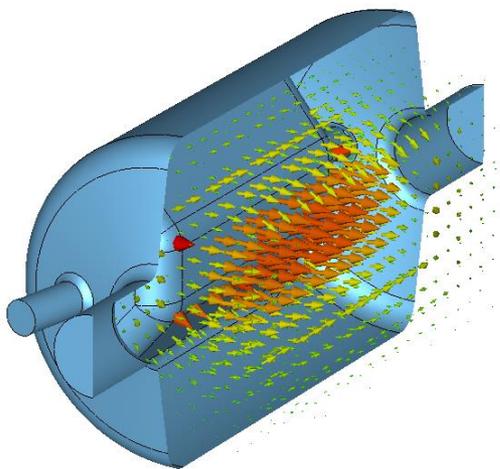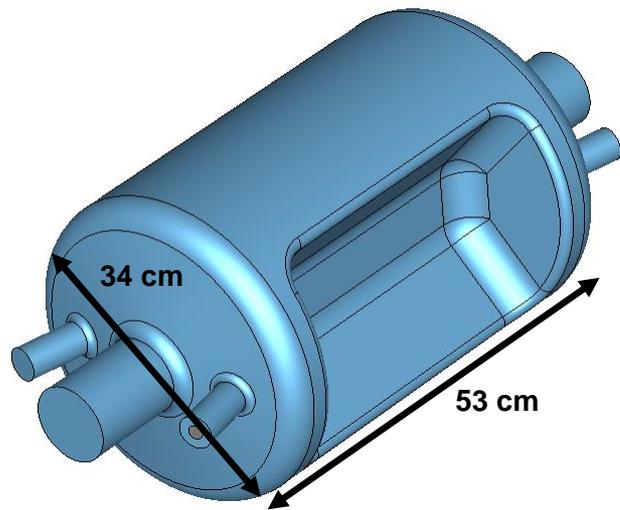# CAVITY II – RF-DIPOLE CAVITY TEST RESULTS
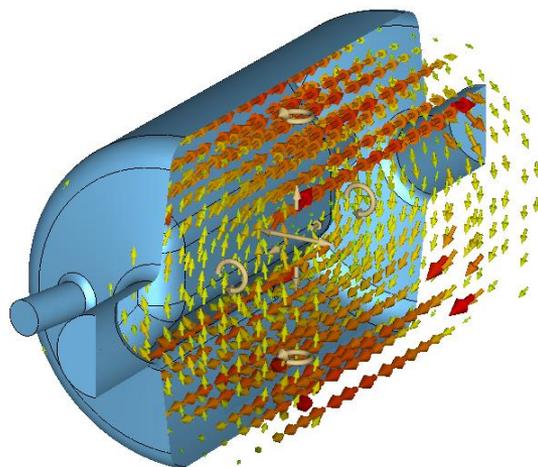
Subashini De Silva

**Center for Accelerator Science
Old Dominion University**

Proof–of–Principle RF–Dipole Design


34 cm

53 cm

E Field

B Field

Parameters	Value	Units
Frequency	400	MHz
Deflecting Voltage (V_T^*)	0.375	MV
Peak Electric Field (E_p^*)	4.02	MV/m
Peak Magnetic Field (B_p^*)	7.06	mT
B_p^*/E_p^*	1.76	mT/(MV/m)
Stored Energy (U^*)	0.195	J
$[R/Q]_T$	287.0	Ω
Geometrical Factor (G)	140.9	Ω
$R_T R_S$	4.0×10^4	Ω^2
At $E_T^* = 1$ MV/m		

OLD DOMINION UNIVERSITY

SLAC
NATIONAL ACCELERATOR LABORATORY

Proof–of–Principle Cavity Fabrication

- Proof-of-Principle cavity fabricated at Niowave Inc.

- Cavity thickness – 3 mm
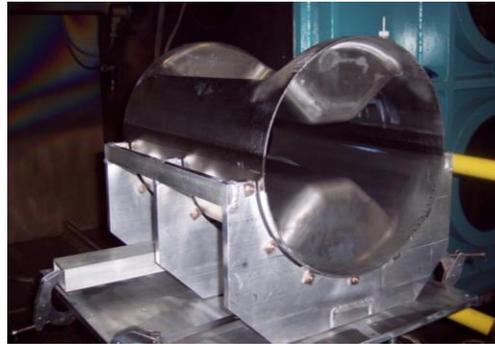
- Bead pull measurements of on axis electric and magnetic field components
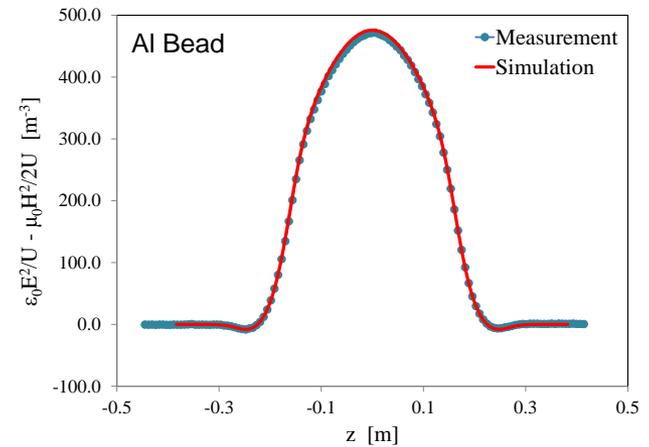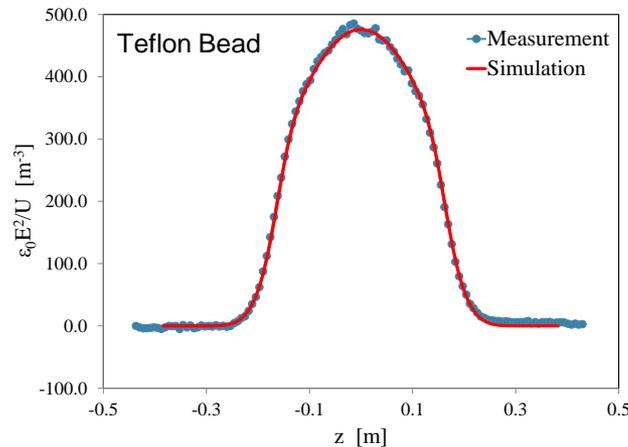
Proof–of–Principle Cavity Surface Treatment

- Surface treatment and rf testing done at Jefferson Lab

- Procedure:
  - Bulk BCP
    - Average removal – 85 μm
    - Planned total removal – 120 μm
    - Reduced etch rate from 2.7-2.8 μm /min to 1.8 μm/min due acid mixture contamination with glycol
  - Heat treatment – At 600^0 C for 10 hours
  - Light BCP – ~10 μm
  - High Pressure Rinse – 3 passes

- Cavity assembly and leak check in clean room
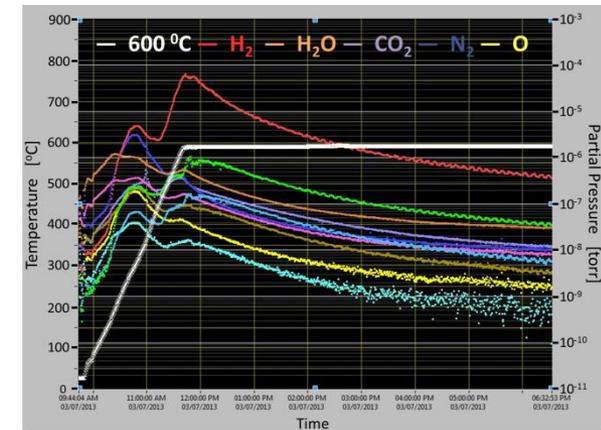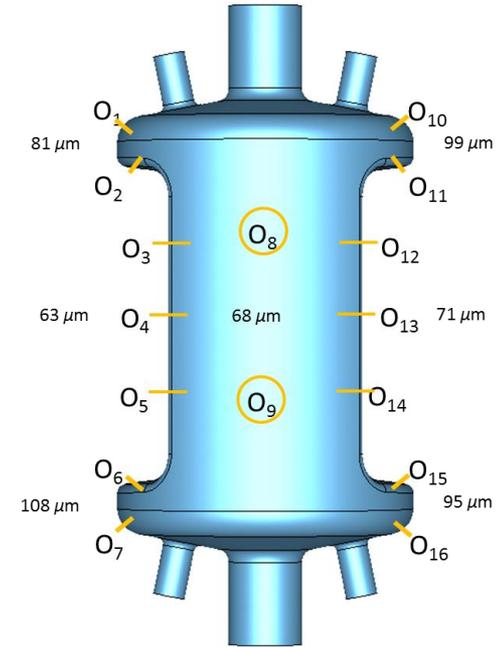
Multipacting in Proof–of–Principle Design

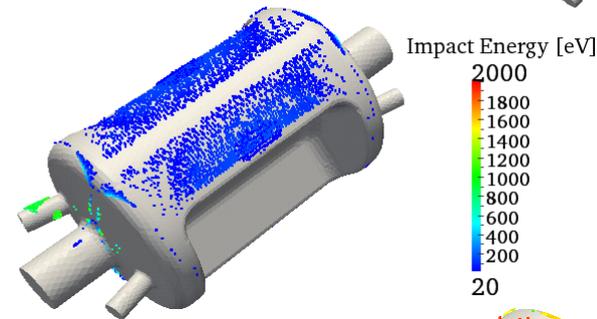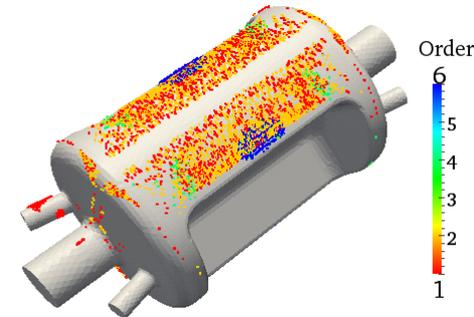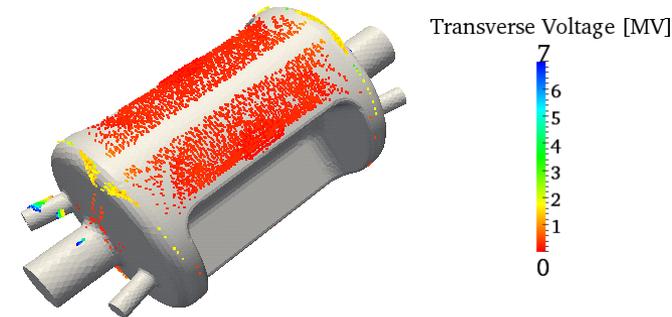- Multipacting analysis using Tack3P in SLAC – ACE3P suite
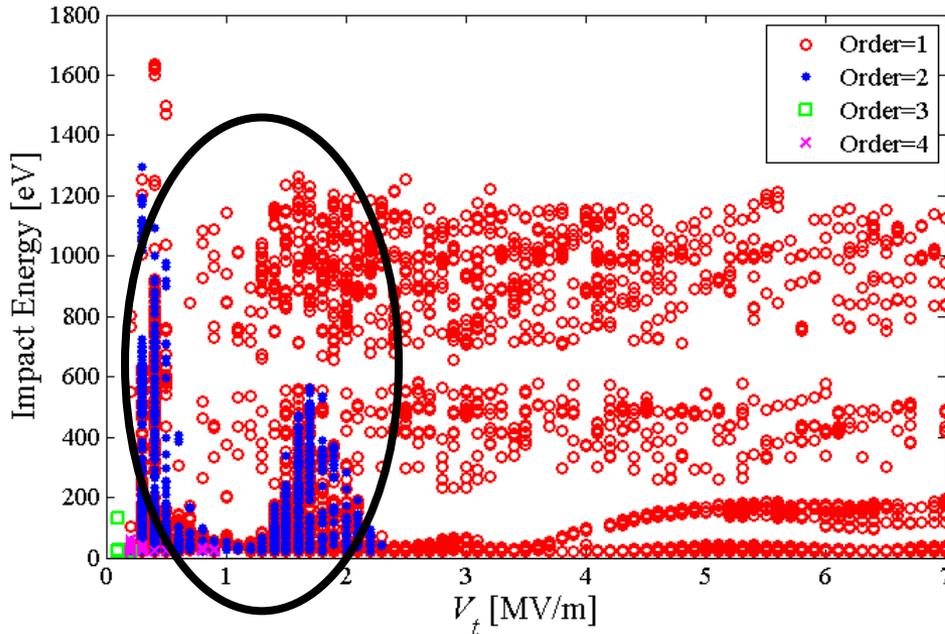
Expected multipacting levels at very low V_T of low orders with low impact energies

- A multipacting barrier was observed in the first 2 K test at very low fields

- Increasing the power processed the cavity and no multipacting was observed in the following 4.2 K and 2 K tests

P-o-P Cavity – 4.2 K and 2.0 K Test Results

- Total design requirement – 13.4 MV

- Design requirement per cavity – 3.4 MV
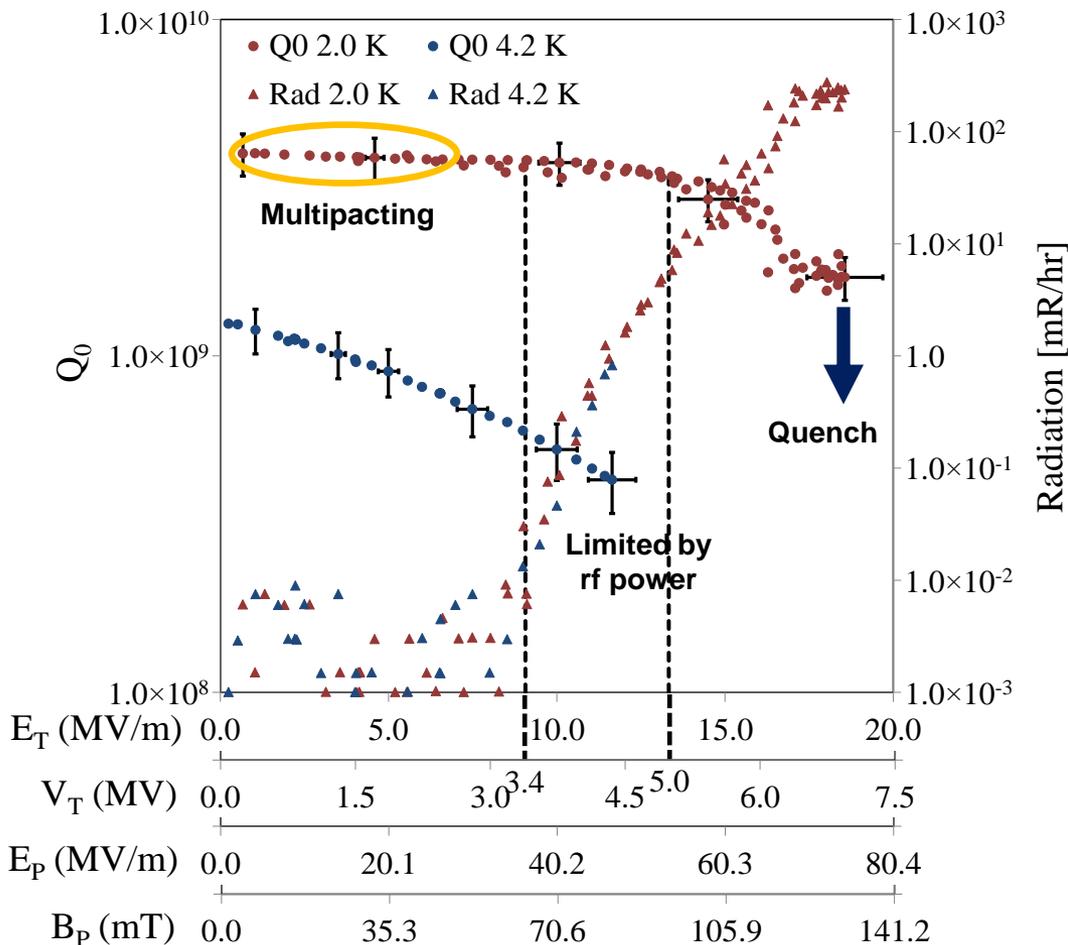
- **Design goal can be achieved with three cavities**

- Multipacting levels observed below 2.5 MV and processed easily

- Achieved fields at 2.0 K:
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

- RF performance was limited at 7.0 MV due to high field emission

- At 2.0 K with R_s = 11.3 nΩ (R_{res} = 10 nΩ)
  - Expected Q_0 = 1.25×10^{10}
  - Measured Q_0 = 4.0×10^9

OLD DOMINION UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

P-o-P Cavity Test Results
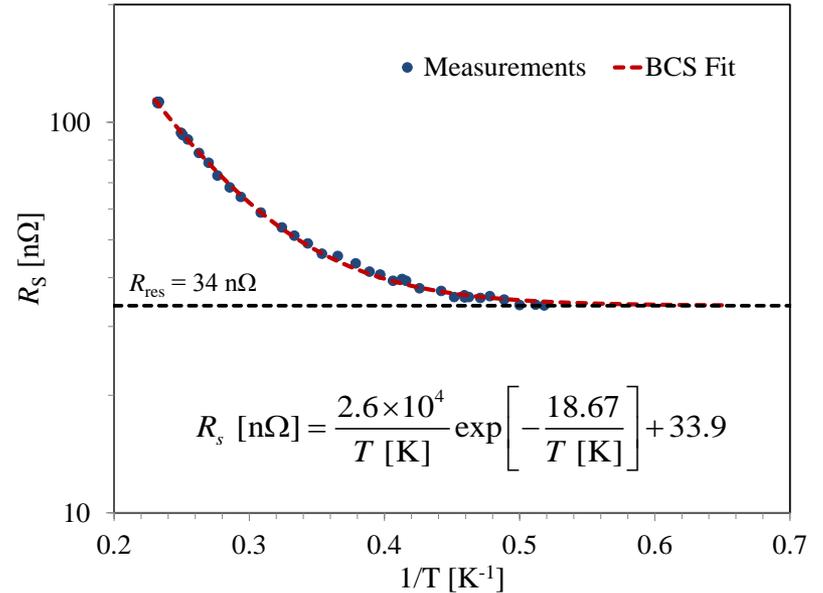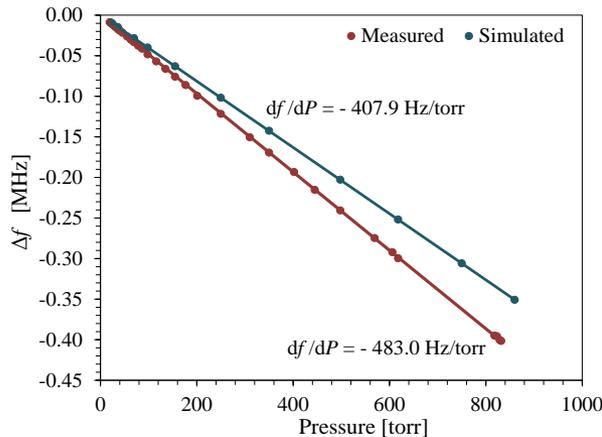
Surface Resistance

- For a R_{res} = 10 nΩ
  - At 2.0 K → R_S = 11.3 nΩ, Q_0 = 1.25 ×10^{10}
  - At 4.2 K → R_S = 81.3 nΩ, Q_0 = 1.8 ×10^9
- Measured Q_0 at 2.0 K = 4.0×10^9
- Q_0 due to power losses at the beam port stainless steel blank flanges → 3.8×10^9

$$R_s \ [\text{nΩ}] = \frac{2.6 \times 10^4}{T \ [\text{K}]} \exp\left[-\frac{18.67}{T \ [\text{K}]}\right] + 33.9$$

R_{res} = 34 nΩ

- Measurements
- BCS Fit

R_S [nΩ] vs 1/T [K^{-1}]

Magnetic field and surface field on the beam port

df/dP = - 407.9 Hz/torr
df/dP = - 483.0 Hz/torr
- Measured
- Simulated

Pressure Sensitivity

k_L = - 121.94 Hz/(MV/m)^2
- 2.0 K
- 4.2 K

Simulated k_L– 117.3 Hz/(MV/m)^2

E_t^2 [MV/m]^2

Lorentz Detuning

OLD DOMINION UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

499 MHz RF-Dipole Cavity

44 cm

24 cm

RF Properties – 499 MHz Cavity		
Aperture Diameter (d)	40.0	mm
Nearest HOM	777.0	MHz
E_p^*	2.86	MV/m
B_p^*	4.38	mT
$[R/Q]_T$	982.5	Ω
Geometrical Factor (G)	105.9	Ω
$R_T R_S$	1.0×10^5	Ω^2
At $E_T^* = 1$ MV/m		
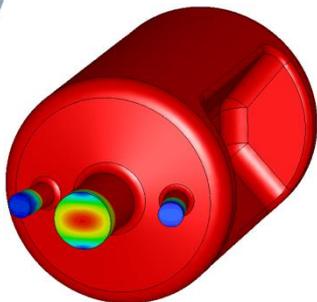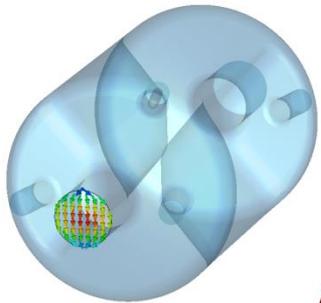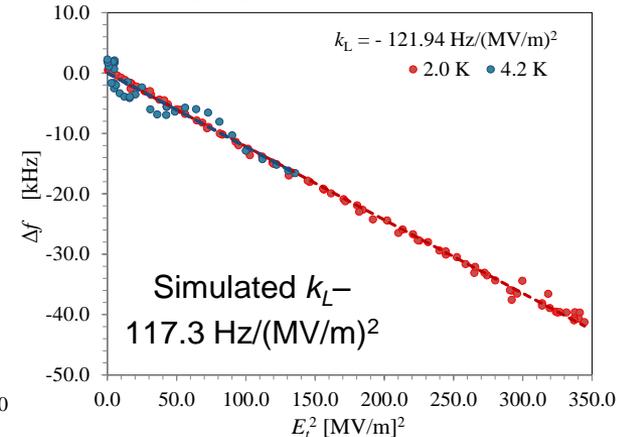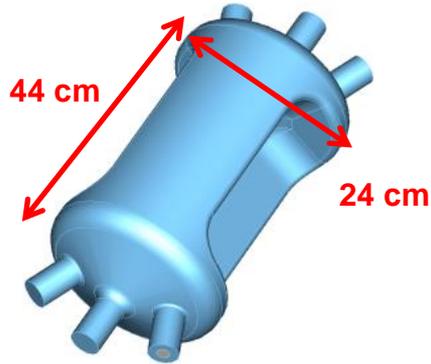
Surface Processing Procedure

- Bulk BCP of ~150 μm

- Average removal
  - 1st treatment: 108 μm
  - 2nd treatment: 200 μm

- Heat Treatment → H_2 degassing at 600^0C – 10 hours

- Light BCP – Removal of 10 μm (2nd time: 20 μm) after heat treatment

- High pressure rinsing in 2 passes

- Cavity Assembly – with fixed coupling

OLD DOMINION UNIVERSITY

SLAC
NATIONAL ACCELERATOR LABORATORY

499 MHz – 4.2 K and 2.0 K Test Results
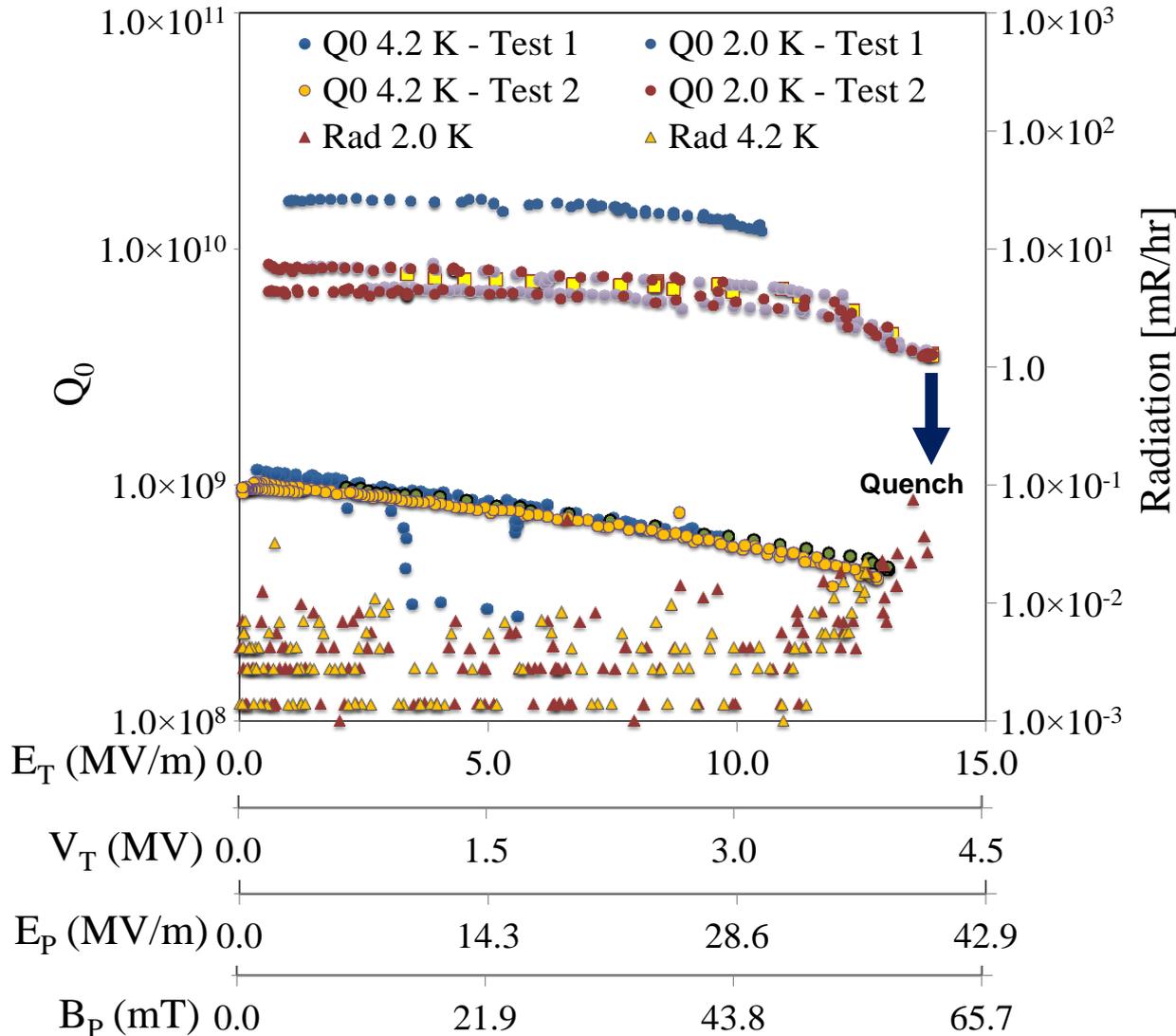
- Multipacting was easily processed during the first rf test at 4.2 K rf test
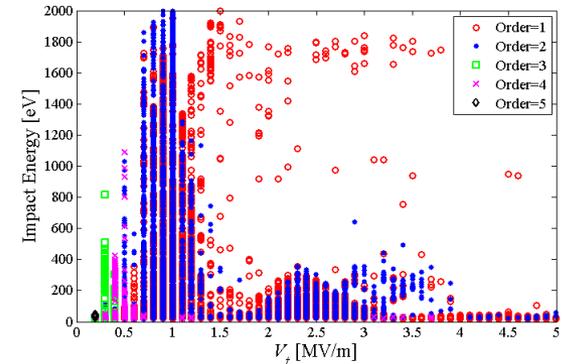
- No multipacting levels were observed in the reprocessed cavity

- Hard quench observed at 4.2 MV

- Achieved fields at 2.0 K
  - E_T = 14 MV/m
  - V_T = 4.2 MV
  - E_P = 40 MV/m
  - B_P = 61.3 mT

499 MHz – Surface Resistance

Left chart: R_S [nΩ] vs 1/T [1/K], legend: Measurements, BCS Fit, $R_{res} = 5.5$ nΩ
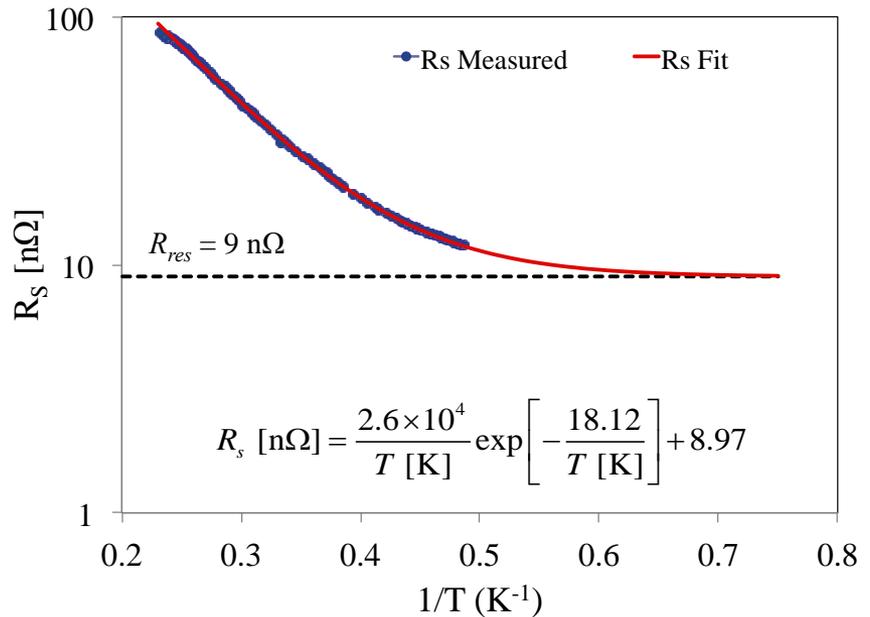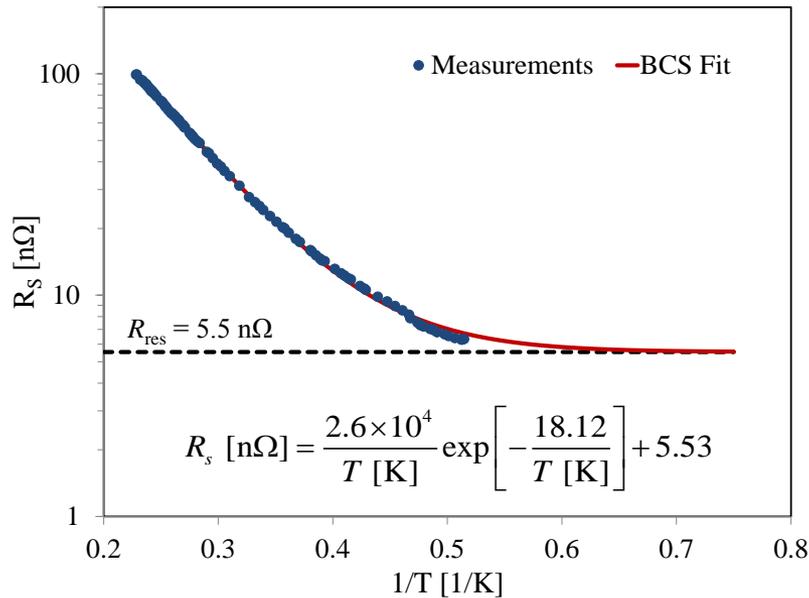
$$R_s \; [\text{n}\Omega] = \frac{2.6 \times 10^4}{T \; [\text{K}]} \exp\left[-\frac{18.12}{T \; [\text{K}]}\right] + 5.53$$

Right chart: R_S [nΩ] vs 1/T (K^{-1}), legend: Rs Measured, Rs Fit, $R_{res} = 9$ nΩ

$$R_s \; [\text{n}\Omega] = \frac{2.6 \times 10^4}{T \; [\text{K}]} \exp\left[-\frac{18.12}{T \; [\text{K}]}\right] + 8.97$$

- Measured Q_0
  - 1st Test: 1.6×10^{10}
  - 2nd Test: 8.1×10^9
- Reduced Q_0 at 2.0 K with surface reprocessing
  - 1st bulk BCP removal: 108 μm
  - 2nd bulk BCP removal: 200 μm

- Q_0 dropped with the increase in residual surface resistance

- Residual resistance
  - 1st Test: 5.5 nΩ
  - 2nd Test: 9.0 nΩ

Prototype RF–Dipole Design

- Electromagnetic mode is the same
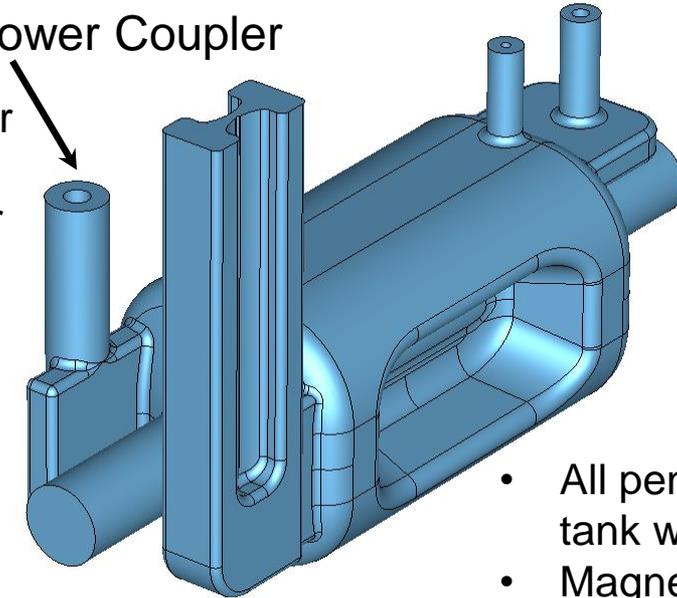- Prototype design has improved rf-properties

28.1 cm

54 cm
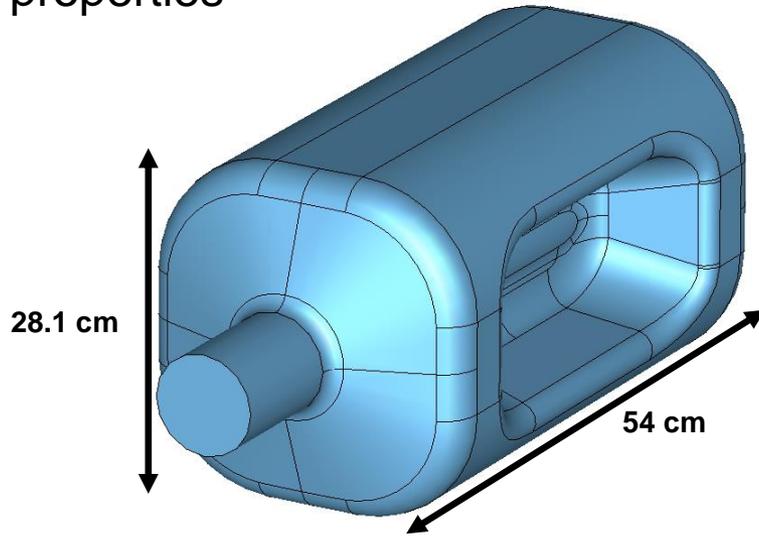
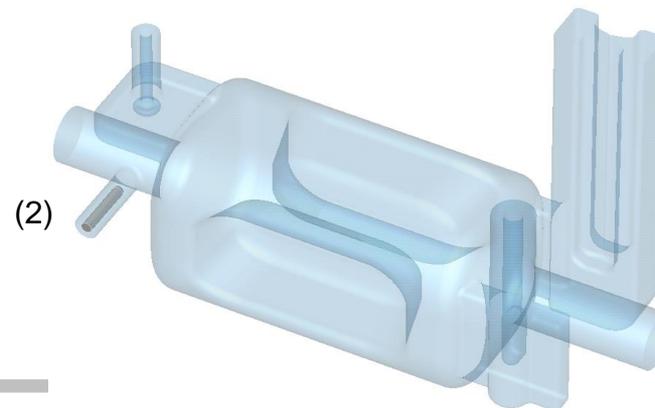| Parameters	Prototype	P-o-P	Units
Frequency	400.79	400	MHz
Deflecting Voltage (V_T^*)	0.375	0.375	MV
Peak Electric Field (E_p^*)	3.65	4.02	MV/m
Peak Magnetic Field (B_p^*)	6.22	7.06	mT
B_p^*/E_p^*	1.71	1.76	mT/ (MV/m)
Stored Energy (U^*)	0.13	0.195	J
$[R/Q]_T$	427.4	287.0	Ω
Geometrical Factor (G)	106.7	140.9	Ω
$R_T R_S$	4.6×10^5	4.0×10^4	Ω^2
At $E_T^* = 1$ MV/m			

E Field

B Field
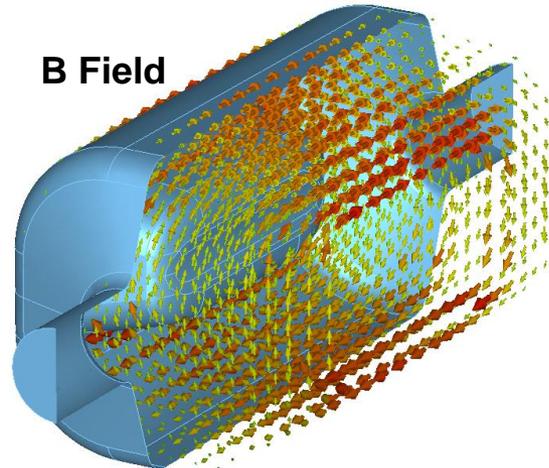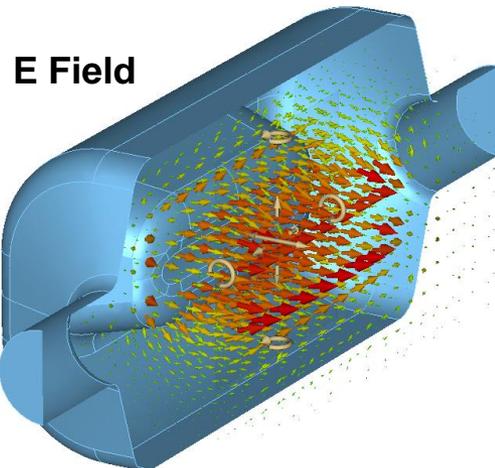
Prototype Design – FPC and Pick Up Ports

Fundamental Power Coupler

- Outer conductor = 62 mm
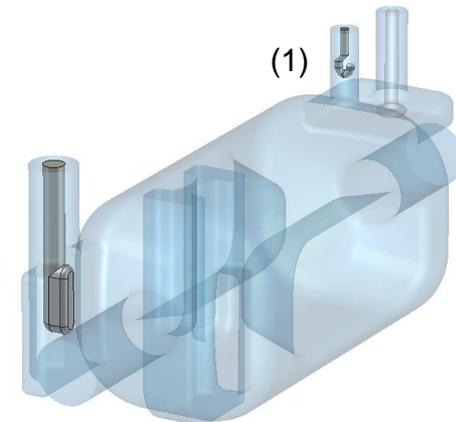- Inner conductor = 27 mm
- $Q_{ext} = 1.0 \times 10^6$

Pick Up Port Options

- Outer conductor = 36 mm
- Inner conductor = 27 mm
- To achieve 1.0 W at 3.4 MV
- Q_{ext} = ~3.0×10^{10}

- All penetrations to the He tank will be from top
- Magnetic coupling → Field enhancement at the port
- 75 Ω inner conductor

(1)

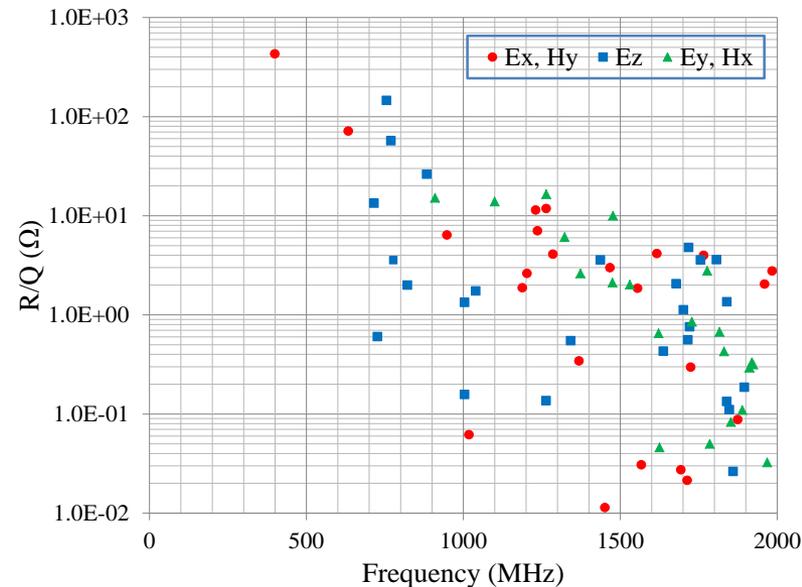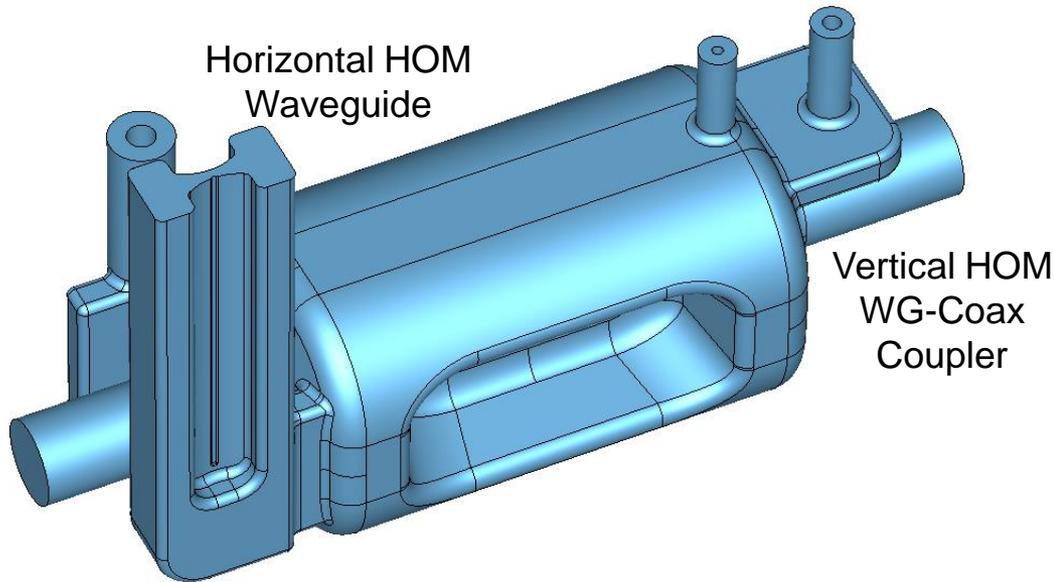- Port losses at the SS flanges on the beam pipes
  - Beam port 1 (shorter): 1.1 mW
  - Beam port 2 (longer): 0.3 μW
- Is not an issue on assembled cavity in the cryomodule

(2)

- Electric coupling → No field enhancement
- 50 Ω inner conductor

Prototype Design – HOM Damping

- Analysis of HOM damping – Zenghai Li

Horizontal HOM Waveguide

Vertical HOM WG-Coax Coupler

- Horizontal HOM Coupler
  - Ridged waveguide coupler
  - Couple to both horizontal dipole and accelerating HOM modes
  - Operating mode below cutoff – naturally reject operating mode
  - Groove reduces multipacting levels at the waveguide

- Vertical HOM coupler
  - Selective WG-stub-coaxial coupler, does not couple to operating mode - no filter needed
  - Damps both vertical HOM and accelerating HOM modes
  - Modified V-HOM coupler meets impedance threshold requirements

Prototype Design – HOM Damping

- Current design specifications per cavity
  - Longitudinal impedance threshold – 0.2 MΩ
  - Transverse impedance threshold – 0.125 MΩ
- Vertical and horizontal HOM couplers optimized to damp high Q modes at 1.265 and 1.479 GHz
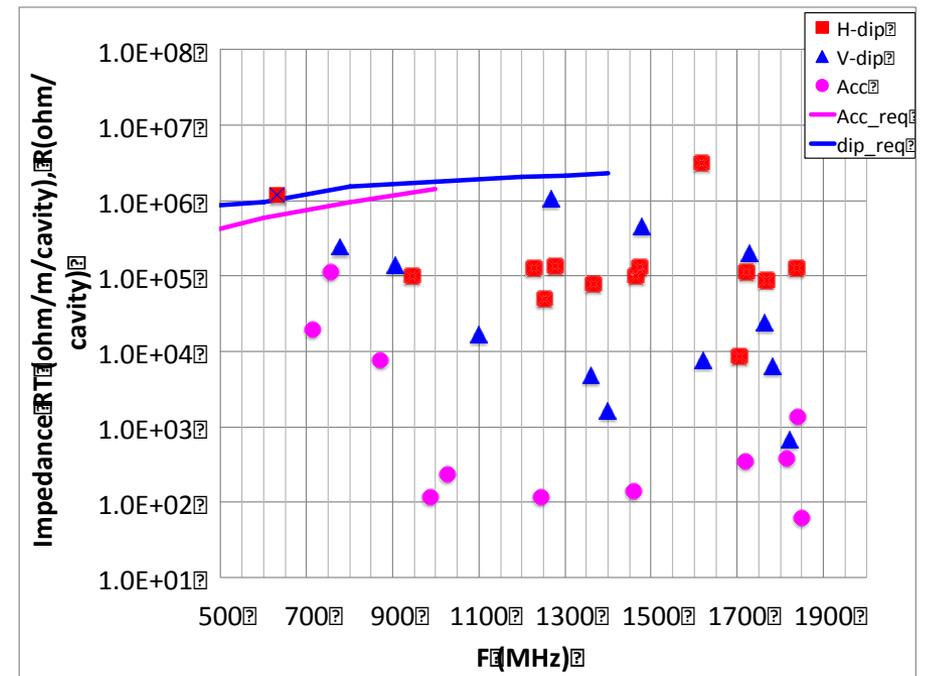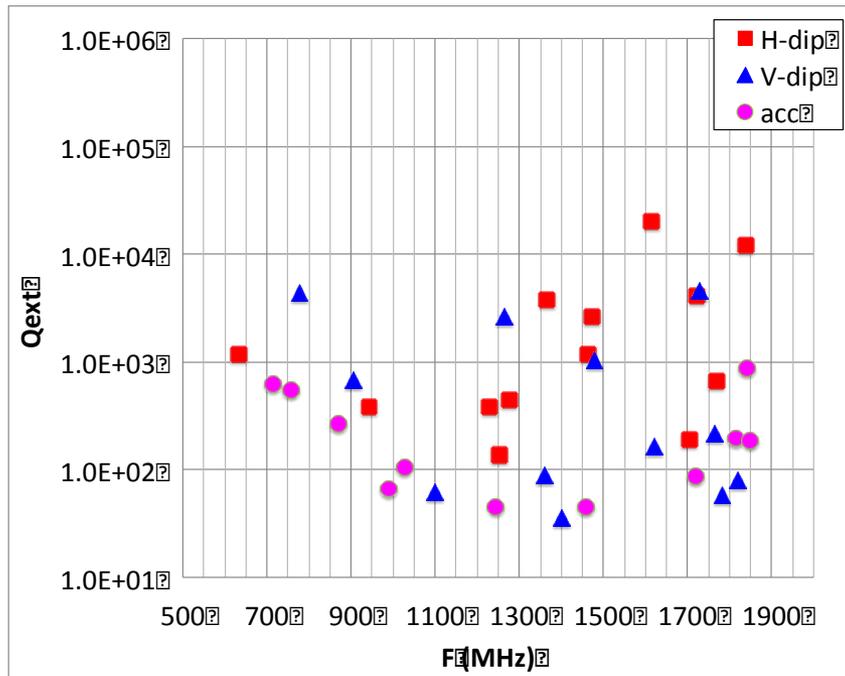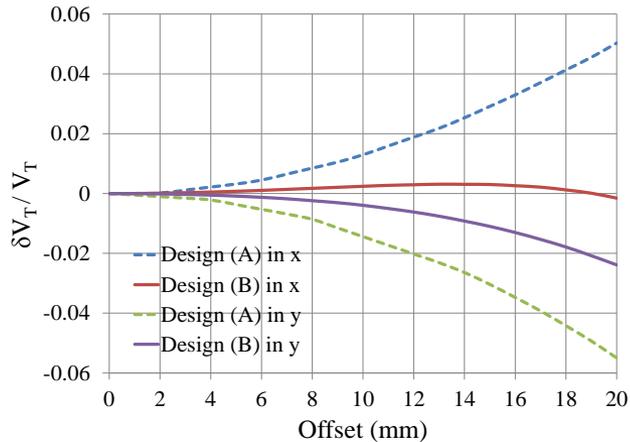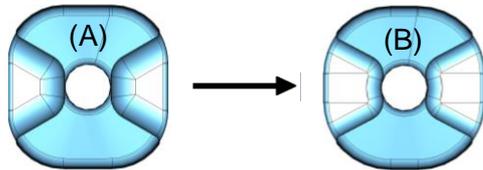
Prototype Design – Field Non-Uniformity

- Curvature around beam aperture to
  - Reduce field non-uniformity
  - Suppress higher order multipole components

Voltage deviation at 20 mm
  - Horizontal: 5.0% → 0.2%
  - Vertical: 5.5% → 2.4%

Higher Order Multipole Components

				Full Cavity with Couplers	Units
V_Z	0.0	0.0	0.0	0.46	kV
V_T	1.0				MV
b_3	300	410	100	37.4	mT/m
b_4	0.0	0.0	0.0	-1.8	mT/m^2
b_5	-4.6×10^4	-4.1×10^4	-2.2×10^4	-1.9×10^5	mT/m^3
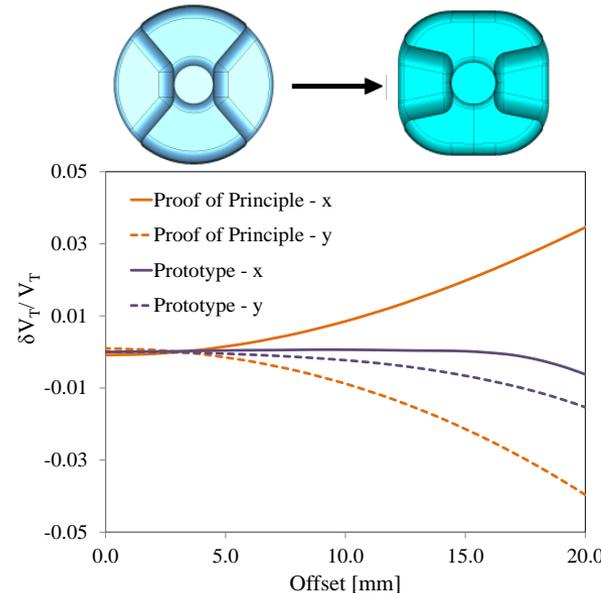
- Multipole component b_3 is reduced below requirements
- Any specifications for other higher order multipole components?

Prototype Design – Multipole Analysis

- Effect of cavity imperfections on multipole components – R. Olave

- Strength of the multipole components is mainly determined by the aperture region of the poles near the beamline.
- Initial analysis focused on individual imperfections or departures from the ideal cavity poles due to fabrication or welding errors (no deformations due to tuning processes considered).
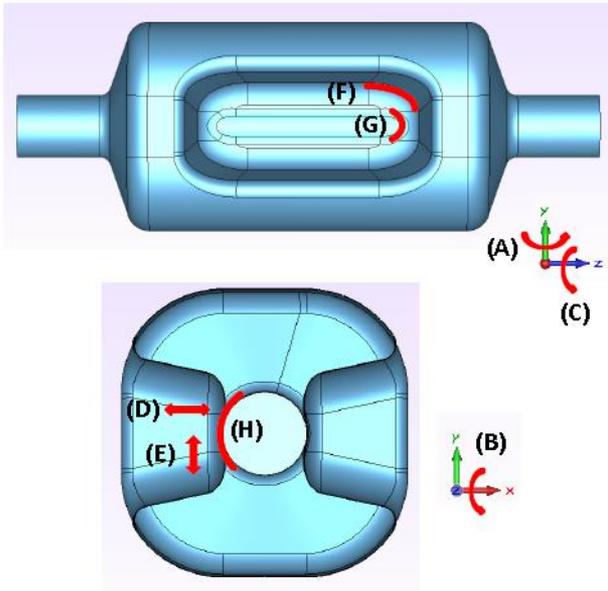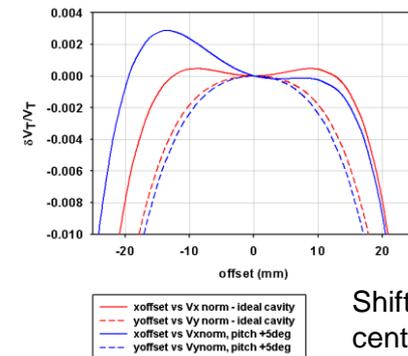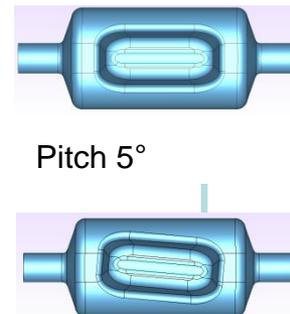
- (A) Yaw (rotation about y-axis) of one pole.
- (B) Pitch (rotation about x-axis) of one pole.
- (C) Roll (rotation about z-axis) of one pole.
- (D) Horizontal displacement of one pole.
- (E) Vertical displacement of one pole.
- (F) Blending radius at the outer corner of one pole.
- (G) Blending radius of the feather-like structure near the beam line of one pole.
- (H) Aperture radius in one pole.

* Small individual imperfections have negligible effects on the multipole components, but may shift the electrical center and operating frequency.
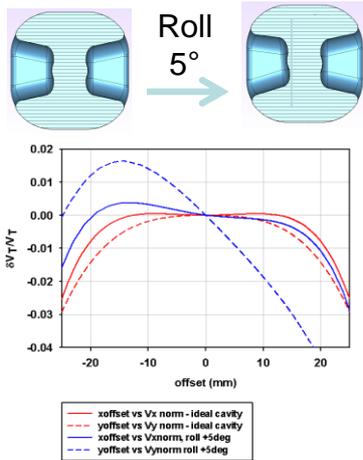

Pitch 5°

Shift of electrical center observed

Prototype Design – Multipole Analysis

The largest effect on the multipole components observed is produced by the roll of a pole

Roll 5°

- xoffset vs Vx norm - ideal cavity
- yoffset vs Vy norm - ideal cavity
- xoffset vs Vxnorm, roll +5deg
- yoffset vs Vynorm roll +5deg

The largest frequency shift observed is produced by the horizontal displacement of a pole

- yaw, degrees
- pitch, degrees
- roll, degrees
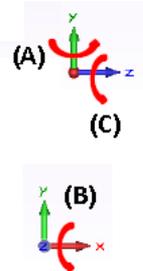- Horizontal pole displacement, mm
- Vertical pole displacement, mm

So far there are no individual imperfections that would make the cavity non-compliant with the multipole component requirements for the LHC system.
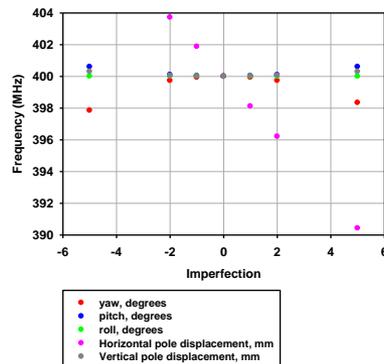
(A) Yaw
(B) Pitch
(C) Roll

Multipole component		Units
V_T	1	MV
b_1	3.3	mT m
b_2	0.001	mT
b_3	37.4	mT/m
b_4	-1.8	mT/m^2
b_5	-1.9x10^5	mT/m^3

| Imperfection	b_1	b_2	b_3	b_4
Yaw 1°	3.3	-0.003	36.1	41.1
Yaw 2°	3.3	-0.0003	33.2	158.1
Yaw 5°	3.3	-0.02	13.8	983.4
Pitch 1°	3.3	-0.01	38.2	-18.1
Pitch 2°	3.3	-0.05	40.4	-86.1
Pitch 5°	3.3	-0.35	55.1	-561.4
Roll 1°	3.3	-0.2	44.1	-171.0
Roll 2°	3.3	-0.5	51.9	-374.6
Roll 5°	3.3	-1.6	85.2	-1115.8

Studies of the effects of individual imperfections due to fabrication and welding of the cavity + couplers are underway.

OLD DOMINION UNIVERSITY

SLAC
NATIONAL ACCELERATOR LABORATORY

Prototype Cavity Cryomodule

Cryomodule design for rf-dipole cavity

Room Temp Cavity

- Mechanical analysis

Stiffening ribs
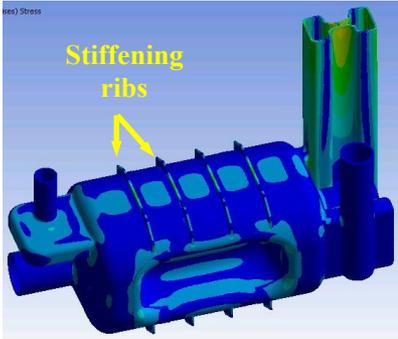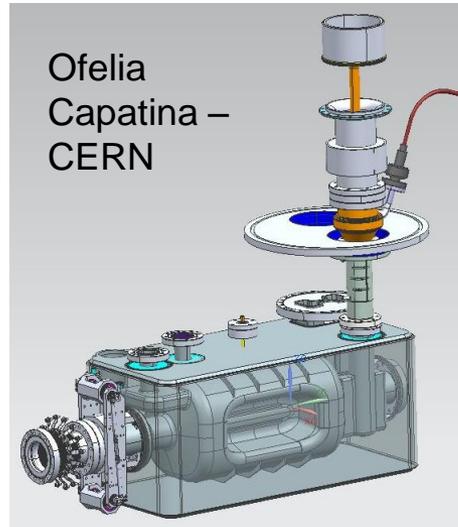
- Prototype cavity

fabrication by Niowave Inc.

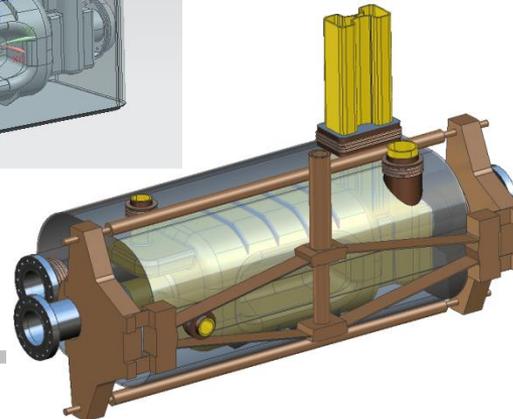Ofelia Capatina – CERN

Cryomodule Design

- He tank
  at

Tom Nicol – Fermilab
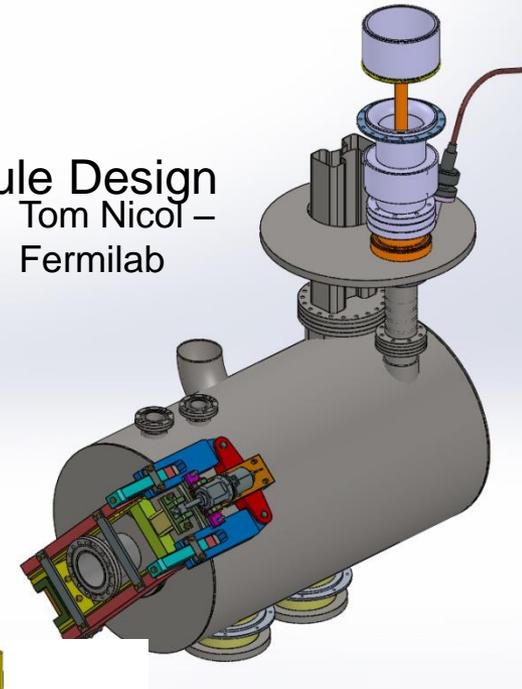
Jim Henry – JLab

Current Status and Future Plans

Proof-of-Principle Cavity

- First cryogenic tests of proof-of-principle cavity is completed
- Cavity performance reached higher gradients and is capable of achieving design specifications
- Achieved a total transverse deflection of 7 MV CW (twice the design voltage)
- Multipacting conditions were processed easily and did not reoccur
- Retesting the cavity on improving Q_0 → Further testing at CERN is on the plan

Prototype Cavity

- Electromagnetic design is complete including multipacting levels, HOM damping, reduced multipole components
    - Multipole analysis on design sensitivities shows that cavity design is extremely robust against mechanical imperfections
    - Higher order mode damping meets current impedance threshold requirements
- Mechanical model study for SPS test and SM18 test cryostat stress requirements are ongoing
- Several approaches of He tank design has been studied → Converging the ideas into a single design

Acknowledgments

- ODU – Jean Delayen, HyeKyoung Park, Rocio Olave, Chris Hopper, Alex Castilla, Kevin Mitchell

- JLab – Peter Kneisel, Tom Powers, Kirk Davis, Joe Preble, Tony Reilly

- SLAC – Zenghai Li

- Niowave – Terry Grimm, Dmitry Gorelov, Chase Boulware

- Fermilab – Tom Nicol

- CERN – Rama Calaga, Ofelia Capatina