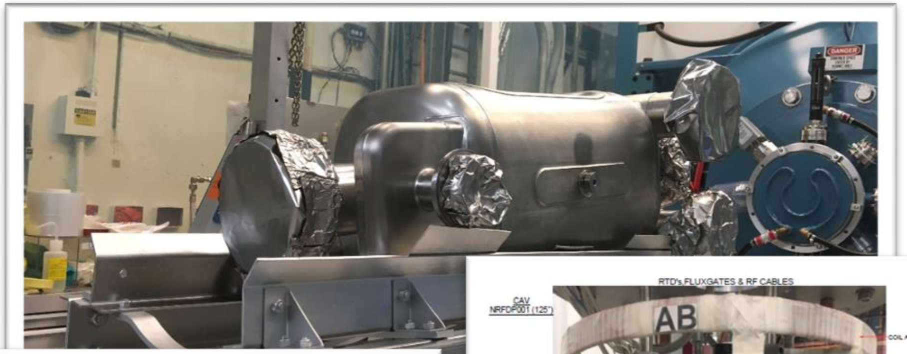
US-AUP RFD Testing

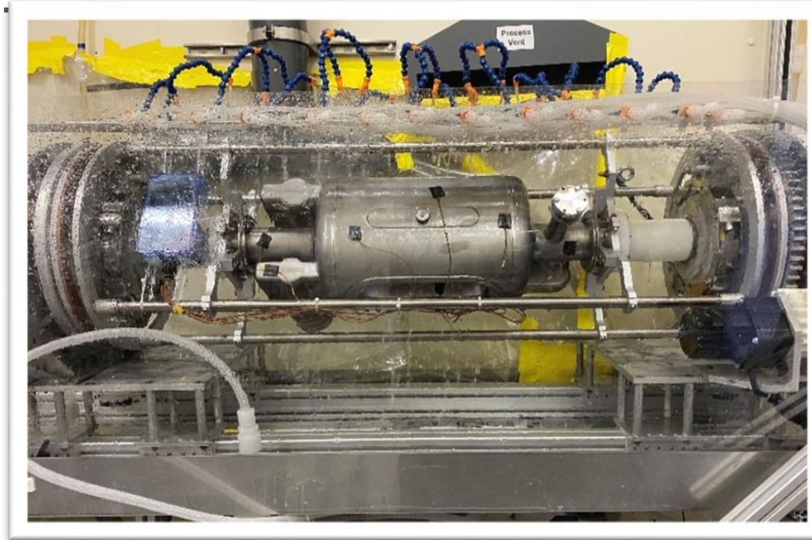
A. Castilla, N. Huque, P. Owen – Jefferson Lab
S. De Silva, J Delayen - ODU
P. Berrutti, M. Narduzzi, C. Narug, L. Ristori - FNAL

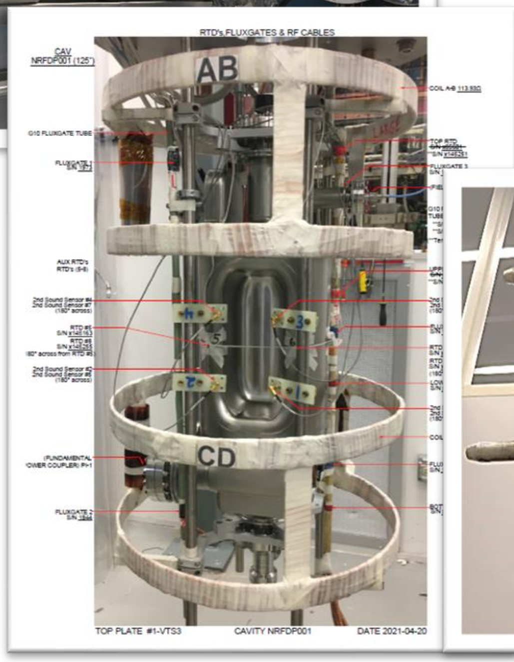
13th HL-LHC Collaboration Meeting. – Sep. 25th–28th 2022

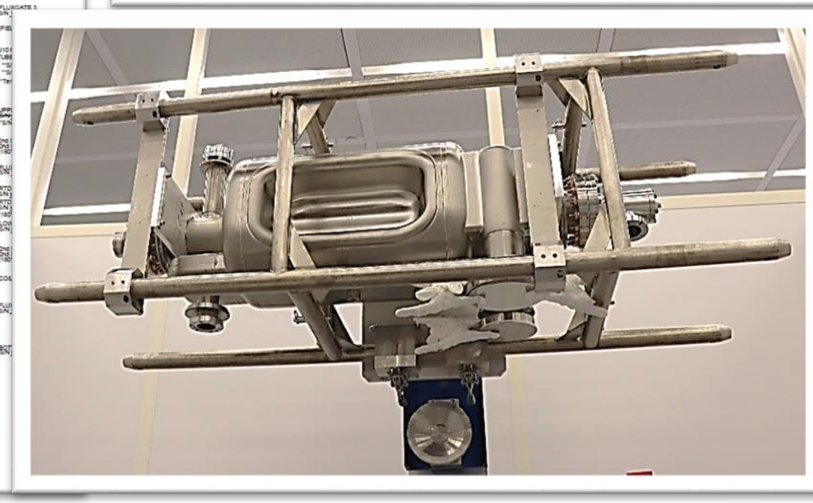
Prototypes (NRFDP001 & 2)

- 2 prototypes manufactured by ZRI in 2020.
- Rotational BCP at ANL/FNAL facility (ave. removal 130+40 um).
- 600 C for 10 h heat treatment performed at FNAL.
- 1st HPR+Assy.+test at FNAL.

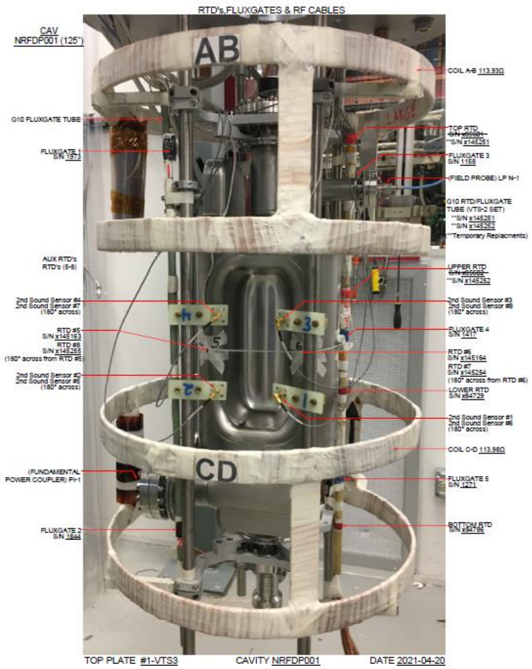


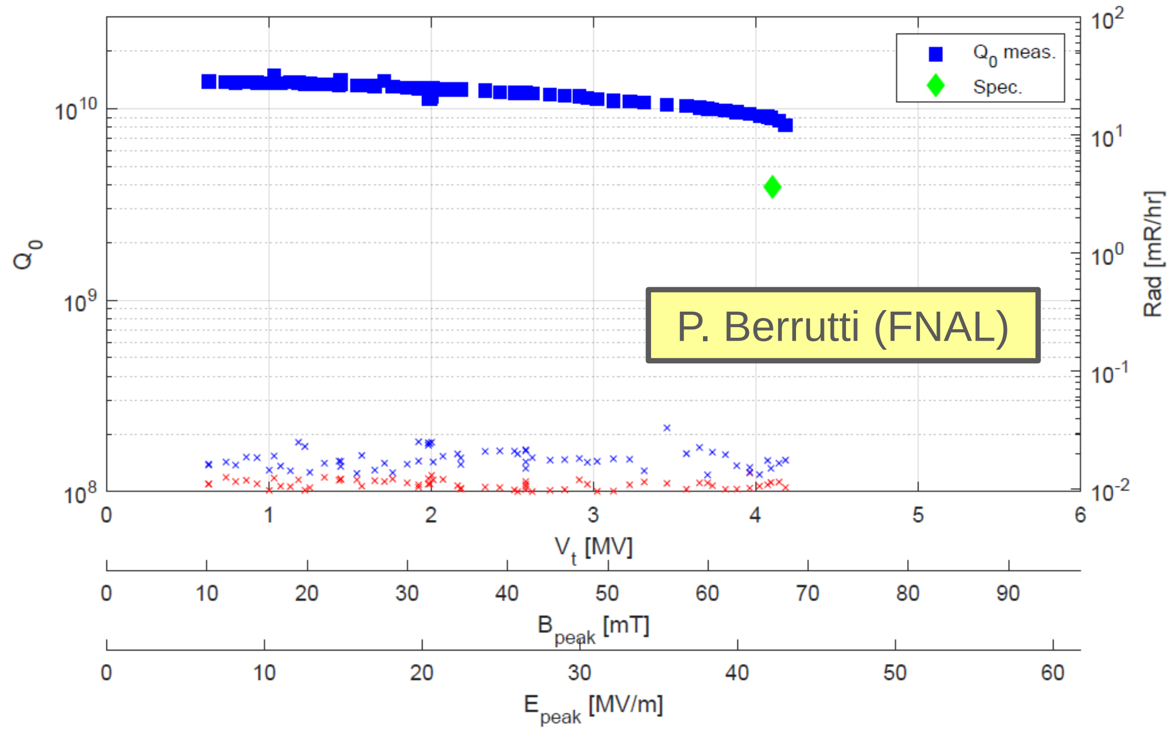




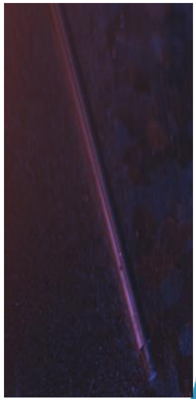


NRFDP001 Bare Cavity Test Results



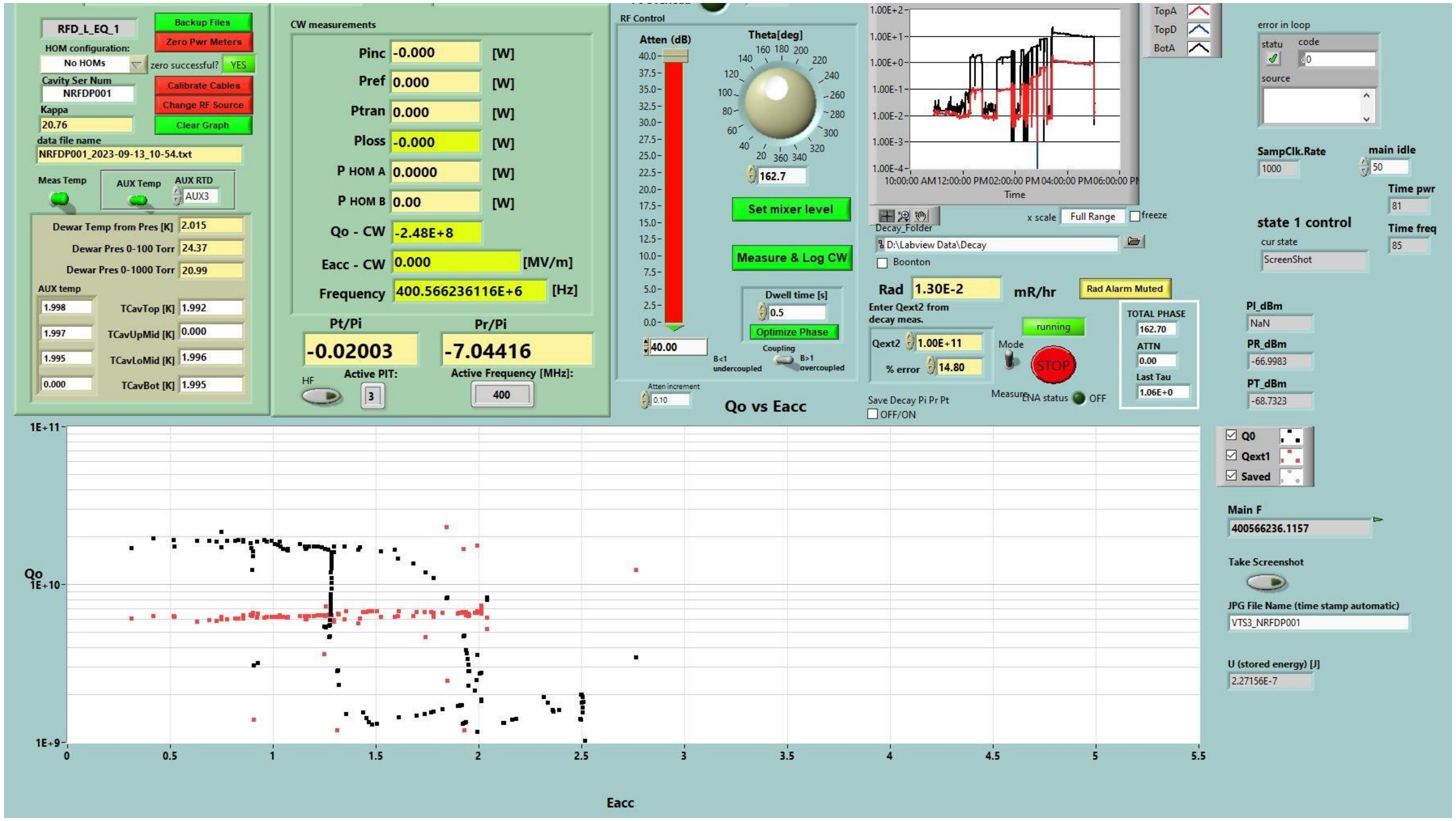


- Q_0= 8.2E9 V_t=4.18 MV at quench, Low field Q_0= 1.5E10, B_{ext}= 0.6 mG.
- **No FE detected**: effective HPR and clean assembly
- OST indicates quench spot between corner and end-cap weld and optical inspection showed defect in the quench area (final weld).
- **This cavity was sent to ZRI for complete re-processing in order to validate their procedures and improve the cavity performance.**



Latest NRFDP001 VT: Inconclusive

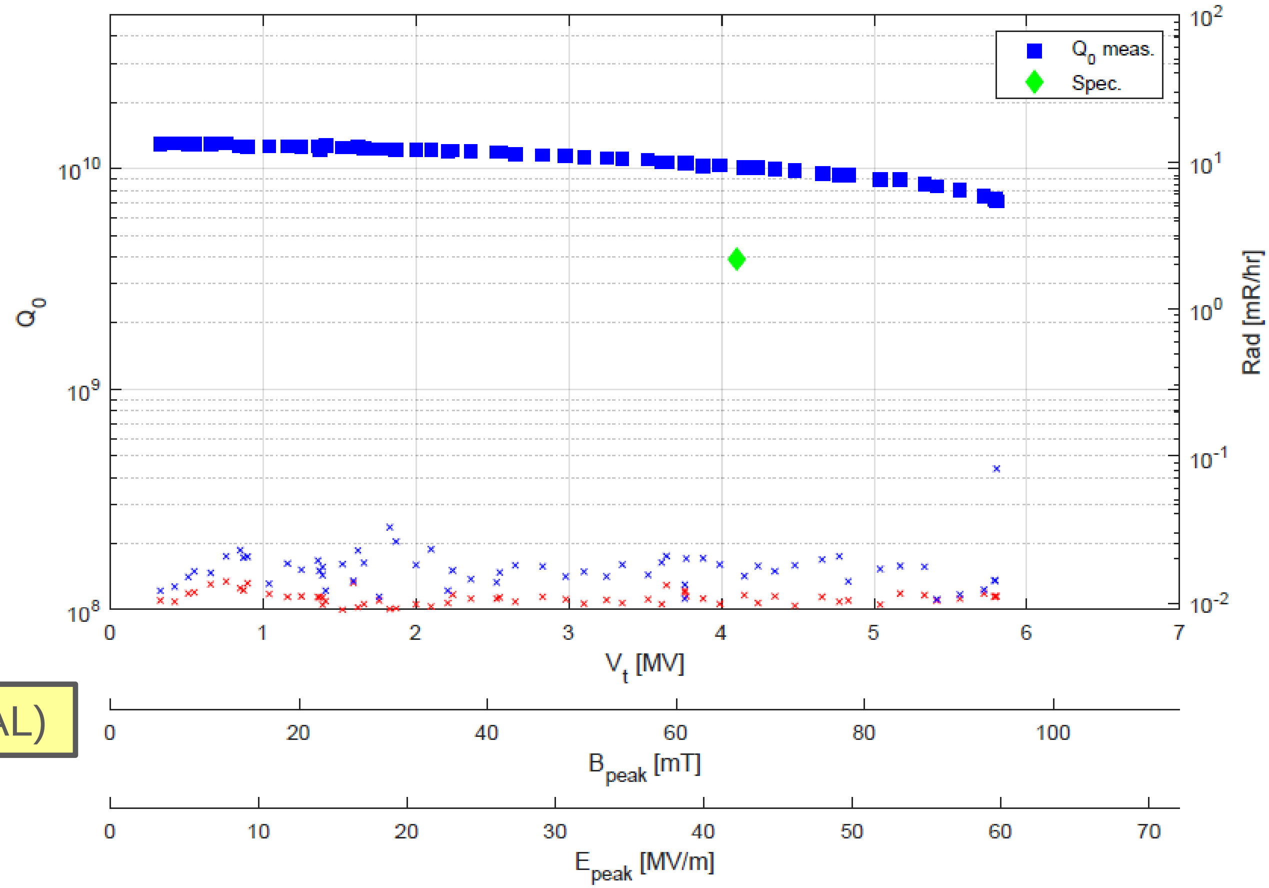
A. Netepenko & L. Ristori (FNAL)



- A recent test at FNAL after re-processing at ZRI, proved inconclusive due to an early FE onset and suspected multipacting.
- The cavity will be sent to Jefferson Lab to:
  - Test as is.
  - Open and inspect.
  - HPR and re-test.

NRFDP002 Bare Cavity Test Results

- Excellent results: hard quench at 5.8 MV, **no detectable FE during the test.**
- Low field **Q_0 exceeding 1.3E10, Q_0(@4.1MV)=1E10**
- E_{peak}= 59.7 MV/m B_{peak}= 94 mT @ 5.8 MV (quench)



P. Berrutti (FNAL)

Bare cavity (prototype 2) + HOMs Testing

- Several iterations to our hardware/procedure to seal the cavity.
- Mixing hardware with US – EU [and CERN] standard has not made it easier (full "hardware kits" to be provided by CERN for the series).
- Assembly prioritized seal over cleanliness.
- Full cycle sequence is well understood.

Hand port rinse before HPR

Clean room assy.

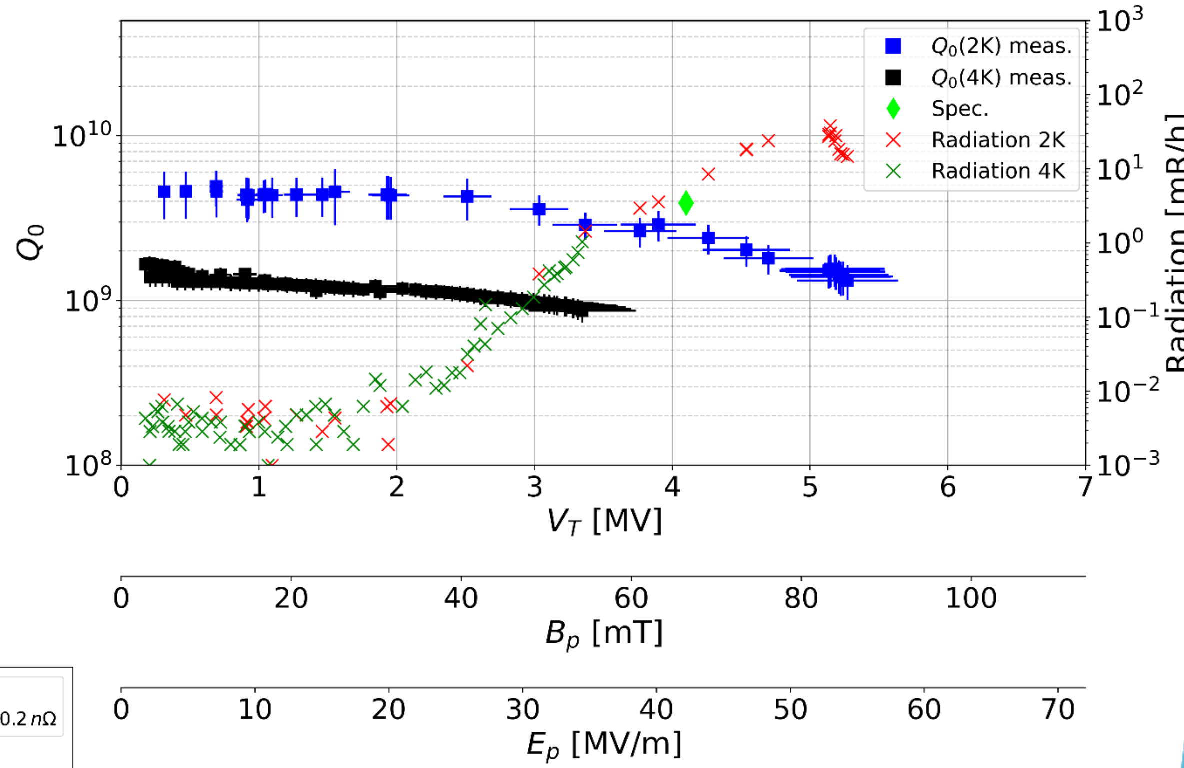
48h @120C Bake

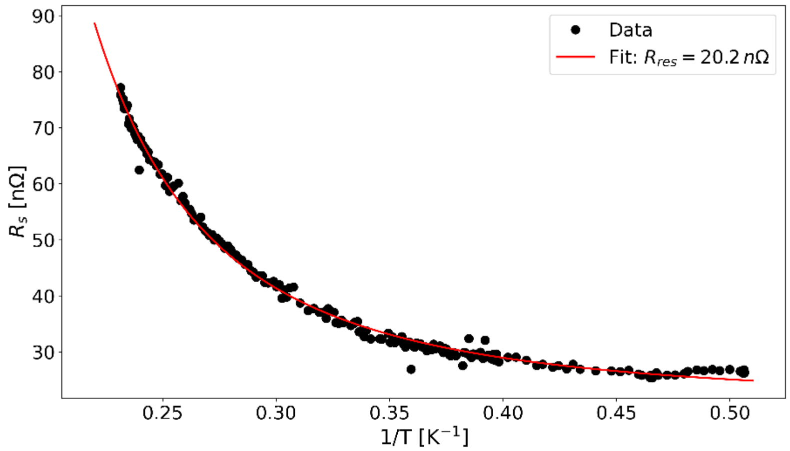
Instrumentation

NRFDP002 1st test w/HOMs

@2K:

- Low field $Q_0 \approx 4.6E9$.
- $Q_0(@4.1MV) \approx 3E9$.
- Max E_{peak}= 51 MV/m.
- Max B_{peak}= 80 mT.
- Power limited (150 W, no Quench).
- $R_{res} \approx 20$ nΩ.



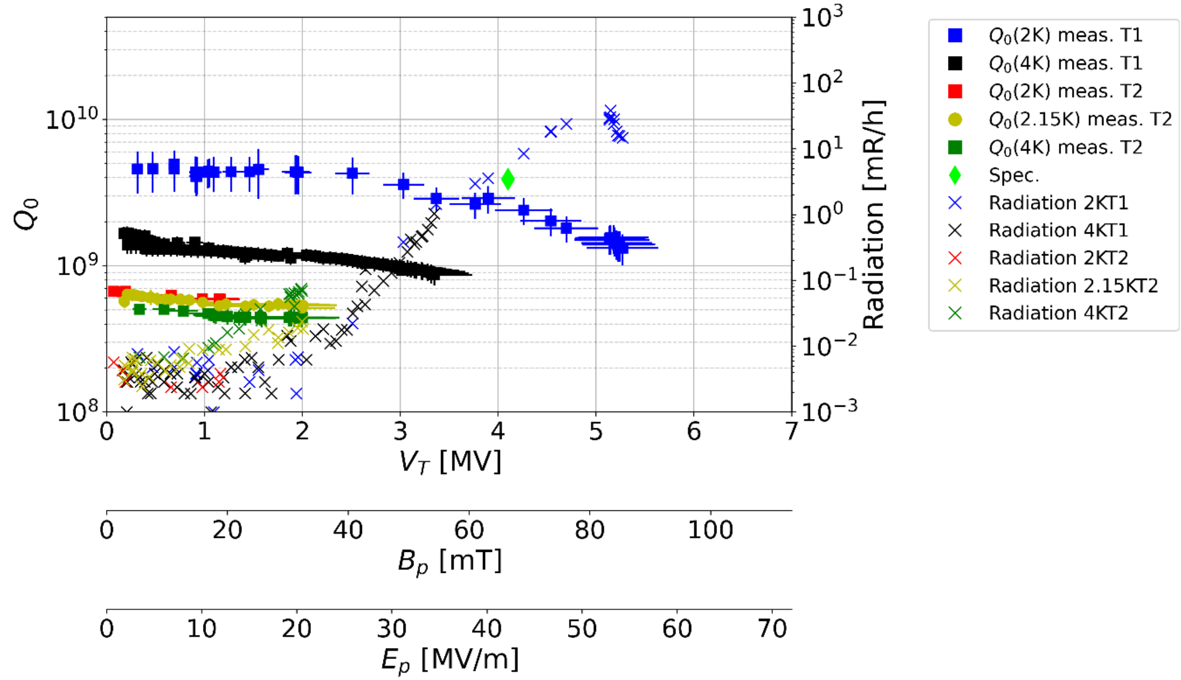


- Early FE onset (~2.5 MV/m) consistent with assembly trade-offs.
- Indications extra losses:
  - Bad RF-gasket contact (dejavu?)

NRFDP002 2nd test w/HOMs

@2.15K:

- Low field $Q_0 \approx 6E8$.
- Max $E_{peak} \approx$ 21 MV/m.
- Max $B_{peak} \approx$ 33 mT.
- No change in Q between 4 K and 2 K
- $R_{sur} \approx 175\ n\Omega$.
- Early FE onset = dirty assy.

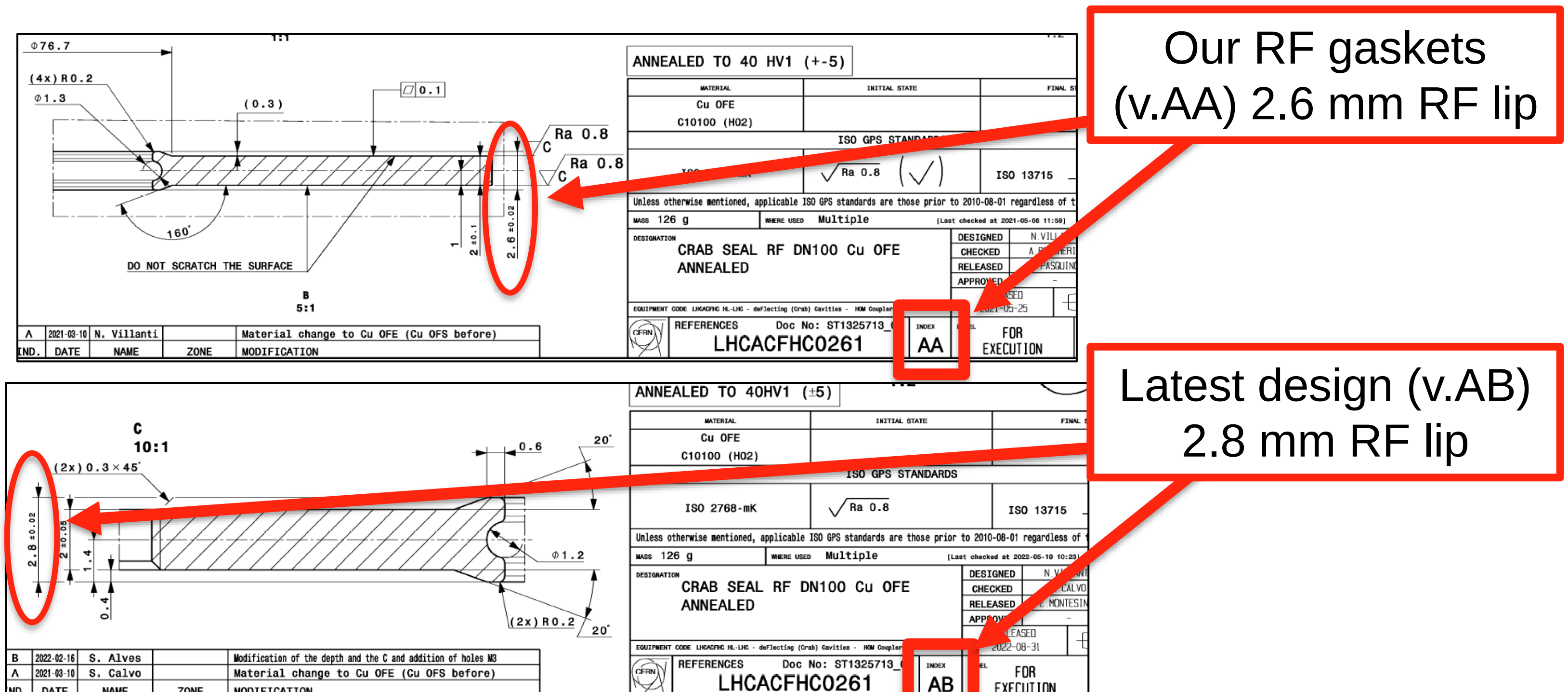


- A superfluid leak (~5E-5 torr) limited the FWD power (25 W) at 2 K.
- Vacuum conditions were stable at 2.15K but we were still power starved at 2 MV due to large reflections (~85 W FWD).
- At this point is more than sure that the poor RF shielding on the HHOM RF gasket is the culprit of our high losses (learned from LARP).

NRFDP002 test w/HOMs

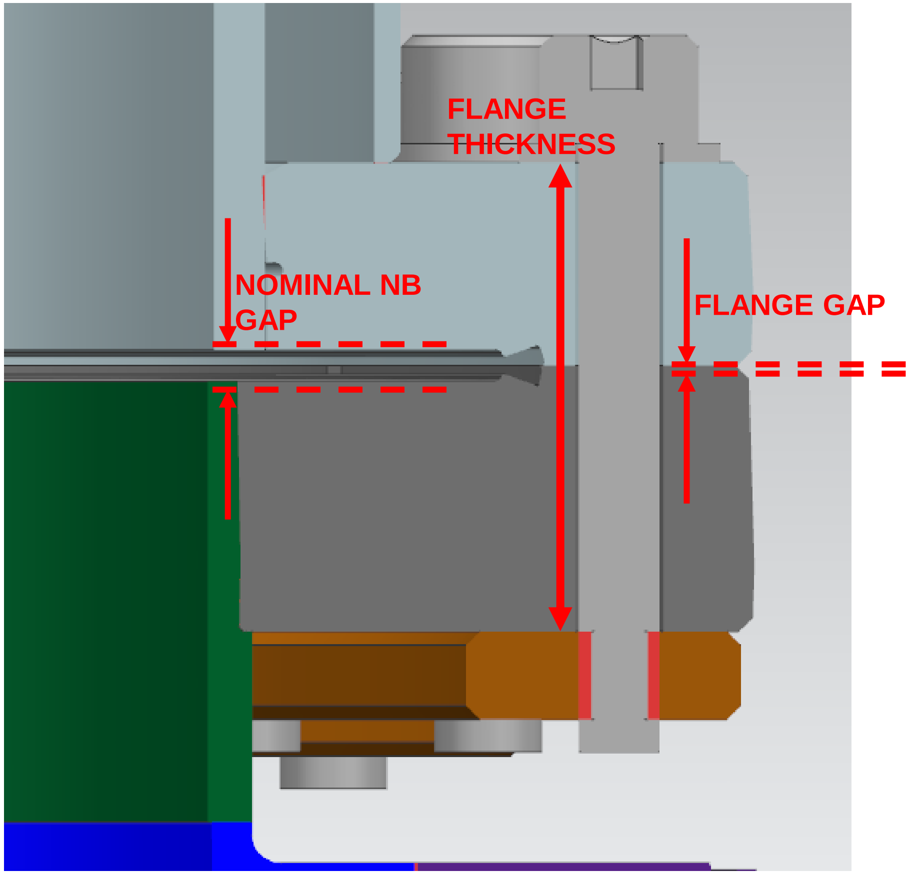
Amongst the different problems to solve we had:

- Improvement on the cleaning and assembly procedure needed to reduce FE onset.
- Understanding on the Qext for the VHOM is necessary.
- Poor RF contact on the HHOM RF gasket:
  - Needed new hardware to sustain higher torques.
  - Needed a new procedure to ensure full compression of the RF gasket.



Flange Connection Measurements (1)

- Nominal values in the table.
- When the flange gap reaches zero, the lips would be compressed by 0.2mm and desirable RF contact can be achieved.

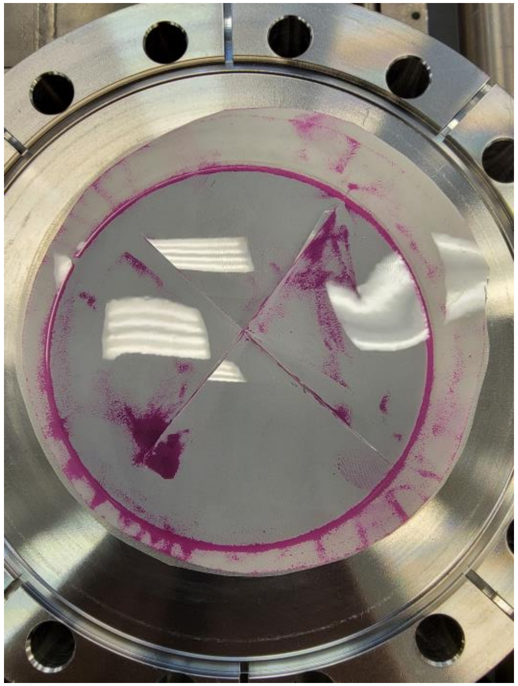


Quantity	Value (mm)
Cavity Flange Thickness	19.7
HHOM Flange Thickness	15.01
Total	34.71
Nominal Nb Gap	2.4
Seal Lip Height (+/-0.1)	2.6

Flange Connection Measurements (2)

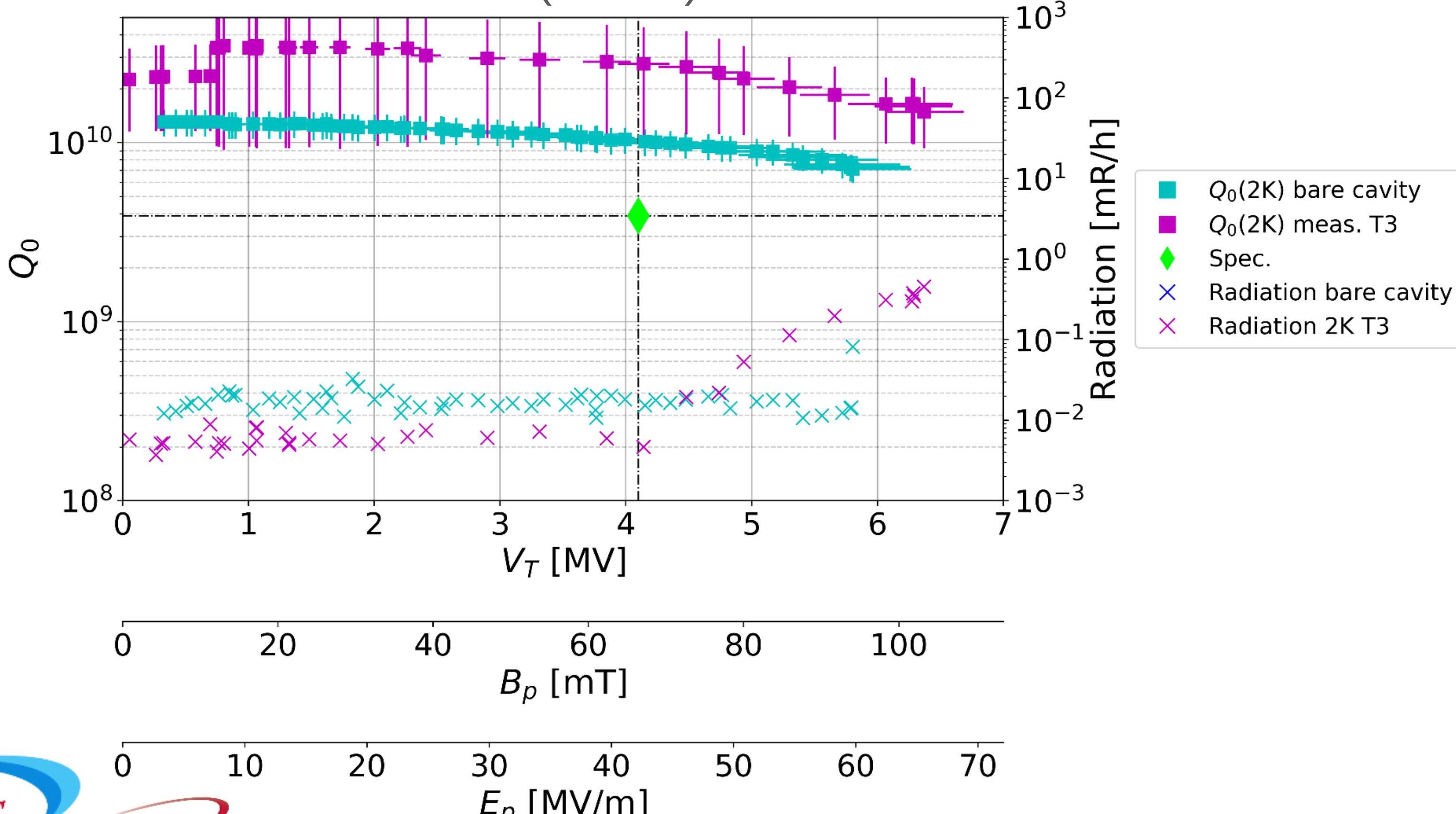
- Dry assy. tested w/pressure sensitive paper on the RF lips.
- At appropriate torque, the paper showed contact and a uniform crush.
- The maximum thickness of the paper (4 plies in total: 2x top + 2x bottom) is 0.22 mm. The effective thickness will be less due to compression.
- After disassembly, the gasket lips were measured and found to be 2.41mm (originally 2.6 mm), indicating that they were definitely crushed enough to plastically deform the lips.
- Successfully repeated dry assy. using A286 SS socket bolts and Ag-coated nuts to reach higher torques and smaller gap.
- This configuration was adopted as baseline for subsequent VT's.

Quantity	Nominal	Measured
Flange Thickness	34.71	34.82
Flange Gap	0	0.11
Nb Gap	2.76	2.51
RF Seal gap (calculated)		-0.09

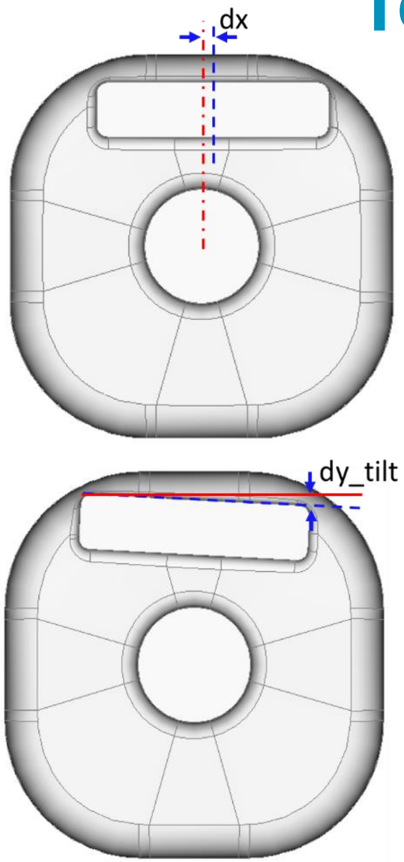


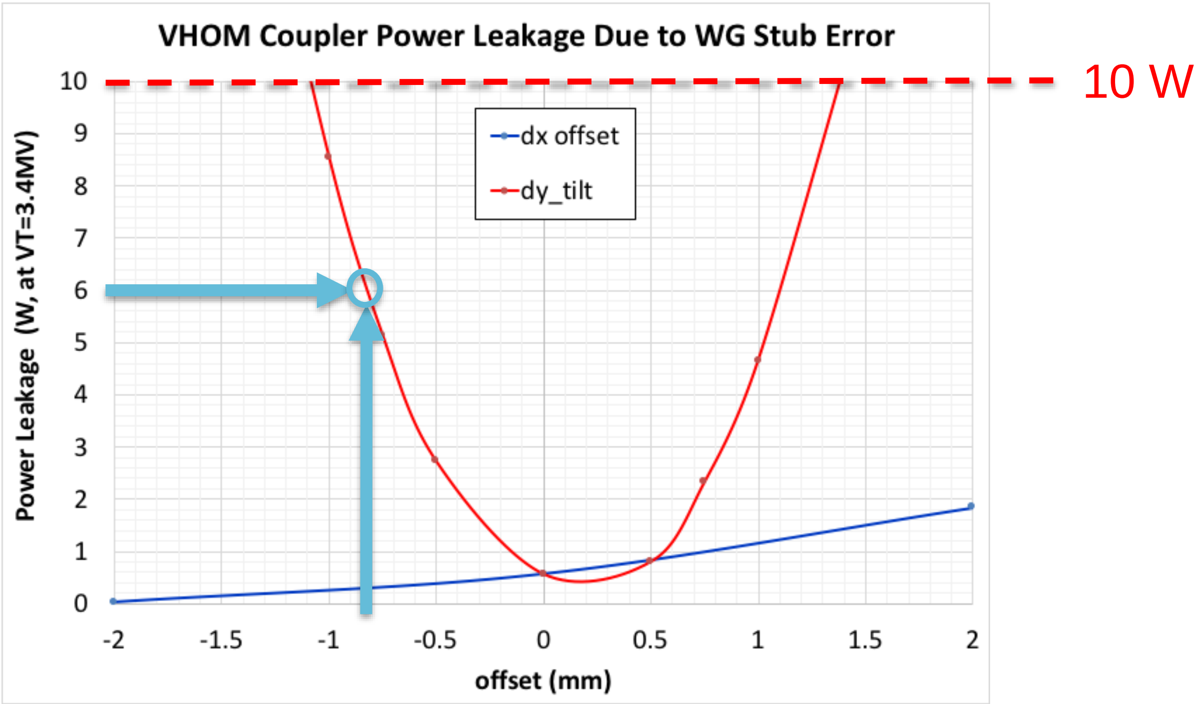
NRFDP002 3rd test w/HOMs

- The unfortunate coupling of the VHOM introduces a huge uncertainty to the Q-measurement. ($Q_0 \approx$ 2.6E10+/-1.1E10)
- At least there is no obvious performance reduction from the bare cavity.
- $Q_0(4.1\ MV) \approx$ 2.7E10 +/-1.7E10 and max $V_T \approx$ 6.37+/-0.31 MV.
- Total fundamental power leakage from both couplers remains below the 12.5 W threshold at 4.1 MV (~10 W).



VHOM Coupler Waveguide Stub Geometry Tolerance On Power Leakage



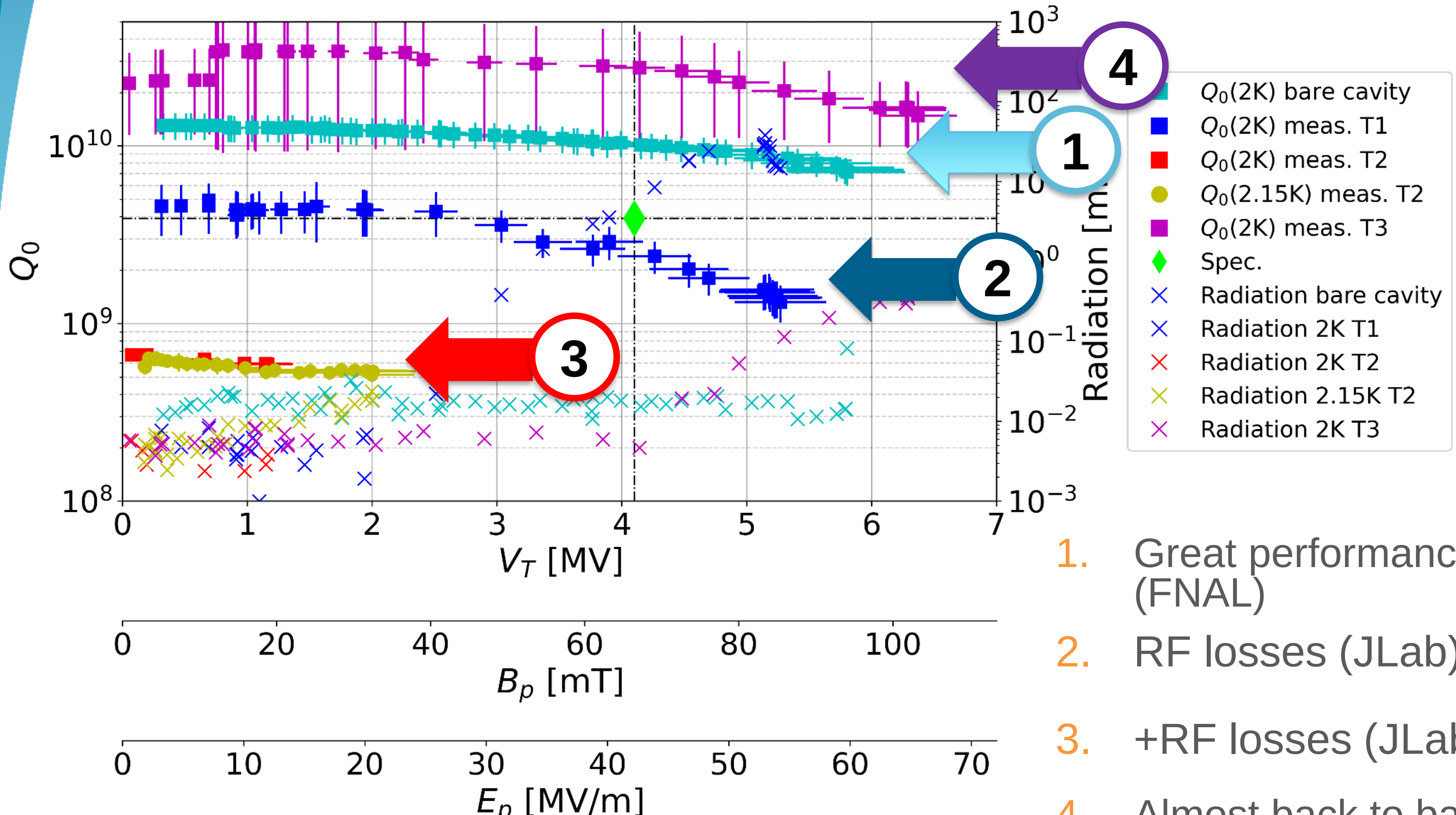


Not sensitive to stub horizontal shift

Stub vertical tilt need be < 1 mm to limit power leakage to under 10 W

Z. Li (SLAC)

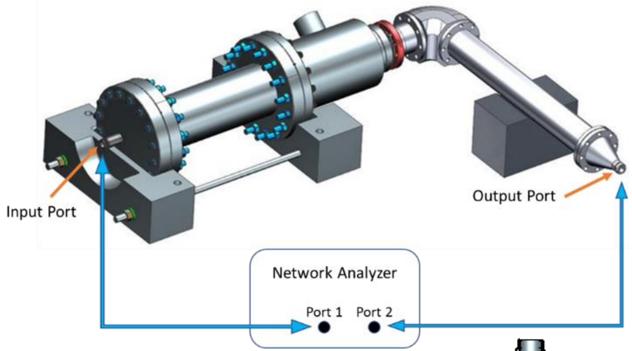
Prototype 2 Tests Summary



1. Great performance (FNAL)
2. RF losses (JLab)
3. +RF losses (JLab)
4. Almost back to bare (JLab)

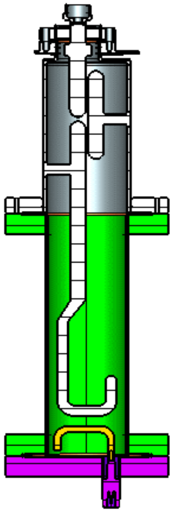
HOM Prototypes' Warm Meas.

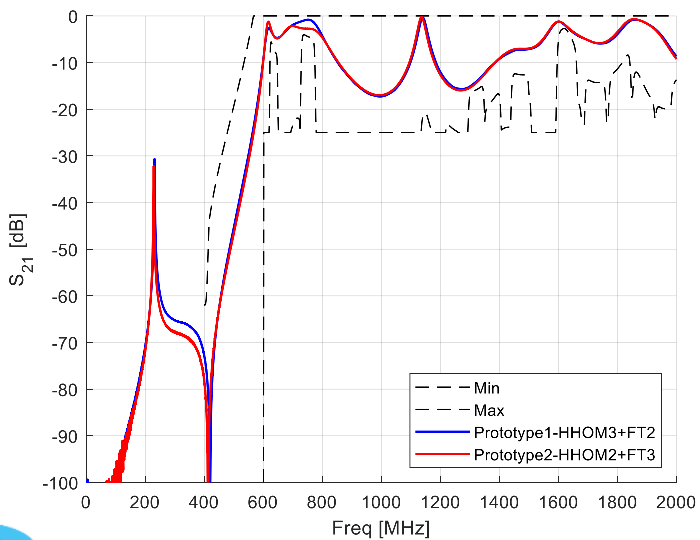
S. De Silva (ODU)

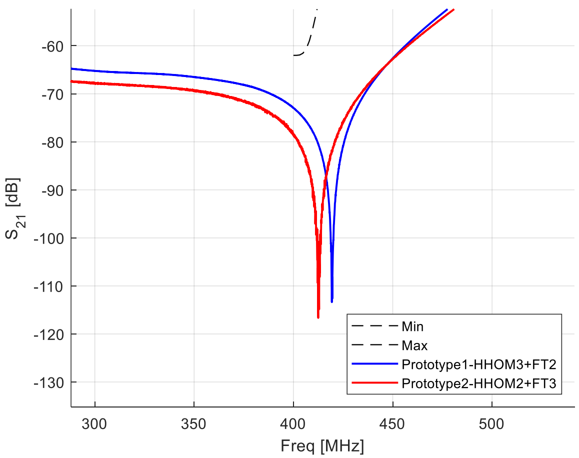


RF Box measurements:

- Two RF test boxes designed and fabricated by ODU
- Both test box cans and test probes were qualified with detailed CMM data and no effect on fabrication offsets
- 2 HHOM dampers sets were measured and qualified with the CERN mask
  - Prototype set 1: HHOM3+FT2 was used in RFD2 VTA cold test
- Prototype 1 (HHOM3+FT2): FT2 were trimmed to lower the notch → To reduce fundamental power
- FTs will not be modified for pre-series and series sets

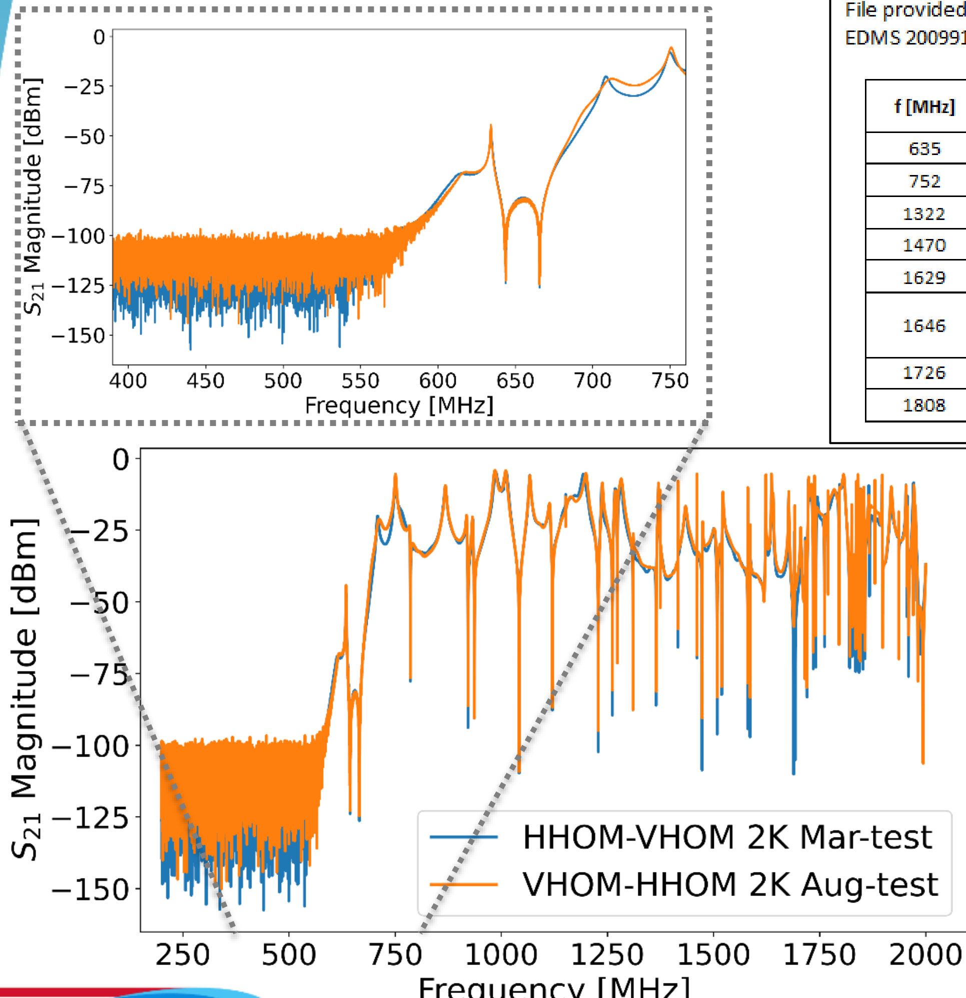






NRFDP002 2 K HOMs meas.

- Good fundamental rejection and trans. of HOMs of interest (e.g. '750 MHz').
- Q_L calculated from S_{21} at 2 K using test input and HHOM coupler.



RFD (dressed)
File provided by Z. Li (SLAC): ImpedanceTable_RFDwFT_20191118_Zenghai.csv (19/11/2019)
EDMS 2009911 [1], model at 2K, windows with $\varepsilon_r = 9.6$

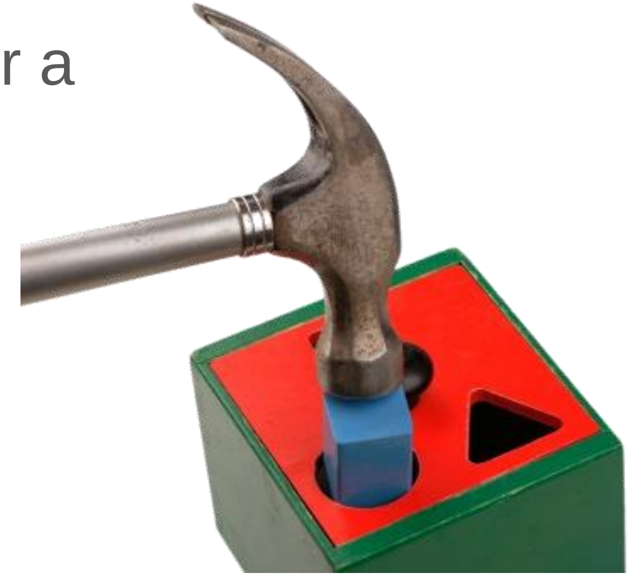
f [MHz]	Qe	$R_{\perp v}$ [kΩ/m]	$R_{\perp h}$ [kΩ/m]	$R_{\parallel}$ [kΩ]	Notes
635	1121	0	**573**	0	
752	192	0	0	**17**	High power mode.
1322	2974	0	**625**	0	Mode over transverse threshold.
1470	38208	0	**348**	0	
1629	10404	1	**758**	0	
1646	10742	2	**63**	**8**	Close to bunch spacing harmonic.
1726	39216	11	**355**	0	
1808	7574	2	**389**	0	

Comparing w/HOM Annex (EDMS 2488213).

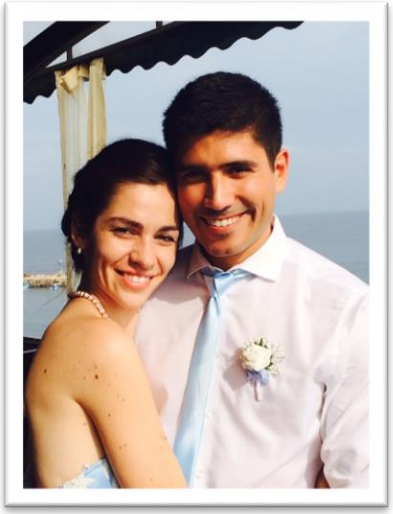
f (MHz)	Q_L	R_T[kΩ/m]	$R_{\parallel}$[kΩ]
634.2	1262	645	
750.3	254		22.6
1,310.7	2,517	525	
1,460.7	100,515	909	
1,636.6	3,008	220	
1,691.3	34,157	54.5	
1,723.8	2,289	10.6	
1,825.7	11,236	482	

Summary

- LARP experience extremely valuable!
- Mixing hardware & standards made for a bumpy start.
- Hardware (for the prototypes) and procedures are finetuned.
- Hardware (“kits”) for production to be provided by CERN.
- A set of HHOM and VHOM prototypes validated by warm and cold measurements.
- No evident reduction in performance or field reach observed on the cavity (prototype 2) from the HOM couplers.
- Next: Jacketed cavity! (prototype 2).
- Prototype 1 waiting for validation.



Thanks!

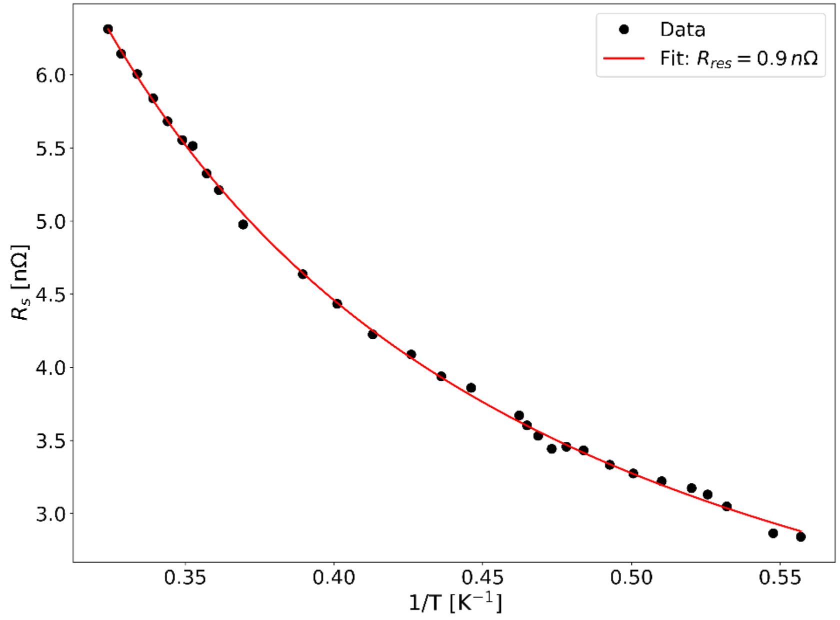


…and happy anniversary to my wife!

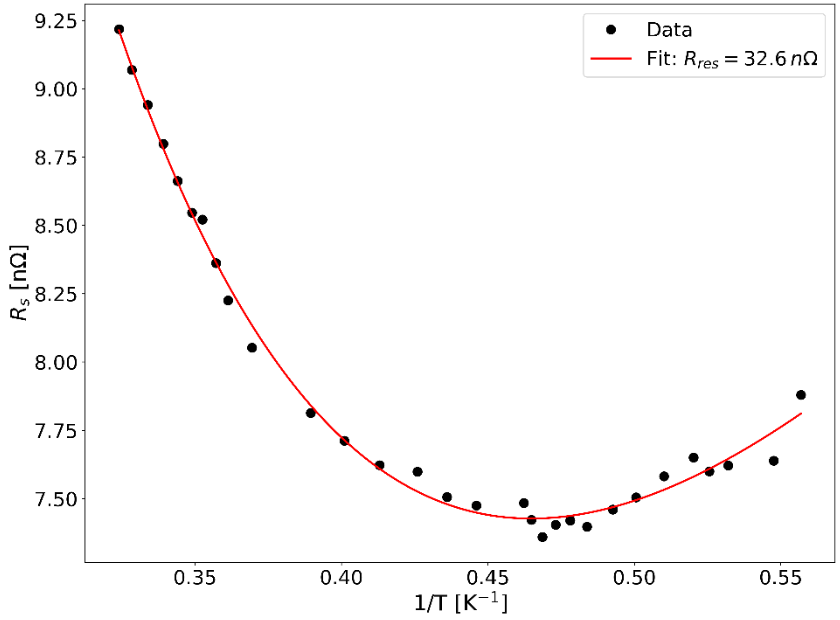
Backup

NRFDP002 3rd test w/HOMs

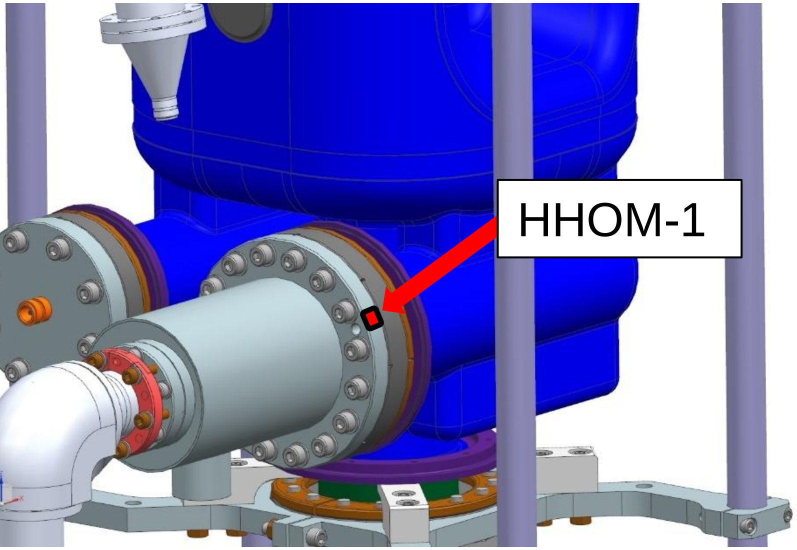
Surface Resistance (min)

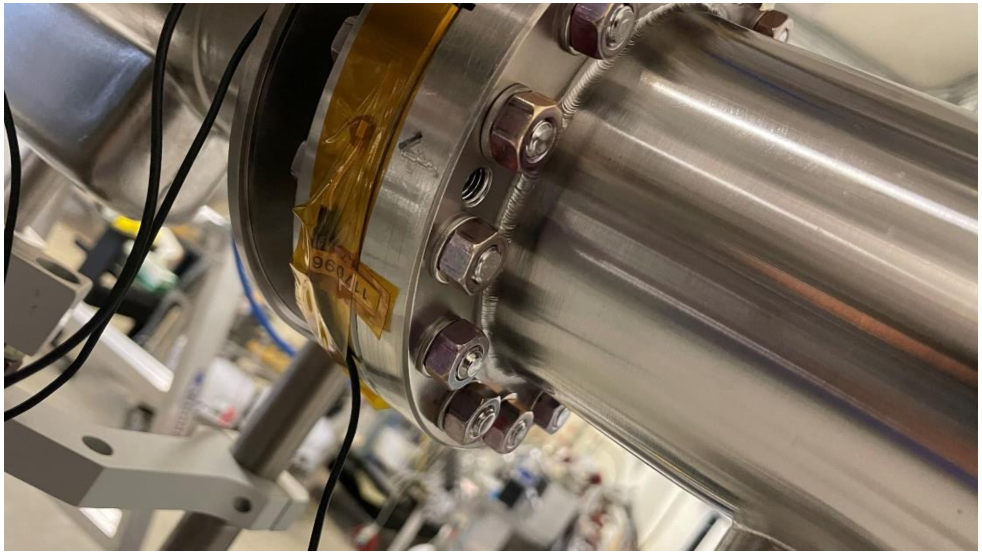


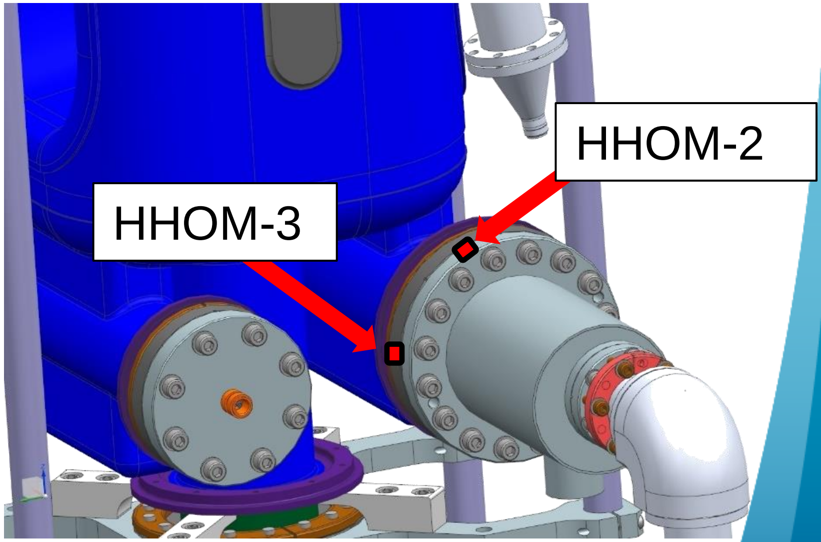
Surface Resistance (max)



Temperature Sensors

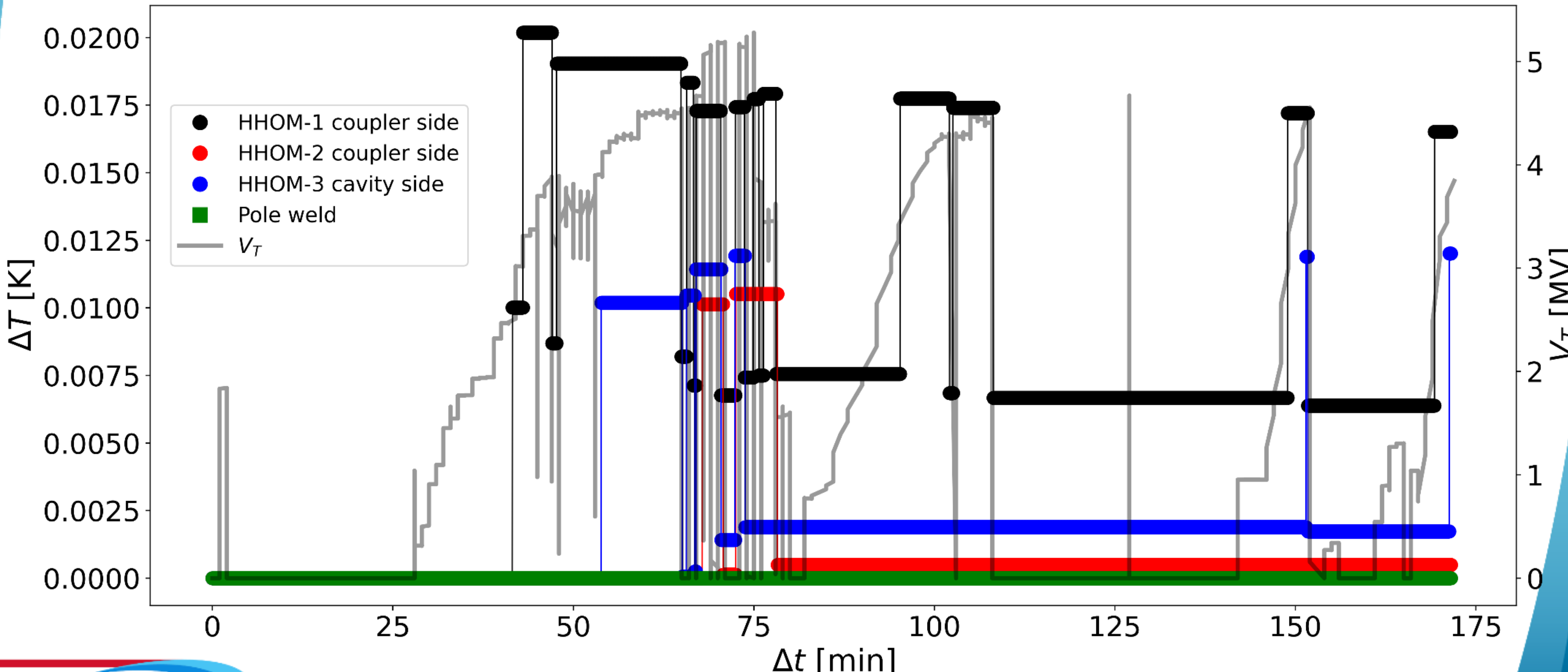




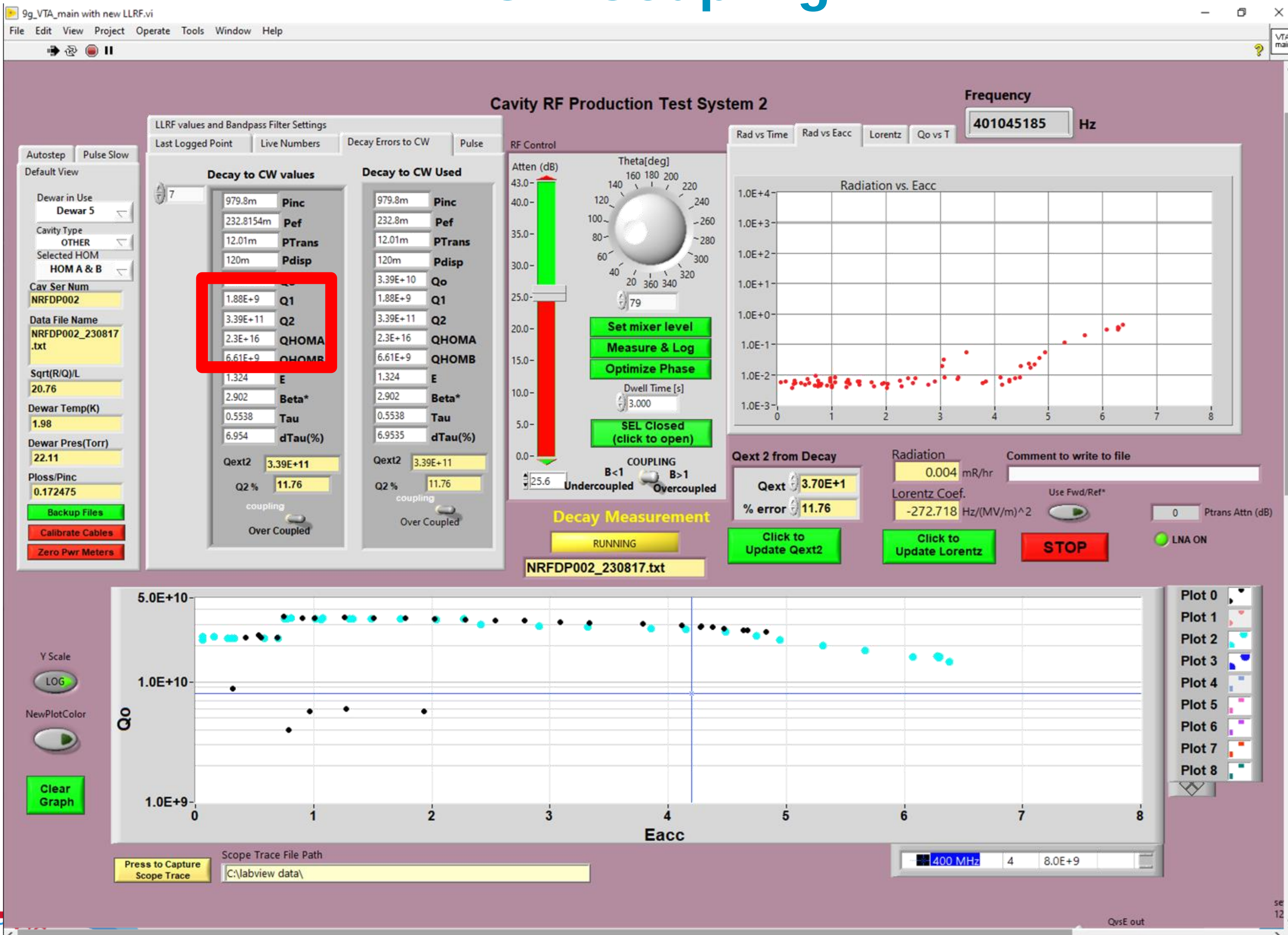


HHOM Heating Signature

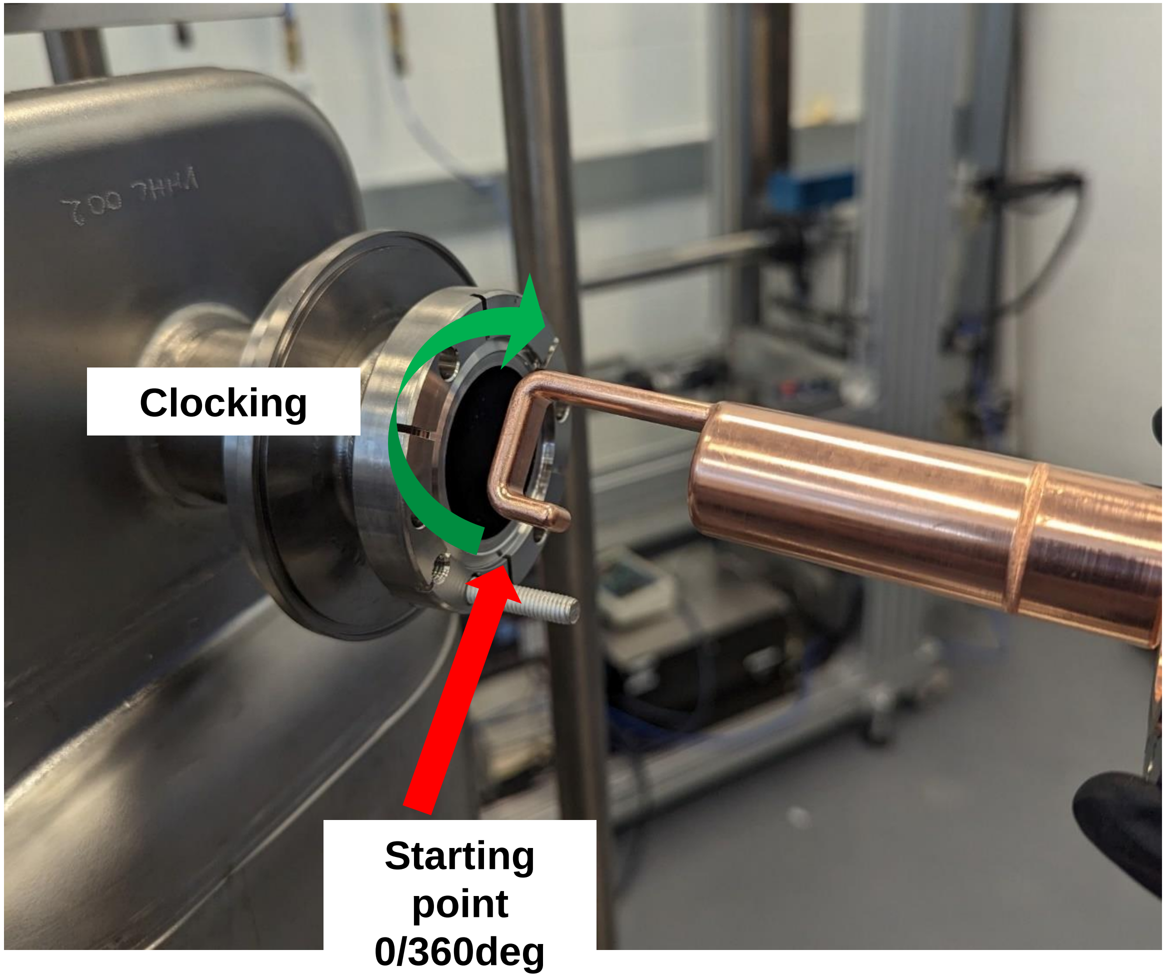
- Some mild heating signature seen in the HHOM flange (coupler flange, next to hook weld).
- Poor RF-gasket contact is suspected (contribution to the R_{res} ?).
- Ongoing investigation



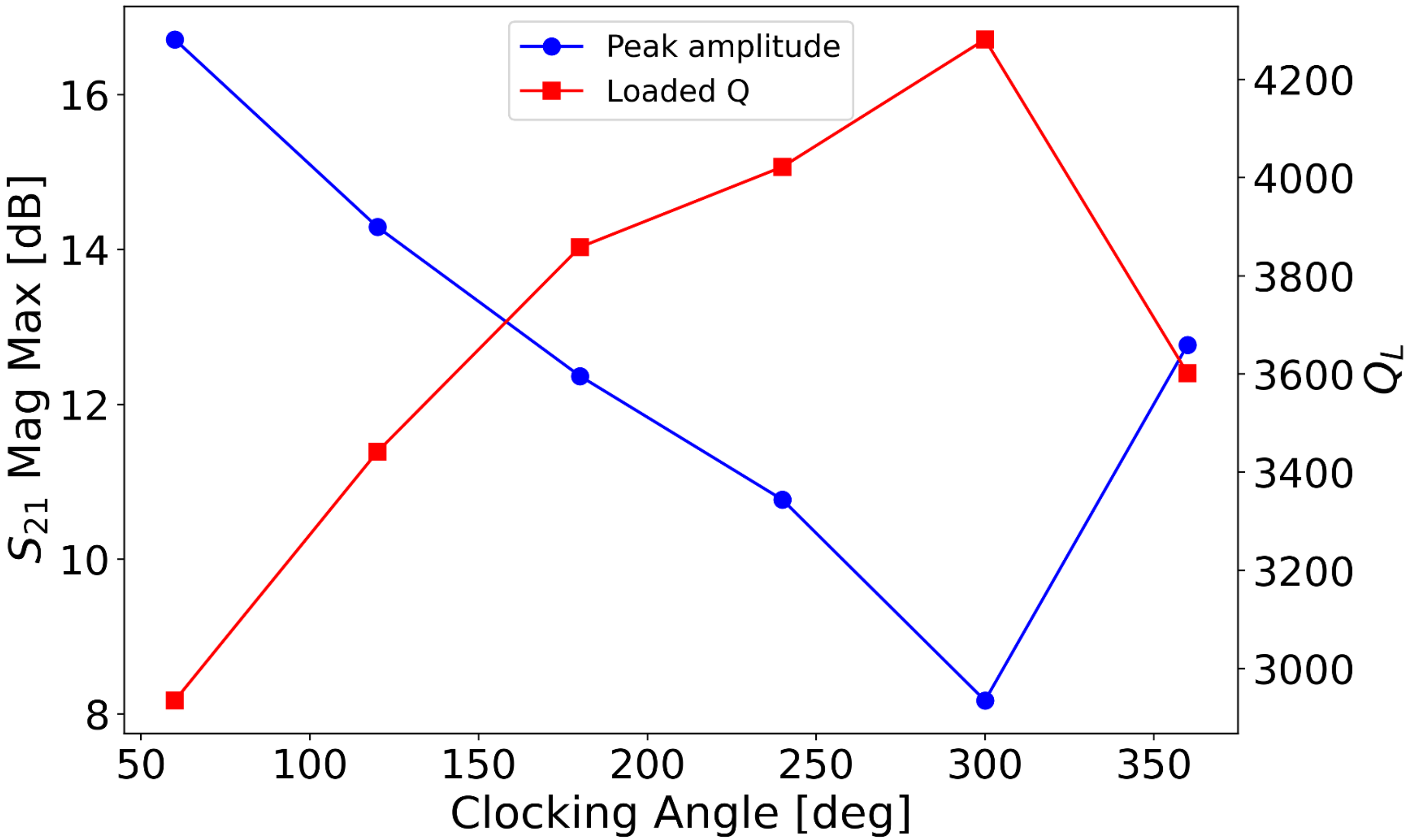
VHOM Coupling



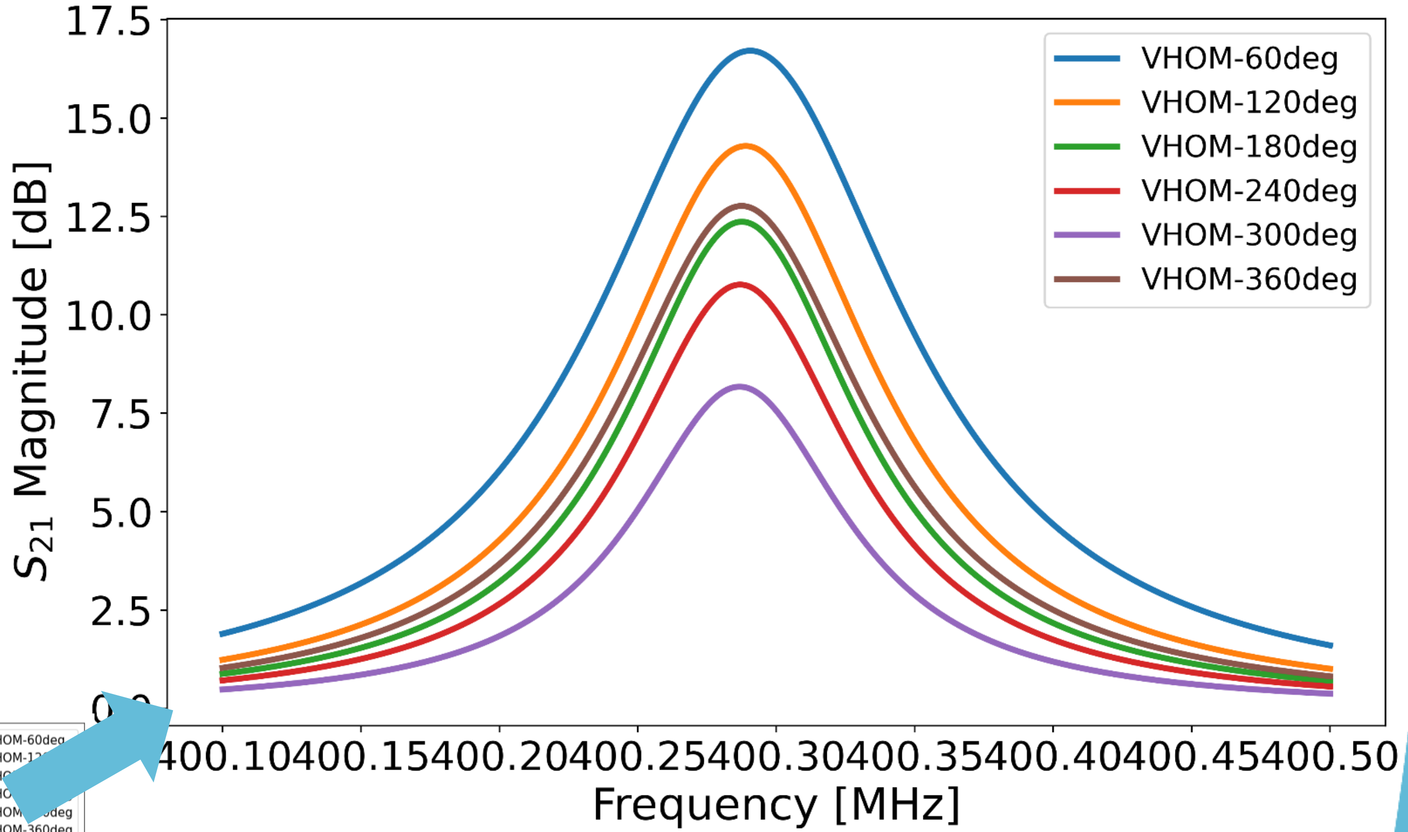
VHOM Warm Clocking Measurements (1)

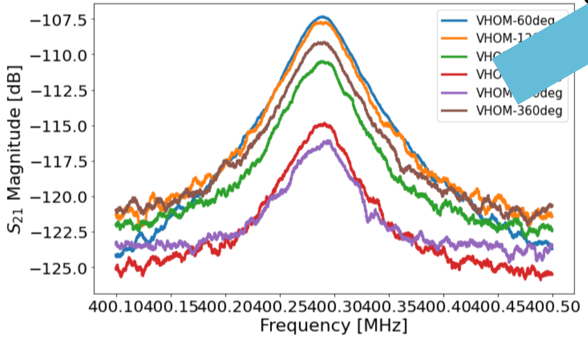


VHOM Warm Clocking Measurements (2)



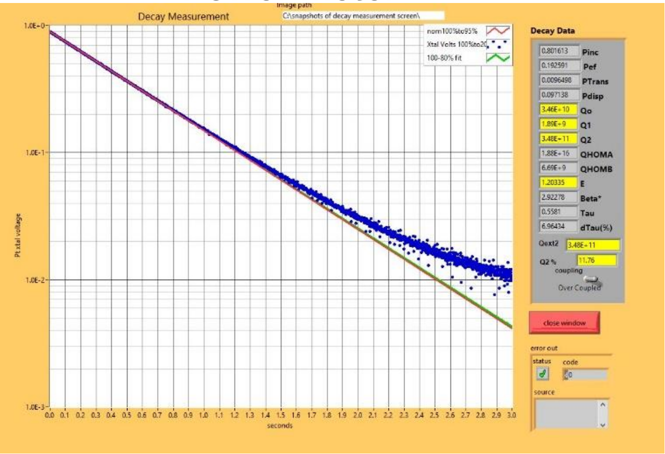
VHOM Warm Clocking Measurements (3)





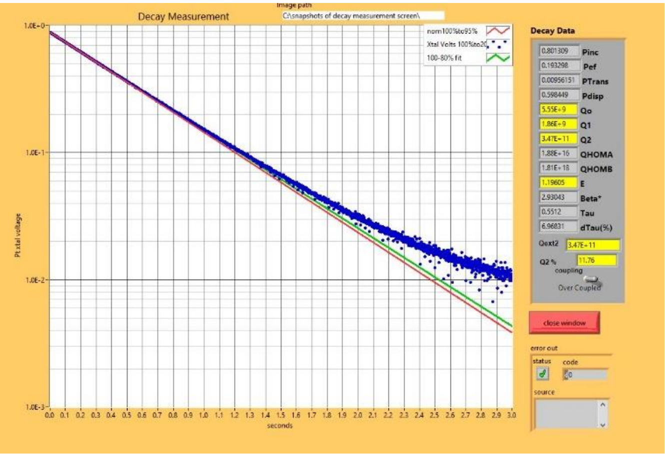
Decays with different VHOM terminations

Power meter



Open

Load



Short