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Experience of testing TEM cavities in FREIA laboratory: ESS series double-spoke cryomodules and CERN Crab cavity

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Briefly about FREIA laboratory

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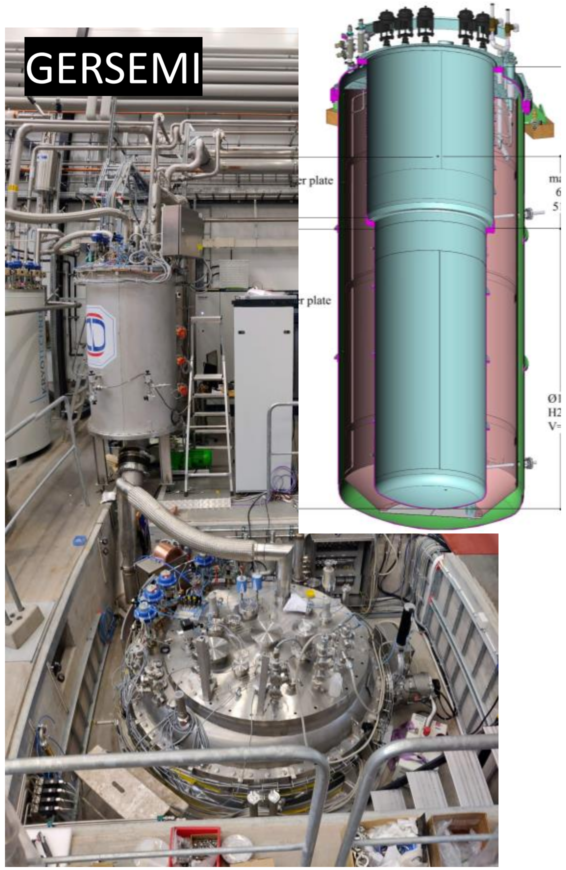
- ~ 120 l/h liquid He production
- 90W of continues power dissipation
- Two tetrode based 352MHz 400kW pulse amplifier. Up to 16kW @ CW.
- NI PXI based LLRF

Cryomodule test stand

Everything needed for cryomodule (CM) + valve box (VB) installation.



Vertical cryostat

Multiple bare cavity testing is available
Active magnetic field compensation.

- 3.2m x ø1.1m total volume
- 2.65m x ø1.1m below lambda plate

Horizontal cryostat

- Inner size 3.3m x ø1.2m
- For a cavity **with a helium jacket**
- Ideal for **coupler testing**: FPC, HOM
- **Multiple cavities** may be tested at the same time

ESS prototype Medium-β Double spoke cavities

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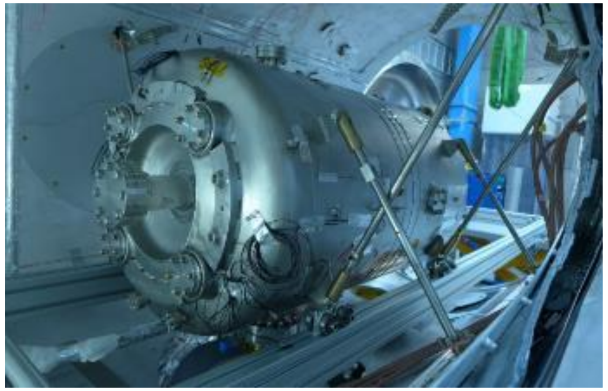
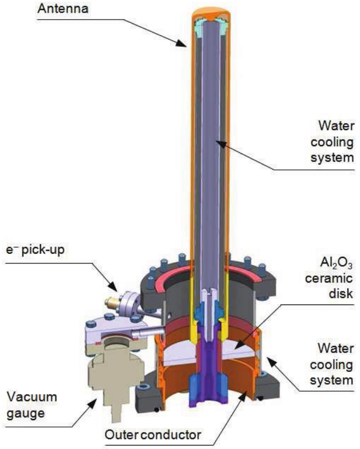
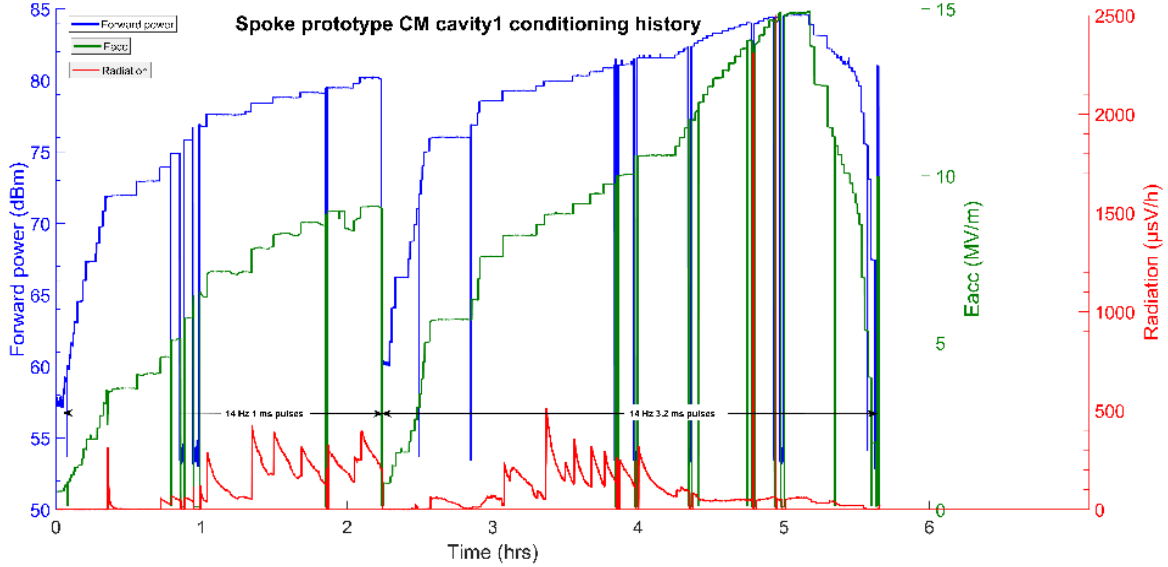
2 cavities equipped with FPC was tested.

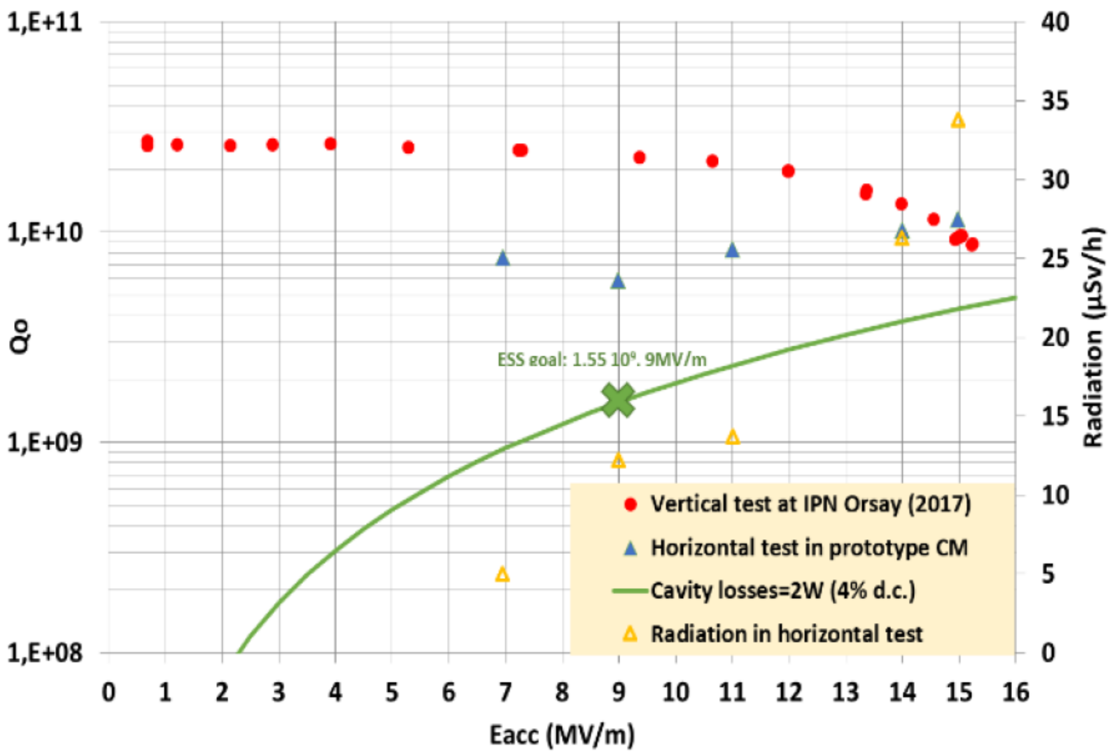




Q factor is done by the calorimetrical method.
Both SEL and PID operation method are implemented.
The maximum gradient higher than 9 MV/m was achieved.

Cavity conditioning history





Multipacting conditioning of series CM

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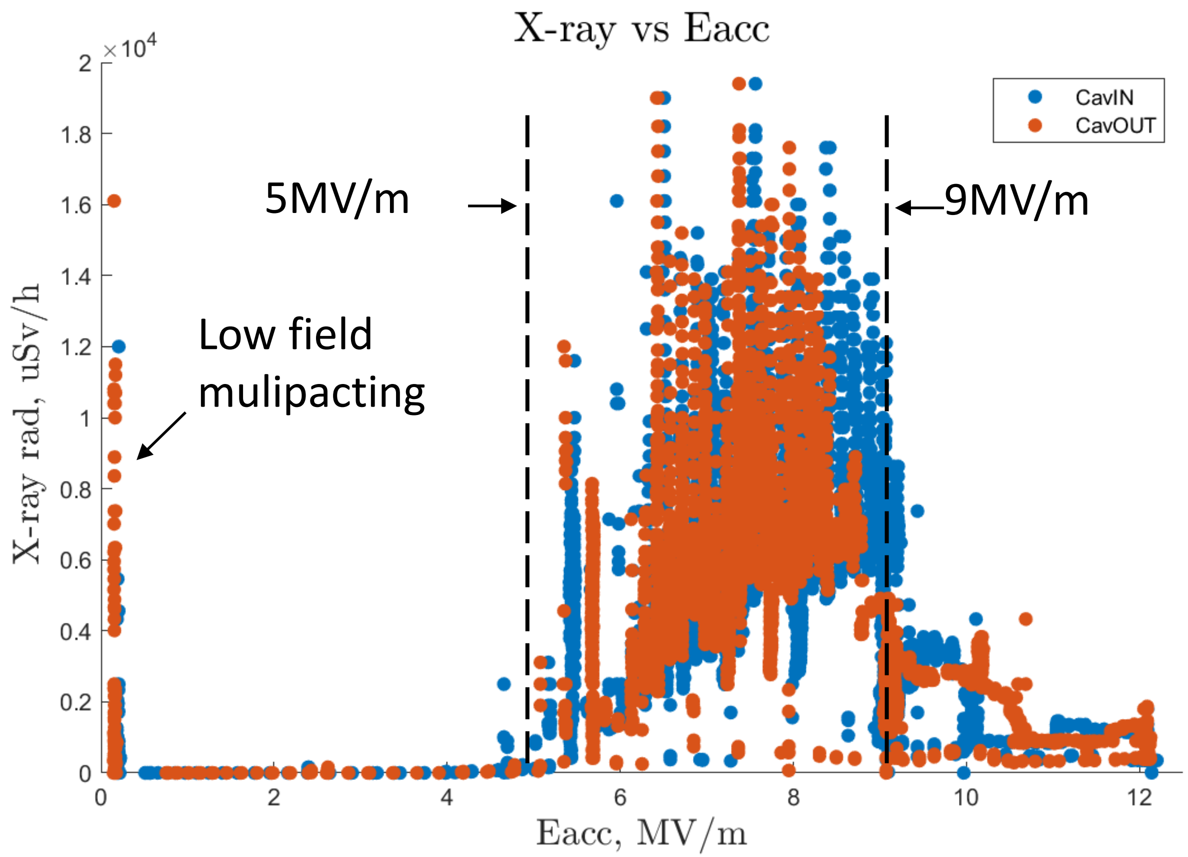
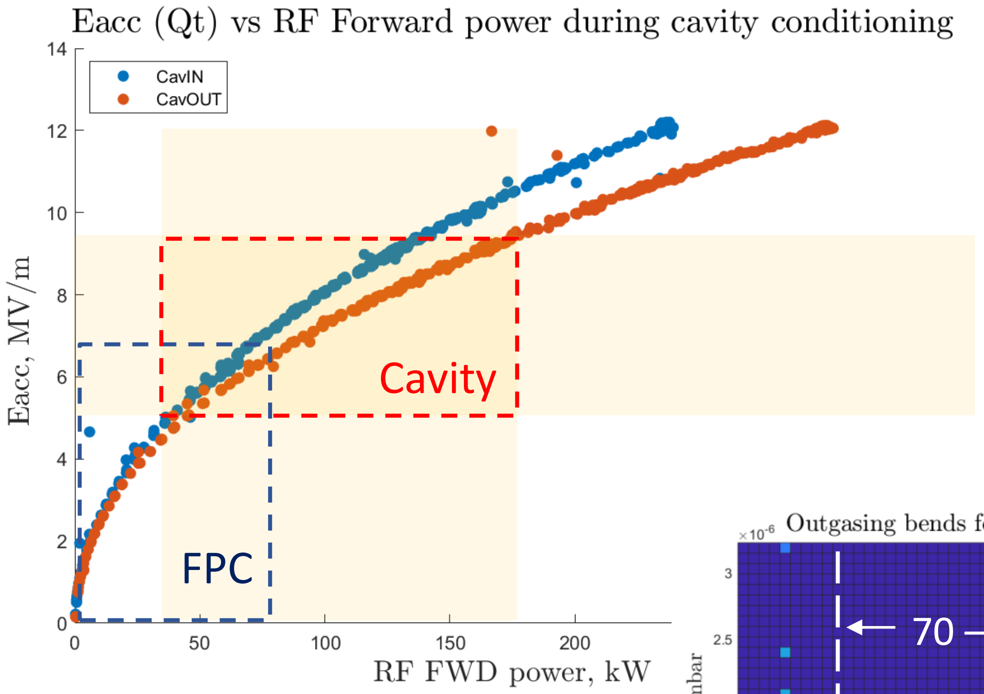
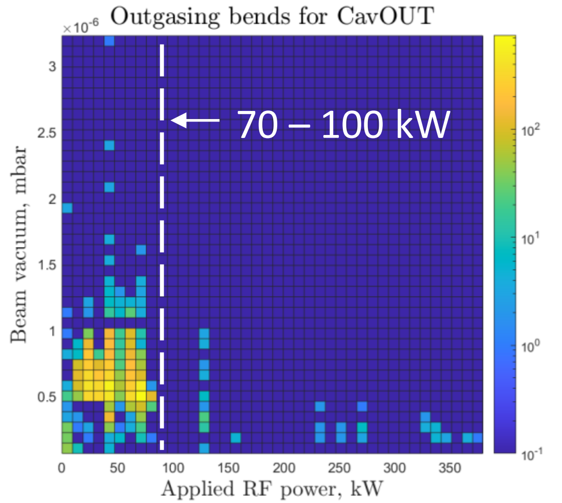
- During cavity MP conditioning we deal with superposition MP bands from cavity and FPC.
- Both MP sources have influence on the beam vacuum.
- Usually, only MP from cavity generate X-ray.



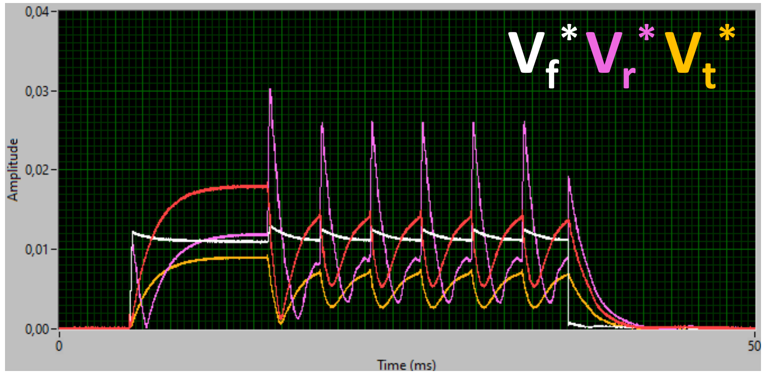


Outgassing during **warm** FPC conditioning

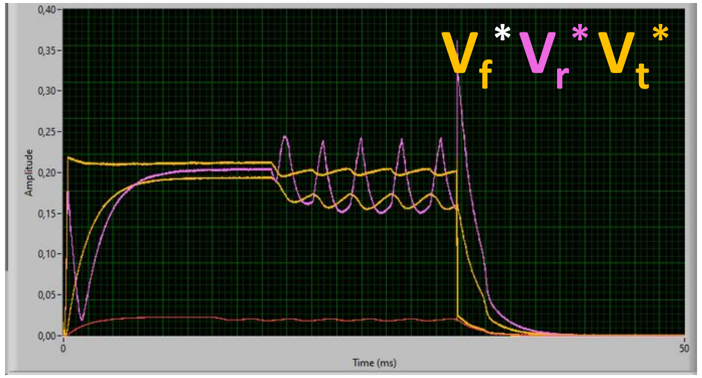


Local quench at low cavity field

Local quench & thermal feedback is **ALWAYS** observed at very low field in the spoke cryomodules so far



Eacc_pk_Pt	Eacc_pk_Pf
0,637747	0,755588



Eacc_pk_Pt	Eacc_pk_Pf
0,661242	0,946428

- Low field multipacting can be easy conditioned.
- Pulse operation during cavity conditioning prevent from global quench.
- Small influence on cryogenic is observed.
- He bathe pressure interlock should be activated from the beginning.

* - uncalibrated voltage from LLRF ADC

Field emission, VT vs Cryomodule. Power dissipation

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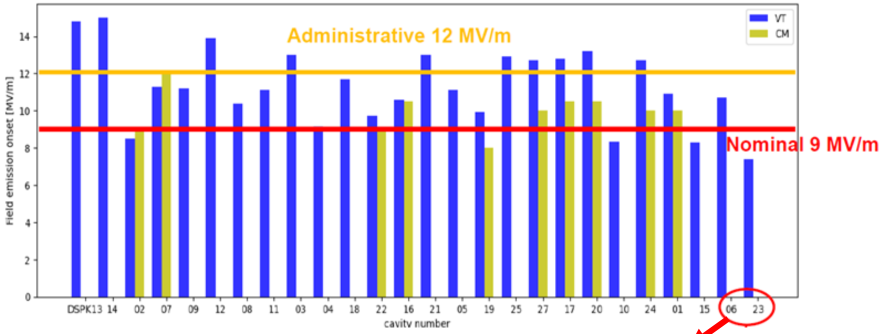
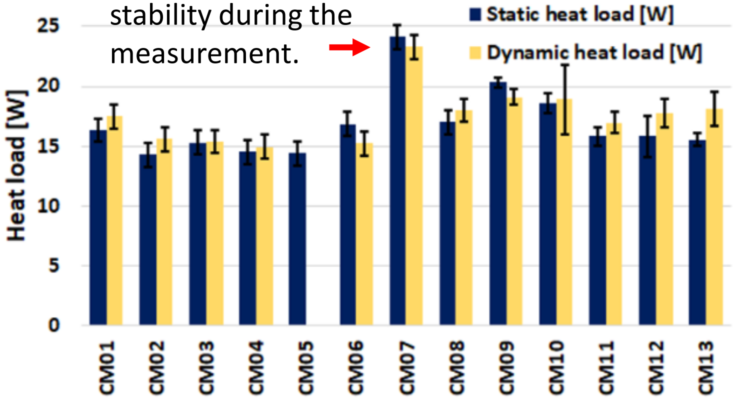
Field emission onset measured from behavior of X-ray* during RF powering with reference to influents to cryogenics.

Field emission onset (DSPK#) comparison between vertical VT (IJCLab) and cryomodule CM (FREIA) tests.

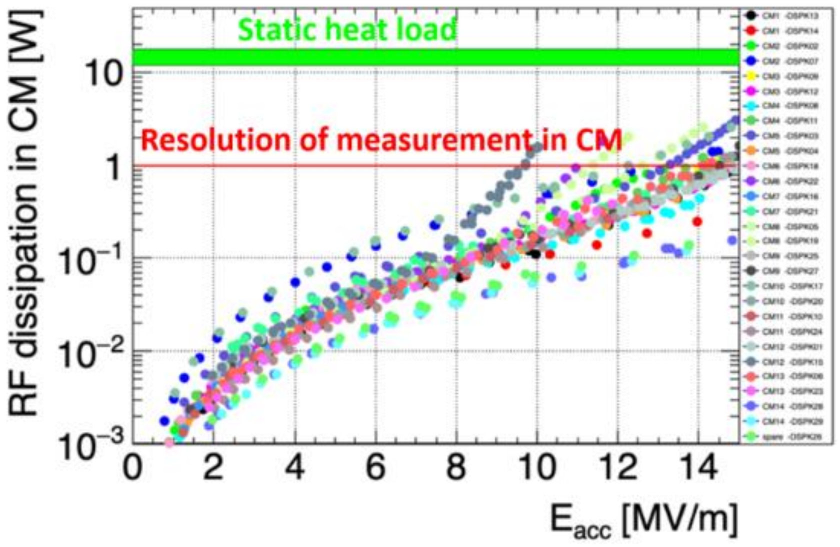


HPR after VT, not tested afterwards

Issue with pressure stability during the measurement.



Static vs Dynamic (9 MV/m both cavities) heat load



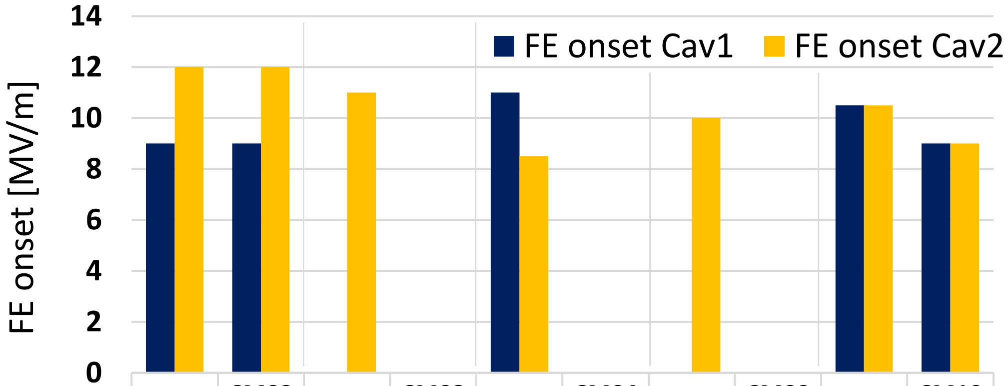
Expected RF heat loss based on VT data is of the order of mW (after multipacting conditioning), which **is much lower than the measurement resolution of the calorimetric method at FREIA**. This indeed proves that cavity performance has not been significantly degraded after the vertical tests.

* By "historical reasons" **both cavities share the same X-ray detector** which placed transversal to beam axis between cavities.

Field emission treatment

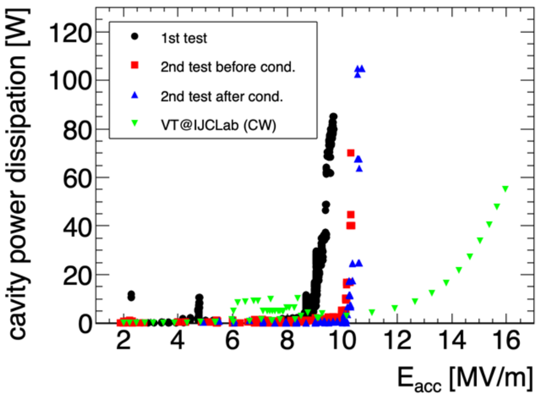
- Field emission onset was degraded in CM11
- The thermal cycle (Cryogenic failure) to 300K after the 1st test improved the performance.
- The cavity power dissipation shows a sharp rise.
  9 MV/m in the 1st test → 10MV/m in the 2nd test
- RF conditioning was tried but small impact.
- **2nd thermal cycle helped a lot →** why?
- Future investigation to be continued.

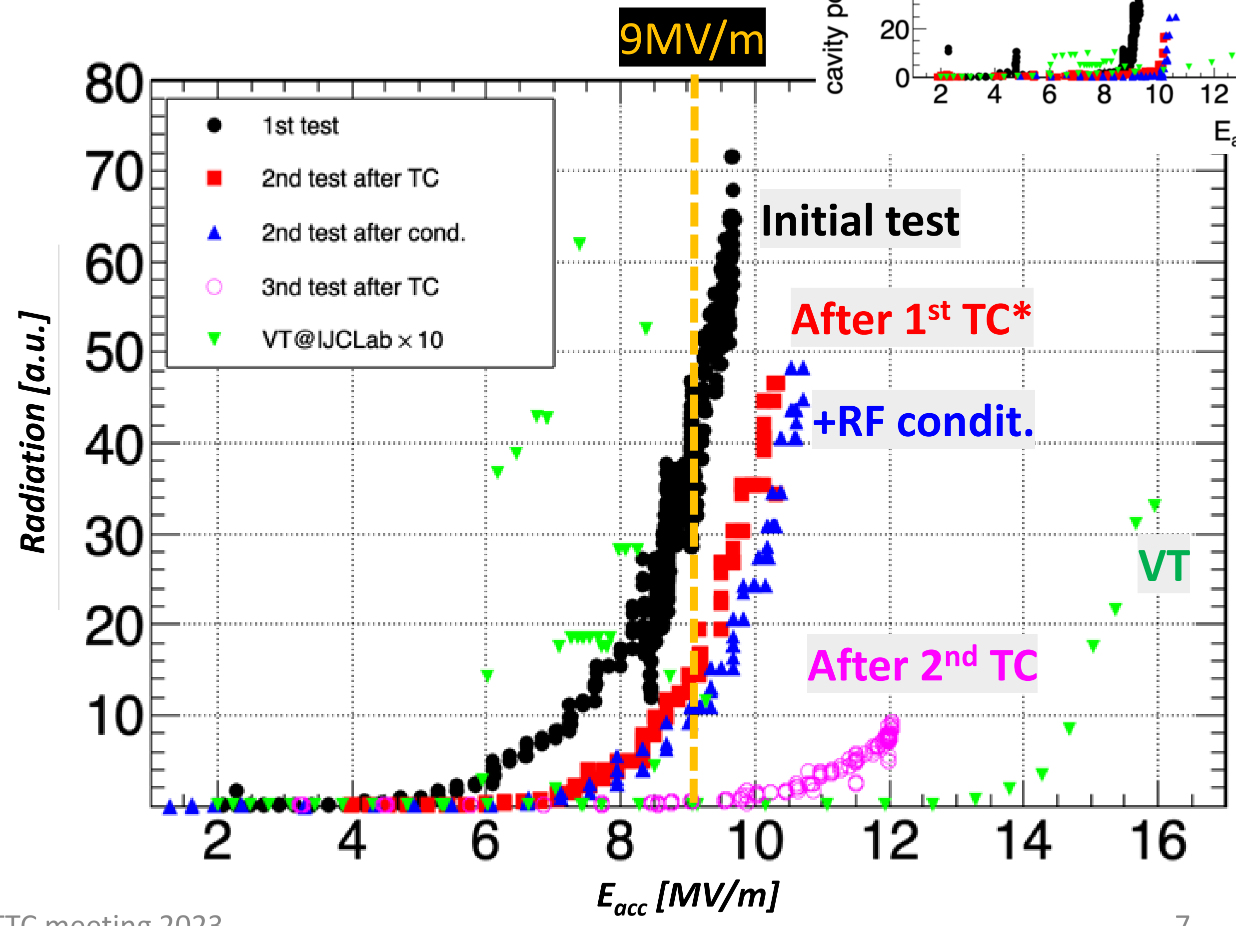
FE onset evolution for CMs which was retested



	CM02	CM02 2nd	CM03	CM03 2nd	CM04	CM04 2nd	CM09	CM09 2nd	CM10	CM10 2nd
FE onset Cav1	9	9			11				10,5	9
FE onset Cav2	12	12	11		8,5		10		10,5	9

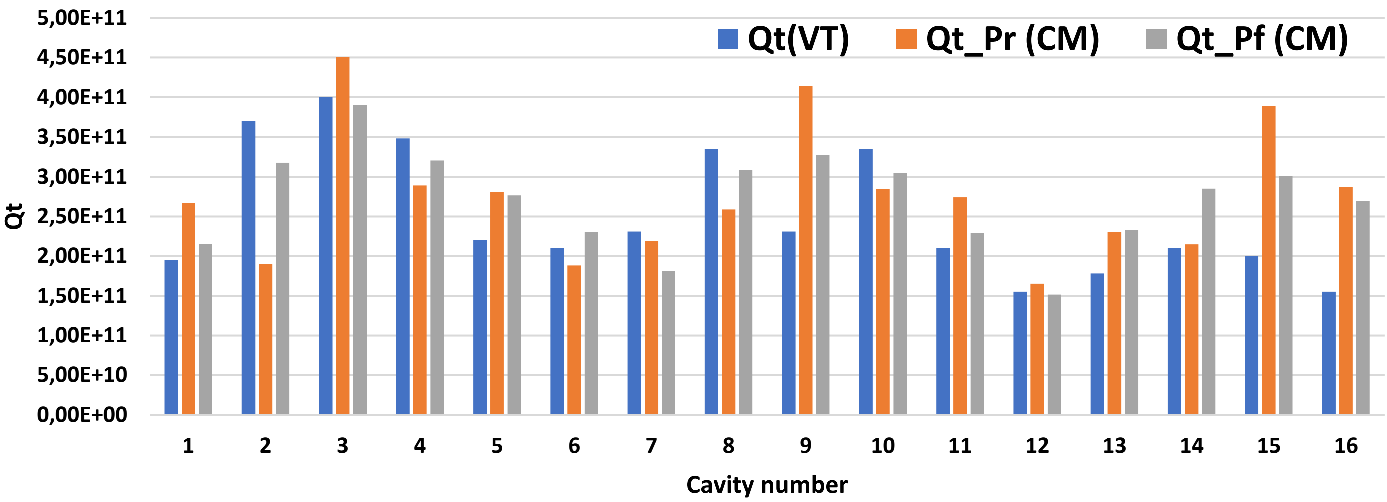
FE treatment example. CM11



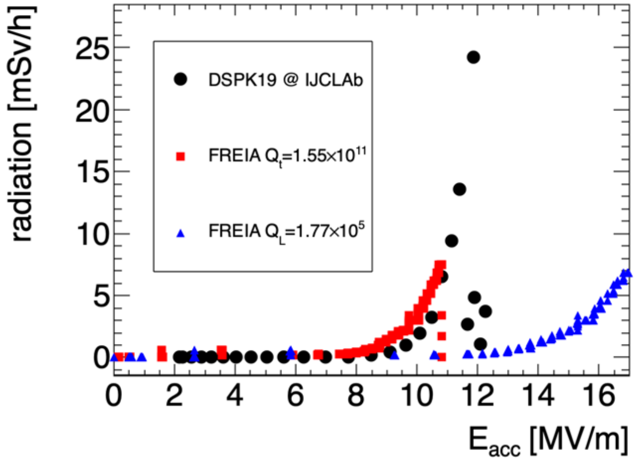


Uncertainties, VT vs Cryomodule test stand

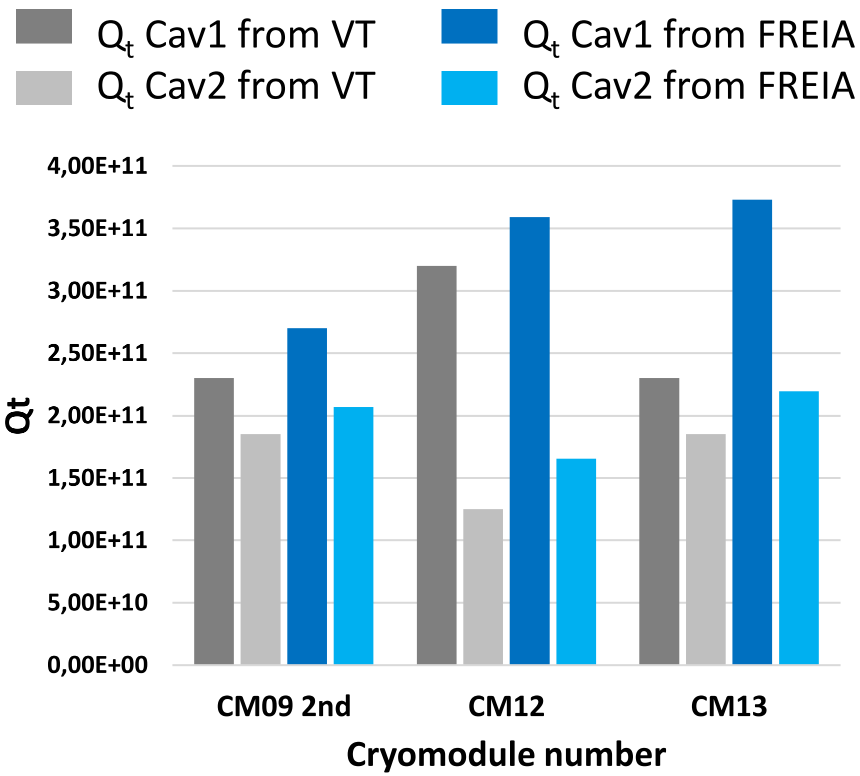
For E_{acc} estimation we using Q_t value measured at VT → official numbers



E_{acc} estimation from provided Q_t well enough fit with some cavities features as field emission onset.



- Additionally, Q_t estimation from integration of P_r after end of the pulse was implemented for last several CMs.
- Visible consistent Q_t underestimation from VT.



He accumulation on cavity walls

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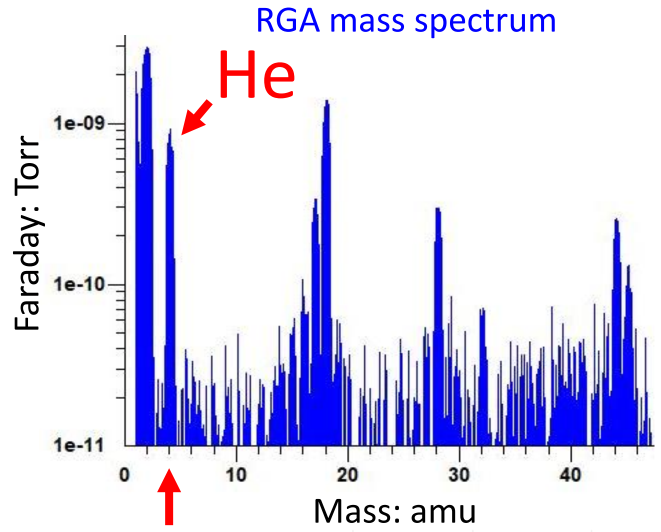
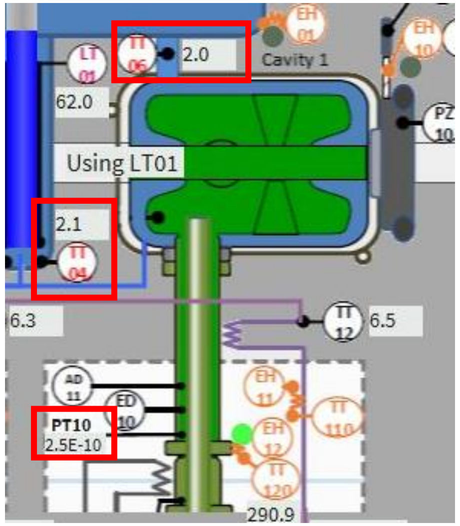
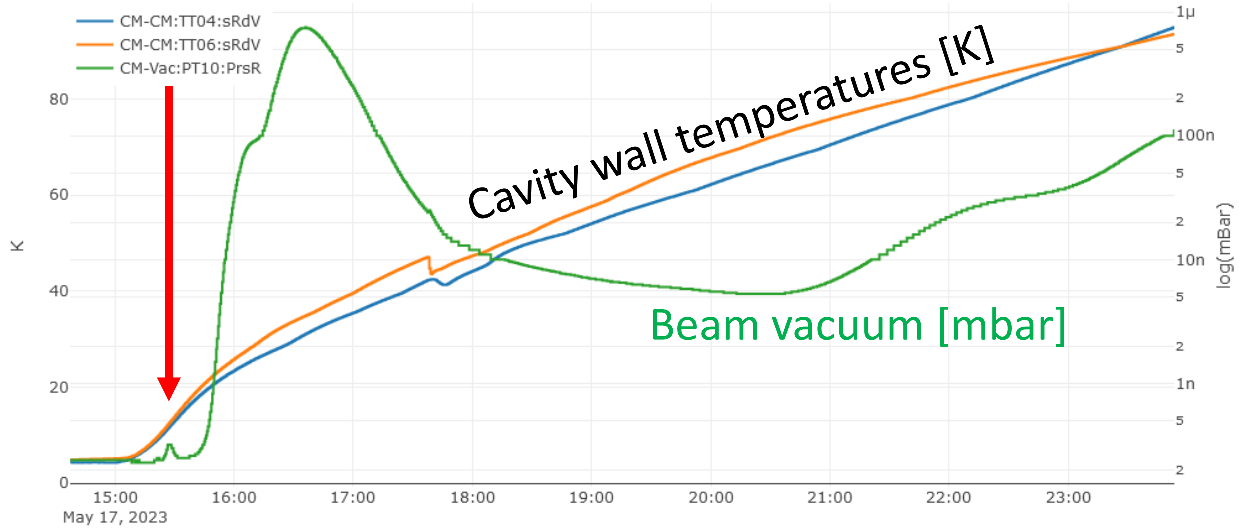
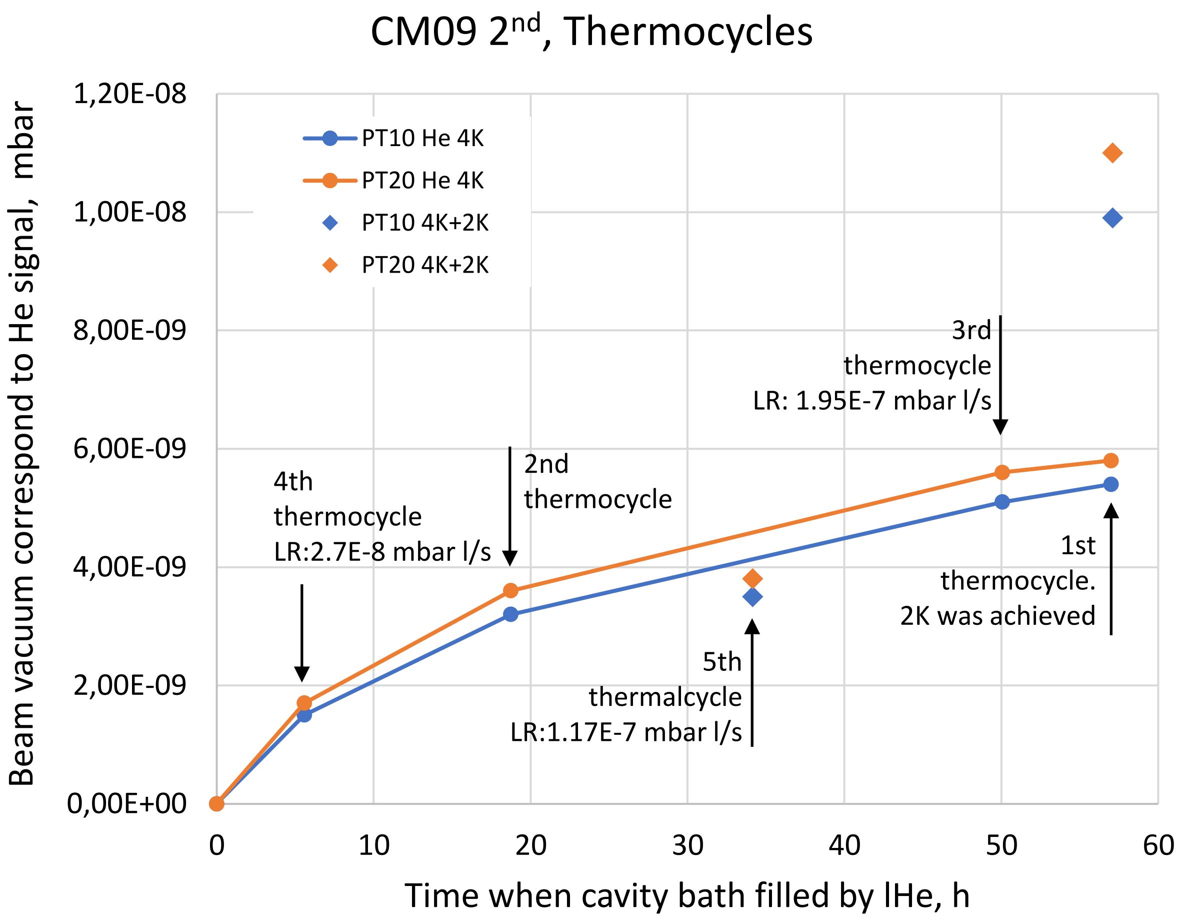
He signal often observed in beam vacuum during warmup when cavity wall temperature exceed ~10K.









Results of CM testing

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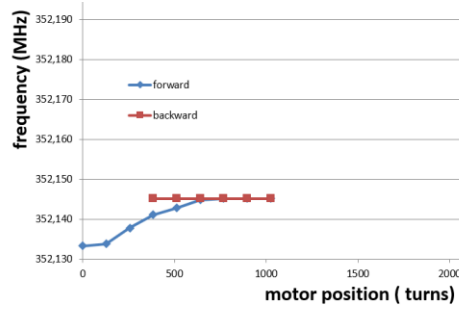
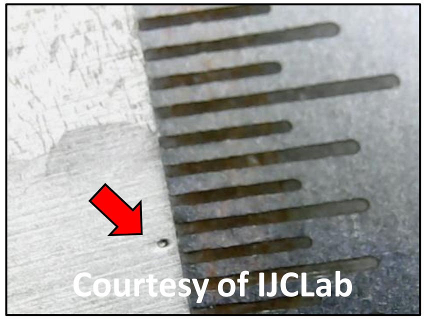
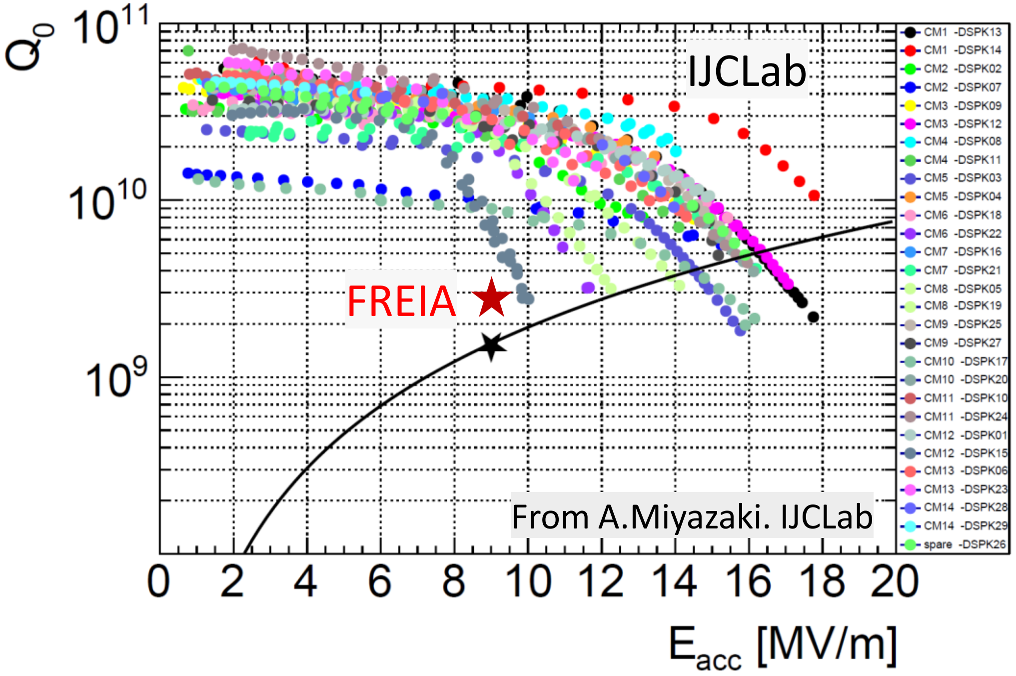
2 types of major issues cause a CM disqualification:



CM02, CM03, CM04, CM10
Under ILCLab investigation

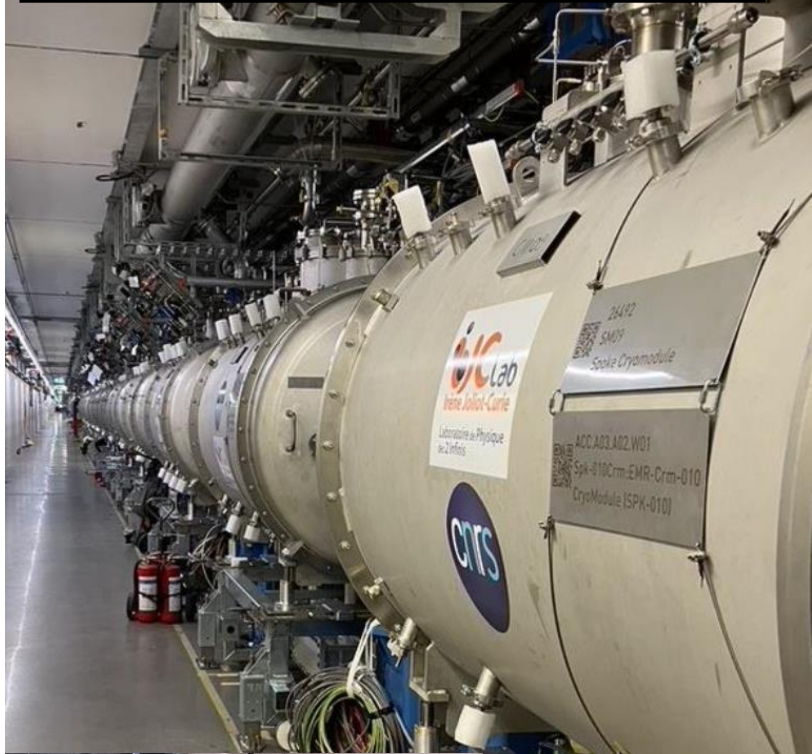


CM04, CM09



After repairing in IJCLab CMs were retested in FREIA, successfully approved and delivered to ESS.

All 13 CM are installed in the tunnel



Last, spare, CM under assembly

CERN DQW “Crab” prototype cavity

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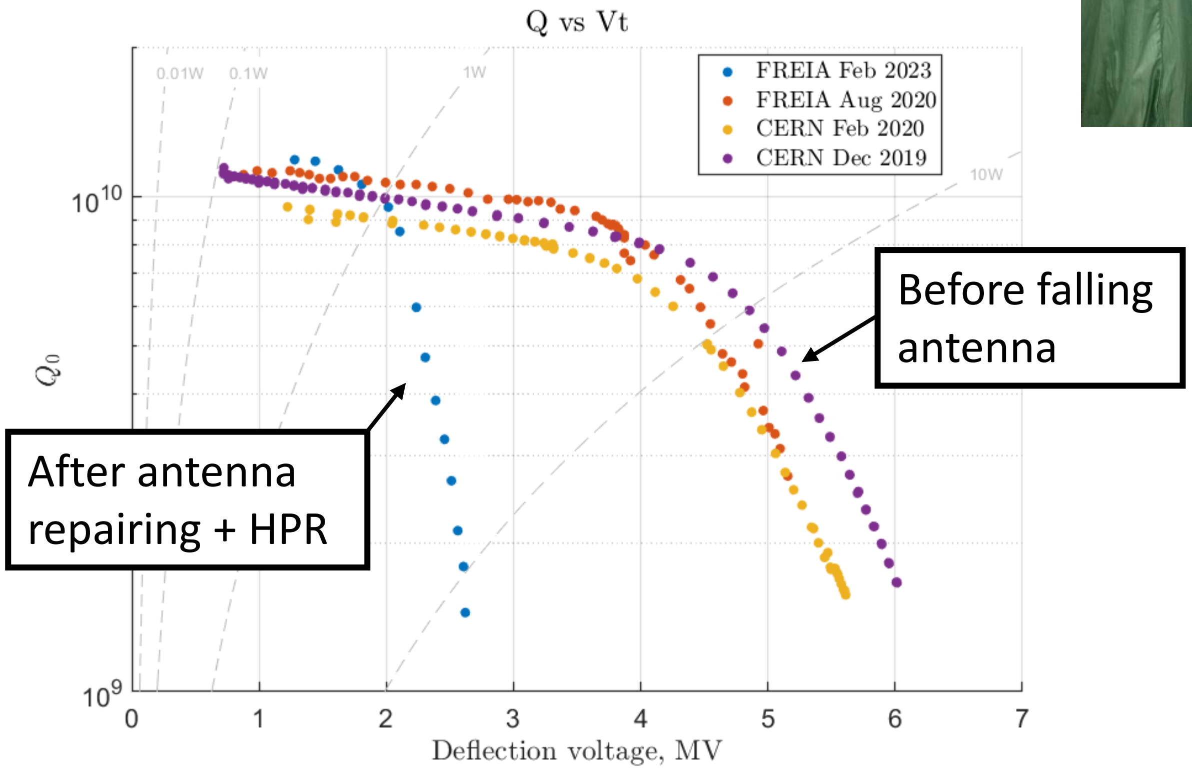
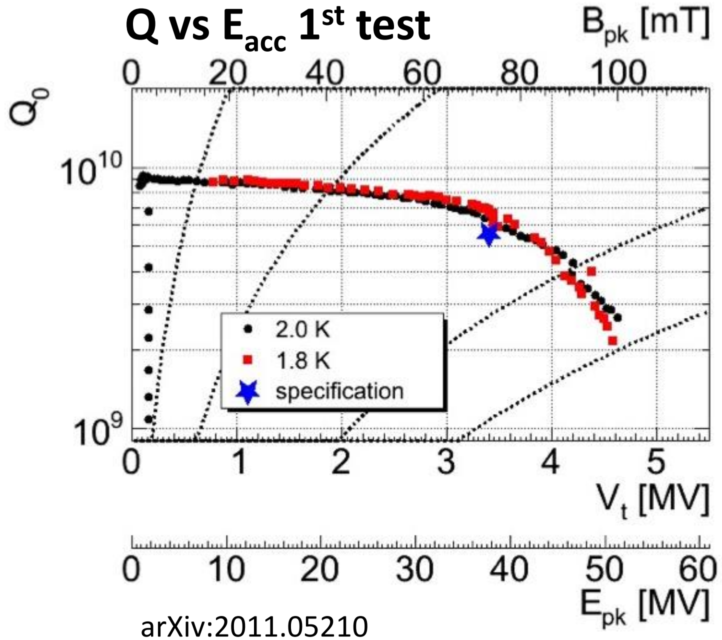
“Cryogenic” foams used to reduce liquid helium volume

Was performed a series of VT at FREIA and CERN, Try to track a variation in cavity performance over the time, transportation, and multiple venting.

During reception test after cavity arrival, we didn't found HOM by VNA. Cavity was opened in clean room (**Class 10**), found broken antenna and attached back for VNA test.





arXiv:2011.05210

Learned lessons

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From ESS double spoke cavities:

- DSPC are robust, ridged and well predicted cavities.
- Multipacting relatively tuff but its “field bands ” is well defined and repetitive.
- It is **easy to quench cavity at low field** (<1MV/m), specially, during CW operation.
- Low field multipacting can cause difficulties for field probe calibration in VT.
- In our case, **thermal cycles help a lot to treat FE**.
- Cold cavity walls able to accumulate He → making small cold leaks invisible during cold operation until warm up.
- Having connected RGA to beam vacuum is a good practice.
- Accurate Q_0 measurement in strongly over coupled case is a big challenge.

From CERN prototype Crab cavity:

- Transportation of SRF cavities on long distance is not a greater idea.
- Chemical treatment of cavity surface is mandatory to recover performance after mechanical interaction, like foaling down field probe.
- SRF cavities do not become better with age. Clear visible performance degradation with every venting.

Thank you for attention!