Crab Cavities Collaboration Report

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LBNL

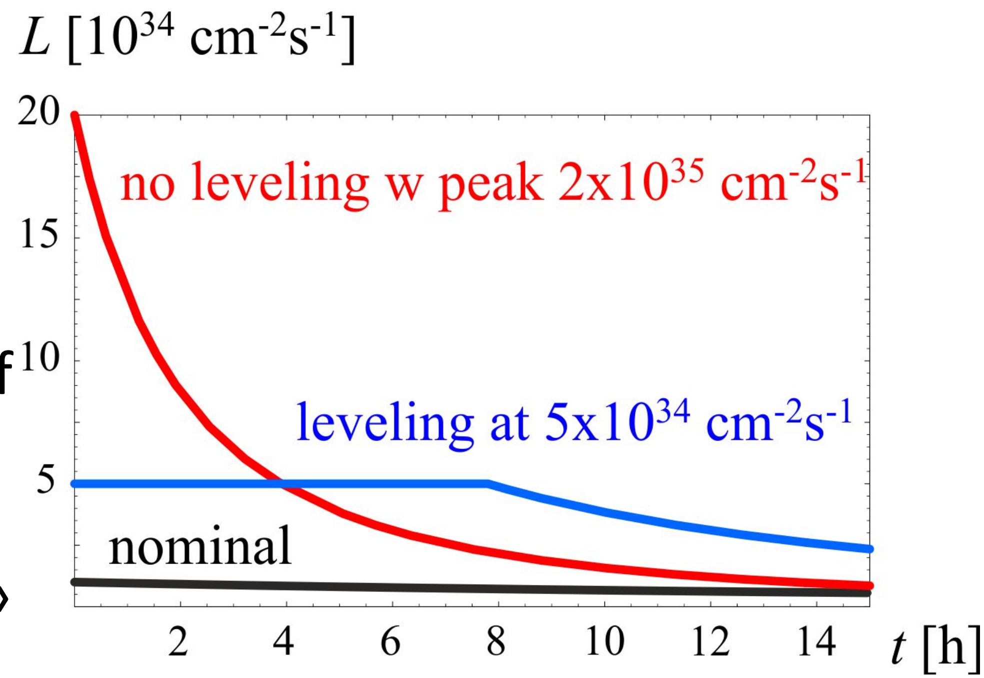
Why crabs?

- Luminosity leveling represents a substantial upgrade of integrated luminosity
  - Increasing effectiveness with larger crossing angles
  - Only known way to improve luminosity during the store
- Significant R&D on cavity technology for several years
  - Encouraging results are making this possible
  - Three designs under study in Europe and the US

Note: The WP4 session this afternoon will cover many more details on cavity design, and expand to cover beam dynamics and machine protection

Luminosity Levelling

- Lumi decreases for proton burning (neglecting effects like emittance growth due to b-b, IBS, etc…)
- Total number of collisions ***∫Ldt*** in a run is limited by number of stored protons
- ⇒ store a lot of protons but keep instantaneous lumi «low» by detuning one (or more) parameter.
- ⇒keep the lumi constant by re-tuning the paramter(s) to compensate proton loss (and possibly any other effect).



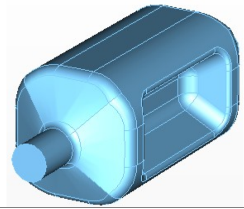
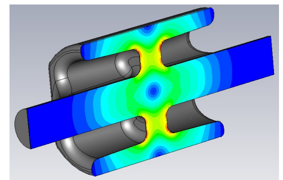
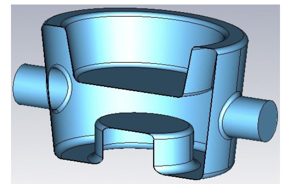
System Requirements

- Voltage = 10 MV (~ 3MV/cavity)
  - SPS test 2 cavities/module
  - LHC 3 cavities/module
- Frequency = 400 MHz
- $Q_{ext} = 10^6$, R/Q ~300 W
- Cavity tuning/detuning ~ ± 1.5kHz (or multiples of it)
- RF power source = 60 kW (< 18 kW nominal)
- Beam current ~ 0.5-1 A

LARP

High Luminosity LHC

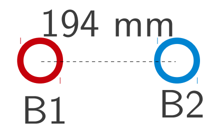
Cavity Design Overview

Geometrical

RF

	Double Ridge (ODU-SLAC)	4-Rod (UK)	¼ Wave (BNL)
Cavity Radius [mm]	**147.5**	**143/118**	**142.5/122**
Cavity length [mm]	597	500	330-405
Beam Pipe [mm]	84	84	84
Peak E-Field [MV/m]	33	32	43
Peak B-Field [mT]	56	60.5	61
R_T/Q [Ω]	287	915	345
Nearest Mode [MHz]	584	371-378	657



< 50 MV/m

< 80 mT

Present Status

- 4Rod Cavity
  - Build by Niowave
  - At CERN/SM18 for vertical test

EuCARD + CERN

- Double Ridge – RF Dipole
  - Built by Niowave + at JLAB awaiting tests

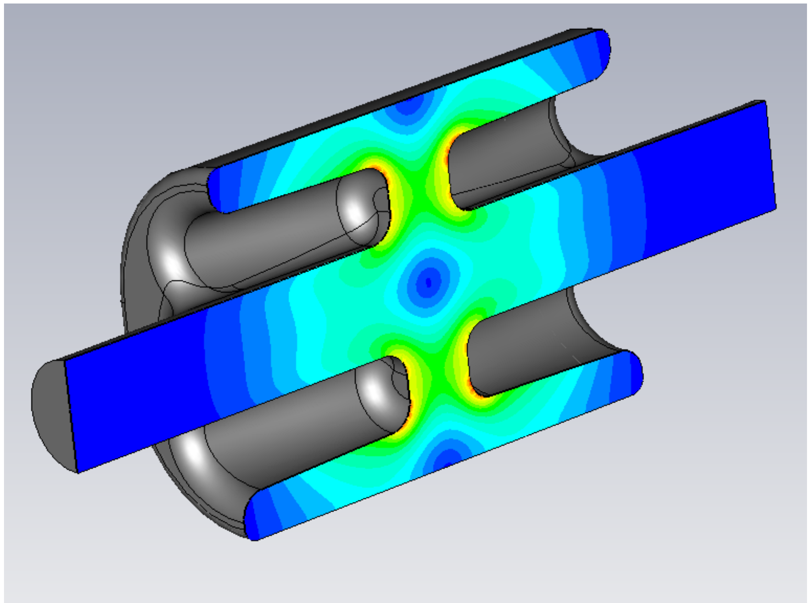
LARP + SBIR

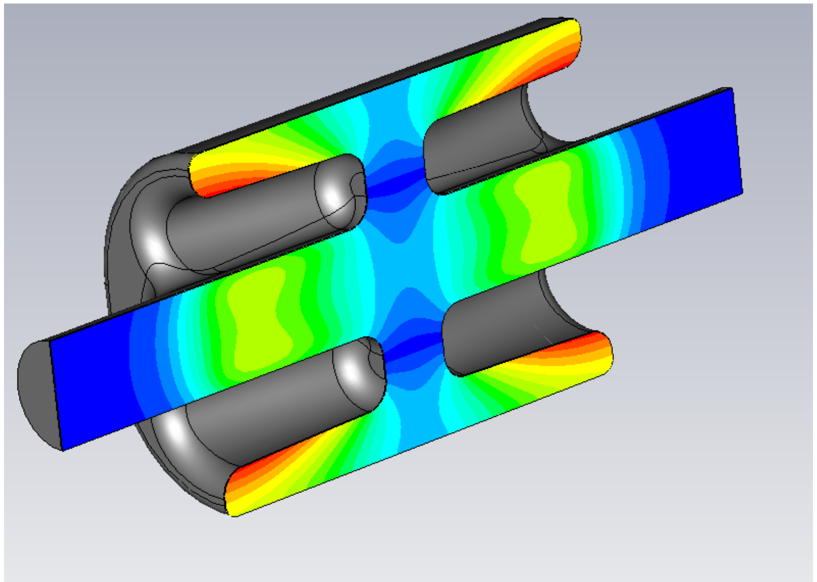
- Quarter Wave
  - Due from Niowave by Dec. 2102

4 Rod - Cavity Shape

Cavity fitted LHC scenario (84 mm aperture compact transverse size) and has tolerable fields at the design gradient.

Removal of voltage variation.

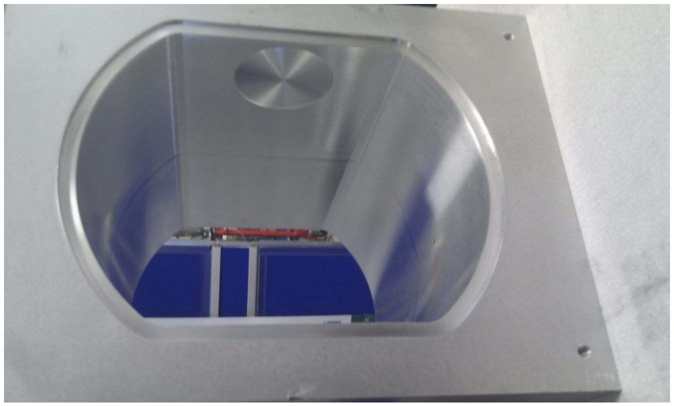


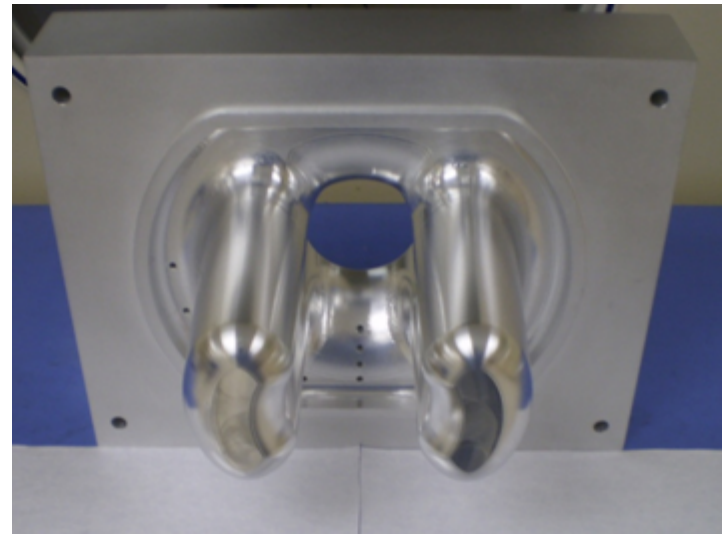


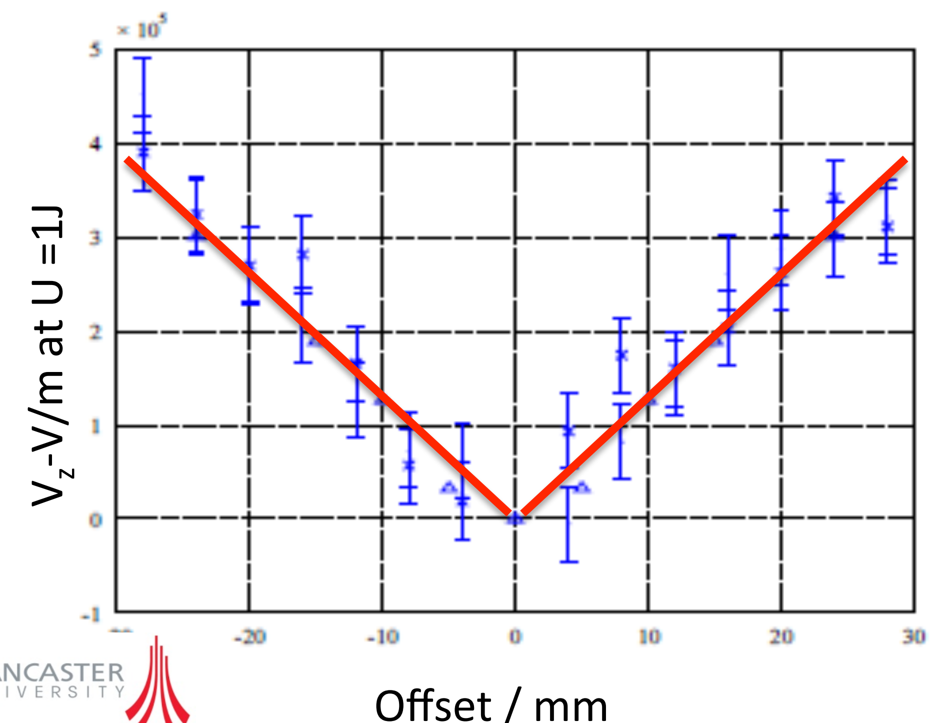
Emax @3MV	32.0 MV/m
Bmax @3MV	60.5 mT
Transverse R/Q	915 Ohms

$R_T/Q=(V(a)^2/wU)*(c/\omega a)^2$

Field Measurements







- Measurements are fairly linear but have error bars of 8%.
- Error bars are due to a low signal to noise ratio and a drift in the Q during measurements.
- The measurements are now being retaken with a higher power and checking the Q for every measurement

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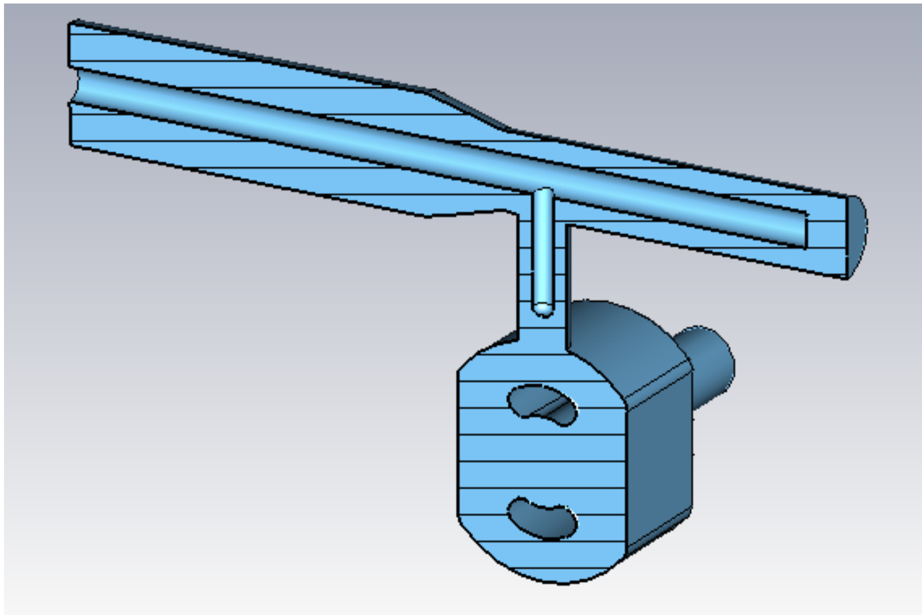
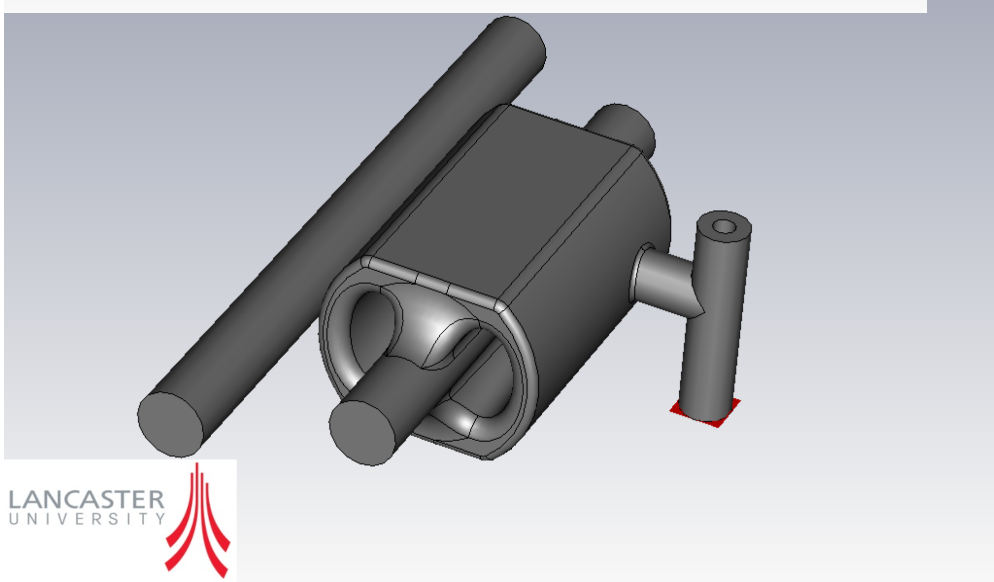
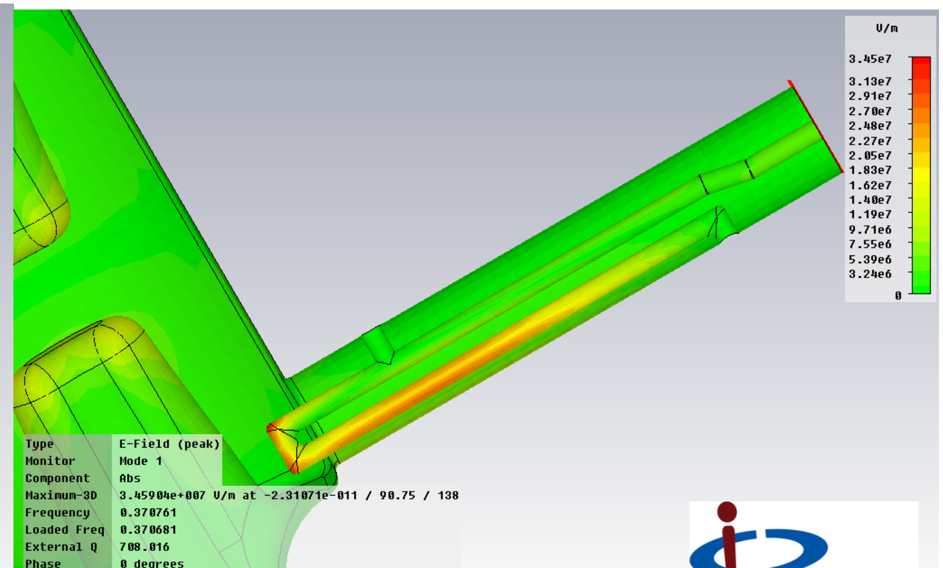
Input and LOM Couplers



- Couplers have been developed for the LHC crab.
- Input coupler interfaces with existing LHC coupler
- LOM coupler reaches a low Q (100) and must handle 6 kW.
- Couplers are attached to the cavity body and demountable to aid cleaning.





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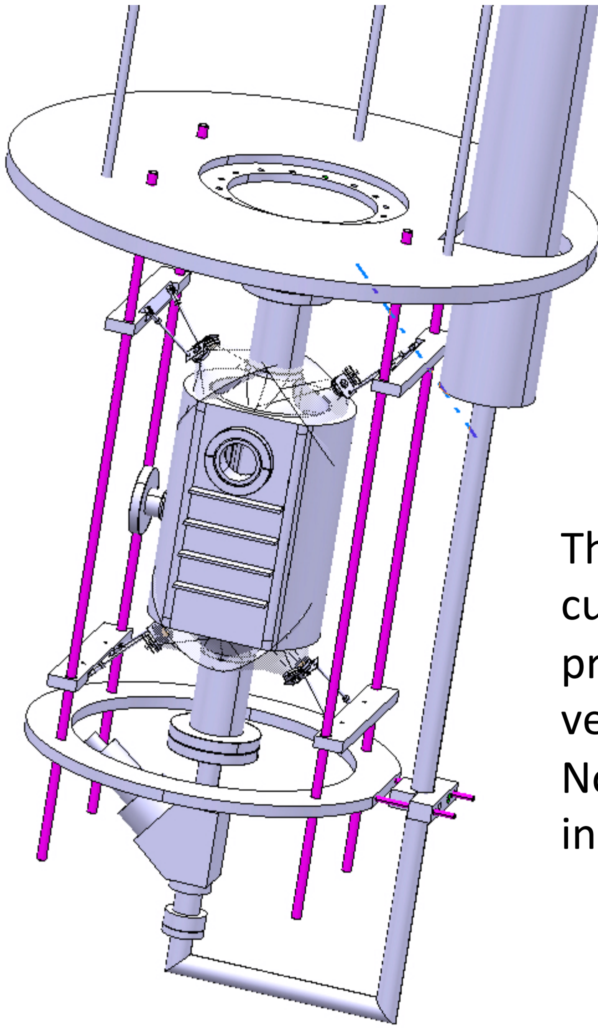
LARP

Tests at CERN SM18 – Ready

High Luminosity LHC



The cavity is currently being prepared for vertical testing mid-November at CERN in SM18.

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CERN

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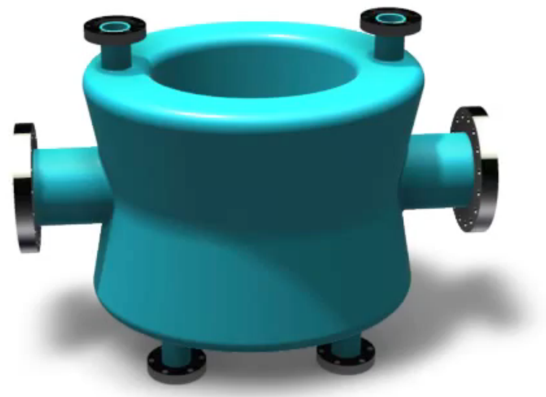
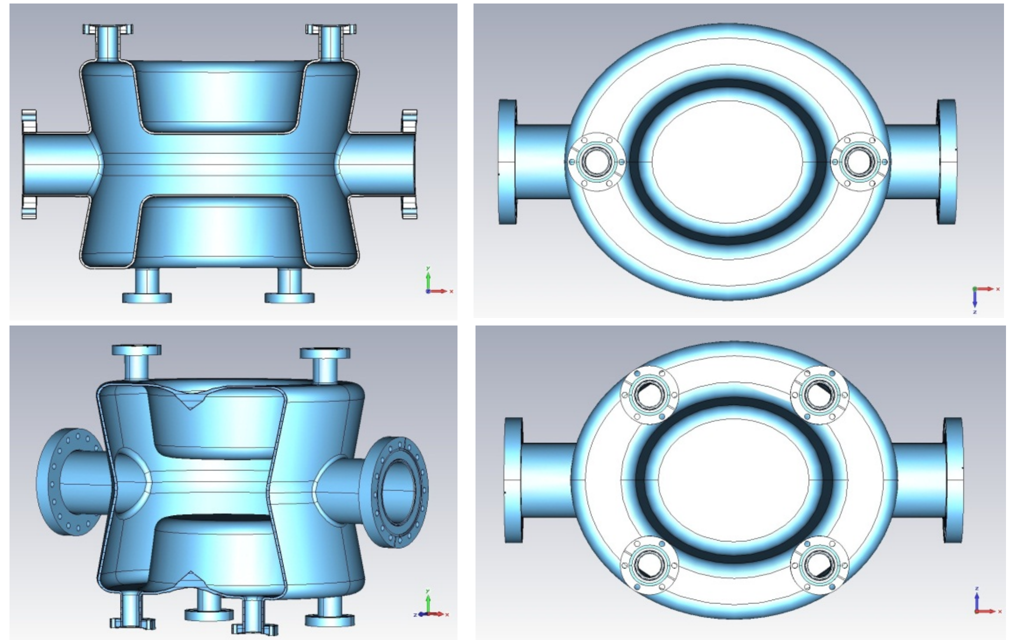
4 Rod Plans

- Initial vertical testing starting now at CERN
  - Cavity only has basic cleaning.
- The cavity will go through additional chemistry for further testing
- Need to reduce errors in the beadpull to verify field linearity to 2% level.
- LOM and HOM coupler will be further developed, including EM design, multipactor studies, thermal management and integration into the cryostat.
- Plan to improve the strength of the outer can
- Need to decide how to tune the cavity and start work on a tuner.
- Planning **a bid to STFC for SPS and LHC P4 tests** inc. cavity, cryomodule, LLRF, HPRF, diagnostics, beam dynamics and experiment.

Quarter Wave Cavity

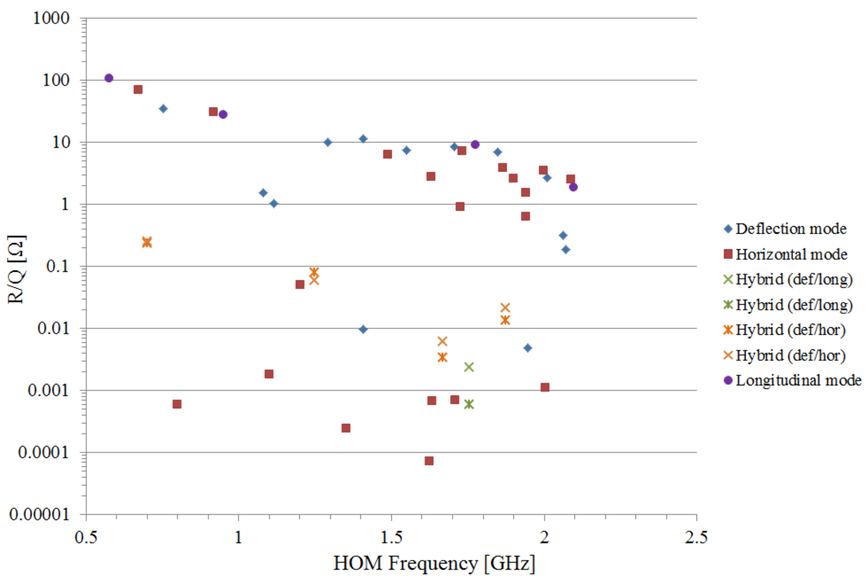


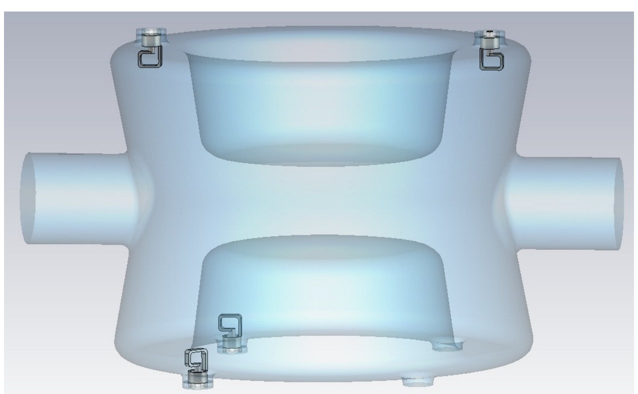


- Double quarter-wave resonator: Compact design at low frequencies; No Lower Order Modes and Same Order Modes, nearest Higher Order Mode is well separated from the fundamental mode ➔ easier damping than in other designs; Very little parasitic acceleration (1.6 kV).
- 6 RF ports: 4 for HOM damping, 1 for FPC, and 1 for pickup.
- The cavity is developed as part of LARP and satisfies very strict space constrains near the LHC IPs.

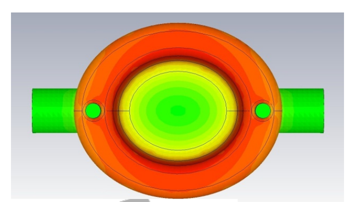
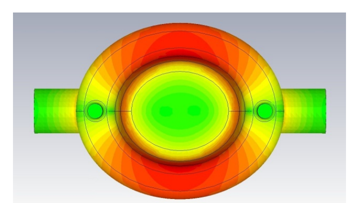
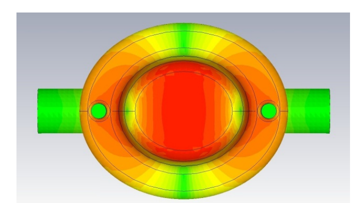
Crabbing (fund.) mode	1st HOM	Cavity length	Cavity width	Beam pipe diameter	Deflecting voltage
400 MHz	579 MHz	38.4 cm	14.2 cm	8.4 cm	3 MV

HOM damping





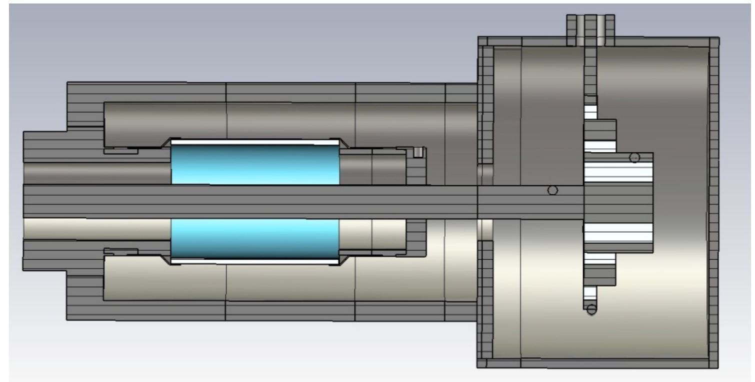
HOM frequency [GHz]	Mode Config.	R/Q [Ohm]	Qext
0.579	Longitudinal	108	1130
0.671	Horizontal	70.5	2340
0.700	Hybrid (y, z)	0.24/0.25	1140
0.752	Deflection	34.9	1750
0.800	Horizontal	6.02e-4	3160
0.917	Horizontal	30.9	2050
0.949	Longitudinal	28.1	3180
1.080	Deflection	1.54	1240
1.102	Horizontal	1.84e-3	1380
1.114	Deflection	1.06	1380
1.202	Horizontal	5.07e-2	7880
1.247	Hybrid (y, z)	8.0e-2/6.0e-2	1730
1.291	Deflection	10.0	926

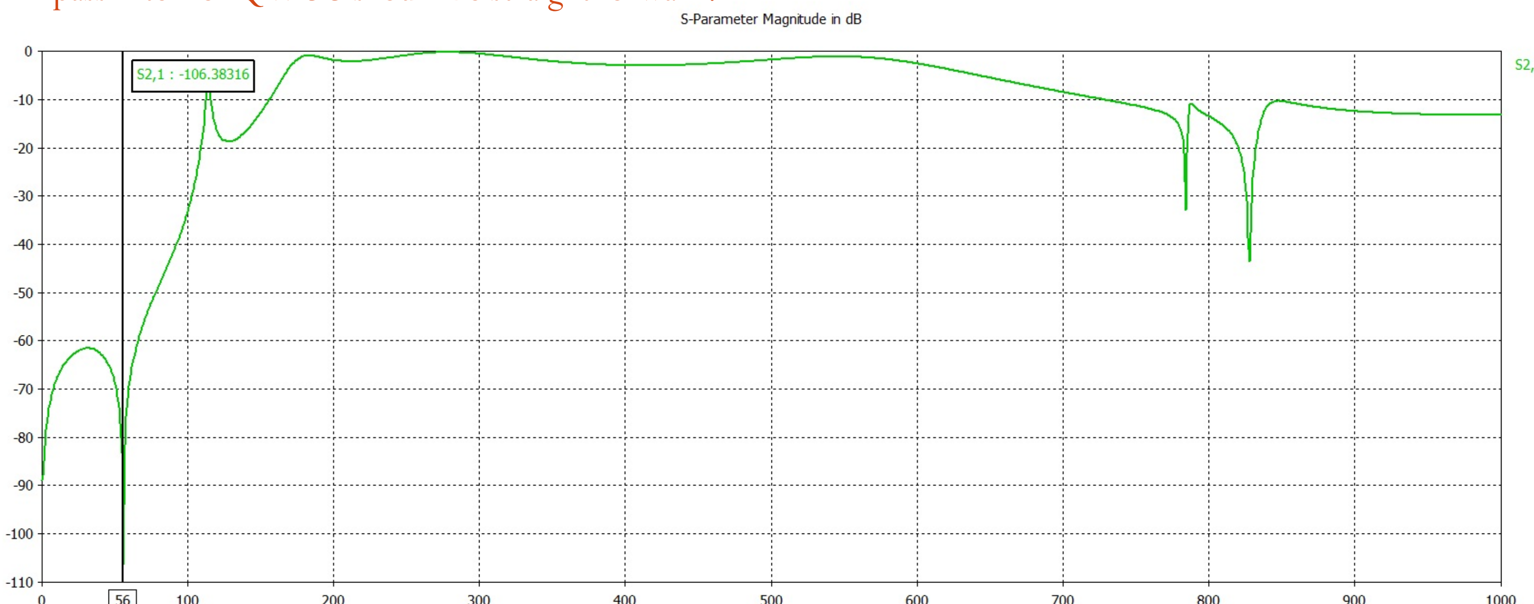




Coaxial Design

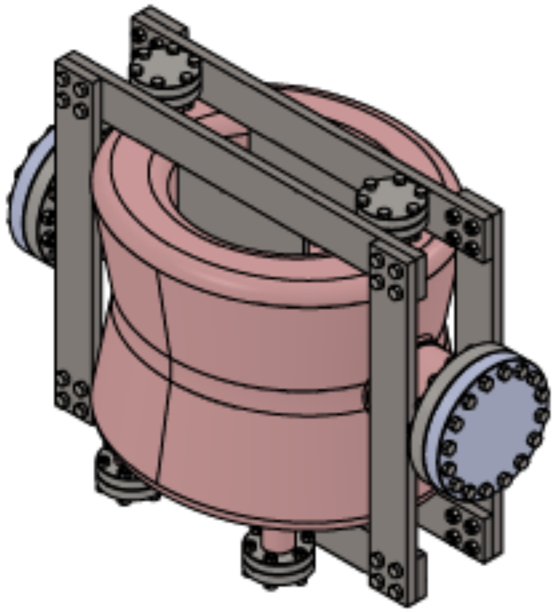
High-Pass Filter

- We have successfully designed high-pass filter for 56MHz QWR at BNL. The reflection for fundamental mode is below -100dB. This first HOM is 168MHz, and the reflection has decreased to -5dB.
- With such experience, high performance high-pass filter for QWCC should be straight forward.





Prototype Status



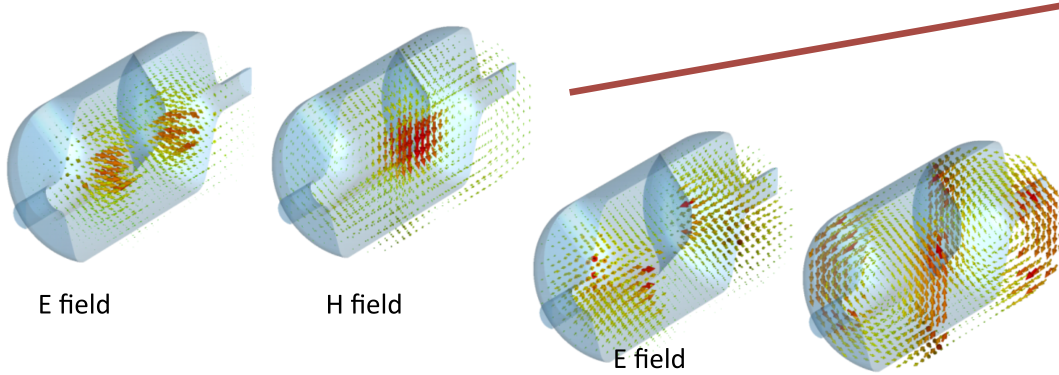
- Fabrication of a prototype cavity has started at Niowave.
- The cavity will be made of 4-mm thick Nb.
- There will be special stiffeners welded to the cavity as there is no helium vessel on the prototype.
- In the future a helium vessel will stiffen the cavity.
- VTF tests – early 2013.
- Design of HOM couplers, FPC, tuner is in progress.

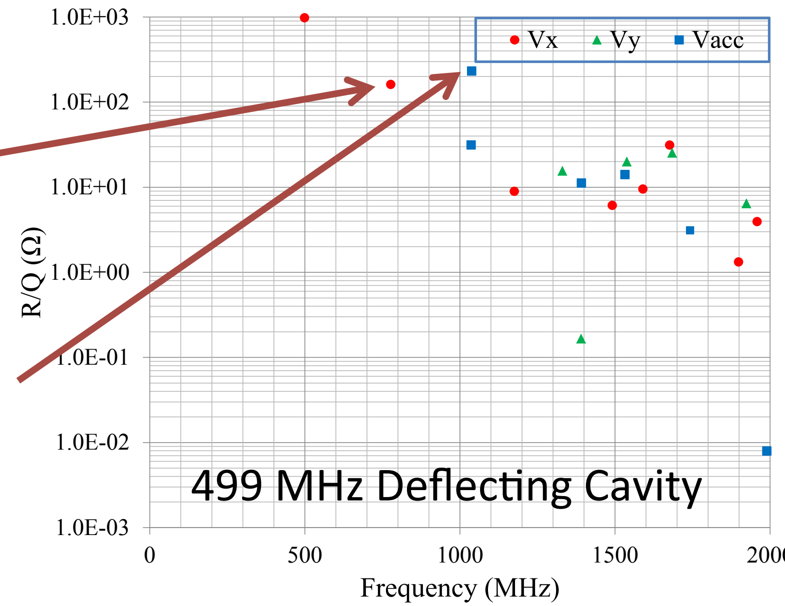
Quarter Wave Cavity Planning

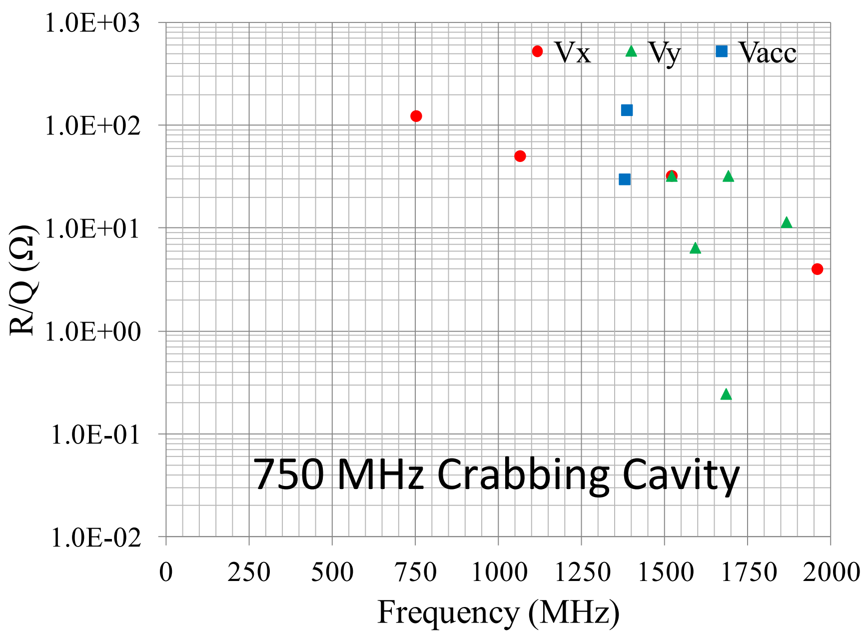
- Parts being fabricated
  - Cavity completion due in December 2012
- HOMs and tuners under study
- Mechanical and thermal analysis
- Start design of full system for SPS test

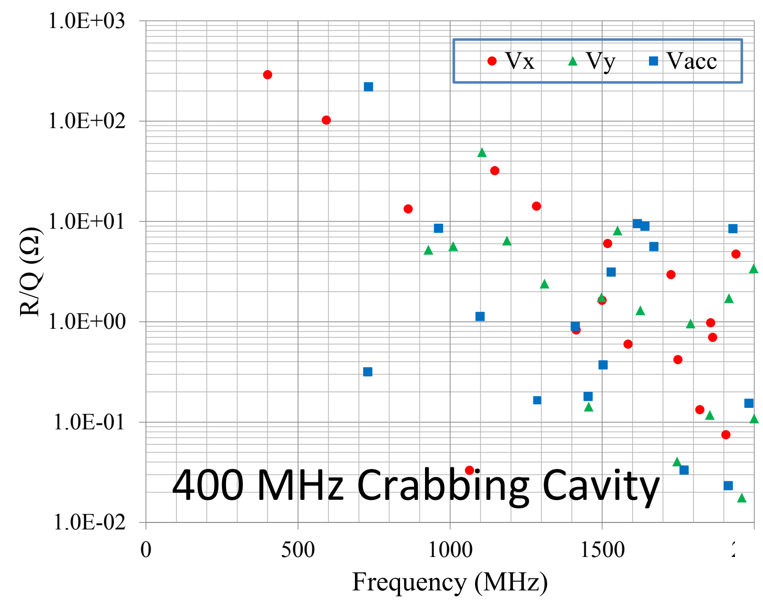
RF-Dipole - HOM Properties

- Widely separated Higher Order Modes
- No Lower Order Modes







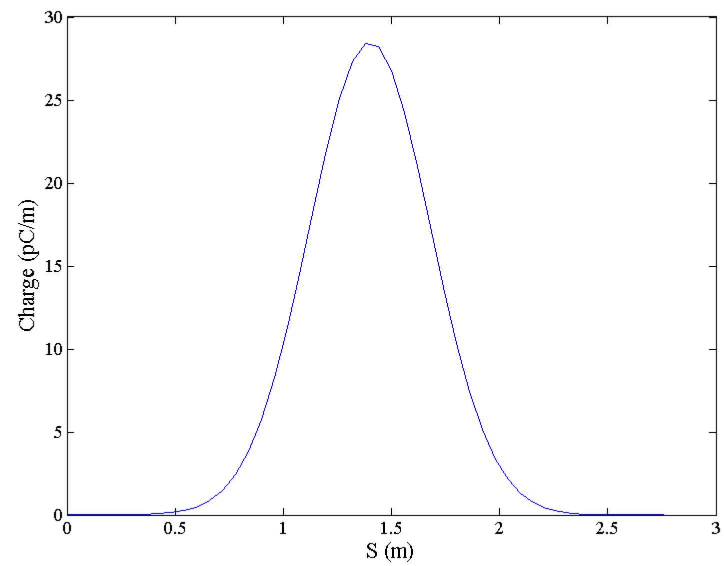


Wakefield and Impedance (400 MHz)

- T3P – EM Time Domain Solver in the SLAC ACE3P Suite

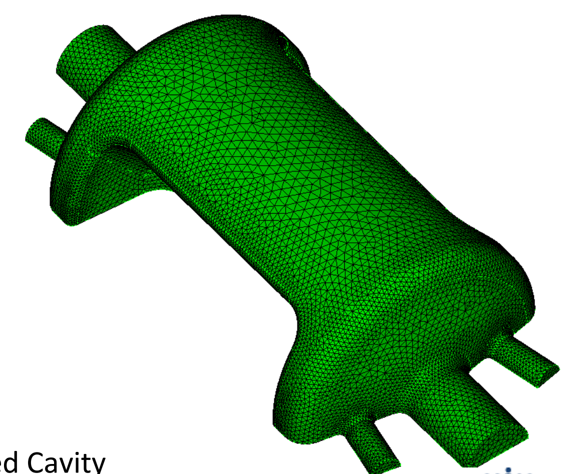
- Bunch Parameters
  - σ = 0.014 m
  - charge = 1 pC

$$\lambda(s) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{(s-s_0)^2}{2\sigma^2}]$$



- Wakefield Parameters
  - # of points = 50,000
  - Time stamp (dt) = 0.2 ns
  - Maximum wakefield distance (S) = 3000 m
  - RMS frequency for a 1.4 cm bunch ≈ 2.5 GHz

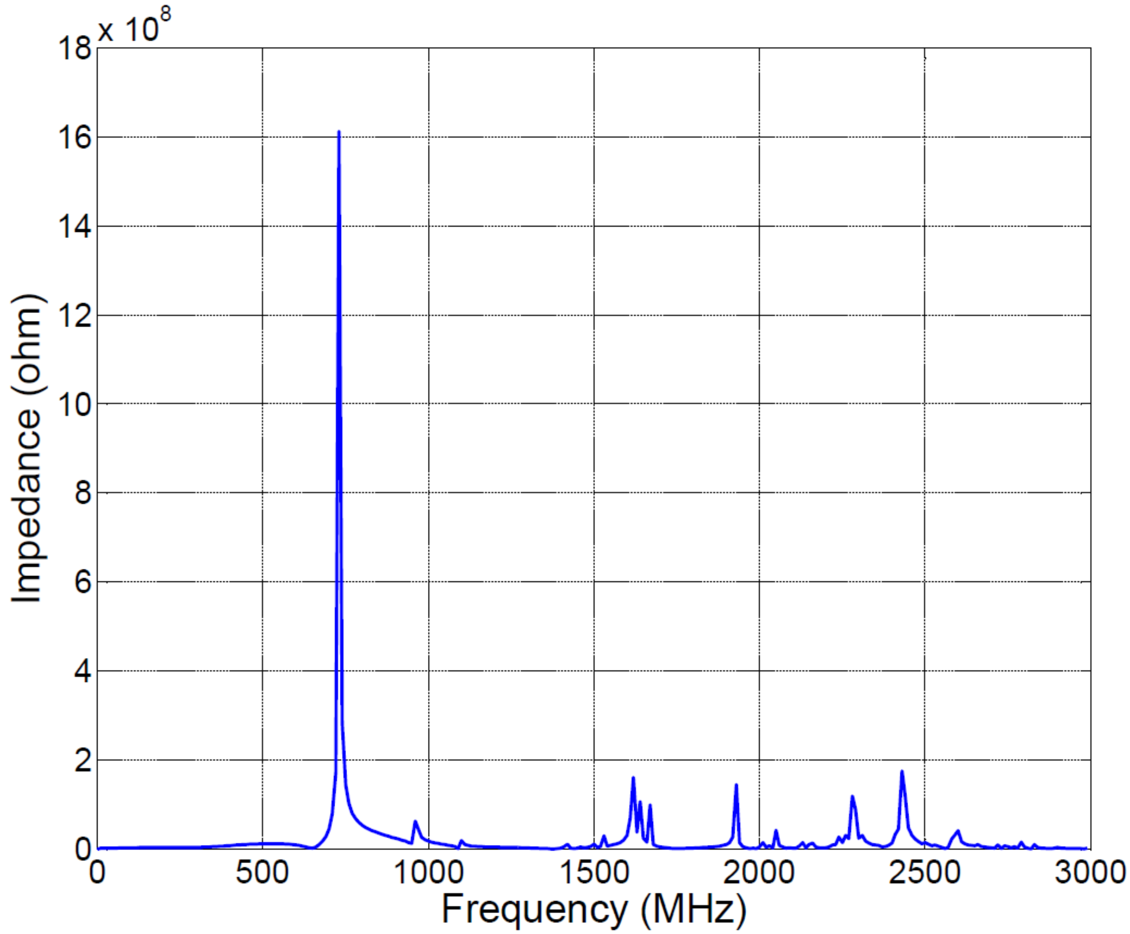
$$f_{RMS} = \frac{c}{\sqrt{2\pi}\sigma}$$

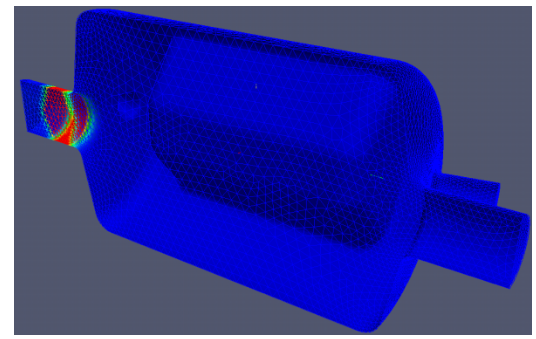


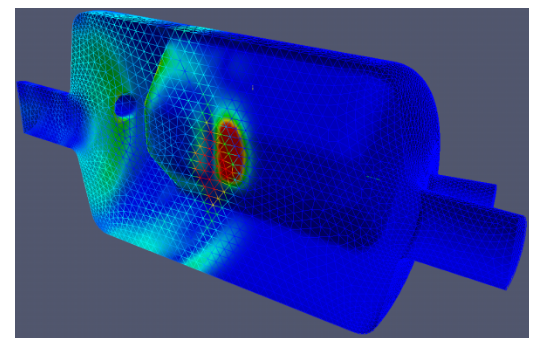
Meshed Cavity
No. of elements = 324560

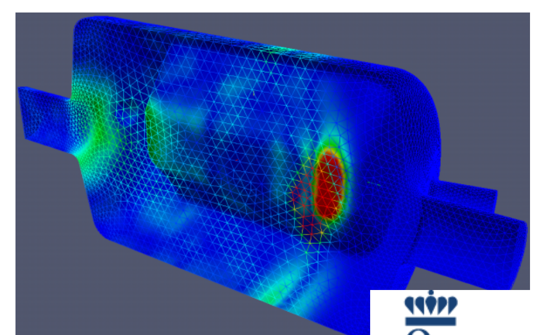
Jefferson Lab SLAC Old Dominion University

Single Bunch Wakefields (400 MHz)









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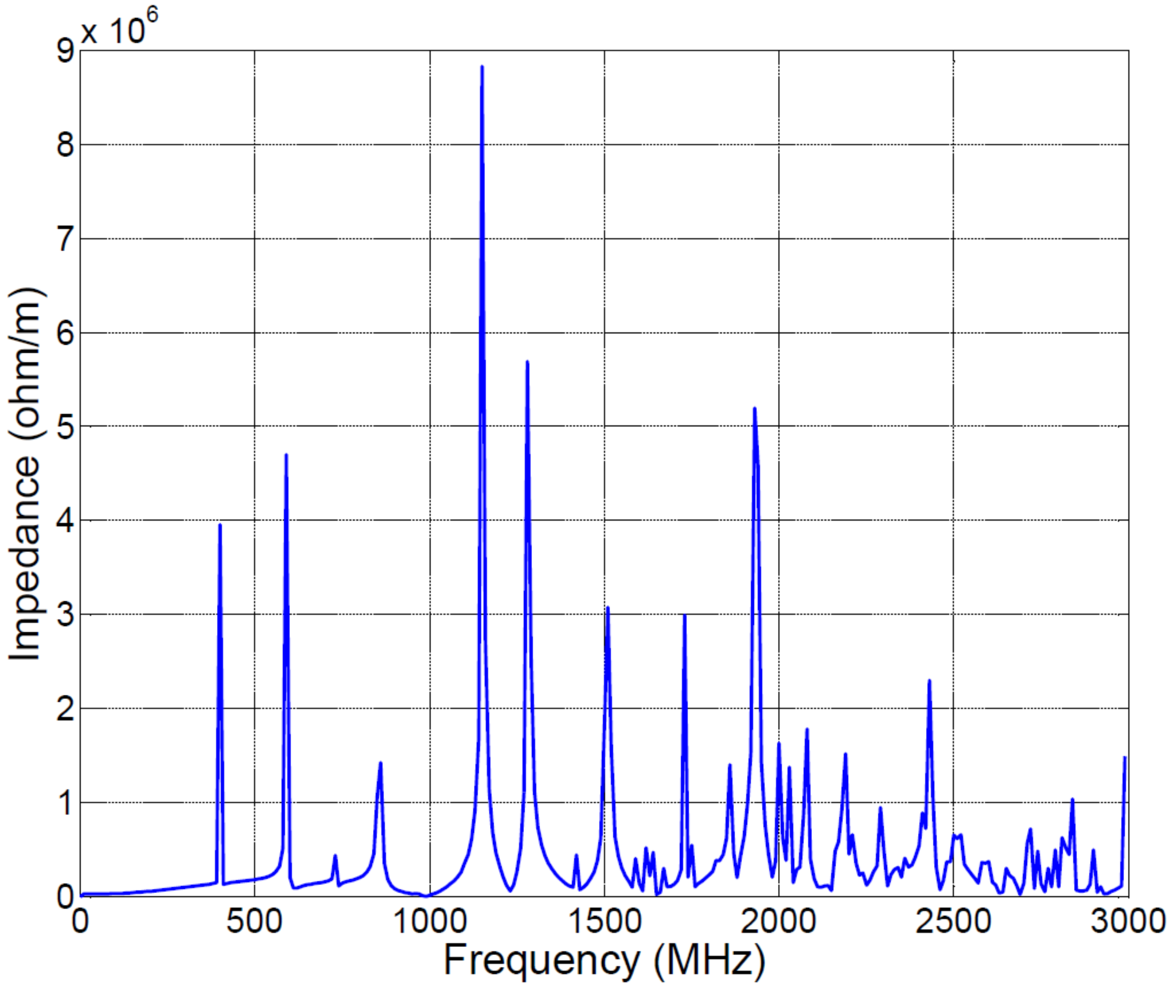
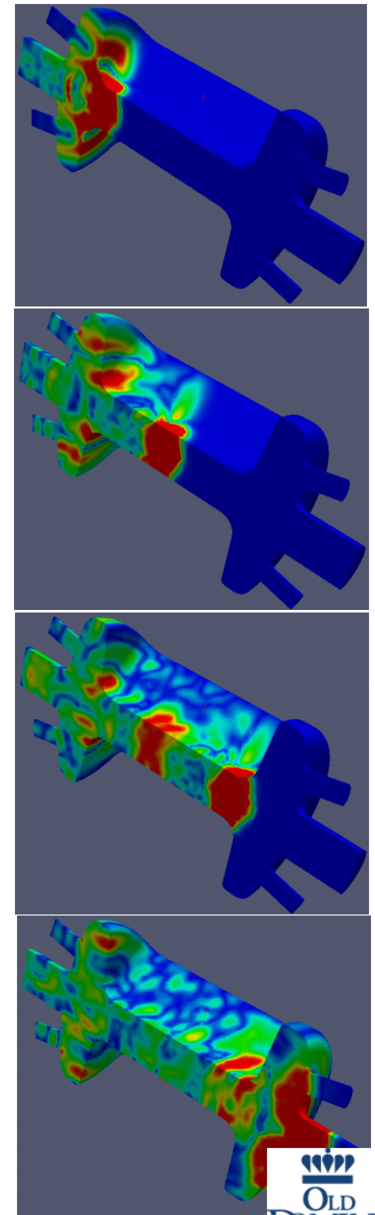
Two Bunch Wakefields (400 MHz)



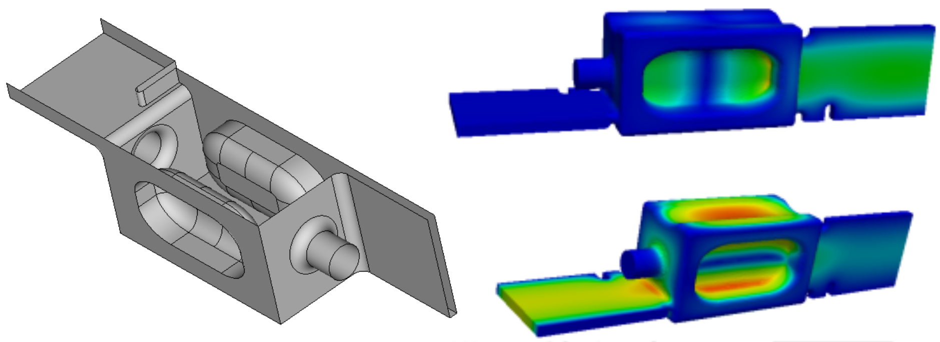


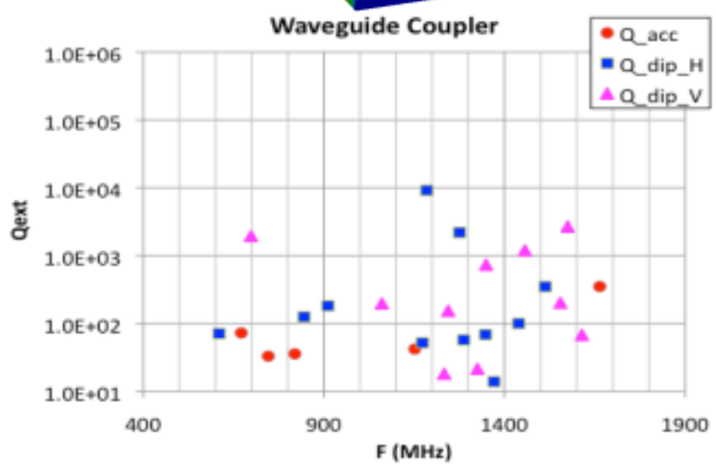
HOM Damping

- Widely separated HOMs from the operating mode allows more options in the design of damping schemes

Waveguide Damping

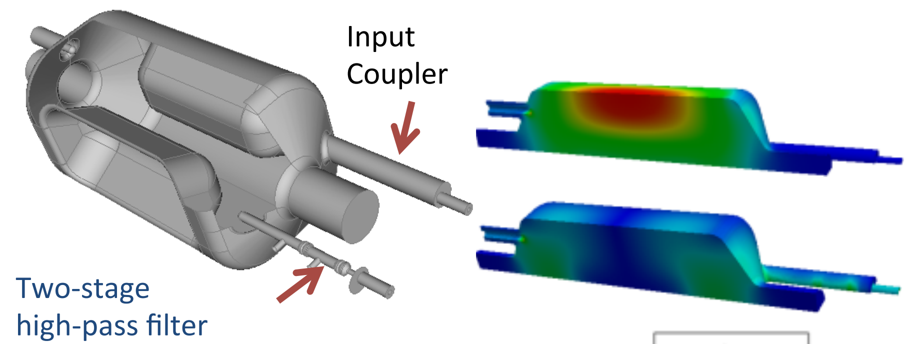
- Strong damping was achieved with waveguide couplers

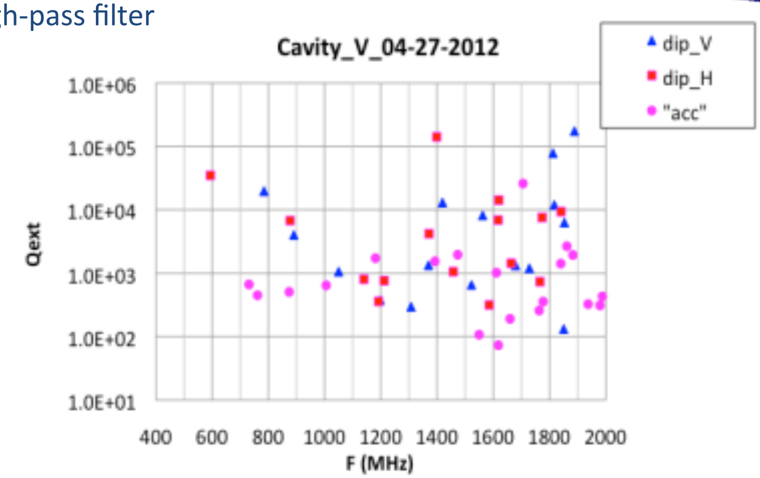




Coaxial Coupling

- A high pass coaxial couplers to exclude the operating mode





Jefferson Lab

Z. Li et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2185

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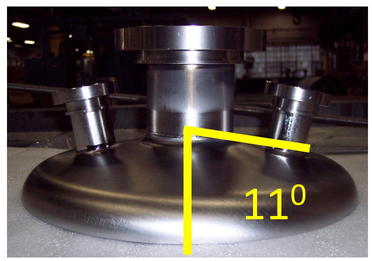
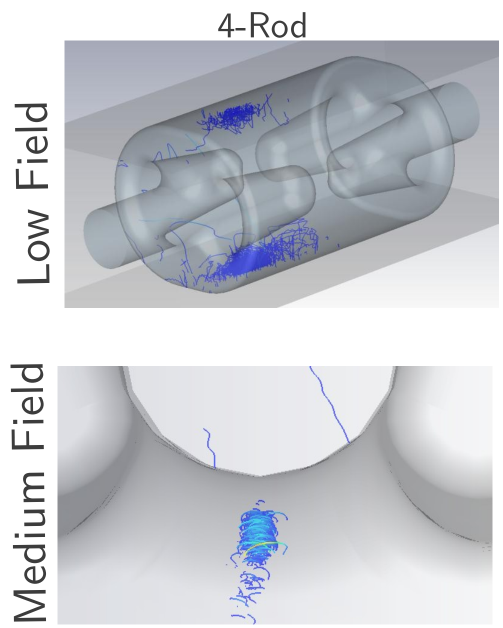
RF-Dipole Cavity Fabrication

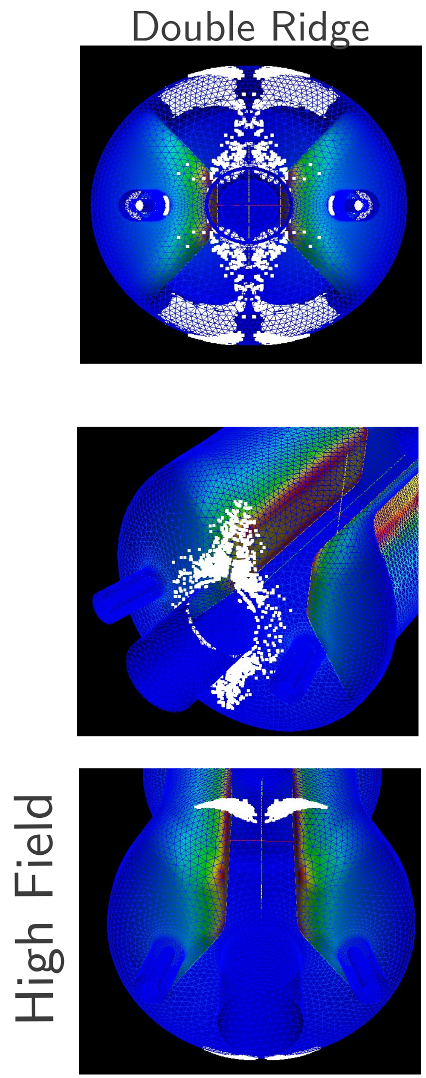


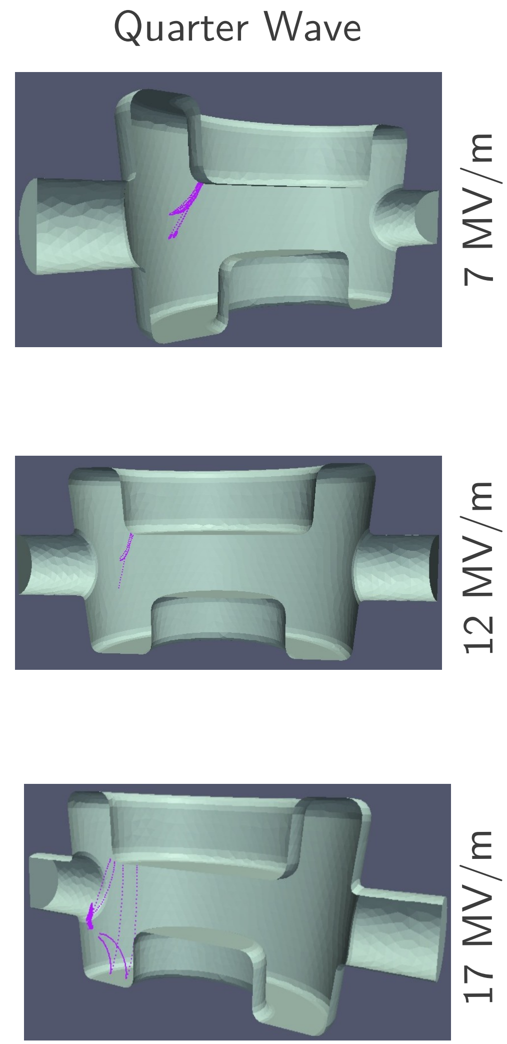
Status of RF dipole Cavity

- Awaiting surface treatment and testing at JLAB
  - Considering alternate events if JLAB test stand does not become available as planned
- HOM damping scheme under study
  - Waveguide or Coaxial
- Design of an LHC-compatible full system for SPS test to start soon

Multipacting Analysis





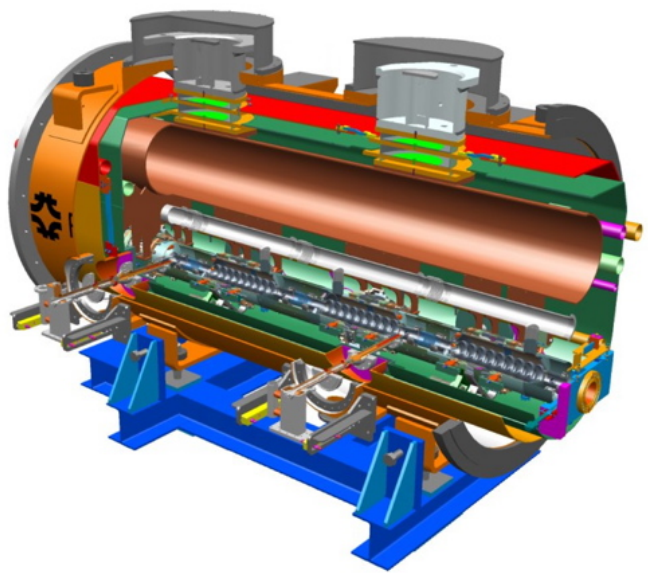


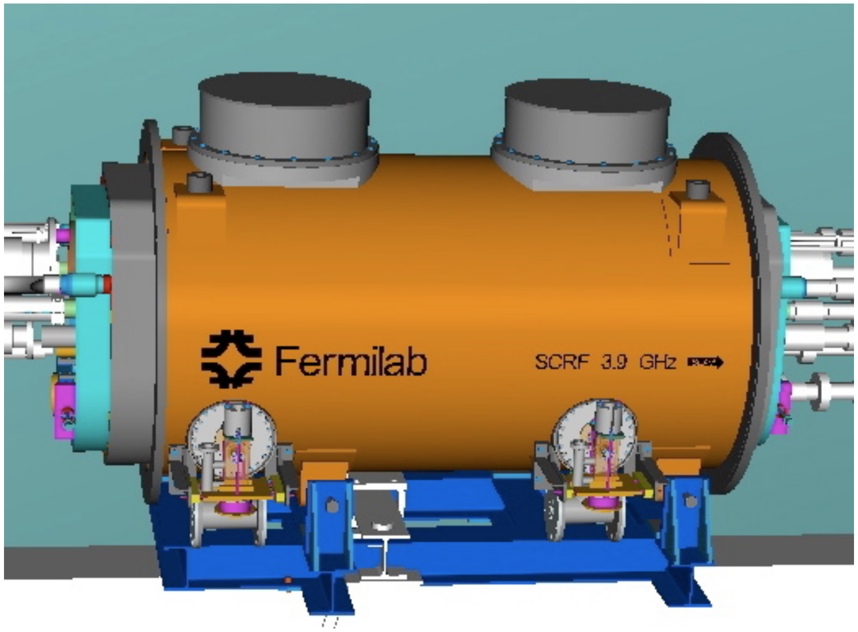
Based upon Track3D

Cryomodule Design and Integration

- Cryomodule to be developed at FNAL
- Adapted from linearizer system for FLASH
  - ~2m long, 1m OD
- Final integration and testing at FNAL before shipping to CERN
- Engineering integration meeting at FNAL on December 13-14, 2012
  - Kicks off global collaboration with technical issues

Cryomodule Reference Design





Cavity Development Summary

- All three candidate designs will go through comprehensive vertical testing in early 2013
- Starting integration into a cryomodule design for SPS test (and consistent with LHC implementation) with a meeting at FNAL on December 13-14, 2012
- Auxiliary systems designs (HOM dampers, tuners, diagnostics…) underway

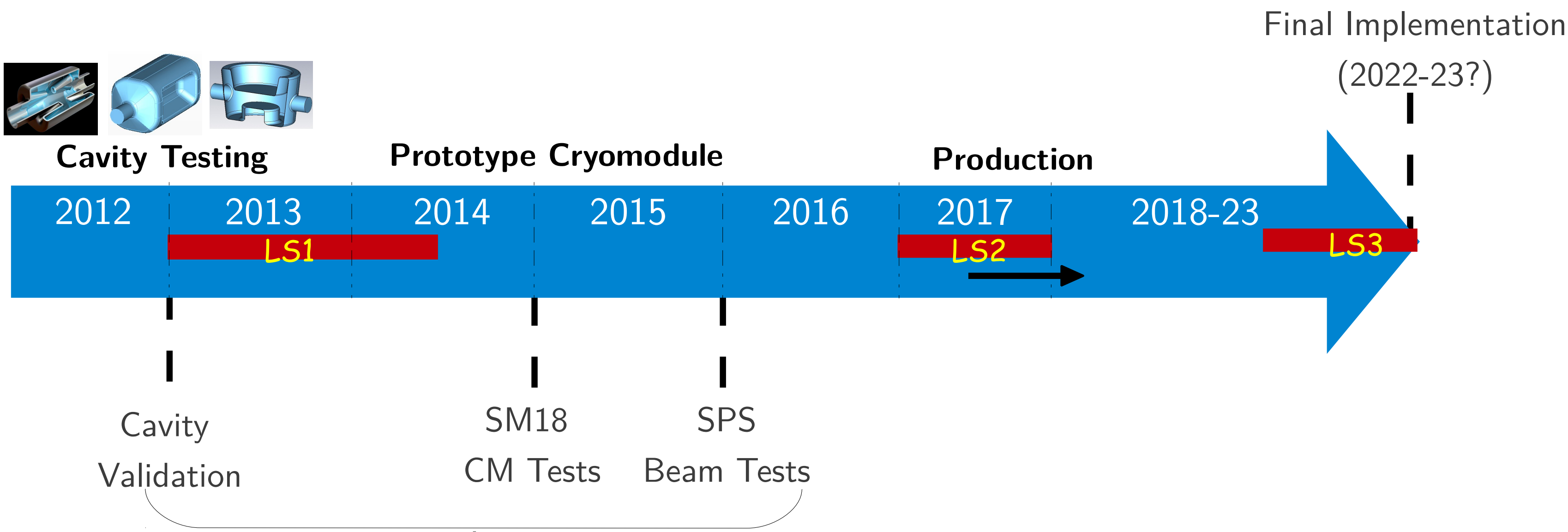
Present Focus

- Demonstration cryomodule under development for a possible beam test in the SPS before LS2
  - Vertical tests of all three cavities
- Cross functional working group in place at CERN to develop feasibility for SPS test
  - Operations, RF, Vacuum, Cryogenics, Beam Dynamics, Machine Protection, Collimation, Instrumentation…
- Recommended as a result of CC-11

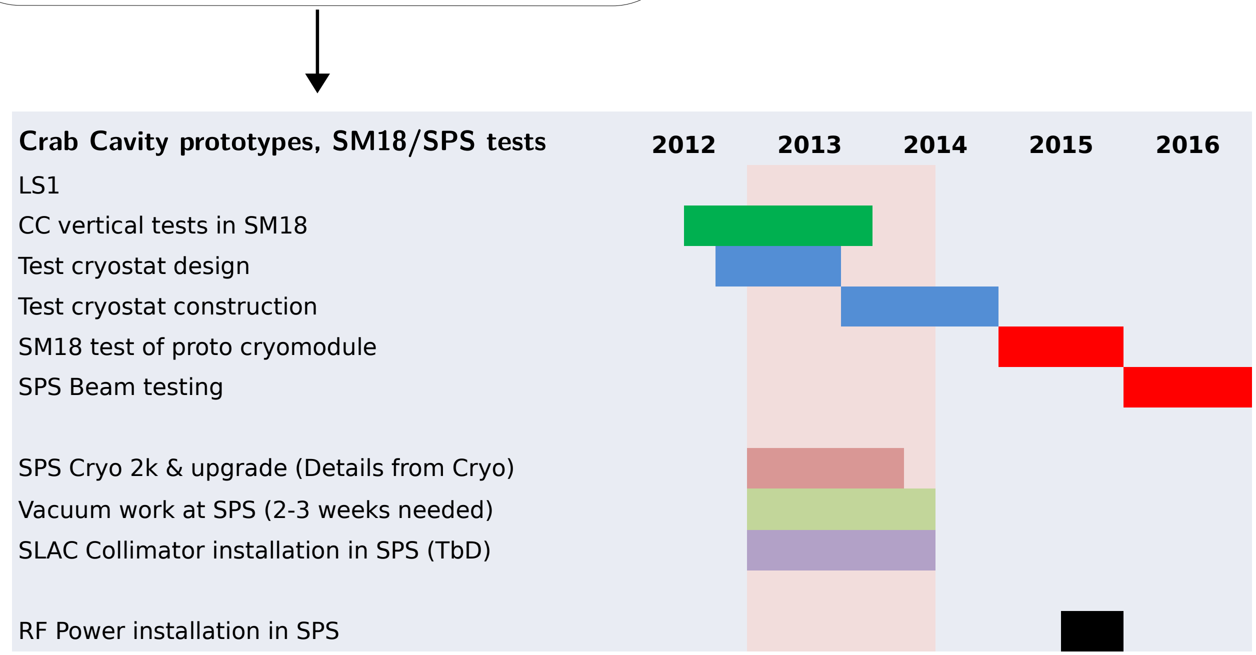
Phased approach

- Prototype Phase
  - Ongoing R&D through LARP and EuCard
    - Demonstrate feasibility, validate design and prototype through a test with protons in the SPS
    - Through 2015
- Construction
  - Cryomodule production (US construction project and/or EU funding)
    - From 2016 to HL-LHC

Timeline



Final Implementation
(2022-23?)
Cavity Testing
Prototype Cryomodule
Production
2012
2013
2014
2015
2016
2017
2018-23
LS1
LS2
LS3
Cavity
Validation
SM18
CM Tests
SPS
Beam Tests



Crab Cavity prototypes, SM18/SPS tests
2012
2013
2014
2015
2016
LS1
CC vertical tests in SM18
Test cryostat design
Test cryostat construction
SM18 test of proto cryomodule
SPS Beam testing
SPS Cryo 2k & upgrade (Details from Cryo)
Vacuum work at SPS (2-3 weeks needed)
SLAC Collimator installation in SPS (TbD)
RF Power installation in SPS

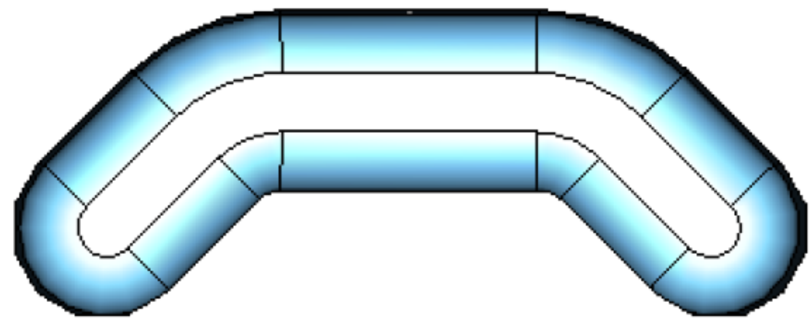
Conclusions

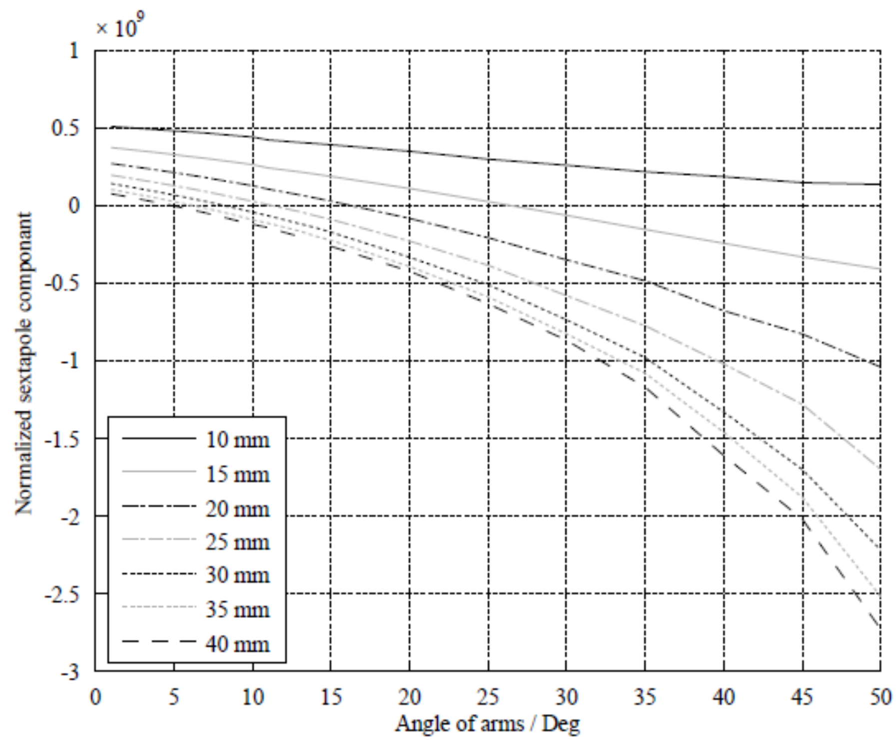
- Recent developments show very promising potential for RF deflecting cavities
- Plan to perform RF testing and measurements in 2013
- CERN is developing a plan for testing one cryomodule with beam in the SPS by LS2
- Upon successful completion of the SPS test, the collaboration is planning to request funding to build a system for installation during LS3

Questions

Sextupole Component

- Due to symmetry the 4R cavity doesn’t have even components to the crab kick (monopole, quadrupole, octopole etc)
- The dominant error term comes from the sextupole component (m=3).
- The m=3 term of a simplified shape was studied.
- It can be seen that the m=3 term can be reduced to zero by simply modifying the angle of the focusing electrodes



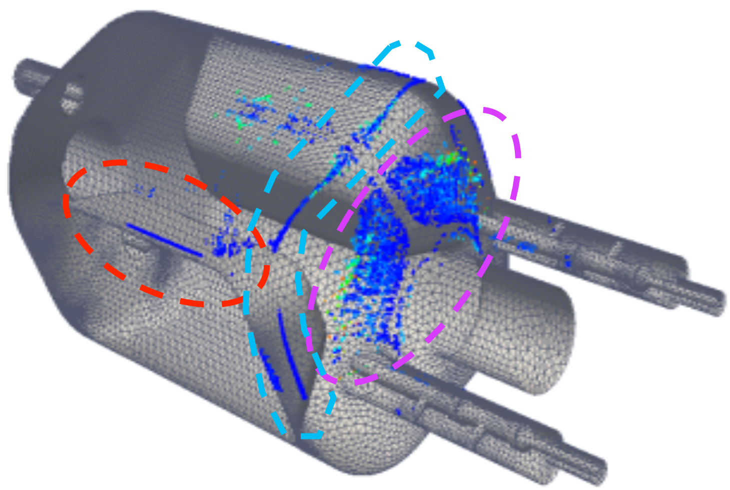


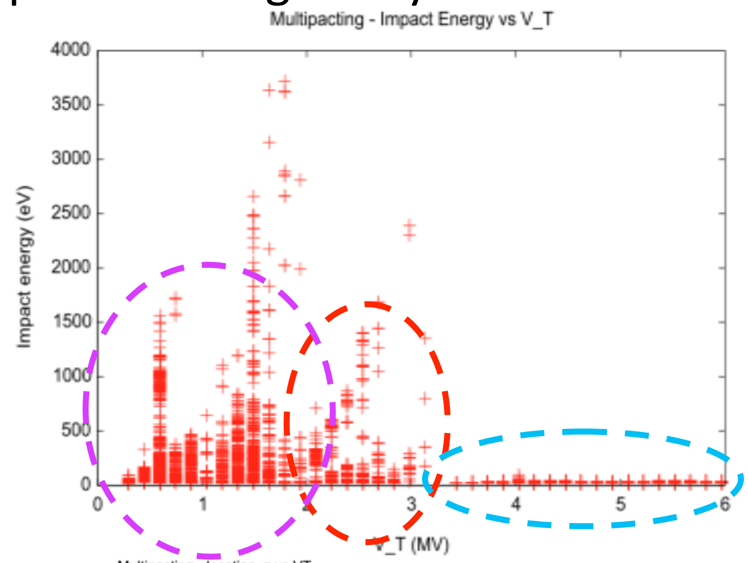
4 Rod Prototype

NIOWAVE

Multipacting Analysis

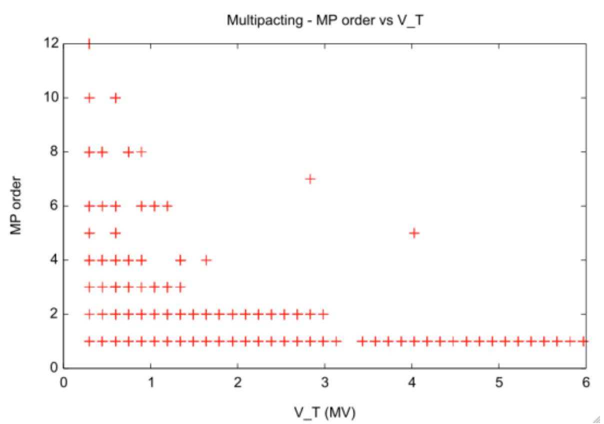
- Track3P – Particle tracking code in the SLAC ACE3P Suite
- For the 400 MHz square-shaped crabbing cavity

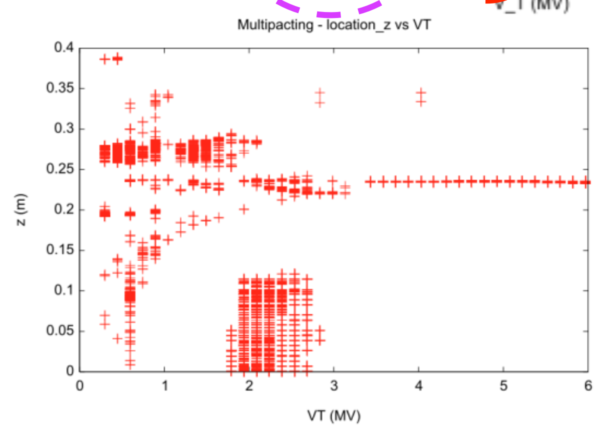


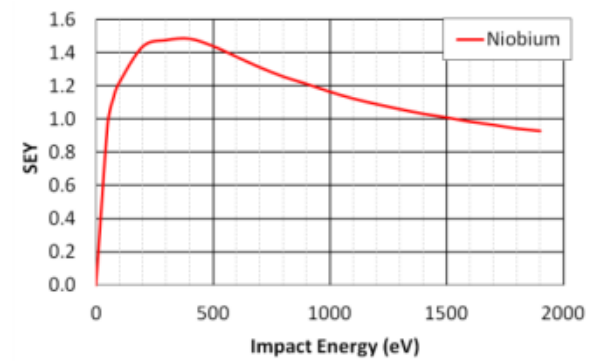


<u>Deflecting Voltage</u>

- *0.5MV to 2.6 MV*
- *1.8 MV to 2.8MV*
- *3.0 MV to 6.0 MV*



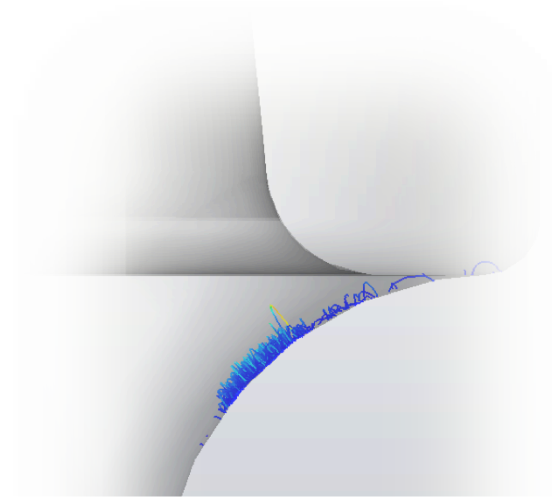


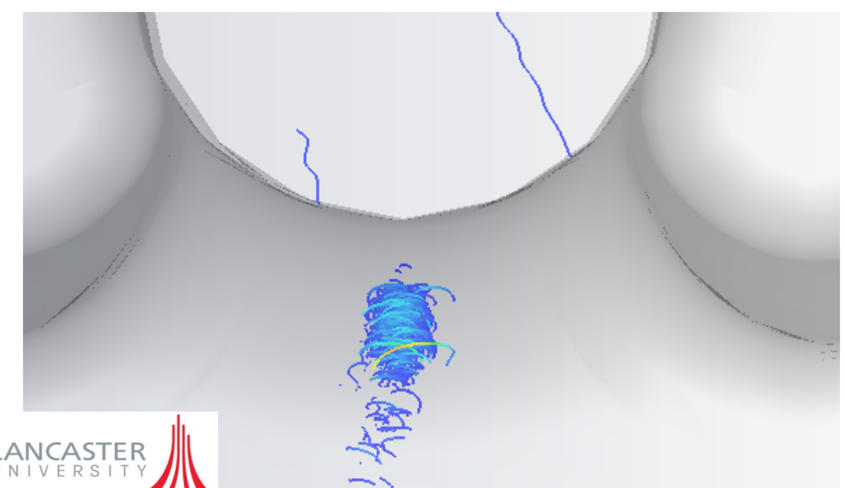


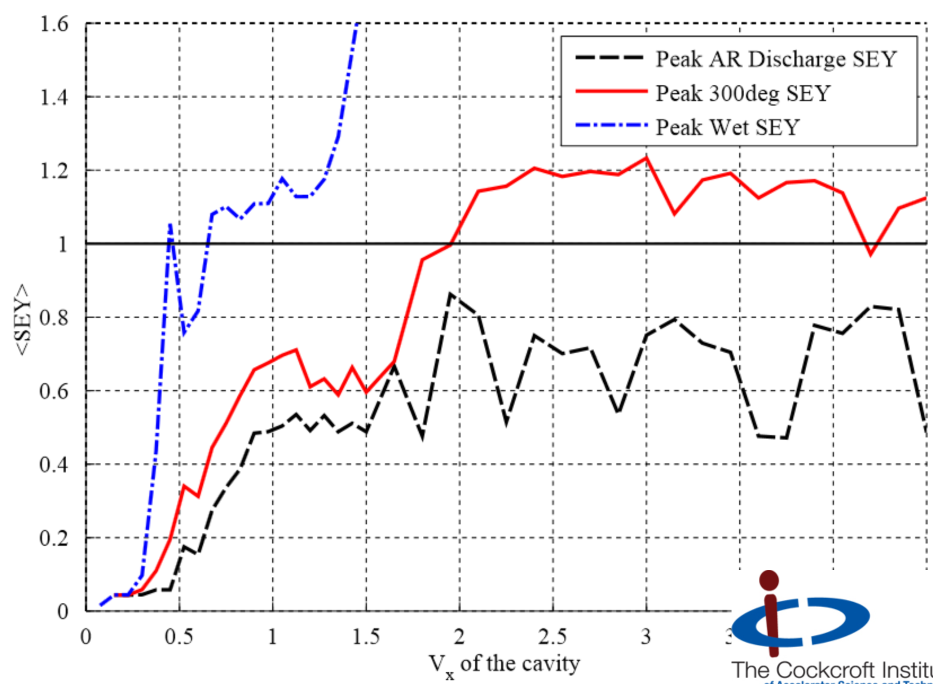
Z. Li et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2185

Multipacting

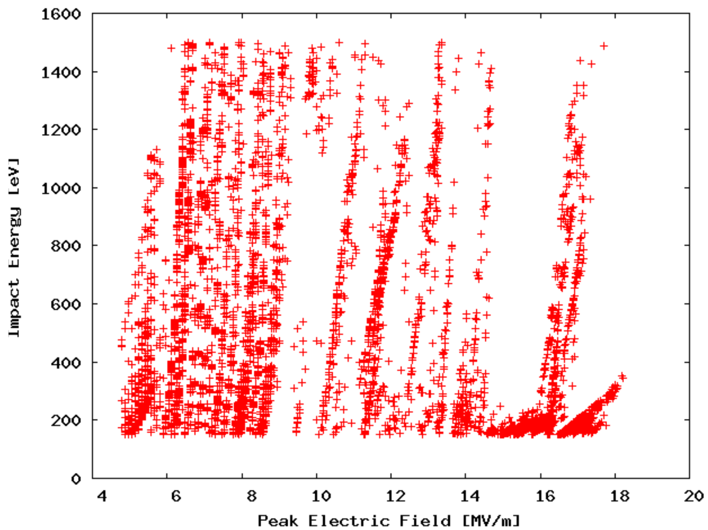
- Multipactor on the beam pipe was found on the beam pipe at ~1.6MV.
- Same multipacting was seen on KEKB crab cavity.
- Methods of removing the multipactor are being looked into;

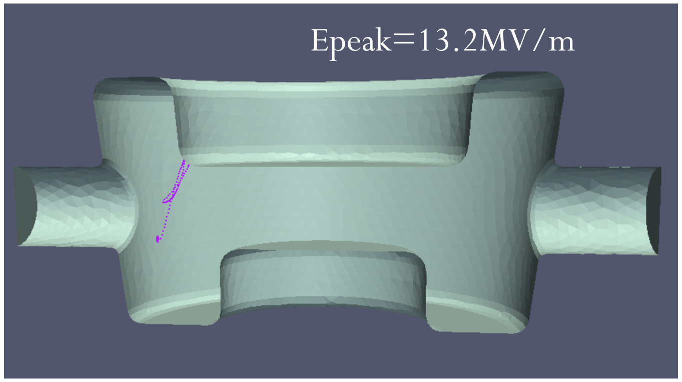


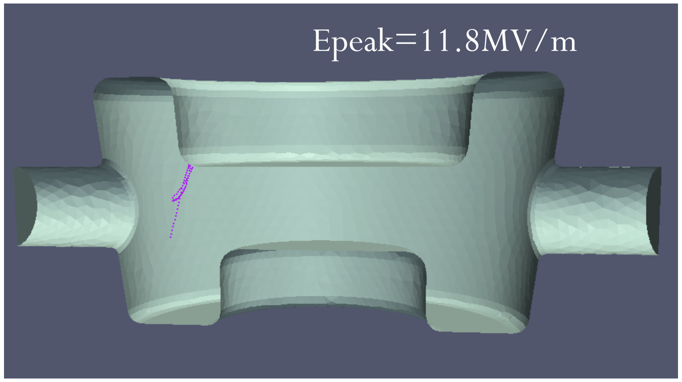


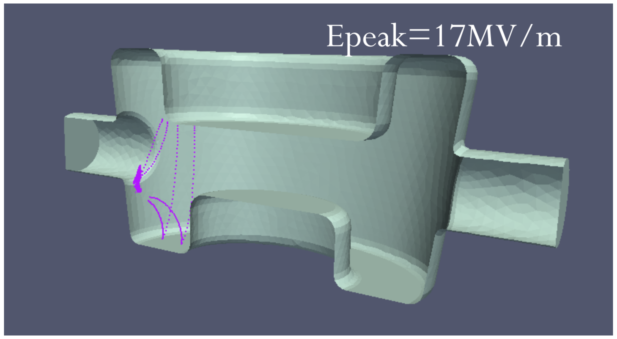


Multipacting









From Track3P