Superconducting RF at CERN

Frank Gerigk for the CERN SRF teams in BE-RF, TE-VSC, EN-MME, TE-CRG, …

TTC2020@CERN, 4-7 Feb 2020

Content

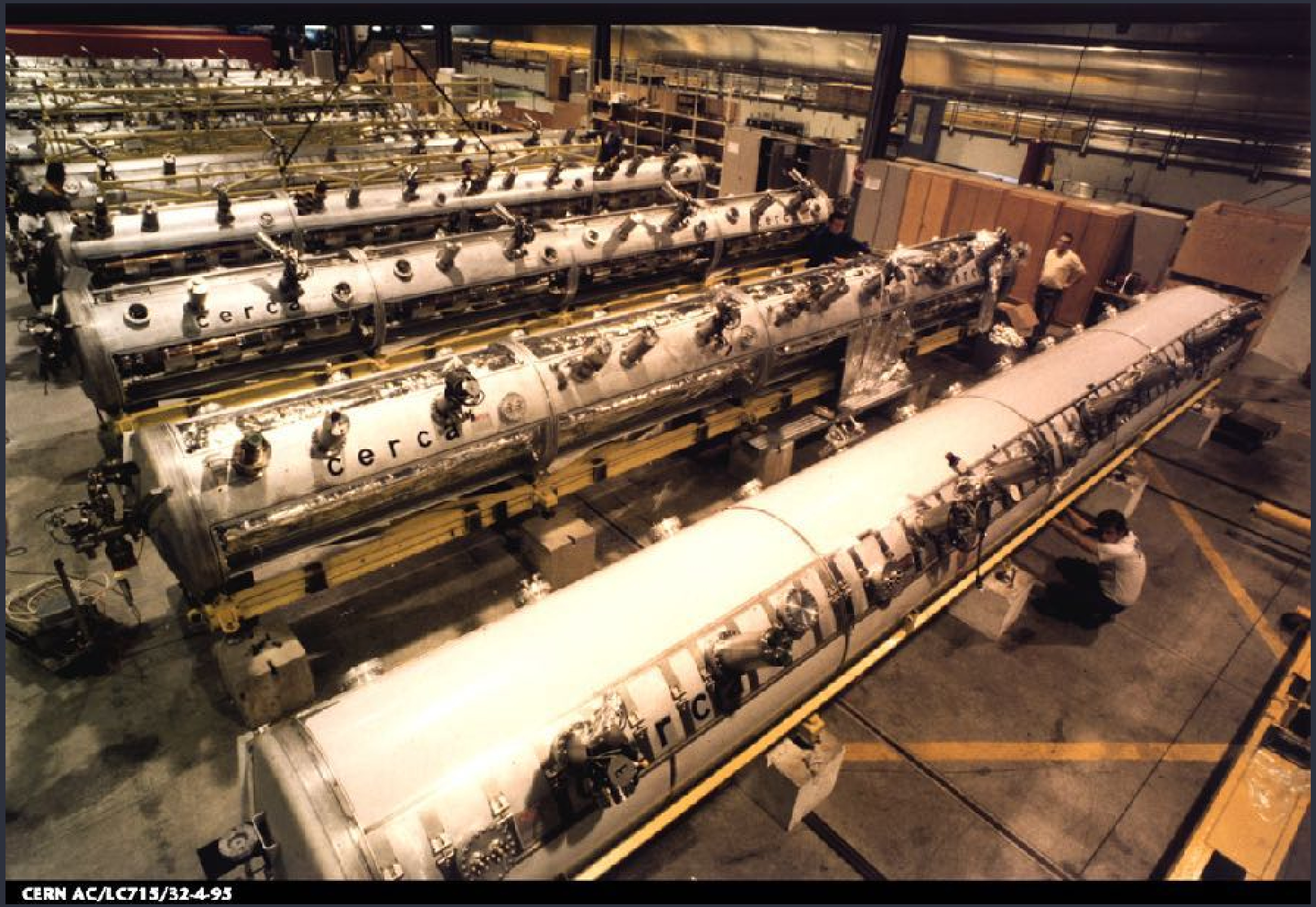
01 Past Glory

02 SRF in operation: LHC, HIE-ISOLDE, HL-LHC

03 SRF infrastructure at CERN

04 R&D

LEP cavity tuning, 1980



In 1999 288 SC cavities were installed in LEP

LHC cavities

Recent Glory…

LHC cryomodule

Test of first LHC module (2000)

2008: 16 SC mono-cell cavities (4 CMs) operational in LHC

LHC spare CM

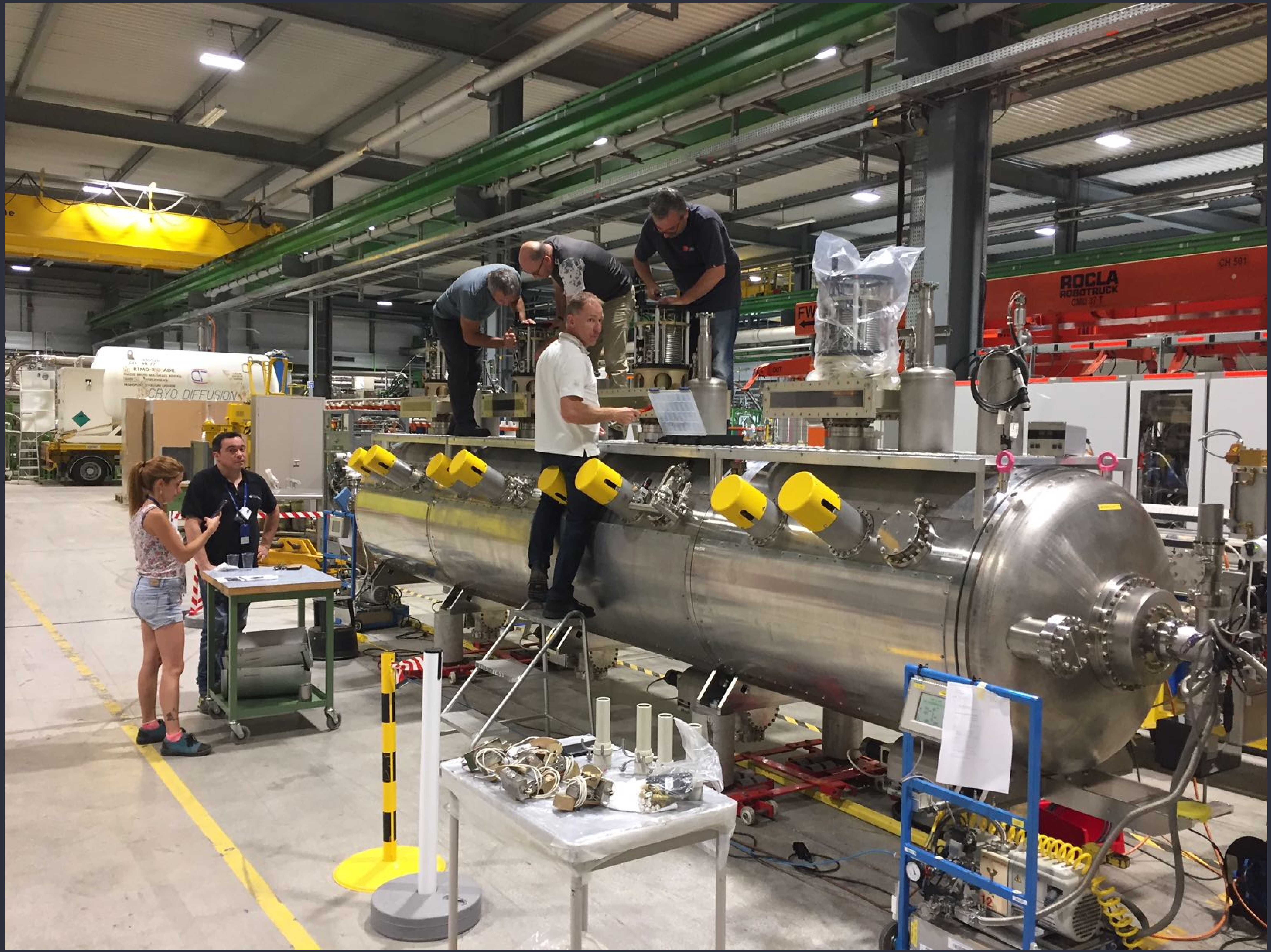
Take the SM18 tour on Friday!

1 spare module for 4 installed CMs

- 4 modules with 4 Nb coated Cu cavities each are installed in the LHC.
- operating at 4.5 K, 400.790 MHz, providing 8-16 MV/beam.

LHC CM tests:

- CM exchange and re-qualification in 2015 via pulsed high-power processing.
- Re-tested in 2018 with a partly new technical team, confirmed operational status.
- 2019/20 another exchange because of a small vacuum incident: CM test in 2020 in SM18 + high-power processing, or repair if necessary.

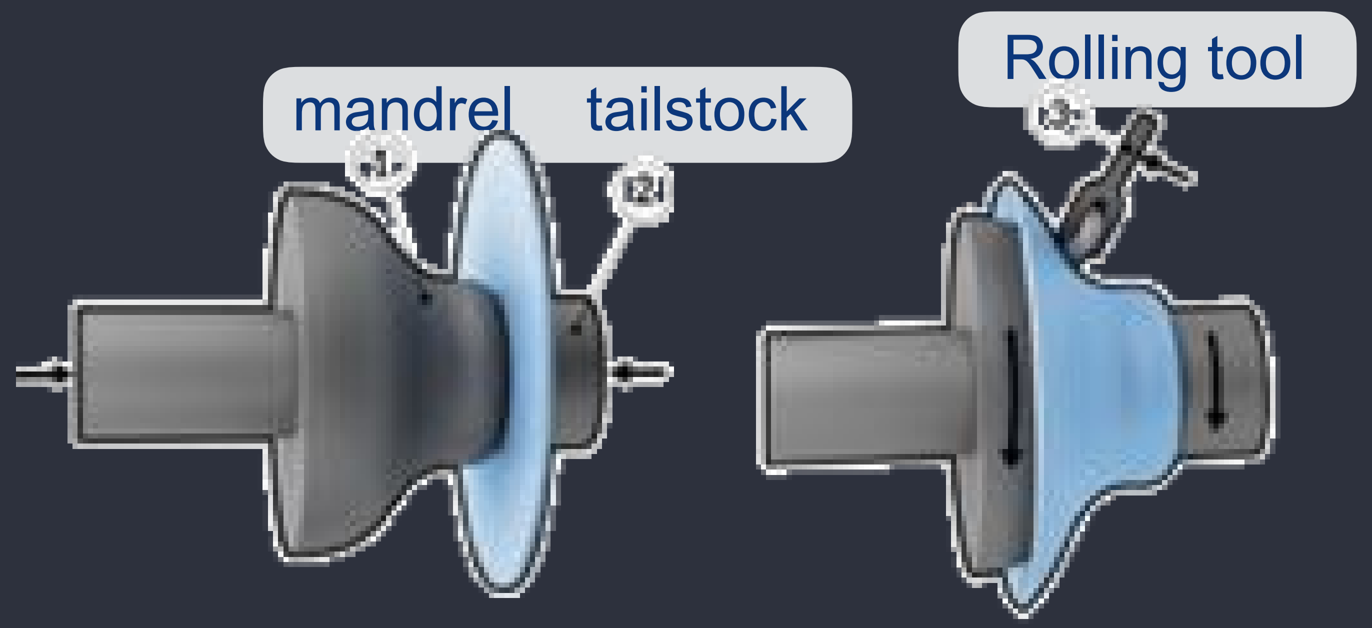


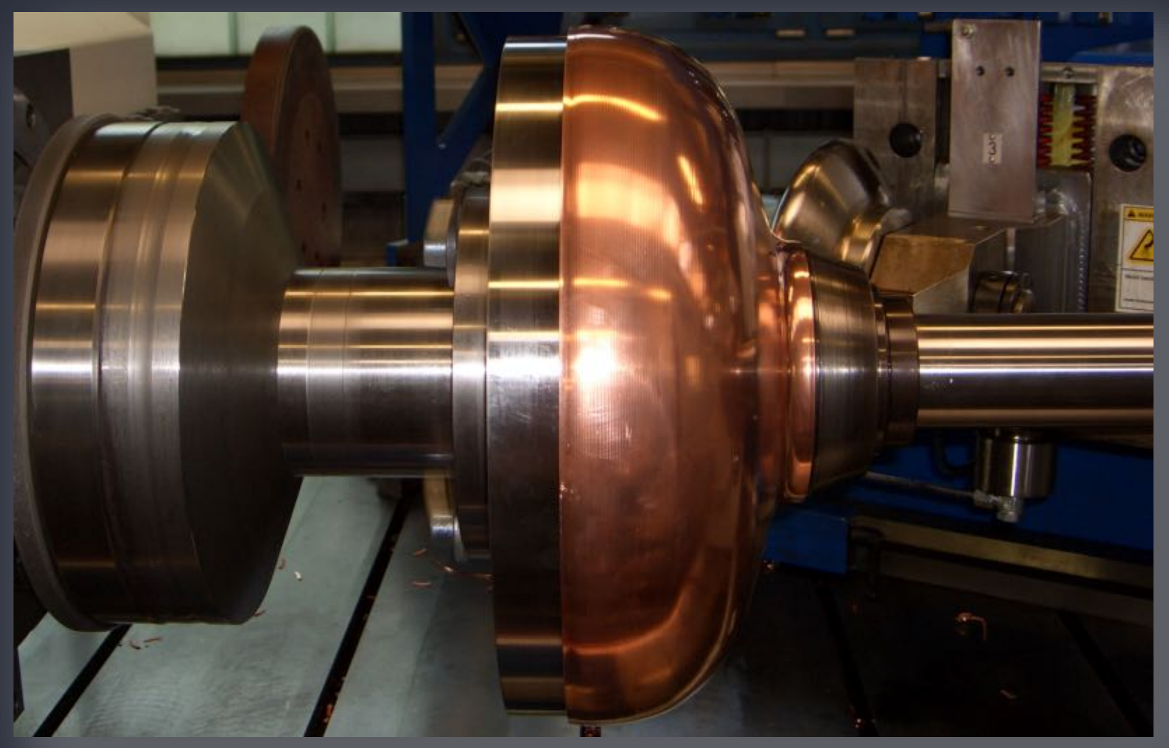
see K. Turaj, TTC19@TRIUMF

courtesy K. Turaj, F. Peauger

LHC spare cavity program

Spinning (Heggli)



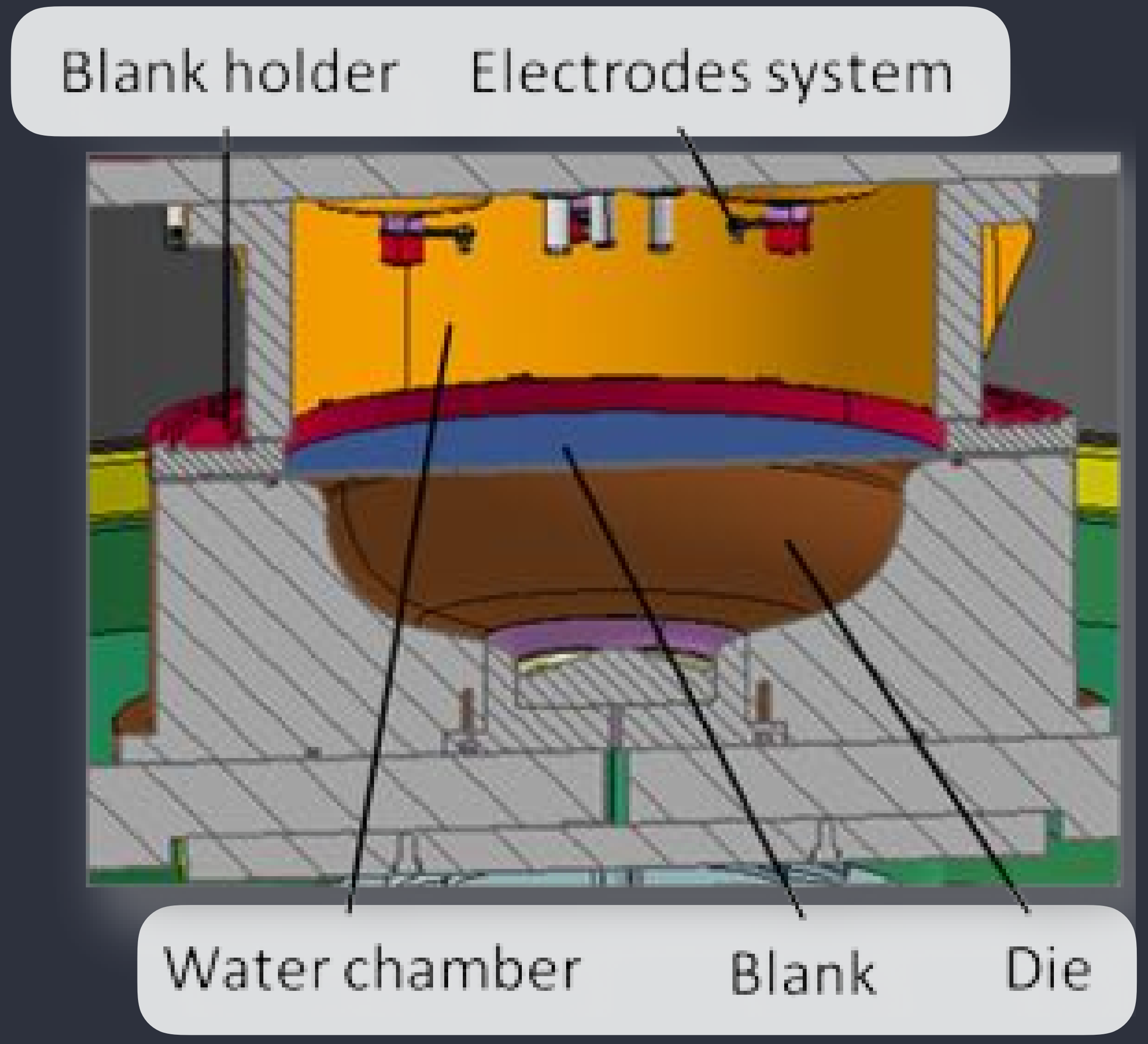


4 spare LHC cavities:

- EHF formed half cells are now qualified, collaboration with BMAX. ✔
- Re-establishment of spinning process with industry (Heggli). ✔
- Establishment of complete manufacturing folder for cavities and cryomodule incl. QA criteria & conformity with pressure vessel code, **ongoing**.
- Re-establishment of coating procedure ✔
- Production and test of several practise (✔) and model cavities before final cavities. ✔
- Testing of actual spare cavities, **ongoing.**

see F. Peauger, Wedn 14:55, WG3

ElectroHydroForming (BMAX)



LHC 1/4 test module

Purpose:

- Re-establish engineering folder & assembly procedures for LHC CMs.
- Train today's technical team on the LHC module assembly (mechanical tuners, HOM couplers, power coupler insertion, MLI, cryolines, ….).
- Measurements of static & dynamic losses, static thermal losses on HOMs.
- Optimisation of circulator operation during main coupler actuation.
- Cool-down and conditioning procedures, use of local clean rooms in the tunnel, processing (pulsed high-power or even plasma), …
- Development of 2nd generation LLRF & controls for LHC.

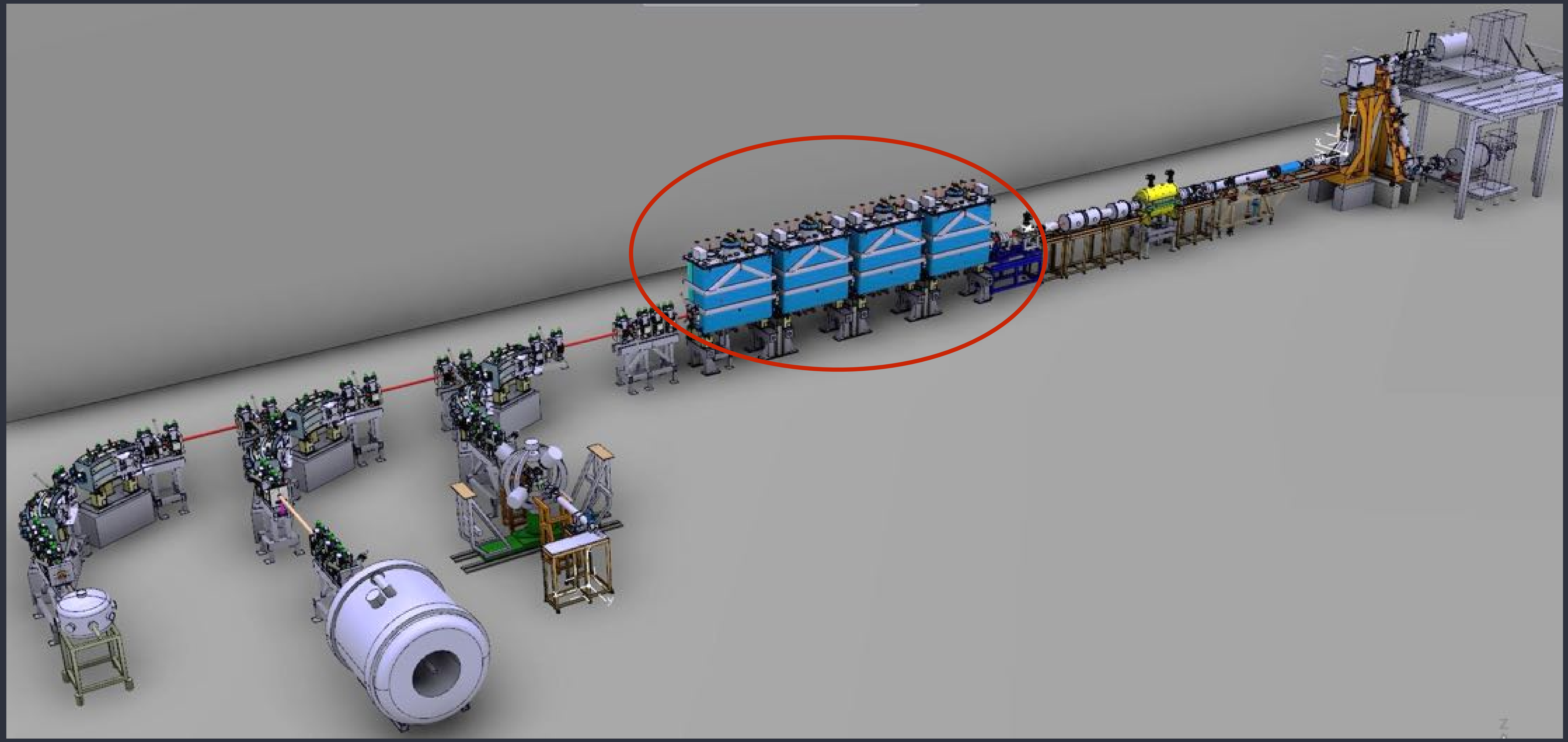
Take the SM18 tour on Friday!

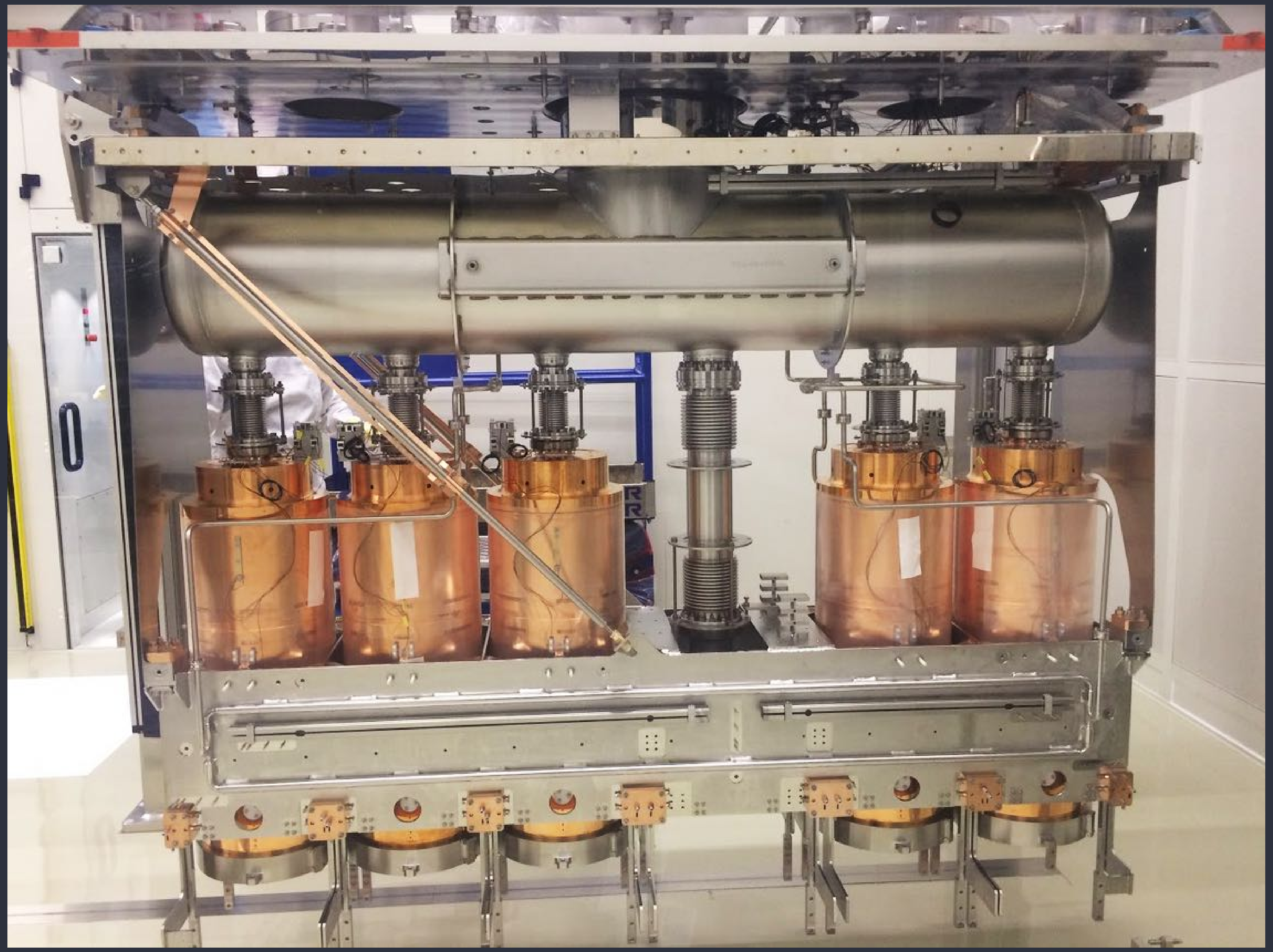
courtesy D. Smekens, EN-MME, EN-SMM, TE-CRG, TE-VSC, …

HIE-ISOLDE

Nb coated quarter wave resonators

HIE-ISOLDE

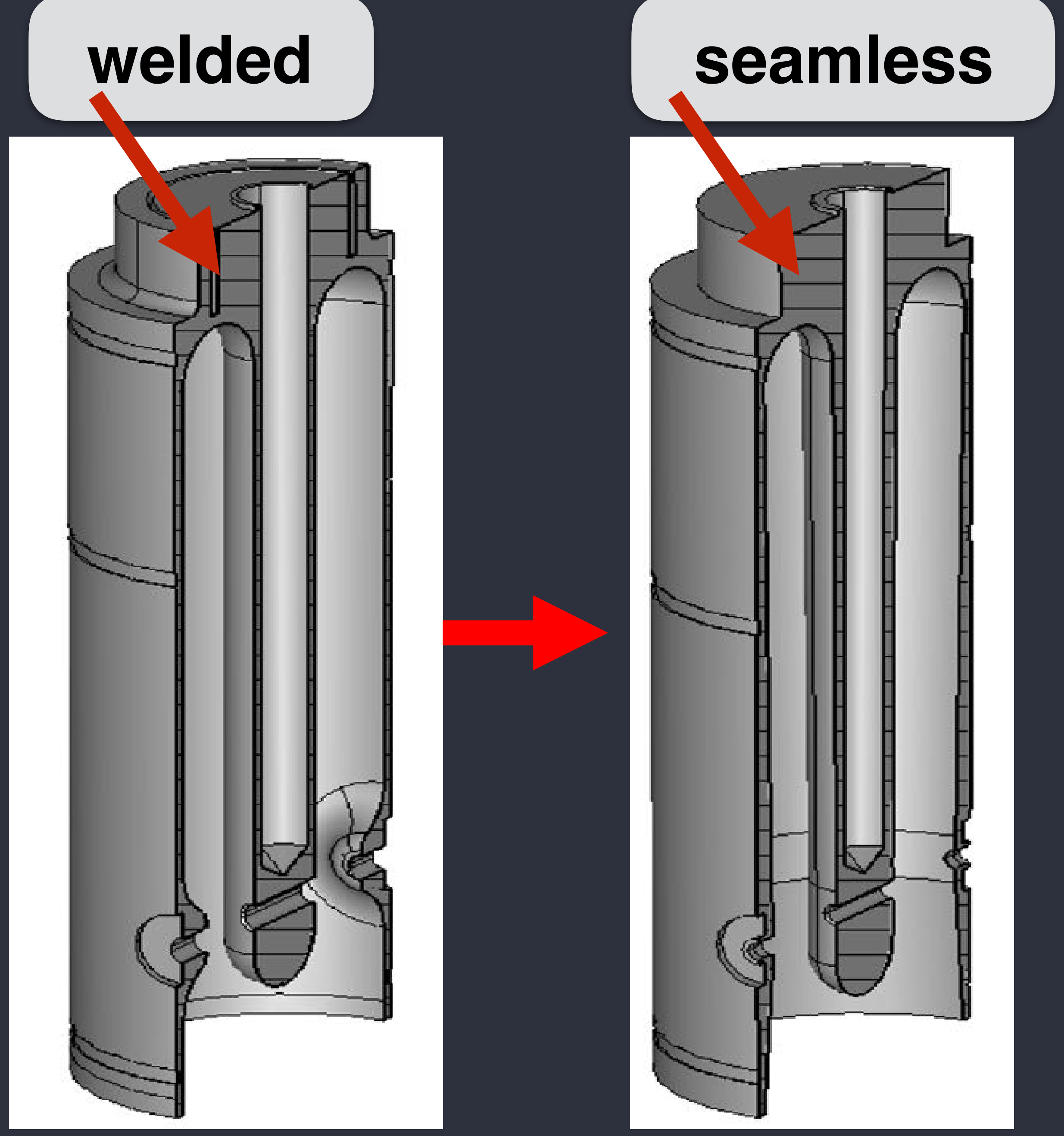




4 CMs with 5 cavities each:

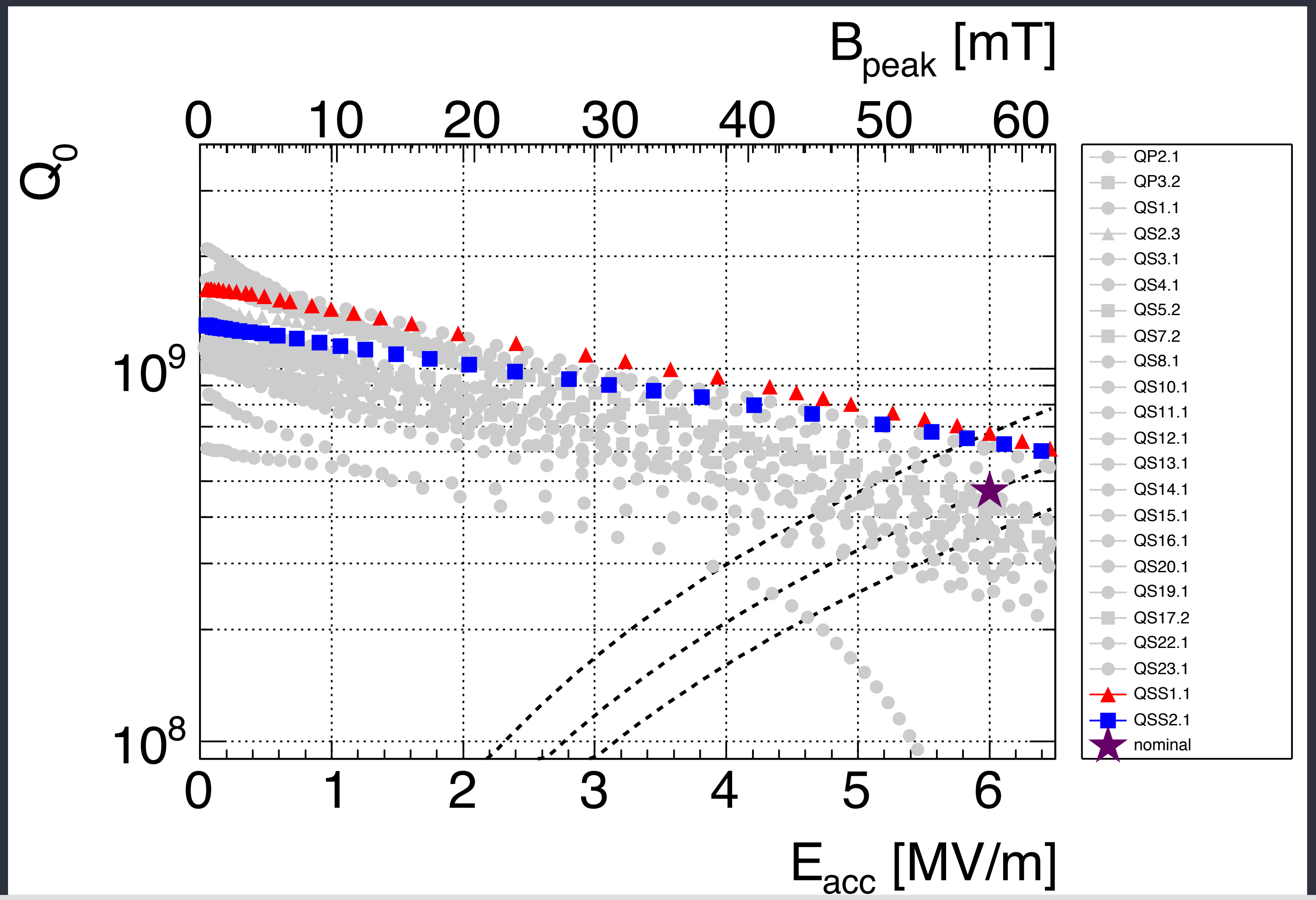
- launched in 2010 to increase energy of Radioactive Experiment (REX) post-accelerator from 3 to 10 MeV/u,
- first module installed in 2015, 2nd in 2016, 3d in 2017, 4th in 2018 with subsequent physics runs.
- Performance goal: **6 MV/m @ Q>5x10^8, 100 MHz,** very sensitive to cool-down procedures, repair on 4th module done last year. Anticipate 1 module exchange/long shutdown (~4-5 years).

courtesy V. Parma, W. Venturini, A. Miyazaki, …

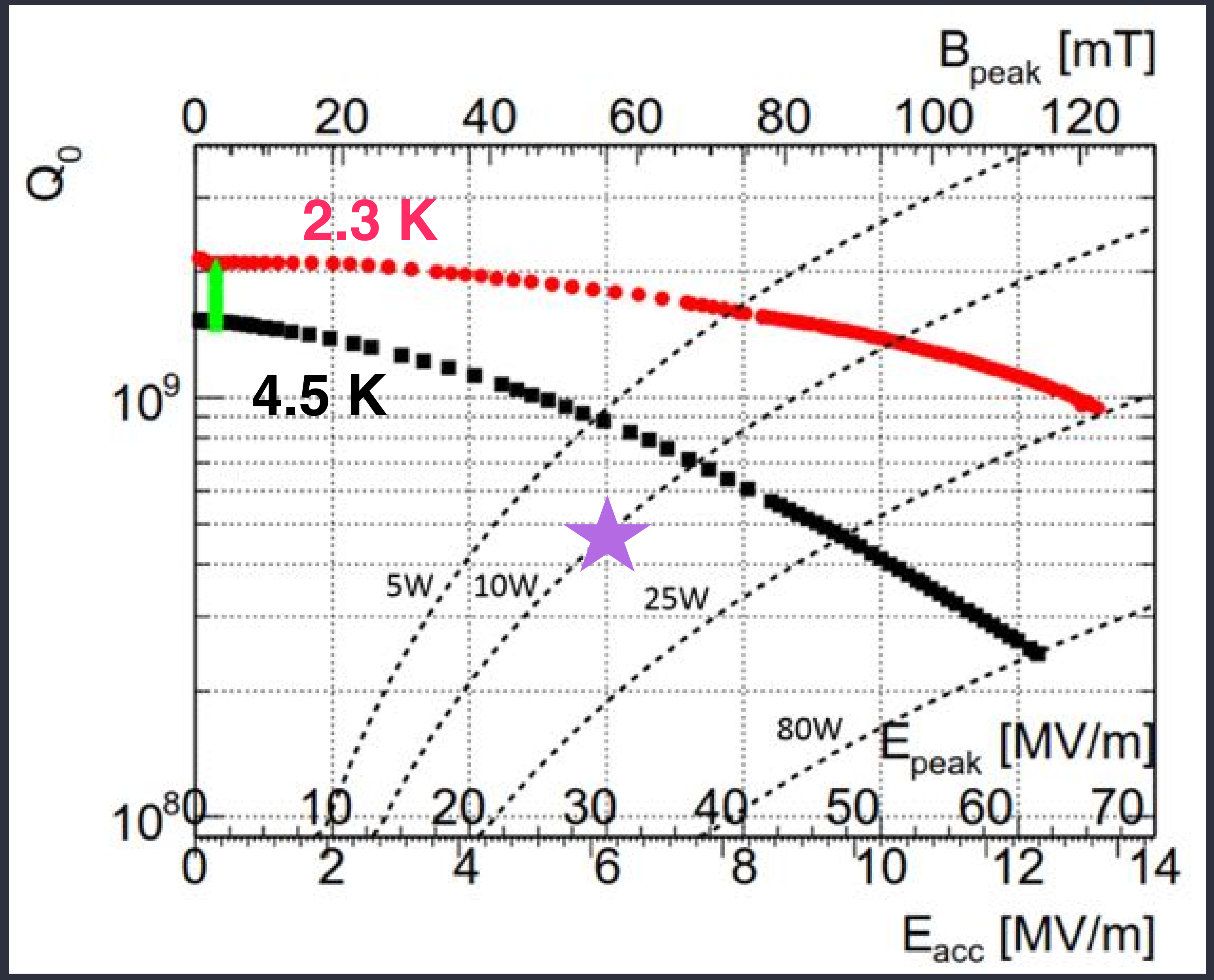


Seamless cavities reach world record fields (for Nb on Cu)

- Due to difficulties with welded HIE ISOLDE cavities a new seamless design was designed and tested.
- At 2.3 K with partially screened magnetic fields (< 5 uT), 65 MV/m and 120 mT peak field was reached with Q ~10^9.



2 seamless cavities compared with all other cavities

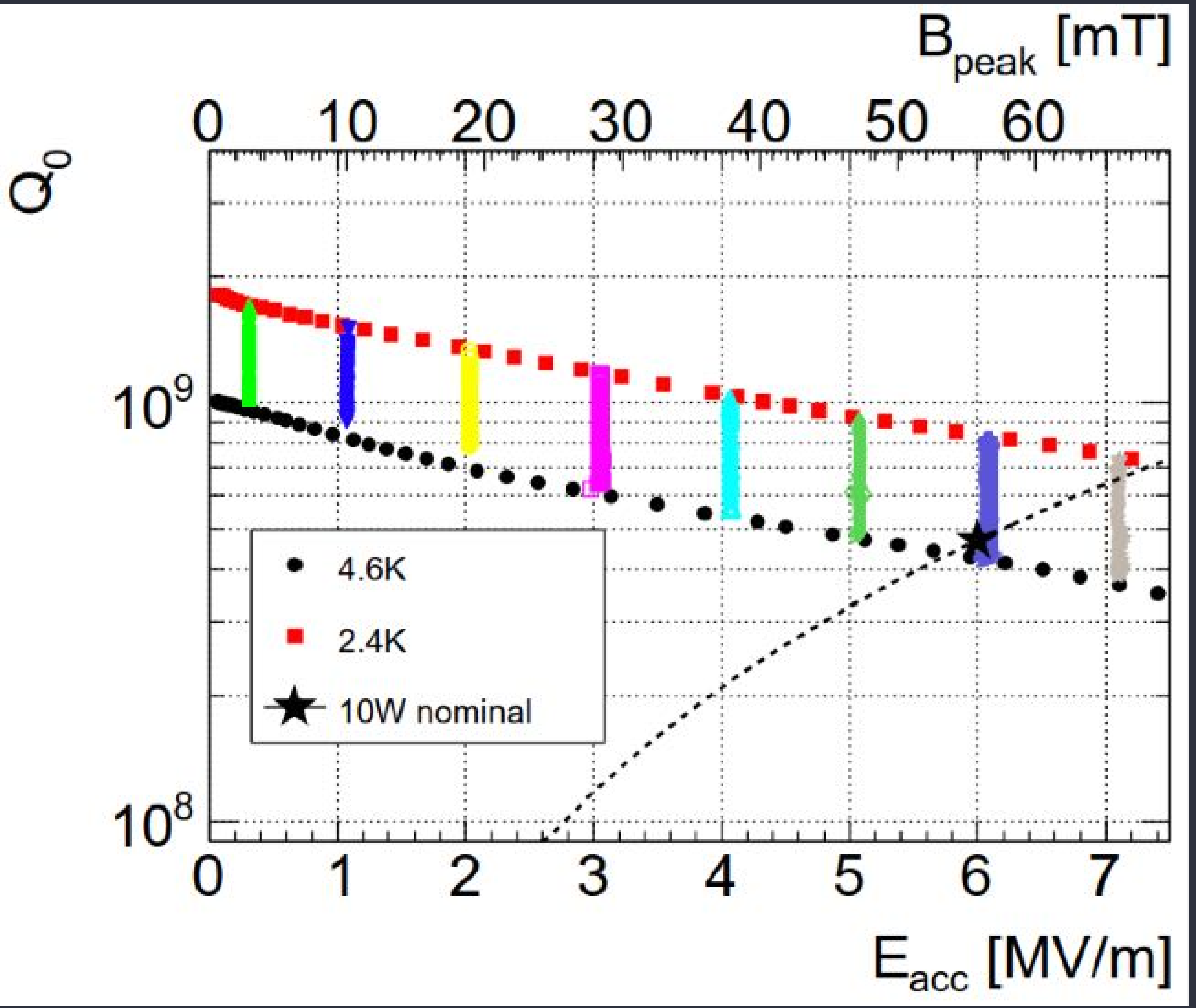


Test of seamless cavity at 4.5 and 2.3 K with magnetic shielding

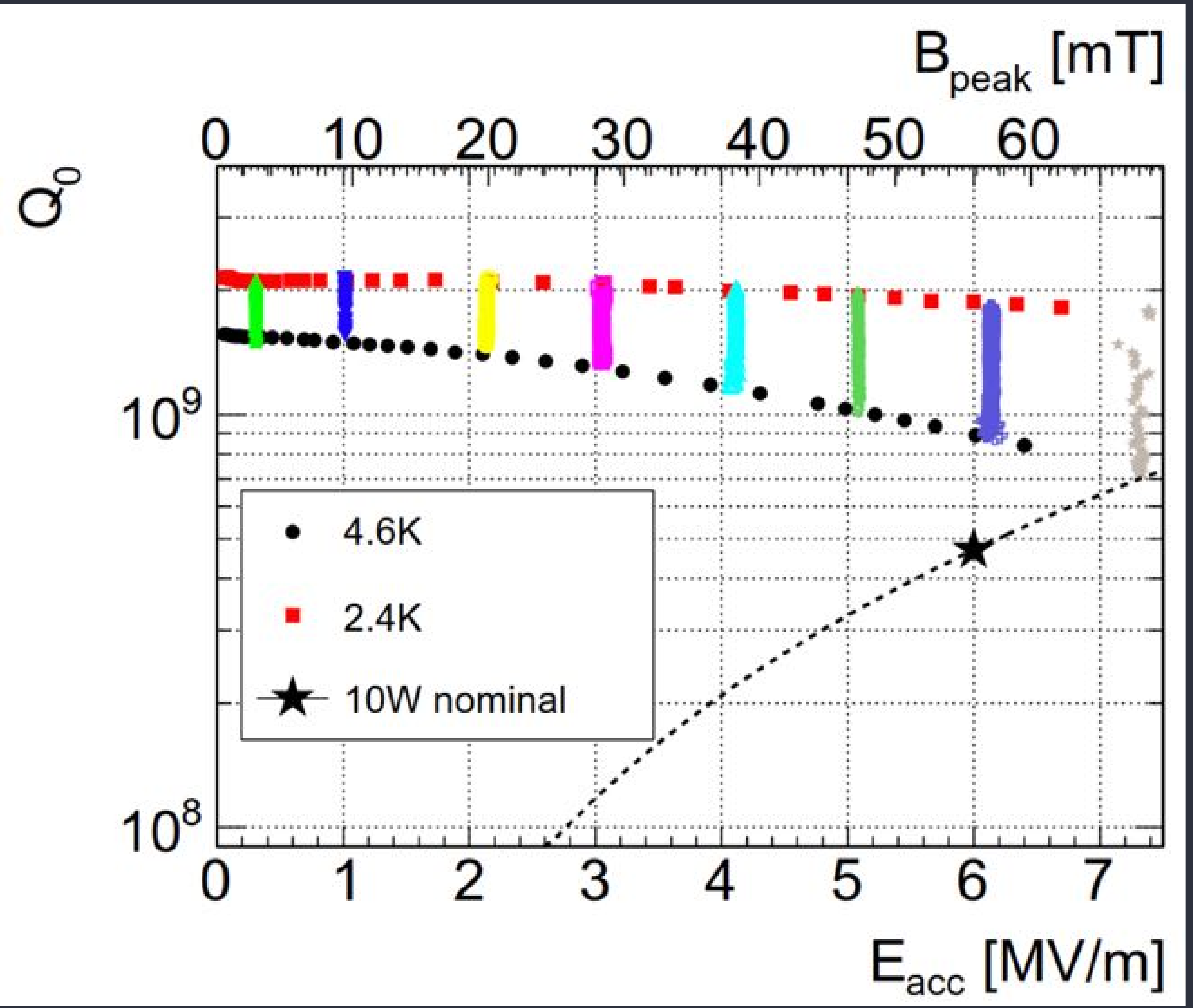
see W. Venturini, TTC 2018, Milano

HIE-ISOLDE seamless cavity

LEP, LHC, and HIE-ISOLDE were built w/o magnetic shielding, but the seamless cavities showed increased sensitivity to ambient magnetic field. Higher sensitivity for flux trapping was measured in comparison to the welded cavities (not shown here).



Test with increased B_{ext} (100 µT) during crossing of T_c

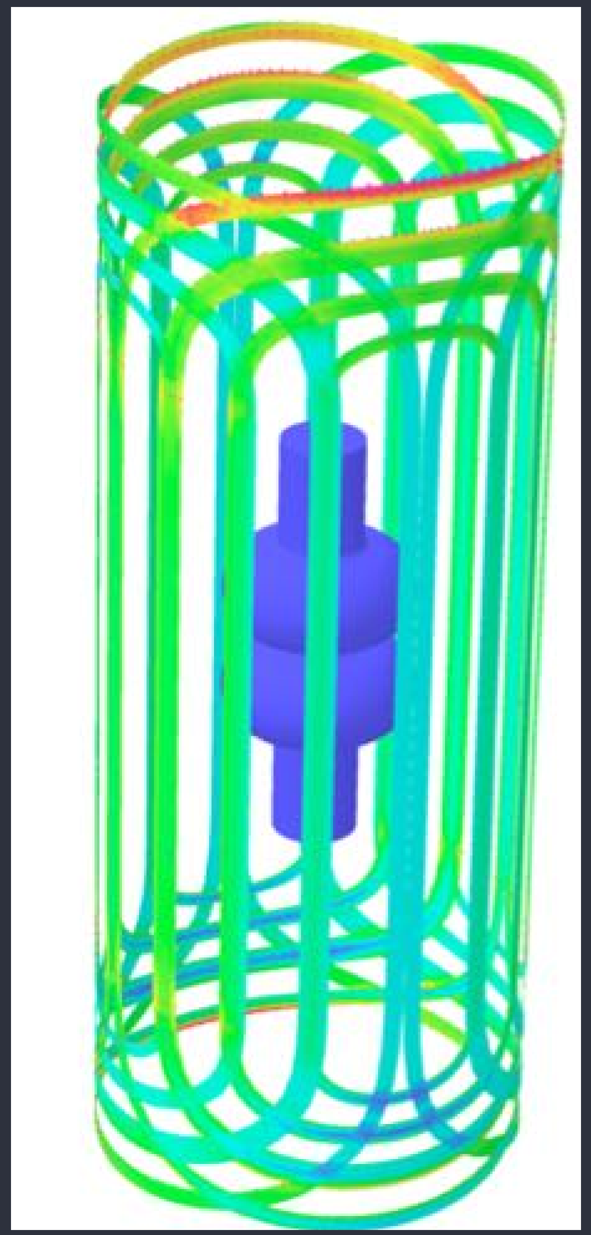


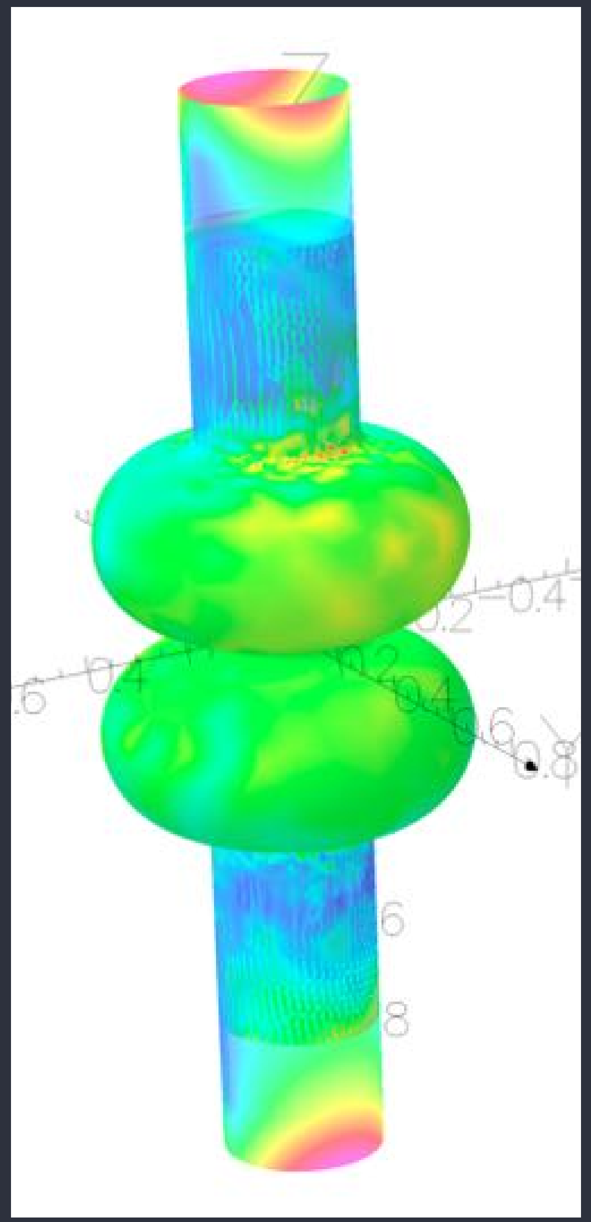
Test with compensated B_{ext} (5 µT) during crossing of T_c

see A. Miyazaki, W. Venturini, PRAB 22, 073101

Further R&D on flux trapping in coated cavities:

- first test of LHC cavity with magnetic shielding is ongoing (**see F. Peauger, Wed 14:54, WG3**)
- improvements on EBW of LHC cavities: internal welding in preparation, study on the influence of polishing welds,
- production of seamless 1.3 GHz "reference cavity" out of bulk Cu,
- plans to exchange our unshielded cryostat for LHC cavities with a new one and adding state of the art magnetic compensation,
- … more news in the coming TTC meetings





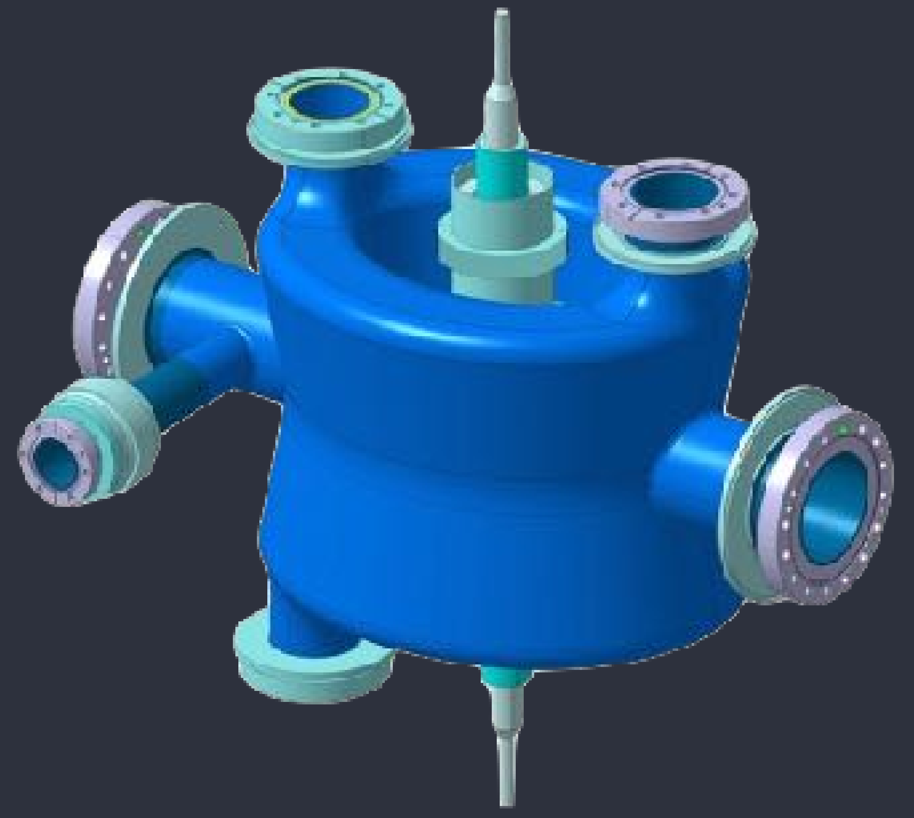
courtesy M. Karppinen

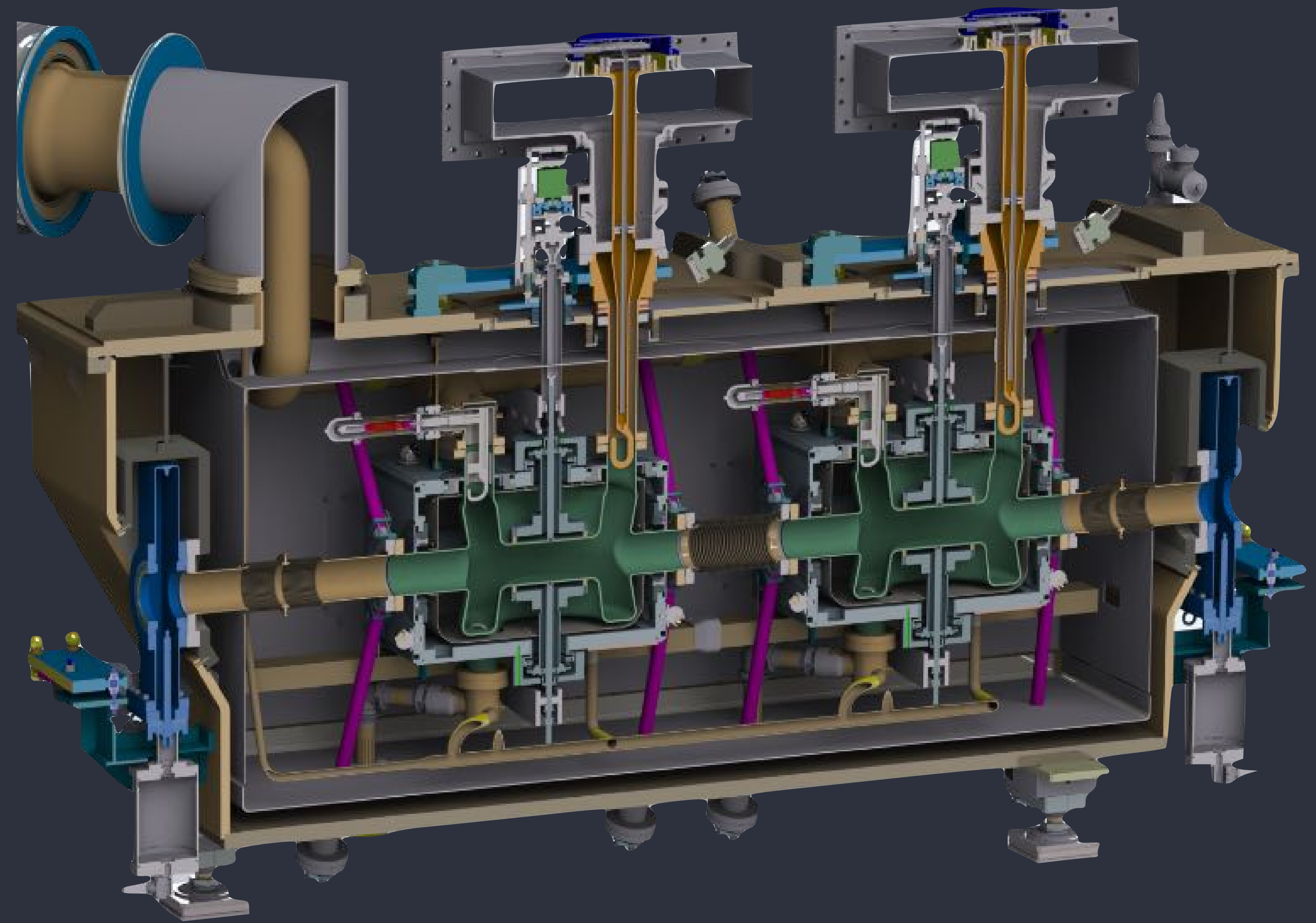
Crab Cavities for HL-LHC

the first bulk Nb cavities in an operational machine at CERN, and the first crab cavities to work with a proton beam

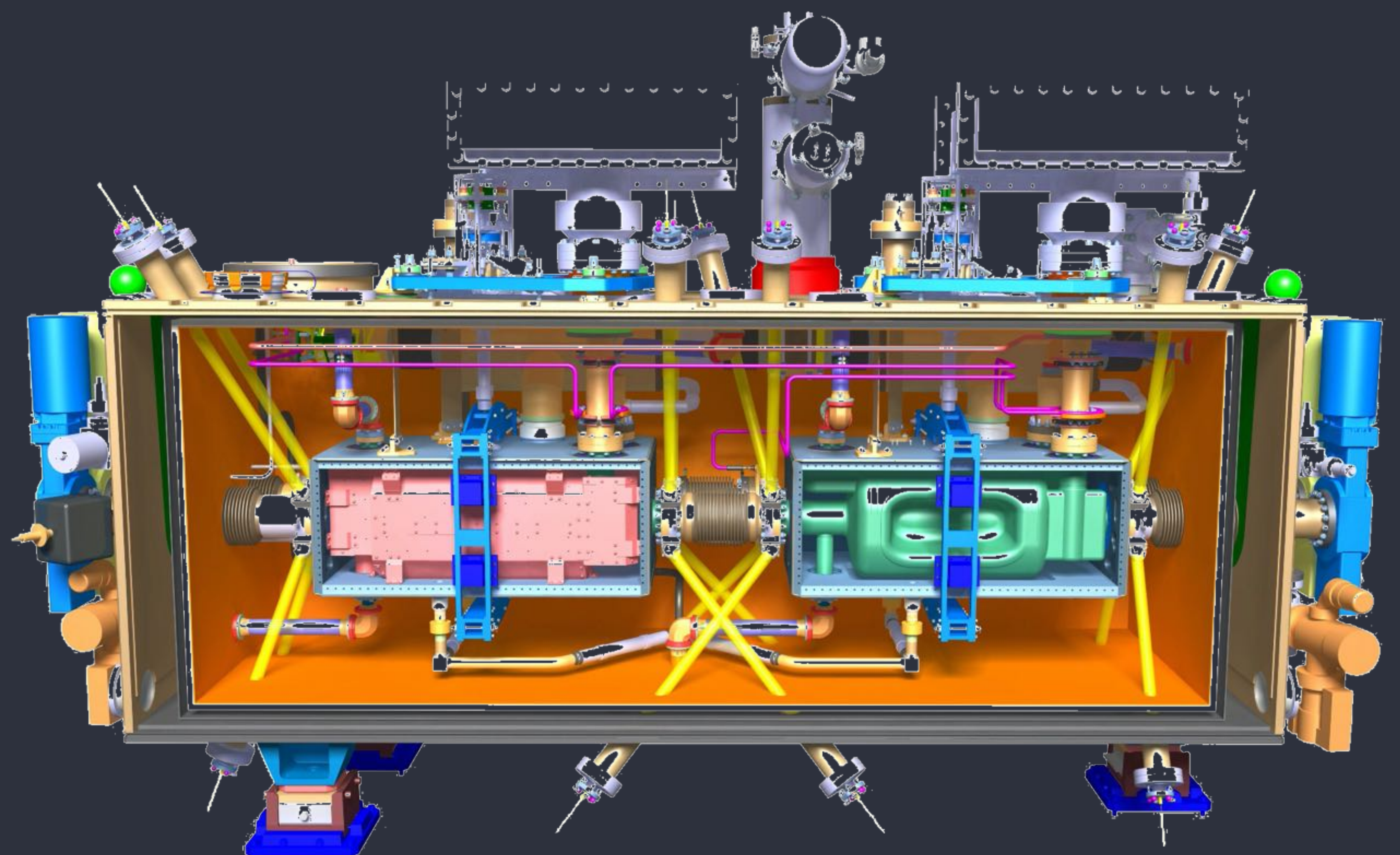
2 types of Crab cavities

Double Quarter Wave
- Vertical crossing for Atlas
- SPS test in 2018





RF Dipole
- Horizontal crossing for CMS
- first vertical test in Feb. 2020
- SPS test in 2021



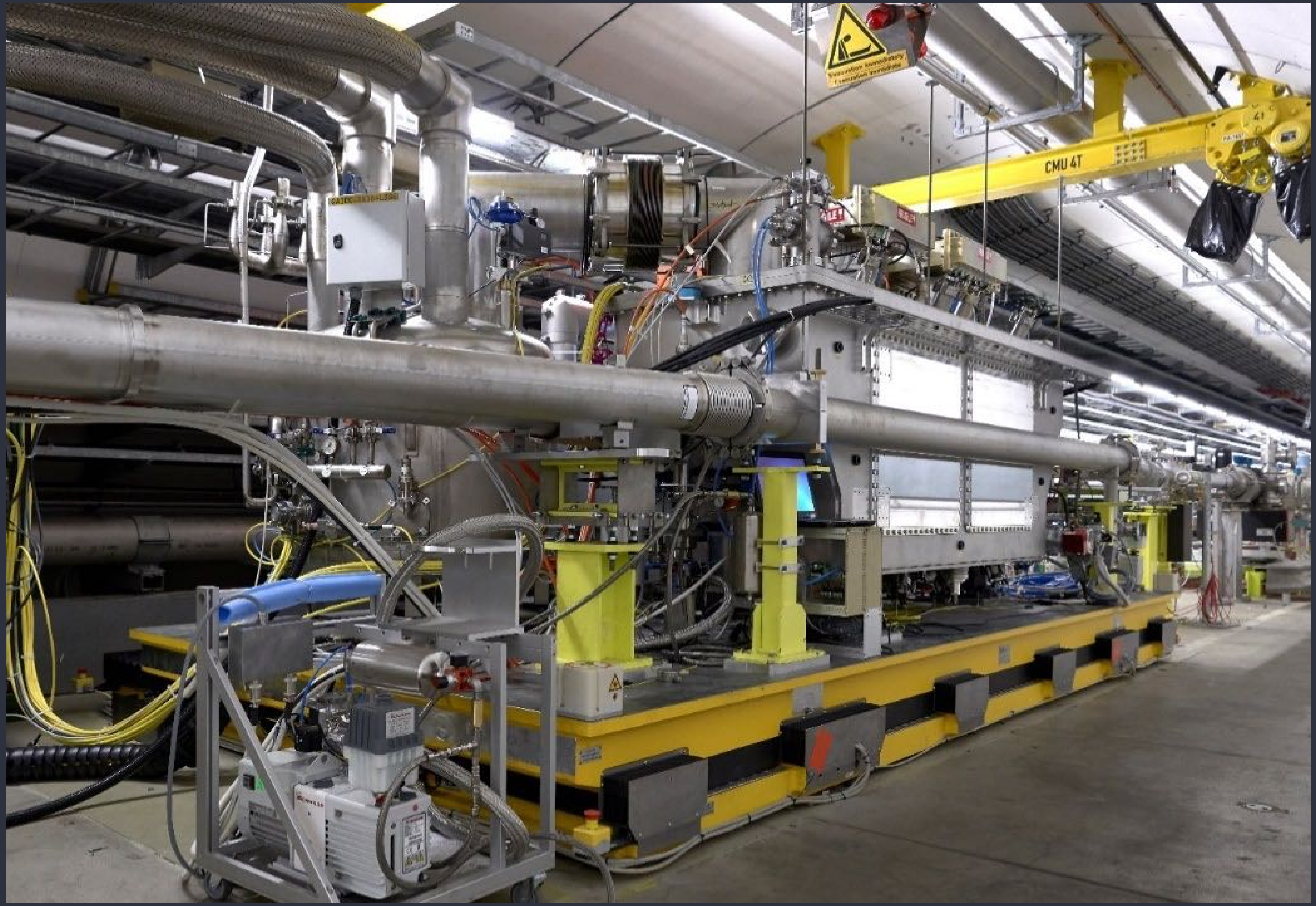
Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power (SPS)	40 kW

➡ 2 cavities/beam/IP side
➡ for ATLAS and CMS
➡ 16 cavities/8 CMs in total

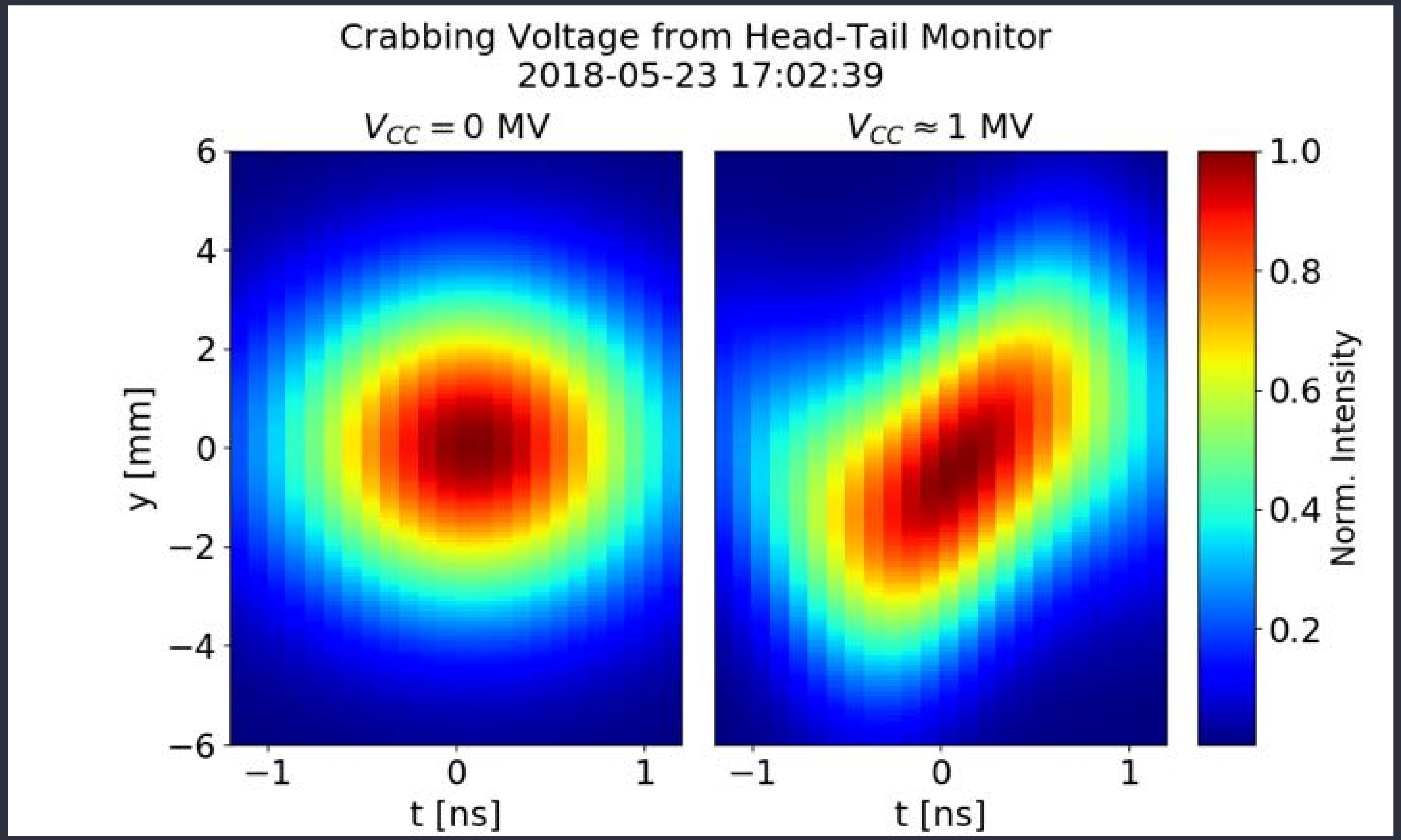
see M. Garlasche, Wed. 15:30, WG4
J. Mitchell, today, 16:18, WG2

courtesy R. Calaga/O. Capatina

SPS test stand layout



23 May 2018: first crabbing with just 1 MV



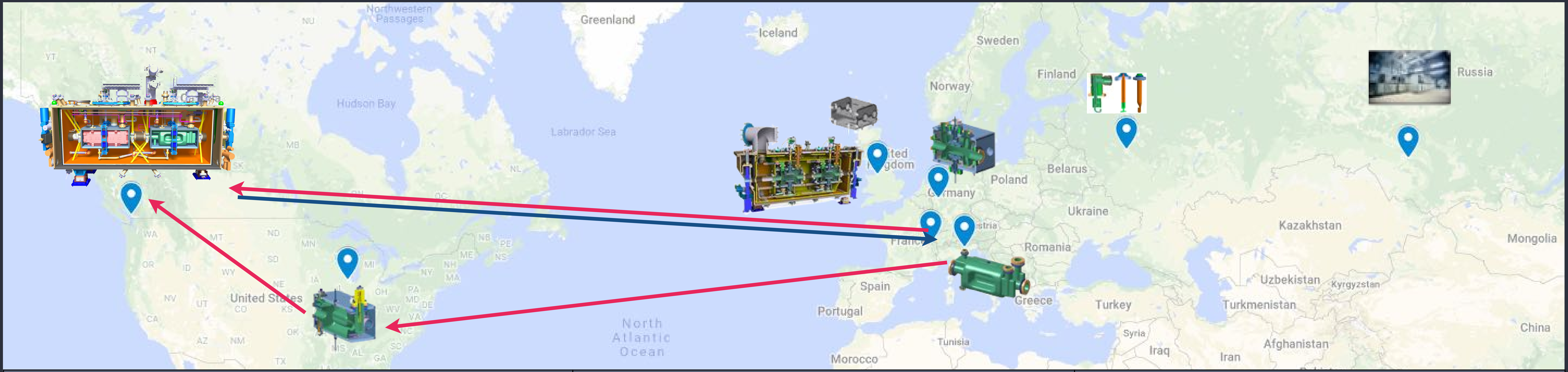
courtesy R. Calaga, G. Vandoni

Crab cavity collaboration

DQW cryomodules (5)	RFD cryomodules (5)	Solid State RF Systems (20)
Cavities + processing + helium vessels by Research Instruments (DE) under CERN	Bare cavities by Zanon (IT) under US-AUP	High power solid state amplifiers by BINP-Russia collaboration
Cold magnetic shields: UK HOM couplers + antennas: MEPHI-Russia & CERN	Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by US-AUP	First step, one amplifier prototype for qualification of SSPA technology
4 CM: UK (STFC) & 1 CM: CERN, with some components by CERN	5 CM by TRIUMF-Canada with some components by CERN	
All cavities & CM cold validation tests at CERN (and a few at Uppsala-Sweden)	CM cold validation tests at CERN	

courtesy N. Valverde, R. Calaga

Crab cavity collaboration



DQW cryomodules (5)	RFD cryomodules (5)	Solid State RF Systems (20)
Cavities + processing + helium vessels by Research Instruments (DE) under CERN	Bare cavities by Zanon (IT) under US-AUP	High power solid state amplifiers by BINP-Russia collaboration
Cold magnetic shields: UK HOM couplers + antennas: MEPHI-Russia & CERN	Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by US-AUP	First step, one amplifier prototype for qualification of SSPA technology
4 CM: UK (STFC) & 1 CM: CERN, with some components by CERN	5 CM by TRIUMF-Canada with some components by CERN	
All cavities & CM cold validation tests at CERN (and a few at Uppsala-Sweden)	CM cold validation tests at CERN	

courtesy N. Valverde, R. Calaga

Crab cavity collaboration

DQW cryomodules (5)	RFD cryomodules (5)	Solid State RF Systems (20)
Cavities + processing + helium vessels by Research Instruments (DE) under CERN	Bare cavities by Zanon (IT) under US-AUP	High power solid state amplifiers by BINP-Russia collaboration
Cold magnetic shields: UK	Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by US-AUP	First step, one amplifier prototype for qualification of SSPA technology
HOM couplers + antennas: MEPHI-Russia & CERN		
4 CM: UK (STFC) & 1 CM: CERN, with some components by CERN	5 CM by TRIUMF-Canada with some components by CERN	
All cavities & CM cold validation tests at CERN (and a few at Uppsala-Sweden)	CM cold validation tests at CERN	

courtesy N. Valverde, R. Calaga

Crab cavities: timeline

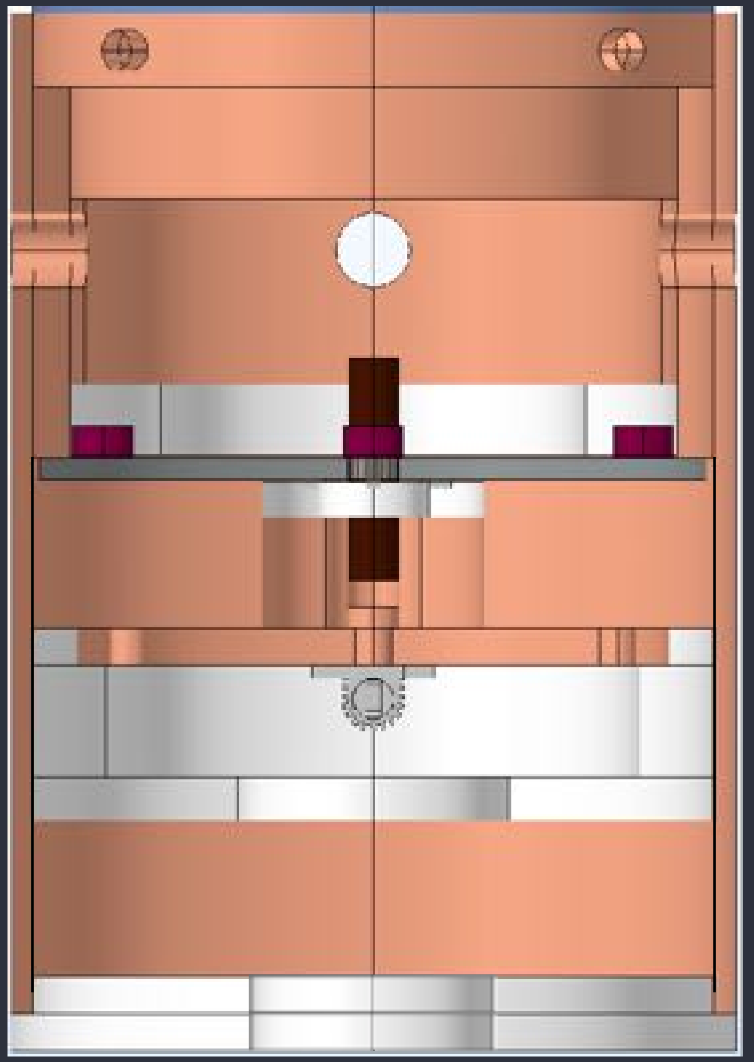
	2016	EYETS	2017	YETS	2018	2019	2020	2021	YETS	2022	YETS	2023	YETS	2024	2025	2026
	Run 2					LS2		Run 3							LS3	
DQW SPS	CM1 construction & SPS preparation				SPS test		SPS test									
RFD SPS					Cavity & CM preparation			CM test		SPS test						
DQW					Dressed cavity production (2+9)			CM assembly & testing (1+4)						Installation		
RFD						Dressed cavity production (2+2+10)				CM assembly & testing (1+4)				Installation		

~5 years of crab cavity and CM testing

Infrastructure for SRF@CERN

Cryolab

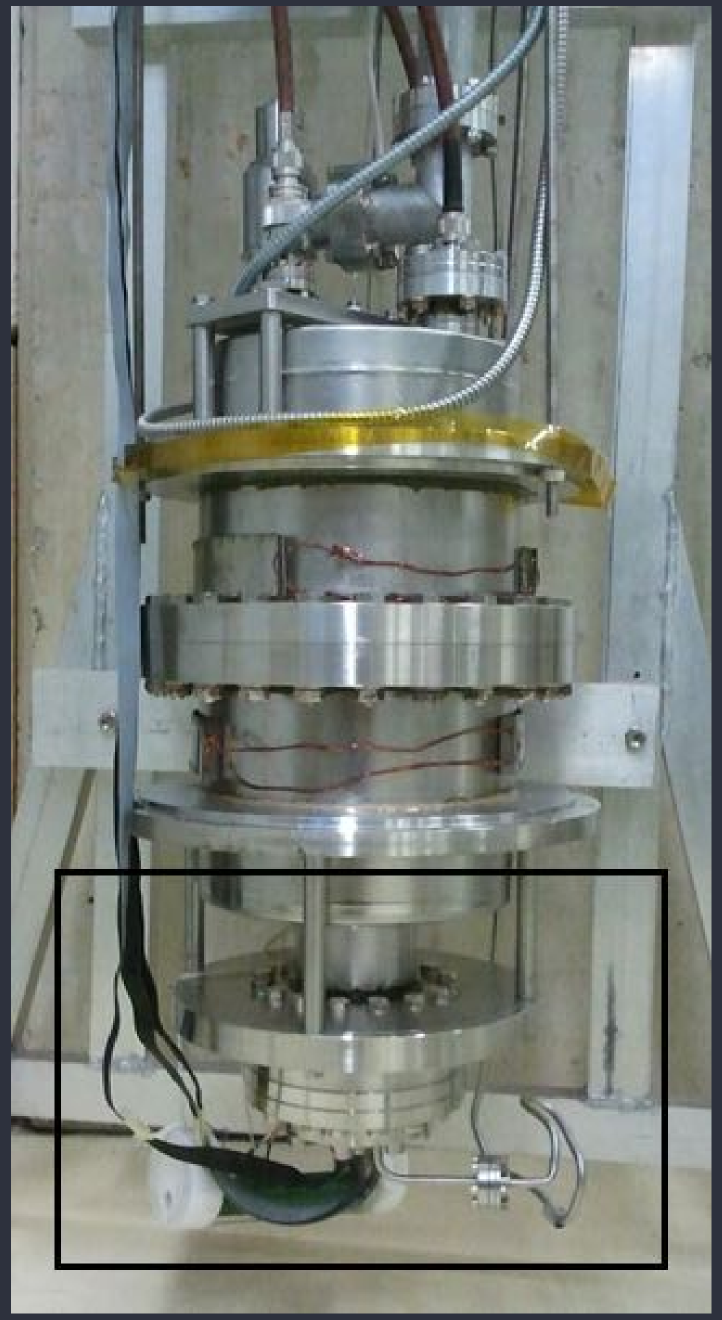
Multi-purpose test facility with cryostats for “small objects” (QPR, or up to 1.3 GHz mono-cell cavity) down to 1.9 K and a cryo-cooler.



Flux lens: a new tool for flux-expulsion characterisation: **Wed. 11:00, WG3 A. Ivanov**

TES, Transition Edge Sensors for quench localisation, **TTC19@TRIUMF, G. Vandoni**

QPR test facility for surface characterisation, **Th. 11:00, WG3 L. Vega Cid**



Coated cavity preparation in 252:

- 12 m2 ISO5 baldachin (horizontal flow) for LPR/alcohol rinsing, cathode insertion, (to be replaced in 2020/21)
- overhead crane
- clean water preparation,
- coating stations,
- **see tour on Friday**

SM18: vertical test stands

4 vertical test stands:

- V3: large volume bulk Nb & Nb/Cu
- V4: small volume bulk Nb
- V5: HIE ISOLDE with clean insertion
- V6: LHC, no magnetic shielding

SM18: HIE-ISOLDE clean room

ISO5-7 clean room:

- horizontal laminar flow,
- 40 m², 5 m high
- lifting/assembly facility,
- high-precision rails for the HIE-ISOLDE CMs,
- operational since 2014.

ISO5:

- 15 m x 4 m x 2.5 m high,
- vertical flow,
- cleaning for ISO4

ISO4:

- 15 m x 4 m x 2.5 m high,
- vertical flow,
- string assembly,
- coupler installation,

SM18: HPR, clean water, ..

Water purification and compressor station for HPR.

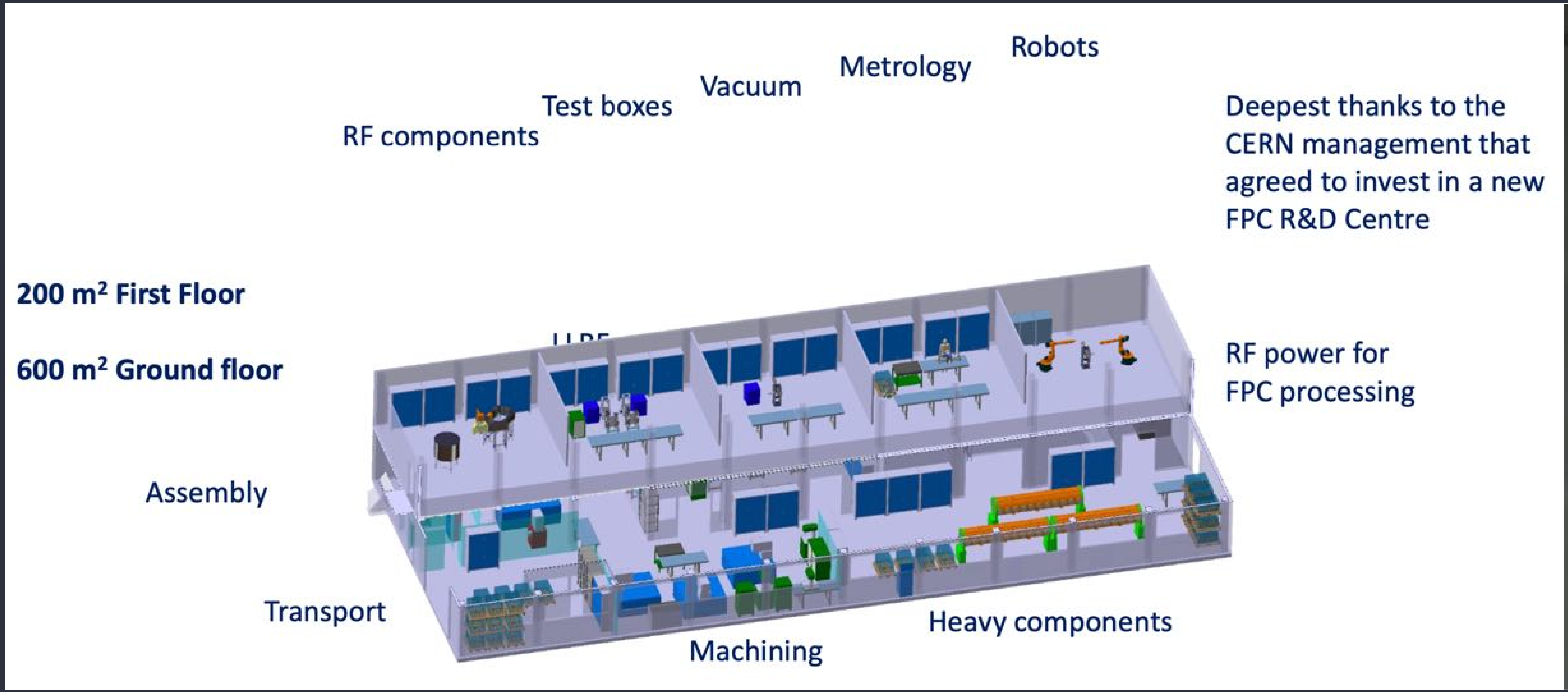
HPR cabinet with clean preparation area (right) and clean room access (left).

HPR

ISO5/4:

- 20 m2, 2.5 m high,
- vertical flow,
- exit from HPR, drying,

FPC R&D centre



800 m² dedicated to design, development, assembly & testing of fundamental power couplers, test & assembly of HOM couplers, coupler test boxes.

see E. Montesinos, World-Wide Fundamental Power Coupler meetings:
https://indico.cern.ch/event/827811/

courtesy: E. Montesinos

FPCs at CERN

Tested or Operation	Frequency	Operation	TW [kW]	SW [kW]
SPS 2	200	CW	500	-
LHC **(SRF)**	400	CW	550	575
ESRF-SOLEIL-APS	352	CW	300	200
SPL 1 – SPL 2 **(SRF)**	704	2 ms – 50 Hz	1000-1000	600-1000
Linac 4	352	2 ms – 1 Hz	-	900
SPS crab **(SRF)**	400	CW	~~100~~ (50)	~~100~~ (50)
Design & construction				
LHC Crab **(SRF)**	400	CW	~~100~~ (50)	~~100~~ (50)
LIU 200	200	CW	1000	-
LIU 800	800	CW	250	-
PERLE **(SRF)**	704 (802)	2 ms – 50 Hz	1500 (150)	1500 (150)
LHC 2 **(SRF)**	400	CW	600	600
FCC **(SRF)**	400	CW	1000	1000

courtesy: E. Montesinos

Chemical- & Electropolishing

New Chemical & Electropolishing facility for niobium (HL-LHC) and copper (FCC).

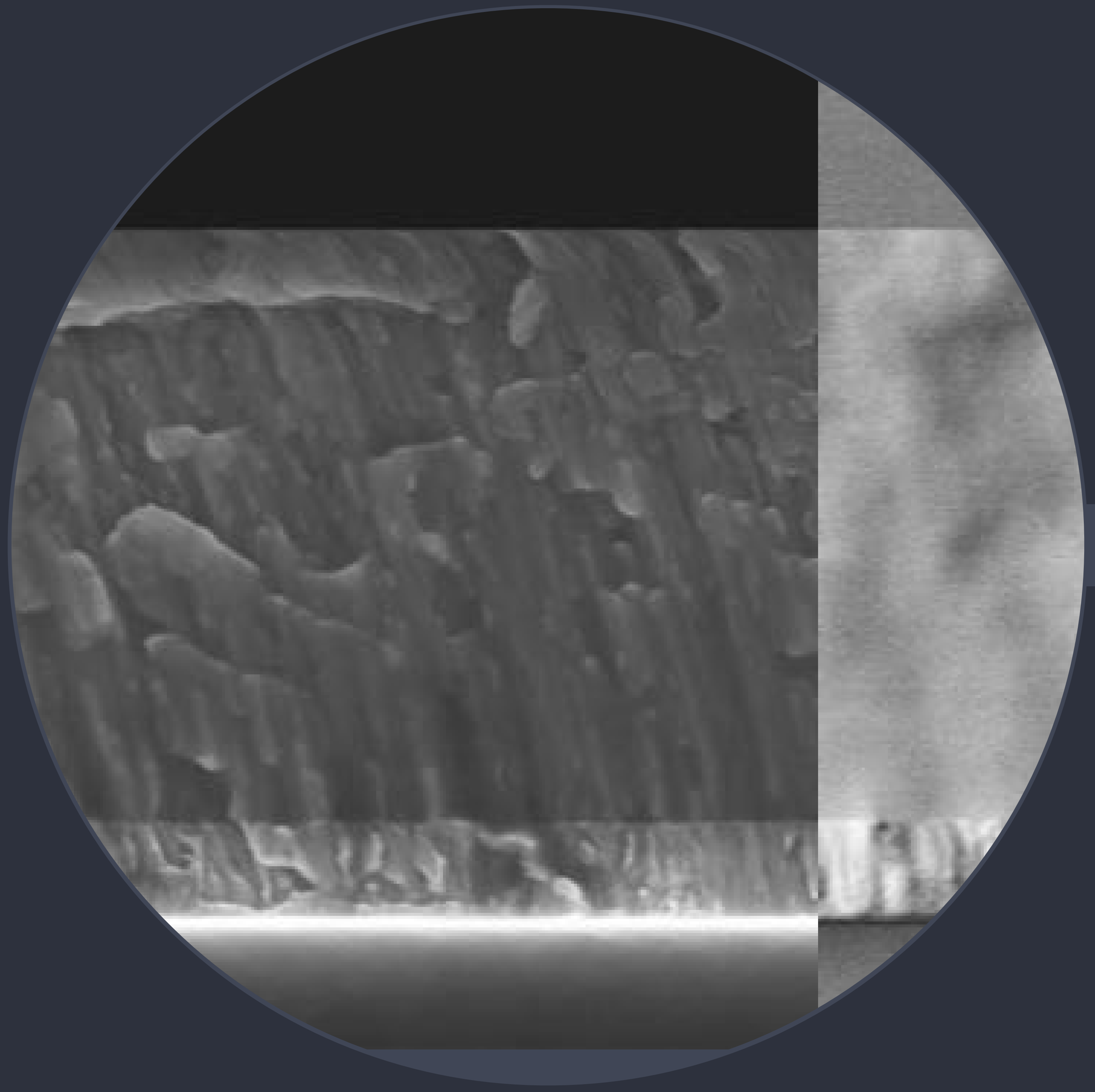
- BCP for crabs (Nb),
- EP for full 400 MHz LHC Cu cavities.
- Presently under commissioning

courtesy: V. Gerbet

further SRF related infrastructure

- **Mechanical workshop:** EB welding, Vacuum brazing, Vacuum baking, high-precision machining, additive manufacturing with Nb (first tests with Nb powder promising), hydroforming
- **Surface chemistry:** SUBU (Cu: HIE-ISOLDE, 1.3 GHz, LHC), BCP (Nb crab cavities, 700 MHz, …), Electropolishing (Cu half-cells for LHC, vertical EP for 700 MHz bulk Nb, 1.3 GHz bulk Nb),
- **Coating technologies:** Diode coating with bias (HIE-ISOLDE), Direct Current Magnetron Sputtering (DCMS, LHC cavities), High Power Impulse Magnetron Sputtering (HIPIMS)

Take the workshop & coating tour on Friday!



SRF R&D

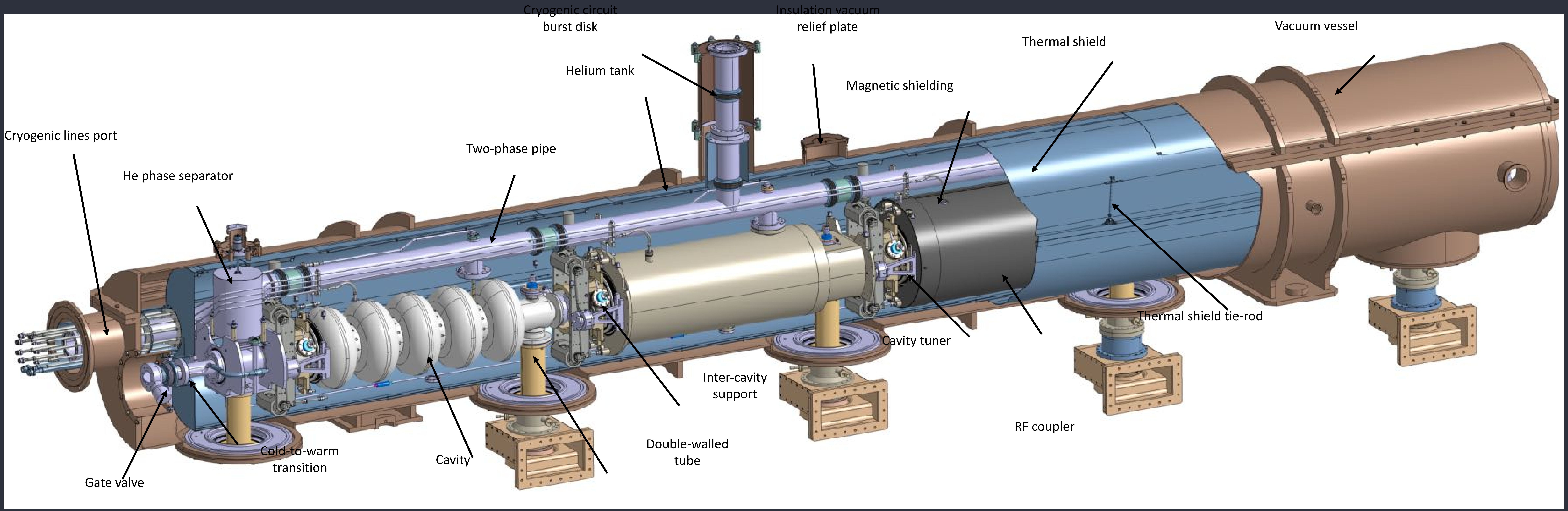
some highlights

Bulk Nb

High Gradient Program

Meant for a Superconducting Proton Linac, it laid the basis for today's Crab Cavity Program and started the upgrade of SM18

Four cavity cryomodule



Originally developed for a Superconducting Proton Linac at CERN, in collaboration with ESS and CNRS Orsay. Existing hardware now foreseen for the PERLE ERL facility at Orsay.

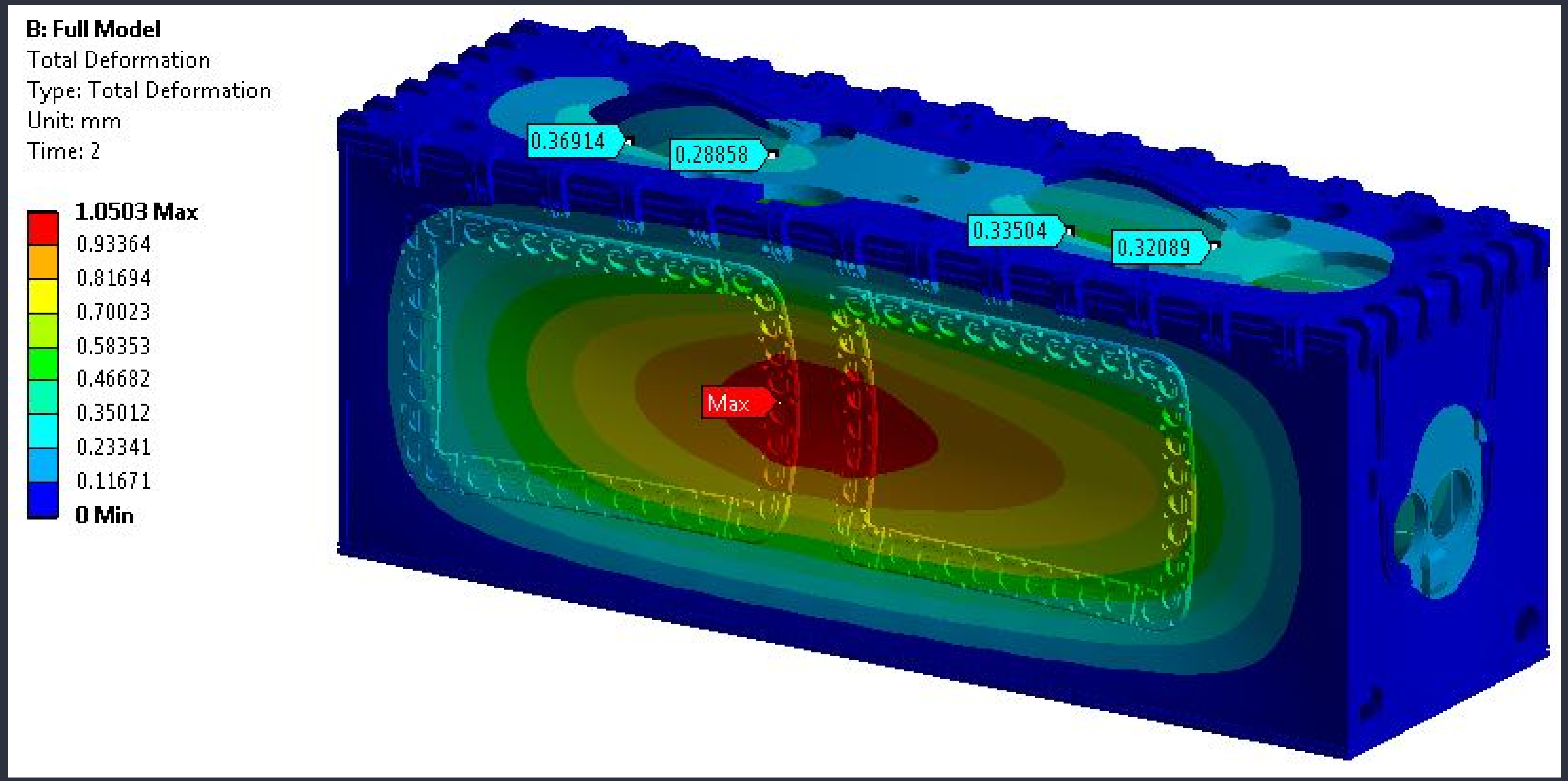
courtesy V. Parma, L. Dassa

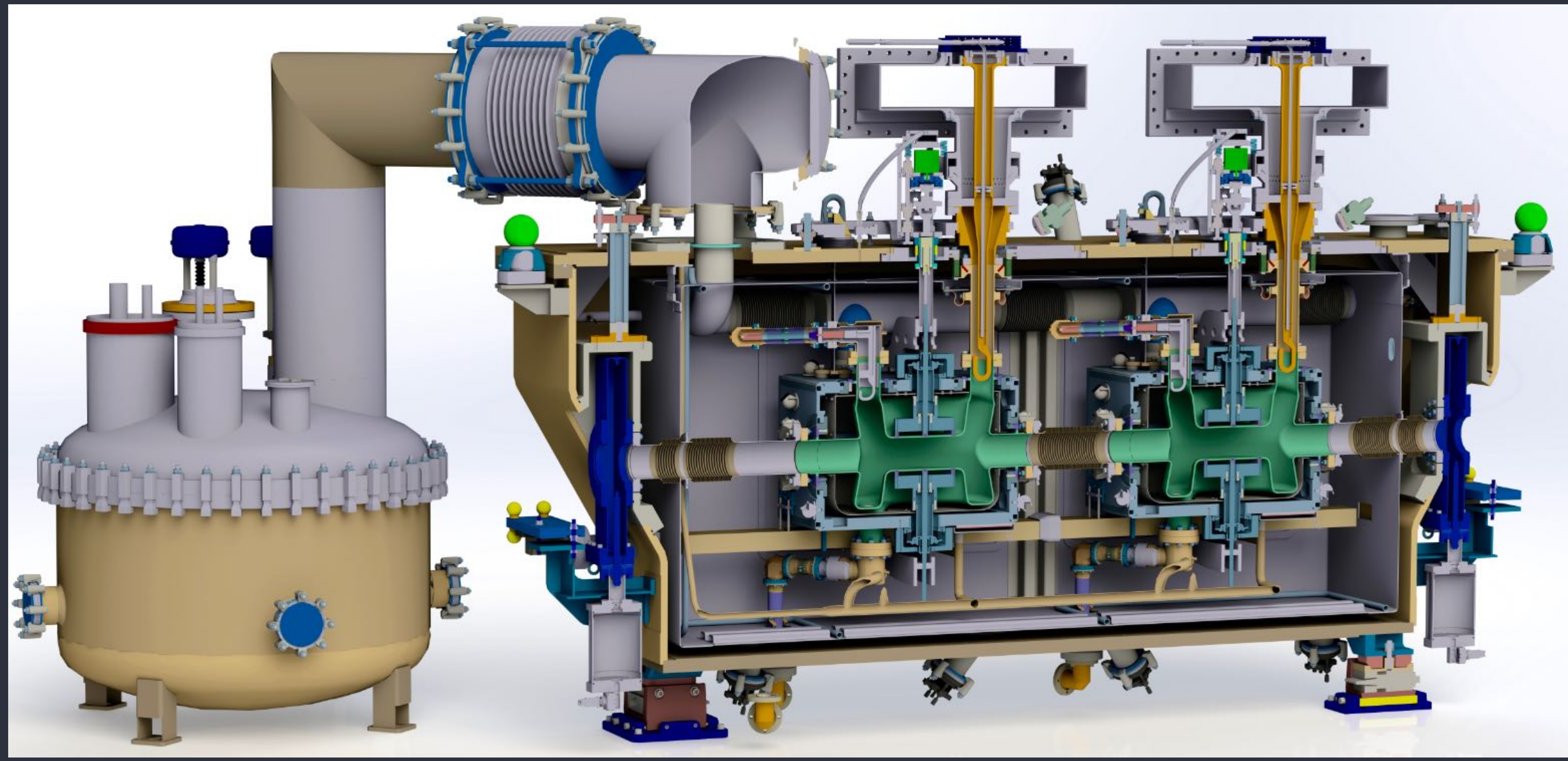
Crab RFD & DQW CM

Cryomodules for Crab cavities

Extensive simulation work on:

- Thermal balance (power coupler, tuning system, radiation, cold-warm transitions, support system, instrumentation, HOMs, pick-ups,..).
- Strength assessment.
- Pressure vessel regulations.
- Transport procedures.





courtesy E. Cano-Pleite

704 MHz: Innovations/developments

over almost 10 years

Successful development and application of **vertical Electropolishing**. Unique facility worldwide (Leonel Ferreira)

Successful mock-up test of **Cavity support via power couplers**. (Rossana Bonomi, Wojciech Zak, Vittorio Parma)

Optimised set-up for **High Pressure Water Rinsing** (A. Macpherson, K. Hernandez Chahin)

Development of cavity shaping via **Electro-Hydro-Forming**. (Said Atieh, Elisa Cantergiani)

Development of **Higher Order Mode Suppressors (HOMS)** for proton linac (Kai Papke).

Coaxial type

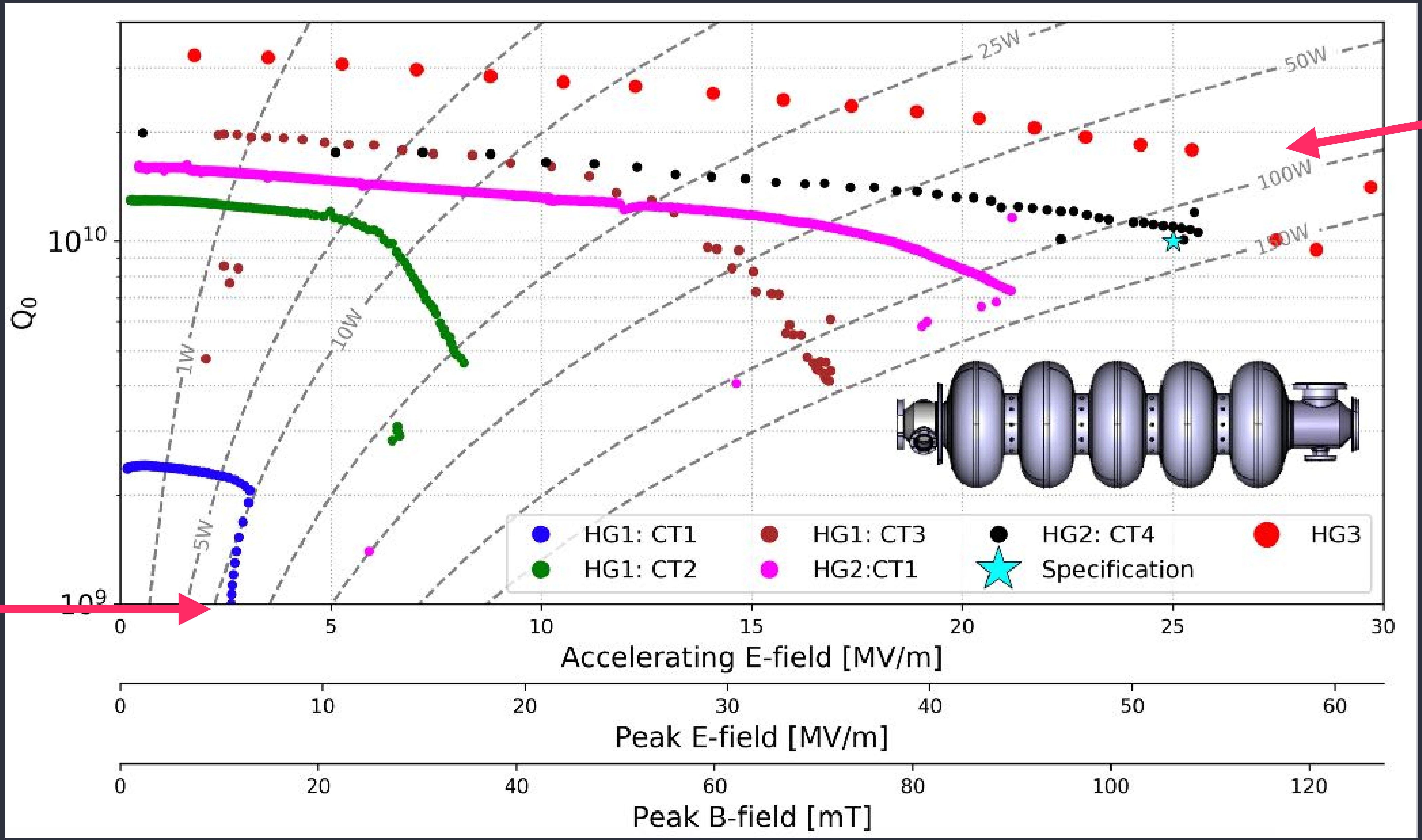
Disc type

Development of 2 **Fundamental Power Couplers**. Disc type is more robust, 3d generation under development (Eric Montesinos)

Cold test results

Oct 2018

September 2014



➜ still trying to get rid of the last 2-4 nOhm…

this was the basis for the fast-track development of the crabs at CERN

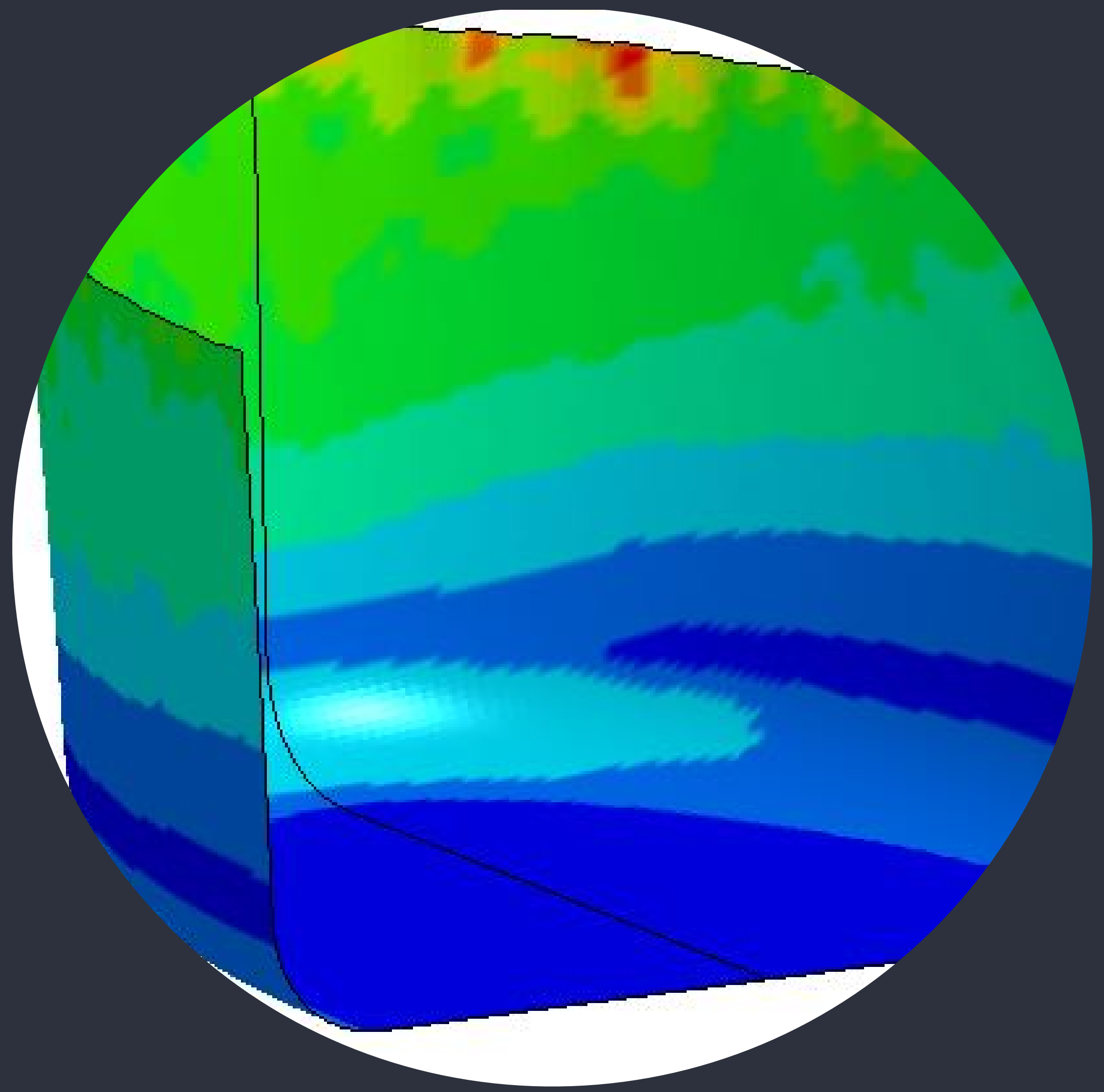
courtesy K. Turaj, A. Macpherson

Manufacturing

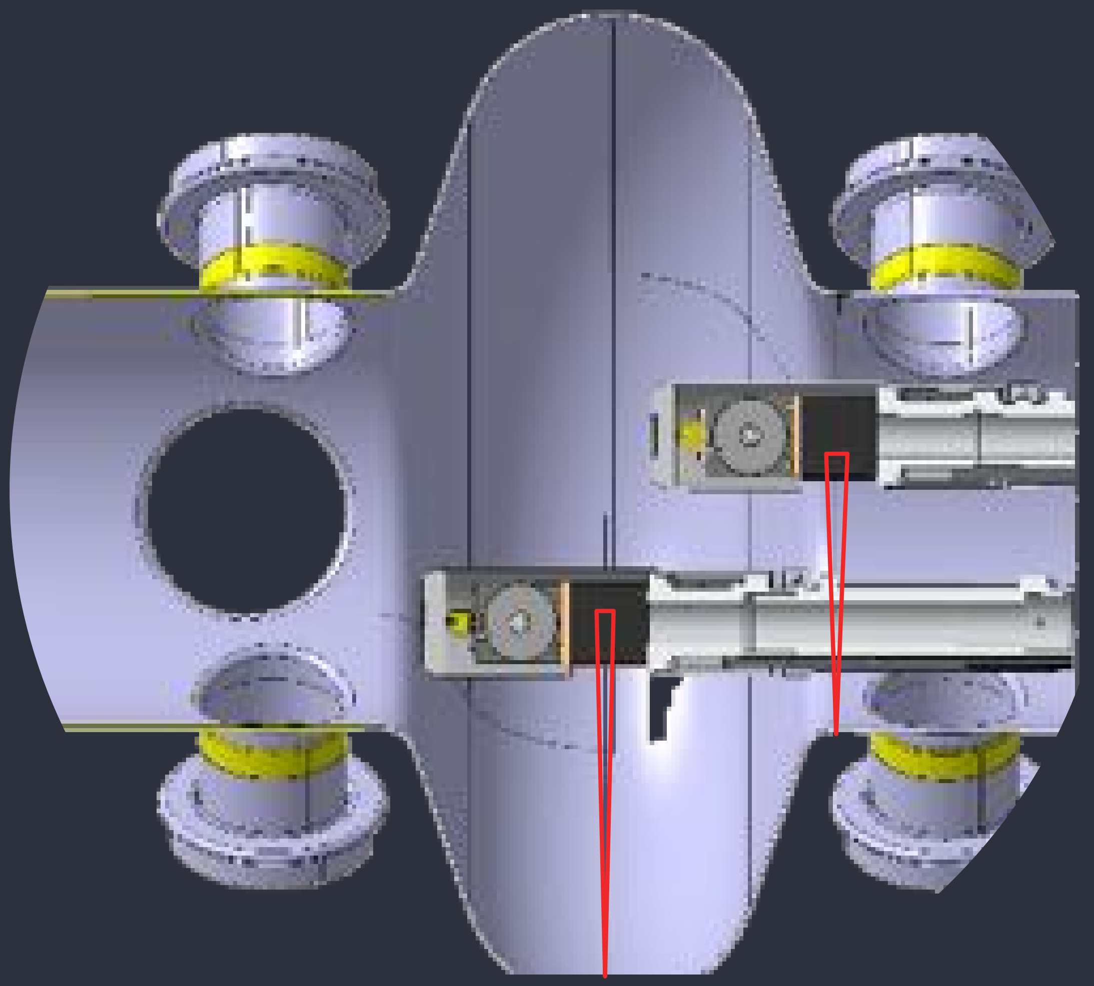
Novel fabrication techniques for SRF cavities & ancillaries

Novel manufacturing

Hydroforming



Modelling of mechanical forming



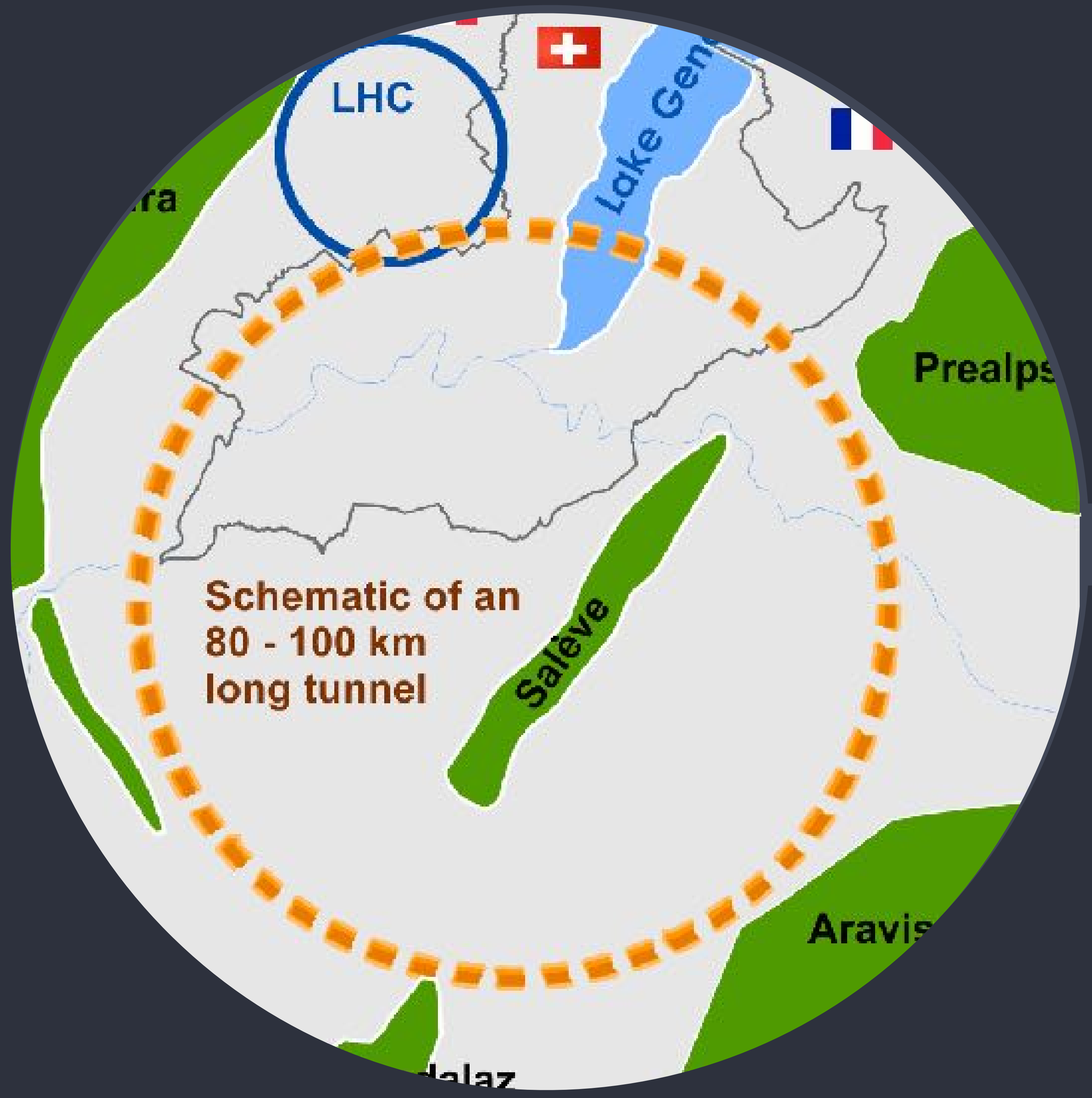
EBW with internal reflector (just starting)

Material testing: OM, SEM, ultrasonic tests, mechanical tests, FIB, EBSD, STEM

… and many more

see: S. Atieh, "Novel Technologies applied to SRF (cavity) fabrication", Wed. 15:00, WG4
R. Gerard, "Metal Additive Manufacturing at CERN in general and SRF Niobium", Wed. 14:30, WG4
L. Lain Amador, "Seamless cavities via electrodeposition", Wed. 14:00, WG4
M. Garlasche, "RFD crab cavities manufacturing experience at CERN", Wed. 16:00, WG4

courtesy M. Garlasche, JS. Swieszek, A. Gallifa, S. Atieh, T. Demaziere, G. Favre, I. Aviles, …



Future Circular Collider Study

Need for R&D on future SRF cavities at CERN

FCC options

"high current" machine

parameter	FCC-ee					FCC-hh
physics	Z		W	H	t	hh
energy/beam [GeV]	45.6		80	120	175	50000
bunches/beam	30180	91500	5260	780	81	
bunch spacing [ns]	7.5	2.5	50	400	4000	25
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	1
beam current [mA]	1450	1450	152	30	6.6	500
luminosity [$10^{34}cm^{-2}s^{-1}$]	210	90	19	5.1	1.3	5-30
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	
RF voltage [GV]	0.4	0.2	0.8	3.0	10	0.32

timeline: Z → W → H → t → FCC-hh

"high gradient" machine

courtesy O. Brunner

FCC cavity options

two different sets of cavities will be needed to cover all scenarios

"high current" machine

Z W hh

- lower frequency, low N_{cells}, low R_s
- **400 MHz, Nb/Cu,** < 100 cavities
- FPC: aim at 1 MW/cavity (movable for hh, fixed for ee)
- HOM power < 1.5 kW/cavity
- 1 RF source/cavity (e.g. high efficiency klystrons)
- CM design to accommodate 1-cell (W) and 4-cell cavities (Z, hh)

"high gradient" machine

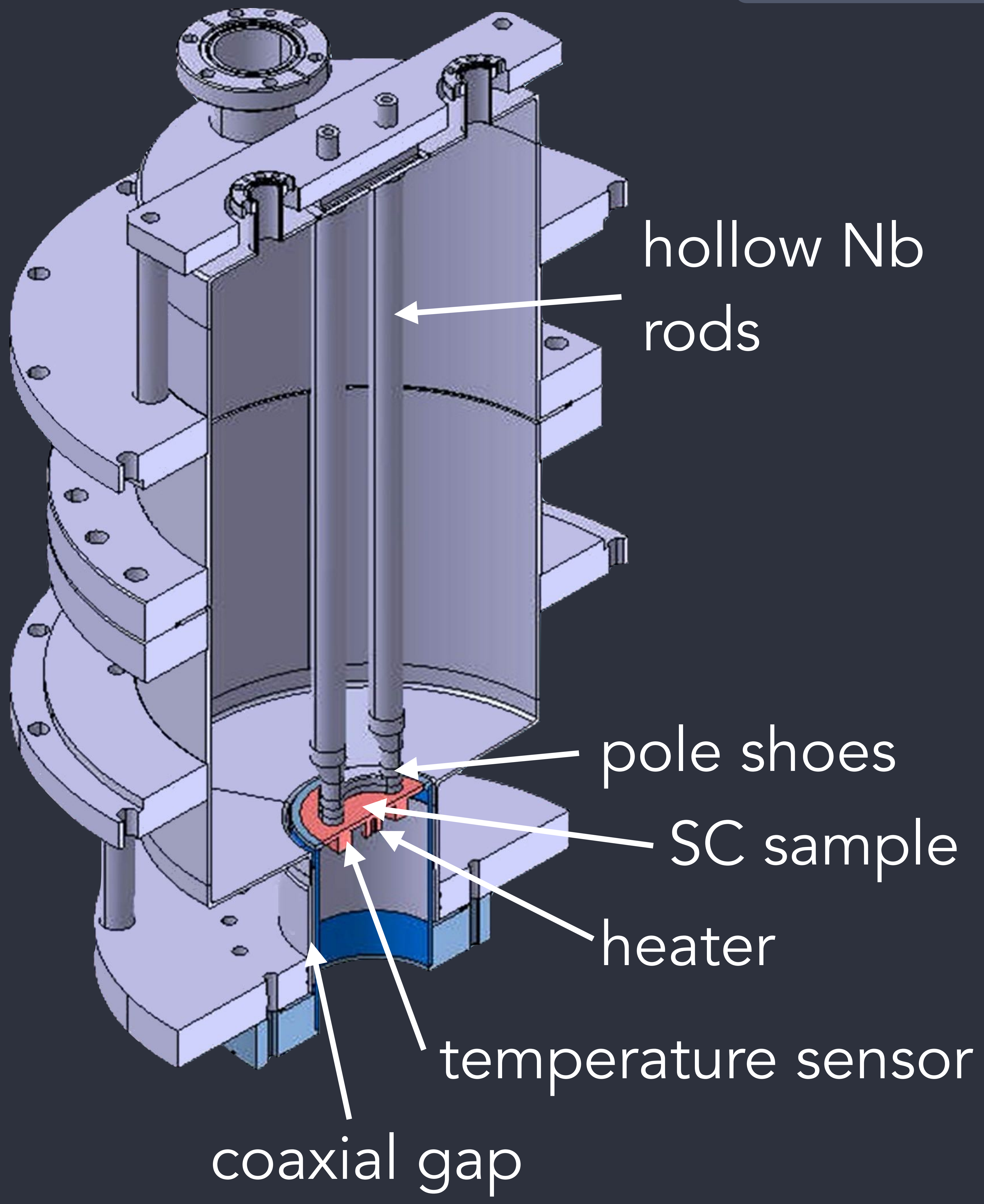
H t

- optimise power consumption, multi-cell, high R_s
- 400 MHz (Nb/Cu) or **800 MHz (Nb)**, O(1000) cavities
- transverse impedance favours low frequency
- N_{cells} defined by beam-cavity interaction, for now assume 4/5

courtesy O. Brunner, R. Calaga, S.G. Zadeh

Quadrupole Resonator

our tool to qualify samples



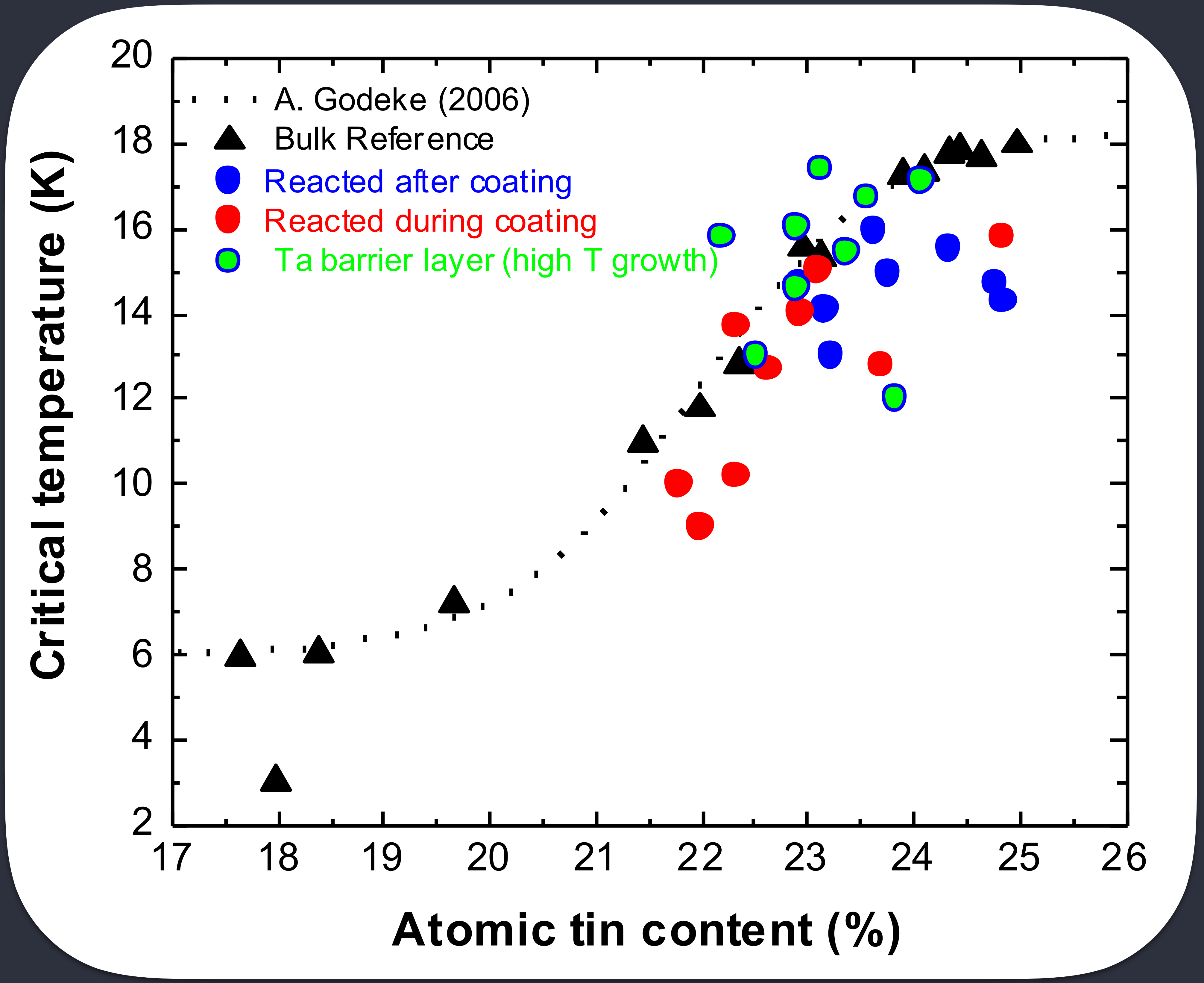
- Operational since 20 years, new QPR under commissioning.
- resonant frequencies: 400/800/1200 MHz
- pole shoes focus magnetic field on the sample
- thermally decoupled sample
- high-resolution calorimetric measurement of surface resistance

courtesy: V. Del Pozo Romano

A15 materials

Nb3Sn on Cu: successful sample test with intermediate Ta layer but still with strong Q-slope, **see M. Arzeo, SRF conference 2019**

see R. Calaga, "Nb3Sn from the lab to the machine", Th. 9:18, WG3



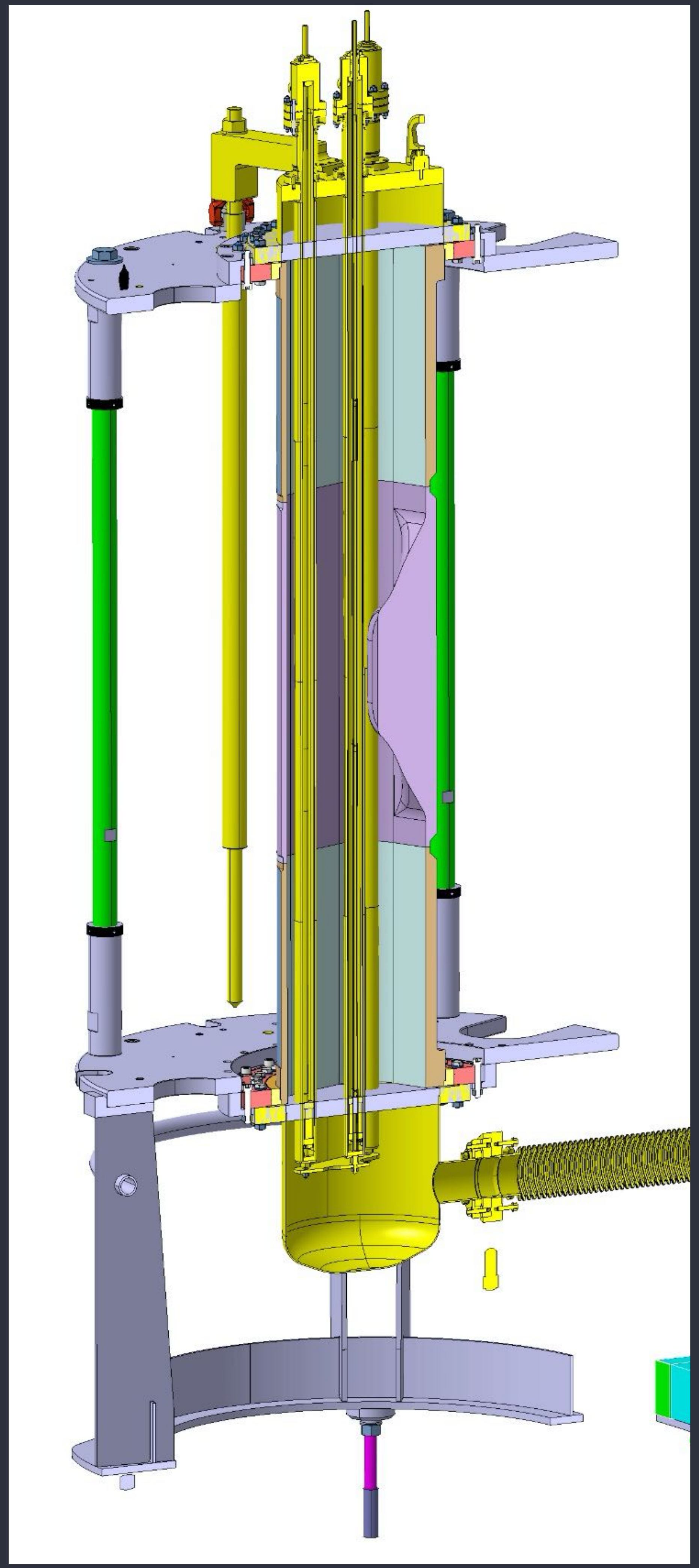
- New results with Vn3Si, **see S. Fernandez Pena, Wed, 16:36 WG3**
- New results with HiPIMS samples, **see L. Vega Cid, Th. 11:00, WG3**

courtesy: M. Arzeo, S. Fernandez Pena

Crab cavity for FCC: WOW

Wide Open Waveguide Cavity

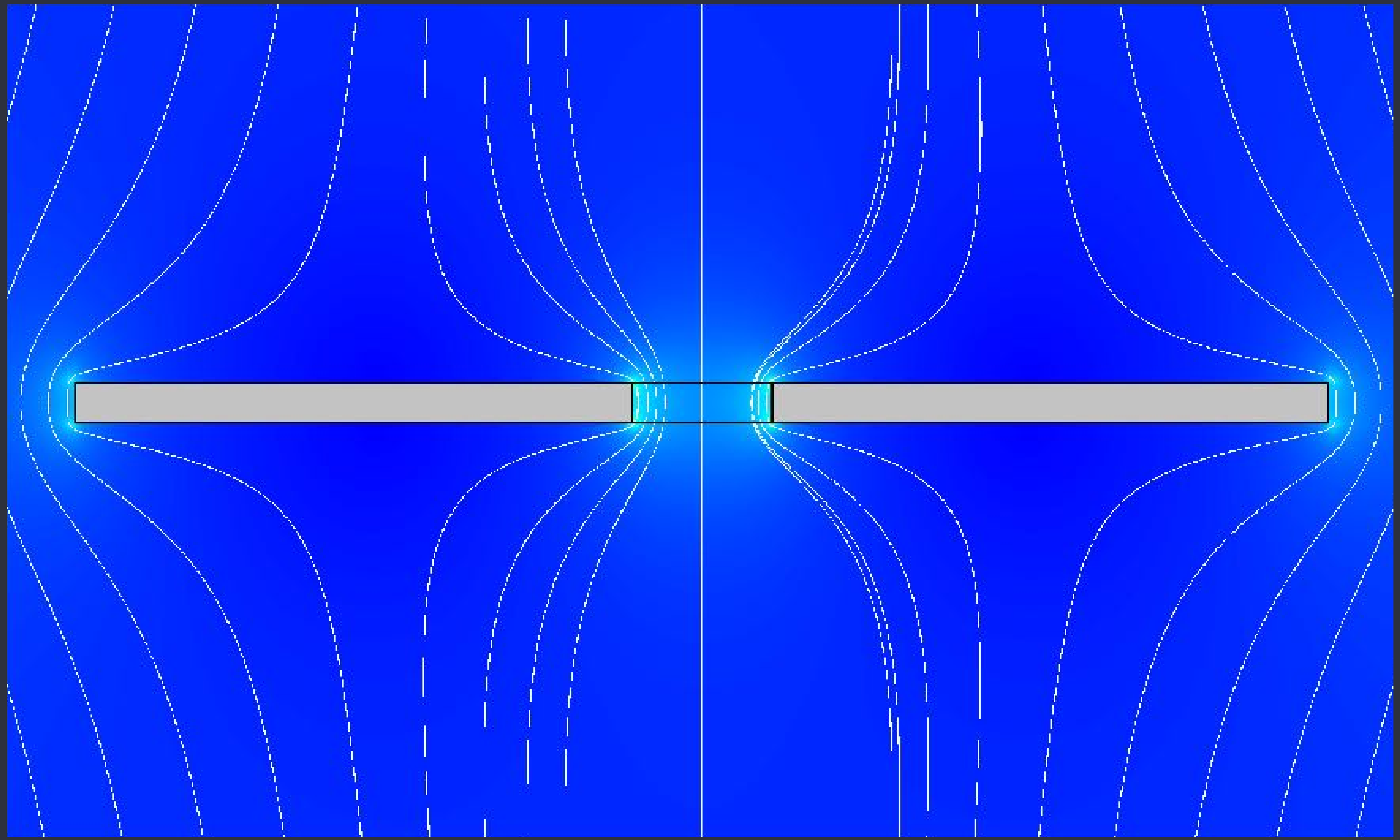
- Low-impedance, Nb-coated Crab cavity.
- 400 MHz, 3 MV deflection.
- 1.4 m long, 290 kg
- Cu substrate is ready, df=12 kHz, 10 um shape accuracy,
- Coating system with 6 electrodes under development, **see F. Avino, Wed. 14:00, WG1**
- **see A. Grudiev et al: DOI: 10.1103/PhysRevAccelBeams.22.072001**



Anton's flux lens

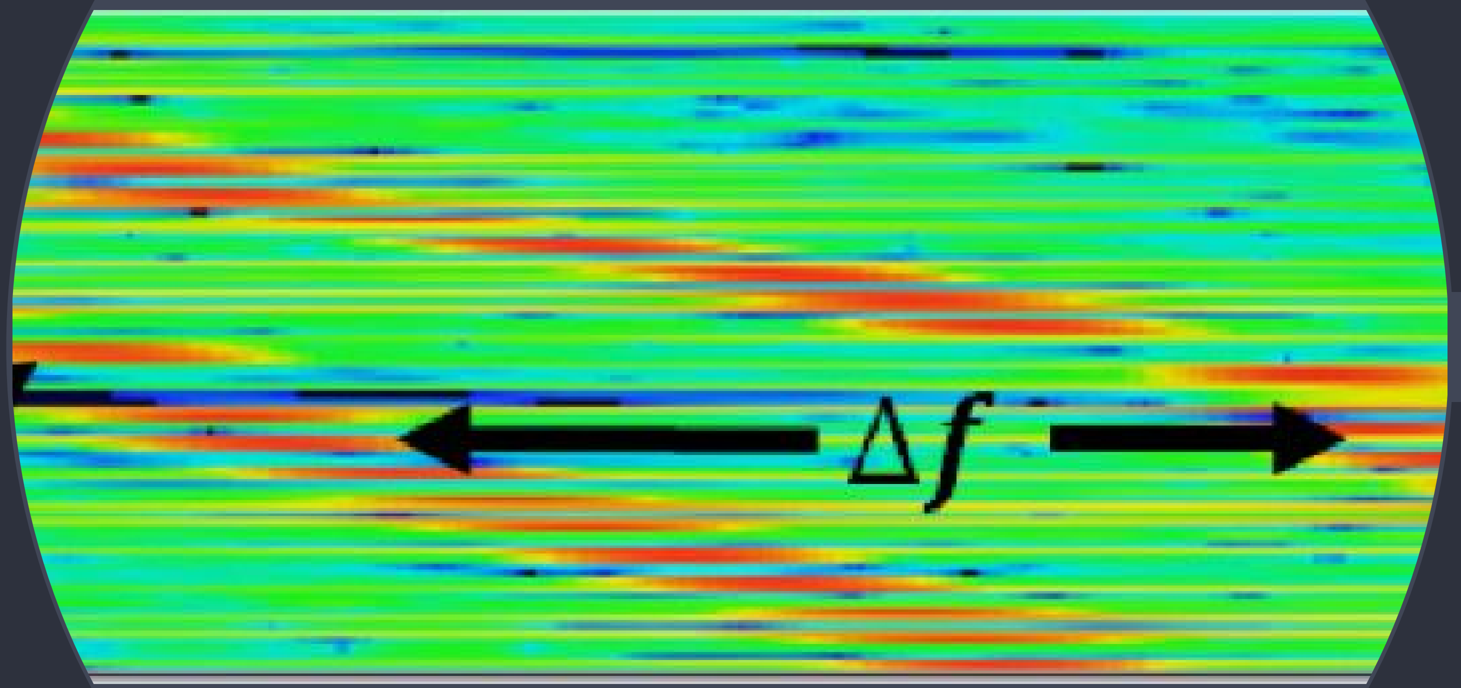
- Flat Nb discs with a hole acting as "flux lens"
- Discs are cooled from the outside to the inside ➜ flux gets expelled towards the hole.
- Magnetic field probe in the hole measures the magnetic field during cool-down.

see A. Ivanov, Wed. 11:00, WG1



➜ allows systematic tests of Nb sheets before fabrication and comparative studies of materials from different vendors and different treatments w/o building cavities.

courtesy A. Ivanov, A. Macpherson

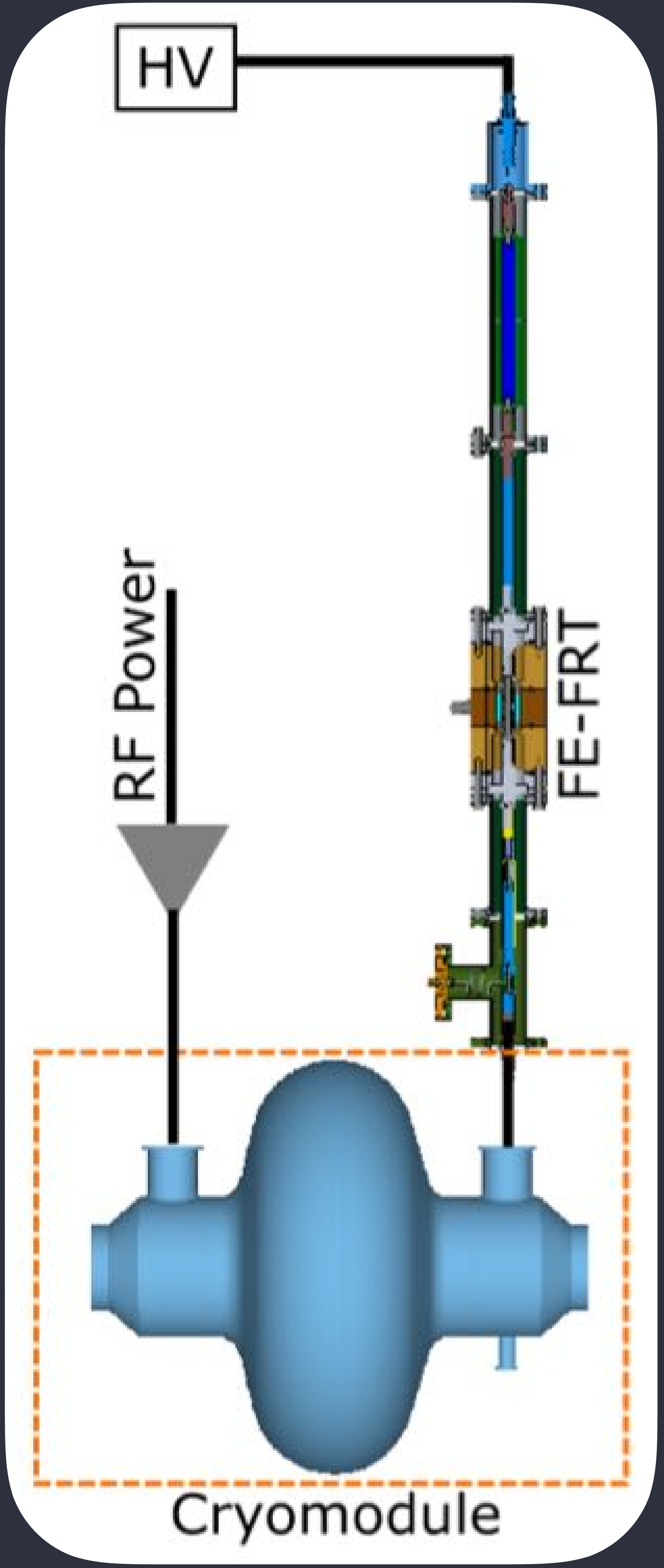


Ferroelectric Fast Reactive Tuner

A new paradigm for microphonics compensation

Ferroelectric Fast Reactive Tuner

- Cavity is coupled to a tunable reactance (FRT),
- Permeability of the ferrite is tuned with a biasing high-voltage ➜ change of "electrical length" of the FRT transmission line ➜ change of cavity frequency.
- **No mechanical tuning of the cavity.**
- Made possible by recent development of low-loss ferroelectric material[1] by Euclid Techlabs LLC.
- The principle was developed in the US (V.P. Yakovlev, I. Ben-Zvi, et al.) and prototyped by BNL and Euclid Techlabs LLC.
- CERN bought this prototype and made a **first** proof-of-principle FE-FRT test on a superconducting cavity[2].



[1] E. Nenasheva et al., "Ceramics Materials Based on (Ba, Sr)TiO_3 Solid Solutions for Tunable Microwave Devices", J. of Electroceramics, **13**, pp 235 - 238, Jul. 2004

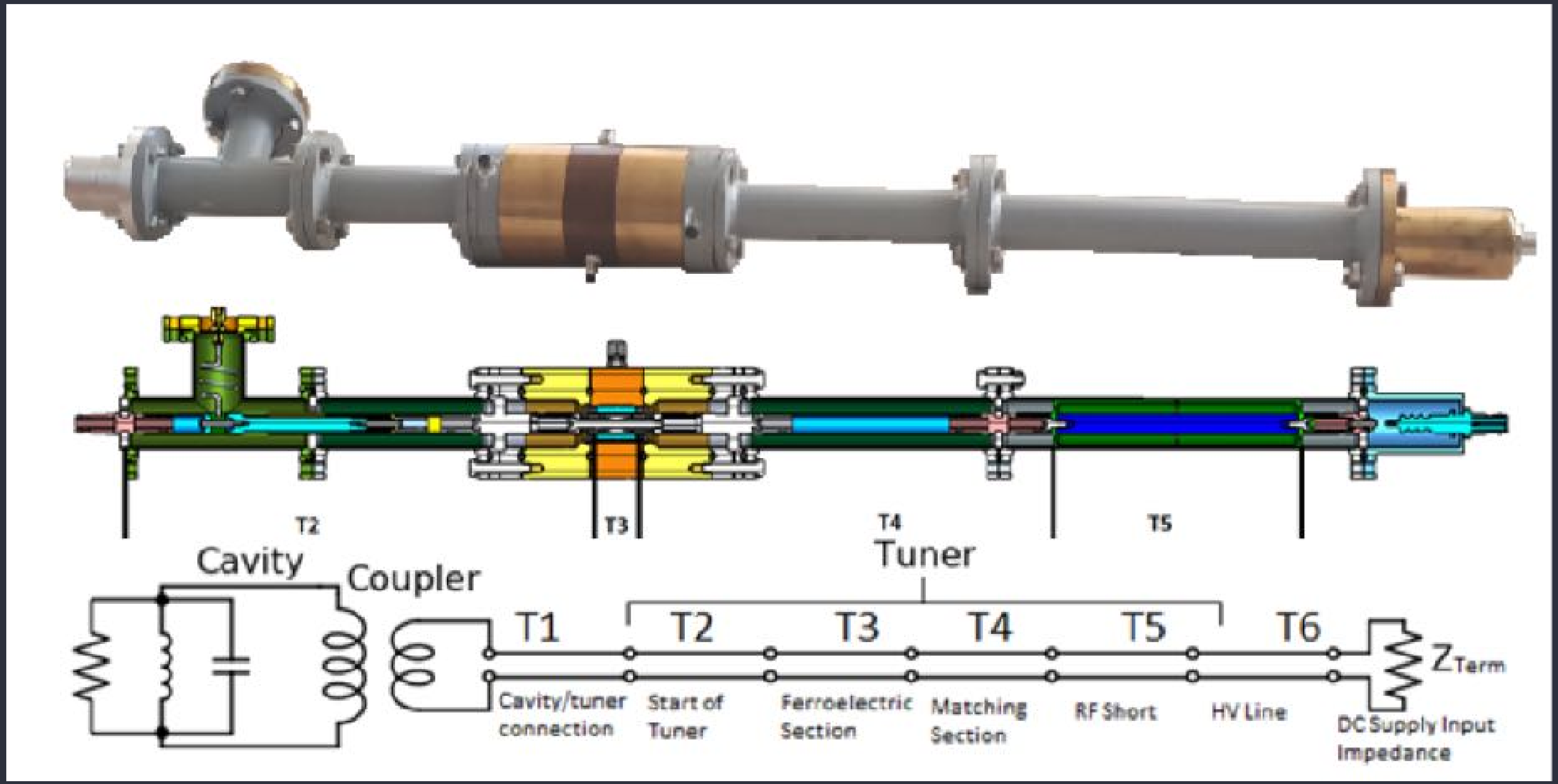
[2] N. Shipman et al., "A Ferroelectric Fast Reactive Tuner for Superconducting Cavities", SRF 2019, Dresden.

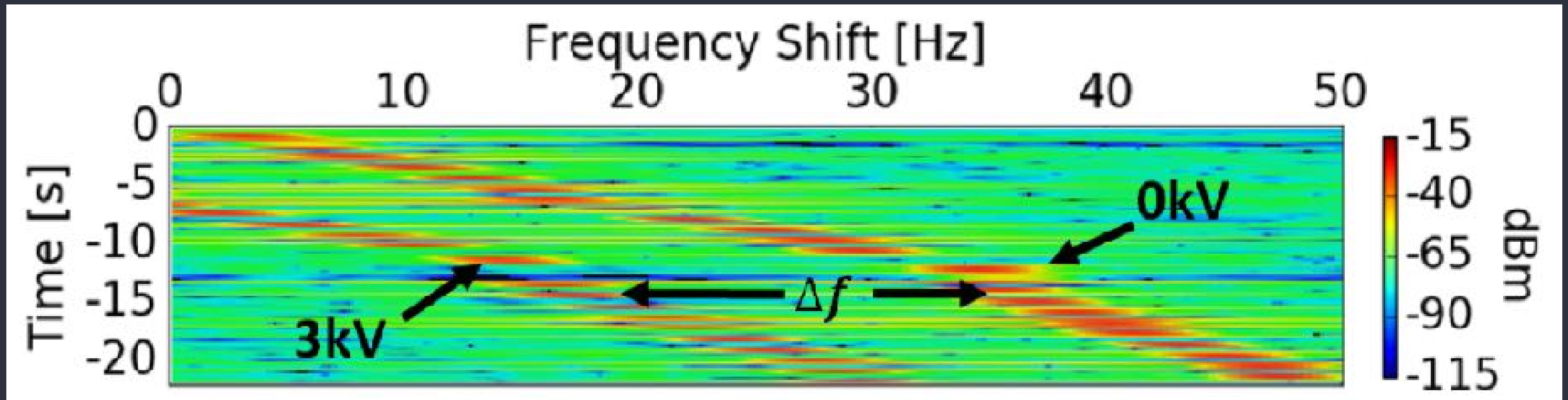
courtesy N. Shipman, A. Macpherson

Fe-FRT proof-of-principle test

- The FRT was sitting outside of cryostat connected by a coax line to the cavity.
- Frequency shift as a function of biasing voltage was verified.
- Measured cavity response to tuner < 50 μs (probably faster, limited by time resolution of measurement system)

➡ frequency shift much faster than cavity time constant!

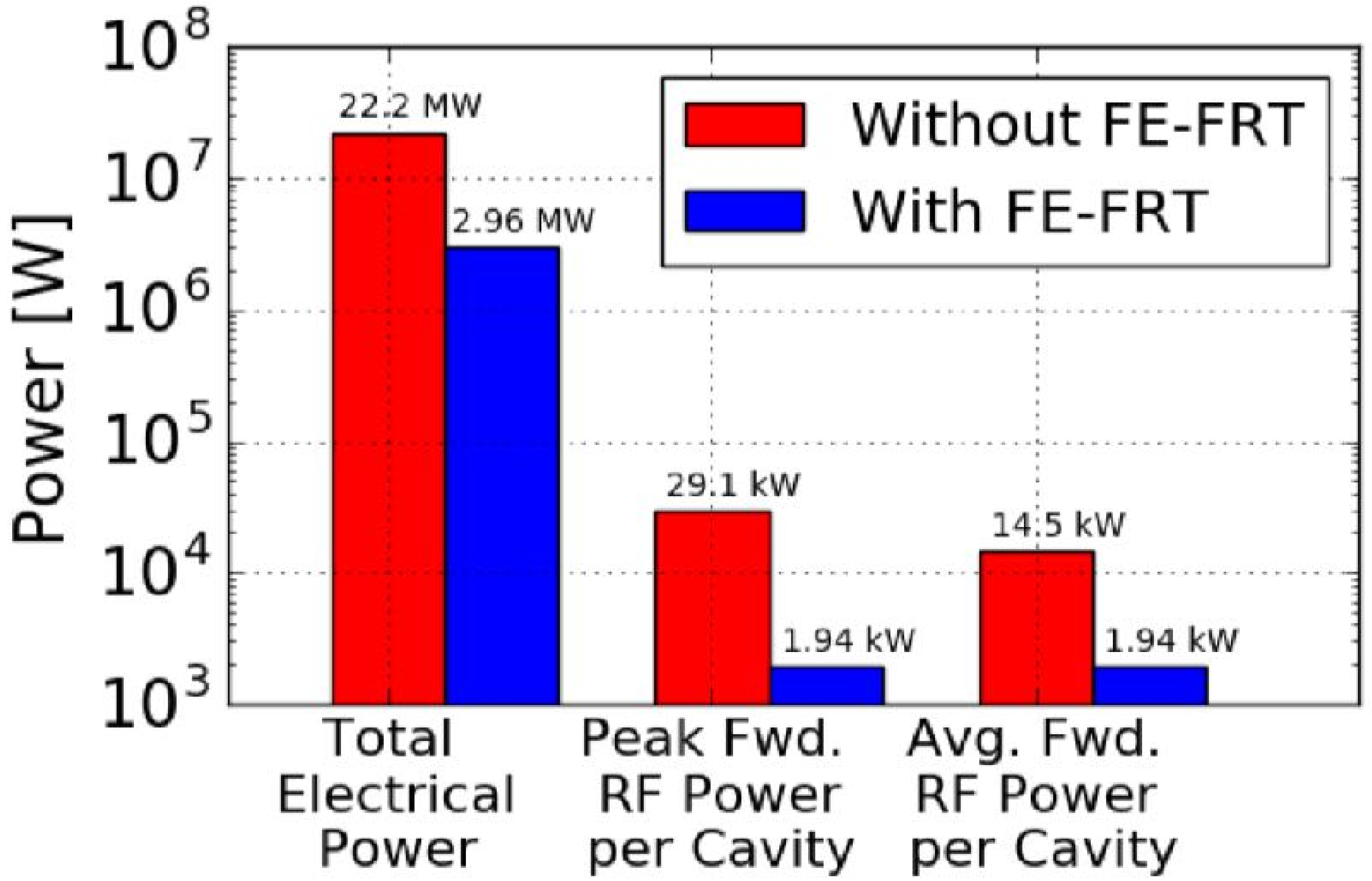




courtesy N. Shipman, A. Macpherson

Case study for LHeC ERL

$$P_{RF} = \frac{V_c^2}{4 R/_Q Q_L} \frac{\beta + 1}{\beta} \left[1 + \left(2 Q_L \frac{\Delta\omega_\mu}{\omega_0} \right)^2 \right]$$



- Peak power per cavity 29.1 kW → 1.94 kW
- Total Electrical Power **22.2 MW → 2.96 MW**

Nominal parameters

Project	LHeC
Frequency	801.58 MHz
Cavity Voltage	18.7 MV
External Q of FPC	1.56×10^7
Cavity Q_0	2×10^{10}
R/Q	393 Ω
Peak Detuning	26.2 Hz
RMS Detuning	4.36 Hz
Cavity gradient	20 MV/m
Beam Energy	60 GeV
ERL passes	3
Number of cavities	**1069**
DC to RF conversion eff.	70%
El. Power for microphonics control	22.2 MW
El. Power for cavity losses at 2K	47 MW

Potential to drastically reduce power needs for microphonics compensation in low-beam-loading machines.

courtesy N. Shipman, A. Macpherson

Summary

- Over the last years, the CERN SRF infrastructure was updated to deal with HIE-ISOLDE, CRAB cavities, elliptical bulk Nb cavities & LHC cavities.
- The crab cavities will be the main SRF project until 2025.
- Bulk Nb cavity preparation and testing reached state of the art (400 MHz Crab & 704 MHz elliptical) but we are still chasing the last nOhms.
- R&D focus is on coatings and new manufacturing techniques: extensive work on Nb/Cu, A15/Cu, seamless substrates, new testing methods with a view towards FCC, 400/800 MHz.
- Rich program on SRF ancillaries: FPC R&D centre, Fast Reactive Tuner, printing of HOMs, …


Thank you