NOTE ON THE SC LINEAR COLLIDER TESLA CAVITY DESIGN

J. Sekutowicz, D. Proch, C. Tang
DESY-MHF
22603 Hamburg, FRG

ABSTRACT

The experience we have gained over the last few years from experiments with superconducting cavities for the TESLA test facility, justifies a revision of the design proposed almost five years ago [1,2]. The proposed new design, presented here, takes the advantage of the high quality factor $Q_o > 10^{10}$ and low electron emission at the specified accelerating field of 25 MV/m, as demonstrated by some tested cavities. The main aim of the design is to simplify production and preparation of superconducting (sc) cavities and thus to reduce the cost of the linear collider. The new cavity shape has an enlarged iris diameter with the following advantages: significantly lower loss factors, a simplified and less expensive scheme for the HOM damping and the suitability of hydroforming and higher stability of the field profile.

1 INTRODUCTION

The quality factor, Q_o, vs. E_{acc} of two 1.3 GHz, 9-cell TESLA cavities is shown in Fig. 1. The Q_o reaches a very high value $\sim 5\ 10^{10}$ at low field region and stays above $1.7\ 10^{10}$ for one cavity and above $3\ 10^{10}$ for the second one, for the accelerating field of $E_{acc} = 25$ MV/m, the

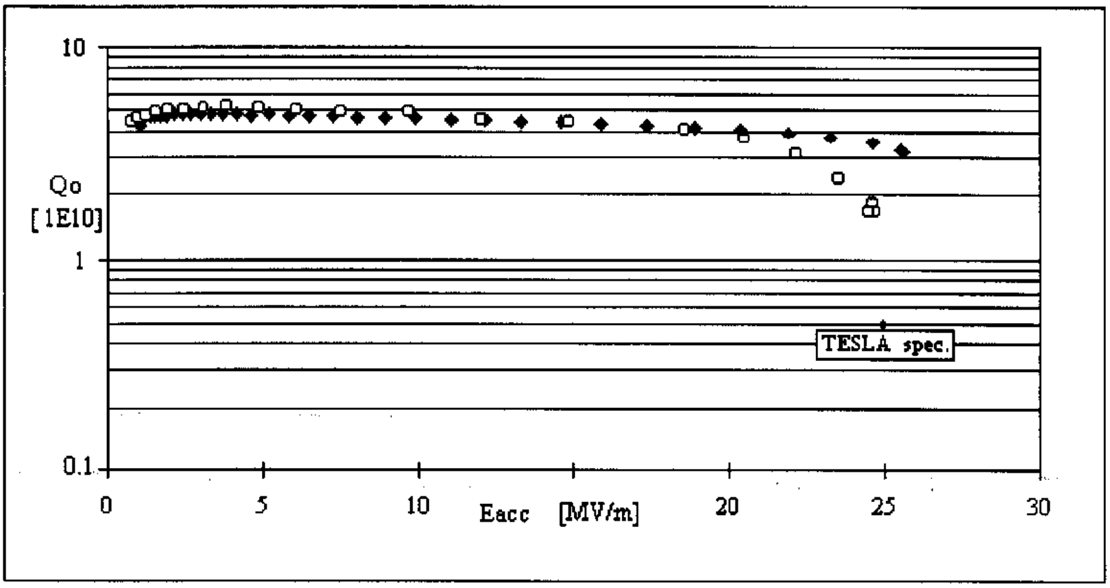

Fig. 1 Q_o vs. E_{acc} as measured in a vertical cryostat.

specified value for the sc linear collider [3]. The power dissipated in the cavity wall P_{diss}, cooled by 2 K LHe, is proportional to:

$$P_{diss} \approx \frac{(E_{acc})^2}{(\frac{R}{Q})*Q_o} \qquad (1)$$

where (R/Q) is the characteristic impedance of a cavity. For cavities with quality factors depicted in Fig. 1, the P_{diss} at 25 MV/m is 3.4 and 6 times respectively, lower than for a cavity with the specified value of Q_o = 5 10^9 [3]. The small slope of both curves demonstrates the important feature that cavities have low electron emission. It results from careful cleaning during the cavity preparation and the low field enhancement factor E_{peak}/E_{acc}.

The shape of the TESLA structure, proposed almost five years ago, has been chosen to :

minimize:

E_{peak}/E_{acc} to keep electron emission loading low,

H_{peak}/E_{acc} to shift quench level towards higher E_{acc},

and

maximize:

(R/Q) to provide low cryogenic load.

Final values of these parameters, listed in Table 1 have been achieved by means of a small iris diameter, but there are few negative consequences of the small aperture.

2 WEAK POINTS OF THE CURRENT DESIGN

2.1 Cell-to-cell Coupling

Since the coupling from cell to cell is small, the profile of the accelerating field is sensitive to the frequency perturbation of an individual cell. The error, ΔA, of the field amplitude in an individual cell for the accelerating π mode is proportional to:

$$\Delta A \approx \frac{(N)^2}{k} , \qquad (2)$$

where N is the number of cells in the structure and k is the coupling. Any mechanical, chemical or thermal preparation of TESLA structures causes a perturbation of the field configuration. Many TTF cavities from the first production had to be re-tuned several times to keep the field unflatness below the specified level of 5 %. Since tuning had to be performed outside the clean room, each re-tuning required that the cavity must be re-cleaned. This makes the preparation more expensive and more time-consuming to an unacceptable level for 20000 sc cavities. After the helium vessel is welded, no access to the cells is possible and therefore re-tuning, even when necessary, is impossible.

2.1.1 Decrease of the Effective Accelerating Gradient

Field unflatness decreases the effective accelerating field. Since the energy of colliding beams has been fixed, a compensation must be made for the lower effective gradient, either with additional length of the collider or by an operation of some cavities at E_{acc} above 25 MV/m. This requires only negligible additional RF power but the operation at a higher gradient may lead to an increased γ-radiation and a higher probability of quenches.

2.1.2 Energy Spread Resulting from Differences in Q_{ext}

The second complication coming from the field unflatness is a difference in Q_{ext}. The acceleration process in the TESLA collider is performed during the transient. This requires all cavities to be at 25 MV/m at the same time, 533 µs after the RF pulse is switched on. Since the cavity fill time depends on the loaded Q (in case of sc cavities mainly on Q_{ext}) differences in Q_{ext} yield to differences in the accelerating gradient during acceleration.

As an example, consider two cavities with Q_{ext}'s differing by ±15 % from the nominal value of $3.14\ 10^6$. At time t = 533 µs, the accelerating gradient in a high Q_{ext} cavity is lower by 0.75 MV and in a low Q_{ext} cavity is higher by the same amount, than E_{acc} in a cavity with the nominal Q_{ext}. The difference in voltage of 1.5 MV does not stay constant for a whole bunch train due to the different beam loading. At the end of the pulse (t =1.33 ms) it shrinks to 0.5 MV. This means that the energy gain, in cavities with non nominal Q_{ext}, changes from the beginning to the end of the pulse. To avoid this source of energy spread from bunch to bunch, two adjustable fundamental mode (fm) coupler designs, based on a coaxial line technique, have been proposed [4,5]. In both designs, the adjustment of Q_{ext} is performed by a change of penetration of the inner conductor in the beam tube. This adjustment unfortunately makes the design more complicated and expensive. Additionally, a fast Vector Control Loop will be used to reduce the energy spread, but this will require more RF power.

2.1.3 Lower Order Modes

A third problem resulting from the field unflatness is an increase of characteristic impedance of other modes belonging to the fm passband. If the cavity is well tuned, then the characteristic impedances of these modes are negligible. Perturbation of an individual cell causes that especially the impedance of the mode 8π/9 increases. The damping of these parasitic resonances is possible only by fm coupler. So, it is expected that the external Q's of these modes are in the range of the nominal value of Q_{ext} of the fundamental mode. A typically observed field unflatness of 15 % increases (R/Q) of the 8π/9 mode from almost 0 Ω to 5 Ω. In this case the impedance of this mode is : 5 $\Omega \cdot 3\ 10^6 = 15\ M\Omega$, as high as the impedance of monopole modes from the TM011 passband with the highest $(R/Q) \cong 150\ \Omega$.

2.1.4 Linac Fill Factor

In the present design, neighboring cavities in a cryomodule are separated by a 3/2 λ long beam tube. Therefore the ratio of the active length to the total length of the TESLA structure is only 0.75. Thus one quarter of both linacs length, 7 km, is not used for the acceleration. The effective average accelerating field is then reduced from 25 MV/m to almost 19 MV/m. One can improve the fill factor by increasing the number of cells per cavity and by shortening the interconnections between the cavities. Since the field profile of the present TESLA structures is already sensitive to frequency errors, an increase of N is impossible, so only interconnections could be made shorter to improve the fill factor.

2.2 Machining of the TESLA Structure

The cost of the electron beam welding is a significant part of the cavity fabrication cost. Eighteen half cells and two beam tubes per cavity must be specially prepared to provide nineteen high quality welds. Alternative fabrication methods are under consideration to lower the production costs. Two of them: hydroforming [6] and spinning [7] show a strong potential but their application to Nb cavities needs more R&D. The hydroforming of Cu cavities proofs that the required shape can be obtained with high precision and good reproducibility. The hydroforming process becomes simpler when the ratio of the maximum radius (equator) to the minimum radius (iris) of a cavity is about 2 or less. In the current design this ratio is almost equal to 3. The shape of the cavity plays also an important role. Also here, the tests performed on copper cavities showed that any narrow or small curvature, especially in the iris region, makes hydroforming more complicated. Unfortunately this is the case for the current cavity design.

2.3 HOM Coupler Adjustment

There are two important components of the performance of a HOM coupler: the achievable damping of parasitic modes and the rejection of the fundamental mode power. Both types of HOM couplers, the welded one and the demountable one, fulfill the HOM damping (Q_{ext}) specification, but the damping is strongly influenced by machining tolerances. If the obtained Q_{ext}'s are too high, a correction, to some extent, is possible, by the adjustment of the output line capacitor. The couplers are equipped with a built-in LC rejection filter to keep the outcoupled fm power low, even at E_{acc} = 25 MV/m. Similarly here, fabrication errors are corrected by adjustment of the filter capacitor. The adjustment of the output line capacitor and the adjustment of the filter capacitor are time consuming preparation steps. This is mainly due to the small dimensions of both capacitors and to the mechanical changes resulting from the cooldown and the warm-up procedures. Keeping in mind, that the TESLA collider needs almost 40000 HOM couplers , it would be recommended to replace current dampers with elements whose electrical performance is less sensitive to fabrication tolerances.

2.4 Energy Deposited by Ultra Short Bunches

The very high intensity FEL (λ= 1 Å) is one of the proposed new applications of the 3 km part of the TESLA e^- linac. This operation requires very short bunches with σ_z = 25 μm, which can excite wake fields to the THz region. Since the longitudinal loss factor $k_{||}$ and thus the energy loss scale approximately with $(\sigma_z)^{-1/2}$, the total energy deposited by single bunch will be big. This will influence the beam. Additionally, the high energy photons may brake Cooper pairs in the superconducting material and increase the wall losses of the fundamental mode. As a remedy, to keep the energy deposition as low as possible, one can decrease $k_{||}$ by changing the geometry of the cavity.

3 NEW SHAPE

3.1 Motivation

Some of the disadvantages we have pointed out in the previous sections can be removed with an increase of the iris diameter [2]. More than five years of manufacturing, preparation and testing experience gives the basis to a revision of the present design. We expect that the improved cavity shape should :

- increase cell-to-cell coupling,
- enable and simplify hydroforming or spinning of the structure,
- reduce the loss factor $k_{||}$,
- simplify HOM mode damping,
- simplify the construction of the fm coupler (not variable),
- increase the ratio of the active length to the total length.

Besides, the new design should keep, as much as possible, the advantages of the current shape. These advantages are parameters like: (R/Q), E_{peak}/E_{acc} and H_{peak}/E_{acc}.

3.2 Modified Shape

The new shape of the inner cell, shown in Fig. 2, is one of the possible alternatives. Parameters of the new and the old shape are listed in Table 1. The last column of Table 1 presents the relative change of each parameter.

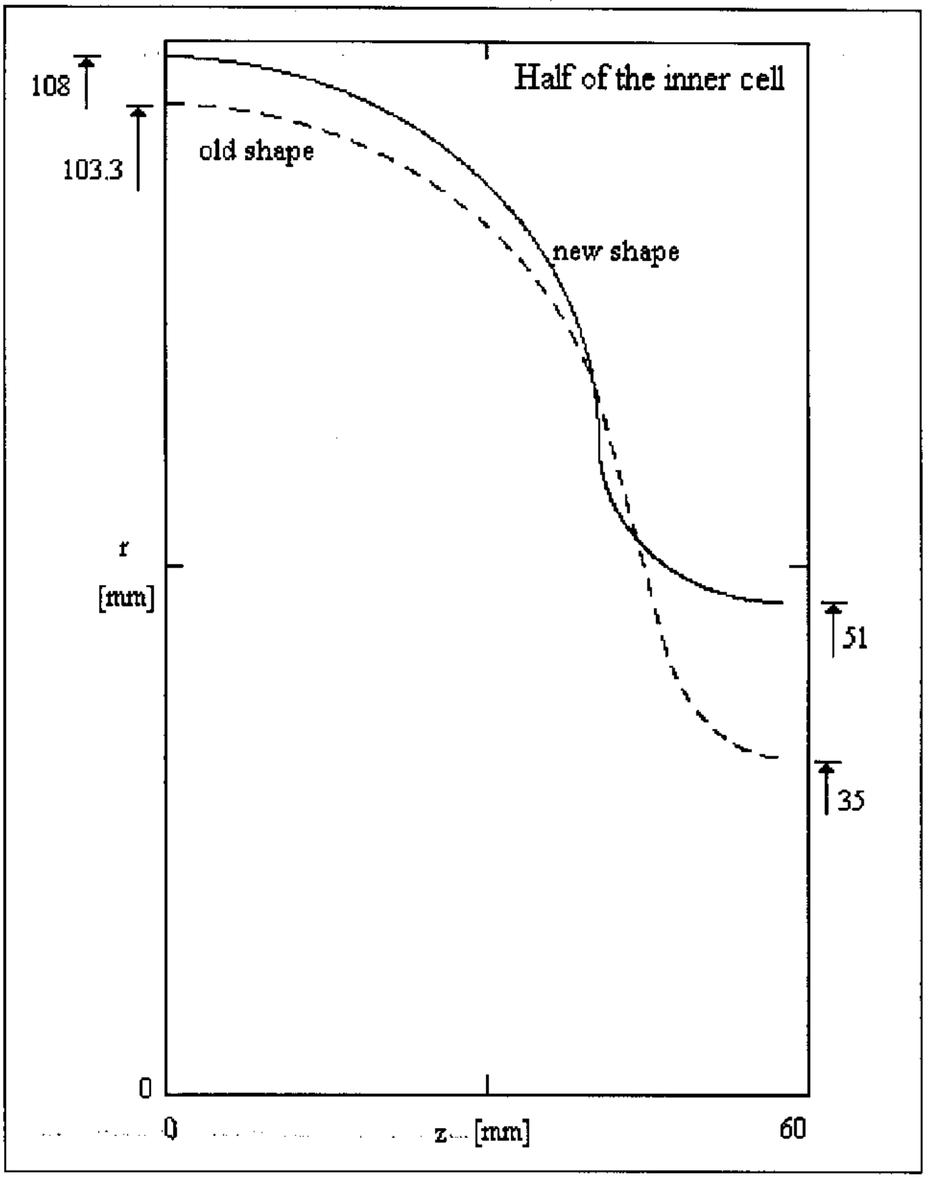

Fig. 2 New and old contour of the inner cell.

Table 1

Parameter	Old shape	New shape	Change
(R/Q) of the fund. mode, 9-cell [Ω]	1035	695	- 33 %
k, cell-to-cell coupling [%]	1.84	5.51	+ 200 %
E_{peak}/E_{acc}	2.0	2.34	+ 17.0 %
H_{peak}/E_{acc} [Oe/(MV/m)]	42.6	50.2	+ 17.8 %
$k_{\|}$ (σ=1mm), long. loss factor, 9-cell [V/pC]	8.7	5.5	- 37 %
$k_{\perp}$ (σ=1mm), trans. loss factor, 9-cell [V/(pCm)]	18	6.7	- 63 %
r_{equ}/r_{iris} inner cell	2.95	2.11	- 29 %
r_{equ}/r_{iris} end cell	2.65	1.94	- 27 %

4 DISCUSSION

4.1 Cell-to-cell Coupling

The cell-to-cell coupling increased by a factor of three as compared to the current design. This makes the structure much less sensitive to any machining tolerances and provides room to increase the number of cells per cavity. With this coupling a structure made of 15 cells will have the same sensitivity to the shape perturbation as the present design with 9 cells.

4.2 Hydroforming, Spinning and Stiffening of the Structure

The new geometry is more suitable for hydroforming or spinning. The ratio of the equator radius to the iris radius is near 2 for the inner cell and even below 2 for the end cell. The iris region is now wider and the wall can be made thicker in this region. Hereby stiffening rings, used in the current design to reduce the Lorentz force detuning, can be avoided [6].

4.3 Loss Factors and HOM Damping

4.3.1 Loss Factors

The loss factors of the new geometry are significantly lower. The single passage deposited energy is reduced by 37 % for the monopole modes and by 63 % for the dipole modes. The decrease of the loss factors indicates a decrease of HOMs characteristic impedances, too. Therefore the energy deposited in the resonantly excited parasitic modes will be reduced. This gives more relaxed requirements for the damping of these modes.

4.3.2 Possible Higher Order Mode Damping Scheme

It has been mentioned, that the adjustment of HOM couplers is a time consuming procedure. This can be changed if their electric performance will be less sensitive to fabrication tolerances and if one could reduce the number of HOM couplers per cavity. The enlarged iris of the new cell enables an increase in diameter of the beam tube. We have fixed this diameter to 0.11 m, since it is the smallest size that allows propagation of all monopole modes in the tube. The fundamental mode passband stays well within cutoff. The first eight dipole modes stay under cutoff as well, but their field in the beam tube seems to be high enough for damping to the BBU limit. Two HOM couplers shifted angularly by 90° and attached at every second beam tube (Fig. 3, only one coupler shown) may be used for the damping of parasitic modes excited in two neighboring cavities. This damping scheme requires only one HOM coupler per cavity. The

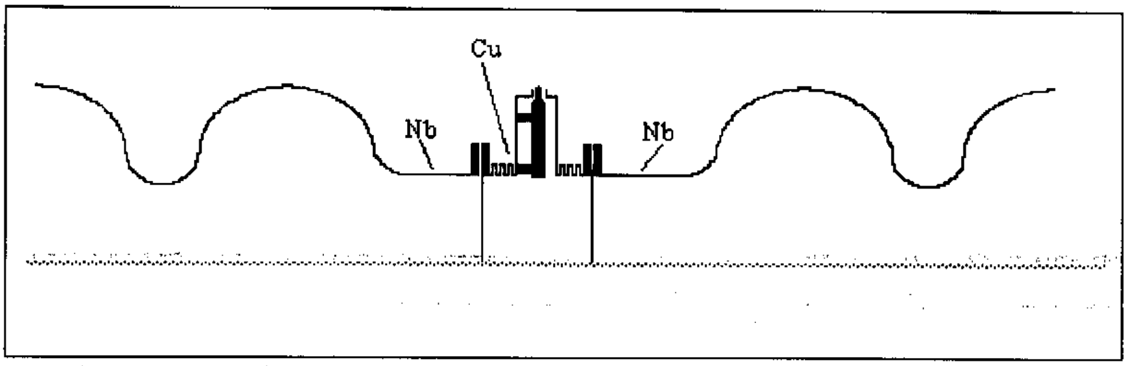

Fig. 3 The HOM coupler placed between two cavities (not in scale, only one coupler shown).

distance between HOM coupler and end cells can be larger than for the current design. For this reason it is possible to weld HOM couplers to the copper tube and to assemble them with standard flanges to the Nb beam tube. Since the fundamental mode is under cutoff and distance to end cells is large, a very little fm rejection, achievable without any additional filter, is needed to prevent output cables and feedthroughs from overheating. This simplifies the design of the HOM coupler.

An example of such a coupler and its computed transfer function is shown in Fig. 4. The achievable Q_{ext}'s were estimated for two couplers attached to a 280 mm beam tube (100 mm Cu and 2x90 mm Nb). The computation showed that 80 monopole modes and 140 dipole modes are damped to the required limit if HOM couplers can couple to magnetic and electric fields. Two passbands, TM012 and TE121, couple hardly to the beam tube, but even these modes have amplitudes of the electric or the magnetic field at the couplers position which allow to get Q_{ext}

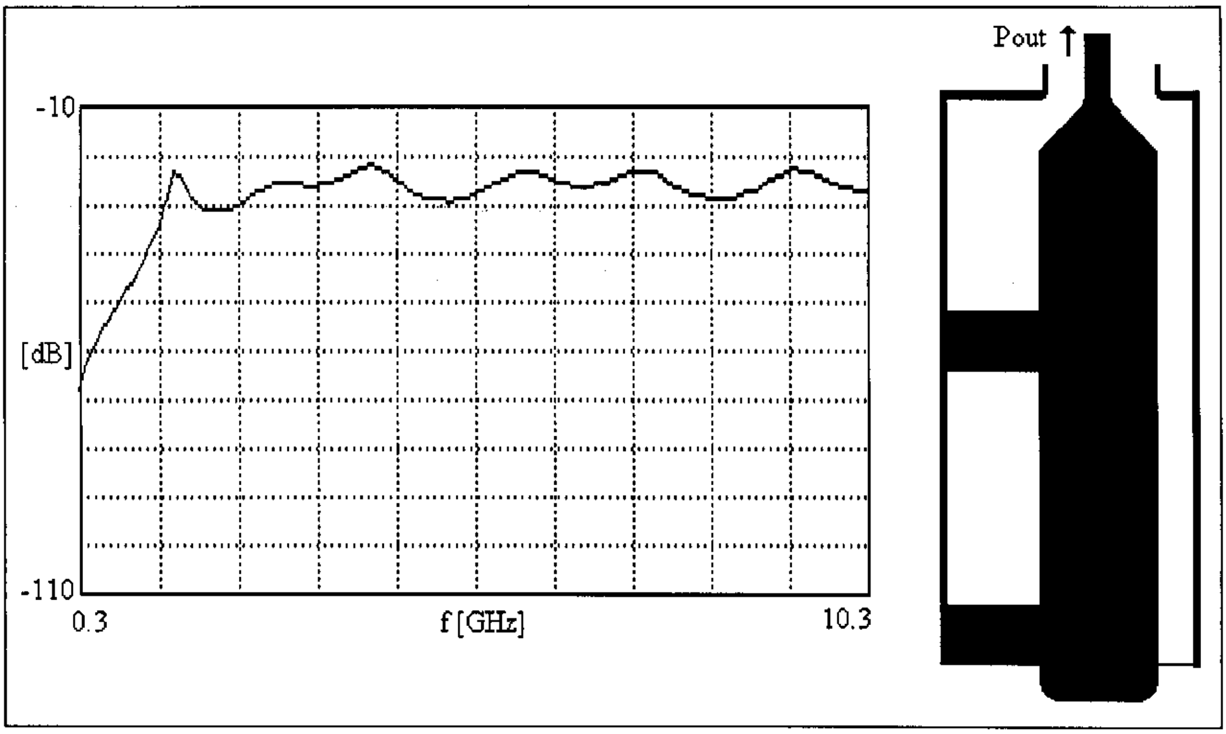

Fig. 4 Simplified design of HOM coupler and computed transfer function of this coupler.

below 10^7. If the tube and couplers are made of copper with RRR = 25, the additional power loss due to the fm at 25 MV/m is only 0.04 W per cavity.

The high frequency part of the spectrum should be damped mainly at the end of the cryomodule by the beam tube absorber. It is assumed, that 85 % of the energy deposited by the beam, will propagate through the string of cavities to this absorber. This is not obvious since some modes may be trapped between cavities. The larger diameter of the beam tube increases the coupling between cavities for HOMs. This should cause better propagation towards the beam absorber and should make the propagation less sensitive to the differences in frequencies of the individual cavities.

4.3.3 Fundamental Mode Coupler and Fill Factor

The layout of a possible arrangement of 8 cavities in the cryomodule is shown in Fig. 5. All intersections are 280 mm long (64 mm less than in the present design of the cryomodule). Intersections with attached input couplers are designed as fixed points. Since the field pattern is stable, variable couplers are not necessary. If operation of the collider should differ from the nominal one, Q_{ext} can be changed by means of a 3-stub waveguide transformer installed in the input line of each cavity. The transformer makes the RF distribution system more flexible for

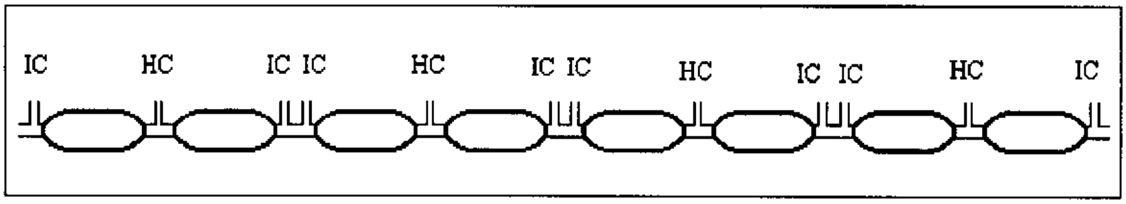

Fig. 5 Possible layout of the cryomodule. IC - input coupler, HC - HOM coupler.

phase adjustment and gives more freedom in the length of intersections. Shorter intersections, as they were chosen above, increase the fill factor from the present low value of 0.75 up to 0.79.

4.4 Negative Aspects of the Proposed Shape

4.4.1 Direct Coupling Between Neighboring Cavities

The direct coupling between cavities for the interconnection based on the 0.11 m diameter and 280 mm long beam tube is still rather weak but stronger than for the old end cell shape. The power radiated into the neighboring cavity at 25 MV/m is of the order of 1 W, and for the loaded structure with the fm coupler, whose $Q_{ext} = 3.14\ 10^6$, the induced voltage due to this coupling is of the order 0.1 MV. As the voltages of neighboring cavities have always constant phase difference and similar or equal amplitudes, small phase perturbations of about 0.2° resulting from this coupling can be easily corrected.

4.4.2 Reduction of (R/Q) for the Accelerating Mode

As predicted, a bigger aperture lowers (R/Q) of the fundamental mode. The 33 % reduction is compensated by a high Q_o and finally the cryogenic loss is smaller. In order to keep cavities matched for the nominal operation: U = 26 MV/cavity and the beam current I_b = 8 mA, Q_{ext} should be increased by 33 %, and fill time will therefore be longer by 240 µs. When Q_{ext} has still its previous nominal value, 2 % of the power will be reflected but fill time will be longer by 180 µs only. This problem should be investigated in more detail.

4.4.3 Reduction of E_{peak}/E_{acc} and H_{peak}/E_{acc}

The ratios of E_{peak}/E_{acc} and H_{peak}/E_{acc} have increased by 17 %. This means more γ-radiation at the specified E_{acc} and higher quench probability. Surface cleaning methods (BCP or high pressure water rinsing) and assembling methods are still in an optimization phase. Also inspection methods of the Nb material, which help to eliminate Nb sheets with defects leading to quenches, are under development. It is the hope that further progress in the fabrication, the assembly and the cleaning methods can compensate for the increase of these parameters.

5 CONCLUSION

Table 2

Parameter	
k cell-to-cell coupling	+
$k_{\parallel}$ longitudinal loss factor	+
$k_{\perp}$ transversal loss factor	+
r_{equ}/r_{iris} inner cell	+
r_{equ}/r_{iris} end cell	+
fill factor of both linacs	+
simplified scheme for HOM damping	+
simplified fm coupler	+
(R/Q) fm characteristic impedance	-
E_{peak}/E_{acc}	-
H_{peak}/E_{acc}	-

A summary of the positive and negative features of the new cavity shape is given in Table 2. We plan to build copper models of the new structure to prove experimentally the stability of the accelerating field, the proposed scheme of the HOM damping and the coupling between structures for the fm and the HOMs. As a next step, Nb prototypes should be fabricated to investigate the hydroforming method, the Lorentz detuning and to check new limitations in the maximum accelerating field.

ACKNOWLEDGMENTS

We would like to express our gratitude to the TESLA collaboration group for many helpful discussions.

REFERENCES

[1] E. Haebel, A. Mosnier, J. Sekutowicz, „Cavity Shape Optimization for Superconducting Linear Collider", Proc.of HEACC'92, Hamburg, July 20-24,1992.

[2] E. Haebel, A. Mosnier, „Large or Small Iris Aperture in SC Multicell Cavities", Proc. of The 5th SRF Workshop, Hamburg, August 19-23, 1991.

[3] D. A. Edwards, „TESLA TEST FACILITY LINAC-Design Report", DESY Print, March 1995, TESLA Report 95-01.

[4] B. Dwersteg, „Mechanical Concept of TESLA Main Coupler Development at DESY" TESLA Report 93-15.

[5] M. Champion, „RF Input Coupler and Windows: Performances, Limitations and Recent Developments", Proc. of 7th Workshop on RF Superconductivity, Gif sur Yvette, October 17-20, 1995.

[6] H. Kaiser, private communication.

[7] V. Palmieri et al., „Recent Experience with the Spinning of 1.5 GHz Seamless Copper Monocells", Proc. of 7th Workshop on RF Superconductivity, Gif sur Yvette, October 17-20, 1995.