DE LA RECHERCHE À L'INDUSTRIE

CEA - Saclay

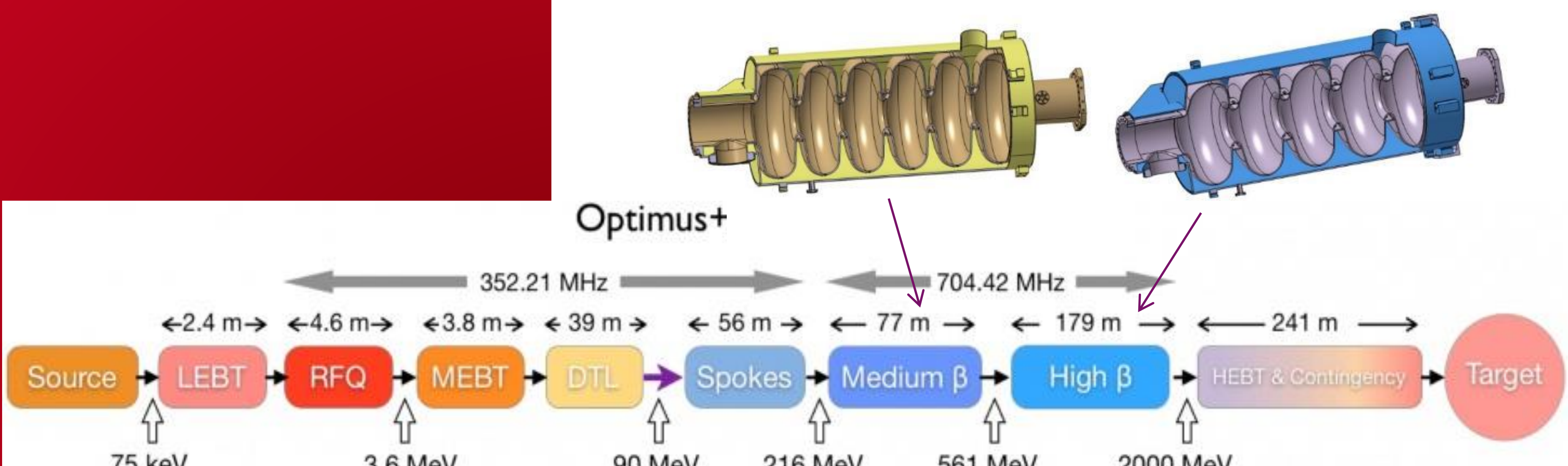
MEDIUM AND HIGH BETA ELLIPTICAL PROTOTYPE CAVITIES

TAC 13

07/04/2016

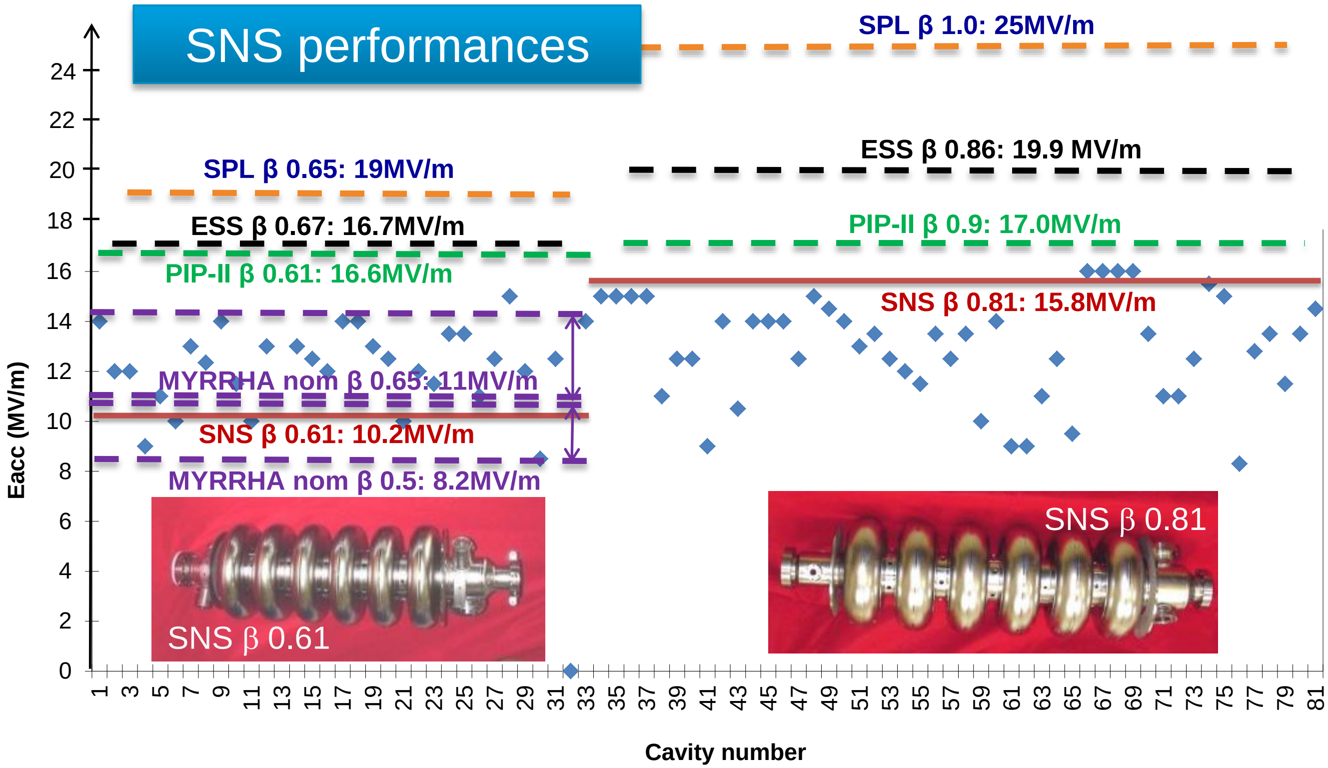
Franck PEAUGER

on behalf of the CEA Saclay Cavity team



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

OUTLINE

1) DESIGN:

- ❖ RF
- ❖ Mechanical

2) PROTOTYPING:

- ❖ Fabrication
- ❖ Surface preparation at CEA
- ❖ Test in vertical cryostat at CEA

  (and then in prototype cryomodule demonstrators ECCTD)

3) COLLABORATIONS

- ❖ Interface drawings

1) DESIGN

RF PARAMETERS

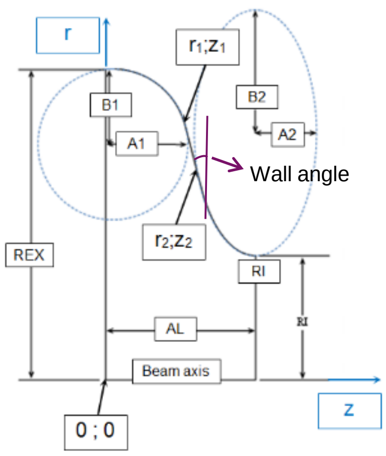
	Medium	High
Geometrical beta - β_{geom}	0.67	0.86
Frequency [MHz]	704.42	
Number of cells	6	5
Operating temperature [K]	2	
Maximum surface field in operation [MV/m]	40	44
Nominal Accelerating gradient E_{acc} [MV/m]	16.7	19.9
Accelerating length $L_{acc} = (n_{cell}.\beta_{geom}.\lambda/2)$ [m]	0.855	0.915
Nominal Accelerating Voltage $V_{acc} = (E_{acc} \times L_{acc})$ [MV]	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	$> 5 \times10^{9}$	
Cavity dynamic RF 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
B_{pk} at β_{opt} and nominal E_{acc} [mT]	80	85.6
Maximum r/Q [Ω] at β_{opt}	394	477
r/Q [Ω] at β_{geom}	367	435
Optimum beta β_{opt}	0.705	0.92
Stored energy [J] at nominal E_{acc} and β_{opt}	117.3	156.9
RF Power P_{fwd} [kW] with power coupler at Q_{ext} and β_{geom} (2)	185	250

(1) $$R_{BCS} = 2\cdot10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^2 e^{-17.67/T}$$

(2) $$P_{fwd} = \frac{V_{acc}^{\;2}}{4\cdot\frac{r}{Q}\cdot Q_{ext}}$$

Designed by:

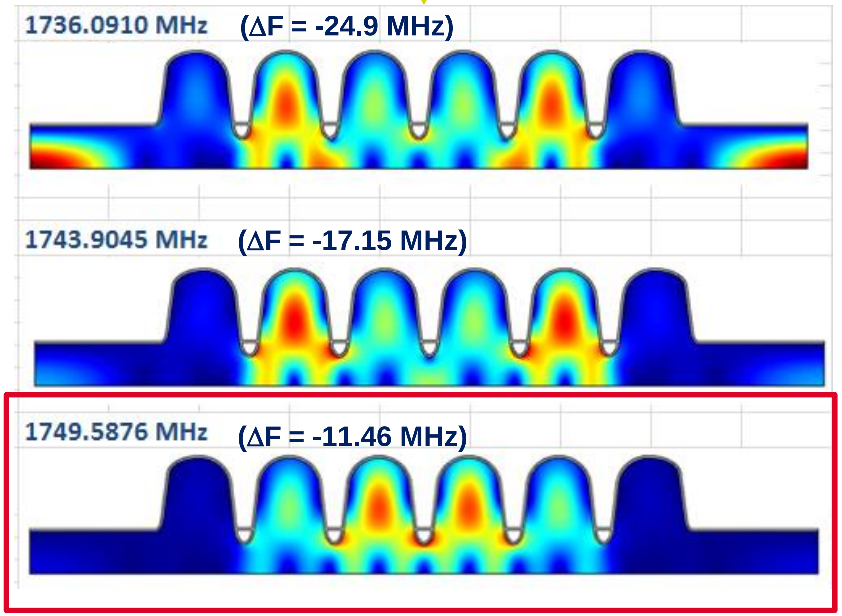
- HB: G. Devanz, J. Plouin, CEA Saclay, 2010-2011
- MB: G. Constanza, Univ. of Lund, 2013-2014

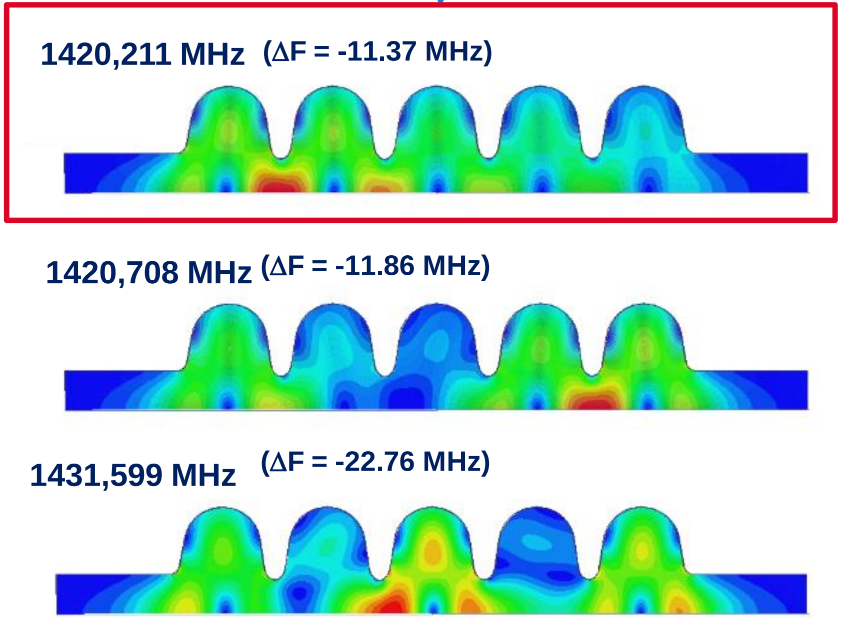


MOST DANGEROUS HIGHER ORDER MODES

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

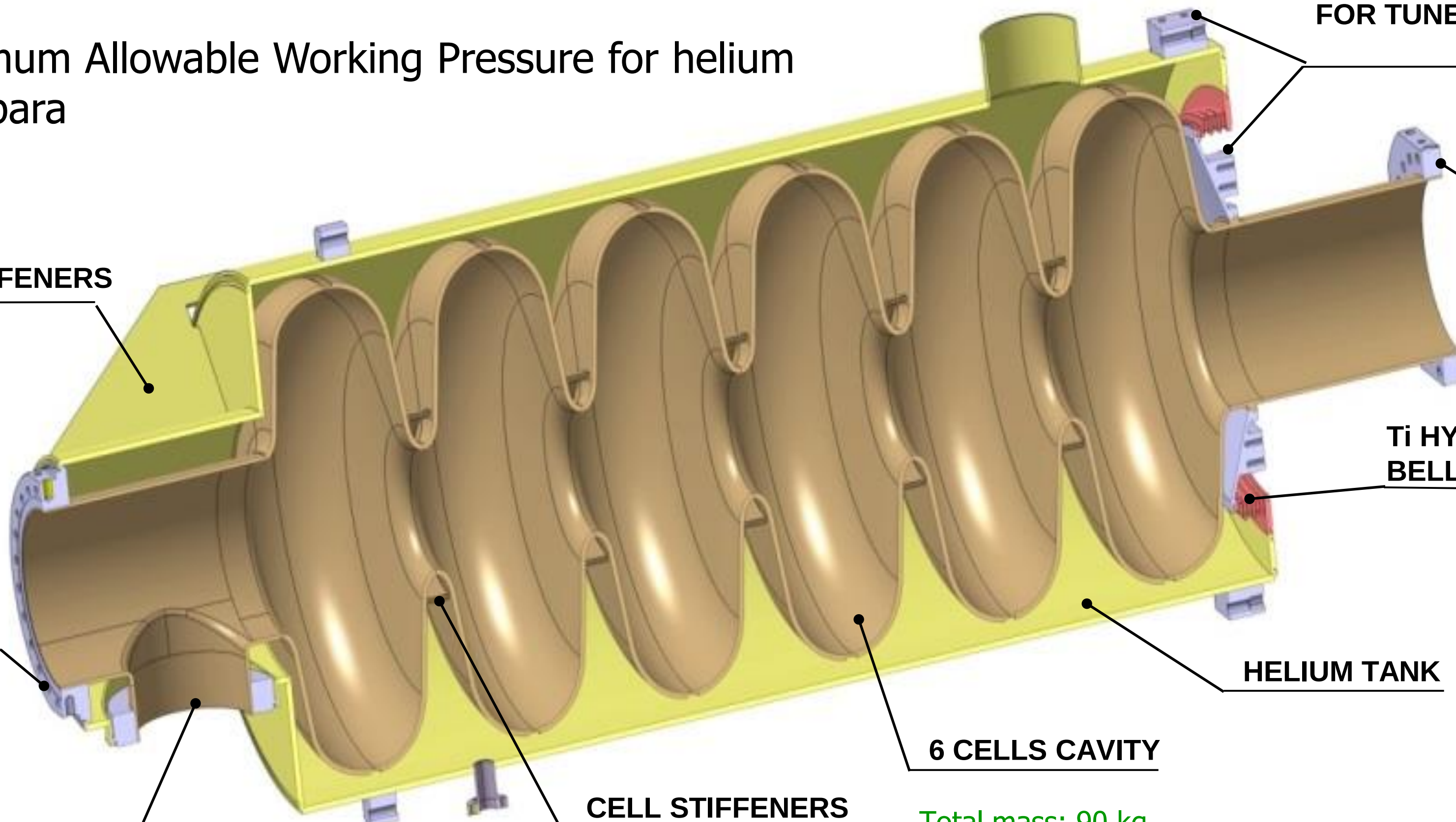




MECHANICAL FEATURES

- 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)

- Maximum Allowable Working Pressure for helium = 2.04 bara



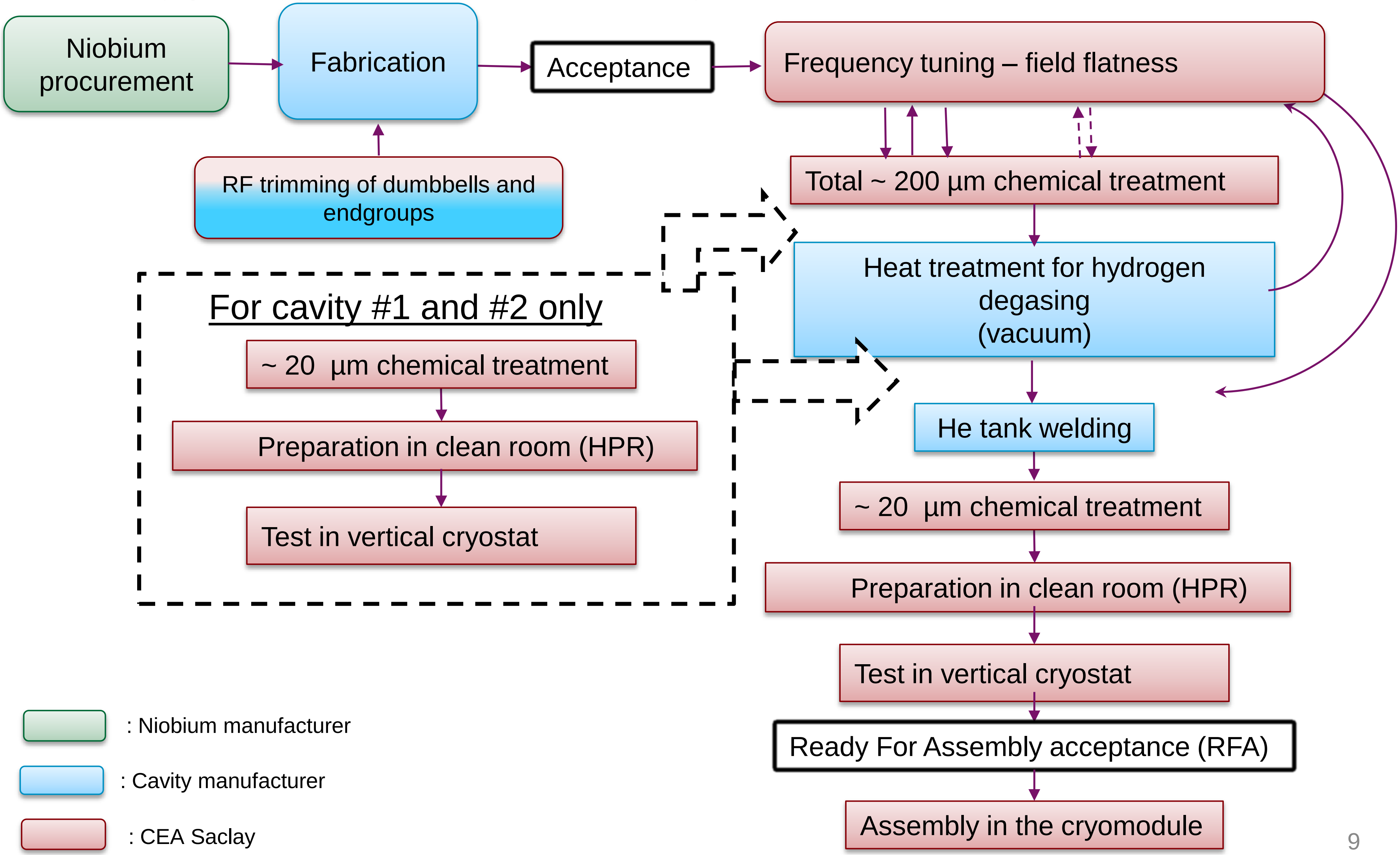
Total mass: 90 kg
Overall dimensions: 1260/1316 mm length, 500 mm diameter

Most of the elements are identical for medium and high beta

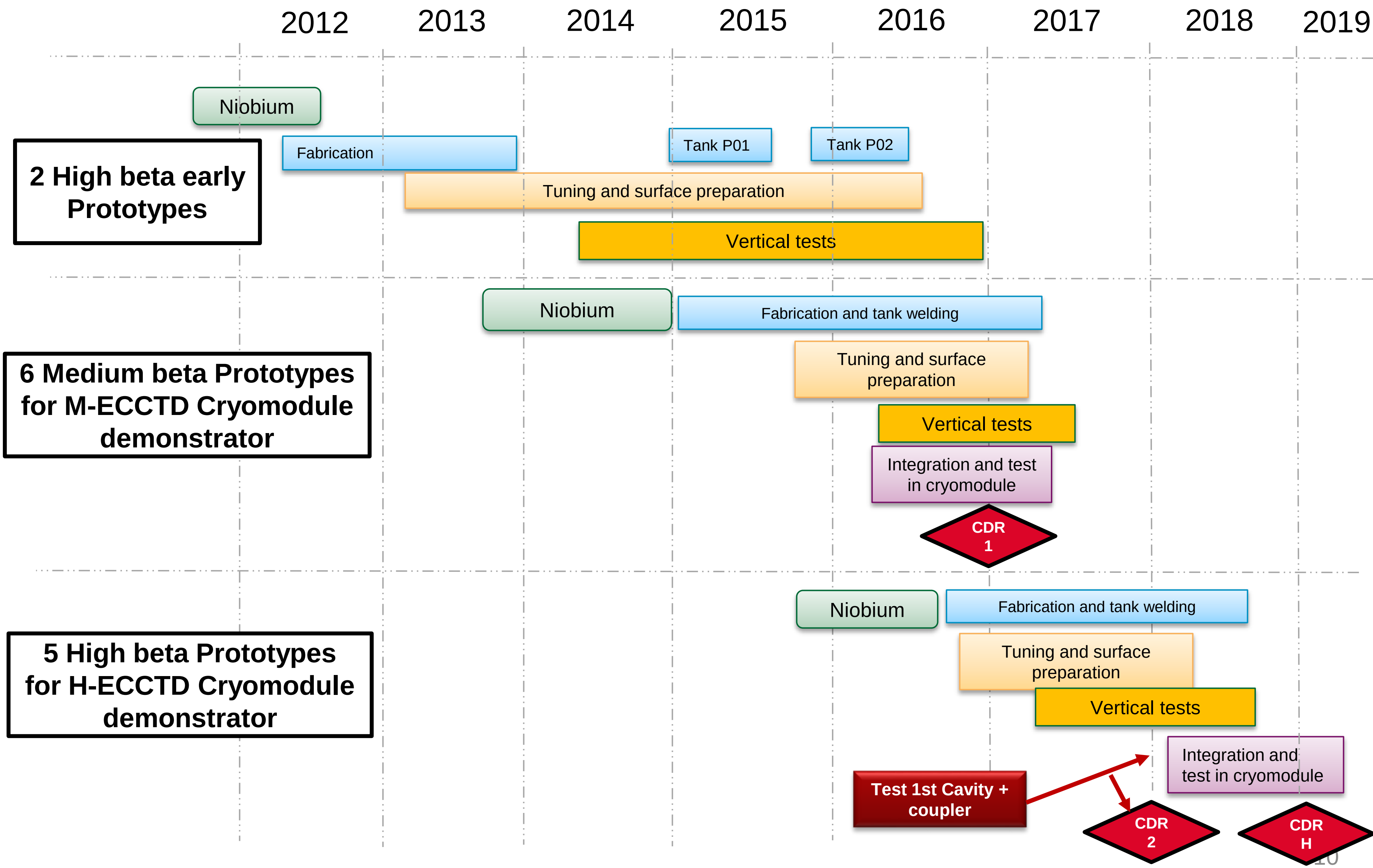
2) PROTOTYPING

CAVITY FABRICATION & PREPARATION BEFORE CRYOMODULE INTEGRATION

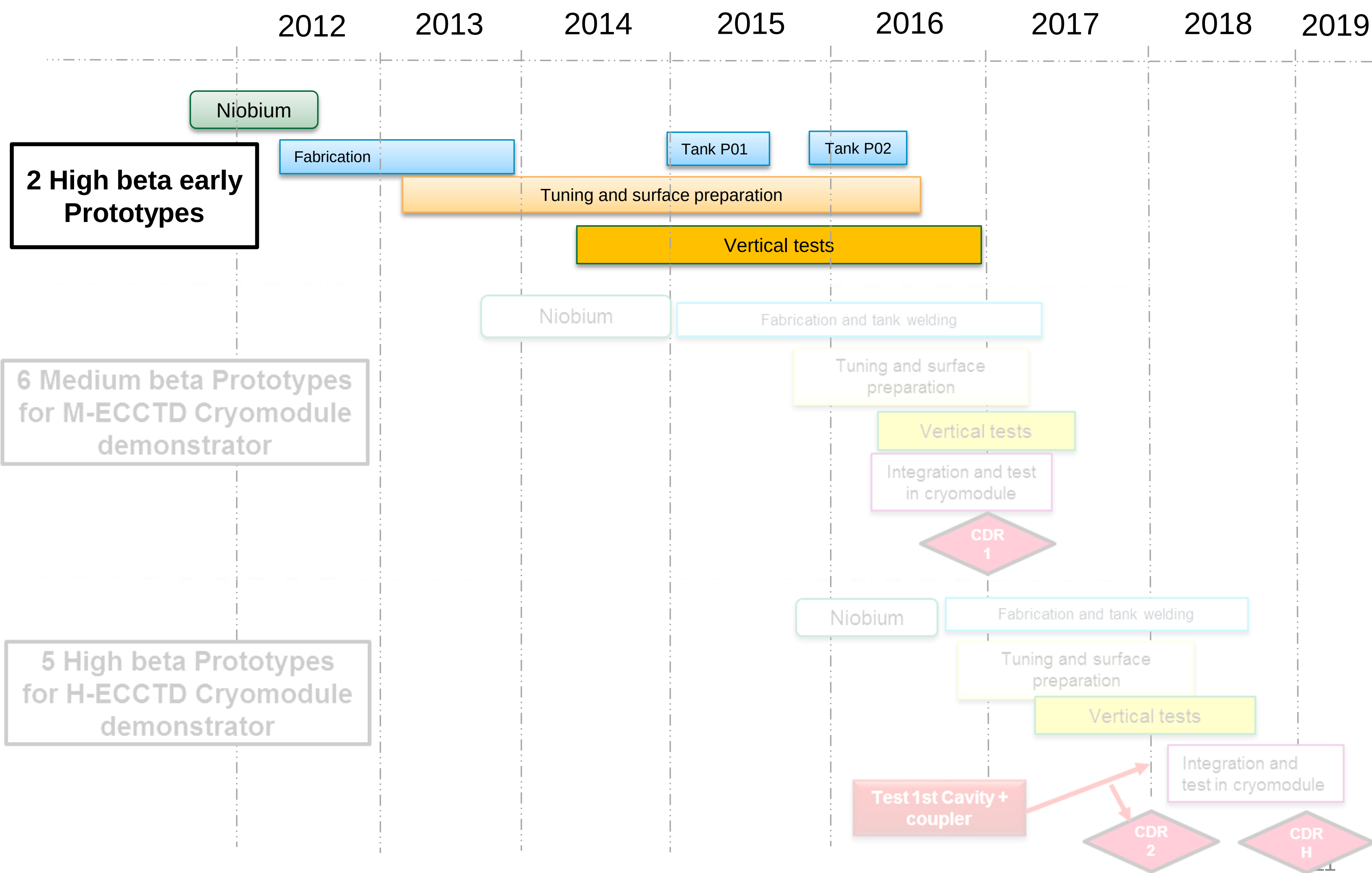
For cavity prototypes used in the Technological demonstrators



DEVELOPMENT PLAN OF ELLIPTICAL PROTOTYPES



DEVELOPMENT PLAN OF ELLIPTICAL PROTOTYPES



THE TWO HIGH BETA « EARLY PROTOTYPE » CAVITIES

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

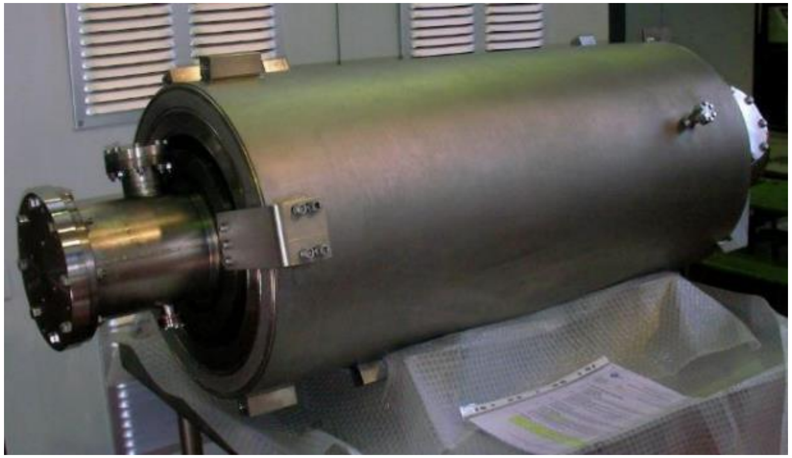
« ESS086-P01 » manufactured by E. ZANON
F_π = 703.553 MHz
Field flatness: 86%

« ESS086-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

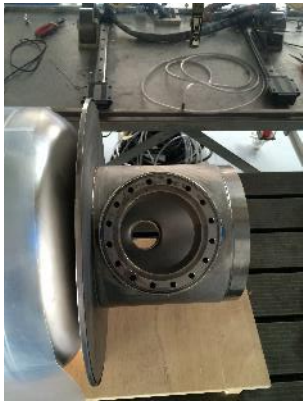
TANK INTEGRATION

ESS086-P01 (ZANON)



- ΔF = +9 kHz only due to tank welding
- Pressure and leak test done successfully
- Delivered at CEA in Feb. 2015

ESS086-P02 (RI)



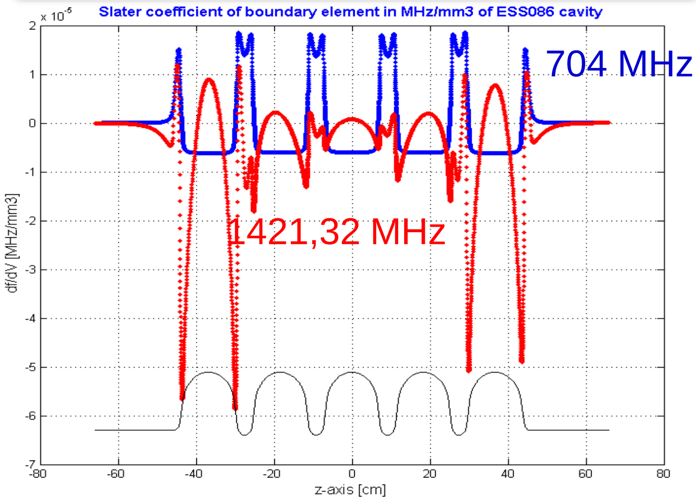
- Tank welding in progress

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

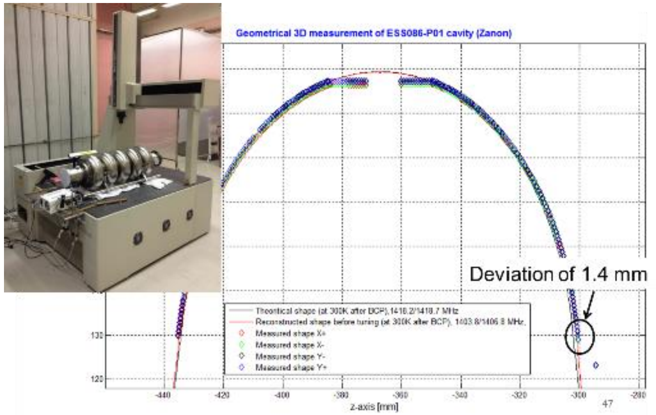
Slater coefficient analysis which represents frequency sensitivity to volume changes:



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

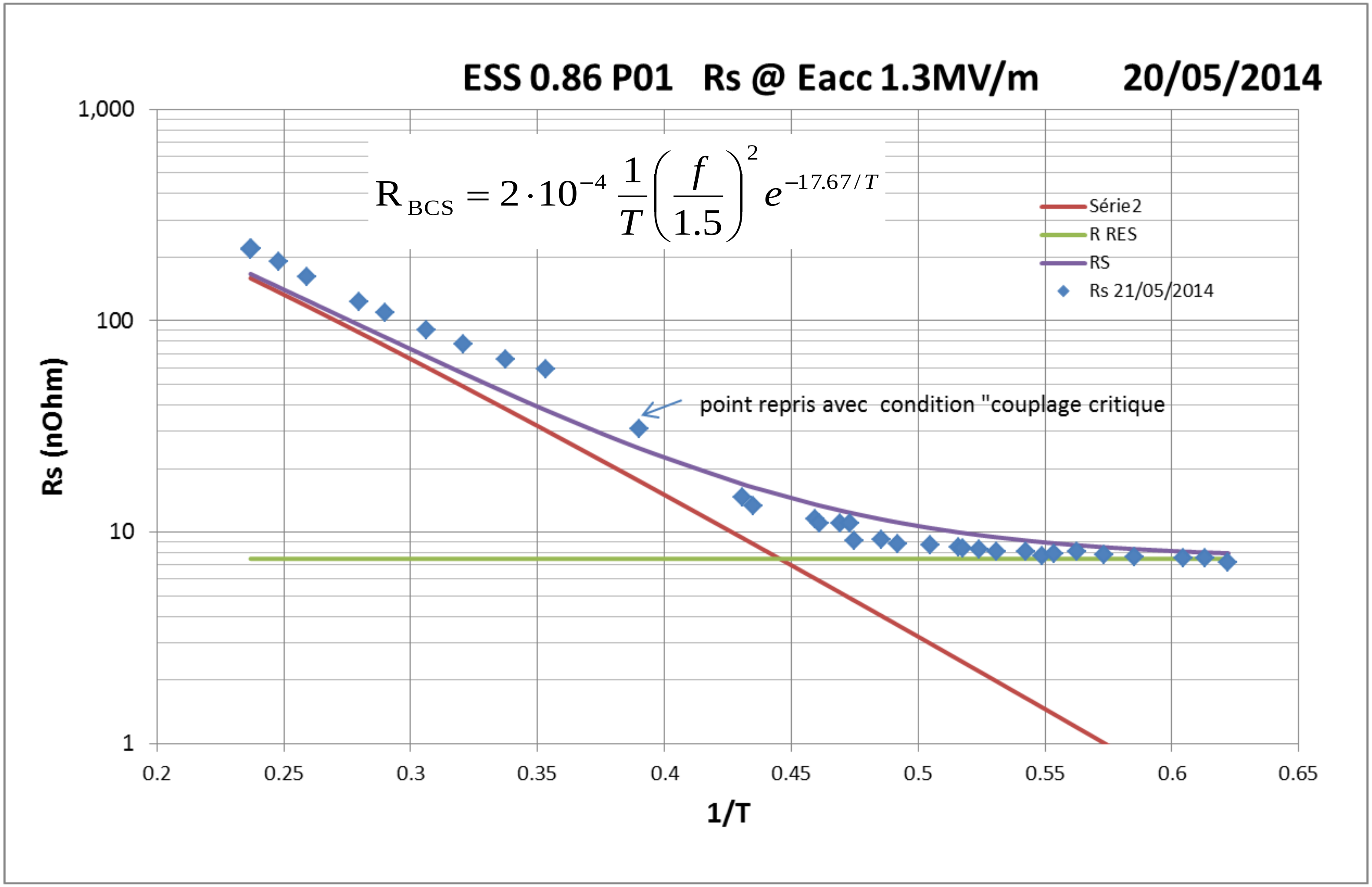
Design (at 300K)	Measured on ESS086-P01	Calculated with measured shape (HFSS)	Measured on ESS086-P02
1418.178	1402.254	1403.8	1407.848
1418.674	1404.666	1406.8	1408.258

⇒ 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



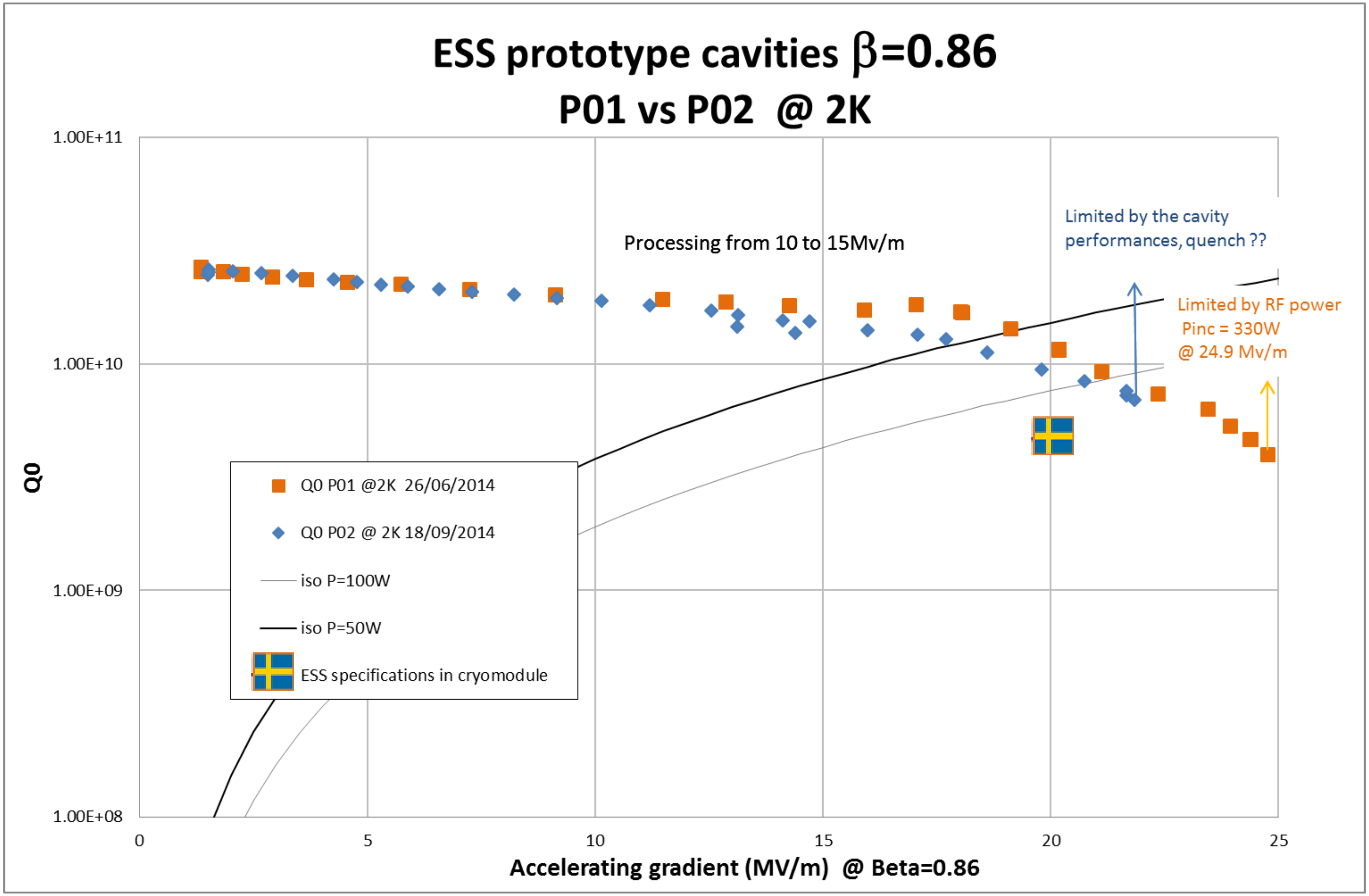
➢ On future cavities, better control of cell shapes and better selection process have been implemented

SURFACE RESISTANCE



- Measured residual resistance: Rres = 7.5 nΩ, 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**

HEAT TREATMENT AT CERN IN OCTOBER 2014

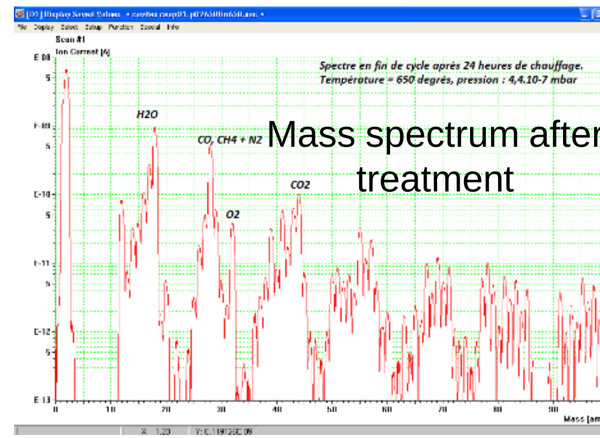
- Not possible at ZANON because the oven was very busy with XFEL cavities
- IPNO not ready yet

→ « grand four » at CERN, already qualified with SPL type cavities

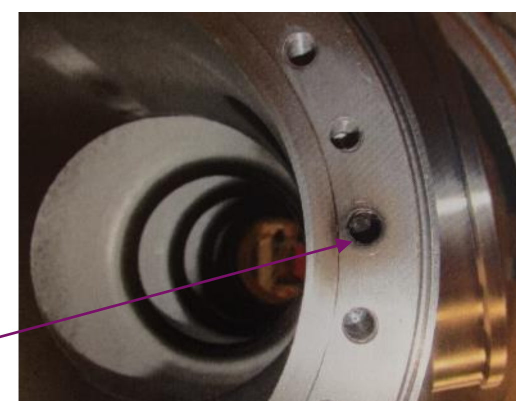
650 °C under vacuum during 24 hours

Degreasing before treatment

« grand four » below

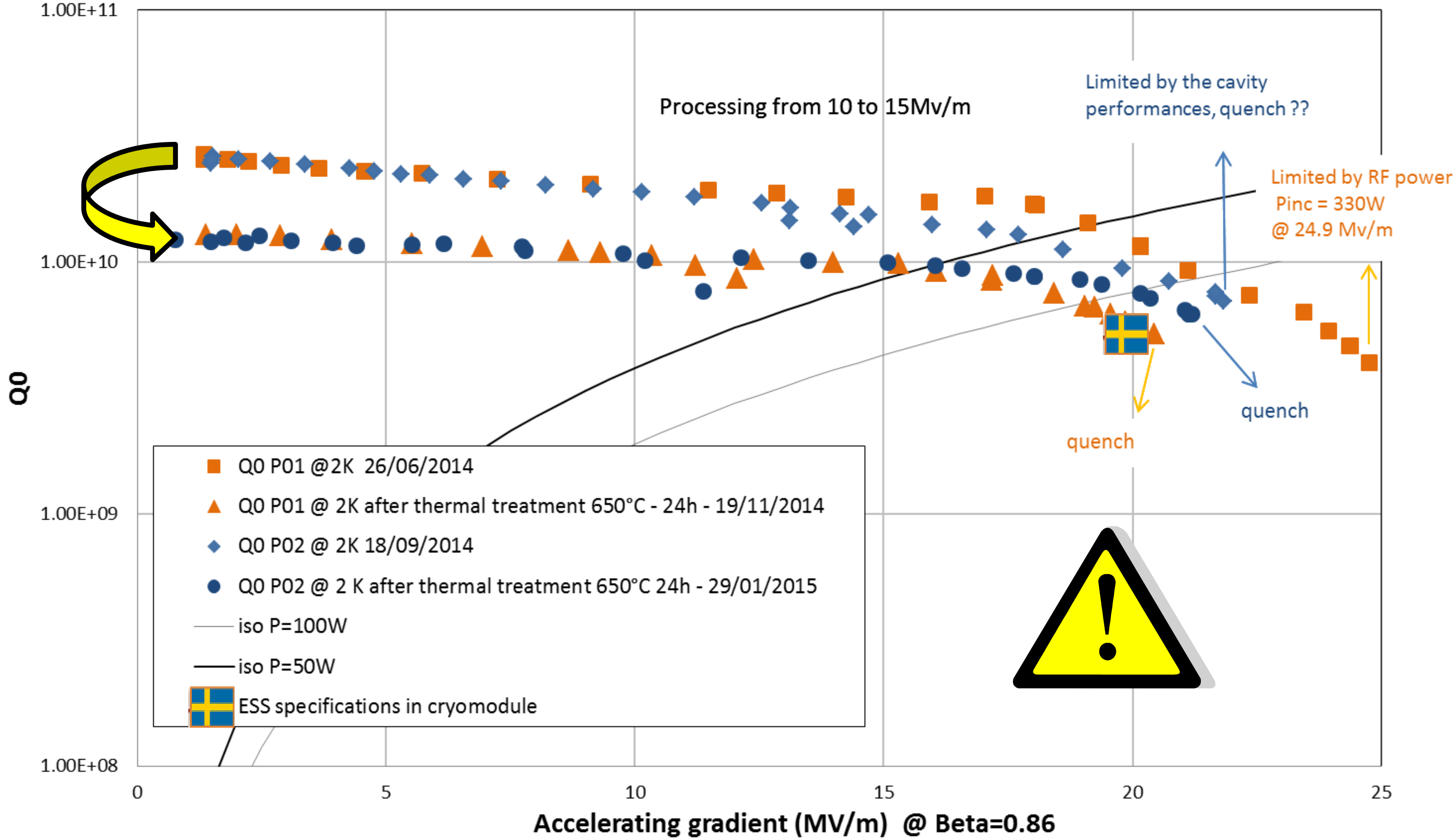


Mass spectrum after treatment



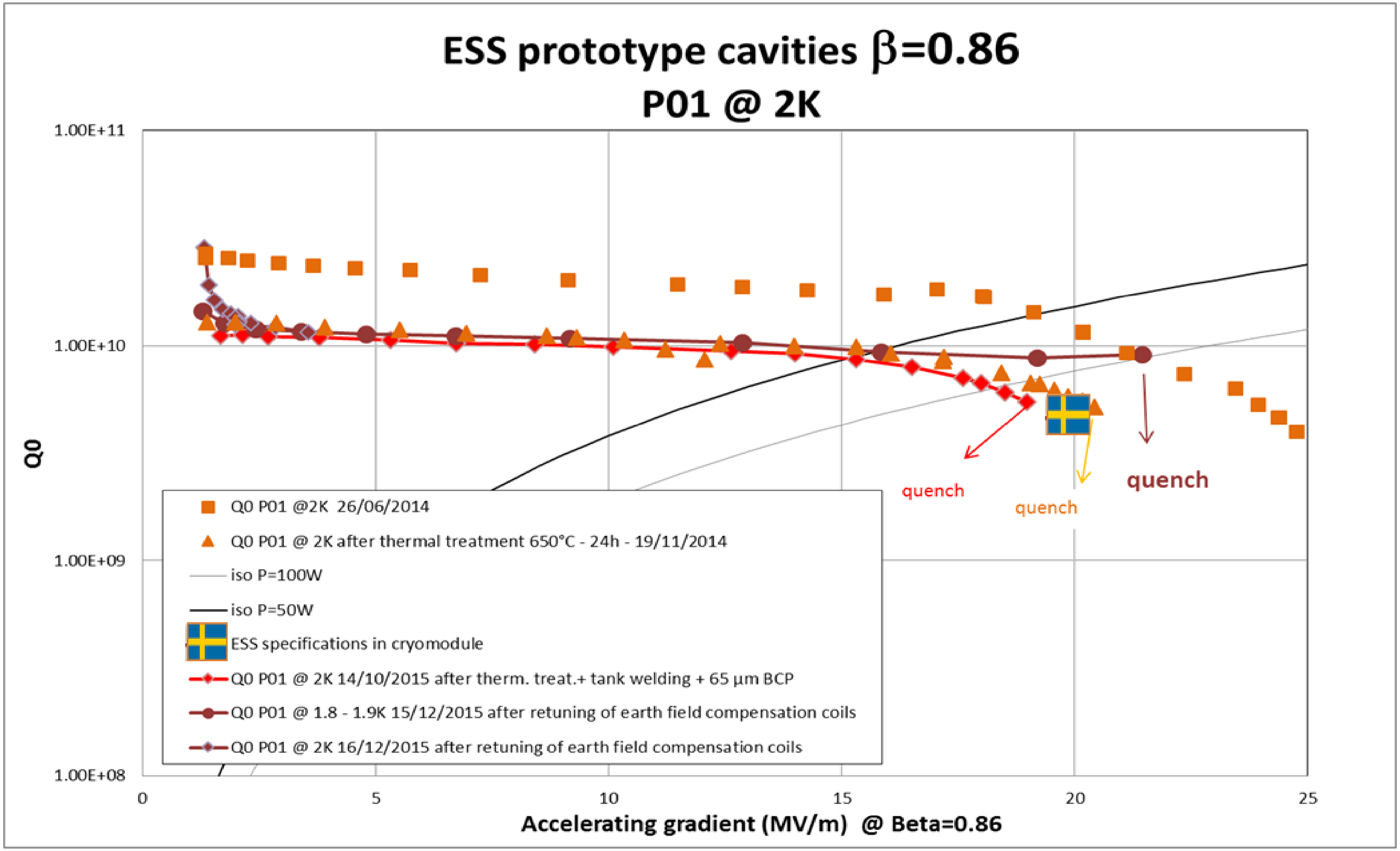
Blind hole not well rinsed ?

VERTICAL TEST RESULTS AT 2K



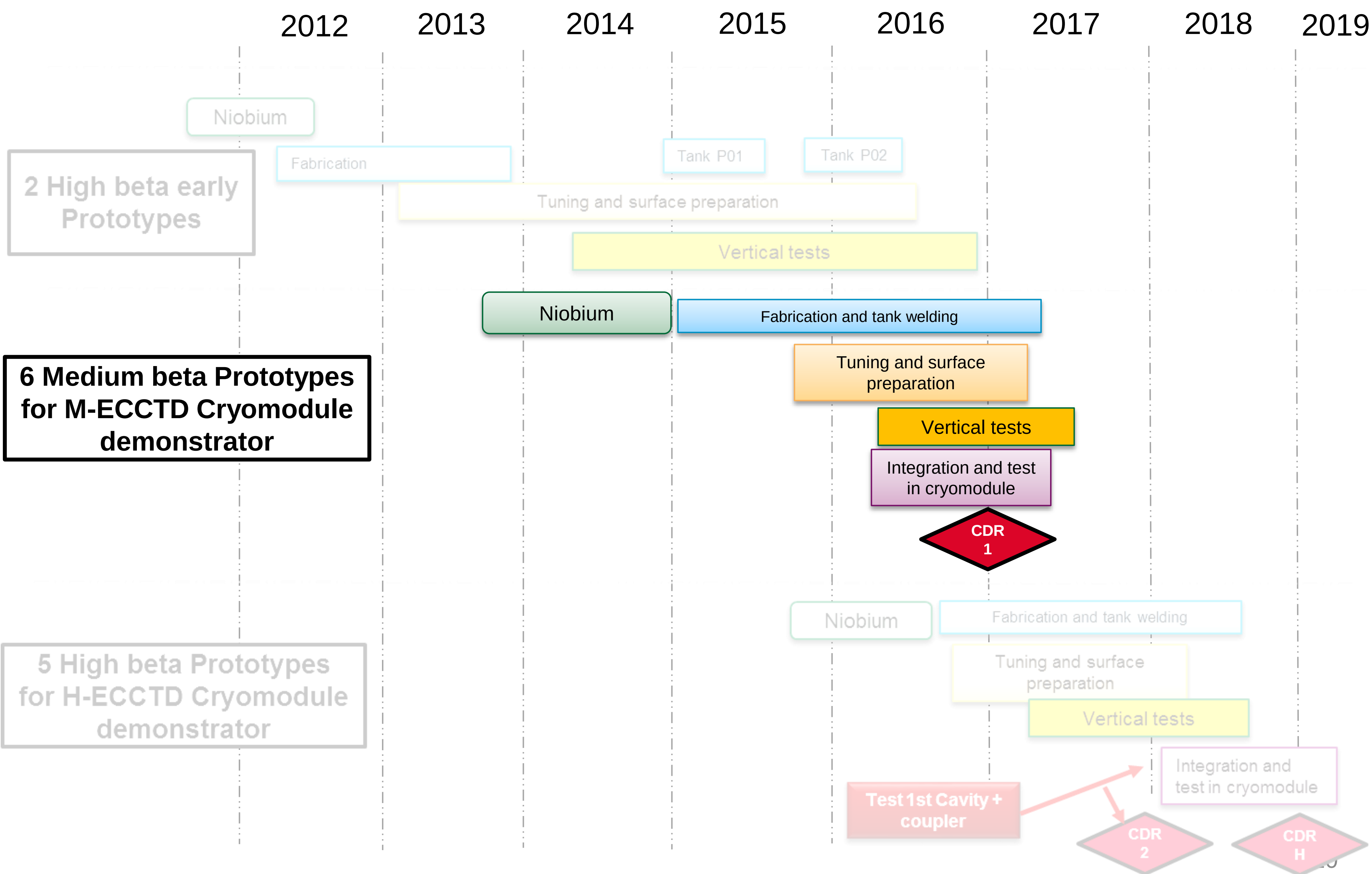
- Slight degradation of the performances after thermal treatment (pollution?)
- Surface resistance doubled (20 nohm)

VERTICAL TEST RESULTS AT 2K



- After 65 µm BCP, surface resistance recovered at low field but still Q0 degradation at gradient
- Cavity put in second priority (after medium beta cavities)

DEVELOPMENT PLAN OF ELLIPTICAL PROTOTYPES



THE SIX MEDIUM BETA PROTOTYPES FOR M-ECCTD

- ⇒ Niobium from Tokyo Denkai, 4.3 mm thickness
- ⇒ Contract awarded by E. ZANON
- ⇒ Kick-off in Sept. 2014

Half cells

selection

Dumbbells

selection

Cavity n°1 (ESS067-P01)

Cavity n°2 (ESS067-P02)

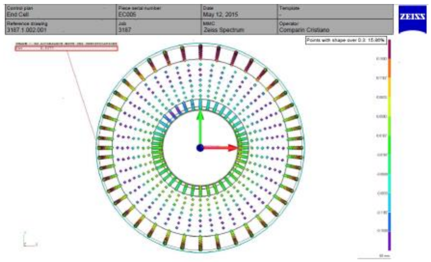
…

FROM HALF CELLS TO CAVITY

Enrico Cenni

- New selection process to reach the accelerating mode frequency, the cavity length and the HOM frequencies at the same time

Stage	Controls criteria	Selection criteria
Half cells	• 3D measures • Zero mode frequency • HOM	Less than 20% of points out of tolerance
Dumbbells & End groups	• 3D measures • Zero and Pi mode frequency • HOM	Bethe formula
Cavity	• Trimming • Passband modes frequency • HOM	Trim and pull formula

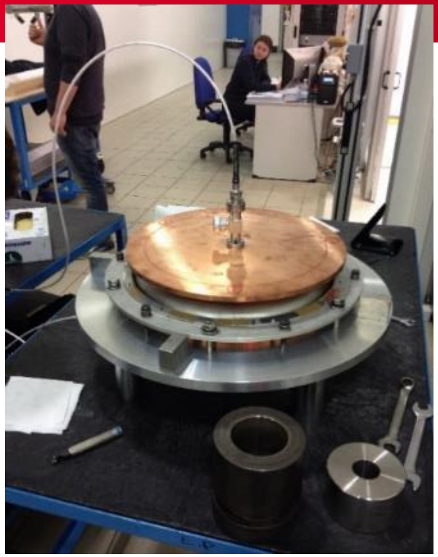


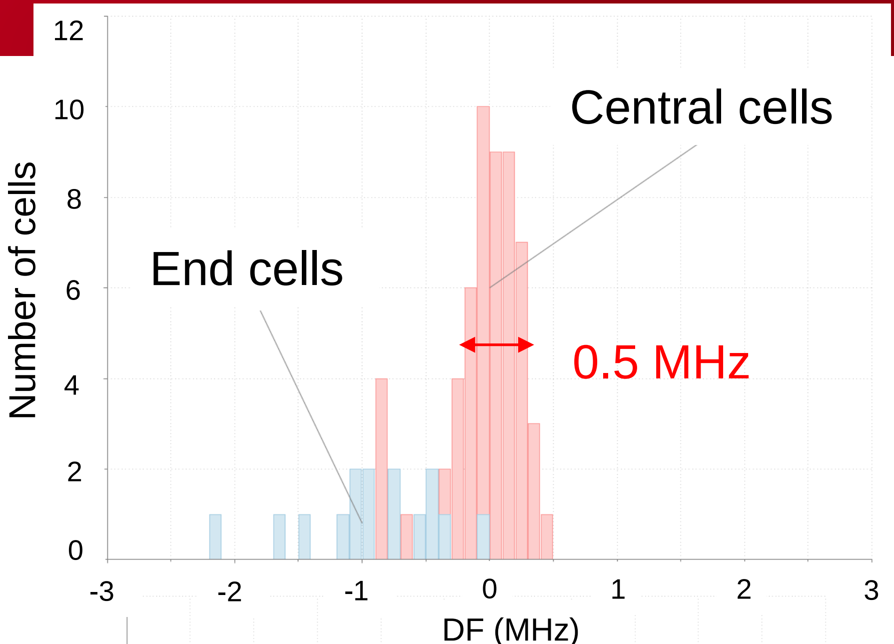
$$f_{DB}{}^2 = \frac{1}{2}(f_a^2 + f_b^2) - K f_0{}^2 \pm \sqrt{\frac{1}{4}(f_a^2 - f_b^2)^2 + K^2 f_0^4}.$$

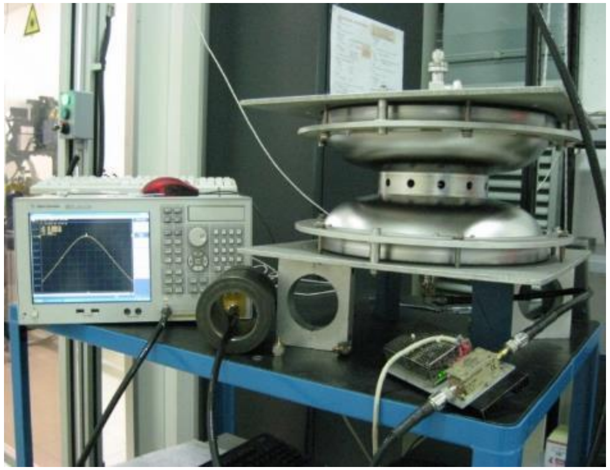
$$t = \frac{dF + S_A(L_0 - L_f)}{S_t + S_A}$$

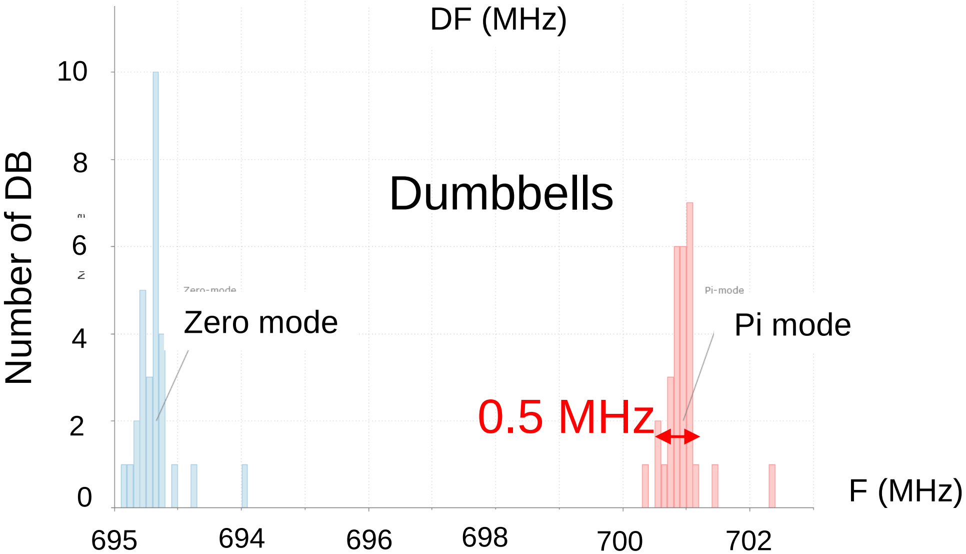
- Best DB are chosen and placed at the center of the cavity where the 5th harmonic $\pi/6$ mode has stronger EM field
- The first two cavities where manufactured within 0.3 mm length and frequency within 150 kHz computed values
- Improvement shall be done into predicting frequency change due to chemistry (300 kHz/µm measured instead of 350 kHz/µm)
- Studying the possibility to replace detailed 3D measurements by RF-HOM measurements

HALFCELLS AND DUMBBELLS: RF MEASUREMENTS



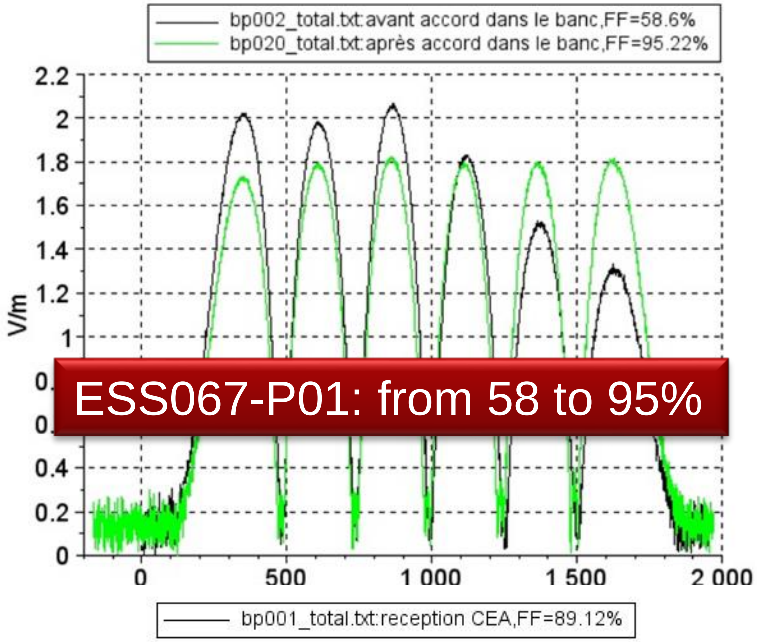


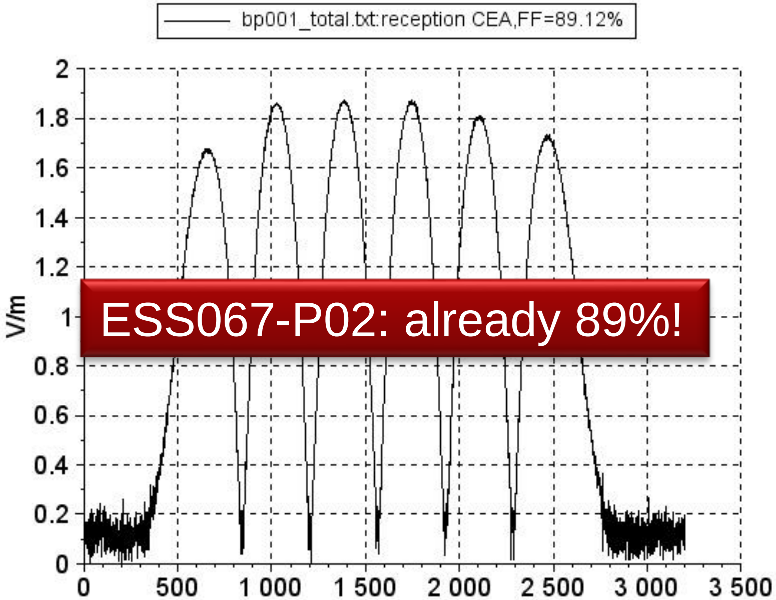


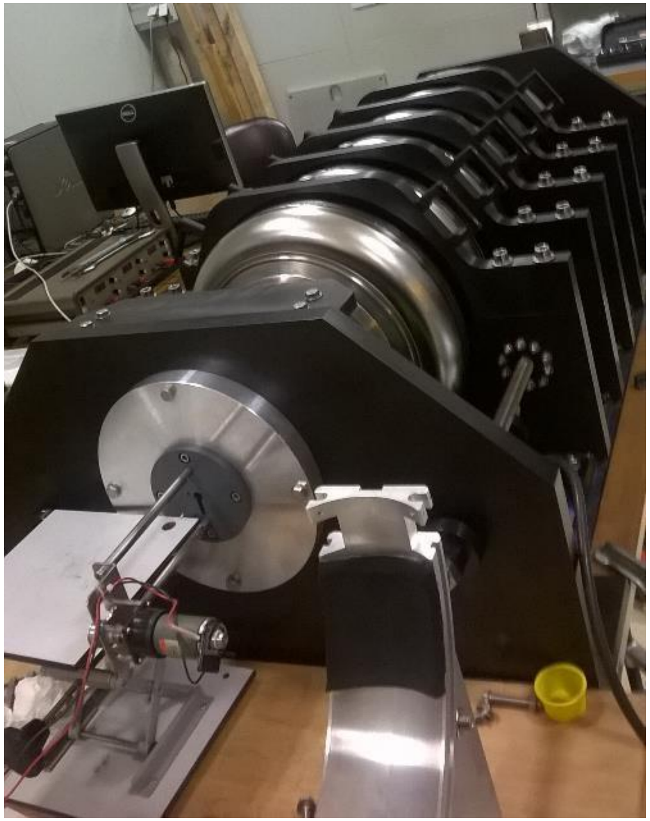


- The frequency spread is conserved between halfcells and dumbbells (~0.5 MHz)
- The larger spread on end cells is due to poor statistic and learning curve. It has no important impact.

FIELD FLATNESS TUNING





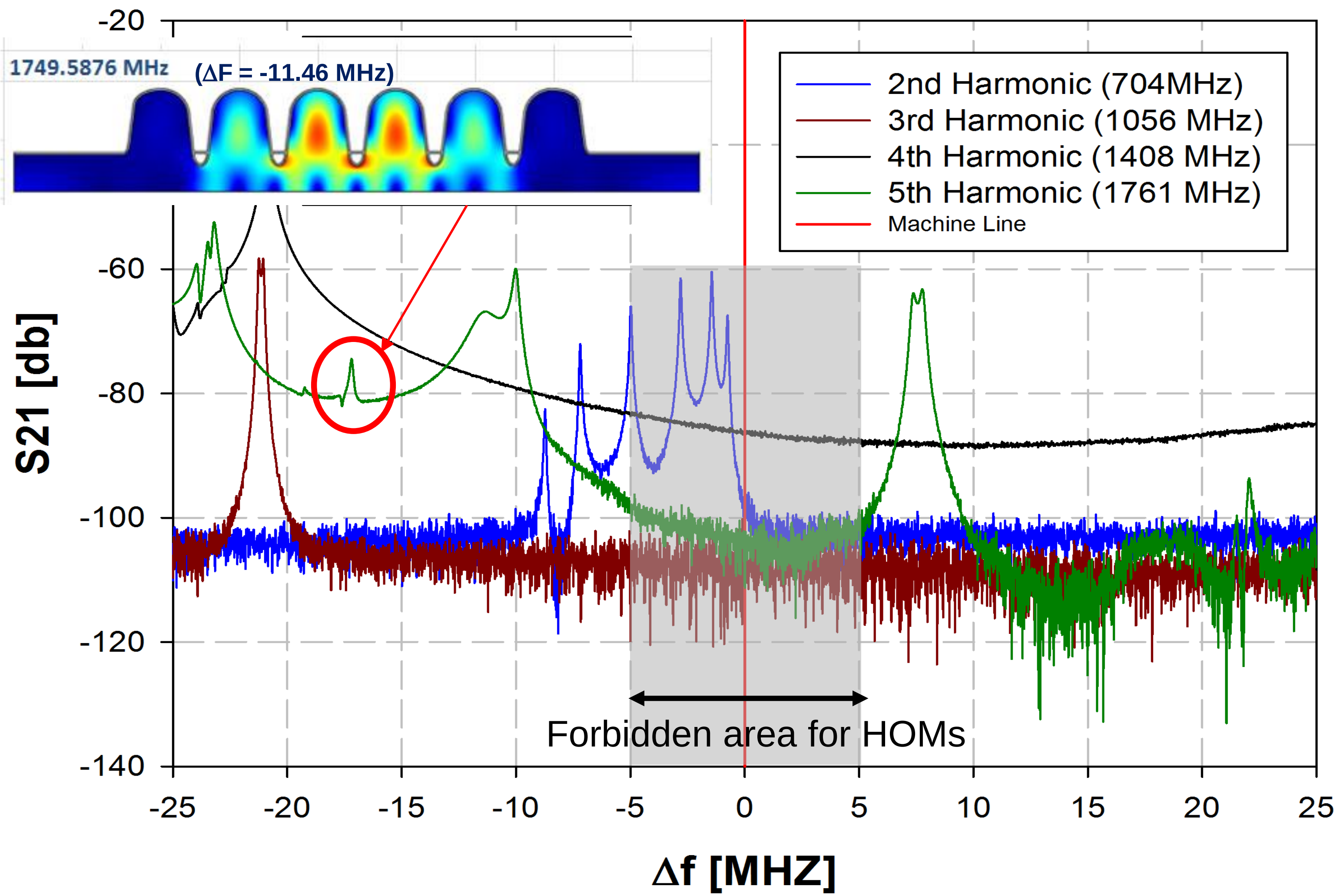


Tuning sensitivity [kHz/mm]	Simulation	Measured
	211.26	**210.8**

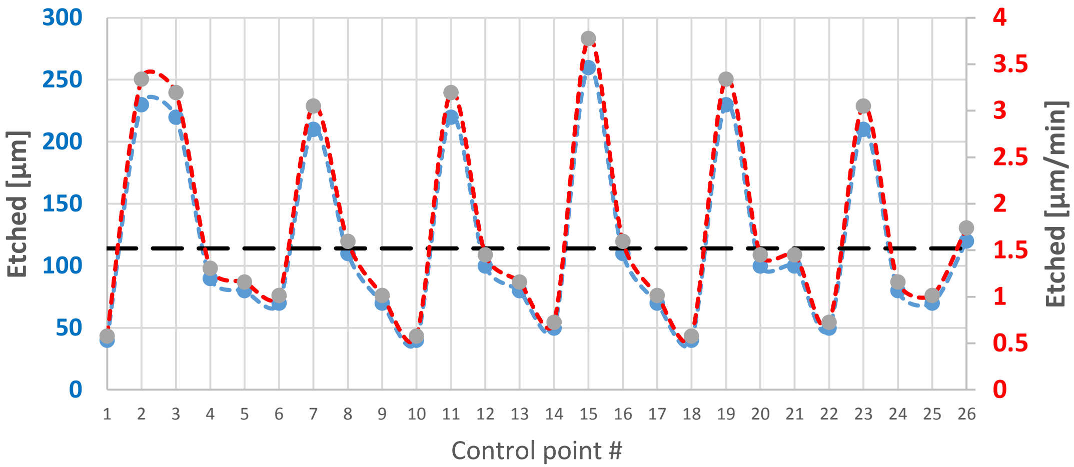
HOMS AND MACHINE LINES

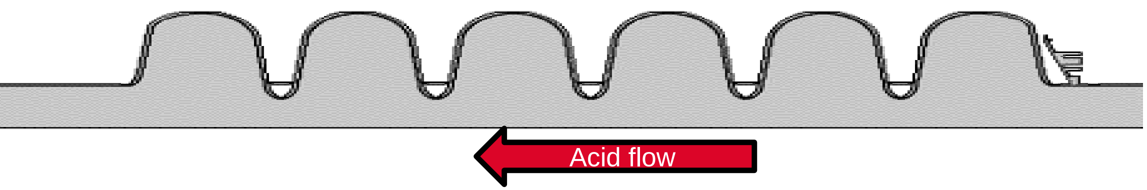
ESS067-P01

S21 Measure
Medium-β pre-tuning results



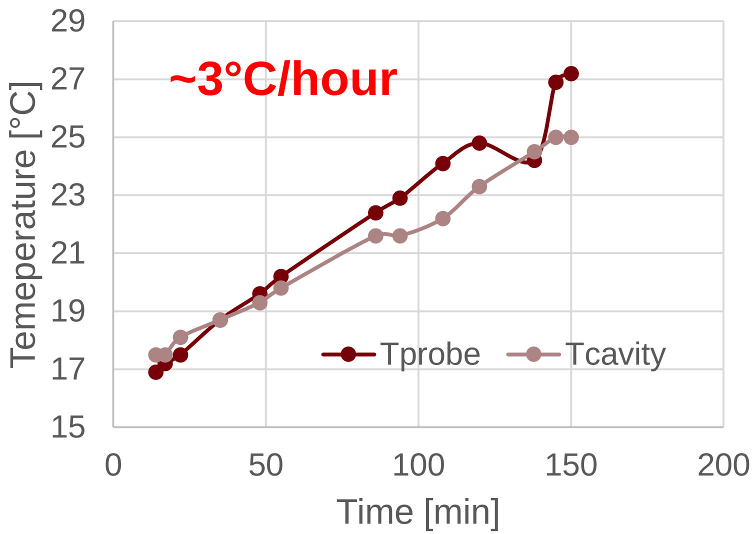
CHEMICAL TREATMENT (BCP) WITH ACID MIXTURE 1:1:2.4



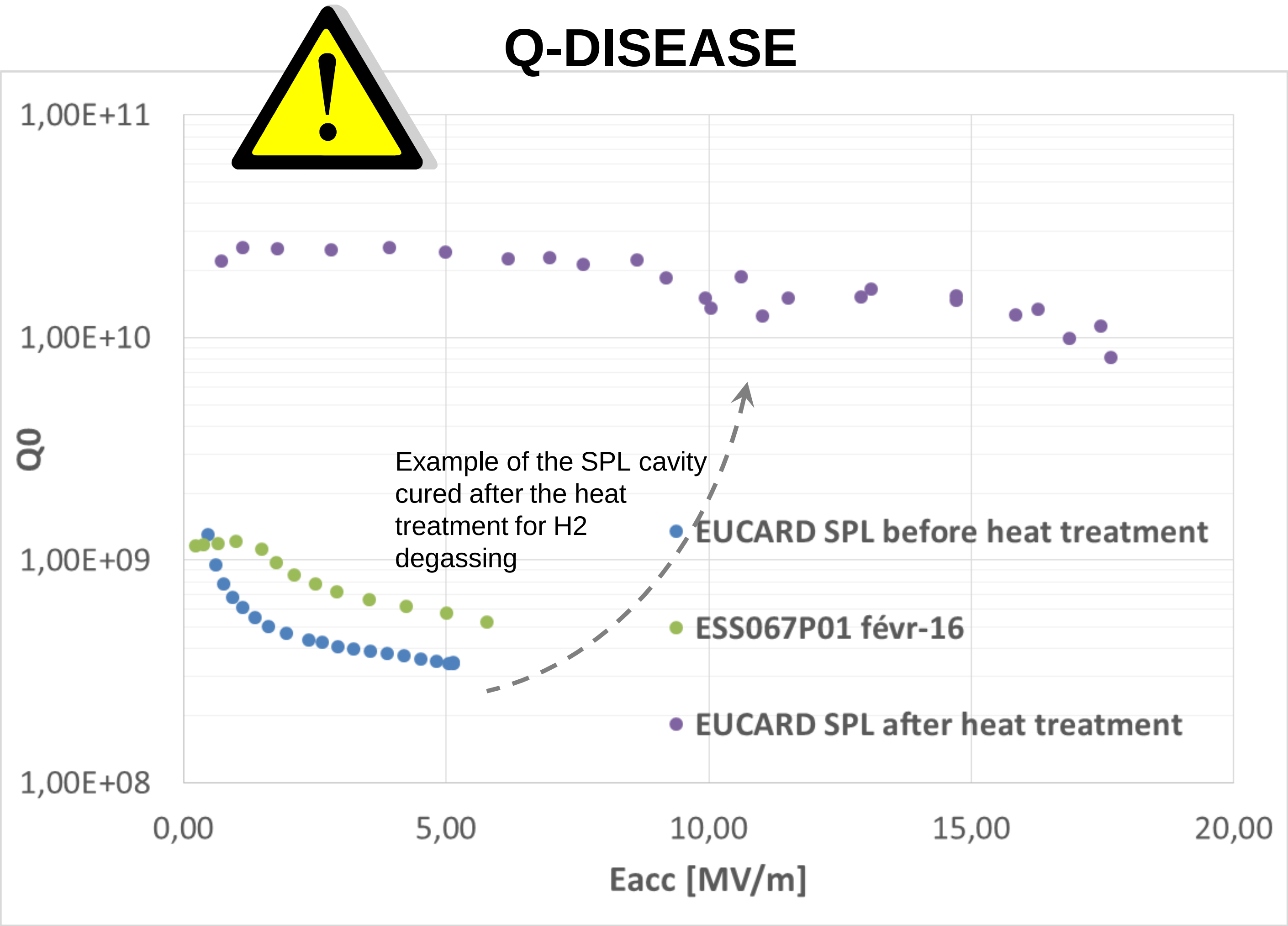


Automatic BCP treatment

Rinsing after the BCP



Q-DISEASE

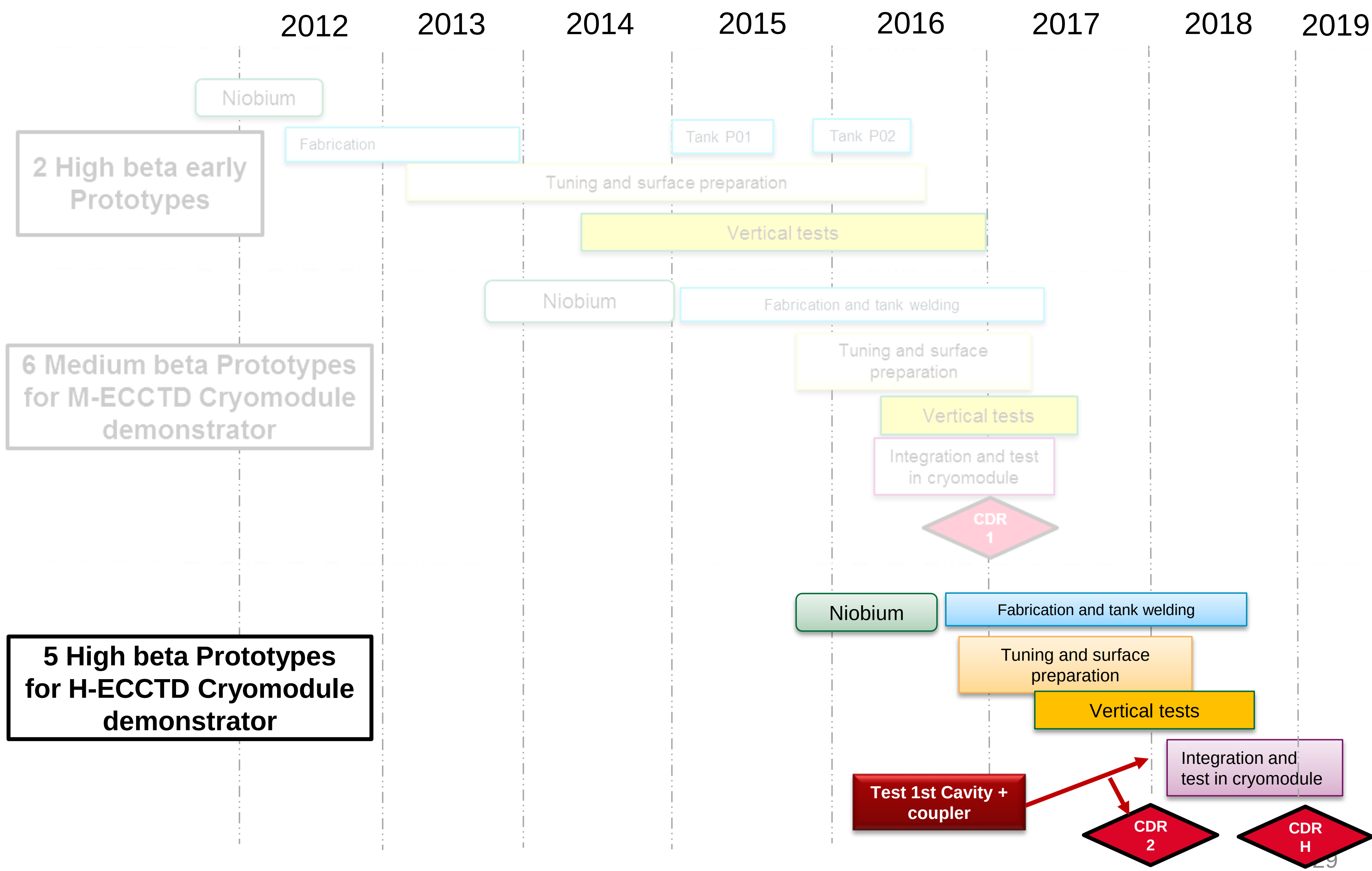


- Hypothesis of the Q-disease: high hydrogen concentration
- The ESS067-P01 has not been heat treated yet and should make significant progress after treatment (like the SPL cavity)

PLANNING OF THE MB CAVITIES

	d	ESS0687-P01	ESS0687-P02	ESS0687-P03	ESS0687-P04	ESS0687-P05	ESS0687-P06
Trimming + Final welding @ EZ + FAT	2+1 sm	ok	08/02 - 11/03	12/05 - 01/06	1/06 - 22/06	22/06 - 12/07	13/07 - 02/08
Conditionning/transport to Saclay	1 sm	ok	18/03	yes	yes	yes	yes
Reception tests @ CEA (SAT)	1 sm	ok	21/03 - 25/03	08/06 - 14/06	29/06 - 05/07	20/07 - 26/07	10/08 - 23/08
Field Flatness 1	2 sm	ok	29/03 - 07/04	16/06 - 01/07	07/07 - 20/07	27/07 - 09/08	24/08 - 08/09
BCP_200	2 sm	18/01 - 09/02	08/04 - 22/04	01/07 - 18/07	21/07 - 04/08	10/08 - 31/08	09/09 - 25/09
HPR + Cleanroom assembly	1 sm	09/02 - 16/02	27/04 - 04/05	no	no	no	no
Mounting on cv-insert	2 j	17/02 - 18/02	11/05 - 15/05	no	no	no	no
CV-test n°1	1 sm	18/02 - 26/02	16/05 - 22/05	no	no	no	no
Heat treatment incl. transport @ EZ	2 sm	03/03 - 15/04	23/05 - 05/06	19/07 - 02/08	05/08 - 18/08	01/09 - 14/09	26/09 - 09/10
Field Flatness 2: verification (+Ajust.)	1 j	15/04	06/06	03/08	19/08	15/09	10/10
Flash BCP	3 j	18/04 - 20/04	no	no	no	no	no
HPR (with ESS067 nozzle)	3 j	21/04 - 25/04	no	no	no	no	no
Cleanroom assembly	2 j	26/04 - 27/04	no	no	no	no	no
Mounting on cv-insert	2 j	28/04 - 29/04	no	no	no	no	no
CV-test n°2	1 sm	02/05 - 12/05	no	no	no	no	no
Transport	1 sm	yes	no	no	no	no	no
He-tank welding	1 ms	18/05 - 17/06	04/07 - 02/08	03/08 - 31/08	01/09 - 27/09	28/09 - 26/10	26/10 - 22/11
Transport	1 sm	yes	yes	yes	yes	yes	yes
Reception tests (SAT)	1 sm	24/06 - 29/06	10/08 - 16/08	07/09 - 13/09	05/10 - 11/10	02/11 - 08/11	30/11 - 06/12
Flash BCP	3 j	04/07 - 06/07	22/08 - 24/08	14/09 - 19/09	12/10 - 17/10	09/11 - 14/11	07/12 - 12/12
HPR (with ESS067 nozzle)	3 j	07/07 - 11/07	25/08 - 29/08	20/09 - 22/09	18/10 - 20/10	15/11 - 17/11	13/12 - 15/12
C/R assembly	1sm/3j	12/07 - 13/07	30/08 - 01/09	23/09 - 27/09	21/10 - 25/10	18/11 - 22/11	16/12 - 20/12
Mounting on cv-insert	2 j	18/07 - 19/07	02/09 - 05/09	28/09 - 29/09	26/10 - 27/10	23/11 - 24/11	21/12 - 22/12
CV-test n°3	1 sm	20/07 - 27/07	06/09 - 13/09	30/09 - 07/10	28/10 - 08/11	25/11 - 02/12	23/12 - 05/01

DEVELOPMENT PLAN OF ELLIPTICAL PROTOTYPES



NIOBIUM AND CAVITY PROCUREMENT

NIOBIUM:

- **TOKYO DENKAI have won the call for tender for the supply of the niobium for the 5 superconducting cavities**
- **The order include spare parts for the cavity manufacturer**
- **The contract have been signed by the company**

Tokyo Denkai Co., Ltd.
3-20, Higashisuna 1-chome, Koto-ku
Tokyo. 136-0074, Japan
TEL: +81-3-3648-2165
FAX: +81-3-3699-7063

Messrs.: CEA Saclay
ref. CEA-ESS-CMD-ST-0002 A
14B-0195

Quotation No.: TDCQ16010801Rev
Quotation Date: January 8, 2016

Quotation

Settled part — Niobium sheets, rods and thick tubes.

Item	Usage	RRR	Dimensions (mm)					Price/Unit [EURO]	Quantity [pcs]	Amount [EURO]
			Length	Width	Thickness	øin	øout			
High beta 5 cells cavity, quantity 5	Stiffeners	> 250	555	220	4.0	---	---		5	
	Half cells	> 250	500	500	3.9	---	---		50	
	Beam tubes	> 250	520	480	3.2	---	---		5	
	Coupler port	> 250	370	345	3.2	---	---		1	
	Pick-up	> 250	250	---	---	0	50		1	
	Ring for tube	> 250	40	---	---	130	160		5	
Additional pieces for spare parts	Half cells	> 250	500	500	3.9	---	---		6	
	Beam tubes	> 250	520	480	3.2	---	---		1	
	Coupler port	> 250	370	345	3.2	---	---		1	

Sub-Total Price	
Shipping and Insurance Fee	
Total Price	

Condition: Technical Specifications applicable to the supply of niobium material destined to the manufacturing of 5 superconducting cavities for the ESS HECCTD cryomodule. Tokyo Denkai request changing tolerances of width and length from (+2/-0) to (+3/-0).

Time of Shipment: Within 3 months after receiving your official order.
Payment: 30 days by T/T.
Valid of the Quotation: February 29, 2016.

Tokyo Denkai Co., Ltd.
Hiroaki Umezawa
Hiroaki Umezawa, CTO

CAVITIES:

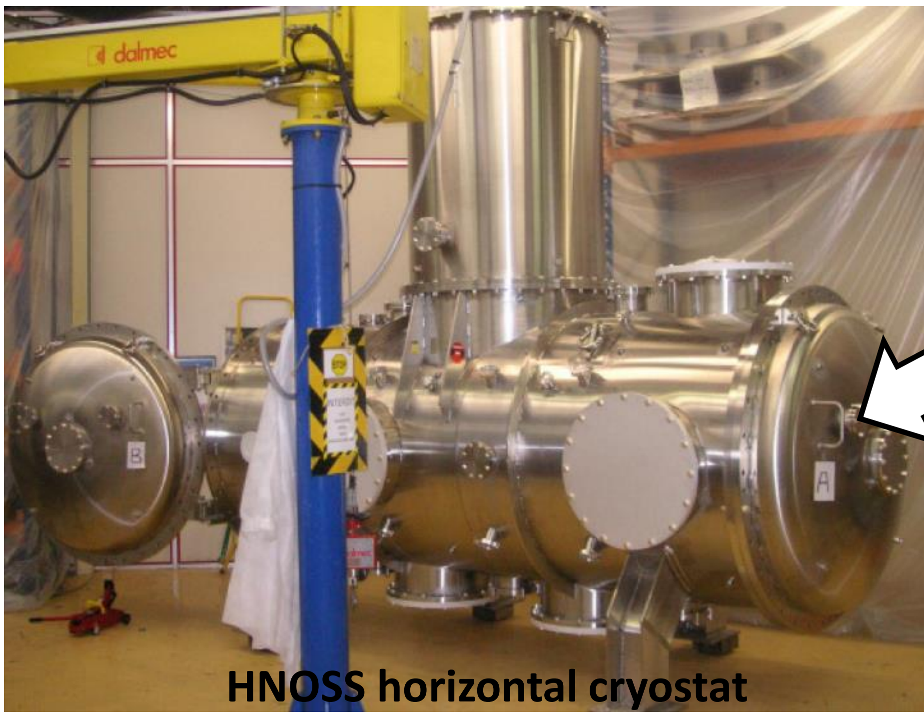
- **Drawings and technical specifications are 95% ready**
- **Call for tender will be launched within few days**

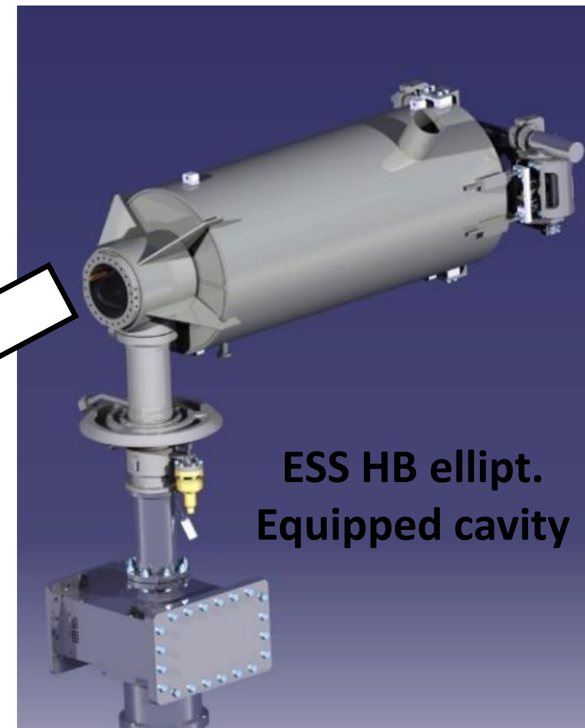
CEA SACLAY	TECHNICAL SPECIFICATIONS FOR THE MANUFACTURING OF 5 HIGH BETA SUPERCONDUCTING CAVITIES	ess
	CEA-ESS-CMD-ST-0001 A	Page 1 / 30

Technical specifications for the manufacturing of 5 high beta superconducting cavities at 704 MHz and beta = 0.86 equipped with their helium tank

HIGH POWER TEST @UPPSALA

- The HNOSS horizontal cryostat at Uppsala could host a high beta ESS elliptical cavity equipped with a power coupler and a tuner
- Uppsala will also have a 704 MHz klystron and a modulator to produce 1 MW RF power





- CEA is interested in such a collaboration opportunity and is open to discuss in order to not delay the CDR and the ESS schedule
- Additional cost should be assessed

3) COLLABORATIONS

SRF COLLABORATIONS FOR ELLIPTICAL CAVITIES

Design and HOM studies

Lund University

Manchester 1824 — The University of Manchester

SLAC National Accelerator Laboratory

ESS — Coordination of the SRF collaboration

CEA — Prototyping, cryomodule assembly and expertise for ESS

INFN — Medium beta cavities

Science & Technology Facilities Council — High beta cavities

⇩

<u>Regular meetings and visits</u>

Cryostat design and test stand

IPN — Institut de Physique Nucléaire Orsay

Uppsala Universitet

SPL

CERN

INTERFACE DOCUMENT AND DRAWINGS IN PREPARATION

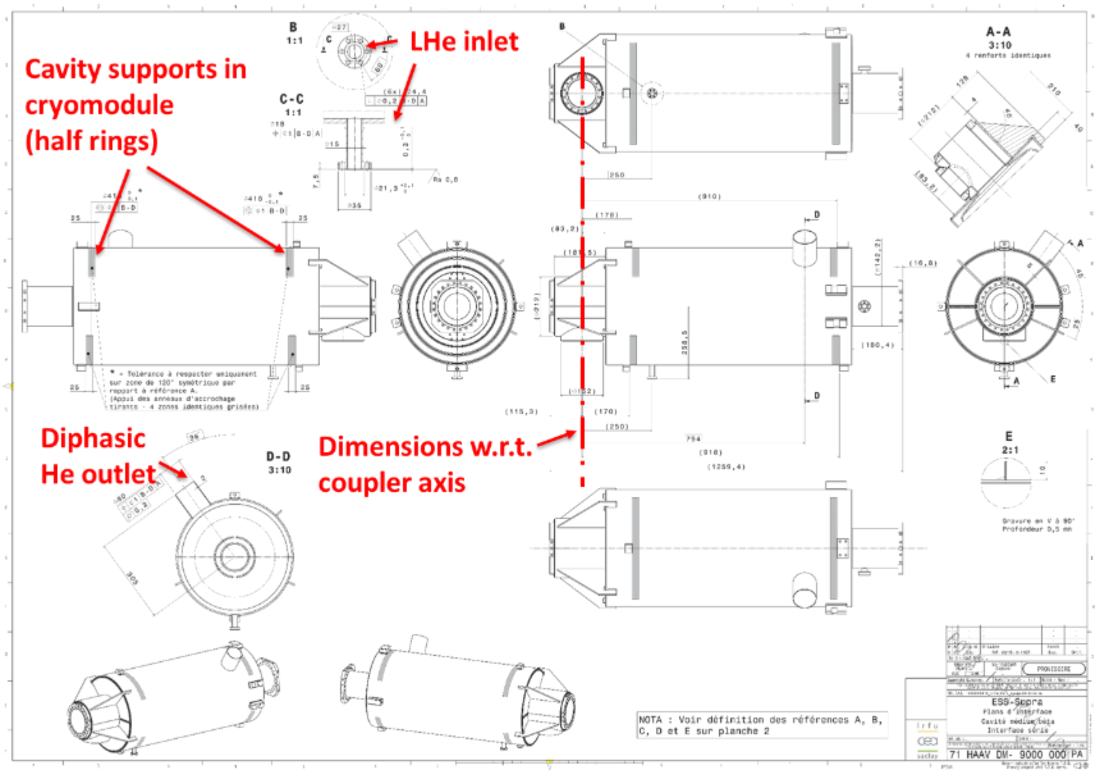
- Cavity manufacturing drawings provided in June 2015
- Interface drawings: preliminary version sent the 30th of March 2016

	Mid-β Elliptical cavities interfaces	Réf
	ESS-I	

TECHNICAL NOTE

Interfaces document
Medium Beta cavities and cryomodules

	REDACTEUR *Edited by*	VERIFICATEURS *Reviewed by*		APPROBATEUR *Approved by*
NOM Prénom *Name*	HENNION Vincent	BOSLAND Pierre	PEAUGER Franck	ARDELLIER Florence
Fonctions *Functions*				
Date et signatures *Date and visas*	30 March 2016			



7 sheets

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 early 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
- The six medium beta prototype cavities for the M-ECCTD are being manufactured. Two of them have already been delivered. The first one tested in vertical cryostat showed a Q-disease maybe due to a high concentration of hydrogen. Heat treatment for H_2 degassing and a BCP with improved acid cooling should allow to mitigate this issue.
- The fabrication of five high beta cavities for the H-ECCTD is being prepared
- A strong collaboration is being established for the production of the cavities of the series and a detailed interfaces documents are being settled

DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

CEA - Saclay

THANK YOU

ESS Cavity team:

CEA - IRFU:

E. Cenni
F. Peauger
G. Devanz
J. Plouin
D. Roudier
L. Maurice
P. Carbonnier
F. Eozenou
C. Servouin

X. Hanus
T. Hamelin
N. Berton
V. Hennion
Ph. Hardy
F. Leseigneur
P. Bosland
O. Meunier

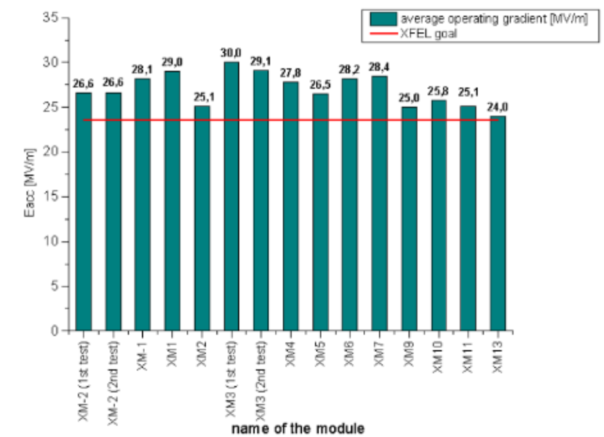
Univ. Lund:
G. Constanza

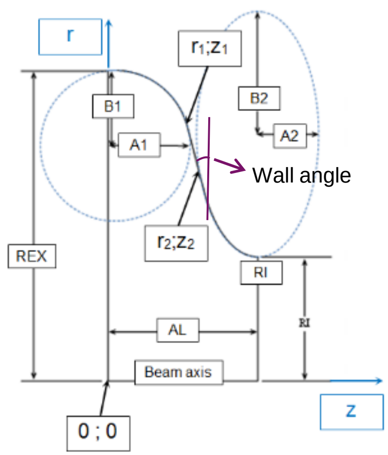
ESS:
C. Darve

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 !!





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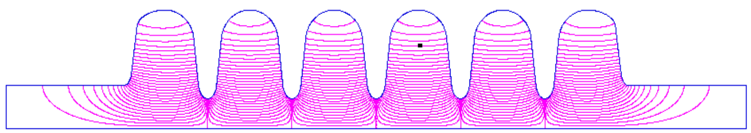
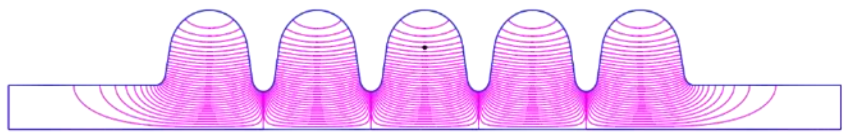
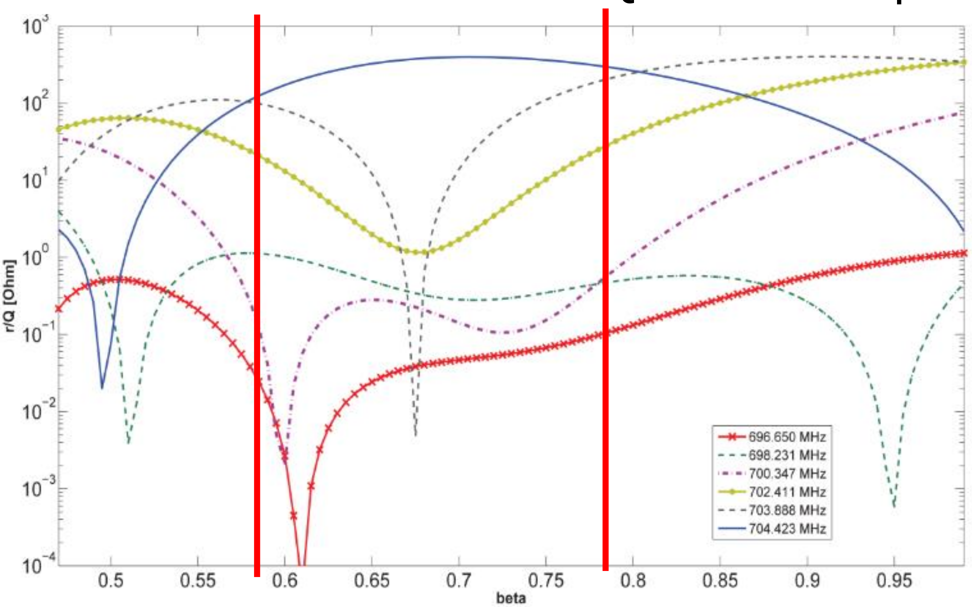
ACCELERATING MODE AND FIRST BANDPASS

Cavity profile and field pattern at 704.4 MHz



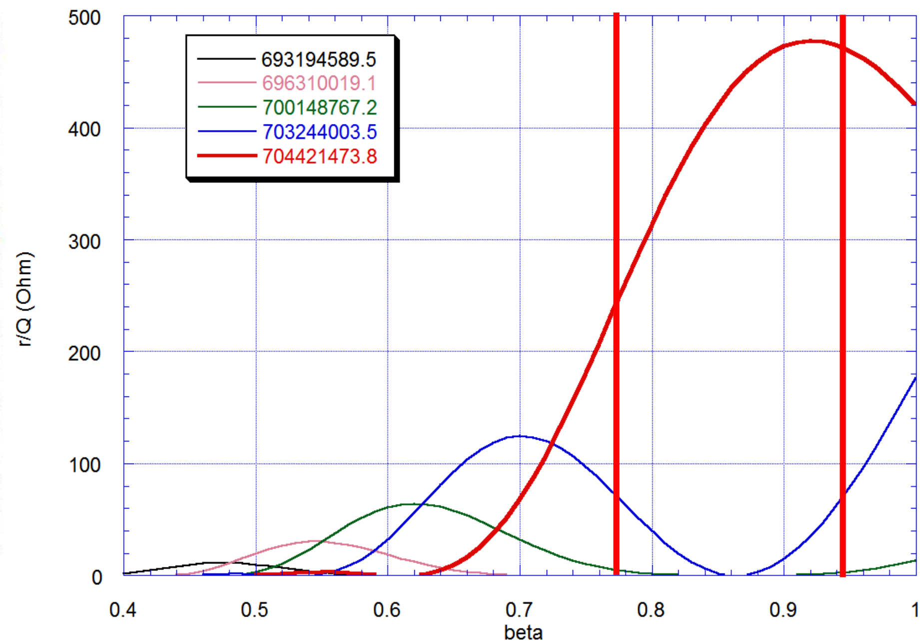


r/Q for the first passband modes.



216 MeV
β = 0.582

561 MeV
β = 0.779

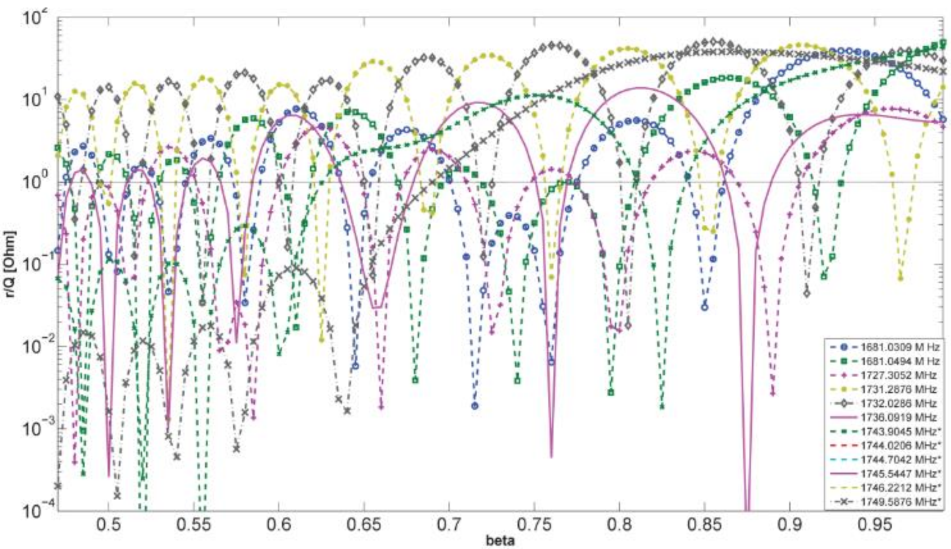


561 MeV
β = 0.779

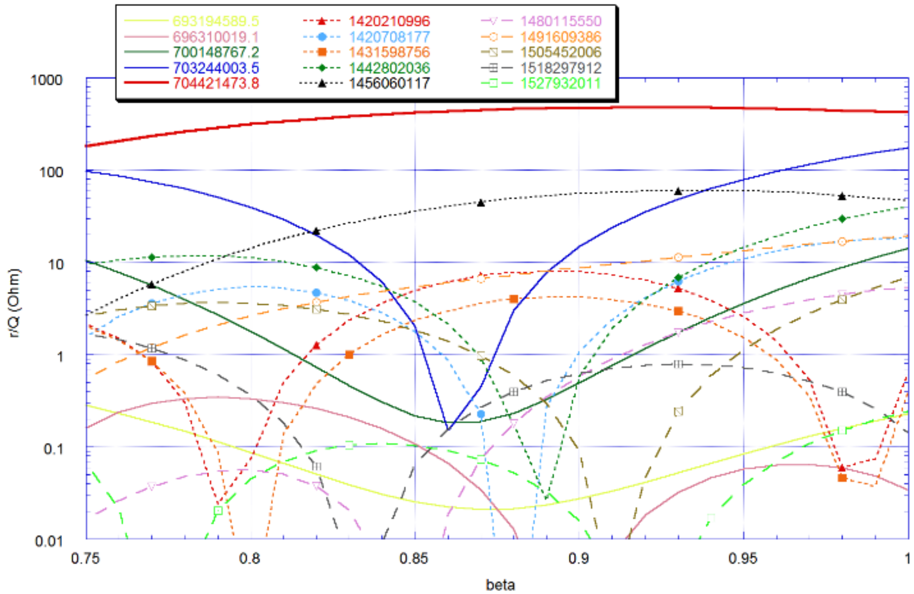
2000 MeV
β = 0.947

MORE HOMS…

Medium beta



High beta

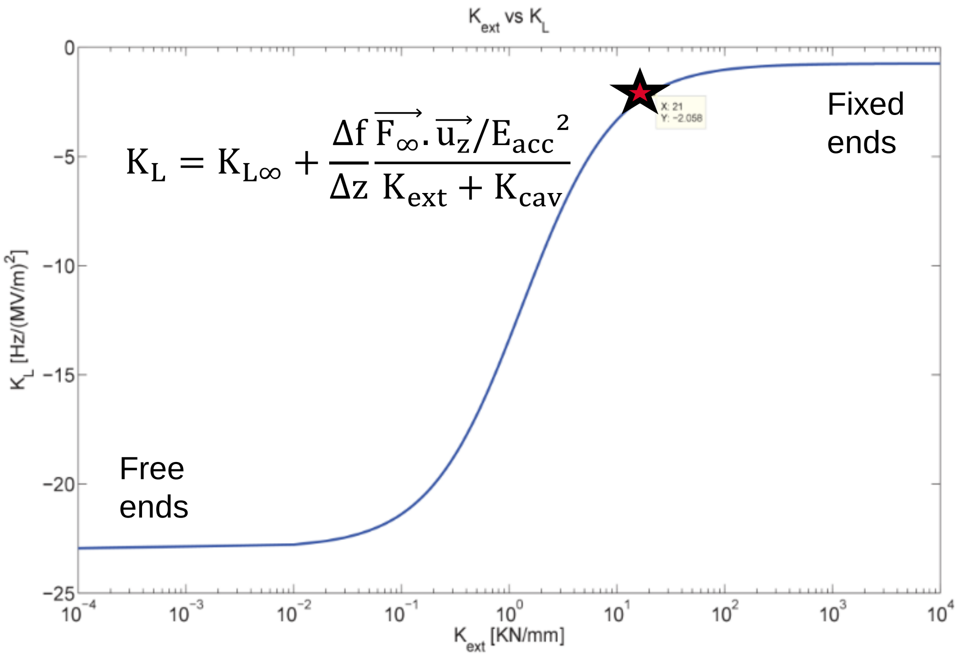


	Cutoff frequencies (GHz)				
Diameter (mm)	TE11	TM01	TE21	TM11	TE01
100	1.7585	2.2989	2.9268	3.6585	3.6585
136	1.293	1.6903	2.1521	2.601	2.601
140	1.2568	1.6420	2.0804	2.6132	2.6132

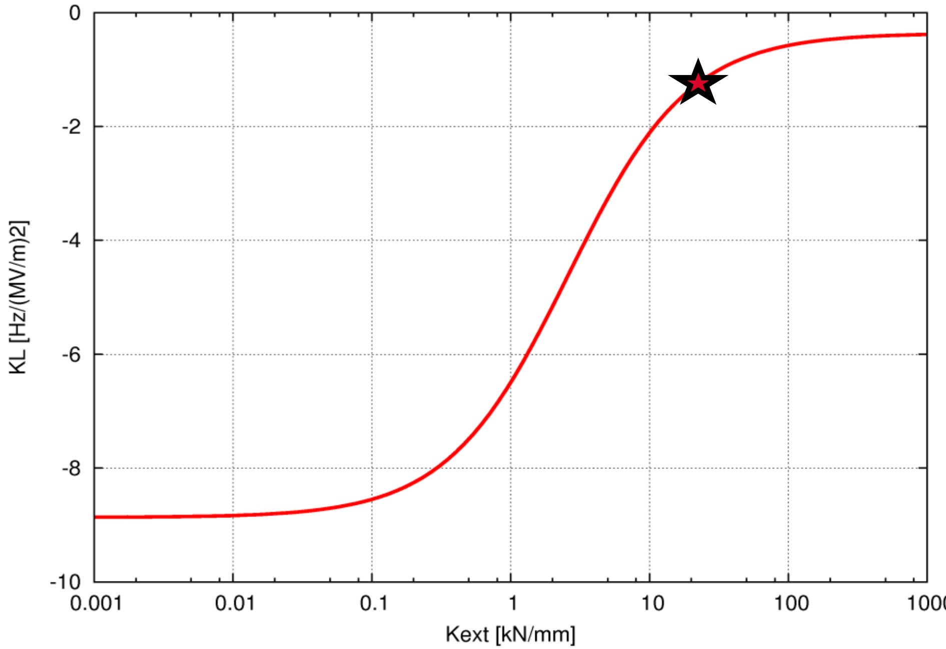
LORENTZ FORCE DETUNING CALCULATION

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



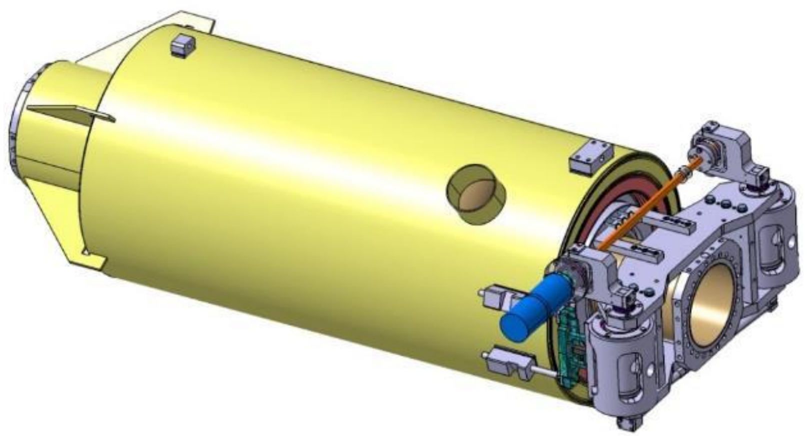
High beta

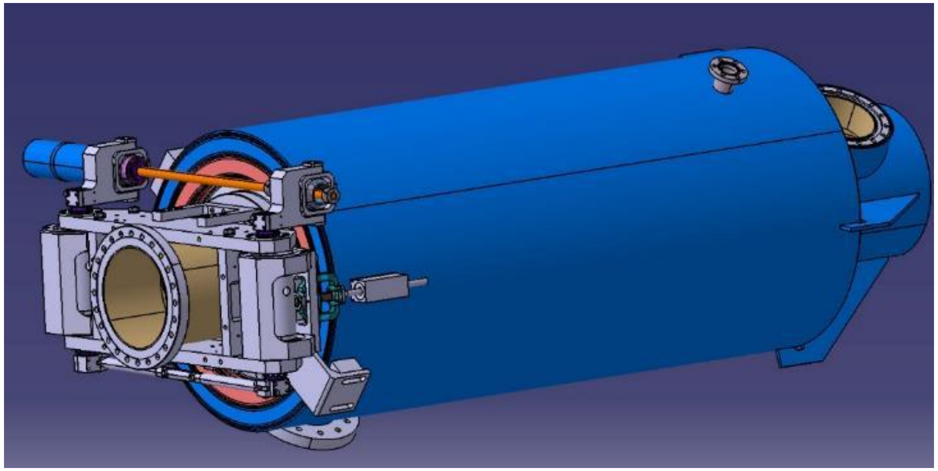


For K_{ext} = 21 kN/mm
→ K_L = -2 Hz/(MV/m)²
→ ΔF = -557 Hz @ 16.7 MV/m
→ ΔL_{piezo} = - 2.6 µm

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

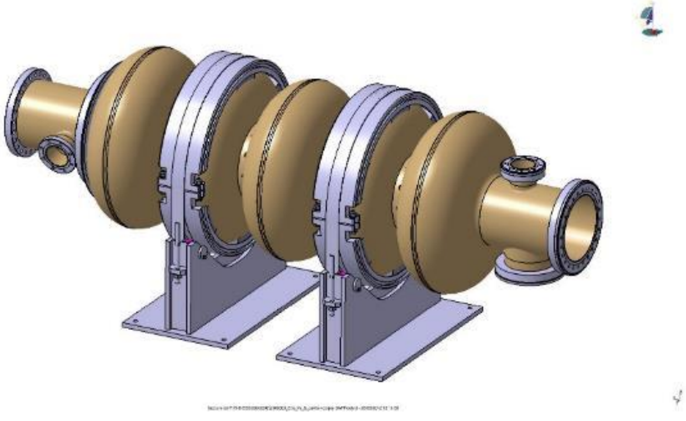
MECHANICAL PARAMETERS

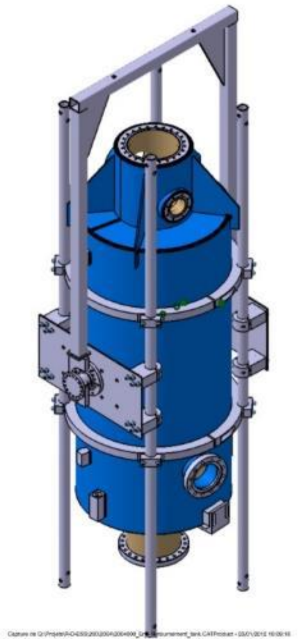


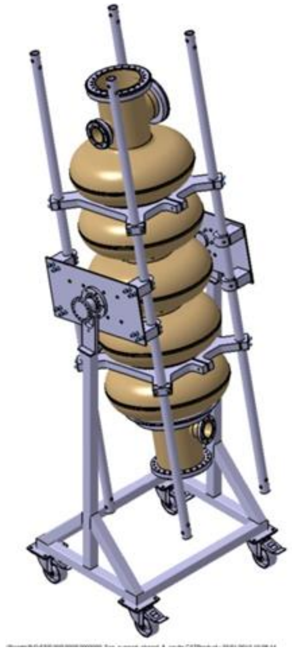


		Medium beta	High beta
Niobium thickness	mm	4	3.6
Cavity stiffner radius	mm	70	84
Tank thickness	mm	5	5
Lorentz Force Detuning coef. K_L fixed ends	Hz/(MV/m)²)	- 0.735	-0.36
Lorentz Force Detuning coef. K_L free ends	Hz/(MV/m)²	-23.35	-8.9
Cavity stiffness	kN/mm	1.286	2.59
Tuning sensitivity $\Delta f/\Delta z$	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

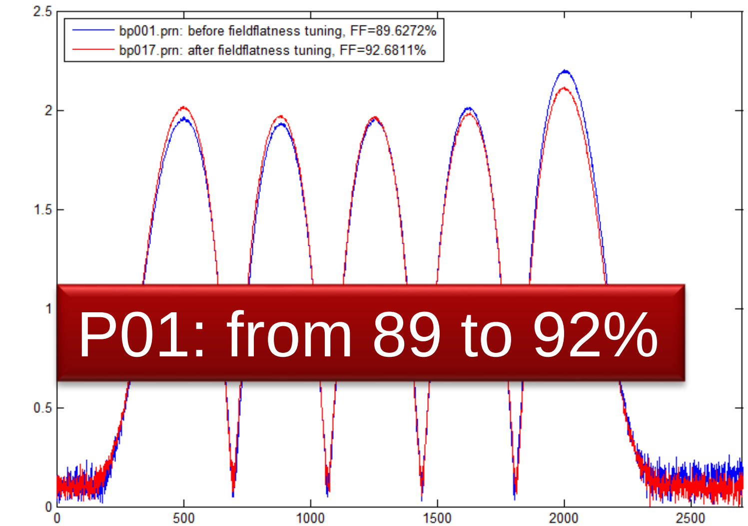
CAVITY HANDLING TOOLS

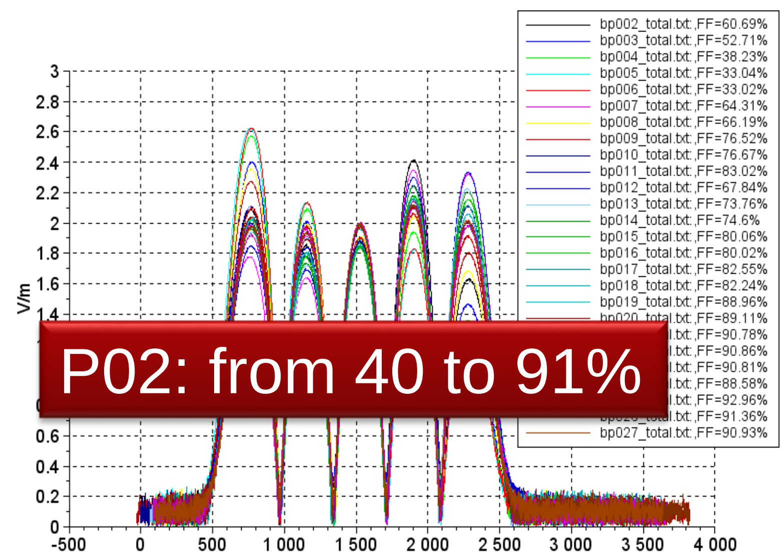






FIELD FLATNESS TUNING





Tuning sensitivity [kHz/mm]	Simulation	Measured
	197	**190**

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CHEMICAL TREATMENT SET-UP

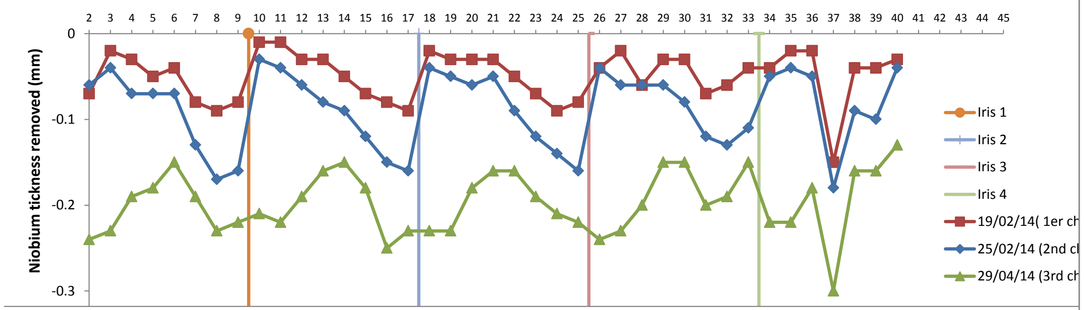
BCP (in vertical EP set-up)
Already used and qualified

BCP
Just modified
Used only once and need to be improved

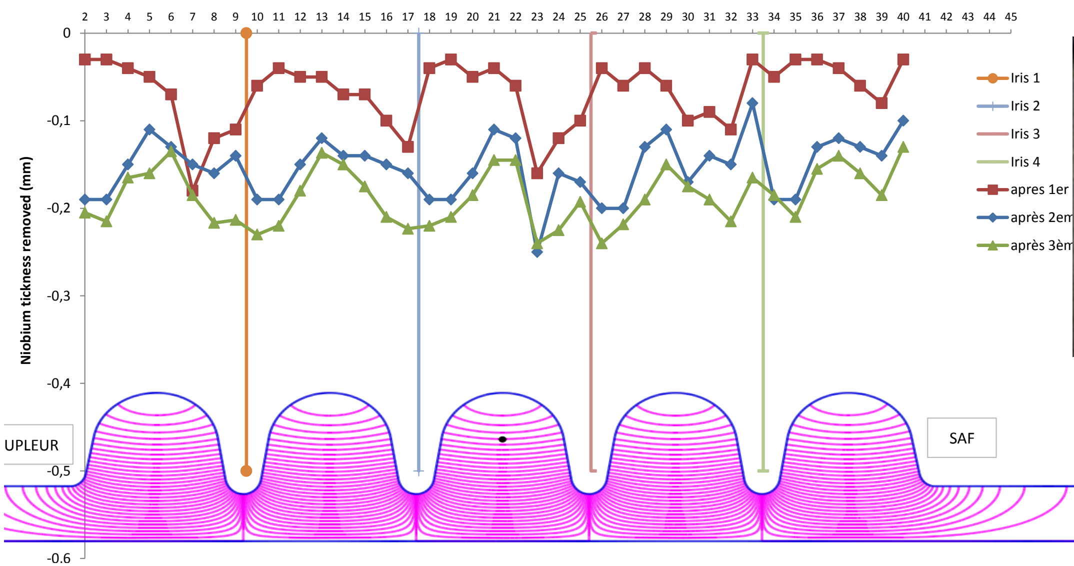
→ Two independant installations compatible with 704 MHz cavities and one is qualified

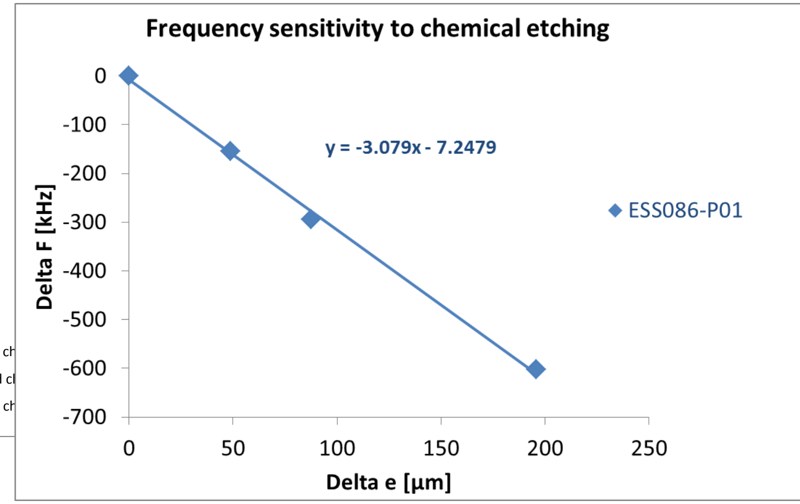
EFFECT OF BCP

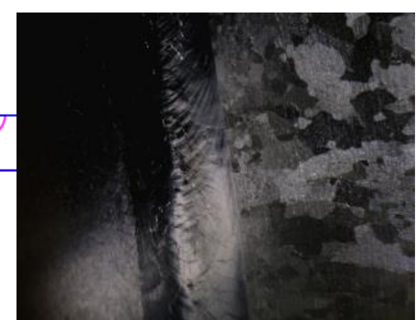
Niobium thickness of ESS086 P01 after chemical etching (BCP)



Niobium thickness of ESS086 P02



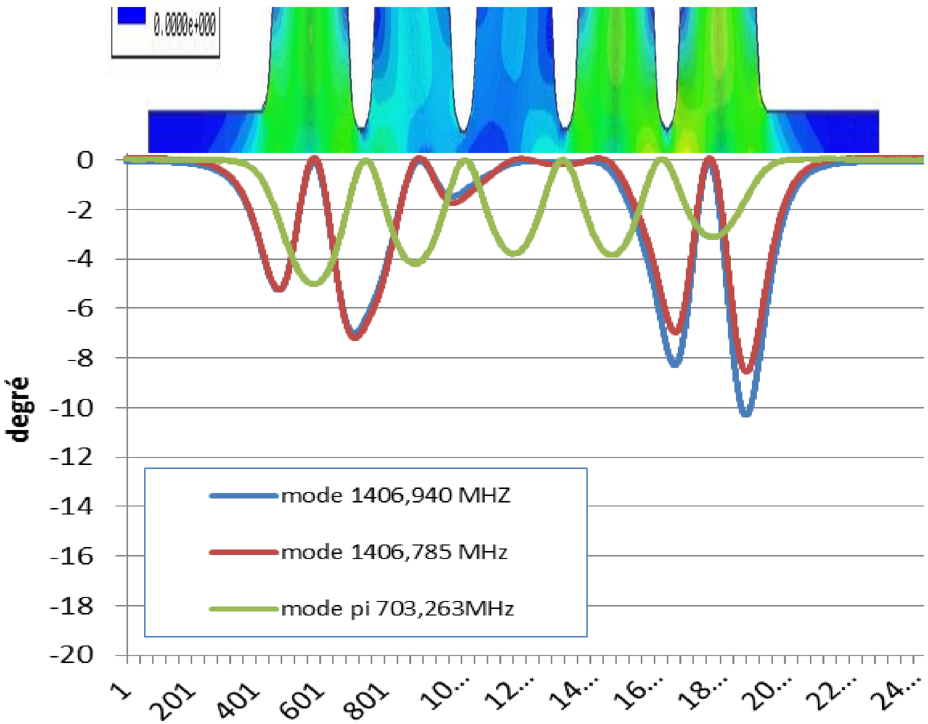


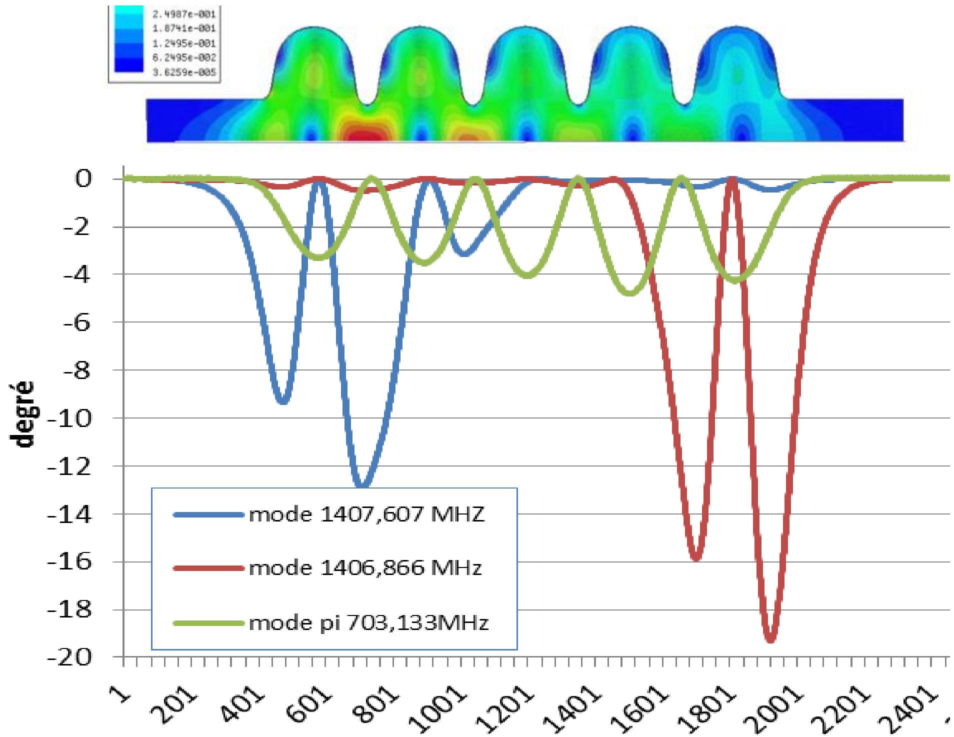


200 µm average removed

HOM IDENTIFICATION BY BEAD PULL MEASUREMENT

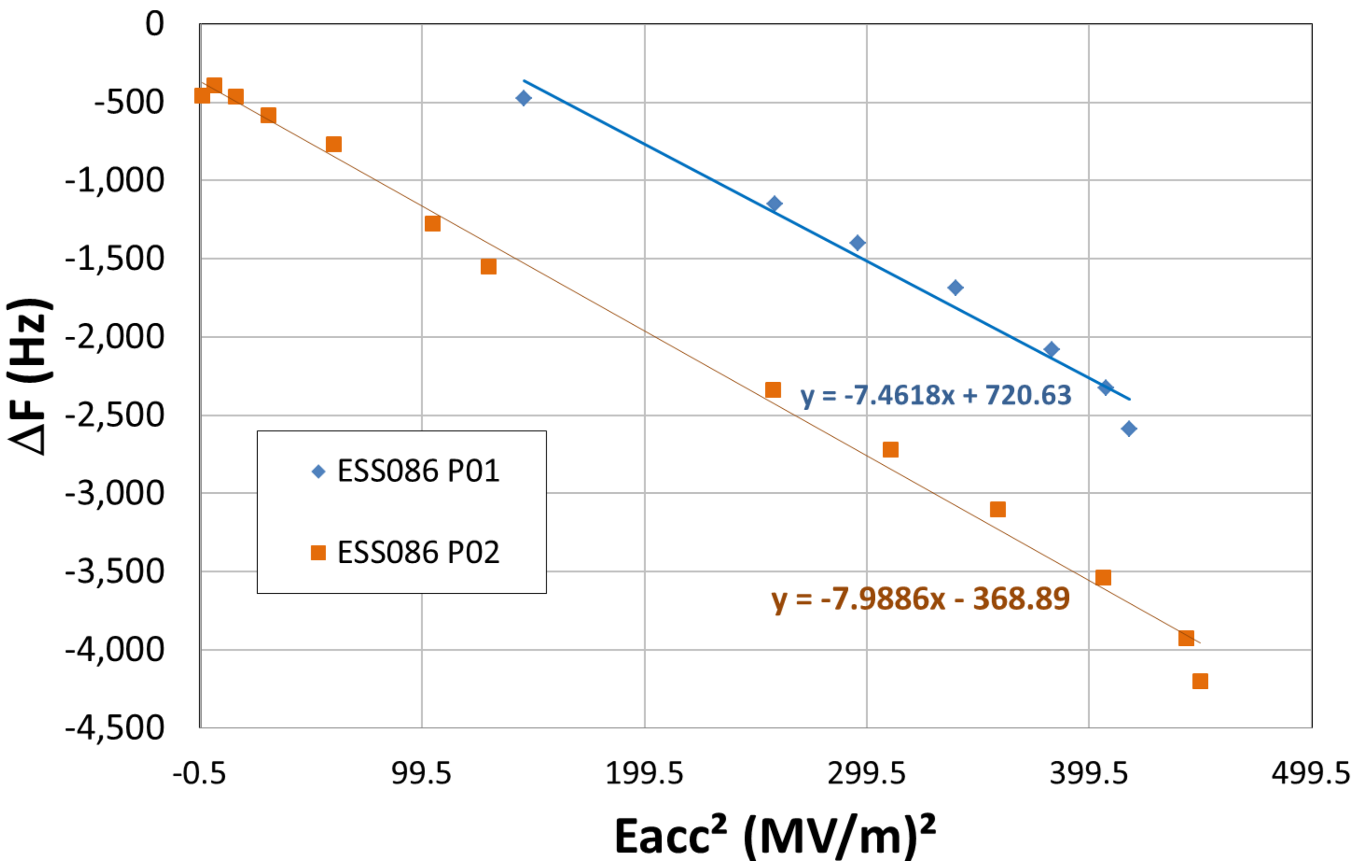
Good identification of the HOM but unsuccessful tests to reshape the cavities with the field flatness tool.





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

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