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SRF Cavity Cell Geometry Options for the CEBAF 12 GeV Upgrade

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During the initial design consideration for cryomodules for upgrading the CEBAF energy (circa 1999), the presumed project timescale was judged to preclude development and commissioning of a new cell shape. The Upgrade CM design, then, used the original CEBAF/Cornell (OC) cell shape, adding two additional center cells. Other changes were implemented on this cavity design: coaxial HOM couplers of the TESLA design, tuner mounting hubs at the endcell irises, ¼ wave short on the waveguide fundamental power coupler, and an integral titanium helium vessel.[1] Cavities of this design were realized in the "SL21" cryomodule, the first 12 GeV prototype cryomodule.[2] A duplicate CM, subsequently modified during assembly to enhance cooling capacity, was ordered for the IR Upgrade FEL, "FEL03." The system design presumed the use of 8 kW klystrons, making high cavity gradients (>13 MV/m) unusable.

As time horizons for the upgrade extended, Peter Kneisel recognized an opportunity to improve the CEBAF cavity cell designs[3], taking advantage of optimization routines developed for the TRASCO project and the recognition that minimizing the ratio E_{pk}/E_{acc} reduces vulnerability to the chief performance-limiting phenomenon: field emission loading. Peter championed the design of an improved cavity cell shape, subsequently labeled the High Gradient (HG) design. [TN-01-015][4] Nearly simultaneously, the first attempt at "6 GeV" running of CEBAF demonstrated that the presumed extensibility of the existing klystron design was not viable.

Spring 2001 saw a reconsideration of the system design parametrization for a 12 GeV CEBAF.[5] The conclusion was that 13 kW klystrons are needed and that SRF cavities should be operable to 21.2 MV/m, with an average usable gradient of 19.2 MV/m with generation of 250 W rf dynamic loss at 2.05 K. Also needed is HOM damping sufficient to preclude BBU with the maximum total beam current in a linac of 460 μA. The HG shape was judged attractive due to its reduced E_{pk}/E_{acc} and increase shunt impedance.

Increasing success by colleagues around the world against field emission by the technique of high pressure rinsing with ultrapure water, prompted us to reconsider the design optimization strategy used for the 12 GeV cavities. CW applications of SRF are quickly constrained in practical operating gradient by the quadratic rise in 2 K load, even with the complete absence of field emission. In February 2002, the challenged was placed: given ideal SRF material performance, what cavity shape meeting the 12 GeV needs would present the lowest 2 K heat load? Jacek Sekutowicz, who was at JLab for an extended visit, picked up the challenge and developed such a Low Loss (LL) design. [TN – 02-023].[6]

In the summer of 2002 there was launched a "100 MV Cryomodule" project to produce a next generation CM of a design consistent with the evolving 12 GeV scheme and building on experience gained via "SL21" and "FEL3." In view of the fact that at that time neither a HG nor LL cavity had yet been built, the decision was taken to construct the 1st 100 MV cryomodule—dubbed *Renascence*—using a combination of the two designs. A subproject was started to develop copper and then niobium prototype 7-cell cavities of each type,

complete with couplers. In view of the limited testing opportunity and also potential application in the JLab FEL, the decision was taken to use four HOM couplers, two on each end, to positively damp any dipole mode without respect for "field tilt." The endgroups for the HG and LL designs were made identical. The HOM damping analysis performed on the HG and LL copper models is reported in TN 03 –012.[7] Fabrication of the prototype niobium cavities was completed in May 2003.[8] Testing of these cavities, including final test of the HG cavity with helium vessel, ran through September 2004.

Fabrication of the production batch of nine cavities for Renascence began in March 2003 and was completed in May 2004. Processing and testing of these cavities ran from March 2004 through early November 2004, concurrent with SNS production.

The following factors have been identified as potentially critical features of 7-cell cavities for use in CEBAF:

1. Susceptibility to field emission gradient limitations
2. Stability of field flatness with reduced cell-to-cell coupling
3. Adequacy of HOM damping with reduced iris diameter
4. Minimization of operating heat load for design gradients (or, alternatively, accessibility of higher gradients with a given cryo capacity)
5. Susceptibility to multipacting gradient limitations or commissioning difficulties
6. Particular fabrication or processing difficulties that might arise from geometrical peculiarities

Each of these factors is addressed in turn below.

Field emission

In a model of practical field emission in SRF cavities which presumes uniform dispersal of potentially emitting particulate contamination, for a given size and type of particulate, the lower the E_{pk}/E_{acc} of the structure, the higher the field-emission-limited E_{acc}. Thus, if processing techniques are insufficient to eliminate field emission as a characteristic limitation, the structure with the lower E_{pk}/E_{acc} will permit attaining higher accelerating gradients. As one may observe from the table below, if preparation techniques provide surfaces which are free of field emission to the range of 45 – 50 MV/m E_{pk}, then this factor would not be a critical design consideration for use in CEBAF. On the other hand, if such surfaces are not attainable, the HG design has a distinct advantage over the OC and LL designs in this regard.

CEBAF 7-cell cavities

	OC	HG	LL
E_{pk}/E_{acc}	2.56	1.89	2.17
E_{pk} @ E_{acc} =20 MV/m	51.2	37.8	43.4

The majority of cavities for the FEL3 cryomodule, which have the OC shape, exceeded 17 MV/m, which corresponds to the same surface E_{pk} for the LL shape at 20 MV/m.

As mentioned previously, the VTA testing of the Renascence production cavities was completed during 2004. The cavity preparation methods employed were the same as those used during that period on the SNS cryomodule production. The Q vs E test results are summarized in Figures 1 and 2 below. The preparation methods are clearly adequate to attain the needed field-emission-free surfaces. The LL shape, with its 15% higher E_{pk}/E_{acc}, was not limited by field emission. In fact, the only cavity which had marginally acceptable field-emission limited performance was of the HG design.

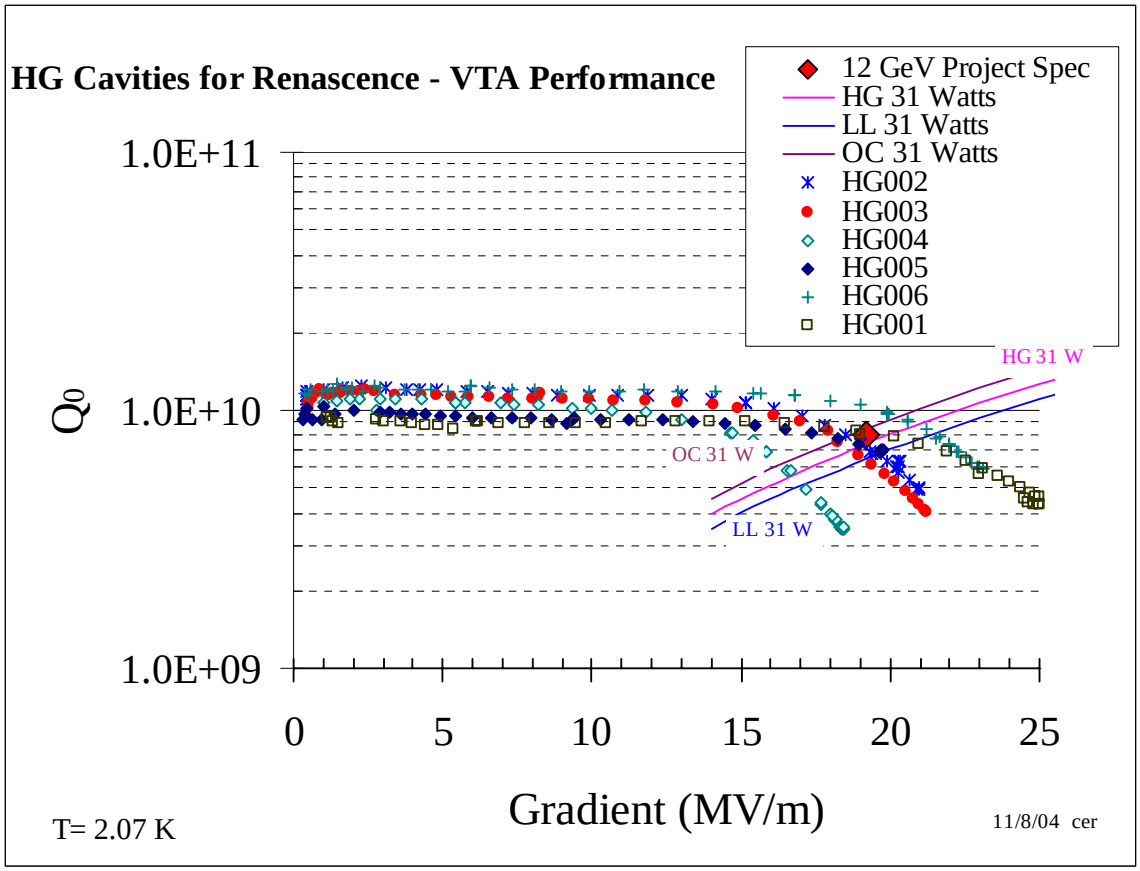

Figure 1

The degradation in Q beyond 18 MV/m is not due to field emission, but another non-linear loss mechanism somehow associated with the niobium surface preparation and not yet fully understood. No cavity quenches were observed during testing of these cavities.

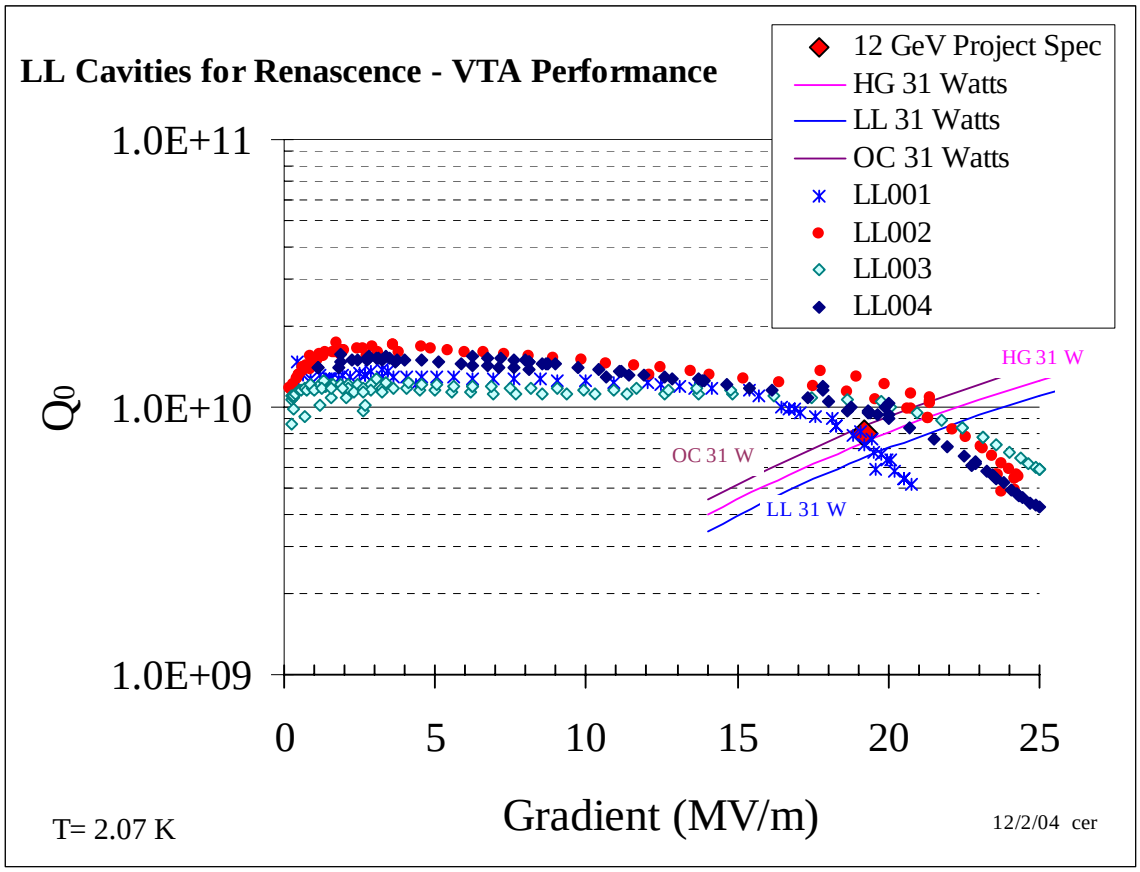

Figure 2

Field flatness control

The weaker the cell-to-cell coupling for a multi-cell structure, the greater the sensitivity of accelerating field "flatness" to the tuning precision of the individual cells. When the field amplitudes in each cell of a multi-cell structure are non-uniform, the peak surface fields will be higher than expected for a given measured stored energy, although the effective accelerating gradient will be only slightly reduced. (10% field unflatness yields only ~1% loss off effective gradient). The HG and LL cavities have significantly lower cell-to-cell coupling than the OC shape, with the LL having the lowest of the set.

CEBAF 7-cell cavities

	OC	HG	LL
k_{cc} [%]	3.29	1.72	1.49

The question then occurs, does the LL shape exhibit a significant sensitivity to tune preservation that would present a difficulty for use in CEBAF?

Unlike the OC-shaped cavities, both the HG and LL multi-cell cavity designs incorporate stiffening rings between the cells and between the endcells and the NbTi extension rings. The action of these stiffening rings is to dramatically stabilize the more shallow-angle sidewalls of the cells.

During the preparation of the set of cavities for Renascence, no difficulty was found in tuning the cavities to the intended frequencies while attaining a peak-to-peak field flatness of better than 3%. No characteristic changes were observed with bulk (200 μm) chemistry, 600 C heat treatment, chemistry and VTA testing, or helium vessel welding. Cell amplitude profiles were preserved across these activities, and the "walk" of cell field amplitudes was less than 1%. The LL shaped cavities showed no more sensitivity to loss of field flatness than did the HG cavities.

HOM damping

In order to guarantee stable beam operation of the CEBAF 12 GeV upgraded machine with design currents of 460 μA, the higher-order-modes (HOMs) of the new 7-cell cavities should be damped such that the dipole mode will not present a risk of beam breakup instability. Byung Yunn performed analyses on the anticipated 12 GeV optics, and these analyses yielded a shunt impedance specification[9] without regard for frequency sensitivity. $Z = (R/Q) * Q_l$ must be less than 6.2×10^8 ohms. This same specification applies irrespective of the cavity structure design used.

Although some difficulty was encountered in appropriately specifying and producing the rf pick-up probe/feedthrough assemblies (a topic addressed elsewhere), the damping of HG and LL cavities HOMs with the four integral coaxial couplers was accomplished in the VTA. Although the LL cavity has smaller irises, and thus might be expected to show weaker damping of the HOMs, no significantly weaker damping has been observed, and both cavity designs comfortably meet the performance specification. See the summary figures below from measurements made by Haipeng Wang. Another Technote will address the VTA measurements in particular. Bench measurements of the HOMs were made earlier on copper models.[10]

[Subsequent measurements have been made on HG007 with the "Type 1" HOM coupler probe design on the JLab sapphire-dielectric rf feedthrough. VTA measurements of HOM loaded Q's were made using all four couplers and using only the "C" and "D" couplers on the field probe end of the cavity. For the later test, the probes were removed from the HOM couplers on the FPC end. These data, cast as shunt impedance for the dipole modes, are presented in Figure 5.] [Rev. 1 addition]

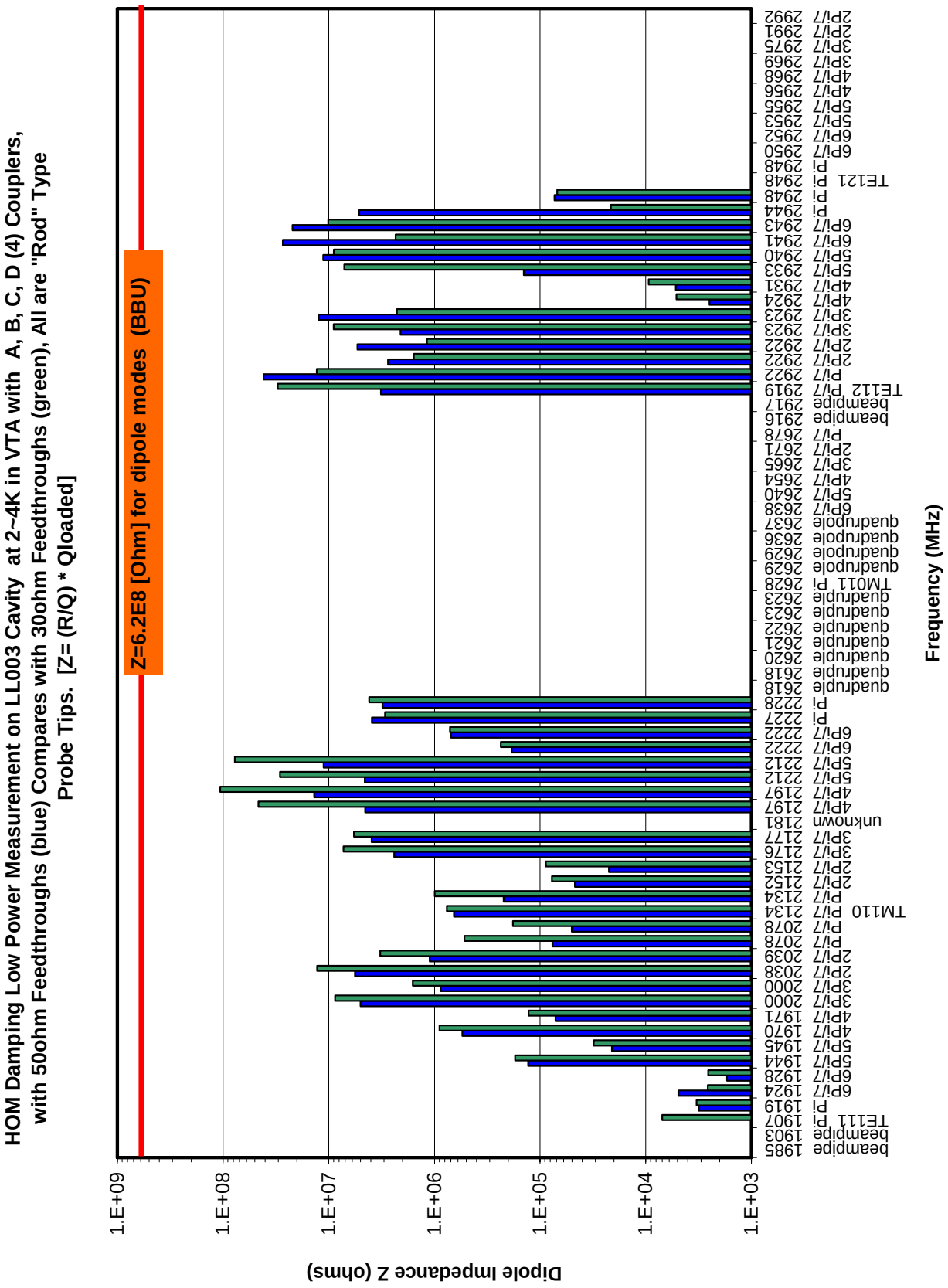

Figure 3. LL cavity HOM damping

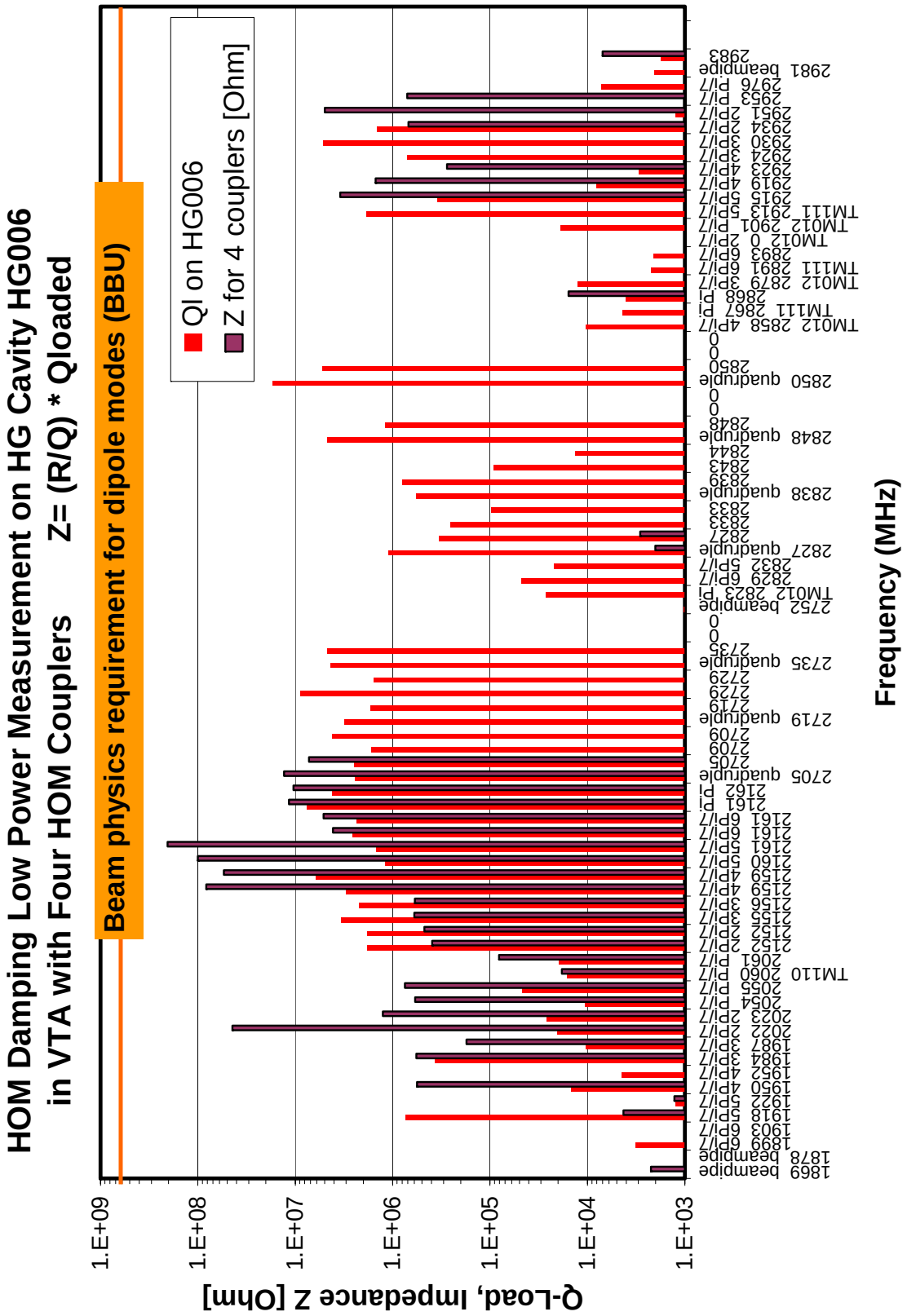

Figure 4. HG cavity HOM damping

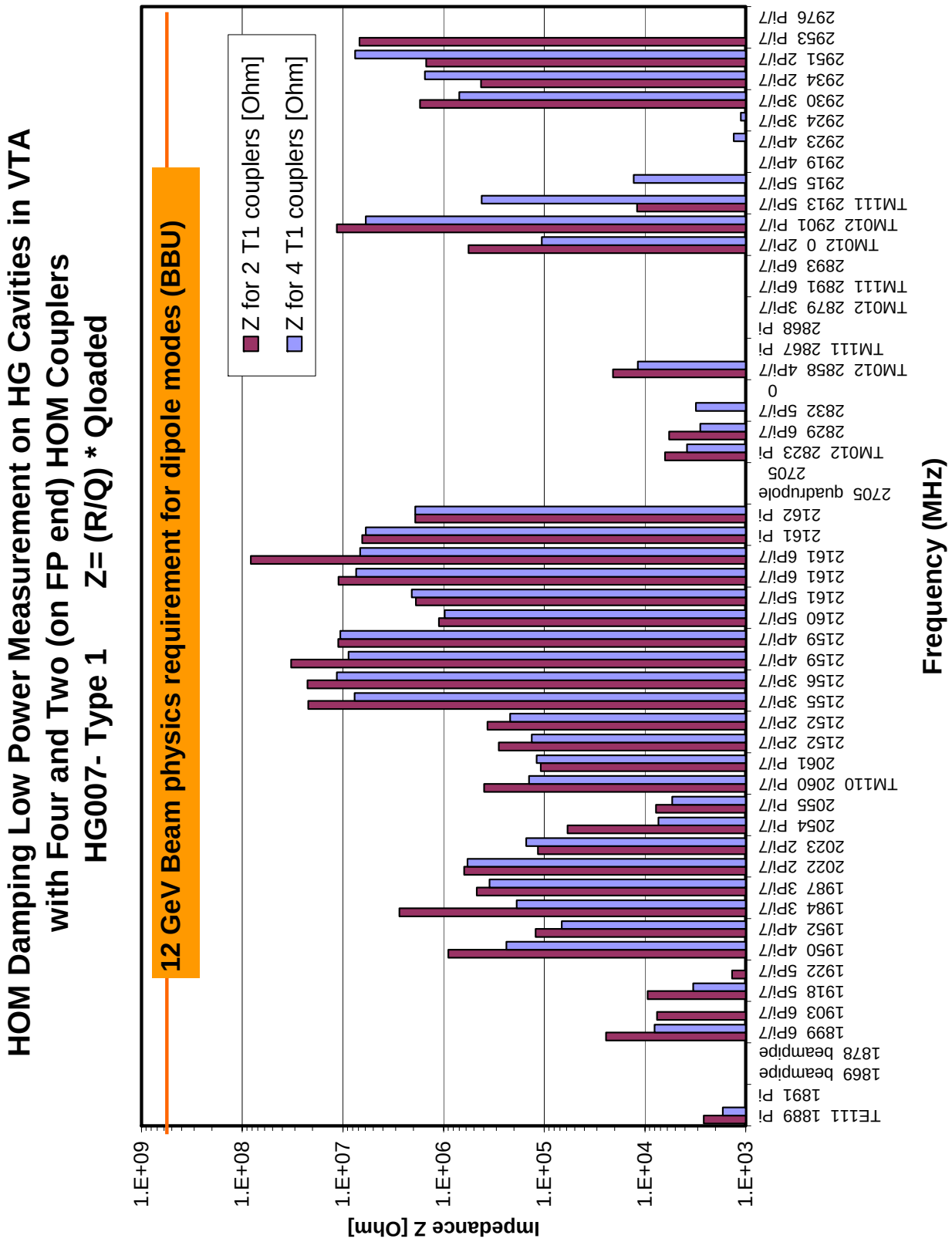

Figure 5. HG cavity HOM damping with four or two HOM couplers.

Minimization of 2 K heat load

For CW accelerator applications, the highest attainable accelerating gradients may not be the economic design choice. At best, the rf dynamic load is quadratic with gradient. An accelerating structure may be optimized so as to increase the shunt impedance (*R/Q*) and the geometrical factor (*G*) of the accelerating mode.

$$P_{\mathrm{diss}} = R_{\mathrm{s}}\,(E_{\mathrm{acc}}{*}l_{\mathrm{active}})^2/(G{*}(R/Q))$$

The rf surface resistance, R_s, depends on temperature, frequency, and quality of surface preparation. One element that falls into the "quality of surface preparation" is the not-yet-understood so-called "*Q*-drop" which occurs in the 18-24 MV/m range for typical cavities. The present best-performing surfaces in this regard in multicell cavities are produced most routinely by electropolishing followed by a 120 C, 48 hour bakeout. As good performance is occasionally obtained without these measures in test cavities, just why is not yet known.

The effective surface resistance of non-field-emission-limited 1.5 GHz srf cavities at 2.07 K in the 18-24 MV/m range can presently be expected to fall in the range of 22–32 nΩ, depending on the applied surface preparation.

The table below includes the corresponding design values for the three cavity shapes, along with the resulting rf dynamic load per cavity when operating at E_{acc} = 20 MV/m with R_s of either 22 or 32 nΩ.

CEBAF 7-cell cavities

	OC	HG	LL
R/Q (ohms)	678	780	891
G	274	266	281
G* R/Q (ohms)	185324	207090	250052
Rs (ohms)	3.2E-08	3.2E-08	3.2E-08
Pdiss (W) @ 20 MV/m	33.8	30.3	25.1
Rs (ohms)	2.2E-08	2.2E-08	2.2E-08
Pdiss (W) @ 20 MV/m	23.3	20.8	17.2

The tentative 12 GeV cryomodules specifications allocate 250 W dynamic load per cryomodules. The labeled contours on Figures 1 and 2 are curves of constant 31 W dissipated power as a function of gradient for the three cavity designs. As is also apparent from the table above, the LL cavity design has the advantage of either being more tolerant of weaker surface quality or operable above required specifications—into the 21–25 MV/m range—without exceeding the 31 W power budget.

Multipacting

Although the adoption of elliptical cross-section shapes for srf accelerating structures has largely eliminated multipacting as a significant performance-limiting phenomenon, developers are careful to investigate each new shape lest some subtle resonance condition occur inadvertently. This is done during the design stage using numerical simulations—

which are becoming increasingly reliable—and experimentally during prototype testing. A set of multipacting simulation codes have been developed by Walter Hartung, et al.[11] These have been used to identify the field strengths at which multipacting may occur in a given cavity geometry if the secondary electron emission yield (SEY) of the surface is > 1. The first-order 2-point multipacting trajectory occurs across the equator of a cell.

Hartung performed an analysis of a variety of cell shapes and identified the bands in E_{pk} for each structure in which multipacting may occur. See his figure below indicating circumstances with impact energies greater than 20 eV, where SEY > 1 may occur on typical niobium cavity surfaces. The analysis correctly predicts the multipacting bands observed (and effectively processed) in SNS cavities during testing and the hard MP barriers encountered with the HEPL SCA cavities. Conditions which produce > 40 eV impact energies could be expected to produce persistent multipacting problems unless specific measures were taken to reduce the SEY of the niobium surface.

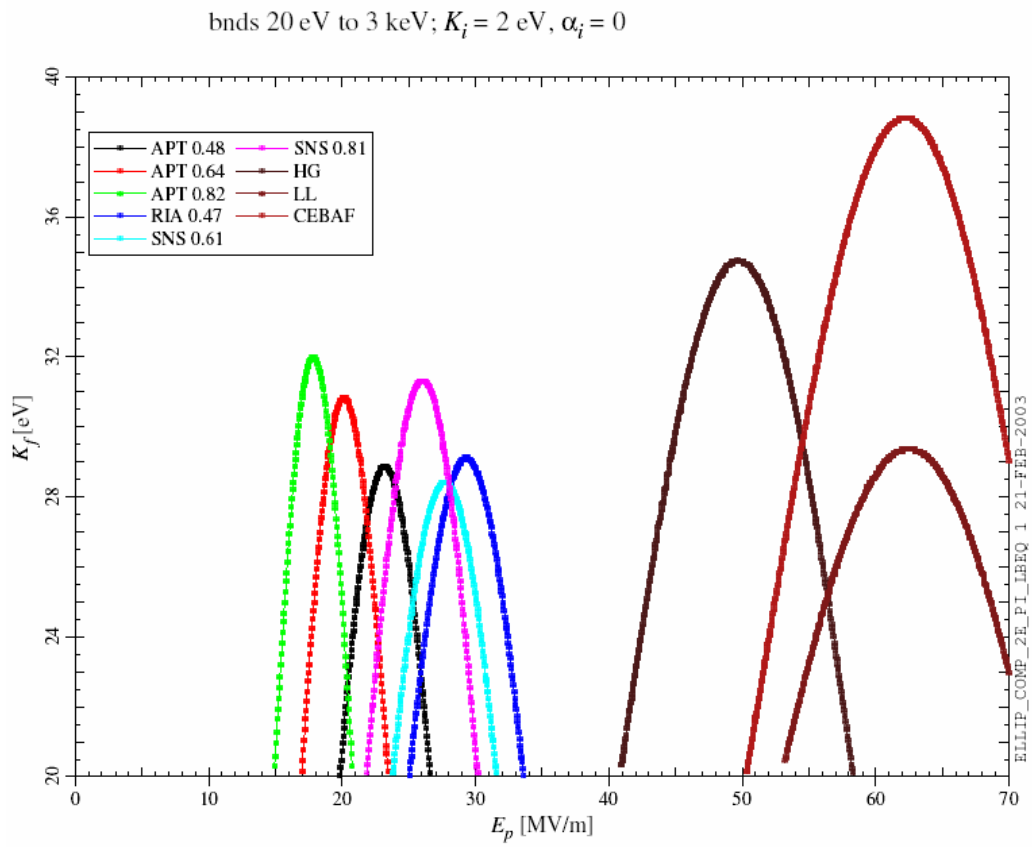

Figure 5. Potential multipacting bands in various-shaped SRF cavities (Hartung)

The predicted E_{acc} bands that could support "soft" multipacting in the CEBAF cell shapes are listed in the table below. No challenges to 12 GeV requirements are identified.

CEBAF 7-cell cavities

	OC	HG	LL
MP band - E_{acc} (MV/m)	19.5-29.3	21.7-30.7	24.4-33.2

During testing of the prototype and production batch of cavities, no multipacting barriers were encountered in the tested field range for either the HG or LL cavities. Thus, by analysis and experiment these cavity designs have been qualified as free of multipacting issue for their use in CEBAF.

Particular fabrication problems

In general, there remains some uncertainty regarding unexpected fabrication challenges for different structure design until they are actually realized. The development of the fabrication dies used for both the HG and LL cavities was guided by Peter Kneisel. He, with active support from others, produced the prototype cavities and documented the process as referenced above. These designs were then translated into a thorough drawing package and set of production travelers.[12] The drawings and travelers were then used to produce the *Renascence* cavities as documented in the Pansophy traveler database.[13] There were no significant differences in difficulty or performance results between the HG and LL designs. The only difference noted that was not fully resolved during the batch production was a small spring-back error in the LL cell shape as fabricated. This resulted in the cells being about 3% shorter than design when trimmed to frequency. Minor trimming of the deep drawing dies can correct this. [In addition, after fabrication, it was found that the FPC external Q is low for all of the cavities, approximately 9×10^6 rather than 2.0×10^7. This disconnect was subsequently traced to an error in propagating the dimensions used on the copper models to the niobium fabrication drawings.] [Rev. 1 addition]

Summary

Three different varieties of 7-cell cavities useful in CEBAF have been built and tested: OC, HG, and LL. Sufficient existence-proof data is now in hand that supports each as being quite viable for use in the 12 GeV upgrade construction. All of the identified potential issue topics have been addressed satisfactorily. As its name implies, the Low Loss cavity design has the distinct advantage of producing a significantly lower cryogenic load. Thus, it is recommended that the LL shape be formally adopted as the 12 GeV design choice.

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[1] http://accelconf.web.cern.ch/accelconf/p99/PAPERS/MOP116.PDF and http://docushare/Get/File-468/MPPH152-Campisi.pdf
[2] http://accelconf.web.cern.ch/accelconf/e04/PAPERS/TUPKF072.PDF
[3] http://tnweb.jlab.org/tn/2001/01-013.pdf
[4] http://tnweb.jlab.org/tn/2001/01-015.pdf
[5] http://www.jlab.org/~harwood/12GeV/SRF/12_GeV_SRF.html
[6] http://tnweb.jlab.org/tn/2002/02-023.pdf
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