Higher Order Mode RF Power Extraction From Polarized Cavities with a Single Output Coupler.*

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Abstract

An important step in simplifying today's superconducting accelerator strucutures is to reduce the number and complexity of couplers. The use of azimuthal shaping to polarize the higher order transverse modes in superconducting cavities has previously been proposed to couple both polarizations through a single output. Two questions remained: would such structures multipactor? Would both polarizations be adequately damped by a single coupler? To answer these questions, 1-cell and multi-cell polarized S-band structures have been designed, constructed and tested. Cold tests have shown that 1-cell and 3-cell structures do not multipactor. The highest surface field level achieved was 31 MV/m, limited by field emission as with non-polarized cavities. A set of 5-cell, S-band copper structures (one polarized and one non-polarized) complete with HOM output coupler have been fabricated and a comparison made in Qext between the two structures for various modes. Results of these experiments are reported.

Introduction

The capital cost for a fully superconducting linear collider is dominated by the structure. Refrigerator associated capital cost, which would be a sizable component for a cw machine, is drastically reduced by using modulated RF with a duty cycle of 1%[1]. The major challenge for the superconducting approach to a TeV linear collider is to improve the gradients from the today's capabilities of 5 - 10 MeV/m by at least a factor of 3, while at the same time reducing the unit costs, also by at least a factor of 3. Research efforts on advancing the capabilities of Nb cavities are described in other contributions to this conference. This paper describes efforts to reduce unit costs by "value engineering", i.e. simplify the structure and associated hardware. These efforts also help reduce the cryostat costs.

Structure Simplification

As a reference baseline we use the 1.5 GHz Cornell/CEBAF 5-cell elliptical cavity. This design is under improvement for application to a future superconducting TeV linear collider. Current experience with fabricating these cavites shows that a large fraction the niobium cavity cost is associated with the complex Higher Order Mode (HOM) and Fundamental Power Coupler (FPC) ports. In the design under development, the number of HOM coupler ports is reduced from two to one by controlling the mode polarizations in the individual cells. This feature is discussed fully in the next section. Elimination of any couplers also reduces the overall heat leak. We have further improved the HOM coupler port to allow removal of the extra stub on the FPC which was previously needed to couple out some of the lowest frequency HOMs. Apart from reducing the niobium structure cost, these improvements will also lower the cryostat cost by reducing the number of penetrations and through a reduction in the overall diameter of the structure and the liquid helium vessel.

Earlier studies[1] indicate that for a fully superconducting TeV linac with modulated RF, an S-band frequency (3 GHz) would be more appropriate than the current 1.5 GHz to reduce the cost associated with dumping the stored energy at the end of each RF pulse. Frequencies higher than S-band are ruled out to keep wakefield growth under control. We anticipate cost reduction by virtue of the smaller structure size; for eg., the Nb material requirement is reduced by a factor of 4 together with the use of thinner Nb. Cavities studied in this work were fabricated from 1.5 mm (1/16") Nb sheet.

Further savings are realized by introducing a battery of simplifications in fabrication procedures. The elliptical profile is replaced by a geometry that can be specified more simply by two circles and a straight segment, allowing less complex numerical milling machine codes used for cutting dies. The machined steps at the mating surfaces between cavity parts are eliminated. Beam welding parameters are developed that allow all cylindrically symmetric welds to be carried out in a single pump-down of the weld chamber, i.e. all equator and iris welds can now be done from the outside in one step. Grinding of iris welds and cavity surfaces is left out. This eliminates labor intensive interruptions for repeated inspections, and chemistry during the fabrication sequence.

Polarized Cavities

The idea of polarized cells was first proposed in refs.[2]. The basic motivation is that in a cavity with only one coupler, the two polarizations of each deflecting mode will be fixed by the coupler itself, leaving one polarization inadequately damped. This difficulty is overcome by deliberate breaking of the cell's symmetry by minor perturbations to the cell geometry.

Each deflecting mode of an ideal cavity is doubly degenerate, having fields which vary azimuthally as $\cos(m\theta-\theta_0)$or $\sin(m\theta-\theta_0)$ about an axis of symmetry (θ_0), determined by the coupler or by accidental asymmetries. Here $m = 0, 1, 2, 3$ modes are known as monopole (non-deflecting or longitudinal modes), dipole, quadrupole or sextupole respectively. A single coupler will break the degeneracy, aligning the fields of one the modes along the coupler axis, and the other at an angle $\phi = \pi/2m$. The external coupling to the two modes will be proportional to $\cos^2(m\phi)$ and $\sin^2(m\phi)$, which will always be zero for one of the two polarizations of each deflecting mode. To break the cell symmetry, the azimuthal boundary of the cavity is made up of twelve chords joined by circular arcs which meet the chords tangentially. Two chords fix the orientation of the dipole modes, four and six are used for the quadrupole and sextupole modes. The width of each chord is reduced linearly with the wall radius vanishing at the start of the iris curvature. The cavity remains cylindrically symmetric at the iris (beam hole). Thus the modes are oriented at an angle $\pi/2m$ about the coupler axis.

In refs.[2], this approach went through initial testing with a machined single cell cavity. All the modes were found properly oriented with respect to the intended location of a coupler port. Mode splittings of 10 to 50 MHz were observed, except for one case (2 MHz).

Benchtop RF measurements were conducted on a 5-cell S-band copper cavity with polarized cells and equipped with a single waveguide end coupler. Parallel measurements were carried out on a similar un-polarized 5-cell cavity, also with one coupler. All cells in the polarized structure were fabricated with the usual deep drawing techniques using "polarized" dies. The new cavity is no more difficult to fabricate than an ordinary cylindrically symmetric cavity.

Two of the most dangerous deflecting dipole mode families (TE111 and TM110) and one quadrupole mode family (TE211) were studied as representative examples to evaluate the effectiveness of the polarizaton. The monopole mode family (TM011) was also measured to make sure the same coupler would work well for the most dangerous longitudinal mode family. In all we studied 70 modes: 3 deflecting mode pass-bands x 5 modes per band x 2 polarizations per mode x 2 cavities = 60 modes, and 1 monopole pass-band x 5 modes x 2 cavities = 10 monopoles.

The mode splitting obtained for 15 members of the 3 deflecting mode pass-bands in the polarized and unpolarized versions are shown in Fig 1. Frequency spreads compare well with those reported in refs.[2] for the machined 1- cell polarized model.

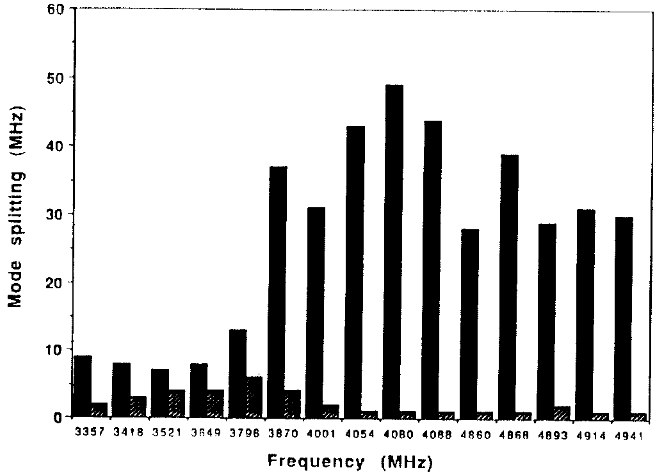

Fig. 1 Frequency splitting in modes of a 5-cell copper cavity from the cell polarizations.

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The coupler Qext was measured as the length of the matching waveguide stub opposite the waveguide port was varied from one to three inches in 10 steps. Fig. 2 gives the representative variation for the both polarizations of a high impedance member of the TE111 mode family in each 5-cell unit. A 15/16" stub length was finally selected as the best for strongest coupling to all 35 modes investigated in the polarized unit.

The external Qs measured for the three deflecting pass bands in both polarized and un-polarized cavities are shown in Fig. 3. The abscissa is the mode number 1a, 1b through 5a, 5b where a and b represent the two polarizations. As expected, in the unpolarized 5-cell cavity, one polarisation of each mode has a high (i.e. poor) Qext, (10^6 or higher). One coupler is clearly inadequate. On the other hand, for the polarized cavity, all the dipole modes have Qext between 10^4 and 10^5, except for two modes which have Qext ~$5x10^5$. For the monopole TM011 family, very satisfactory Qext values between $2x10^3$ to $1.4 x10^4$ were obtained. Fig. 3 also includes for comparison the Qext obtained with two waveguide end-couplers measured some time ago on the LE5 cavity[3]. Only the Qext attributable to the HOM couplers is included here, which excludes any damping from the FPC. Clearly two couplers perform somewhat better, but at the price of increased complexity.

As another benefit, the width of the new single arm waveguide coupler is chosen to provide a major simplification of the Fundamental power coupler (FPC) port in the CEBAF/Cornell design. The improvement arises from elimination of a large stub on the FPC waveguide. This costly stub-on-stub was necessary for extracting, through the FPC, 8 of the lowest frequency transverse TE111 modes[3]. These modes now couple effectively through the single waveguide HOM port.

Although Qext values are interesting to examine when judging the effectiveness of the coupler for each mode, the relevant quantity to consider from the point of view of beam stability is (R/Q)xQext. This is shown in Fig. 4 for the two dipole mode families. When compared with the two waveguide end couplers case, the single waveguide coupler on a polarized 5-cell performs equivalently well for both dipole mode families studied, with the exception of one of the two modes mentioned before. (The other mode does not have significant impedance). Detail examination of the polarization alignment showed that for this mode the coupler perturbation overwhelms the chord perturbations introduced into the cells. Studies are underway to improve the geometry of the coupling region between the beam tube and the waveguide coupler to reduce this disturbance.

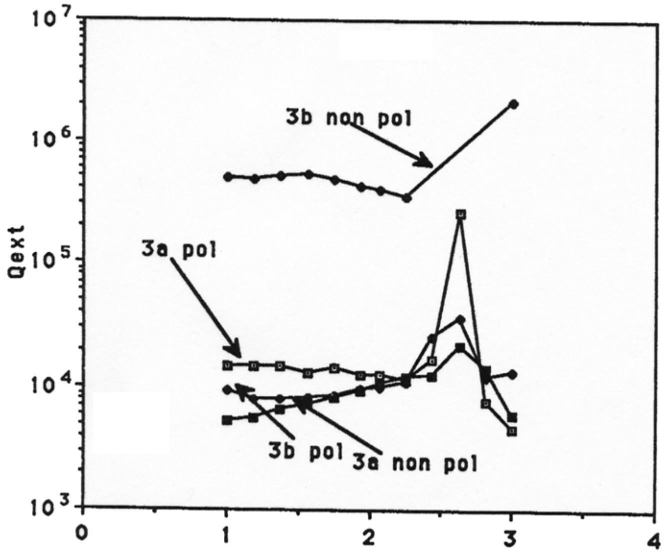

Fig. 2 Measured variations in Qext from changes in length of matching stub opposite single arm waveguide coupler.

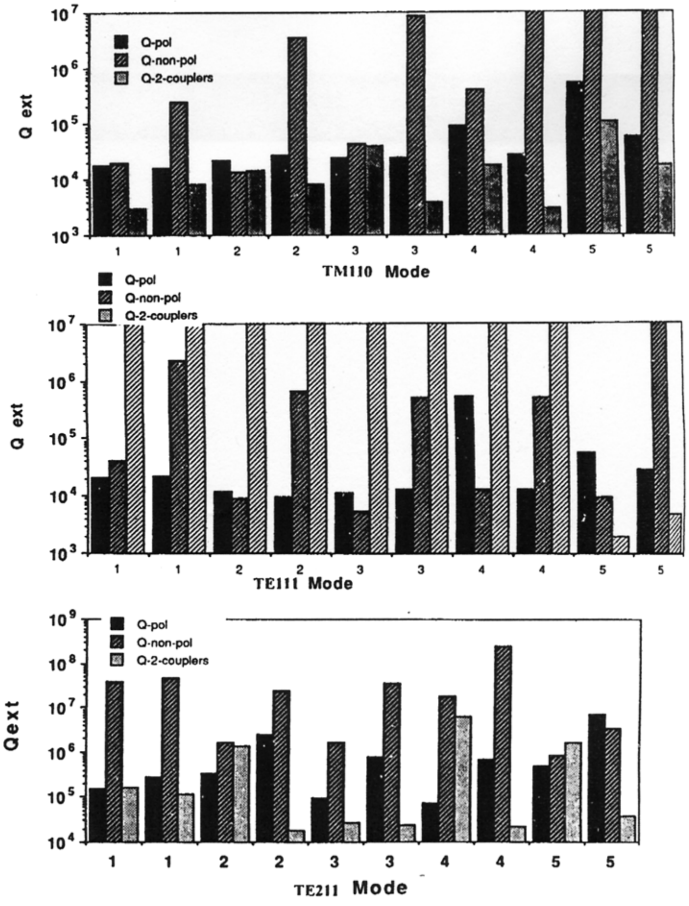

Fig. 3 Measured Qext for 3 deflecting mode pass-bands, TM110, TE111, and TE211. There are 10 modes for each family. For each mode, Qext values for 3 different cases are given: polarized 5-cell cavity/one coupler, non-polarized 5-cell/one coupler, and the reference 5-cell LE-5 cavity with two arm couplers[3]. In the last case, only the Qext attributed to the HOM couplers is included.

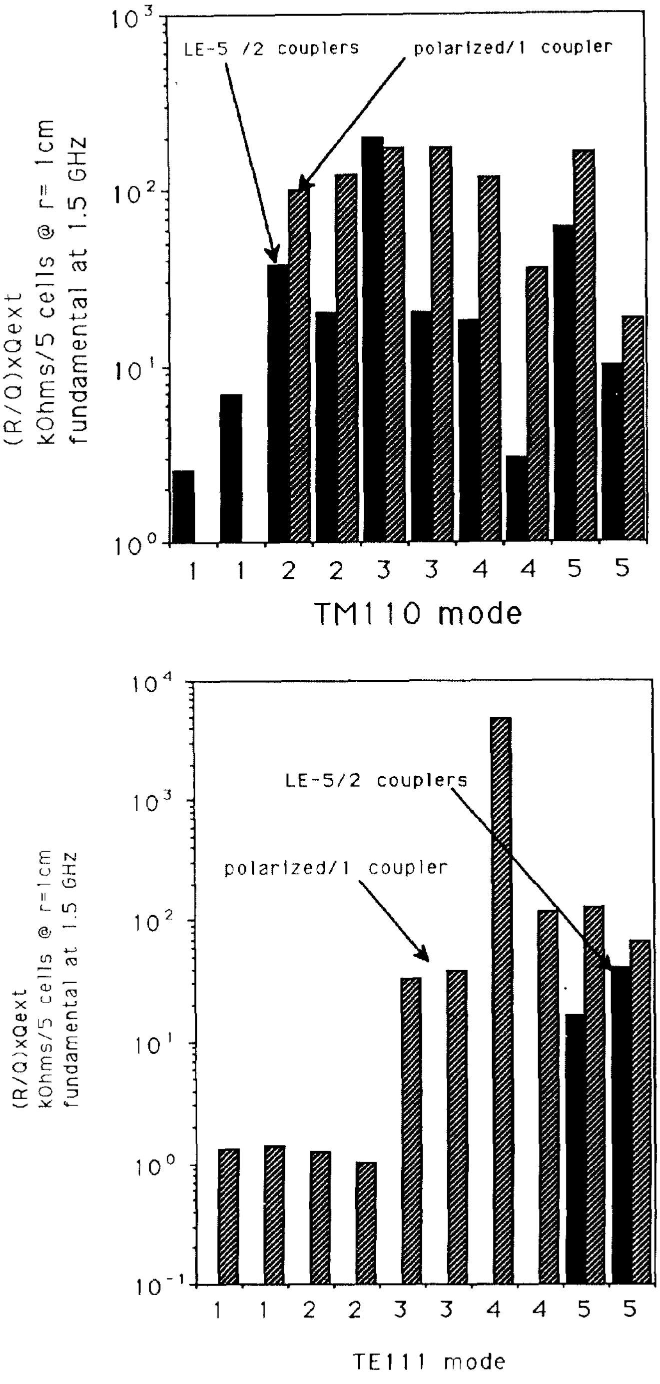

Fig. 4 Impedances, (R/Q)xQext, for the most dangerous dipole mode families: TM110 and TE111. Comparisons are made between the polarized /single coupler cavity and the reference LE-5 cavity (two couplers). For the TM110 mode family, the impedance values for the first two modes in the polarized cavity are too small to appear in the bar chart. For the TE111 family, the impedance of the first 8 modes for the reference cavity are left out as the two-arm HOM coupler does not provide any damping for these modes (Q ext = infinity).

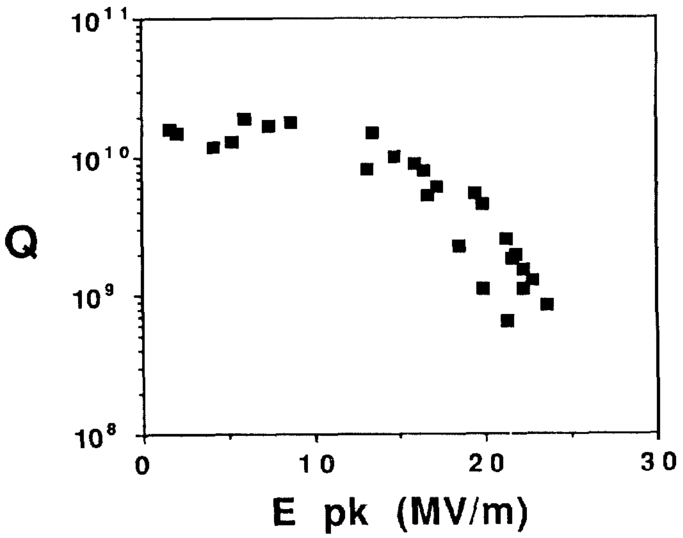

Fig. 5 Performance of a niobium 3-cell polarized cavity prepared by simplified fabrication techniques and with standard chemical surface treatment.

Nb Cavity Tests

A cold testing program for 2.8 GHz, 1-cell and 3-cell Nb polarized cavities has been started. Commercial high purity Nb with RRR = 250 - 300 is used as starting material and improved to RRR = 450 - 500 with yttrification. All Nb cavites are fabricated by simplified techniques discussed above. Tests on companion unpolarized Nb cavities are also started. At low field, best Q values of $2x10^{10}$ and $1x10^{10}$ were reached in 1-cell and 3-cell polarized cavities. After standard chemical treatment, the highest surface electric (magnetic) fields reached were 31 MV/m (610 Oe) and 25 MV/m (490 Oe) in a 1-cell and a 3-cell, limited by heavy field emission in both cases. Fig. 5 shows the best 3-cell performance. These surface field values are comparable to those obtained after standard chemical surface treatment with 1500 MHz cavities.

Shape distortions necessary for polarization did not regenerate any multipacting problems, which settles a key question regarding the suitability of polarized cells for superconducting cavities. It is planned to continue these tests with efforts to reduce field emission using heat treatment and to increase field levels.

Conclusions and Outlook

Substantial progress is registered towards structure simplification both from the design as well as from a manufacturing standpoint. We have shown that by polarizing the cells it is possible to couple out the two polarizations of dipole and quadrupole modes with one waveguide coupler port instead of two ports that are otherwise necessary. Further improvements to the HOM coupler port are now under investigation. Studies using URMEL are underway to improve the geometry of the region where the HOM coupler is introduced onto the beam pipe so as to reduce the disturbance to symmetry.

Simulation calculations are in progress to establish the extent of HOM damping required for a fully superconducting TeV linear collider. At present, results indicate that the damping requirements are at least one order of magnitude less severe than those used in superconducting structures designed for storage rings[4]. Encouraged by these results, we are investigating the possibility of 10-cell modules instead of the current 5 cells.

References

[1] R. Sundelin, Proc. of the 1987 Particle Accelerator Conference, Washington DC, IEEE Cat. No. 87CH2387-9, p. 68.
[2] J. C. Amato, et. al., IEEE Trans. NS-32, 3593 (1985)
[3] J. C. Amato, SRF831003, Cornell U LNS Internal Note.
[4] D. L. Rubin, This conference.