NEW HOM COUPLER DESIGN FOR ERL INJECTOR AT KEK *

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Abstract

The development of superconducting cavities and cavity package for ILC and ERL project is under way at STF (Superconducting RF Test Facility) in KEK. The TESLA-style coaxial HOM couplers have a problem at CW operation, which it is pick-up probe and inner conductor heating of HOM coupler.

The pick-up probe heating was observed at vertical tests. The probe heating study for CW operation (changing pick-up probe geometry and probe gap) tried at vertical tests by using the KEK STF Baseline 1.3 GHz 9-cell superconducting cavity, and simulated by using HFSS code ver9.1 for estimate the relation of the limit E-field of probe heating and the probe surface current.

The design of proto-type coaxial HOM couplers of CW operation for ERL-injector at KEK was tried based on this information. The probe heating is generated due to the probe surface current by the RF load of accelerating mode. Therefore, as one method, it can be controlled if the RF load of accelerating mode is reduced by putting the high pass filter between the coupling loop and the notch filter. In addition, the target beam current of ERL is about 100mA, therefore, we were considered that the cooling of inner conductor of HOM coupler by liquid He. It is necessary to be expected the heating of inner conductor by RF load of accelerating mode and HOM power of excited in the beam. The design was held based on these.

In this report, a design of HOM coupler for ERL-injector at KEK is presented.

INTRODUCTION

The superconducting cavities have been developed for ERL (Energy Recovery Linac) project at KEK [1]. The ERL injector will accelerate bunches from electron source from 10 MeV [2]. The ERL-injector will be based on superconducting RF technology to provide CW operation. There will be 1300 MHz 2-cell cavities that equipped the coaxial HOM coupler. The target of accelerating gradient is 15 MV/m and 100 mA of beam current in the CW operation. In CW operation, the coaxial HOM coupler (like as TESLA style HOM coupler [3]) has the problem of HOM coupler heating [4].

When drives in the superconducting accelerating cavity where it was included into cryomodule, HOM couplers were cooled the heat transmission from He jacket (2 K) and some thermal anchor (5K). Though of course, cavities drive in less than 2 K, but HOM coupler has the possibility that is not 2 K. (In vertical test, the cavity put in the He bath directly, the cooling efficiency is high in comparison with cryomodule. Therefore, the calorific value of HOM coupler is small when have the RF load, because of initial surface resistance is low (about 10 nano Ohm at 2 K). The inner conductor of TESLA style HOM coupler is not observed the heating in the high gradient of over the 30 MV/m, but pick-up probe has the problem of heating due to the flowing of induction current for the structure of notch filter [5].)

The heating point of coaxial HOM coupler (TESLA style or STF model) is the following thing,

(1) Inner conductor heating of TESLA style HOM coupler due to the RF loss on the cryomodule test [4]
(2) Pick-up probe heating due to flowing induction current on the tip of probe from the accelerating load by notch filter [5]

When the CW operation by use the coaxial HOM coupler, it must be controlled the their heating.

To control the heating, its methods is as follow,

(a) Make the structure that liq. He flowing is possible into the inner conductor.
(b) Add the high pass filter between coupling antenna and notch filter for reduce the accelerating load on the pick-up probe.

The HOM coaxial coupler for CW operation was made to consider about two points of the above.

In addition, the enough HOM damping is necessary to stabilise for the beam. The target value of HOM damping is dipole mode parallel = 250 and dipole mode transverse = 1000 by ERL injector design at cornell [6].

The STF Baseline cavity also observed the probe heating [7].

PROBLEM OF PROBE HEATING AT CW OPERATION

The structure of coaxial HOM coupler is shown as figure 1. This coupler is constructed three part as the coupling loop (antenna), the notch filter and pick-up probe [3], where the frequency of the notch filter is tuned the accelerating frequency. The material is used Niobium, when the vertical test, HOM coupler has 2 K of temperature (superconducting state). Usually, the probe has the capacitive coupling for the pick-up of RF power to outside of cavity, when load the accelerating mode, the probe position has the maximum magnetic field, and flow the induction current on the probe tip. If the rf loss of the probe tip over the cooling efficiency of probe then occur the thermal runaway on the probe. Therefore the probe tip has switched to normal conducting state by the heating of the induction current, and observe the degraded the Qo value of cavity system.

Estimate the limit current of probe heating at STF HOM coupler and feed-through

The study of probe heating was made at STF by using STF Baseline 1.3 GHz 9-cell cavities in vertical test [8]. The cavities temperature is 2 K. the probe and coupler material is Niobium. The feedthrough is made by Kyocera.

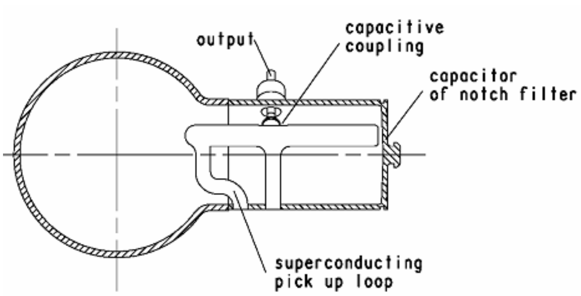
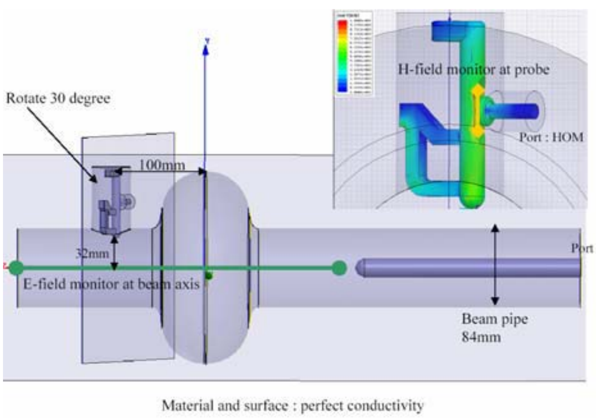
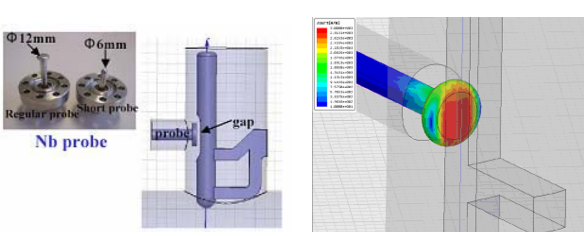


Figure1: TESLA HOM coupler [3]

The probe and feedthrouth is fixed to be threaded connection. The measurement results with each gap are shown in table 1. The gap and niobium probes are shown in figure 2. The occurred the heating gradient has the dependence of probe gap. In comparison with calculated surface current, the critical current for probe heating were form 3800 to 4500 A/m (table 2.). The calculation model (STF Baseline cavity end cell shape) is shown in figure 2 (a). The Qext of accelerating mode of HOM coupler tuned as over the 2x10^{11} in calculation and measurement. The target gradient of ERL injector at KEK is 15 MV/m, and to be achievement the strong damping for HOMs. The probe gap is necessary to short gap.



(a) Calculation model for estimation the probe current



(b) Used probes and surface current on the probe

Figure 2: Calculation model for probe surface current on STF HOM coupler

Table 1: STF BL 9-cell cavity Vertical Test result [8]

Probe gap	Heating Eacc	Mode	date
1 mm	14 MV/m	pi	2006/4
2 mm	19 MV/m	pi	2006/2
6 mm	32 MV/m	8/9 pi	2006/9

Table 2: Surface current on the HOM pick-up probe by calculation

Probe gap	15 MV/m	20 MV/m	25 MV/m	32 MV/m
0.5 mm	4250 A/m	5600 A/m	7200 A/m	Not calc.
1 mm	3950 A/m	5100 A/m	6800 A/m	Not calc.
2 mm	3680 A/m	4700 A/m	6000 A/m	Not calc.
6 mm	Not calc.	Not calc.	Not calc.	4550

ELECTRICAL DESIGN OF HOM COUPLER

To control the probe heating, how to way as follow,
a) More increase the cooling efficiency of feedthrough [9]
b) Reduce the accelerating load by using high pass filter

To be needed the considering of cooling into inner conductor, the design was choice way of b) method.

The steps of the HOM coupler design are as follows;
1) The design of high pass filter by using coaxial line.
2) The design of high pass filter and coupling antenna by using coaxial tube setup.
3) Added the notch filter on the high pass filter.
4) Calculation of probe current with each gradient
5) Calculation of damping of HOMs.

Design of High pass filter and coupling antenna

The high pass filter is made to add the stub in parallel at coaxial line. The calculation model is shown as figure 3. The coaxial line of outer diameter is 42 mm, square cutting of the inner and the stub material is 10 mm x 10mm. The parameters are offset, number of stub and length S. The results of calculation of filter transmission performance are shown in figure 4. The lower frequency of 1.3 GHz doesn't pass through easily to add the stub. Two stubs model (no offset) has a sharp change from 2.2 GHz. When inner conductor has the offset with two stubs model, this transmission performance becomes slow and shifting the low frequency side. Figure 5 is the magnetic field distribution on the cross section of coaxial line.

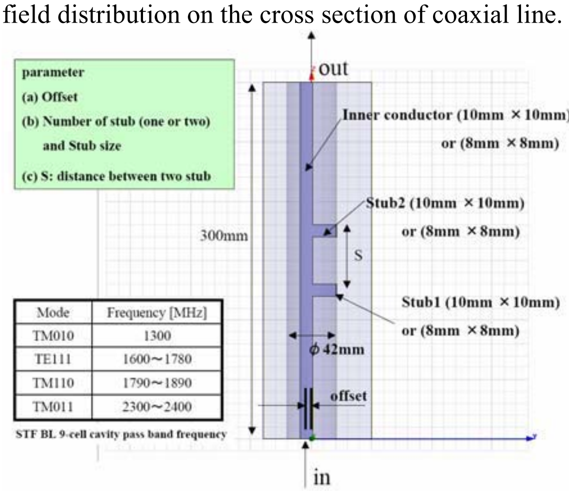


Figure 3: Setup of high pass filter for calculation

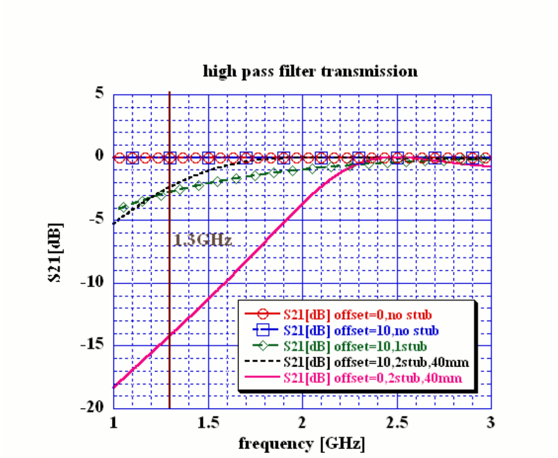


Figure 4: Transmission performance of high pass filter

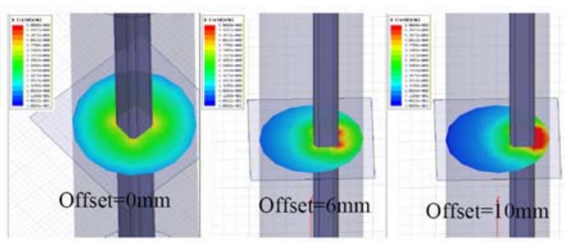


Figure 5: Magnetic field on the cross section of coaxial line

When the coaxial line has the large offset, the magnetic field has the distortion to one side. Therefore, the small offset is small effect of magnetic field on the probe. From these things, no offset model (antenna type) and small offset model (loop type) in less than STF model were designed. The antenna type of coupling antenna is dipole antenna, and loop type of coupling antenna is loop antenna.

Next design, the combined the high pass filter and coupling loop puts on the coaxial tube model to calculate the broadband performance of filter for reduce the accelerating power. The model is shown in figure 6. The length of stub from coupling antenna tip is fixed in consideration of the installation to the beam pipe. The parameters are offset, geometry of stub and length of S, S1 and S2. To obtain the strong damping, tip of antenna type designed big tip (tip (2) is shown in figure 6.).

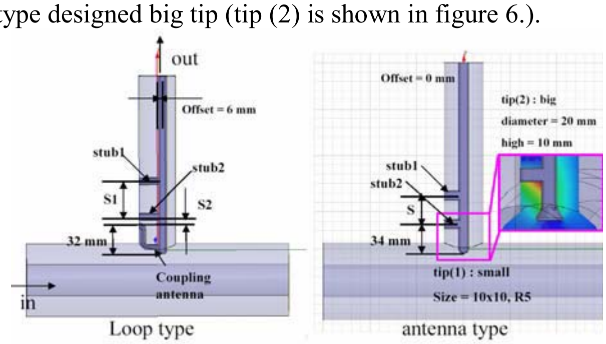
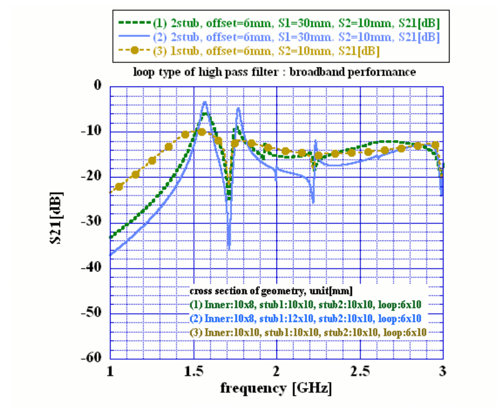
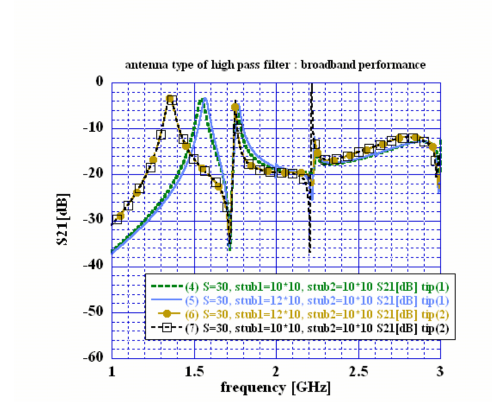


Figure 6: Coaxial model for filter performance



(a) Loop type



(b) Antenna type

Figure 7: Coaxial model of filter performance

The results of the filter performance are shown in figure 7. The (1) in the figure 7 is performance of one stub model as like the STF model. This model is bad about 10dB in comparison with two stubs model of loop type. In antenna type, the small tip of filter is good performance, however, big tip model was shifted the filter performance to low frequency side. It is no effect for the high pass filter. To use the big tip, the optimized filter structure is needed.

The filter geometry choose (2) and (5) of figure 7.

The Notch filter design

The notch filter added on the upper position of high pass filter. The estimation of notch frequency, Qext of TM010 and probe current were made. The line drawing of both HOM couplers is shown in figure 8. The notch filter type applied the STF L-type model. In addition, the projection model designed as figure 8 to reduce more accelerating load by probe position away from inner conductor. The broadband performance of HOM coupler was calculated and measured by using coaxial tube model and copper model of HOM coupler. The broadband performance is shown in figure 9. The broadband performance of calculation model does not change with and without the projection. The antenna model was same with measurement and calculation. However, the loop type of measurement result had a stop band at 4.5 GHz. The copper model and measurement setups are shown in figure 10.

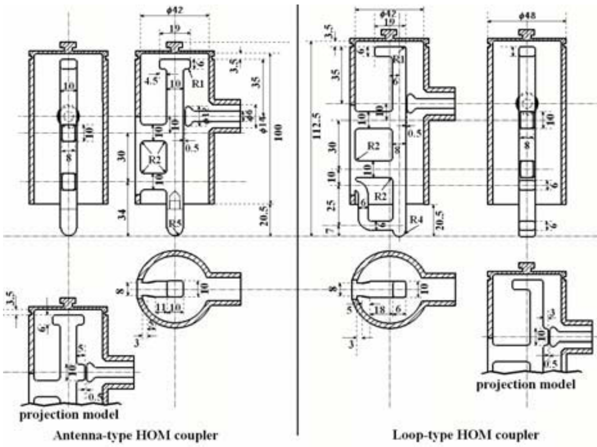
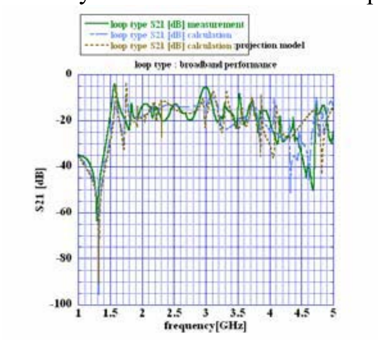
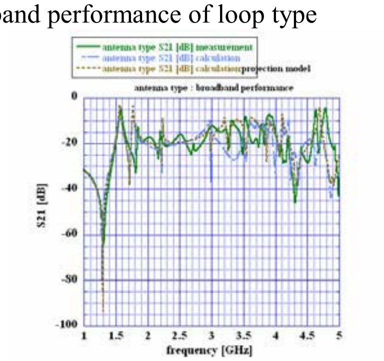


Figure 8: Geometry of added notch filter and projection



(a) Broadband performance of loop type



(b) Broadband performance of antenna type

Figure 9: Broadband performance of both types

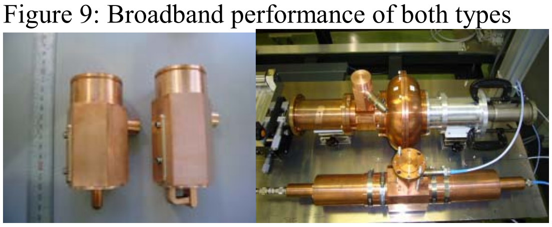


Figure 10: Picture of Cu model (left: antenna, right: loop) and measurement setup (cavity model and coaxial tube)

Probe surface current estimation

The probe surface current with each model and gradient was calculated by using single cell cavity model.

The parameter is within without the projection and rotate angle. Define of this rotate angle (0 deg case) is shown in figure 11. All models were lower than the probe current value of the STF coupler by setting up a projection specially. The probe current could be controlled with antenna type (tip 1) to 1/4 and loop type to 1/7 in comparison with STF model. Where RF loss changes in square of current, the loss of each model become 1/16 to 1/49. And surface resistance of niobium at 2 K is about 10 nano ohm, at 4 K is about 100 nano ohm. It considers that probe temperature can apply with probe fully even with 4.2K. The antenna type tip (2) model was no effect of high pass filter for the accelerating mode.

Table 3: Surface current comparison in each model
unit [A/m], (probe angle [deg])

Model	15 MV/m	20 MV/m	25 MV/m
Antenna type Tip (1)	2850 (0)	3500 (0)	4400 (0)
Antenna type Tip (2)	9000 (0)	12000 (0)	14500 (0)
Antenna type (Projection)	1000 (90) 1340 (0)	1350 (90) 1800 (0)	1650 (90) 2250 (0)
Loop type	2400 (-30)	3150 (-30)	3850 (-30)
Loop type (Projection)	2050 (-30) 2000 (0) 1360 (30) 960 (60) 680 (90)	2720 (-30) 2770 (0) 1810 (30) 1280 (60) 910 (90)	3360 (-30) 3360 (0) 2230 (30) 1580 (60) 1120 (90)
Target: < 4000 A/m at 15 MV/m			
STF model	4250	5600	7200
Probe condition: Probe gap=0.5 mm, diameter=12 mm STF single cell cavity, beam pipe = 84mm			

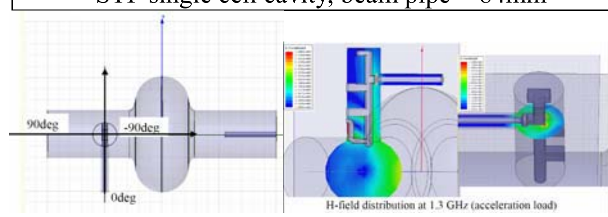


Figure 11: Rotate define on the cavity model (STF cavity). The magnetic field distribution of HOM coupler when has the accelerating load.

HOM measurement and calculation

The Qext of HOMs were calculated and measured. The estimated modes are TE111, TM110 and TM011. The end cell shape of STF cavity used with calculation, and TESLA shape single cell cavity used with Cu model measurement. Though there is a difference in cavity shape and mode frequency, the estimation of HOM damping was made with calculation and measurement. When excite the dipole mode and monopole mode, the movable dipole antenna was used to equip on the beam pipe. The results of calculation and measurement with Qext of HOMs are shown in table 4.

The single cell cavity parameters are shown as following,

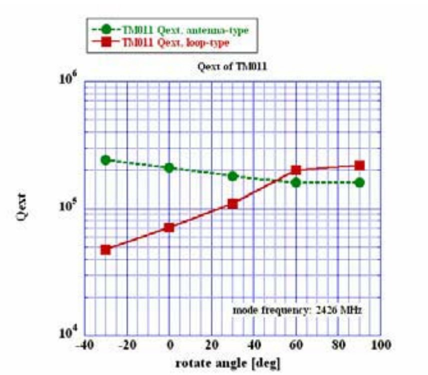
TESLA single cell cavity (beam pipe = 78 mm)
HOM coupler position = 100mm from equator
Insert length 28 mm from beam axis
Probe gap = 0.5 mm,
Probe diameter = 12 mm

In calculation of antenna model coupler, TM011 damping of Tip (2) was strong about one order in comparison with Tip (1) model.

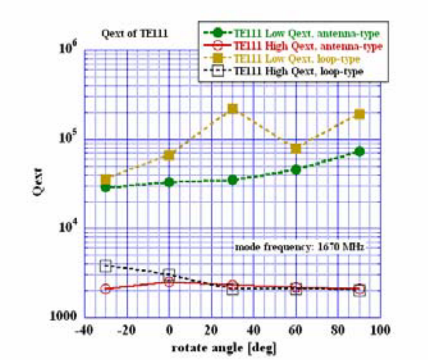
Table 4: Qext value of HOM comparison in calculation and measurement

Calculation result: Qext (angle [deg])

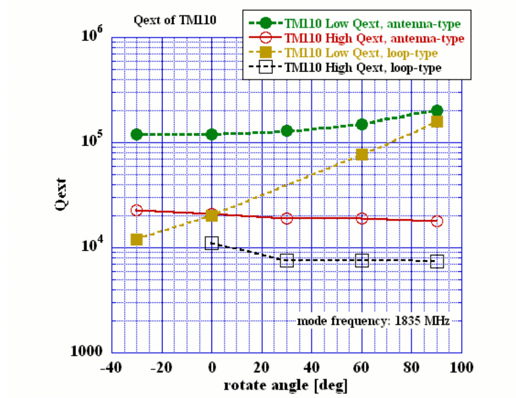
Model	TE111 1600 MHz	TM110 1837 MHz	TM011 2328 MHz
Antenna tip(1) 0deg	L:$2.9x10^5$ H:$7.0x10^2$	L:$3.8x10^5$ H:$9.3x10^3$	$9.7x10^4$
Antenna Tip(2) 0deg	L:$8.3x10^5$ H:$2.3x10^4$	L:$2.1x10^4$ H:$1.0x10^4$	$6.4x10^3$
Antenna Projection Tip(1) 0deg	L:$2.9x10^3$ H:$1.2x10^4$	L:$1.1x10^4$ H:$9.9x10^3$	$8.3x10^4$
Antenna Projection Tip(1)90deg	L:$9.9x10^3$ H:$2.8x10^2$	L:$2.2x10^4$ H:$6.5x10^3$	$6.4x10^4$
Loop type -30 deg	L:$8.9x10^5$ H:$1.2x10^3$	L:$5.3x10^4$ H:$1.7x10^6$	$6.4x10^3$ (-30) $1.1x10^4$ (0) $6.5x10^4$ (-45)
Loop type Projection -30 deg,	L:$2.8x10^4$ H:$9.7x10^4$	L:$5.4x10^3$ H:$6.3x10^3$	$8.2x10^3$ (–30) $9.1x10^3$ (0) $6.3x10^4$ (30) $1.2x10^5$ (60) $2.2x10^5$ (90)
STF single cell cavity (beam pipe 84 mm), HOM coupler position = 100mm from equator 30mm from beam axis Probe gap = 0.5 mm, diameter = 12 mm Material: perfect conductivity			



(a) Damping performance of TM011



(b) Damping performance of TE111



(c) Damping performance of TM110

Figure 12: measurement result of HOM Qext on the TESLA shape cavity

The estimation of Qext is difficult due to be changing the polarize direction that it has the dependent of input antenna position effect. In the projection model of antenna type, the dependent of rotation angle with calculation and measurement was no effect for Qext. The Qext of TM011 with loop type has the dependent for rotate angle. The maximum damping was –30 deg.

In both model, the Qext of TE111 had near 1000, it is good value. But the TM110 mode had a 50,000, it is not enough of Qext. However, the Qext of HOMs are not accurate estimation under the present condition, because cavity shape and beam pipe diameter are not decided.

Notch filter performance and tuning

After fabrication, we were made some measurement as follow. The broadband performance measured on the coaxial tube. The notch filter tuning for accelerating made. The bandwidth of notch filter to keep the rejection measured. The results are shown in table 5.

Table 5. Frequency of before and after tuning at notch filter

Model	Antenna	loop
Notch frequency	1314.463 MHz	1298.820 MHz
After tuning	1300 MHz	1300 MHz
Qext of TM010	> 2 x 10^{11}	> 2 x 10^{11}
Band width	4.6 MHz	5.2 MHz
Cavity frequency	1301.147 MHz	

SUMMARY

The design and fabrication of HOM coupler for ERL injector was made in this report. As a countermeasure of heating with HOM couplers in CW operation, the liquid He flow was made possible structure in the inside conductor, and the probe heating was controlled to equipped a high pass filter and projection in HOM coupler.

The copper model of proto-type HOM coupler was made, and this couplers measured the damping performance, broadband performance and rejection for the accelerating mode by using the single cell cavity and coaxial tube. The Qext of HOMs was not enough about one order.

FUTHER PLAN

The design of HOM coupler must makes re-estimation of the geometry of coupler and Qext as soon as the beam pipe diameter of and a cavity shape are decided for ERL injector.

After improvement and estimation, the niobium models will makes, and will make the vertical test on the 2-cell model cavity to check the probe heating.

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