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Experiences from the series double-spoke cavity cryomodules for ESS

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Uppsala University

TESLA TECHNOLOGY TTC COLLABORATION

EUROPEAN SPALLATION SOURCE

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The FREIA team: international experts from different fields

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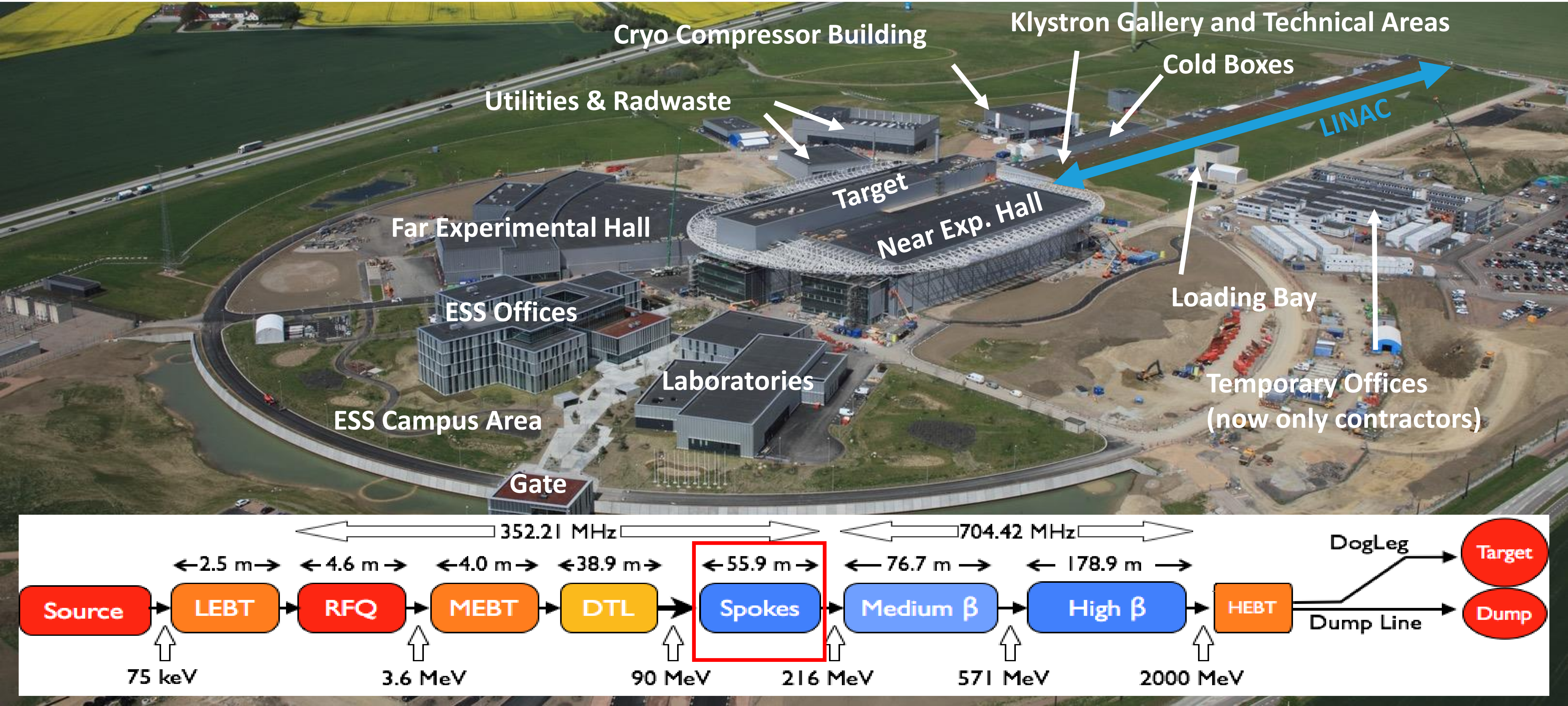
European Spallation Source for science with neutrons

Courtesy C. Maiano



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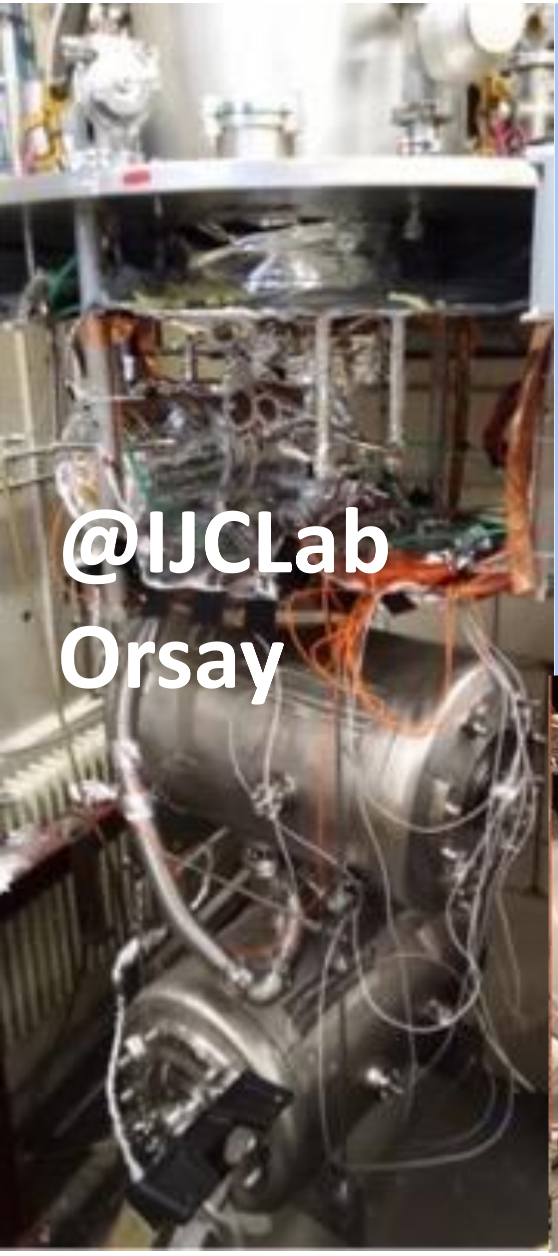
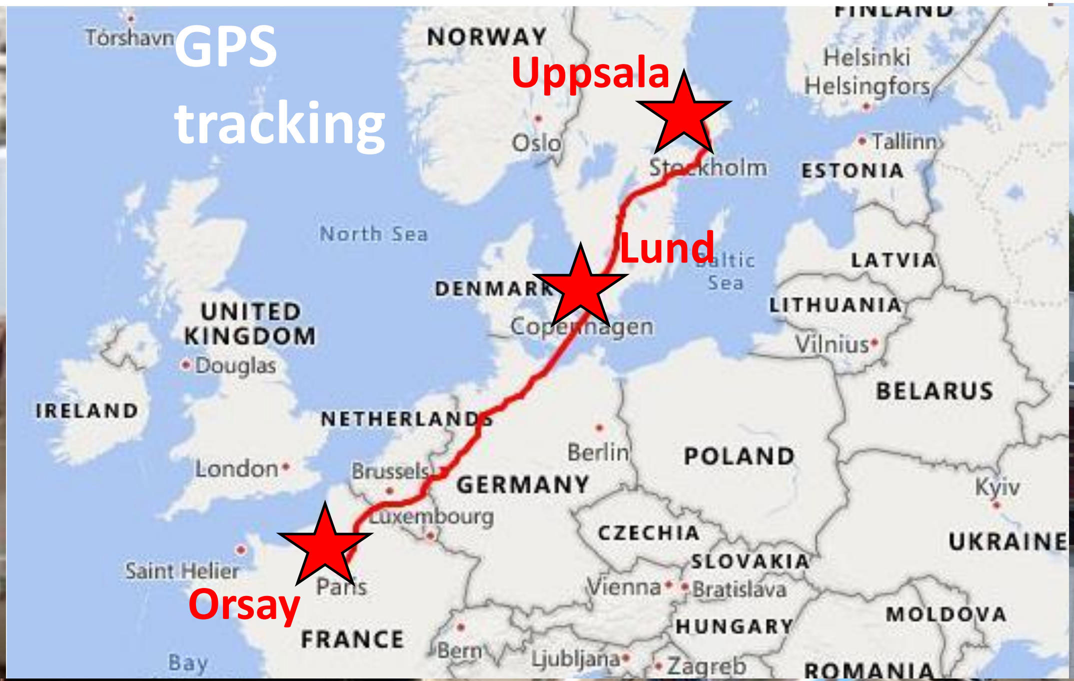
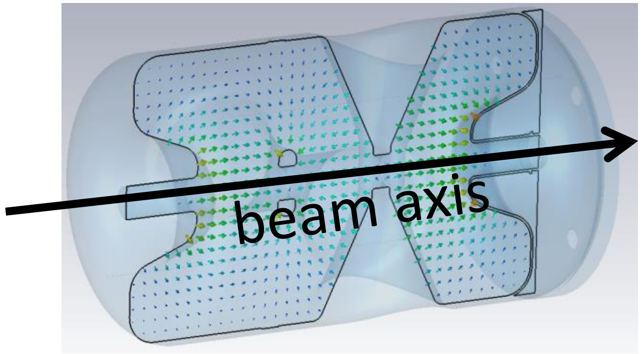
Assembly at Orsay → Assessment at Uppsala → Installation at Lund

FREIA

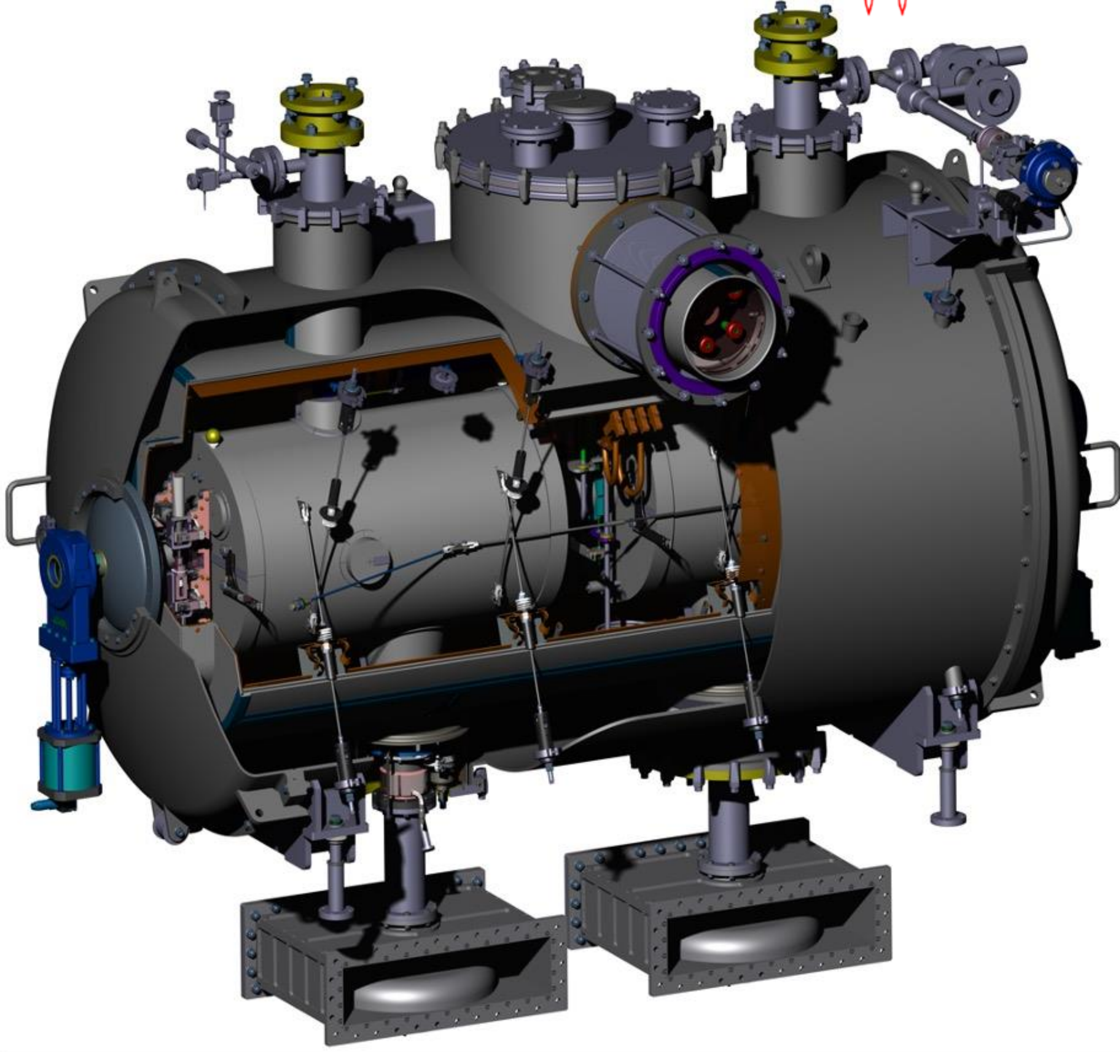




ESS double-spoke cavity cryomodule (x13+1)



parameter	value
f [MHz]	352.210
β_{opt}	0.50
E_{acc} [MV/m]	9.0
B_{pk}/E_{acc} (B_{pk})	6.8 (61 mT)
E_{pk}/E_{acc} (E_{pk})	4.3 (38 MV/m)
G [Ω]	133
R/Q [Ω]	427
L_{acc} [m]	0.639
Q_{ext}	1.75-2.85e5
BW [kHz]	1.2-2.0
Q_0	>1.5e9

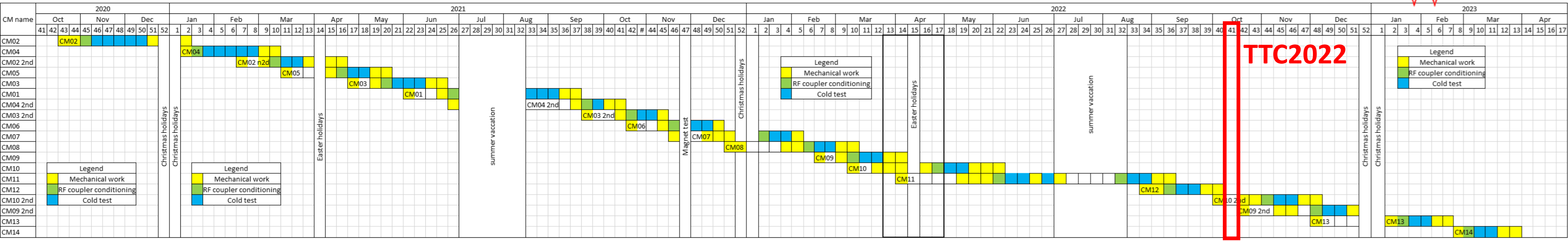


Operation parameters

- 90 MeV → 216 MeV
- Peak current 62.5 mA
- Bunch length 2.86 ms
- RF pulse length 3.2 ms
- Repetition rate 14 Hz
- RF duty cycle 4.5 %
- Temperature 2K
- Max RF power 335 kW

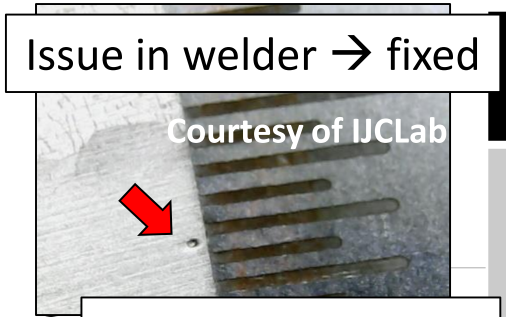
- **ESS offers the first deployment of double-spoke cavities** (difference from SNS)
- Practical challenges beyond mere R&D in the laboratory

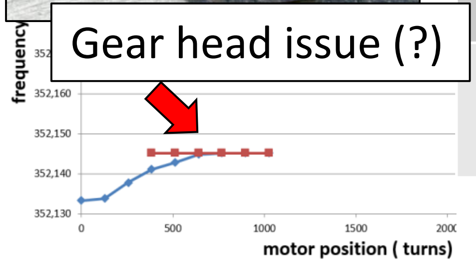
ESS spoke cavity modules at FREIA: progress and planning



	qualified	Disqualified by FREIA	To be tested
Qualification in the 1st test	6 (CM05, CM01, CM06, CM07, CM08, CM11)	5 (CM02, CM04, CM03, CM09, CM10)	3 (CM12, CM13, CM14)
Qualification in the 2nd test	3 (CM02, CM04, CM03)	0	2 (CM09, CM10)

More than two years nonstop during Covid-19





	No problem	Found by IJCLab	Found by FREIA	To be tested
Vacuum leak in SCHe double-wall tube of a coupler	8 (CM02, CM05, CM01, CM06, CM07, CM08, CM10, CM11)	1 (CM03)	2 (CM04, CM09)	3 (CM12, CM13, CM14)
Stepper motor issue	8 (CM05, CM06, CM01, CM07, CM08, CM09, CM11, CM12)	0	4 (CM02, CM03, CM04, CM10)	2 (CM13, CM14)

Lessons learned
& Performance statistics

Warm RF coupler conditioning

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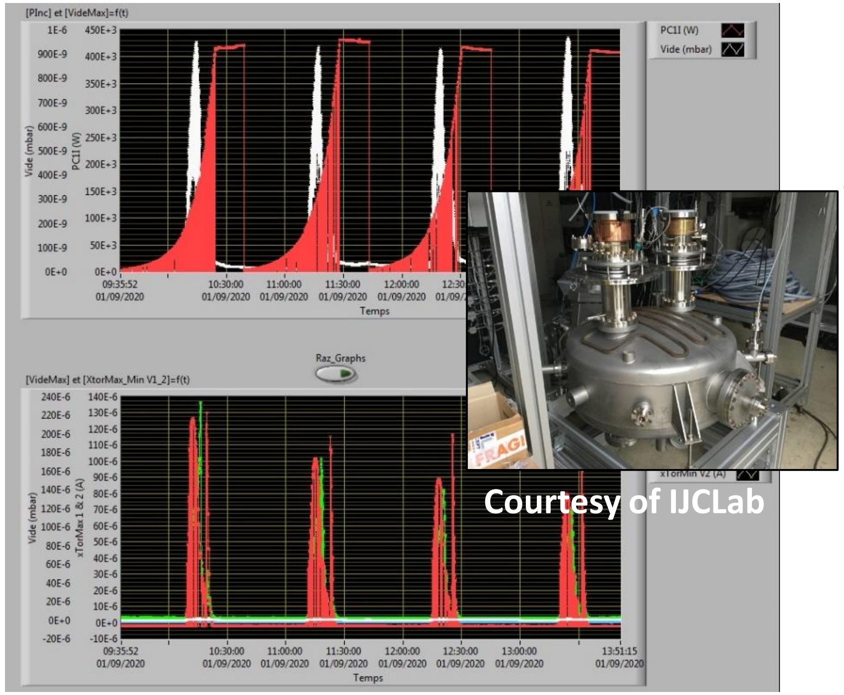
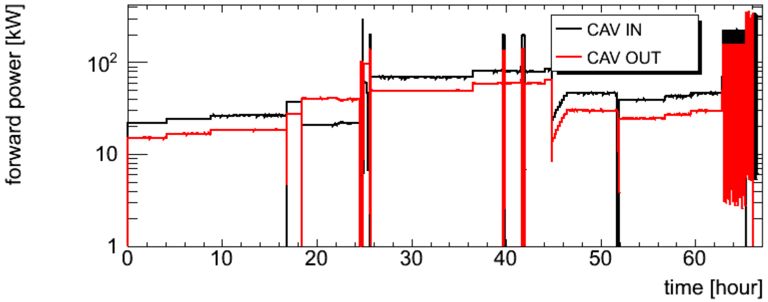
Preconditioning at IJCLab

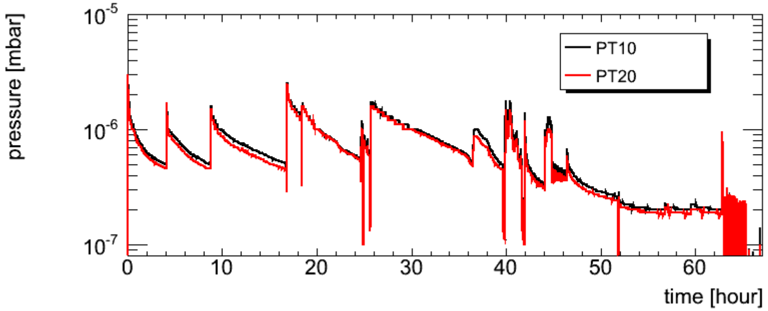


Travelling wave up to 400 kW in a dedicated test bench

Conditioning at FREIA

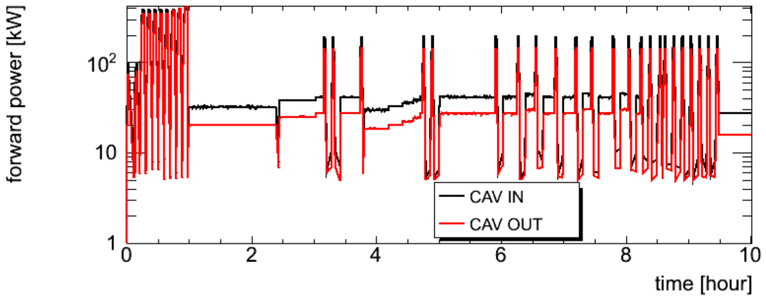


(ESS CM05)

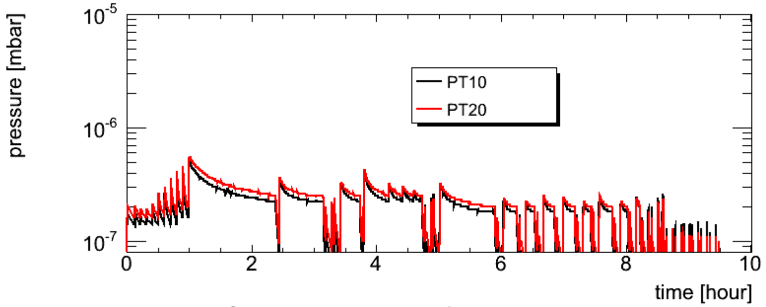


Standing wave up to 400 kW in a cryomodule (off resonance)

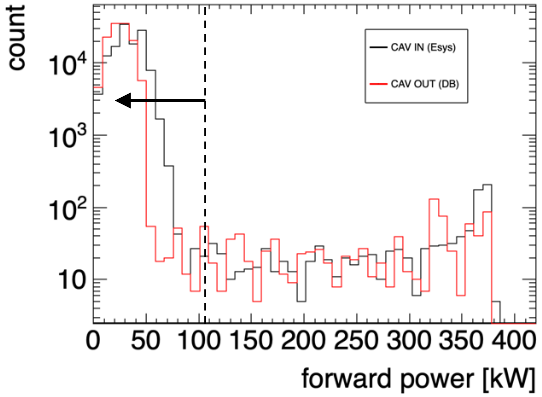
2nd conditioning (i.e. commissioning)



(CM02 2nd)



After 2 months in static vacuum at warm



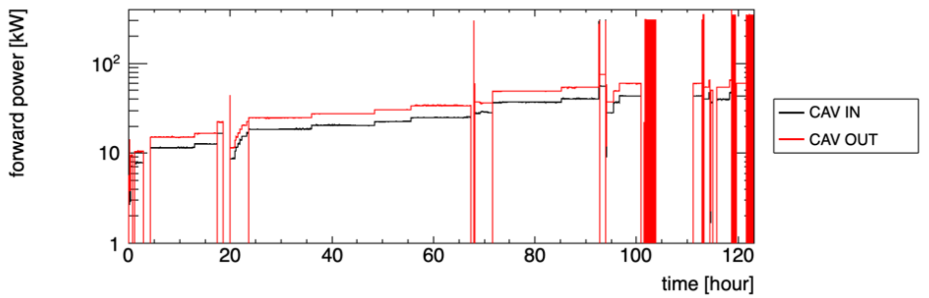
Lesson learned

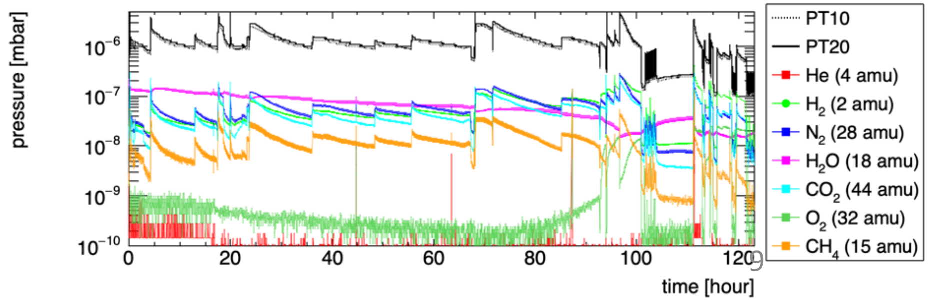
- Out-gassing is below 100 kW (multipacting barrier)
- Travelling wave conditioning before assembly was not enough
- 24h x 3-4 days up to duty cycle 4.5%
- Stability of the RF system for 24 hours is crucial

Warm coupler conditioning summary

CM	FPC1	FPC2	times	# of stations	# of pumps	Live time [hours]
CM02 1st	CPL01	CPL04	1st	2	1	112
CM04 1st	CPL11	CPL03	1st	2	1	67
CM02 2nd	CPL01	CPL04	2nd	2	2	9
CM05	CPL14	CPL18	1st	2	2	66
CM03 1st	CPL06	CPL26	1st	2	1	109
CM01	CPL10	CPL12	1st	2	2	90
CM04 2nd	CPL32	CPL05	1st	1	2	147
CM03 2nd	CPL06	CPL26	2nd	2	2	12
CM06	CPL11	CPL20	1st	2	2	66
CM07	CPL25	CPL30	1st	2	2	48
CM08	CPL21	CPL15	1st	2	2	65
CM09	CPL27	CPL28	1st	2	2	30
CM10	CPL23	CPL24	1st	2	2	10
CM11	CPL22	CPL19	1st	2	2	26
CM12	CPL03	CPL09	1st	2	2	92

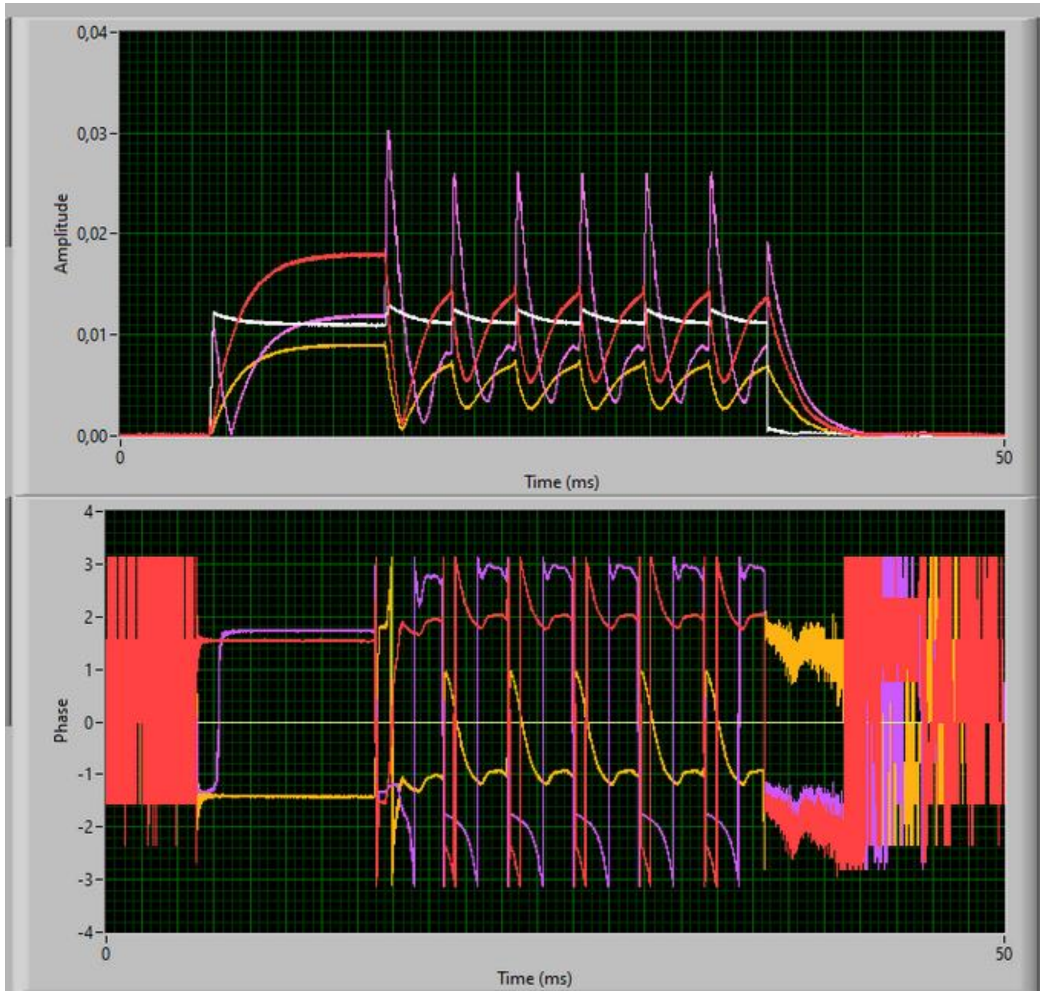
- Huge variation from 10 h to 92 h even with the same condition
- More active pumping during assembly reduces the necessary conditioning time (cf SPIRAL2)
- Residual Gas Analysis indicates peak at 15 amu and 28 amu which are typical sign of CH (cf plasma processing)



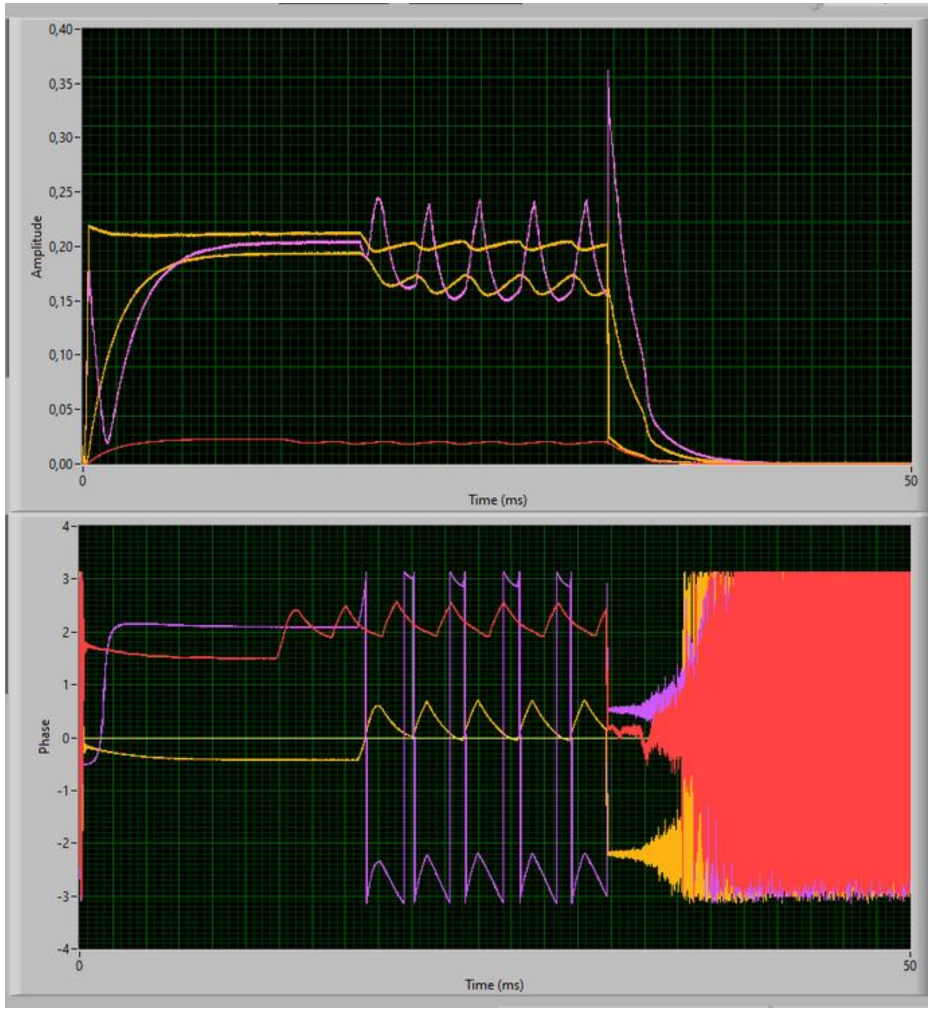


Local thermal quench at very low field (< 1 MV/m)

CAV IN

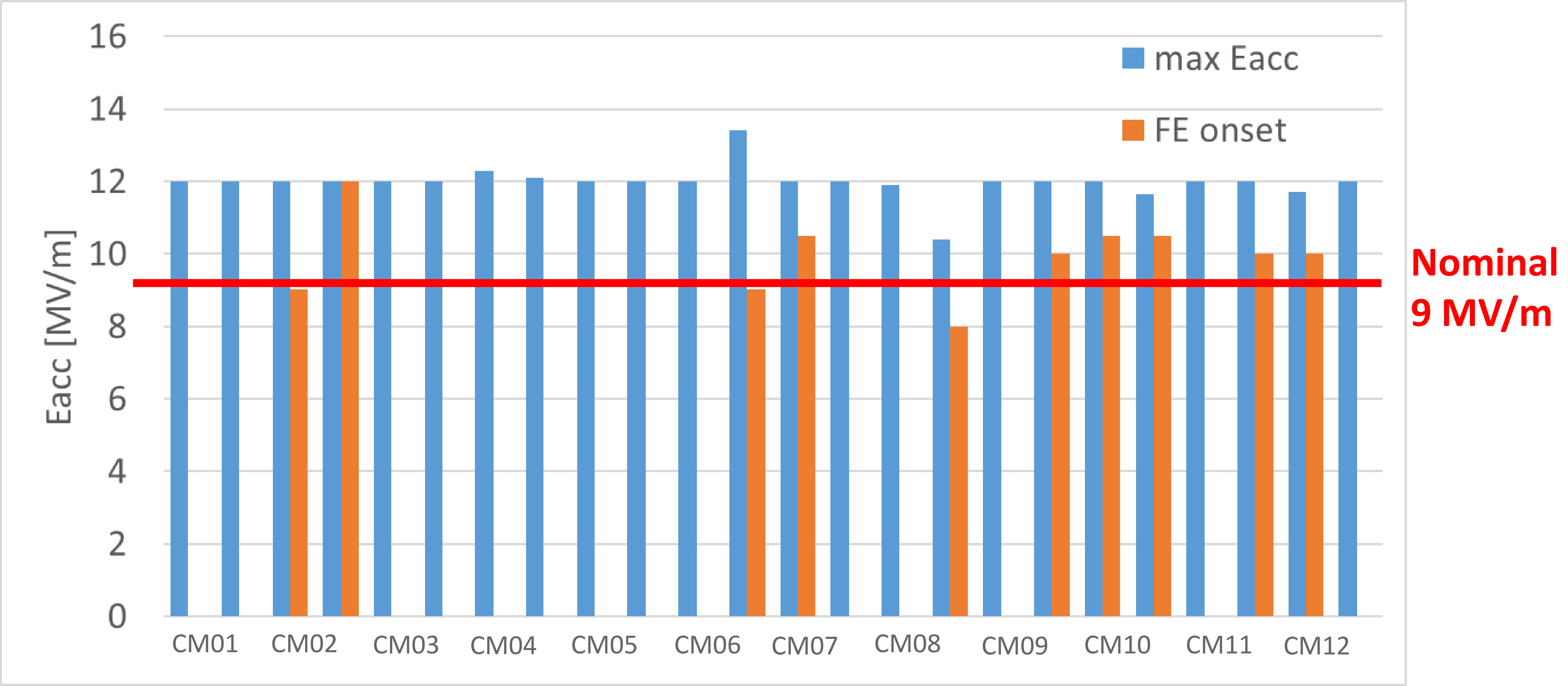


CAV OUT



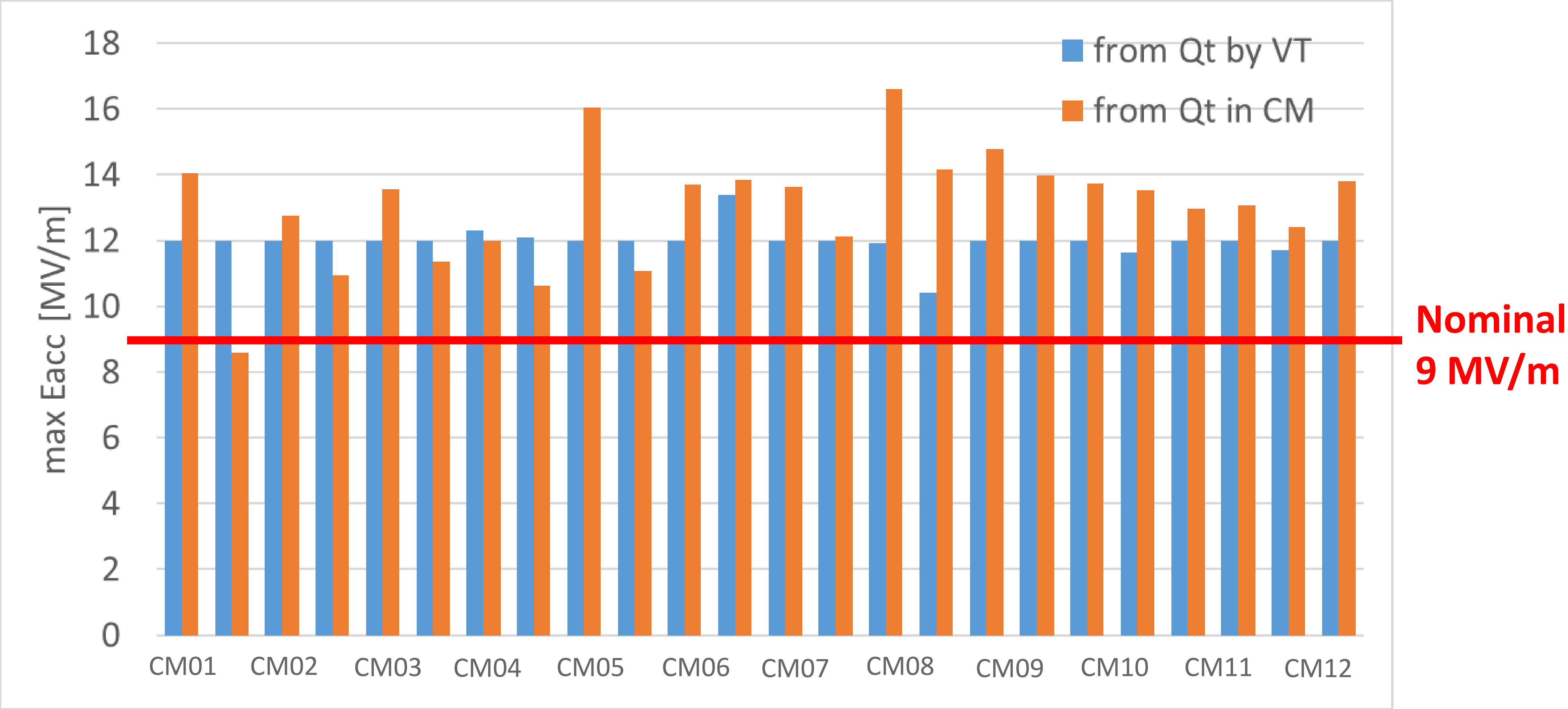
Local quench & thermal feedback is almost always observed at very low field in the spoke cryomodules so far → special care (interlock) is mandatory

Accelerating gradient and field emission



- All the cavities reached the nominal gradient 9 MV/m
- Some cavities showed field emission but probably safe (→ next slide)

Uncertainty in the field calibration (Q_t)

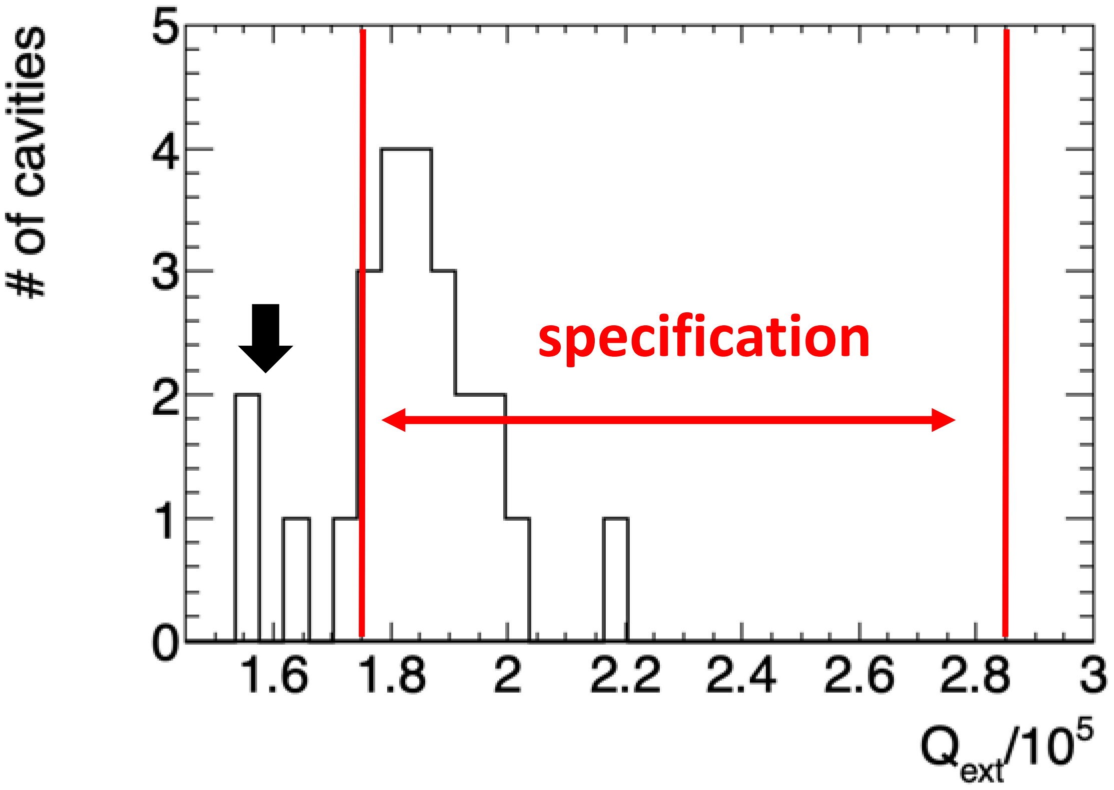


- Q_t from Vertical Test generally ***underestimates*** the field value
- Error estimation in Q_t in CM is 10% mainly from power calibration's uncertainty
  - Stored energy estimated from the integral of decaying reflected power

Static and RF heat loads

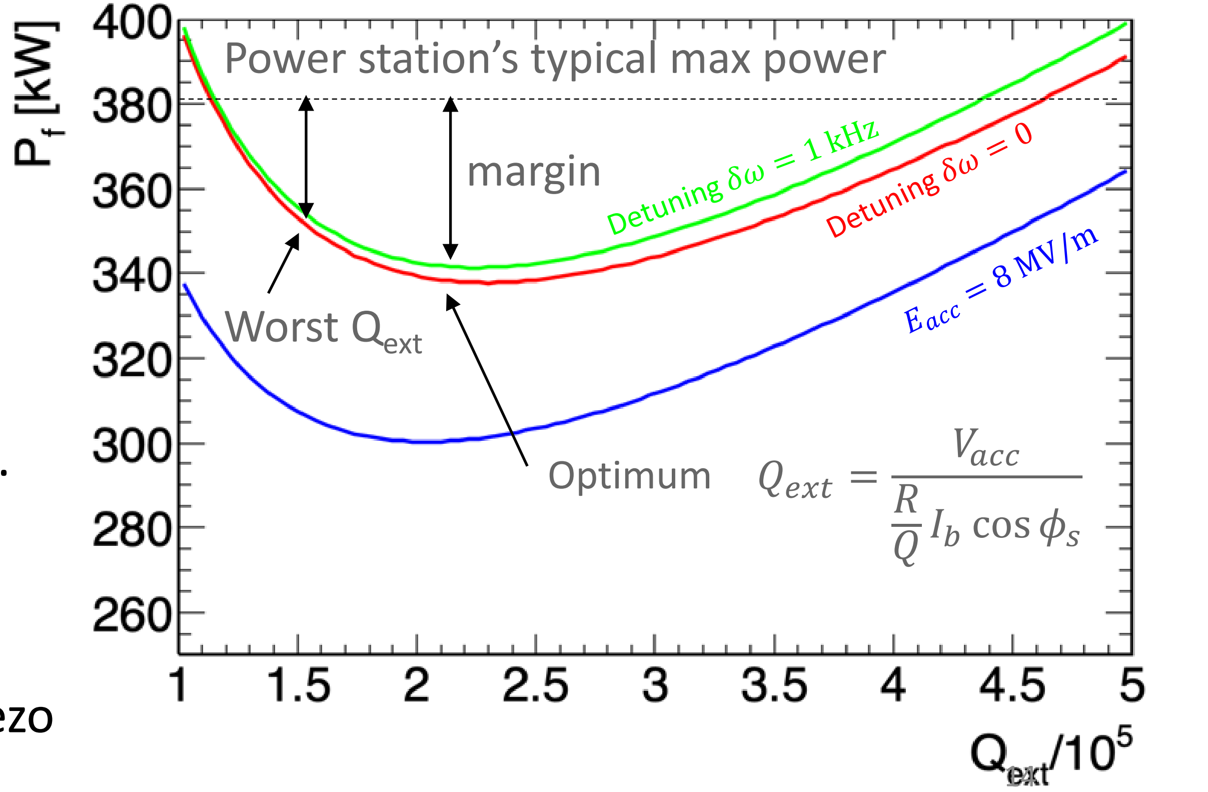
- The temperature of the thermal screen is 80 K while the one in ESS is 40 K
  - Our static heat load is just a reference
- Gas helium flow in the exhaust line has been used to estimate the heat load
  - LHe level drop and pressurizing in closed volume have been taken as spare data
- Averaged static heat load is 16.5 W for each module
  - Thermo-acoustic oscillation has been observed in some cases in the prototype valve box
- Averaged total heat load (9 MV/m for both cavities) is 17.4 W for each module
- RF power dissipation (<2 W) is almost always within fluctuation of helium gas flow (1-2 W) for heat load estimation
  - This is because Q_0 is above spec and duty cycle is only 4.5%

Q_{ext} and required forward power for a given I_b



$$P_f = \frac{V_{acc}^2}{4\frac{R}{Q}Q_{ext}}\left\{\left[1+\frac{I_b\frac{R}{Q}Q_{ext}}{V_{acc}}\cos\phi_s\right]^2+\left[\frac{2Q_{ext}\delta\omega_m}{\omega}\right]^2\right\}$$

$$V_{acc} = 9\ \mathrm{MV/m} \times 630\ \mathrm{mm} = 5.75\ \mathrm{MV}$$
$$R/Q = 427\ \Omega,\ I_b = 62.5\ \mathrm{mA}\,,\ \phi_s = 20^\circ$$



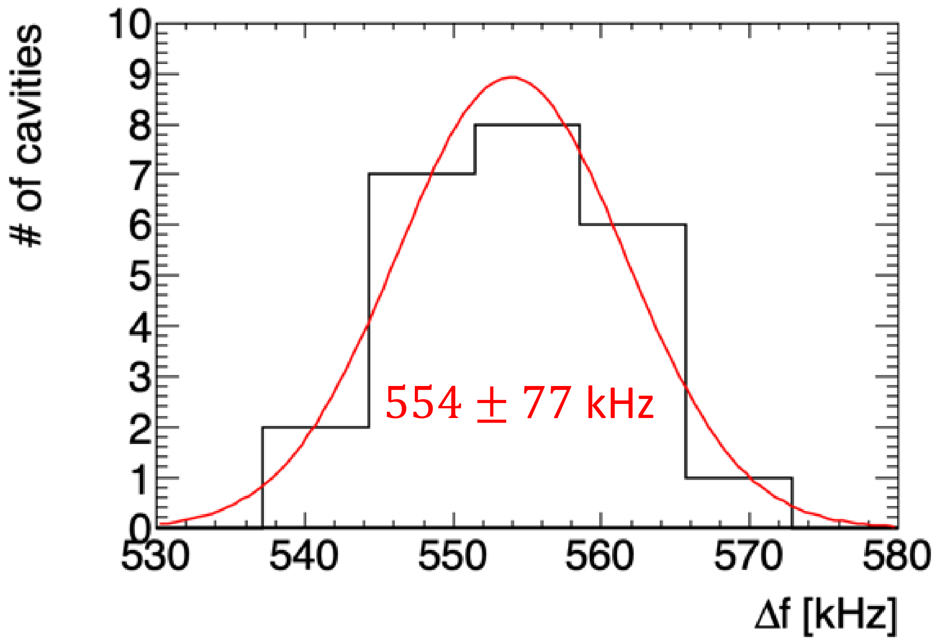
- Statistically distributed around the lower edge of the spec.
  - A few cavities were even out of spec

→ Less margin in forward power in linac

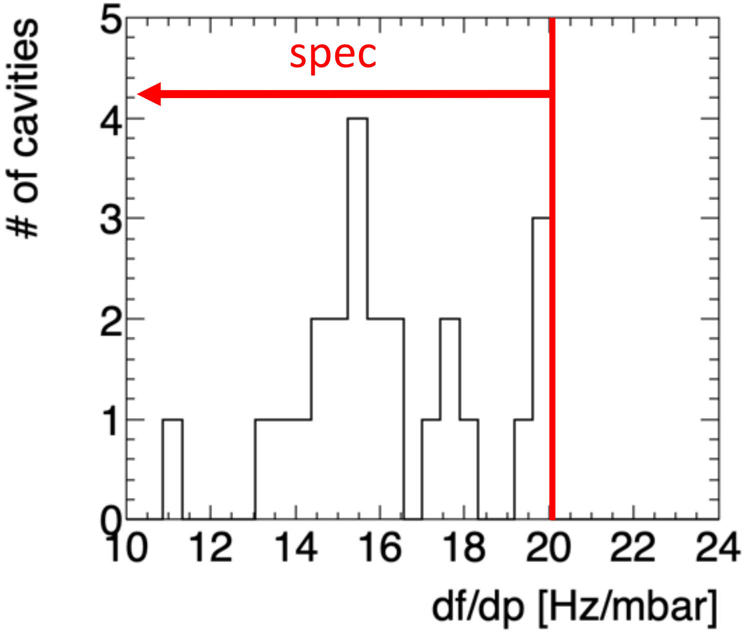
- Option: in the earlier stage of the section with lower E_{acc}
- Is it critical or not → closed loop operation with LLRF + piezo

Frequency tuning

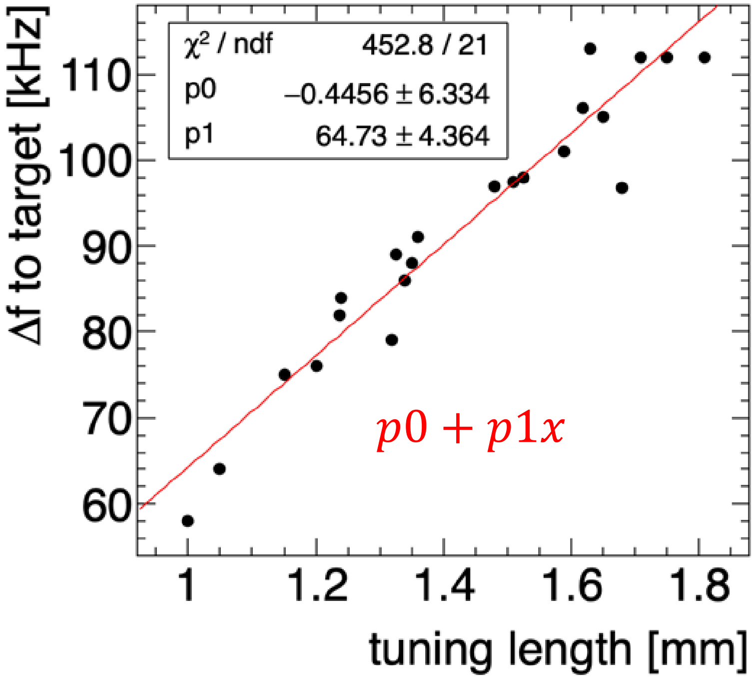
Frequency shift from 300 K to 2K



Frequency sensitivity to pressure

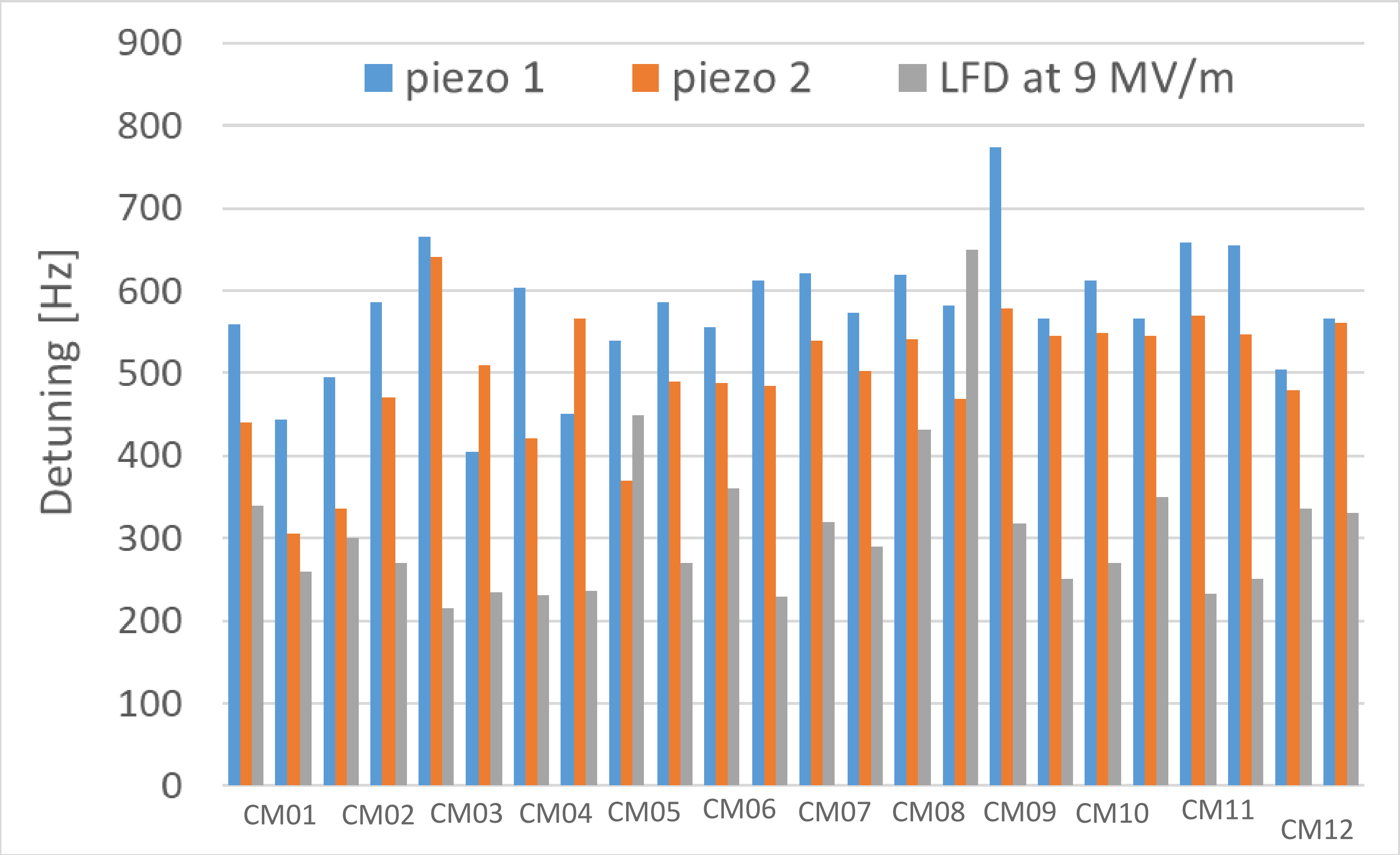


Tuning range vs tuning length

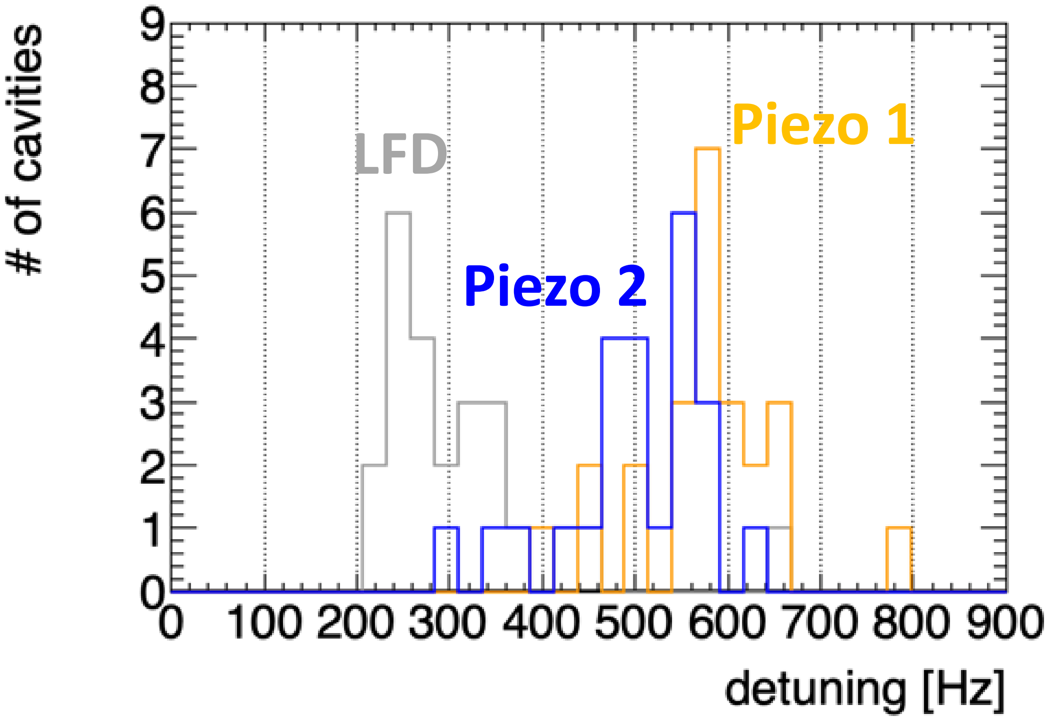


- The frequency tuning is under control
- Mechanical stress might be a problem in the future project and discussions are on-going with MINERVA

Dynamic Lorentz force detuning vs piezo tuning range



Corresponding histogram

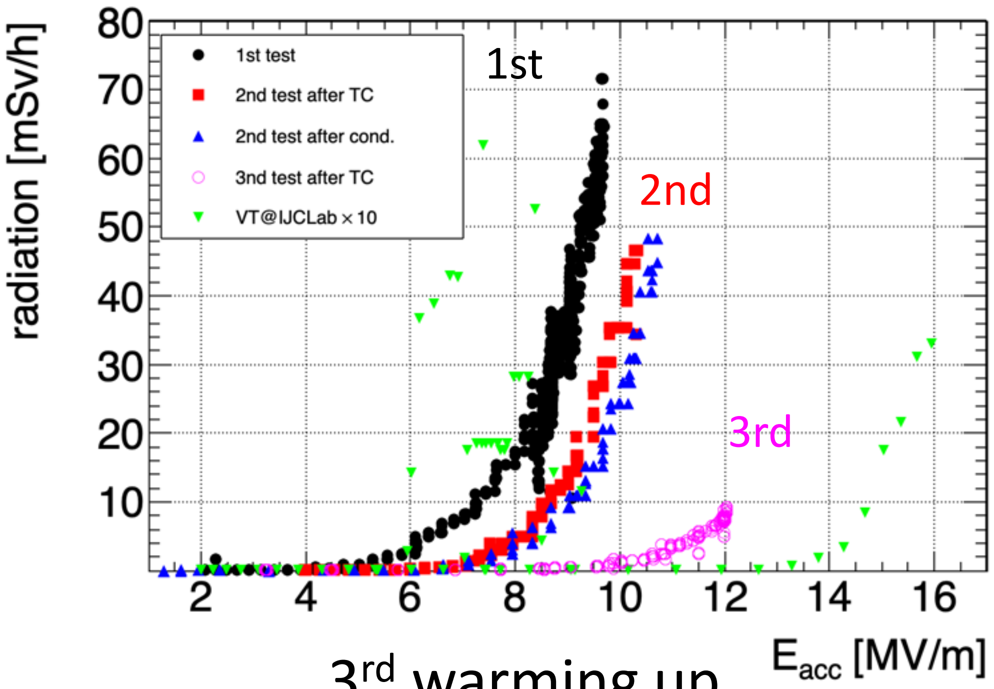


- Piezo tuning range was with unipolar bias (0-200V) in quasi-static condition slower than 50V/1min
- LFD < piezo tuning range is generally applied and active piezo compensation would be feasible
- Simultaneous operation of two piezos or use one a spare

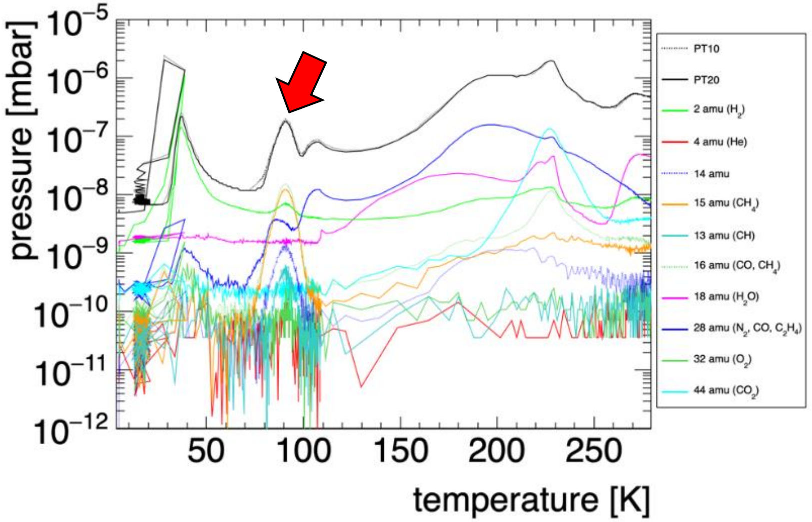
Field emission and thermal cycles (CM11)

- Several thermal cycles dramatically mitigated a strong field emission
- The beam vacuum was never vented
- Nothing except for the tuner was moved
- The residual gas analysis indicates outgassing of 15 amu (CH_4) and could be a sign of CH removal (?)

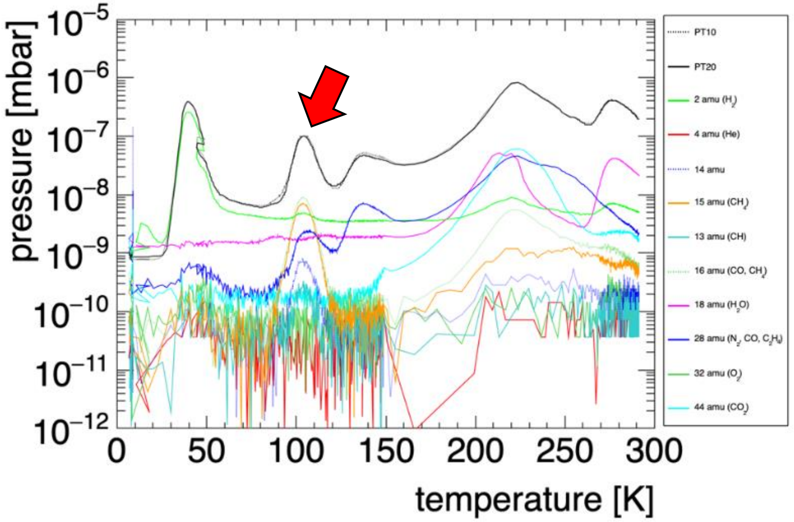
→ Plasma processing in spoke cavities may give us some hints in this phenomena



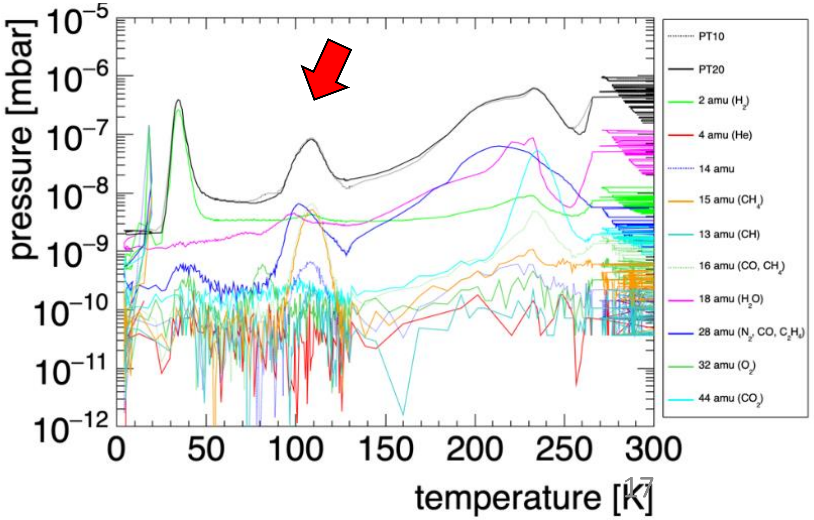
1st warming up



2nd warming up



3rd warming up

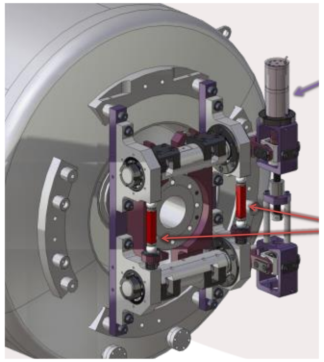


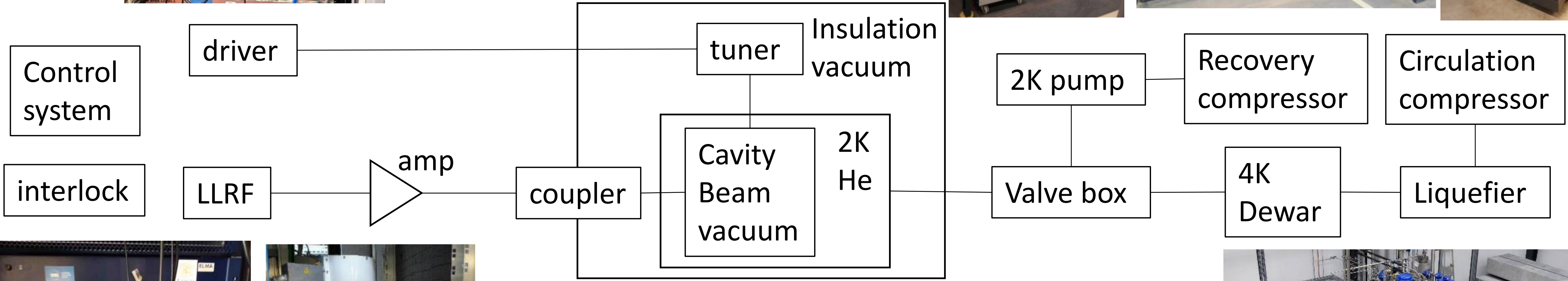
Conclusion

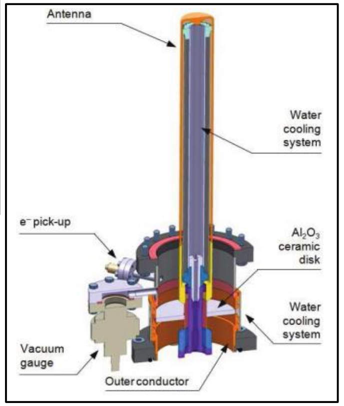
- FREIA laboratory in Uppsala University is in charge of qualification of series spoke-cavity cryomodules for ESS in collaboration with IJCLab
- 9 modules have been qualified and 5 modules will be tested by March 2023
- Lessons learned
  - Coupler conditioning in CM can take time but its duration has been statistically very different
  - Thermal quench happens at very low field and interlock setup is crucial even at very low field
  - All the cavities so far reached the spec (9 MV/m) with some disagreement of field calibration between vertical tests and high-power cryomodule tests
  - Field emission was observed in some of the cavities but may not be critical for the machine
  - External Q of couplers are statistically at the lower edge of the spec for unknown reason
  - The thermal screen temperature is different from ESS and static heat load may not be relevant
  - RF heat dissipation is so small that precise measurement seems not feasible
  - Coarse tuning was under control and piezos can compensate Lorentz force detuning
- Some speculations about field emission and potential CH contamination
  - This may motivate plasma processing studies in spoke cavities

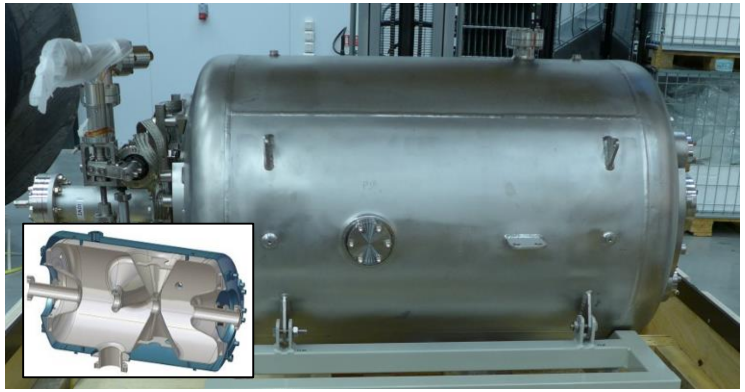
backup

Challenges in cryomodules: complicated integration









FREIA is leading **low-β cryomodule** assessment in Europe

Standard test of one spoke-cavity module

week	1st week											
day	MON		TUE		WED		THU		FRI		SAT	SUN
	m	a	m	a	m	a	m	a	m	a		
activity	departure from Orsay		transport				**reception**		reception test			

week	2st week											
day	MON		TUE		WED		THU		FRI		SAT	SUN
	m	a	m	a	m	a	m	a	m	a		
activity	doorknob mounting		installed in bunker		cryogenic connection		vacuum connection		RF calibration at warm		pumping	

week	3rd week											
day	MON		TUE		WED		THU		FRI		SAT	SUN
	m	a	m	a	m	a	m	a	m	a		
activity	coupler warm conditioning								LN shield cooling			

week	4th week											
day	MON		TUE		WED		THU		FRI		SAT	SUN
	m	a	m	a	m	a	m	a	m	a		
activity	cooling down to 4K		4 K filling	thermalization	2K pumping		multipacting conditioning		CTS test			
	f vs T measurement		coupler cold conditioning		f vs p	calibration at cold						

week	5th week											
day	MON		TUE		WED		THU		FRI		SAT	SUN
	m	a	m	a	m	a	m	a	m	a		
activity	heat load measurement		start warming up		warming up				warming up completed			

week	6th week											
day	MON		TUE		WED		THU		FRI		SAT	SUN
	m	a	m	a	m	a	m	a	m	a		
activity	out from bunker		dismount doorknob, dry N2		out going test		departure		**arrival at ESS**			

Legend	
(yellow)	Mechanical work
(green)	RF coupler conditioning
(blue)	Cold test

Main part of the test takes 4 weeks

Enevitable 18 days

- Pumping 3 days
- Coupler conditioning 24h x 3-4 days
- Thermalization 7 days for CTS
- Warming up 4 days

Mechanical work takes more than 1 week but **overlap** with other modules help

The closed loop operation of LLRF is not included in the plan and was not tested except for the prototype module because

- Fully functional LLRF has not been ready
- Simply no time to fit the 4-weeks plan (additional one week must be considered)