ESS medium-beta cavities

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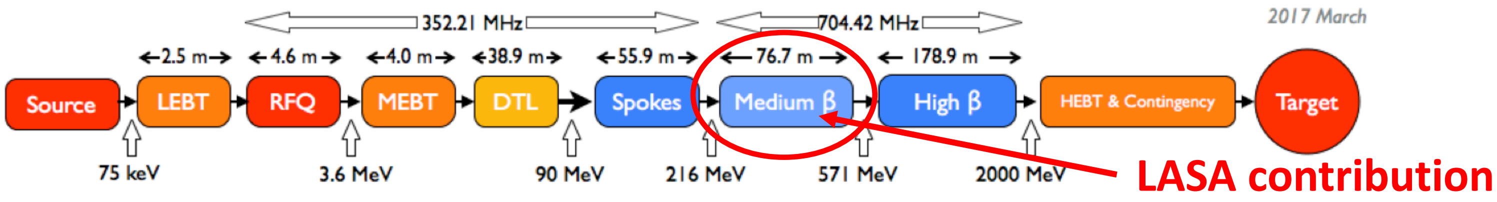
Outlook

- INFN contribution to ESS
- Production strategy
- Cavity parameters
- From design to prototype and then to series production
- Transports
- Production status, statistics and measurements

INFN-LASA contribution to ESS linac



- **INFN LASA In-Kind contribution for 11.6 M€**
  - Design of the Medium β cavity family
  - 36 cavities in the industry**, including treatments**, tuning and He tank following a
  - **Built to Print** strategy.
  - Cavities delivered **ready for the cold test**.
    - Analogous strategy as for the XFEL successful experience
  - Cold test in a qualified infrastructure (DESY).
  - Delivery at CEA **ready for the cryomodule** assembly.
- Series cavities production at the industry:
  - **Prototypes** cavities for design verification, treatment optimization, know how transfer to the industry.
- Series cavities production at the industry:
  - Expected delivery rate: 2 cav/3 weeks

ESS Parameters	
Max Energy	2 GeV
Average beam power	5 MW
Peak beam power	125 MW
Peak beam current	62.5 mA
Pulse length	2.86 ms
Repetition rate	14 Hz
Energy from SC sections	96 %

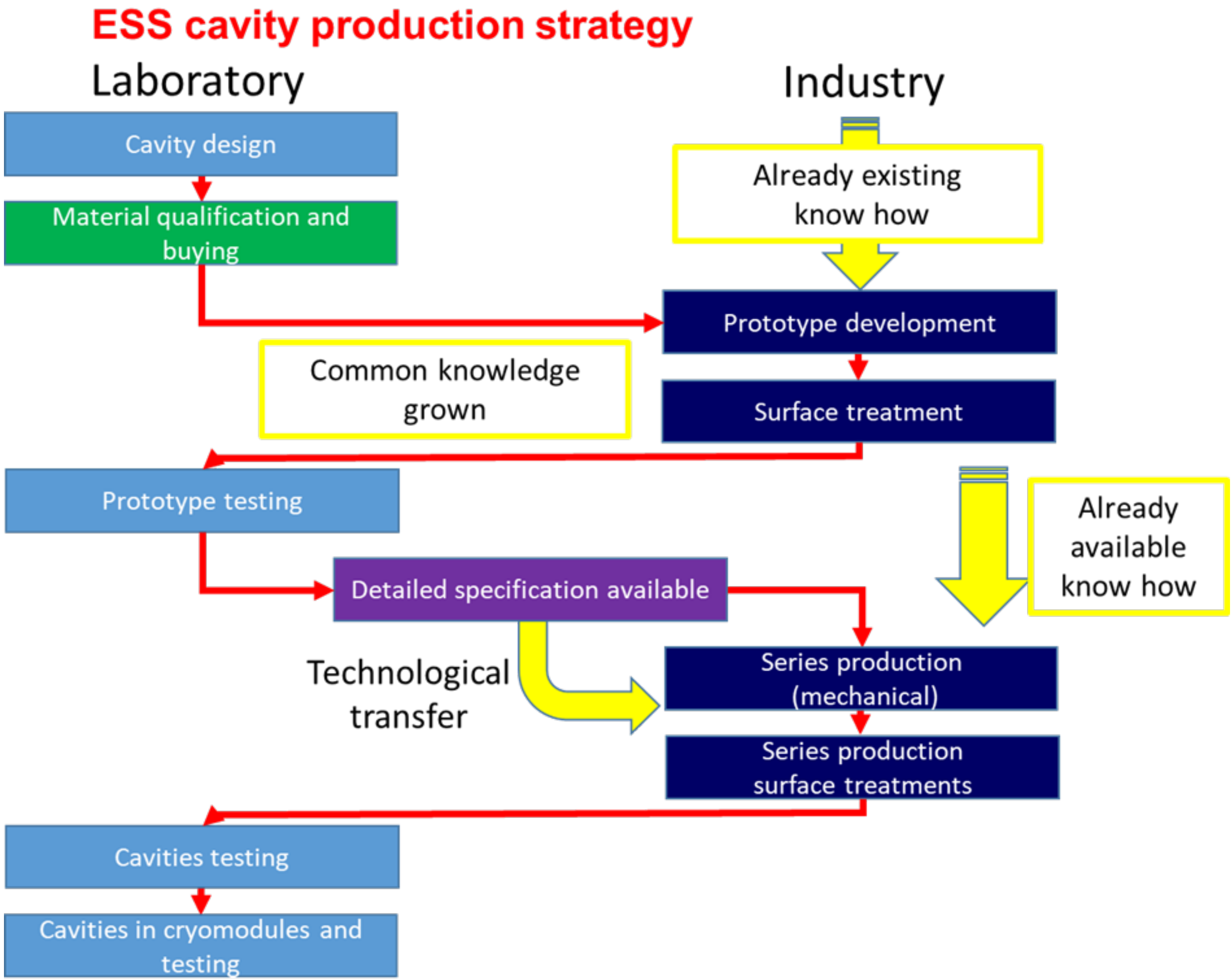
Major procurements

- **Niobium** procurement for the fabrication of 38 medium beta cavities.
- **Cavity fabrication** of 36 medium beta cavities (+ 2 spares) in the industry
  - Including treatments, tuning, Helium tank integration, etc.,
  - Accomplishing the ESS requirements in terms of performances and functional interfaces.
  - Documentation, QA/QC
- **Ancillaries**
  - Vacuum valves
  - Antennas, Feed-throughs
- **Cold test** at DESY.
- **Transportation** in special boxes and delivery at the cryomodule assembling facility.

Strategy

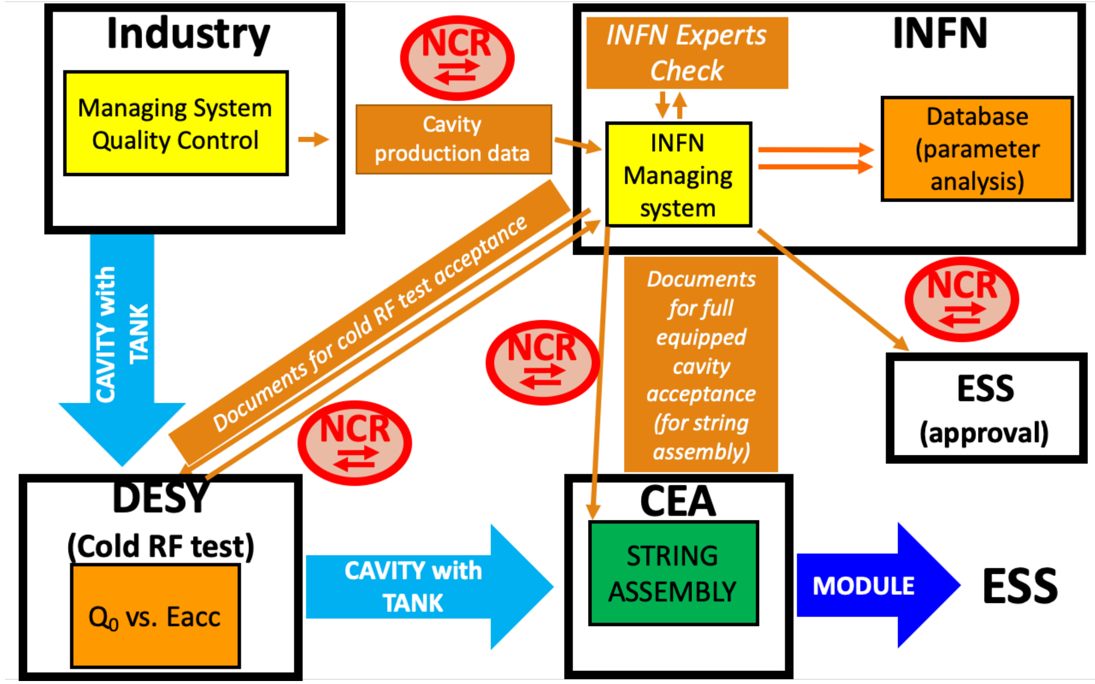
ESS cavities production strategy similar to XFEL

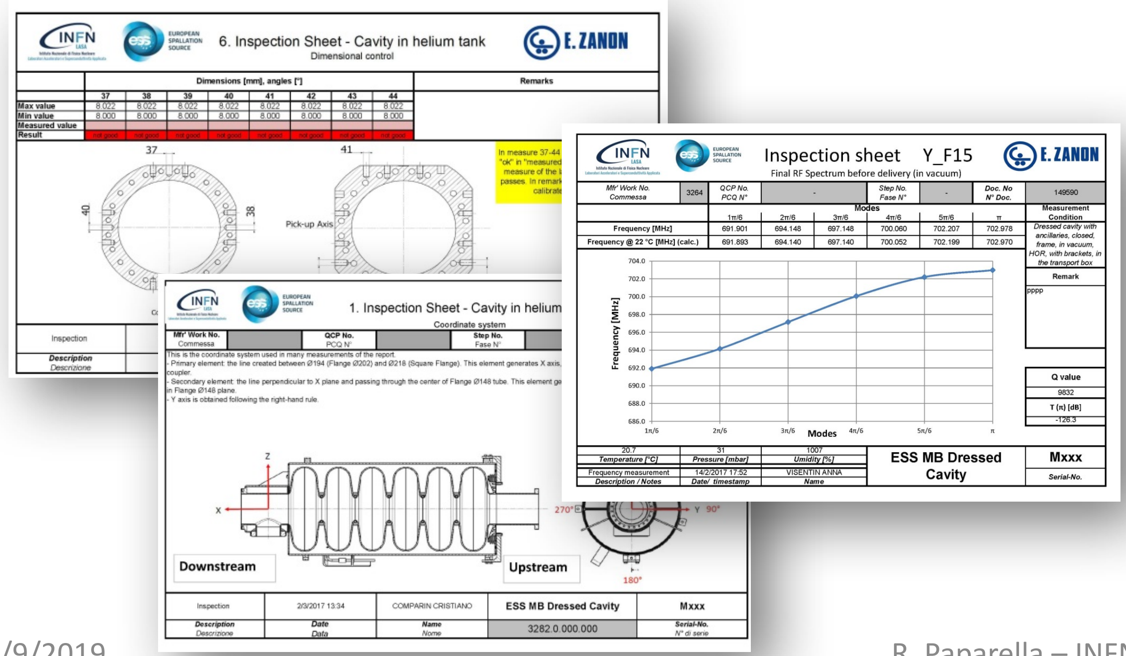
- **One company**: 36 cavities.
- Company already "**experienced**" by previous activities as E-XFEL.
  - Prototypes completely produced by the company, both for mechanical construction and treatments.
- **INFN experts** for QA/QC set up, reviewing of operative instructions, vacuum, RF measurements, chemical treatments etc.
- Niobium vendor selected by public tender in 2017 (2.6 M€): **NINGXIA OTIC**
- Cavity vendor selected by public tender in 2017 (3.7 M€): **Ettore Zanon**

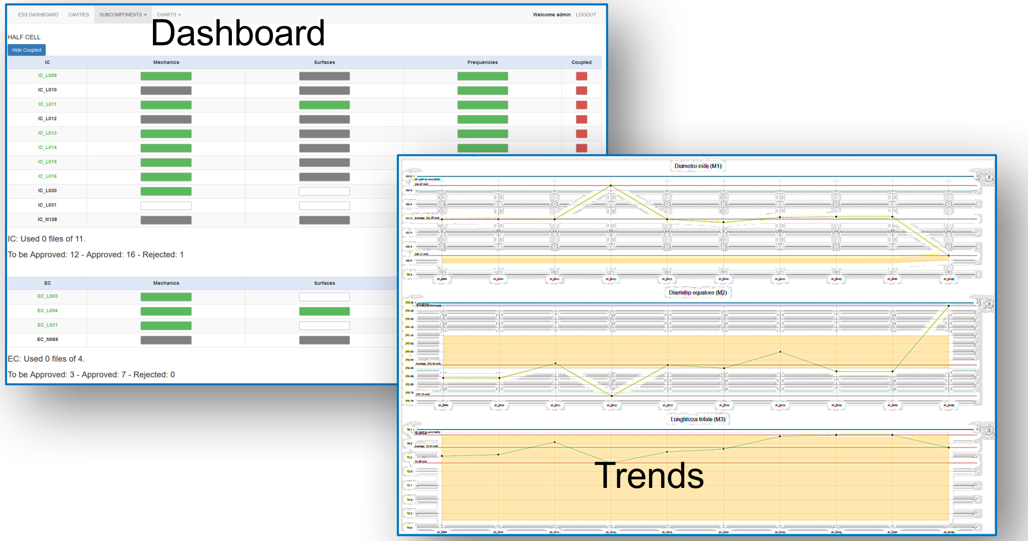


Quality control

- Documental SW developed within brightness
- ≈ 100 documents per cavity
- Total of > 4000 documents to be:
  - Exchanged among EZ, INFN, ESS and CEA
  - Managed and stored with INFN ALFRESCO DMS
  - Analyzed for statistics, deviations, guidance and feedback for production







INFN cavity parameters

Requirements:

- Boundaries fully compatible to ESS requirement.

Design philosophy:

- Larger cell-to-cell coupling factor, k>1.5%
- Accept light modest sacrifice on E_{peak} and R/Q

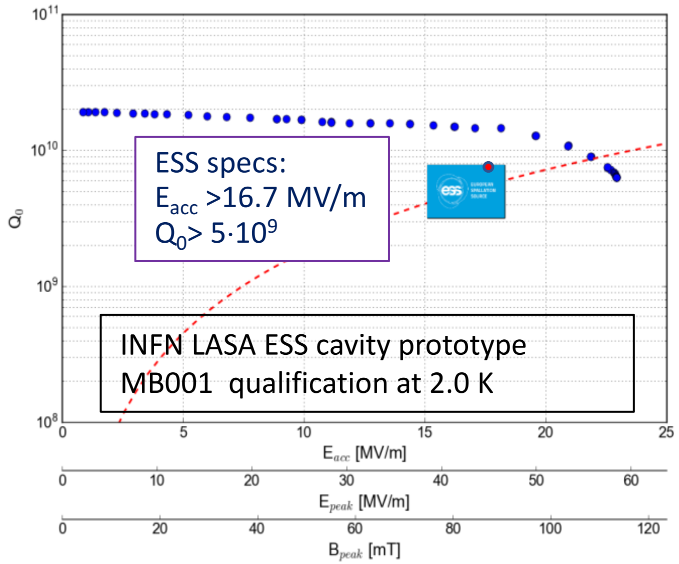
Mechanical Parameters	INFN design
Cavity wall thickness (mm)	4.2
Stiffening ring radius (mm)	70
Internal volume (l)	69
Cavity internal surface (m^2)	1.8
Stiffness (kN/mm)	1.7
Tuning sensitivity K_T (kHz/mm)	205
Vacuum sensitivity K_V - k_{ext} ~ 21 kN/mm (Hz/mbar) -	-8
LFD coefficient K_L - k_{ext} ~ 21 kN/mm (Hz/(MV/m)^2) -	-1.8

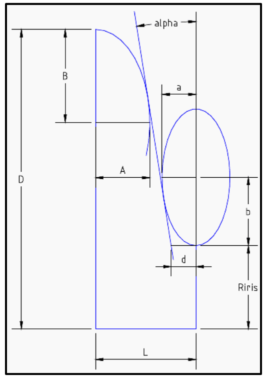
RF Parameters	INFN design	ESS spec.
R_{iris} (mm)	50	≥47
Geometrical beta	0.67	0.67
Frequency (MHz)	704.42	704.42
Acc. length (m)	0.855	0.855
Cell to cell coupling k	1.55%↗(+26 %)	
π-5π/6 mode sep. (MHz)	0.70↗(+30%)	>0.45
G (Ω)	198.8	
Optimum beta, β_{opt}	0.705	0.705
Max R/Q at β_{opt} (Ω)	374 ↘ (-6%)	
E_{acc} at β_{opt} (MV/m)	16.7	16.7
E_{peak}/E_{acc}	2.55 ↗ (+7%)	
E_{peak} (MV/m)	42.6	< 45
B_{peak}/E_{acc}(mT/MV/m)	4.95 ↗ (+3%)	
Q_0 at nominal gradient	$>5\times10^9$	$>5\times10^9$
Q_{ext}	7.8×10^5	$5.9\sim8\times10^5$

From the design to prototype

INFN R&D on ESS prototypes MB001:

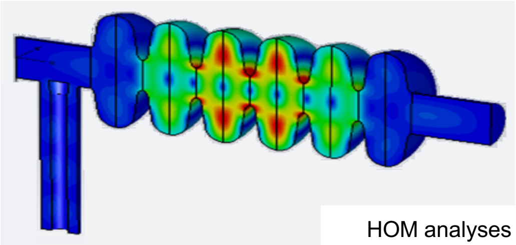
- INFN design, plug compatible with ESS cryomodule.
- Know how transfer to the industry
- Built prototypes at industry with same procedures as for series.
- Final handling and test done in the qualified infrastructure at LASA.
- Successful result well over specification



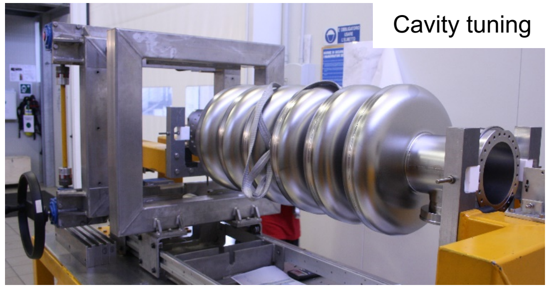


Cell shape design

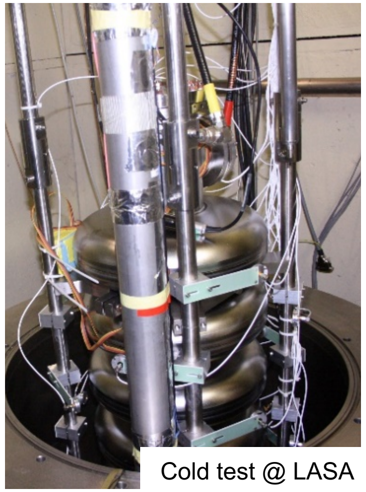
Dumb-Bells



HOM analyses



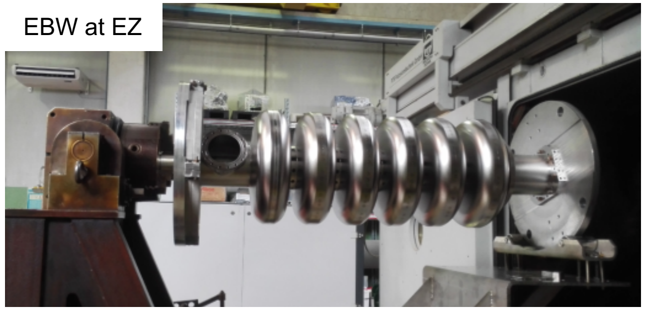
Cavity tuning



Cold test @ LASA

BCP

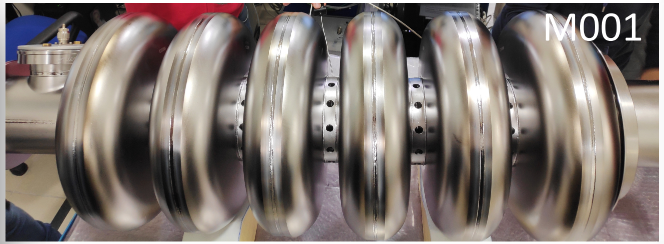
EBW at EZ



INFN

Series cavity fabrication


Nb sheets water cut


M001


2-phase pipes

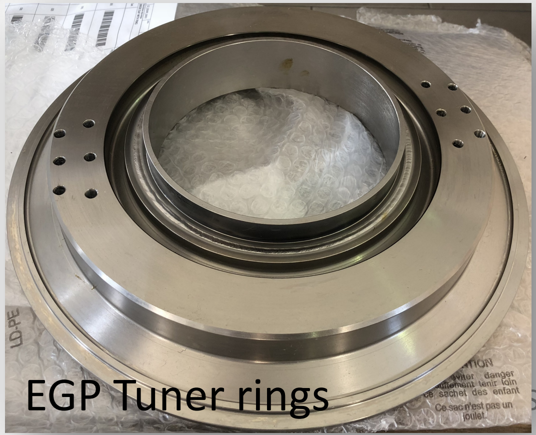

End Group Coupler side


He Tank parts

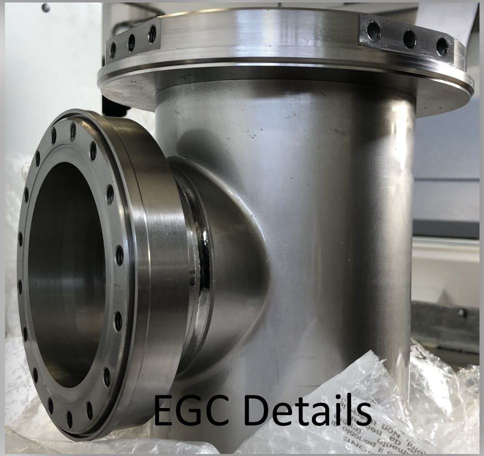

Dumb Bells


He tank


COmponent COntrol DEvice

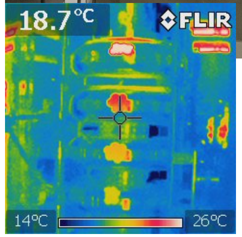

EGP Tuner rings

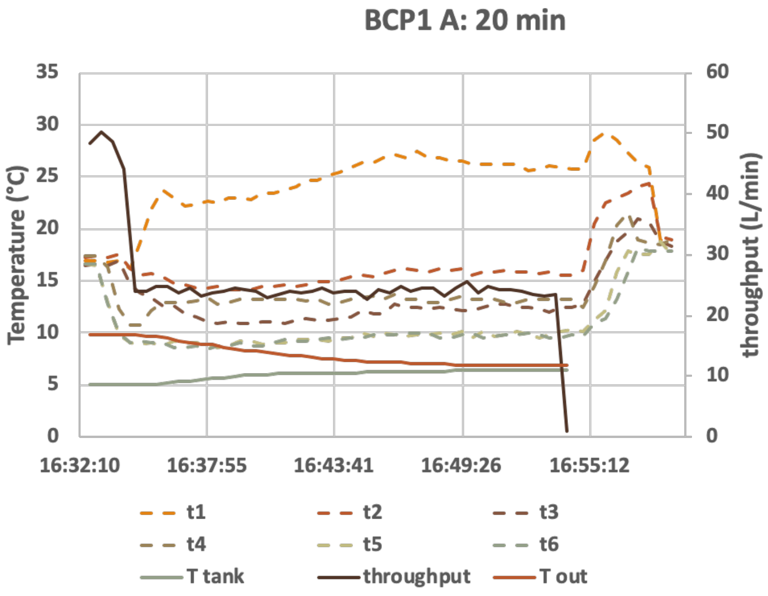

Pick Up Antennas

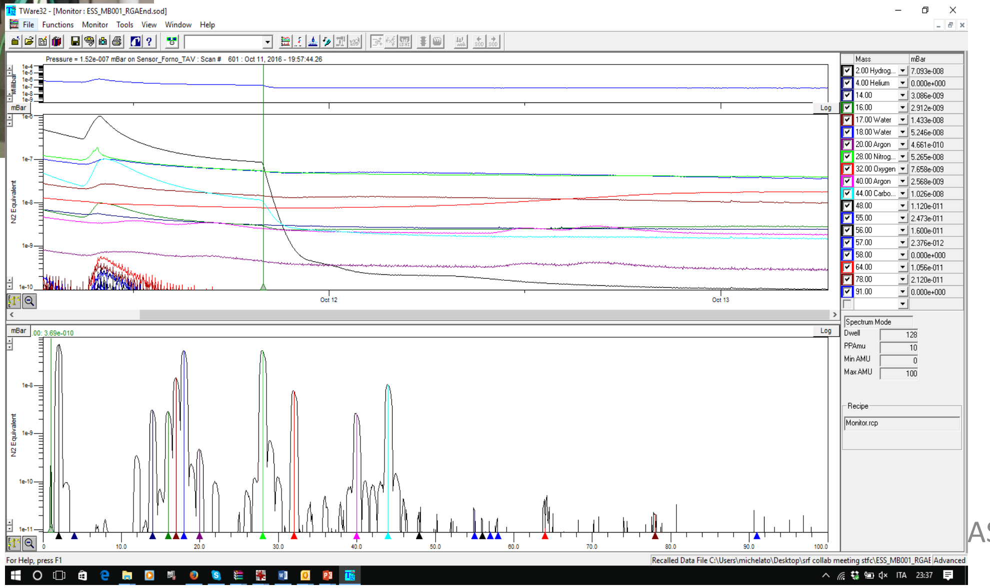

EGC Details

EUROPEAN SPALLATION SOURCE

Surface treatments



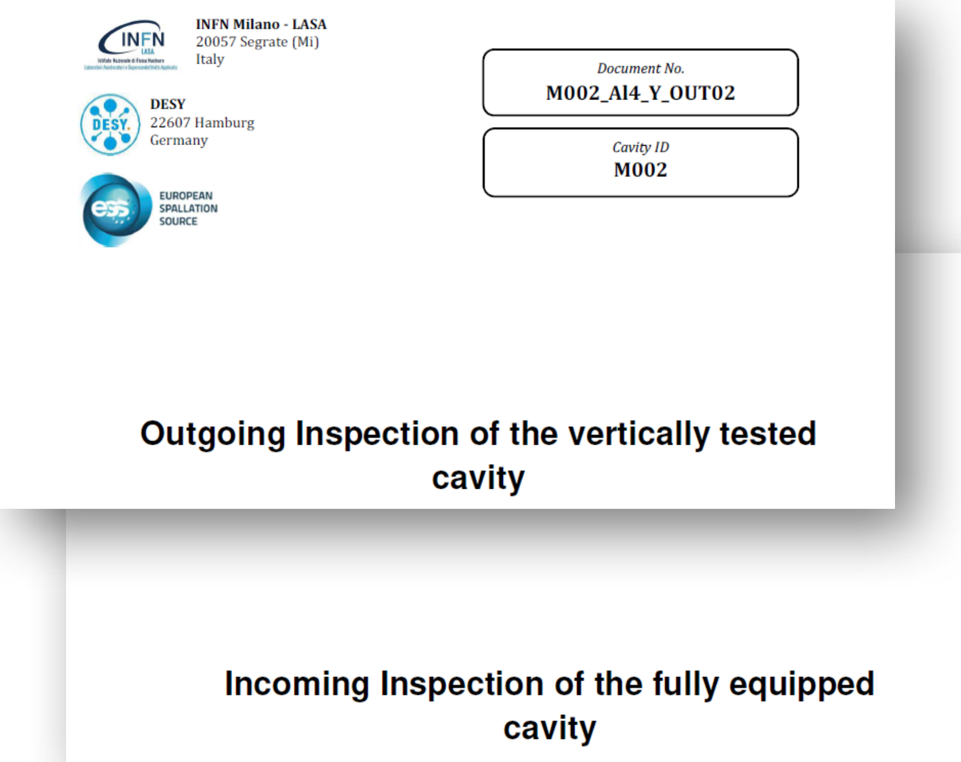




- Bulk & final **BCP: 1:1:2**, (HF HNO3 H3PO4)
- Bulk BCP: about **200 µm**, subdivided in two steps.
  - Cavity is turned upside down after the first step.
  - Cavity weight monitoring for each treatment
  - For each BCP treatment, barrel and output acid temperature are acquired, together with acid throughput
  - 6 thermocouple sensors (t1,…,t6) are placed on cavity surface, continuously acquiring temperature during chemical etching
  - Option for IR camera with standard emissivity dots monitoring during BCP
  - A Nb sample is placed inside cavity (through MC) for monitor etching rate and RRR variation
  - Cavity thickness measurement with ultrasound gauge before and after etching
- **Heat treatment in vacuum**, at 600 °C, 12 h. Temperature, pressure, RGA recorded. Nb sample treated together with each cavity.
- Final BCP: **20 µm**
- Proper rinsing and **HPR treatment** done between each steps

Transports

- 39 cavities transported so far, different configurations:
  - 4 prototype boxes (blue ones), 20 series boxes (black ones)
  - Naked cavity (with frame) w or w/o foam cushions
  - Dressed cavity w or w/o frame, w or w/o foam cushions
- EZ-DESY route: EZ responsibility, done using always the same company used for E-XFEL
- DESY-CEA route on few different dealers from Germany (dedicated transport, point to point, no intermediate storage during transportation). Dealer choice not possible.
- Hopefully, cavity configuration for transport should be now assessed


INFN Milano - LASA
20057 Segrate (Mi)
Italy

DESY
22607 Hamburg
Germany

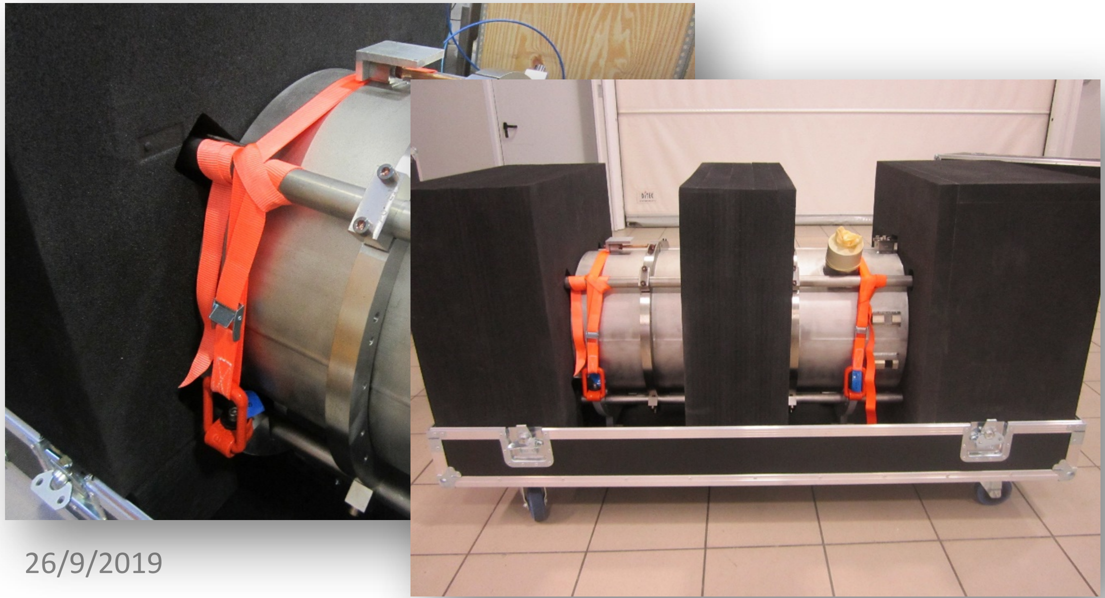
EUROPEAN SPALLATION SOURCE

Document No.
M002_AI4_Y_OUT02

Cavity ID
M002

Outgoing Inspection of the vertically tested cavity

Incoming Inspection of the fully equipped cavity



RF Transportation Acceptance Criteria	
Max p mode frequency difference	± 0.1 MHz
Max p mode RF power transmission	-100 dB
Min p mode RF power transmission	-135 dB
Max Mean Spectrum Frequency Deviation	10 kHz
Peak acceleration (baseline subtracted)	< 3 g

Box tests

Series boxes tested on a vibrating platform

- Cavity mockup from CEA
- 2 h duration equivalent to 1600 km road transport
- Spectral analysis before and after, single impulse test up to 6 g
- Results OK:
  - Modal frequency lowered to 7 Hz (10-15 Hz for E-XFEL)
  - 6-8 shock damping factor (2-3 for E-XFEL)
  - Identical before/after spectra

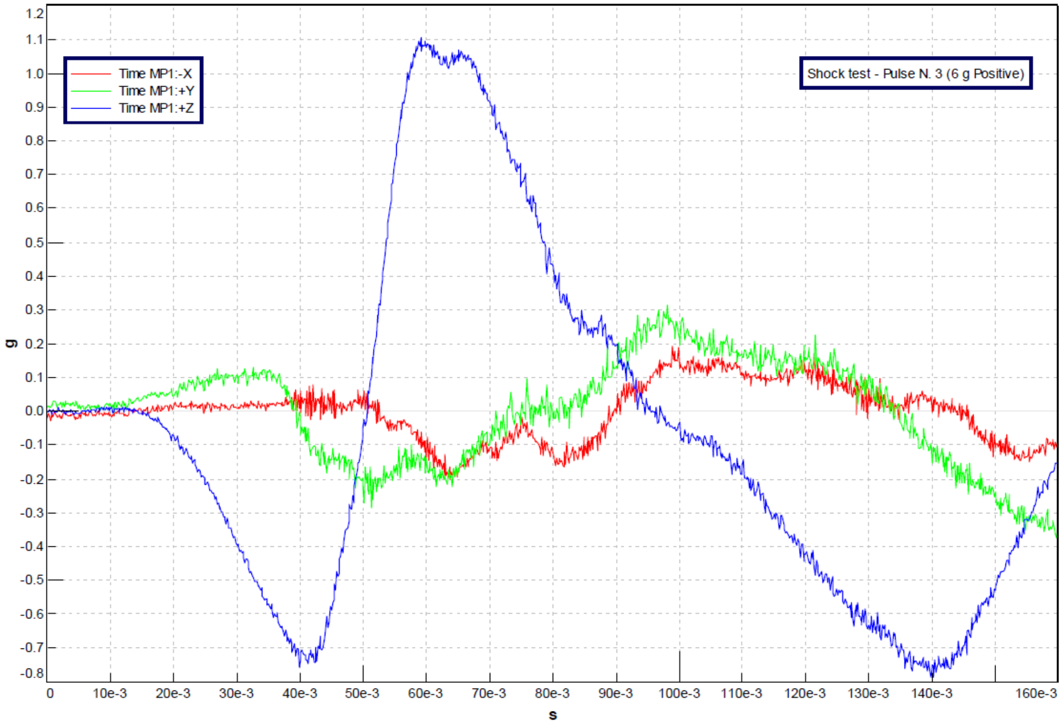


Photo 1: Vibration test mounting techniques

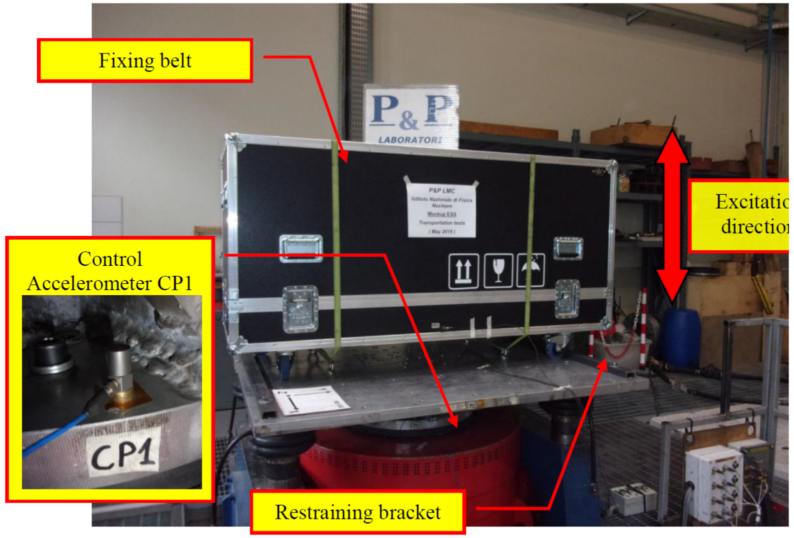
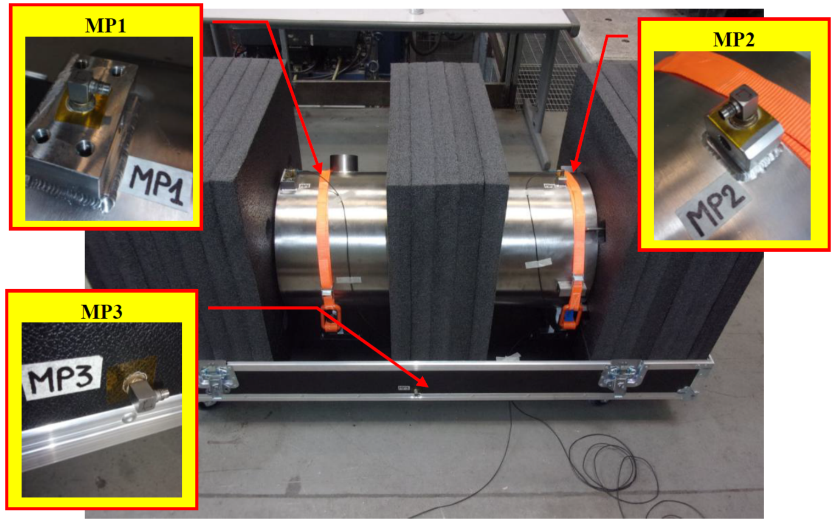
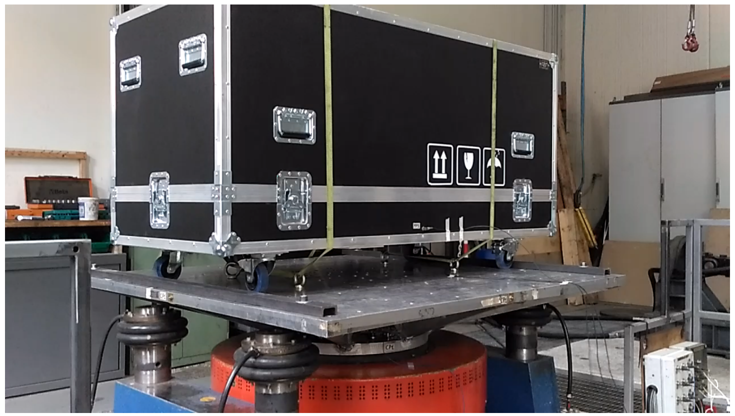


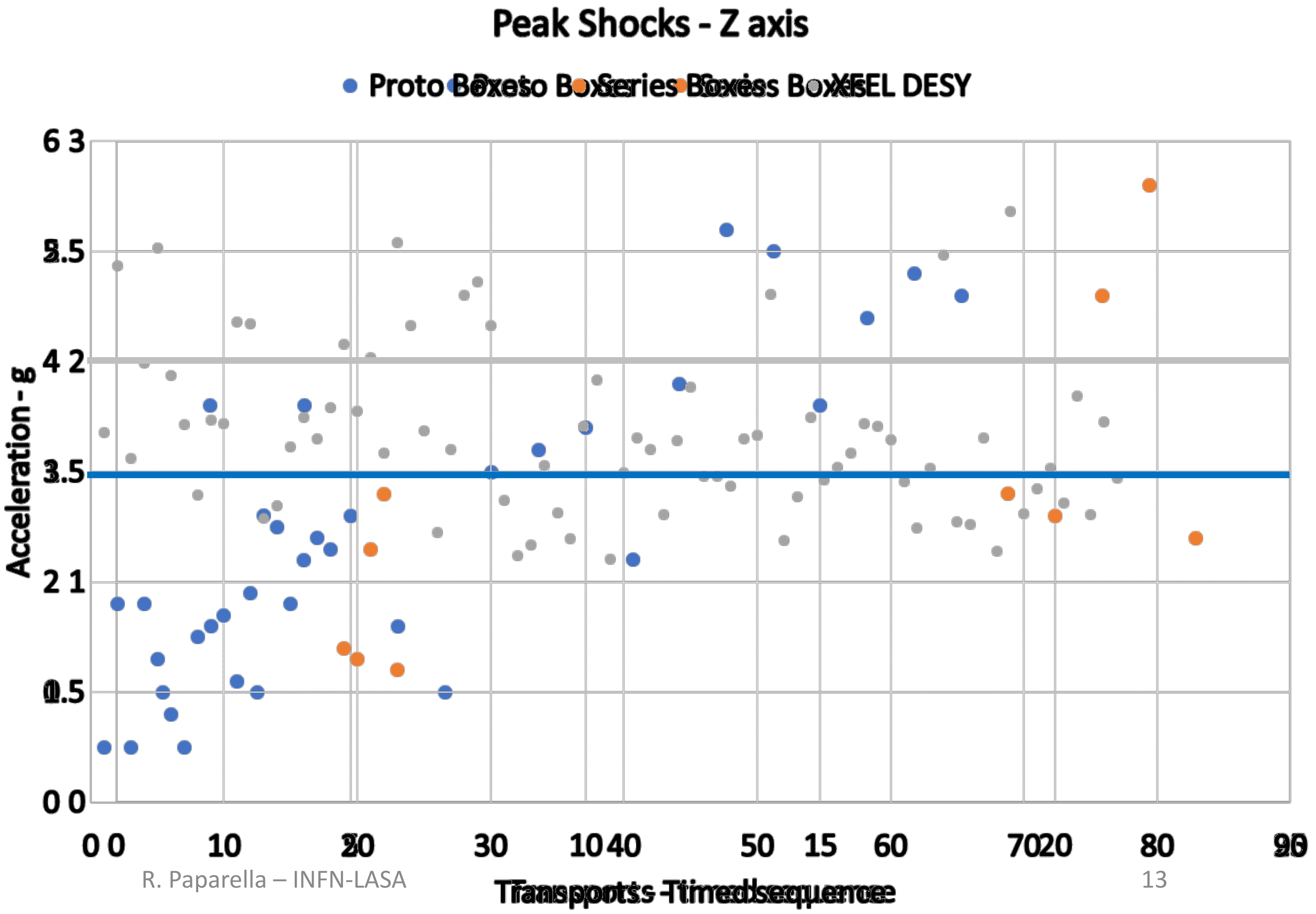
Photo 2: Measuring positions





Recorded shock analysis

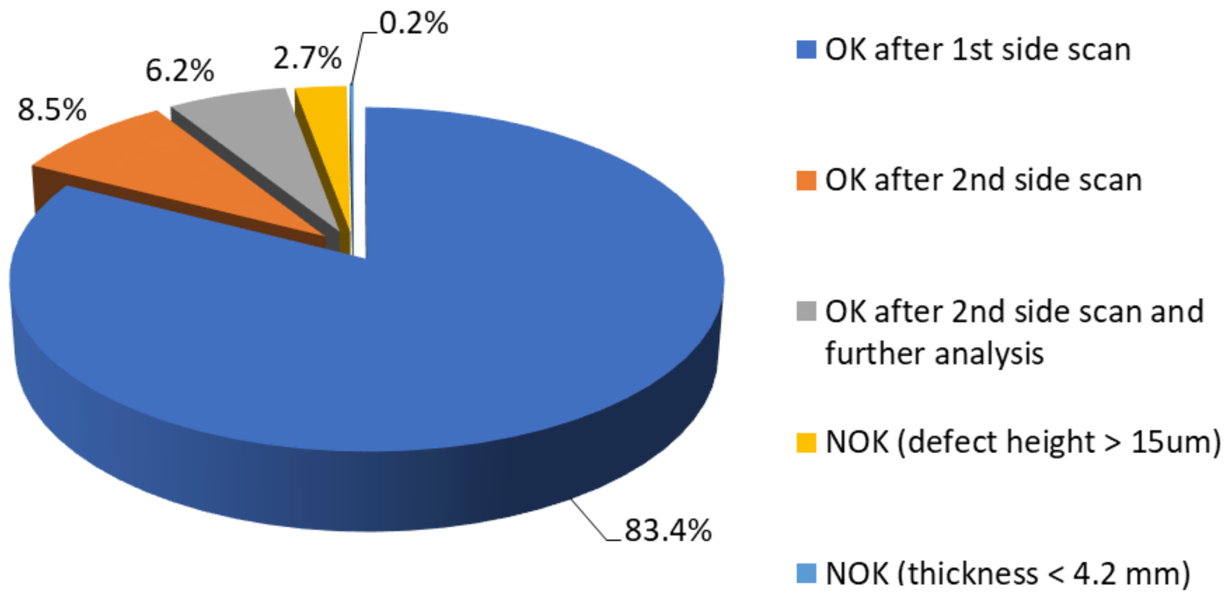
- 30 out of 39 transports analyzed so far, plus:
  - 2 with old SL
  - 2 SL data missing
- No transport-related issues so far
- On average:
  - Av. Z peak 1.6 ± 0.7 g
  - Av. X,Y peak 1.0 ± 0.5 g
- SENSR SL setup for E-XFEL was auto-unbiasing:
  - By subtracting 1 g to vector magnitude
  - With AC coupling: low frequency shocks lowered by 1 g!

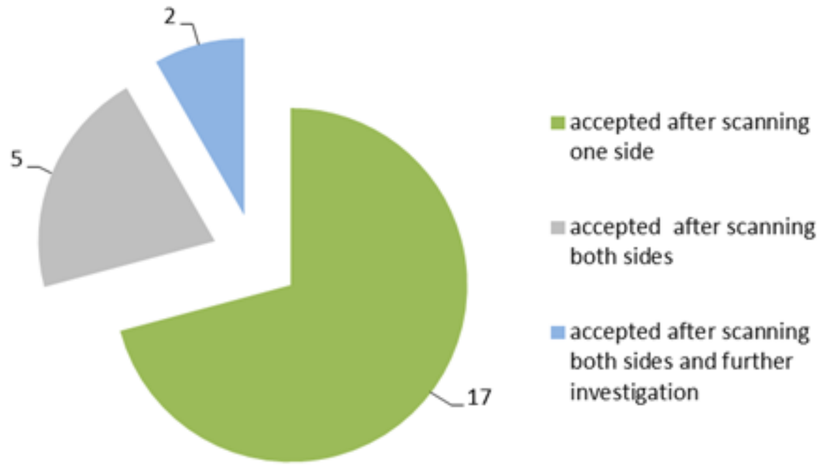


Medium-beta cavities for the ESS
SLHiPP 9, September 2019, IMPCAS Campus, China

Niobium scanning summary

- Series sheets
  - All 456 sheets have been scanned.
  - 83.4 % accepted after first scan
  - Only 1 sheet rejected due to thickness below specs
  - Sheets with geometrical defects are all recoverable
- Spare sheets
  - All 24 sheets have been scanned.
  - 70.8 % accepted after first scan
  - All sheets accepted





Components production status

Component	Produced	Expected	Percentage
Inner Half Cell	304	304	100
Penultimate Half Cell	76	76	100
End Half Cell	76	76	100
Inner Dumbbells	114	114	100
Terminal Dumbbells	76	76	100
End Groups	76	76	100
Cavities	32	38	84

Series cavity status

Level	Cavity status	Needed documents	If Level reached
AI1	Cavity after mechanical fabrication	Mechanical, RF, vacuum, visual documents	Proceed to Level Two
AI2	Cavity before He-tank integration	Mechanical, RF, vacuum, Treatment documents (bulk BCP, annealing)	Proceed to Level Three
AI3	He-tank integration, Final BCP and surface treatments, assembly of accessories for the cold RF test	He-tank integration and pressure tests (mechanical, RF, vacuum, visual documents, transfer measurements), last surface treatments, final vacuum and RF checks, outgoing inspection	Integrated cavity ready to be cold RF tested
AI4	Cavity cold RF tested	Documents of the cold RF test, incoming/outgoing checks	Cavity can be sent to CEA for string assembly
AI5	Cavity accepted for string assembly	Documents with incoming inspection at CEA	Cavity final approval

Cavity	AI1	AI2	AI3	AI4	AI5
M001					At CEA/CM1
M002					At CEA/CM1
M003					At CEA/CM1
M004					At CEA/CM2
M005					At CEA/CM1
M006					
M007					
M008					At CEA/CM2
M009					At CEA/CM2
M010					At CEA/CM2
M011					
M012					
M013					
M014					
M015					
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M017					
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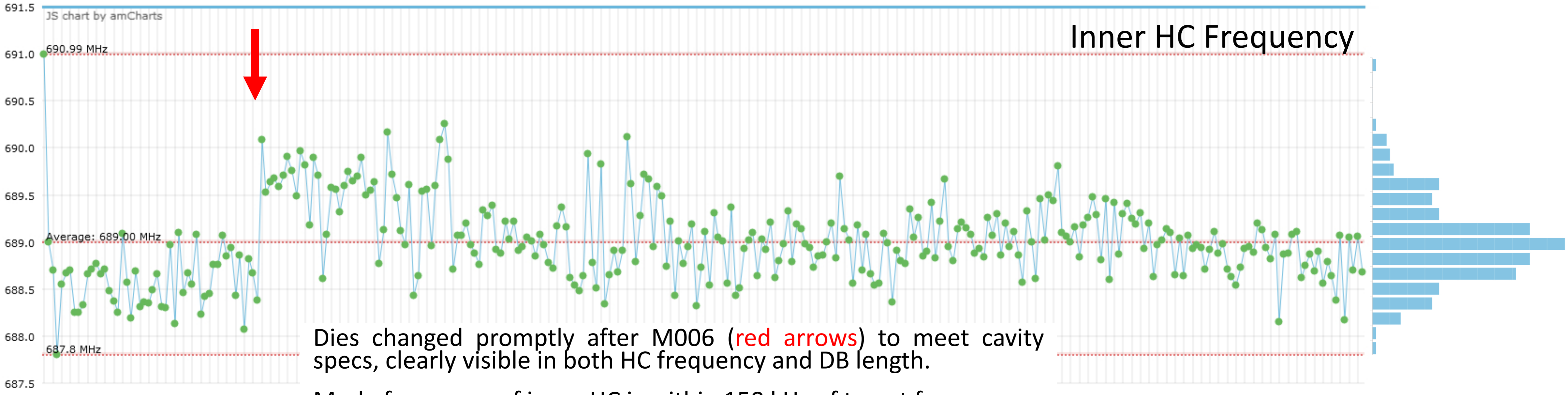
M037					
M038					

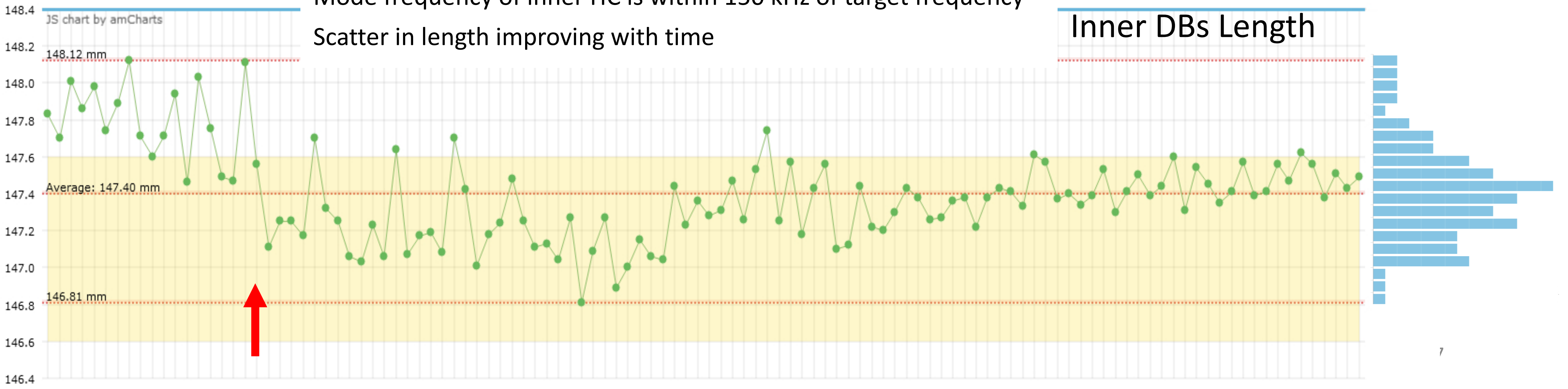
Production statistics



Dies changed promptly after M006 (red arrows) to meet cavity specs, clearly visible in both HC frequency and DB length.

Mode frequency of inner HC is within 150 kHz of target frequency

Scatter in length improving with time



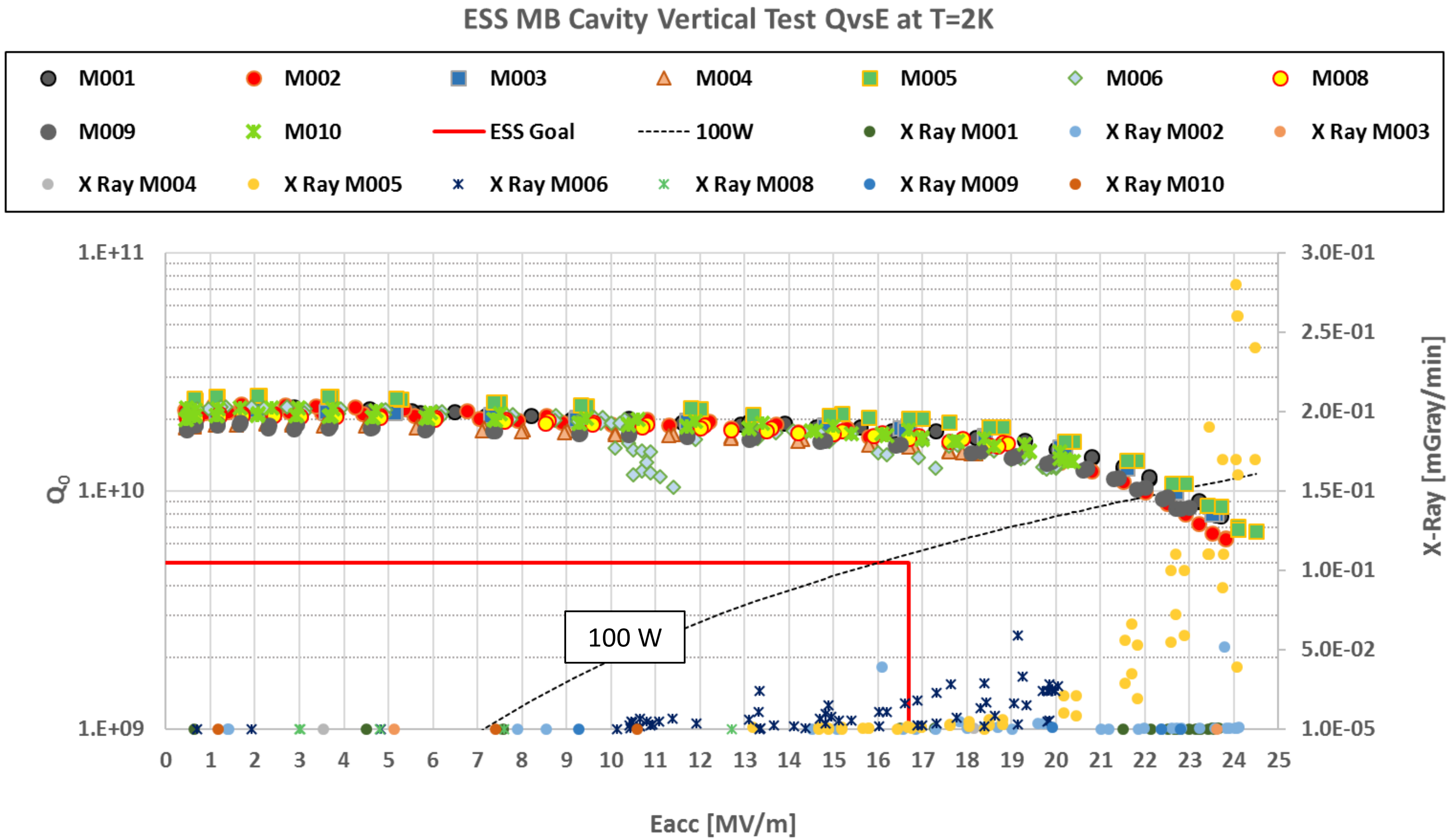
Qualification of dressed cavities at DESY AMTF

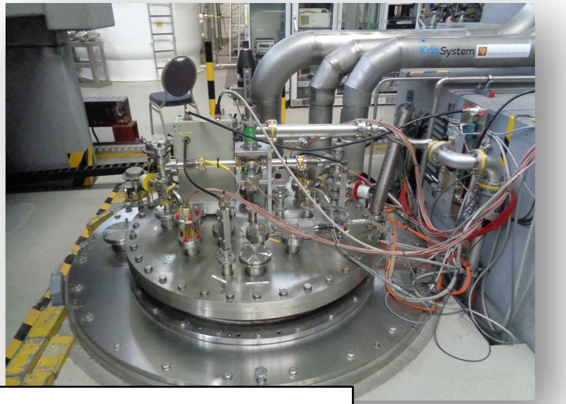
Q vs E_{acc} curve acquired at 2 K temperature only

External radiation measurement by Proportional Counter and NaI scintillator

Criteria of acceptance of the cold RF test:

- $Q_0 \geq 5 \cdot 10^9$ @ 16.7 MV/m
- $Q_{PU} \sim 2\ 10^{11}$
- HOM - at least 5 MHz away from 5th ML





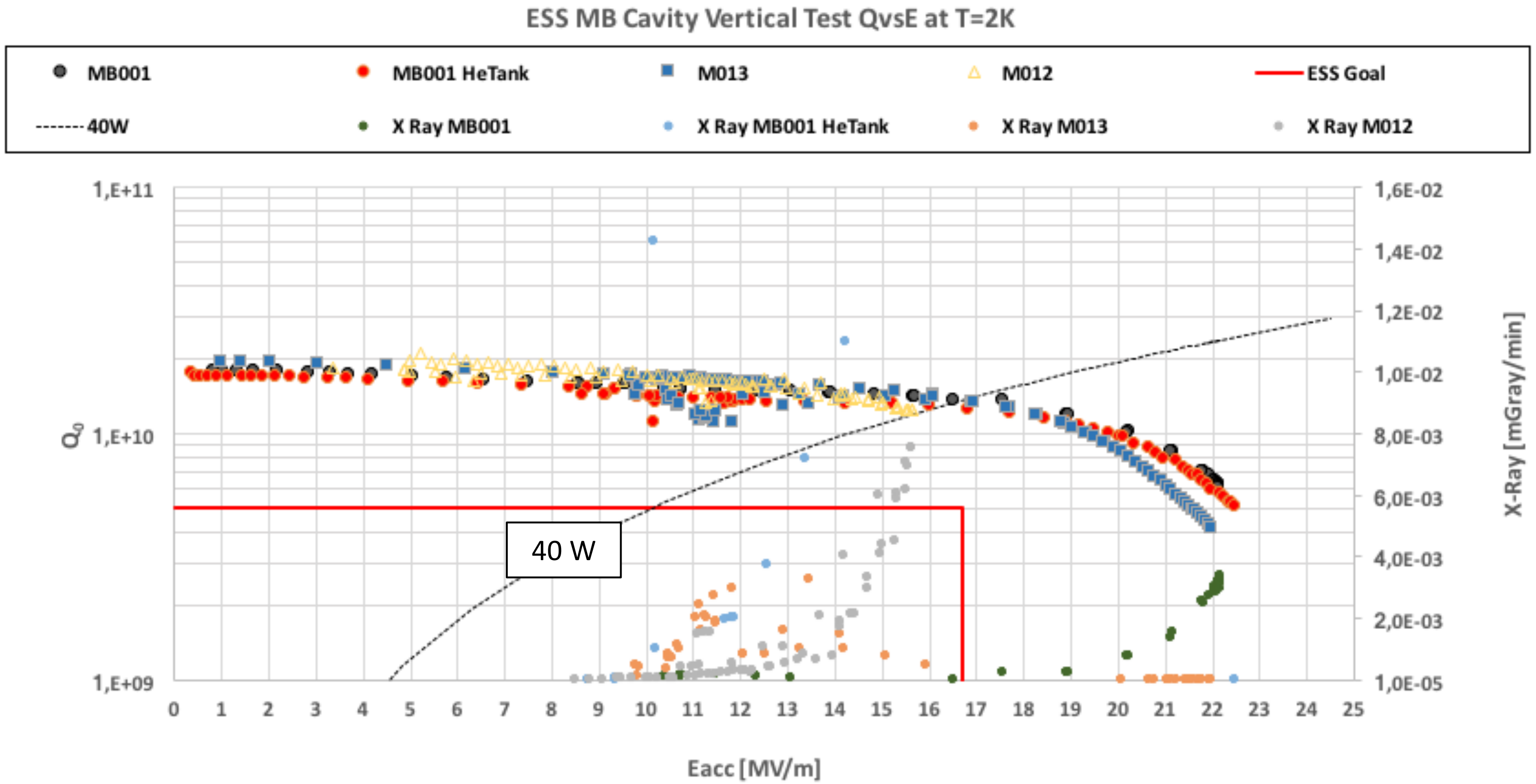
ESS insert at AMTF

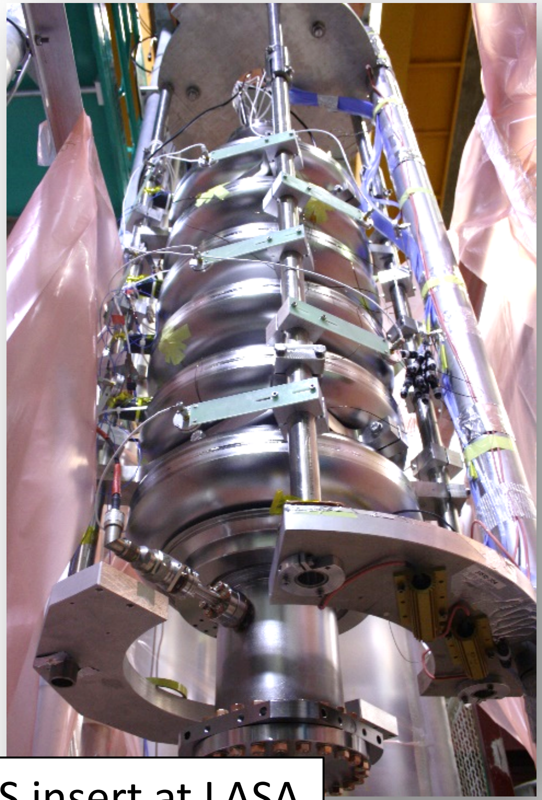
Additional VTs of undressed cavities

Cavity	Issue	VT	Current Status
M004	Grinding – not fully penetrated EBW	DESY	OK
M006	Grinding - pitting	LASA	Quarantined
M010	Pitting w/o grinding	DESY	OK
M013	HT in refurbished oven	LASA	OK
M012	Pitting w/o grinding	LASA	Pending

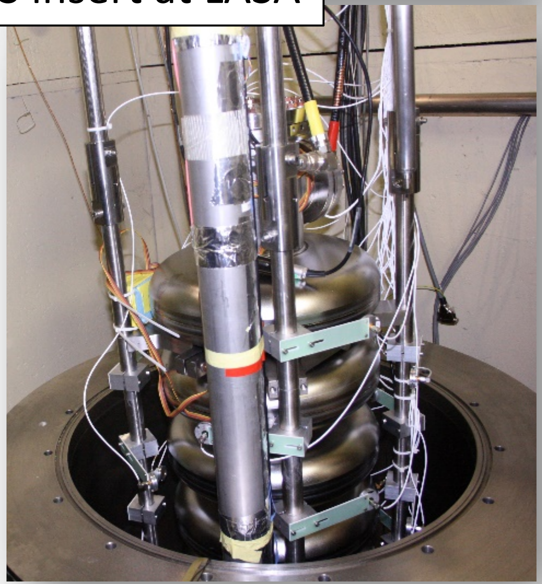
LASA facility used for cavities that required dedicated VT with lower T or diagnostics:

- X ray spectroscopy
- Photodiode for cryo X-ray detection
- Second sound
- Fast thermometry

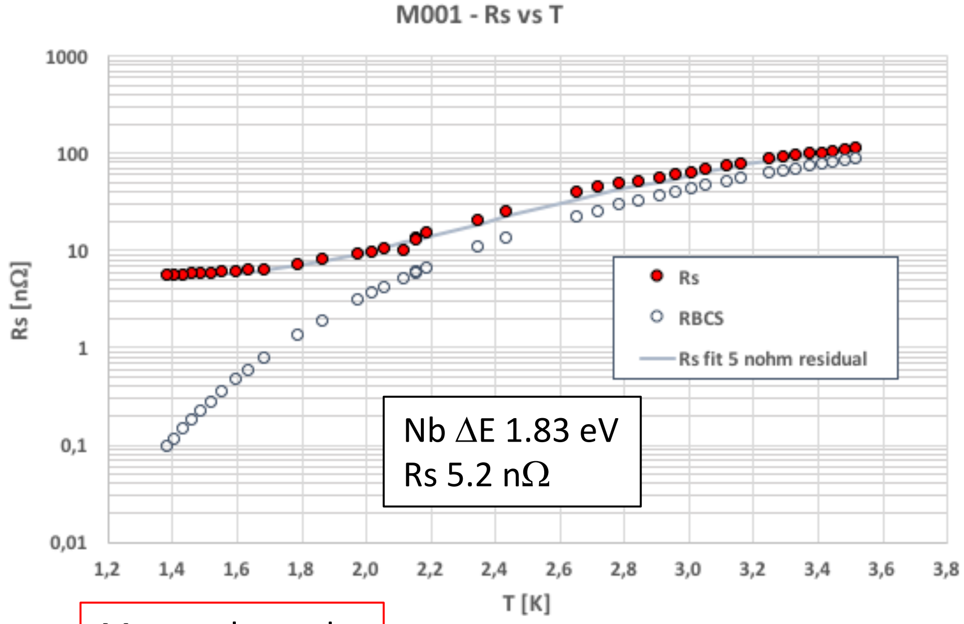


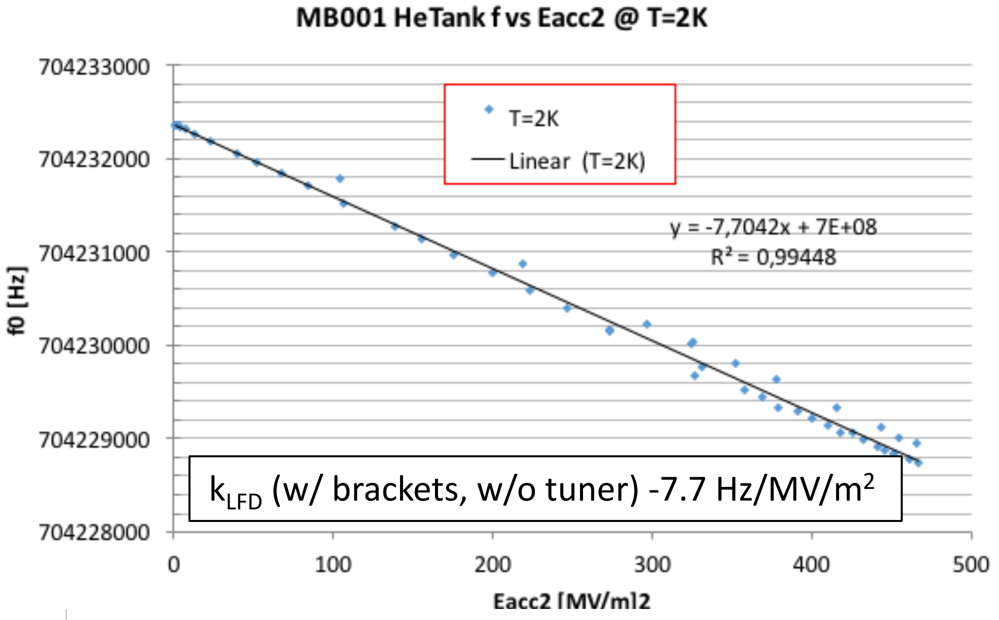


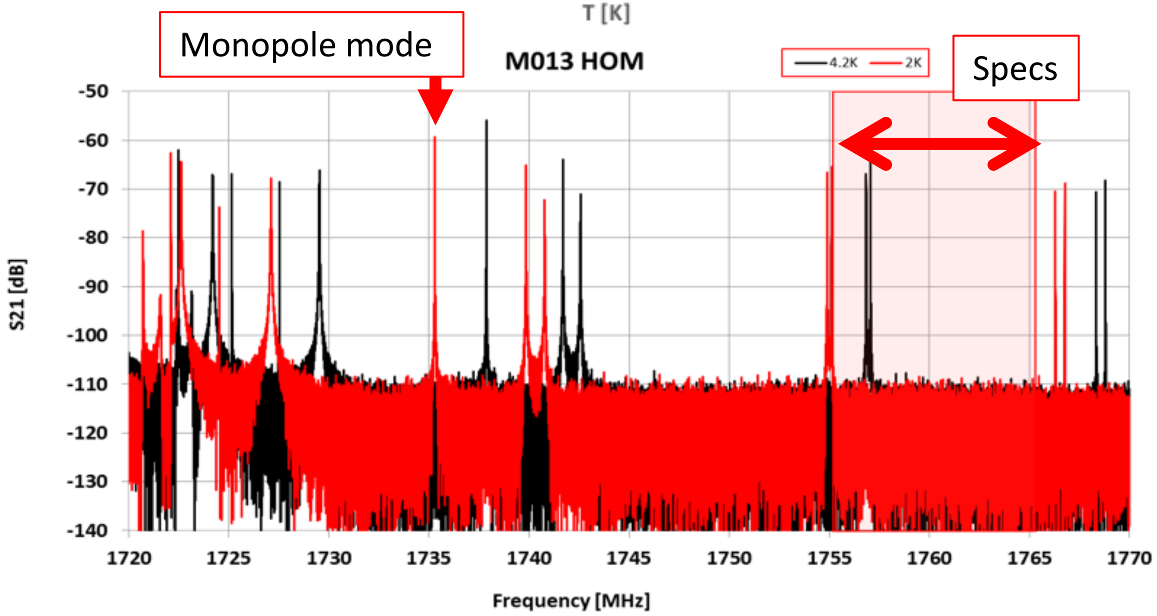
ESS insert at LASA

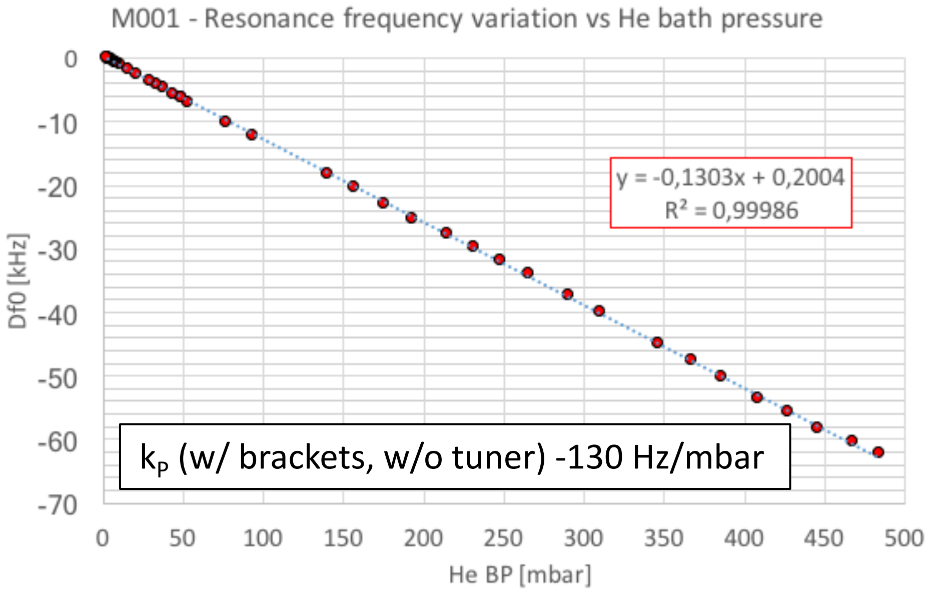


Example of additional measurements









Further efforts

- Analysis of cavity diagnostics
  - Quench spot detection with second-sound trilateration and fast thermometry
  - Radiation dose and spectrum: end-point, continuous registration
- Defect detection and analyses
  - Pitting (spherical / round shape) on the equator area (HAZ boundary) typically found during optical inspection after the bulk BCP (≈200 μm) on a few cavities.
  - No defect or any kind of foreign structure visible before the bulk BCP during the optical inspection
  - Replica, 3D microscopy, SEM analysis of local defect
- EZ oven requalification
  - RRR measurement as well as GDOES and SEM analyses on samples