DE LA RECHERCHE À L'INDUSTRIE

CEA - Saclay

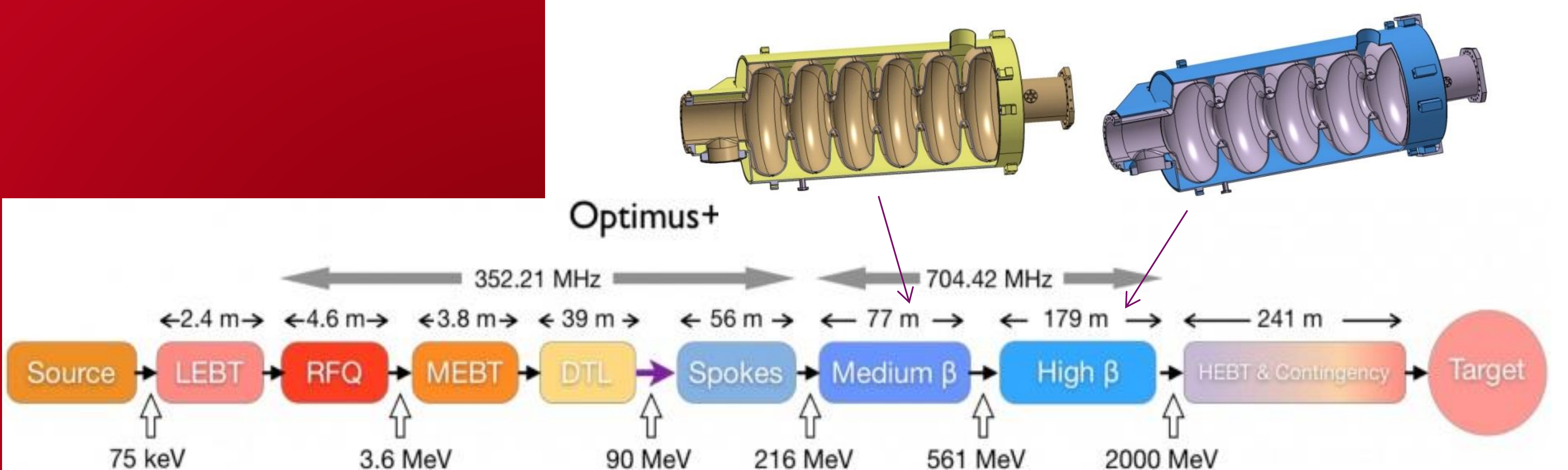
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

THE ESS MEDIUM AND HIGH BETA ELLIPTICAL CAVITIES : DESIGN, FABRICATION AND TESTS RESULTS

SLHIPP#5 MEETING

18/03/2015

Franck PEAUGER



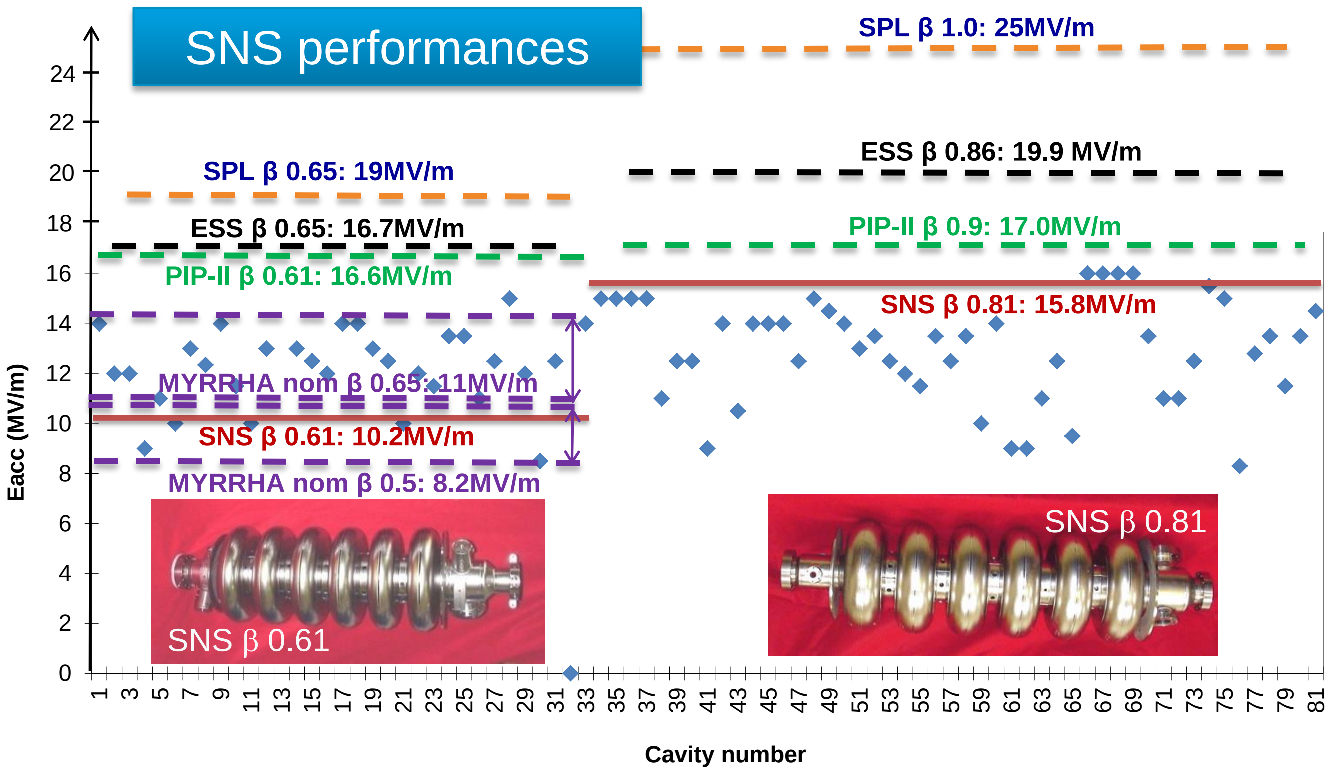
CONTEXT

- **A large experience on 704 MHz cavities at CEA Saclay:**
  - ✓ R&D programs, single and multi-cells, beta = 0.65 (1999, Safa et al.)
  - ✓ CARE HIPPI program, 5 cells, beta = 0.47 (2007, Devanz et al.)
  - ✓ EUCARD program, 5 cells, beta = 1 (2012, Chel, Peauger et al.)

- **CEA contribution to ESS with a common strategy:**
  - ❖ Design of medium and high beta cavities (and cryomodules with IPN Orsay)
  - ❖ Fabrication and test of prototypes before launching the series
    - In vertical cryostat (Supratech platform)
    - In ESS prototype cryomodule called ECCTD (new test station under construction)

CHALLENGING REQUIREMENTS FOR ESS

ESS requirements	Medium beta	High beta
Frequency (MHz)	704.42	
Nominal Accelerating gradient (MV/m)	16.7	19.9
Q_0 at nominal gradient	> 5e9	
Cavity dynamic heat load (W)	4,9	6,5



From JL. Biarotte, SLHIPP-4 meeting 2014

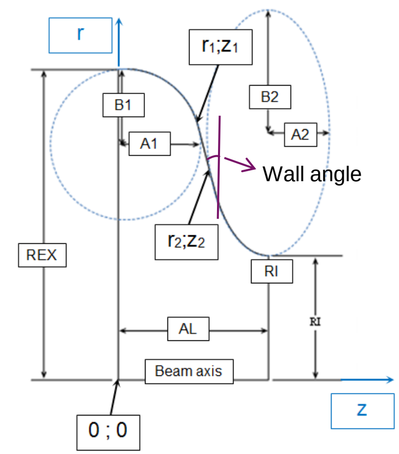
DESIGN

RF PARAMETERS

	Medium	High
Geometrical beta - β_{geom}	0.67	0.86
Frequency [MHz]	704.42	
Number of cells	6	5
Operating temperature [K]	2	
Maximum surface field in operation [MV/m]	40	44
Nominal Accelerating gradient E_{acc} [MV/m] at β_{opt}	16.7	19.9
Accelerating length $L_{acc} = (n_{cell}.\beta_{geom}.\lambda/2)$ [m]	0.855	0.915
Nominal Accelerating Voltage $V_{acc} = (E_{acc} \times L_{acc})$ [MV] at β_{opt}	14.3	18.2
Theoretical R_{BCS} (1) at operating temperature [nΩ]	3.2	
G [Ω]	196.6	241
Q_0 at operating temperature for R_{BCS}	6.14×10^{10}	7.53×10^{10}
Q_0 at nominal gradient	$> 5 \times 10^{10}$	
Cavity dynamic heat load [W]	4,9	6,5
Q_{ext}	7.5×10^{5}	7.6×10^{5}
Iris diameter [mm]	94	120
Beam tube diameter [mm]	136	140
Cell to cell coupling κ [%]	1.22	1.8
π and $5\pi/6$ (or $4\pi/5$) mode separation [MHz]	0.54	1.2
E_{pk}/E_{acc} at β_{opt}	2.36	2.2
B_{pk}/E_{acc} [mT/(MV/m)] at β_{opt}	4.79	4.3
Maximum r/Q [Ω] at β_{opt}	394	477
Optimum beta β_{opt}	0.705	0.92

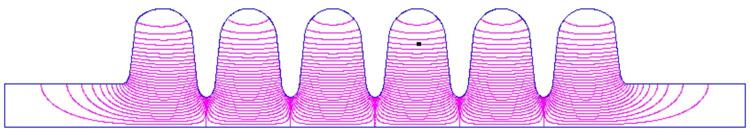
Designed by:

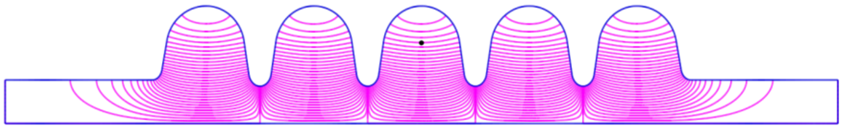
- HB: G. Devanz, J. Plouin, CEA Saclay, 2010-2011
- MB: G. Constanza, Univ. of Lund, 2013-2014



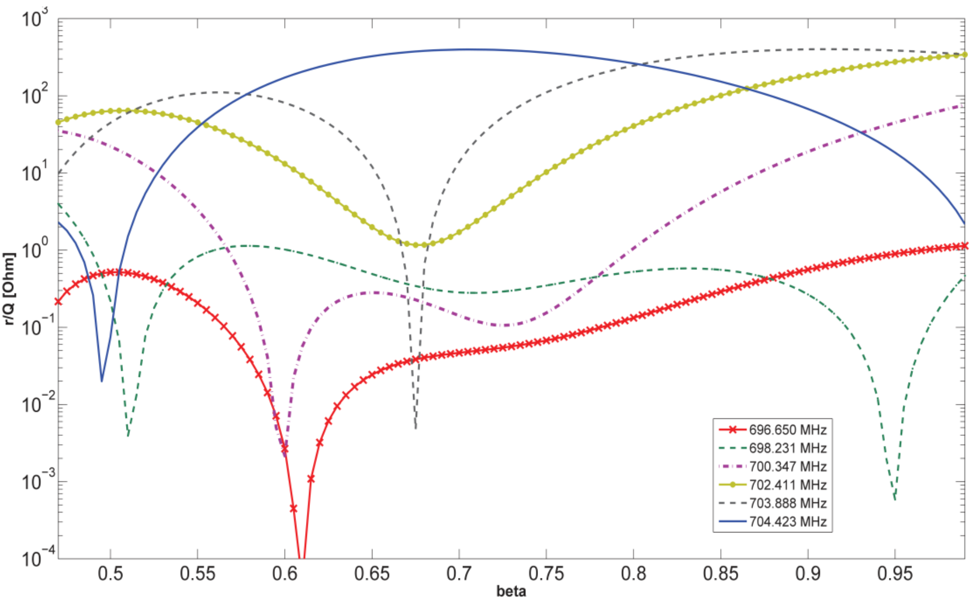
ACCELERATING MODE AND FIRST BANDPASS

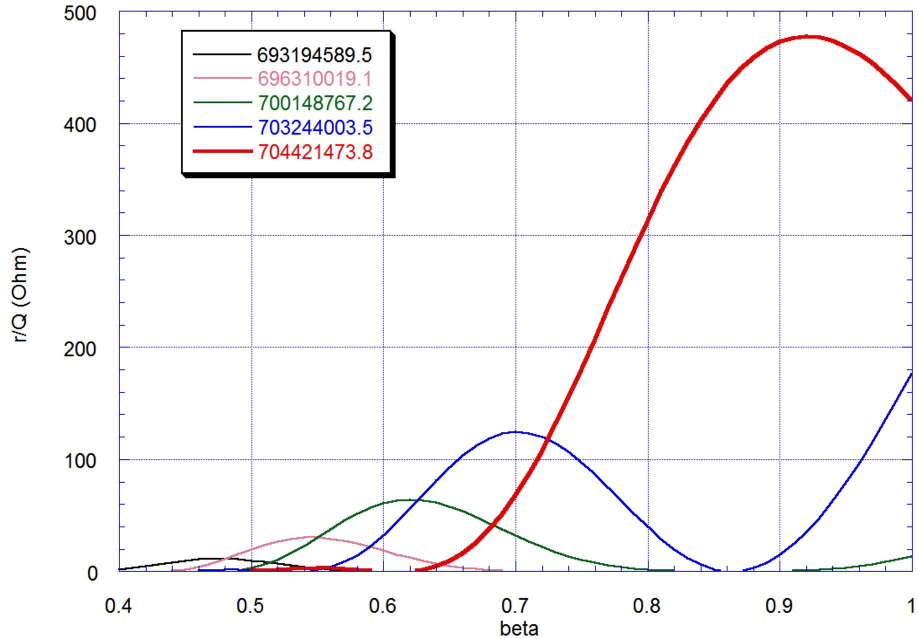
Cavity profile and field pattern at 704.4 MHz





r/Q for the first passband modes.

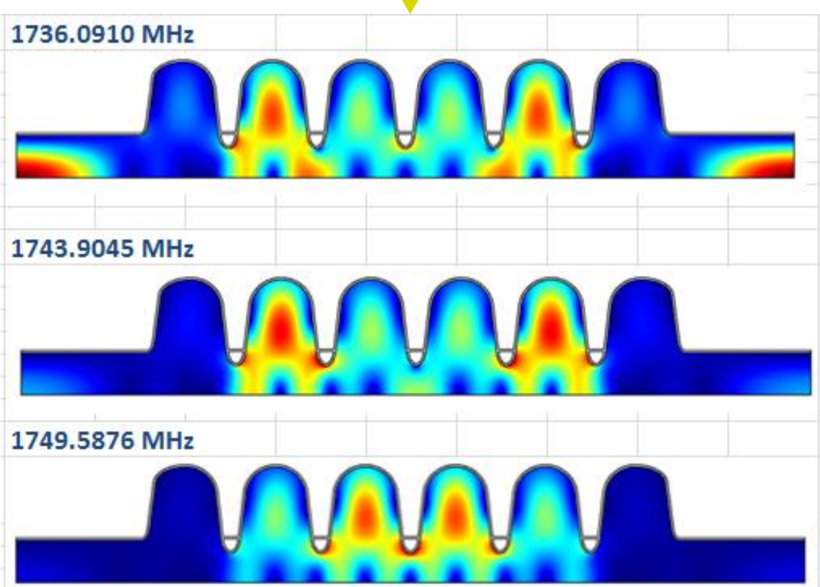


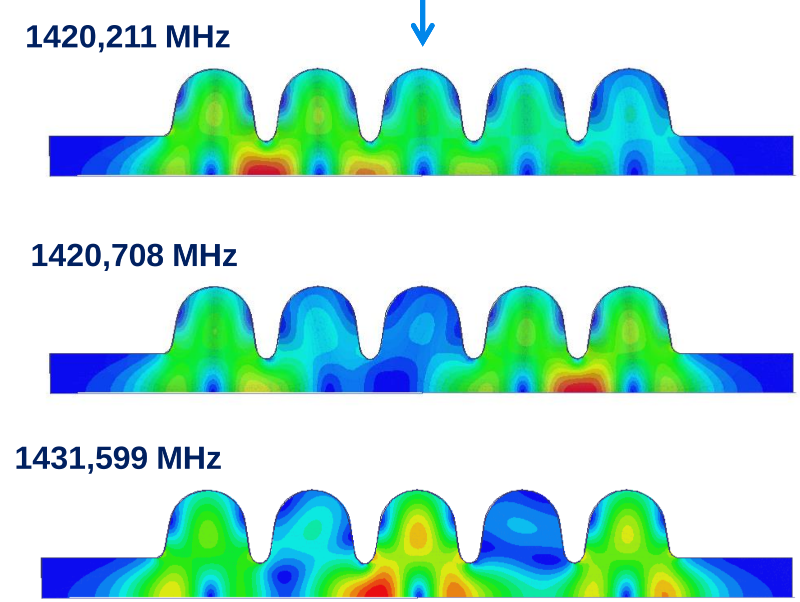


MOST DANGEROUS HIGHER ORDER MODES

Both cavities are designed to have HOM at more than 5 MHz from beamline frequencies

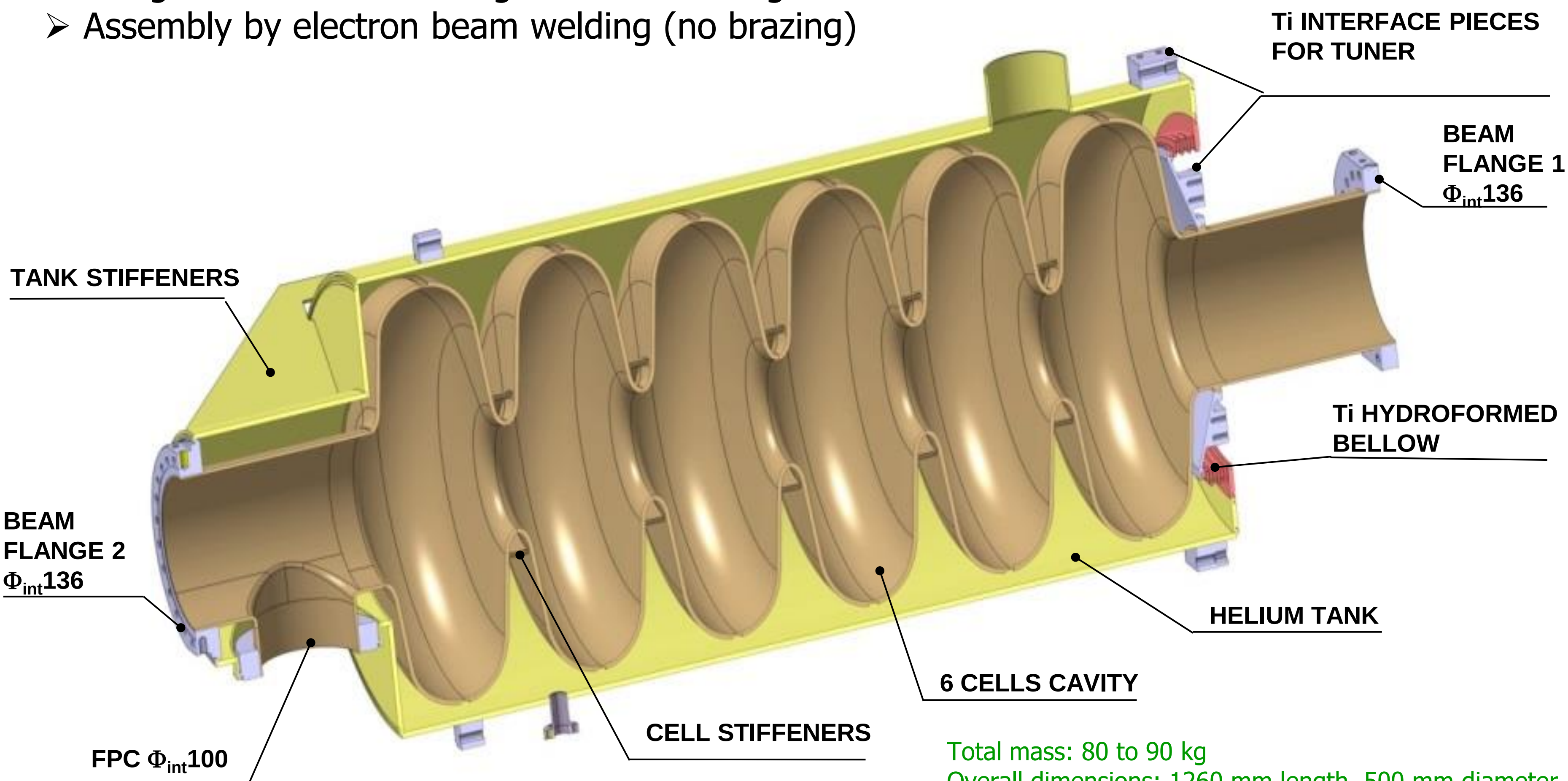
	F [MHz]
Beam frequency	352.21
2nd harmonic frequency	704.42
3rd harmonic frequency	1056.63
4th harmonic frequency	1408.84
5th harmonic frequency	1761.05
6th harmonic frequency	2113.26
7th harmonic frequency	2465.47





MECHANICAL FEATURES

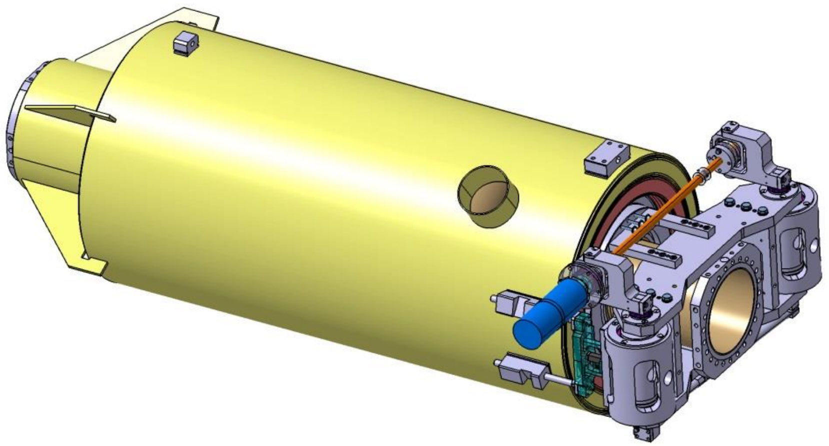
- Half cells, beam pipes and ports in pure Niobium RRR > 250
- He tank in Titanium
- Flanges in NbTi with hexagonal aluminium gaskets
- Assembly by electron beam welding (no brazing)

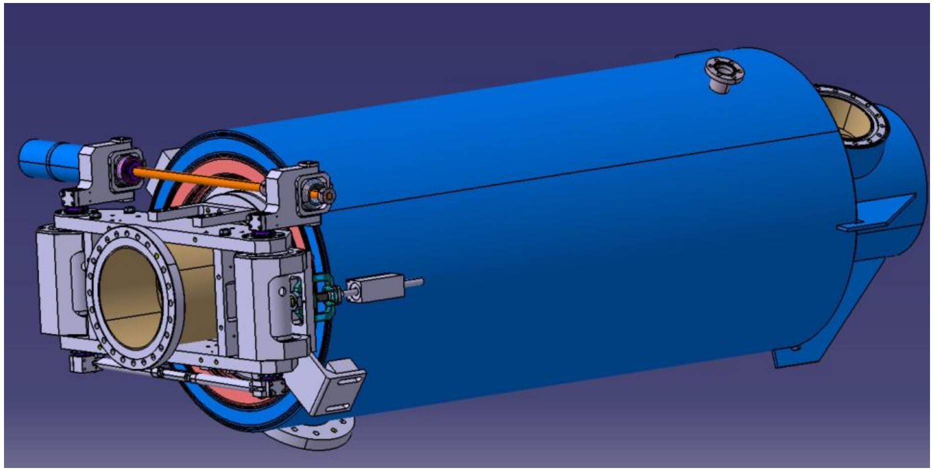


Total mass: 80 to 90 kg
Overall dimensions: 1260 mm length, 500 mm diameter

Most of the elements are identical for medium and high beta

MECHANICAL PARAMETERS



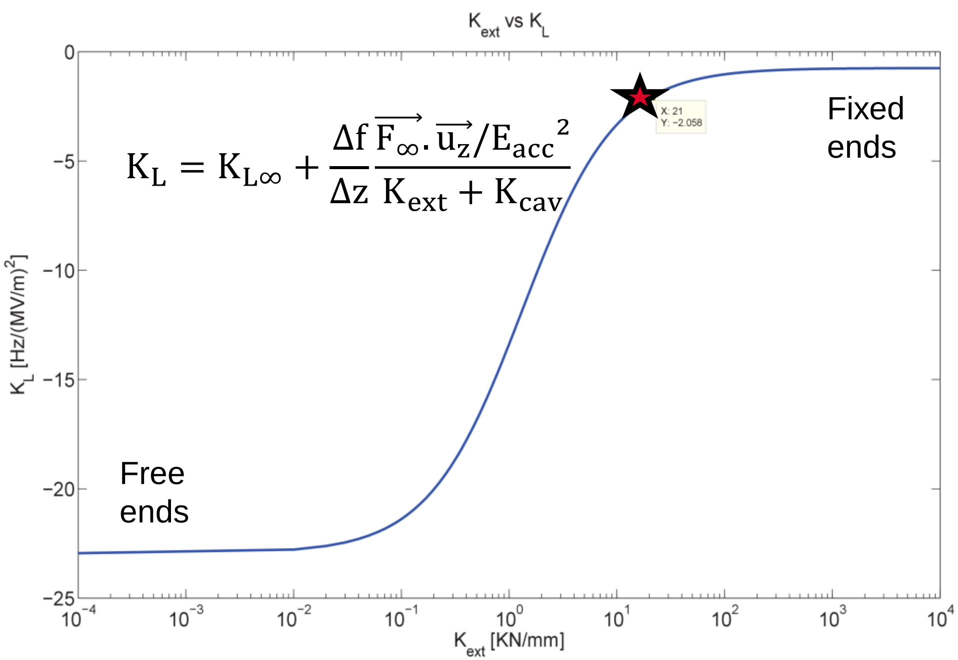


		Medium beta	High beta
Niobium thickness	mm	4	3.6
Cavity stiffner radius	mm	70	84
Tank thickness	mm	5	5
Lorentz Force Detuning coef. K_L fixed ends	Hz/(MV/m)²)	- 0.735	-0.36
Lorentz Force Detuning coef. K_L free ends	Hz/(MV/m)²	-23.35	-8.9
Cavity stiffness	kN/mm	1.286	2.59
Tuning sensitivity $\Delta f/\Delta z$	kHz/mm	214.8	197
max VM stress /1mm elongation	MPa		25
Pressure sensitivity K_P fixed ends	Hz/mbar	23.08	4,85
Pressure sensitivity K_P free ends	Hz/mbar	-364.94	-150
max VM stress /1bar fixed	MPa	30.6	12
max VM stress /1bar free	MPa	31.4	15

LORENTZ FORCE DETUNING CALCULATION

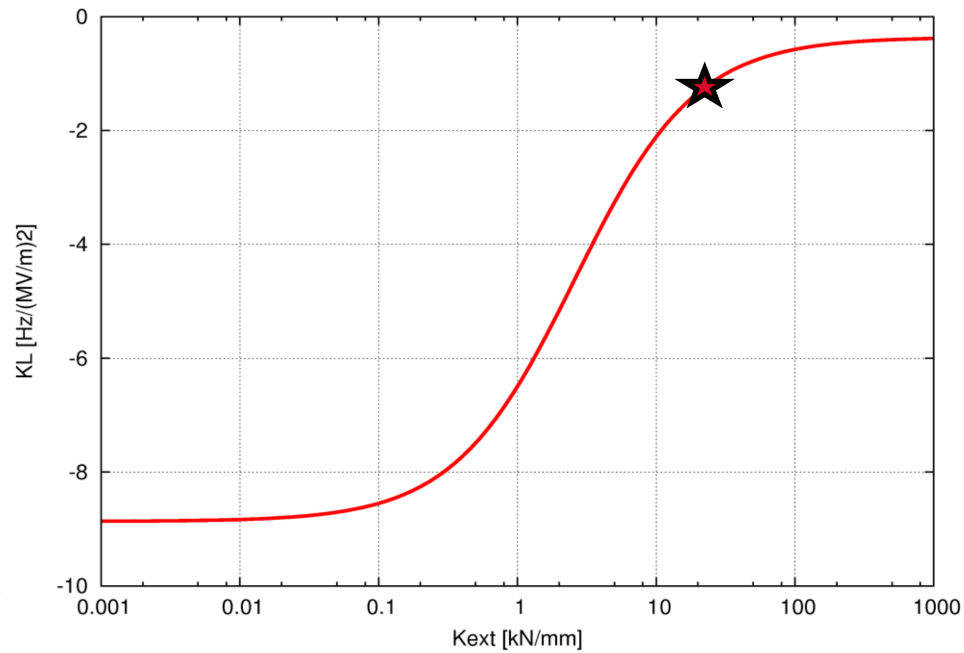
Designed stiffness of the tank: K_{tank} = 75 kN/mm
Measured stiffness of the tuner: K_{tuner} = 30 kN/mm
Total external stiffness (tank + tuner): K_{ext} = 21 kN/mm

Medium beta



For K_{ext} = 21 kN/mm
→ K_L = -2 Hz/(MV/m)²
→ ΔF = -557 Hz @ 16.7 MV/m
→ ΔL_{piezo} = - 2.6 µm

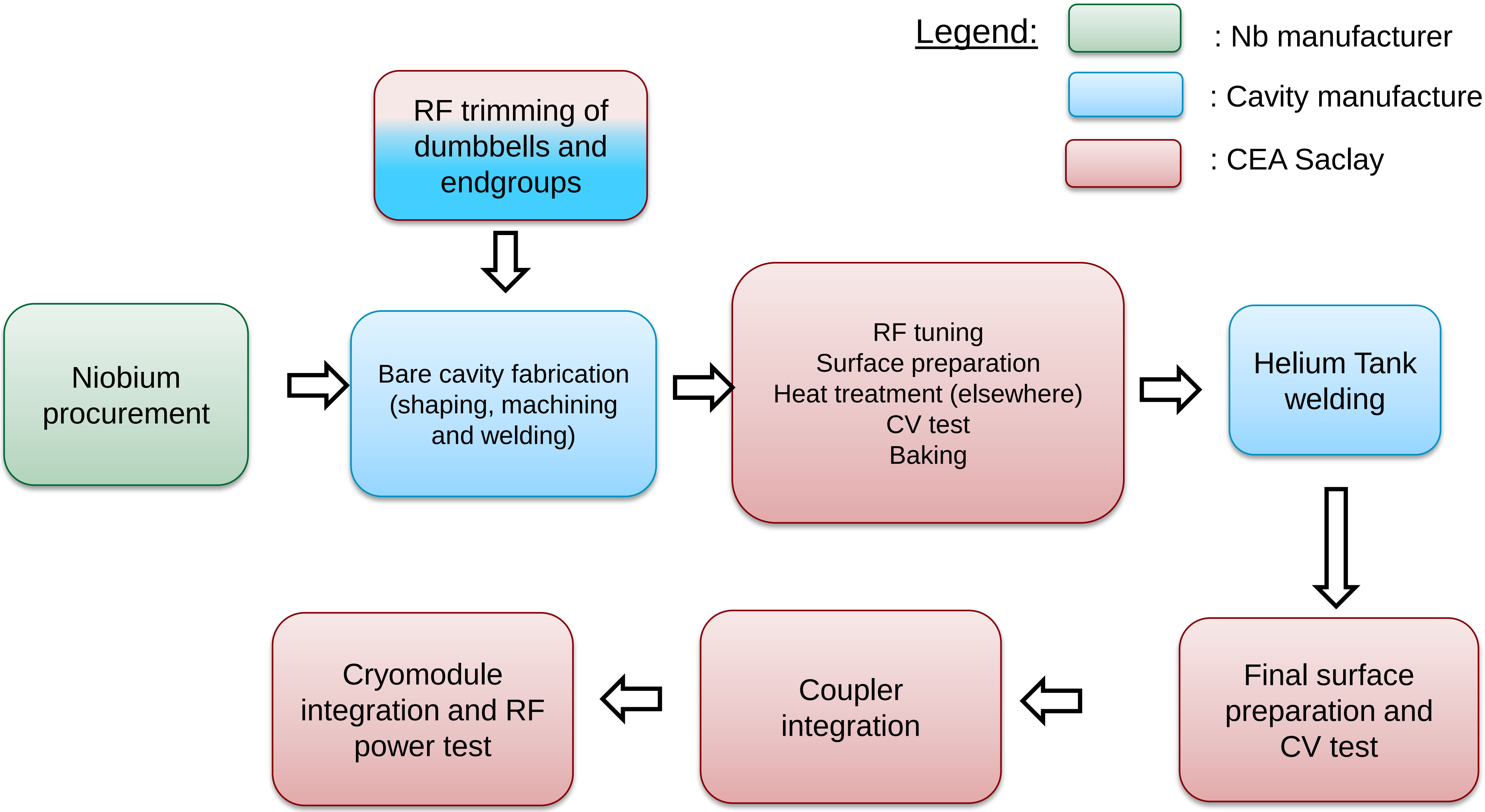
High beta



For K_{ext} = 21 kN/mm
→ K_L = -1 Hz/(MV/m)²
→ ΔF = -396 Hz @ 19.9 MV/m
→ ΔL_{piezo} = - 2 µm

FABRICATION

CAVITY FABRICATION AND QUALIFICATION STRATEGY FOR PROTOTYPES



- No cryomodule test with beta = 1 antenna (without power coupler)
- No test of single cavity+coupler unit in horizontal cryostat (Cryolab)

THE TWO PROTOTYPE HIGH BETA CAVITIES

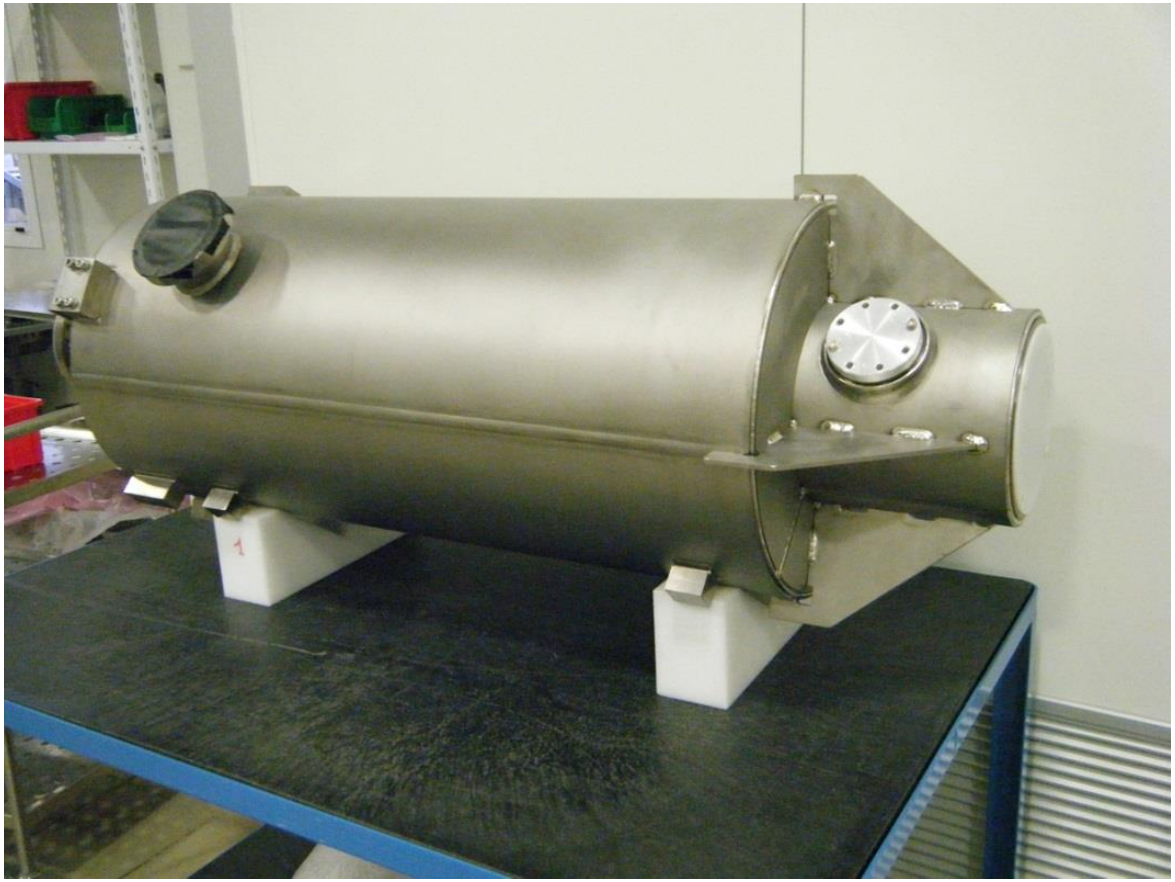
- ⇒ HOM ports only for HOM measurements (suppressed in the cryomodule)
- ⇒ Niobium from Tokyo Denkai, 4.5 mm thickness
- ⇒ Kick-off in Sept. 2012
- ⇒ Trimming operations of dumbbells in presence of CEA staff

P01 manufactured by E. ZANON
F_π = 703.553 MHz
Field flatness: 86%

P02 manufactured by RI
F_π = 703.704 MHz
Field flatness: 40%
Bad angles stiffning rings

Target frequency, at 300 K before chemical etching:
F_π = 703.822 MHz

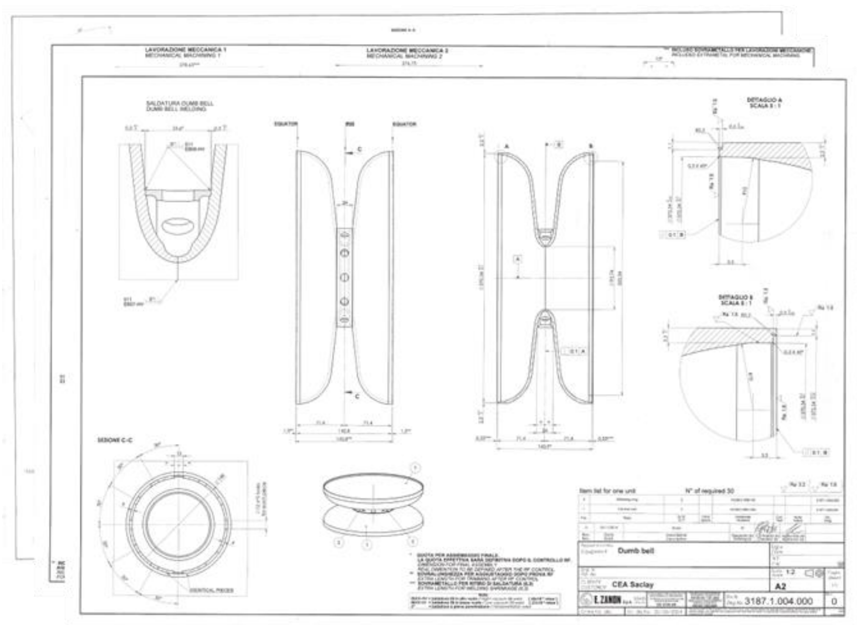
TANK INTEGRATION OF ESS086-P01 AT ZANON



- ΔF = +9 kHz only due to tank welding
- Pressure and leak test done successfully
- Delivery at CEA in 1 or 2 weeks for CV test only (not compatible with the cryomodule)

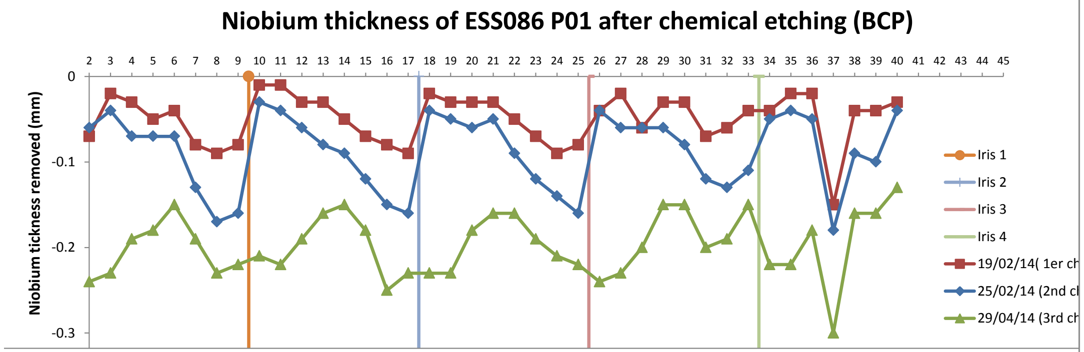
MEDIUM BETA CAVITY FABRICATION STATUS

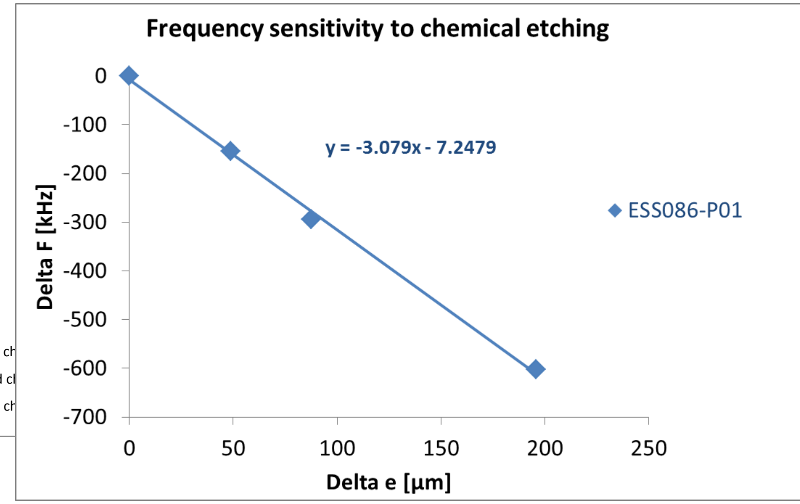
- 6 cavities ordered at ZANON, 4 of them will be integrated into the M-ECCTD cryomodule
- Niobium received and sent to ZANON
- Fabrication drawings sent to CEA and under validation
- Deep drawing tests on copper plates
- Preparation of RF measurement equipements for half cells and dumbbells

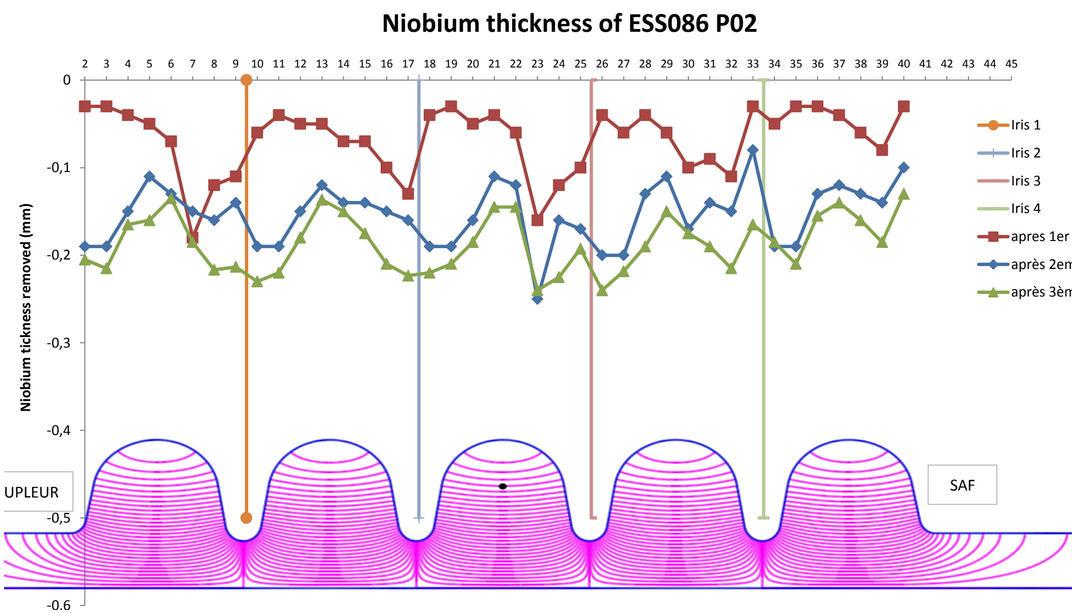


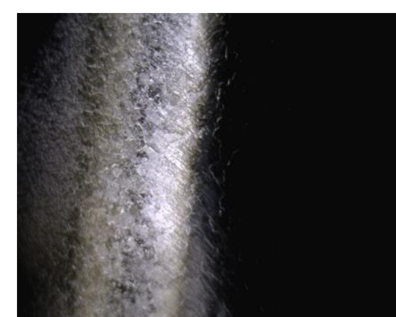
MEASUREMENTS and TEST RESULTS

EFFECT OF BCP









FREQUENCY SENSITIVITY OF ACCELERATING MODE 704.4 MHZ

Bare cavity with beam tube flanges and free ends condition (CV test conditions)

Tuning sensitivity ΔF/Δz (kHz/mm)	ESS067	ESS086
Calculated	214.8	197
Measured		190

Stiffness (kN/mm)	ESS067	ESS086
Calculated	1.286	2.59 (3.6 mm thick) 3.3 (4.5 mm thick)
Measured		3

Frequency shift ΔF due to cooldown and vacuum (kHz)		ESS067	ESS086
Calculated	300K to 4.2 K	+1.0067	+1.00138
	Ɛr to Ɛo	+0,211	+0.211
Measured	300K to 4.2K		~ +1.08
	Ɛr to Ɛo		+0.015

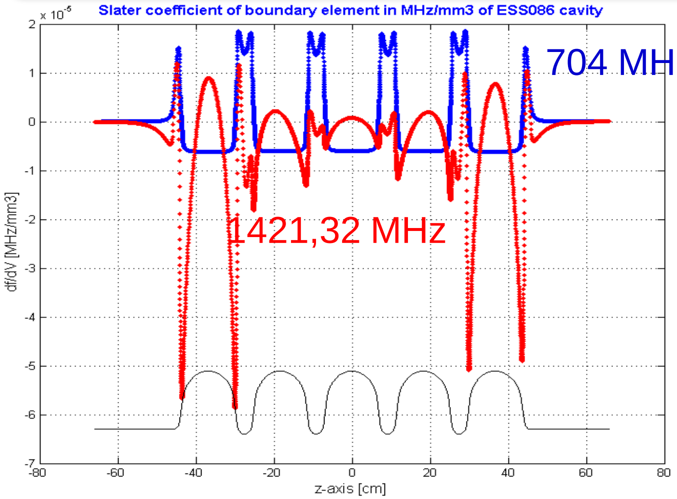
Frequency shift ΔF due to cooldown and pressure (kHz)		ESS067	ESS086
Calculated	4.2 K to 2 K		
Measured			~ + 0.207

DANGEROUS HIGHER ORDER MODE CLOSE TO 1408.8 MHZ

Both high beta prototype cavities are not conform with the ESS HOM Requirement

Reminder: HOM shall be at more than 5 MHz from beamline frequencies

Slater coefficient analysis which represents frequency sensitivity to volume changes:



- 3D measurements of the cavity shape have been done
- Shape have been reconstructed in the simulation software HFSS

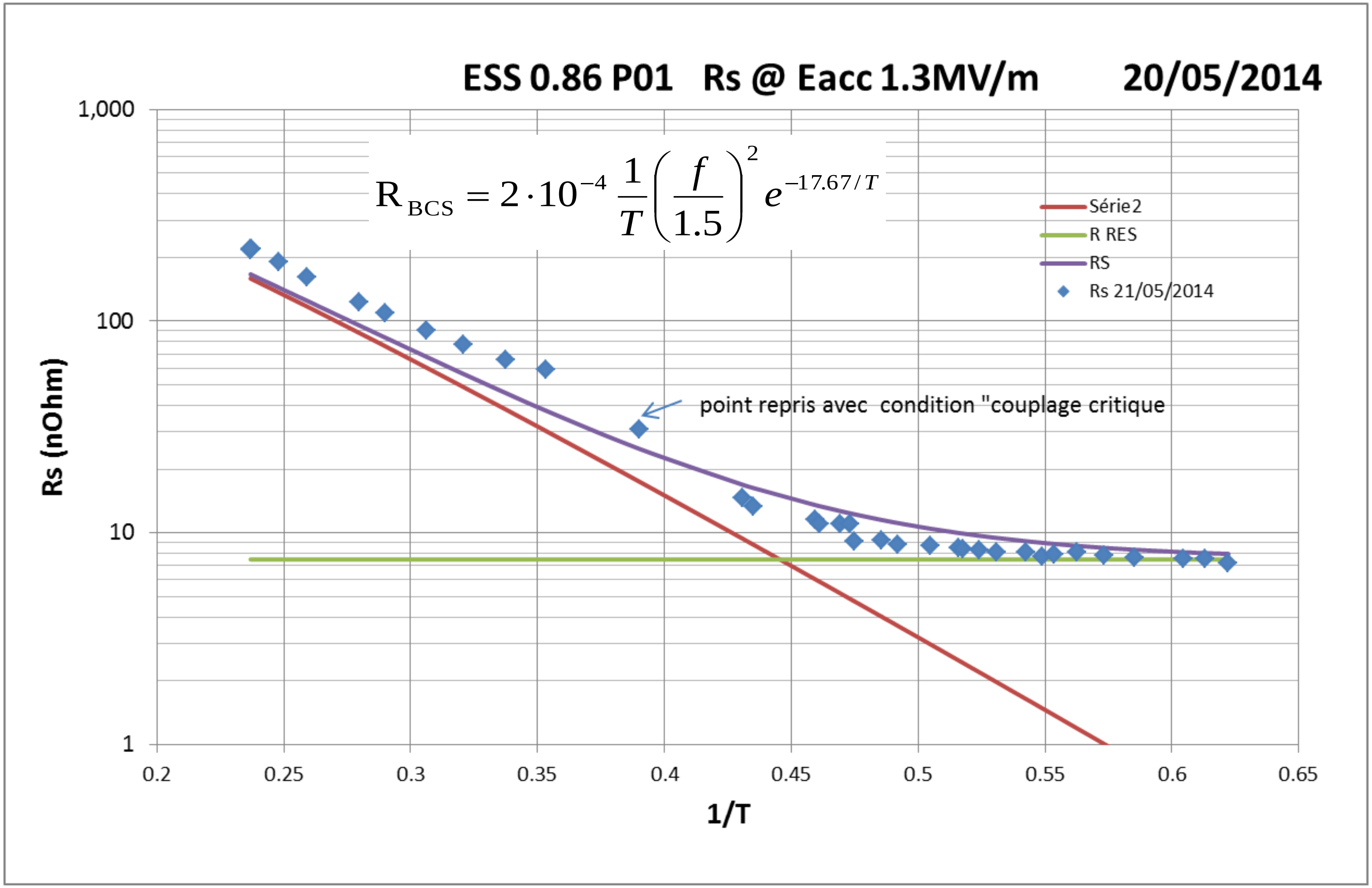
Design (at 300K)	Measured on ESS086-P01	Calculated with measured shape (HFSS)	Measured on ESS086-P02	Calculated with measured shape (HFSS)
1418.178	1402.254	1403.8	1407.848	
1418.674	1404.666	1406.8	1408.258	

⇒ On P01 cavity (from ZANON), a strong internal shape deviation in this dome region (more than 1 mm instead of 0.3 mm) explains very well the frequency decrease of the two dangerous HOM

⇒ Study under progress on P02 cavity (from RI)

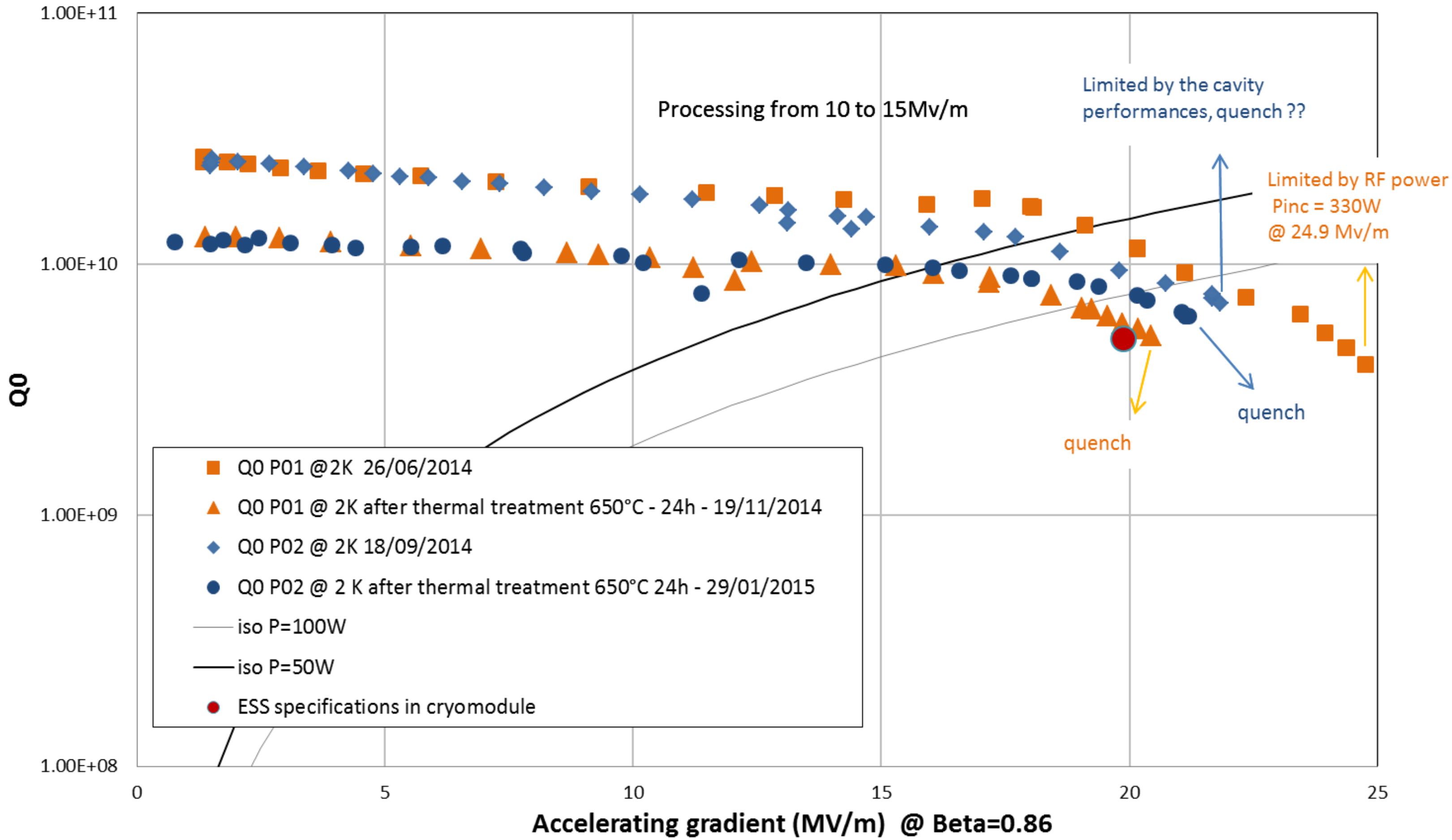
➢ **Cells reshaping has to be implemented in the fabrication process of future cavities**

SURFACE RESISTANCE



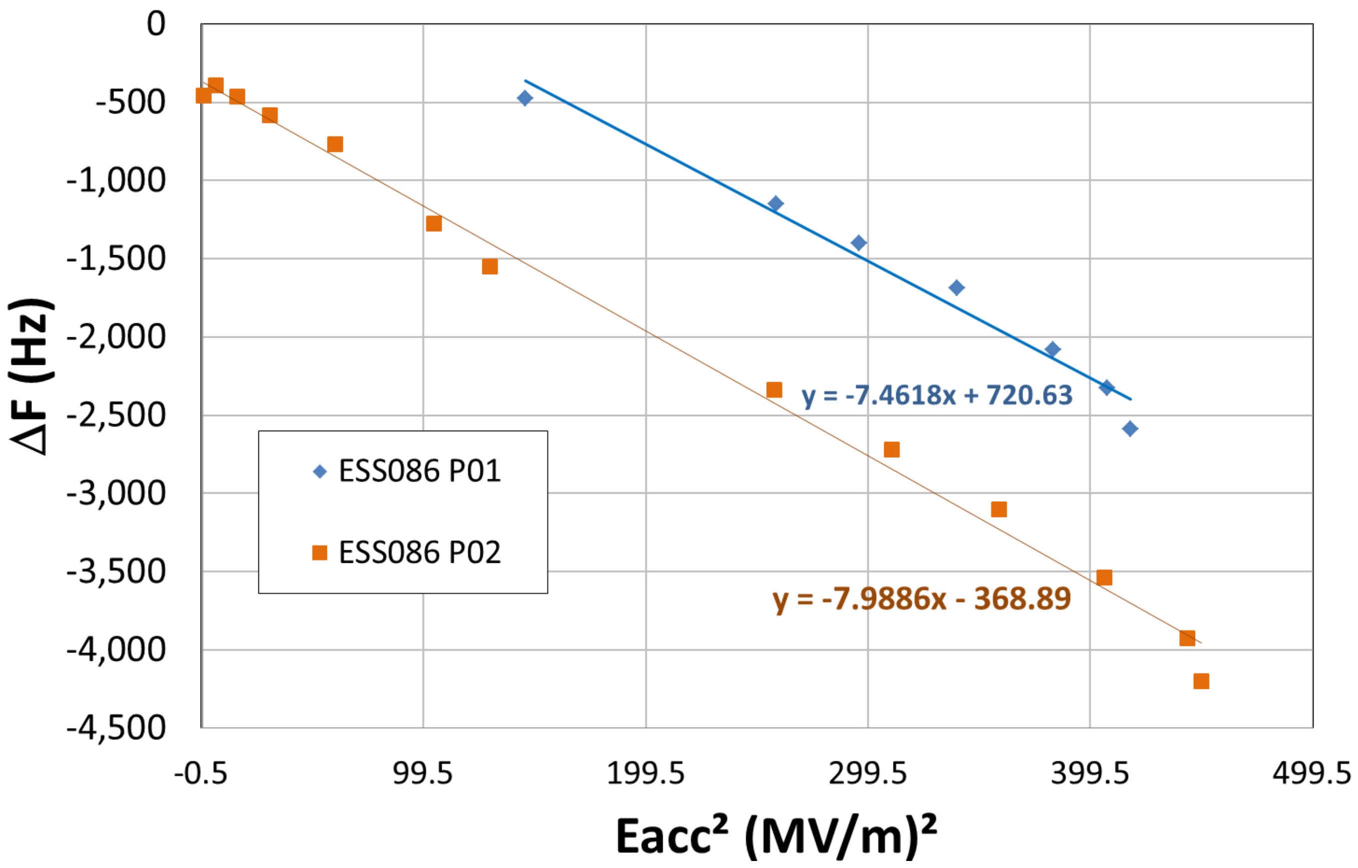
➢ Measured residual resistance: Rres = 7.5 nOhm, compatible with usual measured values on 704 MHz cavities

VERTICAL TEST RESULTS AT 2K



- **Both prototype cavities already met the ESS requirements after the first test: → Very encouraging results**
- **Slight degradation of the performances after thermal (pollution?)**

STATIC LORENTZ FORCE DETUNING MEASUREMENT



- Measured LFD coefficient: KL = -7.65 Hz/(MV/m)²
- Close to the calculated value of -8.9 Hz/(MV/m)² in free ends conditions

CONCLUSION

- The full design of the medium and high beta cavities have been completed to be compliant with the ESS requirements and the state of art performances
- The two high beta prototypes have been successfully tested in vertical cryostat and reached an accelerating gradient of 20 to 24 MV/m and a Q_0 above the specification of 5^e9
- Important parameters such as frequency shifts, tuning sensitivity and LFD have been measured and are conform to the predictions
- Some dangerous HOM have been unexpectedly measured too close to beam harmonics. The problem is partially understood
- The six medium beta are under manufacturing and first half cells and dumbbells should be ready for RF measurements and trimming in few weeks

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THANK YOU

ESS Cavity team:

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ESS:
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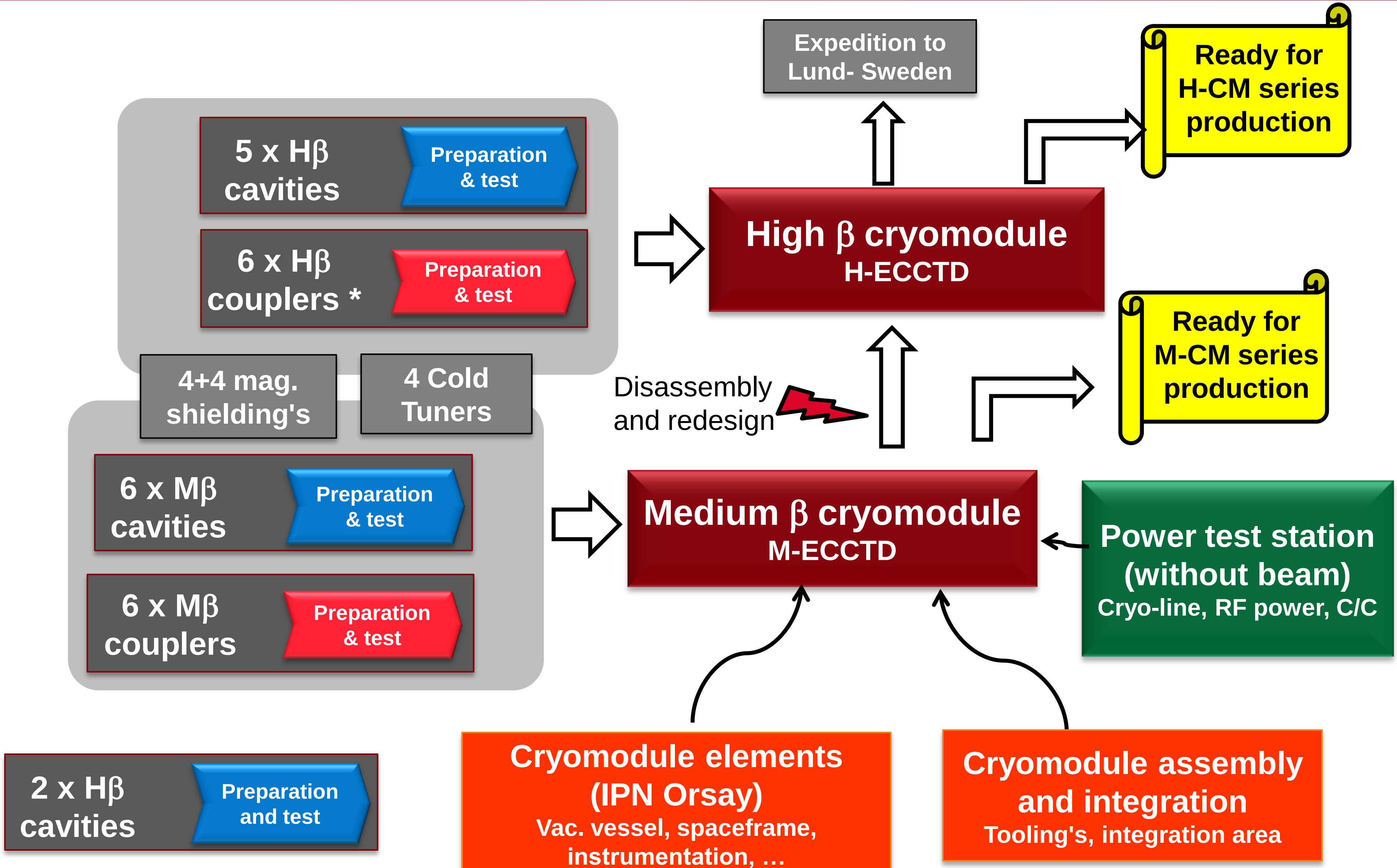
CNRS – IPNO:
G. Olivier

CRYOMODULE DEVELOPMENT STRATEGY

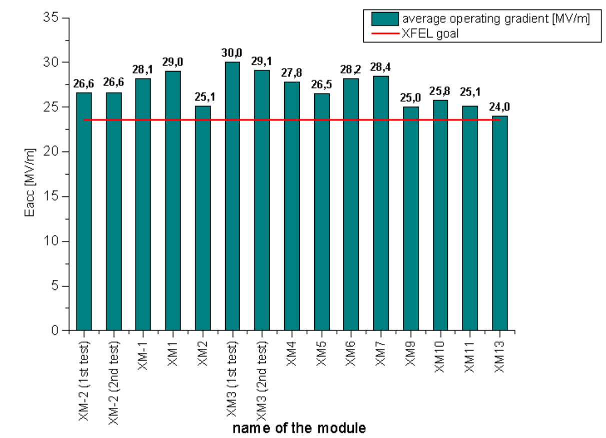


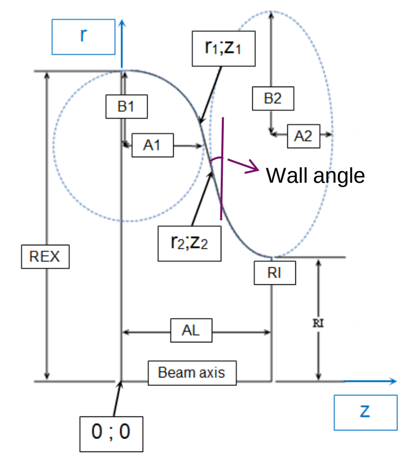
(*) partially re-used from M-ECCTD

RF DESIGN APPROACH

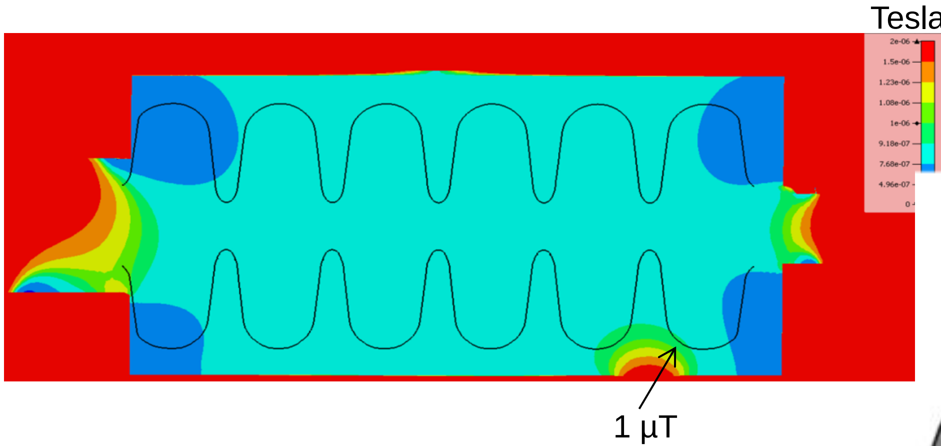
- Consider state of the art performance of bulk Nb cavities with High Pressure water Rinsing (HPR)
  - ✓ XFEL specifications (Eacc= 23.6 MV/m, corresponding to Epk = 47 MV/m, and Bpk = 100 mT) on series production
- Minimum wall angle of 6 degrees with respect to the vertical direction to easier the cavity preparation (chemical etching, HPWR and drying) and the cavity mechanical behaviour (sensitivity to Lorentz Force Detuning (LFD))
- High cell-to-cell coupling factor κ to easier the even field distribution in the cavity (and peak surface fields), to increase the frequency mode separation (first passband) and to allow high order mode (HOM) propagation (because of high iris diameters)
  - drawback: reduce the efficiency and require higher power source
- Automatic cavity shape generator (specially developed by G. Constanza for the MB cavity design) and electromagnetic simulation codes: SUPERFISH, COMSOL and ANSYS/HFSS

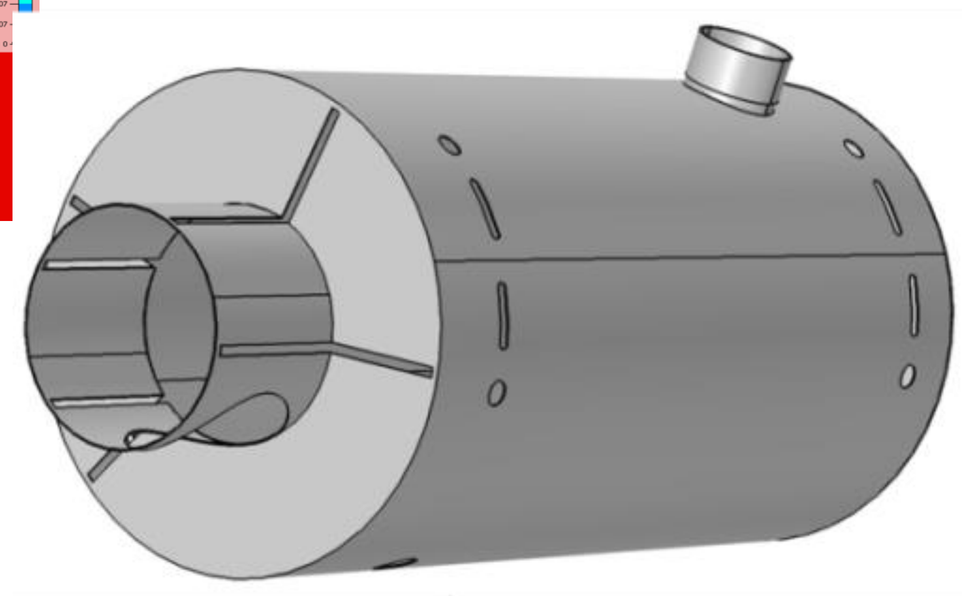
All modules can be operated above 23.6 MV/m !!





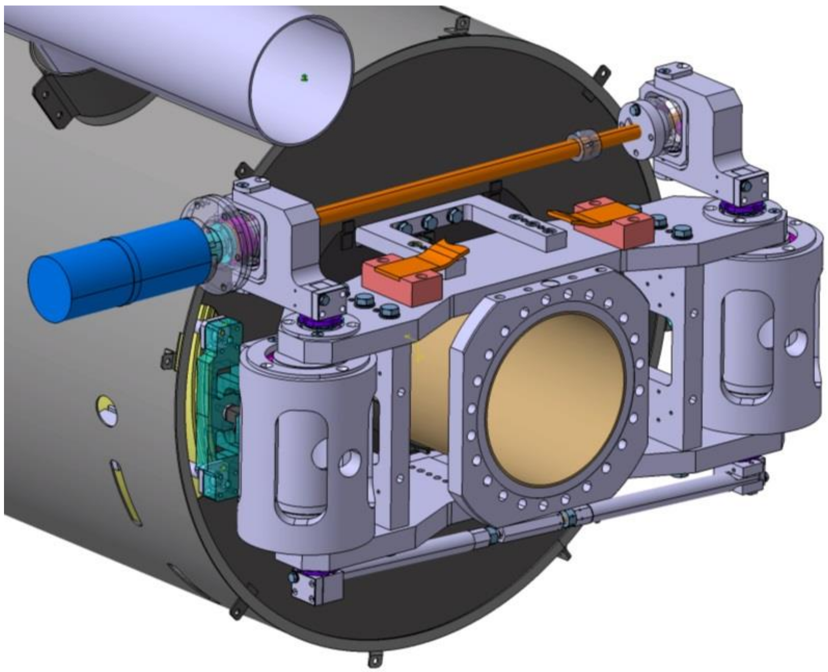
MAGNETIC SHIELDING DESIGN





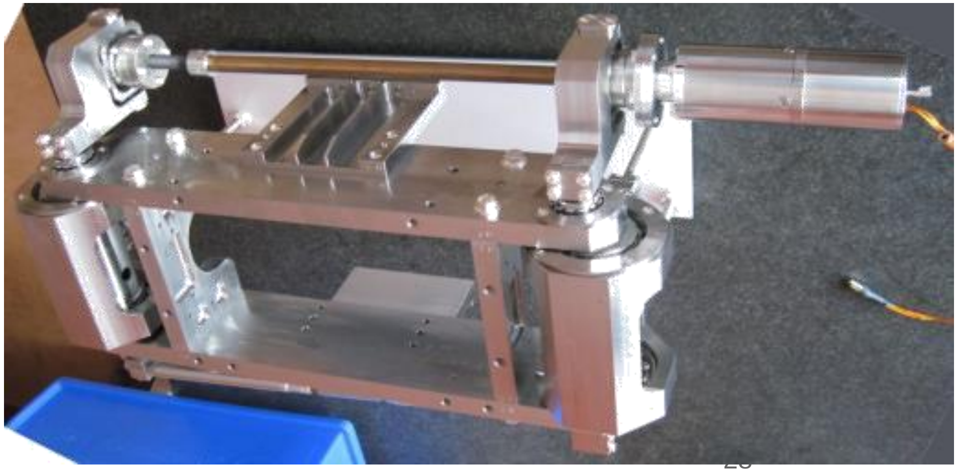
- ⇒ Technical specification and call for tender will start beginning of 2015
- ⇒ 4 (medium beta) + 4 (high beta) will be ordered

COLD TUNING SYSTEM



- Saclay V type adapted for ESS cavities
- +/- 3 mm range
- 1+1 piezo
- Cold motor and planetary gearbox (1/100e)
- Piezo support has a stiffness 10 times higher than the cavity ⇨ piezo preload at 2K is independant of the cavity springback force

Type V for SPL beta = 1 5-cell prototype



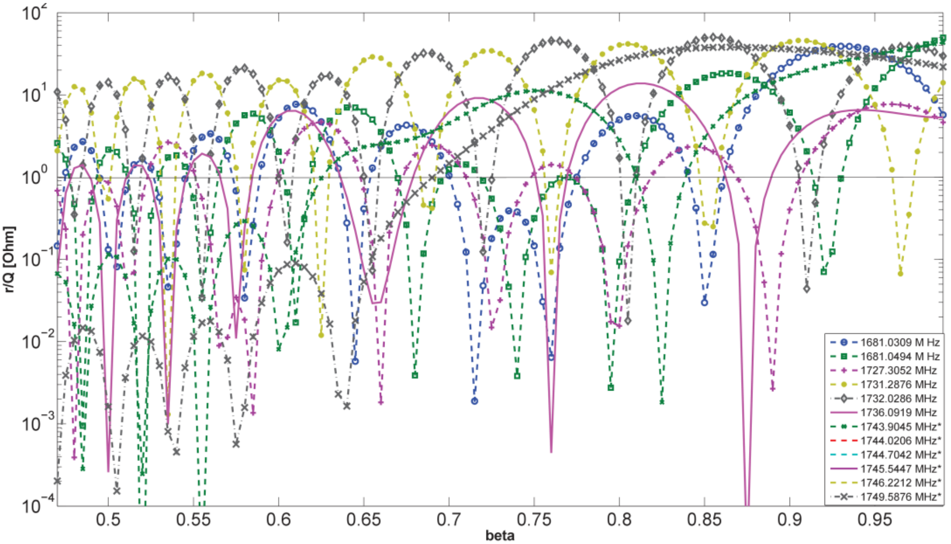
⇒ Waiting for mechanical data of cavity to finalize the design

⇒ Technical specification and call for tender will start beginning of 2015

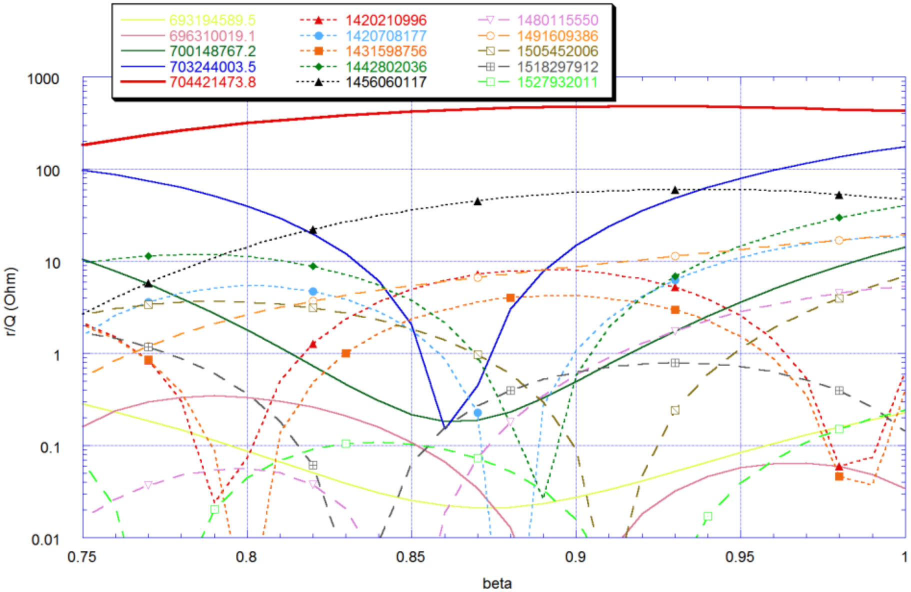
⇒ 4 (medium beta) + 4 (high beta) will be ordered

MORE HOMS…

Medium beta



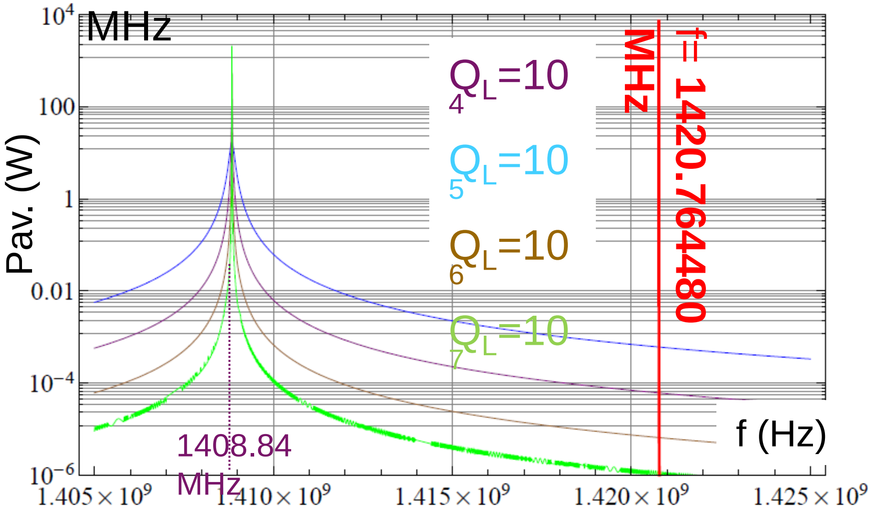
High beta



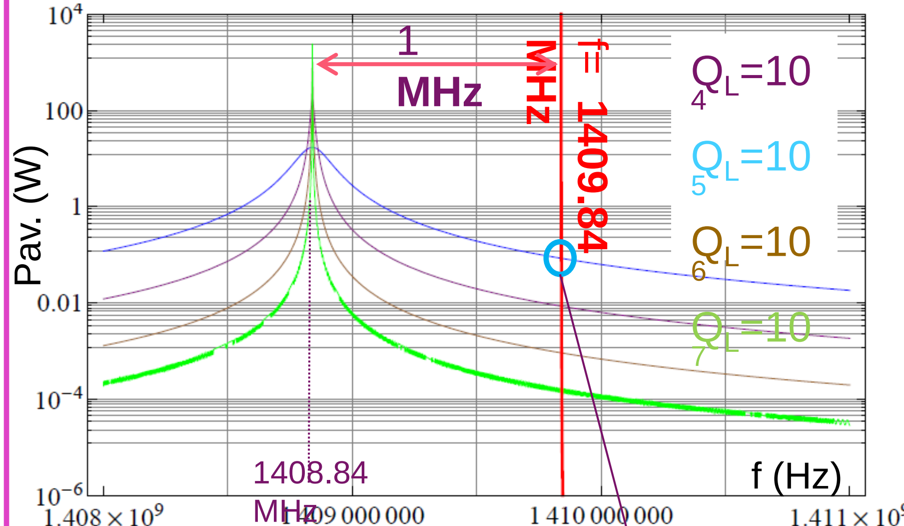
	Cutoff frequencies (GHz)				
Diameter (mm)	TE11	TM01	TE21	TM11	TE01
100	1.7585	2.2989	2.9268	3.6585	3.6585
136	1.293	1.6903	2.1521	2.601	2.601
140	1.2568	1.6420	2.0804	2.6132	2.6132

Power deposited on the non-propagating longitudinal modes

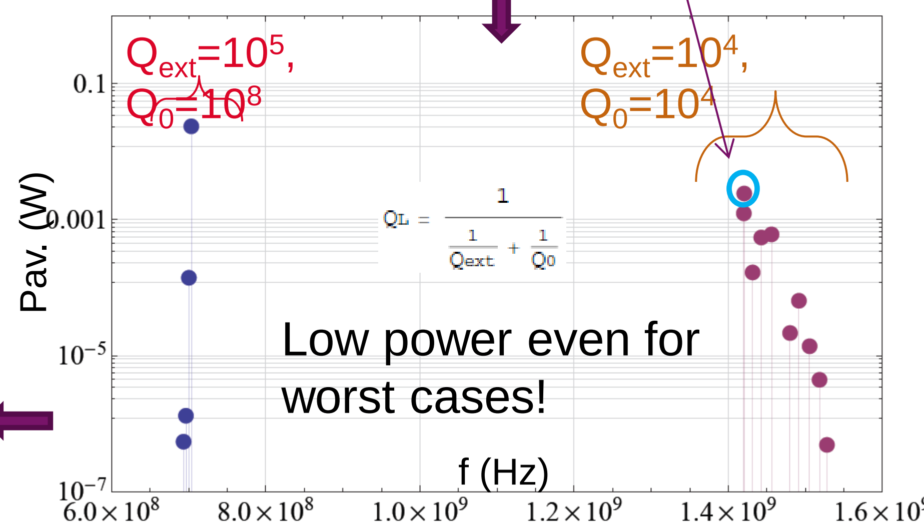
Most dangerous mode : 2nd mode of the 1st HOM L-band at f= 1420.764480 MHz



What would happen if this mode was at 1 MHz from the beam line ?



Very important : distance between mode and beam harmonics

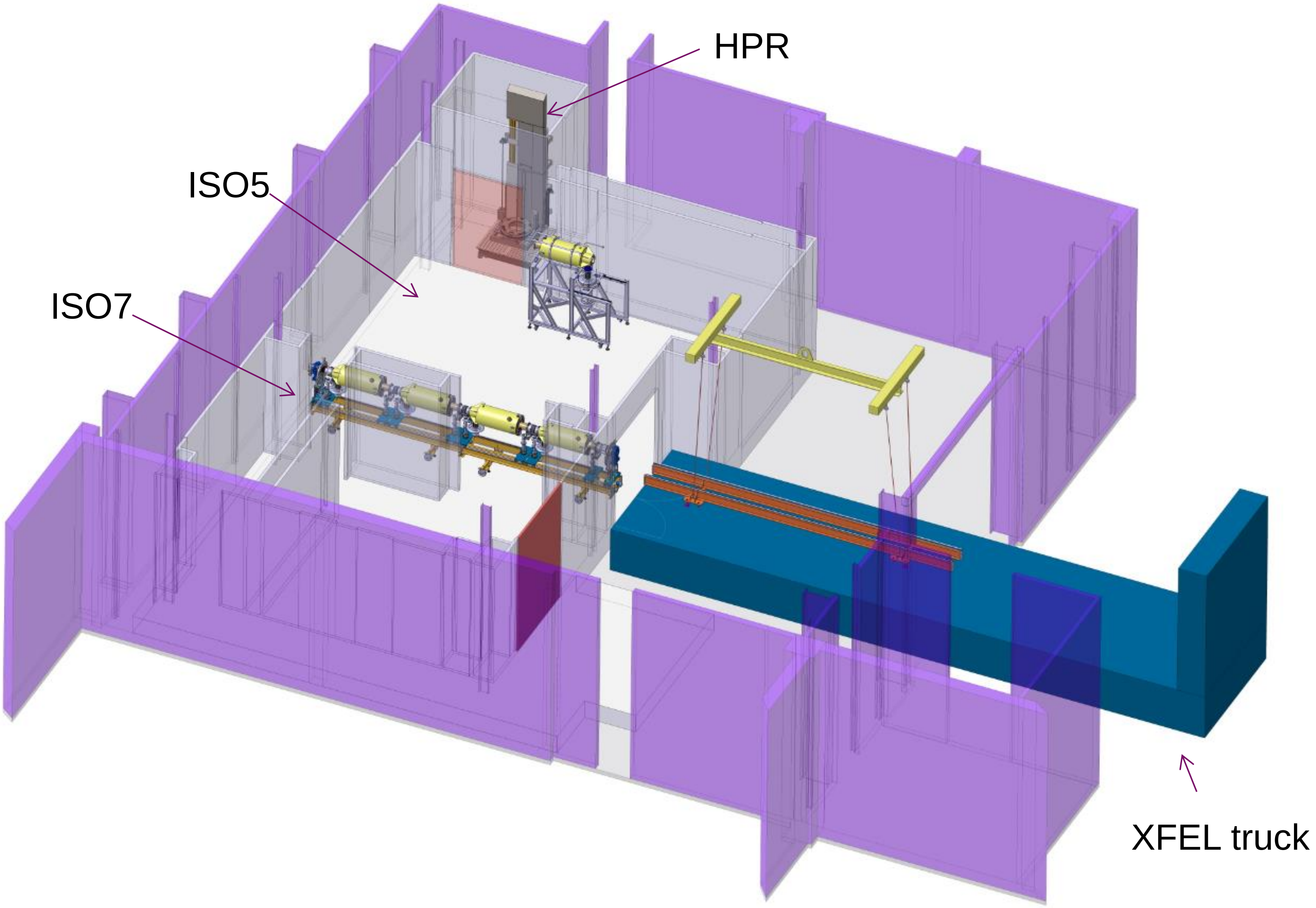


Conclusion: If longitudinal HOMs are more than 1MHz away from beam harmonics:

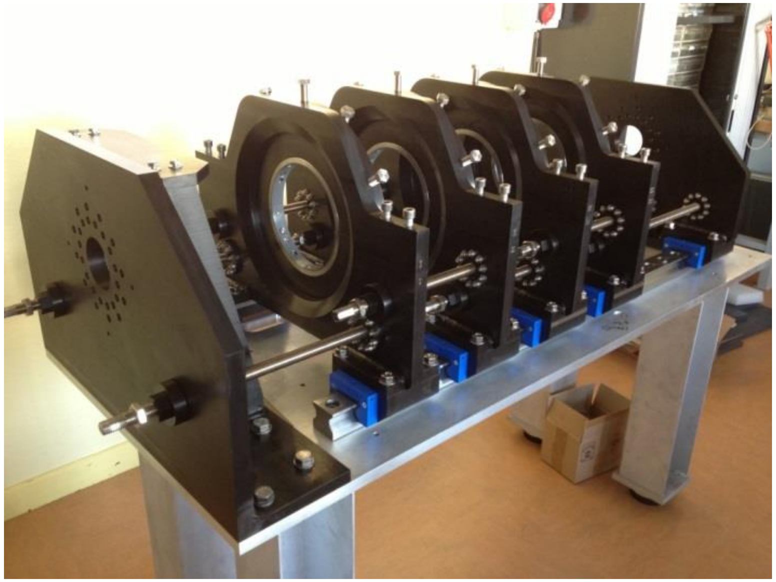
-no extra damping is necessary

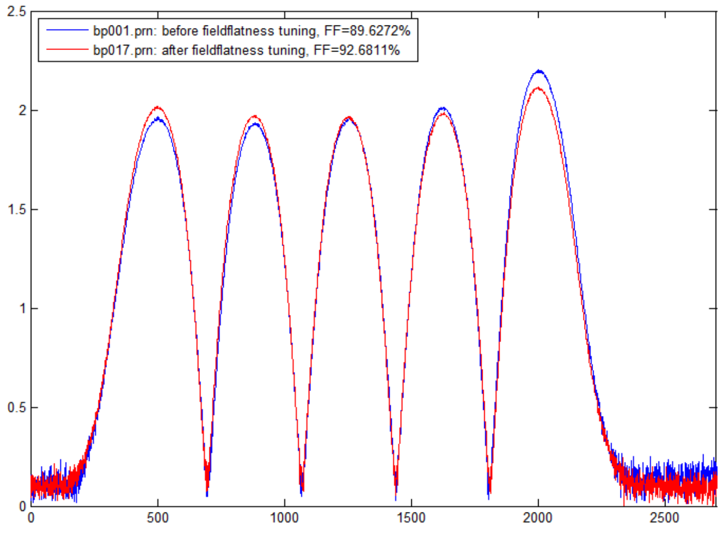
-more damping harmful

CAVITY STRING CLEAN ROOM ASSEMBLY IN BLG 124EST



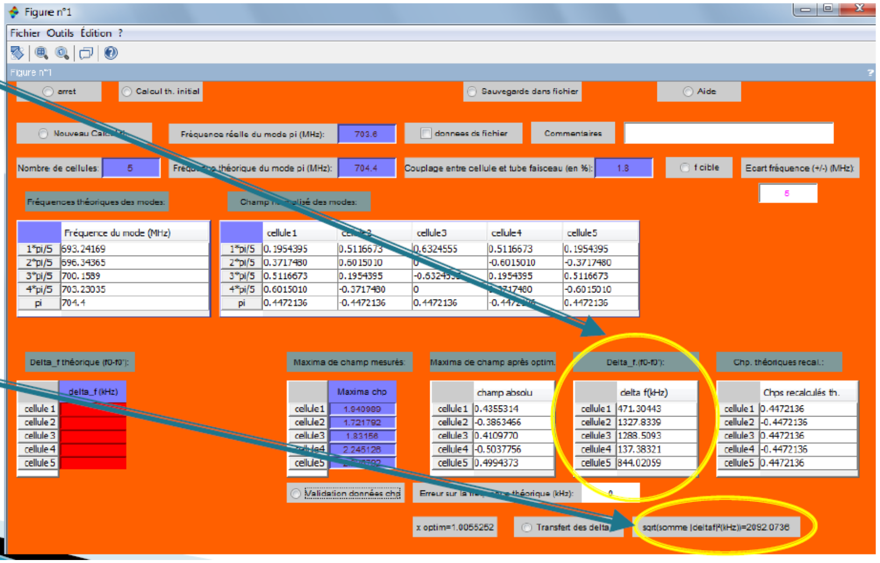
FIELD FLATNESS TOOLING AT CEA

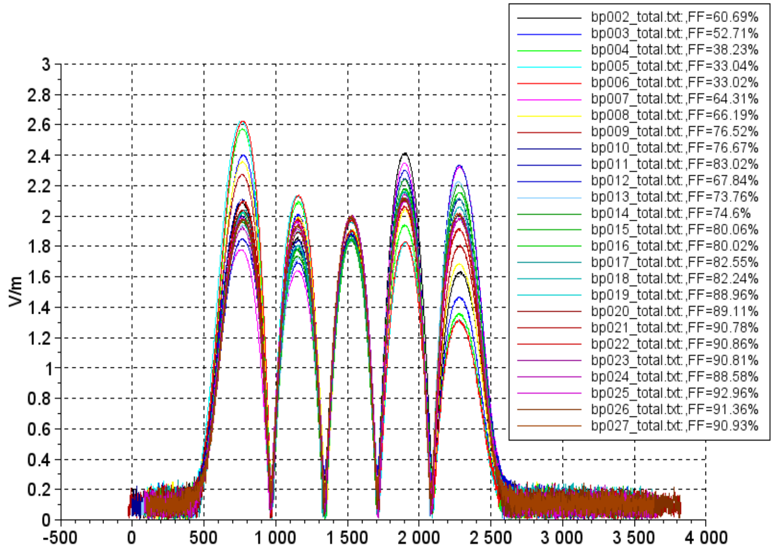




Δf calculés

erreur





CHEMICAL TREATMENT SET-UP

Vertical EP or BCP

Already used and qualified

BCP

Just modified

Used only once and need to be improved

→ Two independant installations compatible with 704 MHz cavities and one is qualified

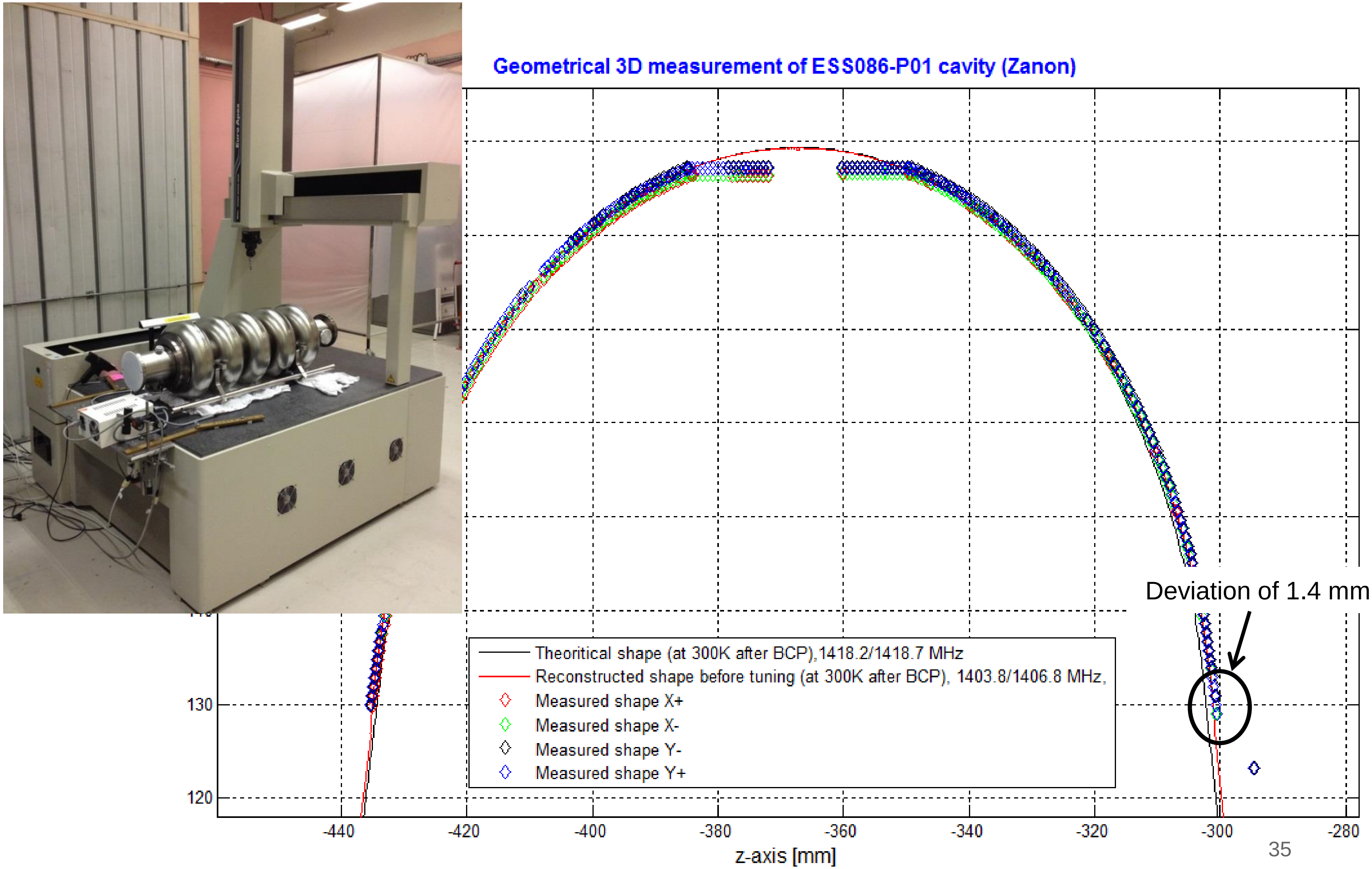
CAVITY CLEAN ROOM ASSEMBLY WITH HIGH PRESSURE RINSING

HPR 100 bars - Ultra pure water

Flanges and antenna pick-up assembly under class 100 laminar flow

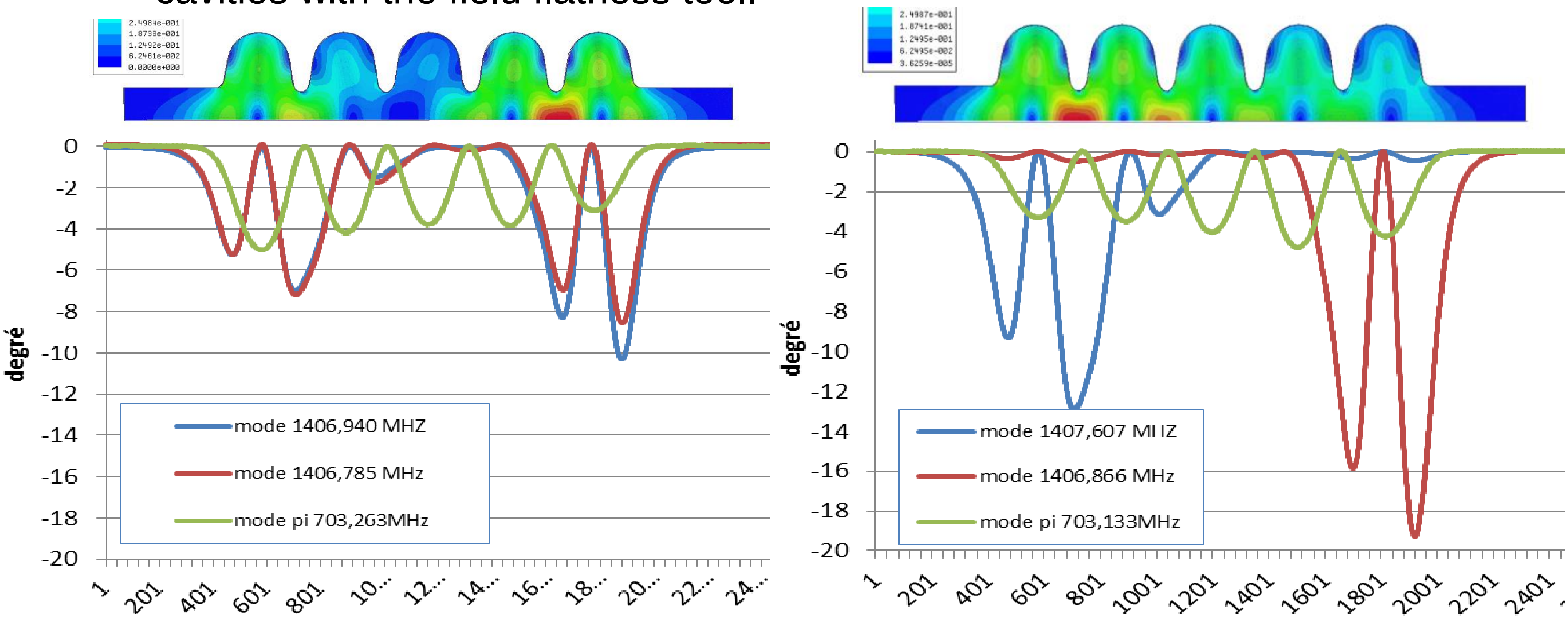
- **For the moment we have used our “historical” small clean room (Orme des Meurisiers site)**
- **New HPR in new clean room (bld.124est) hopefully ready in April2015**

3D GEOMETRICAL MEASUREMENTS



HOM BEAD PULL AND TUNING TENTATIVE

Good identification of the HOM but unsuccessful tests to reshape the cavities with the field flatness tool.



Bead pull on ESS086 P02 (03/11/2014) after +/- 0,5mm traction / compression of cell 1