UPPSALA UNIVERSITET

COMPLETION OF TESTING SERIES DOUBLE-SPOKE CAVITY CRYOMODULES FOR ESS

Rocío Santiago Kern

on behalf of the FREIA team

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

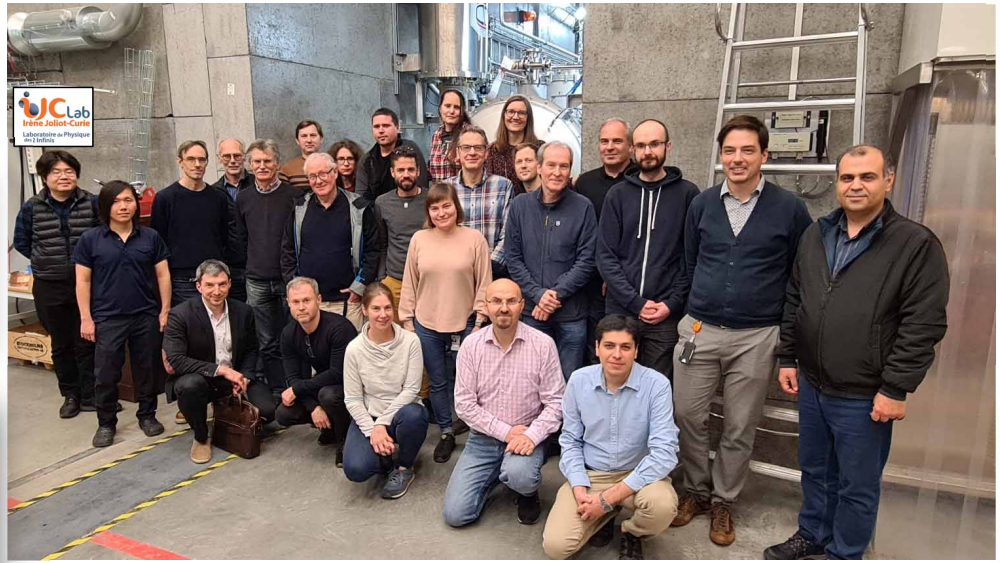
EUROPEAN SPALLATION SOURCE

Overview

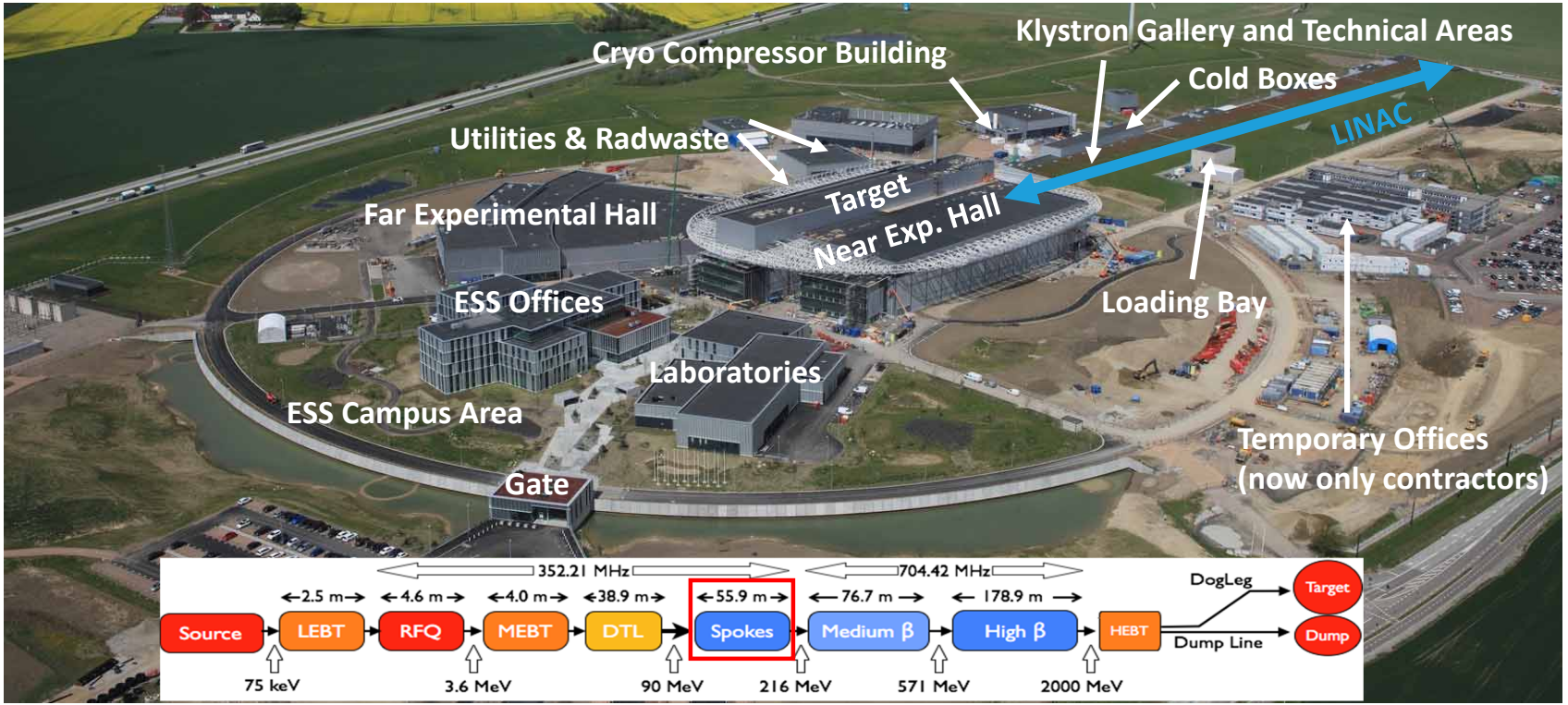
- The FREIA Team
- The ESS double-spoke cryomodules
- Cryomodules' Journey
- Challenges in Cryomodule Testing
- Measurements
  - Standard Testing Schedule per Cryomodule
  - Series Cryomodule Testing Qualification Overview
  - Warm RF coupler conditioning
  - Cryomodules' cooling
  - Cryomodules' Heat loads and Q_0
  - Field Emission
  - Risk of quench and protection
  - Cold tuning system and Lorentz-force Detuning
- Lessons learned
- Future prospects

The FREIA Team

International experts from different fields

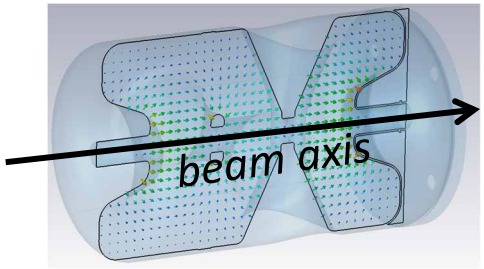


The European Spallation Source



Courtesy C. Maiano

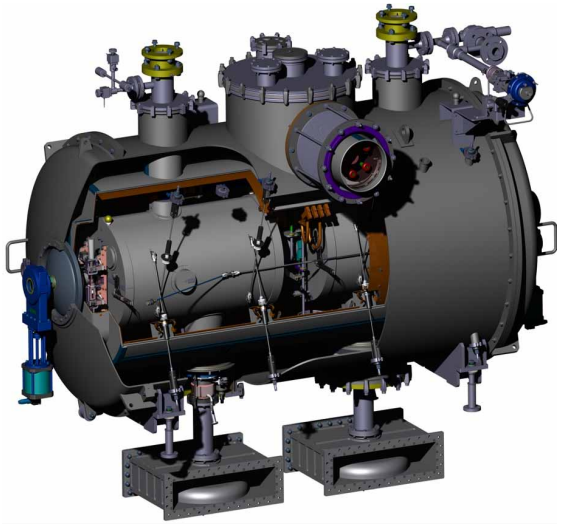
ESS double-spoke Cavity Cryomodule Parameters



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 2 K
- Max RF power 335 kW

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

CM= x2 double-spoke cav



(x13+1)

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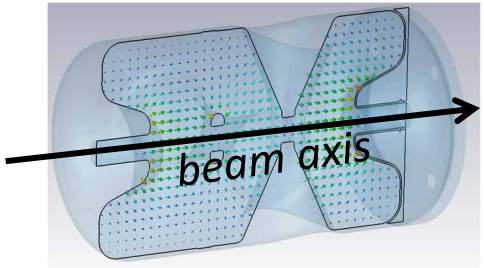

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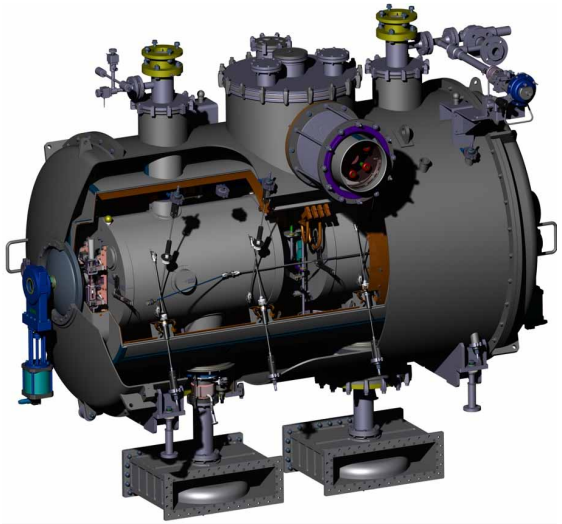

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Cryomodules' Journey

Cryomodule Assembly at Orsay

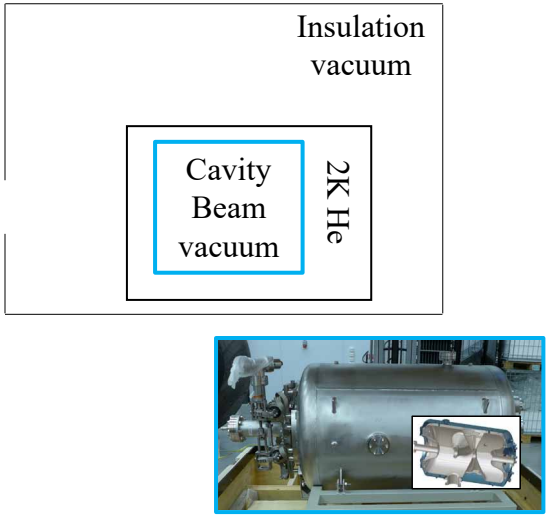
2 000 km

700 km

Installation at Lund

Assesment at Uppsala

Challenges in Cryomodule Testing



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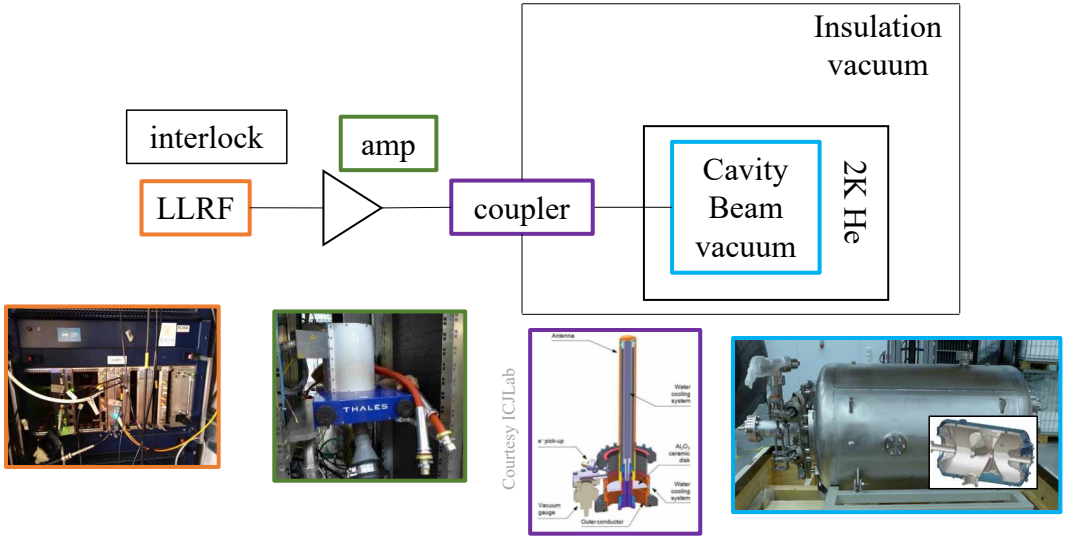

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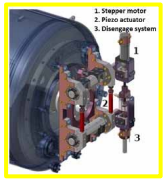

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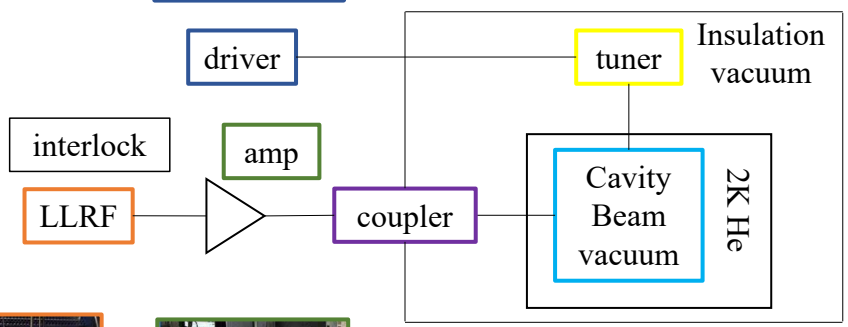

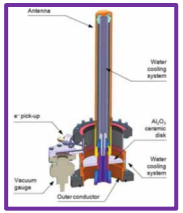

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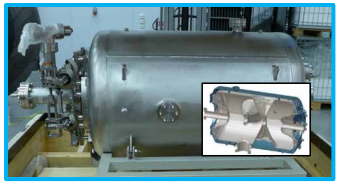

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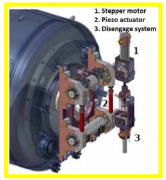

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driver

tuner

Insulation vacuum

interlock

amp

LLRF

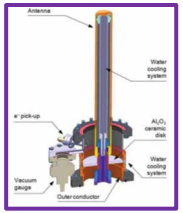
coupler

Cavity Beam vacuum

2K He

Valve box

4K Dewar



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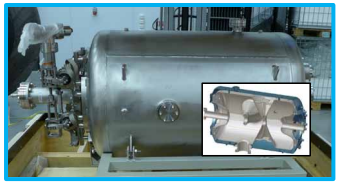

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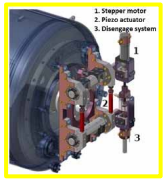

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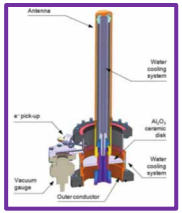

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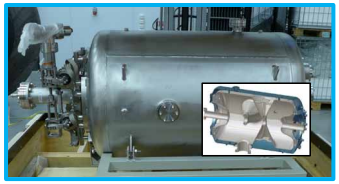

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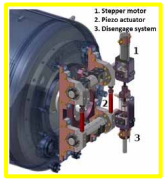

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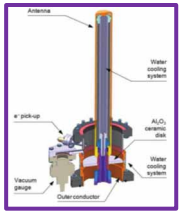

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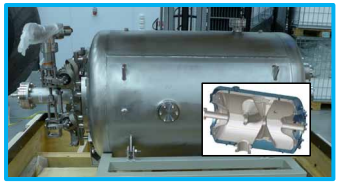

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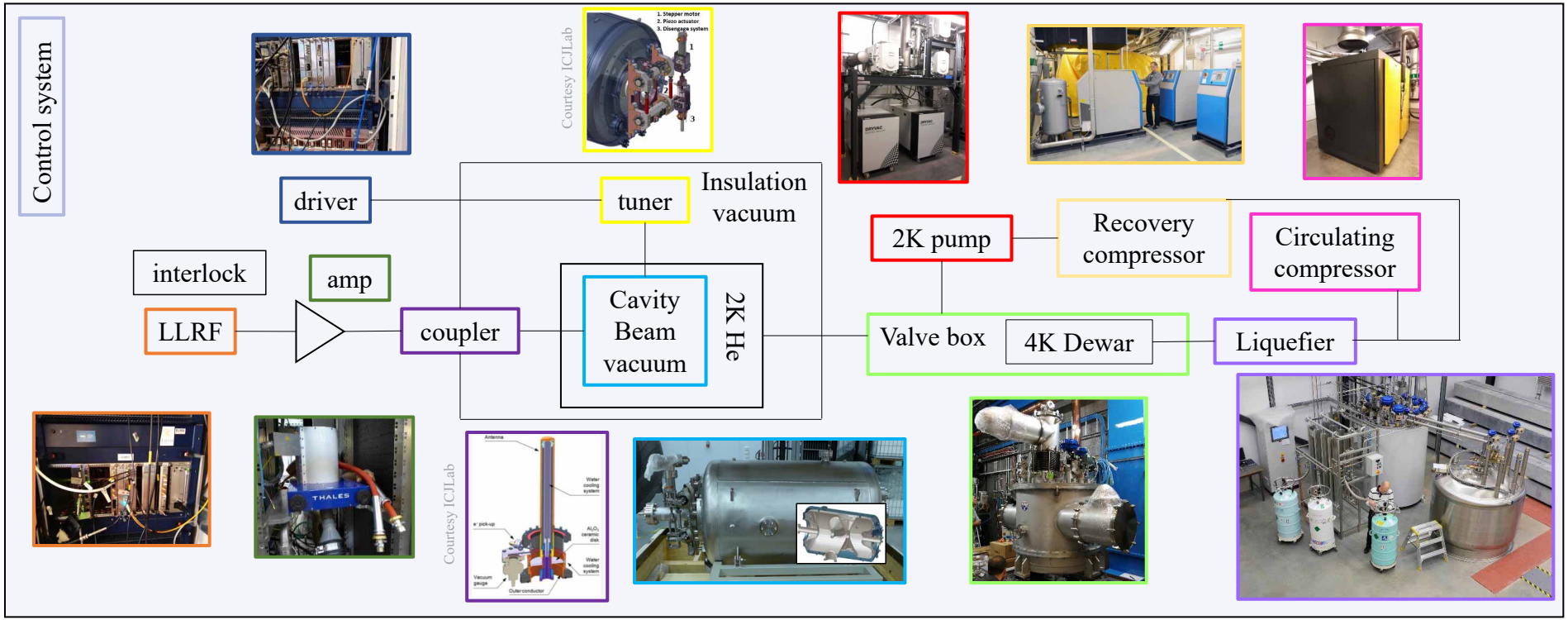

FREIA is leading **low-β cryomodule** assessment in Europe

Standard Testing Schedule per Cryomodule

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
Mechanical work
RF coupler conditioning
Cold test

Standard Testing Schedule per Cryomodule

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			

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activity	out from bunker		dismount doorknob, dry N2		out going test		departure		arrival at ESS			

Legend
Mechanical work
RF coupler conditioning
Cold test

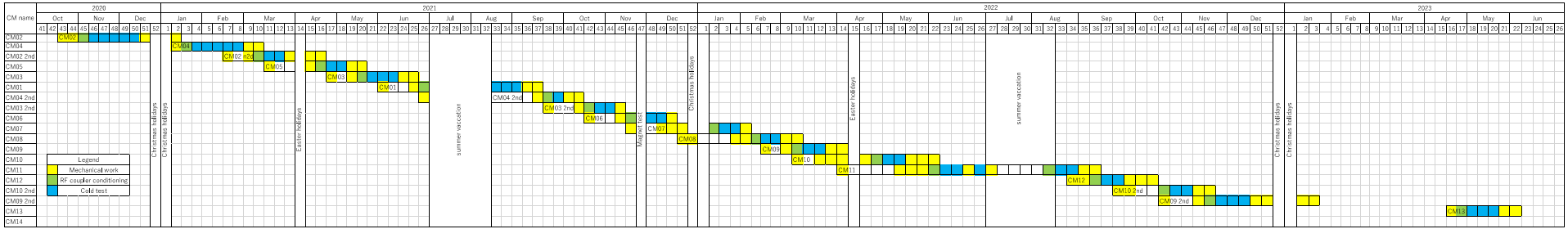
Main part of the test takes 4 weeks

Inevitable 18 days

- Beam Vacuum 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 **overlapping** with other modules helps

Series Cryomodule Testing Qualification Overview



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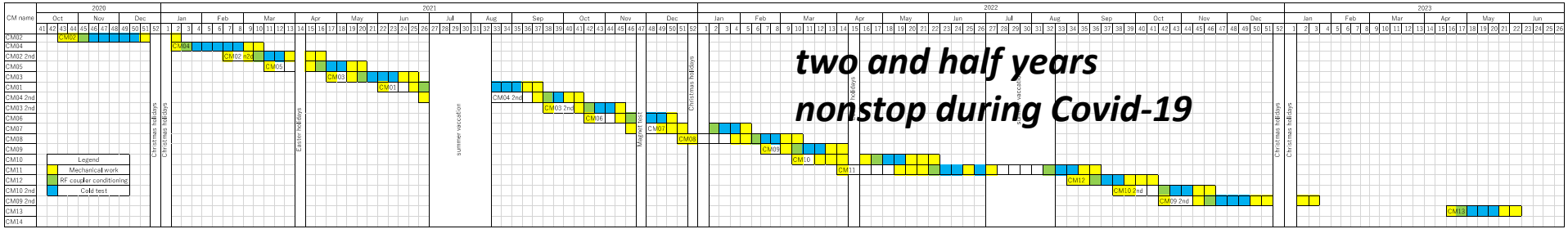

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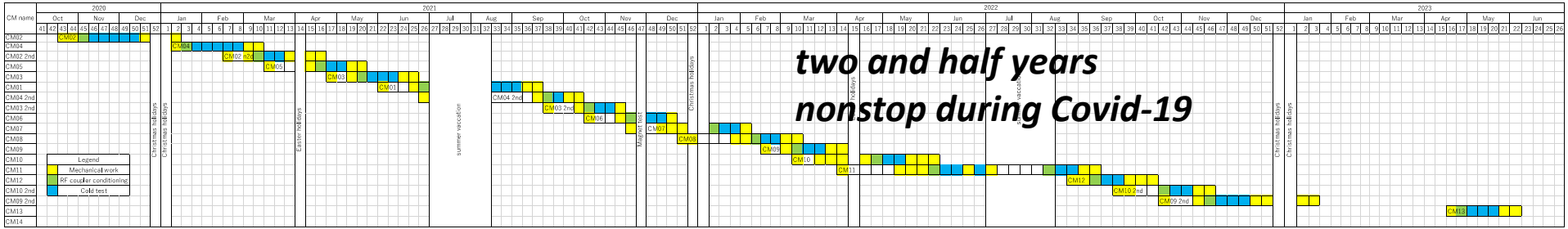

13 CMs tested

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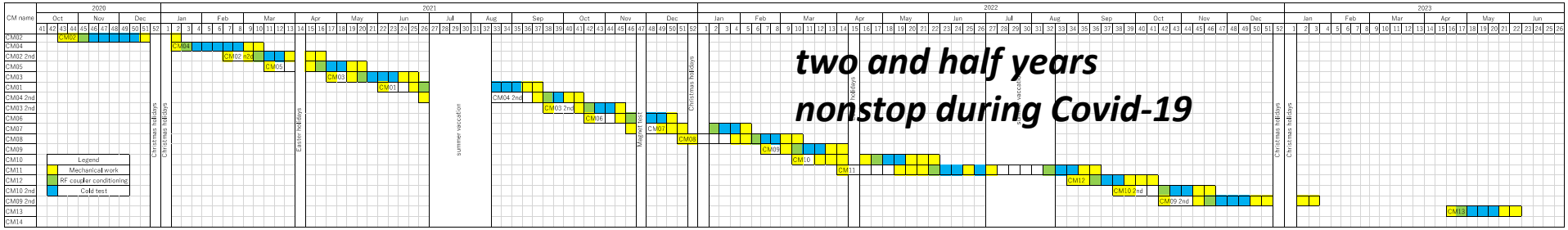

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8 CMs qualified in 1st round

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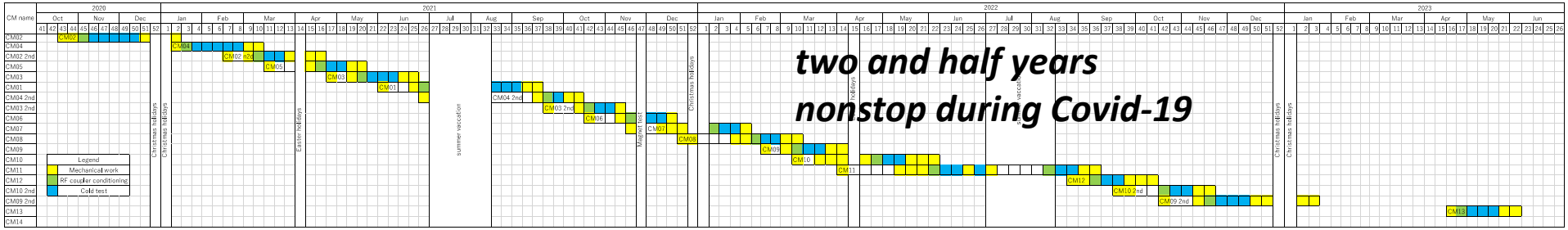

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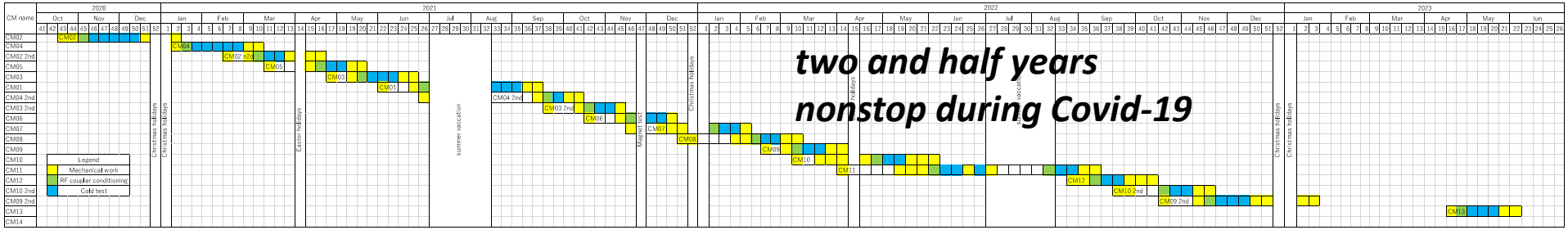

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CM03	Stepper motor lack of response
CM04	Stepper motor lack of response Vacuum leak in FPC's double wall tube
CM09	Vacuum leak in FPC's double wall tube
CM10	Stepper motor lack of response

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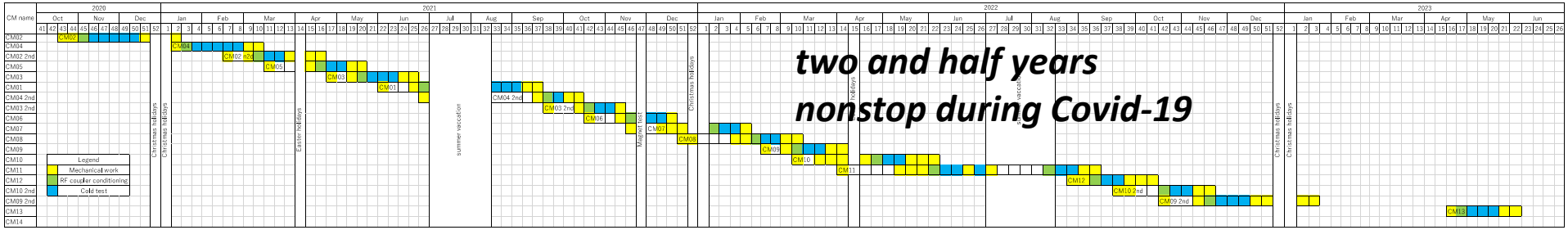

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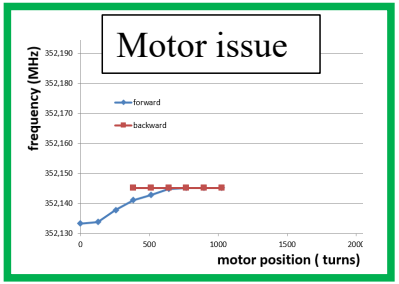

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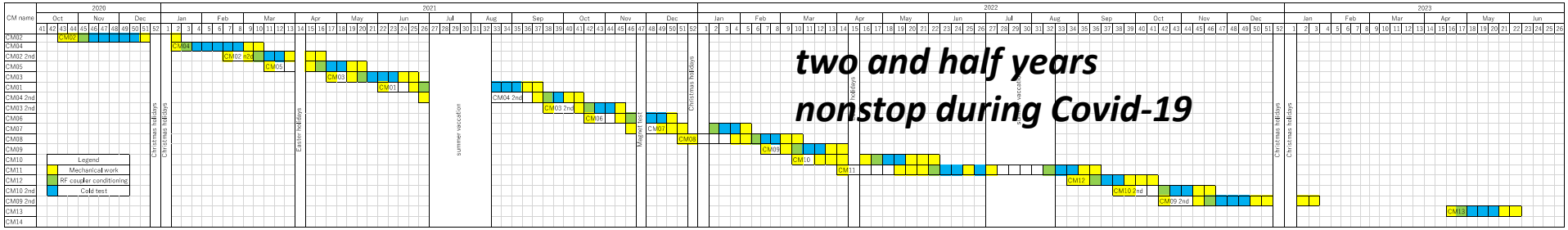

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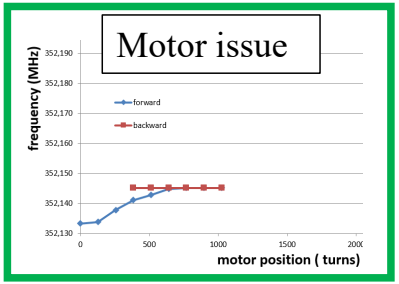

Under investigation by IJClab and the vendor

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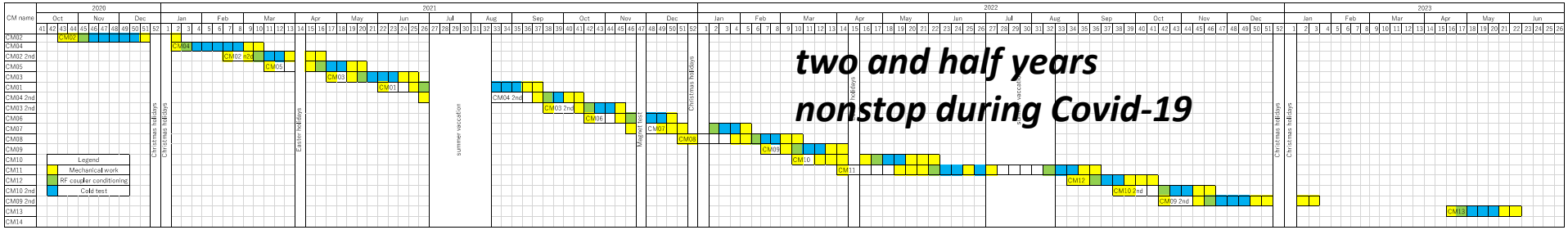

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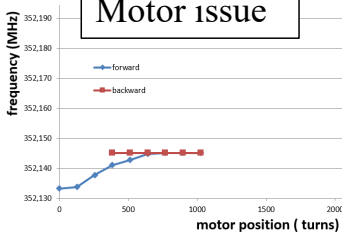
Motor issue



Issue in weld → fixed

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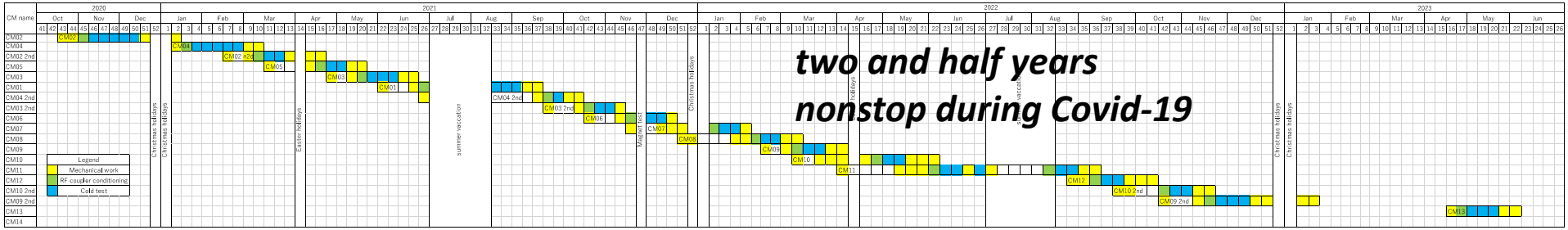

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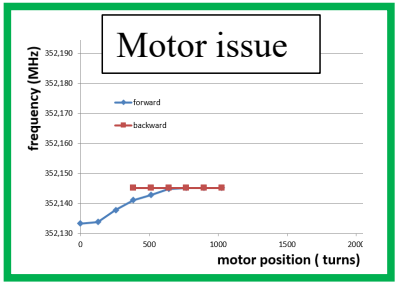

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Found only after cooldown!

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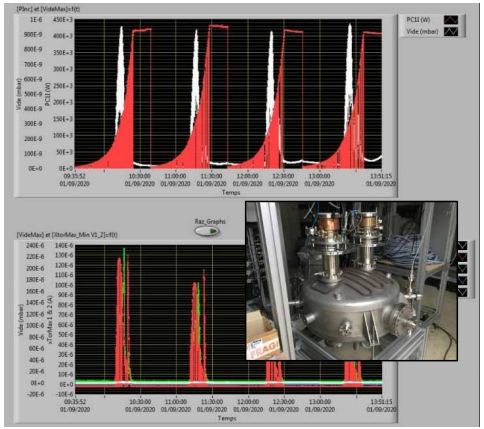
Warm RF coupler conditioning

Pre-conditioned in pairs at IJCLab



Travelling wave up to 400 kW
Standing wave up to 170 kW

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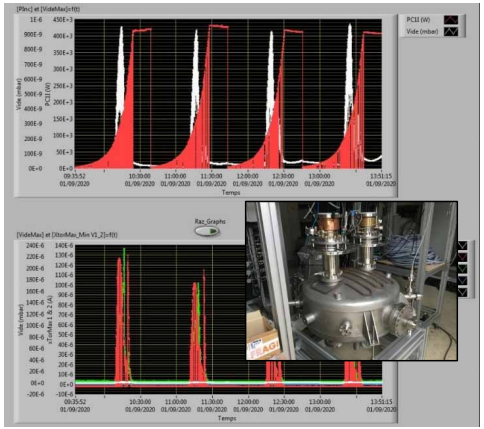

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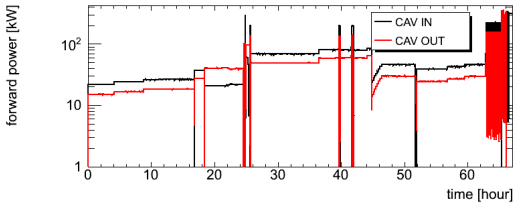
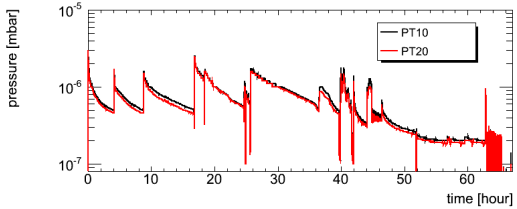
Standing wave up to 170 kW

Conditioning in the CM at FREIA



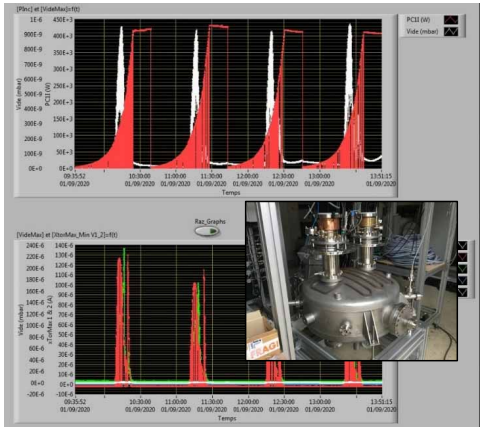
(ESS CM05)



Standing wave up to 400 kW in a cryomodule (off resonance $\Delta f \gg$ BW)

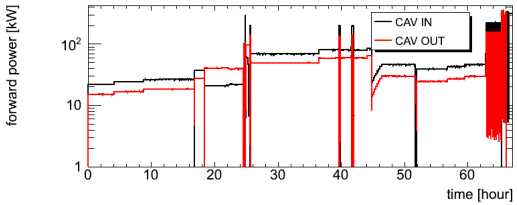
Warm RF coupler conditioning

Pre-conditioned in pairs at IJCLab

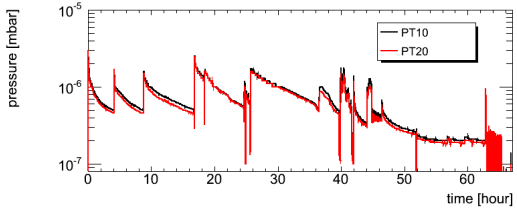


Travelling wave up to 400 kW
Standing wave up to 170 kW

Conditioning in the CM at FREIA

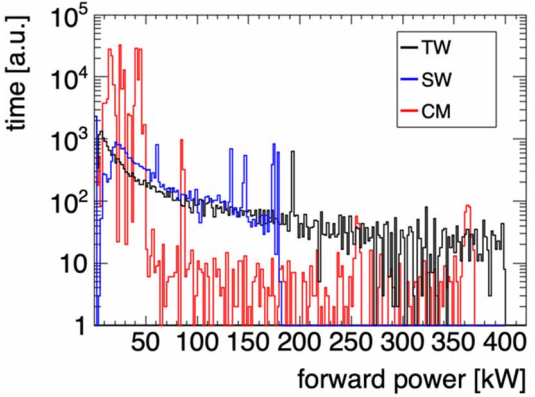


(ESS CM05)



Standing wave up to 400 kW in a cryomodule (off resonance $\Delta f \gg$ BW)

Comparison



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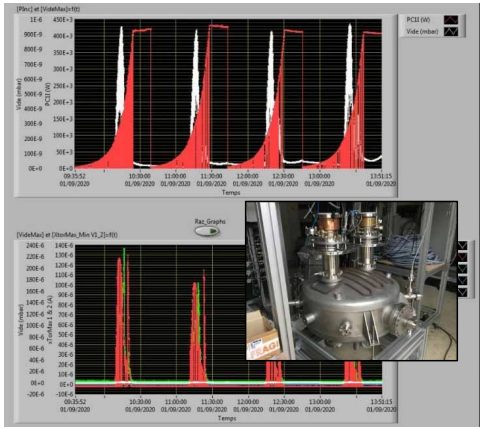
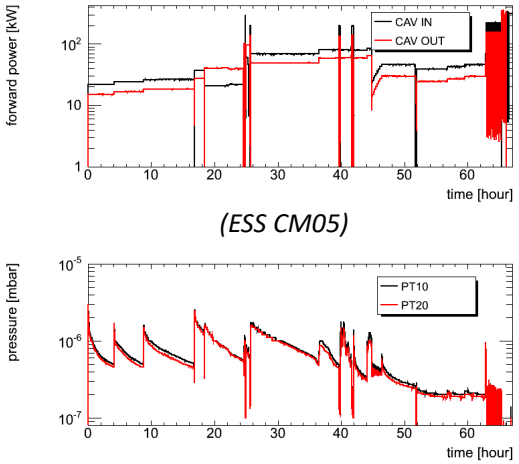


Travelling wave up to 400 kW
Standing wave up to 170 kW

Conditioning in the CM at FREIA



(ESS CM05)

Standing wave up to 400 kW in a cryomodule (off resonance $\Delta f \gg$ BW)

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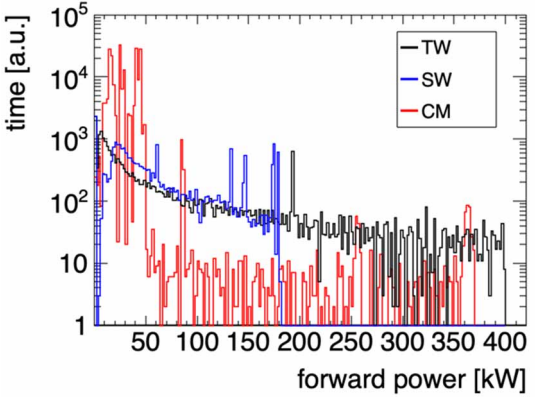

Outcome

- Outgassing in CM is mainly below 100 kW (multipacting barrier MP)
  - Spatial distribution of RF is different from the configuration in CM
- In CMs, 24h x 3-4 days up to duty cycle 4.5% to completely clean the MP bands
- Reliability of the RF system during this time is crucial

Warm RF coupler conditioning (cont'd)

CM #	FPC1	FPC2	# of pumps	hours
CM02	CPL01	CPL04	1	112
CM04	CPL11	CPL03	1	67
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Warm RF coupler conditioning (cont'd)

- Some couplers were conditioned twice without being exposed to air when broken stepper motors were replaced

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- Some couplers were conditioned twice without being exposed to air when broken stepper motors were replaced
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- There is a big variation in conditioning time: from 10 h to 100 h, even under the same conditions

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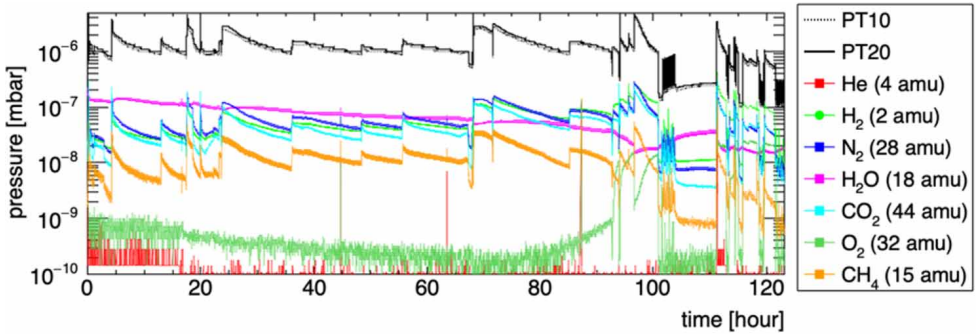
- More active pumping during assembly might reduce the necessary conditioning time
- RGA sometimes observed CH and oxygen have a negative correlation



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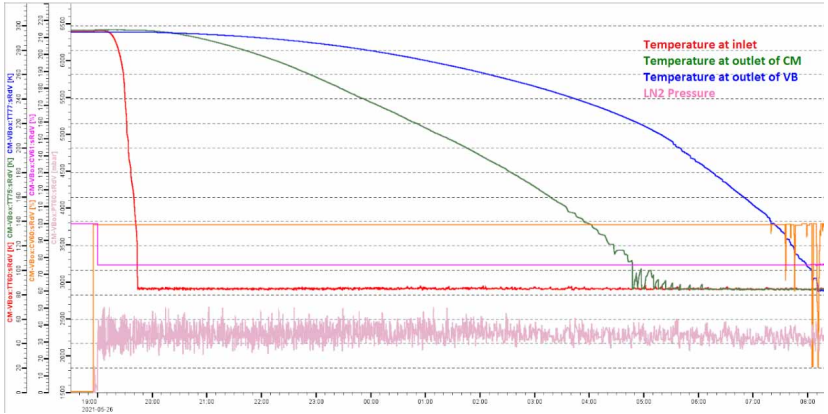
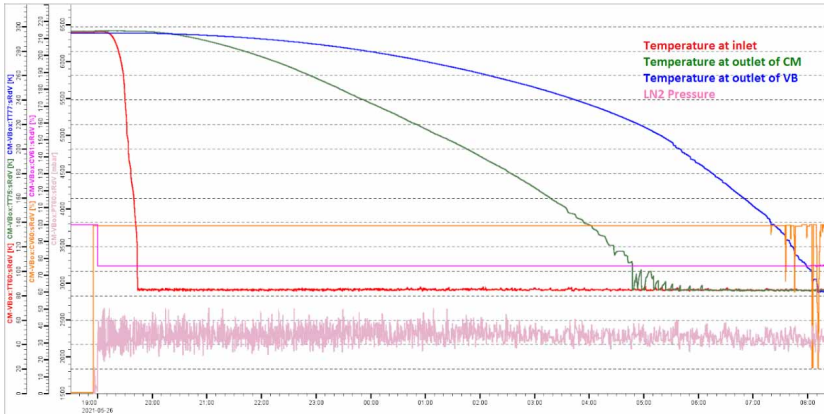
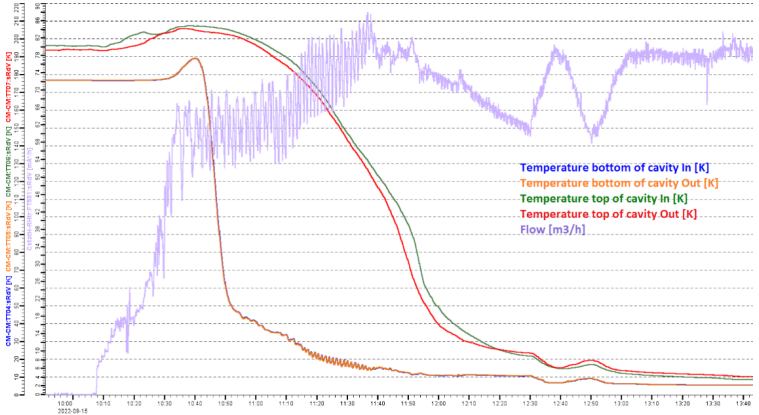
Cryomodules' Cooling



- Thermal shields cooled with **LN2** (24 h min)

Cryomodules' Cooling





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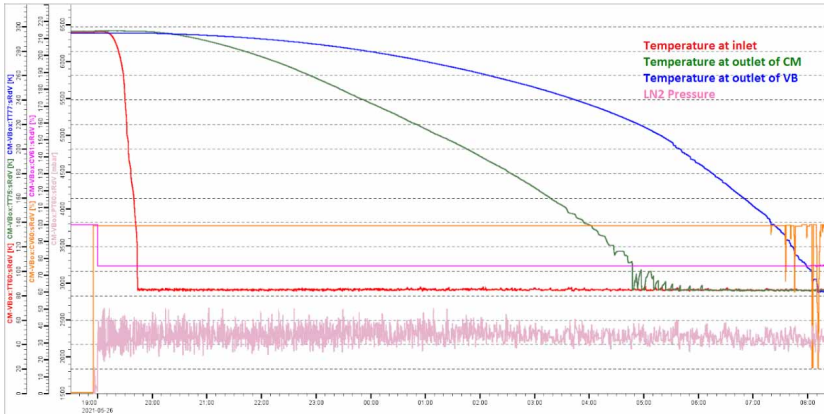
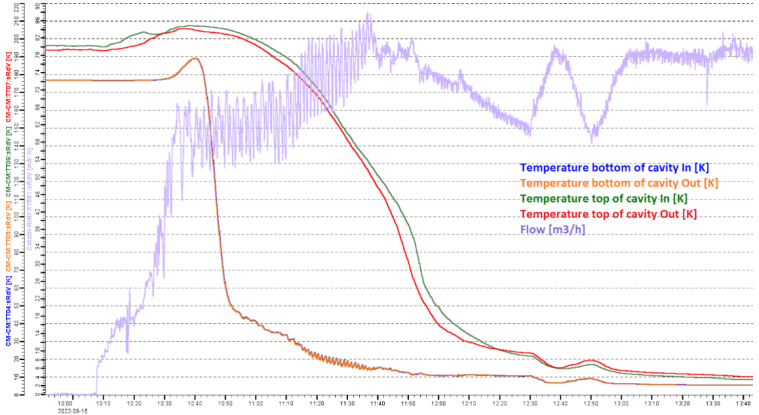
- Thermalization times are very important for when cooling with LHe
  - Shorter cooling times, so
  - Less LHe spent during cooldown

Cryomodules' Cooling





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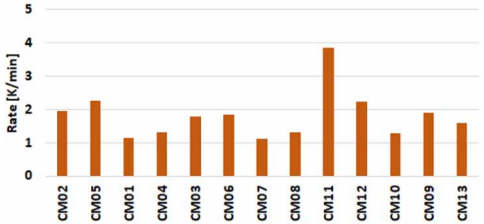

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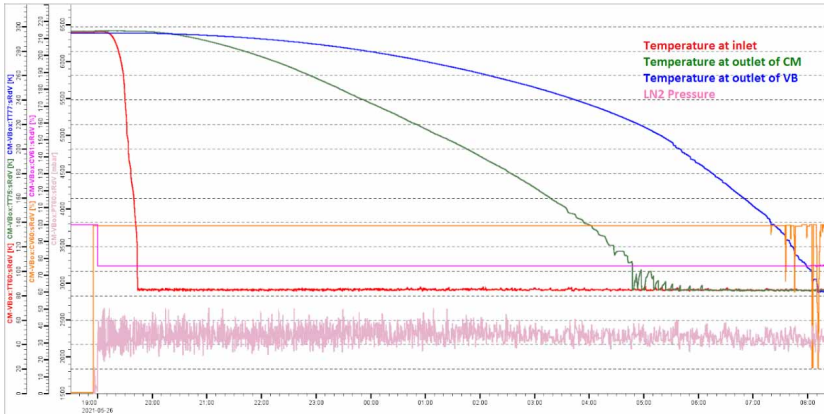

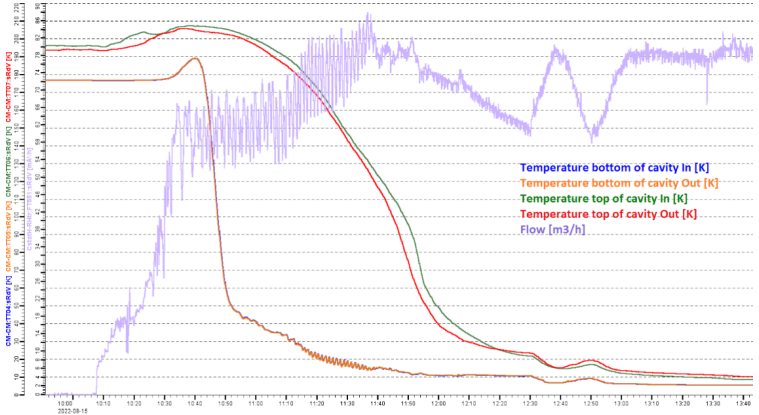

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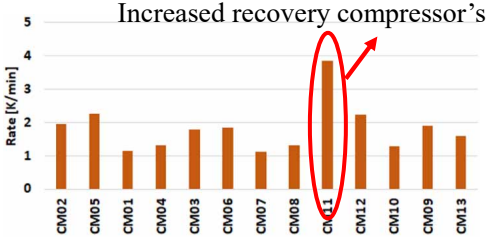
Increased recovery compressor's capacity



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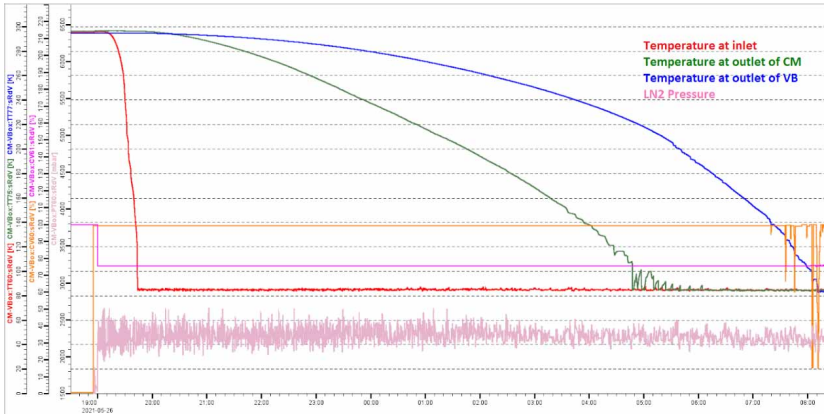

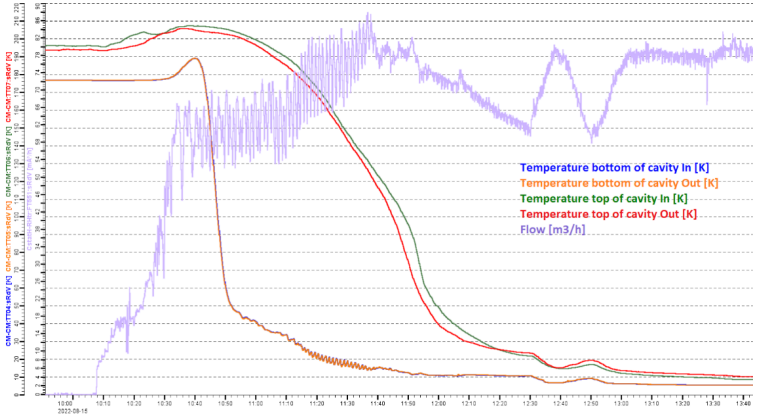

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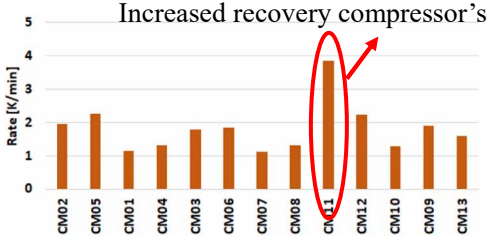

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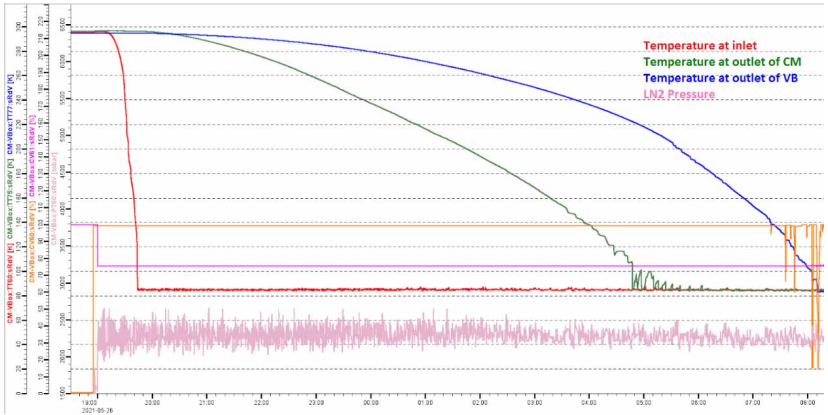

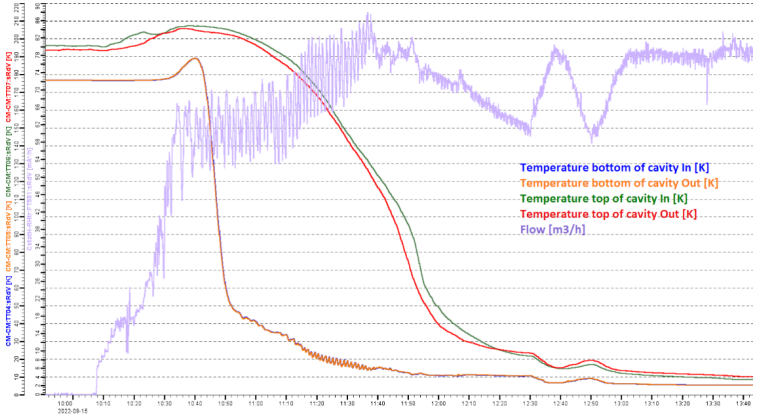

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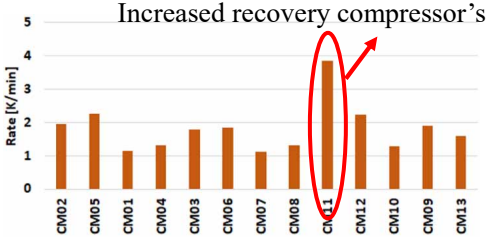

As A. Miyazaki presented:
no flux expulsion required for these spoke cavities

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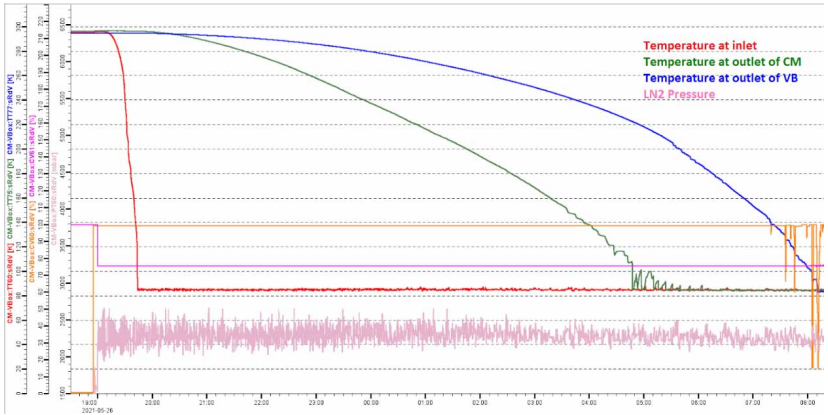

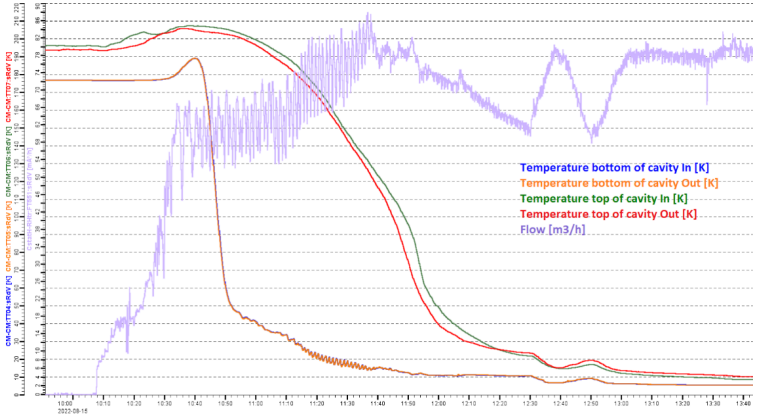

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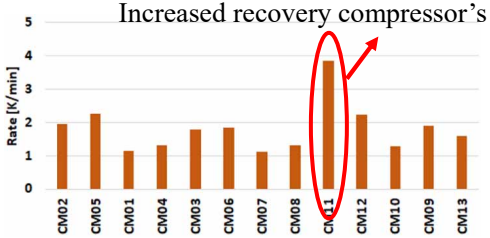

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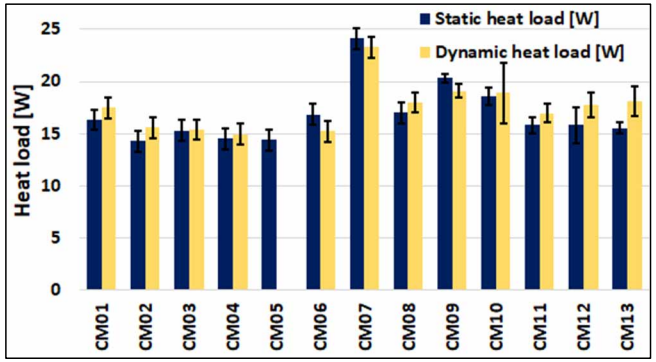
no flux expulsion required for these spoke cavities

wide spread BUT no individual difference among modules and no problem for normal operation

Cryomodules' Heat Loads and Q_0

With both cavities at 9 MV/m



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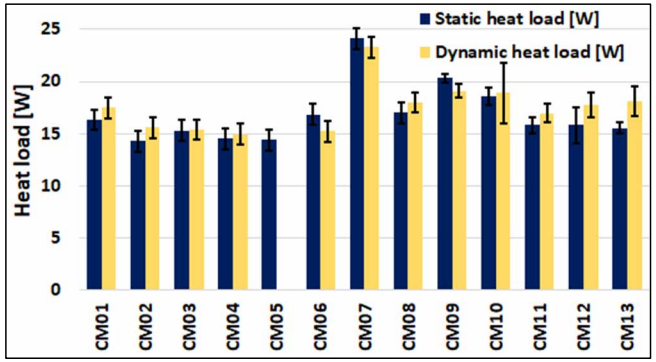

HLs measured with a volumetric flowmeter at T room and P atm

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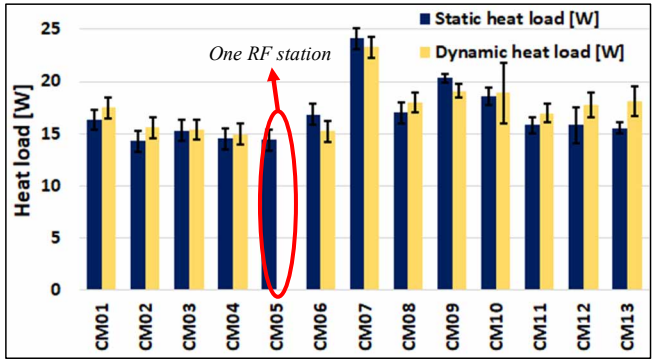

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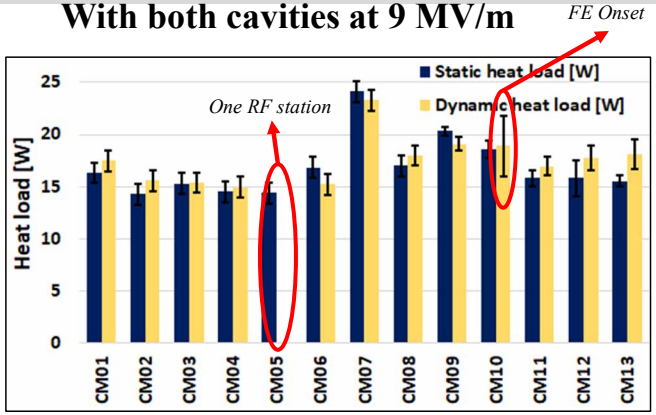

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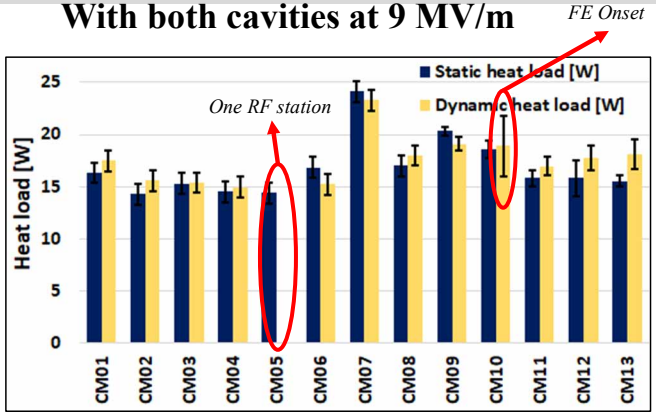

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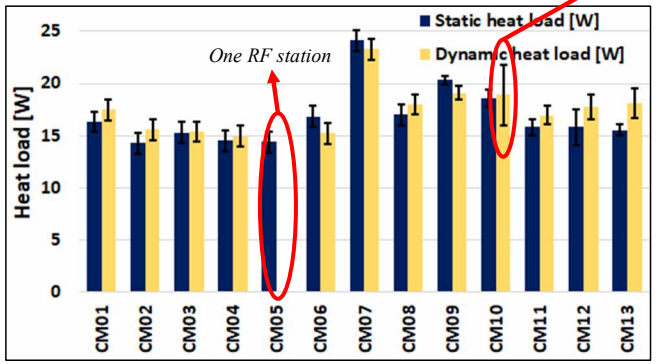

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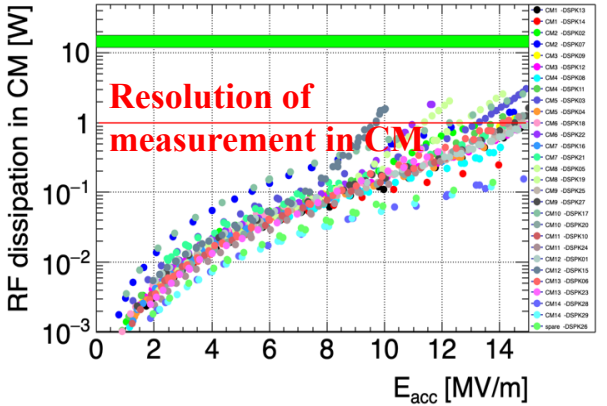

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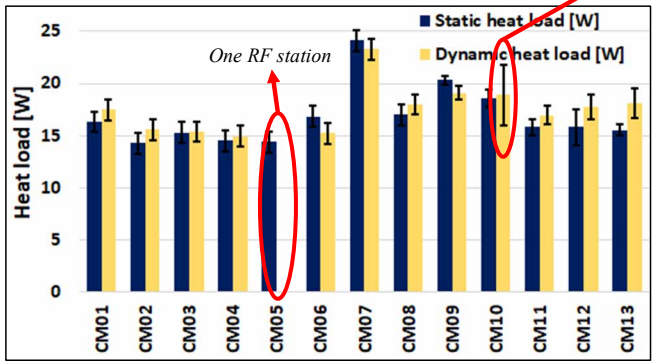

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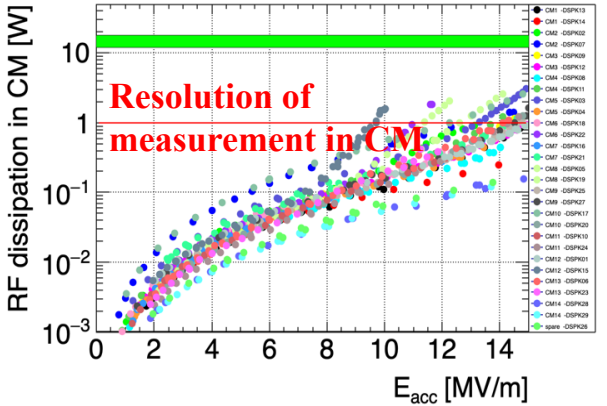

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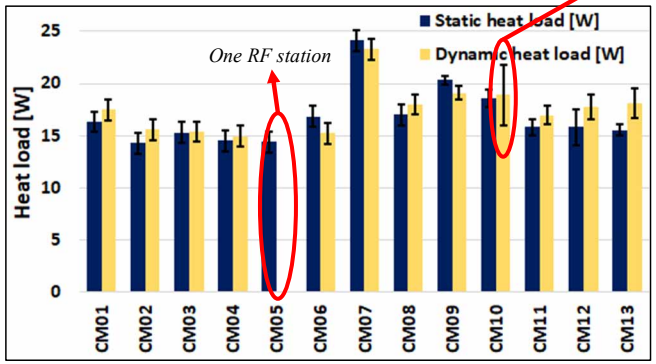

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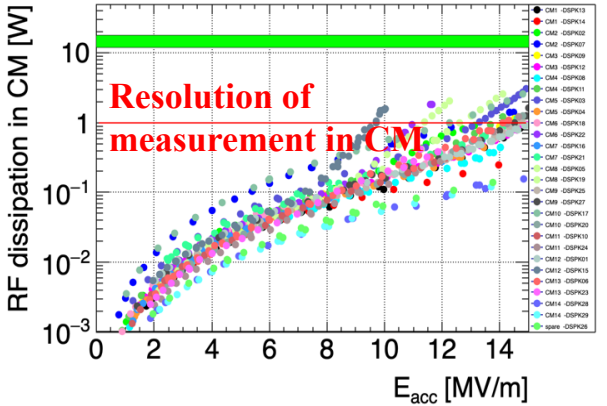

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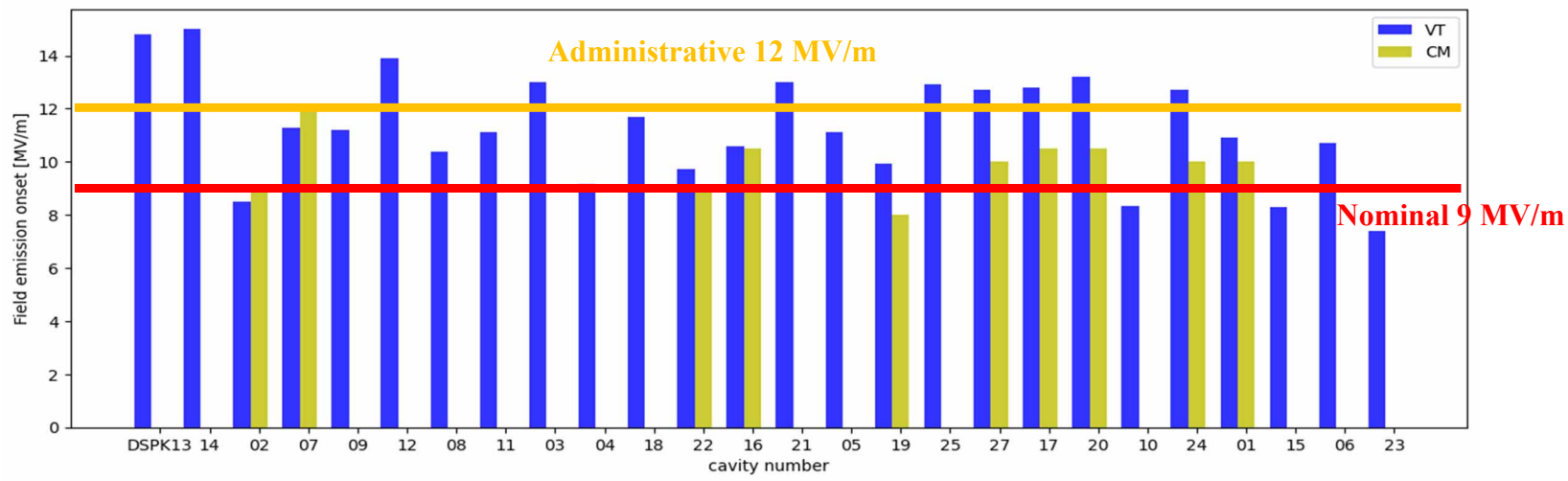
Thermal screens LN2 cooling → 50 K at ESS → improvement of static heat load is higly expected

No significant cavity degradation after the vertical tests

Field Emission



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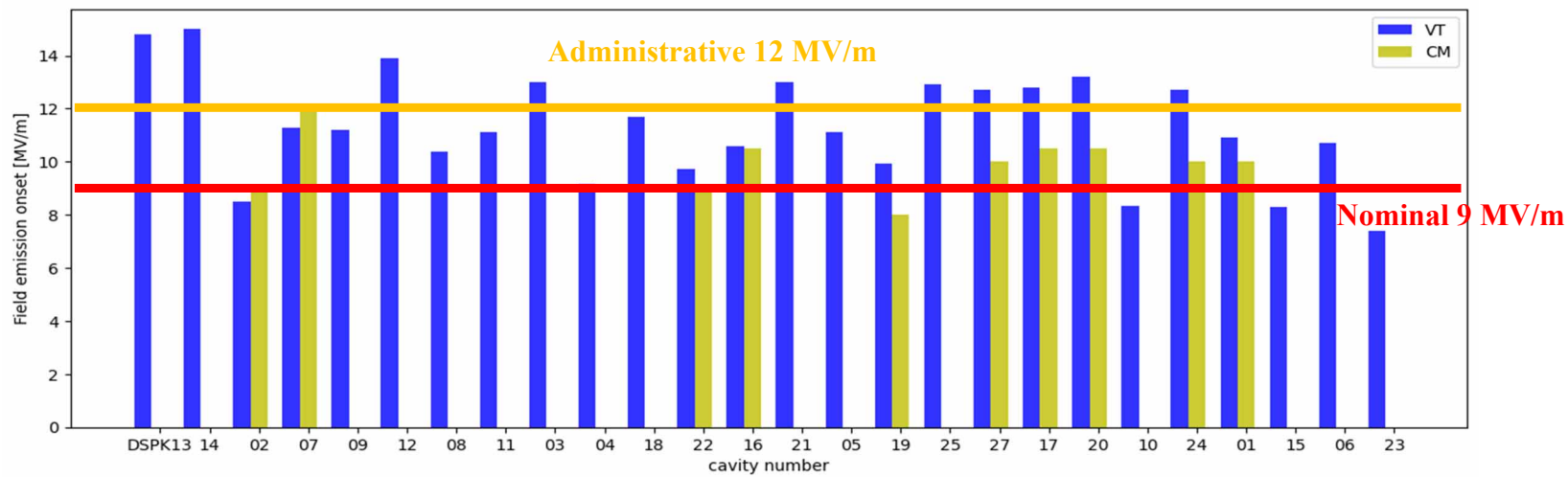

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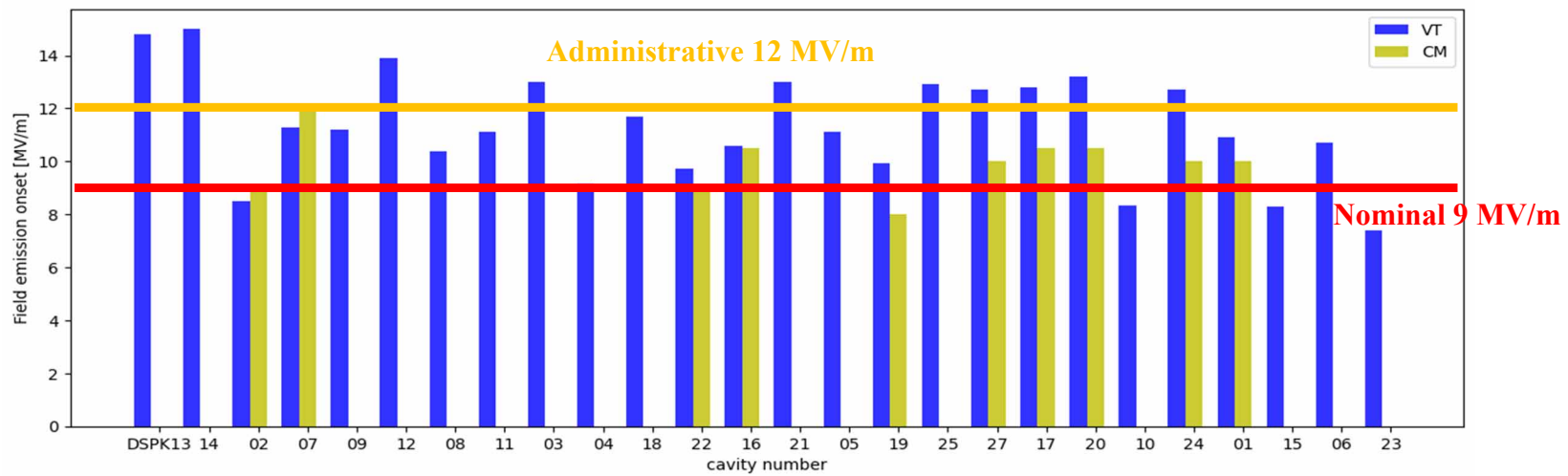

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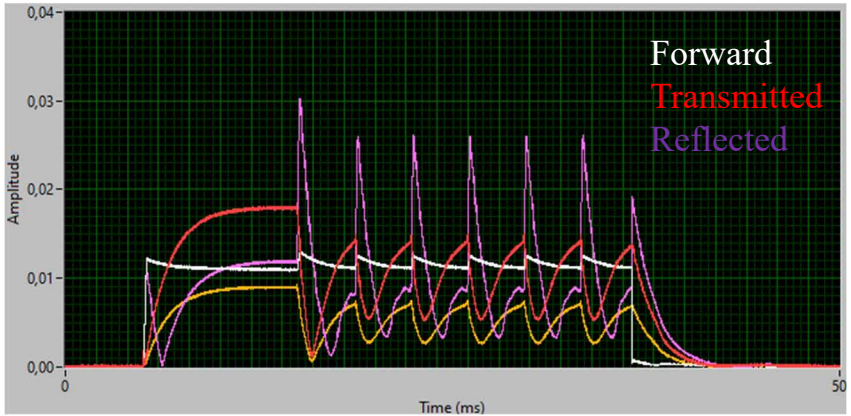
All cavities reached the nominal gradient 9 MV/m

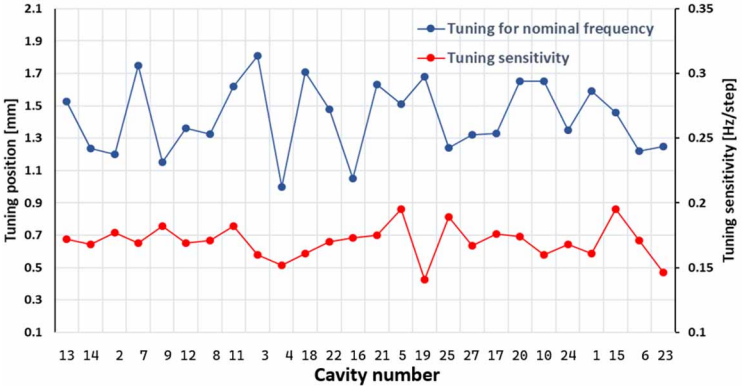
IJCLab's method proved succesful

Risk of Quench and Protection



- Multipacting is a major challenge in spoke cavities
- Quench at low fields (< 1MV/m) is possible → trigger "global" quench → problem for ESS
- Need to stop RF powering in case of "local" quench
- Quench detection and interlock strategy were crucial
  - fast interlock at low field BEFORE the first powering
  - pressure interlock
  - quench detection system via on-line evaluation of decay constant with FPGA

Cold Tuning System and Lorentz-force Detuning



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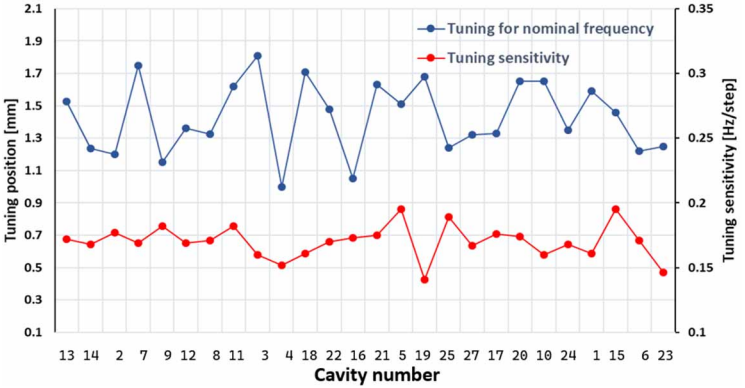

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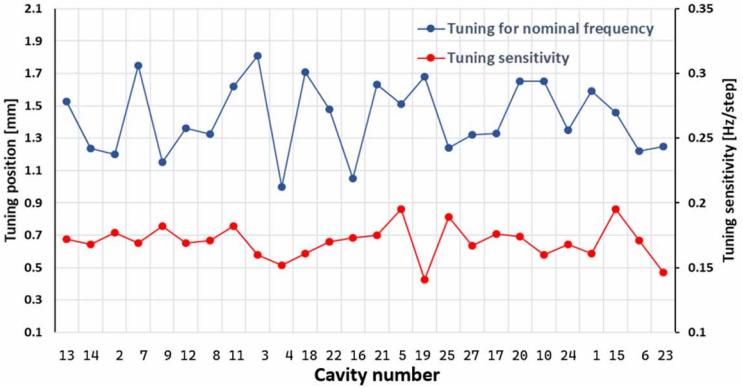

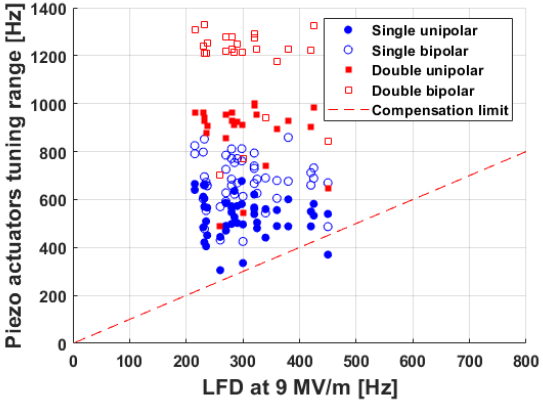

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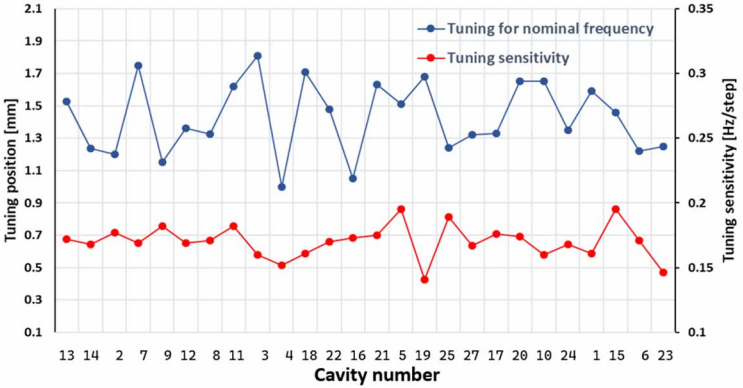

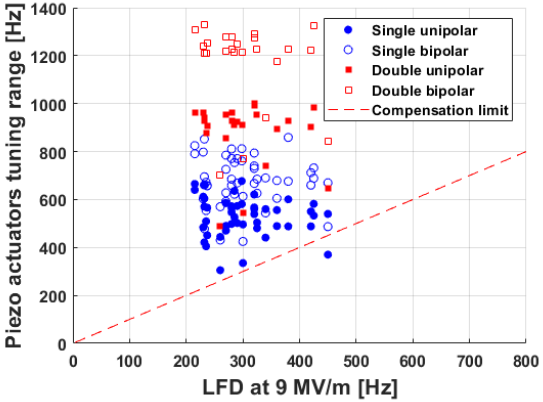

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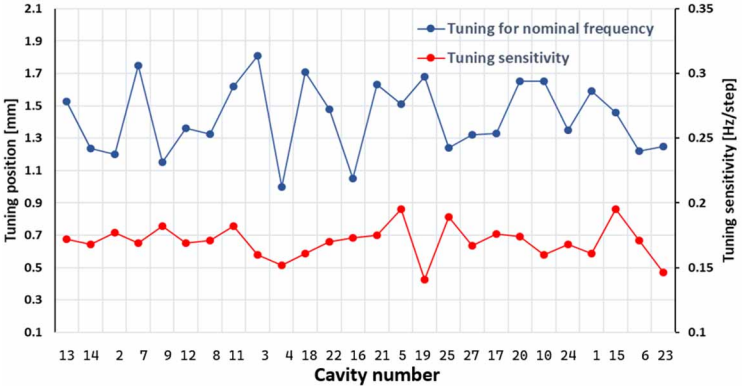

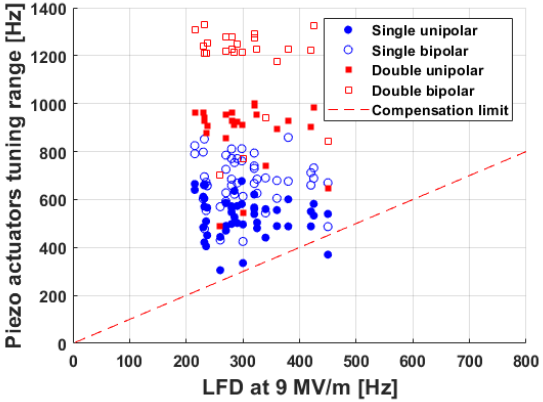

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  - FPC cooling: add ScHe circuit
  - RF stations
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Thank you for listening

And also thanks to:
- FREIA team for all the hard work
- IJClab' and ESS' colleagues for fruitful discussions
- The SRF23 organizers for the opportunity to give this talk