HOM DAMPING AND POWER EXTRACTION FROM SUPERCONDUCTING CAVITIES

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Abstract

Damping of Higher Order Modes plays an important role in achieving and preserving low emittance and low energy modulation of beams in accelerators based on the superconducting technology. Various damping schemes and devices are discussed in this paper.

INTRODUCTION

Suppression of Higher Order Modes (HOM) plays an important role in the operation of accelerators based on the superconducting technology. Very high value of intrinsic quality factors Qo due to the superconducting state of the cavity wall, which is the advantage over normal conducting cavities in case of the accelerating mode, makes beam impedances of HOMs also very high. This may lead to a strong beam–cavity interaction causing growth of the emittance, bunch-to-bunch energy spread and/or additional cryogenic load. The beam impedance of a HOM:

$$Z = \frac{(R/Q)\cdot Q_L}{1 + iQ_L\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right)}$$

depends on the characteristic impedance (R/Q), loaded quality factor $Q_L=(1/Qo\ +1/Qext)^{-1}$ and the relative detuning from the mode frequency ω_o. Z must be kept low to mitigate the above mentioned phenomena. While (R/Q) values depend only on the geometry of an accelerating structure, low Qext and thus low Q_L result from the HOM energy dissipation in external devices. The beam induced energy in an accelerating structure is coupled out by HOM couplers or/and radiates via beam tubes towards the beam line absorbers. The dissipation causes an exponential decay of the HOM energy W(t):

$$W(t) = W(0)\cdot e^{\left(-\frac{\omega_o \cdot t}{\tau}\right)}$$

where τ is the decay time of a mode. When τ is several times shorter then the time t_B between bunches, every bunch passes through the HOM free cavity (single pass excitation). However, when τ is longer than t_B the multi-bunch excitation of a HOM takes place. A bunch passing the cavity interacts with HOMs excited by all preceding bunches.

In the single pass excitation the beam loses the smallest amount of energy to a HOM. This lowest energy deposited by a point-like charge q is:

$$\Delta W = \frac{\omega_o}{4}\cdot(R/Q)\cdot q^2$$

The power loss by the beam to a higher order mode in the multi-bunch excitation is:

$$P = \mathrm{Re}[Z]\cdot I_B^2$$

where I_B is the beam current.

HOM TRAPPING

Trapping inside cavity

In a multi-cell superconducting accelerating structure HOM couplers must be placed at the beam tubes. Experience showed that HOM couplers attached to the cells limited the performance of a cavity to low accelerating gradients. Unfortunately some HOMs have very little stored energy in the end-cells. Their suppression is difficult. The phenomenon is commonly called: trapping inside the cavity. The reason for the trapping is the difference in mode frequency of the end- and the inner cells. A computed example is shown in Fig. 1. In a 13-cell TESLA-like structure the 2.4 GHz monopole mode has very little stored energy in the end cells. The difference in frequency between end- and inner cells for this resonant pattern is 30 MHz. Since cell-to-cell coupling is 3% for this passband the end cells cannot resonate "together" with the inner cells [1].

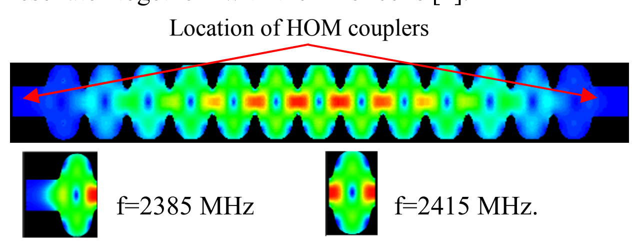


Figure 1: Example of mode trapping in a 13-cell cavity. End-cells and inner-cells have different frequencies for this resonant pattern.

Trapping inside cryomodule

A similar phenomenon happens in a multi-structure cryomodule. The frequency difference (due to fabrication errors) between neighboring structures cause trapping of propagating modes. Fig. 2 displays a computed example for the 8.878 GHz monopole mode in a part of the TESLA Test Facility (TTF) like cryomodule. The mode is excited by the beam in the middle cavity. It does not propagate towards a beam line absorber located between cryomodules due to the $\Delta f = \pm 32$ MHz of frequency difference for this mode for both outer cavities. The chosen Δf is a statistic value measured for the first three cavity series installed in the TTF linac [2].

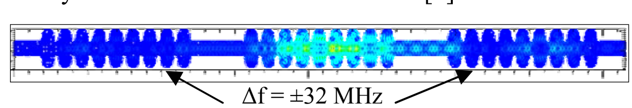


Figure 2: Computed example of trapping in cryomodule.

MEASURES AGAINST TRAPPING

Number and Matching of Cells

Fewer cells in a structure reduce trapping probability. The mode in the first example (Fig.1) demonstrates less trapping when the number of cells is reduced to nine or five (see Fig. 3). This obvious advantage of short cavities needs to be weighted against their main disadvantage, namely fast cost increase of an accelerator based on shorter structures.

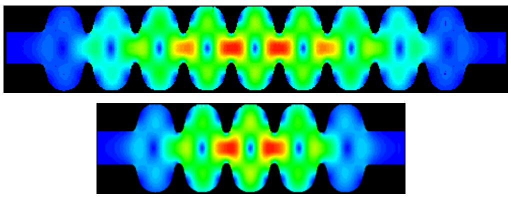


Figure 3: Shorter structures make trapping less probable.

The second way to minimize trapping probability is by means of matching the end- and inner-cells and enlarging the irises leading to enhanced cell-to-cell coupling for HOMs.

The 5-cell 704 MHz structure for the electron cooling at RHIC (Fig.4) fulfills all mentioned features to provide excellent mode damping and avoiding the trapping [3]. Computer simulations showed that this structure can accelerate, for the proposed RHIC cooling scheme and optics, beams up to 2A (forty times more than the specification). The HOM energy radiates out of the cavity and is dissipated in beam line absorbers. There is no need to attach HOM couplers. We should note that the shape of end-cells is very similar to the inner-cells. The niobium prototype of the structure was built by Advance Energy Systems in 2006 and will be tested soon at Brookhaven National Laboratory.

This kind of design is suitable for short accelerators operating at moderate gradients since enlarging of irises leads to strong reduction of the intrinsic impedance for the fundamental mode and to an enhanced cryogenic load.

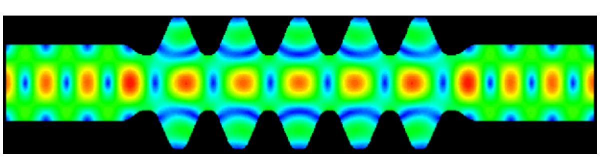


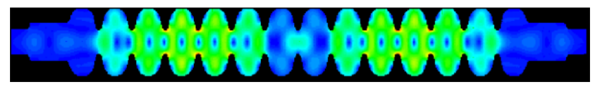
Figure 4: 5-cell 704 MHz structure for the electron cooling at RHIC.

To avoid partially HOM trapping in longer multi-cell structures, designed for high gradient operation, one can use two differently shaped end-cells (asymmetric cavity). The method has been applied to TESLA structure [4] as remedy against trapping of the highest impedance mode in the third dipole passband. The modification of end-cell geometry resulted in increased stored energy in the dipole mode, improving its damping, but led to less suppression of the highest impedance monopole mode. The two applied end-cells in the TESLA design compromise damping of both passbands.

Weakly Coupled Structures

The other way preventing the HOM trapping in a long high gradient structure which keeps its cost advantage (one fundamental coupler supplying many cells) is splitting it in short subunits connected by $\lambda/2$-long tube(s). The length of the interconnections ensures synchronism between the beam and the accelerating mode, enables energy flow between weakly coupled subunits and offers space for the attachment of HOM couplers. The layout of 2x7-cells was tested successfully with beam at the TTF linac in 2002.

In the computed example (Fig. 5) a 14-cell TESLA like structure has been split in two 7-cell subunits. The displayed TM011-like mode, trapped in the fourteen-cell structure, can be easily damped by HOM couplers attached to the tube connecting two subunits.



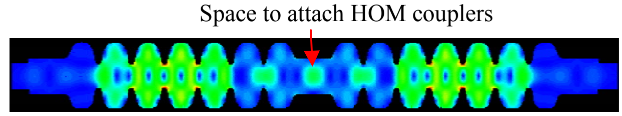


Figure 5: TM011-like monopole mode trapped in the 14-cell structure. The mode can be damped by HOM couplers located at the interconnecting tube of the 2x7-cell structure.

HOM COUPLERS

Coaxial Line Couplers

The HOM couplers based on the coaxial line technique were proposed in 1985 and applied few years later to 500 MHZ 4-cell HERA cavities and 352 MHz 5-cell LEP cavities. All forty-eight HERA couplers are still in operation [4]. Their construction and location (couplers are immersed in the helium bath) allowed for the continuous wave (cw) operation at moderate gradients. The HERA couplers provide excellent suppression of dangerous modes to Qext<1000 ensuring stable operation with electron and positron beams up to 45 mA.

The 1.3 GHz TESLA HOM couplers (Fig. 7) are similar to the HERA HOM couplers. Their RF-design has been simplified due to rather moderate damping specification (Qs of the order of 10^5). The couplers are located outside the helium vessel to minimize the cost of their production and assembly. This positioning is possible because of a negligible small heating in the coupler due to the low, 1% duty factor of the collider.

The TESLA HOM coupler has been scaled and implemented in other applications. The 805 MHz SNS HOM coupler resulted from the low frequency scaling with some minor additional modification. The 3.9 GHz HOM coupler for the third harmonic injector cavity is the high frequency scaling. In the recent version of that coupler less magnetic coupling (first post is straight) will be compensated with more electric coupling (enlarged diameter of the inner conductor). The computer modeling showed that the new version provides better cooling of all inner parts and has multipacting levels above the operating gradient [6].

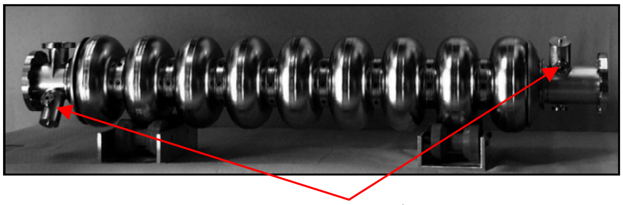


Figure 6: TESLA cavity with two HOM couplers.

CW Operation of TESLA HOM Coupler

The 1.5 GHz version of the TESLA HOM coupler has been proposed for the 12 GeV CEBAF upgrade cavities. The CEBAF accelerator operates in cw mode. Also many future applications of the TESLA cavities, mainly for linacs driving coherent light sources (4GLS, ELBE, BESSY…) will require HOM couplers operating in the cw mode or at least with large duty factor at high gradients. Enabling such an operation requires improvements in cooling of the TESLA HOM couplers if one wants to keep them outside the helium vessel. The problem here is heating of the output antenna by the residual magnetic field of the fundamental mode (several percent of the field on equator) and a heat leak of the output line. The phenomenon was first observed in 2002 in cw cold tests of SNS and CEBAF 12 GeV upgrade cavities at JLab. The first cw test for the fully equipped TESLA cavity was performed in 2004 at DESY. In this test a continuous decrease of the intrinsic Q due to the niobium antennae heating begun already at moderate gradient of 5 MV/m.

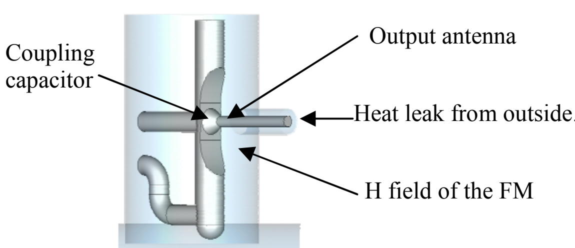


Figure 7: Heat sources in the coaxial HOM coupler.

Three modifications of the HOM coupler design are currently under investigation:

- Enhanced heat conduction N-type feedthrough with sapphire window and cooling Cu blocks [7].
- HOM coupler with hidden antenna [8].
- HOM coupler without coupling capacitor and direct connection between the inner conductor and the output line.

All three modifications follow the general assumption that the output antenna must stay superconducting to minimize heat load in the HOM coupler.

Parts of the improved RF feedthrough designed, manufactured and tested at JLab are shown in Fig. 8. The result of thermal tests T vs. applied heat for two feedthroughs is displayed in Fig. 9. In both cases temperatures were measured at the Nb antenna tip and at the flange. The sapphire feedthrough curve crosses 9.2 K, the critical temperature of Nb, at 43 mW power dissipated in the tip. The curve of the commercial available feed-through having good heat conductivity does it at 20 mW.

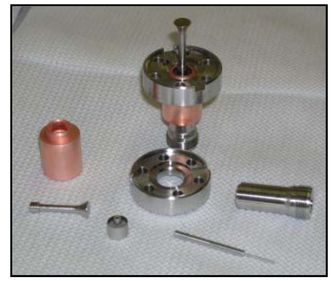


Figure 8: Parts of the feedthrough with improved heat conduction. *Courtesy of JLab*.

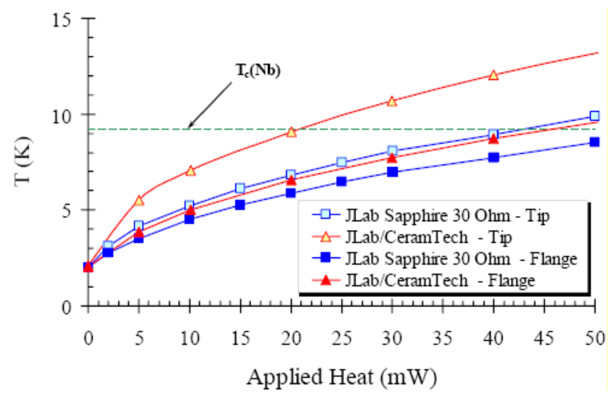


Figure 9: Thermal test results T vs. heat applied to the antenna tip. *Courtesy of JLab*.

A single cell cavity has been built at JLab for the cold test of the HOM coupler with hidden antenna. The inner conductor of the coupler has an additional inductive post directed to the output tube (Fig 10). The antenna is recessed into the tube and thus is not exposed to the residual H field of the fundamental mode.

The first cold test with the cavity immersed in 2 K helium bath showed significant improvement in achievable gradients up to 28 MV/m for the new design as compared to 15 MV/m for the original TESLA coupler.

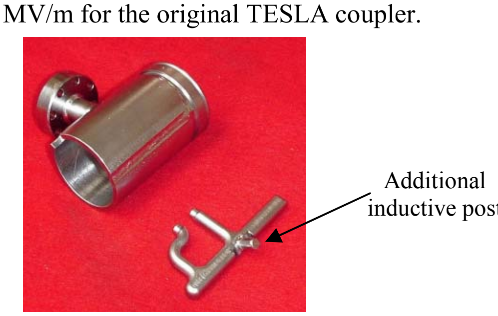


Figure 10: Parts of the HOM coupler with the hidden antenna.

A Two-cell cavity was designed at DESY to perform cold tests of the HOM coupler with direct connection between its inner conductor and the output line. The cross-section of the coupler is shown in Fig. 11. This time an additional inductive stub is terminated with a pin to be inserted into a slotted inner conductor of a feedthrough. The cavity is in a final fabrication stage at the ACCEL Company and should be ready for the test by the end of this year. The output antenna is cooled down to the temperature of the HOM coupler inner conductor.

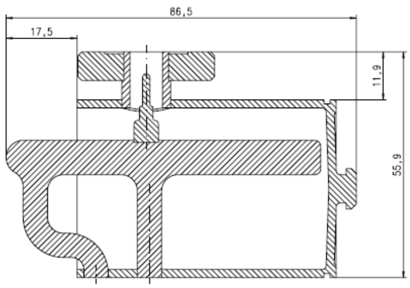


Figure 11: HOM coupler with direct connection between its inner conductor and the feedthrough.

A copper model of the coupler was built to investigate suppression of HOMs and an achievable Qext for the accelerating mode. The measurements on the TESLA cavity Cu model proved that both the HOM damping spec for ILC and high Qext (> 10^{11}) for the fundamental mode are provided by this new version of the TESLA HOM coupler.

Waveguide Couplers

The HOM couplers based on the waveguide technique were first designed at Cornell University in 1982 for the 1.5 GHz cavities (Fig. 12). 160 of these cavities operate very successfully in the CEBAF accelerator. Low nominal beam current of CEBAF and very small amount of the HOM power allow termination of the HOM couplers with waveguide loads inside cryomodules. The experience with the CEBAF waveguide couplers showed that they do not have the discussed heating problems when they operate cw but their mechanical dimensions strongly influenced the size of cryomodules. In case of higher beam current the terminating loads must be located outside the cryomodule. This would be mechanically rather complicated and would cause additional heat leakage and shielding problems.

New applications of waveguide HOM couplers for structures operating with high current were proposed at JLab by G. Wu [9] and R. Rimmer [10]. The first structure, shown in Fig. 13, can accelerate beams up to 100 mA, the second one shown in Fig. 14 is meant for 1A class accelerators.

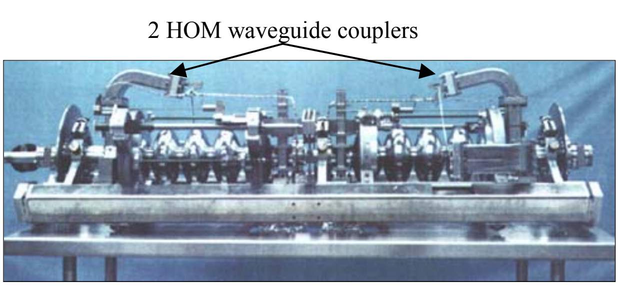


Figure 12: Pair of 5-cell 1.5 GHz CEBAF cavities with HOM waveguide couplers.

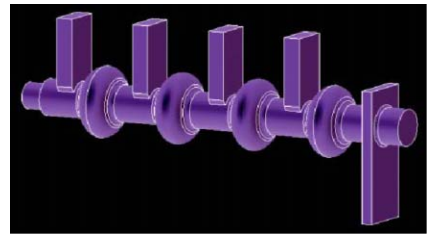


Figure 13: Weakly coupled 1.5 GHz cells with waveguide HOM couplers proposed in [9].

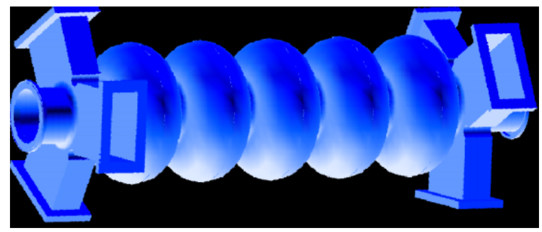


Figure 14: 750 MHz 5-cell structure with six waveguide HOM couplers discussed in [10].

Recently an idea of a circular waveguide damper was re-investigated at KEK [11]. The scheme (Fig. 15) has been tested on the copper model of the TESLA single-cell and 9-cell cavities (Fig. 16). Good HOM suppression was obtained for the single-cell. The damping on 9-cells needs further investigation. It is expected that the ILC specification can be reached with dampers attached closer to the end-cells.

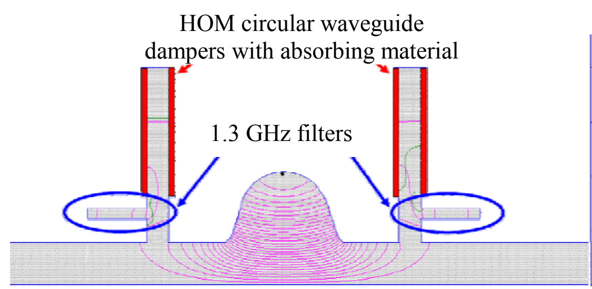


Figure 15: Two circular HOM dampers as modeled with single TESLA cell.

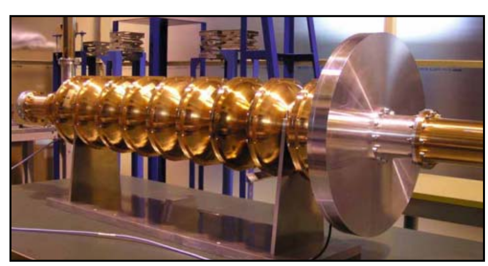


Figure 16: TESLA 9-cell structures with circular damper.

BEAM LINE ABSORBERS

Room Temperature Absorbers

Single cell superconducting structures in B-factories, synchrotrons or light sources operate with high currents and therefore need strong HOM suppression. The common idea is to make all HOMs propagating into the beam tubes and dissipate their whole energy at room temperature outside the cryomodule. While operating gradients are rather low for these cavities, a low intrinsic impedance of their fundamental mode, a consequence of the enlarged irises, does not cause big cryogenic load.

Four 500 MHz cavity designs: KEK-B in Tsukuba, CESR at Cornell [12], Taiwan Light Source and BEP-II in Beijing utilize ferrite beam line absorbers to dissipate several kilowatts of the HOM power. The CESR cavity absorber is shown in Fig. 17. Similar absorber will be used for the RHIC electron cooling 5-cell cavity.

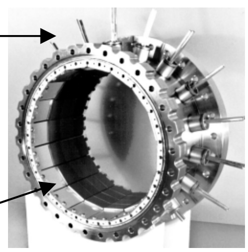


Figure 17: Ferrite beam line absorber used for CESR cavity.

Low Temperature Absorbers

The ERL at Cornell will operate with nominal beam current up to 100 mA. The stable operation of the linac requires suppression of about 130 W of the HOM power per 7-cell cavity. For this, beam line absorbers will be installed between cavities inside the cryomodule. It is still under investigation what kind of material (ferrite or ceramic) will be used for the absorption. The absorbers will be thermally connected to the liquid nitrogen line keeping their working temperature near to 80 K for the nominal current operation. Two bellows will match the length of the absorber and isolate it thermally from the 2K environment. Fig. 18 shows the present design of the absorber [13].

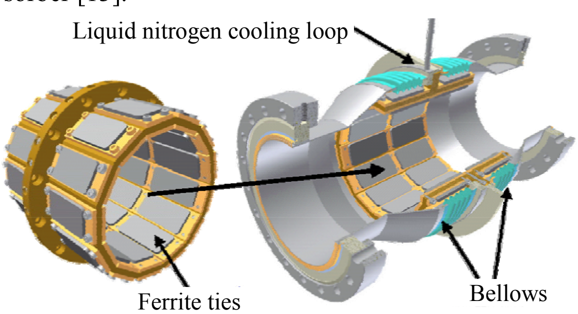


Figure 18: Ferrite beam line absorber as proposed at present for the ERL at Cornell.

A high frequency part of the HOM spectrum of the European XFEL facility will be dissipated in the beam line absorbers installed between 8-cavity cryomodules. The propagating HOM power will be 5.4W/cryomodule for the operation with 40000 bunches/s and the nominal bunch charge of 1 nC. CERADYNE ceramic rings will be used for the absorption (Fig. 19). Dissipated power will be transferred to the liquid nitrogen line by the copper stub brazed directly to the ceramic. The stub holds the ring in the vacuum chamber made of stainless steel. Heat capability of the absorber is more than 100 W. This capability margin is foreseen for the future upgrade of the facility. Manufacturing of the prototype is almost finished. It will be tested in the TTF linac in 2007.

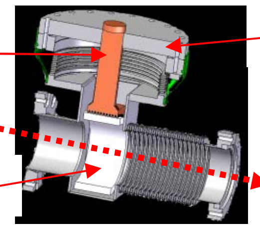


Figure 19: Beam line absorber for the European XFEL facility.

REFERENCES

[1] J. Sekutowicz, "Lectures on the SRF Technology", Tsinghua University, Beijing, November 2005, jacek.sekutowicz@desy.de.
[2] J. Sekutowicz, "HOM Damping" 1st ILC Workshop, KEK, Tsukuba, November 2004.
[3] I. Ben-Zvi et al., "Electron Cooling of RHIC", PAC2005, Knoxville, TN, May 2005.
[4] E. Haebel et al., "Cavity Shape Optimization for a Superconducting Linear Collider", HEACC, vol. 2, 957-959, Hamburg 1992.
[5] J. Sekutowicz, "HOM Couplers at DESY", Proc. of SRF'87 Workshop, ANL, 597-604. Argonne, USA.
[6] T. Khabiboulline, private communication.
[7] C. E. Reece et al., "High Thermal Conductivity Cryogenic RF Feedthroughs for Higher Order Mode Couplers", PAC2005, Knoxville, TN, May 2005.
[8] P. Kneisel et al., "Coaxial HOM Coupler Designs Tested on a Single Cell Niobium Cavity", this Proceedings.
[9] G. Wu et al., "A Four-Cell Periodically HOM-Damped RF Cavity for High Current Accelerators", LINAC2004, Lübeck, August 2004.
[10] R. Rimmer et al., "Concepts for the JLab Ampere-Class CW Cryomodule", PAC2005, Knoxville, TN, May 2005.
[11] K. Umemori et al., "New scheme of HOM damping of L-band cavity using a radial transmission line", ERL2005, Newport News, VA, March 2005.
[12] S. Belomestnykh, et al. "Superconducting RF System for the CESR Luminosity Upgrade: Design, Status, and Plans", EPAC96, Sitges, Spain, June 1996.
[13] G. H. Hoffstaetter et al., "The Cornell ERL Prototype Project", PAC2003, Portland, OR, May 2003.
[14] N. Mildner et al., "A Beam Line HOM Absorber for the European XFEL Linac", SRF2005, Ithaca, NY, July 2005.