Notes from tuning the 5 cell Nb SCRF separator for a K^+ beam at Fermilab.

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Abstract

This note describes measurements and calculations made on the 5 cell niobium superconducting RF separator made for the R & D effort to develop a separated K^+ beam at Fermilab. The apparatus used to make the measurements, the models used to simulate the tuning process and the results of the tuning itself are described. Additionally, the results of several studies and calculations made after the tuning of this cavity are included. Further necessary work is also described.

1) Description of the Cavity

This 5-cell cavity was constructed of reactor grade Nb and was initially intended as a study in fabrication methodology. As a result, the welds of the different cells were created with different e-beam parameters. The cell design was the A15 prototype, with the narrow (3.31mm) iris bend radius and no end cell compensation. Nb-Ti end flanges were welded on prior to the tuning. Polarization was introduced by squashing the entire cavity after construction; that proved to be a very simple operation although we are still not certain that it will be possible to introduce the ultimately required amount of polarization t with this technique.

Data from the cell polarization process is in table 1. Cell numbering is from the end of the cavity with a second, test weld circling the beam pipe. The net splitting of the two polarizations from the deformation, which reduced the diameter of the cavity in one direction by 3.17mm on average, was initially 8.025MHz. The 'natural' splitting, *i.e.*, the polarization from the manufacturing process, was 2.425MHz. The polarization process shifted the average frequency up by about 6.1MHz. The diameters of the irises at the end of the tuning process were measured by Rob Riley in the Fermilab Technical Division, and are listed in table 2. Iris A is between cells 1 and 2, iris B is between cells 2 and 3, and so on.

Again, the cavity had *no* end cell compensation. In this note, "tuning" always refers to the process designed to correct manufacturing defects.

Cell	Diameter before Polarization (mm)	Diameter after Polarization (mm)	Diameter 90° from polarization (mm)
1	97.36	94.21	97.26
2	97.23	94.23	97.38
3	97.51	94.26	97.54
4	97.36	94.26	97.66
5	97.16	94.21	97.16

Table 1: Initial cavity polarization data, in millimeters. The diameter 90° from polarization was not measurably changed by the polarization process.

Iris	Diameter
A	30.094
B	30.472
C	30.264
D	30.038

Table 2: Diameter of cavity irises, measured after tuning.

2) The Lumped Equivalent Element Model

The tuning was accomplished using the Lumped Equivalent Element Model described in Chapter 7 of *Padamsee et.al.*, hereafter called the LEEC model. It is sketched in figure 1.

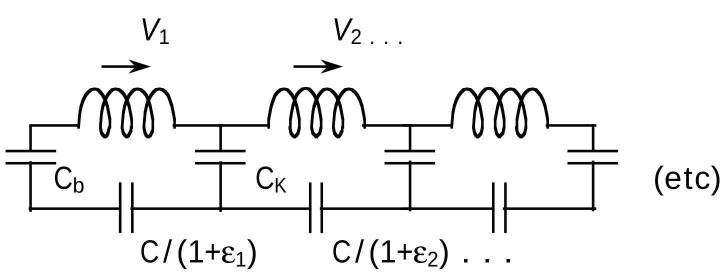

Figure 1. The Lumped Equivalent Element Model.

The mechanical imperfections of the cells are described with the e_i, the coupling to the neighbor cells is given by C_K, and coupling to fields in the beam pipe are described with C_b.

The five oscillator amplitudes V_i are taken to correspond to the magnetic field amplitudes in the five cells. These amplitudes were taken from the five maximum points in the bead pull plot when a round 3.04mm diameter metal bead was pulled down the axis of the cavity. In the center of a cell in a periodic structure, or a structure that is well compensated for beam pipe effects, that amplitude corresponds to $(3f_o\, \delta v\ /\ 8U)\ (\mu_o H^2)$. However this cavity is not compensated in the end cells and the end cell amplitudes obtained in this way are systematically low, probably at the few percent level.

Pulled a round conducting bead down the center of the cavity reads the electric field of the irises as well; the frequency perturbation in the iris is negative, in amount $(3f_o\, \delta v\ /\ 4U)\ (\varepsilon_o E^2)$. These fields also provide a sizeable fraction of the total deflection – something like 1/3 of it. We have also pulled a dielectric needle longitudinally down the axis and off-axis. The dielectric needle, at least in the limit of high aspect ratio, measures $\varepsilon(E_z)^2$, where E_Z is the longitudinal electric field. The value of E_Z is interesting because the transverse gradient, when integrated twice, gives the total deflecting voltage:

$$V_\perp = -c \int_0^L dz \int_{t_0}^{z/c} d\tau\, E_Z \qquad (1)$$

This result, the Panofsky-Wenzel theorem, gives the entire deflection, from both electric and magnetic fields. The possibility of determining $V_\perp$ directly with a long sapphire rod inserted down the entire length of a cell or cavity also needs investigation. Perhaps this will be useful in quantifying the uniformity of the deflection across the aperture of the cavity; the uniformity should be perfect only in the limit of a cylindrically symmetric cavity.

The LEEC is immediately converted through the substitutions $\Omega = LC\omega^2$, $k = C/C_K$ and $\gamma = C/C_b$ into the matrix form

$$\begin{pmatrix} 1+k+\gamma+e_1 & -k & 0 & 0 & 0 \\ -k & 1+2k+e_2 & -k & 0 & 0 \\ 0 & -k & 1+2k+e_3 & -k & 0 \\ 0 & 0 & -k & 1+2k+e_4 & -k \\ 0 & 0 & 0 & -k & 1+k+\gamma+e_5 \end{pmatrix} \vec{V} = \Omega \vec{V} \qquad (2)$$

where $\vec{V}$ is the vector representing the oscillator amplitudes of the LEEC (or the magnetic field amplitudes in the cells of the cavity), and the e_i are the effects of mechanical imperfections in each cell. At each step of the tuning process, the bead pull results are interpreted as the squares of $\vec{V}$, the values of e_i are calculated with perturbation theory, and these frequency corrections are converted into mechanical distortions to be applied to the cavity.

In this model, the cells are capacitatively coupled. That is usually the case in the accelerating mode, and these cavities are no exception. In the deflection mode however, the coupling for these cavities is inductive. Replacing capacitive coupling with inductive coupling only changes the sign of k in the matrix; all of the matrix manipulations are totally unchanged. The numeric value of k may be determined by the spacing between any two modes; I evaluated it by comparing the frequency of the π mode with that of the $4\pi/5$ mode. Using the results of the MAFIA simulation for the "_ tune" (described below), $k = -0.00889$; at each step in the tuning of the real cavity, I reevaluated k, resulting in some variations in this number. Solving the matrix equation above for γ while using the MAFIA simulation to obtain $\vec{V}$, k, and e_i, shows that $\gamma = 0.00605$; coupling to the beam pipes is capacitive.

Three minor modifications were put in place as the tuning progressed. After iteration 3, the frequency shift due to cavity contraction when cold was estimated at 6631 kHz from data taken with the Cornell 2-cell cavity[1]. At this point it also became apparent that the desired tune condition was one in which the field amplitude in the end cells was _ the amplitude in the center 3 cells (see section 4). Ad-hoc corrections were introduced to obtain the desired tune starting at this point in the process. Finally, the scaling constant (see section 5) was changed from 25.6 MHz/mm to 8.9 MHz/mm after iteration 3.

The LEEC does not allow for next-to-nearest neighbor couplings. These can be quantified by measuring the eigenvectors and resonant frequencies for all N modes of an N cell cavity and deducing the matrix of equation 1 directly, without a lumped equivalent element mode. But the interpretation of bead pull results in terms of oscillator amplitudes is not straightforward; the problem of interpreting end cell amplitudes in the π mode have been mentioned, and more serious problems exist in the other modes. The matrix resulting from this calculation appears unphysical. We suspect that there are important effects from cross coupling to TE_{111} mode, as in the model of *Bane and Gluckstern*. Mike McAshan is working on applying this model to our system, and it has become apparent that this will be needed for several things that we have to do.

[1] Actually, this correction was erroneously entered into the algorithm with the wrong sign. No great ill consequences ensued.

The LEEC does not provide allowance for the finite resistance of the cavities when warm. The frequency shift due to finite Q (*Jackson*, pg 360) is f/(2Q) ≅ 390 kHz, but it will be difficult to separate this effect from the overall shift due to overall contraction of the cell as it is cooled.

I developed a mildly improved LEEC, which allows for finite resistance and inductive inter-cell coupling while retaining capacitive coupling to the beam pipes. It also expresses mechanical imperfections in terms of a relative change in frequency rather than in terms of a relative change in capacitance. The intention of this model was to interpret bead pull results in terms of individual cell frequencies; it was unable to do so to the required level. This will be described in more detail in section 5. I also used it to study the problem of mode mixing, as described in section 6.

3) Modeling in MAFIA

The tuning process was modeled in MAFIA. Several different meshes were employed, but most of the results were computed using 200,000 points to simulate the full 5 cell structure. Automesh was used, setting zdensity to 1/√10 at the centers of cells and half that at the ends of the beam pipes. The rdensity was set to 1/√10 at r = 0 and at r = 26.7mm, which is about _ way between the points (R_1,Z_1) and (R_2,Z_2) as shown in figure 2. As a result, the mesh density was increased by about a factor of ten near the irises and the equatorial bend.

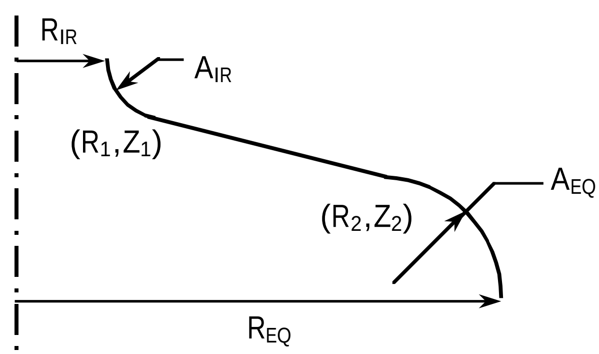

Figure 2. Yet another notation convention for cavity dimensions. Z_{IR} (not shown) is the distance in Z between the equatorial plane and the iris.

In the real tuning process, the cell shape was deformed by the application of force parallel to the Z direction in the vicinity of (R_2,Z_2). The way in which this distorted the shape was not known at the time. It now appears (see section 7) that for expansion the effect was mostly to deform the irises rather than the cell itself, and that for compression the effect was to transform the arc of radius A_{EQ} into an ellipse. For the MAFIA model, tuning was handled by changing Z_{IR} while leaving R_{IR}, A_{IR} and A_{EQ} unchanged. The distance R_{EQ} was expanded in proportion to the compression of Z_{IR}; the ratio dZ_{IR} / dZ_{EQ} was set to 7.5, based on measurements taken with a dumbbell which had been created as part of a production quality study.

4) Simulation of the Tuning Process: The B_{MAX} Condition

Using the above model of how the cavity deforms under compression, and simulating the pulling of a spherical metal bead down the center of the cavity with the MAFIA postprocesser, the tuning process was simulated. The initial state was a cavity with no mechanical imperfections but which was, like the real cavity, devoid of end cell compensation. As a result, the simulated tuning process was –in effect- an end cell compensation process. The simulation confirmed that the tuning process as implemented was converging in a reasonable manner. The convergence was quite slow, because the tuning algorithm assumed that each cell had the same response to any specific distortion – specifically that a 1mm compression of a cell's length lowered the cell frequency by 8.9MHz. This is a workable type of approximation when there is about the same amount of RF energy in each cell, but that is not the case for this system. The simulation also revealed the so-called B_{MAX} condition.

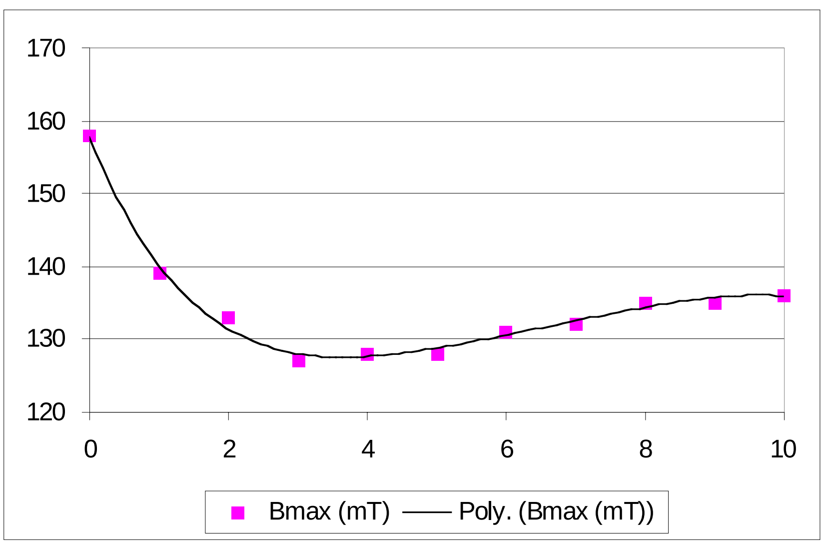

Figure 3. Peak magnetic field (for 5.7MV/m deflection) in 10 successive simulated tuning cycles.

Figure 3 plots the peak magnetic field calculated by MAFIA as the tuning simulation progressed. Each point corresponds to a new simulation for a geometry given by applying the LEEC model to the simulated bead pull results of the previously simulated geometry. The best performance occurs 2/3 of the way between iterations 3 and 4. Figure 4 plots the applied deformations for the end, second, and center cells as the simulation progressed.

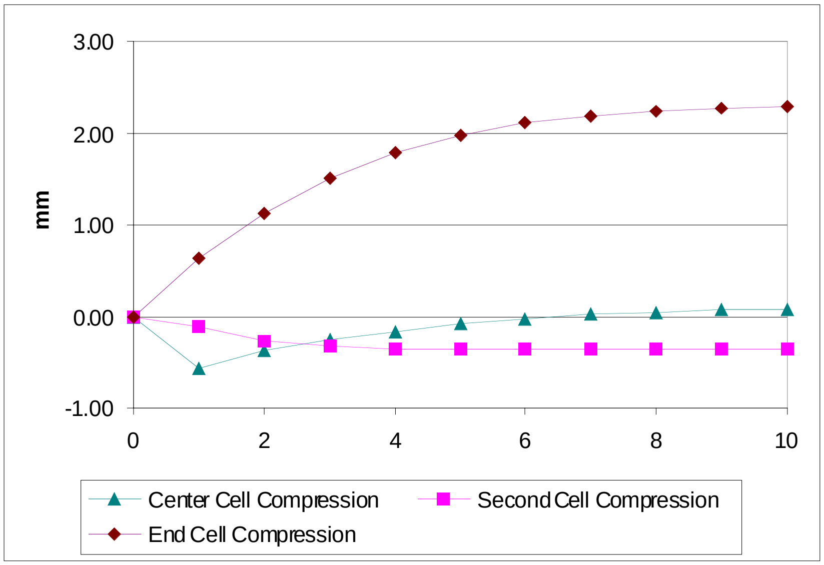

Figure 4. Mechanical deformations in 10 successive simulated tuning cycles.

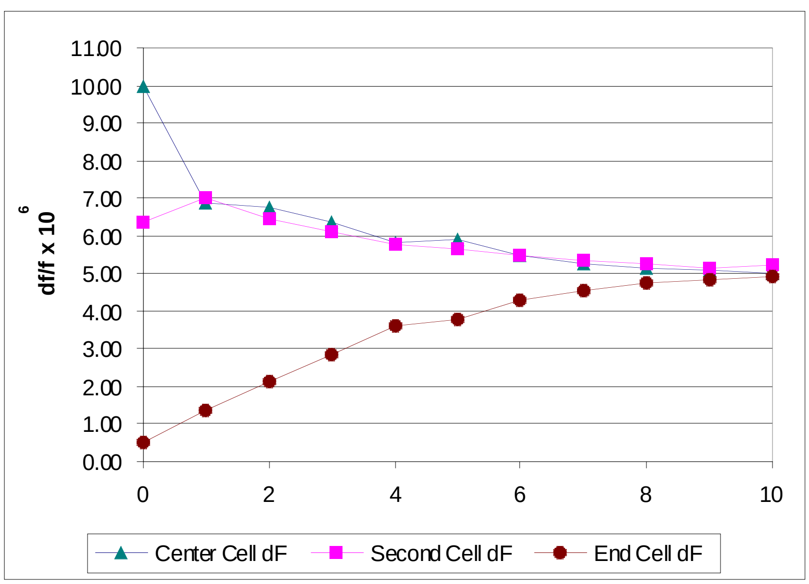

Figure 5. Bead pull results in 10 successive simulated tuning cycles. The vertical axis is maximum upward excursion in δf, which occurs when the bead is in the center of the cell and sees only a magnetic field.

The vertical scale is the compression of the entire cell, iris-to-iris ($2Z_{IR}$). As expected, large deformations of the end cells result from the lack of compensation in them.

Study of the MAFIA field maps reveal what happened at the point 2/3 of the way between iterations 3 and 4. Before tuning, at iteration zero, the field is largely in the center cell. The amplitude of the end cell is 22% of the amplitude of the center cell and the second cell is 80% as large. As a result the peak B field occurs at the iris slightly to the inside of the center cell. After the first tuning cycle, the center and second cells are at about equal strength, and the field in the end cell is still weak – but it grows steadily stronger as the tuning progresses. This can be seen in figure 5, which plots the peaks of the bead pull results for each of the cells through the tuning sequence. The lowest B_{MAX} corresponds to the point where the field in the end cell is large enough to move the point of maximum B from the central iris to the iris between the end and second cells. Because the field shape in the end cell is so weird, the field in the center of the end cell is still not very strong; from figure 5, it is about $(\_)^2 = 0.56$ times as strong as the field in the center and second cells. This is the "_ tune" case, which is the result of requiring the "B_{MAX} condition", *i.e.*, the condition that the maximum B field in all of the irises be the same. The B_{MAX} condition is a possible alternate to the standard method of end cell compensation.

Does the B_{MAX} condition produce the same end cell compensation as the traditional end cell compensation method? Not exactly. The traditional method compares the frequency of a finite structure, usually that of an end cell with some appropriately chosen boundary condition, to the frequency of an infinitely periodic structure. I simulated a full 5 cell structure with end cell compensations of 0 and 0.37mm. These compensations are increments to R_{EQ}; the 0.37mm number was the one found by Rainer Wanzenberg as the appropriate compensation for a 13 cell cavity. Comparing the frequencies with the results of a similar simulation of a periodic structure, I concluded that the convention compensation method for a 5 cell cavity gives a 0.32mm increase in R_{EQ}. Adjustment to the B_{MAX} condition produced a compensation of 0.41mm. The use of a 0.32mm compensation gives a B field in the irises of the center cell about 10% larger than the B field in the irises of the end cell.

With the B_{MAX} compensation, the field in the end cell as found with a simulated bead pull was $\sqrt{0.7051} = 0.8397$ times that of the field in the central cells. The best way to correct for this effect is probably to divide the $\delta f'^{(N)}_j$ quantities of

Eqn. (7.48) in *Padamsee, Knobloch and Hayes* by 0.7051 and leave the rest of the algorithm unchanged.

Table 3 lists some parameters from the _ field (uncompensated) tune simulation and the 0.41mm (untuned) compensation simulation. Results are scaled up to 5.7 MV/m deflection. This is a bit different from scaling up to 5.7MV/m on a 13 cell cavity, since 2/5ths of the cavity is end cells.

Parameter	_ tune	B_{MAX}
f_{π} (MHz)	3904.849	3902.152
$f_{4\pi/5}$ (MHz)	3911.717	3911.478
Cavity Energy (J)	0.183	0.183
Warm Q (Nb)	5010	4860
$R_{\perp}^{SHUNT}/Q$ (Ω)	133.4	133.3
B_{MAX} (mT)	130.8	94.7
E_{MAX} (MV/m)	25.8	23.1

Table 3: Parameters from MAFIA simulation of cavities meeting the _ tune and B_{MAX} conditions. The warm Q is calculated using σ = 58.0 e6 $(\Omega\text{-m})^{-1}$; $R_{\perp}^{SHUNT}$ is defined as in *McAshan & Wanzenberg*.

5) Lorentz Pressures – a First Look

The pressure from Lorentz forces is given by _$(\mu_0 H^2 - \varepsilon_0 E^2)$, where H and E are (presumably!) the peak fields and a positive value indicates an outward expanding pressure, normal to the surface. Figure 6 shows this pressure, with the appropriate φ dependence, for the central cell of the simulated _-tuned 5 cell cavity. Calculation of the deformation induced and the change in cavity frequency are underway.

6) The Scaling Parameter: MHz per mm

The tuning of a deflecting mode cavity differs from the tuning of an accelerating mode cavity in that there is no physically measurable quantity that corresponds to the frequency of a cell. In the TM_{010} mode, there is an electric node in the iris connecting two cells. One may put disks of copper on the end of sticks and slide them into the cavity to create a ground plane in the iris, thereby decoupling a cell from its neighbors. This makes the frequency of an individual cell a measurable quantity. In the TM_{110} mode there are substantial fields in the irises, and insertion of a ground plane modifies the field beyond recognition. There is a node in the center of the cell, in the equatorial plane, but it is not at all clear how one might insert a disk of

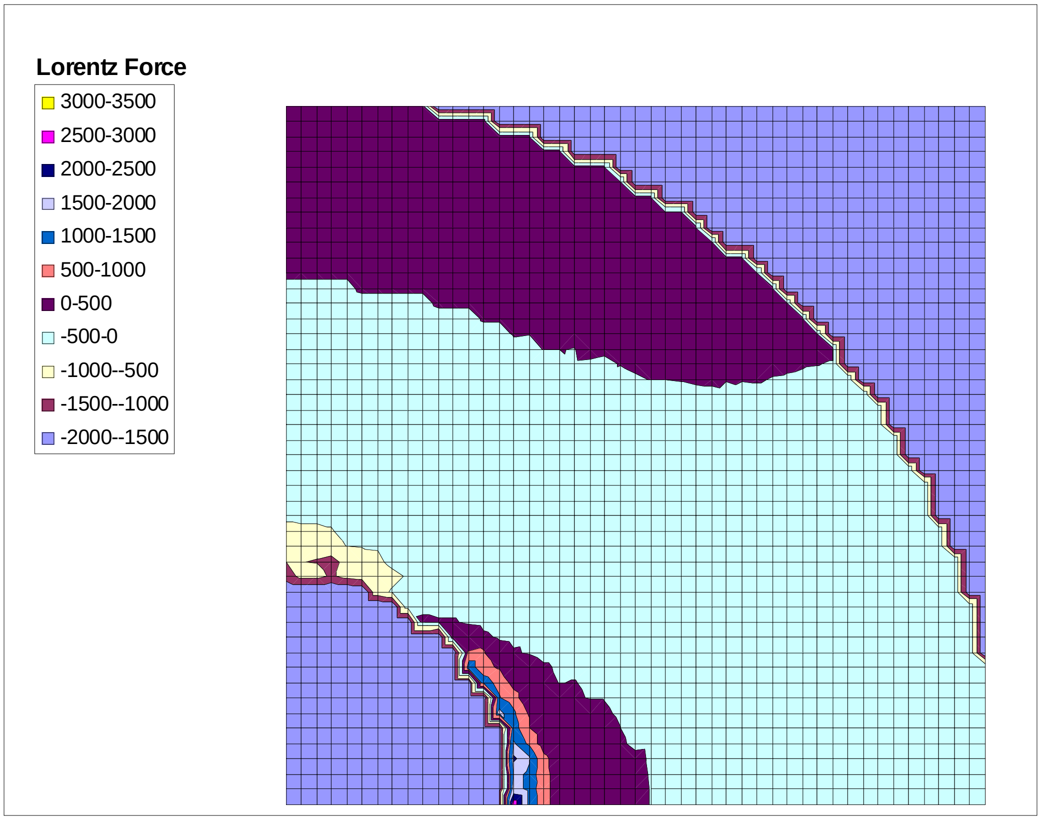

Figure 6. Lorentz pressures, normal to the surface. The scale is in N/m^2, with positive values corresponding to an outward pressure or equivalently that an inward dimple on the surface would raise the frequency of the cavity.

94.36mm diameter through an iris and beam pipe of 30mm diameter.

The result is that the per-cell frequency correction produced by the LEEC model has to be scaled by a scaling parameter giving the cell's frequency shift in MHz per mm of longitudinal compression. That number should then be weighted by the fraction of the energy in any given cell. Several methods were employed to find this number.

Using 5000 mesh points for a cell, the same automesh parameters described in section 3, and prescribing magnetic boundaries for the irises, the frequency in an infinite periodic structure was found in MAFIA as a function of cell length.

The cell length was adjusted by changing (R_1,Z_1) and (R_2,Z_2) but leaving A_{IR} and A_{EQ} unchanged. In this way, the scaling parameter was found to be about 19.25 MHz/mm, with a compression acting to lower the cell's frequency.

Direct measurement of the scaling parameter was made by taking a single cell with end pipes and squashing it. The cell was made of Cu. This was first done by Tim Koeth for *Edwards et al.*; he obtained a value of 24MHz/mm. I reproduced his results, obtaining 26.4MHz/mm, but in my data, the cell compressed nearly 10 mills = 0.010 inches before this rate of frequency shift set in. For the first 8 mills or so, the scaling parameter was 0.59MHz/mm followed by a smooth turn-on to the higher value in the next 2 mills. Again, in retrospect, the deformation applied to the physical cell was very likely different from deformation applied in the simulation.

Finally, an attempt was made to interpreting bead pull results with a mildly improved LEEC model to yield frequencies for individual cells.

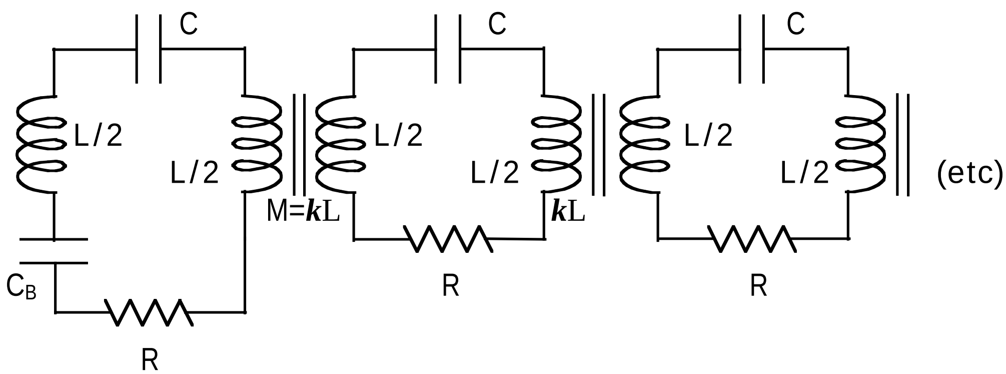

Figure 7. The mildly improved lumped equivalent element model.

This model is shown in figure 7; it is described by equation 3 for cells *1* and *j*.

$$\left(\frac{-i}{\omega C_B} + \left(R + i\omega L - \frac{i}{\omega C}\right)\right)V_1 - (i\omega\kappa L)V_2 = 0$$
$$\left(R + i\omega L - \frac{i}{\omega C}\right)V_j - (i\omega\kappa L)\left[V_{j-1} + V_{j+1}\right] = 0. \tag{3}$$

Dividing by $i\omega L$, defining the uncoupled-cell parameters $\omega_0 = 1/\sqrt{LC}$ and $Q_0 = \omega_0 L/R$, the end cell coupling as $\tilde{\gamma}$ = (C/C_B) / [1 + $i\omega/Q_0\omega_0$], and $\tilde{\Omega} = \left(\frac{\omega_0}{\omega}\right)^2\left(1+\frac{i\omega}{Q_0\omega_0}\right)$, this becomes the almost-eigenproblem

$$\begin{pmatrix} (1-\tilde{\gamma}\tilde{\Omega}) & -k & 0 & 0 & 0 \\ -k & 1 & -k & 0 & 0 \\ 0 & -k & 1 & -k & 0 \\ 0 & 0 & -k & 1 & -k \\ 0 & 0 & 0 & -k & (1-\tilde{\gamma}\tilde{\Omega}) \end{pmatrix} \vec{V} = \tilde{\Omega}\vec{V}. \qquad (4)$$

The eigenvalues of a real symmetric matrix are real; from the form of $\tilde{\Omega}$, this means that ω will be complex (neglecting the frequency dependence of the beam pipe coupling). The imaginary part of ω corresponds to the damping with time of field strength due to power dissipation.

To attempt to extract cell frequencies, I applied some approximations. In the 5 cell prototype, both k and γ are on the order of 10^{-3}, Q_0 is about 5000, and ω_0/ω never deviates from 1 by more than a few parts in 10^3. Define $\Omega = (\omega_0/\omega)^2$, $\gamma = (C/C_B)$ and $\phi = [1 - i/Q_0]$; then allow for mechanical imperfections by replacing (for each cell j) the angular frequency ω_0 with $\omega_0(1 + e_j)$, where $e_j << 1$. This leads to the following approximate model:

$$\phi \begin{pmatrix} (1-\gamma-2e_1) & -k & 0 & 0 & 0 \\ -k & (1-2e_2) & -k & 0 & 0 \\ 0 & -k & (1-2e_3) & -k & 0 \\ 0 & 0 & -k & (1-2e_4) & -k \\ 0 & 0 & 0 & -k & (1-\gamma-2e_5) \end{pmatrix} \vec{V} = \Omega\vec{V}\,. \qquad (5)$$

This level of approximation maintains the $e^{-\omega t/Q}$ sort of behavior, although it does not maintain the phenomena of phase slip between cells so well known to the designers of copper linacs.

I numerically solved equation 5 by defining a χ^2-like quantity to describe the differences between the solution $\vec{V}$ and a bead pull result. This χ^2 is a function of γ, k, and the e_i. First, I took the $e_i = 0$, and compared the resulting eigenvector to the bead pull result of the MAFIA simulation for a mechanically perfect cavity. The minimum χ^2 was at $k = 0.010120$ and $\gamma = 0.01730$; k and γ were highly correlated. The values in $\vec{V}$, after squaring and scaling to an appropriate scale, matched the peaks of $\delta f/f$ from the simulated bead pull to 18.0% in the end cells, 2.1% in the second cells, and 1.0% in the center cell. Second, I fixed (k,γ) to these values and let the e_i float. Again, the values in $\vec{V}$ were compared to the MAFIA simulation of a perfect cavity. The constraints $e_1 = e_5$ and $e_2 = e_4$ were imposed. The result was $e_1 = -0.008227$, $e_2 = -0.010093$, and $e_3 = -0.009730$. I conclude that this model can only predict the frequencies of the individual cavities at the 1% level. To tune the cavities, a much higher precision is called for. Mechanically, we can hope to adjust the cells' length to 0.025 mm. At 26 MHz/mm, that is 0.66 MHz, or 0.017% of the frequency.

It is reasonable to ask if the model of equation 4 could do a better job were it not so encumbered with the approximations of equation 5. Perhaps it could, but even without those approximations, equation 4 does a poor job of simulating the spectrum of resonant modes. Notably, the eigenvalue spectrum was a poor match to the MAFIA simulation; the eigenvalue of equation 5 corresponding to the $4\pi/5$ mode was 1.011220, but the MAFIA simulation gives $\Omega = (f_N\ /f_\pi)^2 = 1.003157$. Further, this mildly improved LEEC says that the $2\pi/5$ and $\pi/5$ modes are more closely spaced than the π and $4\pi/5$ modes; the real cavity has exactly the opposite behavior. It is probably better to go straight to the two chain model of *Bane and Gluckstern*.

7) Mode Mixing

When the cavity is tuned to remove mechanical imperfections, it is warm and has a Q of about 5000. As a result, resonances have widths comparable to the intermode spacing. A flat bead pull result at room temperature will not correspond to a flat bead pull result when cold; even when the bead pull is measured at the π mode resonance, there is still an admixture of the other $n\pi/5$ (mostly, $4\pi/5$) modes. To assess this effect, I used the model of equation 3 and calculated the ratios V_{j-1}/V_j to determine the vectors for the finite conductivity case at any given frequency. Then I decomposed these vectors into a linear sum of the 5 eigenvectors for equation 5 with $e_i = 0$, *i.e.*, the infinite-Q case without frequency dependence in the beam pipe term and with $k = 0.010120$ and $\gamma = 0.01730$. The 'π' mode with finite conductivity decomposed into

$$\begin{aligned}&(5.960-1.620i)\{\ \pi \text{ mode }\} &&+(-0.051-0.203i)\{\ 4\pi/5 \text{ mode }\}\\ &+(-0.021-0.126i)\{\ 3\pi/5 \text{ mode }\} &&+(-0.031-0.131i)\{\ 2\pi/5 \text{ mode }\}\\ &+(-0.019-0.111i)\{\ \pi/5 \text{ mode }\}. && \end{aligned} \tag{6}$$

Obviously, the reliability of this method relies on the viability of the underlying model. Again, it appears that we need to move to the two-chain model.

A second effect of finite Q is to distort the Q measurement for the π mode due to the nearby $4\pi/5$ mode. This was not a large effect, but will need to be handled correctly for the 13 cell cavity, where the modes are much closer.

8) Details of the Bead Pull Measurement: Changes Since CKM-27

The bead pull methods of CKM technical note 27 were only slightly modified. Magnetic coupling with loops about 3/8" diameter at each end of the cavity, about 5 – 10 mm from the ends of the end cells, was used. The loops were both horizontal and placed in the vertical plane that contained the axis of the cavity. A few mm of vertical displacement from the cavity axis was applied to the loops to permit the bead to pass down the axis easily, as shown in figure 8. The distance from the resonating cells to the probes was adjusted so that the insertion loss of the cavity was between 33 and 40 dB. This relatively large coupling reduced the Q to the 4100-4800 range, but kept the measured signal well off of the noise floor. As a result, electrical noise effects were low. A series of 14 sequential bead pulls found an RMS variation of $\pm 0.04^{o}$; at a typical (πf/360Q) of 7.5kHz per degree, this is $\pm$300 Hz. The correlation between the readings for the cells was ≅90%. The nonrepeatability due to mechanical alignment problems was the dominant effect. As in CKM-27, the position of the bead upon entering and exiting the cavity could be repeated to within a fraction of a millimeter or so.

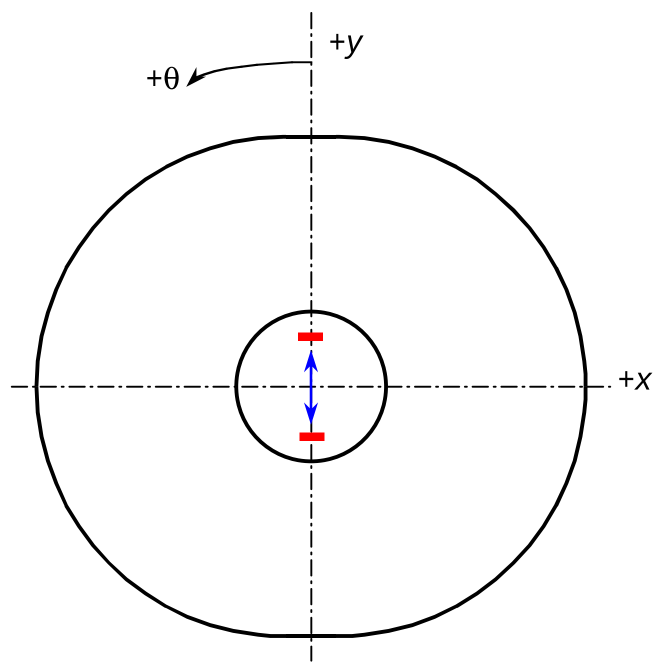

Figure 8. Sketch of cavity, probe loops, and polarization angle. The two horizontal red lines mark the planes of the magnetic probe loops inside the beam pipe; The blue double headed arrow marks the polarization of the magnetic deflection field in the ideal case. Angles are measured as shown; the view is from cell 5 in the direction of cell 1.

One issue is the correct small-bead criteria. For these measurements, the bead size was selected so that the change in the cavity frequency was a fraction of the resonant width. I now think that the correct criteria is to insist that the insertion loss of the cavity be unaffected to the (say) ±5% = 0.2dB level as the bead passes through the cavity. The reason is that fluctuations in the insertion loss correspond to fluctuations in the field strength in the cell in which the bead is moving.

Two new LabView VI's were created in the course of this work. The VI in MacOS : LeoView : General Tests : Repeated Q find.vi calls the VI described in CKM-27 a number of times to determine Q. In MacOS : LeoView : Data Analysis there is get df.vi, which finds the peaks in the δf excursions of the bead pull data. It fits a line to the two ends of the bead pull data, where the bead is physically away from the resonators, and subtracts that baseline before running a peak-finding algorithm. Also in this area are two spreadsheets which calculate the required frequency corrections. One, named five-cell-pull.xls is the one used for the tuning described here; the other, named five-cell-pull-simv5.xls is an improved version for future use, containing a scaling parameter weighted for the energy fraction in each cell. There is also Rfcorrect_general_form.xls, a spreadsheet to calculate the corrections to a measured frequency for the barometric pressure, ambient temperature and humidity.

A minor note. The temperature probe, when placed in contact with the cavity, introduced a small shift in the phase relationship between the two probes. It is better to move it away from the cavities for bead pull measurements. Measurements of Q or resonant frequencies seem to be unaffected.

9) The Tuning Fixture: What We Need in a New One

The prototype cavity tuner proved to be educational but inadequate. It consisted of two annular pieces which fit into the spaces between cells at the irises. These annuli, or plates, were brought together by small successive turns of three screws controlling the inter-plate spacing. For the center and second cells, force was applied in a circular area near (R_2, Z_2), as described in section 3. For the end cells, a plate holding the large end flanges of the cavity was used; force on the outside of the end cells was applied in the Z direction at the beam pipe.

The device lacked several controls that subsequently proved important. First, there was no easy way to verify that the tuning device was correctly centered about the cavity axis. In later tuning cycles, alignment by eye was attempted, although the value of this procedure was dubious. Second, there were two uncontrolled axes of rotation of the device about its center. Third, although I made an effort to keep the plates parallel, there is some evidence that this did not happen at the level of several mills. The dial and caliper gauges used to measure the spacing between the annuli did not always give consistent readings.

The tuning fixture needs to double as a measurement device; it must also function to measure in some way the length of the cell. The prototype device did not do this very well. The best that could be done was to turn the three spacing screws until they were finger tight and the plates were also more-or-less parallel, and then measure the inter-plate spacing. Repeatability of this process was not better than ≈0.1mm at best.

To introduce a permanent deformation, the metal must be distorted beyond the elastic regime into the plastic regime. To the level that I could determine, there was a constant offset that had to be added to the desired deformation to get the deformation that had to be applied. This offset was near 24 mills for cell expansion and 32 mills for cell compression. Note that this is much larger than the actual desired distortions. Also, the smaller offset for expansion suggests that in expansion the iris was being bent quite a bit. The line between (R_1,Z_1) and (R_2,Z_2) in figure 2 forms some angle α to the cavity axis. Expansion, where the annuli contact the adjacent cells rather than the cell being tuned, probably changed this angle considerably in the adjacent cells.

Finally, it seemed (although this is not a quantitative observation) that better control over the deformation process was possible when the cavity was removed from the fixtures that hold the RF probes. There is little doubt that any longitudinal motion of the end flanges would have been restricted by binding in these fixtures.

10) Sequence of Tuning Results

Figures 9 and 10 show the initial and final bead pull results. Table 4 details the intermediate stages, giving the peak $\delta f/f$ values for each cell.

After iterations 5 and 11, I attempted tuning several cells at once. In both cases, the result was a setback in cavity flatness. The best results were obtained by applying the largest of the corrections requested by the LEEC model to the appropriate cell and then remeasuring the cavity. After iteration 15, the process was discontinued, largely because there did not seem to be any additional information to be gained by continuing. Overall, the final result is good, although there is little doubt that it could be made better with more tuning cycles.

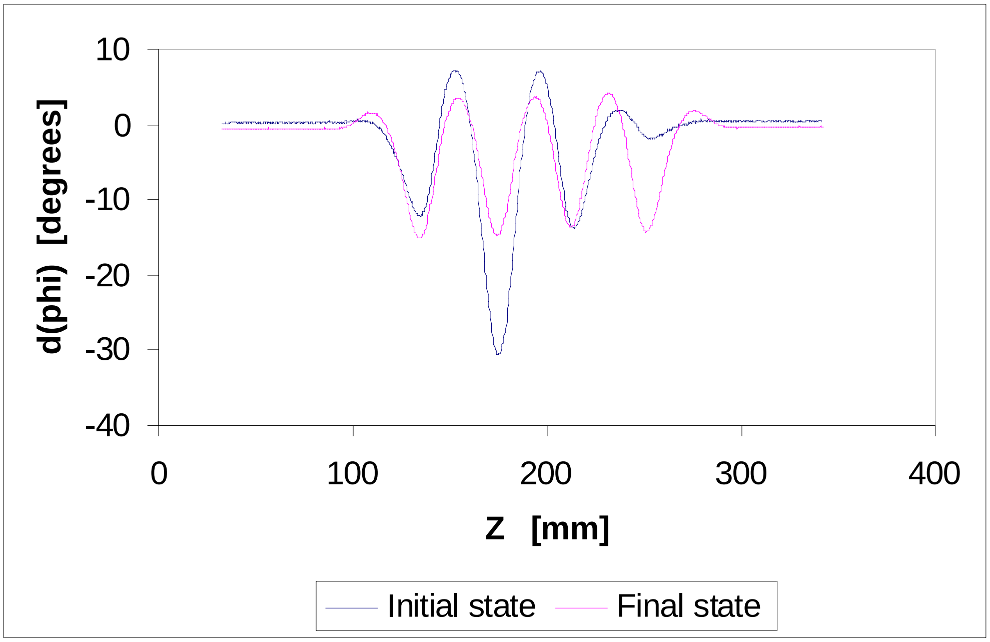

Figure 9. Raw bead pull results before and after tuning.

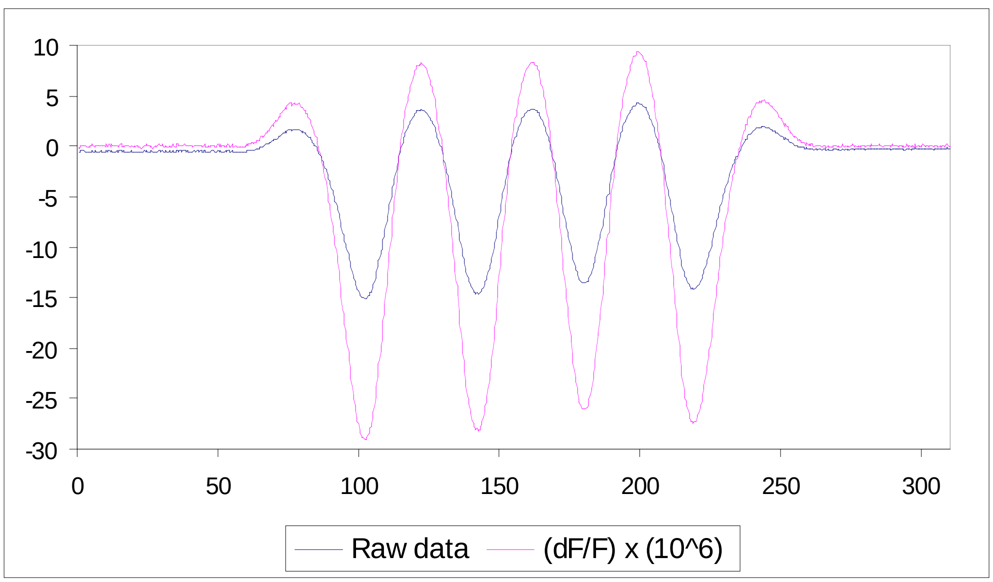

Figure 10. Final bead pull results. Corrected form includes baseline subtraction and conversion to $\delta f/f$.

Iteration	df(1)	df(2)	df(3)	df(4)	df(5)	Decision, notes
0	2.2	51.3	51.0	11.5	0.0	Compress cell 4 0.62 mm At 25.6 MHz/mm
1	0.8	34.3	55.4	34.3	0.8	Compress both end cells 0.31 mm Algorithm still wanted to compress end cells 0.28 mm
2	1.1	32.5	49.0	32.0	1.4	Extend center cell 0.13 mm
3	2.1	33.4	49.4	34.0	1.3	Compress both end cells 0.45 mm Change to 8.9MHz/mm; aim for _ tune
4	2.7	34.7	47.8	33.9	1.4	Compress both end cells 0.41 mm
5	14.7	39.8	34.9	32.9	10.1	Compress end cells 1 0.14 mm, expand cell 2 0.20 mm, cell 4 0.14 mm. A big mistake.
6	22.0	42.6	31.3	25.7	9.5	Expand cell 2 0.16 mm
7	20.8	40.5	32.3	28.7	10.1	Expand cell 2 0.17 mm; Tried expansion with cavity off bead pull rig
8	11.2	13.7	14.4	11.1	6.1	Did not change cavity Bead alignment probably poor
9	19.1	37.4	34.1	33.9	13.2	Expand cell 2 0.14 mm Differs from Iteration 8, but no change in cavity
10	16.8	33.2	34.0	36.4	14.6	Compress cell 4 0.15mm
11	18.5	35.8	35.1	35.7	14.4	Expand cells 2 and 4 0.12mm, cell 1 0.03 mm. A big mistake.
12	12.3	29.3	35.1	40.4	16.4	Expand cell 4 0.10 mm
12a	11.4	29.1	35.3	40.0	16.5	Expand cell 4 0.09 mm Previous expansion had little effect
12b	14.0	31.5	35.0	36.9	16.0	Compress cell 1 0.15mm
13	18.5	35.8	32.9	32.2	12.6	Compress cell 5 0.16mm Algorithm wanted to compress center cell 0.21 mm
14	15.6	30.9	31.4	34.7	16.8	Compress cell 1 0.10mm Algorithm still wanted to compress center cell 0.21 mm
15	16.7	32.0	32.5	36.4	17.4	Stop tuning process Algorithm wanted to compress center cell 0.22 mm

Table 4. Tuning history.

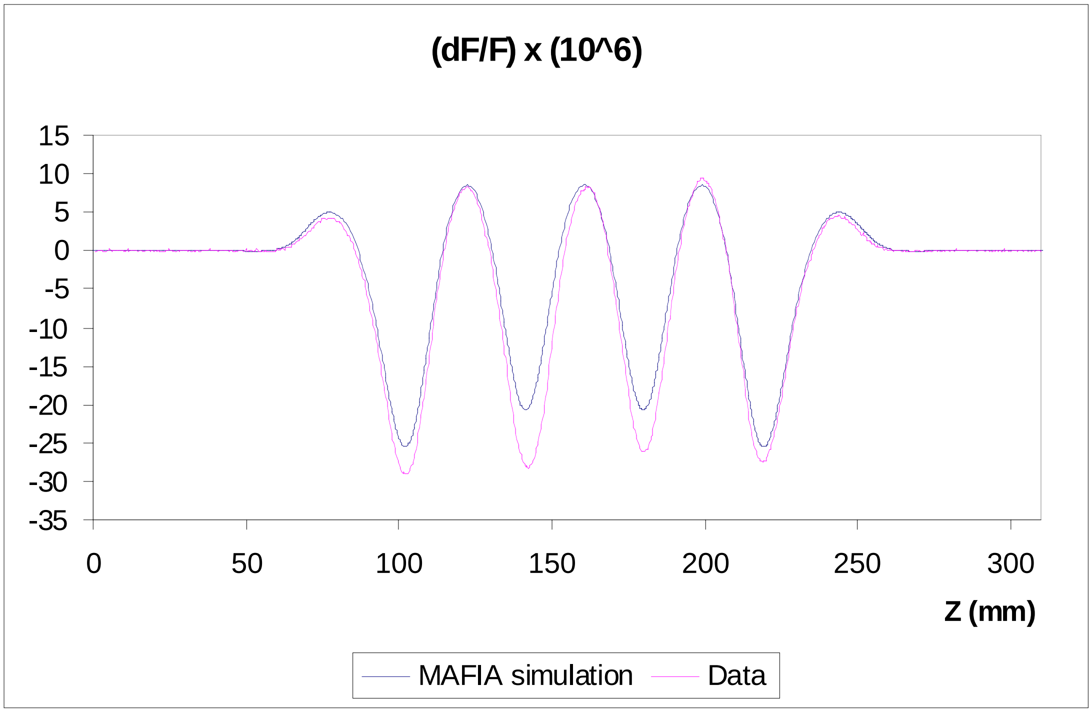

Figure 11. Final bead pull result *vs*. MAFIA simulation of _ tune result. The MAFIA results have been multiplied by a factor of 1.44 for this plot.

Figure 11 compares the bead pull result after tuning with the tuning goal specified by MAFIA simulation. As in CKM-27, there still seems to be an overall scale factor by which the frequency shifts of the bead pull are underpredicted[2]. In figure 11, the MAFIA results have been scaled by an ad-hoc factor of 1.44 to allow for this.

Of some concern is the mismatch between the bead pull prediction and the data in the irises. At Z ~ 100, 140, 180 and 220 mm, the electric field in the iris regions creates a minimum in δf. MAFIA underpredicts the iris fields. The data also shows that the fields are not uniform across the different irises. Table 2 shows the diameter of the irises, but there are a number of other defects that are in principle possible: the irises could be elliptical, off-center, or have wrong curvatures. Because of the history of the cavity as a study in fabrication methods, the e-beam welds in the different irises were made with different beam and weld parameters. Assuming the differences between the irises were only in diameter, the dependence of the relative change in the iris bead pull result upon the diameter of the iris was roughly determined using both data and MAFIA. The variation in the bead pull dip is about 2/3 the variation in the diameter in mm, *i.e.*, an iris of diameter $(30+\Delta)$mm will have a

[2] The correction of the volume of the bead for the interior volume of the hole, used in CKM-27, was dropped for this work.

dip in the bead pull which is larger than the dip in a 30mm iris by a factor of ($2\Delta/3$). The electric field and the deflection of course will go as the square root of this variation. There is no known technology to tune the irises; we will have to rely upon manufacturing precision to keep cavity performance levels high in this regard.

11) The Unpleasant Surprise: Polarization During Tuning

At the first step in the tuning, the compression of cell 4, the polarization of the cavity rotated. After this compression, which was the first and the largest compression applied, the best transmission of the resonant signal from one end of the cavity to the other happened when the flat applied to polarize the cell was rotated to $\theta = 45°$. After some of the other tuning cycles, the polarization measured in this way rotated in either direction in various amounts of same sort of magnitude. The splitting of the two polarization mode frequencies also changed. Initially, the two polarizations were 8.025 MHz apart; after the first tune, they were 7.015 MHz apart. At the end of the tuning process, the two polarizations were about 6 MHz apart, and the best transmission occurred with the flat at $\theta \cong 20°$.

The polarization measured above is the overall polarization of the 5 cell system. The polarization of the individual cells is of obvious interest; two cavities with different sets of individual cell polarizations could have the same overall cavity polarization, and yet have very different abilities to deflect a beam of charged particles. The cell polarizations cannot be measured directly, because insertion of a grounded outer coax connector down the beam pipe unalterably destroys the fields of the deflecting modes.

The cavity polarization for each of the 5 modes of the 5 cell cavity is different. The splitting of the different resonances of the TM_{110} band appear and disappear as the cavity is rotated about its axis. Because each of the different resonances correspond to different amounts of energy in each cell, it should in principle be possible to determine something about the cell polarizations from measurements of the cavity polarization for all the modes. This has yet to be investigated in detail.

A more direct measurement was attempted by pulling a dielectric bead off axis. A dielectric bead will measure only the electric field, which goes as $\sin(\theta)$ for a bead along the $+y$ axis, and as $\cos(\theta)$ for a bead displaced along the $+x$ axis. Figure 12 shows the results of pulling the red plastic bead of CKM-27 down the center, and with 10 mm displacement in the x and y directions. The pull with the bead on axis shows δf returning to zero at the centers of each of the three central cells, indicating nodes in the electric field. Also, δf is zero at the end cells. The pull with the bead displaced in the +*x* direction shows local maxima at the center (in z) of the three central cells; δf is largest when the bead is near the iris. In this curve we can see minor inflections at the end cells, but they are not clear enough to assign a value to δf at the center in z of these cells. So it is not possible to measure the polarizations of the end cells with this method. The viability of this method with correctly compensated end cells is still an open question. We also see that for a bead displaced in the +*y* direction, the bead is not located upon an electric node. Comparing the values of δf from the two displaced pulls as found with the bead in the centers in z of the three central cells constrains $tan^2(\theta)$. The value of θ for cells 2, 3, and 4 works out to be $\pm$25.4°, $\pm$23.4° and $\pm$21.4°, respectively. There is an ambiguity in the direction of the rotation as found in this way.

Noting the similarity of these measurements and the angle between the cavity polarization and the flat after tuning, the measurements with the dielectric bead displaced in +*y* were repeated twice: first with the cavity oriented with

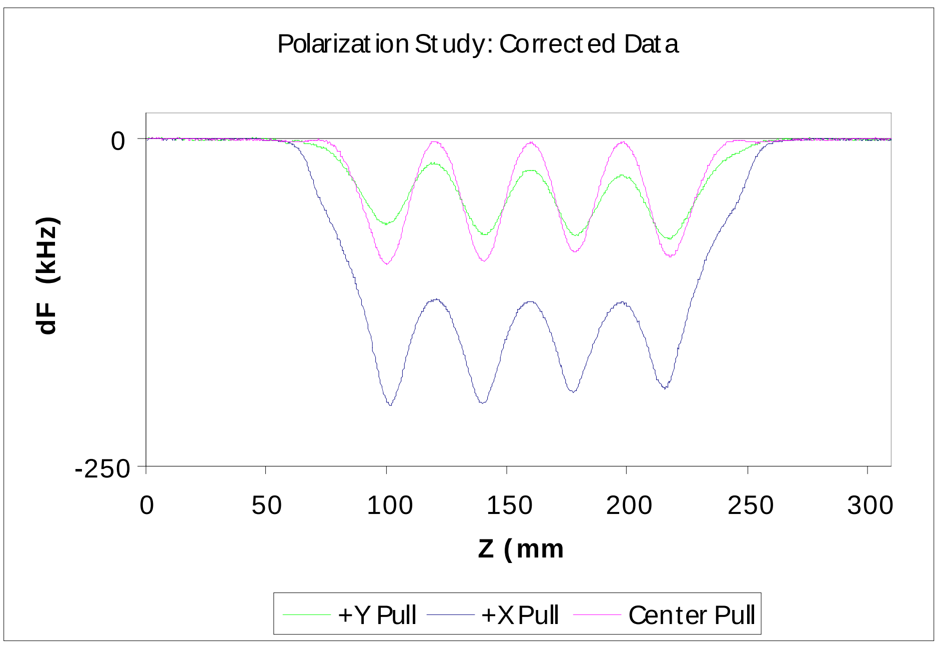

Figure 12. Pull of dielectric bead on axis, and displaced in two directions by 10 mm. The cavity was aligned so that its overall polarization was vertical.

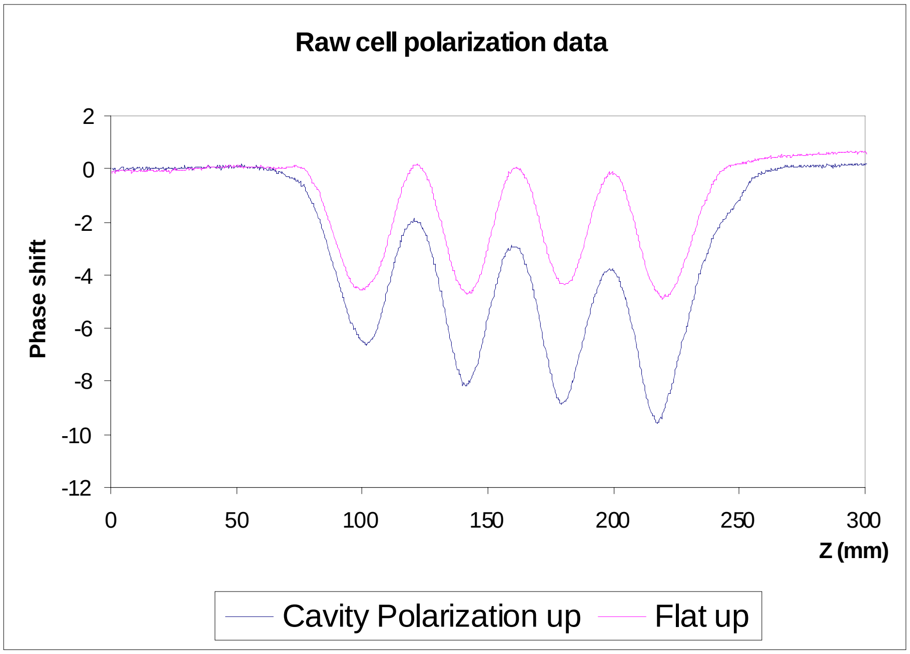

Figure 13. Dielectric bead pull results with the cavity in two different orientations.

its overall polarization vertical, as before, and then second with the cavity oriented so that the flats were vertical, as shown in figure 8. The results, shown in figure 13, strongly support the hypothesis that the three central cells are polarized along the applied flats to within a few degrees.

12) Stuff to do

We have shown the capability of achieving field flatness in a 5 cell deflecting mode cavity. A great deal still needs to be done in regard to tuning however:

1. Cell polarization measurement techniques need further development.
2. We need a better tuning fixture.
3. With items (1) and (2) we will see if a greater cell polarization is needed; if so, we need to see if it can still be achieved without the use of polarized dies to form the half-cells from which the cavity is made.
4. Once a new tuning fixture exists, a few sample deformations should be measured and then simulated in MAFIA. This should be compared with the deformations computed using the finite element models now being employed to design a second generation tuner. This study will also provide an initial estimate for the scaling factor that reflects the actual deformation.

5. Once a new tuning fixture exists, we will need to obtain better information about what level of deformation is needed to move a niobium cell into the plastic deformation region.
6. We need to investigate further different bead pull configurations – eg, dielectric needle off axis, *etc.* The central problem seems to be to get a quantity that maps readily to a lumped equivalent element model.
7. The Lorentz pressure calculation needs to be redone with a more realistic cavity geometry. The impact of Lorentz pressures as estimated at this time also must be evaluated.
8. The two-chain model must be developed for the mode mixing calculation and to determine individual cell frequencies. Finite Q and beam pipe effects need to be included. Optionally, we might choose to investigate a single chain model with some combination of inductive and capacitive coupling.
9. The effects of the side ports on the end cells of the 13 cell cavity's bead pull profile needs to be thought about. Should we use the coupling ports to drive the cavities during bead pull measurements?
10. Some of the LabView software will need ugrading before we tune the 13 cell; the effect of the $12\pi/13$ mode upon the measurement of Q in the π mode has to be handled, and the existing 5 cell get_df.vi and five-cell-pull-simv5.xls have to be modified and tested.

There are a number of closely related problems which also need to be tackled:

1. The B_{MAX} end cell compensation criteria needs to be applied to a 13 cell system.
2. Frequency shift estimates due to chemical etching and contraction during cooldown need to be refined.
3. Quality control by measuring dumbbell frequencies before e-beam welding into a cavity has to be developed.
4. Will modes like the $\pi/13$ TE_{111} mode be trapped in a 13 cell cavity?
5. What about multipacting?

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