HOM-FREE 2-CELL CAVITY WITH STRONG INPUT COUPLER FOR THE SC ERL INJECTOR

V. Shemelin#, H. Padamsee, S. Belomestnykh

Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853

Abstract

For the ERL injector, superconducting cavities are needed to deliver to the beam 100 kWCW RF power. With a beam current of 100…33 mA, gap voltage of 1…3 MV, the coupler must have the external *Q*-factor in the range $4.6\times10^4 \ldots 4.1\times10^5$. The cavity shape and coupler design presented provide the possibility to work in the range of parameters without substantial transverse kick to the beam and HOM-losses in the system. In order to drive out a low-frequency dipole mode the 2-cell cavity has a protruding iris between the cell and the larger beam pipe. A twin-coaxial coupler has high coupling but low kick because of its symmetry. Calculation and optimization of the coupler-cavity system are performed with a 2D SLANS and 3D Microwave Studio® codes.

Key aspects: Superconducting RF cavity, RF couplers, Higher order modes, Energy recovery linac

1 INTRODUCTION

Radio frequency superconductivity has become an important technology for particle accelerators [1]. Superconducting cavities have been operating routinely for many years in a variety of accelerators for high-energy physics, nuclear physics research and free-electron lasers. A multi-GeV Energy Recovery Linac (ERL), proposed by Cornell University in collaboration with Jefferson Lab, is a low emittance, high average beam current CW accelerator for X-ray science [2]. An injector and a main linac of the ERL are based on the superconducting RF technology.

One of driving ideas behind this machine is to create a low emittance beam using a high-brightness photoemission electron gun and then to preserve the emittance while the beam is accelerated in the injector and in the main linac. The goal is to have the beam with the normalized emittance of 2 mm·mrad in undulators. An extension of existing technology in several directions is required to achieve this ultimate goal. Development of a 100 MeV, 100 mA average current ERL prototype is in progress at Cornell University [3].

One of the possible sources of emittance dilution is a kick caused by non-zero on-axis transverse electromagnetic fields of fundamental power couplers in superconducting cavities. This effect is especially strong in the injector cavities, where a high average RF power per cavity must be coupled to a vulnerable low-energy beam. The requirements here are far more demanding than in any existing system. Our design goal is to allow a maximum emittance growth of no more than 10% total for five injector cavities out of the initial emittance of 1 mm·mrad [4].

The five injector cavities are superconducting 2-cell niobium structures. They provide a total of 500 kW of RF power to the beam. Consequently, the permitted beam current depends on the injector energy and varies from 100 mA at 5 MeV to 33 mA at 15 MeV. The injector cavity coupler has to deliver to the beam $P_{\text{beam}} = 100$ kW of RF power and provide matching conditions for a cavity gap voltage of V = 1 through 3 MV and corresponding beam current of 100 through 33 mA. In accordance with the formula

$$Q_{\text{ext}} = \frac{V^2}{\rho P_{\text{beam}}},$$

where $\rho = R/Q$ is the characteristic impedance of the cavity, the coupler must be adjustable with the external Q factor overlapping the range from 4.6×10^4 to 4.1×10^5. Such small values of Q_{ext} may demand a deep insertion of the antenna into the beam pipe that adds to the problem of the kick.

There are several possibilities to completely or partially suppress the transverse kick from the fundamental RF power coupler and associated with it emittance growth. They are analyzed in detail in [5]. We settled on the twin-coaxial coupler as a more practical option. The influence of possible mechanical asymmetry of installation and electrical asymmetry caused by phase shift between two inputs is also discussed in [5]. This influence is shown to be negligible. Here we will examine the influence of the low frequency dipole mode.

Another source of the emittance dilution is an interaction of the beam with high Q transverse higher-order modes (HOMs). A charge moving slightly off-axis in the accelerator beam pipe will excite dipole, quadrupole, and other axially asymmetric HOMs. If any of such modes has high Q factor and is in resonance with the beam, it will provide strong deflecting field enlarging small initial emittance. Especially dangerous are lowest dipole modes whose frequencies can be below cut-off frequency of the beam pipes. However, it is possible to find a cavity shape so that the frequency of the lowest dipole mode is high enough to propagate into the beam pipe. In this case its impedance becomes small as well as its impact on the beam. Examples of such shapes are single-cell superconducting cavities developed at Cornell [6] and at KEK [7].

#vs65@cornell.edu

In this paper we present an optimization of the 2-cell superconducting cavity shape with a propagating lowest dipole mode and detail study of this mode in the presence of the twin-coaxial coupler. 2D codes SLANS and SLANS2 [8] were used to optimize the cavity shape. The 3D MWS 4.0 code was used to verify the obtained results, to optimize the coupler and to study the dipole modes in the presence of the coupler.

2 OPTIMIZATION OF THE CELLS SHAPE

Having the same frequency as in the TESLA project [9] and planning to use the TESLA-like nine cell cavities in the main linac of ERL, we first chose the shape of the 2-cell cavity also TESLA-like (Fig. 1a). However, it turned out that this geometry has a trapped dipole mode. In order to allow this mode to propagate into the beam pipe we decided to use the KEK approach by enlarging one of the beam pipes. We chose the inner radius of one of the beam pipes and the radius of the iris equal to these of TESLA. Scaling of the KEK single-cell dipole-mode-free cavity gave us bigger inner radii. A decrease of the inner iris radius increases the frequency of the dipole mode significantly, so we stayed at the TESLA value for the inner iris radius. The larger beam pipe (right-hand one on the Fig. 1, b and c) serves for propagating the dipole mode from the cavity. The right iris (Fig. 1 c) secures identity of fields in both cells but does not preclude the coupling of the dipole mode with the beam pipe.

We analyzed the influence of different cavity parameters on the TE11-mode frequency and on the maximal values of the surface fields, electric and magnetic, and on the value of $\rho = R/Q$ of the fundamental mode.

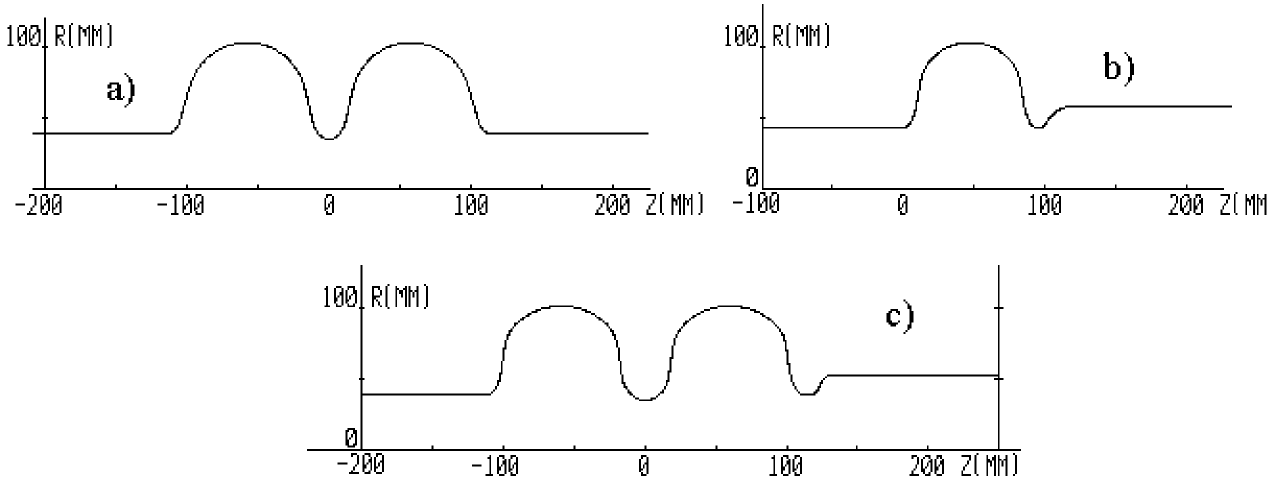

Fig. 1. a) Geometry with a trapped dipole mode (TESLA-like), b) Geometry of KEK with a propagating dipole mode, c) Optimized geometry for ERL injector with a propagating dipole mode.

After preliminary optimization we chose a goal function

$$Z = \ln\left(\frac{\rho}{e \cdot h}\right),$$

where e is a normalized peak electric surface field, and h is a normalized peak magnetic surface field. We used the normalization to the TESLA cells fields, where the peak values are

$$E_{\mathrm{pk}}/E_{\mathrm{acc}} = 2.0, \qquad H_{\mathrm{pk}}/E_{\mathrm{acc}} = 42 \ \text{Oe/(MV/m)}.$$

E_{pk} and H_{pk} are peak surface electric and magnetic fields, respectively, and E_{acc} is acceleration in the cell divided by cell length. We used here as the length of the 2-cell cavity the value of the wave length (π-mode). So, for the case of TESLA, it would be e = 1, h = 1. The other obligatory condition for the goal function was taken as $\Delta f\,(\mathrm{TE11}) > 10$ MHz, *i.e.* the frequency of the dipole (TE11-like) mode was kept not less then 10 MHz higher than the cut-off frequency of the beam pipe.

The optimization consisted in increasing the value of Z by changing the parameters of the cavity. Since

$$\Delta Z/Z = \Delta\rho/\rho - \Delta e/e - \Delta h/h,$$

a sum of relative improvements of these 3 variables should increase but any particular ratio can degrade. The preliminary optimization secured that no one of these ratios can degrade to an unacceptable value.

The geometry of the cavity (Fig. 2) is built of 4 equal big elliptical tori; each pair of them makes “a cell”, inside each pair a small-height cylinder is inserted (it presents an equatorial line on the picture because of small height); 2 beam pipes: left and right; 3 irises, left, central and right, made also with help of elliptic tori, the right iris has a straight (cylindrical) segment; 4 cones with side profile lines conjugated with the tori. Transition to the right beam pipe is made in the form of a round torus. The equatorial radius of the big tori was defined by the fundamental mode frequency (1300 MHz).

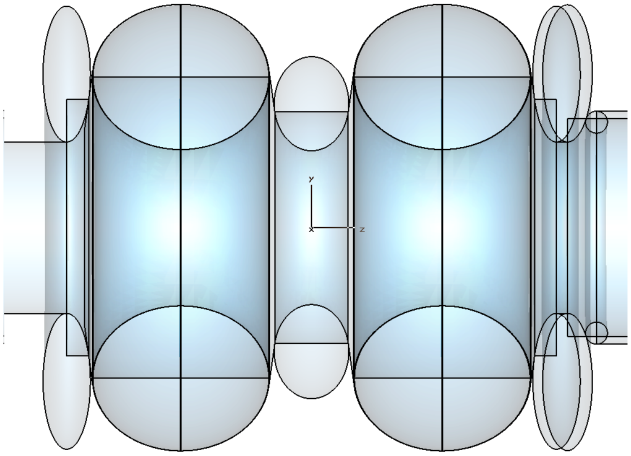

Fig. 2. Composition of the cavity.

As the parameters of optimization, the following 7 variables were used: *A* and *B* – half-axes of big tori, *a* and *b, ac* and *bc* – half-axes of the side and central elliptic tori, respectively, and *sr* - height of the cylinder in the middle of the right cell. All other dimensions were fixed, the most important of them are: radii *Rbpl* = 39, *Rbpc* = 35, *Rbpr* =53 (all dimensions in mm) of the left beam pipe, central iris and the right beam pipe, respectively. The cut-off frequency of the TE11-mode in the tube with a radius of 53 mm is 1657.53 MHz.

It is essential that the right iris have the same inner radius as the left pipe. The bigger right-hand beam pipe radius causes only small asymmetry of the fundamental mode and its influence is compensated by insertion of a small height (*sr)* cylinder (see above).

Finally, the following optimized values were obtained:

$e = 0.97$, $h = 1.02$, $\rho = 220.9$ Ohm (two cells).

Even having strong restrictions upon the frequency of the dipole mode, we have found main cavity parameters being not much different than those of the TESLA cavity (ρ = 114.4 Ohm per cell). This can be explained by an additional freedom: we have no limitations for the cell length. As one can see (Fig. 1), the injector cavity has a thicker iris than in TESLA. This is connected with the quest for higher frequency of the dipole mode. The cell to cell coupling is weaker (0.7 %) but still sufficient for 2 cells.

3 OPTIMIZATION OF THE COUPLER SHAPE

Fig. 3 shows the geometry of the cavity with twin-coaxial coupler and some details of the coupler. Because the ERL injector cavity coupler has to transfer average power of 100 kW, we have decided to use 60 mm diameter outer conductor [5]. To minimize losses in the inner conductor we choose an impedance of 60 Ohm. A shape of the antenna tips presents a bended elliptic disc. Parameters of this disc were found reasoning from two requirements: to keep the dipole mode frequency as high as possible, and provide necessary coupling with the cavity. The bending of the disc, for example, increases coupling by 20 % as compared with a flat disc.

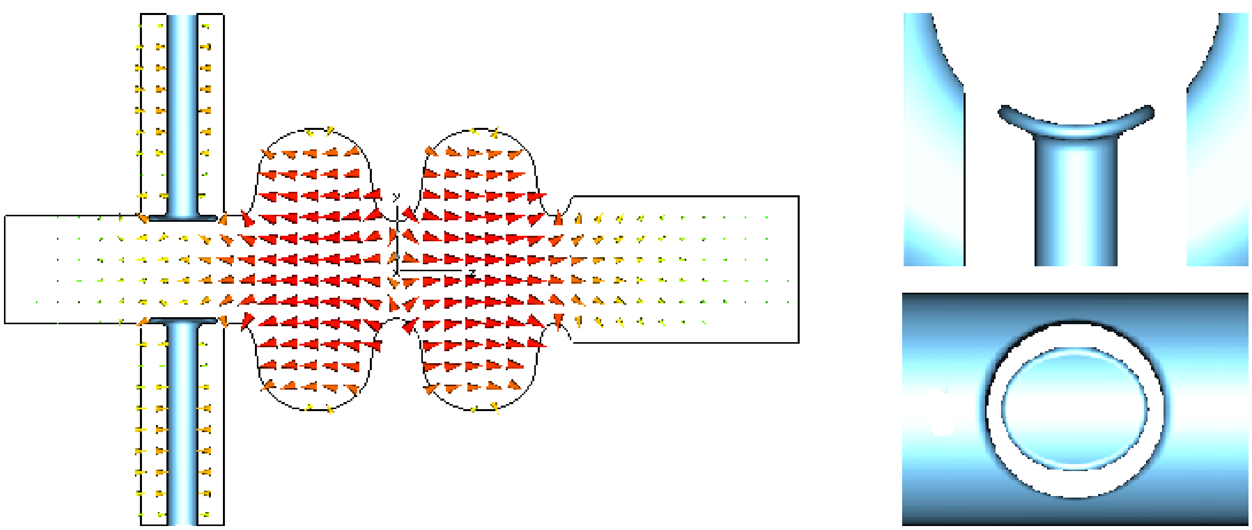

Fig. 3. Geometry of the cavity with the fundamental mode excited in it and details of the coupler.

The coupler should be made adjustable by changing the depth of penetration of the antenna tip. The depth is measured relative to the inner cavity iris: when the distance axis – antenna tip center is 35 mm, the *depth* = 0.

The edges of the cross-sections between the outer tube of the coaxial line and the beam pipe are rounded (with the help of MWS operation *blend*) with a radius of 4 mm. This rounding helps to exclude high values of electric field on the surface and increases coupling but decreases the dipole mode frequency.

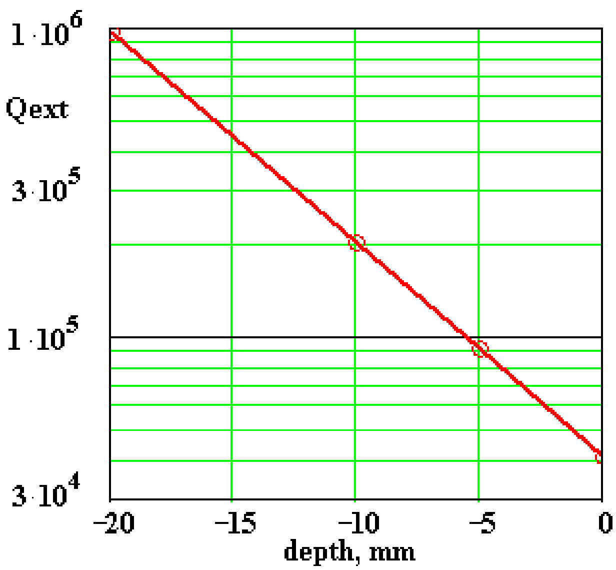

Fig. 4. Dependence of Q_{ext} on the depth of antenna penetration.

Finally (see Fig. 3), the smaller radius of the elliptic cross-section and the ratio of its half-axes were used for optimization.

The final value $Q_{ext} = 4.08\times 10^4$ satisfies the specified requirements. The value of the $\rho = R/Q$ obtained with MWS was 218 Ohm that is slightly different from the SLANS results.

4 PROPERTIES OF THE DIPOLE MODE

We aimed to keep the condition $\Delta f\,(\mathrm{TE1}) > 10$ MHz for the dipole mode by optimization of the cavity shape (see above) to secure adequate propagation. Calculation with the SLANS2 2D code gave $\Delta f\,(\mathrm{TE1}) = 10.01$ MHz whereas the MWS result was 9.99 MHz. The last result was obtained with two planes of symmetry for axially symmetric (without coupler) geometry and with a number of mesh nodes about $1.1{\cdot}10^6$. However, this value changed to 8.17 MHz for the mesh with $2{\cdot}10^5$ nodes with the same symmetry. We could not use the mesh with the number of nodes bigger than $1 \ldots 1.5{\cdot}10^6$ because the time for calculation of a single geometry became more than 2 hours. So, data for the asymmetric case, with the antennas added to the geometry may have an error about 2 MHz.

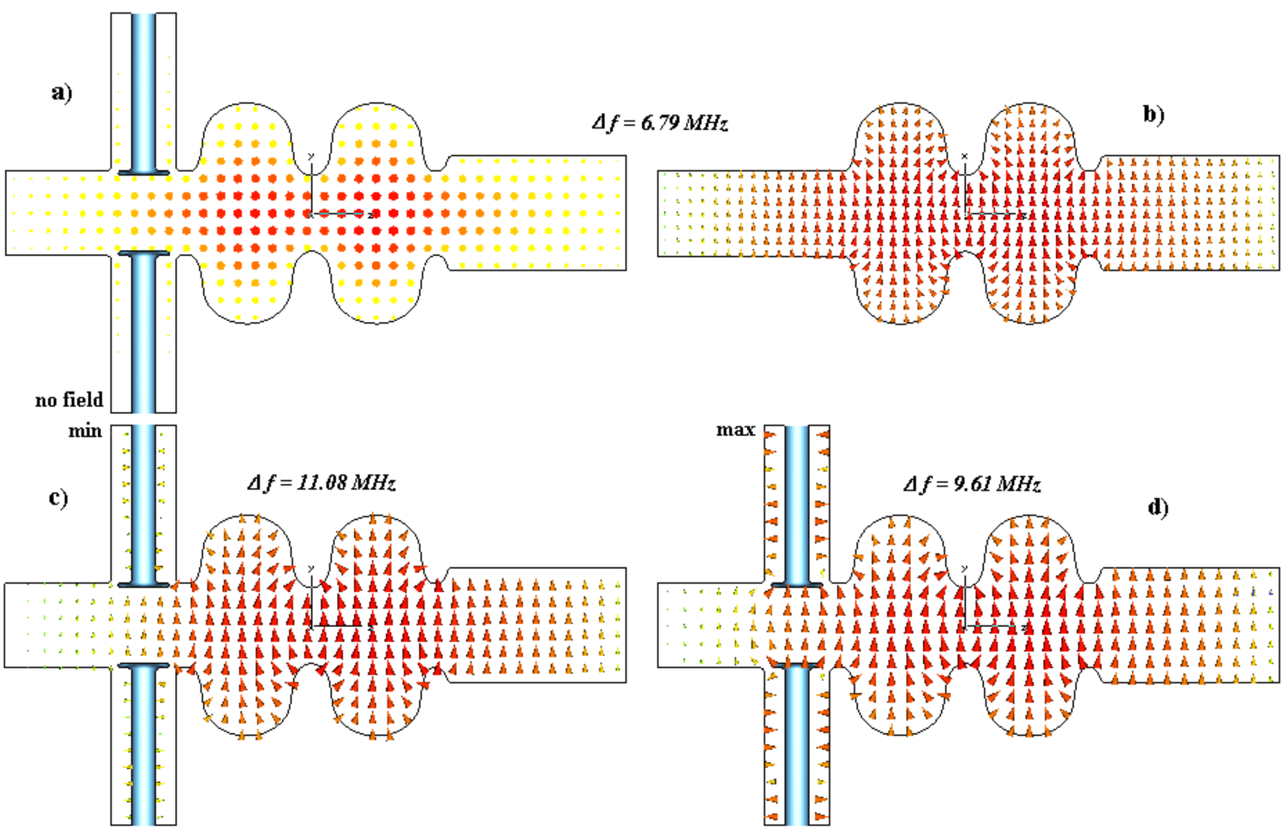

Fig. 5. Splitting of the dipole mode: the electric field is shown. a) and b) - the transverse mode; c) and d) - the parallel mode with electric and magnetic walls at the ends of coaxial lines, respectively.

When two coaxial couplers are added to the geometry, degeneracy of the dipole mode is cancelled, and the mode splits into 2 modes: parallel mode, with the electric field parallel to the coaxial line, and the transverse mode (Fig. 5). Their frequencies now depend on the parameters of the coupler, and for the chosen set of these parameters are: 11.08 and 9.61 MHz above the cut-off for the parallel mode, and 6.79 MHz above the cut-off for the transverse mode. Frequencies are given for the electric boundary condition at the end of the larger beam pipe.

Two values of the parallel mode frequency are presented because the frequency of this mode depends on the boundary condition at the ends of the coaxial line: the higher value (11.08) is for the electric boundary condition ($E_t = 0$) and the lower (9.61) for the magnetic one ($H_t = 0$). This means that the parallel mode is excited not only in the larger beam pipe but in the coaxial line also and thus has all the more low external *Q*. With the method described in detail in [5] and extended for round waveguides, the value of Q_{ext} of the parallel dipole mode was found as $Q_{ext,p} = 250$.

The transverse dipole mode has lower frequency than the initial value (without coupler) but still propagates into the beam pipe. It has $Q_{ext,t} \sim 1000$.

5 MWS ISSUES, DETAILS AND DIFFICULTIES

CST MICROWAVE STUDIO® is a powerful and vivid software package adequate to the problem we have. When the results are obtained, one has many possibilities for their presentation in a convenient form.

However, we had some problems with the code on different stages of the work. For example, the geometry of the cell without the coupler composed of about 20 objects could not be calculated until the coordinate axes were rotated. It appeared that the same values of the *X* and *Y* coordinates for different *Z* on the shape contour line were inappropriate if these were the points of connection between objects.

In another case, an introduction of the symmetry plane led to errors in the mesh construction whereas before this introduction the program ran properly.

It would be useful to have a possibility to print out the *History* in the form that is seen on the screen, without details that open in the *Edit* field.

In the *Edit History List Item* for *Cones* the values of *Xcenter* and *Zcenter* are swapped. You need to keep it in mind when editing. But if you do not know about it, you need to spend some time to grapple with it.

It would be convenient if the program after a long run reports about finishing by a sound signal.

Hence, the package needs improvements.

A lot of hints and tricks being used by the supporting team are not described anywhere, the idea to have the USER MEETING is really very helpful but can not resolve all the questions at once. More detailed manuals and online help are needed.

6 CONCLUSIONS

Calculation of a 3D cavity-coupler system was performed using the MWS 4.0 software package. The results are partly checked and confirmed with other codes: 2D-codes SLANS and SLANS2, a good precision and reliability of which are well known to users. These codes were also used for optimization of the cavity shape.

Some useful parameters of the 2-cell cavity with a coupler are summarized in Table.

The completion of calculations allows us to begin production of the injector cavity with the twin-coaxial coupler.

Table. Calculated parameters of the 2-cell cavity with the twin-coaxial coupler.

Fundamental π-mode frequency	1300 MHz
E_{pk}/E_{acc}	1.94
H_{pk}/E_{acc}	42.8 Oe/(MV/m)
Coupling cell to cell	0.7 %
R/Q, fundamental mode (FM), SLANS	220.9 Ohm
R/Q with the coupler, FM, MWS	218 Ohm
Q_{ext}, FM, required range	$4.6\times10^4 \ldots 4.1\times10^5$
Q_{ext}, FM, penetration of the antenna *depth* = 0…-15 mm	$4.1\times10^4 \ldots 4.6\times10^5$
Cut-off frequency for the lowest dipole mode (TE11), beam pipe *R* = 53 mm	1657.53 MHz
$Q_{ext,p}$, dipole mode, parallel	250
$Q_{ext,t}$, dipole mode, transverse	1000
Cut-off frequency for the lowest monopole mode, beam pipe *R* = 53 mm	2164.96 MHz

The authors thank Mathias Liepe for helpful discussion and Ivan Bazarov who wrote a useful macro.

In the course of this and some other works with Microwave Studio the authors got a highly qualified, very friendly and timely help of the CST supporting team. We express special thanks to Fred Beihold, Wigand Koch and Jingsong Wang and hope for further collaboration.

7 REFERENCES

[1] H. Padamsee, J. Knobloch and T. Hays, *RF Superconductivity for Accelerators*, New York, John Wiley and Sons, (1998).

[2] Study for a proposed *Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University*, ed. by S. Gruner and M. Tigner, CHESS Technical Memo 01-003 and JLAB-ACT-01-04 (4 July 2001).

[3] I. Bazarov, et al., "Phase I Energy Recovery Linac at Cornell University", *Proceedings of the 8th European Particle Accelerator Conference*, Paris, France, June 2002, pp. 644-646.

[4] S. Belomestnykh, et al., "High Average Power Fundamental Input Couplers for the Cornell University ERL: Requirements, Design Challenges and First Ideas," Cornell LEPP Report ERL 02-8 (9 September 2002).

[5] V. Shemelin, S. Belomestnykh and H. Padamsee, "Low-kick Twin-coaxial and Waveguide-coaxial Couplers for ERL", Cornell LEPP Report SRF 021028-08 (28 November 2002).

[6] H. Padamsee et al., "Accelerating Cavity Development for the Cornell B-Factory, CESR-B", *Proceedings of the PAC'91*, pp. 786-788.

[7] S. Mitsunobu et al., "Superconducting RF Activities at KEK", *Proceedings of the 5th Workshop on RF Superconductivity*, Hamburg, Germany, 1991, pp. 84-94.

[8] D. G. Myakishev, V. P. Yakovlev. "The New Possibilities of SuperLANS code for Evaluation of Axisymmetric Cavities", *1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators*, Texas, May 1995, pp. 2348-2350.

[9] B. Aune et al., "Superconducting TESLA Cavities", *Phys. Rev. ST Accel. Beams* **3** 092001 (2000).