X. Zhao, Y. L. Liu
IHEP, Beijing, 100049, China

Abstract

In order to study the Higgs boson in more detail, construction of Higgs factory is proposed. This article mainly introduce the preliminary RF superconducting system design of 704MHz e+e- Higgs Factory (CEPC) proposed by Chinese scientists. RF parameters related to choosing of cavity, main coupler, HOM coupler and cryogenic system have been given.

INTRODUCTION

CERN announced that the detection of new particle before is suspected Higgs particle [1]. Chinese scientists are also actively involved in the research of the construction of the Higgs Factory for study the new particle. Compared with linear collider, the circular collider has mature technology and rich experience. So, design of circular Higgs Factory is proposed and several proposals have been put forward [2]. The electron and positron eventually are accelerated to the centre of mass of energy 240GeV. In order to ensure the normal operation of the machine, the RF superconducting system is essential. RF system is used to provide energy to compensate the synchrotron radiation and higher order mode loss when the machine is in operation. At the same time it also provides longitudinal force for bunches.

PARAMETERS OF STORAGE RING RF SYSTEM

High Frequency Voltage

High frequency voltage is expressed as follows

$$V_{rf}\cos\varphi_s = \frac{cC\alpha_p E\sigma_\varepsilon^2}{e\omega_{rf}\sigma_z^2} \quad (1)$$

where V_{rf} is the high frequency voltage, φ_s is the synchrotron phase, ω_{rf} is the frequency of fundamental mode, c is the velocity of light, C is the circumference of storage ring, α_p is the momentum compaction factor, E is the energy of the ring, σ_ε is the energy spread, σ_z is the bunch length.

Beam Power

Beam power is

$$P_b = P_{SR} + P_{HOM} + P_{wiggler} \quad (2)$$

where P_b is the beam power, P_{SR} is the synchrotron radiation power, P_{HOM} is the higher order modes power and $P_{wiggler}$ is the radiation power loss produced by wiggler. P_{SR} is given by

$$P_{SR} = \frac{I_b U_0}{e} \quad (3)$$

P_{HOM} is given by

$$PP_{HOM} = 2k_{//}.Q_{bunch}.I_b \quad (4)$$

where $k_{//}$ is the longitudinal loss factor and Q_{bunch} is the bunch charge. There is a factor 2 because the CEPC storage ring has two beams.

Machine Parameters Related to High Frequency System

The designed operation frequency of superconducting cavity is 704 MHz. Machine parameters (see Table 1) related to high frequency system can be obtained by CEPC beam designed parameters.

SUPERCONDCUTING CAVITY

Cavity Type Choice

This article uses low loss cavity shape [3] which is used for ILC to do the related calculation. The ILC cavity is scaled by a scaling factor 1300/704 [4]. The low loss shape is used to reduce the power dissipated on the cavity wall. At first, we did not do any optimization of cavity shape. With high R/Q*G value and small iris diameter,

Table 1: Machine Parameters Related to RF System

	Symbol	704MHz	704MHz
Numbers of IPs	N	1	1
Energy (GeV)	E	120	120
Circumference (km)	C	50	50
Beam current (mA)	I_b	5.07	16.9
Bunch length (mm)	σ_z	2.2	2.2
Bunch number	n_b	19	22
Particle number/bunch	N_b	0.28	0.79
Momentum compaction (10^{-4})	α_p	0.38	0.38
SR loss/turn (GeV)	U_0	2.96	2.96
SR power/beam (MW)	P_0	15	50
Parasitic mode loss/beam (MW)	U_k	0.509	4.787
Harmonic number (10^5)	h	1.174	1.174
Cyclotron frequency (kHz)	f_0	5.996	5.996
Longitudinal oscillation wave number	υ_s	0.176	0.176
RF voltage (GV)	V_{rf}	6	6
Luminosity (10^{34}cm^{-2}s^{-1})	L_0	1.58	3.1

#zhenghj@ihep.ac.cn

this type of cavity has large HOM loss. According to the experience, the best accelerating gradient of CW machine is 15-20 MV/m [5]. The accelerating gradient of BEPC is chosen by 15MV/m according to the 700 MHz superconducting cavity design experience [6-8]. The accelerating voltage of a single cavity is given by

$$V = E_{acc}.L \quad (5)$$

where L is the effective length of cavity. According to the simulation result, the effective length of 704MHz cavity is 1059 mm. The total voltage of CEPC needed is 6 GV from Table 1. With equation (5), we can get that 378 cavities are needed to accelerate the beam. All of the cavities are symmetrically placed on both sides of the collision point.

HOMs Loss

Higher order mode damping is one of the most challenging problems in storage ring [9]. HOM absorber is used to absorb the energy loss on the cavity when beam passes through the cavity. The losses include both broadband loss and narrowband loss.

We choose the beam length σ=2.2mm. The total loss factor of cavity can be calculated by ABCI. The loss factor calculated by ABCI includes both fundamental mode and HOMs. The result is shown in Figure 1. For a certain beam length σ, the loss factor of the fundamental mode is

$$k_0 = \frac{\omega_0}{4}.\frac{R}{Q}.e^{-\omega_0^2\left(\frac{\sigma_z}{c}\right)^2} \quad (6)$$

where ω_0 is the fundamental mode frequency, R/Q is the shunt impedance and σ_z is the longitudinal beam length. So the loss factor of HOMs is

$$k_{HOM} = k - k_0 \quad (7)$$

Under the condition of main parasitic modes are deeply damped, we choose the narrowband impedance loss factor equals broadband impedance loss factor. So the total loss factor is

$$k_{total} = 2k_{HOM} \quad (8)$$

We can get $k_{total} = 5.93V/pC$ from equation (6) (7) (8) and the parameters given by Table 1. The total HOM power absorbed by absorber in every cavity can be calculated from equation (4).

$$P_{HOM} = 2.694kW$$

The modes with frequency lower than the tube cut-off frequency can be extracted by coaxial coupler [10] while the other modes can be absorbed by beam pipe load [4, 11].

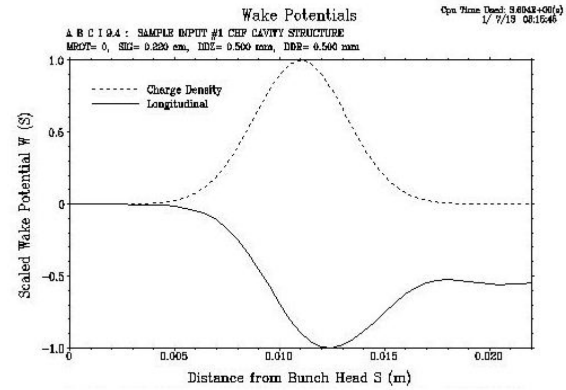
Operating Temperature and Q_0

The quality factor Q_0 depends on the cavity surface treatment, operating temperature and magnetic shielding.

$$Q_0 = \frac{G}{R_s} \quad (9)$$

where G is the geometry factor and R_s is the surface resistance of superconducting material.

$$R_s = R_{BCS} + R_{res} + R_{mag} \quad (10)$$



Longitudinal Wake Min/Max=-5.261E+00/0.000E+00V/pC Loss factor=-3.656E+00V/pC

Figure 1: Wakefield and loss factor of cavity.

The first item of equation (10) is BCS surface resistance [12].

$$R_{BCS} = 2.10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.76}{T}\right) \quad (11)$$

When the operating temperature is chosen by 1.8K and frequency is 704 MHz, R_{BCS}=1.335 nΩ.

The surface resistance caused by external magnetic field is

$$R_{mag} = \frac{H_{ext}}{2H_{c2}}R_n \quad (12)$$

When we choose H_{c2}=2400 Oe, RRR=300, f=704 MHz and H_{ext} =30 mG [11], we can get $R_{mag} = 7.551n\Omega$. According to the current multi cell processing experience, surface resistance can be controlled between 5~10 $n\Omega$. From equation (9), we can get Q_0 is about 2×10^{10} ~ 5×10^{10} . Through the analysis above, we choose Q_0= 2×10^{10} under 1.8 K for the design goal.

INPUT POWER COUPLER AND RF POWER RESOURCE

The input power coupler is mainly used to transfer RF power from the generator to the cavity and the beam. Most of accelerators such as LEP [13], Cornell ERL [11], ILC [10] and BNL use the type of coaxial coupler as input coupler. Q_e of the input coupler is

$$Q_e = \frac{V^2}{R/_Q P_b} \quad (13)$$

where V=15.885MV for CEPC cavity, then we can get Q_e = 5.1×10^6 .

The CW mode klystron working around 700MHz at present is VKP7952 which is produced by CPI [14]. The largest positive transmission and average power are 1 MW. Its efficiency is 65% and the klystron to beam transmission efficiency is about 44% [10]. CPI has already produced klystron with peak power 1 MW and works on CW mode for BNL. We can choose klystron with peak power 1MW for CEPC. The total number of klystron is about 70.

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COLLECTIVE INSTABILITIES

The limitation of the longitudinal broadband impedance is coming mainly from bunch lengthening. Because of the coupling impedance of the vacuum bow in the storage ring, with the increase of beam current, the bunch length will be stretched due to potential well distortion and microwave instability. In particular, microwave instability is the cause for the degradation of the luminosity at the electron positron collider. It demands that the designed current under the microwave instability threshold. According to Boussard or Keil-Schnell criterion, we can make the threshold of longitudinal impedance as follows

$$I_{th} = \frac{\sqrt{2\pi}\alpha_p E\sigma_{e0}^2\sigma_z}{eR\left|\frac{Z^{//}}{n}\right|_{eff}} \quad (14)$$

where σ_{e0} is the energy spread, R is the radius of storage ring and I_{th} is bunch current. From equation (14) and beam parameters, we can get the threshold of impedance. The result is shown in Table 2. In contrast, we give the LEP3 and TLEP results [15].

Table 2: Threshold of Longitudinal Instability [15]

	CEPC				LEP3	TLEP
Beam current (mA)	0.768	0.367	0.32	0.27	1.8	0.45
$\left\|Z^{//}/n\right\|_{eff}$ (Ω)	0.007	0.015	0.02	0.02	0.039	0.009

From above, we can see when the bunch charge of CEPC is 0.768 mA, its impedance is smaller than TLEP. The impedance is so small that it may cause bunch lengthening and energy spread increasing.

In a storage ring, the beam instabilities in both the longitudinal and the transverse directions caused by a RF system are mainly from the HOMs of the RF cavities. The basic contribution in the narrowband impedance is made by the parasitic higher order modes of accelerating cavities. It requires the multi-bunch instability rise time longer than radiation damping time. The radiation damping time is given by

$$\tau_x = \frac{2E_0T_0}{U_0} \quad (15)$$

$$\tau_y = \frac{2E_0T_0}{U_0} \quad (16)$$

$$\tau_z = \frac{E_0T_0}{U_0} \quad (17)$$

From Table 1, we can get $\tau_x = \tau_y = 0.014s$, $\tau_z = 6.761\times10^{-3}s$.

The multi-bunch instability growth in longitudinal is

$$\frac{1}{\tau_{//}} = \frac{I_b\alpha_p}{4\pi(E/e)\nu_s}\sum_{p=-\infty}^{\infty}\omega_{pn}e^{-(\omega_{pn}\sigma_z)^2}\operatorname{Re}Z_l(\omega_{pn}) \quad (18)$$

where $\omega_{pn} = 2\pi f_0\times(pn_b + n + \nu_s)$, f_0 is cyclotron frequency, n_b is bunch number, I_b is the beam current.

Similarly, in the transverse

$$\frac{1}{\tau_\perp} = \frac{I_b f_0}{(E/e)}\sum_{p=-\infty}^{\infty}\omega_{pn}e^{-(\omega_{pn}\sigma_z)^2}\operatorname{Re}Z_\perp(\omega_{pn}) \quad (19)$$

We choose $<\beta>$=50m in the cavity region.

The main contribution to the longitudinal impedance is from the monopoles and the transverse instability is caused by the dipoles and the dipole components of the quadrupole mode. Here, we only consider the first three band of the HOMs. The impedance threshold value is shown in Table 3.

The calculation results show if the HOMs $Qe<10^4$, there are no instability issues. This needs more detailed HOM damping design.

Table 3: Impedance Threshold Value

		Longitudinal τ_z=0.007s	Transverse $\tau_{x,y}$=0.014s	
Mode		TM011	TE111	TM110
f(MHz)		1175.7	917.6	1040.7
R/Q		146.0Ω	1.0Ω/cm^2	2.7Ω/cm^2
Qe		1000	1000	1000
Ztot		0.06GΩ	0.2GΩ/m	0.5 GΩ/m
16.9mA	τ(s)	1	0.1	0.05
	Z_{th}	8.3 GΩ	1.8 GΩ/m	1.8 GΩ/m
8.45mA	τ(s)	2	0.25	0.1
	Z_{th}	16.6 GΩ	3.5 GΩ/m	3.5
6.76mA	τ(s)	2.5	0.3	0.13
	Z_{th}	20.7 GΩ	4.4 GΩ/m	4.4 GΩ/m
5.07mA	τ(s)	3.4	0.41	0.17
	Z_{th}	27.7 GΩ	5.8 GΩ/m	5.8 GΩ/m
Requirement		$Qe<10^5$	$Qe<10^4$	

CRYOGENIC SYSTEM

CEPC storage ring totally needs 378 cavities to compensate synchrotron and HOMs loss. We plan to put 4 cavities into 1 cryomodule. There are components between cryomodules and cavities, such as HOM absorber, valves and bellows [16].

In order to select refrigeration capacity at low temperature, the thermal load estimation of srf system is as follows. The total cryogenic loss is shown in Table 4.

- Static heat loss at 1.8 K is about 7.28 W/module [11]. The cavity wall loss is

$$P_C = \frac{V^2}{R} = \frac{(E_{acc}L)^2}{R/_{Q}Q_0} \quad (14)$$

We can get the wall loss of every cavity is 20.16W from the cavity's parameter.

- The 5~8K transmission line is mainly used to transport helium to cryogenic device. The use of LHe cooling coupler, tuner and the other components bring about 55W/module loss.
- The 40~80K transmission line is mainly used to cool HOM absorber and radition shield. This will bring 10.8kW/module loss.

CONCLUSIONS

This article mainly gives parts of basic design of RF system of CEPC after beam parameter optimization. The cryogenic loss is reduced because the beam decrease, however, the HOMs loss is still very large. The extraction of HOMs loss is a big problem. More optimization and design will be preceded next.

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REFERENCES

[1] G. Aad et al. [ATLAS Collaboration], Search for the Standard Model Higgs Boson in the Diphoton Decay Channel with 4.9fb^{-1} of pp Collision Data at √s=7TeV with ATLAS, Phys. Rev. Lett. 108, 11803 (2012).

[2] D. Wang, J. Gao, M. Xiao, H. Geng, S. Xu, Y. Guo, N. Wang, Y. An, Q. Qin, G. Xu, S. Wang, "Optimization Parameter Design of a Circular e+e- Higgs Factory", Chinese Physics C Vol. 37, No. 9(2013) 097003.

[3] Z. G. Zong, J. Gao, H. Sun, F. C. Zhao, M. Q. Ge, J. Gu, Q. J. Xu, J. Z. Zhai, Z. G. Zong, L. Zhang, L. Q. Liu, Researh and development of 1.3GHz low loss cavities mode of China large grain at IHEP.

[4] Zhongquan Li, Doctoral thesis, RF Superconducting cavity design and structure optimization of BEPCII, May, 2003.

[5] Sergey Belomestnykh, Superconducting Radio-Frequency Systems for High-β Particle Accelerators, Reviews of Accelerator Science and Technology, Vol.5 (2012) 147-184.

[6] Liu zhenchao, Gao jie, Li zhongquan, Zhai jiyuan, Zhao tongxian, Li dazhang, Liu yilin, Sun yi, An ADS 650MHz medium beta cavity study and design. Chinese Physics C, Vol. 37, No. 1(2013) 017005.

[7] B. Visentin#, J. P. Charrier, D. Roudier, F. Simoens, E. Jacques, A. Aspart, Y. Gasser, J. P. Poupeau, P. Sahuquet, D. Braud, H. Saugnac, Ph. Szott, S. Bousson, J.L. Biarrotte, T. Junquera, S. Blivet, Experimental recults on 700MHz multicell superconducting cavity for proton linac, Proceedings of the 2003 Particle Accelerator Conference.

[8] S. Belomestnykh[#,1,2], I. Ben-Zvi[1,2], C. Brutus[1], H. Hahn[1], D. Kayran[1], etc. Superconducting RF systems for eRHIC.

[9] Charles E. Reece, Gianluigi Ciovati, Superconducting Radio-Frequency Technology R&D for Future Accelerator Application, Reviews of Accelerator Science and Technology, Vol.5(2012) 285-312.

[10] ILC TDR Volume3 II: Accelerator-Baseline Design.

[11] Georg H. Hoffstaetter, Sol M. Gruner, Maury Tigner, Cornell Energy Recovery Linac, Science Case and Project Definition Design Report.

[12] Hasan Padamsee, Jens Knobloch, Tom Hays, RF Superconductivity for Accelerators, Second Edition

[13] Editor: C. WYSS, by the LEP2 team, "LEP design report", Vol. III LEP2, CERN-AC/96-01(LEP2), June 1996.

[14] Yaogen Ding, Kunpu Liu, Zhaochuan Zhang, Yong Wang, The State Art and Research Progresses of High Power Klystron, Vacuum Electronics, 1001-8935（2010）06-0001-08

[15] A. Blondel, U. Geneva, M. Koratzinos, Geneva, etc. LEP3: A High Luminosity E+E- Collider to Study the Higgs Bosn, CERN-ATS-NOTE-2012-062 TECH

[16] Sergey Belomestnykh, Superconducting Radio-Frequency Systems for High-β Particle Accelerators, Reviews of Accelerator Science and Technology, Vol.5(2012) 147-184.

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Table 4: Cryogenic Loss [10, 11]

Beam current (mA)	16.9	8.45	6.79	5.05
P_c / cavity (W)	20.16	20.16	20.16	20.16
SR loss/turn (GeV)	2.96	2.96	.2.96	2.96
SR power/beam (MW)	50	25	20	15
β_{IP} x/y (m)	0.2 0.001	0.071 0.00048	0.056 0.00042	0.041 0.00035
Luminosity (10^{34} cm^{-2}s^{-1})	3.1	2.31	1.97	1.58
P_c (kW)	7.62	7.62	7.62	7.62
P_{HOM} / cavity (kW)	25.33	6.093	4.233	2.694
$P_{HOM\ total}$ (MW)	9.575	2.303	1.6	1.018
RF-beam power efficiency	44%	44%	44%	44%
$P_{klystron}$ (MW)	250	119	95	70
RF source efficiency	65%	65%	65%	65%
1.8K heat load (kW)	8.312	8.312	8.312	8.312
5K heat load (kW)	5.225	5.225	5.225	5.225
80K heat load (MW) (cold HOM absorber)	9.575	2.303	1.6	1.018
80K heat load (kW) (HOM coupler and warm absorber)	6.4	6.4	6.4	6.4
1.8K efficiency W/W	800	800	800	800
5K efficiency W/W	200	200	200	200
80K efficiency W/W	16	16	16	16
Cryogenic safty factor	1.5	1.5	1.5	1.5
1.8K AC power (MW)	9.974	9.974	9.974	9.974
5K AC power (MW)	1.567	1.567	1.567	1.567
80K AC power (MW)	229.8	55.272	38.4	24.432
80K heat load (MW) (HOM coupler and warm absorber)	0.15	0.15	0.15	0.15
Cryogenic AC power (MW) (cold HOM absorber scheme)	241.341	66.813	48.695	34.727
Cryogenic AC power (MW) (HOM coupler and warm absorber scheme)	11.691	11.691	11.691	11.691
RF AC power (MW)	384.615	183.077	146.154	107.7