SC 3rd Harmonic (3.9 GHz) cavity development at Fermilab

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Fermilab

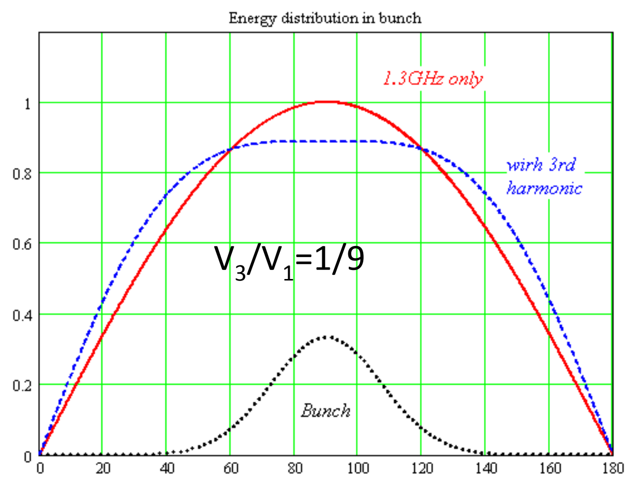
Seminar at ANL, May 21, 2010

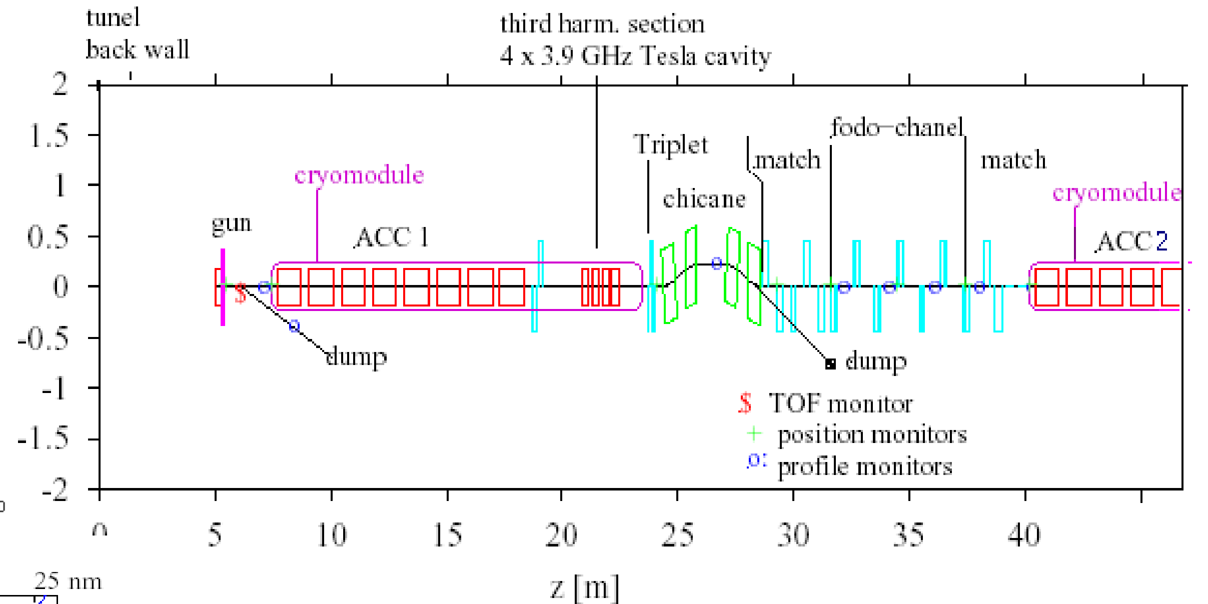
Outline

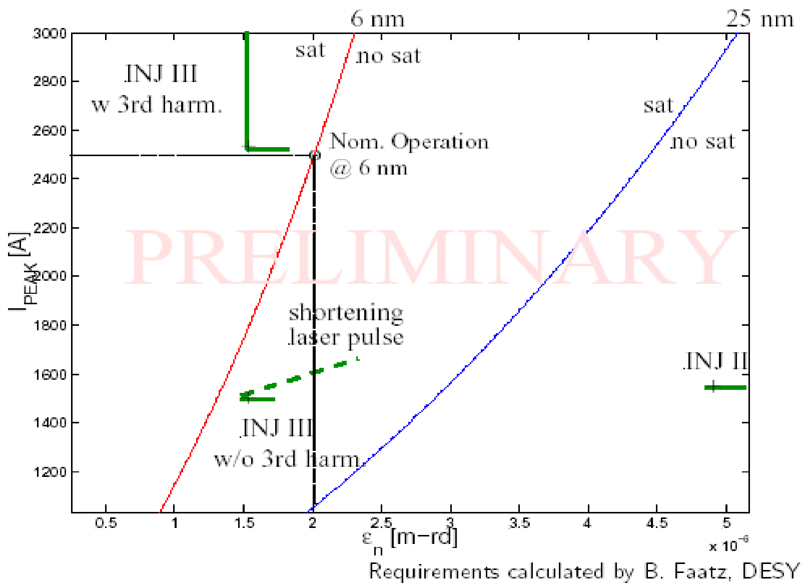
- Introduction
- 3rd harmonic cavity design
- HOM damping and HOM coupler design
- Main coupler: design, production, tests
- Prototyping and Production, tuning
- Cavity tests, Lessons
- Limitations: MP, thermal breakdown,
- Infrastructure
- Cryomodule assembly, tests
- ACC39 at FLASH/DESY

- Deflecting SC cavities at FNAL

Why FLASH needs 3rd harmonic cavity ?



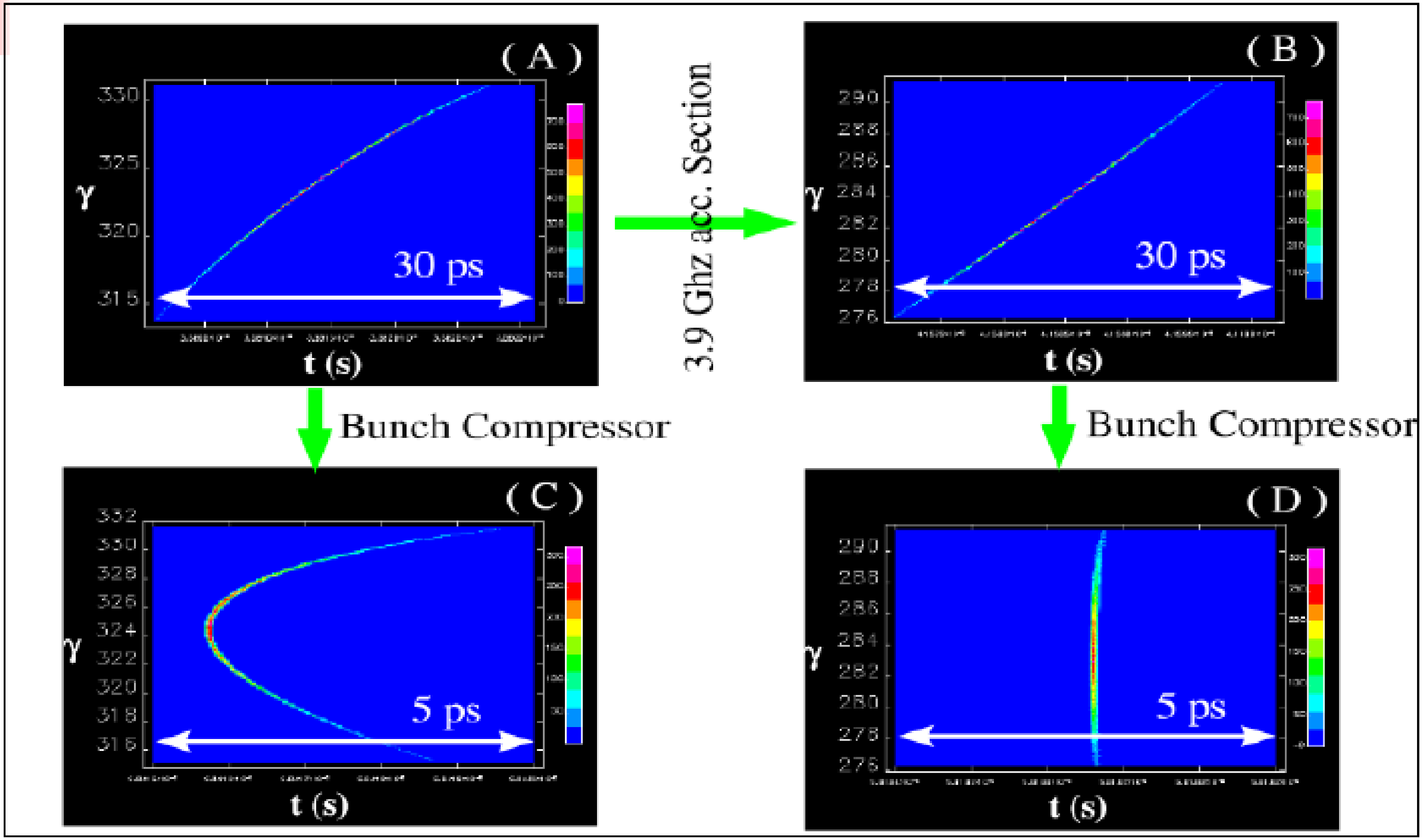




Third harmonic cavity -3.9GHz was proposed to compensate nonlinear distortion of the longitudinal phase space due to cosine-like voltage curvature of 1.3 GHz cavities (K.Floettmann et al., TESLA-FEL-01-06, 2001)

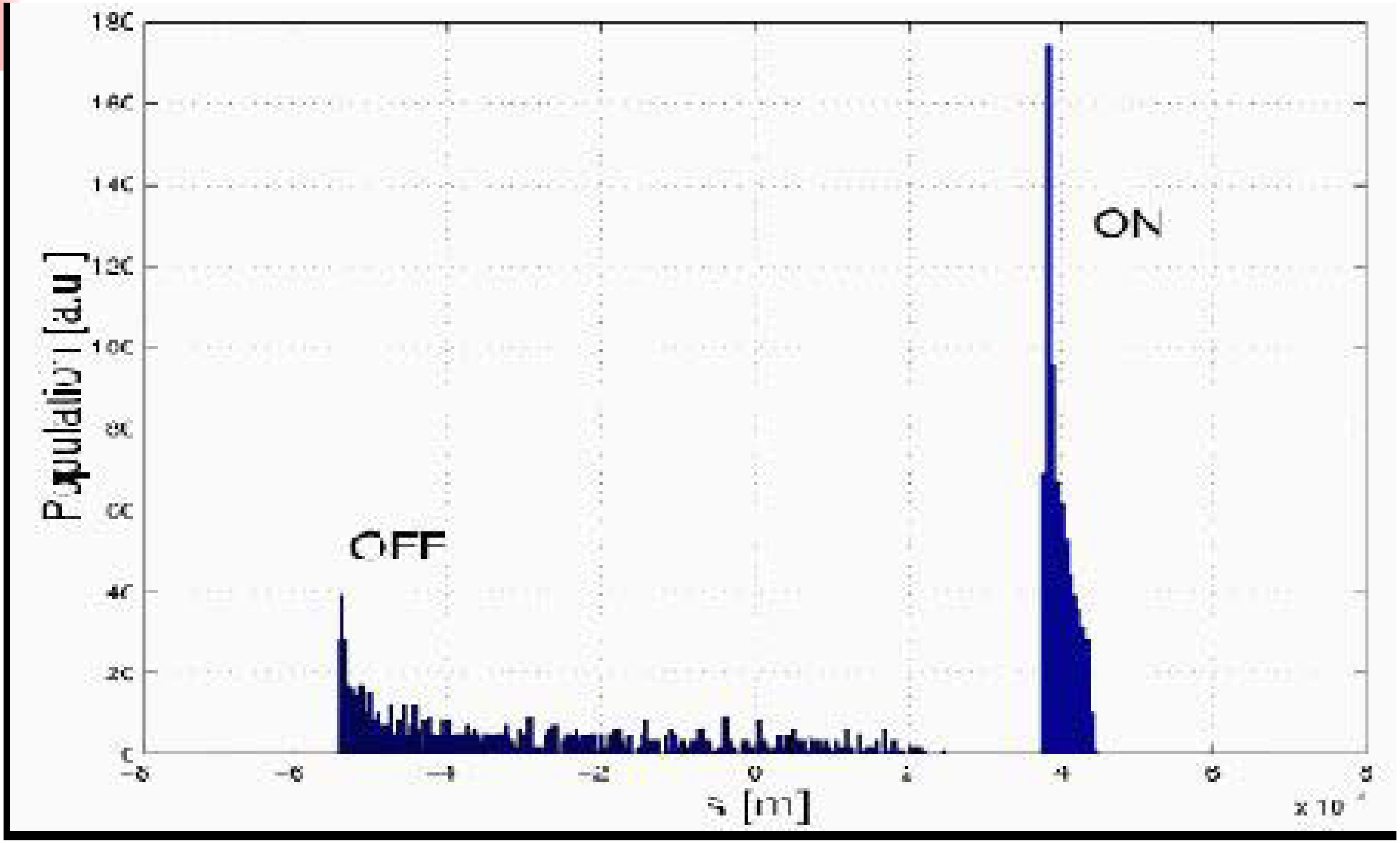
- Increase peak current of the bunch
- Reduce beam emittance

3rd Harm. cavity to Improve Beam Characteristics (FNPL, X-ray FEL, LC, …)



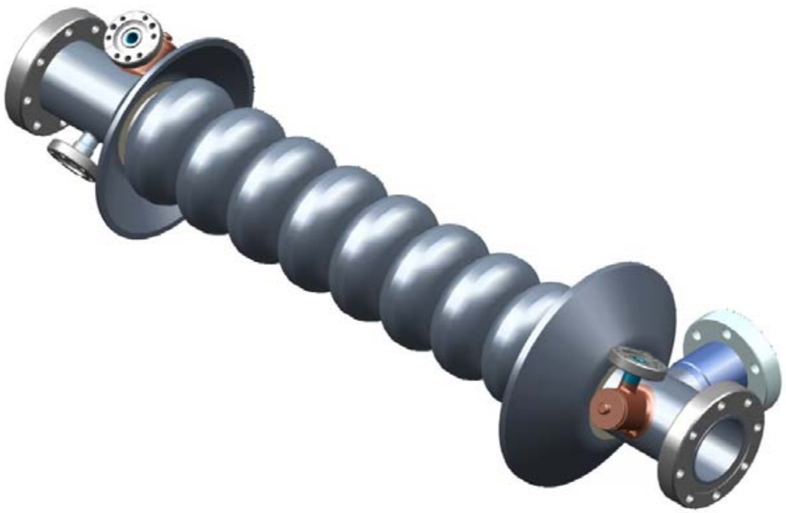
Example: bunch phase space before and after bunch compressor without (left) and with (right) the 3rd harmonic cavity, calculated for TTF-2 photoinjector.

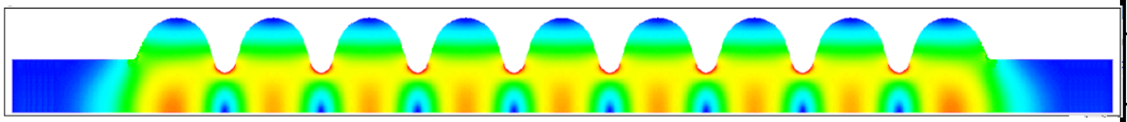
3^{rd} Harm. cavity to Improve Beam Characteristics (FNPL, X-ray FEL, LC, …)



Example: bunch phase space before and after bunch compressor without (left) and with (right) the 3^{rd} harmonic cavity, calculated for TTF-2 photoinjector.

TM_{010} Cavity general parameters





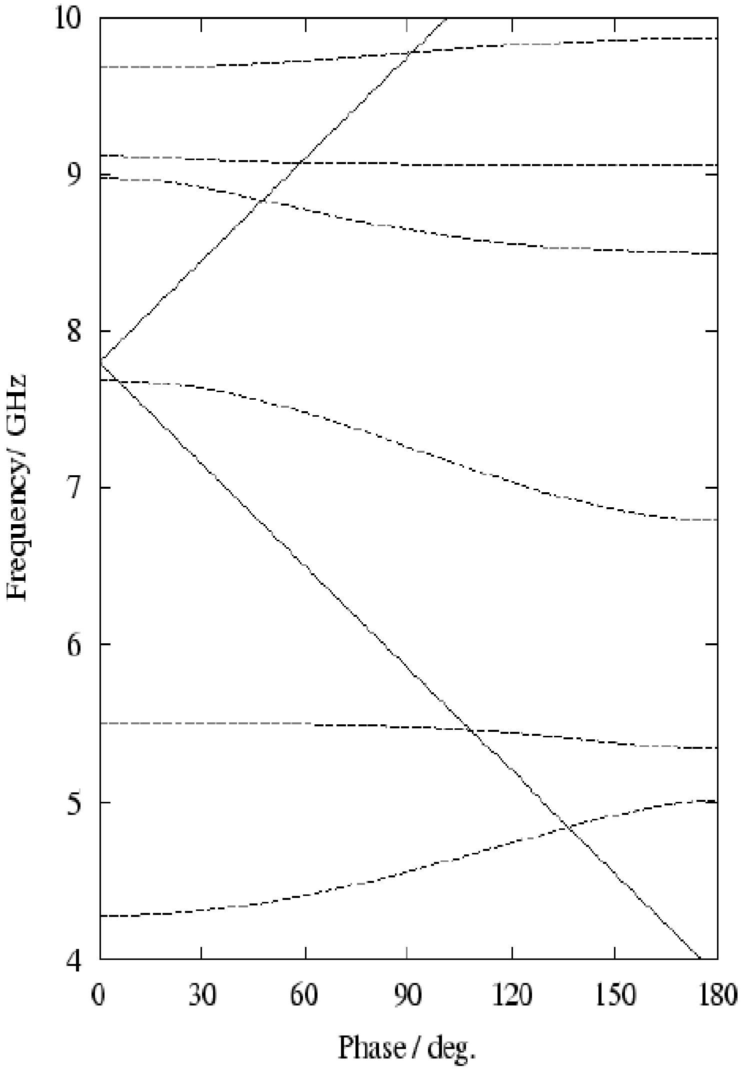
- Decreased surface fields in end cells
- Regular cells -30mm iris diameter
- End-cells iris from the tube side increased up to 40mm for better coupling with the power coupler
- Two HOM couplers are mounted in both ends
- Ports for power coupler and pick-up antenna
- 2.8 mm bulk niobium

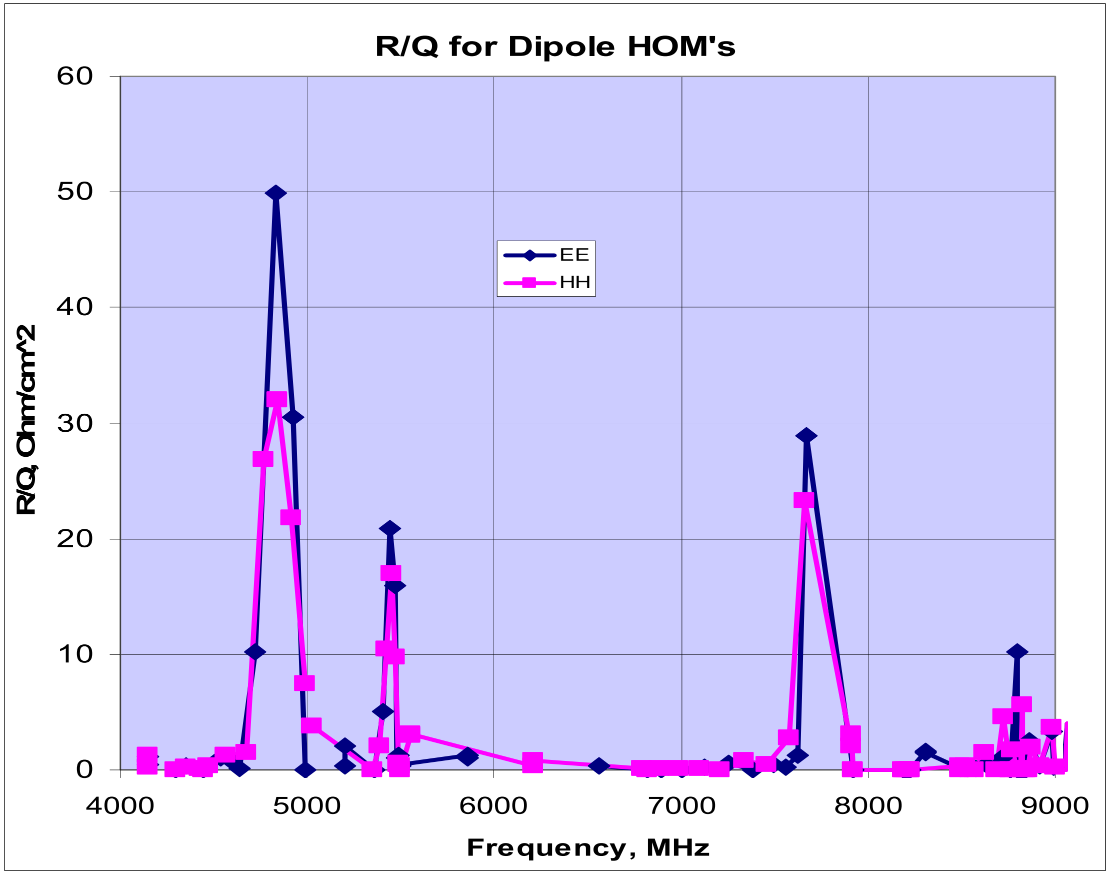
Parameter List for 3.9 GHz cavity:

Number of cavities	4
Active Length	0.346 m
Gradient	14 MV/m
Phase	-179 deg
R/Q	375 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc}=14 MV/m)	68 mT
Qext	$9.5 \cdot 10^5$
BBU threshold, Q	<1.e+5
Total energy	20 MeV
Beam current	9 mA
Forward Power	11.5 kW
Power in Coupler	45 kW

Damping of the High Order Modes

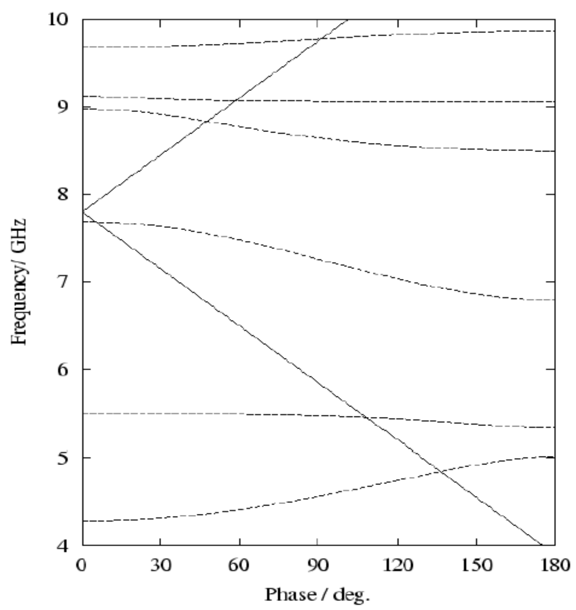
R/Q for dipole modes in 9-cell cavity





Requirements: Q_{ext} (HOM)< 1.e-5

“Quasi-trapped” modes in 5th pass-band



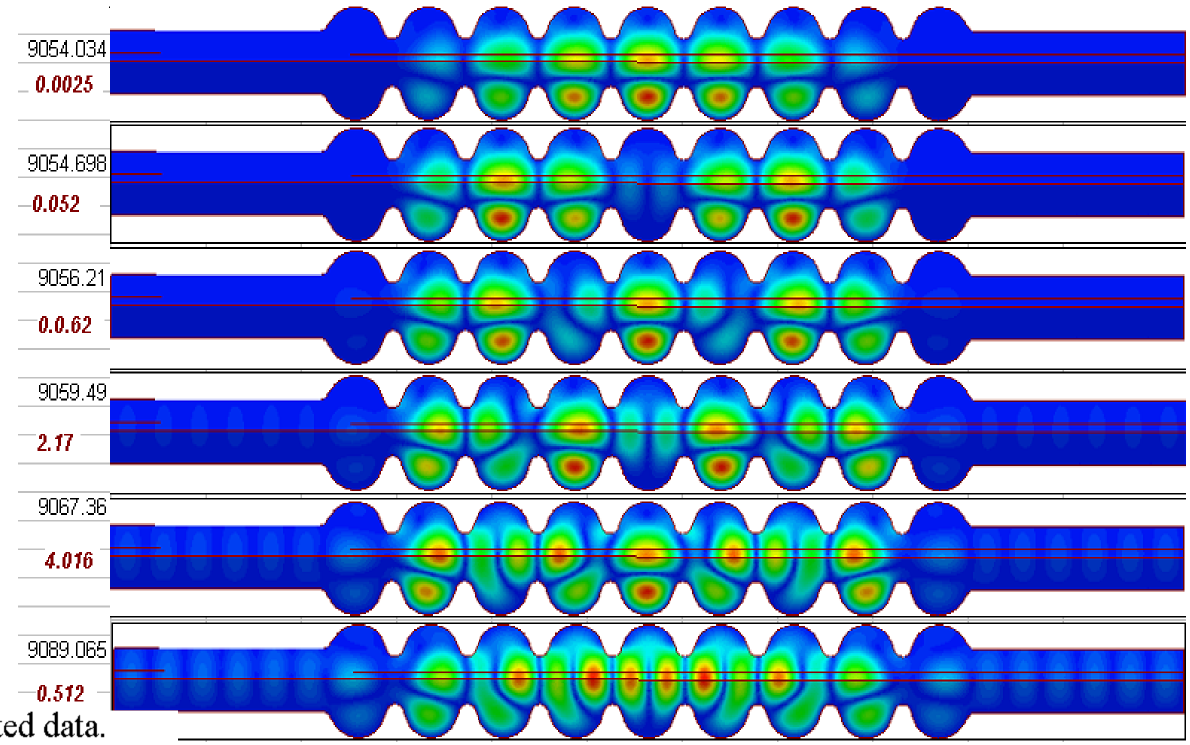
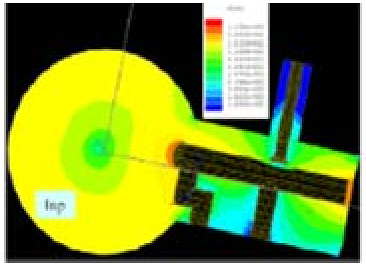


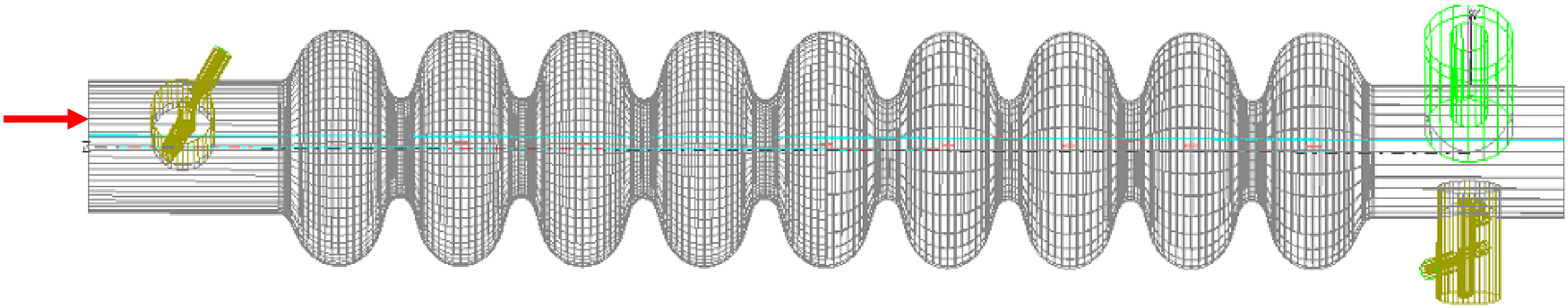
TABLE II. HOM couplers Qext calculated data.

Frequency, MHz	R/Q, Ohm	Q, BBU limit	Qext, Loaded beam tubes	Qext, HOM couplers
9054.03	0.002	2.0e9	2.29e6	2.29e7
9054.70	0.05	8.0e7	5.76e5	5.76e6
9056.21	0.061	6.6e7	2.11e5	2.11e6
9059.49	2.17	5e6	7.81e4	7.81e5
9067.36	4.053	1e6	2.57e4	2.57e5
9089.07	0.565	1e7	1.08e4	1.08e5

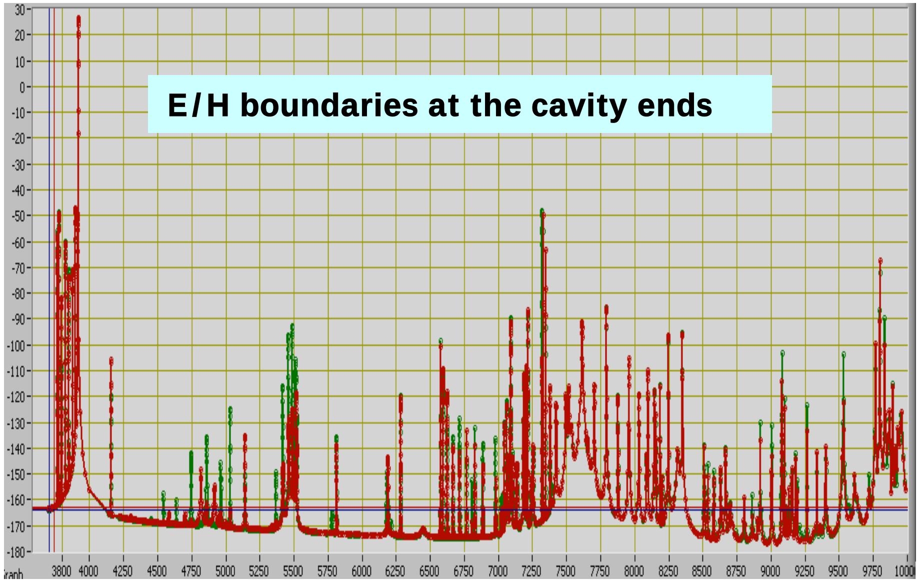
Measured coupling HOM coupler to tube better 10dB.

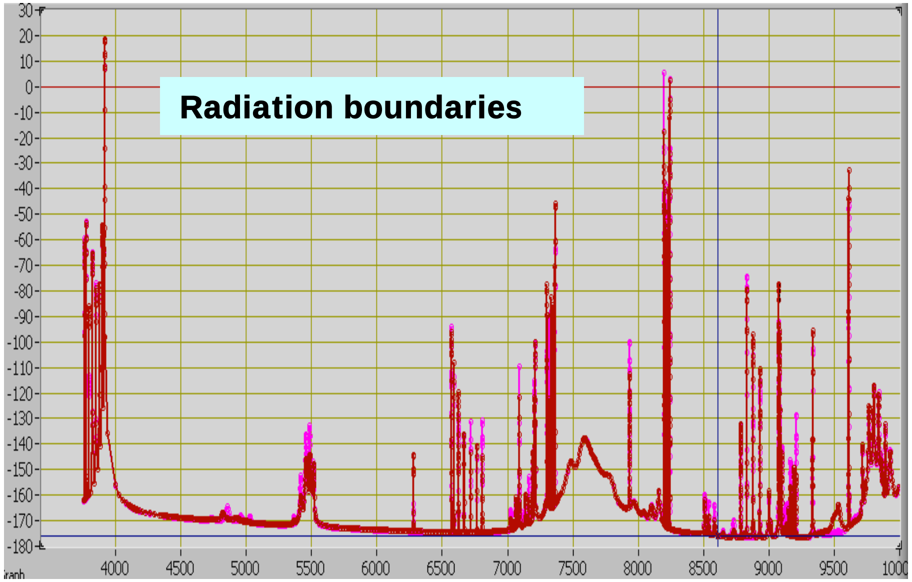


Studying Higher Order modes in SC cavity



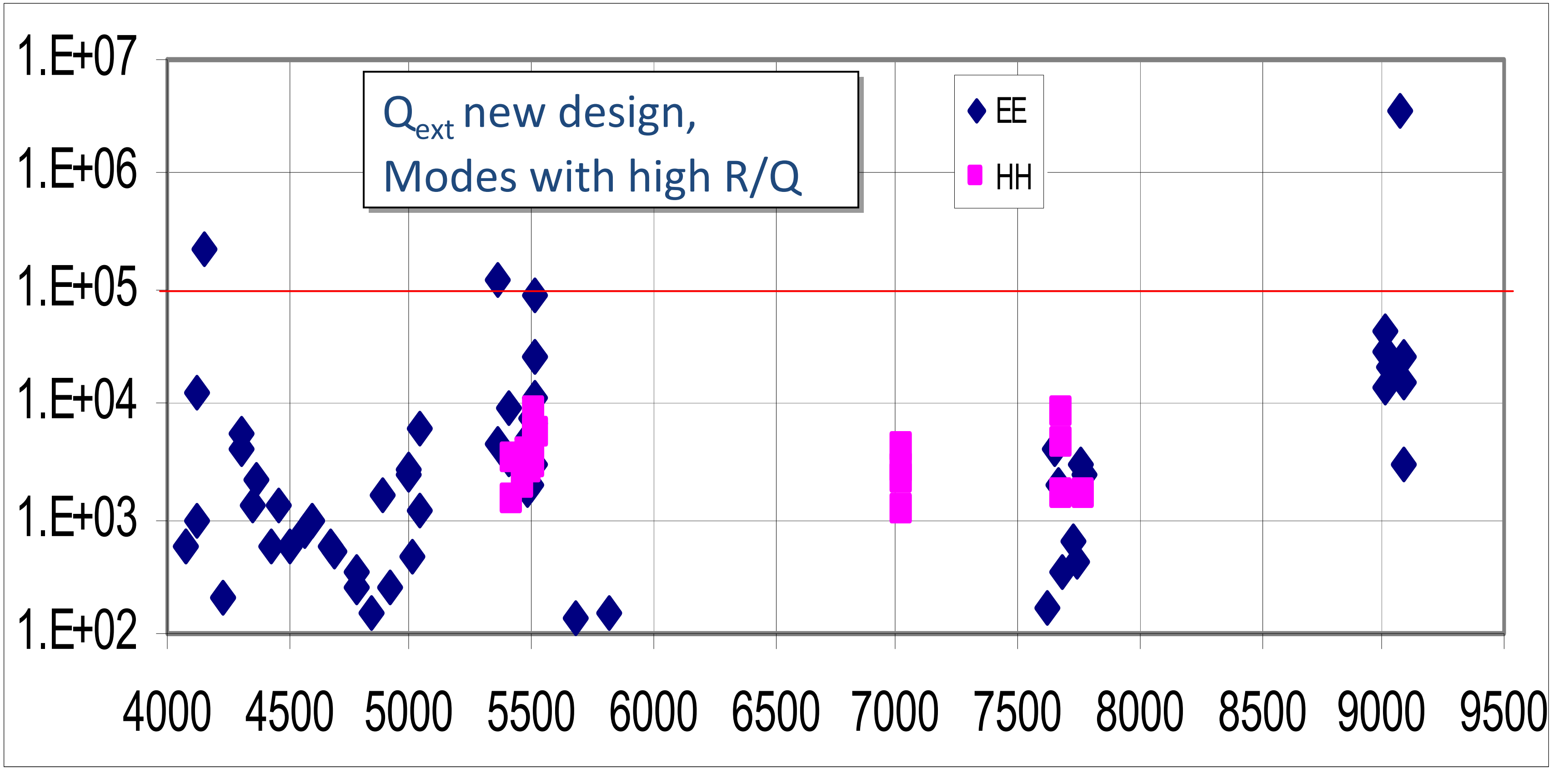
3D HFSS model. Beam excitatition is imitated by RF antennas placed in each cell. Dipole mode will excited if antennas have 2mm off-set in x or y direction.



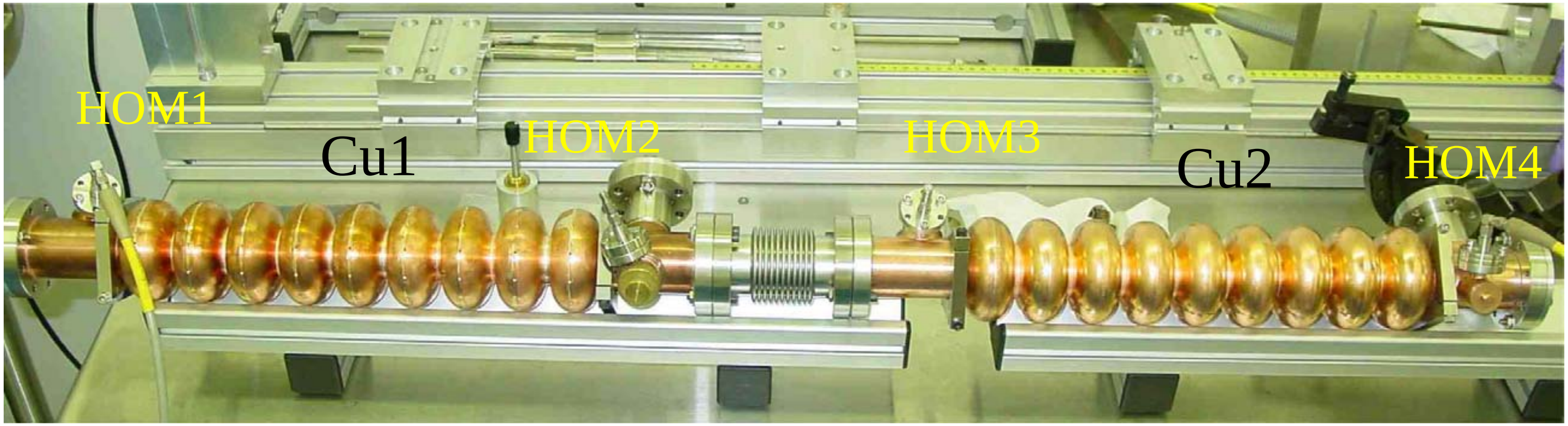


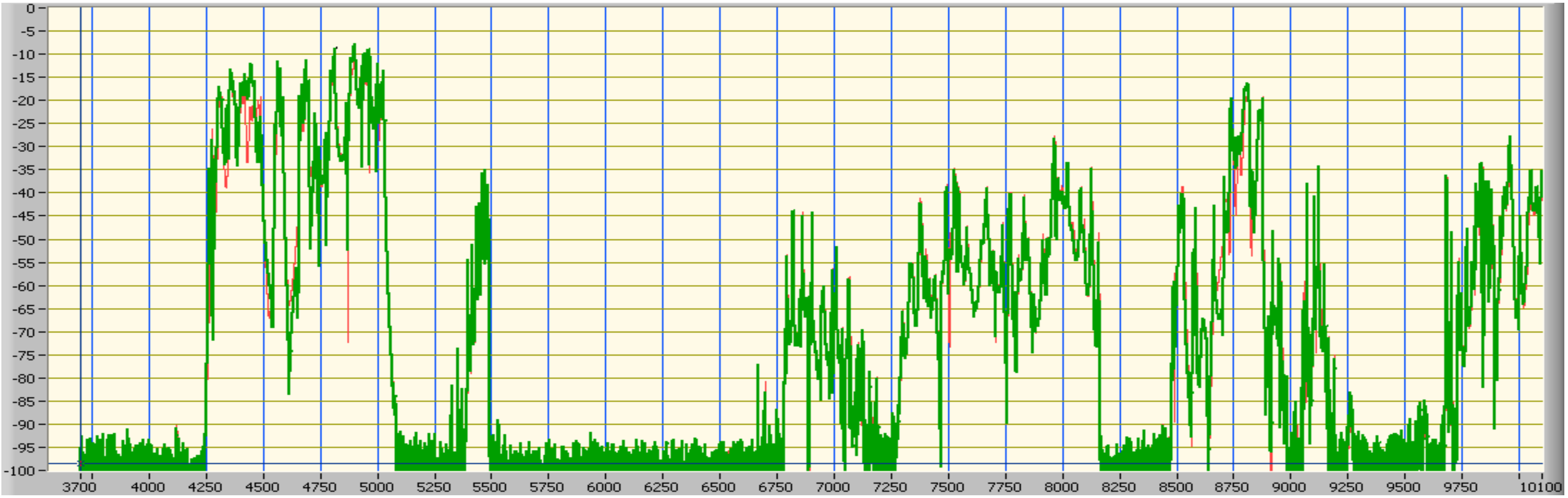
Q depends from boundaries. Needs experimental study in chain of two cavities

Results of HFSS simulations
Q for dipole modes



HOM study in a chain of two copper TM_{01} cavities



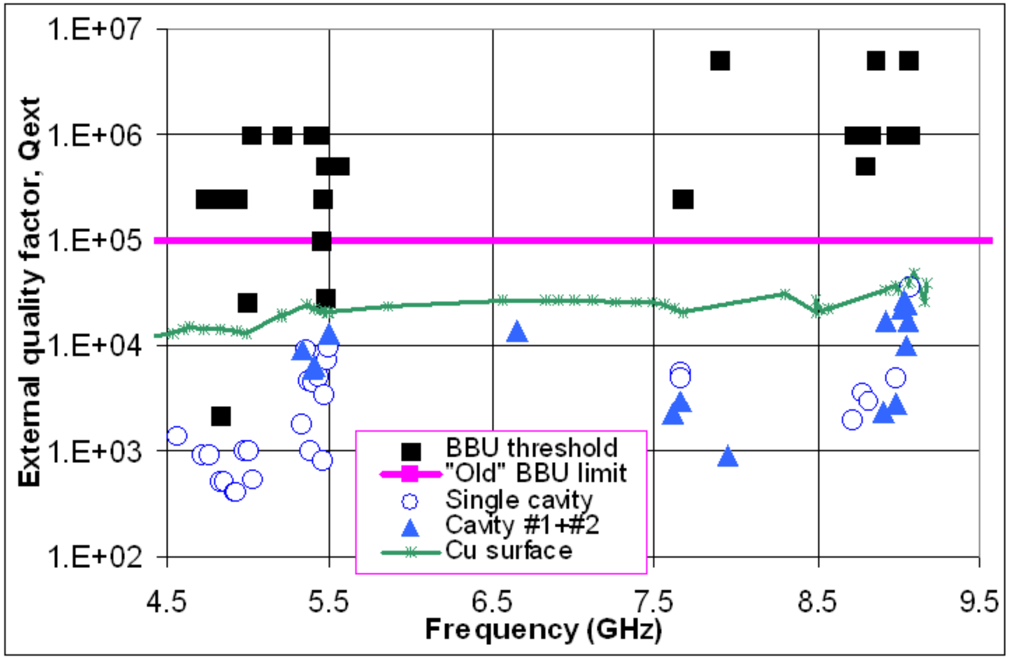


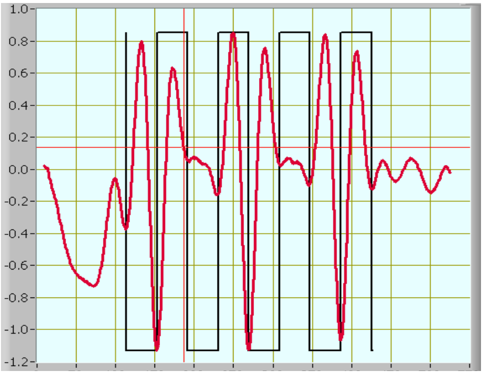
F=4813 MHz. Qmax=2180, Q2=1160, Q4=890

F=4994 MHz. Qmax=26000, Q2=4990, Q4=4320

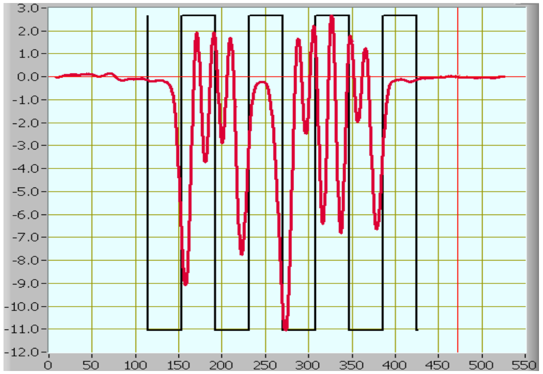
F=5474 MHz. Qmax=28300, Q2=12500, Q4=9300

HOM: Q_{ext} and Bead-pull measurements





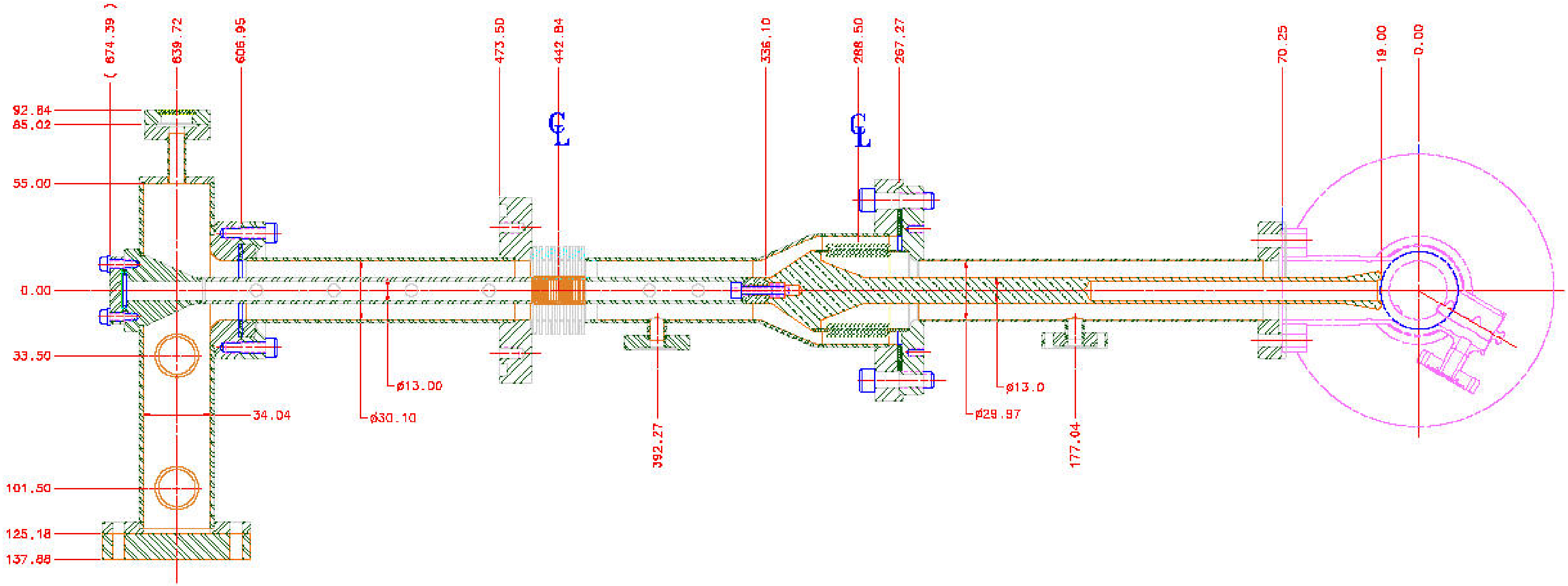
2-nd dipole band “6/9Pi” mode.
F=5418.7 MHz. Q=11600.



5-th dipole band.
F=9029.1 MHz. Q=32000.

- Some HOMs in 5th passband have highest Q-values,
- Fields are very sensitive to errors in cell frequencies

3.9 GHz Main Coupler

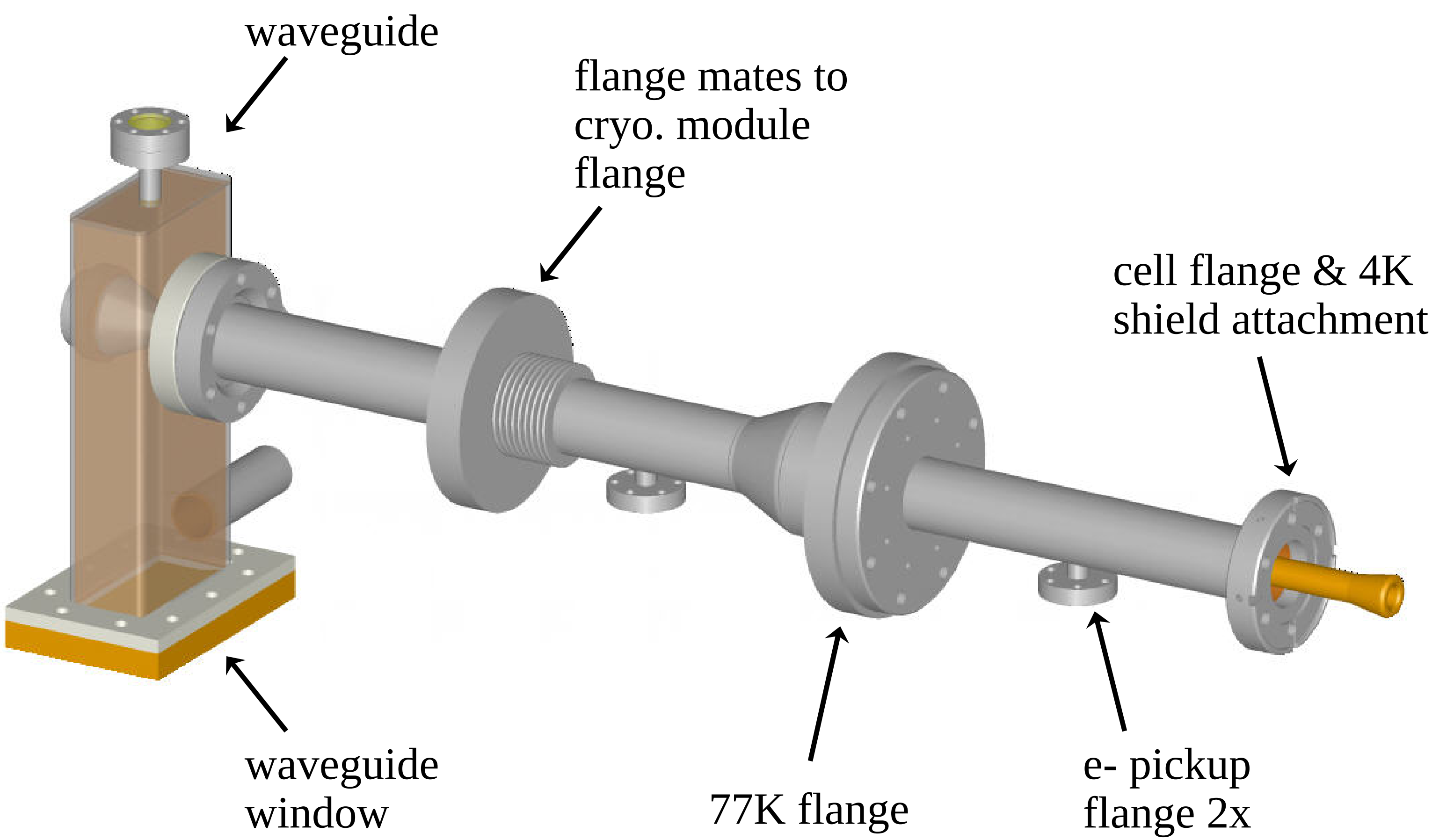


Relatively simple design (relative to TTFIII)

	Bias	Tuning	No. of parts	No. of Joints	
				Welded	Brazed
FNAL-3.9	no	no	40	3 ?	25
TTF-III	yes	yes	66	45 total, ~10 brazed	

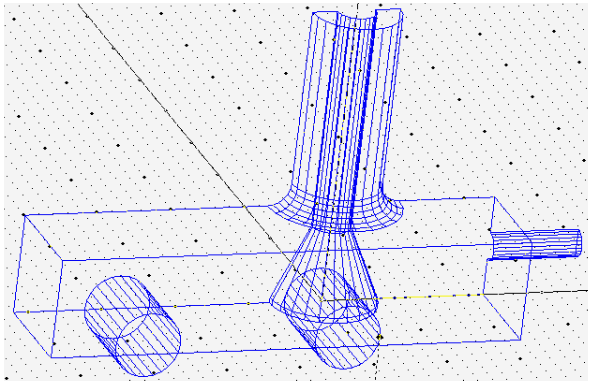
note: counts are approximate

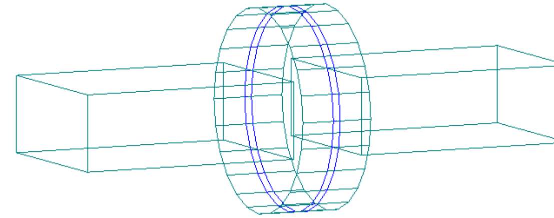
Main Coupler Assembly

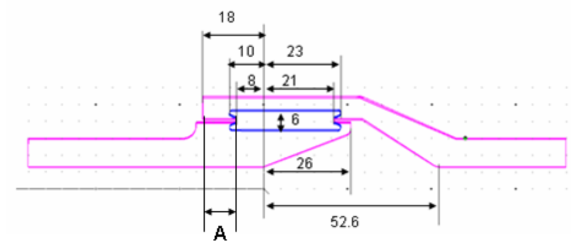


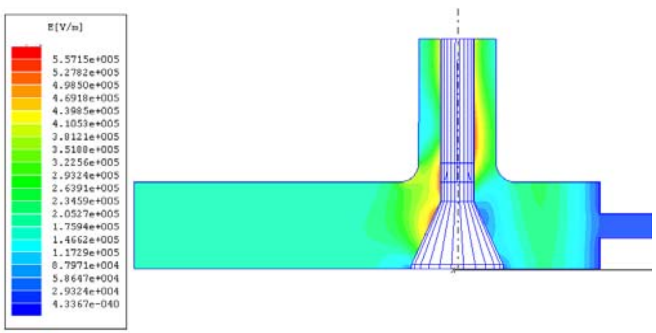
RF design

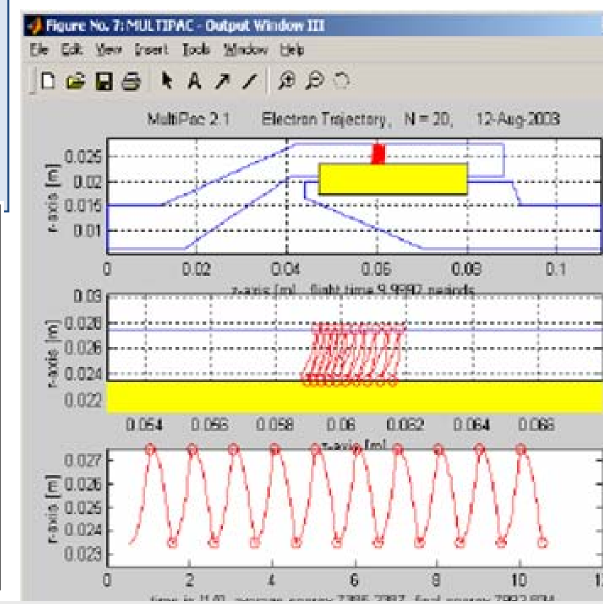
- Two Windows
- Shepe Optimization
- Coax-WG transitions,
- Vacuum Pumping
- Multipactoring
- Thermo-analysis
- Tolerances,
- Materials,
- Testing
- Tuning to cavity
- Etc.

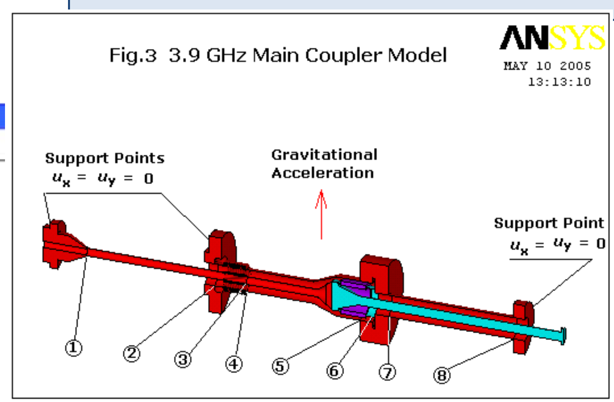


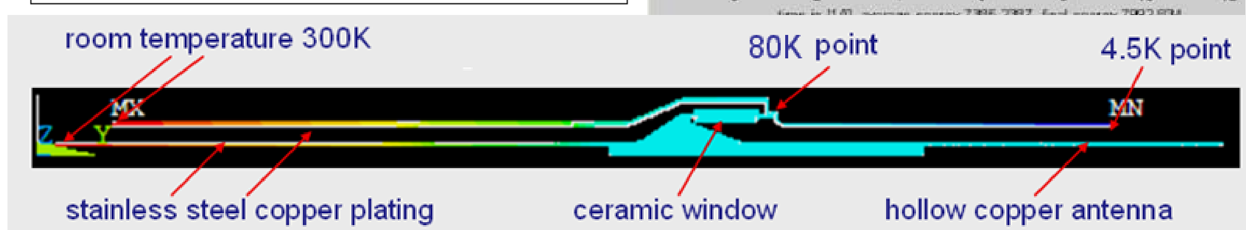






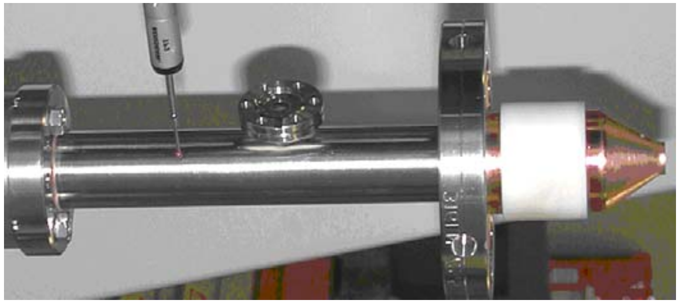


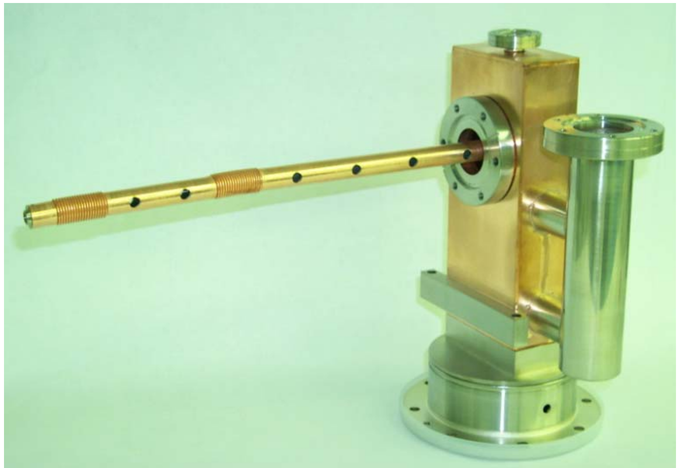




Main Coupler Production

- Six input couplers (+1 spare) were received from the vendor (CPI) in June 2006. Parts initially rejected for failing quality control checks have subsequently been replaced or reworked by the vendor and are currently undergoing QC.





__Input Coupler Qualification and Test__

- Visual inspection (Cu plating, threaded holes, flange orientations, sealing surfaces, and overall workmanship)
- Mechanical measurements
- Leak check of all subassemblies
- Low power test
- Trimming couplers antennas to adjust Q_{ext}
- High power RF cycling to condition

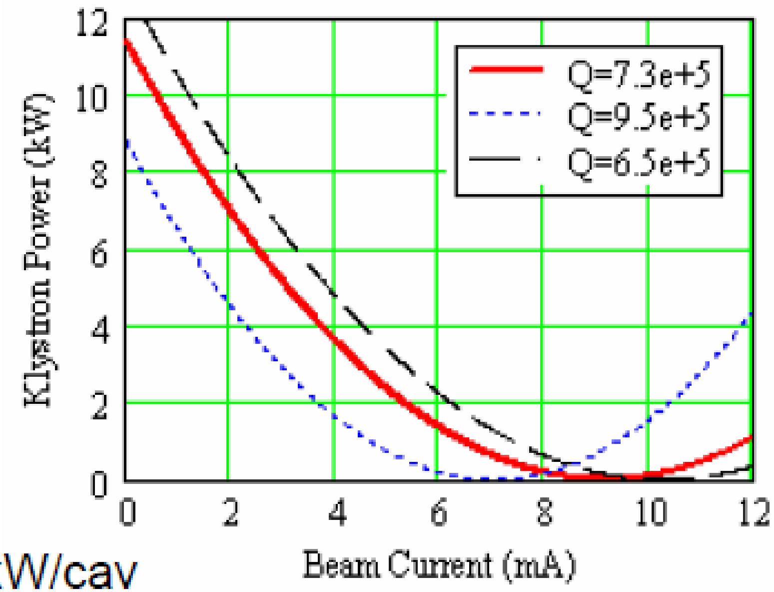
Coupler Power consumption

Power from klystron:

$$P = \frac{V^2}{4(r/Q)Q_L}\left[\left(1+(\frac{r}{Q})Q_L\cdot\frac{I}{V}\cos\phi\right)^2+\left(\tan\psi+(\frac{r}{Q})Q_L\cdot\frac{I}{V}\sin\phi\right)^2\right]$$

Where: *(r/Q)=750 Ohm, V= 5 MV,* $\psi=0$, $\phi=-179°$

I_beam \ Q L	$Q_L=6.65*10^5$	$Q_L=13.3*10^5$
I = 0 mA	12.5 kW (12)	6.25 kW (6.25)
I = 8 mA	0.5 kW (40.5)	-2.25 kW (42.25)
I = 10 mA	0 kW (50)	-6.25 kW (56.25)
I = 12 mA	-0.5 kW (60.5)	-12.3 kW (72.3)



Parameters for 3.9 GHz cavity (optimized for 9mA current):

Forward power for 4 cavities	46 kW
Losses waveguide, 50m,1.1dB	14 kW
Losses circulator, 0.2 dB	3 kW
Regulation reserve 25%	17 kW
Klystron power	80 kW

P=11.5 kW/cav

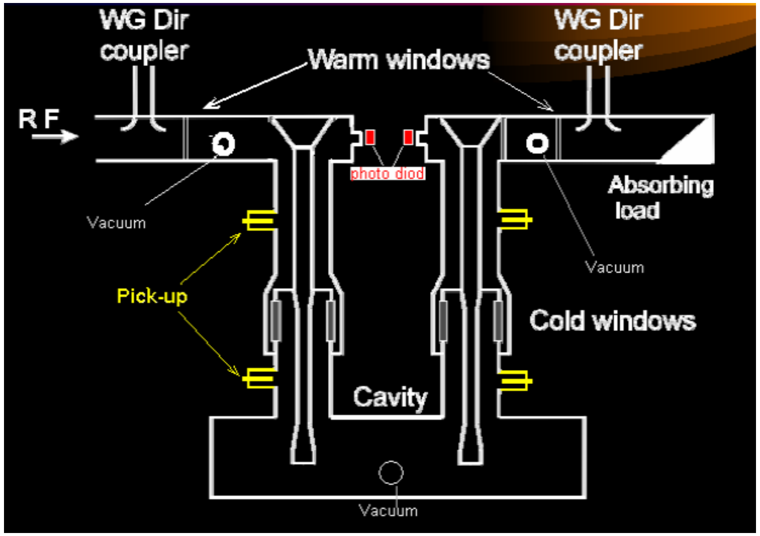
$Q_{ext} = 9.5*10^5$

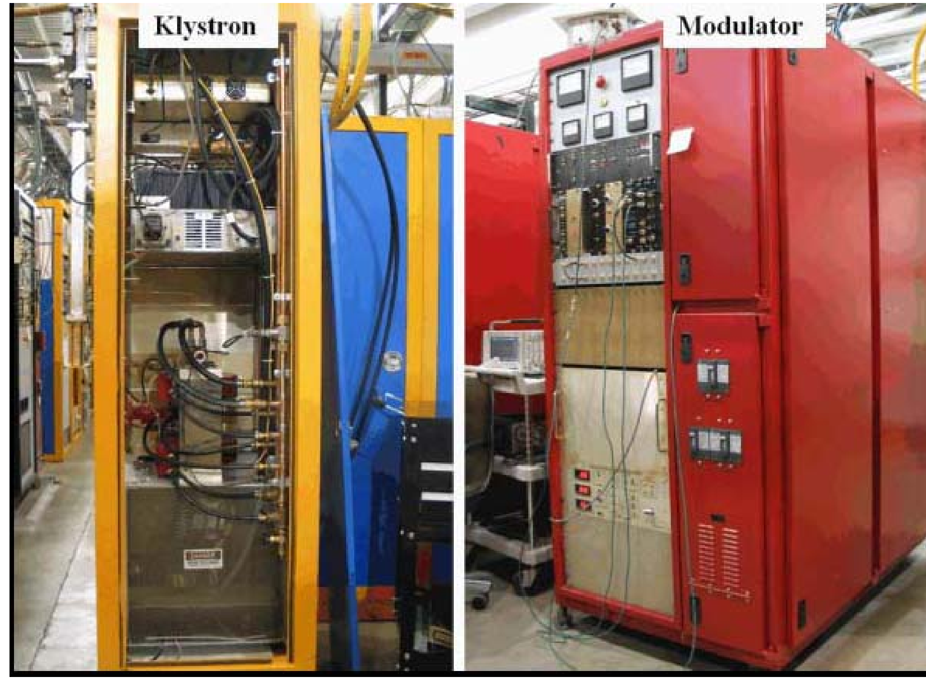
(at $\tau \approx$150 µs)

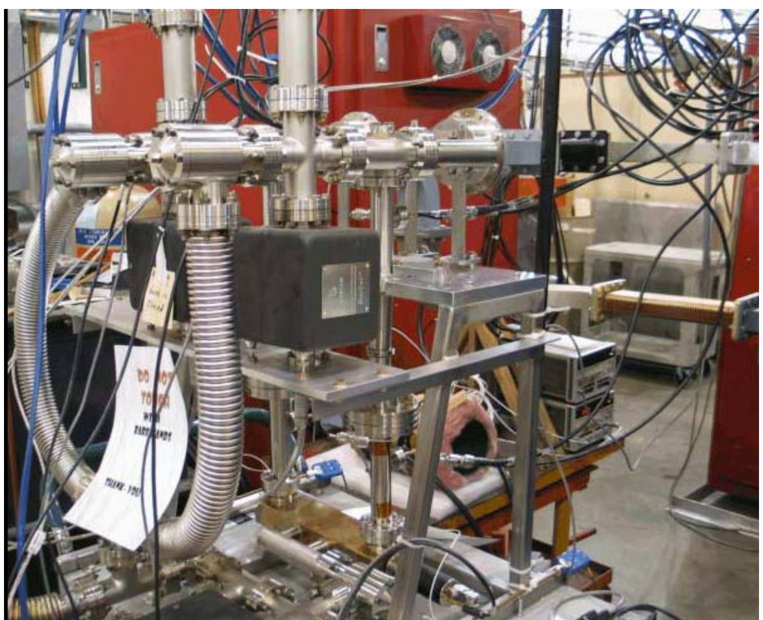
$P_{klystron}$ (9mA) = 0

$P_{coupler}$(9mA)= 46kW

Coupler HP testing and Processing

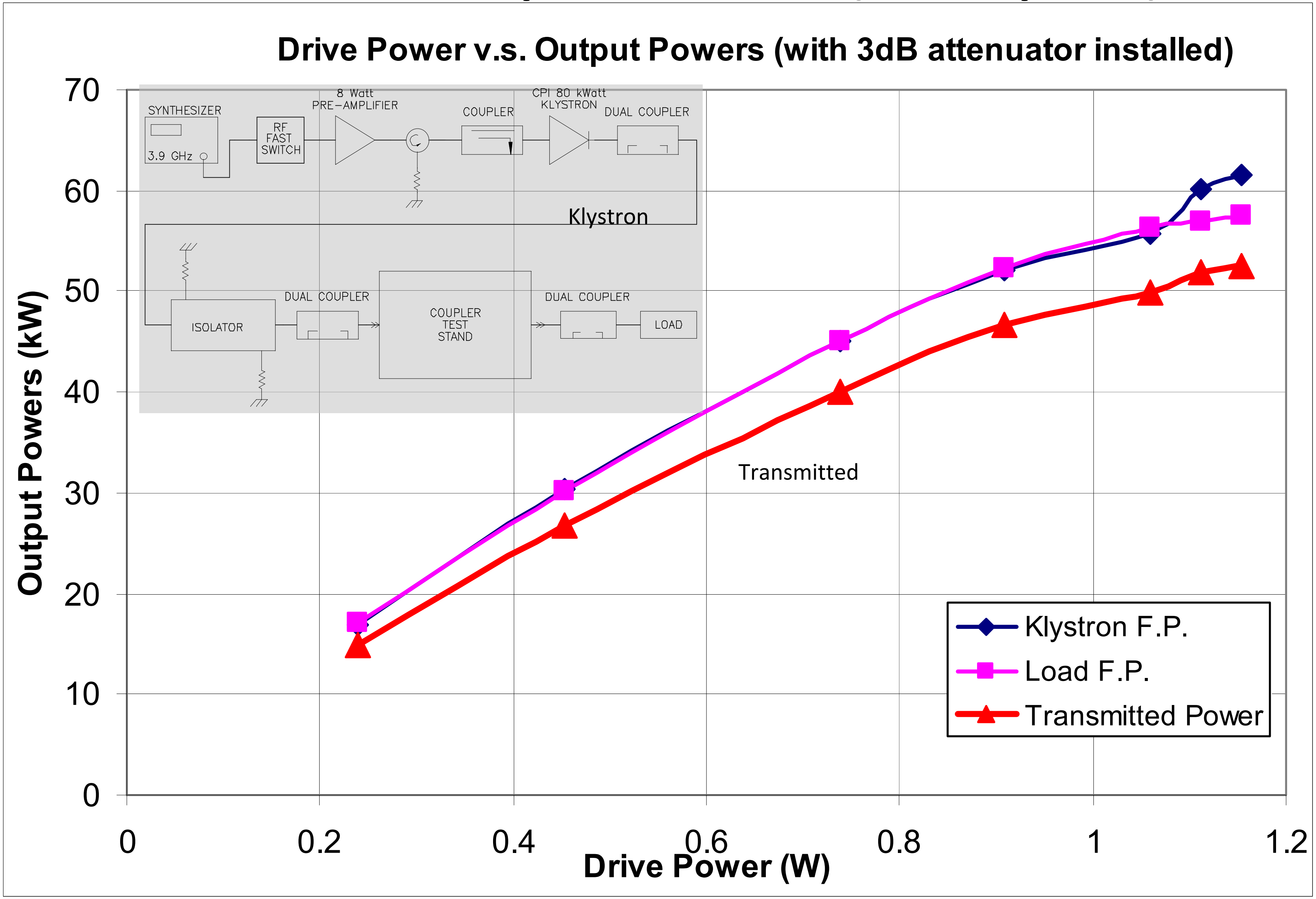






The power coupler designed in this way has a great RF performance and can meet the system strict requirements. Processing is very quiet without any problems or accidents till now. Most power is fed into the test stand with very low power reflection.

Main coupler tests (first pair).



Production. EB welding

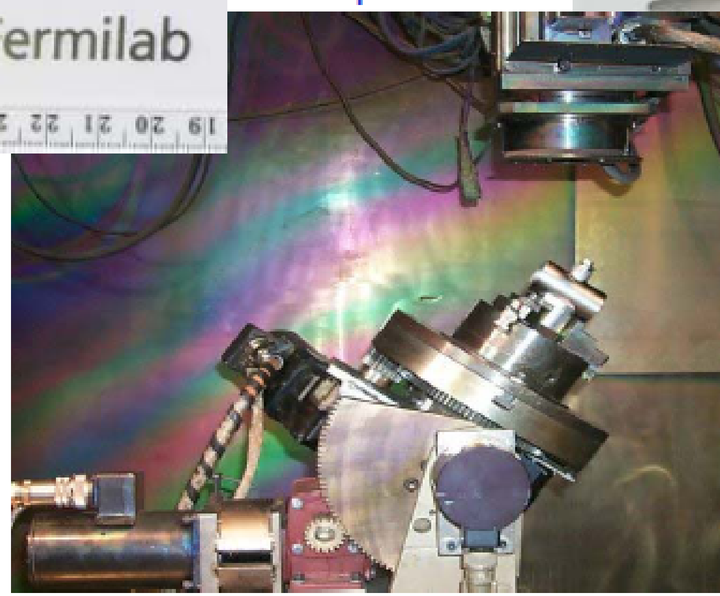
Welded dumbbells of the 3rd harmonic cavity

Cut weld for inspection

Test welds on the end-tube group.

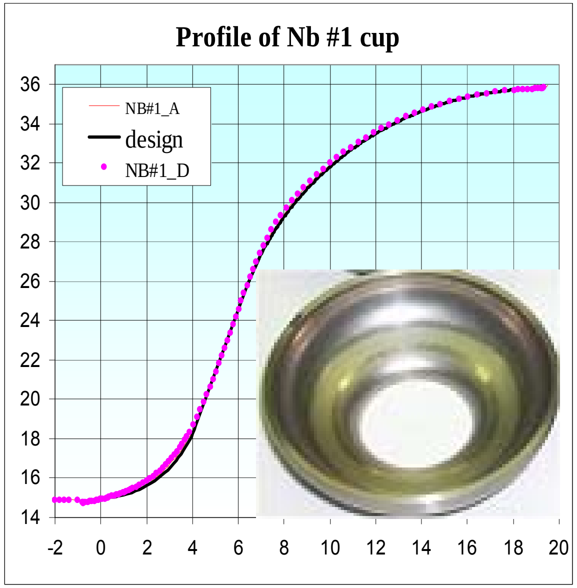
All components (except two flanges were e-beam welded to specify weld parameters.

E-beam welding machine at Sciaky, Chicago.



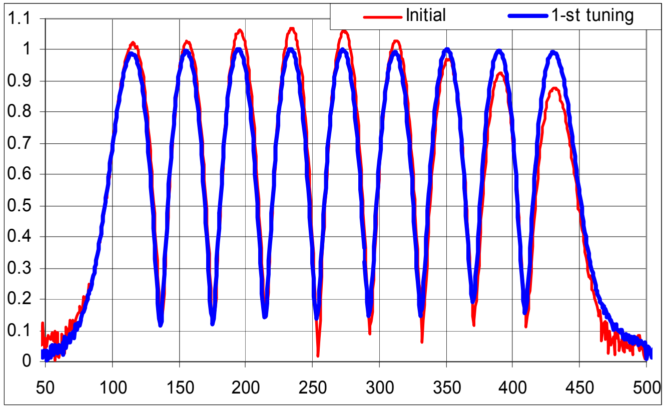
Production and RF control

Tooling for deep-drawing

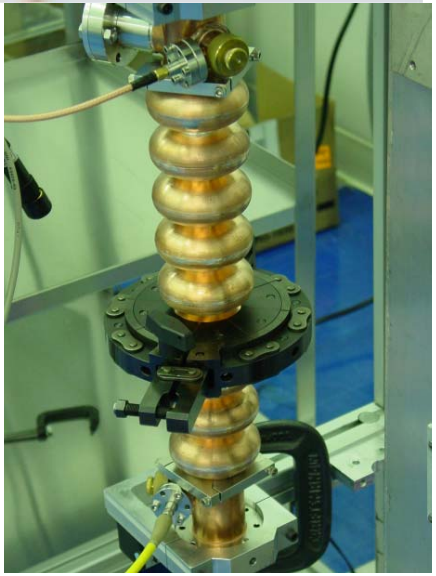


CMM profile measurement

Electron beam welding

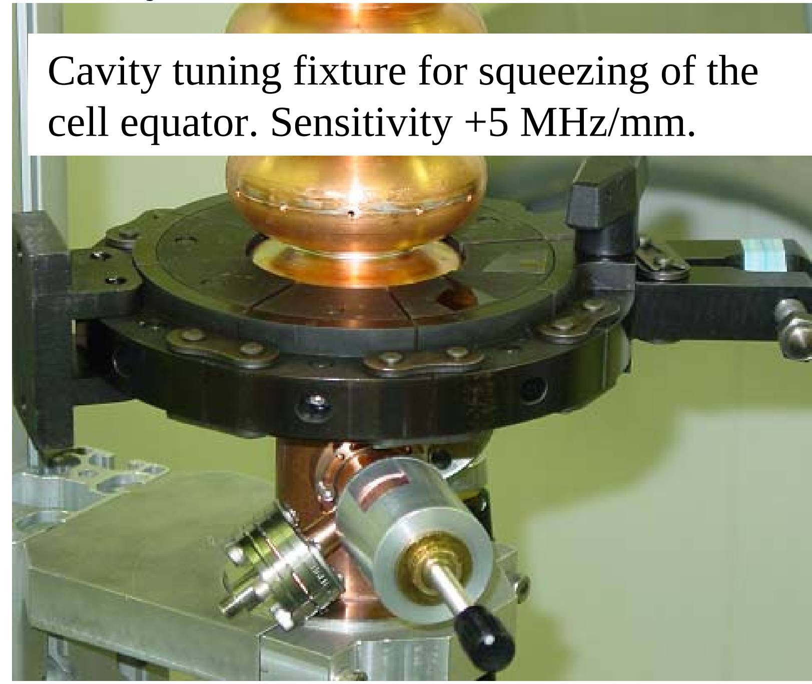


Frequency and field flatness tuning



RF Qc of the half cells, dumbbells and cavity.

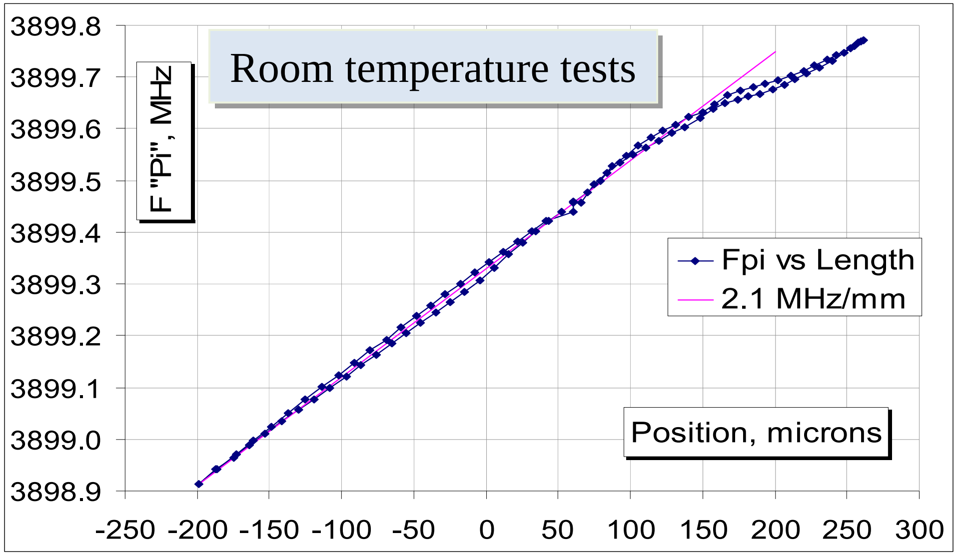
Dumbbell RF QC.

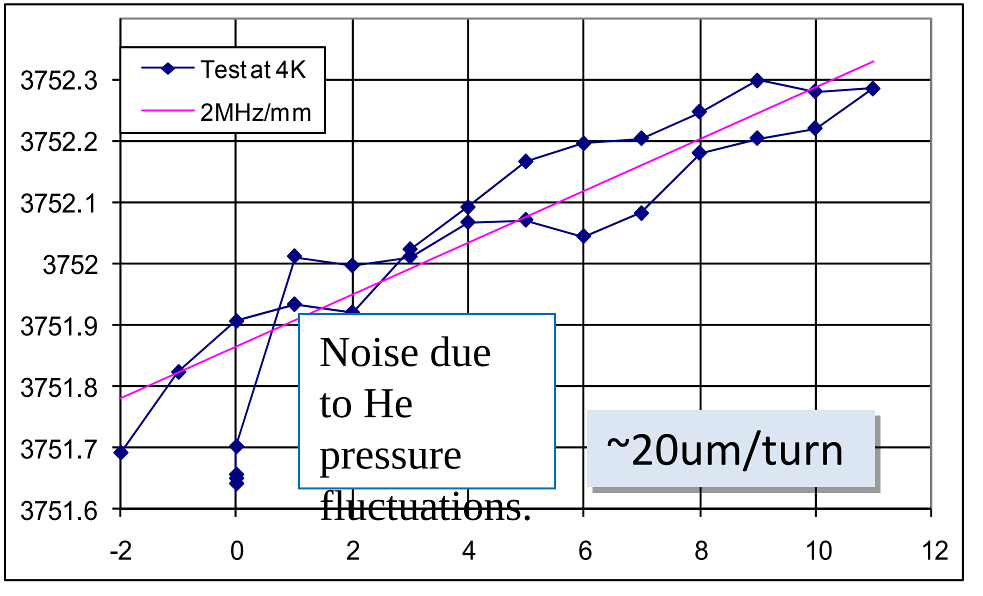


Cavity tuning fixture for squeezing of the cell equator. Sensitivity +5 MHz/mm.

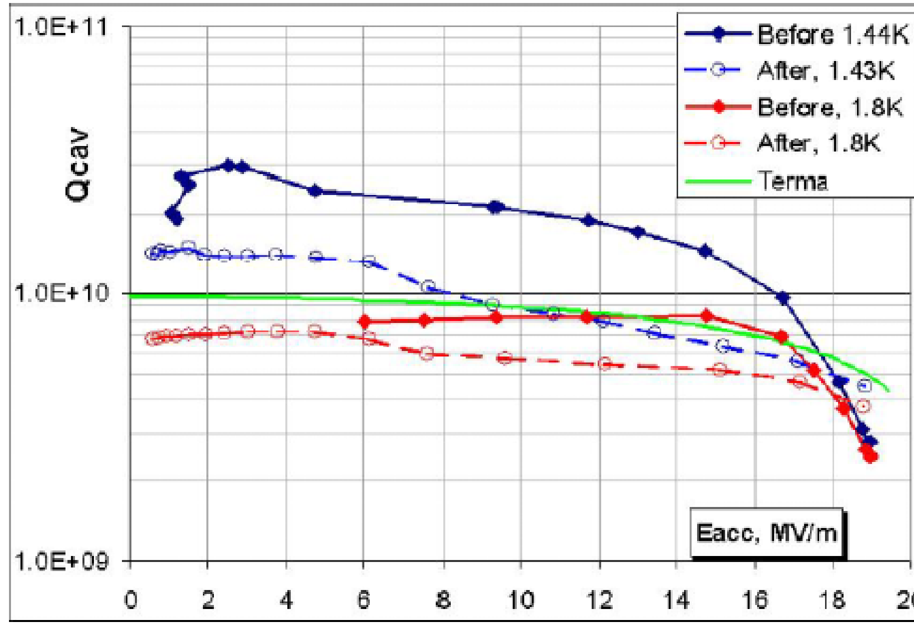
Cavity tuning fixture for pull-push in axial direction. Sensitivity ±2.5 MHz/mm.

Blade tuner tests





3-cell prototype



Q vs. accelerating gradient at different temperatures

First tests of the 3-cell cavity, we achieved
Rs~6nΩ; Eacc = 12MV/m (w/o HPR)

After an additional 5µm etch and ~2hrs HPR:
Rs~6nΩ, Eacc = 19MV/m, Hpeak=103mT

➔ 9-cell cavity will have a gradient of 21MV/m for the same surface magnetic field.

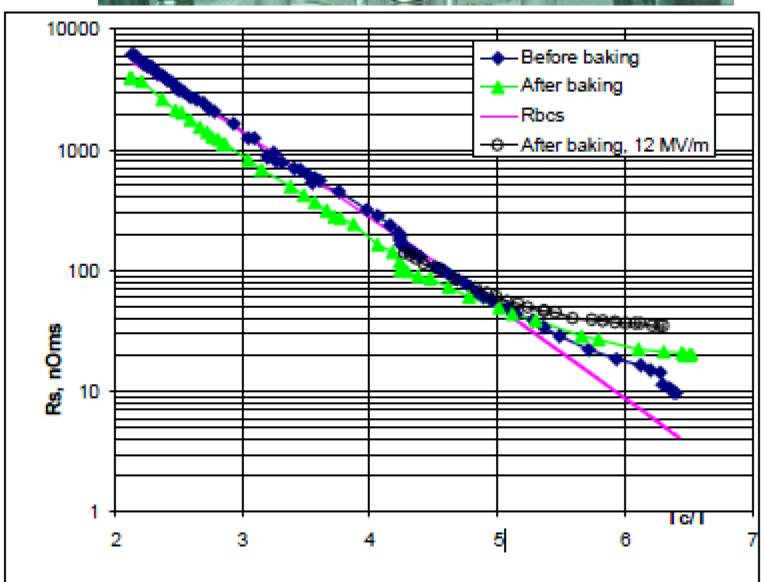
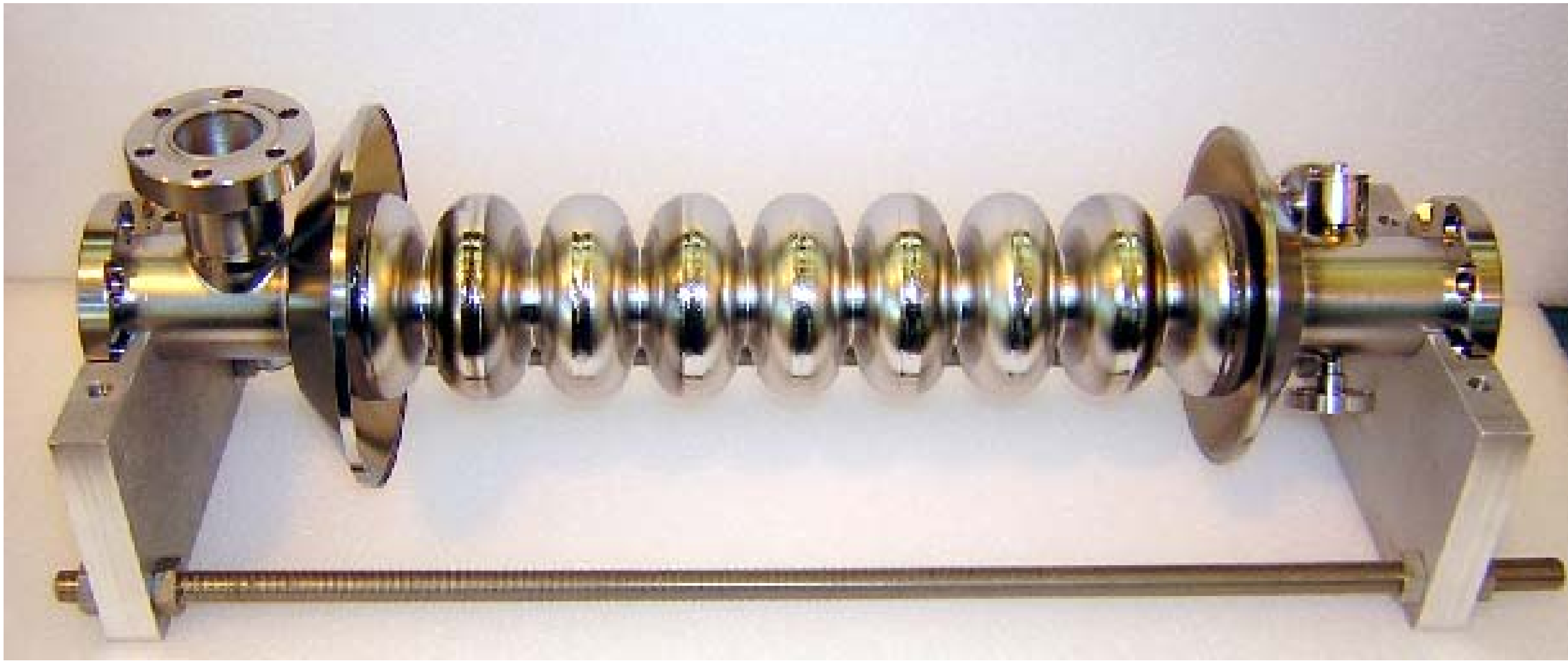


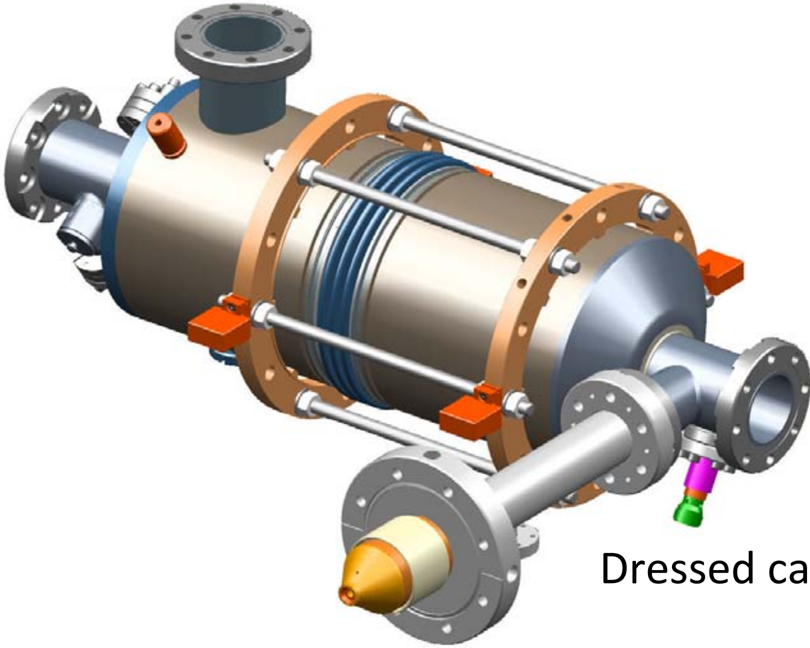
Figure 8: Resistance vs. Temperature

Final assembly of the 9-cell cavity

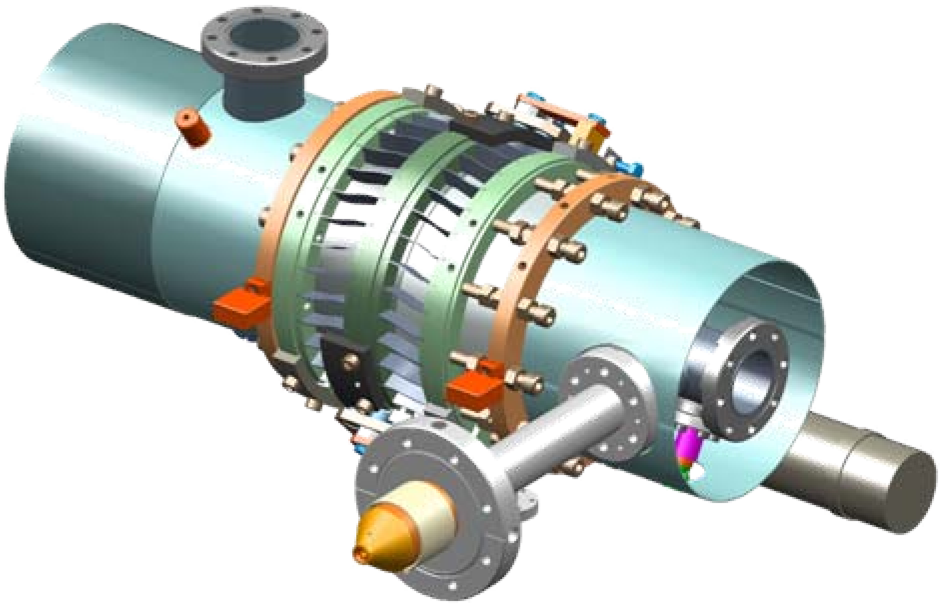


Welded at Sciaky and Jefferson Lab
For cavities starts in parallel

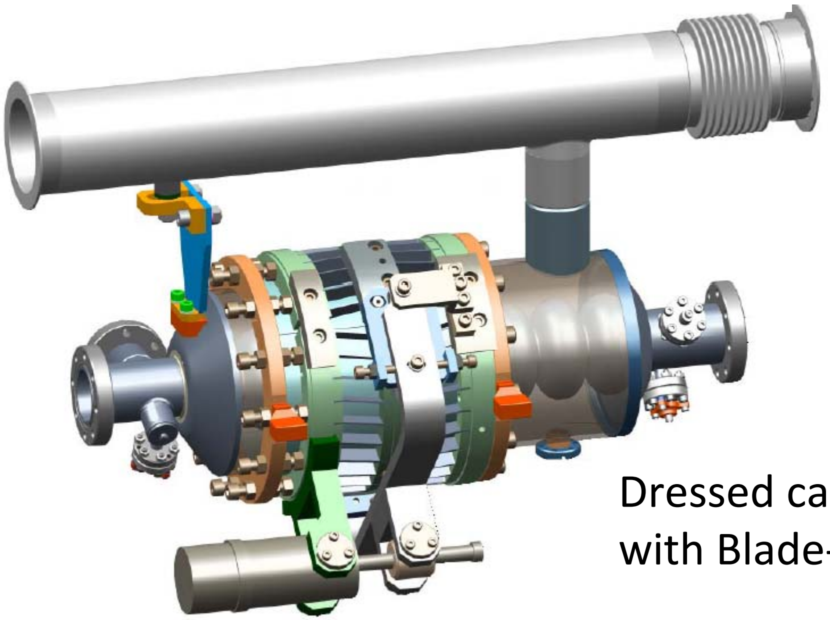
Cavity Construction



Dressed cavity



With Magnetic Shields
and Blade-tuner



Dressed cavity
with Blade-tuner

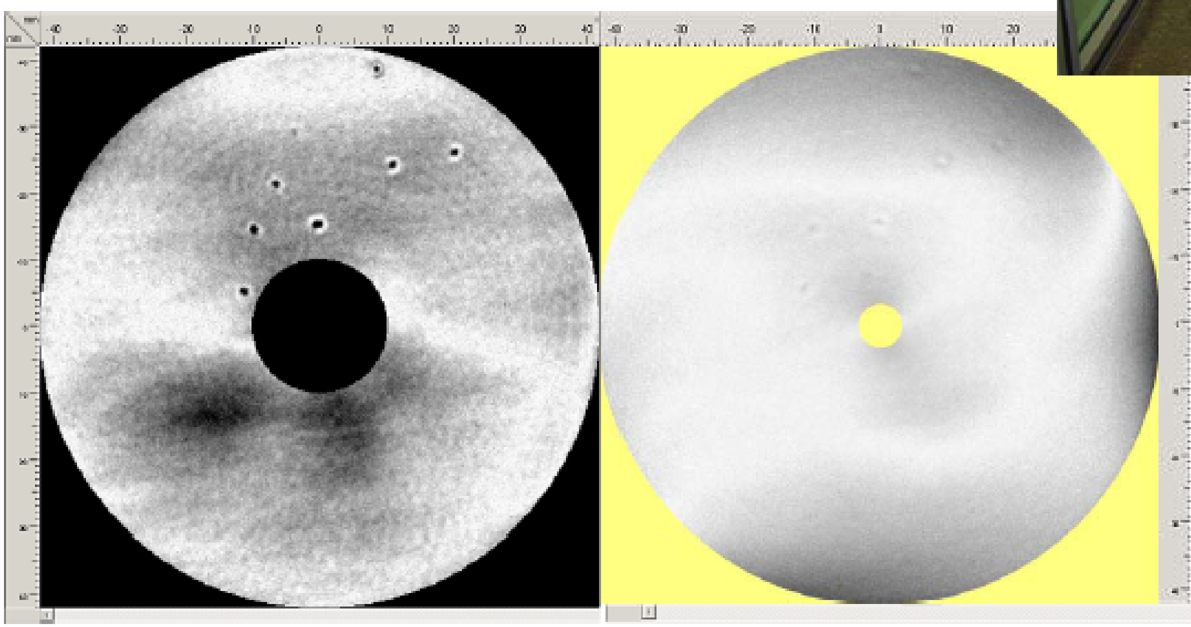
SRF Infrastructure at FNAL

Clean Rooms
Chemistry (ANL-FNAL): BCP, EP, HPR
Tumbling machine
Vertical Test Stands
Horizontal Test Stand
RF power sources
String Assembly clean room
CM assembly Tooling
RF Lab
.....

Nb material Control

Eddy Current Scanner donated by SNS

- Good to detect inclusions (100μm Ta, 10 μm Fe, etc.), not enough for pits and scratches.
- Built disk holders for CKM and 3rd harm disks
- Upgrading to improve Scanner resolution: - new alignment system, new coils, etc.



Disk 3harm_b1_22_2

scanned at DESY (left) and

FNAL (right).

Size of pits ~50-100μm

FNAL/ANL BCP/EP facility

- Existing U.S. facilities at Cornell, TJNL, and ANL are being upgraded to process the 1.3 GHz ILC cavities but not sufficient
- A new FNAL/ANL BCP facility built at ANL (operational ~March)

- Electropolishing
- Buffered Chemical Polishing
- High-pressure Rinsing
- Clean Room Activities

- An Electro-polishing facility is being designed by the ILC Collaboration
- A prototype will be built at ANL/Fermilab Cavity Processing Facility at ANL.

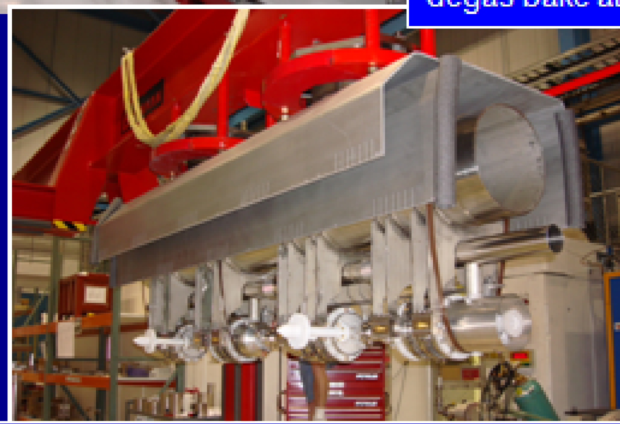
TD-MP9 CRYOMODULE ASSEMBLY FACILITY

CAF-MP9

1.3GHz bare cavity hydrogen degas bake at CAF-IB4

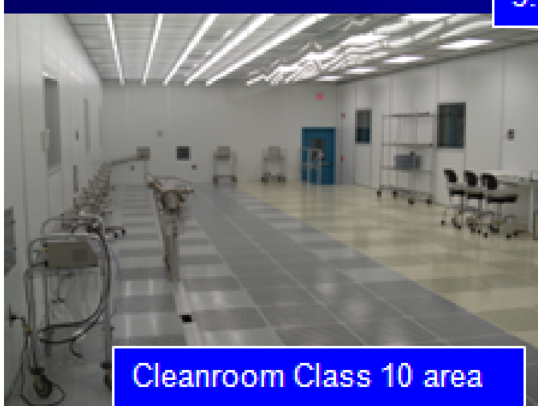
- **Cavity string** and **Cold mass** Assembly Areas
- Fully Operational (June 2007)

1.3GHz dressed cavity



3.9GHz Cryomodule Mockup Assembly

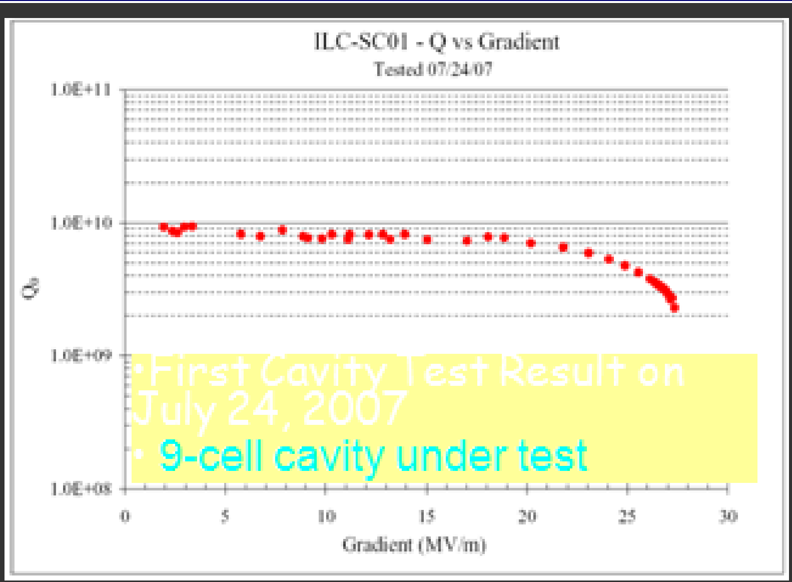
Clean room technicians from FNAL & DESY working together during CM1 string assembly



Cleanroom Class 10 area

Cryomodule #1 (CM1) string assembly in the cleanroom

Cavity Vertical Test Stand (VTS)

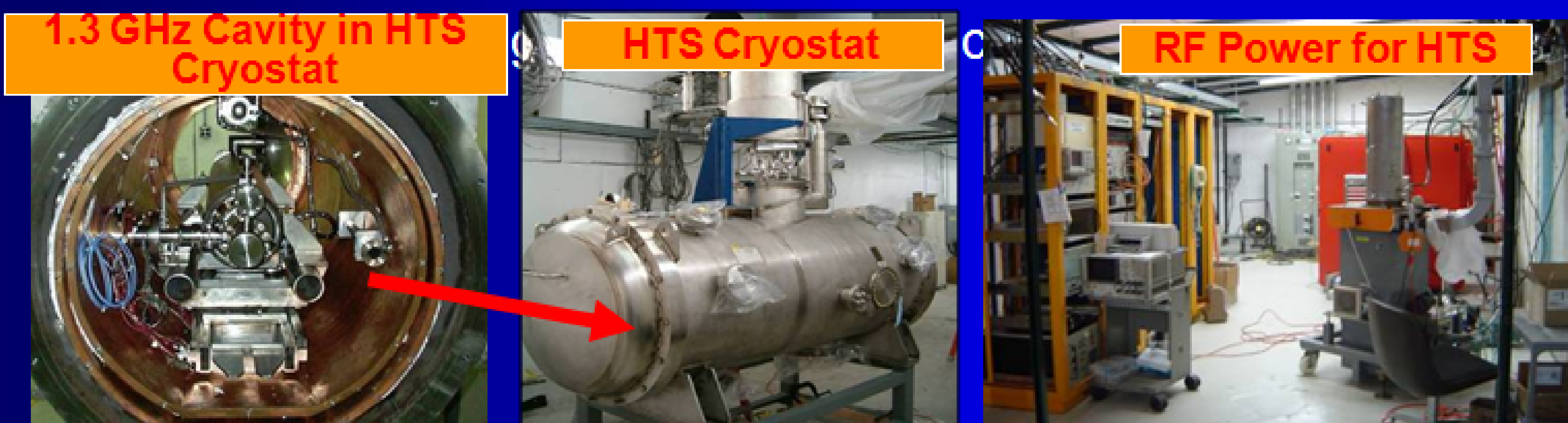


- VTS-1 Upgrades:
  - Vacuum pumping
  - Variable coupler
  - Two cavity operation
  - T-mapping
- To increase capacity of the VTS
  - Add 2 more VTS pits (~200test/yr)
  - Upgrade cryogenic 125W→300W

Horizontal Test System (HTS)

- HTS facility is complete at FNAL
- After vertical test extensive cavity handling ensues
  - Cavity welded inside He vessel
  - Cavity opened to install main coupler
  - Tuner added

  } "Dressing"
- Horizontal Test
  - First test of the cavity with high pulsed RF power
  - R&D Test bed: tuners (slow), couplers, LLRF, etc



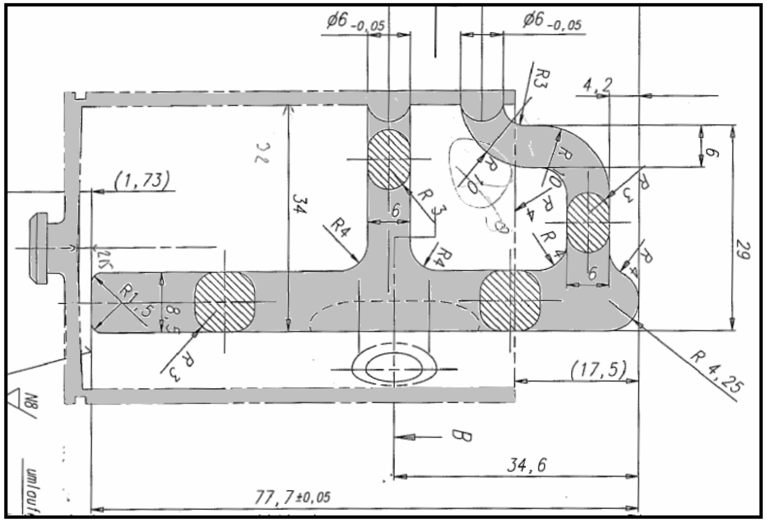
FNAL CRYOMODULE ASSEMBLY FACILITY

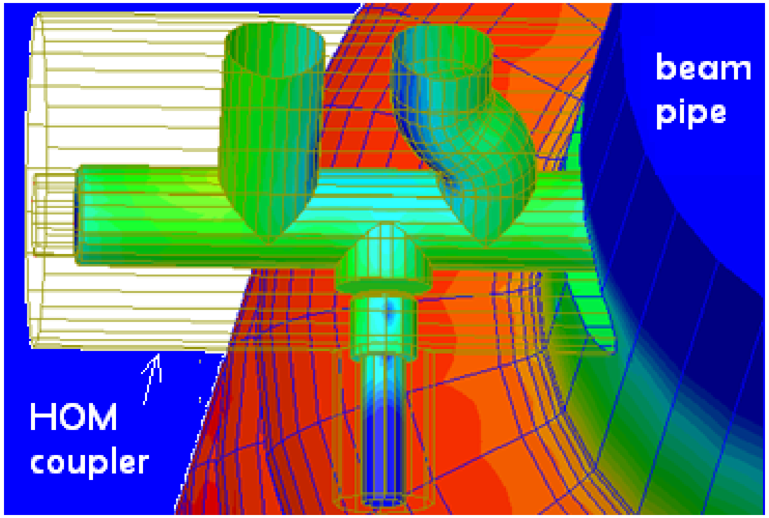
Big Bertha
at CAF-ICB

Prototyping, Lessons learned

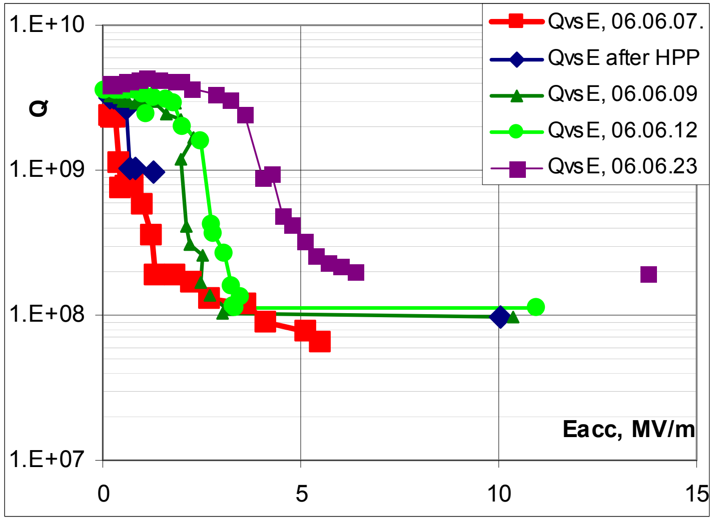
- *MP and HOM coupler failure*

  Lesson: Steps by step progress in developing and testing new unknown components

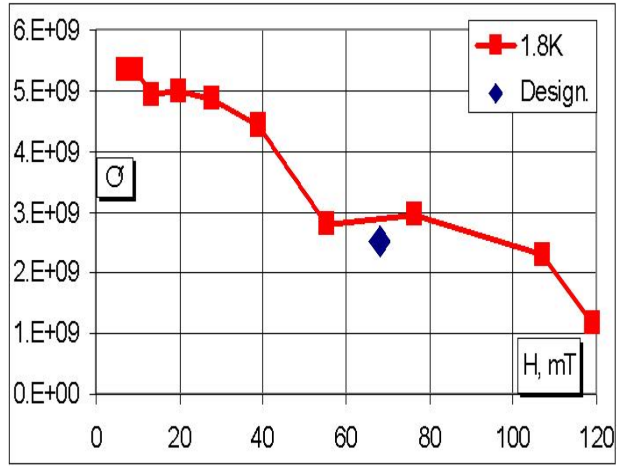


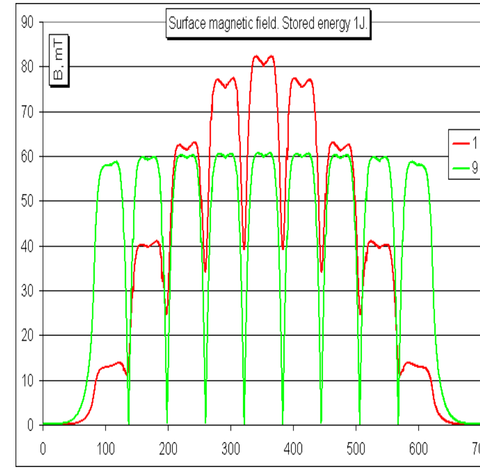


Problems with HOM coupler during vertical test of the 2nd cavity.

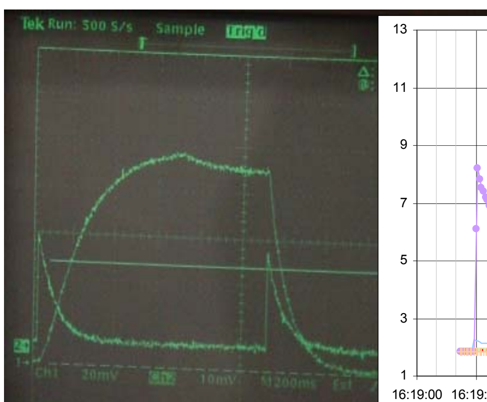


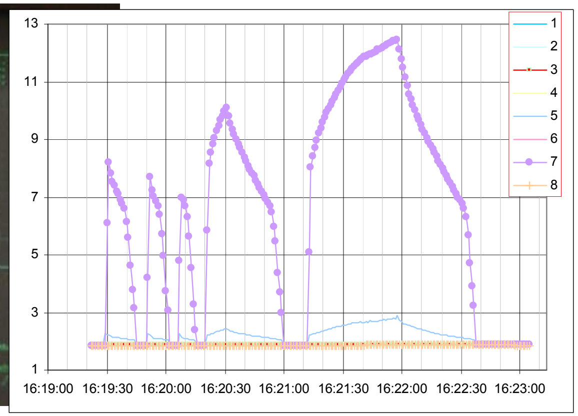
QvsE measurements in “Pi”-mode.

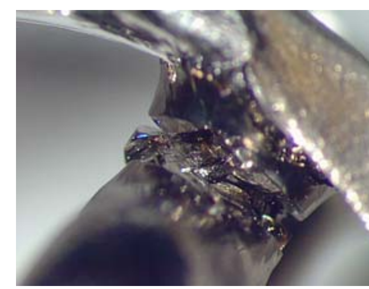




Surface magnetic field in “0”-mode.







“Multipactor”. Transmitted and reflected power.

Temperature sensors installed in the HOM shows heating.

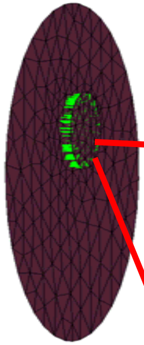
Both HOMs coupler fractured after high power vertical tests.

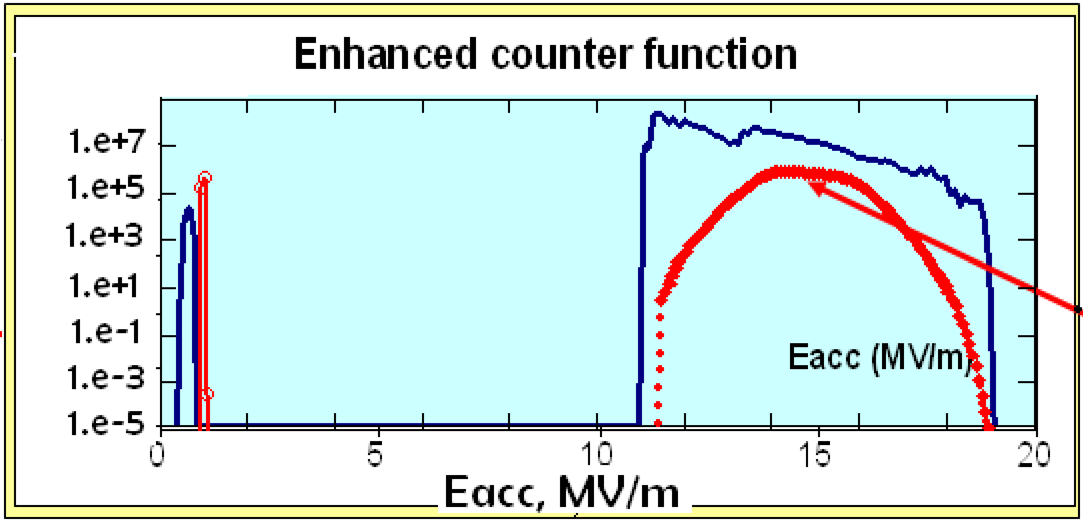
MP in original design of HOM coupler

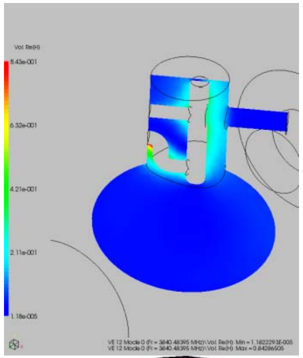
3D simulation

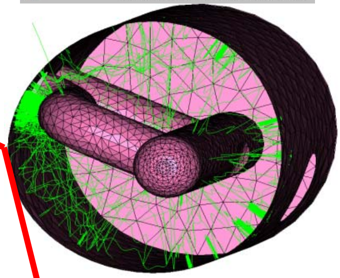
Omega 3P(Analys

MP in
notch gap
0.6 mm

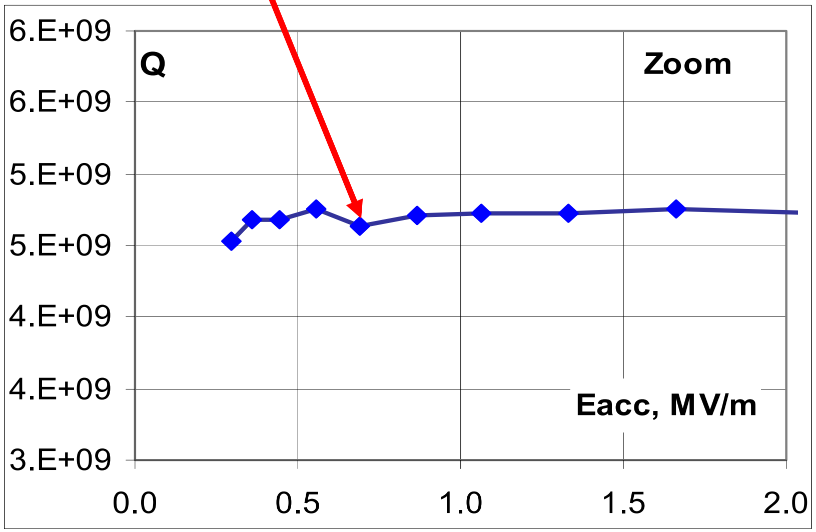


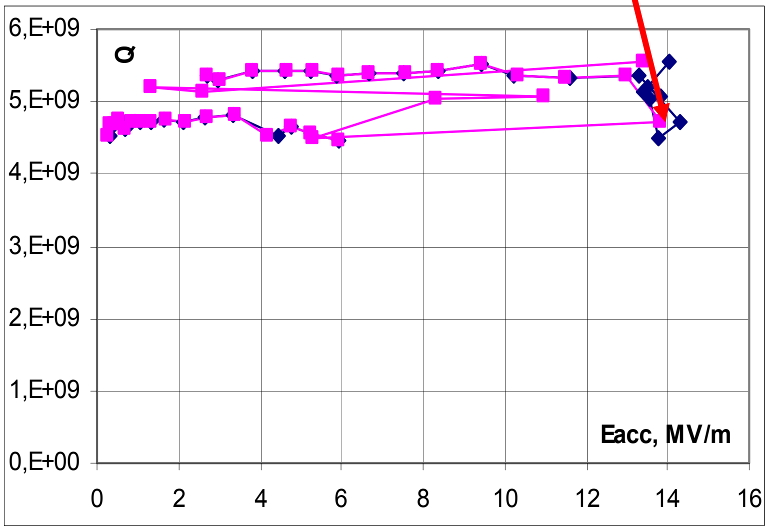






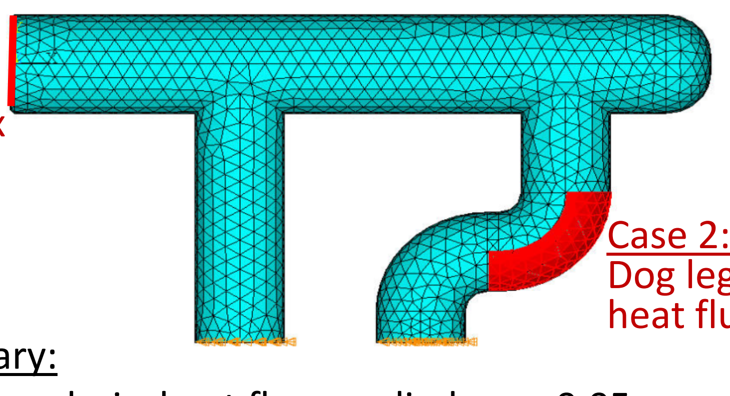
MP in 2 mm leg-wall gap





Cavity No.3. Results of vertical test#2: MP observed at Eacc~0.7MV/m (Q drop). Quench at Eacc~14MV/m. Second resonance frequency of HOM was tuned higher than designed value.

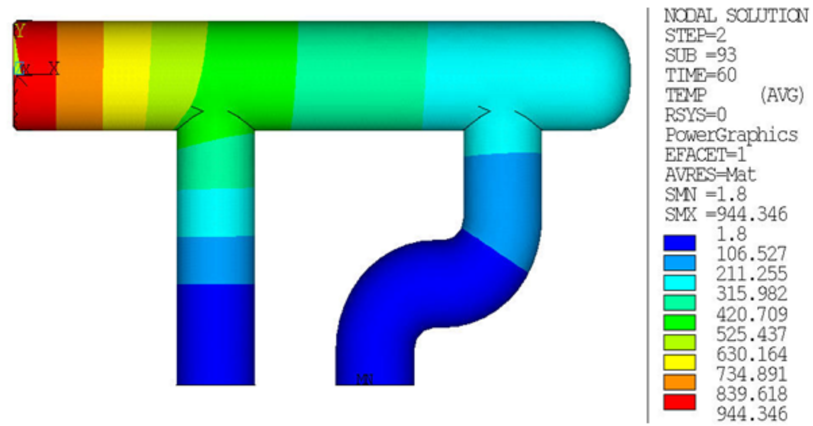
3.9GHz Formteil: Analysis Results @ 50W



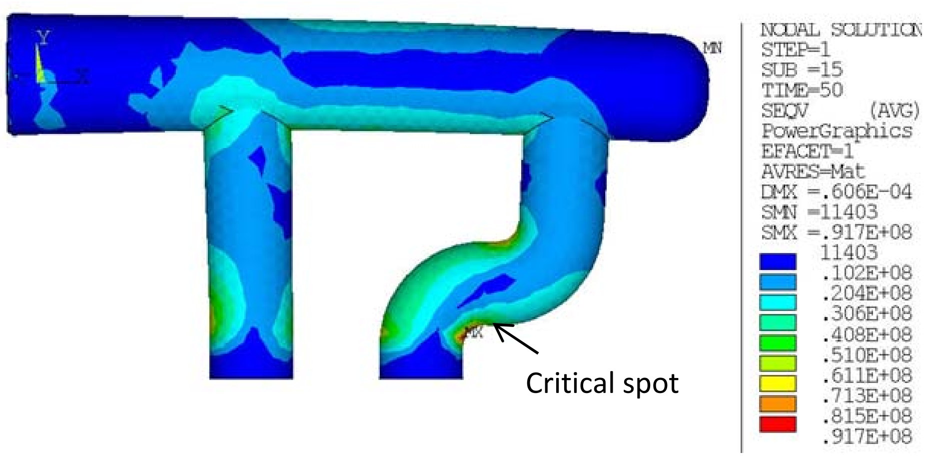
FEA Summary:

- transient analysis, heat flux applied over 0.05 sec
- 4 cases analyzed @ 20W, 50W, & 100W
- thermal stresses calculated for each case

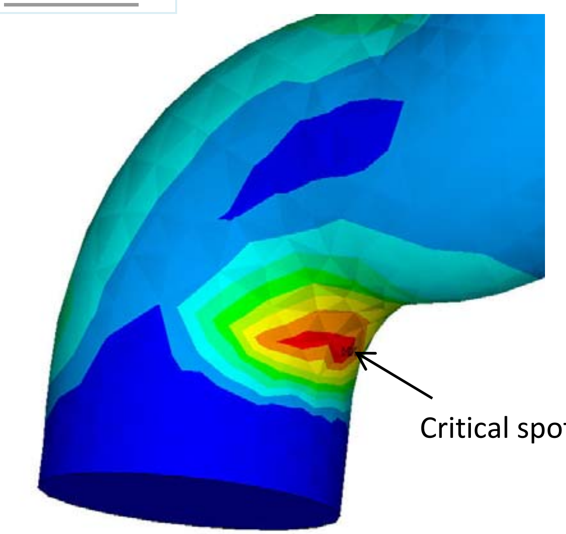
Temperature Results



Structural von Mises Stress (Pa)



CASE 1

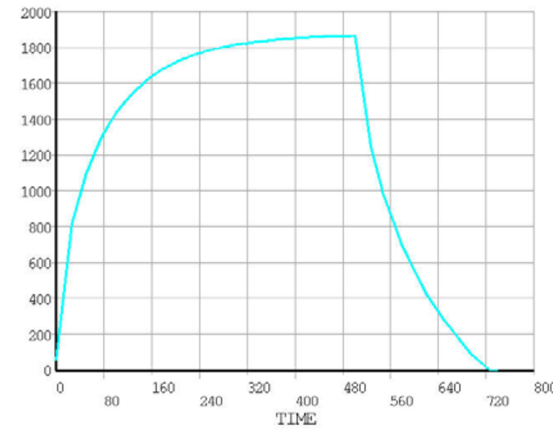


Salman Tariq, Rob Polera /FNAL

Results Table (3.9GHz Formteil)

	CASE 1			CASE 2		
	1.8K can boundary condition Multipacting @ End Gap			1.8K can boundary condition Multipacting @ Dog Leg		
	20W	50W	100W	20W	50W	100W
Max Temp. reached (K)	323	944	2075	81.8	375.6	855.5
Temp. at critical spot (K) (node 1722)	8.8	16.7	40	16.4	55.9	213.7
Max von Mises Stress at critical spot (MPa)	7.8	91.7	261	2.6	38.5	123
Max Stress Intensity at critical spot (MPa)	8.2	96.5	275	2.9	41.4	136
Max Principal Stress at critical spot (MPa)	-13.7	-155	-438	-2.5	-53.3	-224
Approx time to reach 80% SS temp (secs)	8	15	18	0.65	5	9
Approx cool down time to 1.8K (secs)	6	12	40	1	8	24

Transients (Case 1)



<u>100K Nb (heat treated) physical properties</u>
Yield strength: 400 MPa (58 ksi)
Ultimate strength: 470 MPa (68.2 ksi)

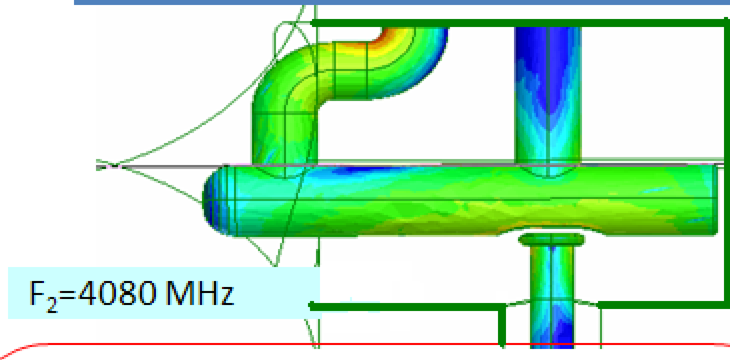
<u>300K Nb (heat treated) physical properties</u>
Yield strength: 60 MPa (8.7 ksi)
Ultimate strength: 125 MPa (18 ksi)

<u>Main conclusions</u>:

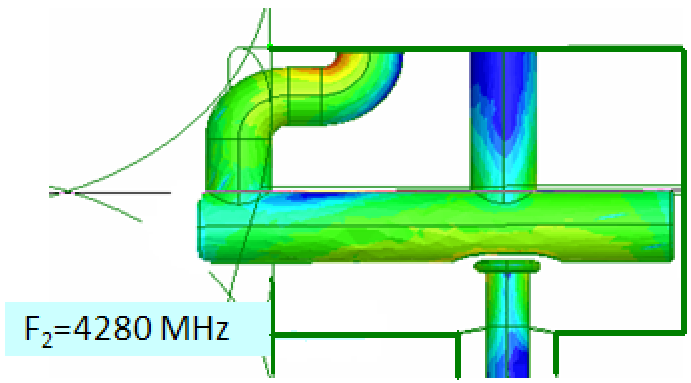
- Critical spot was same for all cases = 'exact' location where failures occurred!!
- Fatigue at brittle temp.'s could cause failure at much lower stresses (from thermal cycling)
- Necking at the weld will further weaken the Formteil (not included in the FEA model)

New Designs of the HOM coupler

Initial design No.1

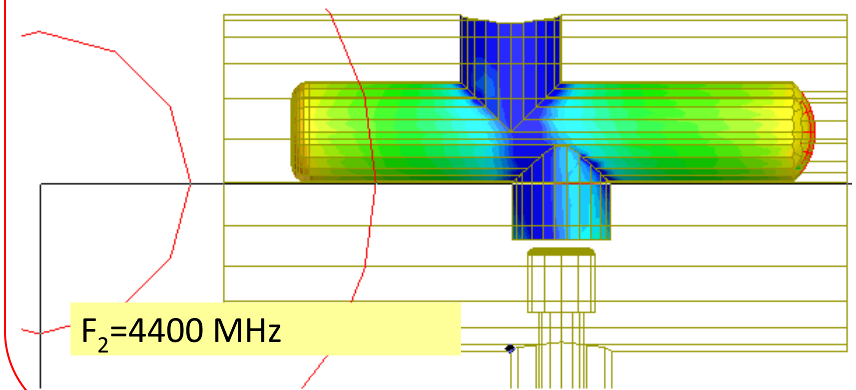


Trimmed Initial design -1a



No MP up-to 23 MV/m in modified design

1-post design



New design:
- one post, rounded gap
- Thicker, 6mm vs. 4mm

Fields in HOM (comparison)	Hpk/H	Epk/E
cavity	**7.4**	**3.5**
HOM-original	1	1
HOM-modif	**0.4**	**0.4**
HOM-1post	**0.67**	**0.31**

Cavity Test Results

Cryomodule Assembly

Shipping to DESY

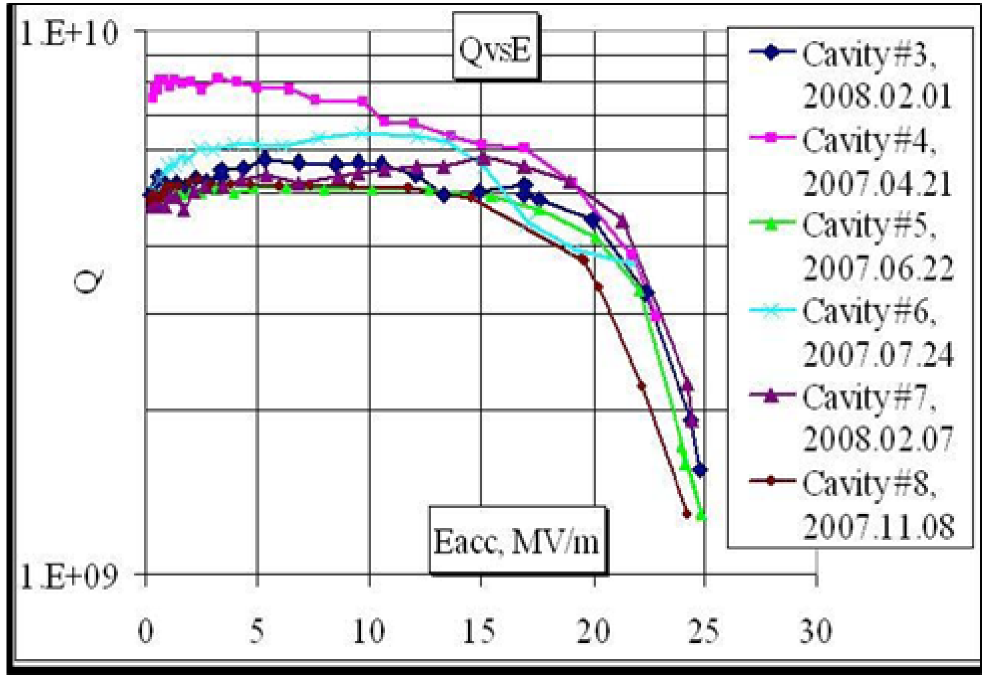
ACC39 CM test

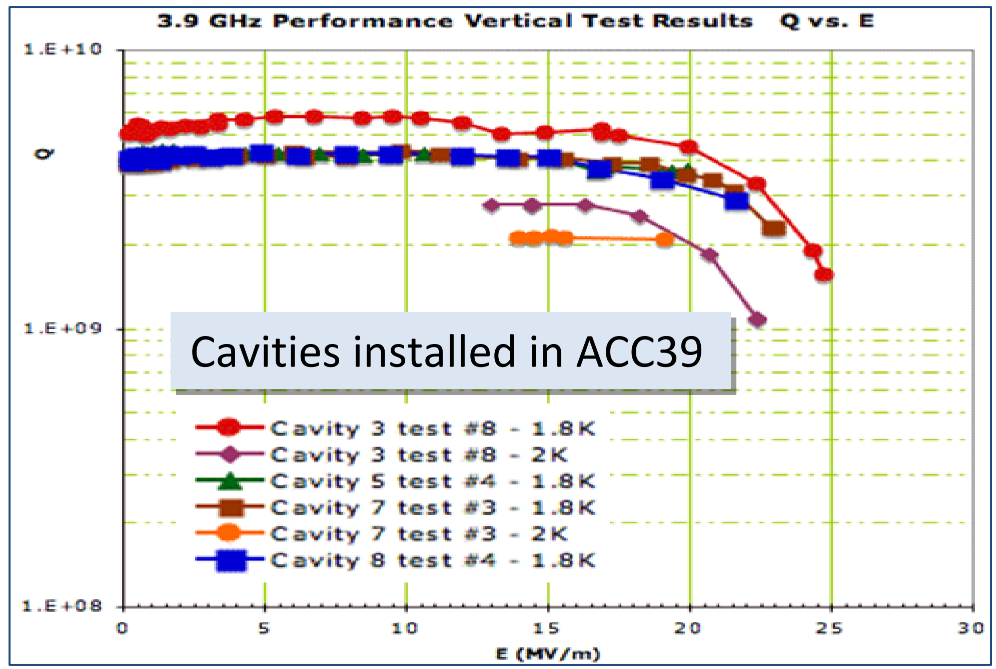
Installation

Vertical Testing

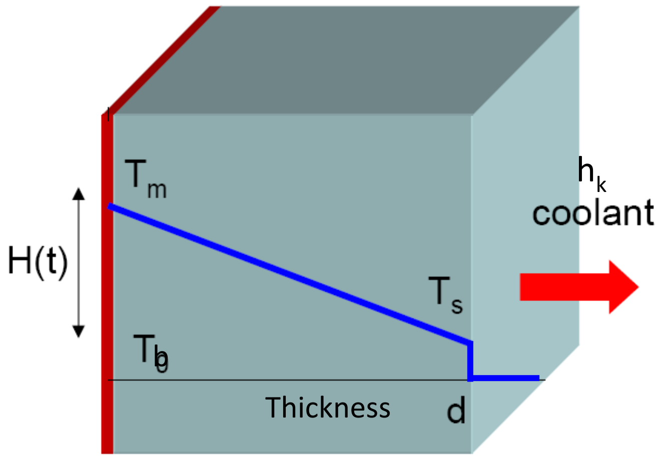
- All fabricated cavities tested at the A0 vertical test stand as ‘bare’ cavities
- To date there have been a total of 67 tests performed (1.8K and 2K).
- Those welded into helium vessels were given an additional test prior to dressing to ensure that the welding process did not significantly degrade each cavity’s performance.
- Two production cavities, #’s 4 and 6 have yet to be fully qualified as spares.
- Cavities #9-10: part are ready

E.Harms, SRF2009, Berlin





Thermal Breakdown in pure Niobium

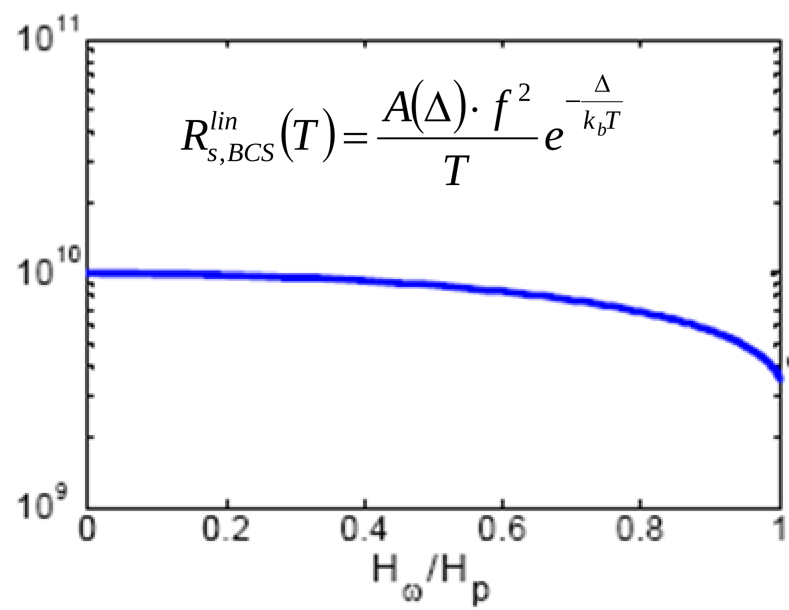


Power dissipation: $$P_{diss} = \frac{1}{2} R_s(T_m, H_{RF}) H_{RF}^2$$

Bulk: $$\frac{\partial}{\partial x}\kappa(T)\frac{\partial T}{\partial x} + P_{diss}(T_m, H_c, ..)\delta(x) = 0$$

Nb-He: $$\frac{1}{2} R_s(T_m, H_c, ..) H_{RF}^2 = h_K(T_s, T_b)(T_s - T_b)$$

Quality factor (an example)



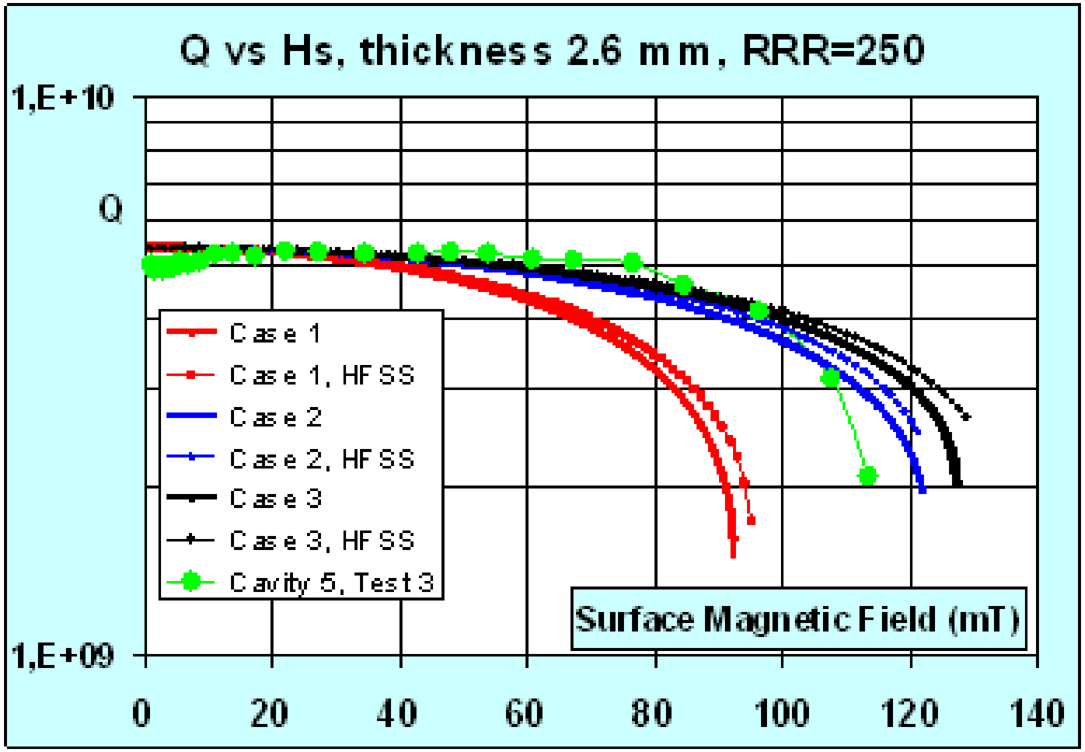
Run away solution for 2°K and

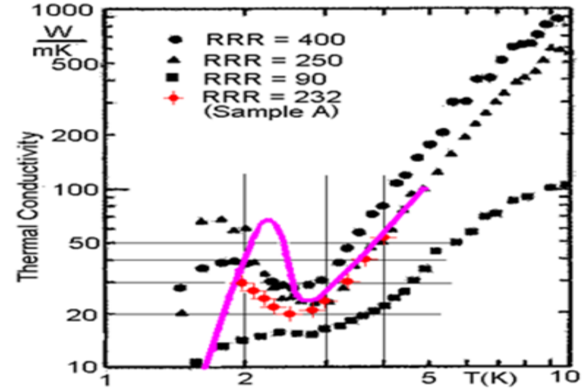
k(T₀)=30 W/(m•K); h(T₀)= 10⁴ W/(m²•K);

$$\delta T = \frac{T_0}{2\cdot\left(\Delta\cdot\frac{T_c}{T_0} - 1\right)} = 0.137^\circ K$$

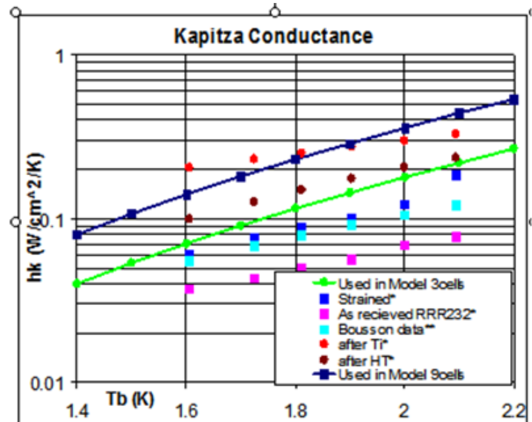
$$H_b^2 = \frac{T_0^3}{2\cdot R_s(T_0)\cdot(\Delta\cdot T_c - T_0)}\cdot\left(\frac{k\cdot h}{k + h\cdot d}\right)$$

Thermal breakdown





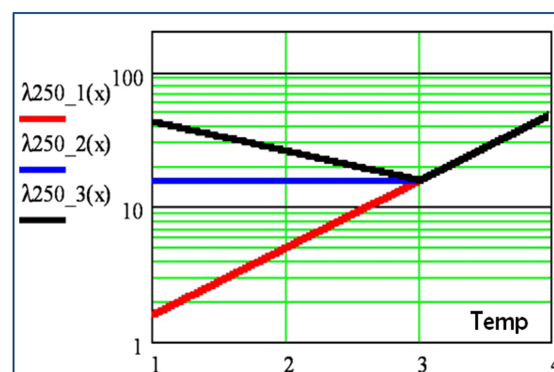
Measured thermal conductivity and values used in models (pink)



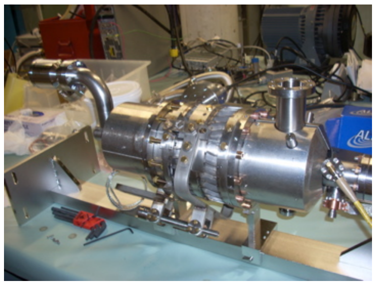
Measured values of Kapitza conductance and values used in model (solid lines)

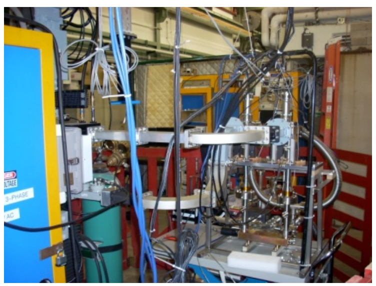
Comparison of measured data for cavity #5 (dashed) with model for the three thermal cases.
Case 1 - RED, Case 2 - BLUE, Case 3 – BLACK.
Solid lines are for the constant surface magnetic field model, dotted for real fields calculated by HFSS.

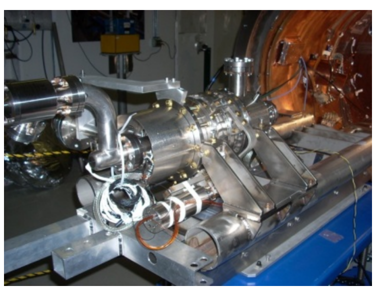
h_k=0.3 W/cm^{2}K at 1.8K.



History of all 3rd harmonic cavities







Cavity	Assembled	Completion	Test results and status
#1: 2-leg HOM	Fermilab	January 2006	Never tested: HOM membrane break during cleaning - Used as horizontal test prototype
#2: 2-leg HOM	Fermilab	February 2006	- Best vertical test: 12 MV/m limited by HOM heating - Fractured Formteils - Repair attempted
#3: 2-leg trimmed HOM	Fermilab JLab	August 2006	- Best vertical test: 24.5 MV/m, achieved after HOM trimming -Horizontal testing: 22.5 MV/m limited by quench - Part of final string assembly
#4: 2-leg trimmed HOM	Fermilab JLab	March 2007	- Best Vertical test: 23 MV/m - Horizintal testing: 18 MV/m limited by quench
#5: 2-leg trimmed HOM	Fermilab JLab	May 2007	- Best Vertical test: 24 MV/m - Welded into Helium vessel - Horizontal testing: 22.5 MV/m limited by quench - Part of final string assembly
#6: 2-leg trimmed HOM	Fermilab JLab	May 2007	- Best Vertical test: 22 MV/m - Faulty welds repaired - Awaiting final vertical test with HOM feedthroughs
#7 single-post HOM	Fermilab JLab DESY	November 2007	- Best Vertical test: 24.5 MV/m - Welded into Helium Vessel - Horizontal testing: 26.3 MV/m limited by quench - Part of final string assembly
#8 single- post HOM	Fermilab DESY	October 2007	- Vertical test: 24 MV/m - Horizontal testing: 24 MV/m limited by quench - Part of final string assembly

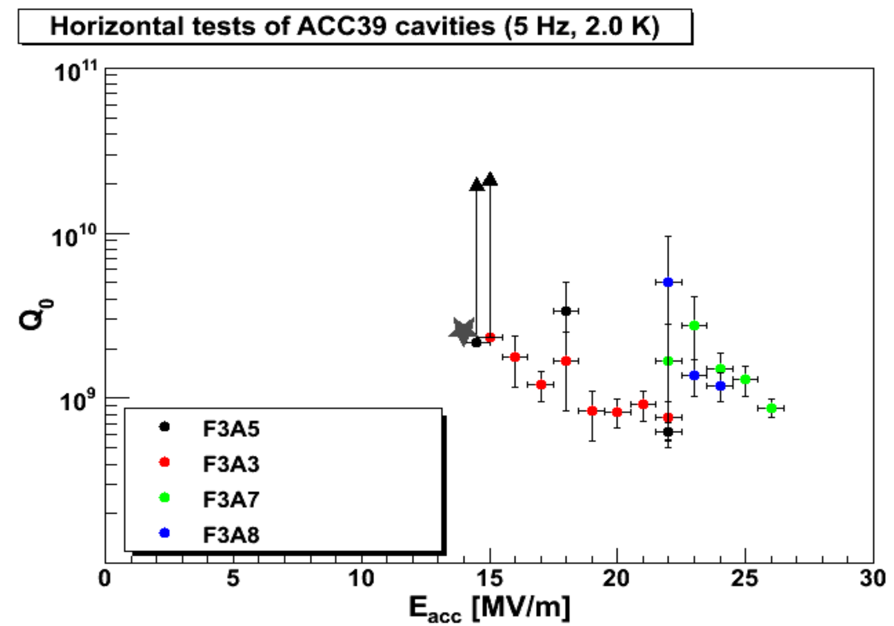
E.Harms, SRF2009, Berlin

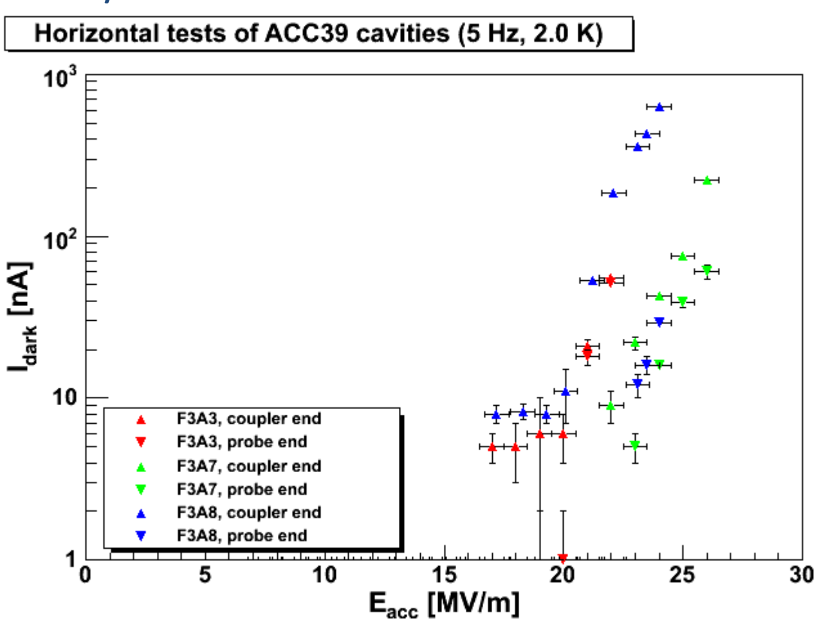
Horizontal Test Stand

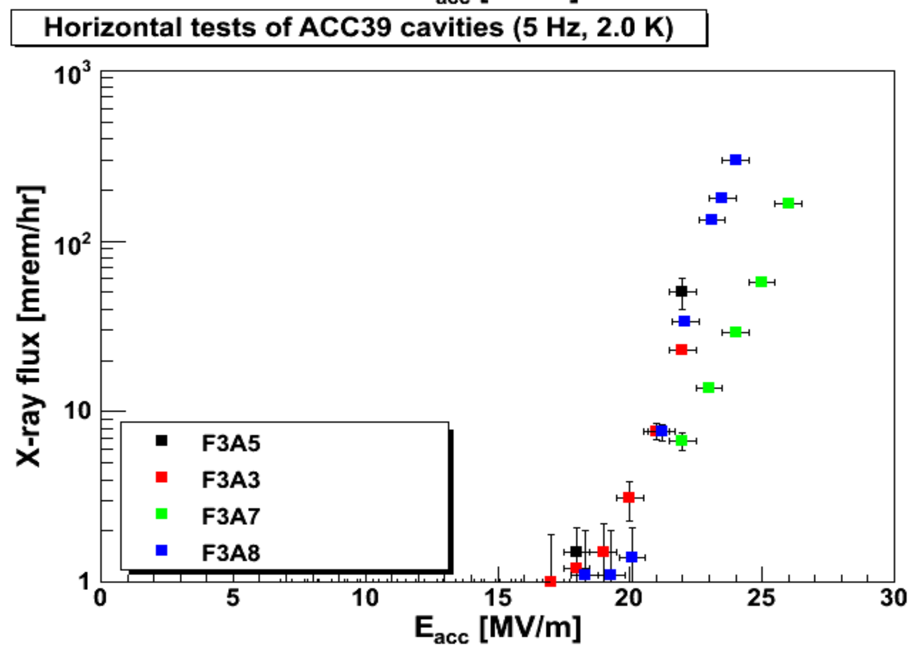
- Dressed cavity testing at 1.8 K
- Pulsed RF power from 80 kW 3.9 GHz klystron
- Measurements of X-rays, dark current, temperatures for diagnostics

Horizontal Testing

- Five cavities are now welded into helium vessels and have undergone Horizontal tests at the Fermilab Horizontal Test Stand (HTS)
- All tested cavities have reached gradients of at least 18 MV/m. Of the four selected for ACC39 string assembly, all reached at least 22 MV/m.



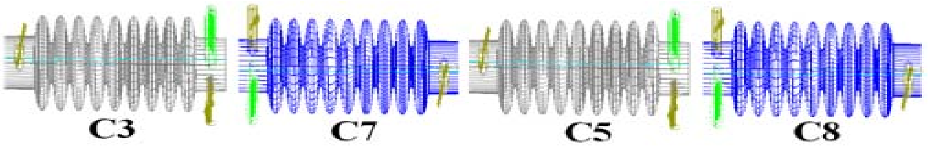




ACC39 Schedule Highlights

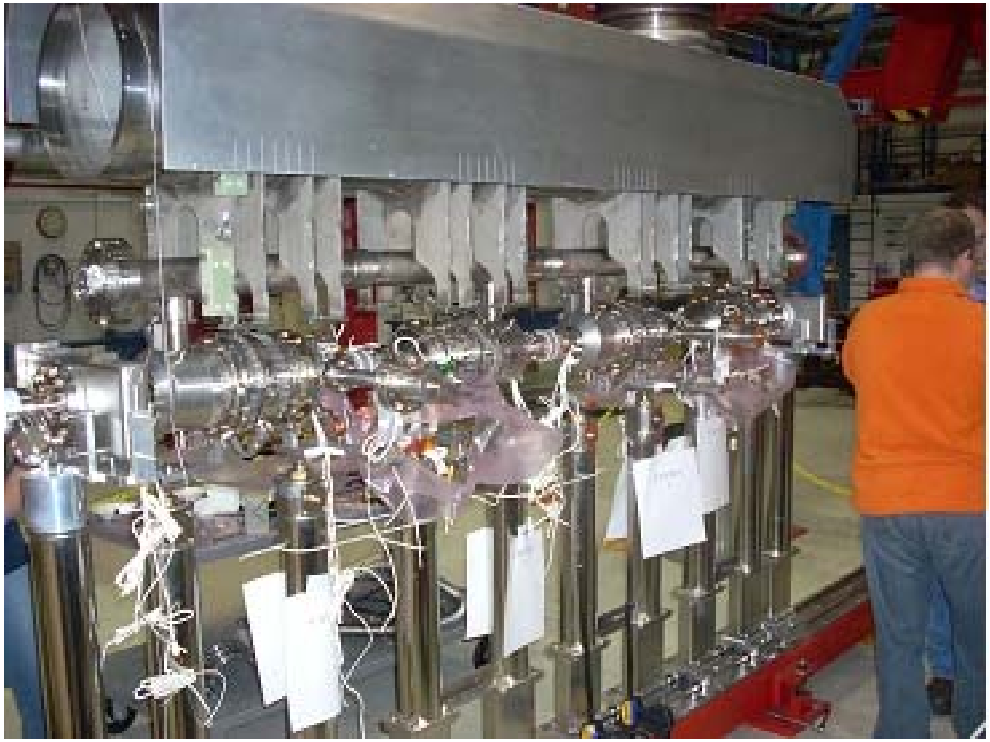
- 2002 TESLA Facility Phase 2 Report with 3.9 GHz module for bunch compression (TESLA-FEL 2002-01)
- 2002-3 Cavity design documents (TESLA-FEL 2002-05, 2003-01/FNAL TM 2210)
- 2005 DESY-FNAL MOU on 3.9 module
- 2006, 03-06 C1,C2 failures, Multipacting & HOM wall thickness
- 2006, 08 C3 fabrication finished - first usable cavity
- 2007, 05 C3 good vertical test after HOM formteils cut, 24MV/m
- 2007, 10 C5 vertical tests with HOM feed-throughs complete 19MV/m
- 2008, 02-09 C5 in horizontal test stand (HTS)
- 2008, 04 C5 achieved 22.5MV/m in HTS
- 2008, 12 C7 last cavity of four removed from HTS
- 2009, 01 String assembled in MP9 CR
- 2009, 02 Cold mass to ICB
- 2009, 04 Module finished and shipped to DESY
- 2009, 09 ACC39 tested in CMTB
- 2010,03 ACC39 installed in FLASH

String Assembly



Mixed. Each beam pipe has both type of HOM couplers. Some D2 path band modes of the 2nd cavity (#7) is trapped.

- Two cavities with original 2-post HOM coupler and with the re-designed single-post Formteil. Assembly alternate style
- Assembly, leak checked from 11 Dec. 2008 - early Jan. 2009.
- Transport to ICB for Cold Mass Assembly on Feb. 2009.
- Assembly was loaded onto the shipping fixture designed for the complete module and outfitted with vibration and g-force sensors to measure the response during truck transport.

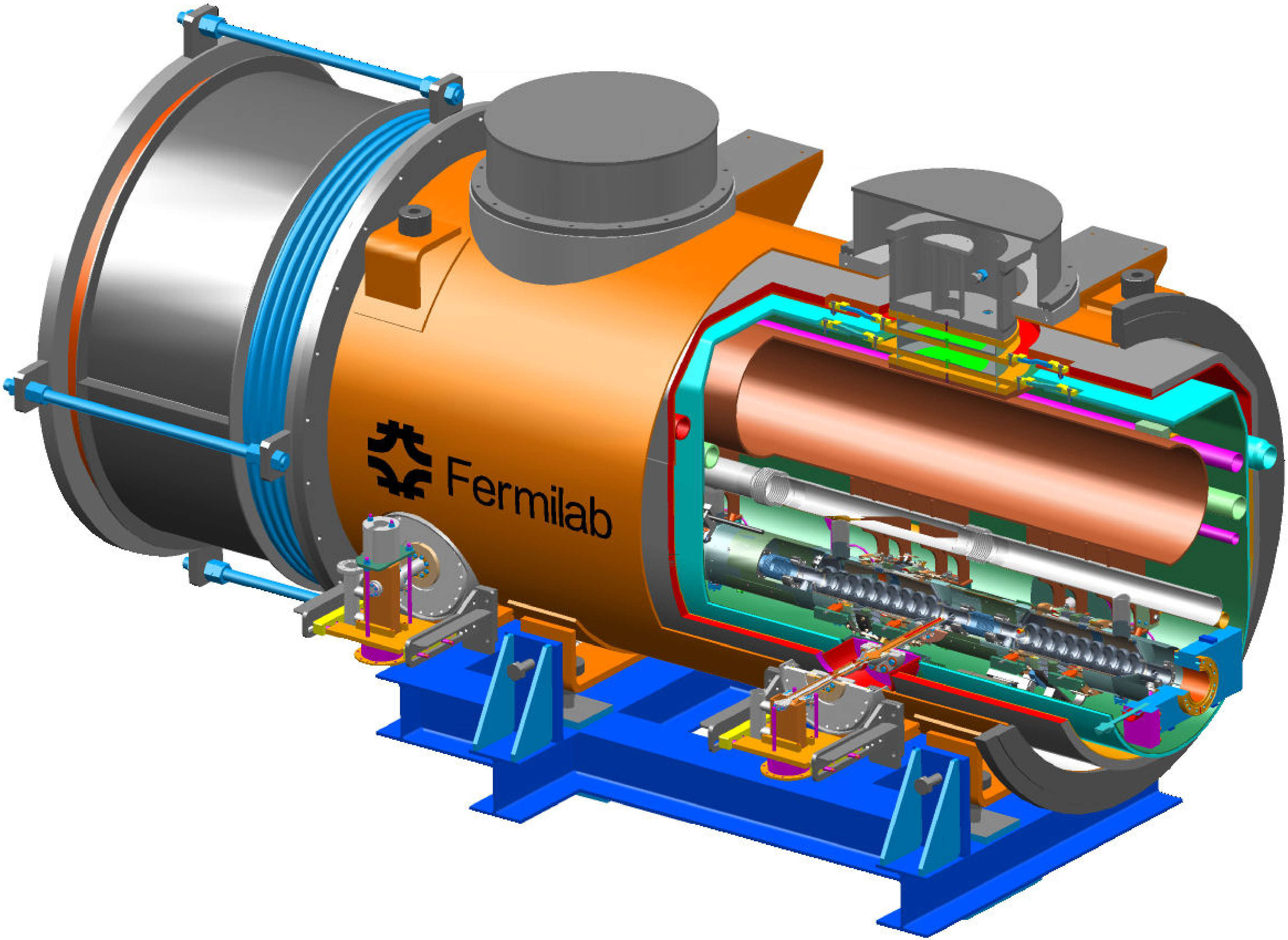


Cold Mass Assembly

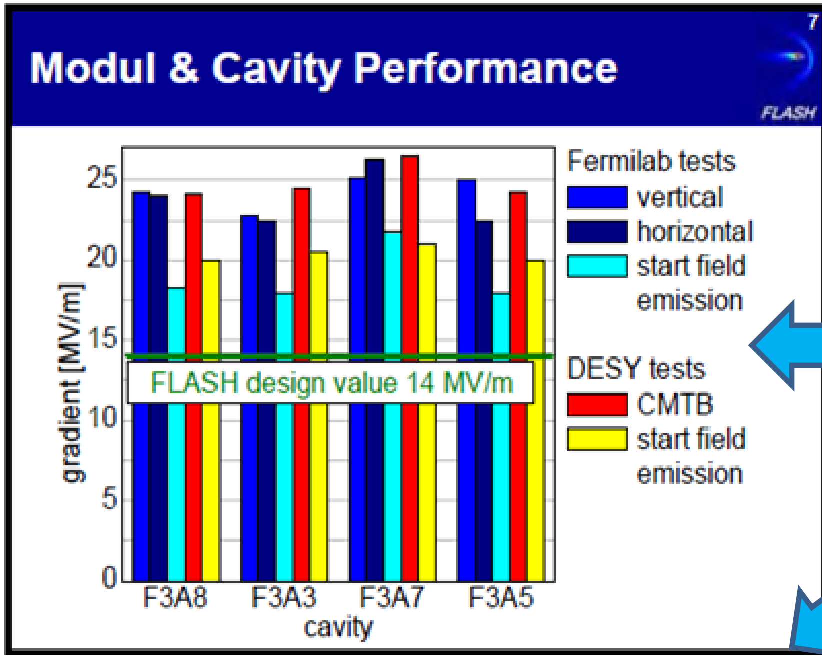
- The final major assembly work at Fermilab was the Cold Mass assembly including
  - encasing the cavity string in 4K shield and 10 layers of MLI
  - 80K thermal shield and 30 layers of MLI
  - All additional piping installed
  - Entire assembly was then inserted into its vacuum vessel
  - Final alignments performed.

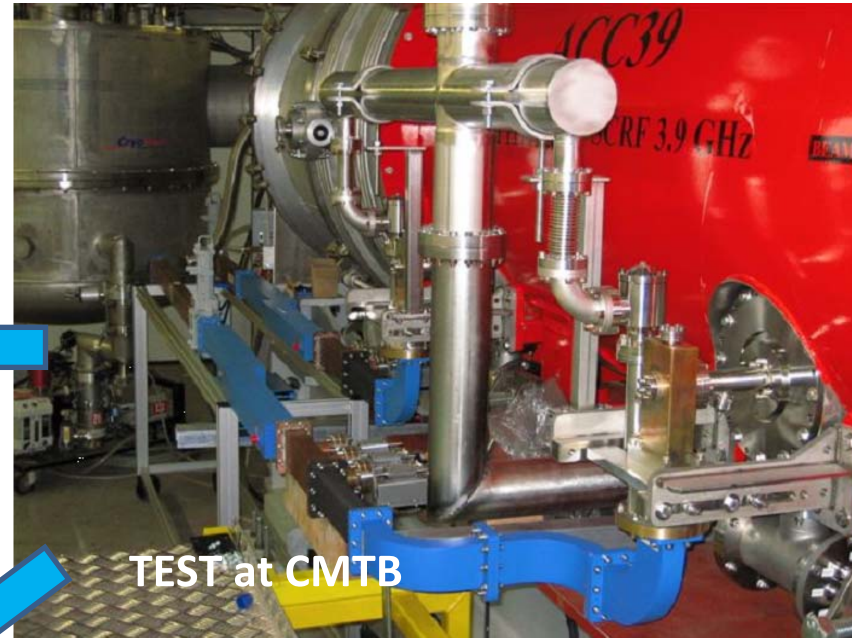
- Instrumentation cabling routed, terminated, and checked for functionality
- Final quality assurance checks including
  - vacuum leak checking
  - test fit of warm part input couplers

- All external joints verified leak tight
- Vacuum vessel was slightly pressurized to 50 mbar with dry nitrogen just prior to shipment
- Review of the Operation Readiness


Fermilab

ACC39 at DESY





RF control stability achieved at CMTB in November 2009

ACC39	required	measured
$\frac{\Delta A}{A} =$	$1 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
$\Delta\phi =$	$0.03°$	$0.003°$

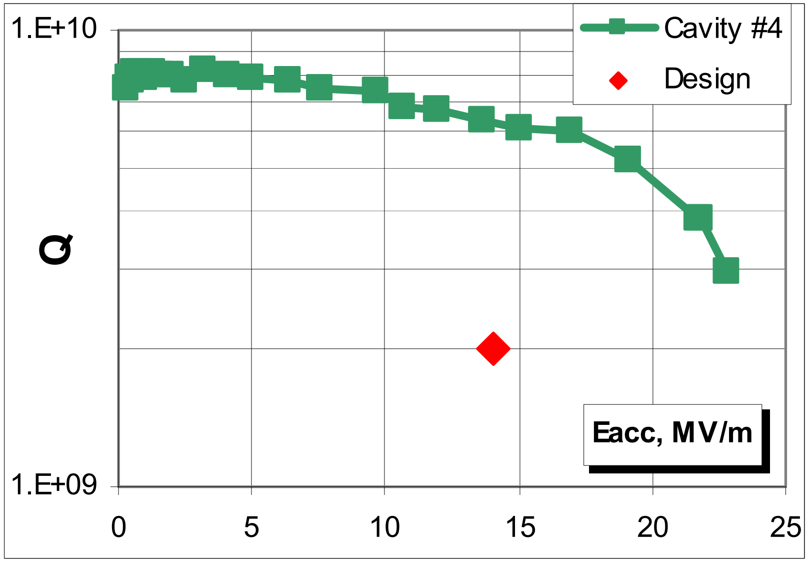
See FLASH Seminar Talk 'Status of 3.9 GHz LLRF' from Markus Hoffmann given at January 12th 2010

Summary

- Fermilab has now successfully completed construction of a Superconducting RF module containing four 3.9 GHz cavities each of which have achieved a gradient in excess of 22 MV/m and met all other design criteria.
- The module was transported to DESY and is installed on FLASH
- This effort has proven to be far more than merely a scaled version of a 1.3 GHz TESLA module.
- With this work largely complete, Fermilab has gained valuable experience in designing, fabricating, and assembling SRF devices as well as building up the necessary expertise and infrastructure.
- A collaborative effort especially with colleagues from DESY, Jefferson Lab, Cornell, Argonne, INFN - Milano.

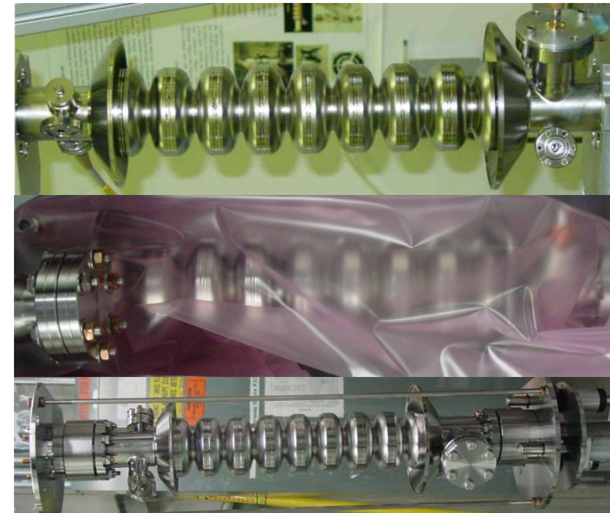
Acknowledgements

- Many thanks to all members of the Third Harmonic Collaboration
  - DESY, Argonne, JLab, INFN



3.9 GHz 3[rd] harmonic cavity #4 reached 23 MV/m, limited by quench in the cavity. No x-rays, no multipactor was observed.

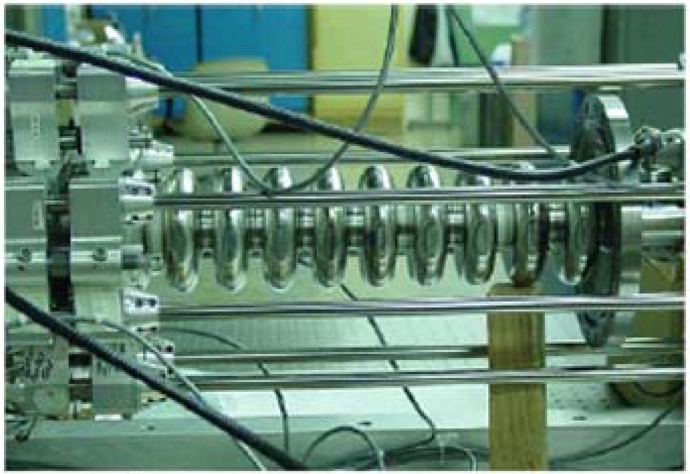
This cavity with HOM antennas installed reached 12 MV/m in CW, limited by quench in the HOM antenna.



Deflecting cavity activity at Fermilab

- CKM, 3.9 GHz
    - deflecting copper cavity at A0
- ILC (3.9 GHz)
- LHC (800 MHz)
- Project X (406.25 MHz)

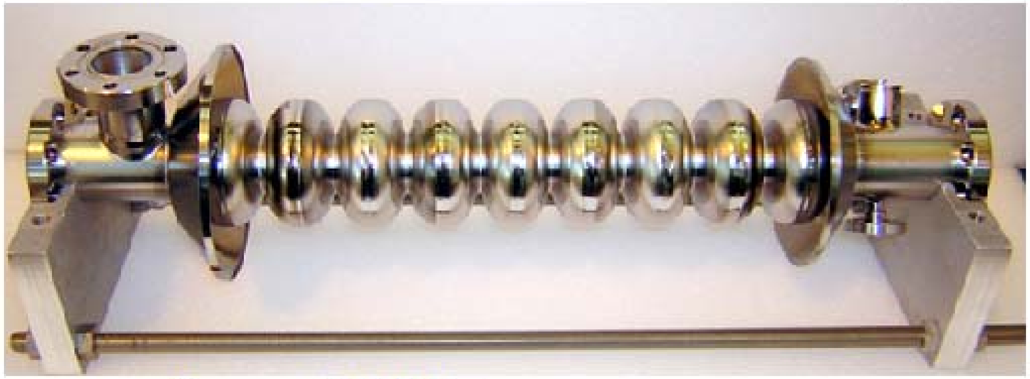
Two 3.9GHz Designs



TM$_{110}$ mode *"CKM"*

K^+ RF separator for $K^+ \rightarrow \pi\nu\bar{\nu}$
Bunch profile measurement at zero crossing

B_{MAX} = 80mT E_{MAX} = 18.6MV/m
L_{eff}=0.5m, $P_{\perp}$=5 MV/m



E_{ACC} = 14MV/m
B_{MAX} = 68 mT E_{MAX} = 31.6MV/m
L_{eff} =0.346m

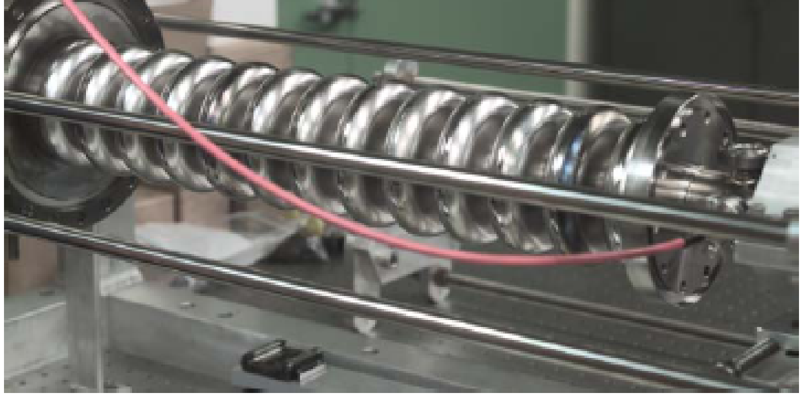
TM$_{010}$ mode
"3[rd] Harmonic"

Linearize energy distribution within bunch before compression for better emittance

Cavities Produced

Eight TM_{110} mode cavities have been made, mostly shorter (3 and 5 cells) structures, but there is one full 13 cell prototype.

One more short structure is in production, and one more 13 cell is planned

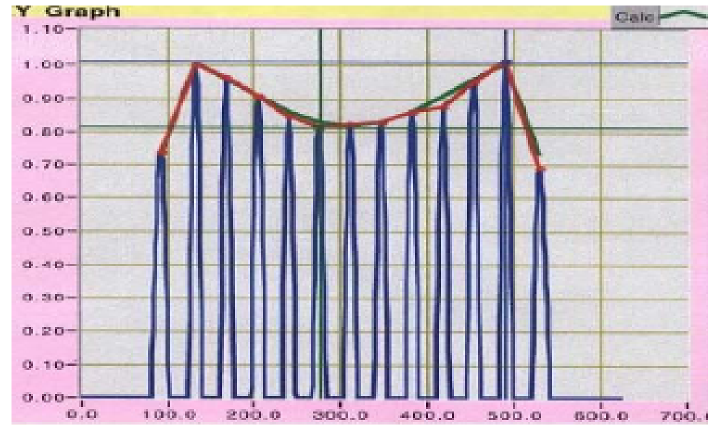


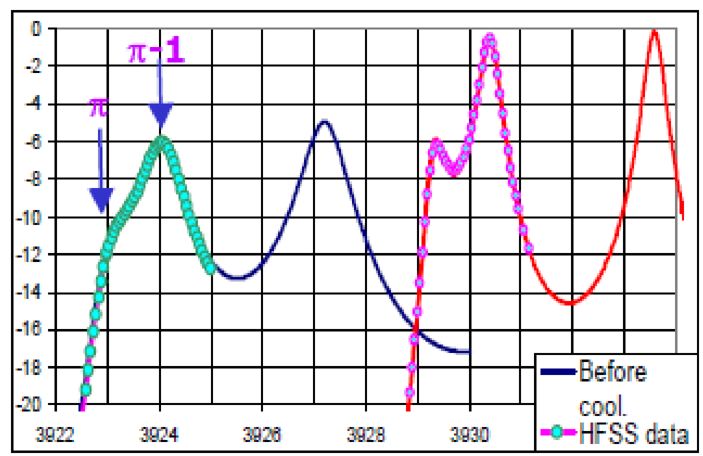
In addition to the two copper TM_{010} mode cavities shown earlier, a 3 cell has been made in niobium and a full 9 cell prototype is in production now

RF Design

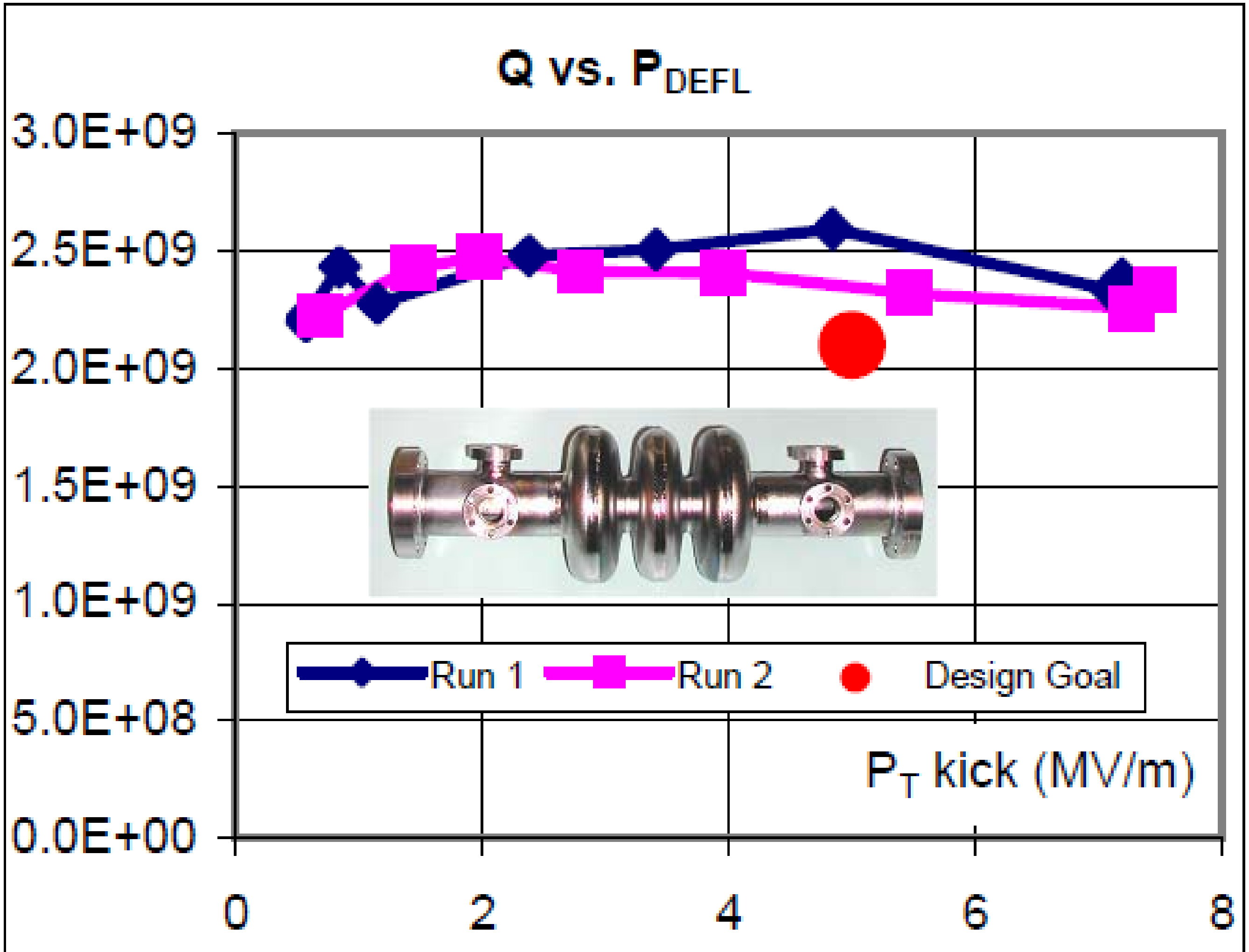
Tuning cavities with overlapping modes

- **First prototype TM_{110} half-cells had large freq scatter**
- **First cavity had π mode and (π-1) modes totally degenerate**
- **Designed mode separation was very close anyway**
- **HFSS predicts "M" type bead pull result for 300K; linear combo of MAFIA eigensolutions similar**
- **At 70K, HFSS gave correct S_{21} vs. f plot, and bead pull result was flatter. Plan to try bead pull at LHe temps.**





3-cell CKM cavity test



Q-value vs. kick gradient in CKM cavity.

ILC Crab Cavity Collaboration

- **Cockcroft Institute :**
  - Richard Carter (Lancaster University)
  - Amos Dexter (Lancaster University)
  - Graeme Burt (Lancaster University)
  - Imran Tahir (Lancaster University)
  - Philippe Goudket (ASTeC)
  - Peter McIntosh (ASTeC)
  - Alex Kalinin (ASTeC)
  - Carl Beard (ASTeC)
  - Lili Ma (ASTeC)
  - Roger Jones (Manchester University)
- **FNAL**
  - Leo Bellantoni
  - Mike Church
  - Tim Koeth
  - Timergali Khabiboulline
  - Nikolay Solyak
- **SLAC**
  - Chris Adolphson
  - Kwok Ko
  - Zenghai Li
  - Cho Ng

Cockcroft Institute

Technology Choice

CKM Cavity design parameters

3.9 GHz

13 cells length = 0.5 m

B_{max} = 80 mT

E_{max} = 18.6 MV/m

L_{eff} = 0.5 m

$P_{\perp}$ = 5 M V/m

Courtesy: FNAL

Our recommendation to the GDE has been to develop a cavity based on a Fermi-lab design.

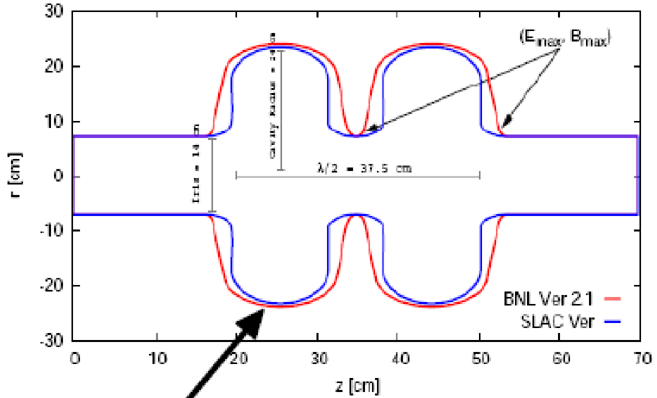
To minimise wakefields for the short time structure of the ILC bunches, the number of cells must be optimised against overall length and new couplers designed.

A 3.9 GHz cavity was favoured it is compact longitudinally and transversely.

Few LHC Crab cavity designs (R&D)

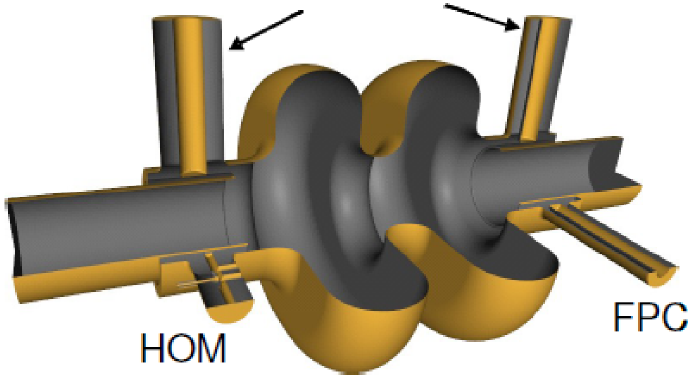
PROTOTYPE CAVITY/COUPLERS

Frequency = 800 MHz

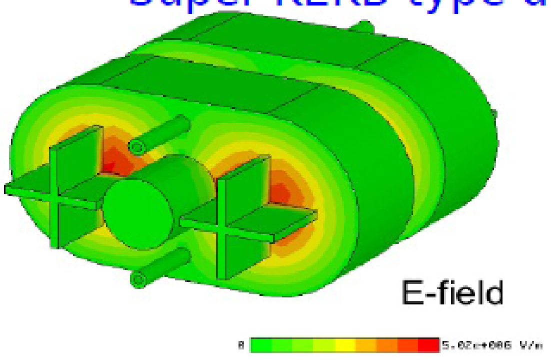


Note the cavity radius ~ 23 cm

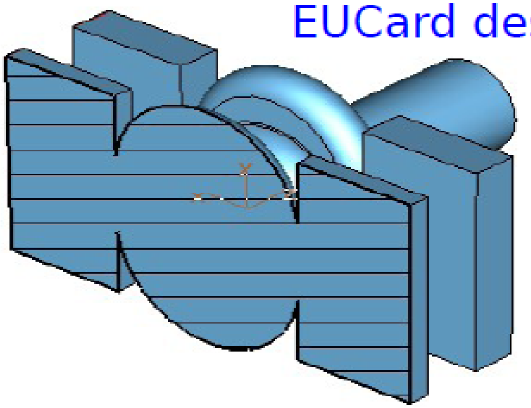
LARP design



Super-KEKB type design



EUCard design

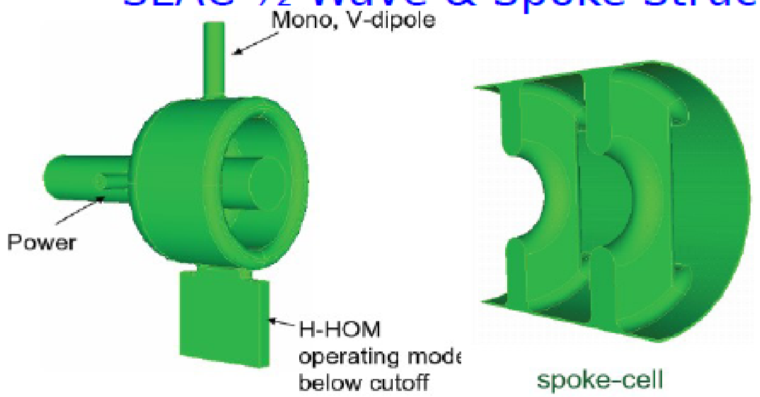


Proposals for compact design (exotic)

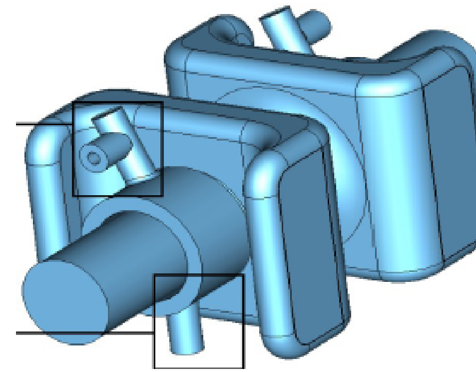
Compact Structure, Phase II

Frequency = 800 MHz

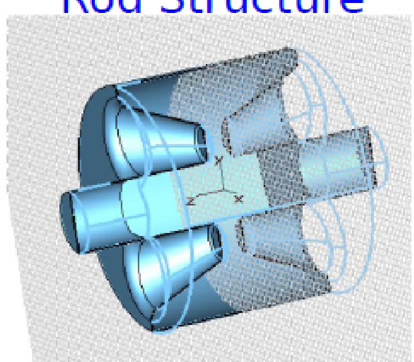
SLAC ½ Wave & Spoke Structures



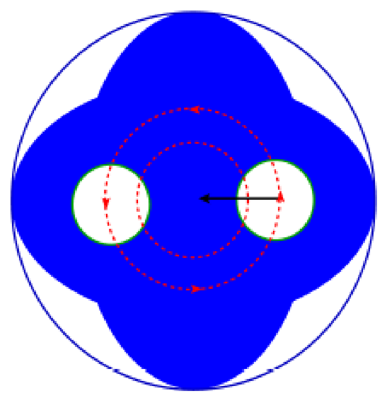
FNAL Mushroom Cavity



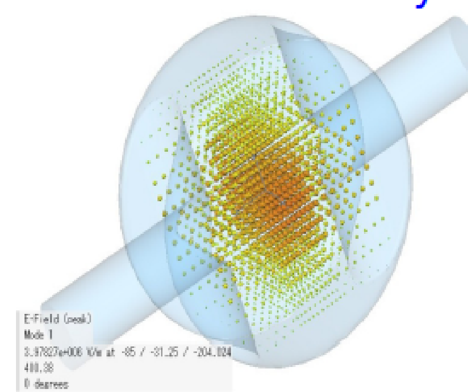
EUCard,UK-JLAb Rod Structure



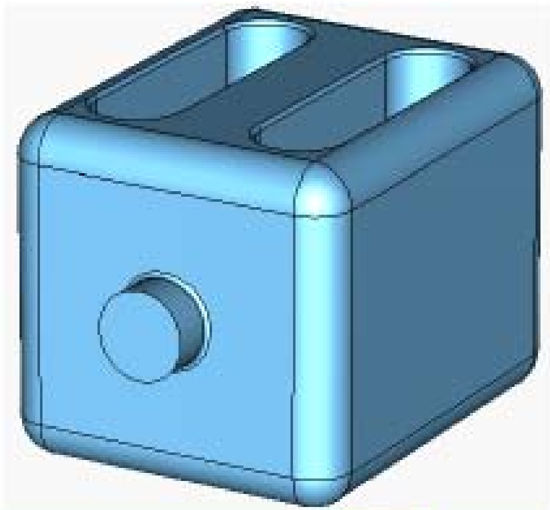
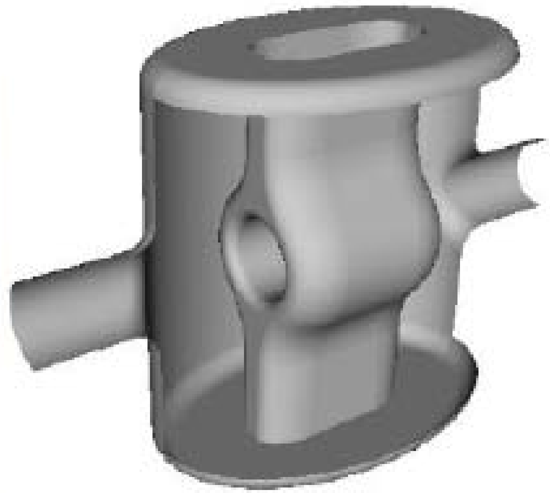
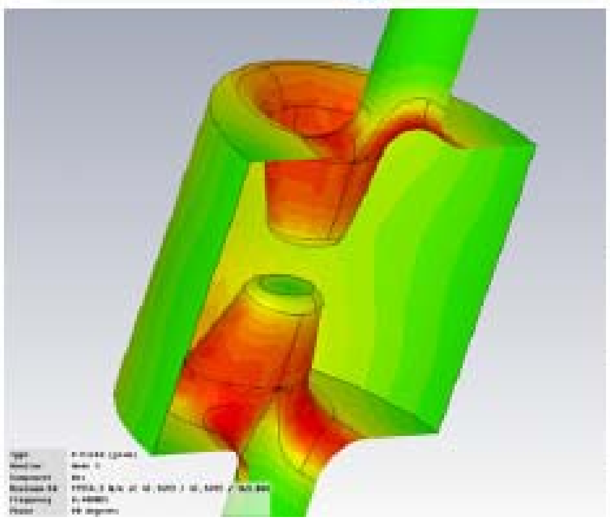
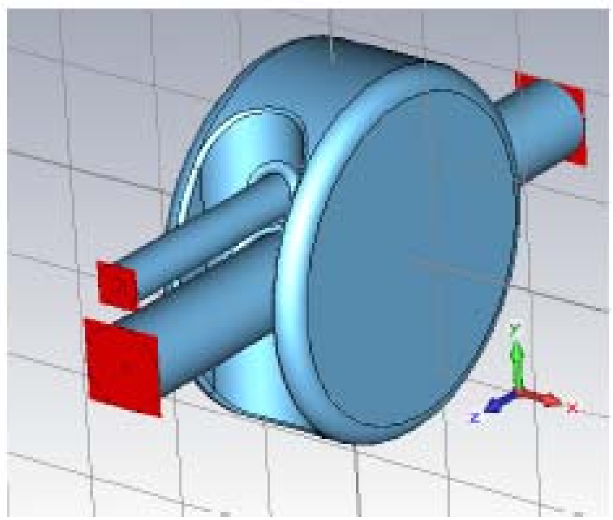
BNL TM010, BP Offset



KEK Kota Cavity



Even more designs

Frequency = 800 MHz

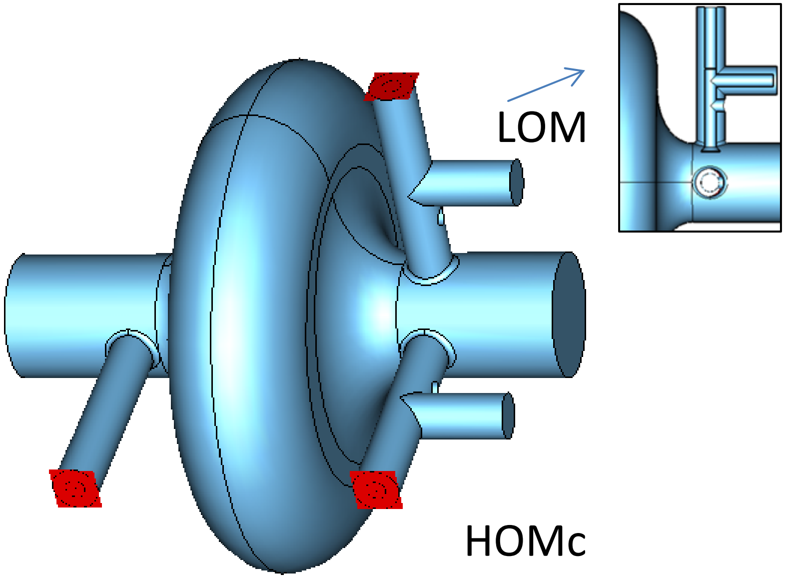
Top left: Half wave double rod cavity.

Top right: Half wave single rod cavity.

Bottom left: Double rod loaded cavity.

Bottom right: Rotated pill-box Kota cavity

Design of Project X SC deflecting cavity



MC

Features:

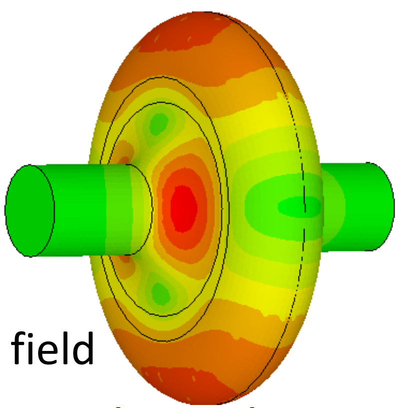
Simple single-cell cavity with elliptical transverse cross-section

Parameters of operating mode

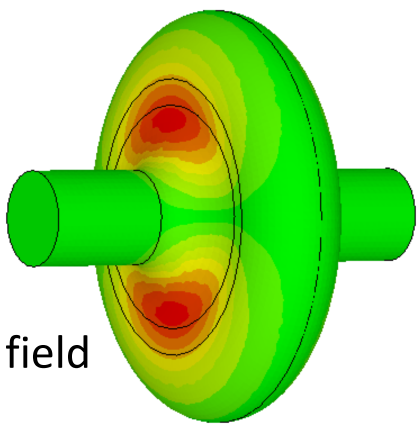
Frequency, [MHz]	406.25
V_{kick} , (MeV)	3.75
E_{sp}/V_{kick} , [(MV/m)/MeV]	7.8
B_{sp}/V_{kick} , [mT/MeV]	19.2**
R/Q* [Ohm]	27
Longitudinal size [mm]	440
Vert/Horiz. size (mm)	865/962

High order modes

MONOPOLE		DIPOLE1		DIPOLE2	
F,MHz	R/Q,Ω	F,MHz	R/Q,Ω	F,MHz	R/Q,Ω
289.2	118	406.25	27.3	427.9	25.2
557.1	1.5	529.1	6.2	528.3	6.1
635.7	6	691.4	0.16	695.7	0.04
692.6	0.001	726.7	0.03	743.6	0.14
730.1	16	759.5	2.8	759.4	2.5
825.2	0.002	797.6	0.08	797.8	0.12



H field



E field

R/Q=$V_{kick}^2/(2\omega W)$

****compared to 41.5 mT/MeV for KEKB CC**

Multipacting analysis

To start multipactoring investigations, we need:

- Realistic cavity design taking into account beam physics requirements and environmental constrains;
- Realistic coupler design.

Example:

CST Particle Studio defined 3 areas with MP activity in KEK Crab cavity (positive growth rate)

1 in long part of racetrack; 2 in coaxial line; 3 In place of connection of coaxial to the cavity wall