

HF2014 REPORT OF WORKING GROUP 5: SUPERCONDUCTING RF*

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Abstract

This report summarizes presentations and discussions that took place during two sessions of the Working Group 5 (WG5) of the HF2014 workshop. In WG5 we reviewed Superconducting RF (SRF) systems of FCC-ee and CEPC and considered SRF structures, peripheral components and other issues relevant to the future circular colliders. In particular, we discussed the validity of cavity parameters and cavity design (frequency, voltage, input RF power, coupling, and HOM damping scheme), high power couplers, HOM dampers, frequency tuners, operating experience and other issues. As the result of WG5, we have come up with a list of important issues that have to be addressed in future studies.

INTRODUCTION

The two proposed future high luminosity energy frontier e^+e^- circular colliders, Circular Electron-Positron Collider (CEPC) in China and Future Circular Collider (FCC-ee) at CERN, would operate as Higgs Factories as well as at other energies of interest (Z, W, top quark) for precision measurements and search for rare processes. Circumference of these machines will be in the range of 50 to 100 km. Radio-frequency systems of these colliders will utilize superconducting RF structures and will have to compensate energy loss of several GeV due to synchrotron radiation with an RF power limit set to ~ 100 MW. As a result, these systems will have a large number of SRF cavities equipped with high-power RF input couplers and with strong damping of higher order modes (HOMs). Working Group 5 of the 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory (HF2014) was dedicated to discuss topics relevant to the SRF systems. In this report we summarize the discussions and outline important R&D issues.

SRF SYSTEM PARAMETERS AND REQUIREMENTS

Both CEPC and FCC-ee would use large superconducting RF systems as the energy loss to synchrotron radiation is very high and the systems would have to compensate power loss of ~ 50 MW per beam.

Table 1: Key Parameters of the CEPC and FCC-ee SRF Systems

Parameter	CEPC	FCC-ee
Beam energy	120 GeV	120 GeV (175 GeV)
Energy loss per turn	3.11 GeV	1.67 GeV (7.5 GeV)
Synchrotron radiation power	103.4 MW	100 MW
Bunch charge	60.56 nC	59.2 nC (13 nC)
Bunch length	2.65 mm	N/A
Beam current (two beams)	33.2 mA	60 mA (13.2 mA)
RF voltage	6.87 GeV	2.7 GeV (11.2 GeV)
RF frequency	650 MHz	400 MHz
Number of cavities	384	568
Number of cells per cavity	5	5
E_{acc}	15.5 MV/m	2.53 MV/m (10.5 MV/m)
Q_0	$2 \cdot 10^{10}$ at 2 K	$2 \cdot 10^{10}$ at 2 K
Number of cryomodules	96	71
RF power per cavity	260 kW	176 kW
HOM power per cavity	3.5 kW	N/A

As a result, requirements to the RF input power couplers are quite demanding. The systems need SRF cavities with strong HOM damping to avoid multi-bunch instabilities and reduce parasitic beam power loss to HOMs. These and some other considerations lead to selecting relatively low operating RF frequencies. Table 1 lists key parameters of the two colliders relevant to the SRF

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system considerations. To make the comparison easier, we list only the beam parameters at 120 GeV for both machines (Higgs Factory regime) and at 175 GeV for FCC-ee (Top Factory regime). More details can be found in references [1]-[2].

CEPC SRF System [1]

The CEPC SRF system will be distributed through all eight straight sections of CEPC. In the baseline configuration, each cavity is driven by an individual RF power source. The total installed RF power will reach 124 MW. Eight 18-kW plants will comprise the CEPC cryogenic system, similar to LHC. The system design optimization led to choosing the SRF parameters listed in Table 1. The RF frequency, 650 MHz, has synergy with other projects, such as ADS and PIP-II.

Within a reasonable CW accelerating gradient range, the number of cavities in the collider ring is limited by an input coupler power of 260 kW. While in the future the project might benefit from alternative cavity materials (Nb/Cu or Nb₃Sn), the CEPC specifications are beyond the state-of-the-art of these materials at present. Therefore bulk niobium cavities operating at 2 K were chosen as the baseline design. The quality factor of $2 \cdot 10^{10}$ can be reached without advanced cavity treatment techniques. However, niobium doping and magnetic flux expulsion will be studied and might lead to a cost reduction.

Very dense beam frequency spectrum and short bunch length require strong HOM damping of the SRF structures with quality factors in a range from 10^3 to 10^4 . An average HOM power loss is calculated to be 3.5 kW per five-cell SRF cavity with 80% of the power at frequencies above the cavity beam pipe cut-off, as illustrated in Figure 1. As a result, in addition to hook-type couplers, ferrite beam pipe absorbers will be installed to deal with the high-frequency portion of HOM spectrum. Waveguide HOM damping scheme is also under consideration.

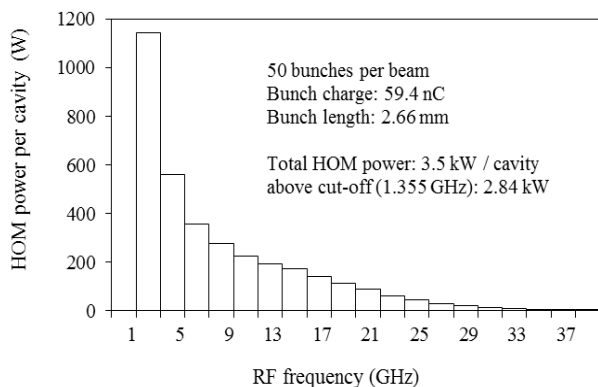


Figure 1: CEPC SRF cavity HOM power spectrum [1].

Large amount of HOM power traveling through the cryogenic environment will introduce an additional heat load. Careful evaluation and design optimisation will have to be carried out to minimize this parasitic heat load.

FCC-ee SRF System Considerations [2]

An SRF frequency of 400 MHz was chosen for the FCC-ee as a starting point. Upon careful optimization it may change in a frequency range between 200 MHz and 800 MHz, but will have to be a harmonic of 40 MHz. As an accelerating gradient was chosen to be quite moderate at 10.5 MV/m, the preferred SRF cavity fabrication technology is thin film niobium on a copper substrate. In addition to cost savings, this would allow scaling to large cavity size (low frequency) if necessary. Three FCC RF R&D areas were identified with the following topics:

- Superconducting RF
 - Cavity technology
 - Power couplers
 - Cavity optimization
 - Cryomodules
- Large RF Systems
 - Availability
 - Reliability
 - Maintainability
 - Operational aspects
- Energy Efficiency
 - Efficient power sources
 - Lowering cryogenic load
 - Energy recovery?

In addition to pushing R&D of Nb/Cu coating techniques, Nb₃Sn research recently produced promising results. New treatment techniques (nitrogen doping) will be looked at as well. The SRF R&D for FCC blends well into a wider R&D program at CERN, which includes developments for LHC, HL-LHC, HIE-ISOLDE, SPL and ERL-TF.

CERN is also pursuing a very high efficiency klystron development. Recent studies make an efficiency of 90% look possible. Another option would be a multi-beam IOT. ESS has revived this research recently in a joint effort with CERN.

SRF CAVITY OPTIONS

There are no SRF structures developed specifically for either CEPC or FCC-ee yet. Both teams just starting this process and consider some existing structures as possible prototypes for their future designs. In particular, SRF cavities under development at BNL and JLab might be considered as such prototypes and were discussed at the workshop.

BNL3 Cavity as An Option for CEPC/FCC [3]

A 704 MHz five-cell SRF cavity, BNL3, was designed at BNL for high current linacs (SPL, eRHIC). One of the cavity's salient features is a compact and efficient HOM damping scheme with three HOM coupler ports on each beam pipe of the cavity, as shown in Figure 2.

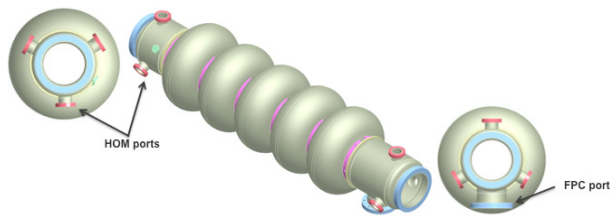


Figure 2: BNL3 cavity [3].

The strong HOM damping offered by this cavity makes it an attractive option as a prototype for future e^+e^- colliders. Two versions of HOM couplers are under development. One version employs a high-pass lump-element filter; the other is based on a dual ridge waveguide. Each of the couplers will be capable of handling ~ 1 kW of the HOM power. Two Nb cavities have been fabricated with one of them reaching ~ 20 MV/m.

Alternative Structures at JLab [4]

JLab is traditionally developing SRF structures with waveguide type HOM couplers. Recently, the focus of these efforts was directed toward the future electron-ion collider MEIC. The MEIC SRF systems face challenges similar to the future e^+e^- colliders. The SRF structures will have to support high beam currents; deliver high accelerating voltage in a limited available space; provide large amount of RF power needed to compensate synchrotron radiation losses. The baseline design frequency is 750 MHz, while 1500 MHz is under consideration.

An “on-cell” damper concept, depicted in Figure 3, was shown to meet stringent HOM damping requirements of MEIC. However, there are still many technical challenges associated with this design.

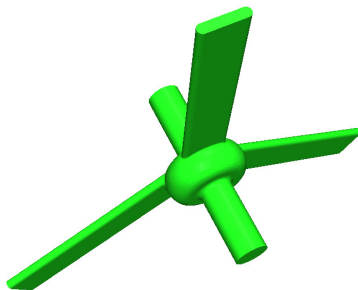


Figure 3: MEIC cavity concept with an “on-cell” HOM damper (courtesy of JLab).

Previously, two five-cell cavities were developed at JLab for high-current ERL applications: a 1500 MHz cavity for 100-mA beam current and an Ampere-class 750 MHz cavity. Both cavities feature waveguide HOM couplers attached to their beam pipes. Prototype cavities of both designs were built and tested, demonstrating very good performance. Figure 4 shows a photograph of the 750 MHz cavity.

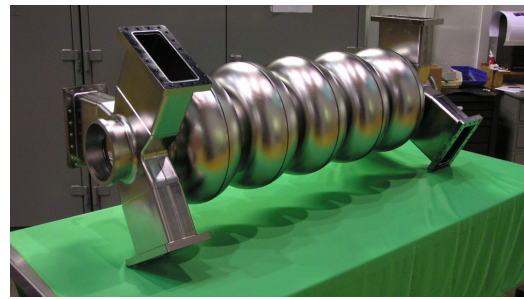


Figure 4: 750 MHz Ampere-class ERL cavity (courtesy of JLab).

HOM DAMPER HARDWARE [5]

There are a large variety of HOM damper designs for SRF cavities. However, very few of those are designed to handle high average HOM power and even fewer demonstrated this in operation. Designs of the HOM dampers, existing and under development were reviewed in WG5 with an emphasis on applicability to future energy frontier circular colliders.

Three main design types were presented. Those types are beam pipe absorbers, rectangular waveguide HOM couplers and loop/antenna HOM couplers to a coaxial line. Then, pros and cons of different HOM damper types were discussed.

The beam pipe absorbers are arguably the most efficient in HOM damping and likely will be required to absorb very high frequency portion of the HOM power, which propagates along the beam pipe. Room temperature HOM loads demonstrated capacity to absorb several kW of HOM power at CESR and KEKB. Drawbacks of the beam pipe absorbers are: i) most absorber materials are brittle, can create particulates that contaminate SRF cavities; ii) parasitic beam-absorber interaction is significant and contributes to the overall HOM power; iii) the main disadvantage for large SRF systems is that the HOM loads occupy real estate along the beam axis and thus reduce the SRF system fill factor.

The waveguide couplers can provide very efficient damping in a broad frequency range and don't compromise the fill factor. In theory, these couplers should be able to handle high HOM power, but this has not been demonstrated in operation yet. The disadvantage of using waveguides is that their large size significantly complicates the cavity and cryomodule designs. This damping scheme is worked on at Jefferson Lab primarily.

The coaxial loop/antenna HOM couplers require means of rejecting the fundamental mode. Rejection filters can be very narrowband and difficult to tune. The LHC HOM couplers were designed for ~ 1 kW HOM power levels, but operate at lower HOM power levels so far. High-pass filters can be used instead of narrowband rejection filters. The high-pass filters, if properly designed, should be easy to tune. A couple of promising designs are under development at BNL for the BNL3 cavity as mentioned in the previous section. Yet another

~1 kW HOM coupler design, which might be suitable for the future colliders, is being worked on for the HL-LHC compact crab cavities.

HIGH POWER COUPLERS [6]

A high power RF input coupler is one of the most critical components of an SRF system. Design of an input coupler strongly depends on a cryomodule structure. Essential considerations for input couplers are: RF power capability ($P_{RF} = I_{beam} \cdot V_{acc} \cdot \cos\phi$); coupler type (coaxial or waveguide); ceramics window type (disk or cylindrical); number of windows (single or double); coupling with cavity (fixed or adjustable); cooling method (air, He-gas, N₂-gas or water); and bias voltage (useful or needless). Important technical issues are: ceramics window (material, purity); metalizing of ceramics; copper plating (thickness, RRR, adhesion, pits, uniformity); TiN coating (thickness, uniformity); joining by brazing; welding by TIG, laser or E-beam; RF properties; thermal characteristics; mechanical analysis; multipacting simulation; cleaning procedure; and assembly in clean room.

TRISTAN-type high power couplers were reviewed. The coupler was originally designed for TRISTAN 508 MHz SRF cavities by S. Noguchi, E. Kako, et al. It has a coaxial disk ceramic window with a choke structure. Couplers of this type are used for cavities at many laboratories around the world in a wide range of frequencies between 500 to 1300 MHz. An RF power up to 380 kW was demonstrated in CW operation and up to 2 MW in pulsed regime. High power couplers developed at CEA-Saclay, CERN and BNL were also reviewed.

At CEPC, the BEPC-II 500 MHz SRF cavity coupler is taken as the baseline for the CEPC main ring SRF cavities. The KEK cERL main linac power coupler is taken as the baseline for the CEPC booster SRF cavities.

Parameters of the input couplers in a frequency range between 650 and 802 MHz were summarized in a table [6]. Main RF parameters were considered for the input couplers of CEPC and FCC, such as the RF frequency, required RF power, range of external Q factors, etc.

Coaxial CW high power input couplers with a single warm RF window have been developed in a frequency range of 500 to 1300 MHz at a power level higher than 100 kW in many laboratories around the world. Design studies of high power couplers at 400 MHz, 176 kW CW for FCC and at 650 MHz, 260 kW CW for CEPC should be started as soon as possible. Fabrication of the prototype high power couplers and RF conditioning at a test stand should be carried out at an early stage.

OTHER ISSUES [7]

Three other issues were presented. Those are frequency tuners, operating experience and performance recovery.

Frequency Tuners

A frequency tuner is an important system for cavity operation to tune the cavity to its operating frequency, detune to compensate the beam loading and help to stabilize its RF amplitude and phase. The frequency tuner designs have well advanced for a variety of requirements. Presently there are many excellent tuner designs from which one can select an appropriate design. Mass production and reliability issues have to be taken into considerations during the tuner design selection. In this talk several tuner design examples were presented.

Four tuner systems from an early stage of the SRF technology development were reviewed. The CESR tuner had a flex hinge system without backlash. The CEBAF tuner had a drive shaft system with a stepping motor driver exterior to the cryomodule. The LEP tuner utilized thermal expansion and contraction of three Ni bars for coarse tuning with a magnetostrictive effect utilized for a fine tuner. The TRISTAN tuner applied a lever system with a piezoactuator for fine tuning. This mechanism was also used for the KEKB 509 MHz, single cell cavity. Furthermore it will be used for the SuperKEKB operation.

The S1-Global cavity string test for the ILC at the superconducting RF test facility (STF) of KEK has three tuner systems. Those are a blade tuner developed by INFN Milan, a double lever system developed by DESY based on the Saclay tuner and a slide jack system developed by KEK. All components of the first two systems are located in a cold section while the driver of the KEK tuner is located in a warm section.

Other tuner examples are a double lever and eccentric shafts system recently developed by Saclay and a scissor jack system for the CEBAF upgrade cryomodule.

Among those tuner designs, the lever and piezoactuator system has been in service for a long time and proved to be a reliable system. The KEK 509 MHz tuner system has really long life. Location of the tuner driver is an important consideration. A cold location makes a tuner system compact, while a warm and exterior to the cryomodule location makes the maintenance easy.

Operating Experience

Operating experience gained elsewhere provides very useful information for designing a new SRF system. As an example, operating experience at KEKB was presented. KEKB is a high luminosity, electron-positron double-ring asymmetric B-factory. Eight single cell SRF cavities, operating at 509 MHz, were operated in its high energy ring. Three main issues were presented. Those are cavity RF trip rate, cavity troubles, and performance degradation.

The cavity trips were mainly caused by high voltage breakdown in the cavity or in the high power coupler. The trip rate was 0.5 trips per day for eight cavities during the 1.4 A operation. In order to keep the trip rate low, maintenance work is important. RF processing of the input power coupler with voltage biasing was emphasized as an effective maintenance tool. There were several

vacuum leak troubles. Some of the leaked cavities were re-assembled at indium seal joints without further surface treatments.

KEKB cavities still provided an accelerating voltage of 2 MV after 10 years of operation. However the cavity's Q factors degraded from $2 \cdot 10^9$ to several 10^8 with strong field emission. Further degradation would make the operation difficult.

Performance Recovery

Performance recovery methods are desired and needed for long-term operation. The recovery should be accomplished with a low risk, low cost and in a short period of time. KEK has developed a horizontal high pressure water rinsing that can be applied directly to a cavity in the cryomodule. Two KEKB cavities successfully recovered their Q factors after horizontal high pressure rinsing.

SUMMARY

In WG5, we have considered parameters of the SRF systems for CEPC and FCC-ee, requirements and challenges. Also, we discussed SRF cavity designs, HOM dampers, RF input couplers, frequency tuners and operational experience, performance degradation and recovery.

There are a number of important issues that have to be addressed in future studies. Among those are:

- HOM studies, including: trapped modes; efficient HOM coupler designs; propagation of the very high frequency portion of HOM power, its absorption, and associated parasitic heat load.
- SRF cavity design: frequency; number of cells per cavity; optimal operating temperature; nitrogen doping at low frequencies; new materials.
- Design of high power RF input couplers.

- Does FCC-ee at Higgs and Z energies require two different SRF systems? It appears that these are two very different regimes: LEP-like vs. B-factory-like.
- General SRF/cryogenic system optimization.
- Efficiency of RF power sources.

Ideally, these studies will be executed in collaborations, utilizing synergy with other projects and labs

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