Development of a 1.3GHz 9-cell superconducting cavity for the Energy Recovery Linac

H. Sakai*, K. Shinoe, ISSP/SRL, Univ. of Tokyo, Chiba, Japan
T. Furuya, S. Sakanaka, T. Suwada, T. Takahashi, K. Umemori, KEK, Ibaraki, Japan
M. Sawamura, JAEA/ERL, Ibaraki, Japan

Abstract

For the energy recovery linacs (ERLs), strong higher-order-mode (HOM) damping is necessary to achieve high current operations. For this purpose, we have newly designed a 1.3 GHz 9-cell superconducting cavity. The cell shape of this cavity is designed and optimized for the high current ERL operation. The HOMs are extracted through the beam pipes and damped with RF absorbers. Furthermore, a new idea of eccentric-fluted beam pipe (EFB) is proposed in order to extract the quadrupole HOMs. In this paper, strategy for the HOM suppression to optimise for the ERL operation and estimated HOM characteristics are described. Other important R&D items are also reported.

INTRODUCTION

The ERL project in Japan has been started with the cooperation of KEK, JAEA, ISSP and other SR institutes, with an aim to realize 5 GeV class ERLs [1, 2]. Especially, more than 100 mA beam current will be expected for the ERL operation. For this aim, we have started to develop superconducting accelerating cavities for the main linacs, which are one of the key components of the ERLs.

Accelerating gradient of 15 $\sim$ 20 MV/m is required to achieve high energy electron beams. The most challenging issue is a strong suppression of HOMs excited in accelerating cavities; the beam-breakup (BBU) instabilities are caused by the dipole and quadrupole HOMs and the heat loads are caused by the monopole HOMs. Especially, the BBU instabilities of the dipole HOMs and the quadrupole HOMs determine the current limitation of the ERL. Typical simulation results, calculated by the Cornell university, show that the dipole and quadrupole HOMs should be damped to $(R/Q)Q/f < 1.4\times10^5$ $(\Omega\cdot\mathrm{cm}^{-2}\cdot\mathrm{GHz}^{-1})$ and $(R/Q)Q/f < 4\times10^6$ $(\Omega\cdot\mathrm{cm}^{-4}\cdot\mathrm{GHz}^{-1})$ respectively, for 100 mA operation [3], where f is the resonant frequency, Q is the quality factor, and R/Q is the ratio of the impedance to the quality factor. Monopole HOMs, which are damped by HOM absorbers, cause the significant heat load in cryomodules. The frequencies of monopole HOMs should not be around multiples of beam repetition frequency. For example, in the case of the beam repetition of 1.3 GHz and the beam current of 100 mA, $(R/Q)Q < 2500$ (Ω) is needed for the resonance condition of the multiples of 2.6 GHz in order to avoid more than 100W heat load in cryomodules.

The TESLA cavity, which is designed for the linear collider(LC) project or XFEL project, is known as a representative L-band 9-cell superconducting cavity. However, for high current ERL operations, it does not have enough HOM damping ability. Furthermore, the loop-type HOM couplers, which are adopted for the TESLA cavity, have a heating problem for the CW operations [4]. Therefore, we decided to develop a 1.3GHz superconducting cavity optimized for the ERL operations, especially for HOM damping. We have designed new cavity cell shapes, applied large beam pipes on which microwave absorbers are mounted, and adopted a new idea of an EFB for the quadrupole HOM damping. Details of the design concepts and its HOM characteristics are discussed below. Other development items associated with the ERL superconducting cavity are also shown in this paper.

DESIGN OF THE KEK-ERL CAVITY

The basic research is started from the TESLA 9-cell cavity and the modification and improvement are applied. Detailed strategy for the HOM damping is as follows.

KEK-ERL model-1 cavity

The basic idea is the extraction of HOMs through the enlarged beam pipe with RF absorbers instead of the loop-type HOM couplers. In order to investigate the effectiveness of the enlarged beam pipes we designed the KEK-ERL model-1 cavity as shown in Fig.1. In this model, the cell shape basically keeps the TESLA cell shape and one side of beam pipe diameter is enlarged from 78 mm to 108 mm. All monopole and dipole modes, except TM010, propagate through the beam pipe and are damped by the absorbers. The calculation with MAFIA indicates the effectiveness of the HOM extraction comparing with the original TESLA cavity. The detail HOM characteristics of model-1 cavity are described later.

KEK-ERL model-2 cavity

Assuming ideal RF absorbers with the enlarged beam pipes, the KEK-ERL model-1 cavity almost satisfies the requirement of suppressing the dipole HOM-BBU instabilities for 100 mA operation as described in next session. However, we would like to increase the current limitation about the dipole HOM-BBU instabilities for fabrication and operation mergin and for possibility of the 2-loop ERL operation. Therefore, next we attempt to reduce the impedances of HOMs by the additional methods except for enlarging the beam pipe.

One effective method for the HOM suppression is to reduce the number of cells [5] and another method is to

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* hrsakai@issp.u-tokyo.ac.jp

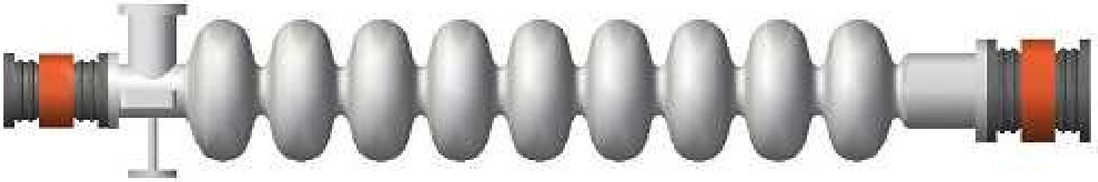

Figure 1: Conceptual view of the KEK-ERL model-1 cavity.

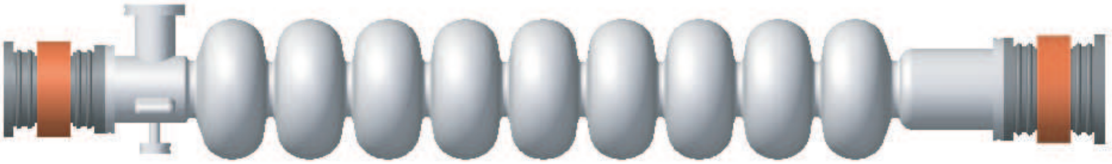

Figure 2: Conceptual view of the KEK-ERL model-2 cavity.

modify the cell shape for HOM suppression. First, we attempted a 7-cell cavity with the KEK-ERL model-1 to check the effectiveness of the HOM suppression. The HOM impedances are reduced by a factor of a few. The shunt impedance (R_{sh}) of the accelerating mode is also reduced by more than 20 %. Next, we kept the 9-cell and modified the cavity cell shapes from KEK-ERL model-1 with the following strategy; impedances of dipole HOMs should be as small as possible, frequencies of monopole HOMs with large $(R/Q)Q$ should be sufficiently far from multiples of 2.6GHz, and R_{sh}/Q of the accelerating mode should be kept as high as possible. After optimizing the cell shapes, the dipole HOM impedances are reduced by a factor of ten. The effect is much drastic comparing to the change of number of cells. By considering these results and packing factor of cavities, we have decided to keep nine cells and adopted the modified cell shapes from KEK-ERL model-1 cavity. Hereafter, we call this cavity as the KEK-ERL model-2 cavity.

Conceptual design of the KEK-ERL model-2 cavity is shown in Fig.2. Main modification from the model-1 cavity is an iris diameter. We have selected 80 mm as the iris diameter to achieve lower impedances of HOMs and to keep the high R/Q for the accelerating field. Detailed approach for the optimization is described in Ref.[6]. We note that the two different diameters of the beam pipes are adopted so as to propagate TE111 and TM011 mode effectively; one is 120mm and called as Large Beam Pipe (LBP) and the other 100mm as Small Beam Pipe (SBP). The input power coupler port of 60mm diameter is set on the SBP side. Main parameters of the accelerating mode are shown in Table 1. Since the cavity design is focused on the HOM damping, the accelerating mode is sacrificed to some extent. Its R_{sh}/Q is reduced to 900 and E_p/E_{acc} is raised to 3.0.

Table 1: Parameters of the accelerating mode for the KEK-ERL model-2 cavity and TESLA cavity

	KEK-ERL model-2	TESLA
Frequency [MHz]	1300	1300
Iris diameter [mm]	80	70
Cavity diameter [mm]	206.6	206.6
Rsh/Q [Ω]	897	1030
$Q_0 \times R_s[\Omega]$	289	270
E_p/E_{acc}	3.0	2.0
H_p/E_{acc} [Oe/(MV/m)]	42.5	42.6
Coupling [%]	3.8	1.9

Eccentric-Fluted Beam Pipe

In order to extract and damp the quadrupole HOMs by RF absorber with beam pipe, we need larger diameter of the beam pipe because their cut-off frequencies of quadrupole modes are generally high. Damping only by enlarged beam pipe is not realistic. For this reason, we have newly proposed the EFB [7].

The EFB is formed by displacing the flute from the beam pipe center [8] and/or jackknifing around the midpoint. It acts as a mode transformer from quadrupole mode to dipole mode as shown in Fig.3. Due to its asymmetric shape, the quadrupole modes can be partly transformed into dipole modes. Then, they propagate through the beam pipes and are absorbed by the RF absorbers. The finite length of eccentric-flute sufficiently transforms the modes. Fig.4 shows the schematic view of the EFB attached to the KEK-ERL model-2 cavity. We adopt the 60 mm length of the eccentric-flute to the beam pipe. Angle of flutes is chosen to be 25° so as to couple with both polarizations of the quadrupole modes. The effect on acceleration mode was checked and found to be negligible. The performance of the EFB is described later.

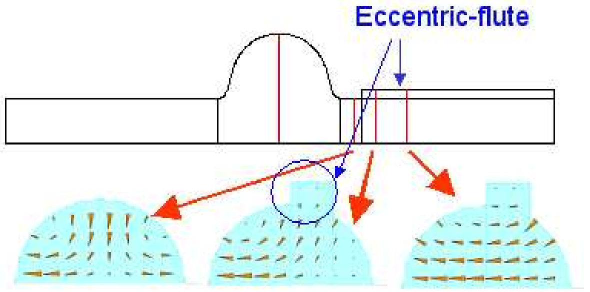

Figure 3: The principle of the EFB. The arrows show the excited electric field at each cross section.

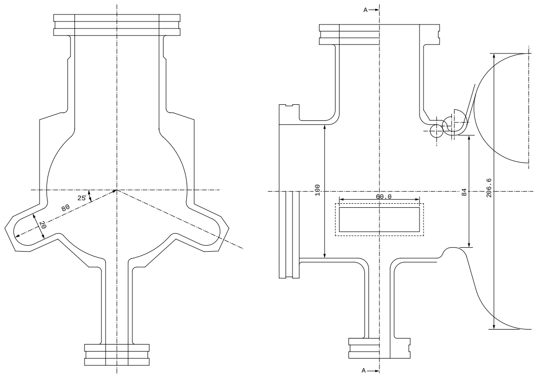

Figure 4: The schematic views of the EFB.

HOM CHARACTERISTICS

The HOM characteristics of the KEK-ERL model-2 cavity are estimated using MAFIA. The results are shown below.

Monopole Modes

The impedances of monopole HOMs are calculated up to 5.6 GHz assuming ideal RF absorber as shown in Fig. 5. Some huge impedances are found up to 5.6 GHz. However, no HOMs exist around 2.6 GHz and 5.2 GHz. We note that when ERL is operated with lower frequency of beam repetition, its frequency should be selected carefully not to excite the monopole modes of high impedances.

In addition, in order to estimate the heat load by beam-induced wakefield, we have also calculated the loss factor by using ABCI code [9]. Fig.6 shows the results of the calculation of the loss factor for the KEK-ERL model-2 cavity. When we assume the bunch length is 3 ps, the loss factor of KEK-ERL cavity is 12 V/pC. Since the loss factor of TM010 mode is 2 V/pC, the loss factor due to HOMs is 10 V/pC.

Dipole Modes

The impedances of dipole modes are calculated up to 4.5 GHz assuming ideal RF absorbers. In Fig. 7, the values of $(R_t/Q)Q_{ext}/f$ for KEK-ERL model-2 cavity are plotted and compared with those of the TESLA [10, 11] and KEK-ERL model-1 cavities. Impedances for the KEK-ERL model-2 cavity are about one order smaller than those for the model-1 cavity. The BBU simulations indicate that the BBU threshold exceeds 600 mA for the KEK-ERL model-2 cavity even without randomization of HOM frequencies as shown in Fig.8 [12]. We note that the model-l cavity also has much advantage of the dipole HOM suppression compared with TESLA cavity as shown in Fig.7 and Fig.8.

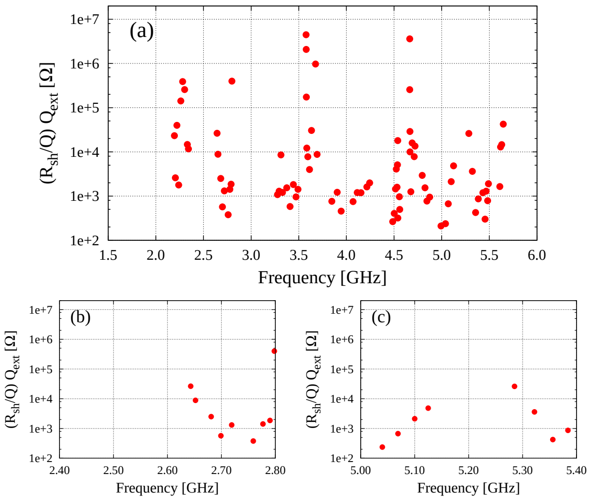

Figure 5: (a) Spectrum of the monopole HOMs and that for (b) around 2.6 GHz and (c) around 5.2 GHz for the KEK-ERL model-2 cavity.

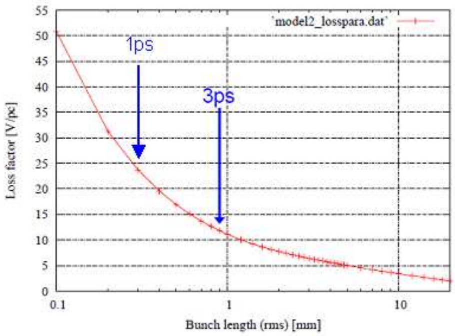

Figure 6: Loss factor of KEK-ERL model-2 cavity.

Quadrupole Modes

The impedances of the TE211 for both degenerate modes (E,M) are calculated for KEK-ERL model-2 cavity with the EFB. The values of $(R_t/Q)Q_{load}/f$, assuming ideal absorbers, are plotted in Fig. 9. The line of model2 in Fig.9 is the case of the calculation of the EFB attached to only SBP side. By using eccentric-fluted beam pipe, quadrupole HOMs are drastically damped by a factor of thousand compared with the case of no-flute beam pipe. However, some impedances of TE211 are slightly larger than the threshold

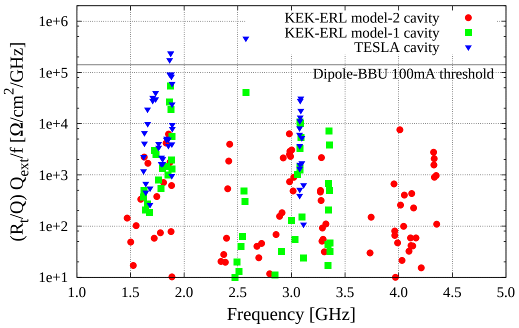

Figure 7: Spectrum of the dipole HOMs. The values of $(R_t/Q)Q_{ext}/f$ are plotted for the TESLA cavity, KEK-ERL model-1 cavity and model-2 cavity.

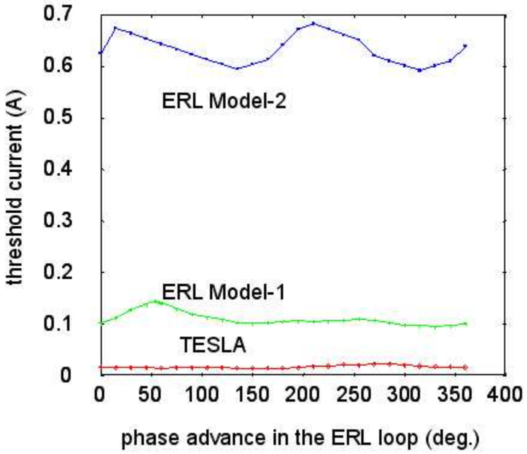

Figure 8: Threshold beam currents of the BBU by dipole mode are plotted for the TESLA cavity, KEK-ERL model-1 cavity and model-2 cavity. The horizontal axis shows the phase advance for the ERL one-loop.

impedance of quadrupole BBU at 100mA; high impedance of $8\pi/9$ mode results from an asymmetry of its field. Therefore, we should adopt the EFB on the both sides. The line of model2-3 in Fig.9 is the case of the calculation of the EFB attached to both SBP and LBP sides. And that of model2-2 in Fig.9 is the case of the calculation of the EFB attached to SBP side and the reversed eccentric-fluted beam pipe attached to LBP side. This reversed EFB is formed by pushing the eccentric flute inside the beam pipe as shown in bottom right of Fig.9. We note that the reversed eccentric-fluted beam pipe also acts as a mode transformer. By adding the EFB to both the beam pipes, impedance of $8\pi/9$ mode is reduced in the case of model2-3. Furthermore all impedances of TE211 modes are much reduced by adding the reversed eccentric-flute in the case of model2-2. From these calculations, it is expected that 100 mA quadrupole-BBU threshold will be satisfied after the optimization.

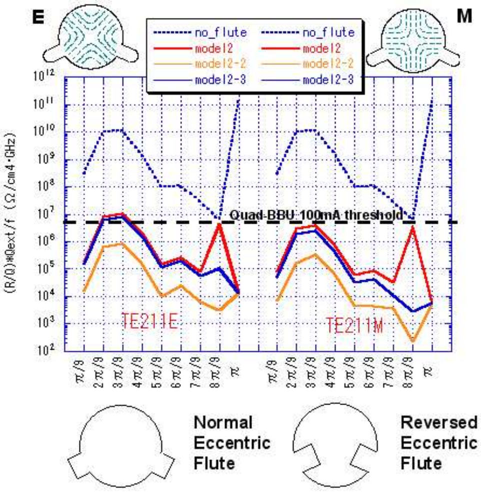

Figure 9: Impedances of the TE211 modes for the KEK-ERL model-2 cavity, for the case with and without the EFB. The results for both polarizations are plotted.

PERFORMANCE OF THE ECCENTRIC-FLUTED BEAM PIPE

In order to investigate the effectiveness of the eccentric-fluted beam pipe, we made a test model of the EFB as shown in Fig.10. The model consists of seven pieces of angularly divided beam pipe to change the flute angle. The EFB is attached to one side of a TESLA single-cell model. A drive antenna is installed at one side of cavity cell and a pickup antenna at the other side. The perturbation anttena is set at the position rotating 22.5° around the beam axis to separate the degenerate modes into different frequencies. A rolled-up ferrite sheet is set inside the beam pipe as an RF absorber.

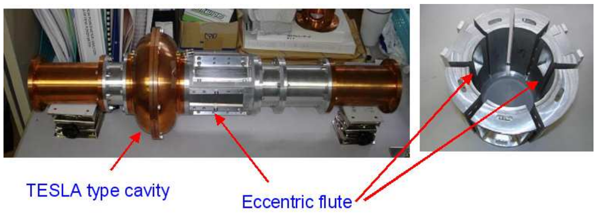

Figure 10: (Left) Picture of the test model of the EFB. (Right) Angularly divided EFB

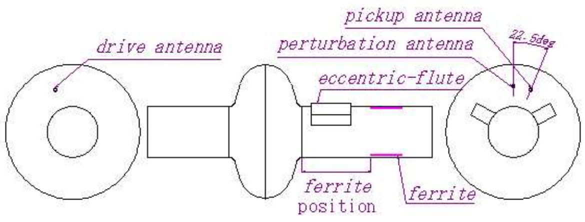

Figure 11: Setup for measurement of EFB

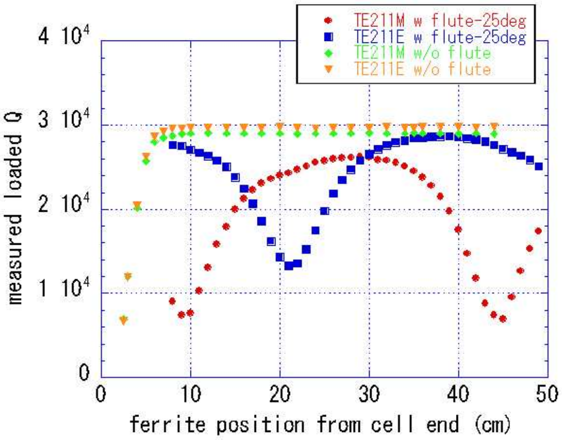

Figure 12: The measurement results of the loaded Q-values of TE211 modes with/without EFB.

Loaded Q-values are measured with a network analyzer. Fig.12 shows the measurement results of the loaded Q-values of the two TE211 modes by changing the ferrite position. The flute angle is set to 25°. The loaded Q-values without EFB is constant unless the ferrite position is close to the cavity. On the other hand, when the EFB is attached to the cavity cell, the loaded Q-values of TE211 modes changes by location of the ferrite and becomes lower than those without EFB. This indicates that TE211 modes propagate through the beam pipe by only adding the EFB.

The position dependence of the measured loaded Q-values can be explained by the reflection from the ferrite itself. Assuming the transmission-line model to the measured loaded Q-values, we can estimate the external Q-values. These measured external Q-values agree well with the calculation by MAFIA. Detailed analysis is explained in Ref.[7]. From these results, we have confirmed that the EFB acts as a mode transformer and can extract the TE211 modes in the cavity to the RF absorber.

OTHER R&D ITEMS

An input power coupler is one of the important items of the superconducting cavity. We now design the input power coupler for the main linac. Thanks to the principle of energy recovery, we can reduce the input power of the main linac. However, the minimum input power will be restricted by the cavity detuning due to the microphonics from the cryomodule. Fig.13 shows the relation between the cavity detuning Δf and the input power corresponding to the several loaded Q-values, Q_L, when the accelerating field is 20 MV/m. For example, the maximum input power of 20 kW is required for the condition of the large cavity detuning of $\Delta f = 50$ Hz and Q_L of 2×10^7. To achieve the low input power, the cavity detuning must be suppressed. Furthermore the lower Q_L is desirable for the short pulse conditioning of the cavity.

Fig.14 shows the design of the input power coupler for the main linac. Our input power coupler is based on the coaxial antenna type couplers for a prototype of ILC baseline in KEK [13]. This prototype coupler used the two choke-mode ceramic windows and was already successfully powered in a test bench up to 1 MW peak power. This is one of the reasons why we select this type of coupler. The following modifications have been made to meet our requirements for ERL operation. Some parts of modification were referred from Cornell ERL injector input power coupler to maintain more than 20 kW CW operation [14]. Instead of a 50 Ω coaxial line, a 60 Ω line is chosen for reducing the heat load of the inner conductor. The choke-mode ceramic window is used and modified to match the 60 Ω line and we adopt the low loss ceramic with the purity of 99.7%. For an easy fabrication, the double ceramics of same size are used for each ceramic window of warm and cold sides. To realize the variable coupling, a bellows is inserted to outer conductor in the downstream of the cold window and a rod to the inner conductor to adjust the coupling. The maximum movable range of inner conductor is ±5mm, which corresponds to $Q_L = 5 \times 10^6 \sim 2 \times 10^7$. One of the problems is the heat load at the bellows in inner and outer conductors. This problem will be solved by blowing the forced cooling air to the inner conductor bellows through the inside of the rod and adding more heat intercepts near the outer conductor bellows of the cold and warm lines. The cold window will be cooled by the liquid N_2 gas at 80 K. Now we are making the test stand for testing the components of the input power couplers, especially ceramic windows and bellows, by delivering the maximum 30 kW CW average power from an IOT.

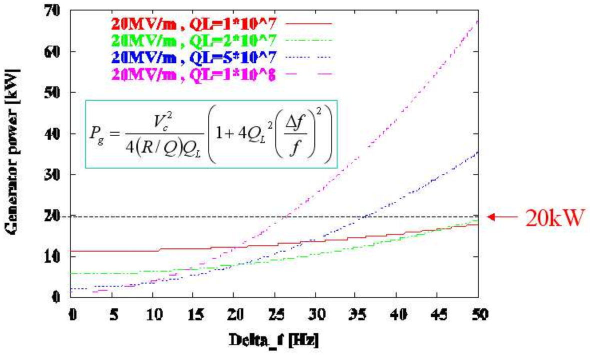

Figure 13: Input power vs. cavity detuning, Δf, corresponding to the several Q_L's.

The RF absorber is the other important R&D item for ERL. The low Q-values of less than 1000 about HOMs are required. Furthermore, HOM heat load is expected to be around 100W. RF absorber material is set in the large beam tubes at the temperature of 80 K apart from the cavity as shown in Fig.2. It should realize enough absorption of the HOM power and low static loss from the RF absorber to the 2 K cavities. Detailed design of the RF absorber is now under way. The frequency tuner and cryomodule are also now under designing for optimizing the ERL high current operation.

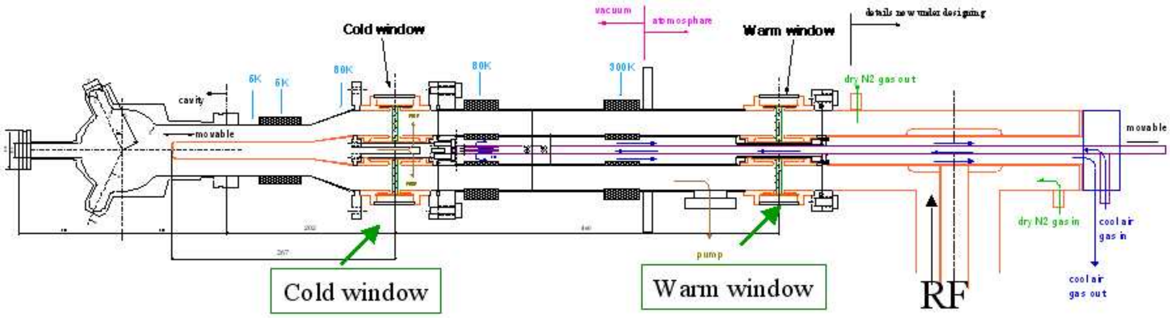

Figure 14: Conceptual design of the input power coupler for the ERL main linac.

SUMMARY

We have designed the 1.3 GHz 9-cell superconducting cavity for the ERL main linacs, which is optimized for the ERL high current operations. With the goal of the strong damping of HOMs, we have designed the new cavity cell shape and adopted large beam pipes with RF absorbers. Quadrupole HOMs are sufficiently damped with the EFB and the effectiveness of the EFB has been confirmed by using the test model. Our cavity design satisfies the conditions for 100 mA CW operations.

At the moment, nine-cell Nb KEK-ERL model-2 cavity is in production. Its performance will be evaluated in the near future. We also proceed the development of components such as the input power coupler, the HOM damper, the frequency tuner and the cryomodule.

REFERENCES

[1] T. Kasuga et al., Proc. of PAC07, p.1016

[2] K. Harada et al., in these proceedings

[3] M. Liepe, Proc. of the 11th Workshop on RF Superconductivity (SRF2003), Lübeck/Travemünde, Germany, 2003.

[4] P. Kneisel et al., PAC'05, p. 4012

[5] R. Rimmer et al., PAC'03, p. 1389

[6] K. Umemori et al., APAC'07, (To be published)

[7] M. Sawamura et al., PAC'07, p.1022

[8] R. Rimmer et al., Proc. of the 11th Workshop on RF Superconductivity (SRF2003), Lübeck/Travemünde, Germany, 2003.

[9] M. Izawa, private communication.

[10] *TESLA Test Facility Linac Design Report*, edited by D. A. Edwards, DESY, 1995.

[11] *TESLA Technical Design Report*, edited by R. Brinkmann et al., DESY, 2001.

[12] R. Hajima, et al., in these proceedings.

[13] E. Kako et al., Proc. of PAC07, p2107.

[14] S. Belomestnykh et al., Proc. of LINAC 2004 Lübeck, Germany, 2004, p694.