The SRF Deflecting Cavities of the CKM Experiment

What little I recall

Bundle of info on Indico

30 Sep 2021

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RF-separated beams for AMBER

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The CKM cavities

- The CKM physics proposal (1998) was aimed at the measurement of $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) \sim 10^{-10}$
- The beam was planned to have relatively little time structure – but debunching was not worked out in detail

- Later, a version for the ILC crab cavities was proposed. Graeme Burt knows more than I about that…
- That beam has LOTS of time structure

- A Cu version of the cavity shape was used for a demonstration of emittance exchange in the Fermilab A0 photoinjector (thesis of Tim Koeth)

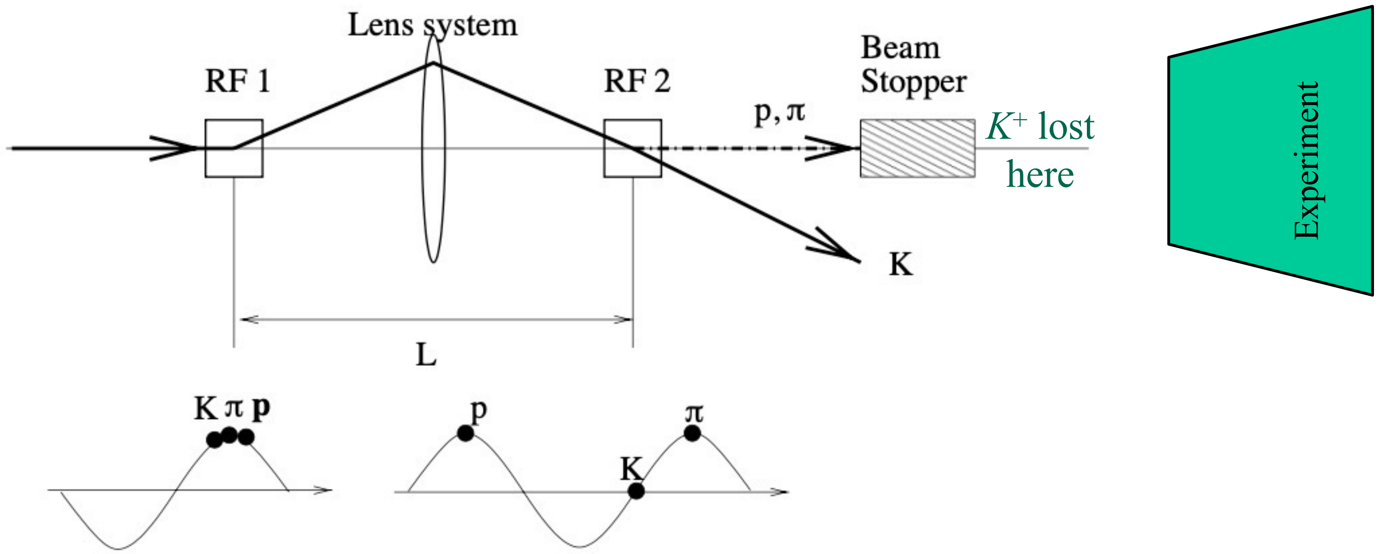
- The use of a device as a beam slicing diagnostic, to analyze the longitudinal structure of a bunch

The "3rd Harmonic" cavities

Accelerating mode (TM_{010}) 9-cell cavities at 3.9 GHz were also made and installed in DESY's FLASH beamline.

The CKM beamline

- **The basic idea was to select length, cavity frequency and beam momentum so that BOTH p and π^+ go into a beam stopper, these being the primary contaminants**



- **I do not have a late-stage detailed drawing of the beamline and its elements**

- p_{BEAM} = 22 GeV/c f = 3.9 GHz L = 86.5 m I = 2.2 nA
  1 s / 3 s duty cycle $p_\perp/\ell$ = 5 MV/m;   Primary beam 120 GeV p

Two axis deflection

Add a vertical deflection out of phase and change the beam stop into a round collimator

Change f, P_{BEAM}, $L \Rightarrow K^+$ are undeflected – get all the K^+

p and π^+ circle in the transverse plane and hit a collimator

Only the K^+ need satisfy the basic phasing equation – more flexibility with f and L

Alternately, could NOT change f, P_{BEAM}, L, keep stopper, spread K^+ out over larger area in detector (high K^+ intensity)

We concluded we could do the experiment with just one deflection axis

What we built

- 13 cells, "elliptical" design
- Phase advance of π between adjacent cells
- Polarization via 1.5 mm deep flat across the top of all the cells, giving ~9 MHz polarization split
- Spacing between primary mode and the next mode ~1 MHz

Table 2: Separator RF Cavity Parameters for C15 design

Frequency	3.9	GHz
mode	π, ≈TM110	
Equator diameter body, (end)	94.36 (95.10)	mm
Iris diameter	30	mm
Cell length	38.4	mm
cells/cavity	13	
Effective RF length/cavity	499.2	mm
$(R/Q)'$/cavity	351	Ohm
$(P = V^2/2(R/Q)' \times Q)$		
V_{trans}	5	MV/m
E_{peak}@ 5 MV/m	18.5	MV/m
B_{peak}@ 5 MV/m	0.077	T
Coupling factor $(f_0 - f_\pi)/f$	0.043	
$f_\pi - f_{\pi-1}$	1.0	MHz
polariz-tune-split.	10 . . . 40	MHz
tuning range	± 1	MHz
$G_1 = Q \times R_{sur}$	228	Ohm
R_{sur} @ 2K, T_c/T=4.6	1.1×10^{-7}	Ohm
Q@R_{sur}	2.1×10^9	
Power dissipated@5MV, 2K	8.5	W/m
Q_{ext}	6×10^7	
full bandwidth f/Q_{ext}	65	Hz
U (stored energy)	0.73	Joules/m

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Fields

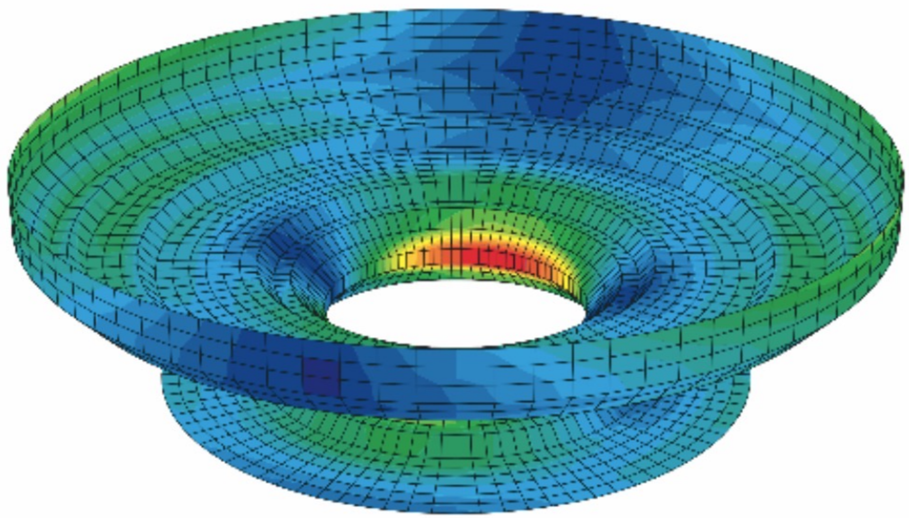


Figure 4: Surface Current Density.

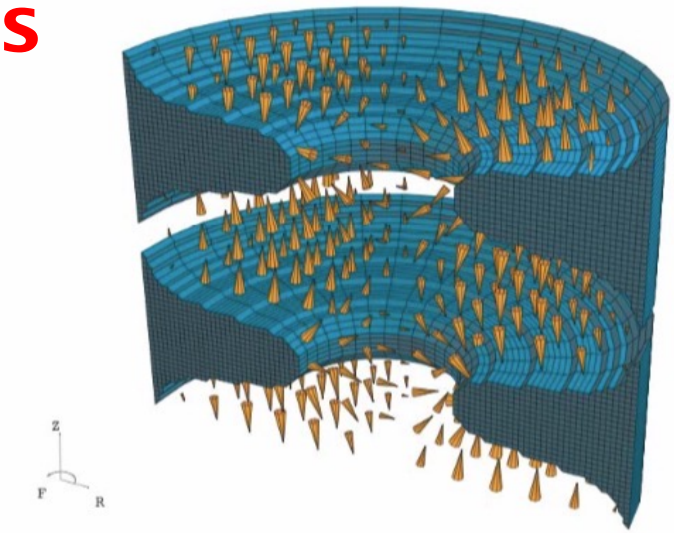


Figure 2: Electric Field

- B, I_{SURF} concentrated in iris
- E not very high compared to TESLA accelerating cavities
- $p_\perp/\ell = 5$ MV/m $\Leftrightarrow$ $B_{PEAK} = 77$ mT which is B_{PEAK} of an $p_{ACC}/\ell =$ 18 MV/m TESLA cavity

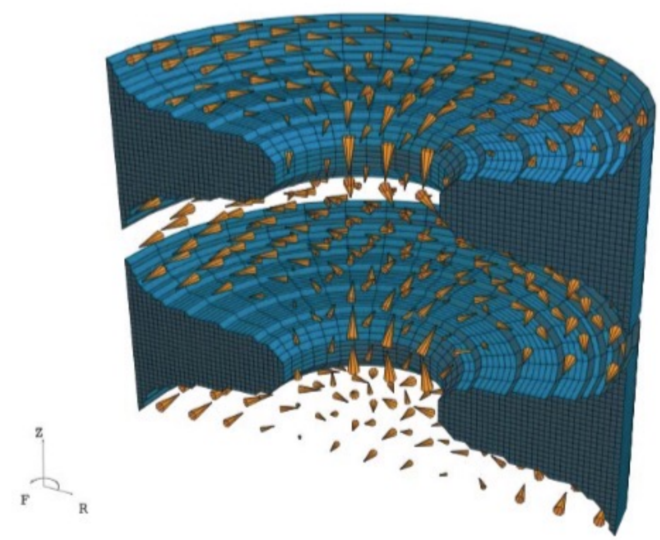


Figure 3: Magnetic Field Lines.

Fields

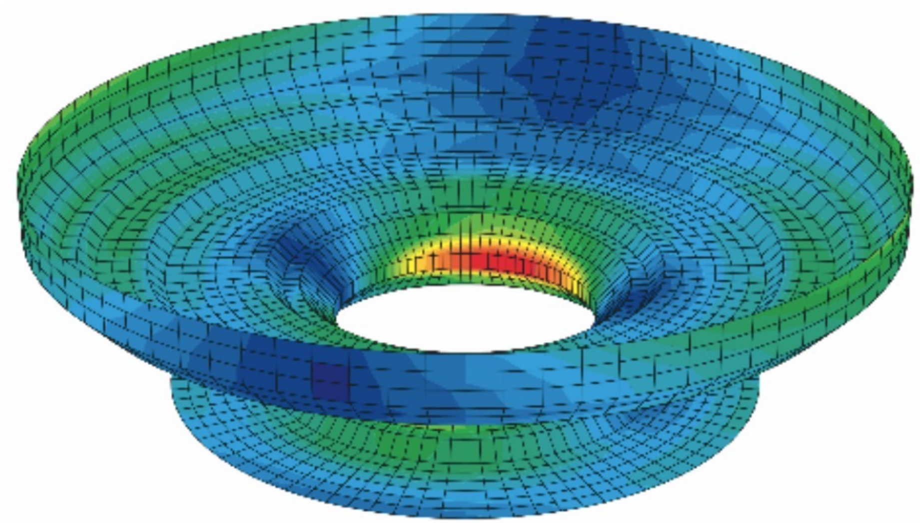


Figure 4: Surface Current Density.

Peak surface current was on an electron beam weld

- Because we were B field limited, we expected to see cavity Q drop as the field increased due to surface heating
- This did not happen – plots later
- We tried to make the cavity walls thinner (1.6 mm vs more standard 2.2 mm) so as to expedite heat flow from the inner wall to the LHe
- Especially after a low-temperature bake, the resulting structure was very soft. Nearly liquid!
- Modelling predicted that we would not see multipacting in the cavity and none was indeed seen, experimentally

Cell dimensions

Table 2: Cell Shape Parameters.

		mid-cell	trans-cup	end-cup
half cell length	g/2 (Z_{ir})	19.2 mm	19.2 mm	18.6 mm
iris radius	a (a_{ir})	15.0 mm	15.0 mm	18.0 mm
iris curvature	r_i	5.5 mm	5.5 mm	5.5 mm
equator radius	b (a_{eq})	47.18 mm	47.37 mm	47.37 mm
equator curvature	r_e	11.41 mm	11.41 mm	11.41 mm

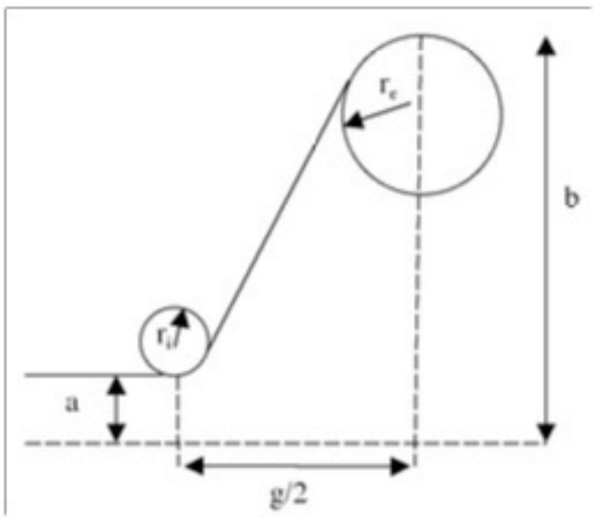


Figure 1: Cell Shape Parameters

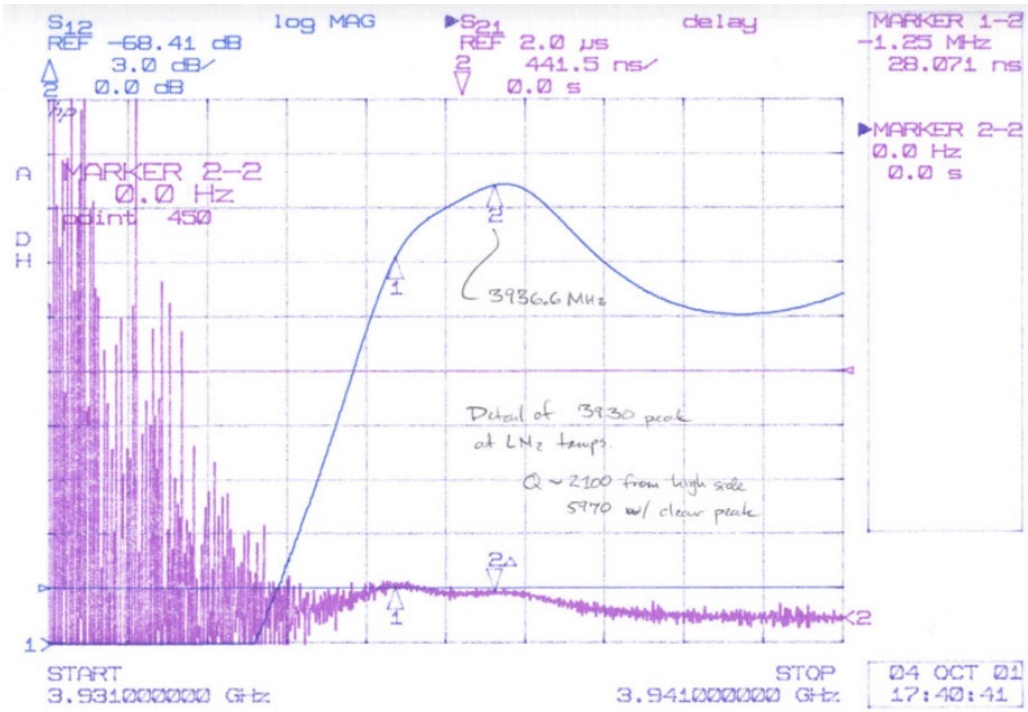
- **Radius *b* was 47.37 mm**
- **Radius *b* of the 3rd harmonic accelerating cavity is 35.79 mm**

⇒ you might not be able to fit a deflecting mode cavity at 3.9 GHz into an accelerating mode cryostat from the 3rd harmonic project

Number of cells

- **We originally thought having ~1 MHz between the primary mode and the nearest other mode would be fine**
- **Limit is ability to mechanically tune cavity for uniform field in each cell while warm (or even at LN_2 temps) where $Q \cong 5000$**
- **What we didn't realize was that the primary mode wouldn't be as "strong" [S_{12}] as the next mode when warm**

- **Ultimately worked out a solution but it wasn't easy to implement**
- **26 modes between 3.9 – 4.1 GHz**



Damping unwanted modes

- If there is beam structure on the scale of t seconds, you will need to put a damping device that removes energy from cavity resonances at frequency $f = 1/t$

- *What does the leading edge of your debunched beam look like? The Fourier transform of a step function ~ 1/ω*

- *Do you know that there is no high-frequency structure left in the beam after the debunching?*

- Damping coupler design was challenging
  - Multipacting
  - Lots of modes
  - Must reject 3.9 GHz.
- Damping manufacturing at 3.9 GHz was somewhat challenging
  - Pure Nb is chewing gum from the machinist's point of view
  - I wouldn't want to e-beam weld Nb much smaller parts
  - Perhaps a purely milled design?

Length tuning

- In an accelerating mode cavity, the EM energy in the cavity is large and cycles predictably; the fields interact with the currents on the inside surface of the cavity and deform it, changing its frequency (Lorentz force detuning)
- In the CKM cavity the surface currents were localized and the primary mode energy cycles in & out of the cavity when the beam is off so we felt this was not a problem we had to solve.

- We did plan a (slow response) device to change the length for in-situ frequency adjustment. This was never designed.

- We did an investigation of the use of adaptive filters to reduce microphonic vibration. It basically worked, but we felt that we'd need an understanding of the vibrations in the actual experimental beamline before going further or even before deciding that it was necessary. For R&D, using air pillar legs from an old optical table helped a lot.

Manufacture

- Pure (RRR=300) Nb sheet, 2.2 mm thick – taken from TESLA
- Buffered Chemical Processing (1:1:2 HF : HNO_3 : H_3PO_4) at Argonne National Lab

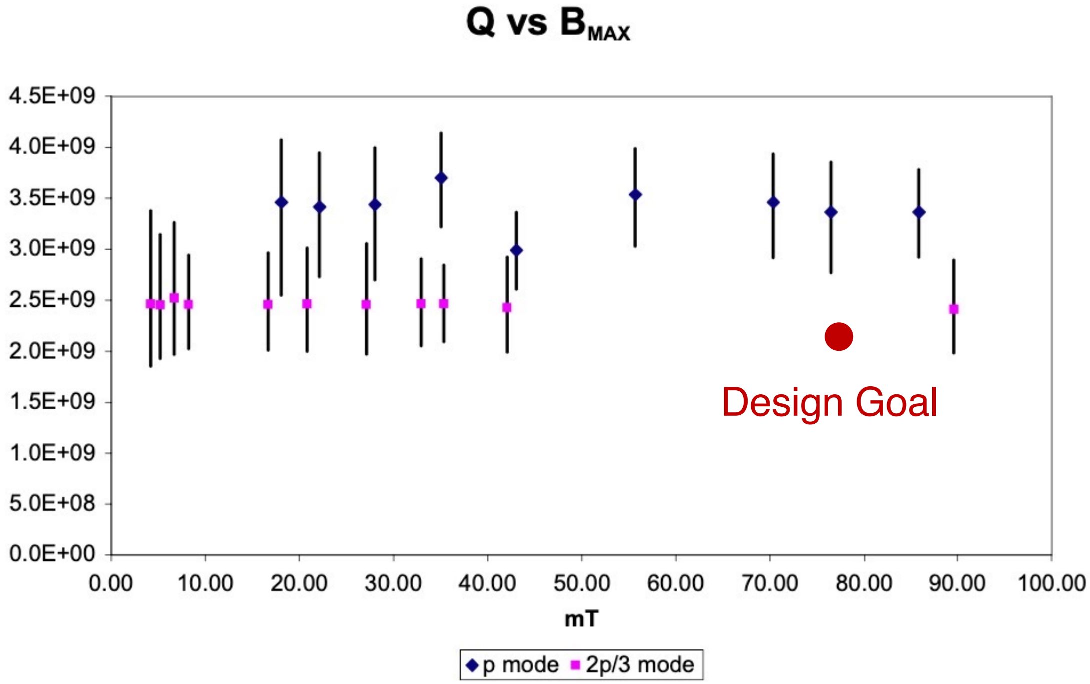
- We built a few prototypes using a local e –beam welder.
- That was valuable in understanding what was and wasn't a good idea – e.g. what about BCP pooling in the cavities? How close was the as-built shape to the as-designed? Can we build those couplers?
- Contracted with AES (Medford NY) to fabricate a few prototypes. I believe they are no longer in business.

- High pressure rinsing with 18MΩ H_2O – every system poses a unique contamination problem. The last step in getting ours to work was a UV light and filter to remove microbe contaminants.

Manufacture

- **We had a single-cell test cavity built with large-grain Nb sheet; its performance was not noticeably better or worse than standard Nb**
- **We tried a few tests with low-temperature bakes (e.g. 100ºC for 12 hours) but the only reproducible conclusion we came to is that this treatment can make the cavity very nonrigid**
- **I expect that CERN's infrastructure knowledge of the LHC crab cavity effort would be valuable here**
- **This is no longer bleeding edge technology; it is commercially available, along with many improvements that came after this time**

Cold test results



3 cell prototype built by John Rathke of AES

EUROTEV 2007-010

- **Magnetic fields of 90-110 mT peak on the inner cavity surface was the state of the art for BCP in those days**

- **We never saw the drop-off of Q_0 as fields increased that is the normal sign of thermal loading.**
- **I suspect that the point-like nature of the thermal load had something to do with this… eg, maybe there was substantial heat flow away from the iris and not just through the Nb sheet? Did the weld have anything to do with it?**

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Cold test results

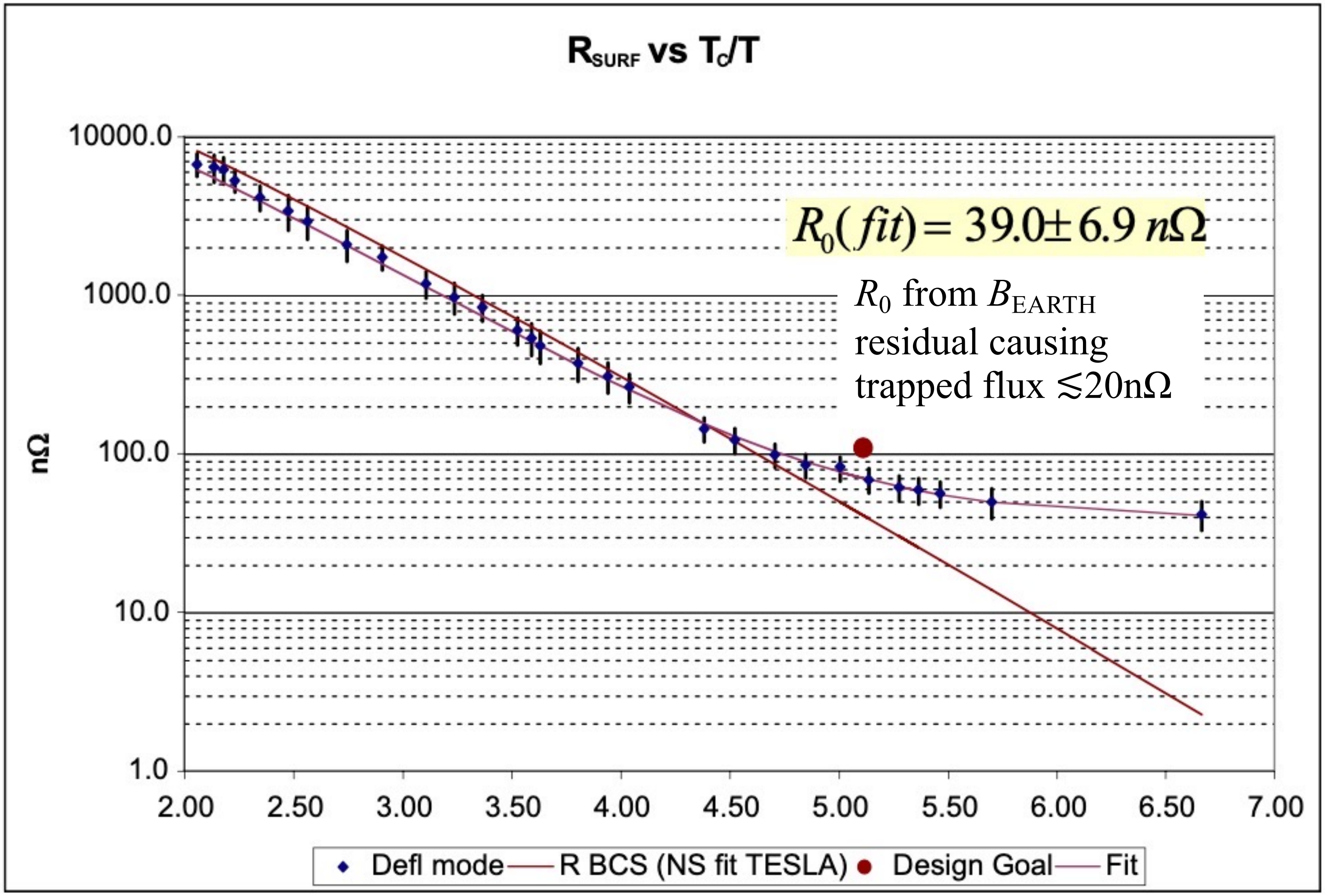

Figure 6: R_{SURF} vs. T_C/T for "John".

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Closing thoughts

- Two axis deflection might give better performance or give you some freedom in designing the beamline. Cost is 2× the cavity fab cost + 2× the RF power; but there are other large fixed costs anyway.
- Determine your beam's time structure early on – if you do have a high-frequency (i.e. GHz) component to the beam, you will need dampers to remove other modes. That is a substantial design and manufacturing prototype effort.
- Try to minimize the number of cells and try to separate the polarizations clearly. The fewer modes you have to deal with, the easier it all will be.
- Don't try a thinner cavity wall to reduce thermal loading. If anything, be concerned about mechanical rigidity of the cavity with a ~2.2 mm thickness.

Closing thoughts

- A CKM cavity *probably* doesn't fit in a 3rd harmonic cryovessel and besides we learned a lot with the CKM cavities that should be incorporated into the next design iteration.
- Perhaps operating the 3rd harmonic cavities in TM_{110} mode will work? You would probably have to polarize them in the same way we did with the CKM cavities, and might still have a lot of modes.
- Possibly a higher frequency cavity design in the 3rd harmonic cryovessel?

- You will probably not need a rapid (piezoelectric) tuner if you keep the cavities sufficiently isolated mechanically. Got an old optical table?

- Existing computational and manufacturing techniques work just as well for the iris-loaded fields of the deflection mode as they do for the much-investigated accelerating mode.

- Involve manufacturing considerations into the design as soon as possible

One axis deflection

The usual scheme is to deflect in one direction & collect contaminants into a beam stopper

$$\Sigma p_\perp = p_\perp(1) + p_\perp(2)$$

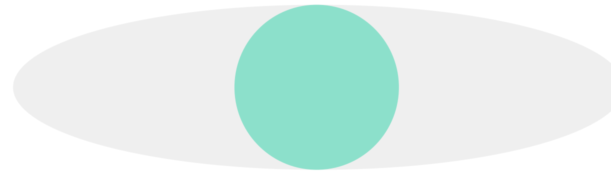
So for species s, net kick is

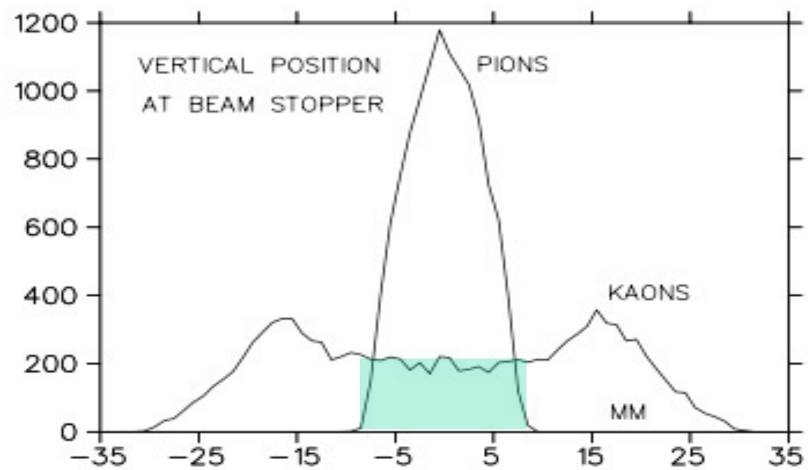
$$\Sigma p_\perp \Big/ p_\perp^{(0)} = \sin\phi_1 + \sin\left(\phi_2 + \frac{2\pi f L}{c\beta_s}\right)$$

for species s to hit the beam stopper, need

$$\left(\phi_2 + \frac{2\pi f L}{c\beta_s}\right) - \phi_1 = \pm 2\pi n$$

…the "basic equation"





Need to satisfy the basic equation for both p and π^+ as these are the 2 large contaminants

Lose a lot of K+ in the center

Why 3.9 GHz?

- What amount of power do you need?
  - If you need klystrons, better pick f to match one already on the market. That's a hard constraint
  - Power into beam is much less than in an accelerating cavity
  - We used TWTs for many of our R&D tests

- K^+ decay in flight ⇒ smaller L is better (as is higher p_{BEAM})

- What is your beam's time structure?
  - A lot of time structure ⇒ complicated damping couplers
  - From the machinist's point of view, pure Nb is chewing gum and hence very hard to work with
  - Fabrication of complicated couplers at 3.9 GHz was challenging but doable – I wouldn't want to go smaller
  - Remember, couplers need to be tuned after fab

Number of cells

- **In an n cell cavity, each "mode" i.e. each cell field shape, appears as an n tuplet. So we had 13 resonant frequencies with accelerating mode TM_{010} shaped fields, 13 with the deflecting TM_{110} shaped fields in each cell etc.**
- **All 13 of the deflecting fields have an orientation about the longitudinal axis of the cavity – e.g. they deflect the beam in (say) the x direction.**
- **There are 13 similar modes that cause beam deflection in the y direction – we called these the "Same Order Modes" (SOM).**
- **All 26 of these modes were between 3.9 GHz and ~4.1 GHz.**

- **To break the symmetry we put 1.5 mm deep flats on the top and bottom – just put the cavity in a big press and squished it a little.**
- **This gives ~9 MHz split between the primary and the SOM π mode. The SOM π mode is inside the 3.9 GHz to 4.1 GHz spectrum.**
- **Then mode mixing between the polarizations could happen.**
- **For the ILC cavity the mixed mode was excitable by the beam and hard to dampen**

Computational tools

- Early modeling was done with URMEL (EM) and SRIMP (thermal)
- We did develop a lumped-element equivalent model for the cavities but didn't use it that much – finite element models are so much easier to use nowadays anyway
- Bulk of our detailed calculations were done in MAFIA, in conjunction with DESY staff (Rainer Wanzenberg)
- Our SLAC colleagues used Omega3P and S3P for the damper work
- Tech-X of Boulder Colorado collaborated with us some on the development of their VORPAL product

Cryogenics

- Cryogenic system cost is determined mostly by passive heat losses through conduction and radiation, which are determined by vessel design.
- We never got to the point of having a detailed vessel design ⇒ we never had a reliable heat load for the cryo system ⇒ we never had a reliable or detailed cost estimate for the cryogenic supply.
- The two non-detailed cost estimates we had were, as I recall, a factor of 5 apart.

In A Single Slide

- **Level 1**
  - **Level 2**
    - **Level 3**

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