Hot Topic: Processing and testing of large elliptical cavities (<1 GHz) for hadron linacs

TESLA Technology Collaboration Meeting

4 - 7th February 2020

TTC Meeting Scientific Program Committee:

Hans Weise (DESY), TTC Chair
Frank Gerigk (CERN), LOC Chair
Sergey Belomestnykh (FNAL), Eiji Kako (KEK),
Robert Laxdal (TRIUMF), Wolf-Dietrich Moeller (DESY),
Paolo Pierini (ESS), Akira Yamamoto (KEK/CERN)

Hosted by CERN

Geneva, Switzerland
https://indico.cern.ch/e/TTC2020

CERN

Grigory Eremeev
Paolo Pierini
Peng Sha

TESLA TECHNOLOGY TTC COLLABORATION

Charge

Several upcoming accelerator **projects** (ESS, PIP-II, SNS upgrade, FRIB upgrade, eRHIC/JLEIC, FCC, CEPC, …) utilize multi-cell elliptical cavities operating at sub-GHz frequencies and medium accelerating gradients.

While the community strives to reach the "**golden standard**" of 1.3-GHz cavities, there are still several technological challenges remaining, from design to the cavity performance in an accelerator.

The **hot topic discussion should concentrate on these challenges**, among which are: cavity design (high Lorentz Force Detuning, helium vessel integration, …); fabrication and handling due to size/weight; processing to achieve high Q and FE-free cavities; challenges during bare and dressed cavity testing; etc.

It is important for the community to start collecting and analyze data and develop performance indicators.

Invitation to community

Dear Colleague,

At the next TESLA Technical Collaboration (TTC, CERN 4-7 February) meeting we will have a “Hot Topic” session on "Processing and testing of large elliptical cavities (<1 GHz) for hadron linacs”. The charge of this session is at the end of this message.

With this message we kindly invite you to **share a few (1-3) provocative slides on any specific challenge you expect (or are already experiencing)** in your activities and projects which involve processing and testing of large elliptical cavities. These will be summarized and used as a base for a discussion in the session. **No formal talks** are foreseen for the "Hot Topic" session. We are circulating this message to representatives of many projects worldwide involved in this activity and to industrial representatives. If you feel you are not the best contact for this task or have no time, please suggest us one of your colleagues who may help us.

As a guideline for the session discussion, we are asking your opinion regarding questions in the following short questionnaire:

“Questionnaire”

1. What are the challenges in the **RF/Mechanical design** of the structures for your project?
2. What are the challenges of the **fabrication and processing workflow**? Can you relate them to the consolidated experience on higher frequency structures (e.g. 1.3 GHz large productions)
3. What are the major challenges in the **testing workflow**? Can you also relate the outcomes to the “golden standard” of 1.3 GHz cavities?
4. **Data collection, sharing and analysis** has proven to be a great asset for the 1.3 GHz community. What are the plans in your project to share testing data with the community? What systems have you in place? Would be a common database useful for the community (assuming someone has resources for its implementation)?

Scenario (pls. forget about RF design details)

Ongoing: Series of 120

Possible: >500

	America					Europe			Asia			
	PIP-II		BNL ERHIC ERL	FRIB	SNS	ESS		MYRRAH	CiADS		CEPC	CSNS
	LB650	HB650		energy upgrade	upgrade	MB	HB	upgrade (200-700 MeV	E062	E082	CEPC	Upgrade (300/440 MeV) B065
	SOON					**ONGOING**		Proto 2023 Series 2027				
Cavity number per cryomodule	4	6		5		4	4	4	4	4	6	4
Operating mode	CW	CW	CW	CW		Pulsed	Pulsed	CW	CW	CW	CW	Pulse
Frequency [MHz]	650	650	647.4	644		704.42	704.42	704.42	650	650	650	648
Number of caviies in Linac/Production batch	**42**	**38**	**144**	**55**		**36**	**84**	**60**	**40**	**24**	**240**	**20/36**
Numer of cells	5	5	5			6	5	5	6	5	2	5
Processing	EP N-doping?		120 um heavy BCP, 600 C 10 hr bake and 20 um light BCP)	EP?		200 um Bulk BCP, 600 C bake, 20 um light BCP			EP	EP	EP	
Production database						at INFN, private	at STFC, private					
Testing Database						at INFN, private	at STFC, private					
High level cavity performance data (Q vs E, rad levels, …)						at ESS, public	at ESS, public					

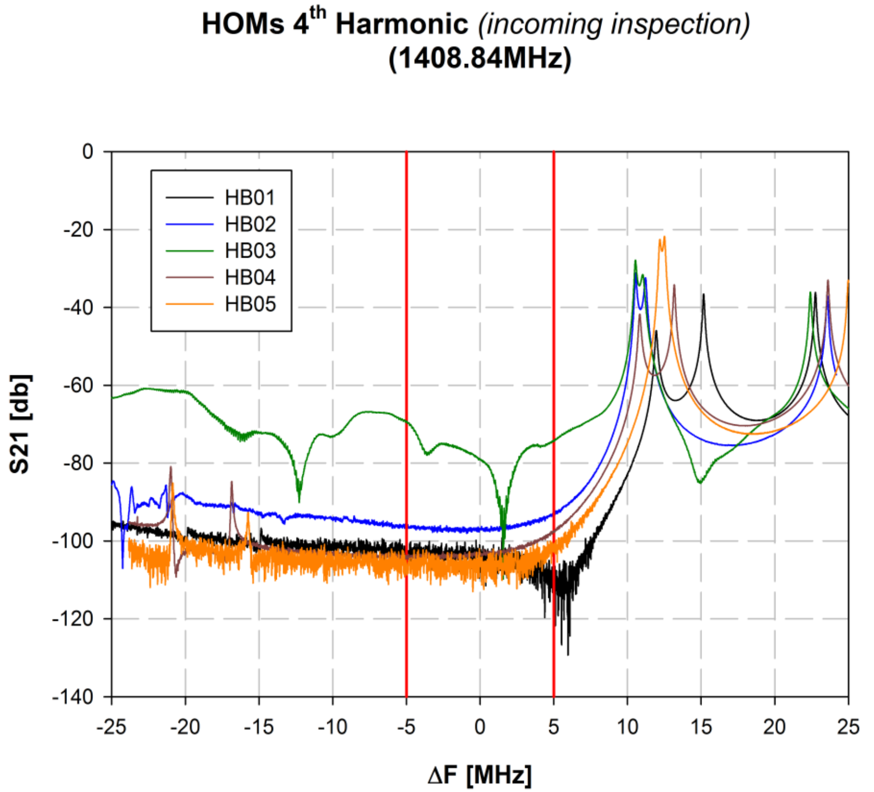
Europe/Contacted

- CEA/ESS – Contributed by E. Cenni
- INFN/ESS – Contributed by M.Bertucci
- STFC/ESS – Contributed by A. May
- ESS – Contributed by C. Maiano
- MYRRAH – Contributed by Dirk Vandeplassche
- CERN/High gradient R&D - Contributed by Alick MacPherson
- CERN/CuNb 400 MHz LHC/FCC - Contributed by David Smekens
- RI
- EZ

ESS ELLIPTICAL CAVITIES AT CEA

1. What are the challenges in the RF/Mechanical design of the structures for your project?
2. What are the challenges of the fabrication and processing workflow? Can you relate them to the consolidated experience on higher frequency structures (e.g. 1.3 GHz large productions)

During design phase the main challenges were related to the HOMs spectra, any TM HOMs should be away from the machine line by more than 5MHz, this required a fine tuning of the cell shape.
This challenge remained also during manufacturing phase were there tolerance on the shape were reduced from 0.6mm (first two prototypes) to 0.2mm (next 6+5 prototypes) to better control HOMs frequency.



ESS ELLIPTICAL CAVITIES AT CEA

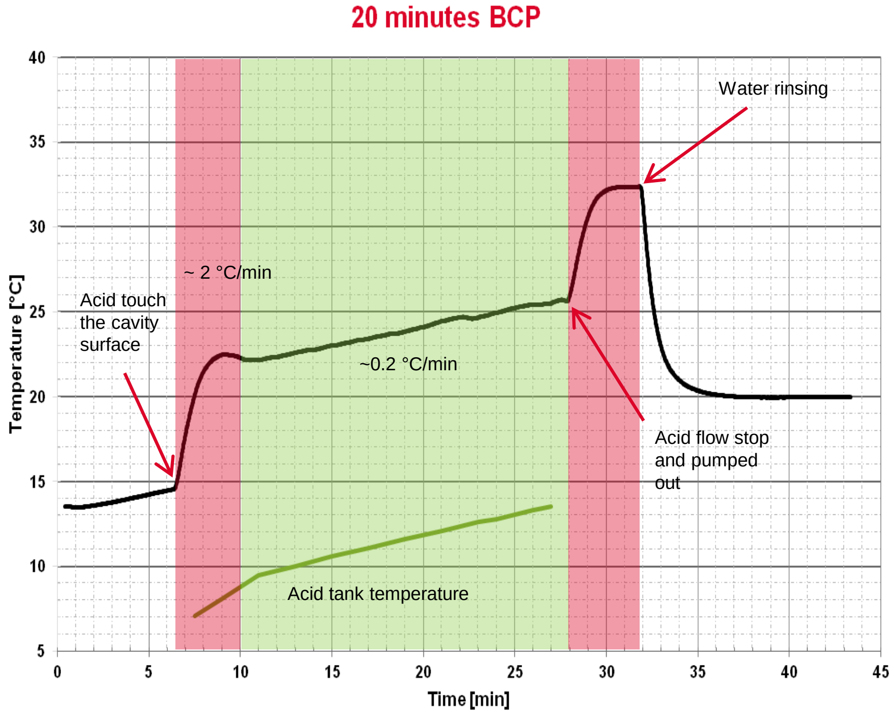
2. What are the challenges of the fabrication and processing workflow? Can you relate them to the consolidated experience on higher frequency structures (e.g. 1.3 GHz large productions)
3. What are the major challenges in the testing workflow? Can you also relate the outcomes to the “golden standard” of 1.3 GHz cavities?

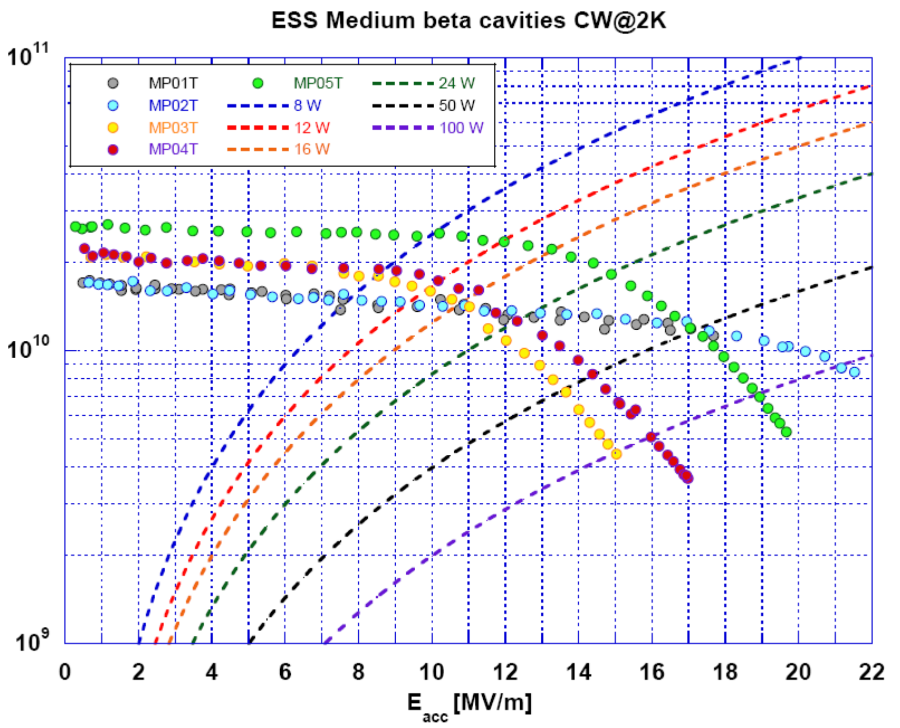
- Tooling and clean room: Some challenge is related to the dimensions of the cavity, specific tooling shall be designed in order to manipulate and transport the cavity inside clean room and outside it, cavity weight is in the region of 100kg.
  - What are the solution in other labs?
  - Which level of automatization/robotization are implemented if any?
- Chemistry and clean room:
  - Usually these cavities are prepared with BCP, we had issue to control the acid temperature due to the large quantity needed (about 70 liters) with respect to the acid tank capacity (200 liters). Someone has investigated this issue? We tried with an external cooling (water spray), still we had better results with larger acid tank.
  - Someone is trying different acid mixture?
  - Someone is trying EP? Which are the issues and results in terms of performance? Are they comparable to 1.3GHz? (On our side we are starting with Vertical electro-polishing equipped with rotating cathode (Ninja_cathode))
  - Field emission does not affect performance much, but it is quite often present and strong. We struggled with HPR (cell shape have different angle and dimension than Tesla-cavity), does exist some design tool/simulation for HPR nozzle?
- Testing:
  - Cooling speed and thermalisation are obviously affected by the cavity mass, at best we reach about 4K/min what are typical values in other installation?

4. Data collection, sharing and analysis has proven to be a great asset for the 1.3 GHz community. What are the plans in your project to share testing data with the community? What systems have you in place? Would be a common database useful for the community (assuming someone has resources for its implementation)?

In our lab there is no real database system (it used to be one based on Microsoft Access), but all data sheets have roughly the same format that could be “easily” imported.

Could be a really valuable source of information to a have common database. Especially during design and prototyping would be very useful to have information about other similar projects, in particular facing issue that are quite common at these stage.(A community repository? With data and issues that worth to share)





ESS 704.2 MHz β=0.67 production

36 (+2 spares) 6-cell cavities. Specifications: E_{acc}=16.7 MV/m with $Q=5\cdot10^9$

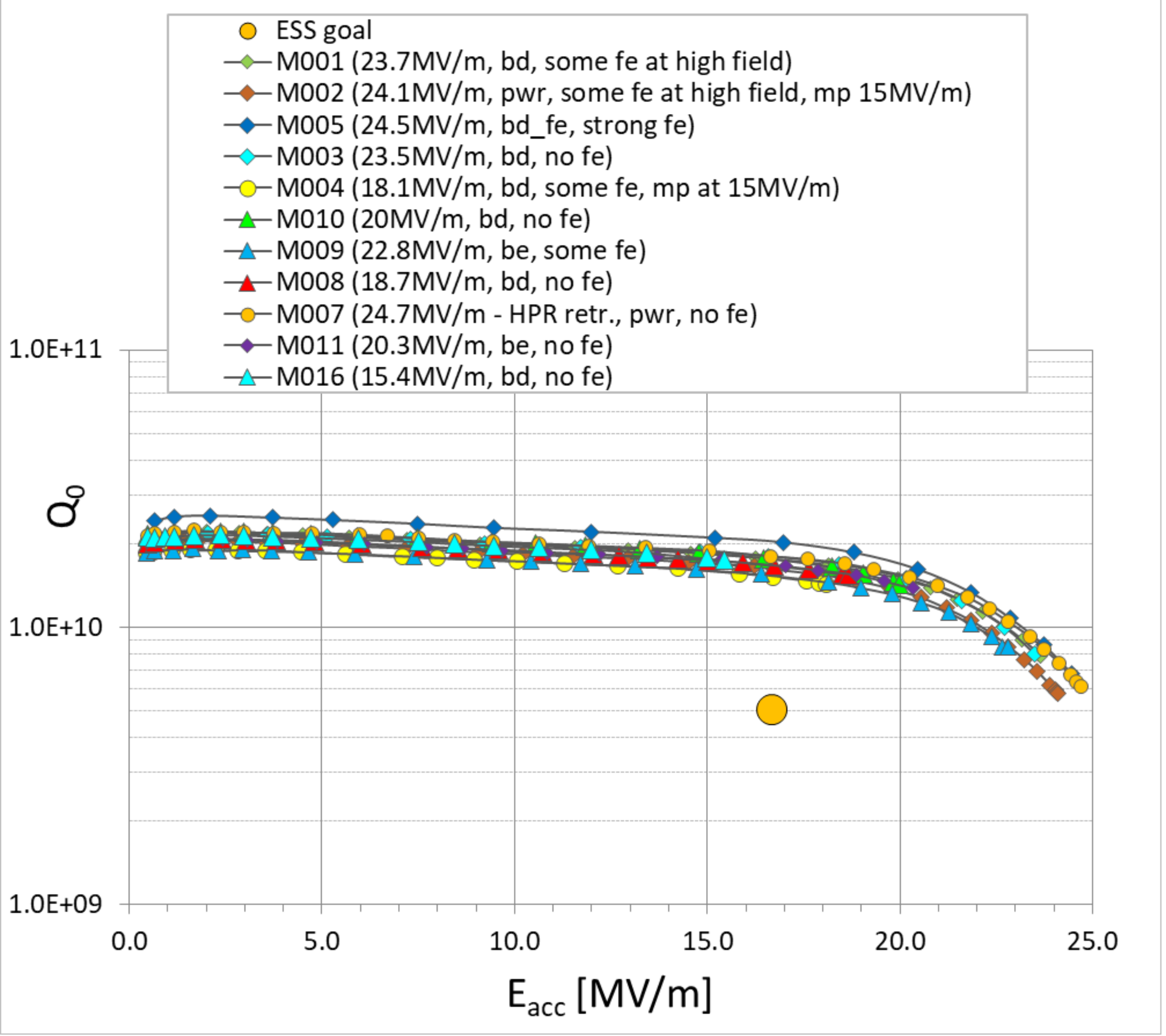
Recipe:

- Fine grain material from Ningxia, RRR>300
- Each sheet scanned with eddy current technique
- 200 um Bulk BCP (90 um MC up, 110 um MC down)
- 600°C HT for 10h
- 20 um final BCP after tank integration

Acceptance criteria for vertical tests:

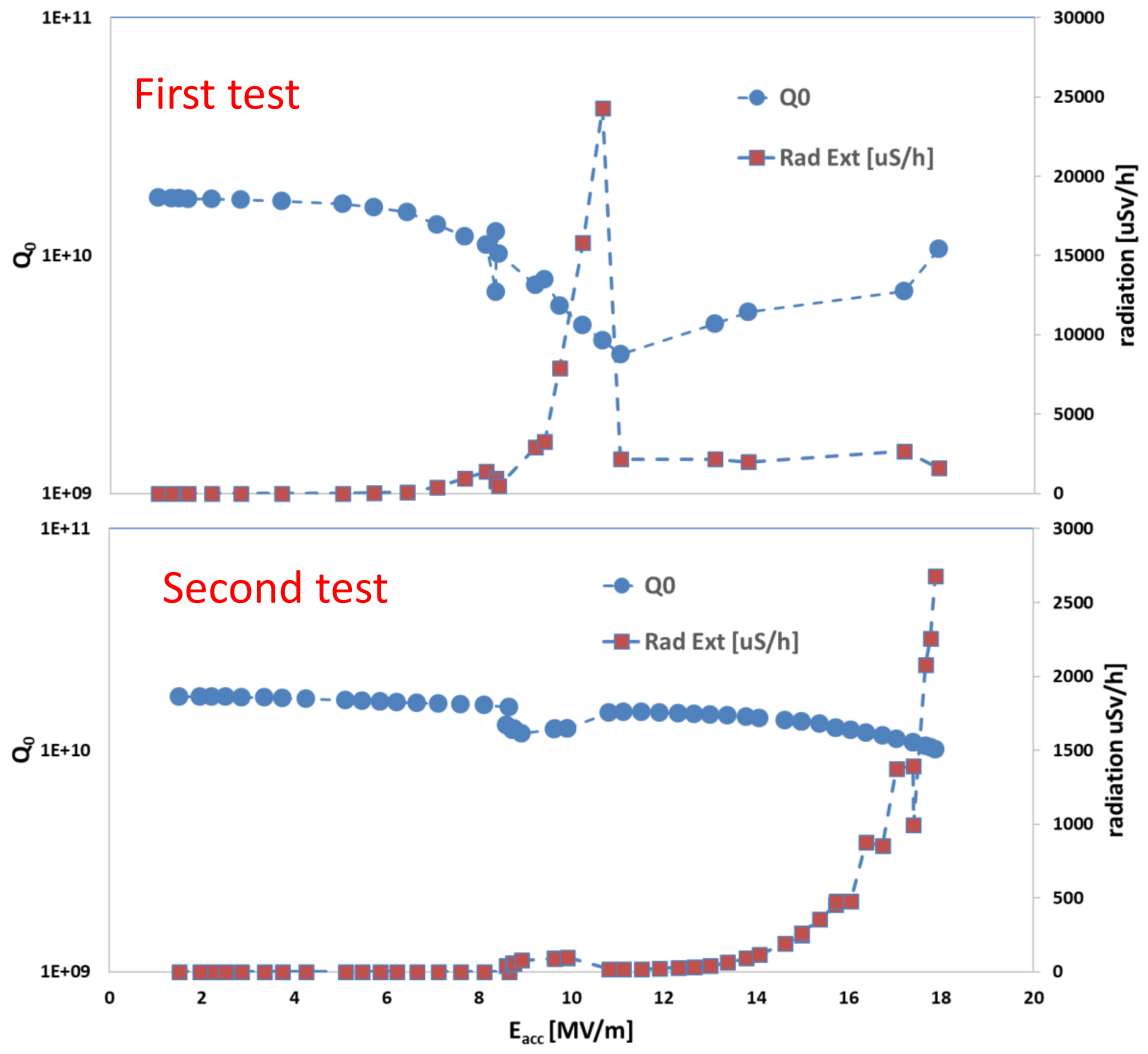
- if everything goes smoothly: with tank @DESY's AMTF
- If something unexpected occurs: without tank@INFN-LASA with full diagnostics
  - second sound, photodiodes, radiation detectors, fluxgate, fast thermometry…
  - Possible further actions: defect grinding, additional BCP etching, HPR…

Current status of tested cavities

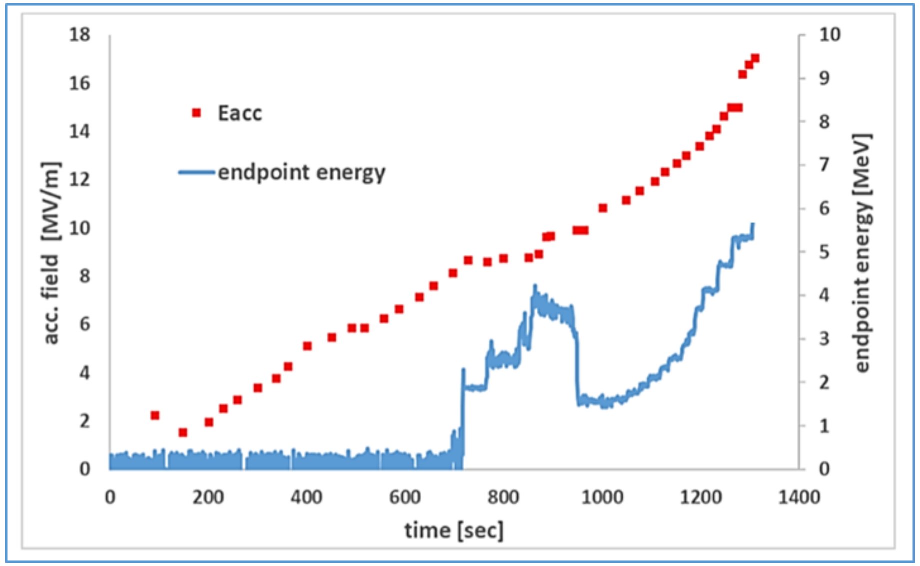


- The best ones: power limited at 24-25 MV/m
- Many of them: hard quench above the spec. gradient
  - In the tests @LASA, second sound analysis usually localizes geometric features near welding
- Some of them: high FE levels, associated with strong MP barrer in the 9-14 MV/m range, succesfully rf conditioned
  - High electron impact energies (up to 5 MeV) according to detectors, despite non-synchronous acceleration (low beta)
- M006: high FE with strong MP barrer only partially conditioned.

Test of M006 @LASA



- First test: high radiation in the MP barrier, Q degradation from 7 MV/m, quench at 18 MV/M (geometric defect)
- RF conditioning at 9 MV/m for some hours
- Second test. Now two zones:
  - MP barrier with drastically reduced radiation level
  - Unchanged FE level at higher field (following Fowler-Nordheim law)

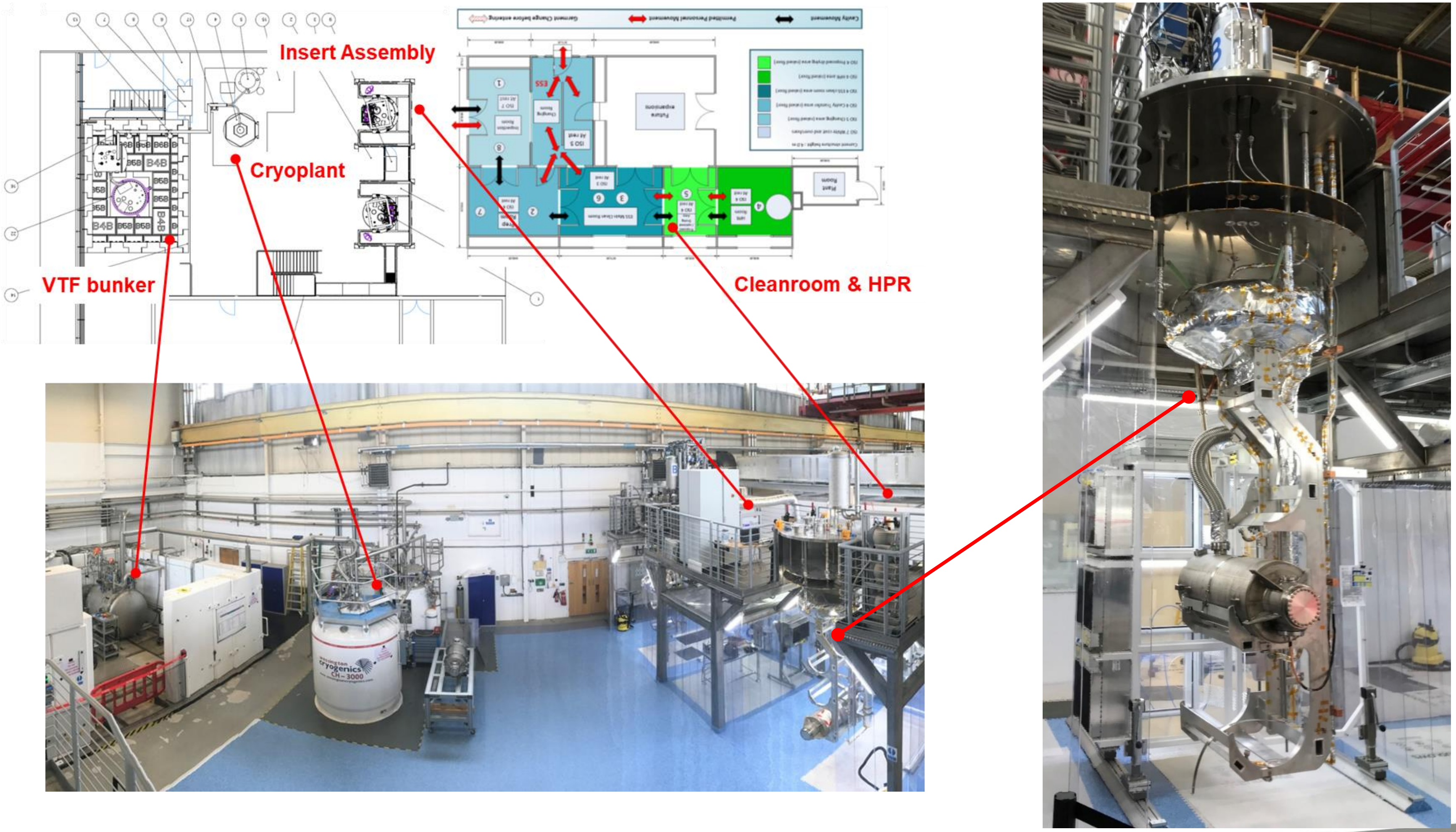


- Cavity integrated, HPR, 20 μm BCP, then shipped to DESY
- Third test @DESY: MP still persists, slightly worsened

lessons learnt and some questions

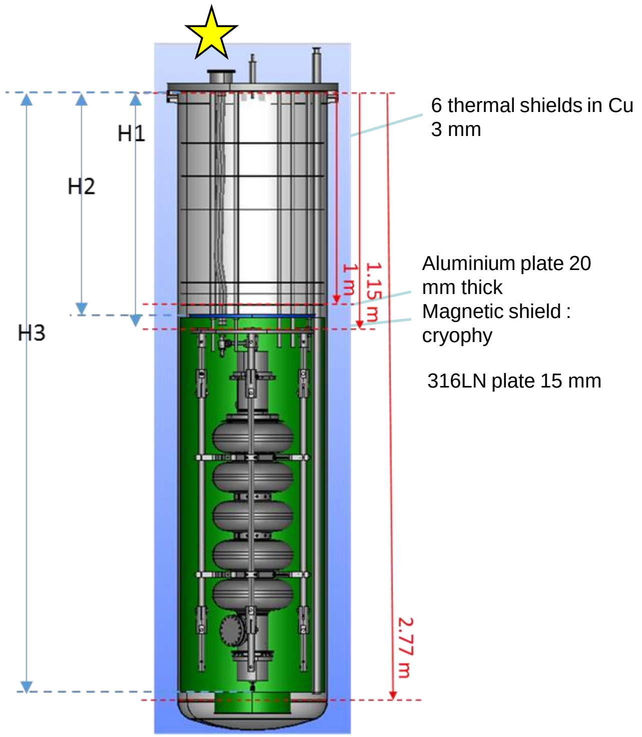
- Sometimes associated with high levels of radiation (FE) at moderate energy (some MeV, below threshold for neutron activation)
- Soft barrier in the 8-14 MV/m zone as predicted by simulations and by the empirical rule for two-point MP onset: $B[mT] = 56 * f[GHz]$
- Some hours of RF processing can often heal MP, but not always
- What are the issues for the operation of a pulsed machine? (even if far from operating gradient)
- Is it linked to non-uniform BCP etching? e.g. pitting, surface roughness…
- What about EP'd low frequency cavities?
- What is the effect of beta-factor? (i.e. cavity geometry)
- What to do in case of persistent MP? better if without tank removal...

New vertical test facility and HPR cleanroom commissioned



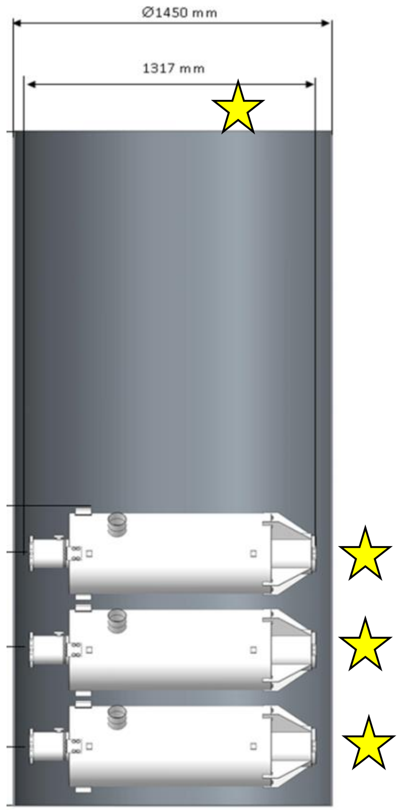
Comparison of radiation measurements for same cavity between vertical cryostats

Collaborator cryostat



	H1 [mm]	H2min/H2max [mm]	d	r
Insert C (ESS)	1240	1110/ 1220	12	325

Daresbury cryostat



Collaborator configuration for radiation measurements

STFC much closer to ends of cavity~30cm

Different type of detector

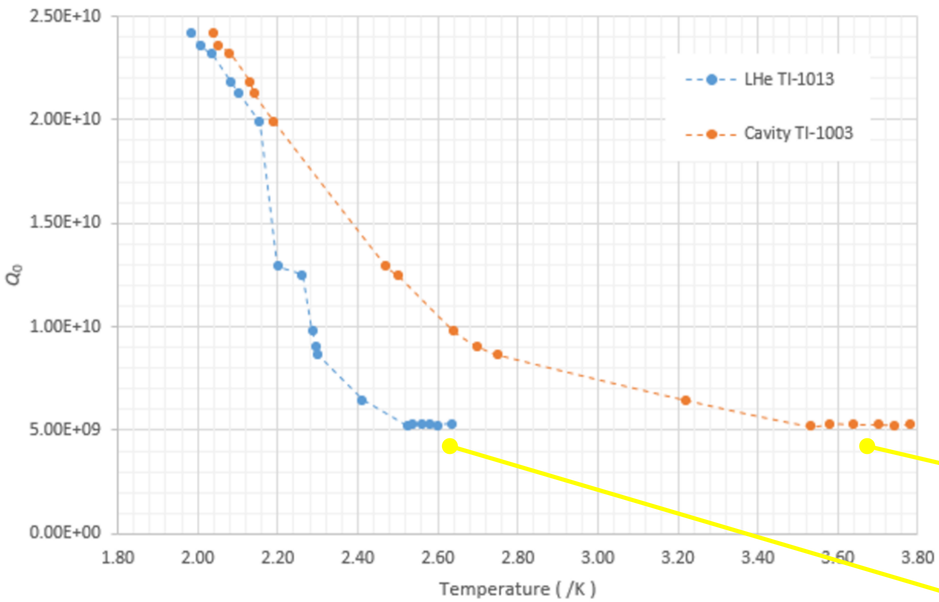
Much less shielding

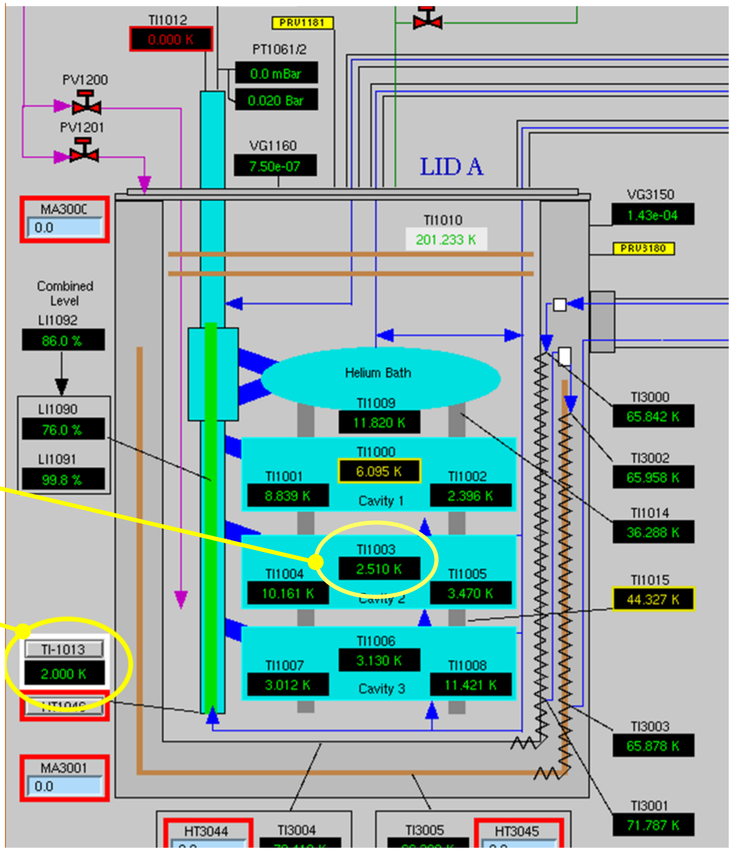
Any way to get good agreement?

Metal between detector & cavity (collab.)
Top plate =29mm
6x3mm Cu =18mm
Al Plate =20mm
316LN plate=15mm
Total~82mm

Distance from detector to cavity ~1m

Q vs T measurements





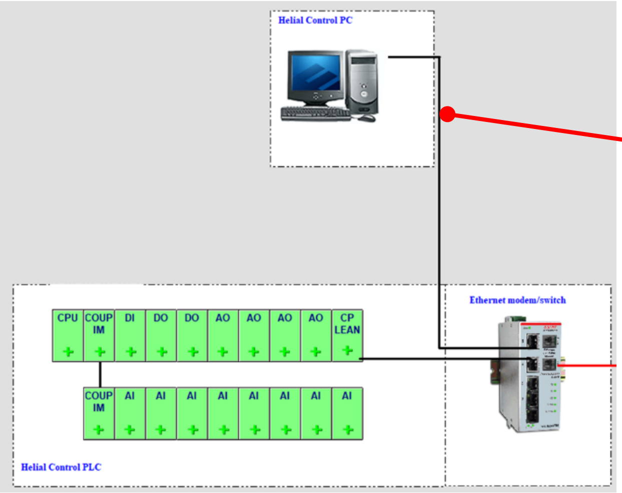
Pumps backed off and Q sampled whilst allowing temperature of liquid to rise slowly

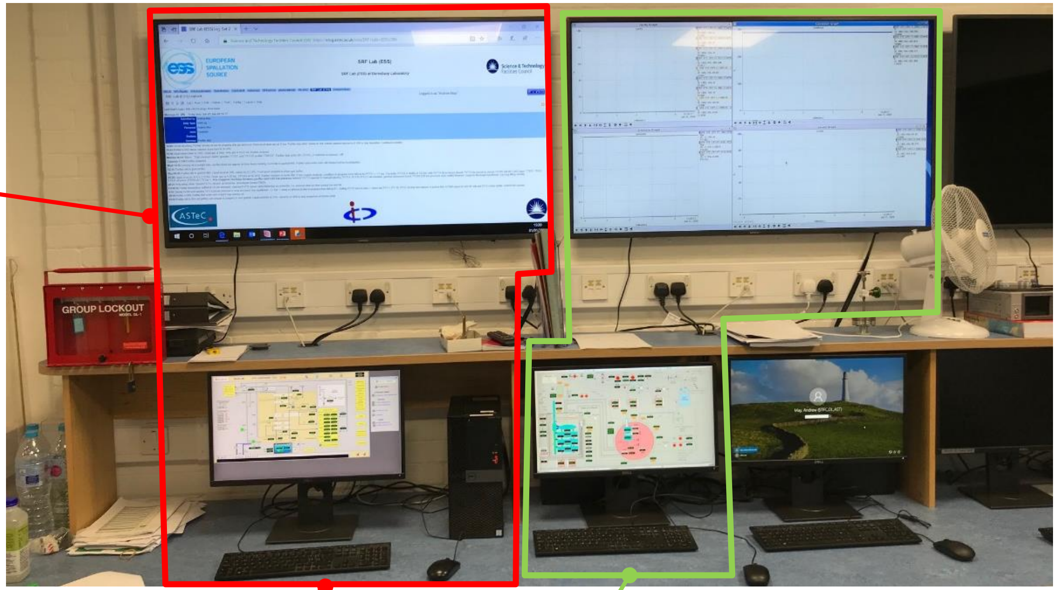
Below λ-point, very small ΔT between liquid and cavity jacket and across cavity => cavity temperature quite tightly constrained

Above T_λ, larger ΔT => gradient across cavity, temp less certain

Is there a way to get cavities ~isothermal for each measurement above T_λ?

Interlocks between Hélial and cryostat control





Two standalone systems:

1. Hélial control PC reading from Hélial PLC
2. Cryostat control PC reading from rack (thermometry, pressure gauges, radiation monitors, etc.)

Both systems have extensive set of interlocks

Ideally, we would like to be able to add to these by reading in pressure values, liquid level, etc. from Hélial, would also allow us to continuously monitor He inventory

Any other groups have experience with this?

ESS - Lund

#4 Cavity DB

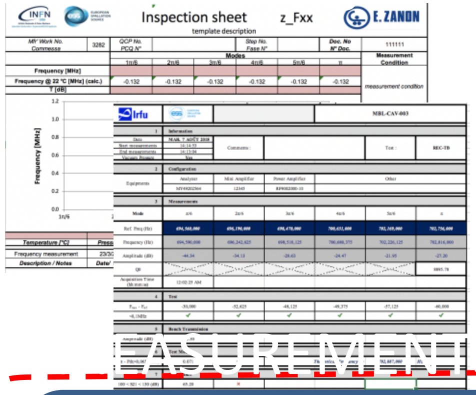
- We receive **Cav/CM from IK**, but **need data for the cavities handover and module testing phase**
  - Cavities send from Cavity IK to Module IK, acceptance by ESS at handover
  - Cross checks performances VT/CM
  - Use calibration data from VT
  - Will collect more data during our testing
- We are retrieving data from IK and **estabilishing a DB**
  - Also a requirement by the licensing process for Asset Management at ESS (cavities and CM as Assets)
  - Our tool to handle the handover process Cavity IK -> CM IK -> ESS reception
  - Multi-Tier operation, many partner involved
    - E.g. INFN cavities (MB) tested at DESY
  - Only a **subset of the data available at IK** are collected, and then extended with our measurements
    - Reference passband spectra in defined production/handover/test phases
    - Q vs E curves, and calibration parameters (Qt, k, QL…)
  - Correlation of performance with cavity fabrication responsibility of the IK
    - Much lighter DB wrt to XFEL Cavity DB

Cavity data at ESS

Following requirements for long term maintenance plan of facility

EUROPEAN SPALLATION SOURCE

IKC
- After fabrication
- Intermediate handover



Transfer (many IK formats)

ESS
- Incoming
- Preparation

ESS Scope

Measurement&Calibration DB (ownCloud service)

https://meas01.esss.lu.se/owncloud/index.php/login

Save

Staging Area (typ. text files or xls)

Script

Normalized Data (HDF files, metadata)

ESS Asset Management ID Installation Structure

ongoing

Tagging (in metadata)

https://gitlab.esss.lu.se/SRF_Section

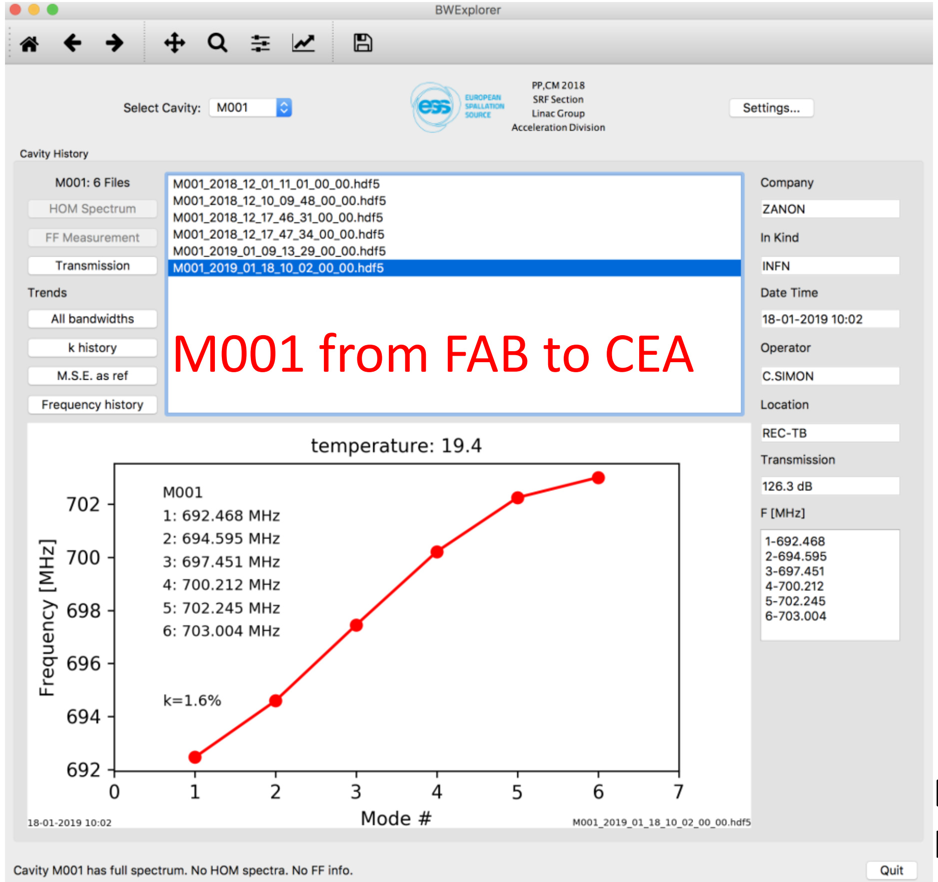
Script

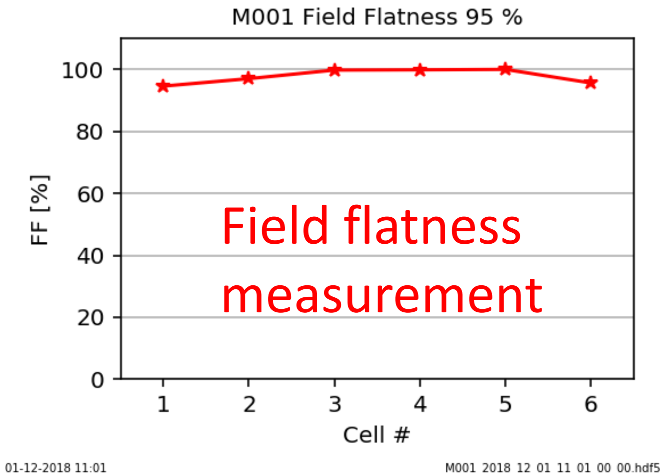
APPLICATIONS
- Browse
- Compare
- Assess

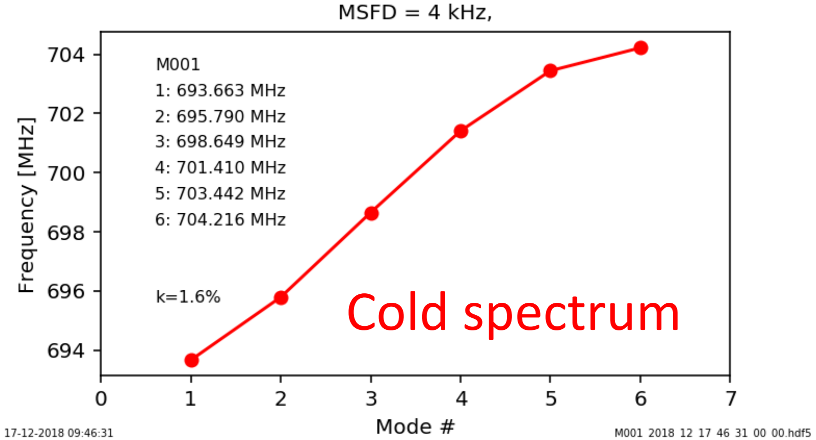
Measured bandwidths & VT

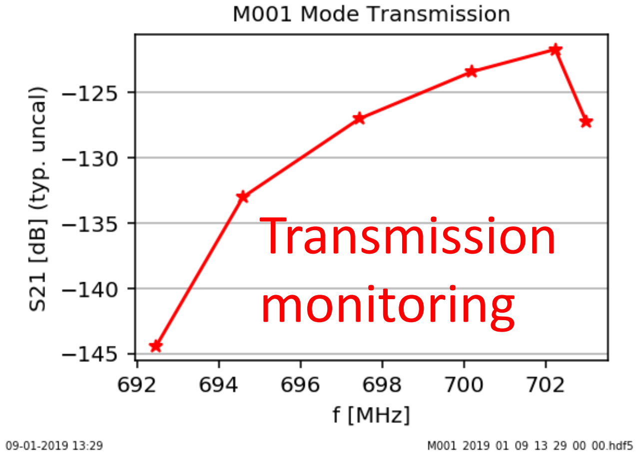
Show fullfillment of specifications or handling the handover conditions

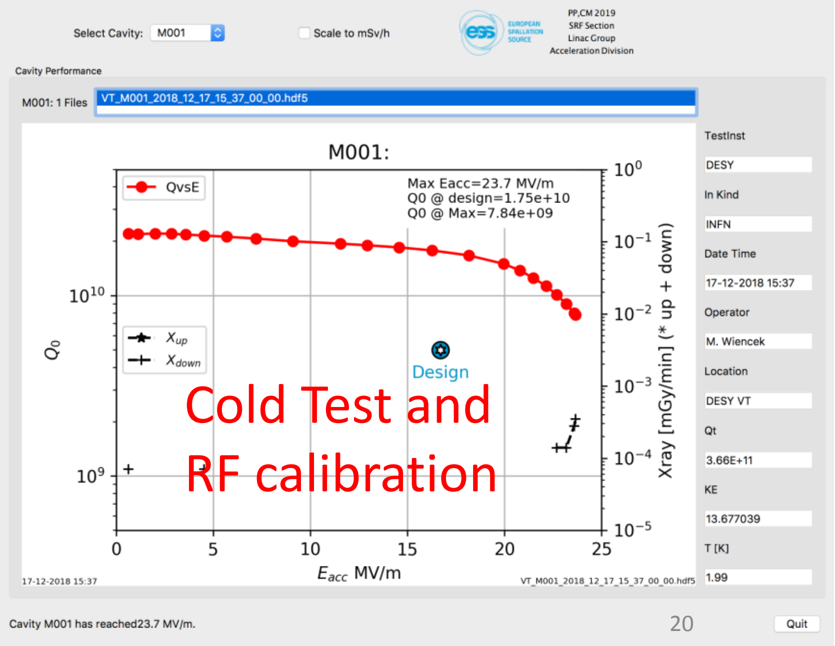
Tools to **browse, display & analyze** the cavity measurements data (warm/cold!)









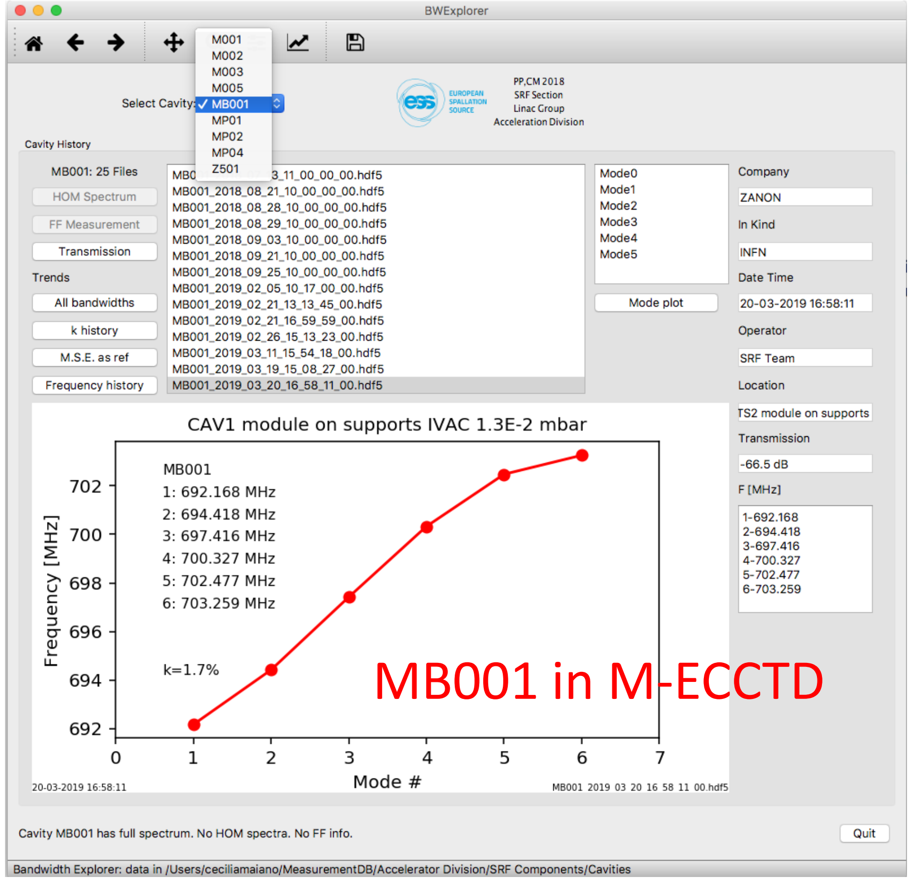


Data taken on cavities at INFN/DESY from INFN DMS (D. Sertore), migrated in ESS DB

Data trends

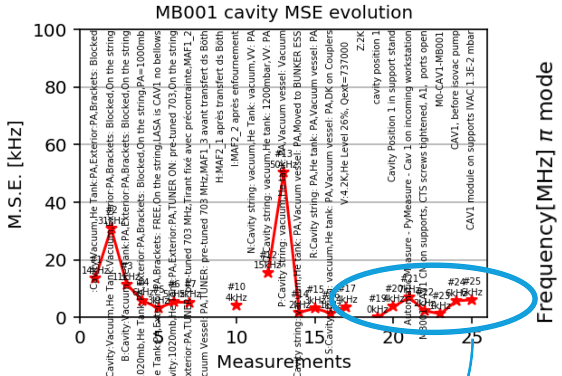
During module lifecycle, below M-ECCTD

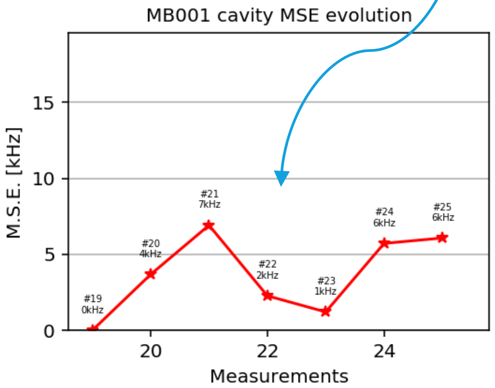
Tool to **browse, display & analyze** the cavity data trends (warm/cold!)



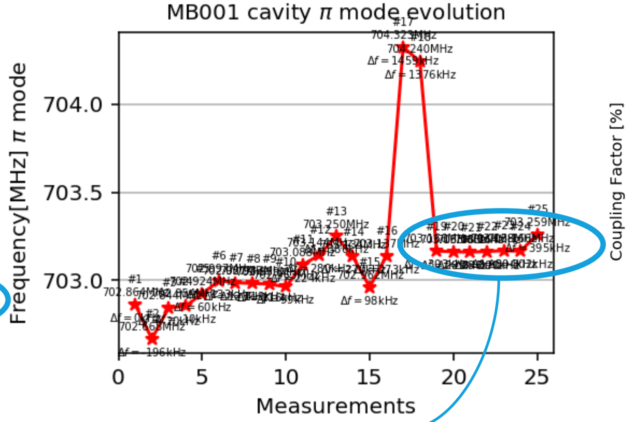
MB001 in M-ECCTD

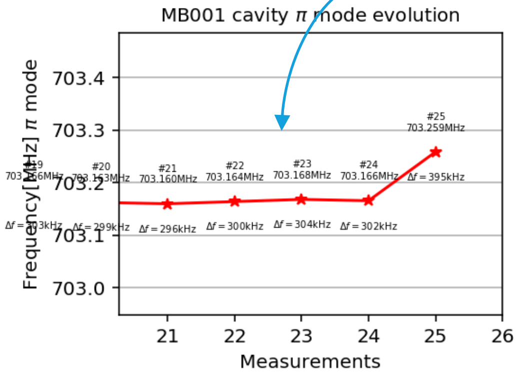
MSE: Mean Spectrum Error



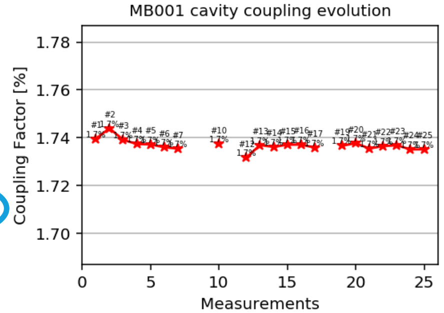


pi-mode



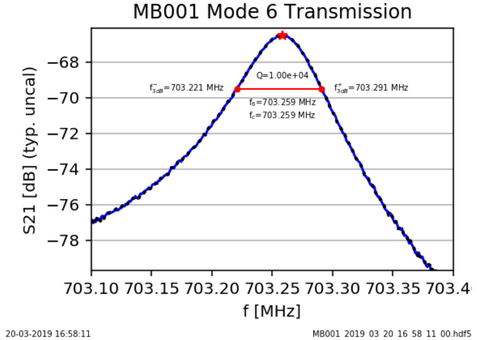


coupling



(...)

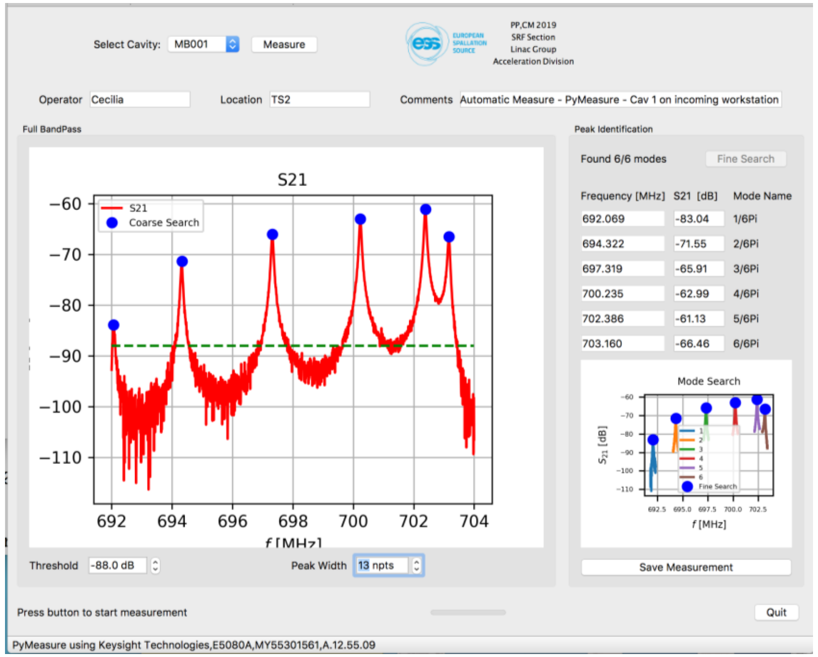
Q values

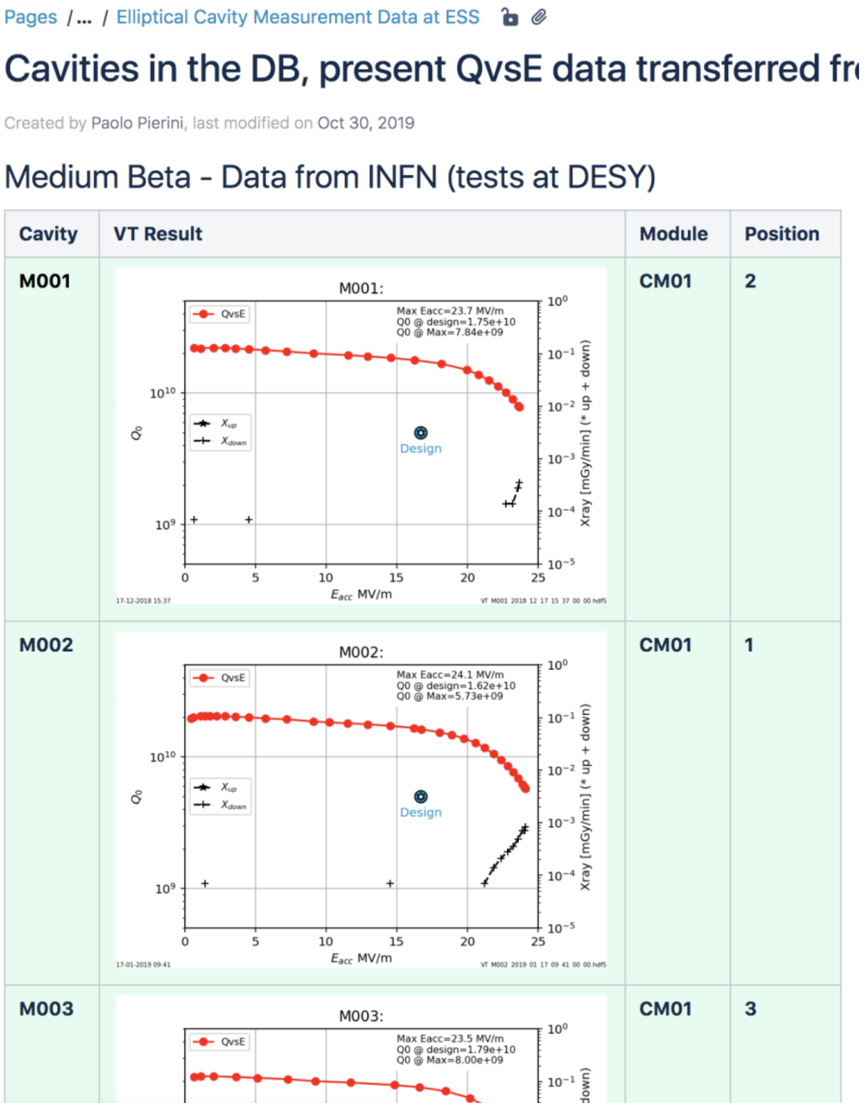


Data taken during MECCTD testing at CEA (E. Cenni), migrated in ESS DB

Cavity measurement tools at ESS

Our data goes live directly on the M&C DB





Accessible within the ESS SRF Collaboration,

- Can be made public
- Will contain QvsE data of all 120+ elliptical cavities
- Fabrication details / analysis need to be addressed with responsible IKs

Ongoing: Series of 120
Possible: >500

	America					Europe			Asia			
	PIP-II					ESS			CiADS			
	LB650	HB650	BNL ERHIC ERL	FRIB energy upgrade	SNS upgrade	MB	HB	MYRRAH upgrade (200-700 MeV	E062	E082	CEPC	CSNS upgrade
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Numer of cells	5	5	5			6	5	5	6	5	2	5
Processing			120 um heavy BCP, 600 C 10 hr bake and 20 um light BCP)			200 um Bulk BCP, 600 C bake, 20 um light BCP	200 um Bulk BCP, 600 C bake, 20 um light BCP		EP	EP	EP	
Production database						at INFN, private	at STFC, private					
Testing Database						at INFN, private	at STFC, private					
High level cavity performance data (Q vs E, rad levels, …)						at ESS, public	at ESS, public					

General

- MYRRHA linac design : elliptical (β = 0.7) 200 – 600 MeV
- linac operation mode : CW
- Scope : 60 5-cell cavities @ 704.4 MHz, 4 cav./cryomodule
- expected nominal gradient = 11 MV/m
- 30% margin for fault tolerance schemes
- tentative calendar :
    - prototyping 2023 – 2026
    - series 2027 – 2029

Source: [TBD]

Questionnaire (1)

1. RF/mechanical design
   - basic geometrical design identical ESS
   - 3 strong specific requirements → challenges
     - CW operation
     - fast full detuning
     - highest achievable reliability/availability
2. Fabrication and processing
   - need for consistent production of highest Q cavities (CW!), probably through new/updated processing techniques → challenge
   - relation to consolidated experience : prototype and ESS

Source: [TBD]

Questionnaire (2)

3. Testing workflow challenges
   - conflict between the need for sufficiently long testing procedures (reliability!) and the foreseeable installation schedule
   - availability of test platforms
4. Plans for sharing testing data
   - nothing in place yet (cfr. calendar)
   - counting on availability of ESS data →
     - convinced about usefulness of common database
     - probability of goodwill in the sense of participating to its elaboration (in spite of MYRRHA being in the nuclear domain)

Source: [TBD]

PED for cavities: a must or nice to have
Hot Topics discussion at TTC 2020

Dr. Alexander Navitski

06. February 2020 – TTC 2020 at CERN

Typical statements from Specifications:

- Cavity fabrication to be performed according to European PED (e.g. ISO9606 and 15614, EN13445) or ASME

  => No further details

Statements left behind but essential for fabrication:

- Fulfilment of the PED norm to which extend required
- Category to be clarified (depending on pressure)

  => determine effort during manufacturing
- Who is “manufacturer” acc. to PED and finally responsible for CE marking if required

  => Normally designer/purchaser as most cavities are built to print
- Material

  => to be placed only depending on PED fulfilment

  => Niobium and Titanium are not generally allowed for pressure vessels

Cost/time vs. “PED” complexity

+ mechanical design in compliance with PED (EN 13445) for load cases
+ 3rd party inspector incl. qualification of material supplier, tracking of material fabrication incl. samples, stamping/re-stamping by qualified operators
+ Radiographic Testing
+ Destructive examination (Baumusterprüfung)
+ Visual inspection (note: no specific standard for niobium welds as part of a pressure equipment, the standard ISO 13919-2 shall be used to assess the quality
+ pressure test together with an external inspector (TÜV)

+ Welding Qualifications (WPQR & WPS; BPQR & BWPS) based on preproduction tests
+ Personnel Qualifications (WPQ, BPQ)
+ Non Destructive Test personnel qualifications

+ micro-/macro investigations of EB samples as POP

In-house visual inspections

“Specialties” of Niobium EB welding vs. PED

- Welding Qualifications done on standardize samples (150 mm x 300 mm)
- Real parts are normally much different in terms of geometry and mass

=> frequently EB parameter fulfilling PED qualification do not work or real parts

=> 1to1 sample required leading to more time, effort, material consumption

Provocative topics

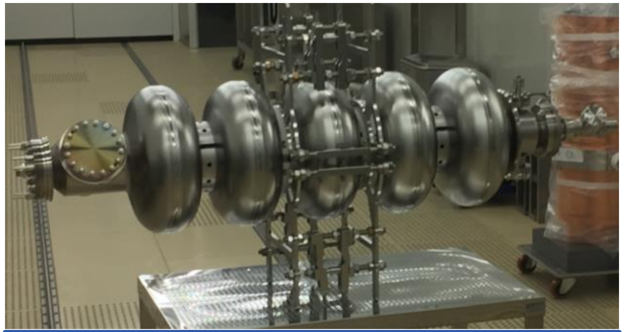
For discussion

- Is fulfilment of PED for cavity required, sometimes it is any way a compromise
- Can cryomodule be the pressure boundary only, it is much easier to qualify as made out of stainless steel

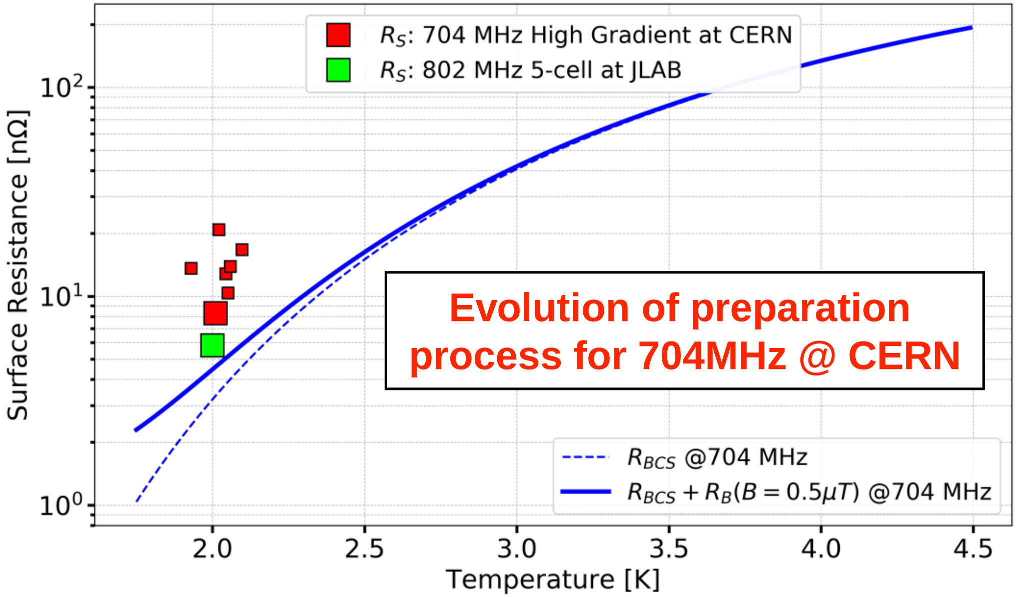
Evolving preparation procedures & RF performance

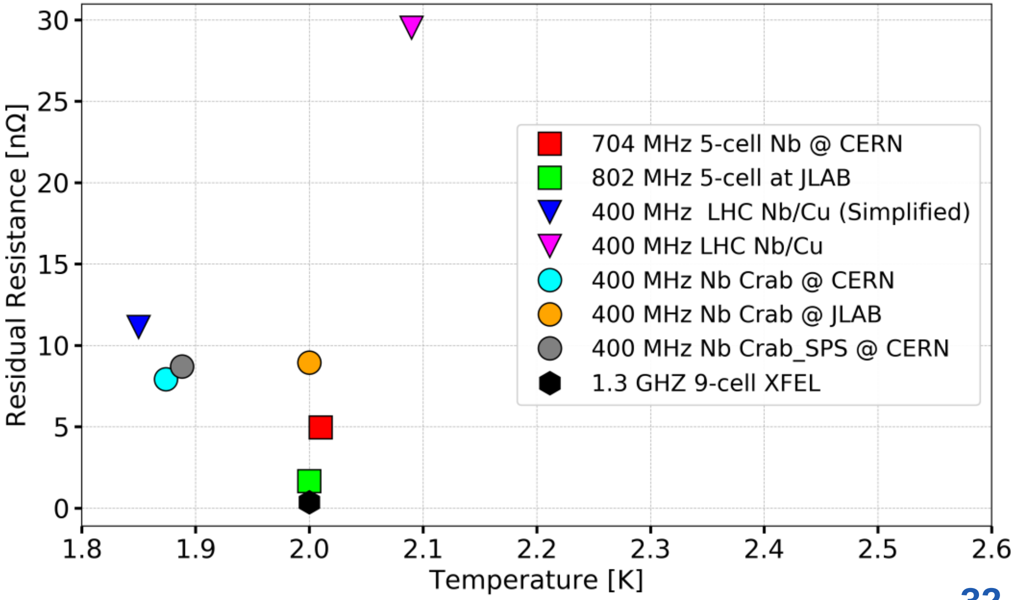
- **Performance comparison with a reference cavity**
  - Calibration of preparation & measurement procedures
    - framework for cross-calibration of labs
- **Comparison of different cavity geometries & sizes**
  - Clear definition of measurement conditions
    - Permits refinement of procedures

FCC 802 MHz 5-cell performance at 2K@ JLAB
E_{acc} = 31 MV/m & Q_0 = 2x10^{10}
Cavity Quench limited (B_{pk} ~ 130 mT)



704 MHz 5-cell performance at 2K@ CERN
E_{acc} = 29.7 MV/m & Q_0 = 1.4 x10^{10}
Cavity not yet quench limited



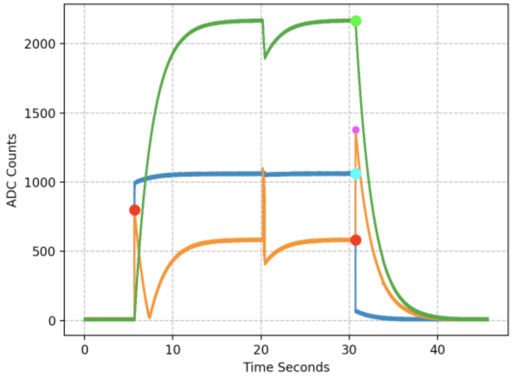


- **Are ‘standard’ configurations for evaluation needed?**
  - Common “working points” for meaningful comparison of results
    - Details magnetic hygiene & procedures, cool down etc
    - Beneficial to both project-focused & developing programs
  - Infrastructure and cost for small series cavity fabrication
    - Need to translate mature 1.3GHz results to larger cavities

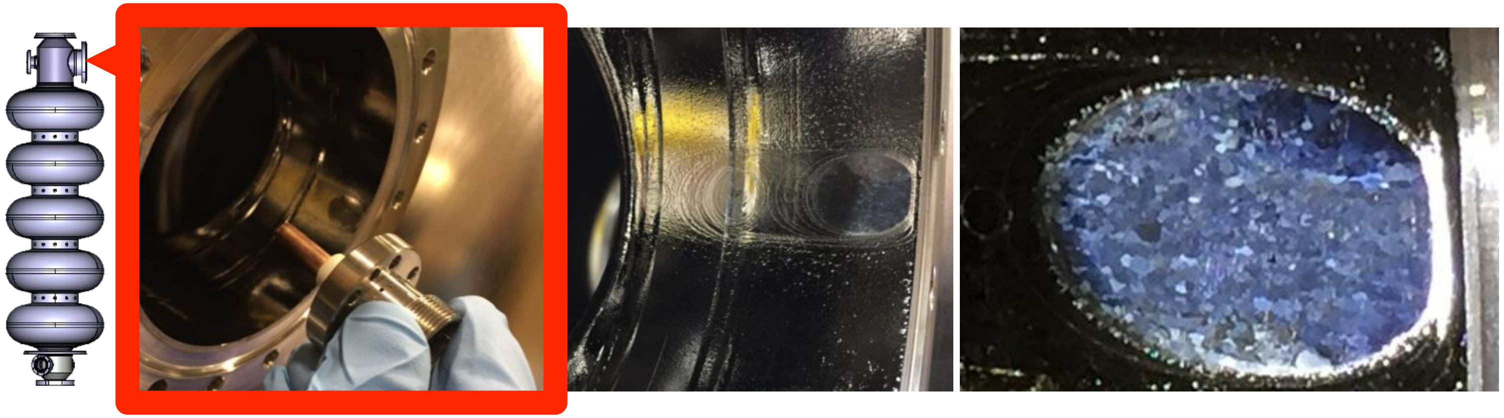
Do we reach performance limits not set by cavity quench threshold?

- **Cavity RF configuration:**
  - Are feedthroughs/flanges/gaskets/antennas in line with pushing beyond BPeak =130mT?

LLRF: Normal quench threshold



High field degradation without quench: Localised structured heating at port



- **Flux expulsion efficiency vs material/cavity integrity?**
  - Full expulsion requires high temperature heat treatment of 900ºC or more
  - Most large bulk Niobium cavities undergo 600-650ºC heat treatment => poor flux expulsion
  - Higher heat treatments can weaken both material strength parameters
    - Implication to mechanical integrity (eg flange brazings), surface resistance & pressure sensitivity

  - => What is acceptable in terms of RF performance and safety standards for large bulk niobium cavities?

High data-volume realtime diagnostics and controls

Are we taking full advantage of technology in our test stands?

Quantifying quality in standard processes

- Example: HPR duration set by monitoring of waste water
- Example: High resolution magnetic field mapping of cryostats

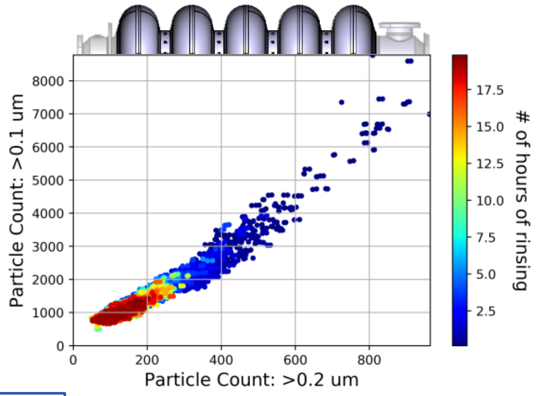
Use of high-volume data monitoring diagnostics

- Example: Ultra-fast sampling radiation monitoring for onset effects
  - Couple measurement to intelligent FE processing algorithms
- Fully digitised LLRF to track cavity behaviour
  - I&Q data streamed to deep acquisition buffers
    - online reconstruction of transient and steady state
      - high-statistics analysis of cavity response

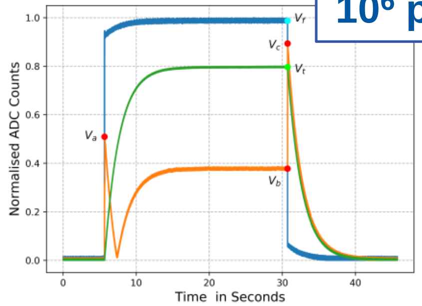
Defining the scope of automation and control procedures

- Example: Cleanroom assembly and cavity preparation tooling
  - Automated cavity rotation during post HPR drying
- Example: Adopt up-to-date control & processing with database archiving
  - Web based monitoring control & user interface
  - Suitable for both production testing and R&D development

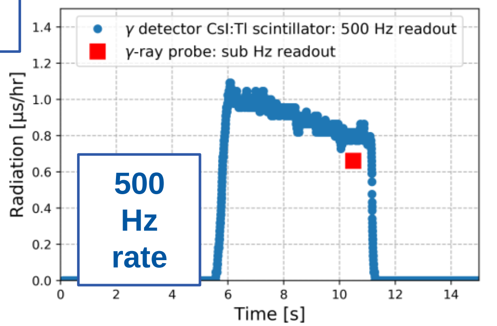
HPR waste water monitoring



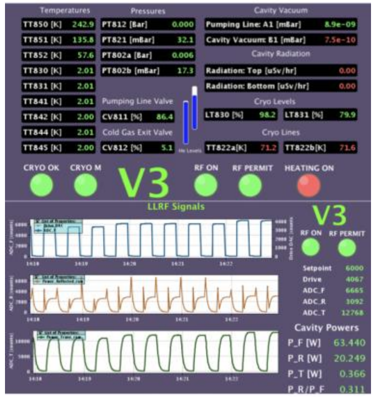
10^6 pts



LLRF: Data buffers



Fast radiation monitors

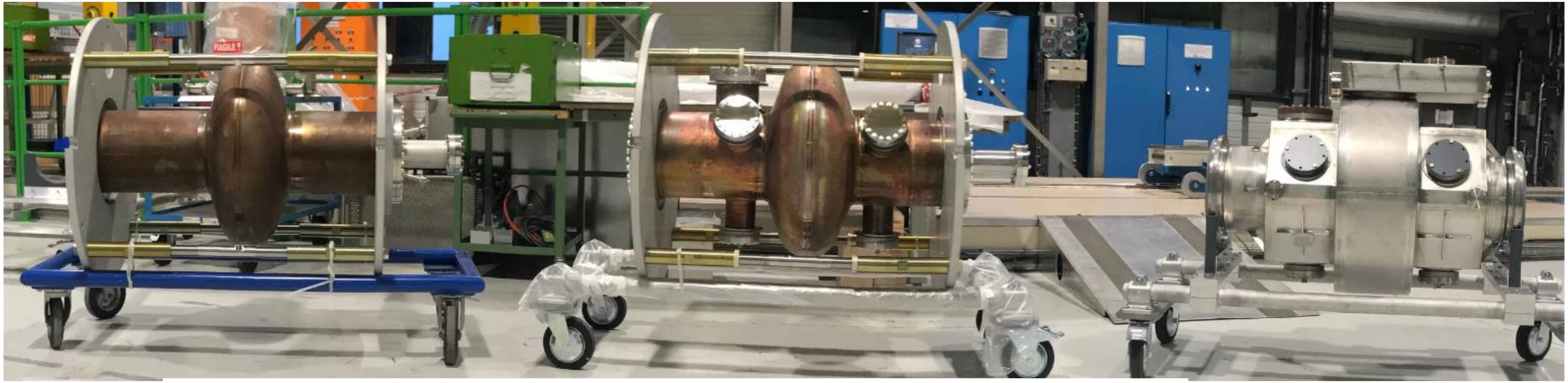


Web based interfaces

Cavity tooling

Large Elliptical Cavities

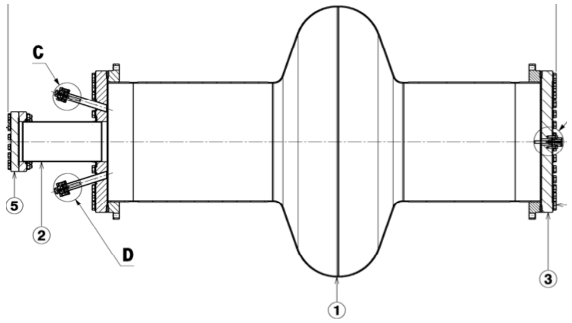
Experience with spares LHC Single-Cell 400Mhz Nb Coated(2016-2020)



From left to right: simplified practice cavity, full bare cavity, full cavity dressed with helium tank

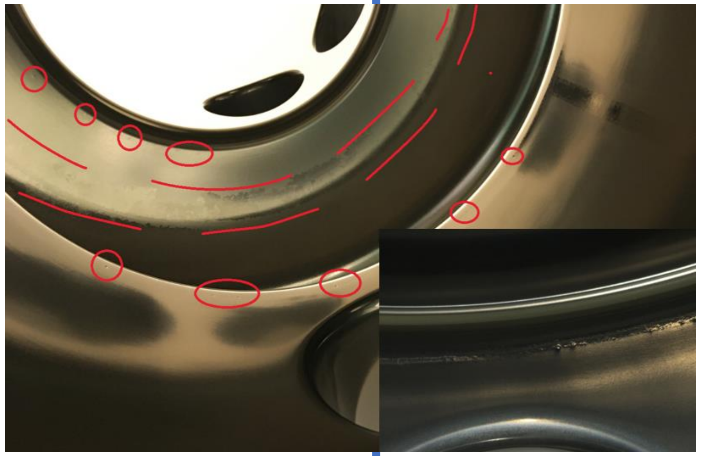
Current status CERN LHC 400MHz Spare Cavities: simplified vs full cavities

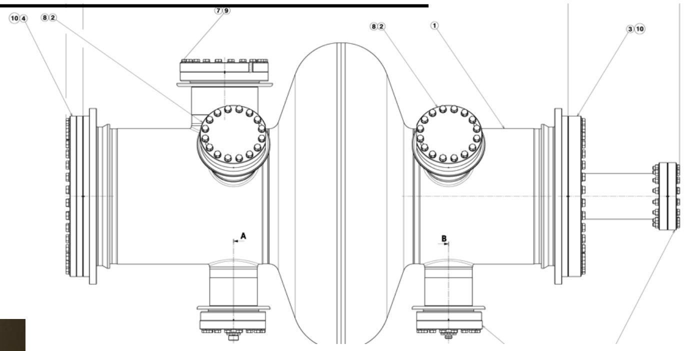
400 MHz Coated Cavities



EASY

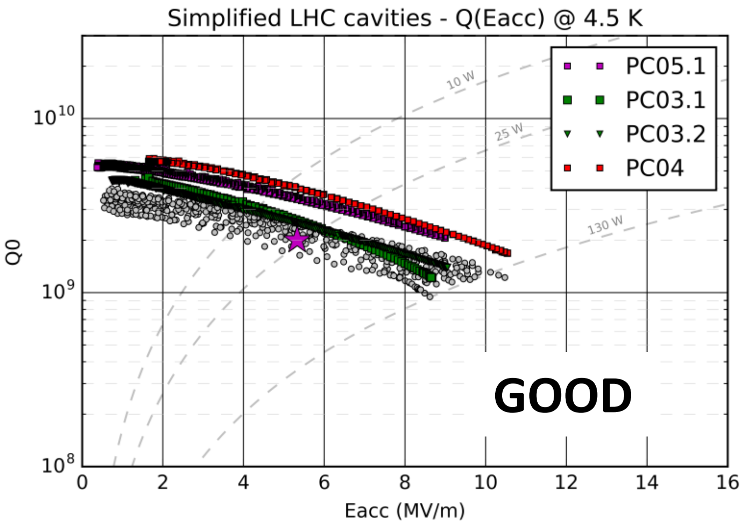
CHEAP





NOT… EASY

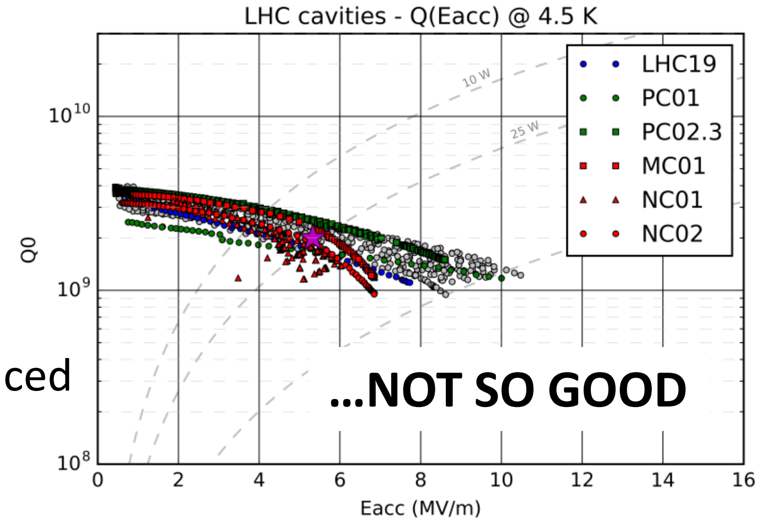
NOT…CHEAP



3 cavities produced and tested (PC03 was coated 2x)

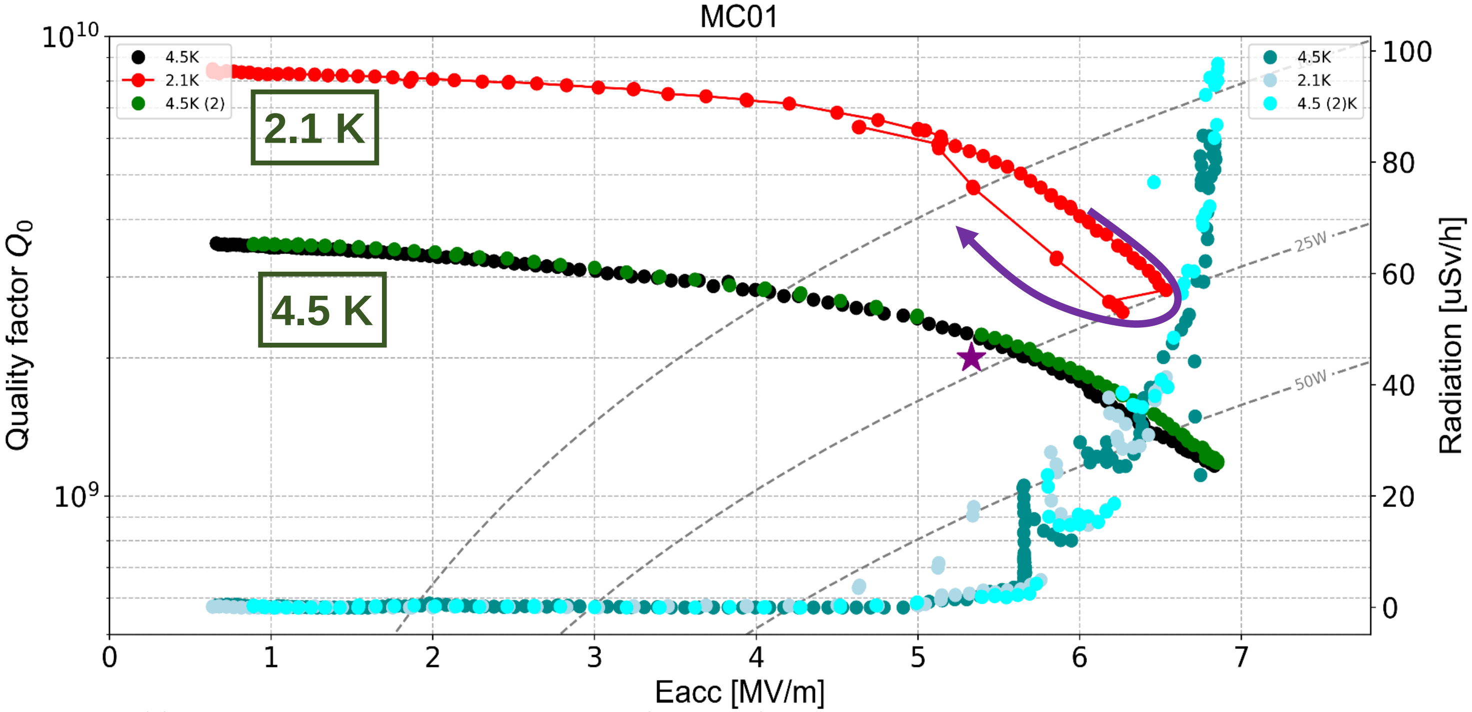
Same half-cells, same welds,
Same process, same coating,
Similar defects visually, but…

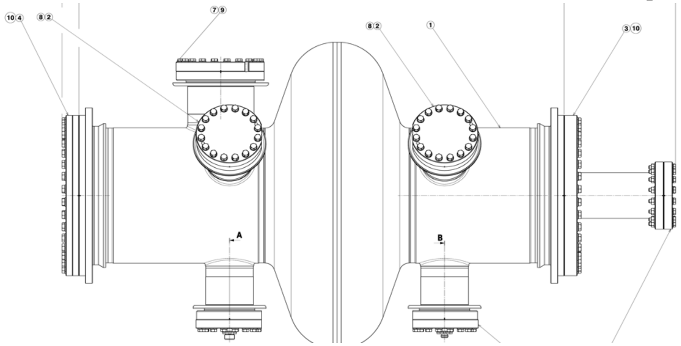
6 cavity produced and tested



Current status CERN LHC 400MHz Spare Cavities : Full Cavity RF behaviour

400 MHz Coated Cavities





- Field Emission
- Hysteretic behaviour at 2K?
  - Locally poor thermal contact Cu-Nb?
  - Substrate cleanliness before coating?
  - Weld defects?
- Why are simplified cavities performing better?
- Can we improve:
  - the weld quality?
  - post-welding electropolishing?
  - HiPIMS of 400 MHz?
  - Flux-trapping on Nb-film?
  - The cold test preparation to limit field emission

Courtesy of M. Karppinen ; " LHC Spare Cavities"
Presented at CERN #4 SRF Workshop, 05 Dec. 2019
https://indico.cern.ch/event/832933/contributions/3644030/

400 MHz Coated Cavities

CHALLENGES: Forming + welding of large cavities

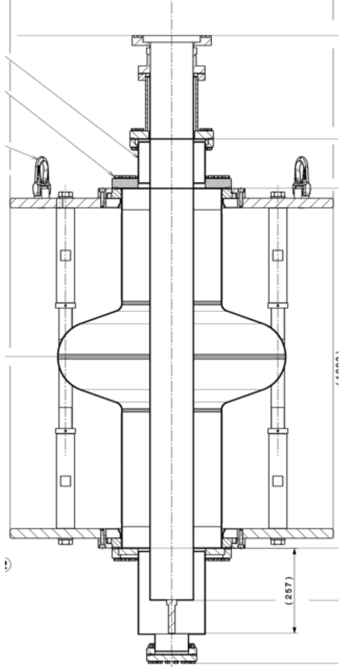
- Manufacturing process used: spinning and electro-hydroforming (EHF)
- Homogeneity of wall thickness and material characteristics very difficult to guarantee for such size (intermediate annealing, inhomogeneous cold working, spring back)
- Reproducibility and geometric tolerances required for EB-welding difficult to reach
- Too many defects adding up during the manufacturing process
- Very few European suppliers for such components
- EHF still to fully qualify
- 3 Simplified cavities: PC03 & PC04 made by EHF, PC05 made by spinning. Similar RF test results

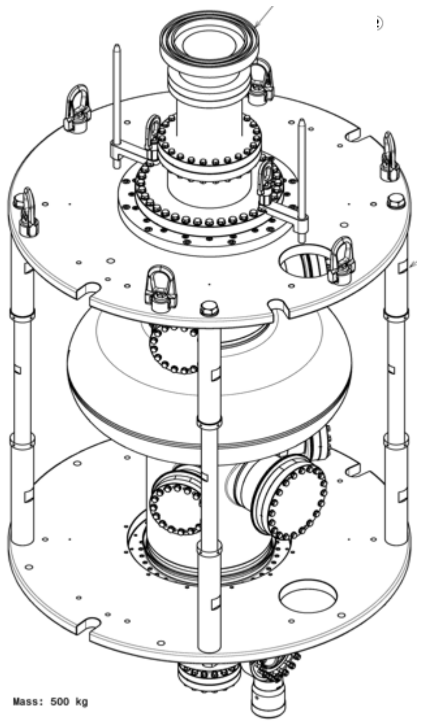
Left: Half-Cell by Spinning + internal machining (HEGGLI, CH),
Center: Half-Cell by Electro-Hydro-Forming (Bmax, F)
Right: Cut-Off Tube (CERN)

CHALLENGES: Substrate Preparation and Sputtering

- Electro-polishing (EP) over the entire surface after cavity welding is suggested as the best solution (to avoid chemical etching), but:
  - Complete EP of such big cavities not yet possible (currently under preparation)
  - Copper very reactive, even for EP, difficult to homogenize etching rate
- After substrate preparation due to copper reactivity, no time for quality control in ambient air, going directly for pure water rinsing and coating
- Nb Sputtering: not discussed here.

- Limited knowledge about the quality of the substrate surface before the sputtering (short time available between etching and coating due to copper reactivity)
- Cleanliness after chemistry before coating (HPWR, drying, cathod insertion) needs to be re-assessed to determine if the process is OK or if improvements are necessary





LHC 400MHz Cavity equipped with the Nb cathod before sputtering

400 MHz Coated Cavities

CHALLENGES: Cold Tests & Diagnostic Equipment

- Currently available at CERN for large cavities:
  - 2 Vertical Test Cryostats (V3 + V6),
  - V3: magnetic compensation (~ 1uT) ; good 1.9 K performance (saturated Ghe/Lhe, no lambda plate/exchanger), SEL-based RF system, 200W amplifier
  - V6: no magnetic compensation ; limited 2K performance, PLL-based RF system,
- No tool available to diagnose/localize thermal behaviour from diffuse/localized defects
- No tool to determine the origin of the defect (defect/damage in the layer, at the interface substrate-layer, poor coating process, pollution from chemistry)
- No tool to determine the topology of the defect (sputtering defect due to relief, corrosion pit underneath the layer ?)

For memory:

1995 LEP Diagnostic tools for coated cavities

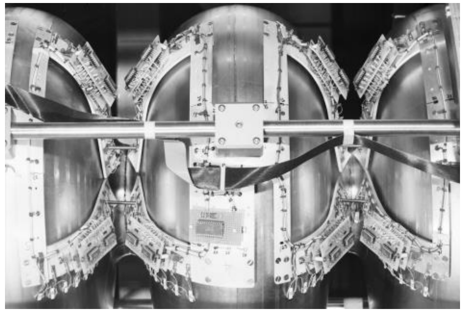
Thermal Mapping
(>100mK dT, +/- 10mm)

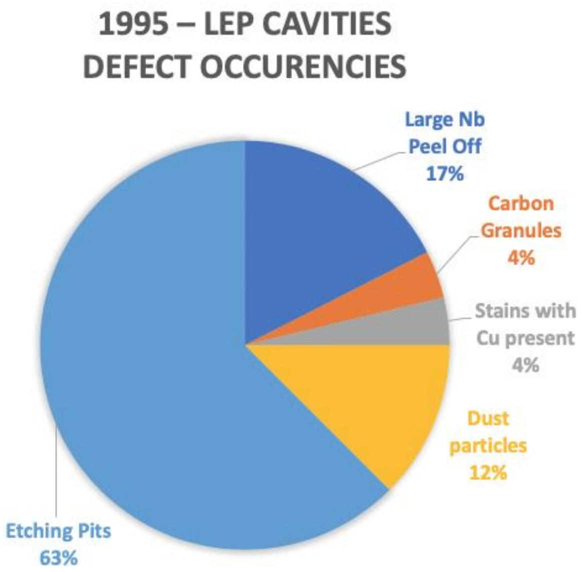
↓

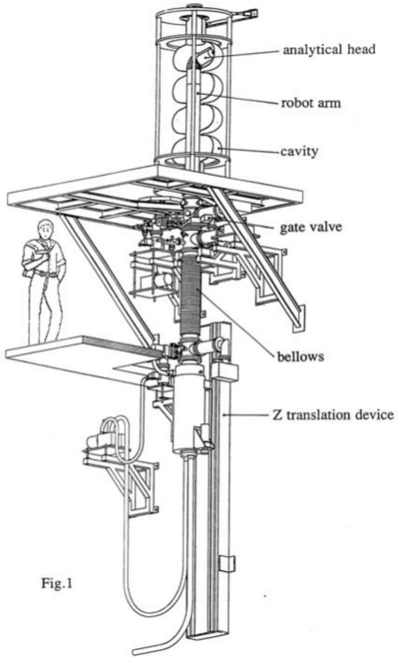
Visual Inspection
Localization +/- 1mm

↓

Layer Spectrometry
Elements Spectrum signature
Topology 0.01 mm







"Microscopic examination and elemental analysis of surface defects in LEP superconducting cavities" C. Benvenuti et al. 1995