Summary ERL19, WG4: Superconducting RF

F. Gerigk, P. McIntosh for WG4

WG4, scientific committee

- Conveners: Frank Gerigk (CERN), Kexin Liu (Peking University),
- Peter McIntosh (STFC), Axel Neumann (HZB), Bob Rimmer (JLAB), Hiroshi Sakai (KEK), Mathias Liepe (Cornell)

4 themes:

i) ERL SRF systems specifications, development, fabrication, commissioning, and performance (excl. SRF guns), 5 talks

ii) High loaded Q cavity operation (including microphonic issues, LLRF, RF power systems, transient beam loading…), 6 talks

iii) HOMs, HOM damping, and high current operation, 3 talks

iv) High Q0 cavity performance (focus on ERL cavities, no repetition of performance pushing measures such a N-doping, etc), 2 talks

SRF talks, part I

Tuesday, 17 September 2019			Theme
14:00	KEK ERL SRF Operation Experience	Hiroshi Sakai (KEK, Japan)	i) SRF systems, comm./oper.
14:25	Superconducting Twin-Axis Cavity for ERL Applications	HyeKyoung Park (ODU, USA)	i) SRF systems, comm./oper.
14:50	Integration of the MESA modules to bERLinPro for high power beam tests	Sebastian Thomas (KPH, Germany)	i) SRF systems, comm./oper.
16:00	Cryomodules for the Mainz Energy-recovering Superconducting Accelerator (MESA)	Florian Hug (KPH, Germany)	i) SRF systems, comm./oper.
16:20	A ferroelectric Fast Reactive Tuner (FRT) to combat microphonics	Alick Macpherson (CERN, Switzerland)	ii) cavity operation
16:45	Characterization of Microphonics in the cERL main linac superconducting cavities	Feng Qiu (KEK, Japan)	ii) cavity operation
17:10	LLRF ERL experience at the S-DALINAC	Manuel Steinhorst (TU Darmstadt, Germany)	ii) cavity operation
	Wednesday, 18 September 2019 (mixed session)		
16:00	Asymmetric SRF dual axis cavity for ERLs: studies and design for ultimate performance and applications	Yaroslav Shashkov (JAI, UK, MEPhI, Russia)	i) SRF systems, comm./oper.

SRF talks, part II

Thursday, 19 September 2019			
09:00	System Identification Procedures for Resonance Frequency Control of SC Cavities	Sebastian Orth (TU Darmstadt, Germany)	ii) cavity operation
09:20	Passive and active control of microphonics at CBETA and elsewhere	Nilanjan Banerjee (Cornell, USA)	ii) cavity operation
09:45	The development of HOM-damped 166.6MHz SRF cavities for High Energy Photon Source in Beijing	Pei Zhang (IHEP, China)	ii) cavity operation
10:10	Beam breakup limit estimations and HOM characterisation for MESA	Christian Stoll (KPH, Germany)	iii) HOMs & high-current op.
10:45	Waveguide HOM loads for high current elliptical cavities	Jiquan Guo (JLAB, USA)	iii) HOMs & high-current op.
11:10	Development of HOM coupler with C-shaped waveguide for ERL operation	Masaru Sawamura (QST, Japan)	iii) HOMs & high-current op.
11:35	Degradation and Recovery of Cavity Performance in Compact-ERL Injector Cryomodule at KEK	Eiji Kako (KEK, Japan)	iv) high-Q cavities
12:00	High Q 704 MHz cavity tests at CERN	Alick Macpherson (CERN, Switzerland)	iv) high-Q cavities

i) ERL SRF systems specifications, development, fabrication, commissioning, and performance (excl. SRF guns)

KEK ERL SRF Operation Experience, Hiroshi Sakai (KEK, Japan)

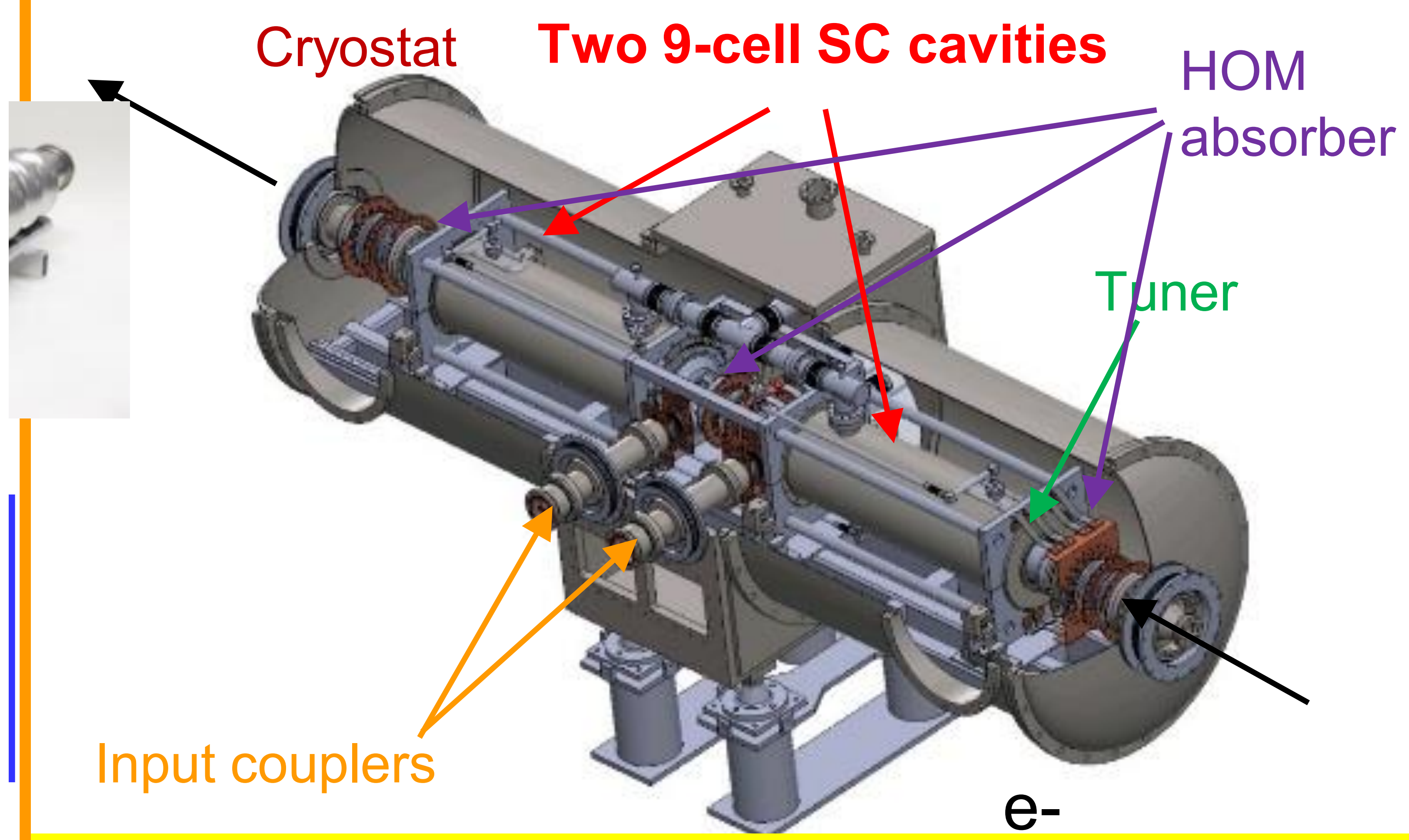
- Reported real-life operational difficulties. cERL start in 2013, 1 mA in 2015/16. Gradient reach declined from 2012 to 14, but could be recovered via high-power pulsed processing.
- Phase and amplitude stability of < 0.01%, 0.01 deg could be achieved by reducing **microphonics**. E.g. rubber feet below rotary pump drastically reduced 50 Hz oscillations.
- Unexplained **burst event** in 2017 reduced gradient reach. Cavity 1 could not be recovered by pulse processing and is now limited at 7 MV (thermal breakdown). Presently total energy gain of 2-cavity module is limited to 19.5 MV.
- Higher **field emission** after assembly, and increasing field emission during operation. Questions on particles getting into the module during operation.
- Future plans: overcome field emission: i) move to Tesla shape with large cut-off tubes to reduce Ep/Eacc, and ii) improve clean assembly work and iii) modify HOM coupler design.

Main linac module

HOM damped (for 100mA circulation to suppress HOM-BBU in design)

9-cell cavity (ERL-model2) × 2

RF frequency:	1.3 GHz
Input power :	20kW CW (SW)
E_{acc}:	15 MV/m (design)
Unloaded-Q:	$Q_0 > 1\times10^{10}$



Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

Cryomodules for the Mainz Energy-recovering Superconducting Accelerator (MESA), Florian Hug (KPH, Germany)

Cryomodule based on ELBE module:

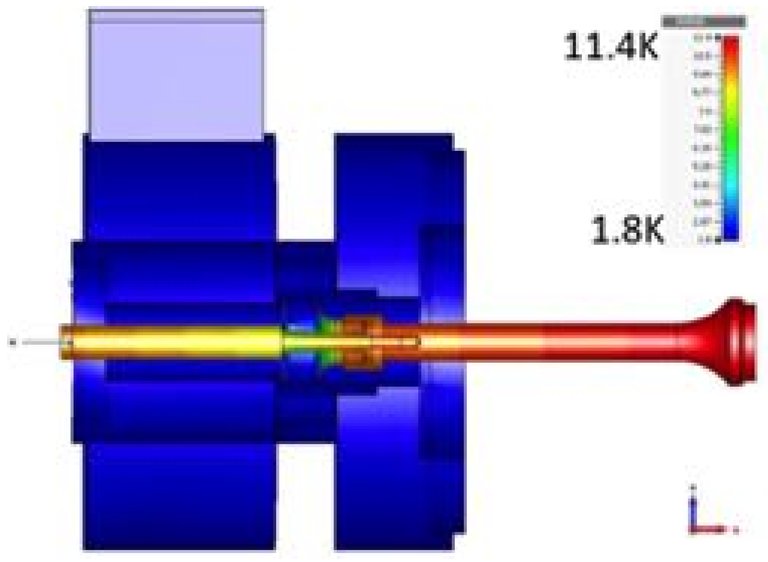
- Piezo tuner added
- HOM antenna improvements:
  - Sapphire window included
  - Strip-line in HOM cable for cooling

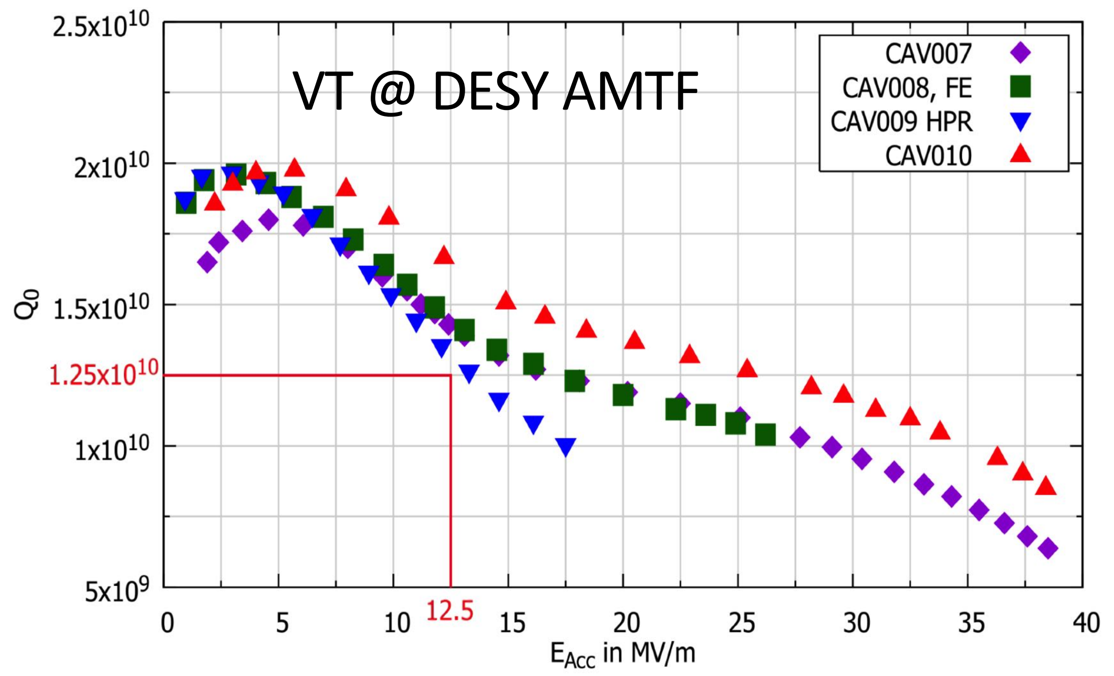
Cryomodule performance:

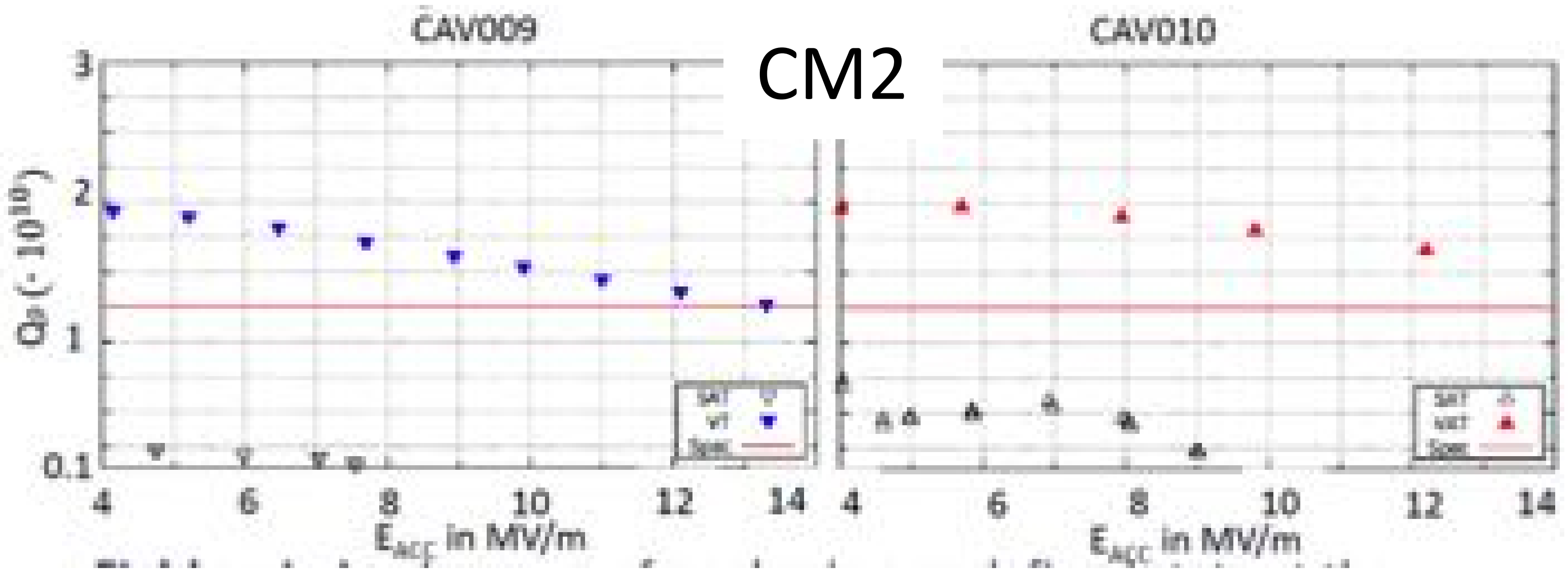
- SAT/FAT performed @ JGU
- CM2 with 2x12.5MV/m @ Qo=1.2x1010, reached at DESY, presently re-test at Mainz.
- CM1 @ RI for refurbishment (cavity HPR, re-installation, …) – FE limited
- Suspect due to undefined state of gate valve during transport

Successful turn-key CM production by industry demonstrated

Variable	Spec
energy gain / module	> 25 MV
static losses	< 15 W
dyn. losses @ 25 MV (CW)	< 25 W
Q @ 12.5 MV/m	> 1.25 x 10^{10}

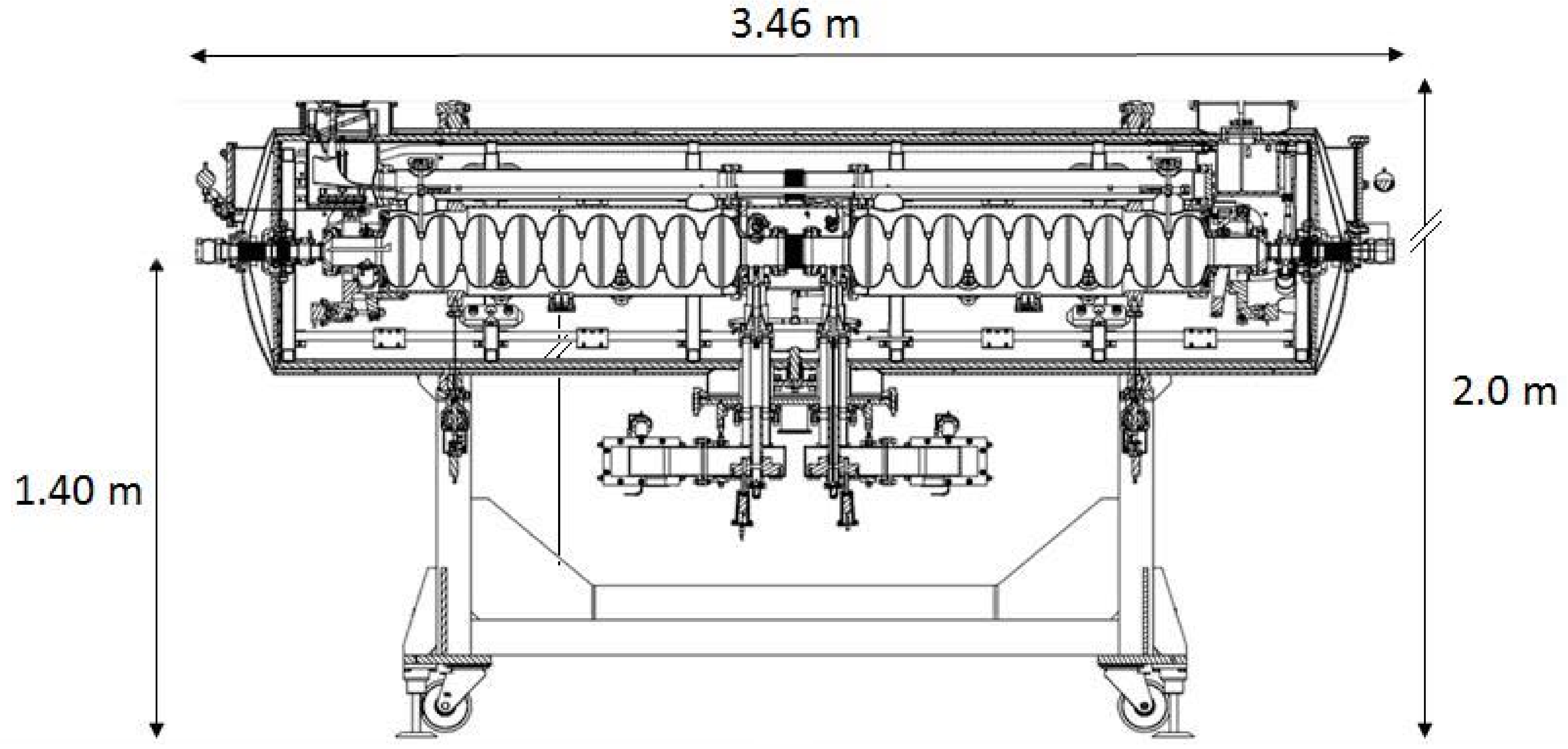


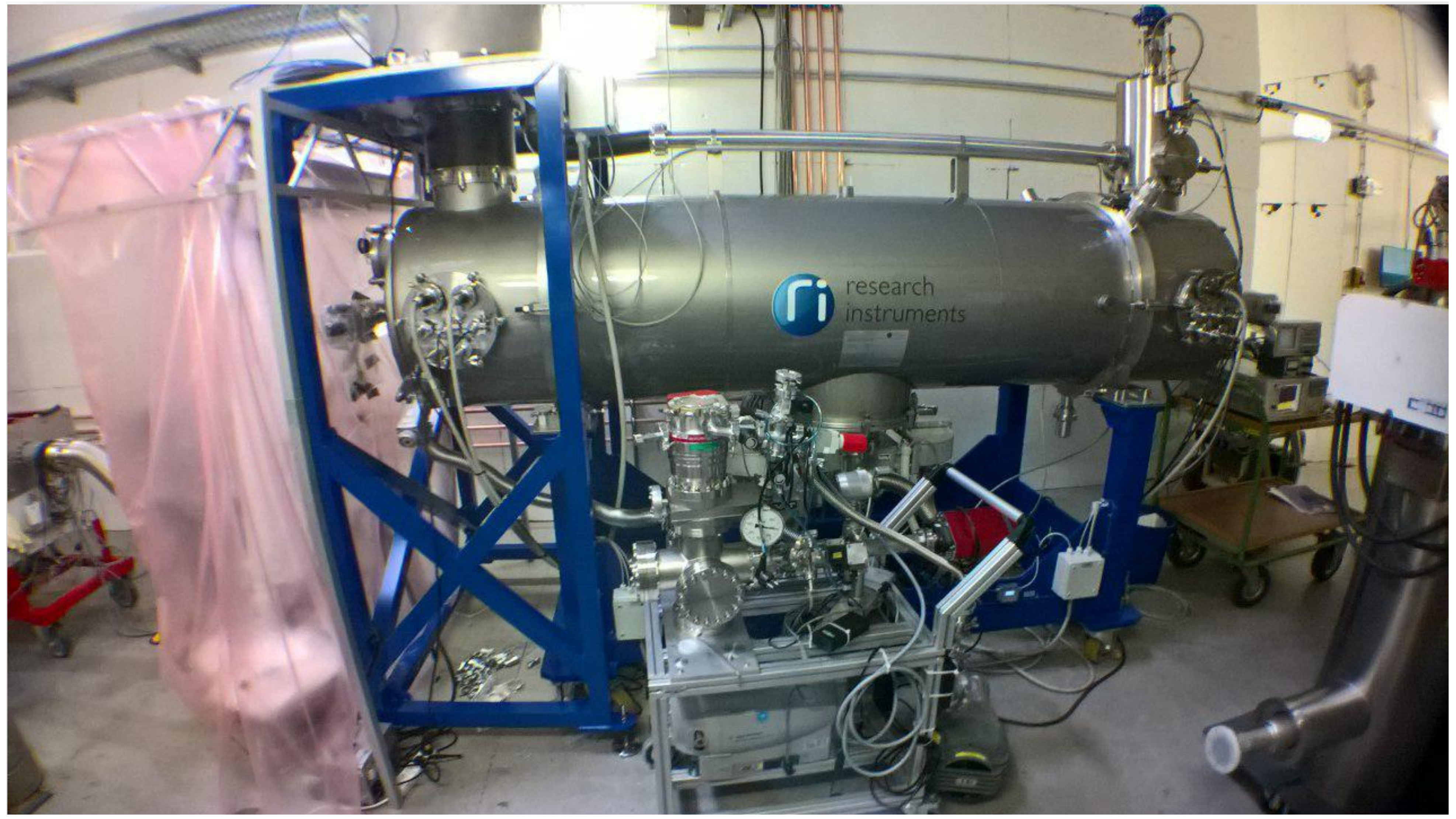




Integration of the MESA modules to bERLinPro for high power beam tests, Sebastian Thomas (KPH, Germany)

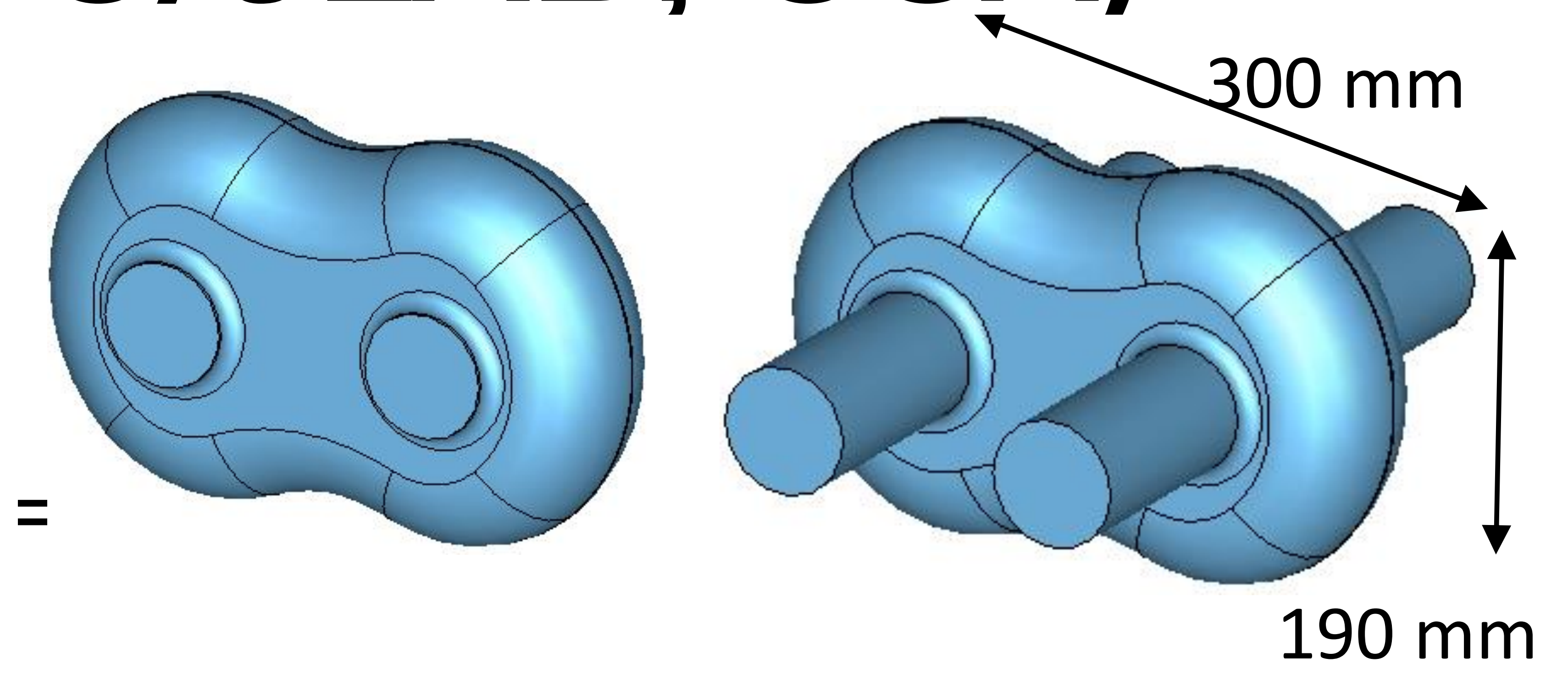
- MESA is waiting for construction to finish, but has a working cryomodule. bERLinPro will soon have infrastructure and beam lines ready but no CM. An early test of the module at bERLinPro will allow for first beam experience. Win-Win!
- ELBE type module with 2x9-cell 1.3 GHz cavities with modified HOM couplers. Performance goal: 12.5 MV/m @ 1.25×10^{10}
- Cryogenics and cryo-safety systems in Berlin need to be adapted. Shipping to Berlin in June 2020, cool-down Jan 2021.





Superconducting Twin-Axis Cavity for ERL Applications, HyeKoung Park (ODU/JLAB, USA)

- Aiming for 15 MV/m at 1497 MHz. Designed for: easy cleaning, maximum beam pipe separation, avoiding MP, HOM & wake-field analysis.
- Fabrication via deep drawing of half cells, welding of end-groups, bulk BCP, 800C, HPR, 120 bake.
- **RF test:** cavity 1 reached 23 MV/m at 7×10^9, cavity 2 only just above 5 MV/m (welding defect, melt through), no MP.
- **Proof of feasibility done**, fabrication more straight forward than anticipated though some issues with old EP machine, non-uniform weld joint thickness. Chemistry and cleanliness can be handled.
- Questions remain on BBU through mixed modes, beam coupling, mechanical tuning

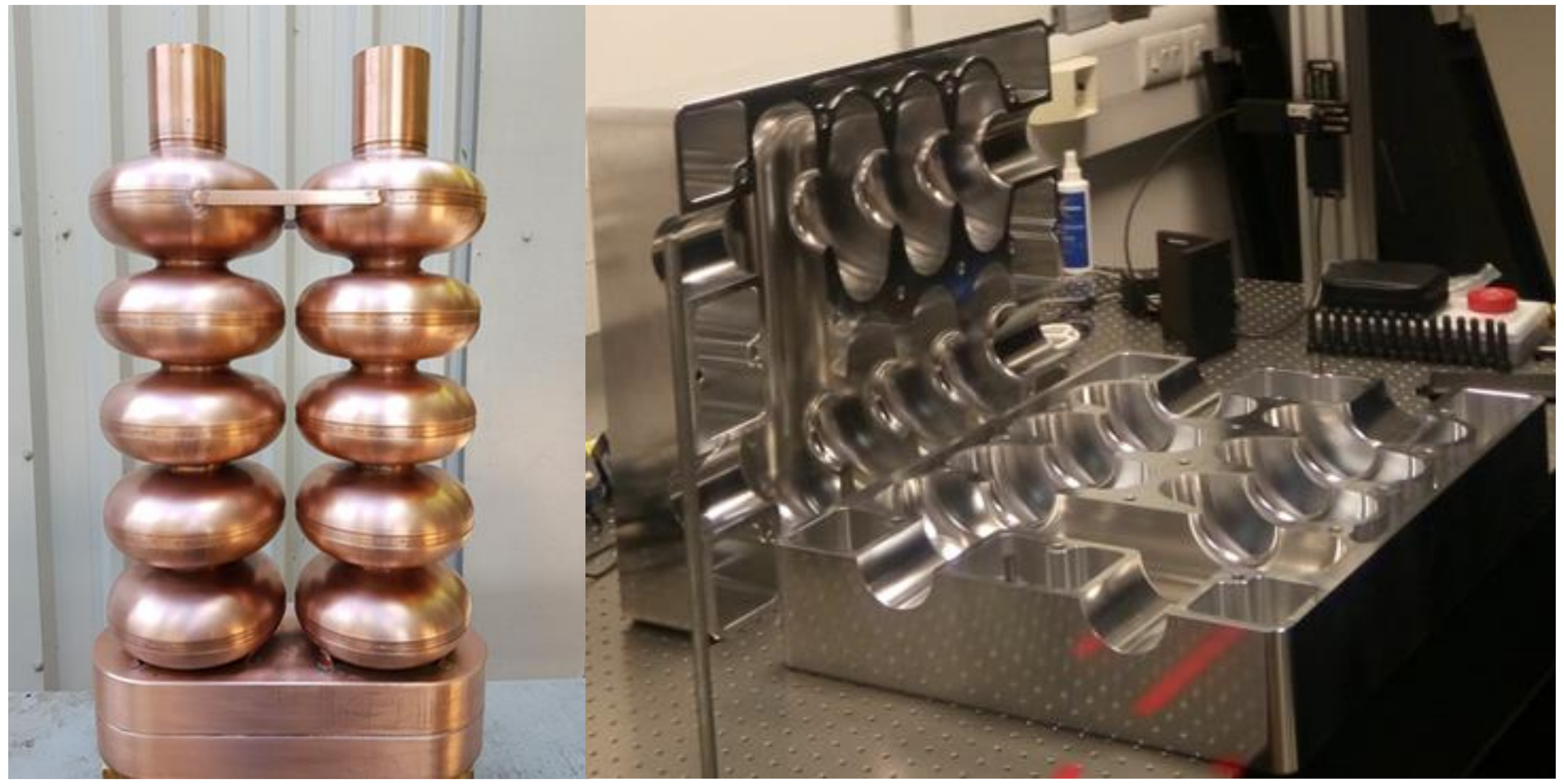


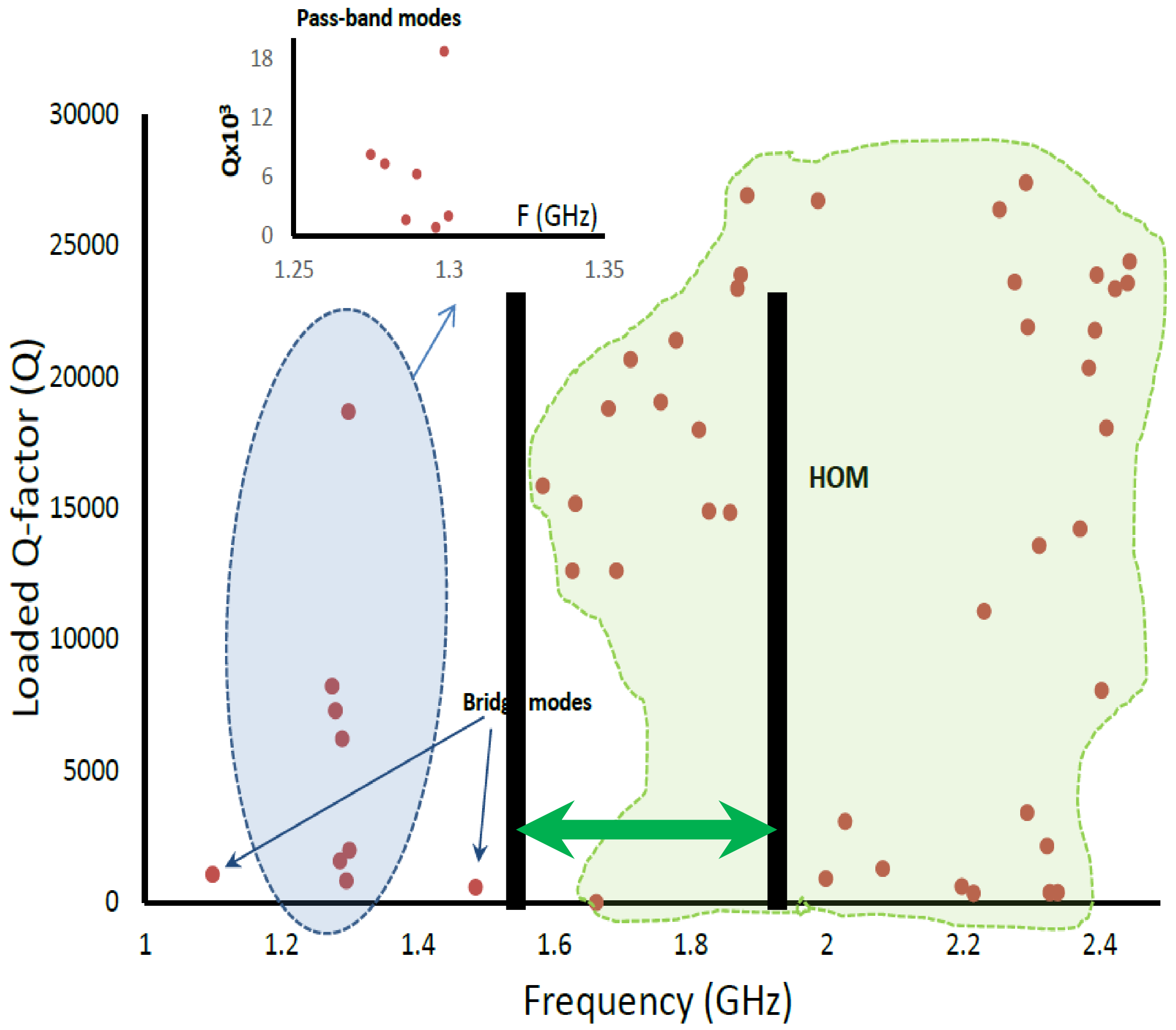
RF Properties	
E_p/E_{acc}	2.42
B_p/E_{acc} [mT/(MV/m)]	5.49
$[R/Q]$ [Ω]	60.7
G [Ω]	318
$R_t R_s$ [Ω^2]	1.9×10^4
LOM [MHz]	1103
1st HOM [MHz]	1806
Beam aperture [mm]	60
k_{cc} [%]	1.80

Asymmetric SRF dual axis cavity for ERLs: studies and design for ultimate performance and applications, Yaroslav Shashkov, MEPhI (Russia)/JAI (UK)

2 warm prototypes built and measured

- 7-cell1.3 GHz Al model with one cell providing the coupling between the 2 cavities.
- 11-cell Cu model.
- Bridge coupling optimisation resulted in similar shape than the ODU twin-axis cavity.
- Passband mode, HOM & bridge mode measurements, with good agreement between simulations and measurements.

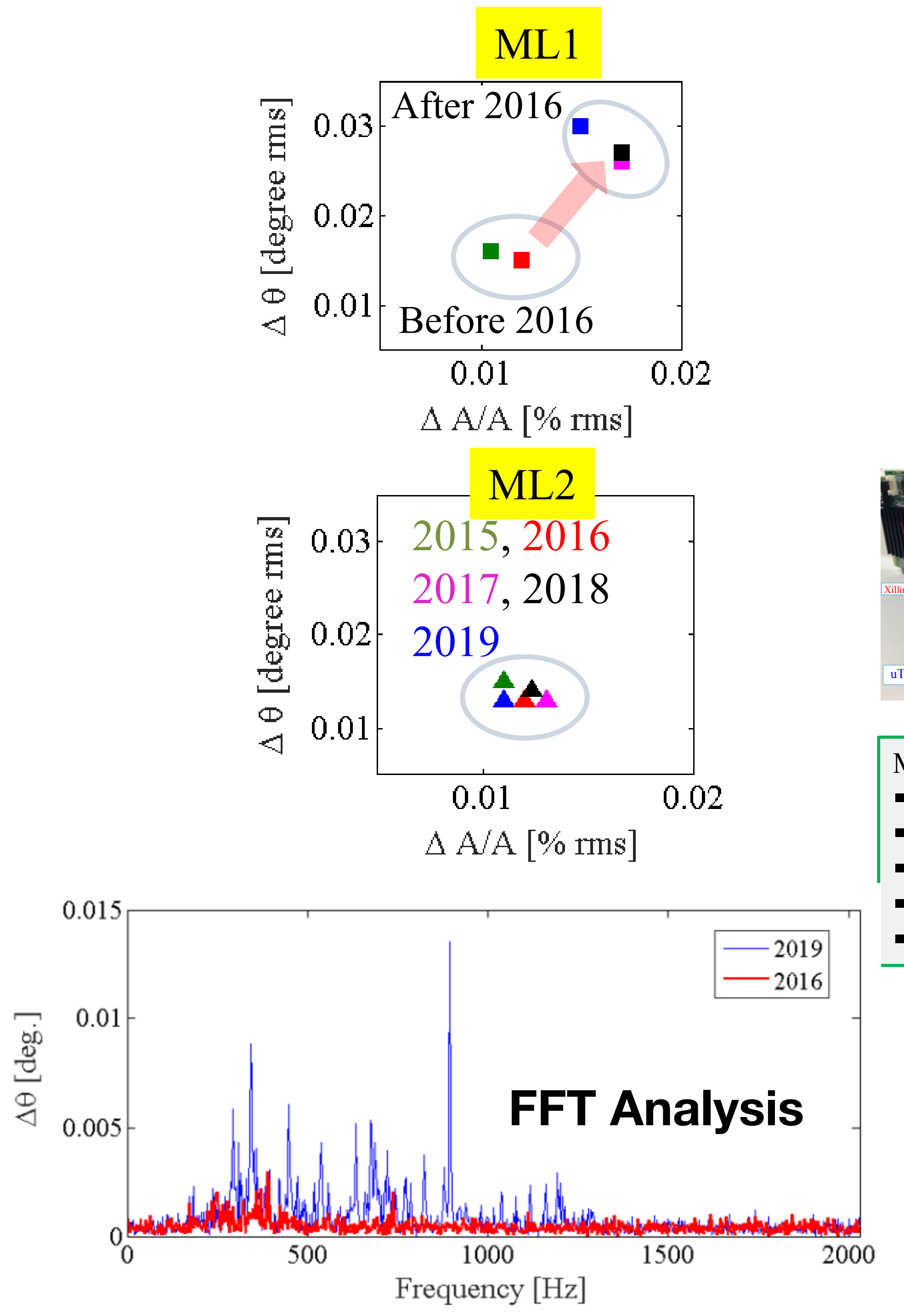


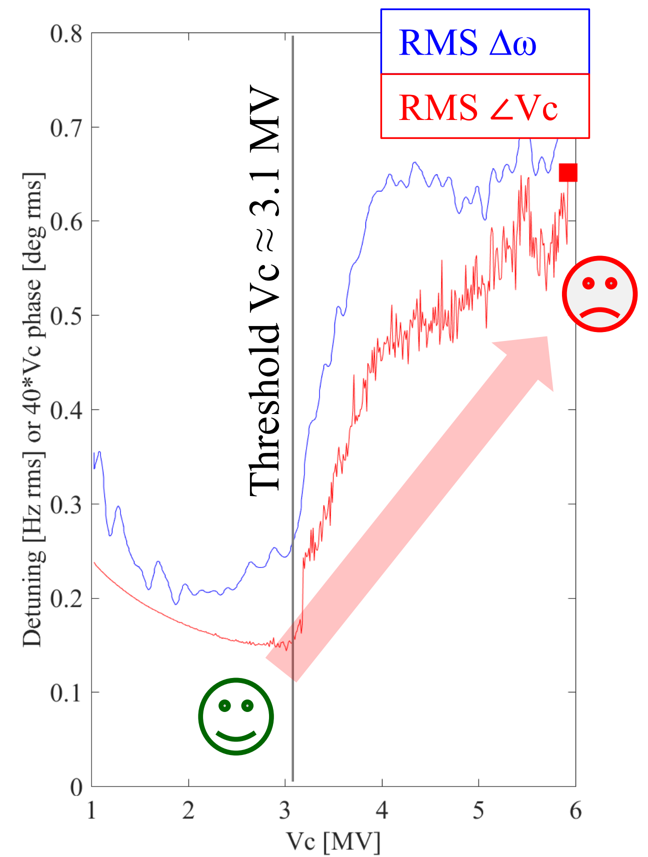


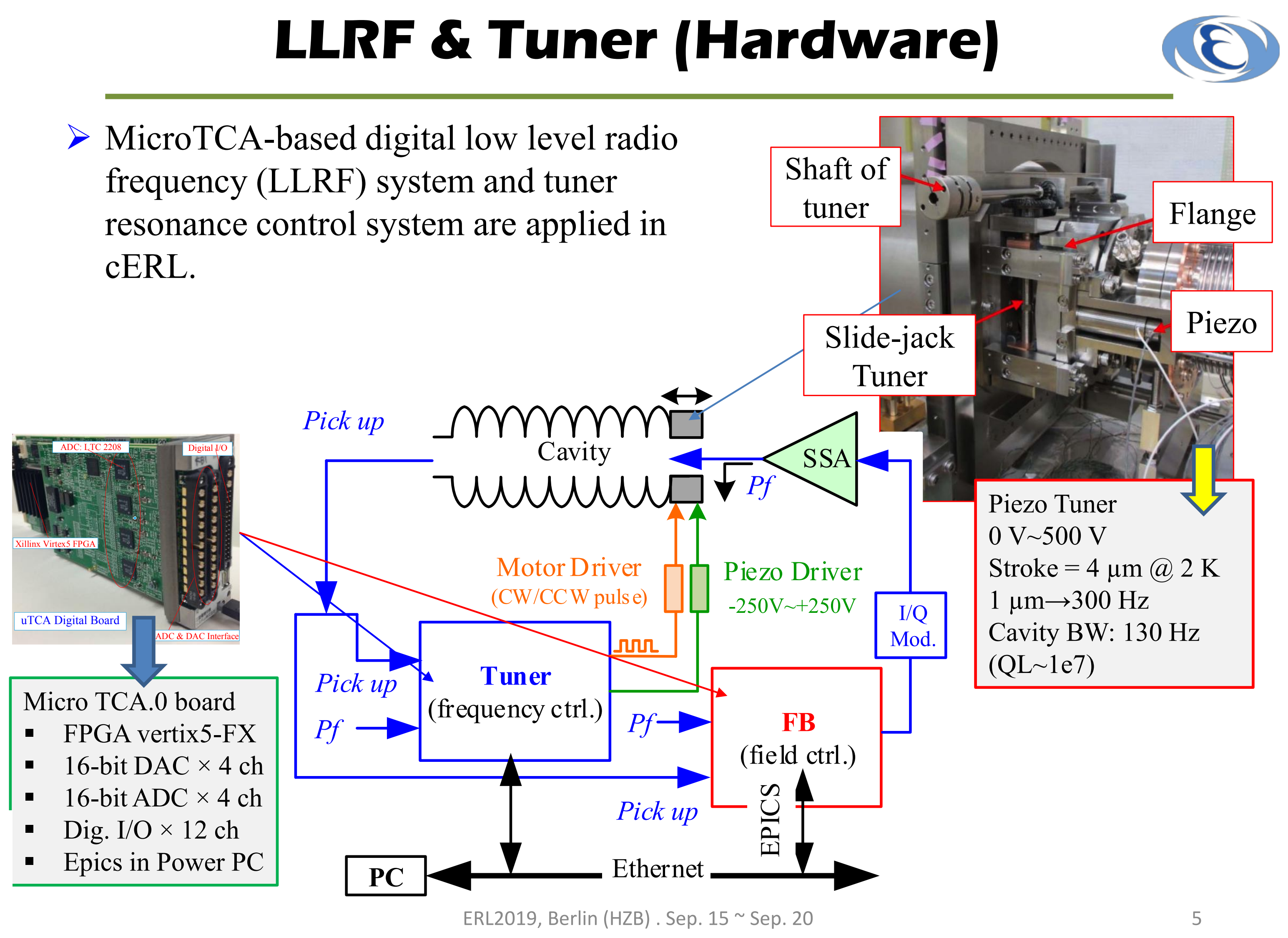
ii) High loaded Q cavity operation (including microphonic issues, LLRF, RF power systems, transient beam loading…)

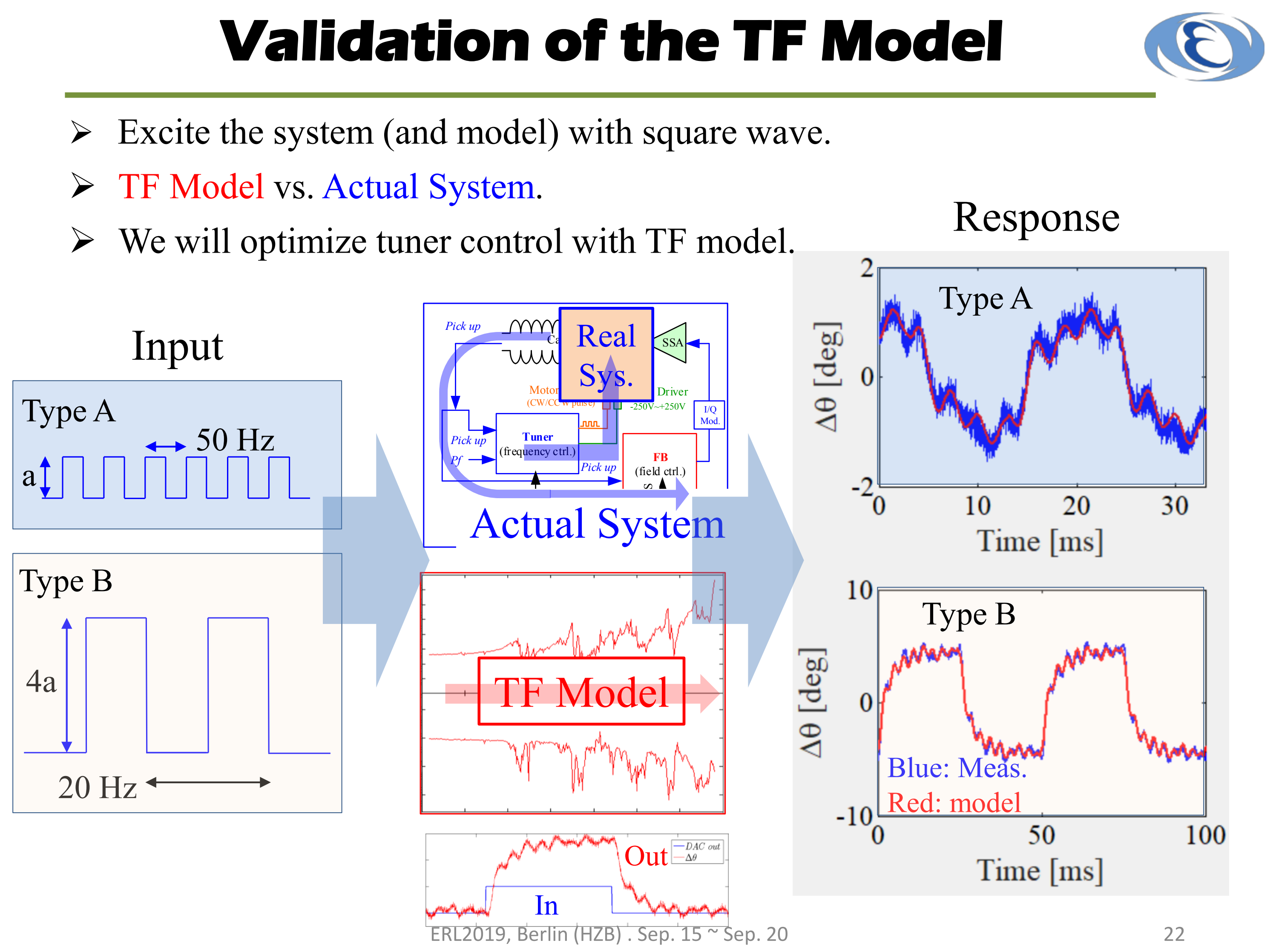
Characterisation of Microphonics in the cERL Main Linac Superconducting Cavities, Feng Qui (KEK, Japan)

- RF stability of ML1 cavity getting worse due to the deteriorated microphonics in the past 5 years. ML2 remains stable.
- A “field level dependency of microphonics” phenomenon is observed.
- The Vc threshold for the deteriorated microphonics is ~3.1 MV, probably related with quench limits level.
- Have identified and validated the transfer function model of the piezo tuner system and plan to optimize the tuner control with this model.



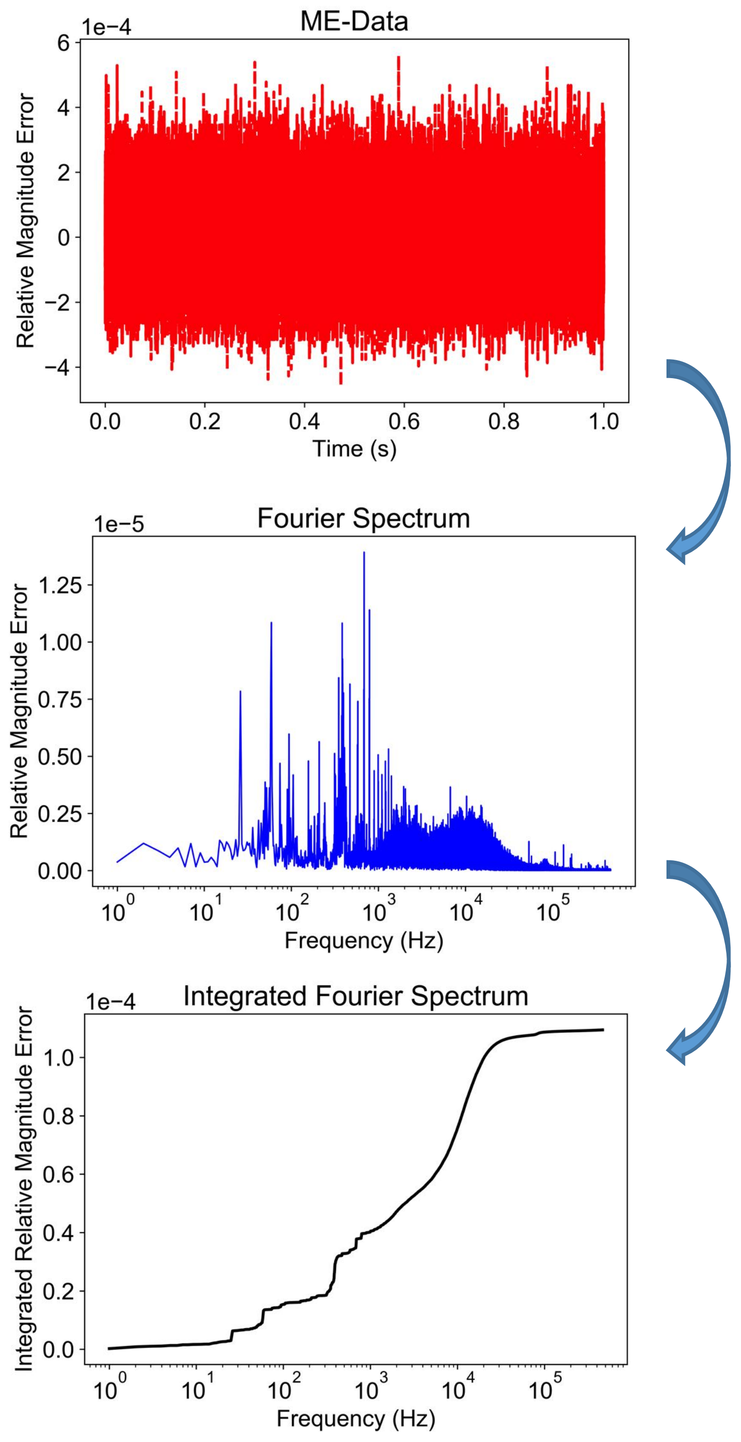




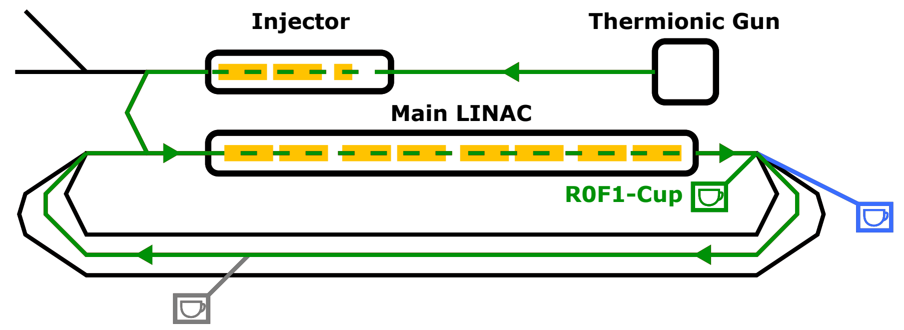


LLRF ERL Experience at the S-DALINAC
Manuel Steinhorst (TU Darmstadt, Germany)

- New LLRF control system: used for first successful ERL operation in 2017.
- Influence of the beam on RF stability negligible <1 μA.
- Amplitude errors so far larger than expected and need further optimisation.
- For 6 out of 8 20-cell cavities ERL efficiency >90%.
- More study of beam disturbance at 52 Hz is needed.
- New RF power measurement system is ready for usage.
- Extremum-seeking control as optimization algorithm for RF Control.

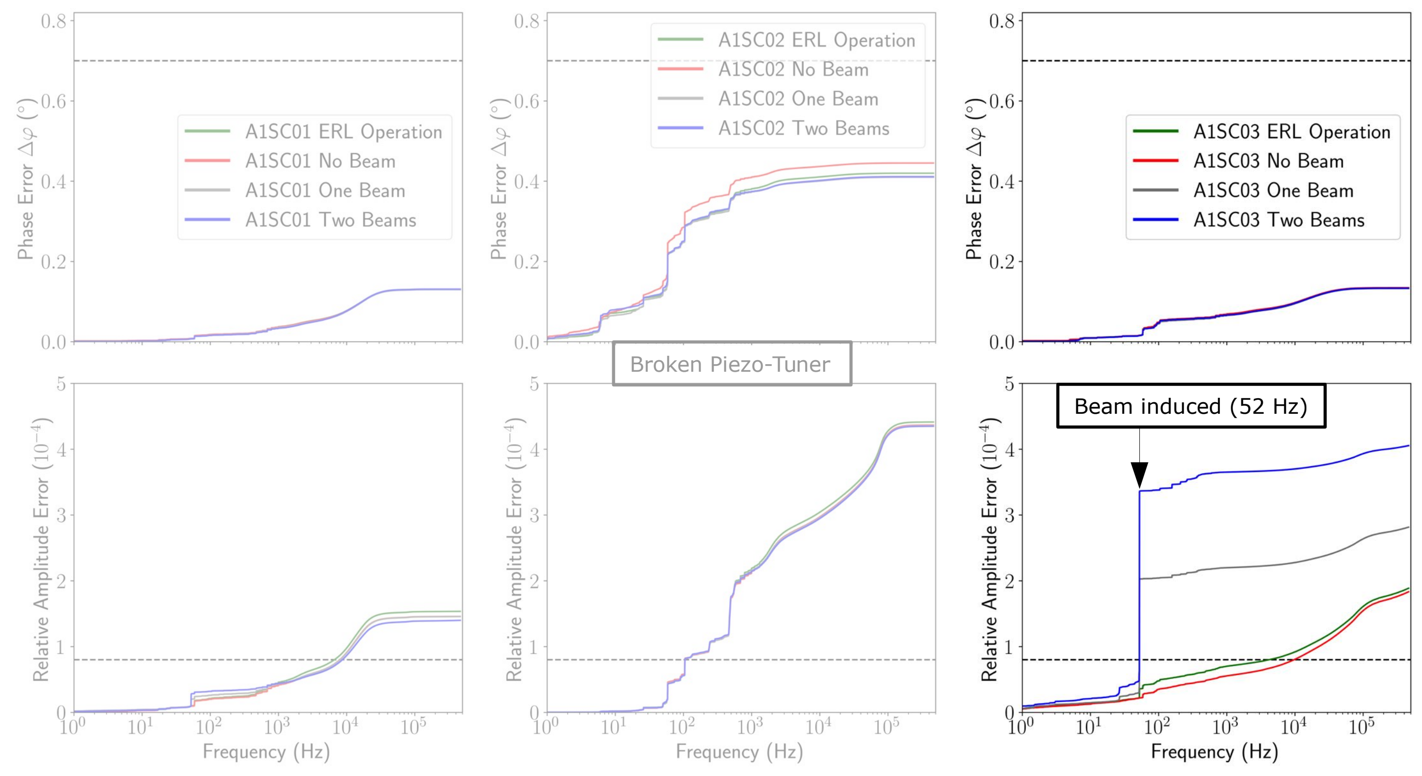


First ERL Operation at the S-DALINAC



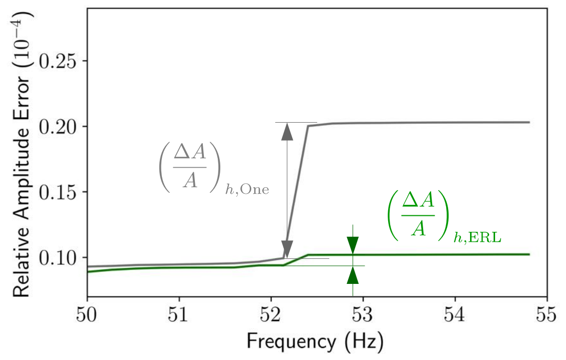
M. Arnold et al.:
First Operation of the S-DALINAC as an Energy Recovery Linac,
In Preparation

- Single turn ERL operation in August 2017
- Beam current of 1 μA
- During ERL operation about 80-90% transmission on R0F1-Cup
- Stability of RF measured



- Efficiencies for ALL cavities via RF Control:

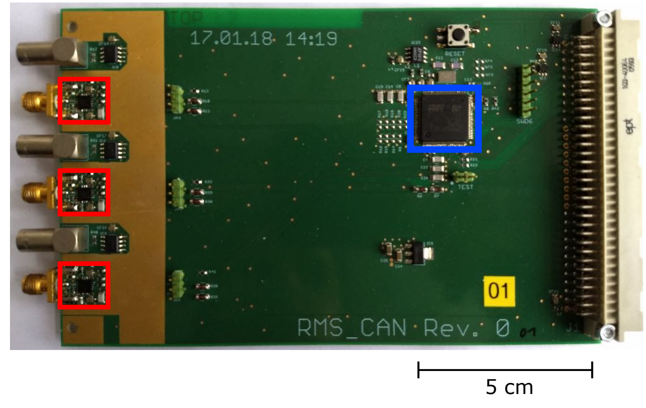
Cavity	Efficiency (+-10%)
A1SC01	92 %
A1SC02	73 %
A1SC03	92 %
A1SC04	98 %
A1SC05	96 %
A1SC06	100 %
A1SC07	100 %
A1SC08	60 %



$$\mathcal{E}'_{\mathrm{RF}} = \frac{\left(\frac{\Delta A}{A}\right)_{h,\mathrm{One}} - \left(\frac{\Delta A}{A}\right)_{h,\mathrm{ERL}}}{\left(\frac{\Delta A}{A}\right)_{h,\mathrm{One}}}$$

Power Detectors

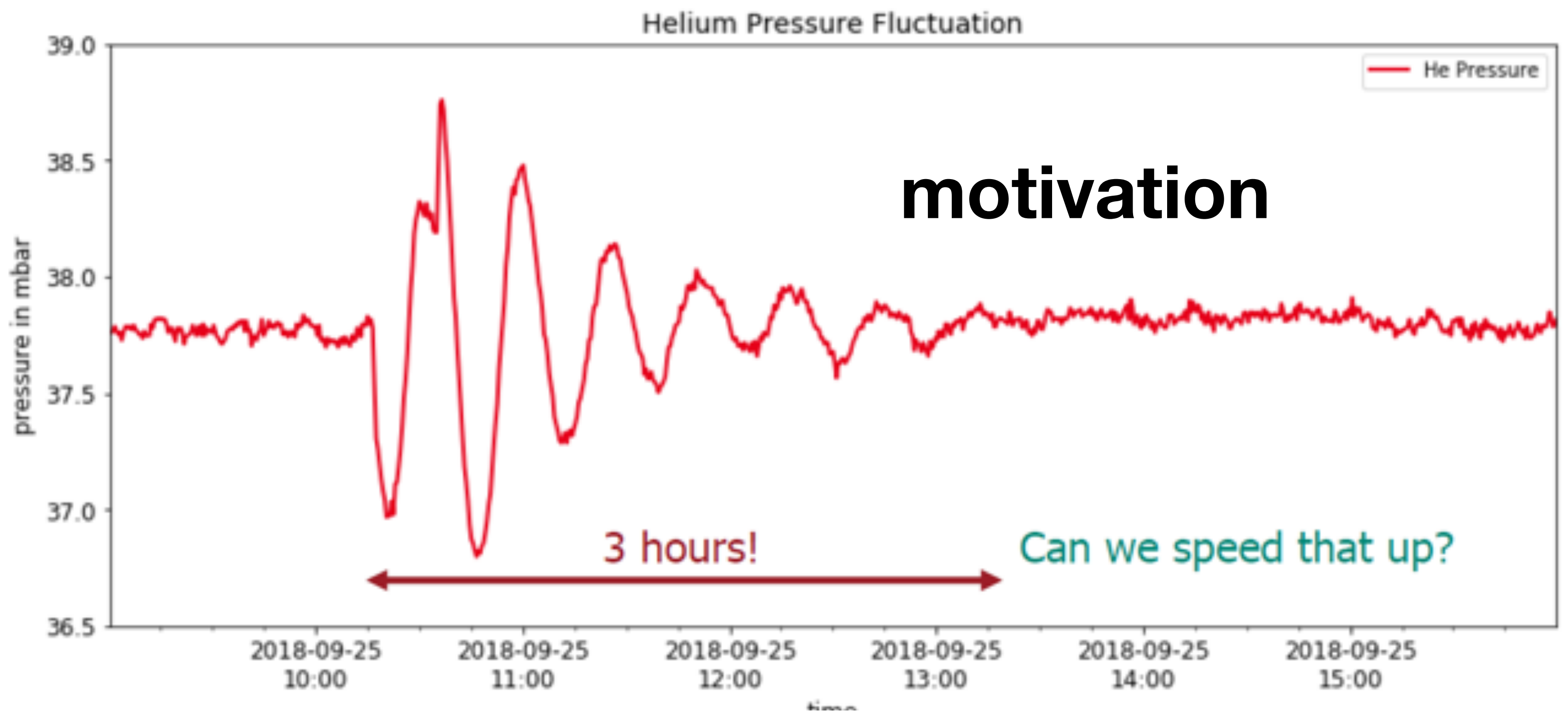
Micro-Controller



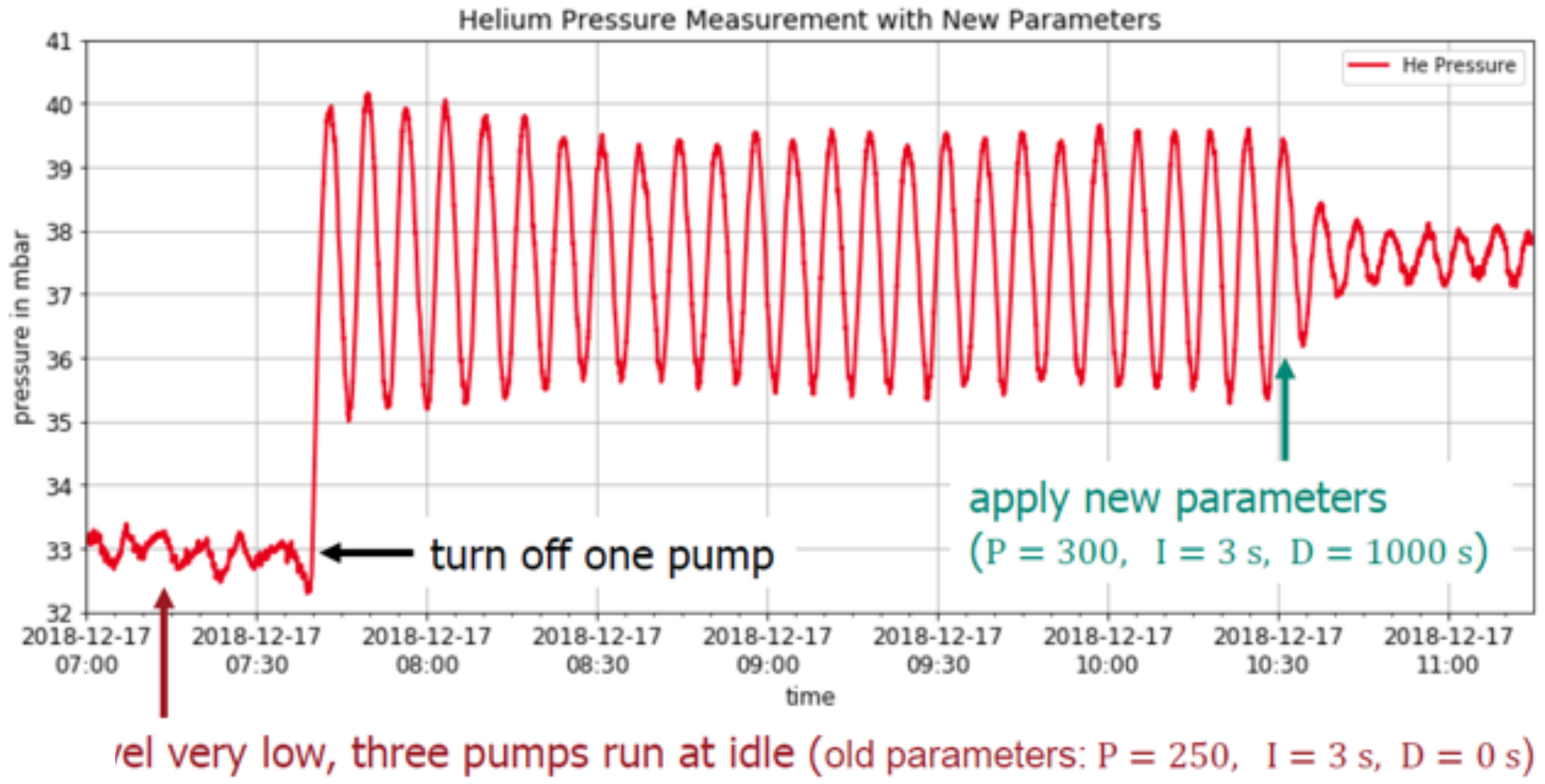
System Identification Procedures for Resonance Frequency Control of SC Cavities, Sebastian Orth (TU Darmstadt, Germany)

2 system identification procedures for model based controller tuning during closed loop operation presented:

- direct method ($u \rightarrow y$) prediction error (least squares)
- indirect method ($r \rightarrow y$) two stage (via $G_{cl} = S_0 G_0$)



success!

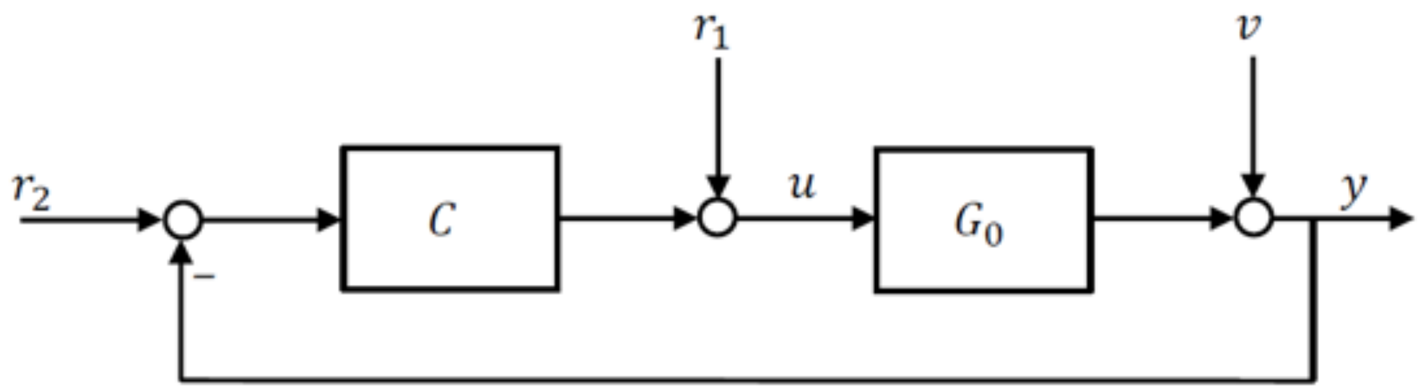


- identified system is the closed-loop system $G_{cl} = \frac{G_{He} \cdot C}{1 + G_{He} \cdot C}$ $(r_2 \longrightarrow y)$
  with the controller $C(s) = \mathrm{P} + \frac{1}{\mathrm{I}s} + \mathrm{D}s$
- extract the He-pressure system TF G_{He}:

$$G_{He} = \frac{G_{cl}}{C(1 - G_{cl})} = \frac{3.988 \cdot 10^{-5} s}{s^2 - 9.034 \cdot 10^{-3} s + 2.901 \cdot 10^{-6}}$$

additional zero to reproduce jumps (already introduced in G_{cl})

PT2 behaviour



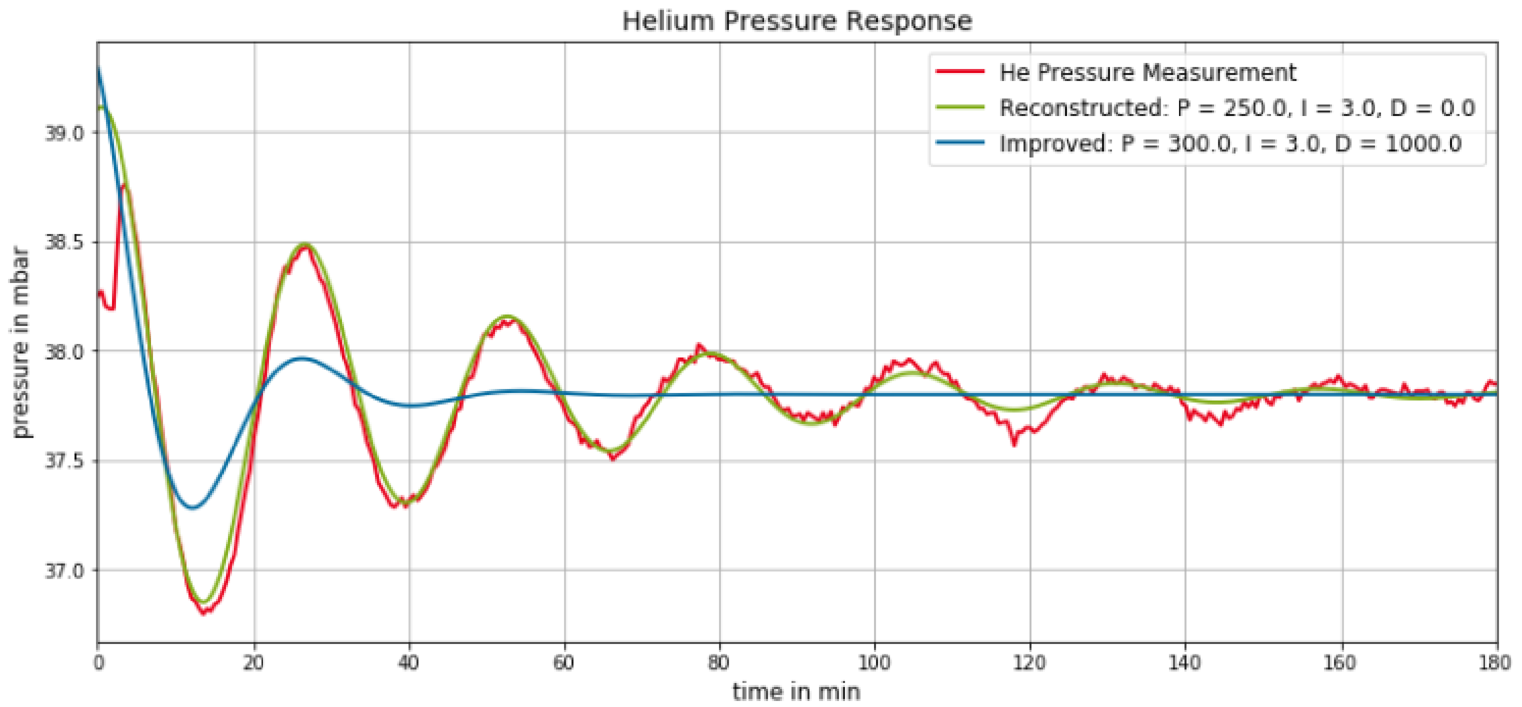
$r(k) = r_1(k) + C(z) r_2(k)$

$v(k) = H_0(z) e(k)$ (filtered white noise)

$S_0 = (1 + G_0 C)^{-1}$ (sensitivity function)

$y(k) = S_0 G_0 r(k) + S_0 H_0 e(k)$

$u(k) = S_0 r(k) - S_0 C H_0 e(k)$

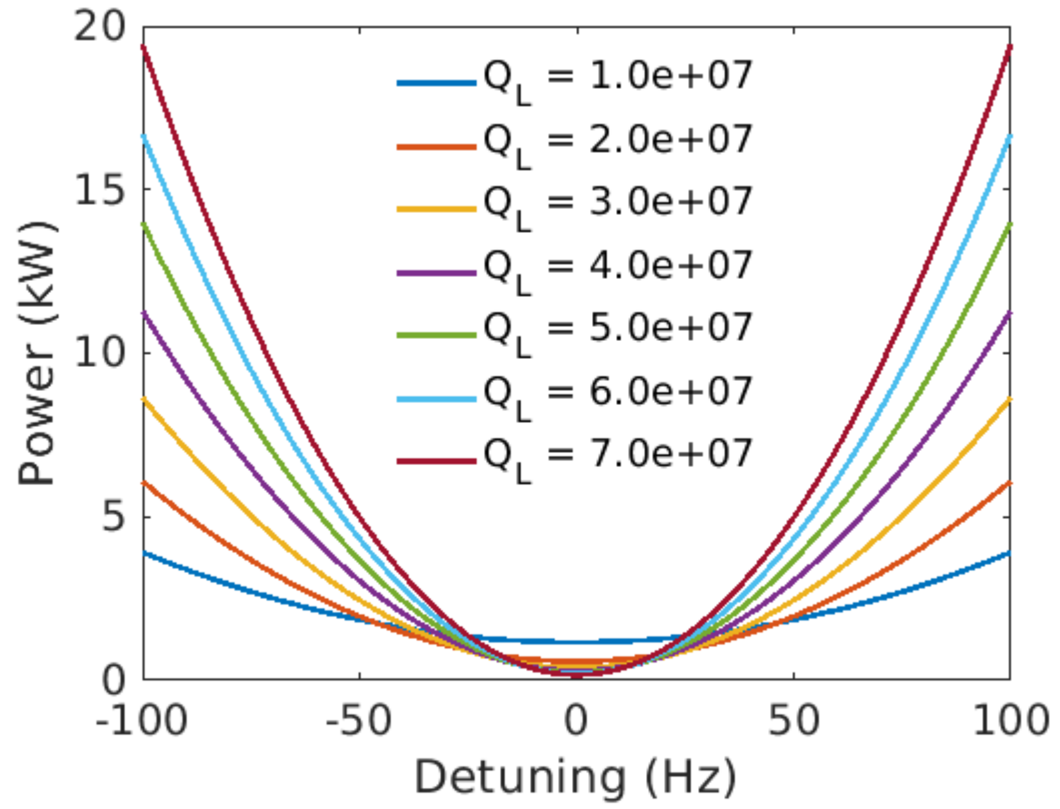


Passive and Active Control of Microphonics at CBETA and Elsewhere

Nilanjan Banerjee (Cornell Univ, USA)

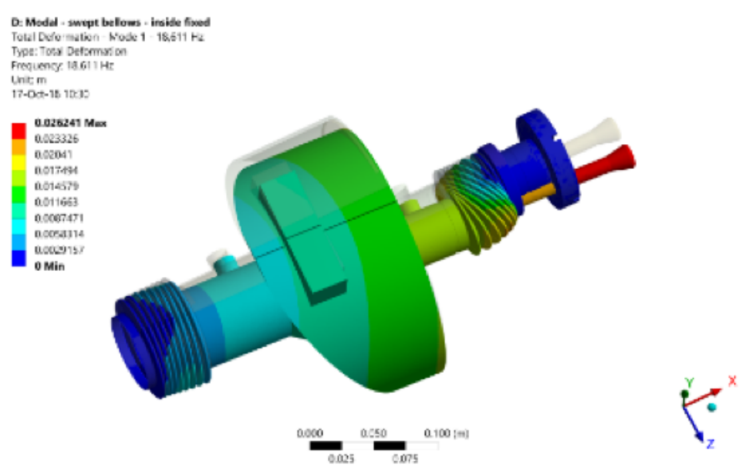
High Q_L Cavities

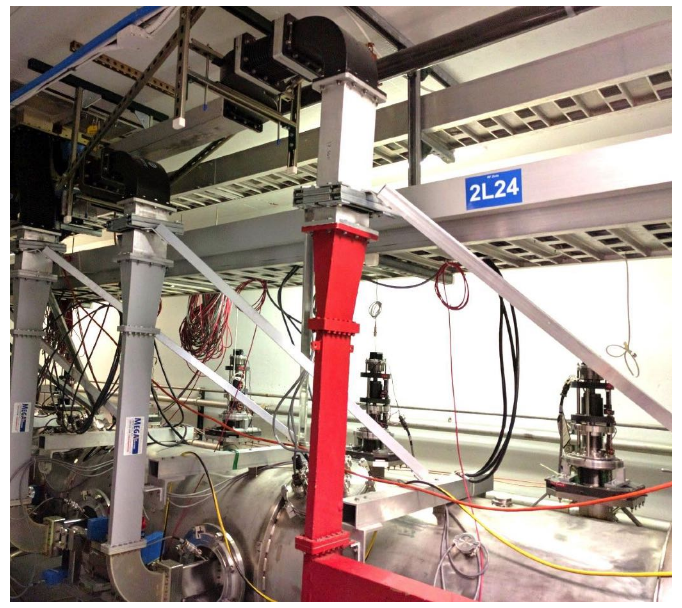
Low beam loading in ERLs allow the use of high Q_L, however this makes the cavities very sensitive to microphonics.

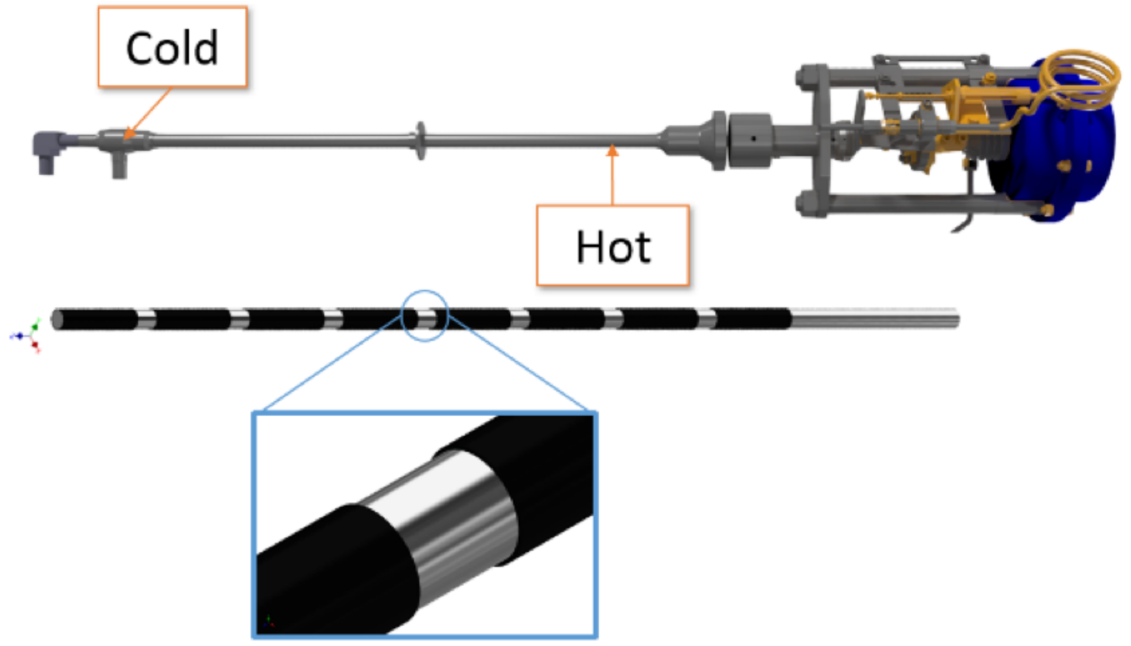


reminder that high Q_L reduces average power but increases the power needed to correct detuning

Passive Control





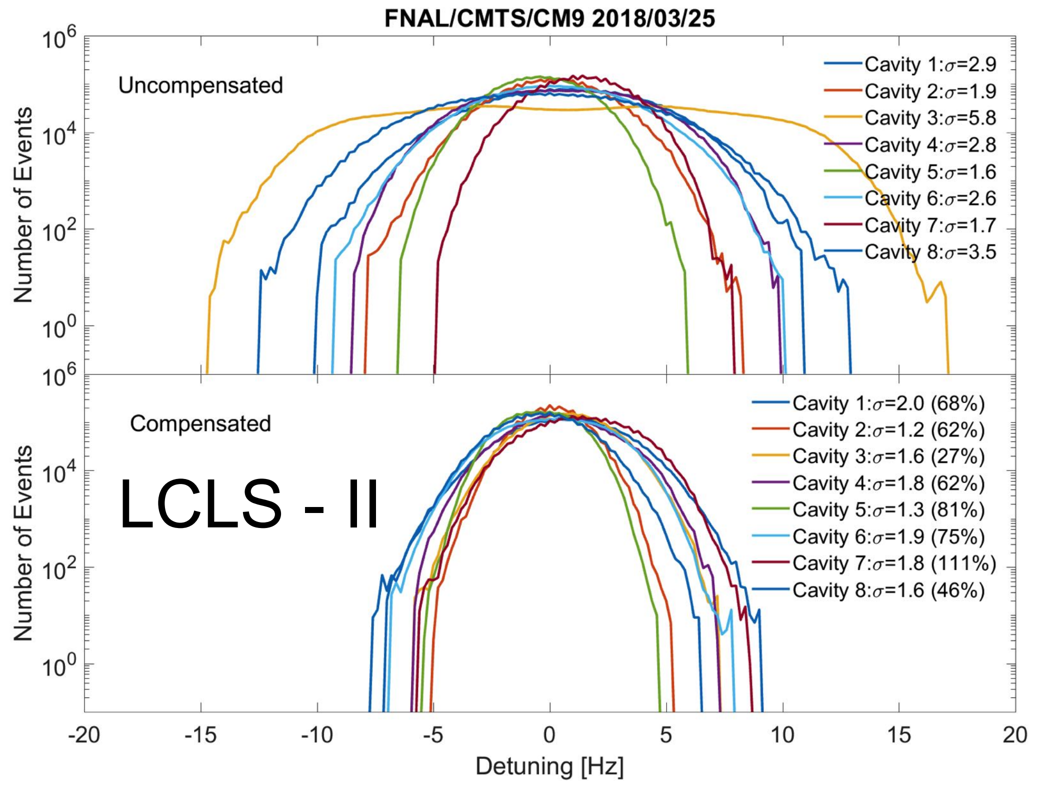


We should analyze the mechanical eigenmodes of all components of the cryomodule and try looking for cryogenic instabilities which might be the major driving terms.

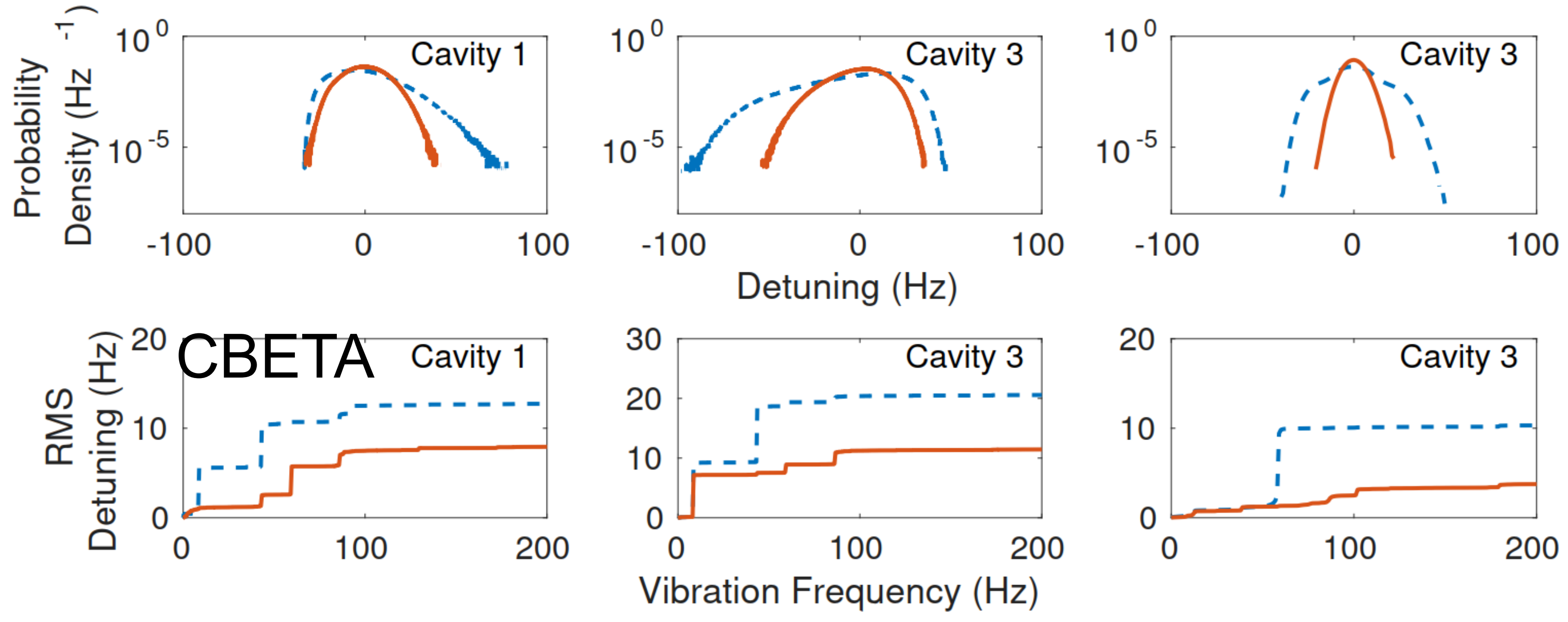
Active Control

Optimal Control

Tuner Model + Microphonics Model



Active Noise Control



Adaptively apply notch filters to suppress narrow band microphonics noise.

A Ferroelectric Fast Reactive Tuner (FRT) to Combat Micophonics
Alick Macpherson (CERN, Switzerland)

Euclid - BNL - CERN collaboration

FE-FRT Prototype results (Euclid, BNL, CERN):

- SRF cavity response to FRT: extremely fast << 50 μs (material response times < 10 ns)
- Not limited by cavity time constant.
- Mechanical & RF design crucial to FRT performance.

FE-FRT Benefits

- FE-FRT ideal for low beam loading application.
- Eliminate microphonics => drastically reducing RF power.
- Tuner is outside of CM.

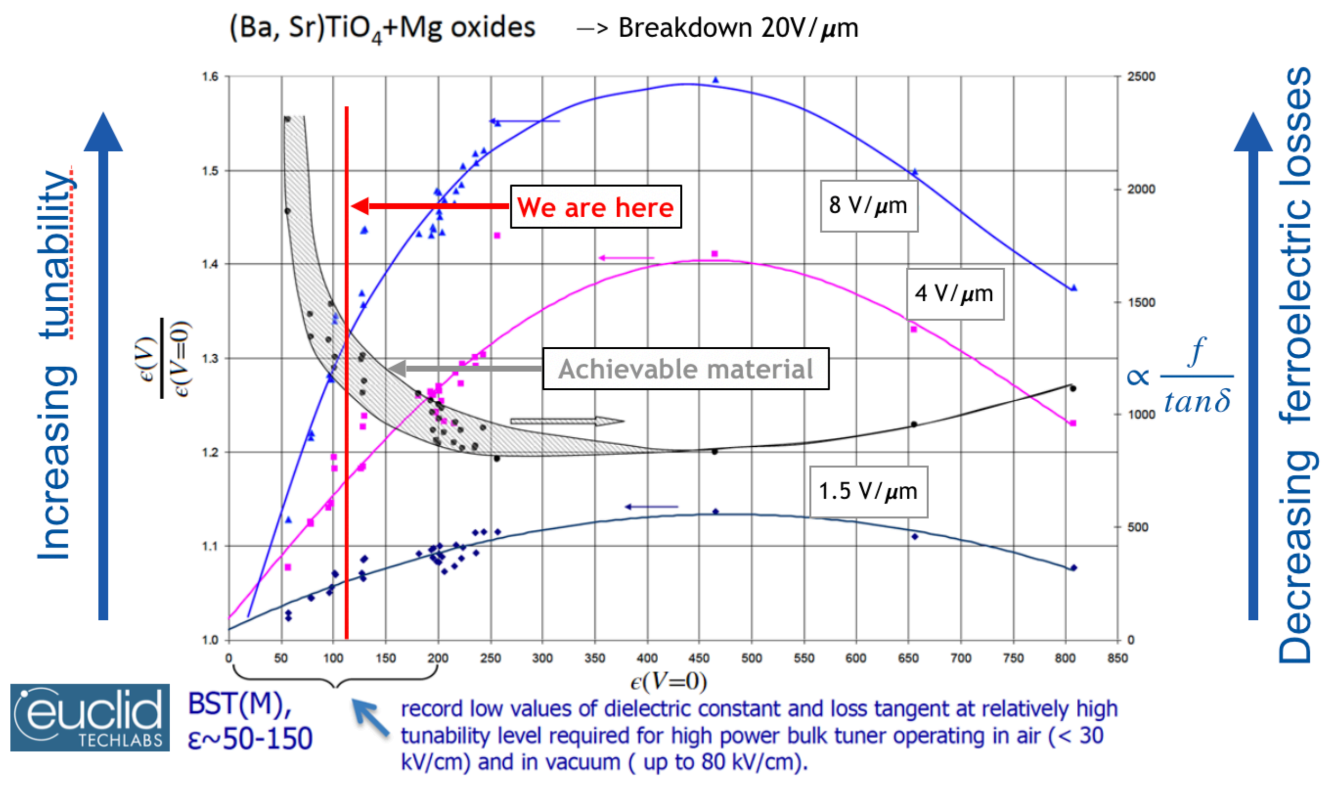
FE-FRT prototype with tuning loop under test at CERN

- Exploring potential use cases at CERN.
- Should be included at cavity/module design stage.

Fast Reactive Tuner: A. Macpherson - ERL2019 19/09/2019

Ferro-electric material

- **Development of ferro-electric ceramic**
  - Material parameters developed sufficiently to consider application
    - May be further development for mechanical/RF considerations



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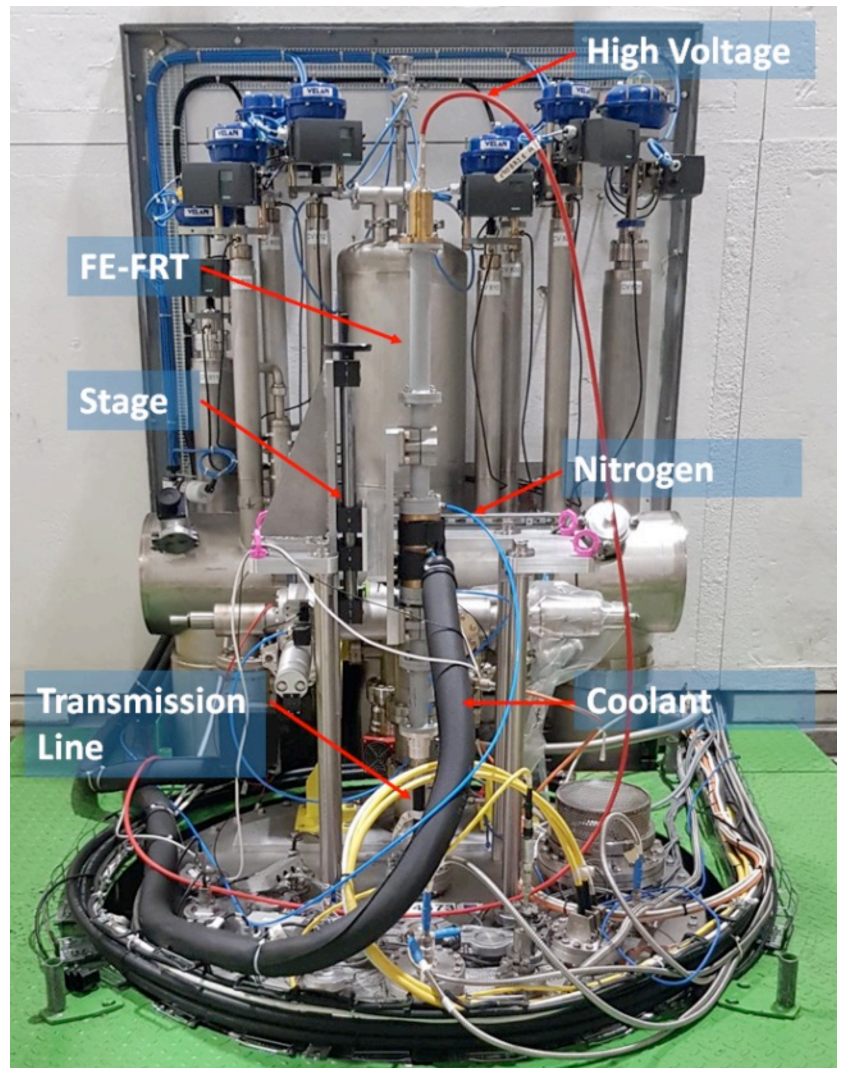
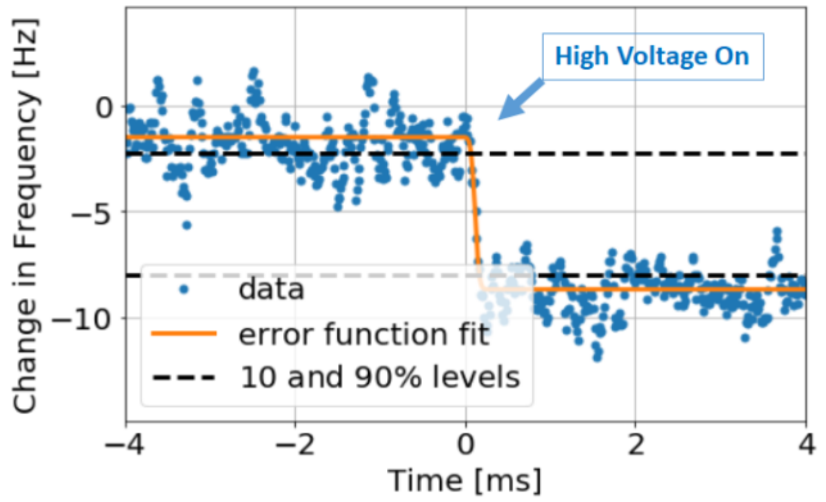
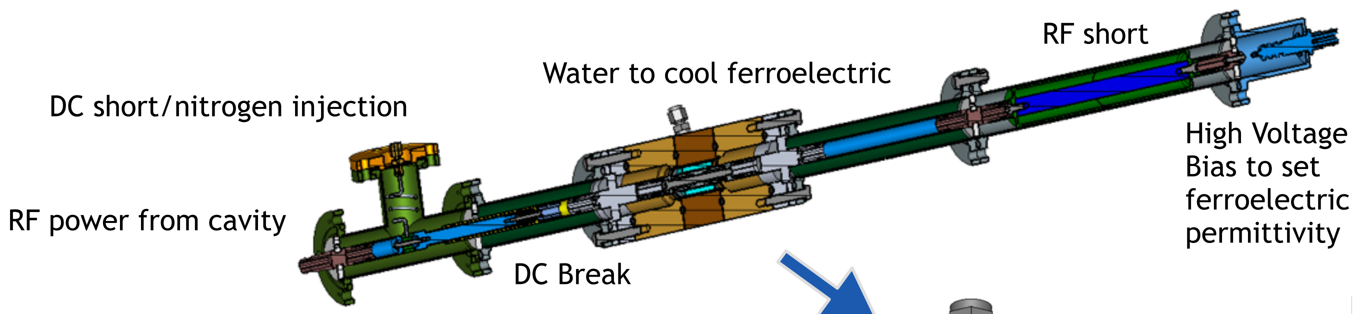




Fast Reactive Tuner: A. Macpherson - ERL2019 19/09/2019

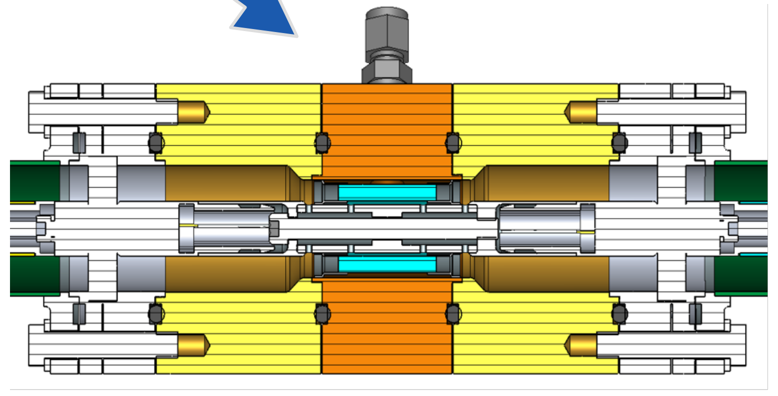
Our Prototype FE-FRT

- **Prototype FE-FRT**
  - RF design: S. Kazakov, FNAL. Fabrication: Euclid Techlabs in USA
  - Testing and development program, now ongoing at CERN



Ferroelectric (light blue)

- Brazed to rings
- Active cooling
- Designed for 400 MHz
- Mechanical design limits HV



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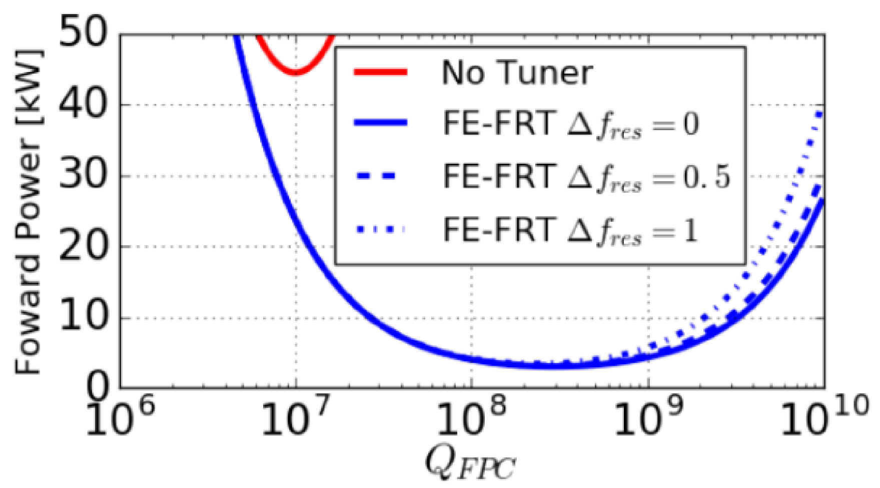
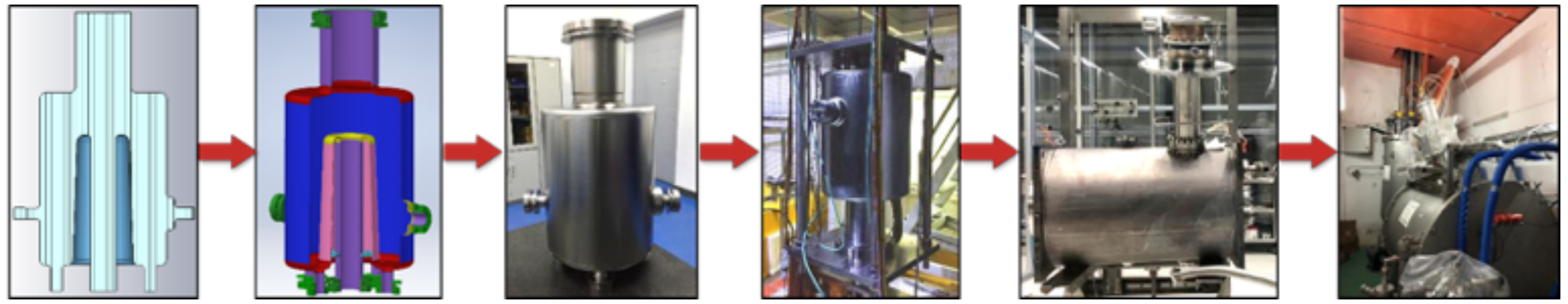
PERLE Application:

- X15 reduction in RF power!

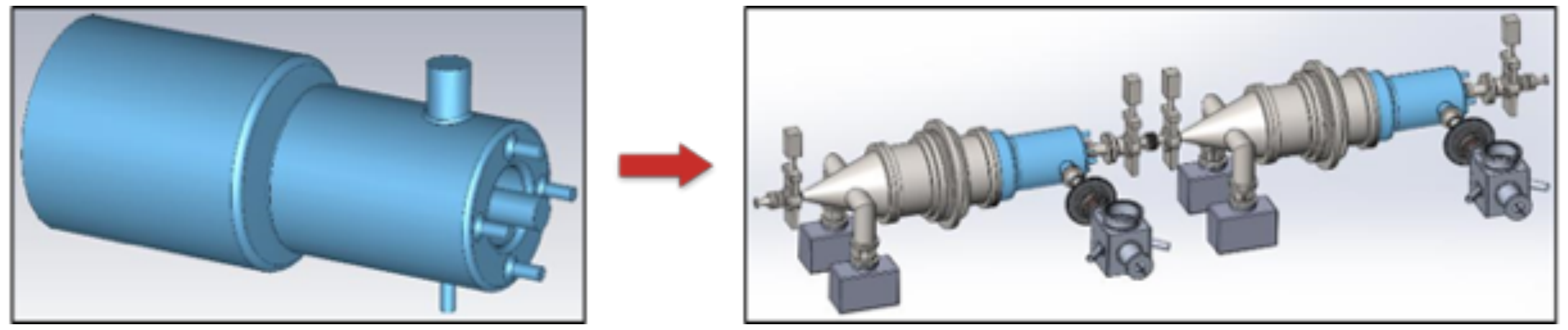


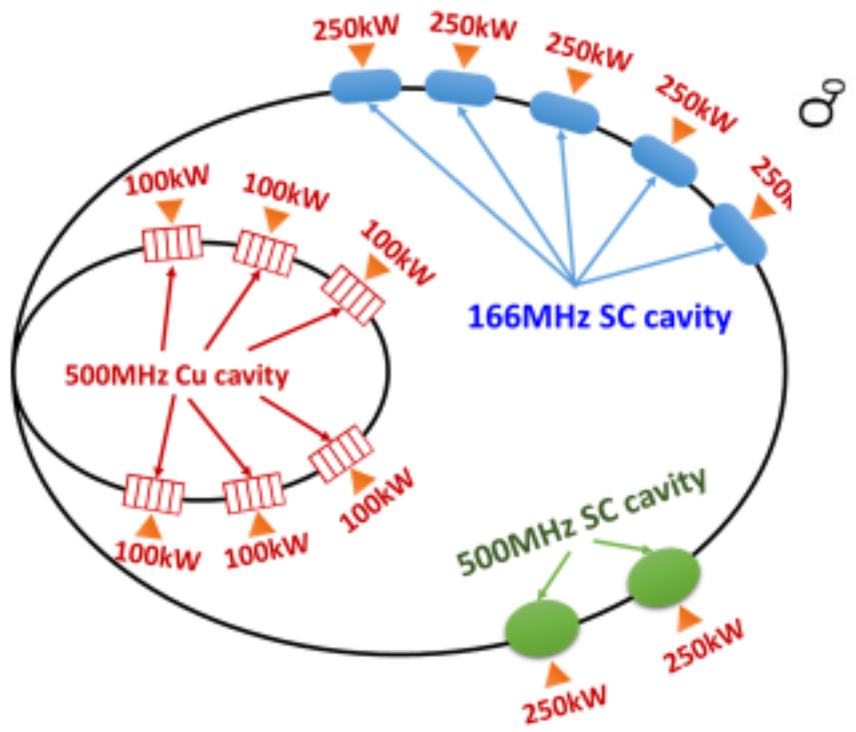
The development of HOM-damped 166.6 MHz SRF cavities for High Energy Photon Source in Beijing, Pei Zhang (IHEP, China)

PoP cavity

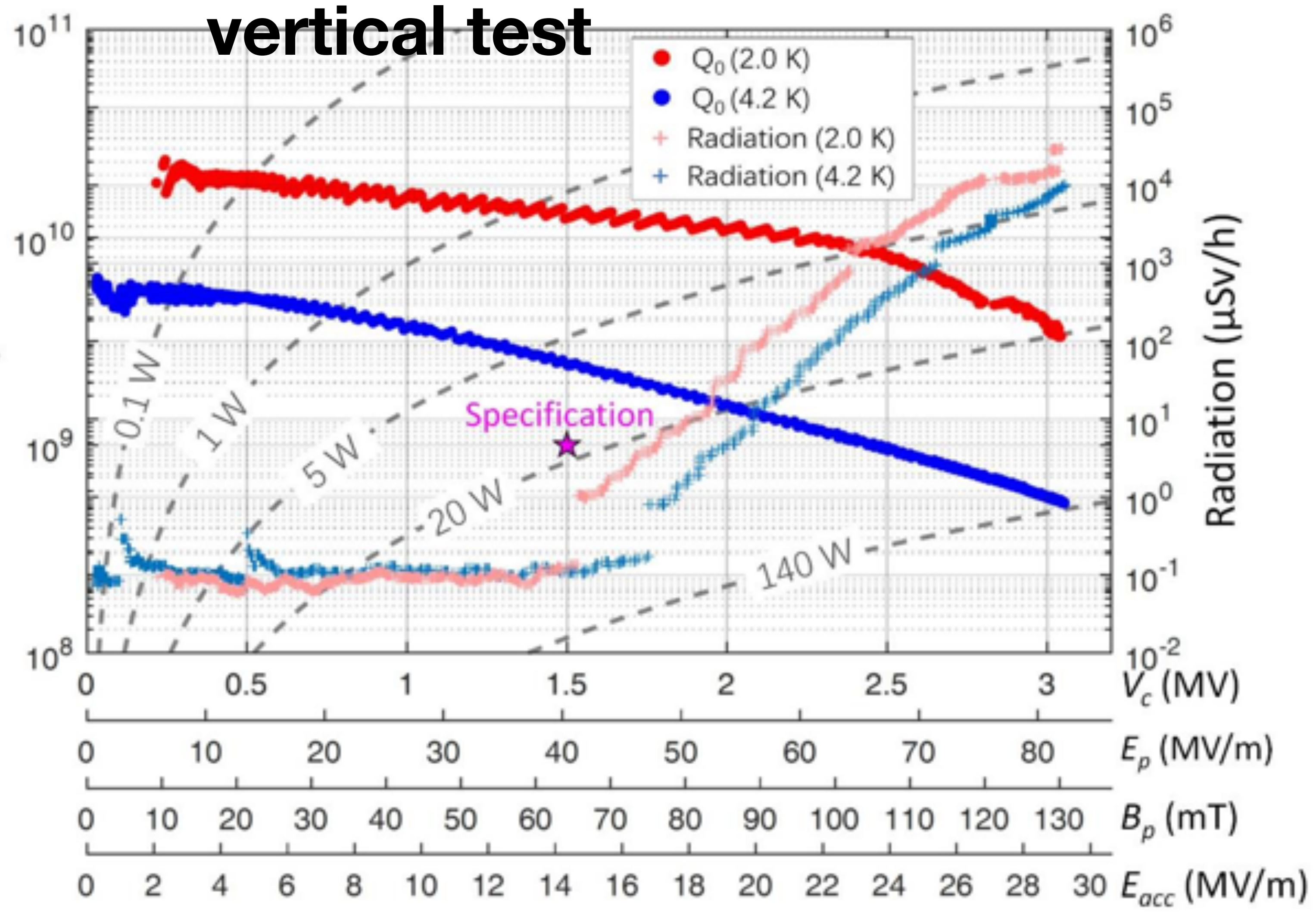


Prototype cavity



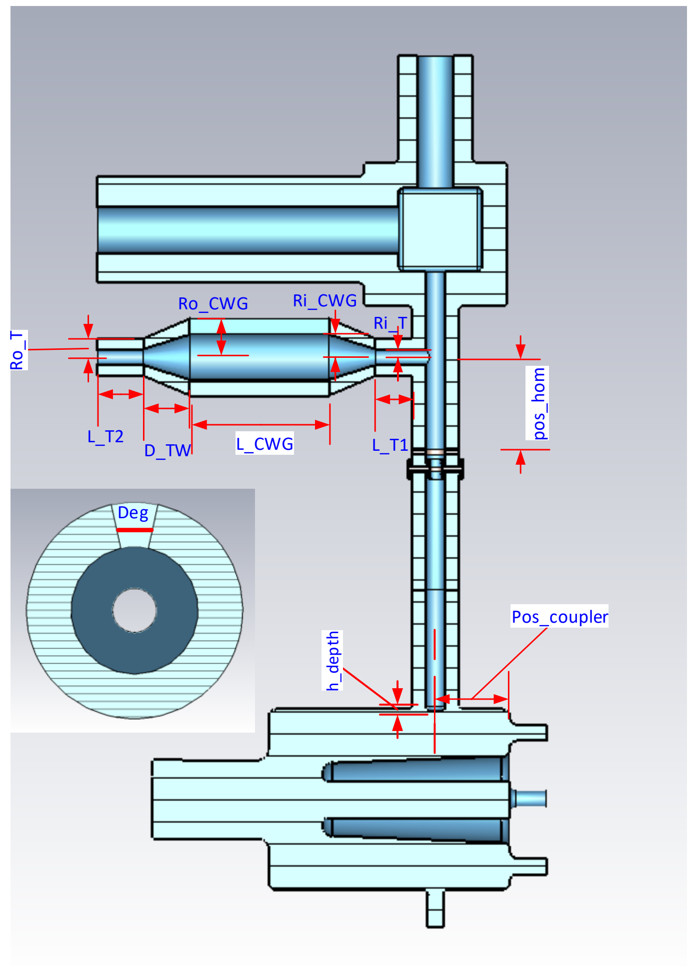


vertical test

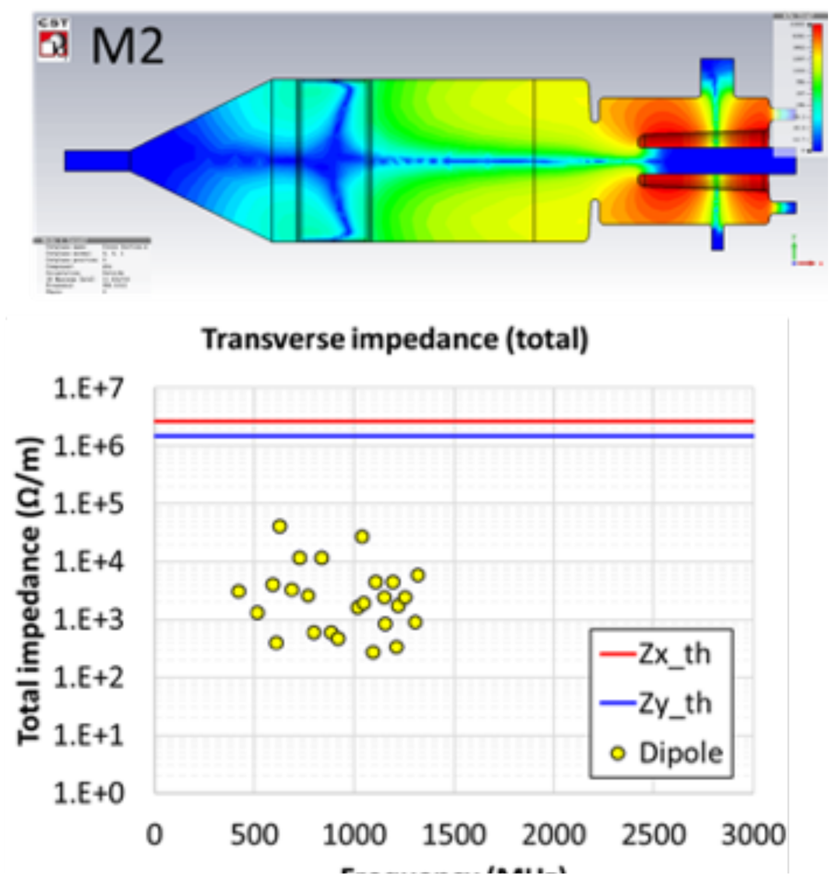


Note: HEPS Phase-II has 40 x IDs and impedance too high for 14 x NC cavities → SRF preferred solution!

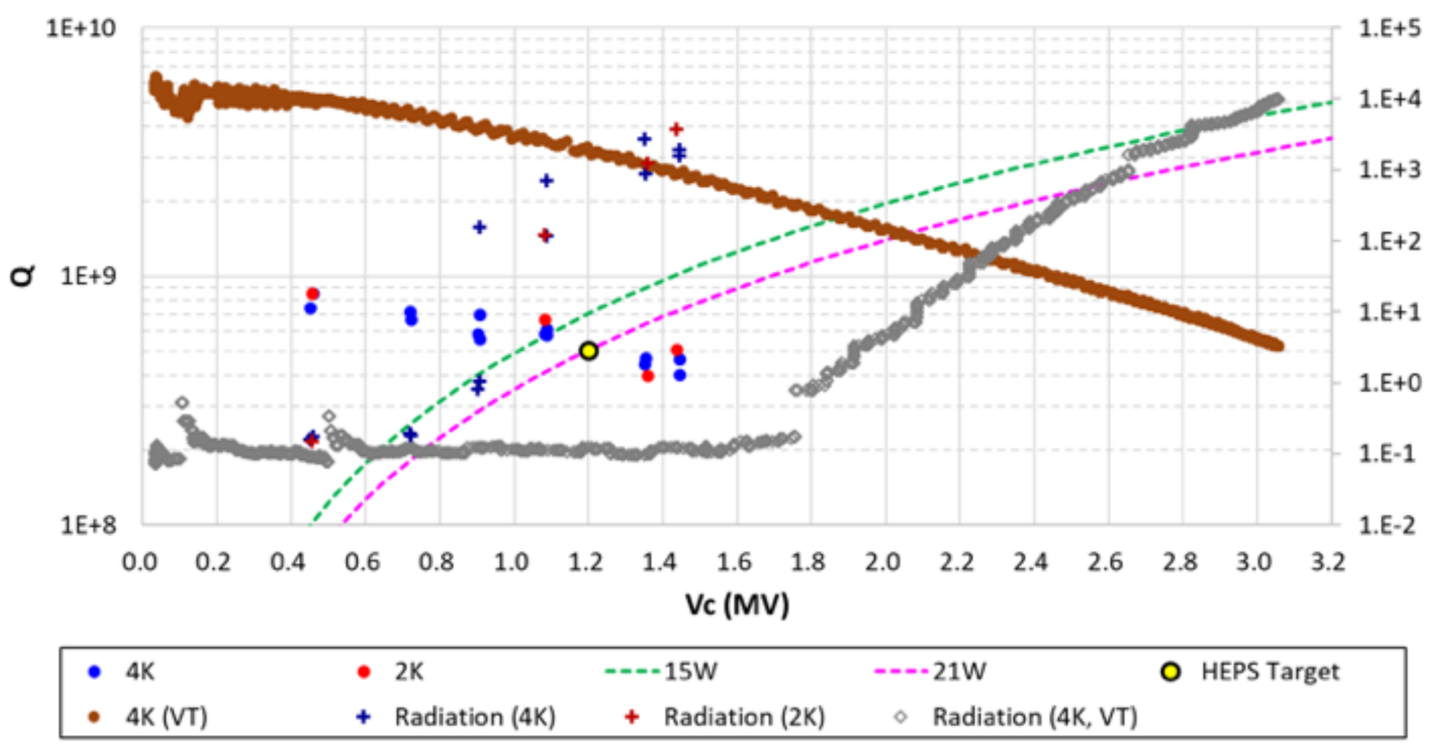
C-shaped WG (ideal HP-filter included with FPC



Enlarged beam-pipe for HOM damping



CM test



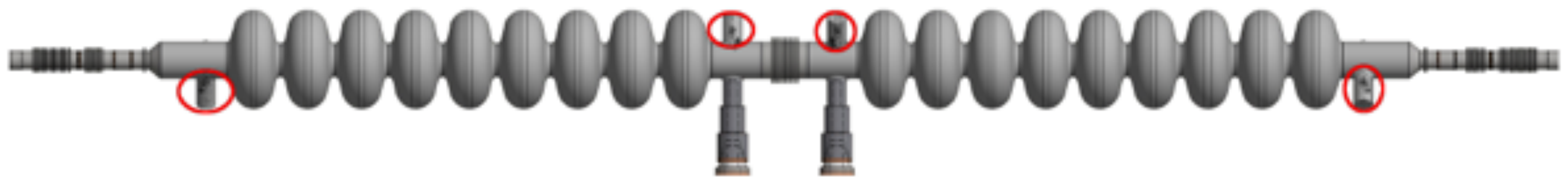
12 W static load measured

Improvements needed:

- Longer Nb tube of FPC port to reduce dynamic loss
- Improve FPC outer conductor cooling
- Larger helium vessel for stable 4K operation

iii) HOMs, HOM damping, and high current operation

BBU limit estimations and HOM characterisation for MESA, Christian Stoll (KPH, Germany)



- Two 1.3 GHz TESLA type 9 cell cavities
- 4 Higher Order Mode (HOM) couplers per module
- Operated at 1.8 K

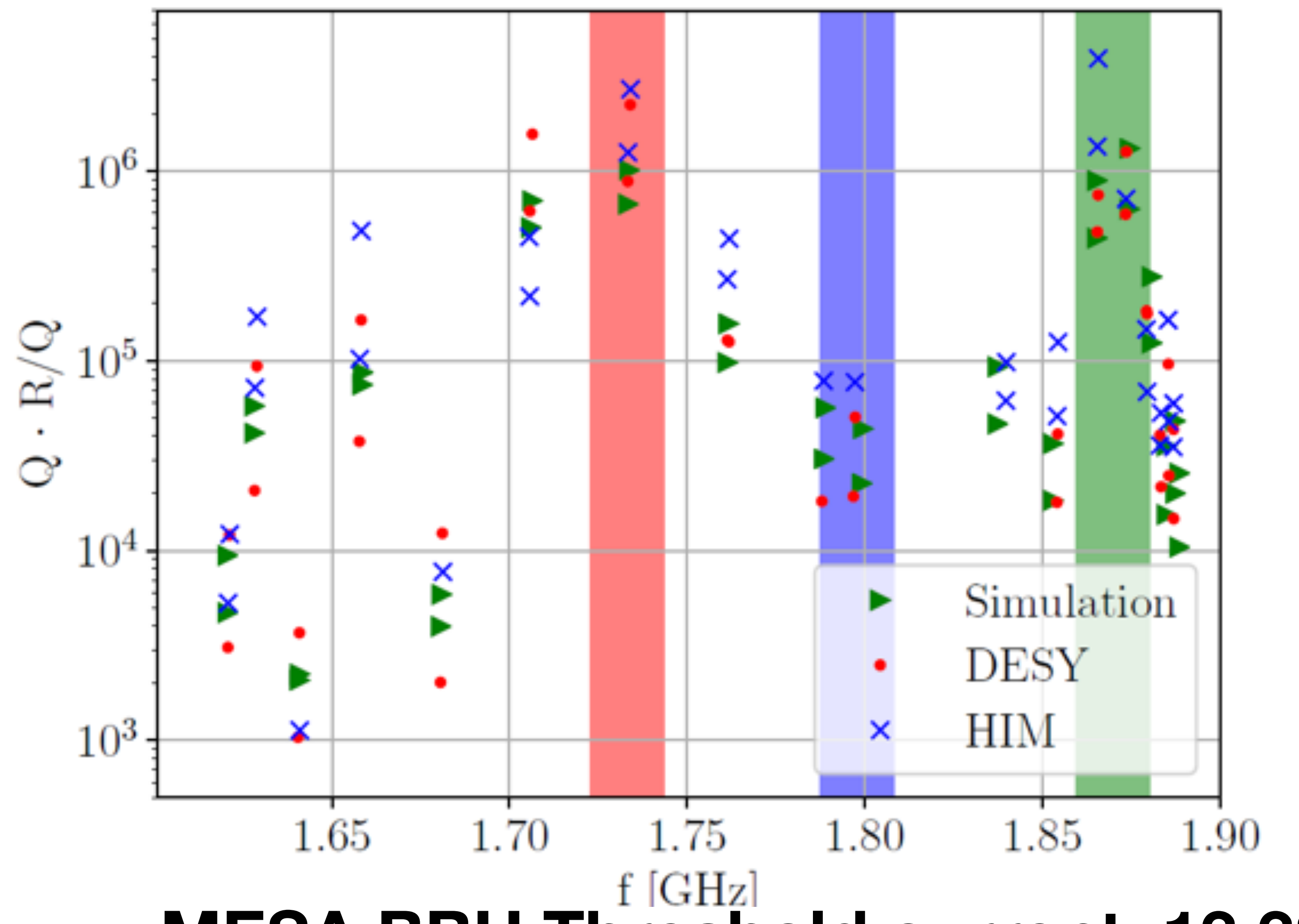
Comparison of HOM measurements on i) single cavity (VT, DESY) and ii) 2 cavities in CM (HIM).

- Frequency deviation because of fundamental mode tuning.
- Frequency spread between cavities (fabrication tolerances).
- Larger Q-spread: deviation from elliptical shape.
- Higher Q-factor: difference in HOM coupler gap (simulation - reality).

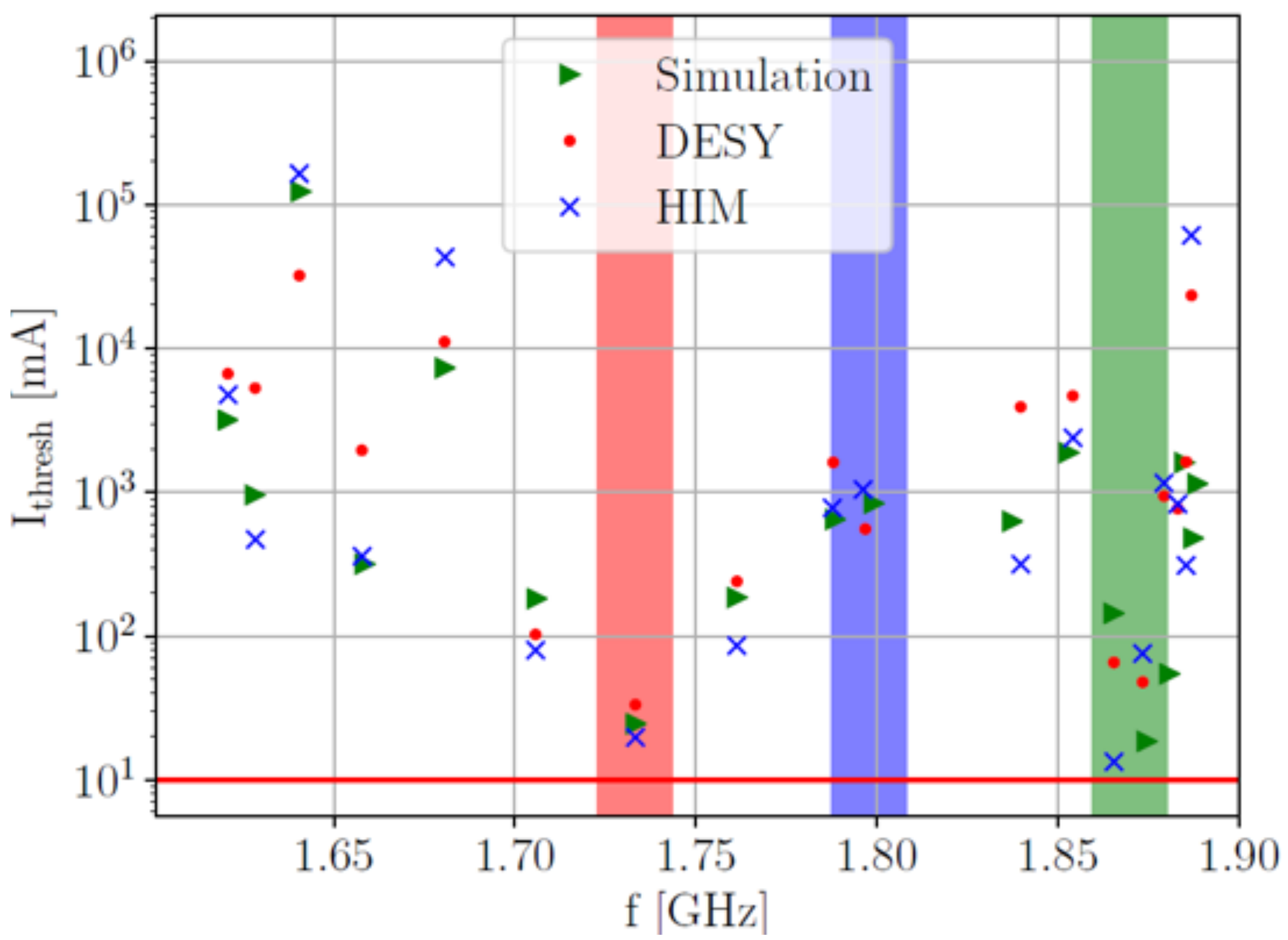
Outlook

- Study MESA beam current limits due to HOM coupler heating.
- HOM behaviour at bERLinPro

Bandwidth comparison

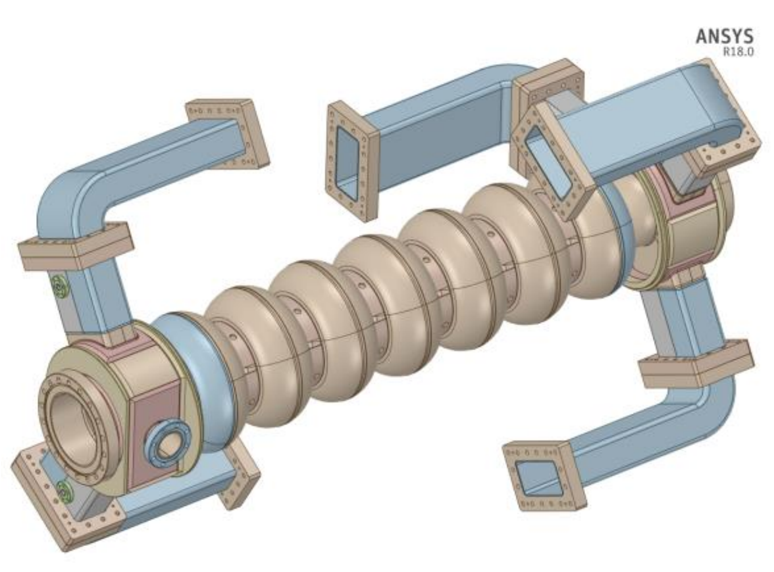


MESA BBU Threshold current, 13.38 mA

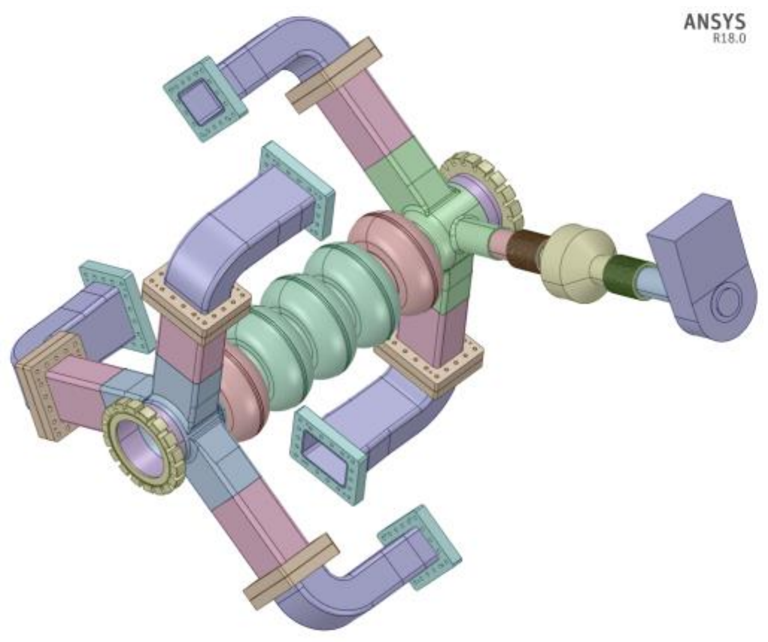


Waveguide HOM loads for high current elliptical cavities, Jiquan Guo, (JLAB, USA)

- JLAB - HZB collaboration
- Previous absorber materials (Ceradyne) no longer available. Alternatives from CoorsTek and Sienna were tested.
- Brazing tests with old Ceradyne and old/new Sienna Tech materials succeeded. Final choice: high thermal conductivity Sienna AlN-SiC composite.
- Both loads now fully prototyped
- Both couplers high-power tested.

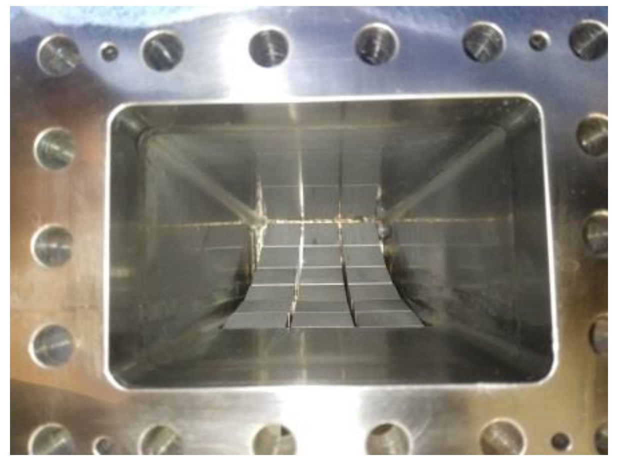


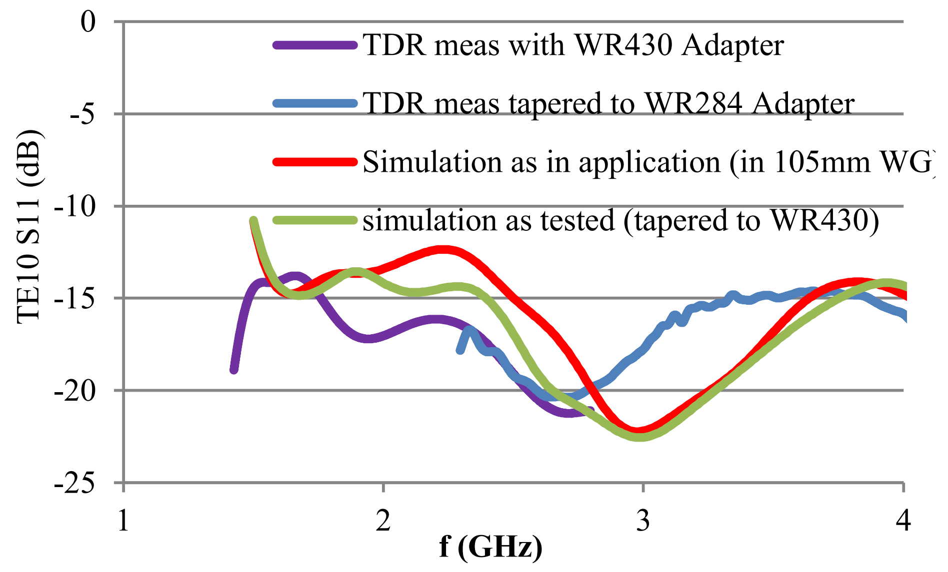
bERLinPro 1.3 GHz cavity model



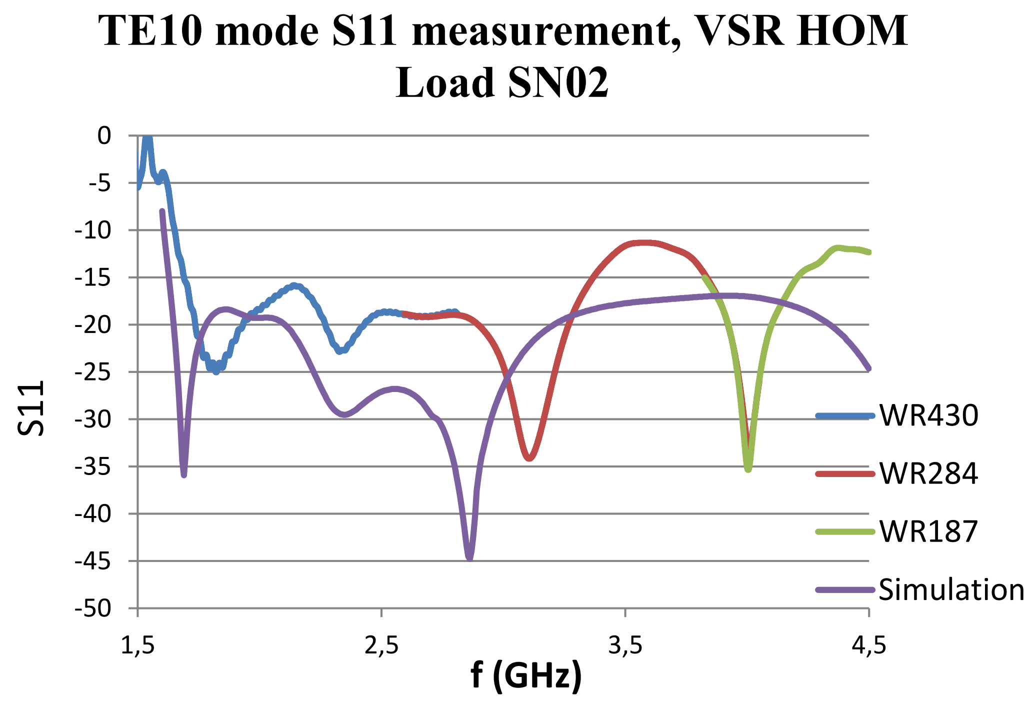
VSR 1.5 GHz cavity model

Brazed load



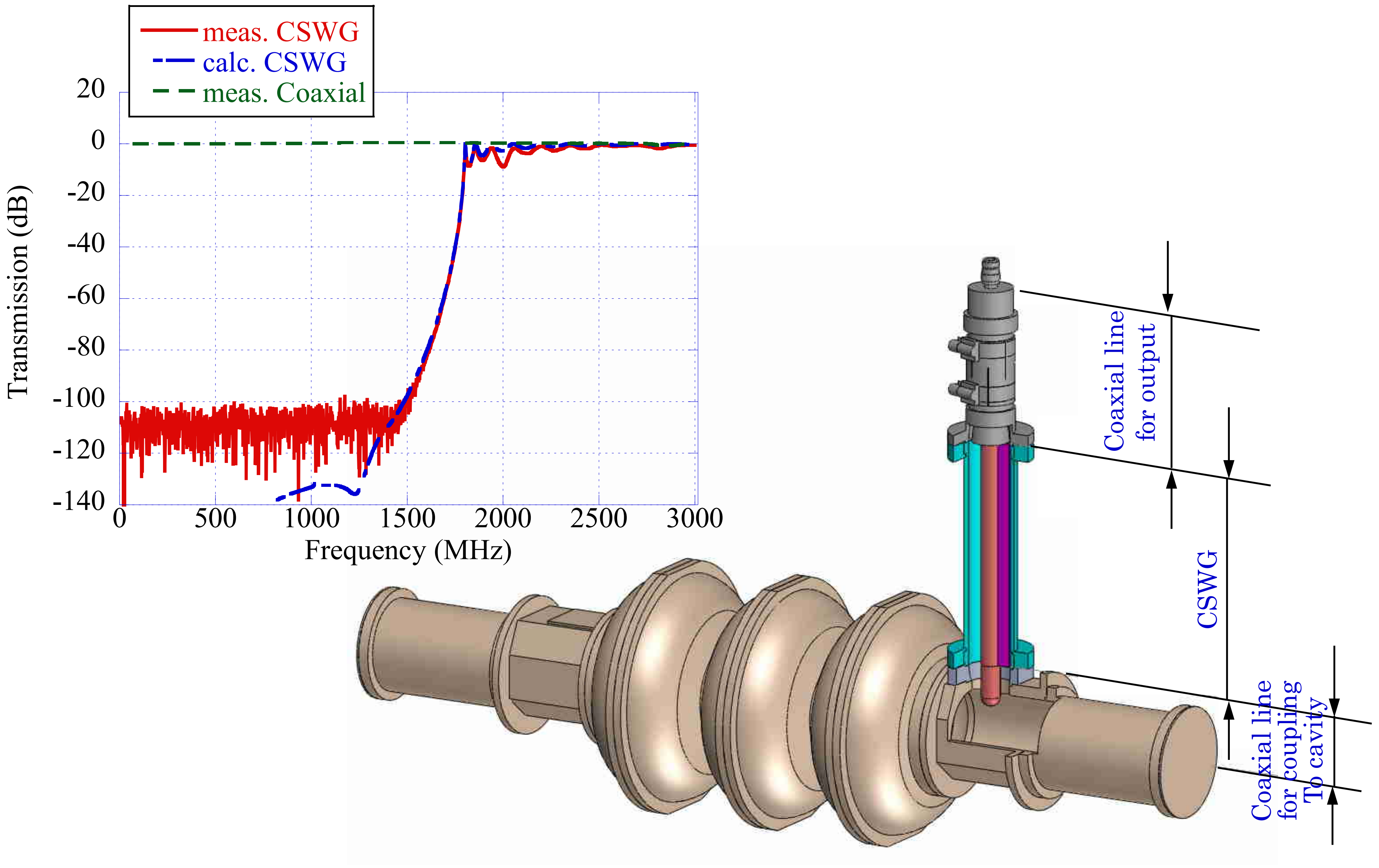


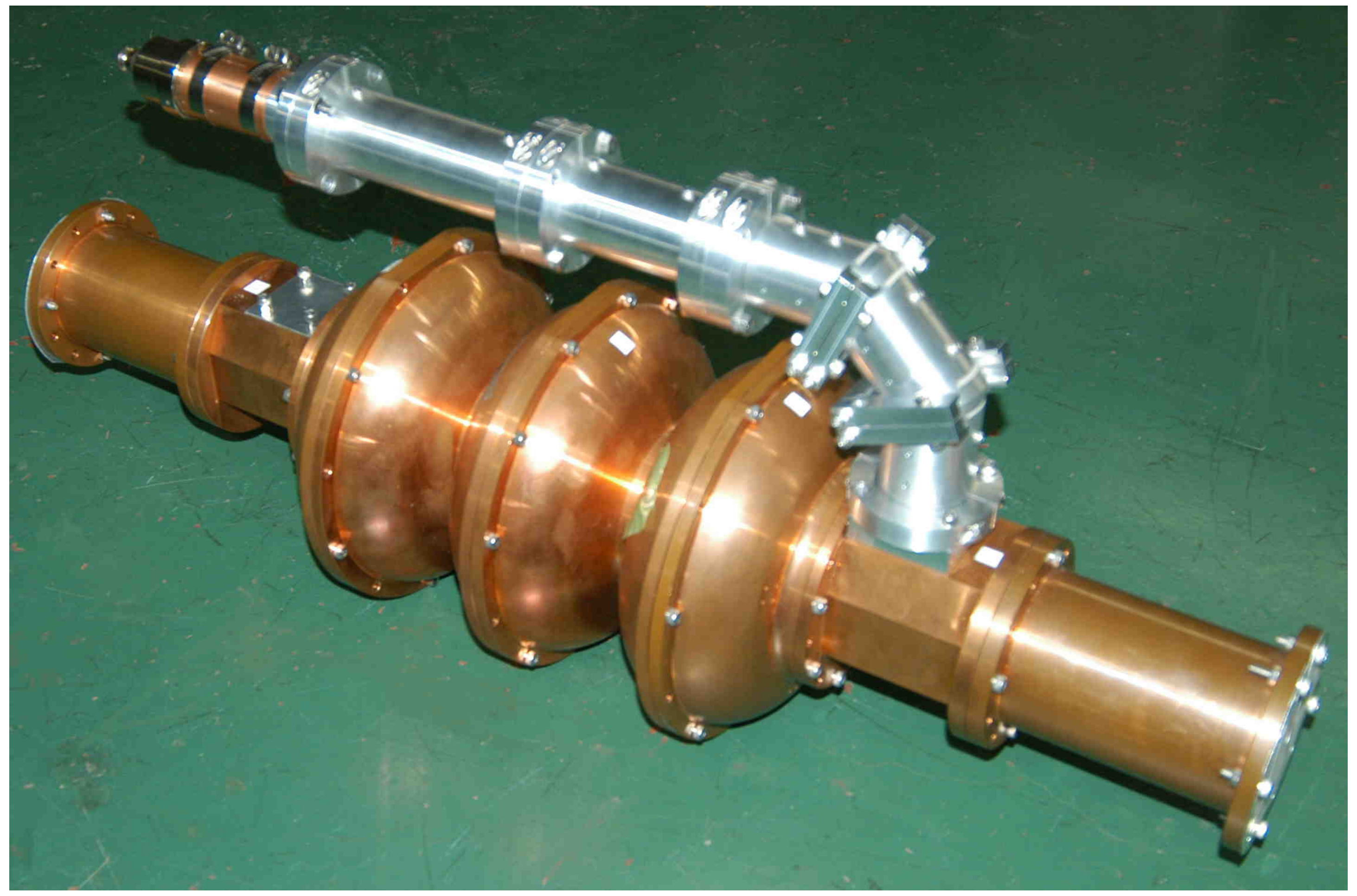
NWA measurement results vs simulation



Development of HOM coupler with C-shaped waveguide for ERL operation, Masaru Sawamura (QST, Japan)

- Cracks in ferrite of existing HOM coupler, together with excessive length and outgassing, triggered the development of an alternative design.
- Coaxial waveguide converter type HOM is desirable but very bulky.
- As alternative a compact c-shaped CWC was studied and developed: easy to cool inner conductor, adjustment free high-pass filter, compact and easy transition to coax-line. but needs a long pipe to not affect the accelerating mode.
- Fabrication is being studied.
- Looking forward to first tests!

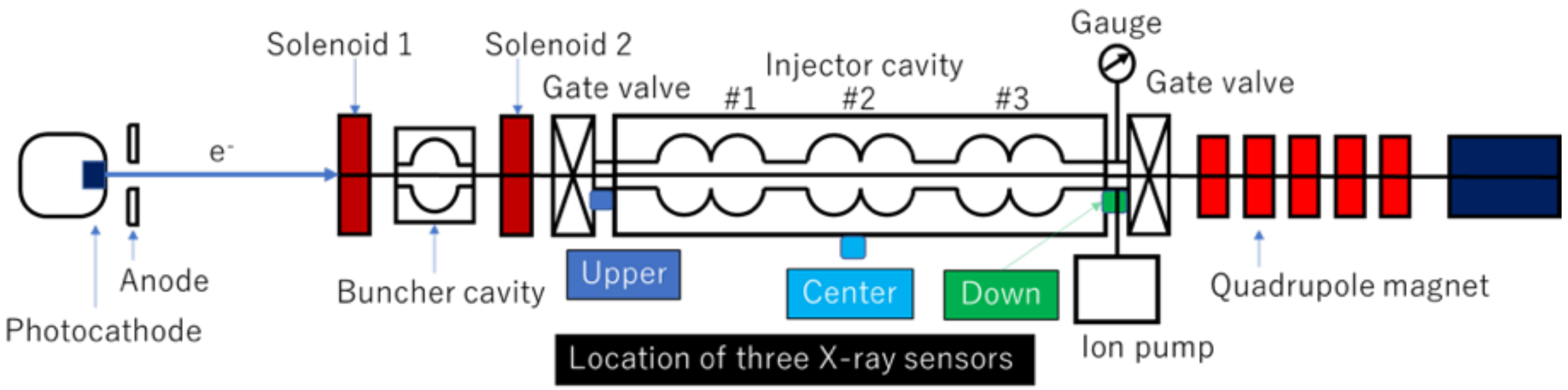




iv) High Q0 cavity performance

Degradation and Recovery of Cavity Performance in Compact-ERL Injector Cryomodule at KEK, Eiji Kako (KEK, Japan)

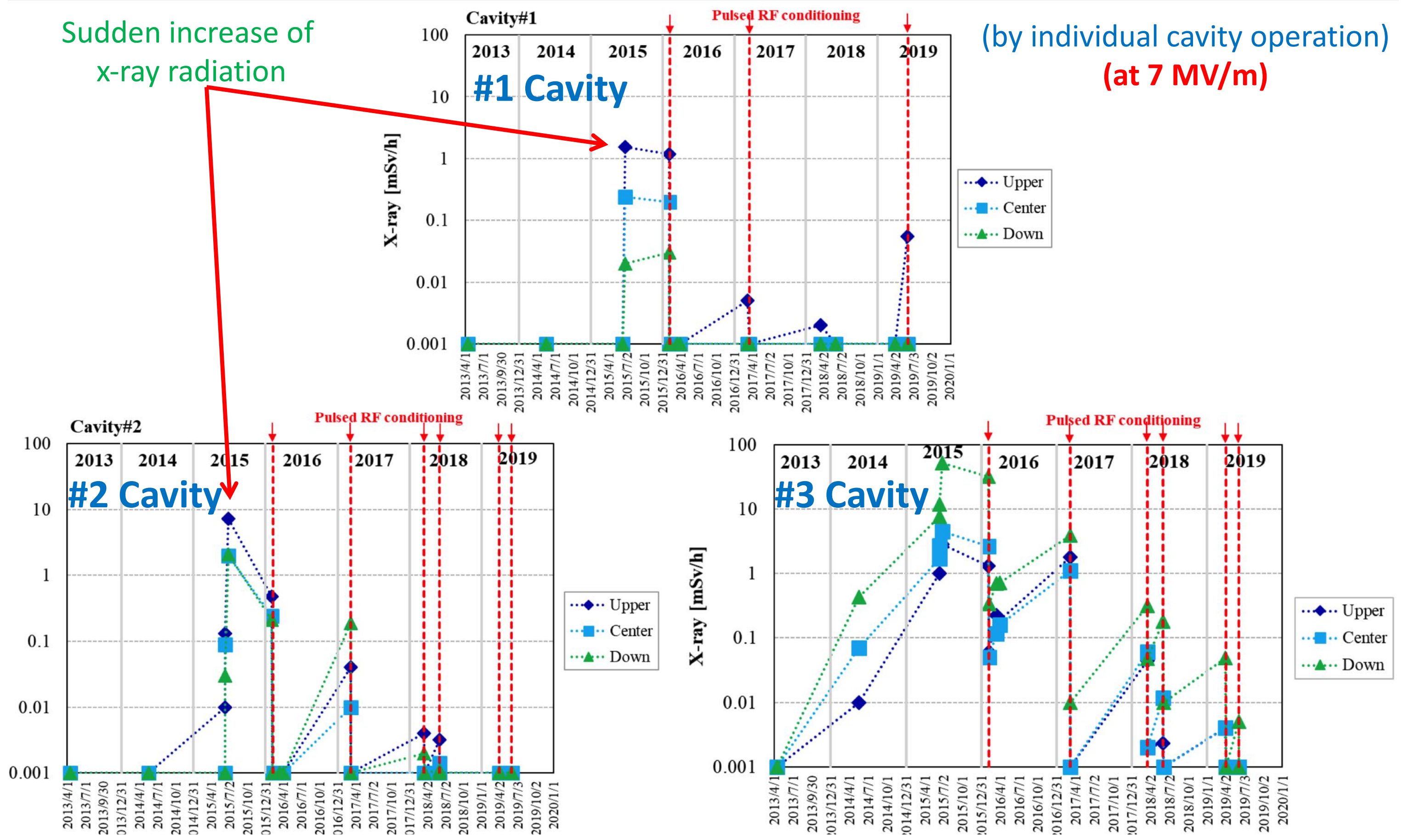
- In VT cavities achieved > 20 MV/m, couplers were tested at 40 kW in CW and 200 kW pulsed (10 kW CW needed for operation).
- X-ray level increased with operation, jump observed in 2015. Degradation seems to start from “dirty” side of machine.
- High-power pulse processing found to reduce radiation level and is now routinely carried out before beam operation.



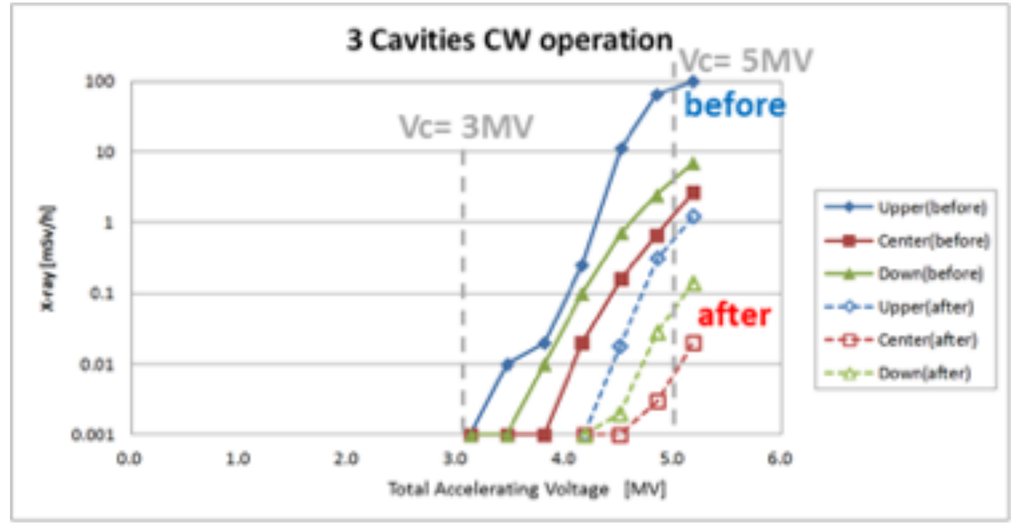
Two exlanations identified

1. Field emitted electrons hitting Faraday cup leading to vacuum discharge.
2. FE electrons hitting the photocathode gun, being re-accelerated and creating X-rays at downstream part of injector.

Change of x-ray radiation levels in 2013’ – 2019’

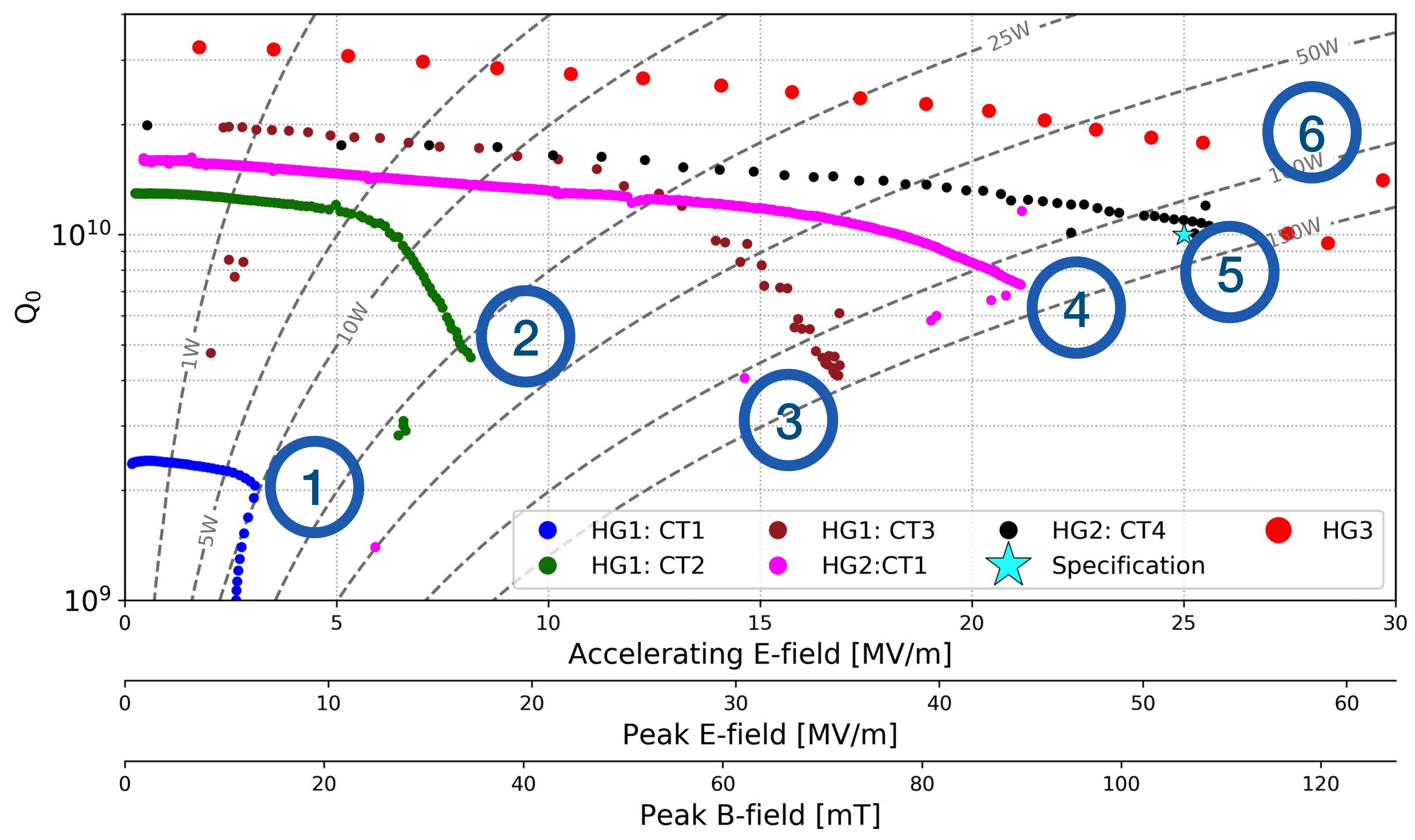


Performance before and after pulsed power processing



High Q 704 MHz cavity tests at CERN, Alick Macpherson (CERN, Switzerland)

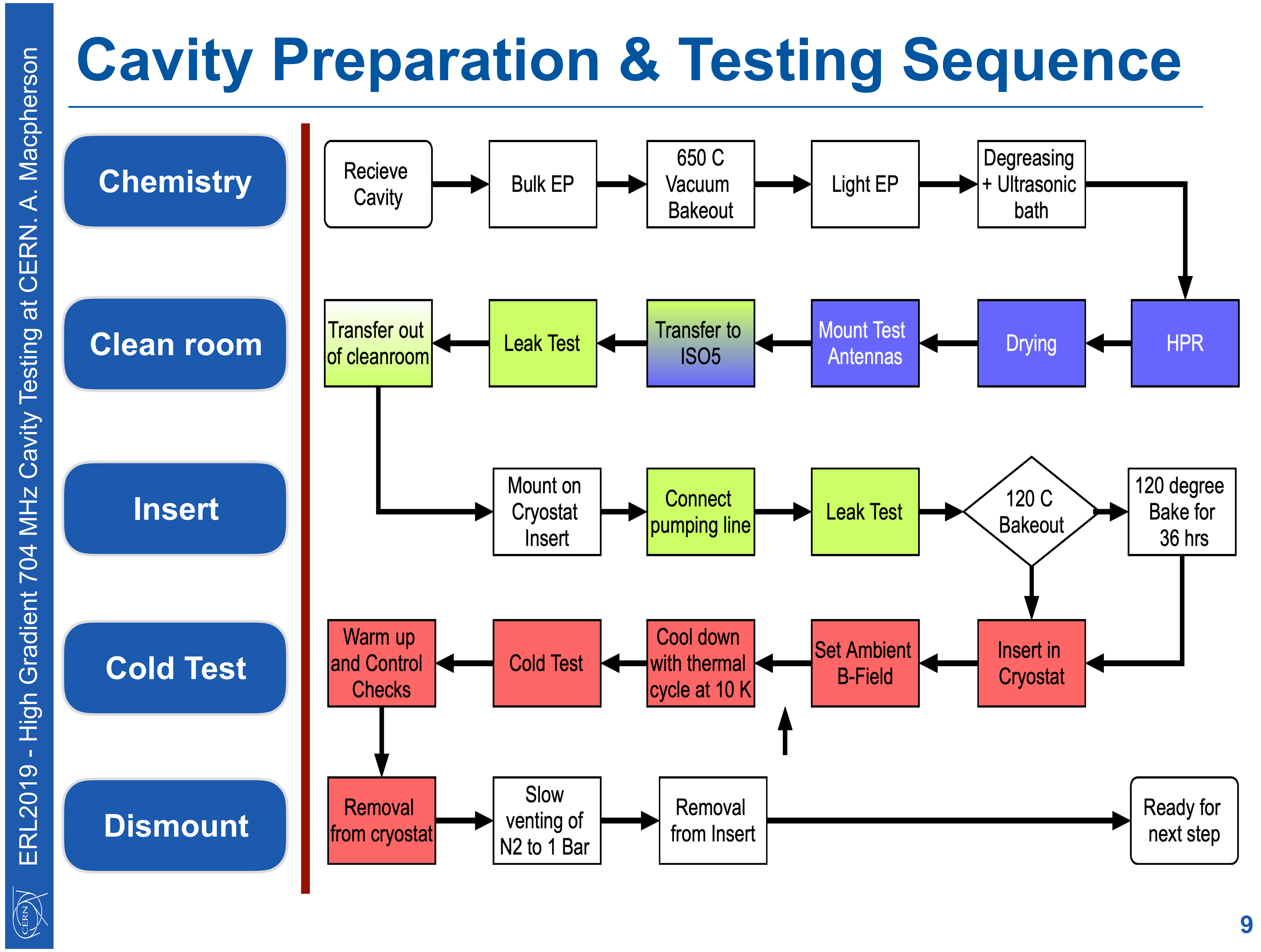
- Detailed description of how CERN re-learned to do SRF bulk Nb cavity preparation & testing.
- Digital LLRF with SEL is replacing old analogue system. Comparison of Q-measurement methods.
- Many lessons learned on clean assembly, power tests, HPR, vertical EP, …
- Improvement on cold-testing results for 704 MHz 5-cell cavities. Existing CM components may be adapted for 1st PERLE 800 MHz module.
- Effort was already highly beneficial for HL-LHC Crab program. Today's results are comparable with state-of-the-art measurements (e.g. JLAB 800 MHz FCC cavity).
- Further effort foreseen to push towards R_s of ~5 nOhm.



1. **Contamination issues and corrosion on antenna:**
   - Improve component cleaning. Improved material management & component control
2. **Unsatisfactory surface finish after electropolishing surface finish**
   - Redesign of EP cathode
3. **HPR rinse quality control issues**
   - Procedural & quality control revision of HPR => Now based on monitoring data
4. **Post-chemistry residues & contaminants from cavity handling steps**
   - Improved quality control and handling. Post chemistry ultra-sonic bath prior to HPR
5. **Field emission limited**
   - Improved pumping line cleanliness: reduce surface contamination during cool down
6. **Cryostat feed through burnout at high power**
   - Cavity not quench limited. R_S ~8nΩ => need to reduce RF surface pollution

Target: Reduce R_S to ~5 nΩ => Refine preparation &assembly steps

It’s all in the process!



courtesy A. Macpherson

courtesy of Brewdog

Summing up

- **ERL CM operation**: 3 modules were presented in detail: cERL (KEK) injector & accelerating module and the MESA module. VT successful in all cases but the modules experienced problems with cleanliness/contamination by surrounding environment (uncontrolled gate valve movements, field emission electrons hitting surrounding elements, vacuum burst event). In some cases high pulsed power processing can help but not always. ***Compared to larger SRF installations the transition area cold/warm or clean/dirty is much smaller and is probably not as rigorously managed as in case of a large machine.***

- **Cavities:** twin axis: 2 talks presenting comparisons between simulations and measurements and ODU demonstrated (in one cavity) high-field performance. ***Proof of principle that this cavity shape can be built***, cleaned and made to work. 166 MHz 1/4 wave cavity as low-frequency option.

- **HOM loads/couplers:** Strong ERL damping needs triggered new development on i) damping materials and ii) C-shaped coaxial waveguide HOM coupler; interesting for other high-current applications.

- **Microphonics/LLRF:** very active field, which shows that ERL LLRF systems need a specific effort and a "practical approach", 1. apply mechanical damping of all parts that can vibrate or induce vibrations. 2. final compensation with LLRF. Promising test of a fast reactive tuner at CERN to combat microphonics without moving parts and without excessive RF power.