RFD cavities processing, warm and cold tests summary

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For the US-HL-LHC-AUP collaboration

HL-LHC Collaboration Meeting, FNAL– October 14th–16th 2019

Outline

- **Bare RFD cavities cold test and processing:**
  - RFD1 test at FNAL prior to processing at FNAL\ANL
  - RFD1 processing (including BULK BCP) at FNAL\ANL
  - RFD1 test after processing → **rotational BCP validation**
- **RFD cavity + HOMs couplers tests and processing:**
  - RFD2 cavity + HHOM coupler (light BCP) cold test at JLAB → **validation of HOMs RF design**
  - RFD2+HOMs couplers Cold\Warm measurements at JLAB
- **HOMs couplers warm measurements:**
  - HHOMs coupler test box warm measurements
- **Bead-pull measurements:**
  - Electric center and multipole calculations for cavity QC

Summary of RFD Cold Tests

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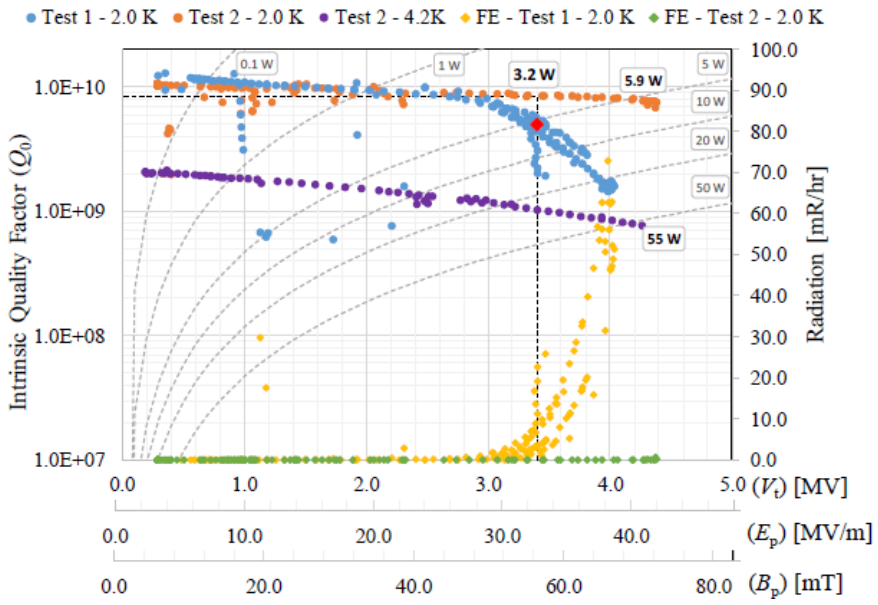
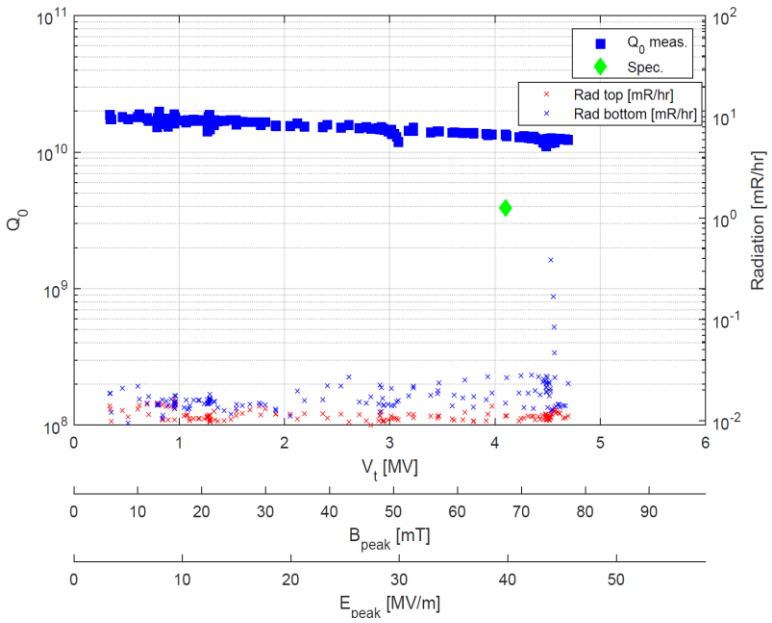
RFD-LARP-001 VTS at FNAL I

- Results of 1st test confirm Jlab results
- Q_0 was consistently higher than 1E10 up to quench.
- Cavity quenched at 4.7 MV of V_t exceeding the requirements of 4.1 MV.



Jlab results



Fermilab results

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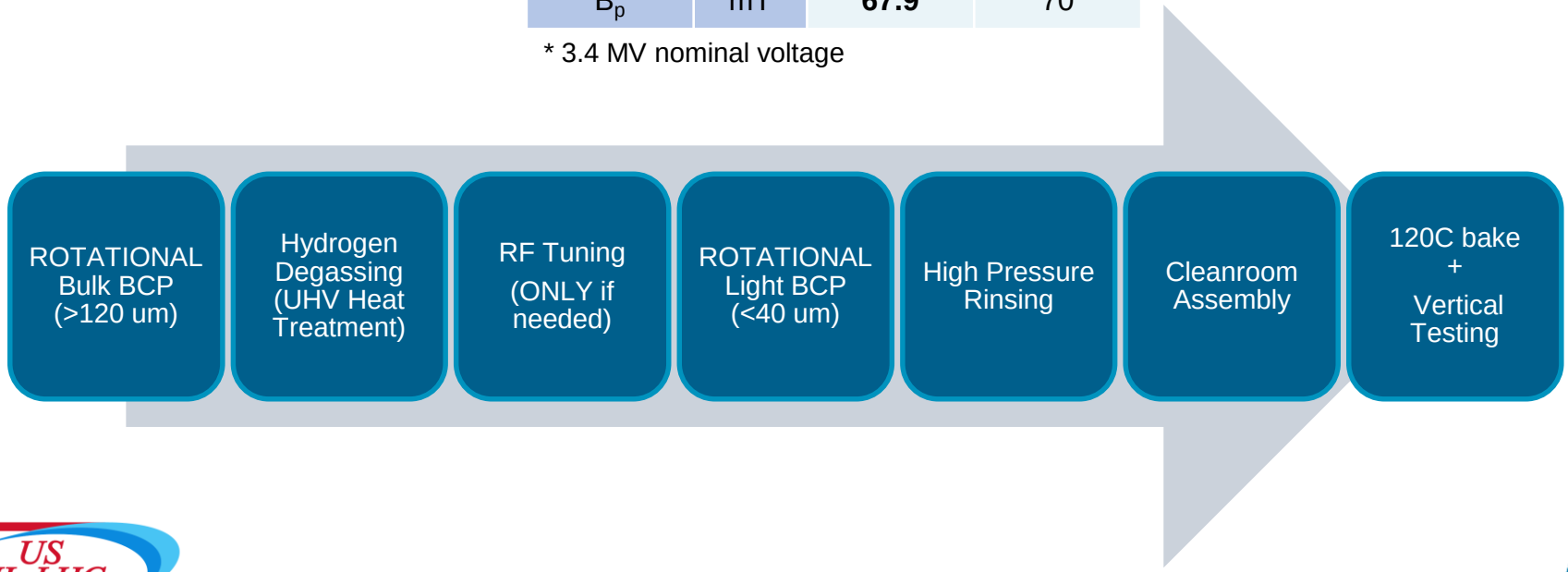
Bare Cavities Processing and Testing

- Buffered chemical polishing based SRF cavity processing plan
  - Electropolishing for complex geometries not easily achievable
- Standard SRF Cavity Cleanroom and Heat Treatment Techniques adapted to RFD geometry

Peak Fields of RFD Cavity
~50% of state of the art

V_t	MV	**4.1***	Peak field limitation
E_p	MV/m	**39.3**	40
B_p	mT	**67.9**	70

* 3.4 MV nominal voltage



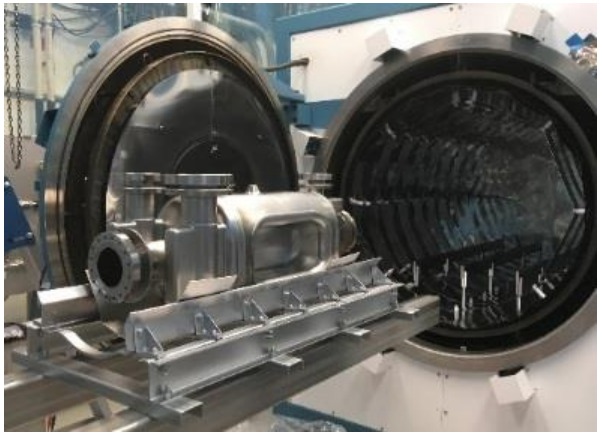
Rotational BCP + HPR Validation

- RFD-LARP-001 has been **successfully tested at FNAL**, after undergoing full processing at APS-TD and ANL facilities: **processing and facilities validation is complete**
- New rotational Bulk & Light BCP
- 600 C degassing
- HPR and clean assembly
- 120 C bake
- VTS test

Rotational BCP tool for RFD cavity (ANL/FNAL facility)

RFD HPR and Cleanroom Assembly (ANL/FNAL facility)

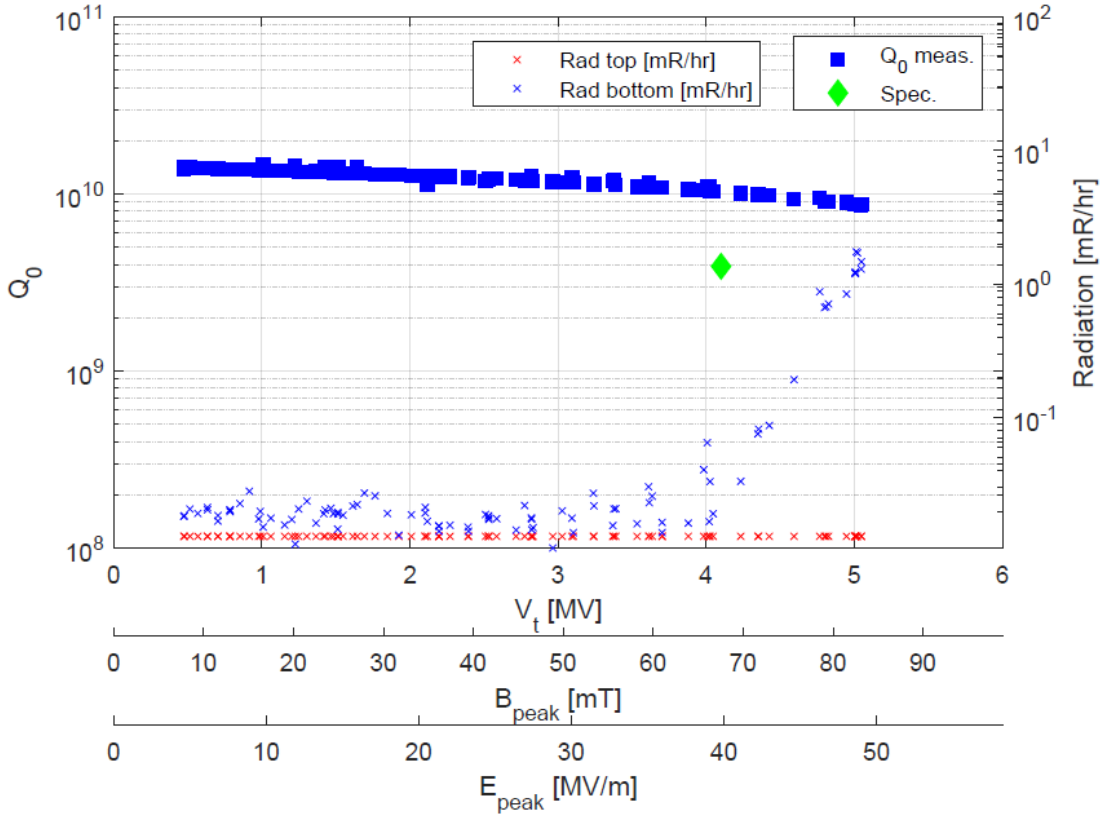
Heat Treatments + Cleanroom Assy Validation



600'C Heat Treatment (FNAL)

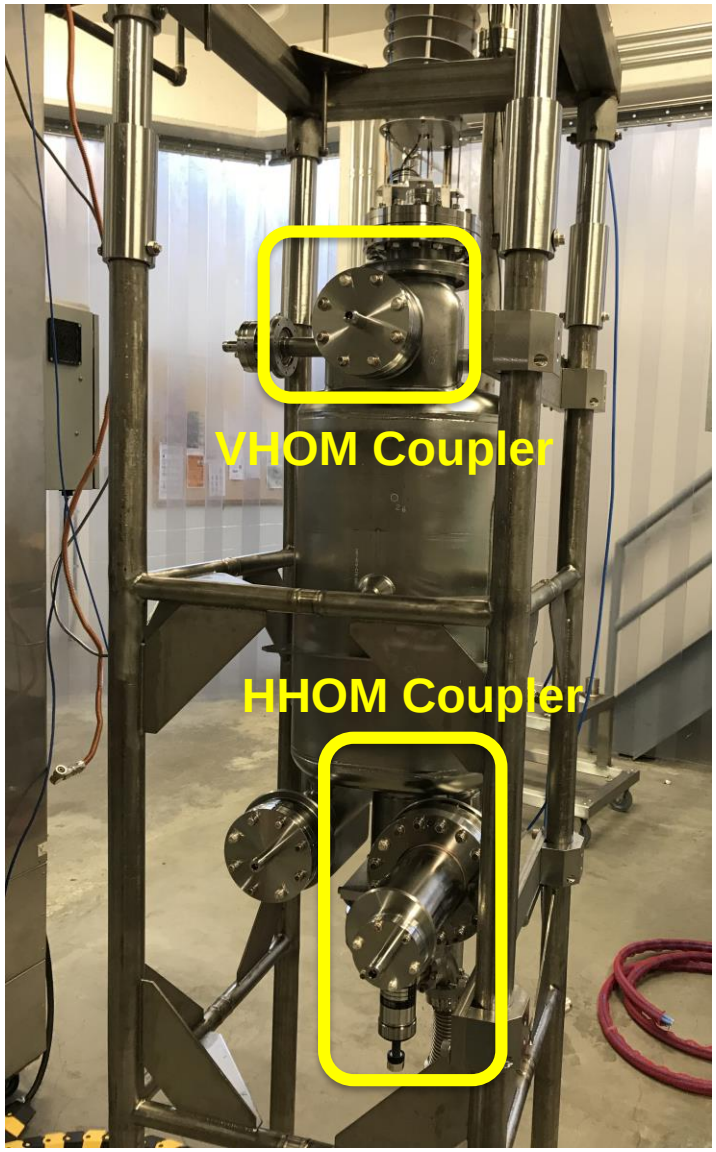
120'C Bake (FNAL)

VTS preparation (FNAL)



RFD-LARP-001 exceeded requirements for HL-LHC

Cold test of RFD Cavity + HOM Couplers



- Cold test of RFD-CAV-002 with HOM couplers
- Measurements were carried out with HHOM and VHOM couplers fabricated at Jlab (HHOM2 and VHOM2)
- HHOM Coupler has no Helium jacket welded
- To maintain consistency – same input probe, pick up probe and similar assembly configuration was followed as for the bare cavity RF test

Processing of LARP Prototype Cavity HOM Couplers

HHOM Coupler

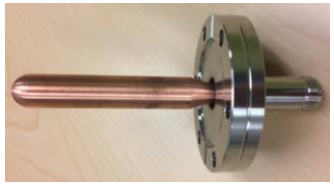
- Bench BCP done on the prototype HHOM filter, fixture can be used in the BCP cabinet
- Total removal
  - 1st iteration: 25 micron of removal and 2nd iteration: 13 micron of removal
  - Total removal from 2 BCPs <40 microns
  - No heat treatment done
- HHOM filter is ultrasonic degreased and manual HPRed before assembly

VHOM and HHOM Probes (Cu)

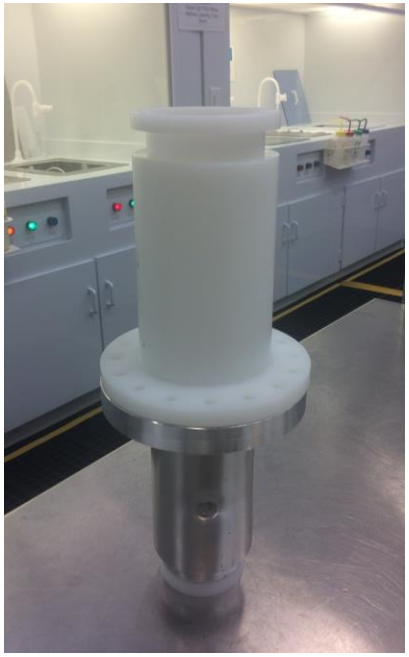
- Ultrasonic degrease

VHOM Probe

HHOM Probe



BCP fixture



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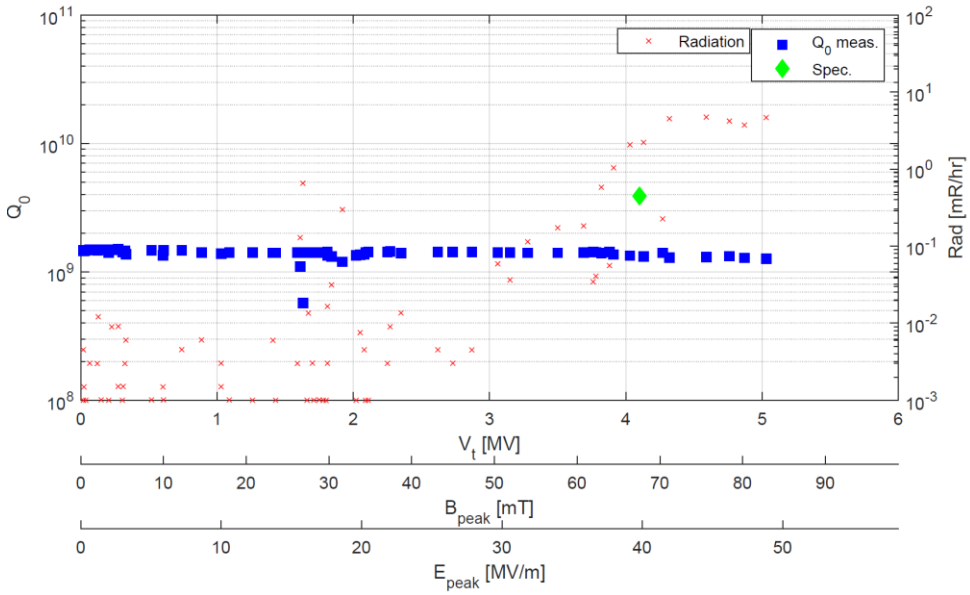
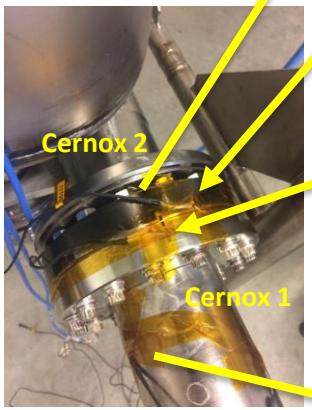
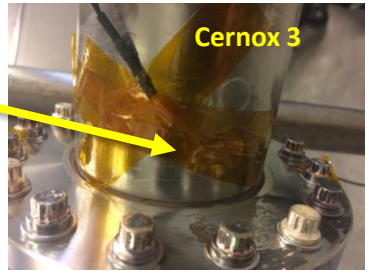
First Test with both HOM Couplers





Cernox 2: On the HHOM cavity port SS flange

Cernox 1: On the HHOM coupler port SS flange



1st Test HHOM&VHOM– Cavity with terminated HHOM and VHOM

- Strong coupling of fundamental mode through VHOM coupler (Q_{ext} ~2×10^9)

Findings:

- Cavity didn't quench → RF power limited
- Reduced Q_0 compared to Q_0 of the bare cavity test Q_0 heating of the HHOM coupler
- No new multipacting levels and similar field emission as in the bare cavity test

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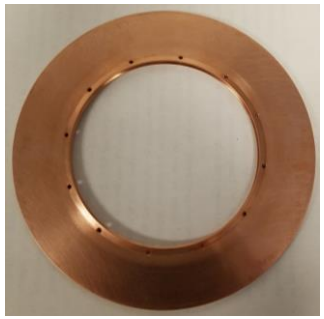
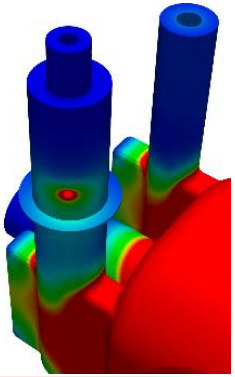
RFD cavity + HHOM and VHOM validation

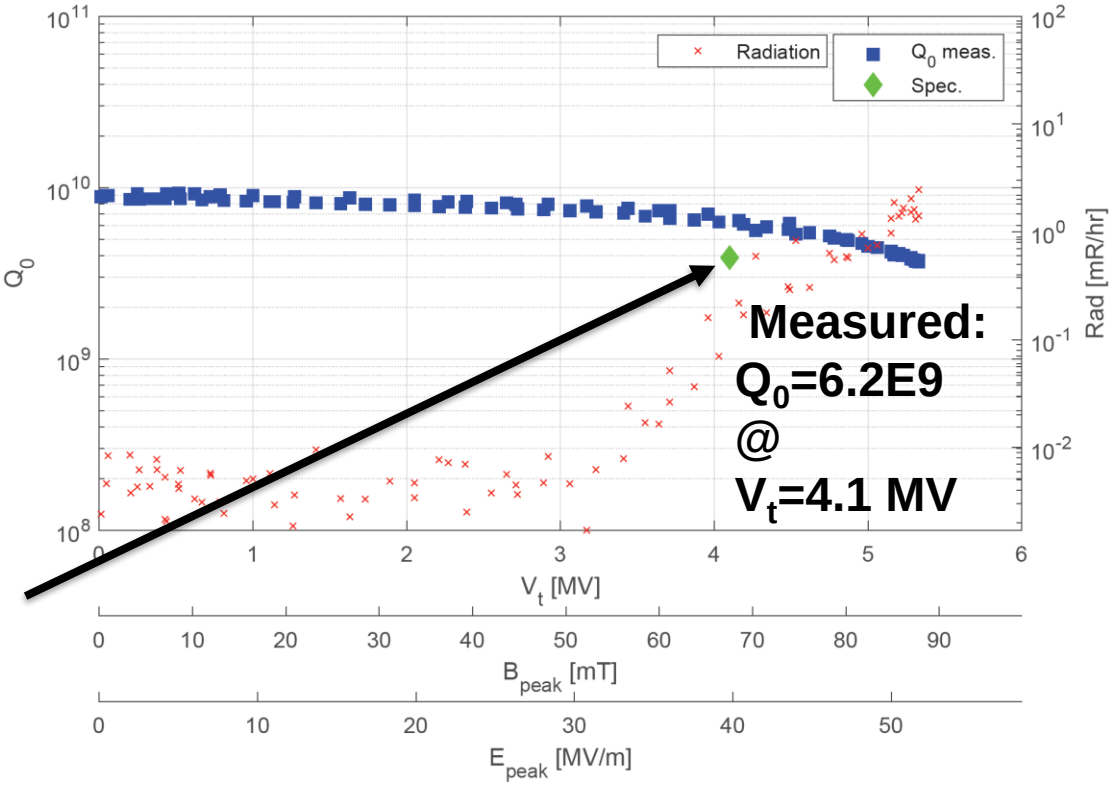
- RFD2 cavity has been successfully tested with all RF ancillaries.
- HHOM RF leakage has been resolved **Q_0 exceeds requirement, quench Vt is 5.3 MV>4.1 MV.**
- HHOM and VHOM dampers design has been successfully tested.
- Fundamental mode rejection has been tuned for both HHOM and VHOM.



Regular gasket on HHOM coupler (left) and RF gasket (right)

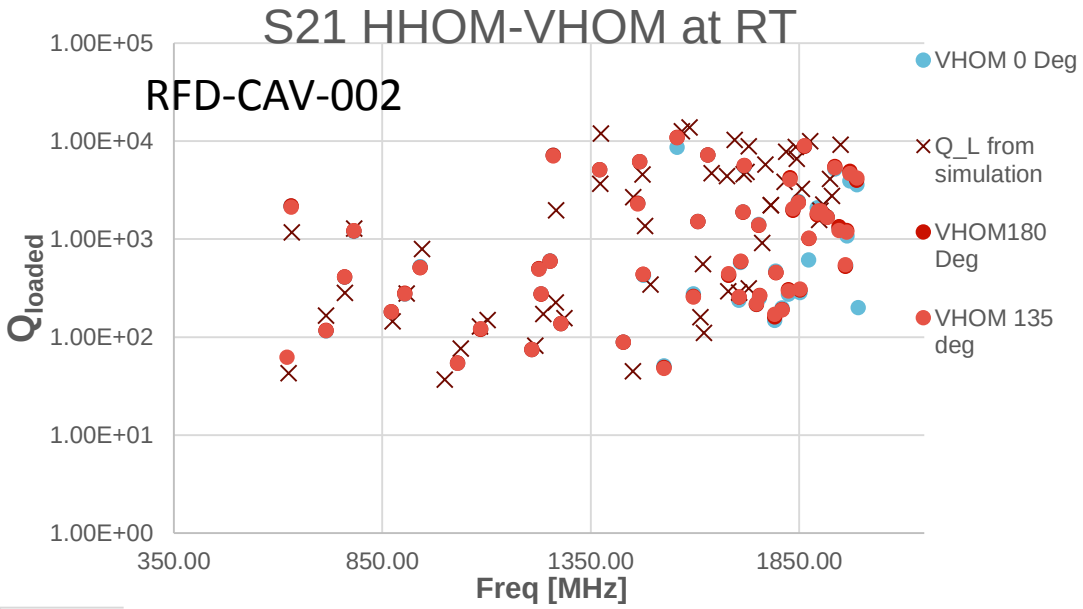


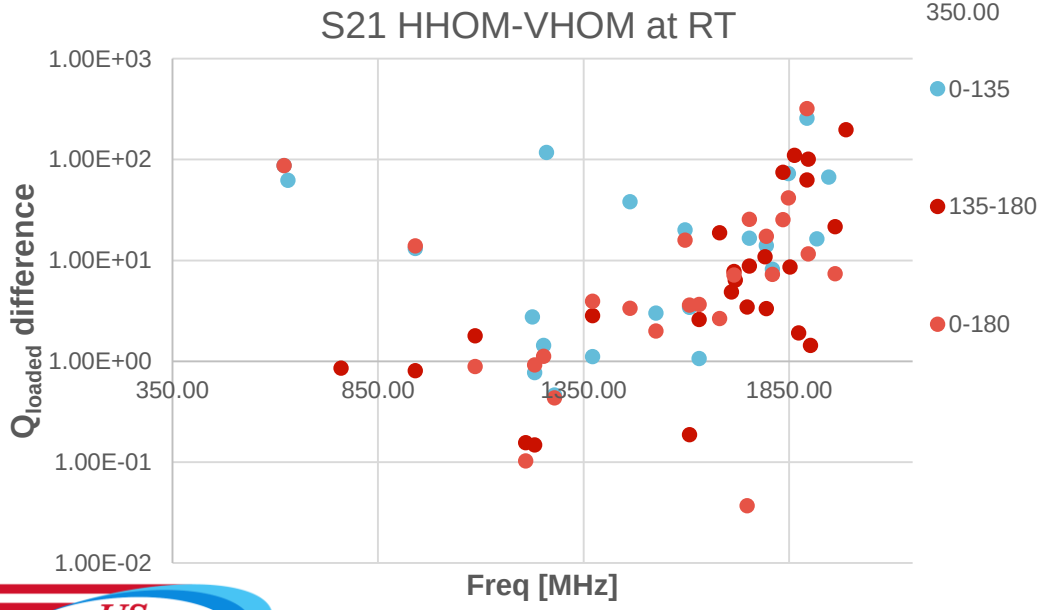
Requirement:
Q_0=3.9E9
V_t=4.1 MV



Measurements of HOMs: Q_L at RT

- Measurements of Q_L are in good agreement with simulation up to ~1.65 GHz
- Q_{ext} of fundamental mode can be tuned rotating the HOMs Cu probes→ minor changes of loaded Q for HOMs

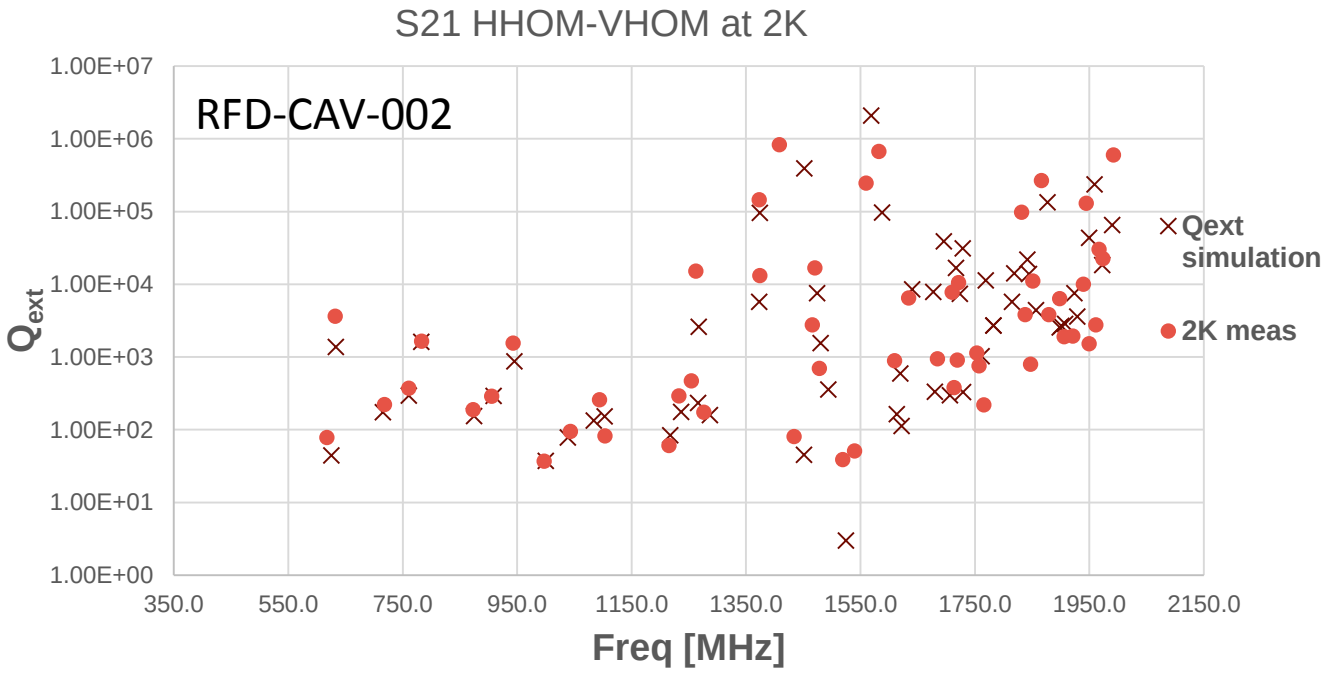




- Difference in loaded Q for all measurable HOMs at RT:
  - VHOM probe at 0, 135 and 180 degrees with respect to design position

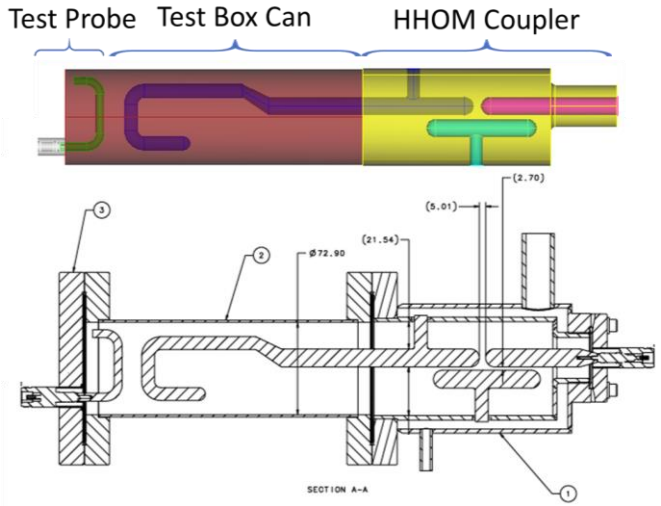
Measurements of HOMs: Q_{ext} at 2K

- Measurements of Q_{ext} are possible for most HOMs when the cavity is in helium bath at 2K.
- Good agreement with simulations despite manufacturing imperfections of cavity and HHOM coupler.



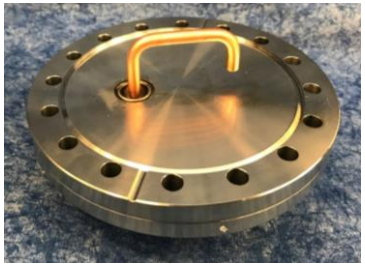
HHOM Test Box

- Fabricated at JLab with HL-LHC-AUP funding to ODU
- Test box can – SS can with 6” conflat flanges
- Test probe – Cu probe brazed on to coaxial feedthrough
- Test box can and test probe dimensions were measured using CMM to determine the offsets in fabrication

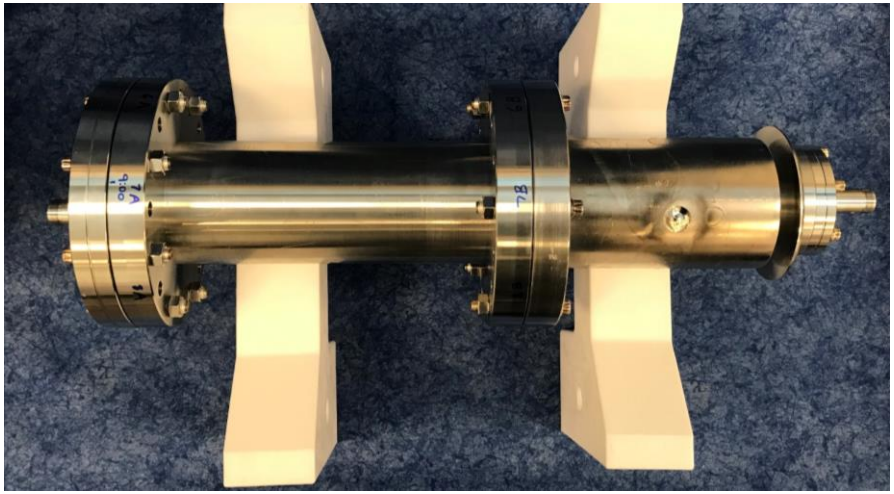


Test box can with HHOM coupler

Test probe

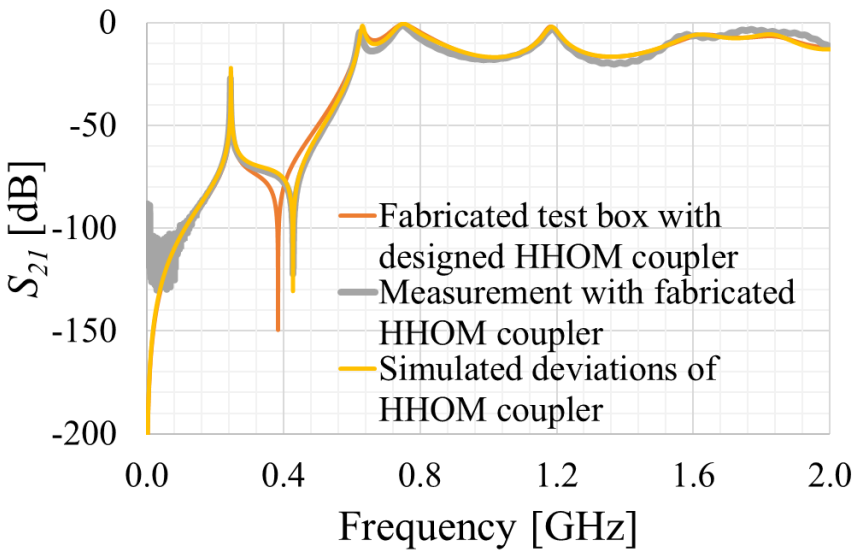


Full test box assembly with HHOM coupler

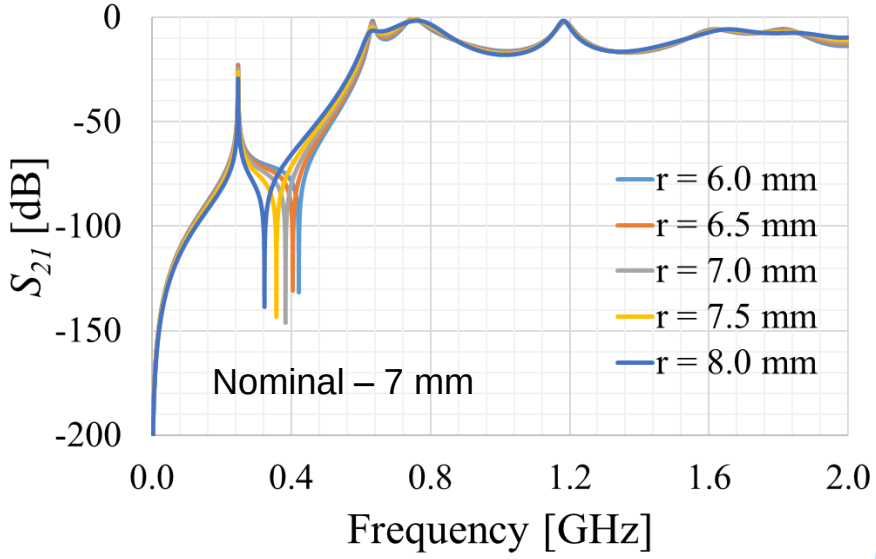


Measurements on RF Test Box

- Test box can and test probe dimensions were measured using CMM to determine the offsets in fabrication
- Comparison of S21 transmission between designed and fabricated rf test box (with designed HHOM coupler)
- Deviations < 0.5 dB in frequency range 620-2000 MHz
- Measured HHOM coupler shows a shift in the notch
- Shift corresponds to a shift of 0.6 mm in T and Hook with respect to Probe
- Rejection of fundamental mode can be tuned adjusting Cu probe (radius and/or length)



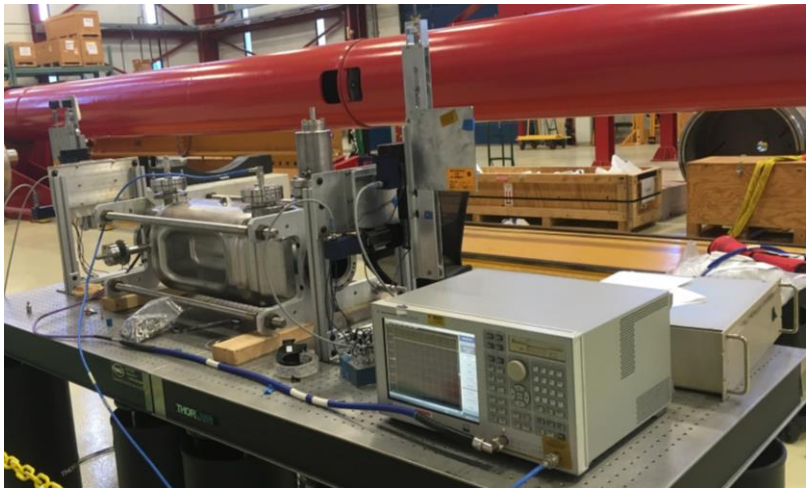
Deviation HHOM S21 measurement from simulation

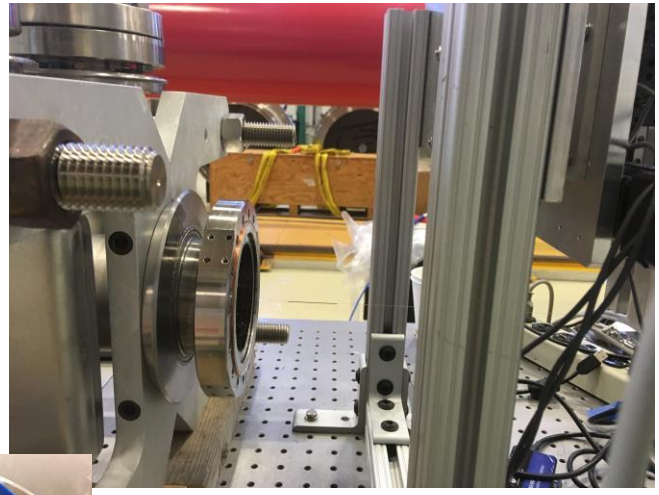


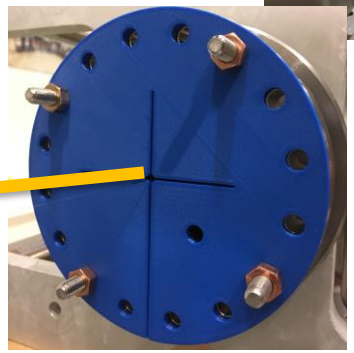
Notch tuning with radius of HHOM probe

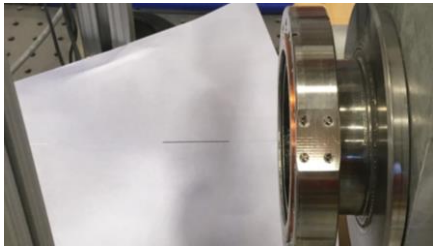
Bead-pull set up

- X-Y motors for positioning the bead within the cavity
- Needle 0.5 mm diameter, 40 mm long
- Bead-pull line is aligned to the cavity flange centers



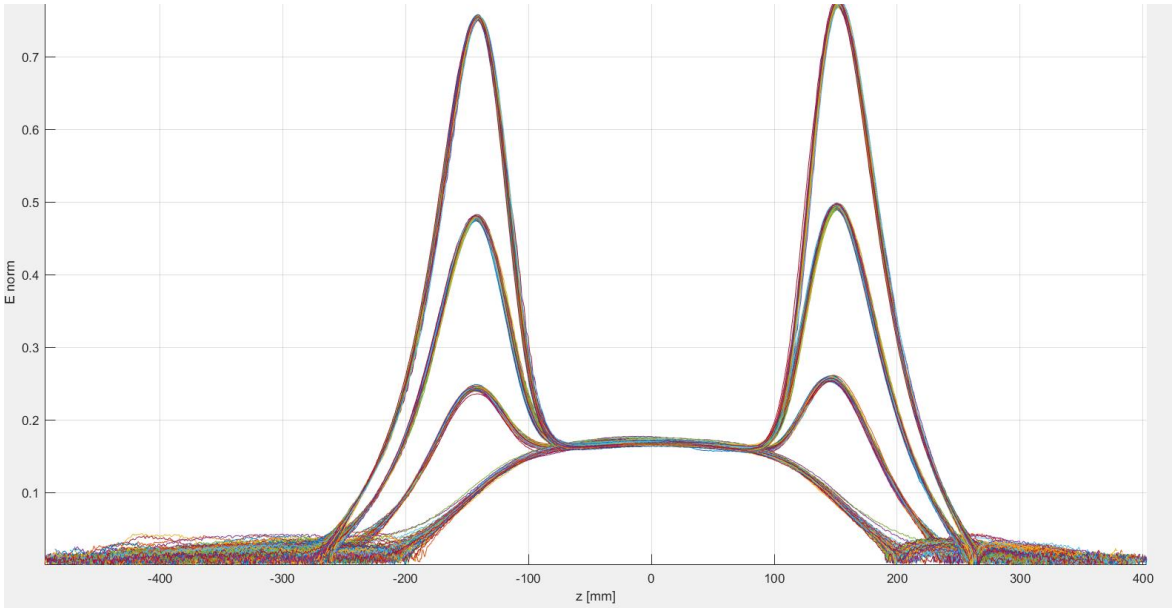


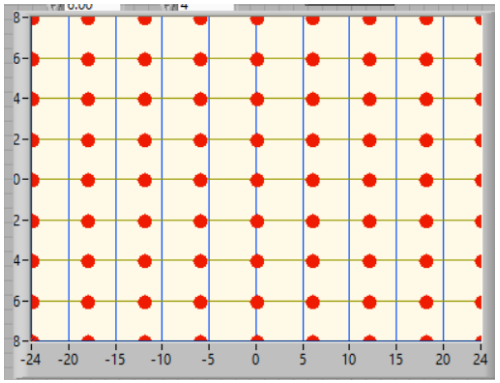


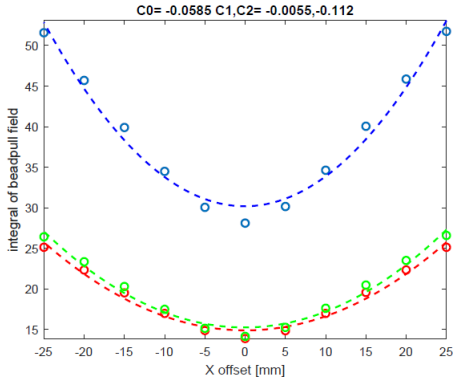


Electric center measurements

- X-Y grid for bead-pull profile measurements



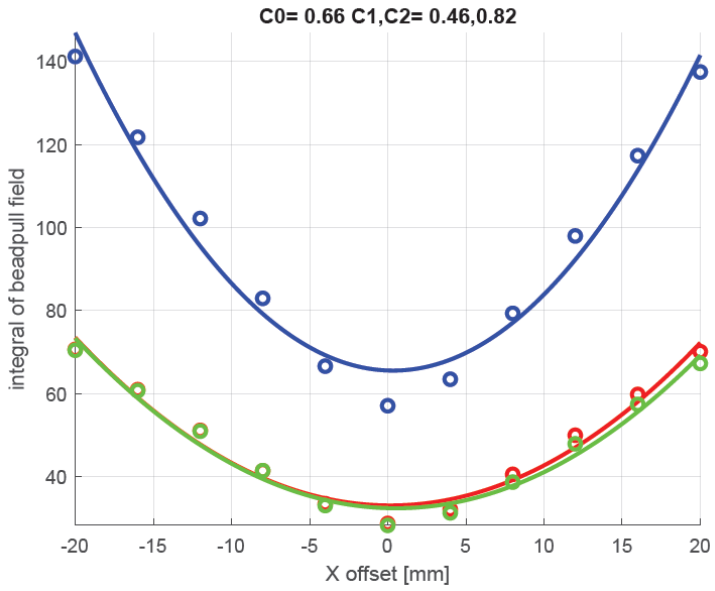


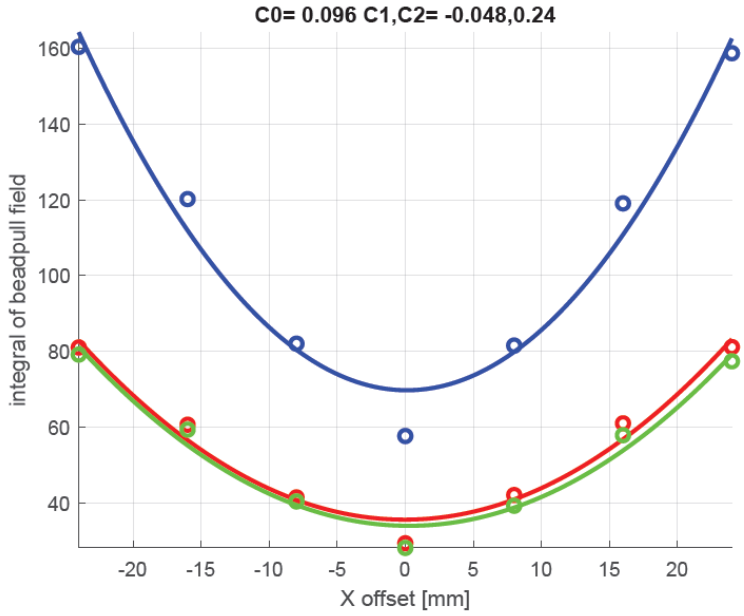


- Integration of the whole BP profile allows getting to X offset of the electric-geometric center. C0
- Integration of two halves of BP profile gives two X offsets, one for each lobe of E_z. C1, C2

Electric center results

- Y sensitivity is negligible, X offsets can be calculated for integrals of bead-pull field

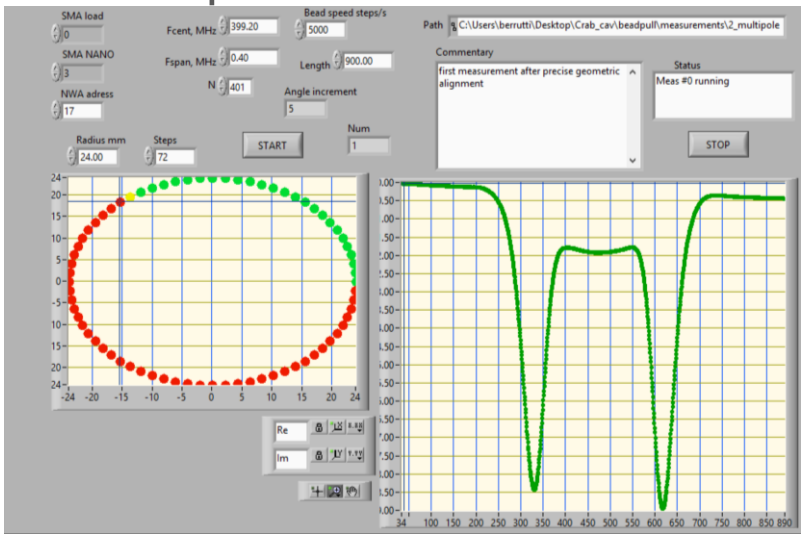


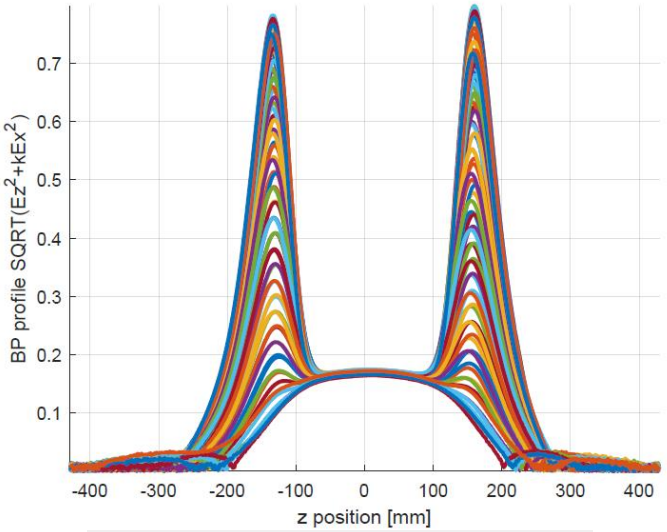


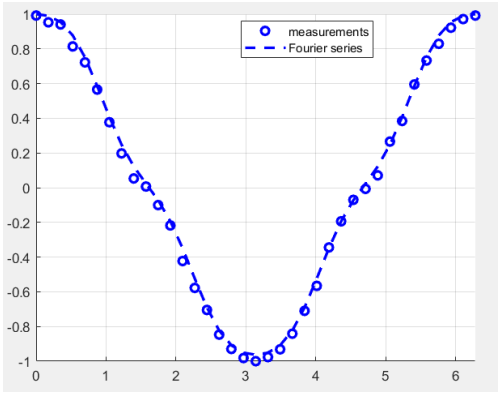
- Measurements after alignment to the Geometric center of the RFD1 cavity+HOMs couplers
- Electric center of RFD1 with HOMs couplers, after alignment of system given by previous measurements; precision approx. 100 microns

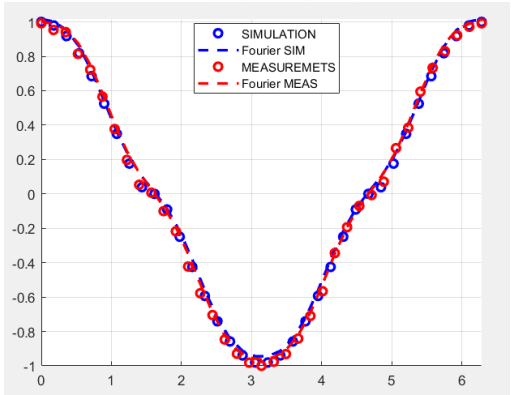
Multipoles measurements

- Bead-pull measurements on a circular profile: each dot represents a BP profile





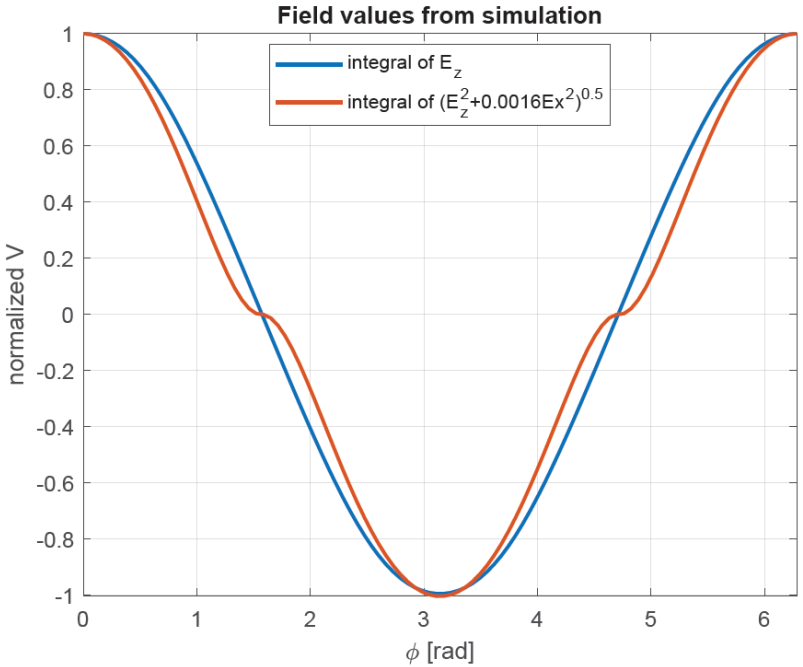




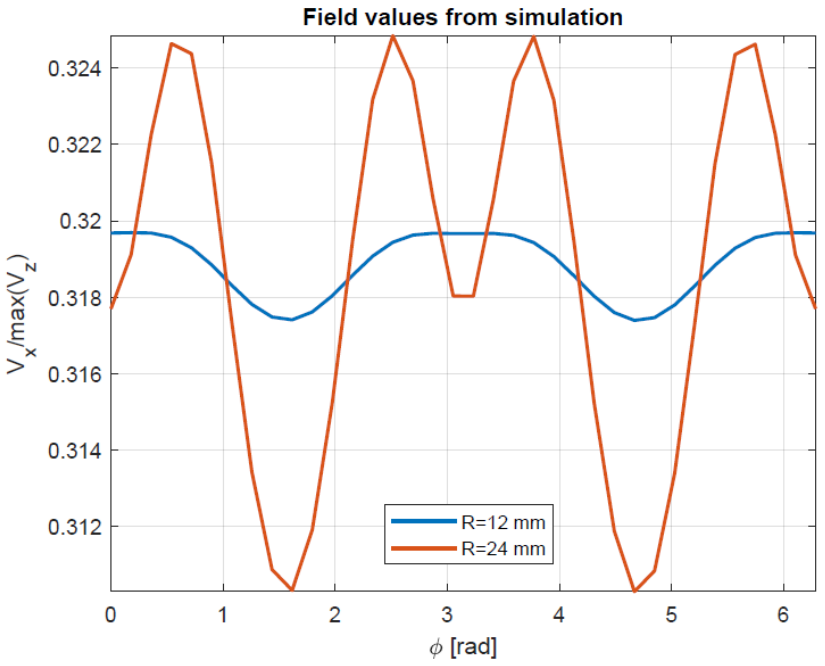
- Good agreement between simulations and measurements, Fourier amplitudes determine multipoles

Multipoles considerations

- The needle used for measurements induces a phase shift $E_z^2+0.0016*E_x^2$
- The effect on multipoles of the x component can be evaluated via simulations: comparing V_z with the integral of the measured field
- The effect of E_x is not negligible on b_3, making its measurement not feasible: b_3 goes from approx. 483 mTm to over 100 times more when considering mix field components.



- For V_t=10 MV: $V_z \rightarrow b_{3z}$ =483 mTm while $V_{z,x} \rightarrow b_{3zx} \approx 100 * b_{3z}$



- V_x contribution depends on R and phi, not negligible compared to V_z

Summary and lessons learnt

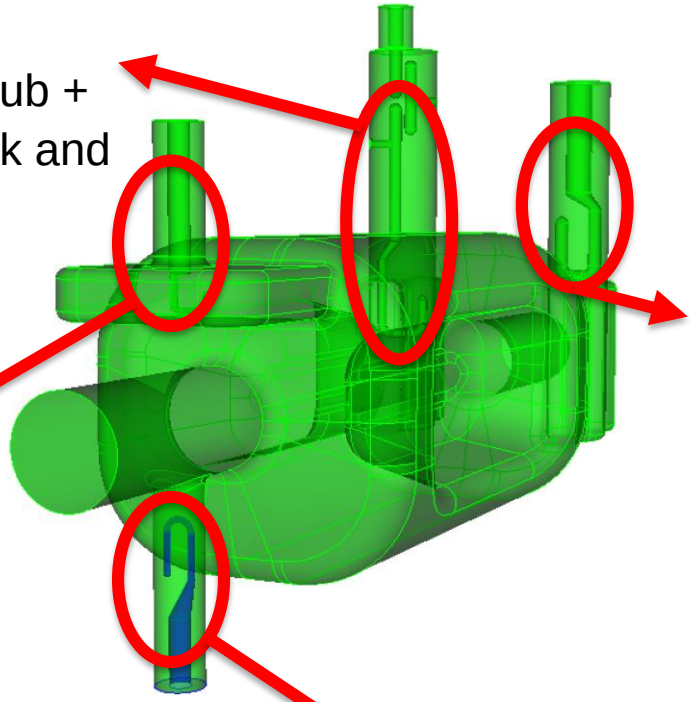
- Bare cavity cold tests were successful:
  - RFD1 met requirements of Q0 and Vt for HL-LHC after → **Full validation of all processing steps and facilities at FNAL\ANL**
- Cavity + HOMs dampers cold tests:
  - Initially low Q_0 has been measured, due to dissipation of magnetic field in the SS flange
  - Cavity and HOM couplers have been tested successfully with RF gasket that avoids heating and additional losses → **RFD cavity + HHOM and VHOM validation**
- HOMs couplers warm measurements:
  - **HHOM test box allows QC and notch tuning of HHOM filter** → it will be used for QC for HL-LHC couplers
- Bead-pull measurements of RFD1+HOMs couplers:
  - The **electric center measurements proved to be reliable**, accuracy of 100 microns good enough to calculate pole symmetry
  - Multipole measurements agree very well with simulation data
  - **E_x component affects too big to effectively calculate b_3** for HL-LHC RFD cavities production.

BACK-UP SLIDES

Couplers for RFD CC overview

HHOM:

- It couples to Horizontal polarization HOMs
- Cutoff waveguide stub + high-pass filter (hook and tee)



FPC:

- Waveguide stub + hook
- Qext: 5×10^5

VHOM:

- Waveguide stub selectively couples to accelerating HOMs and vertical dipole HOMs
- No filter needed

Pickup port:

- On the V-HOM side of cavity
- Qext ~ 2×10^{10}