FROM RESEARCH TO INDUSTRY

HIGH POWER TESTING OF ESS FPCs ON THE ELLIPTICAL CAVITIES CRYOMODULES

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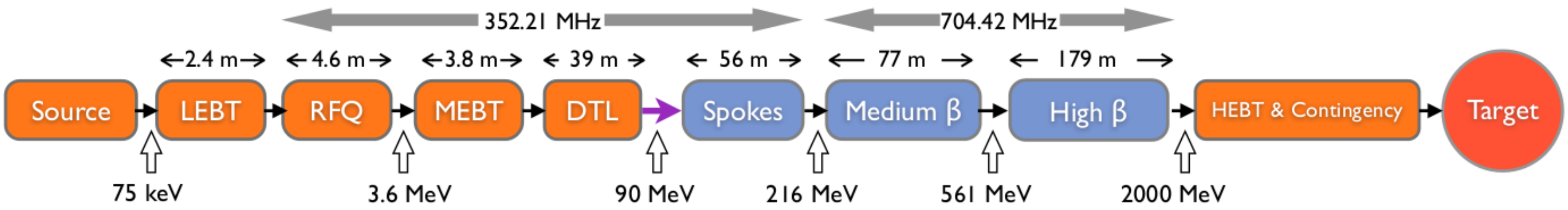
On behalf of CEA ESSI team

ESS - SRF LINAC

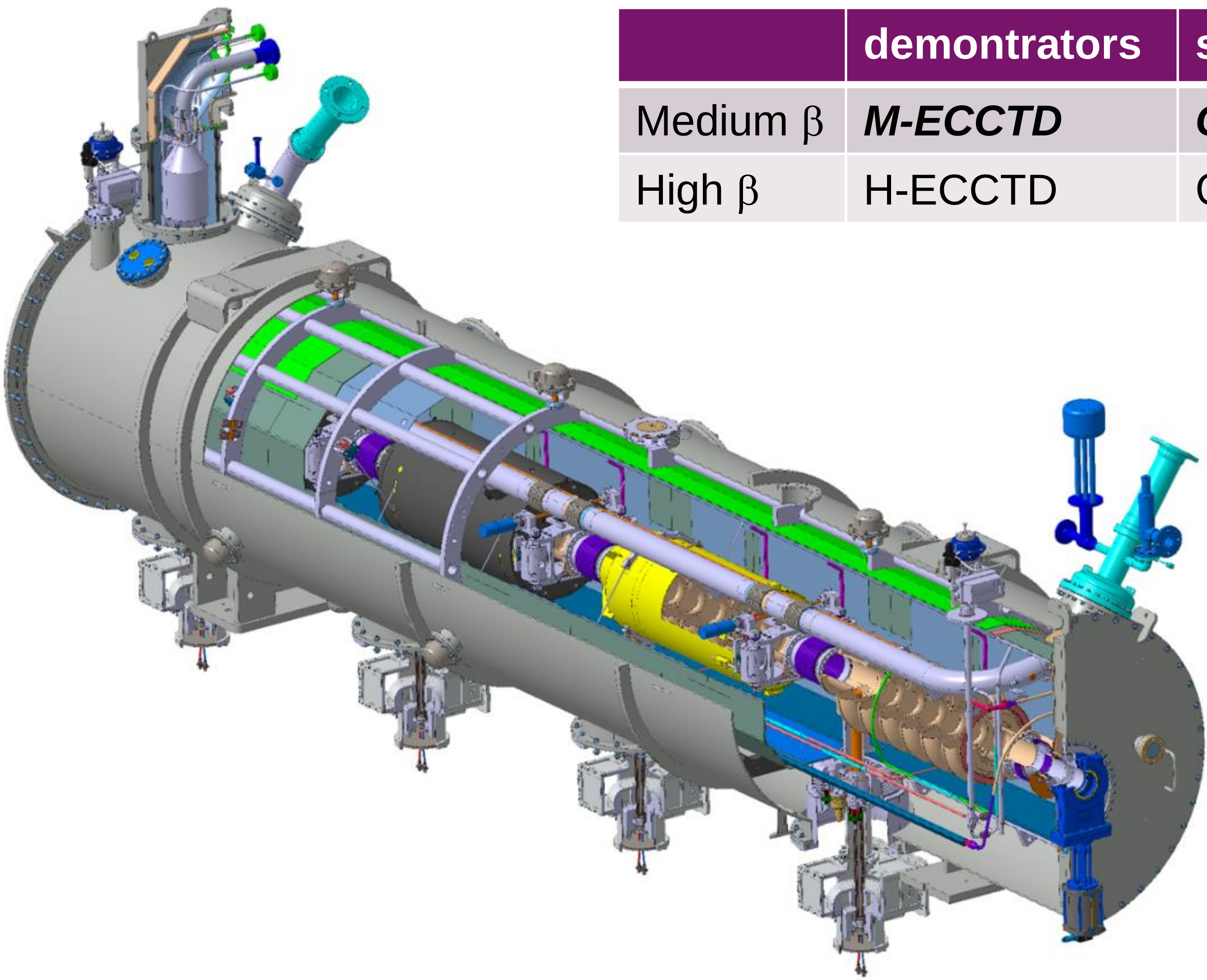


Requirements	Spoke	Medium	High
Frequency (MHz)	352.21	704.42	704.42
Geometric beta	0.50	0.67	0.86
Nominal Accelerating gradient (MV/m)	9.0	16.7	19.9
Epk (MV/m)	39	45	45
Bpk/Eacc (mT/MV/m)	<8.75	4.79	4.3
Epk/Eacc	<4.38	2.36	2.2
Iris diameter (mm)	50	94	120
RF peak power (kW)	335	1100	1100
G (Ω)	130	196.63	241
Max R/Q (Ω)	427	394	477
Qext	$2.85\ 10^{5}$	$7.5\ 10^{5}$	$7.6\ 10^{5}$
Q0 at nominal gradient	$1.5\ 10^{9}$	$> 5\ 10^{9}$	$> 5\ 10^{9}$

	Num. of CMs	Num. of cavities
Spoke	13	26
6-cell medium β	9	36
5-cell high β	21	84

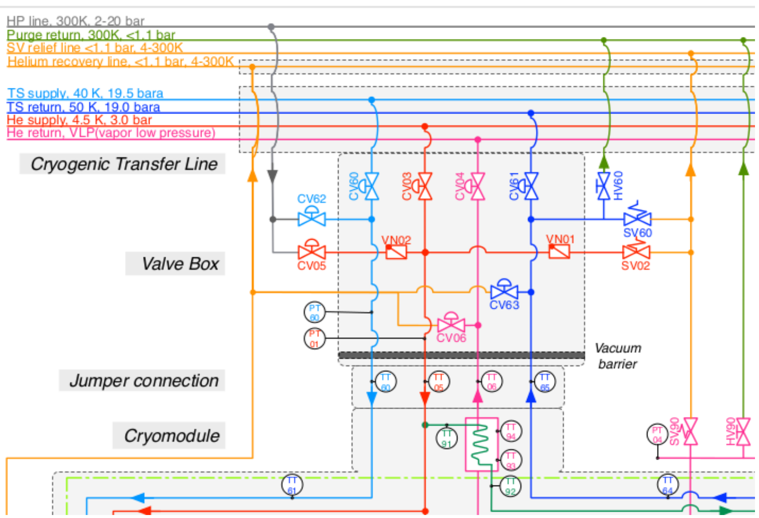
	SNS	ESS	ESS tests
Beam power [MW]	1.4	**5**	
beam current [mA]	38	**62.5**	
Linac energy [GeV]	1	**2**	
Beam pulse length [ms]	0.695	**2.86**	
Repetition rate [Hz]	**60**	14	14
RF pulse length [ms]	1.3	**3.1**	**3.6**
Coupler peak power [kW]	550	**1100**	**1200**
Coupler avg. Power [kW]	43	47.7	**60**

ELLIPTICAL CAVITY CRYOMODULES



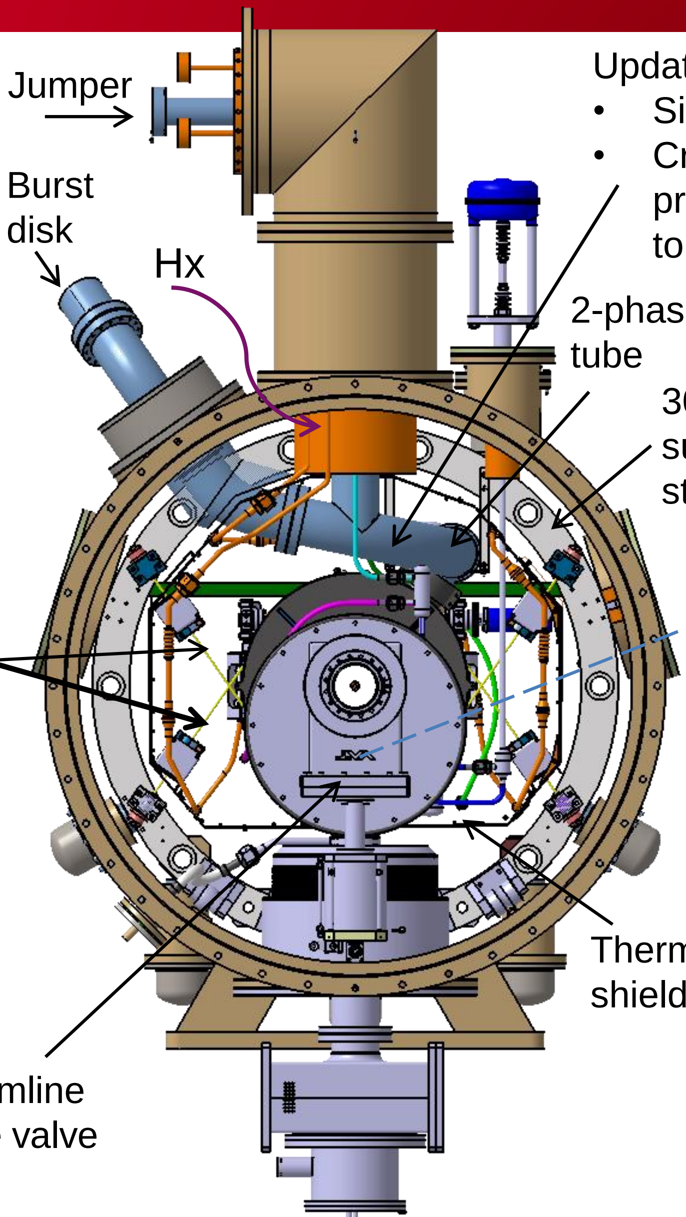
	demontrators	series
Medium β	***M-ECCTD***	***CM01***,...,CM09
High β	H-ECCTD	CM10,…,CM29

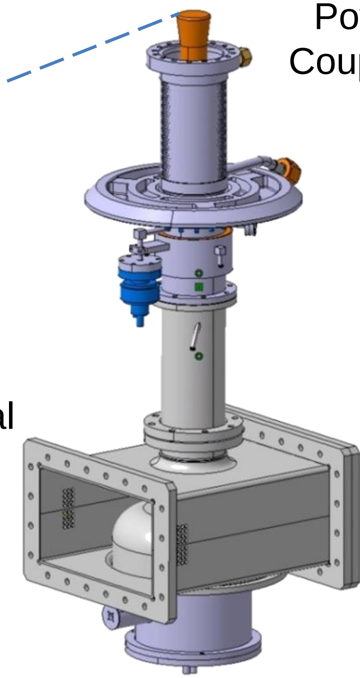
ELLIPTICAL SECTION CRYOMODULE



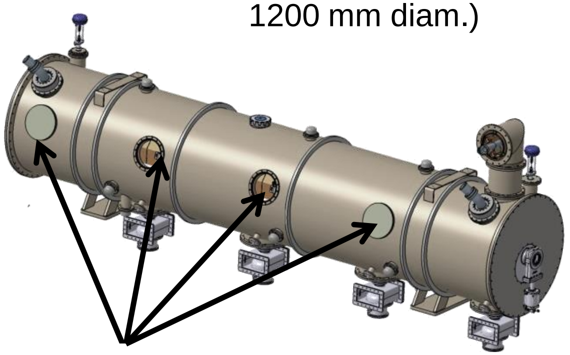
Updated design

- Simpler 40 K thermal shield
- Cryogenics and PED: lower pressure drop from He vessel to safety devices



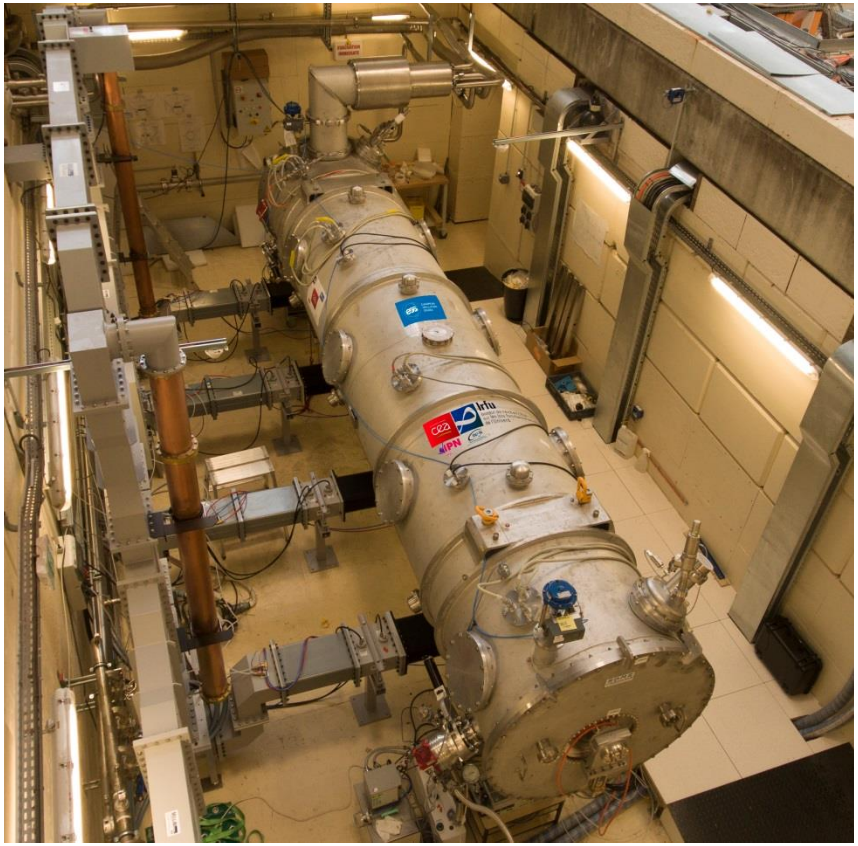


Vacuum vessel (stainless steel, 1200 mm diam.)

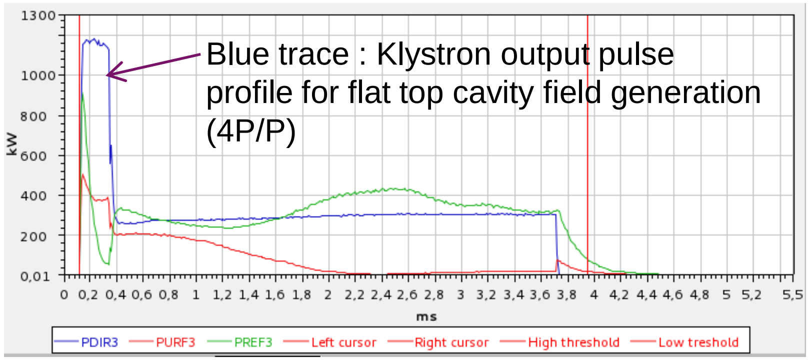


CAVITY STRING WITH PROTOTYPE FPCS

2018 HIGH POWER TEST OF ESS MEDIUM BETA ECCTD CRYOMODULE



- 3 CEA cavities, 1 INFN cavity
- Operated at 2K
- All 4 beta=0.67 cavities connected to a single RF source
- Only single cavity high power operation with 4P/P pulse is possible with the current setup
- Fundamental Power Couplers (FPC) are conditionned at room temperature first, then at 2K up to 1.2 MW peak power

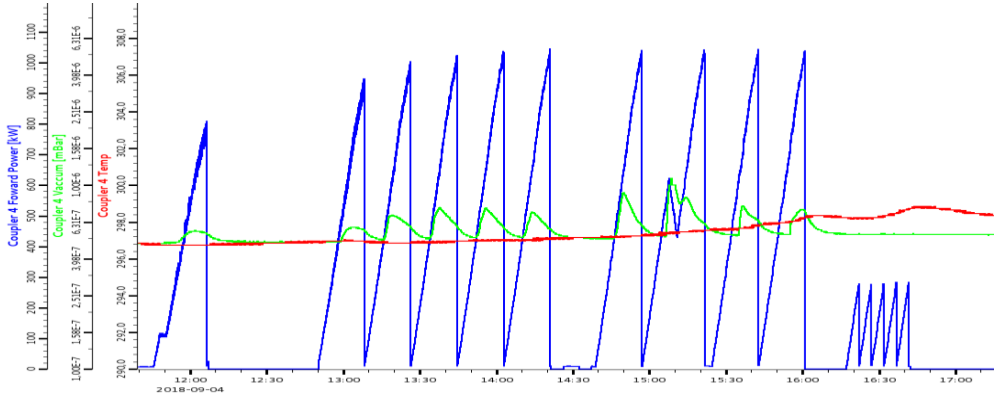


RESULTS:

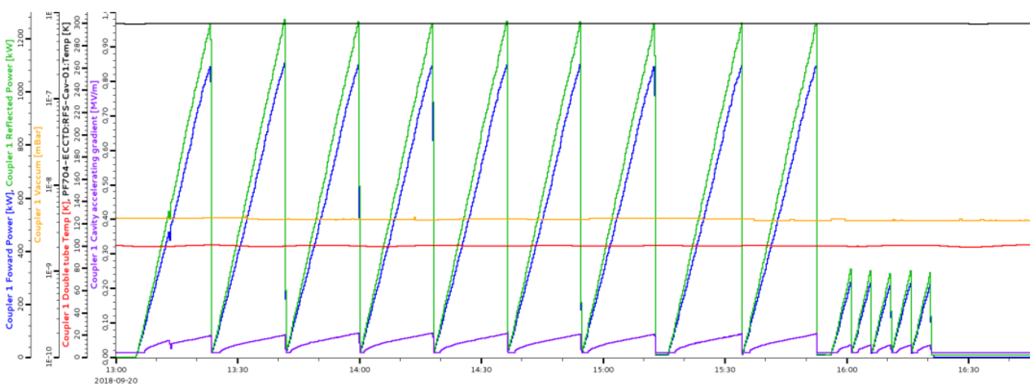
- 4 FPCs pass all conditionning stages (full reflection)
- All cavities tuned to nominal frequency at 704.42 MHz and run with high power
- 3 cavities operated at 2 K above nominal gradient of 16.7 MV/m , RF pulse of 3.6 ms total, @14 Hz, with LFD piezo compensation
- 1 cavity with field limitation at 16 MV/m

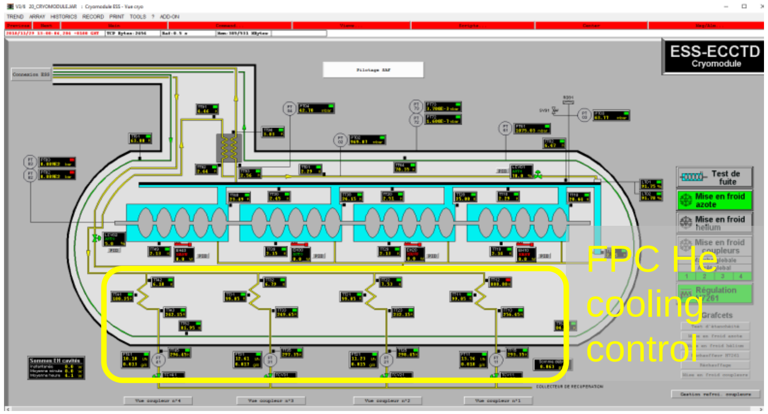
FPC CONDITIONING ON M-ECCTD CRYOMODULE

Room temperature :



After cryomodule cooldown :





Same logic is followed as on FPC conditioning stand, only SW possible, 1 FPC at a time
avg. duration ~4 hours for both warm and cold conditioning

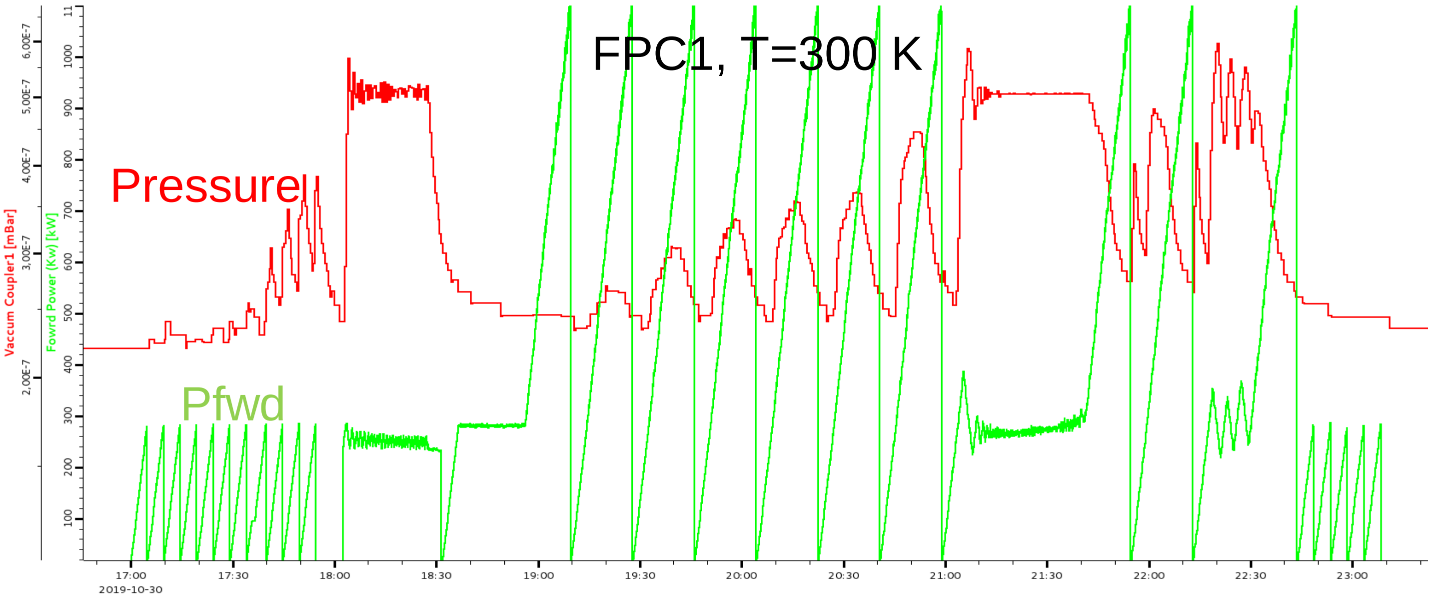
HIGH POWER TESTING OF CM01 AT SACLAY

- First module containing components part of series production, including INFN LASA medium β cavities previously tested at DESY
- Internal instrumentation is reduced w/ respect to the M-ECCTD

RF Test plan on cryomodule :

1. Room temp. conditioning, off resonance
2. Cryomodule cooldown
3. Qext measurement and calibrations at 2 K
4. Cold conditioning, off resonance
5. « Slow » tuner test
6. Field operation, on resonance,
7. LFD compensation with piezo
8. Field test of a pair of cavity with a single klystron
9. HV bias test in operating condition (no beam

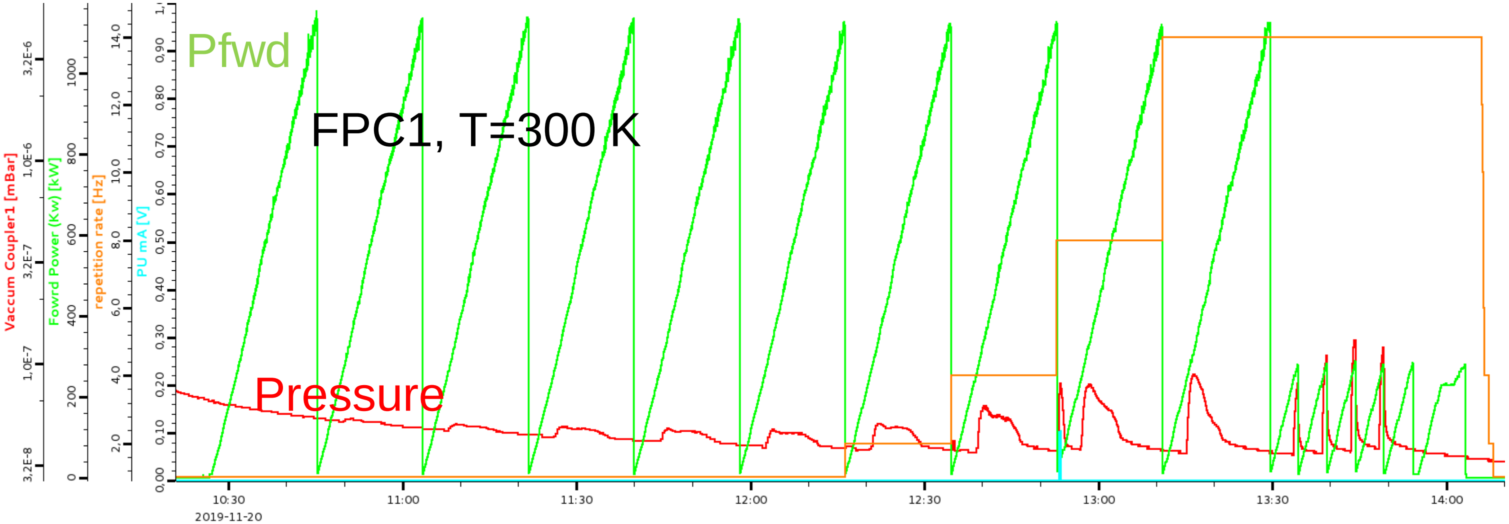
RT CONDITIONING W/ UPGRADED PUMPING SPEED



Low pumping speed system (S< 1l/s) cannot handle outgassing for duty cycles above 0.1 % (2 Hz x 0.5 ms)

Base pressure = 2 10^{-7} mbar

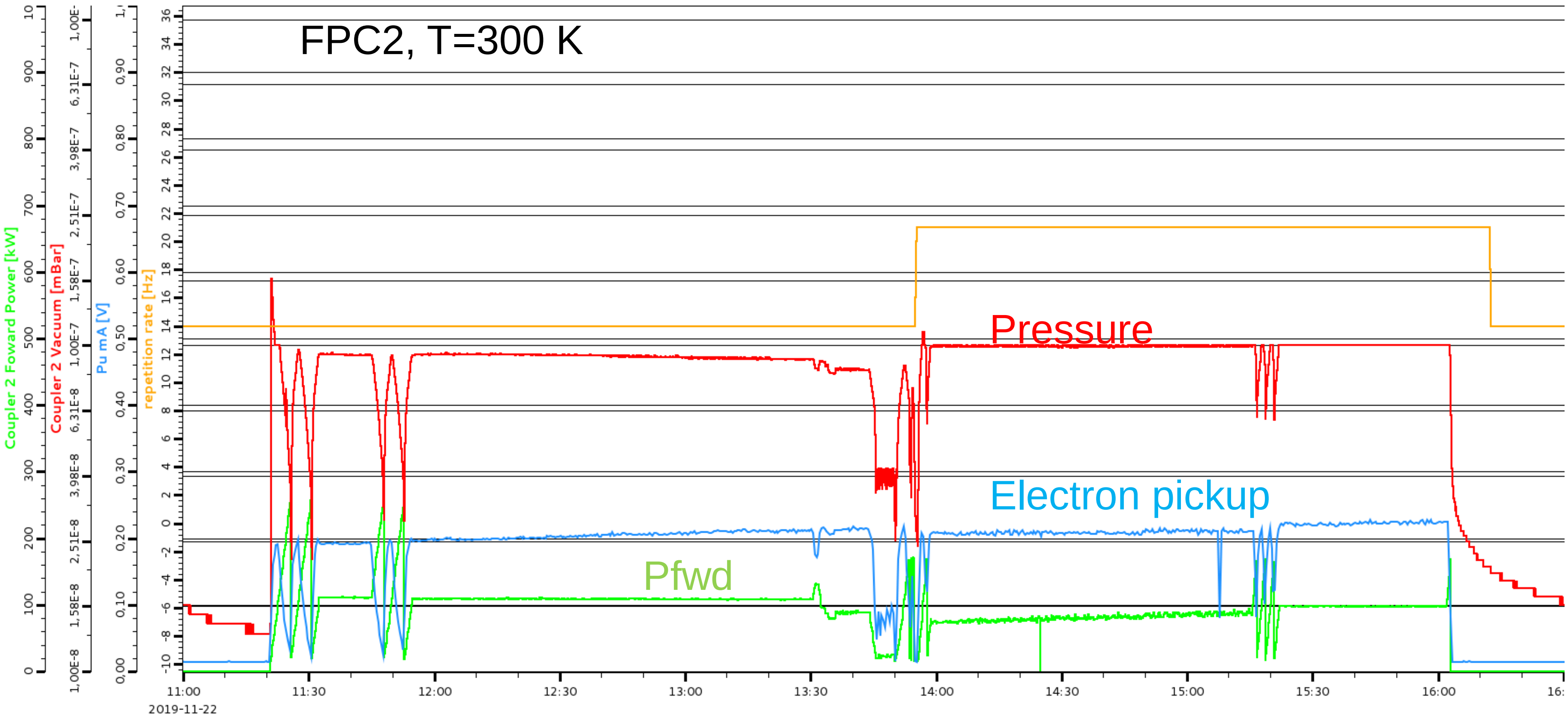
Conditioning of one FPC destroys the conditioning of other FPCs



High pumping speed ~50l/s system installed directly on beamline

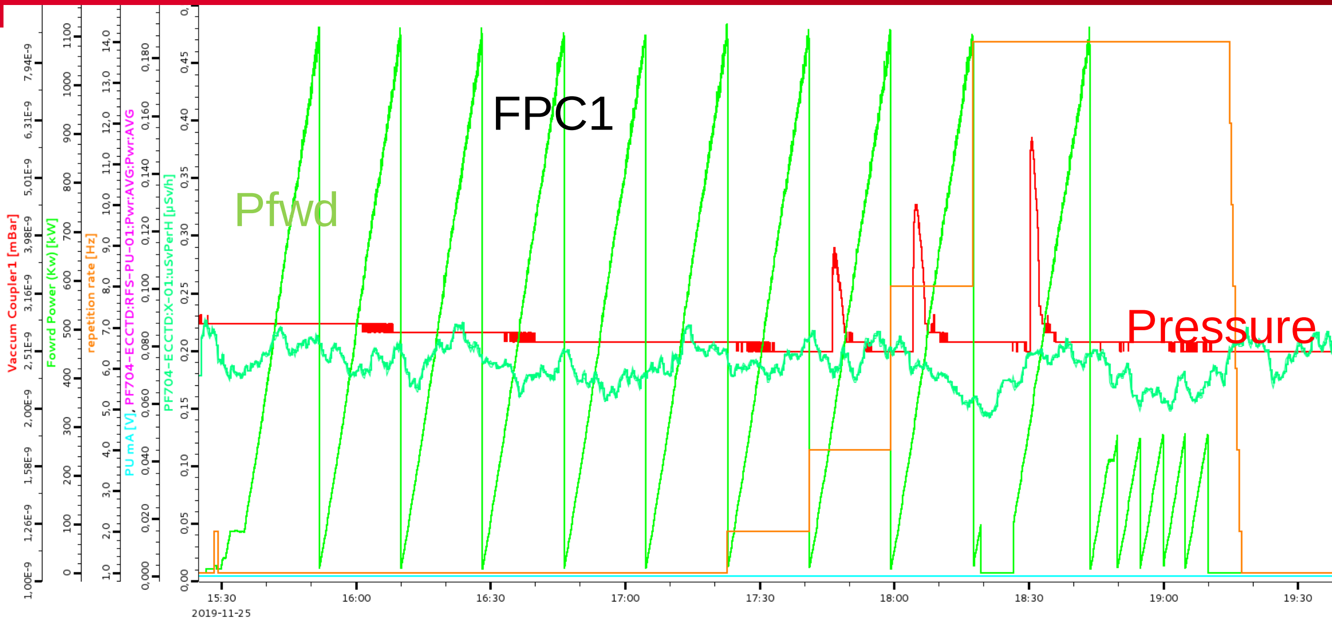
Base pressure = 2 10^{-8} mbar

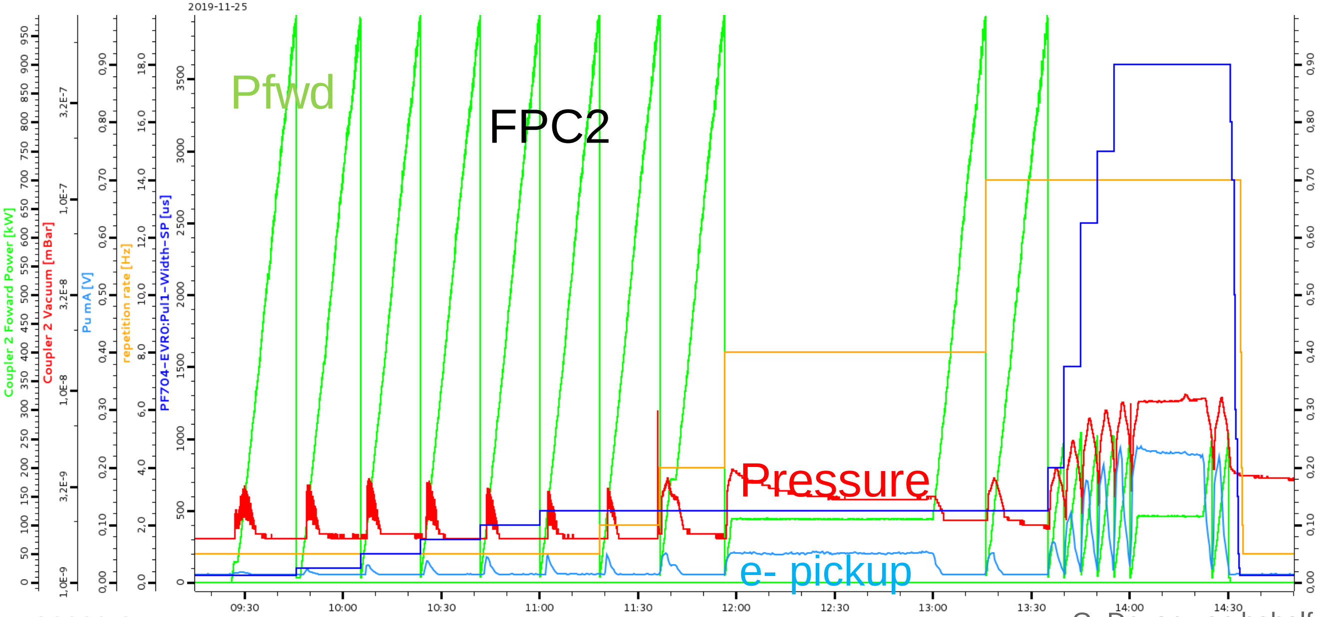
FPC 2 NOT FULLY CONDITIONNED



- FPC 2 pressure at 10^{-7} mbar with correlated electron pickup signal even after tens of additionnal hours of processing in the 100 kW region at T = 300 K. Decision taken to cooldown the cryomodule
- Base pressure = 2 10^{-8} mbar

CONDITIONING AT FIRST COOLDOWN

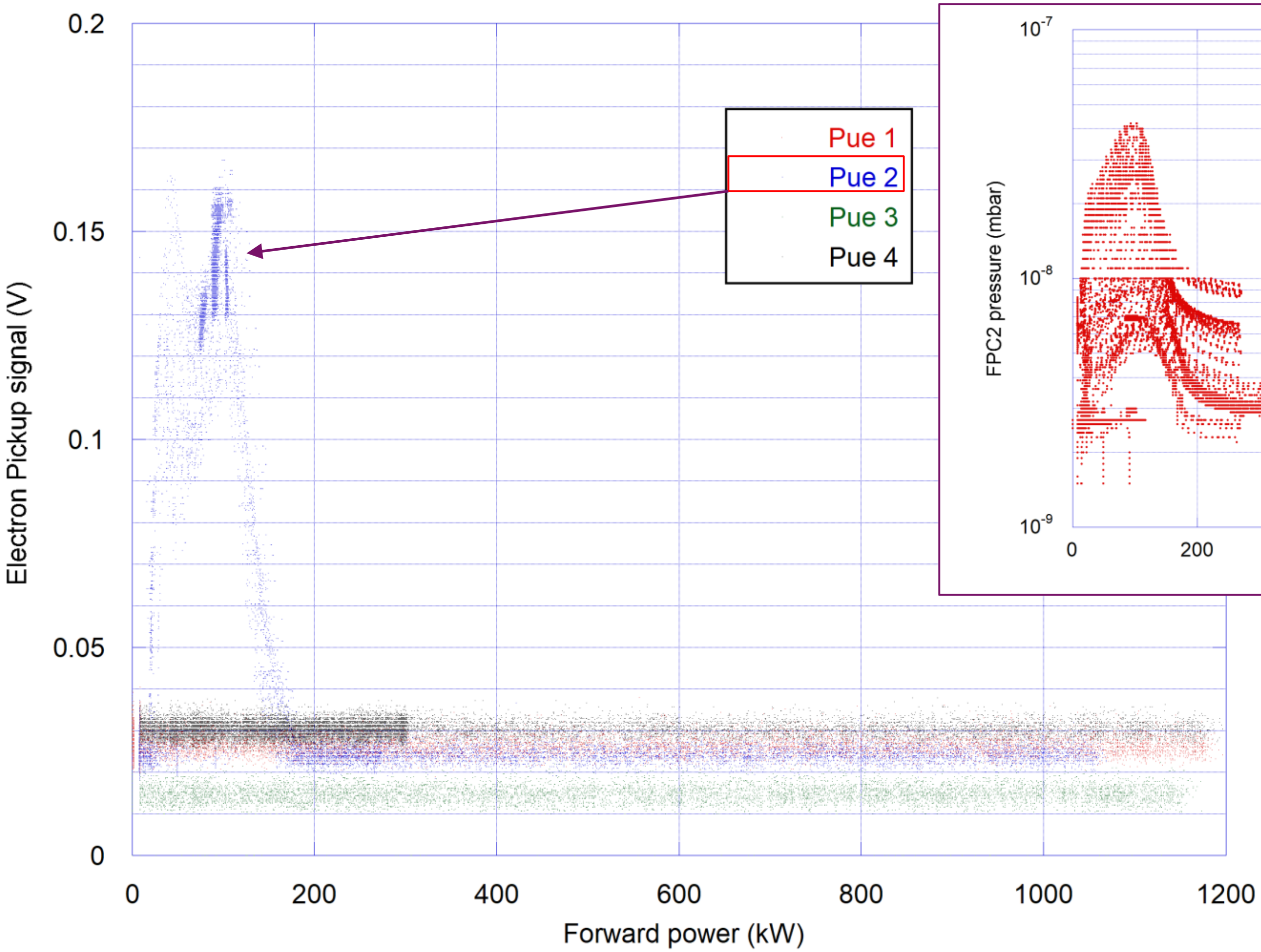


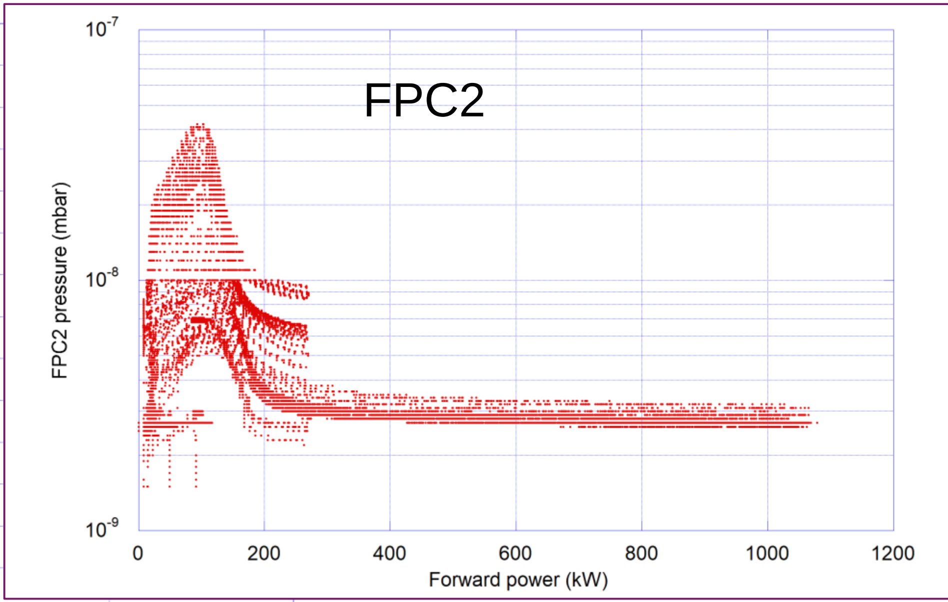


- All cavities are detuned
- Base pressure = 2 10^{-9} mbar (cavities cryopumping)
- FPC 2 pressure below 10^{-8} mbar in any used RF pulse conditions
- Electrons still detected on the FPC2 pickup → good candidate to test the HV bias system

ELECTRON EMISSION FPC2 OF CM01

Room temperature conditioning after thermal cycle (jan 2020)

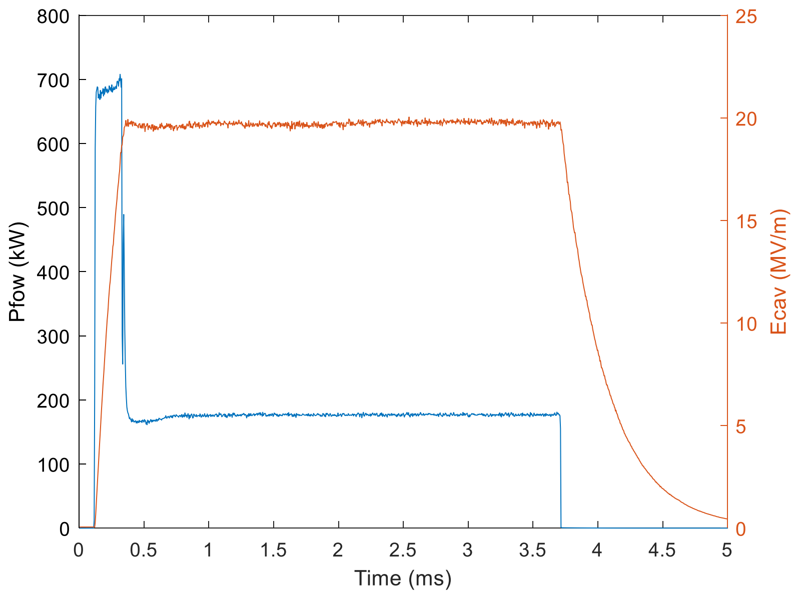


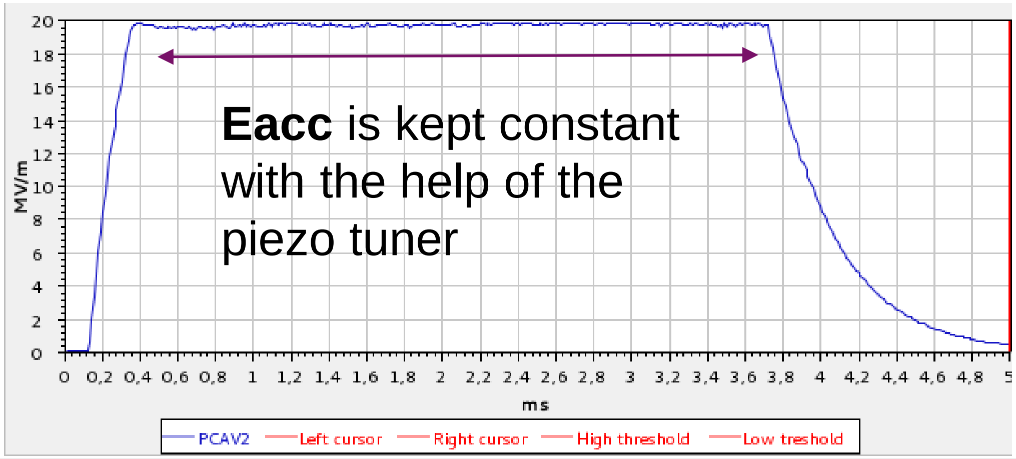


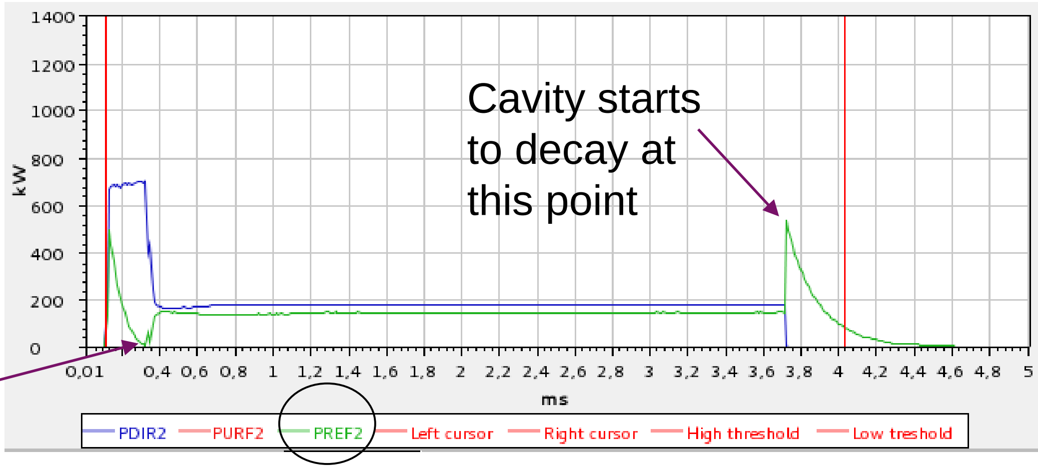
Electron emission remains in FPC2 only (below interlock threshold)

SPECIFIC RF PULSE FOR CAVITY FIELD TESTS

Cavity is at T = 2 K, its resonance frequency tuned to RF source







Filling the cavity:

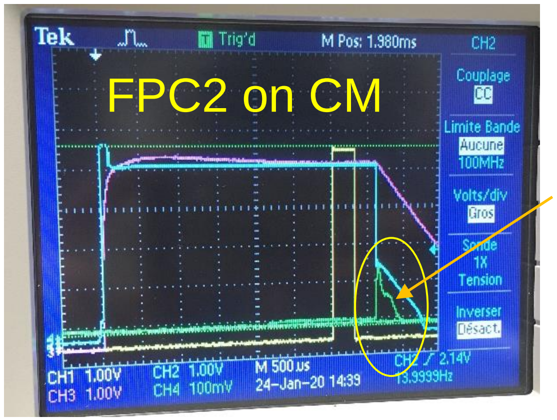
~300 µs pulse Pfwd = P

Maintaining Eacc:

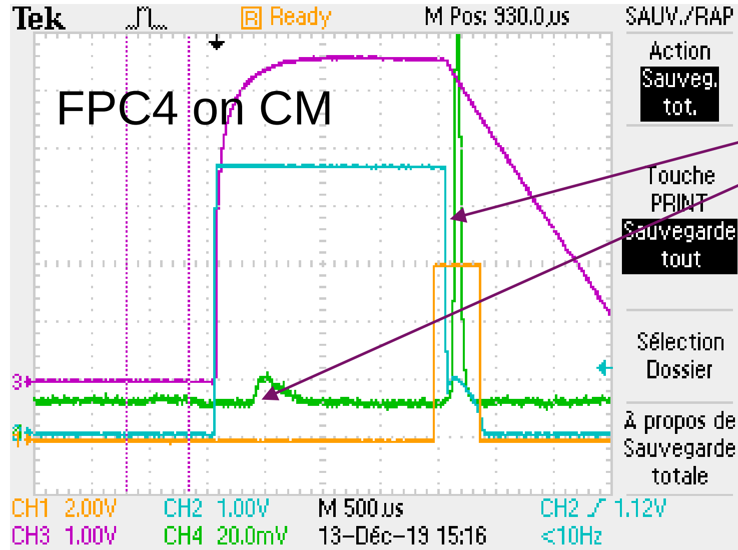
3300 µs pulse Pfwd = P/4

Cavity filled at this point

ELECTRON EMISSION DURING FIELD DECAY



Electron signal in backwards TW mode



Electron signal in mixed mode and backwards TW mode

On the room temperature FPC test bench upstream and downstream FPC behavior differ:
multipacting electrons in a coaxial line propagate in the same direction as the travelling wave

- MP electrons travel towards the RF window in the DOWNSTREAM FPC (on CM similar to cavity decay)
- MP electrons travel towards the antenna tip the UPSTREAM FPC

Cryomodule FPCs	Position on test bench
FPC1	downstream
FPC2	**upstream**
FPC3	upstream
FPC4	**downstream**

Examples above belong to both upstream and downstream

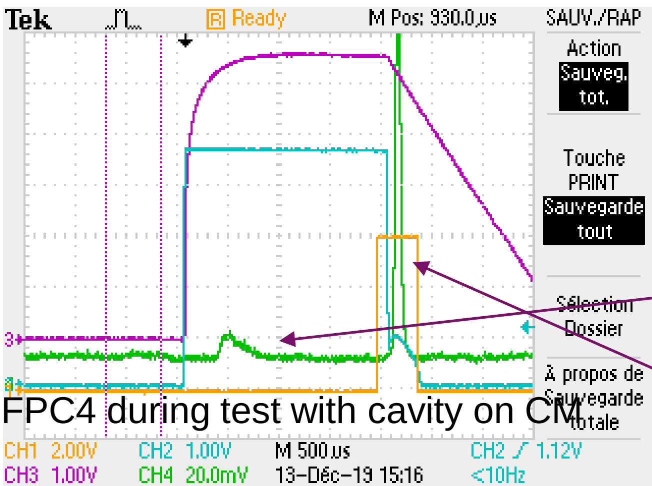
Does this affect the efficiency of TW conditioning? Would switching positions on the test bench improve the quality of conditioning?

ACCELERATION OF FPC ELECTRONS

Gated radiation measurements with a NaI scintillator :

observation of radiation in the test bunker synchronized with electron detection on the RF window e-pickup during the end of filling time

observation of e- on the RF window e-pickup during cavity decay (backwards TW in the coupler) without any radiation observed on the NaI scintillator



FPC4 during test with cavity on CM

	E- current in FPC	Radiation (NaI)	RF wave in the FPC
Start of filling time	no	No	Mixed
End of filling time	Yes*	Yes*	SW
decay	yes	no	TW backwards

*

- e- and radiation are synchronized
- as time goes by the emission is generated later in the pulse and eventually eliminated

FIRST TEST OF ESS FPC HV BIAS

Theory of the FPC biasing : superimpose a static electric field to the RF field in side the FPC, in order to perturb MP electron trajectories, ultimately changing the resonance condition of the MP at a given RF power level.

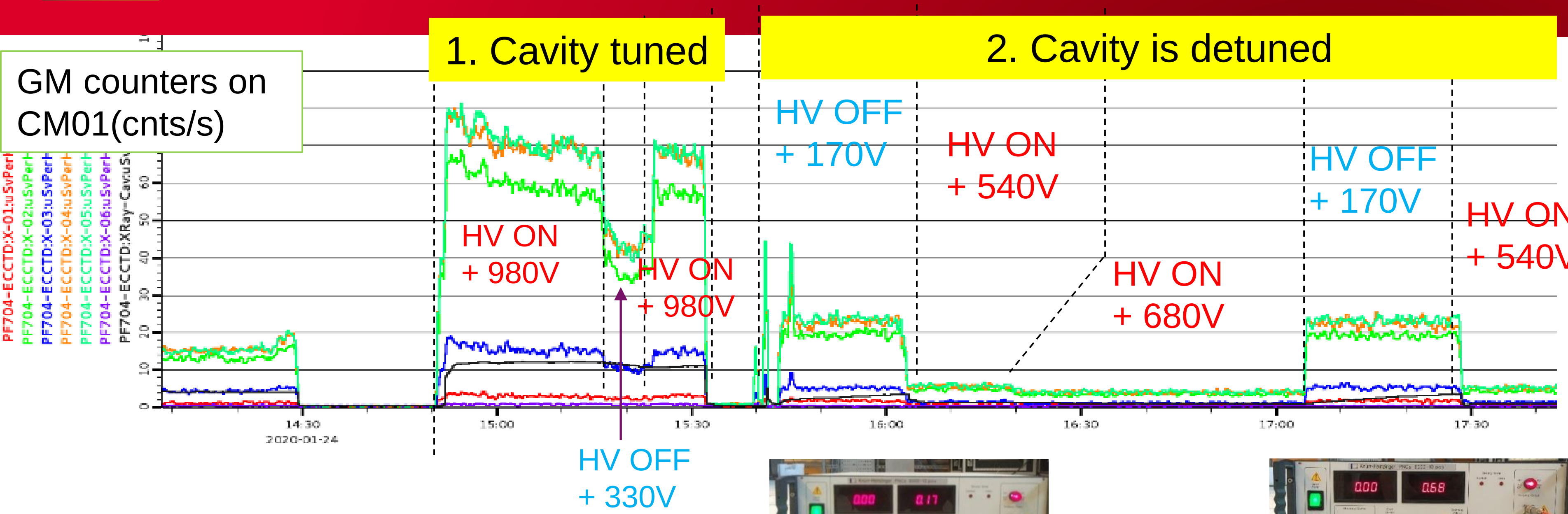
Electron pickup signal can be cancelled by establishing a potential on the FPC antenna.

Test performed on FPC2 only , since other 3 FPCs have been conditionned during tests

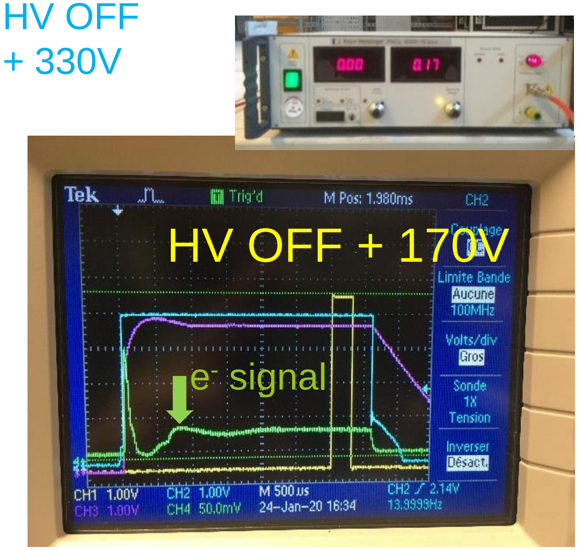
Test condition :

- Positive potential on the FPC antenna with a variable HV power supply
- Outer conductor grounded
- ESS FPC doorknob insulation was designed with a specification of 10kV maximum voltage

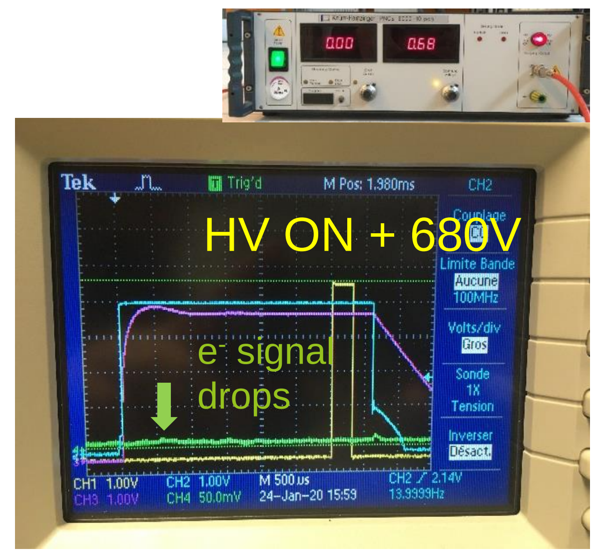
FIRST TEST OF ESS FPC HV BIAS



1. Cavity tuned to 704.42 MHz, Eacc=15 MV/m, field emission occurs
2. Cavity detuned Eacc=8~10 MV/m, looking for a condition where :
   - e- re-appear in in the FPC
   - Field emission from the cavity is negligible



Self biasing (e- current flowing through FPC2 antenna of 8μA)



ACCELERATION OF FPC ELECTRONS

Summary based on first measurements:

Electron emission in FPC during cavity decay

- Can occur in couplers previously at upstream or downstream position in the test bench
- No specific generated radiation observed (not detected with 2 scintillators)

Electron emission during end of filling time or flat top

- Can be correlated to radiation through gated measurements
- Can be reduced using bias along with the associated radiation
- hence the hypothesis of possible acceleration by the cavity of these electrons

Why in specific FPCs only ?

- Lack of conditioning ?
- Less efficient TiN coating?
- Can FPC electrons while undetected (only one electron pick-up antenna close to the window alumina disk) could explain part of cavity radiation?

DO FPC BENEFIT FROM THERMAL CYCLING OF THE CRYOMODULE?

Standard procedure is to bake FPC before initial RF processing

A cold thermal cycling 300K →2K →300K appears to help outgassing of some adsorbed species in SRF Nb cavities : can this be applied to FPC?

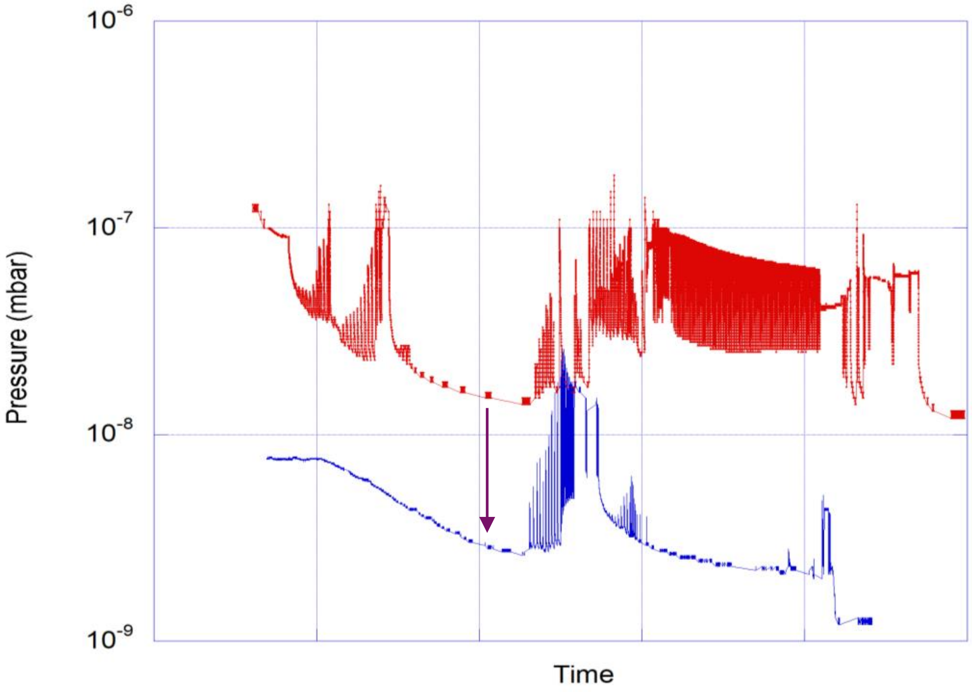
Does this affect conditioning of FPC on the cryomodule?

Comparison of a FPC pressure gauge during coupler conditioning at 300K

- **before** first cooldown (end of 2019) and
- **after** warmup of the cryomodule (jan 2020)

Base pressure is 5x lower after thermal cycling, no conclusion is possible yet regarding the FPC but we have access to much smaller outgassing signals

After 2[nd] cooldown , during 2 K operation, base pressure is 6.10^{-10} mbar at the same gauge



SUMMARY

- Up to now a total of 1 power test of M-ECCTD and 2 power tests of CM01 has been carried out
- One coupler not fully conditioned at the end of tests, but no detected impact on cryomodule behavior
- Shifting to a dedicated vacuum system with large pumping speed has already improved the coupler conditioning phase
- He cooling system in the double wall is working flawlessly
- Starting to use more instrumentation around the cryomodules in order to determine the origin of the radiation (FE electrons, MP electrons, FPC electrons)

Cryomodule/Coupler Test team :

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