Superconducting RF at CERN: operation, project, and R&D

Frank Gerigk for the CERN SRF teams

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on behalf of the CERN SRF team:

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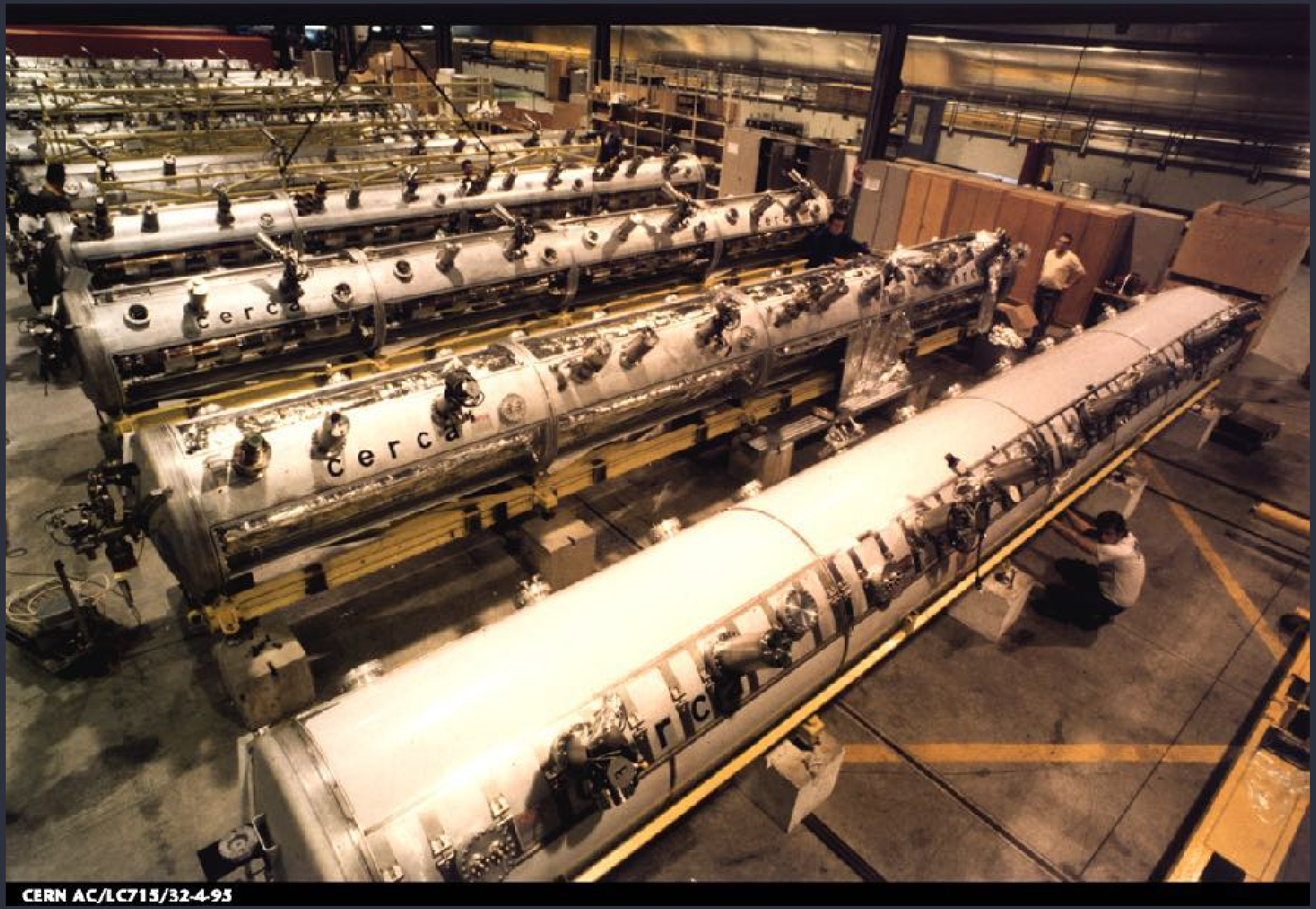
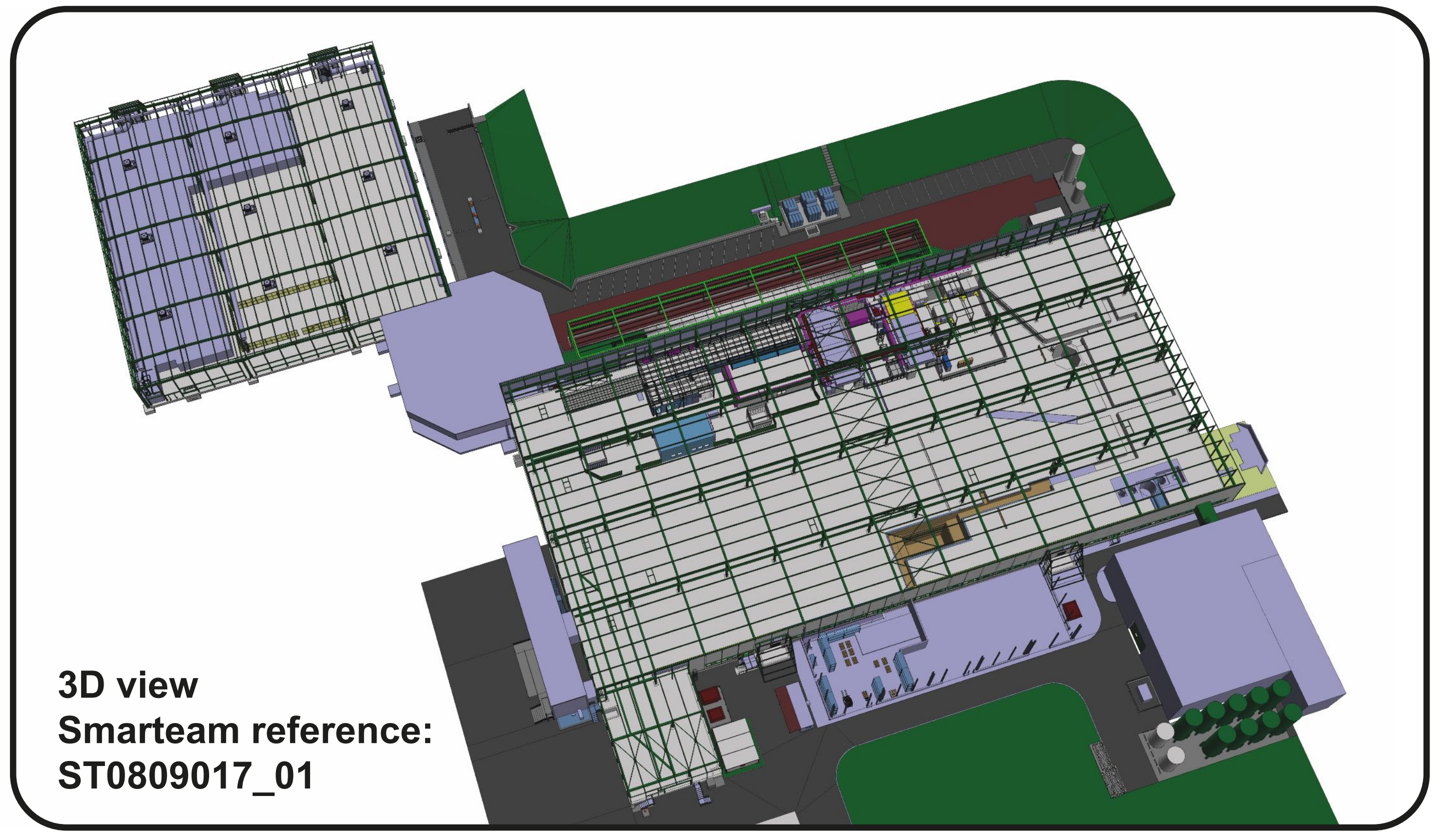
Content

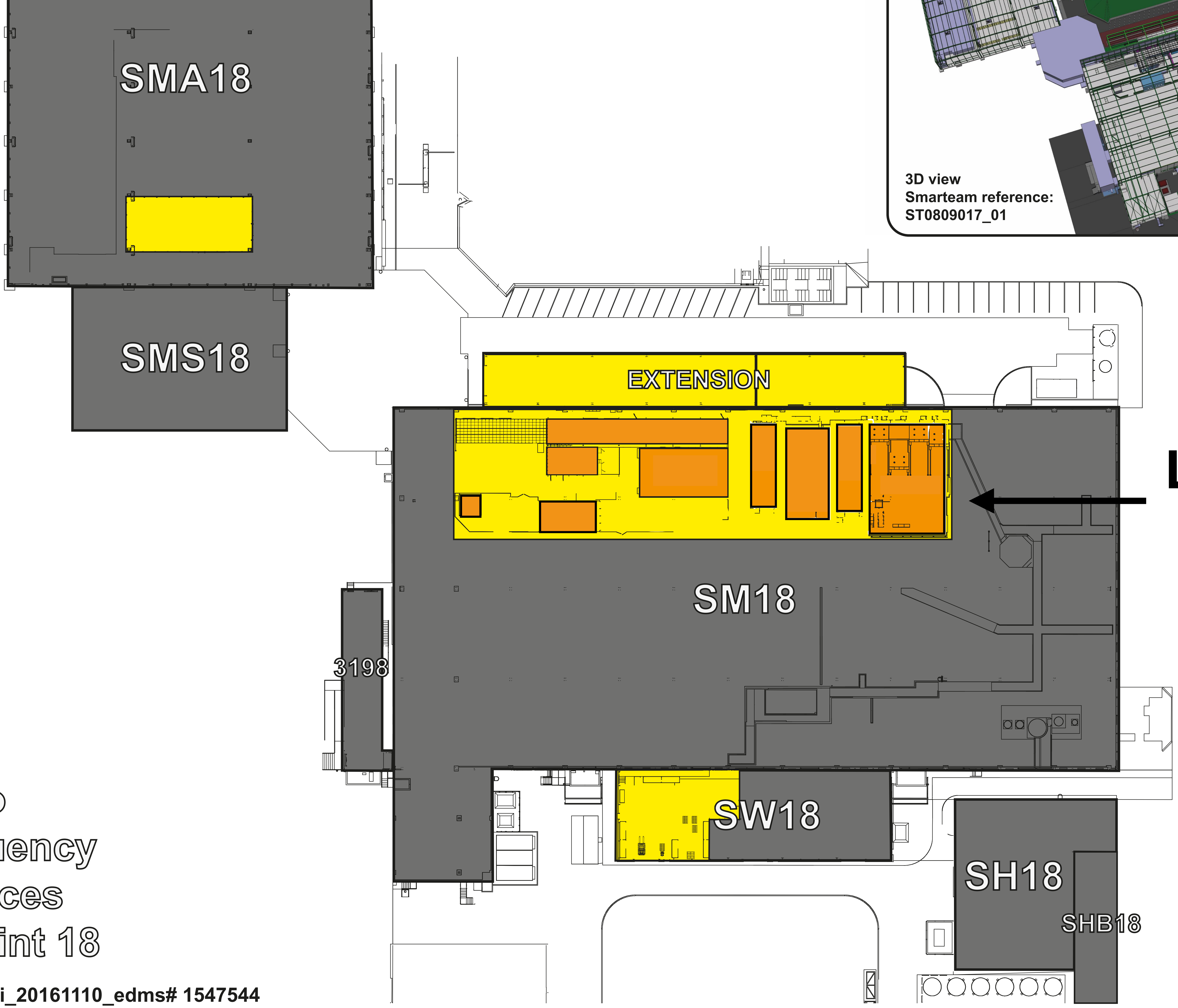
Past Glory…

LEP cavity tuning, 1980



In 1999 288 SC cavities were installed in LEP





LEP module exhibit

Radio Frequency Surfaces @ Point 18

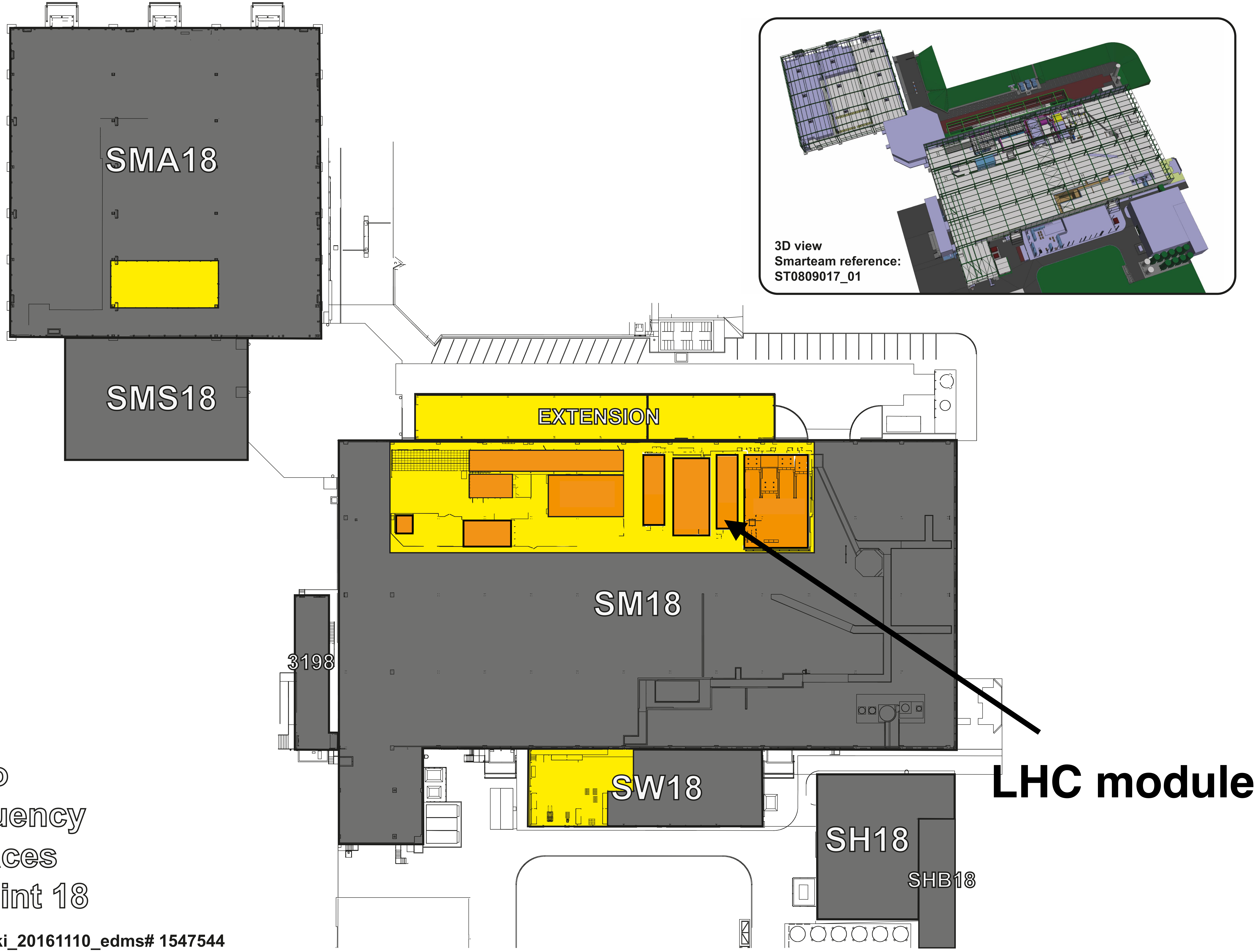
A.Kosmicki_20161110_edms# 1547544

Recent Glory…

LHC cryomodule

Test of first LHC module (2000)

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



Radio Frequency Surfaces @ Point 18

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1992 - 2008

- **2000-2008**: SRF activity **focused on LHC cavity assembly**, testing, installation and very little R&D.
- People retiring or moving elsewhere.
- **By 2008** we had an infrastructure, suitable for coated cavities but not for bulk Nb cavities, which had reached operational gradients of 30 MV/m (instead of ~5-7 MV/m for LHC).
  - **marginal testing capability at 2K in SM18**
  - **two** 15 m long class 1000 (ISO 6) and class 10 (ISO 4) **clean rooms suited for LHC but for little else**
  - a He-transfer line that consumed 8 out of 22 g/s He capacity (2008), which had to be shared with a substantial magnet test facility.

Infrastructure upgrades: 2008-17

2008 2009 2010	**HIE study: definition of infrastructure needs:** clean rooms, chemistry, coating, CM design, cry-infrastructure,	**SPL study: definition of infrastructure needs based on technical choices for SPL**: clean rooms, cold testing, EP, tuning, inspection, coupler development, CM studies and cryogenic infrastructure in SM18
2011	**HIE coating** system operational	
2012	Optical inspection system, first vertical **tests at 2K**, **vertical EP, new EB welding** machine	
2013	**New He transfer line** commissioned + 6 **new service modules**; **HPR** and ultrapure water production (Oct)	
2014	first exchange of LHC module, received ESS modulator for pulsed klystrons, HPR operational (June), 704 MHz klystron/RF loads/circulator delivered and tested, **clean rooms upgraded** (ISO6 to ISO5, additions to connect HPR to ISO5), **HIE clean room operational**	
2015	New Valve-box in M9 (HIE-ISOLDE + LHC)	
2016	B252 floor collapsing, serious space shortage,	
2017	Self-exited loop working, multi-purpose valve-box for M7 (Crab, 800 MHz, HG 704 MHz), recuperation of 400 m2 RATS area in Meyrin	

Today's challenges:

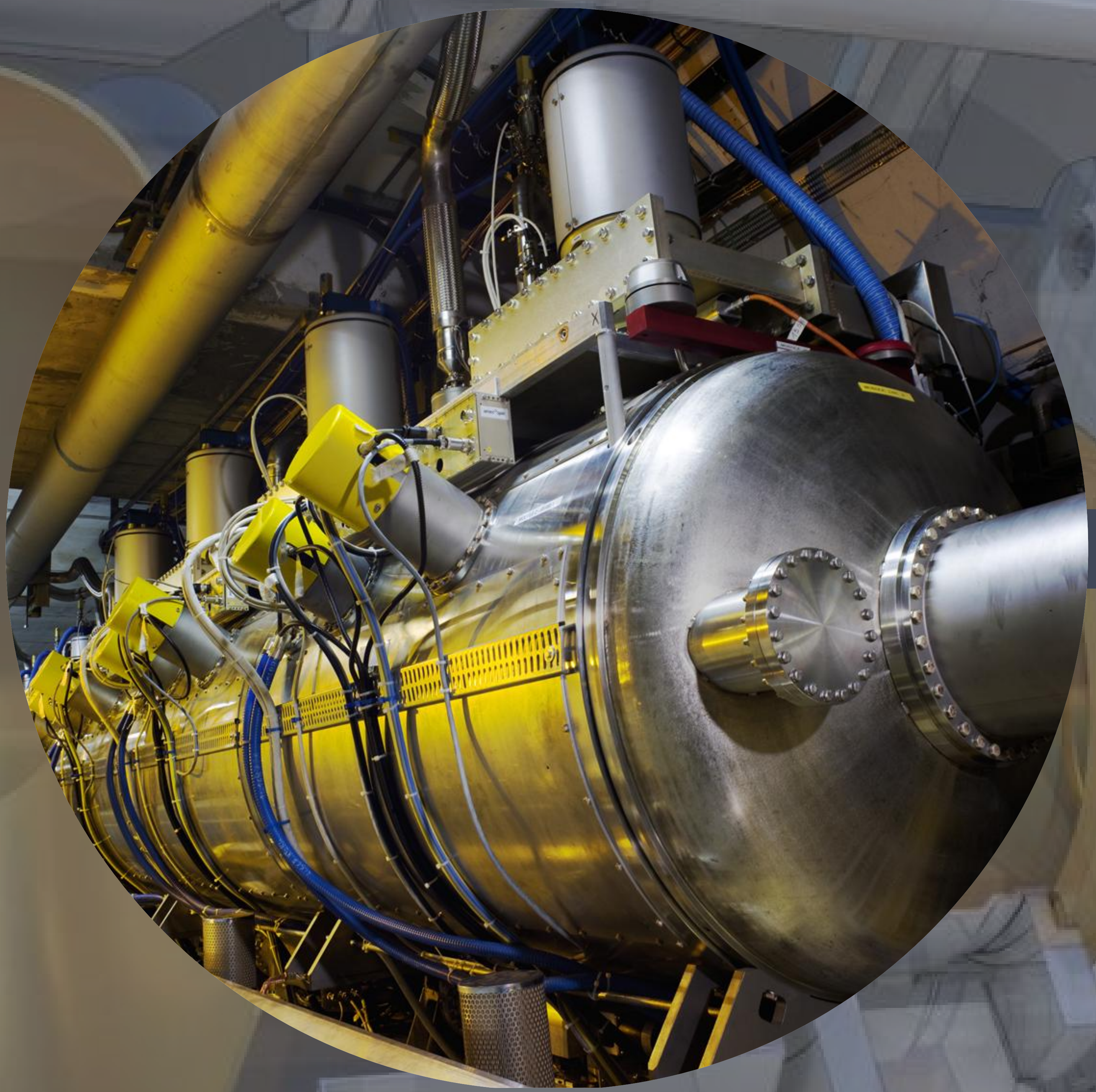
HIE-ISOLDE installation & commissioning

HL-LHC Crab Cavities

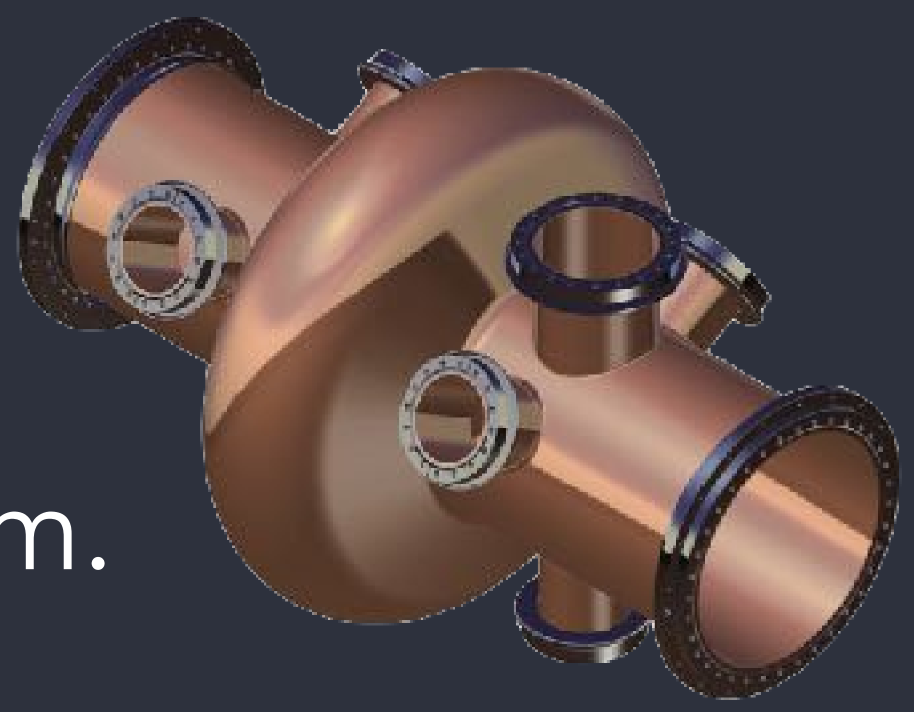
LHC operation & spare cavities

SRF R&D program

LHC cavities



LHC spare cavity program



- **NB-COATED** Cu cavities operating at 4.5 K, 400.790 MHz, 8-16 MV/beam.
- A total of 4 CM (16 cavities) is installed
- **1 spare module and one spare dressed cavity available. Many of the "old" experts have retired.**
- **Installed and operational since 10 years and supposed to run until 2035, or longer. No experience with ageing of LHC cryomodules.**

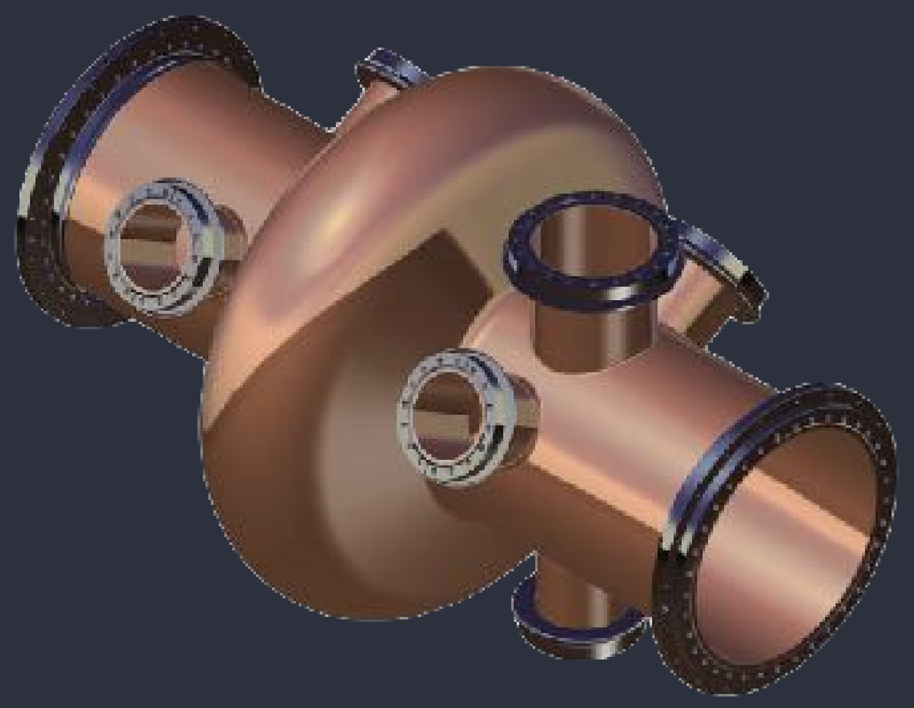
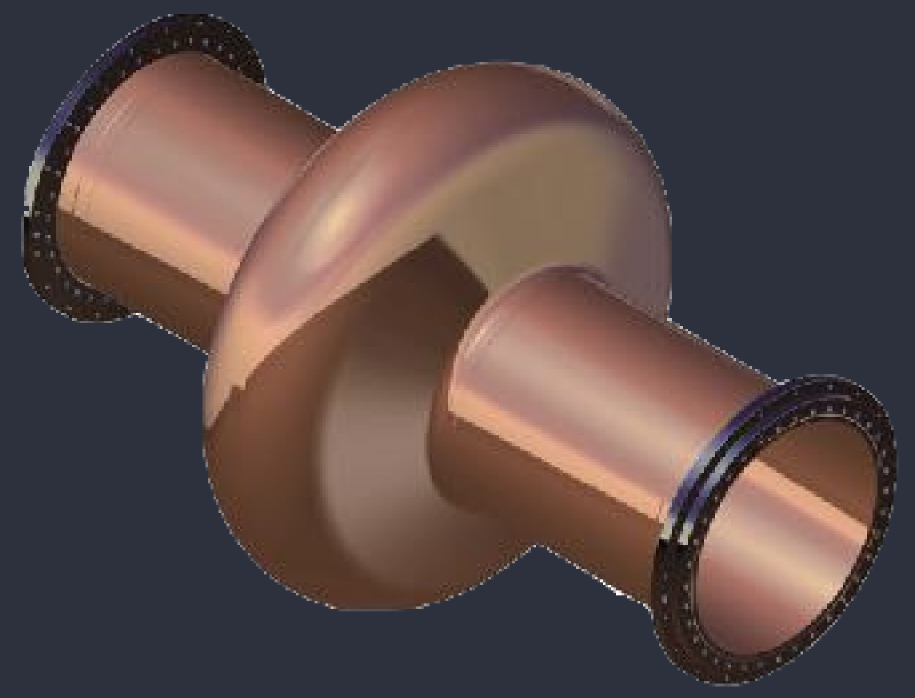
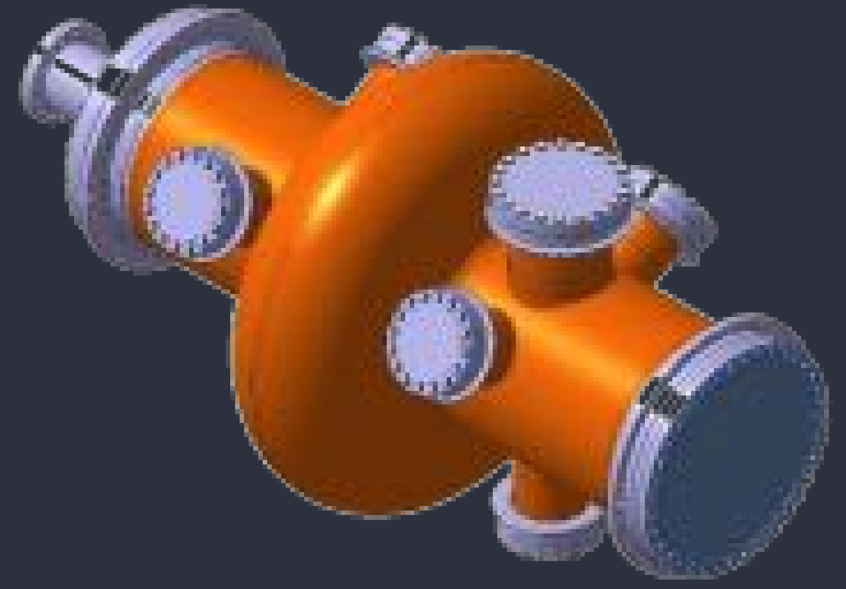
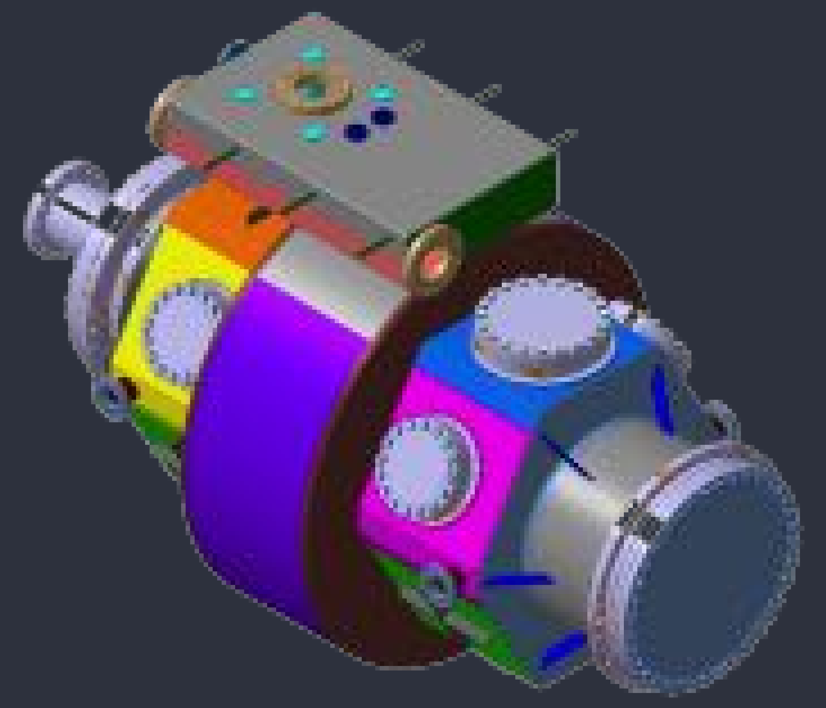
The LHC spare cavity program will produce **1 complete new spare cryomodule and one spare cavity train** (4 cavities).

➡ industrial production of cavities and subsequent coating at CERN

➡ **instead of having spares as quickly as possible: have a CERN team of experts which can maintain, repair, build, exchange, test, LHC cavities & CMs in the long run.**

courtesy M. Karppinen

LHC spare cavity program

Practice cavity 1,2

- full cut-off tubes, but off-frequency
- cavity fabrication tools & process,
- rinsing, chemistry
- Nb-coating (magnetron sputtering),
- qualification & cold tests

validation of coating

Practice cavity 3,5

- half cells by spinning and electro-hydraulic forming (EHF),
- simplified cut-off tubes,

choice of spinning or EHF

Model cavity

- validation of cavity design & fabrication process
- He-tank updated design,
- if successful: the first spare cavity

full engineering qualification

Series production

- 8 cavities + 2 spares,
- cut-off tubes fabrication at BINP,
- production of half cells (spun or EHF) in industry

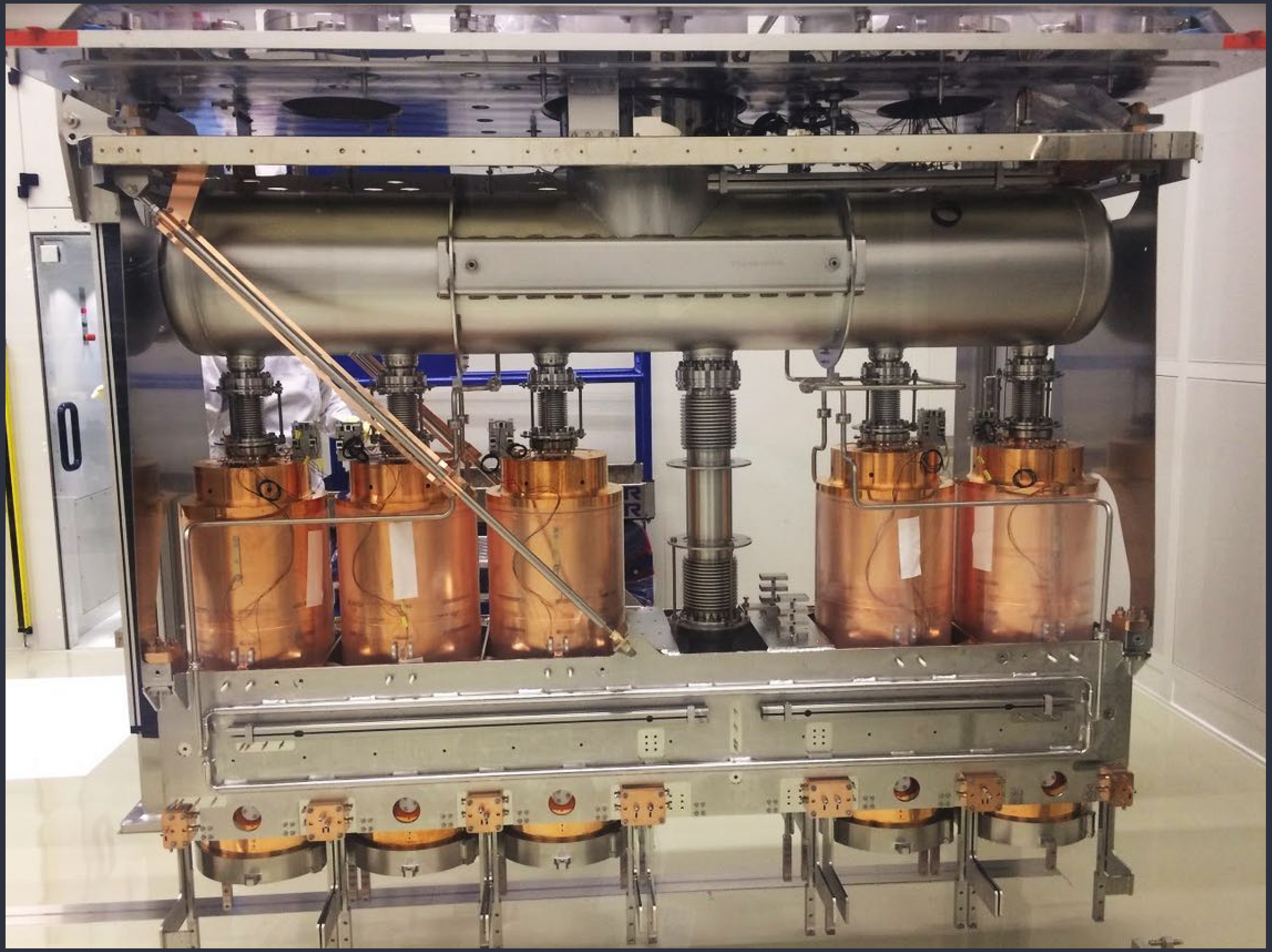
series

courtesy M. Karppinen

HIE-ISOLDE

Probably the first ever coated quarter wave resonators

HIE-ISOLDE project



4 CMs with 5 cavities each:

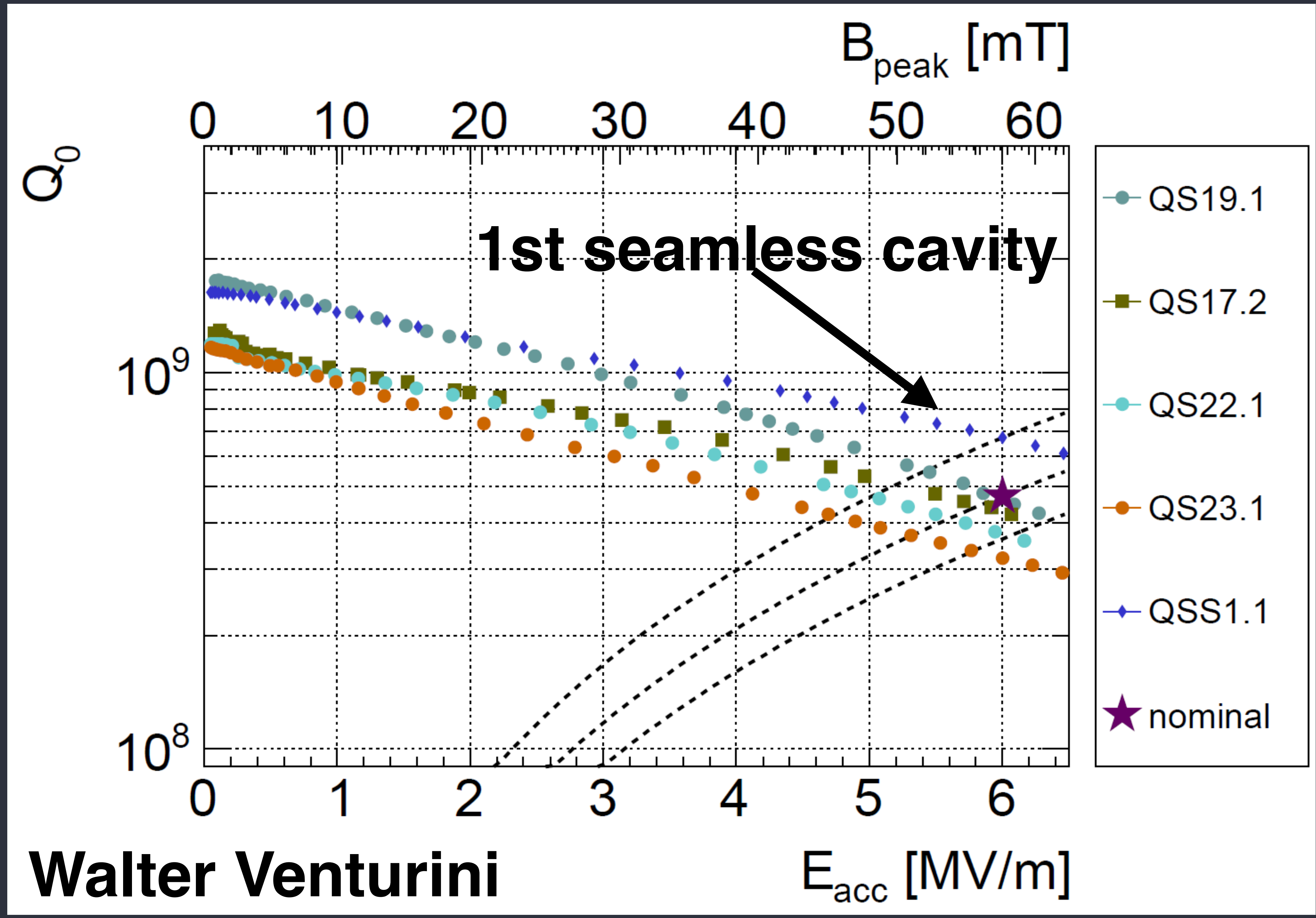
- launched in 2010,
- increase energy of Radioactive Experiment (REX) post-accelerator from 3 to 10 MeV/u,
- first module installed in 2015, 2nd in 2016, 3d in 2017, last module presently under assembly: installation early 2018
- Performance goal: **6 MV/m @ Q>5x10^{8}**
- Collaboration between TE-MSC, EN-MME, TE-VSC, BE-RF

courtesy V. Parma

HIE-ISOLDE project

All three installed cryomodules operate above specifications, which required:

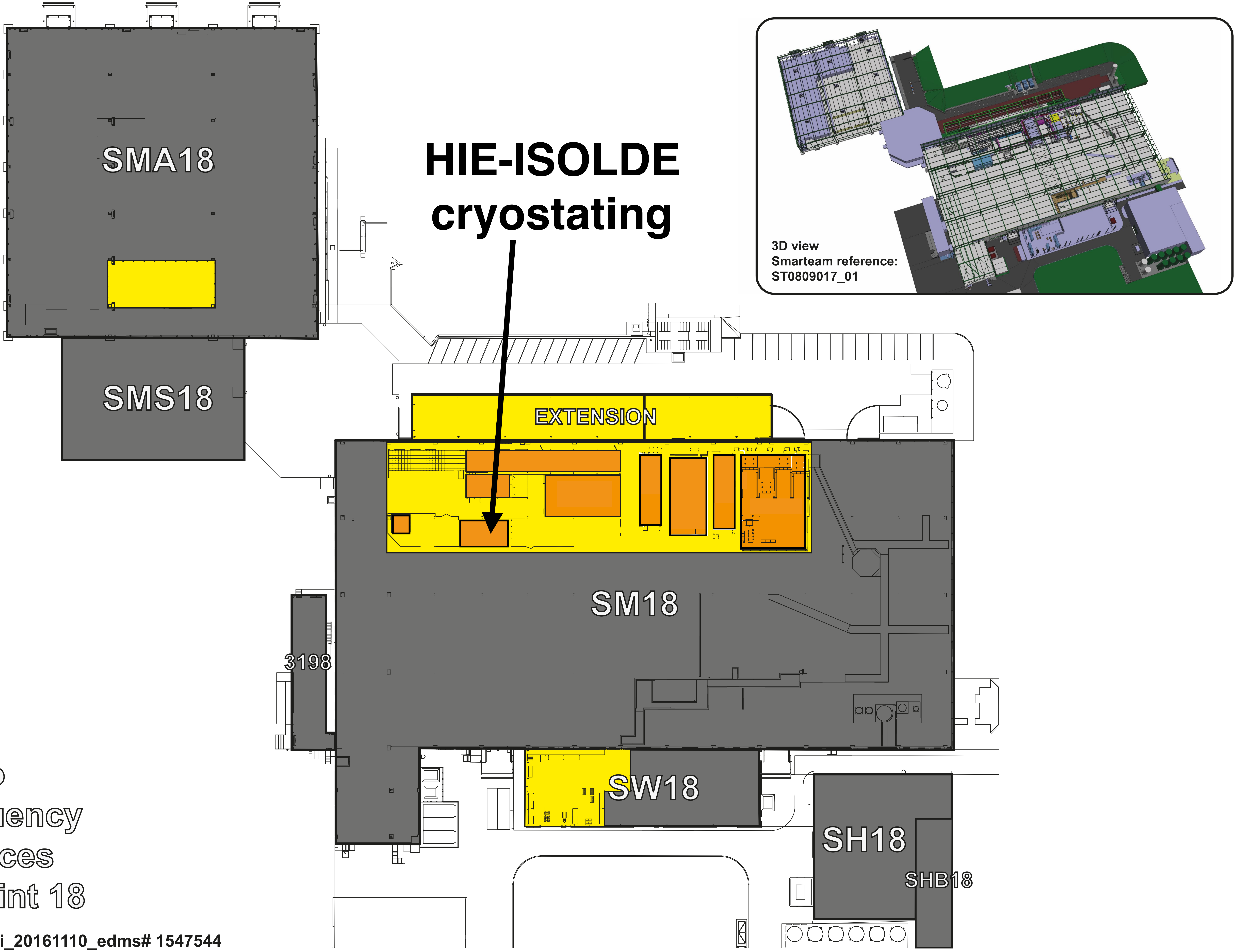
- **Optimisation of welding parameters** to avoid micro-cracks in the Cu substrates,
- Removal of thermal bridges in the coupler area
- Repair of a cold-leak in the Helium supply
- Development of in-situ plasma processing
- **Optimisation of cool-down procedure** to avoid flux trapping
- Tireless effort of all involved groups!



Cold test results of cavities for 4th module

courtesy W. Venturini

HIE-ISOLDE cryostating



Radio Frequency Surfaces @ Point 18

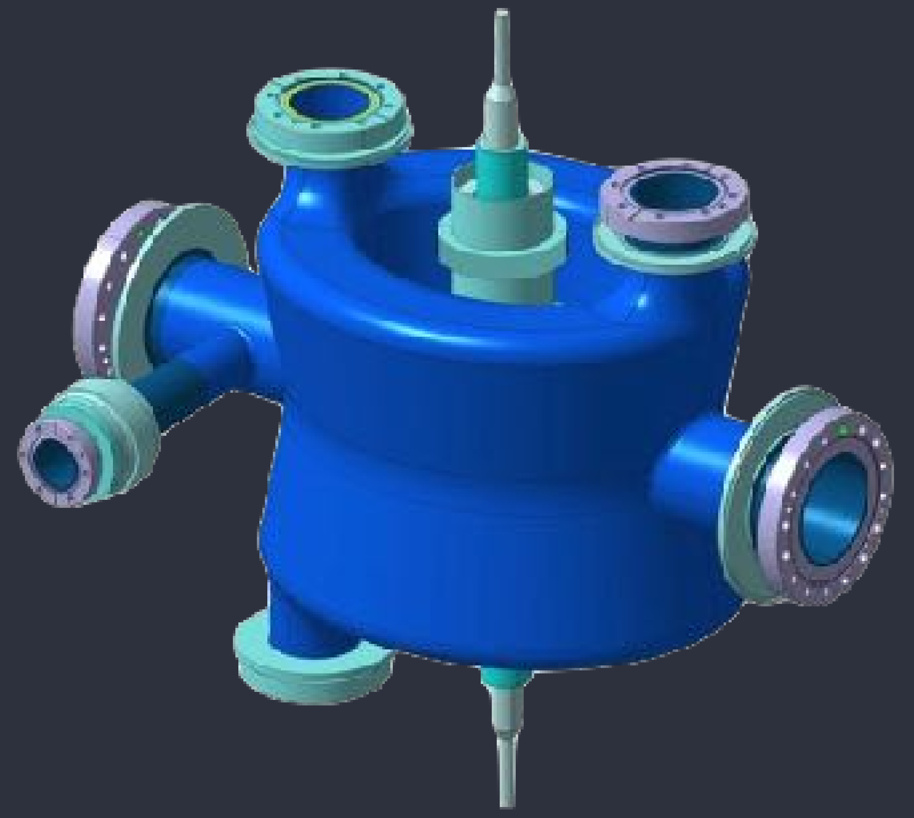
A.Kosmicki_20161110_edms# 1547544

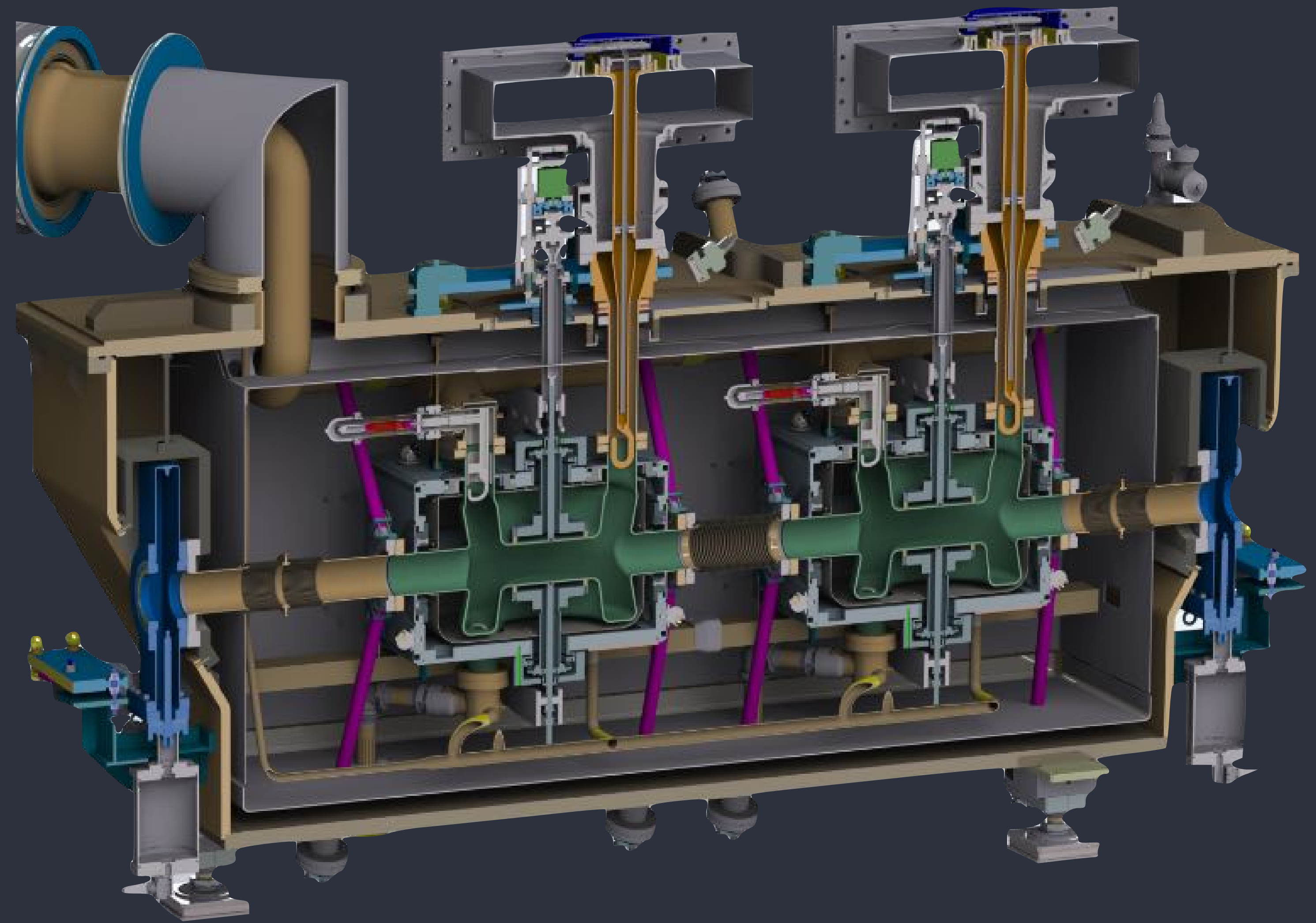
Crab Cavities for HL-LHC

the first bulk Nb cavities in an operational machine at CERN

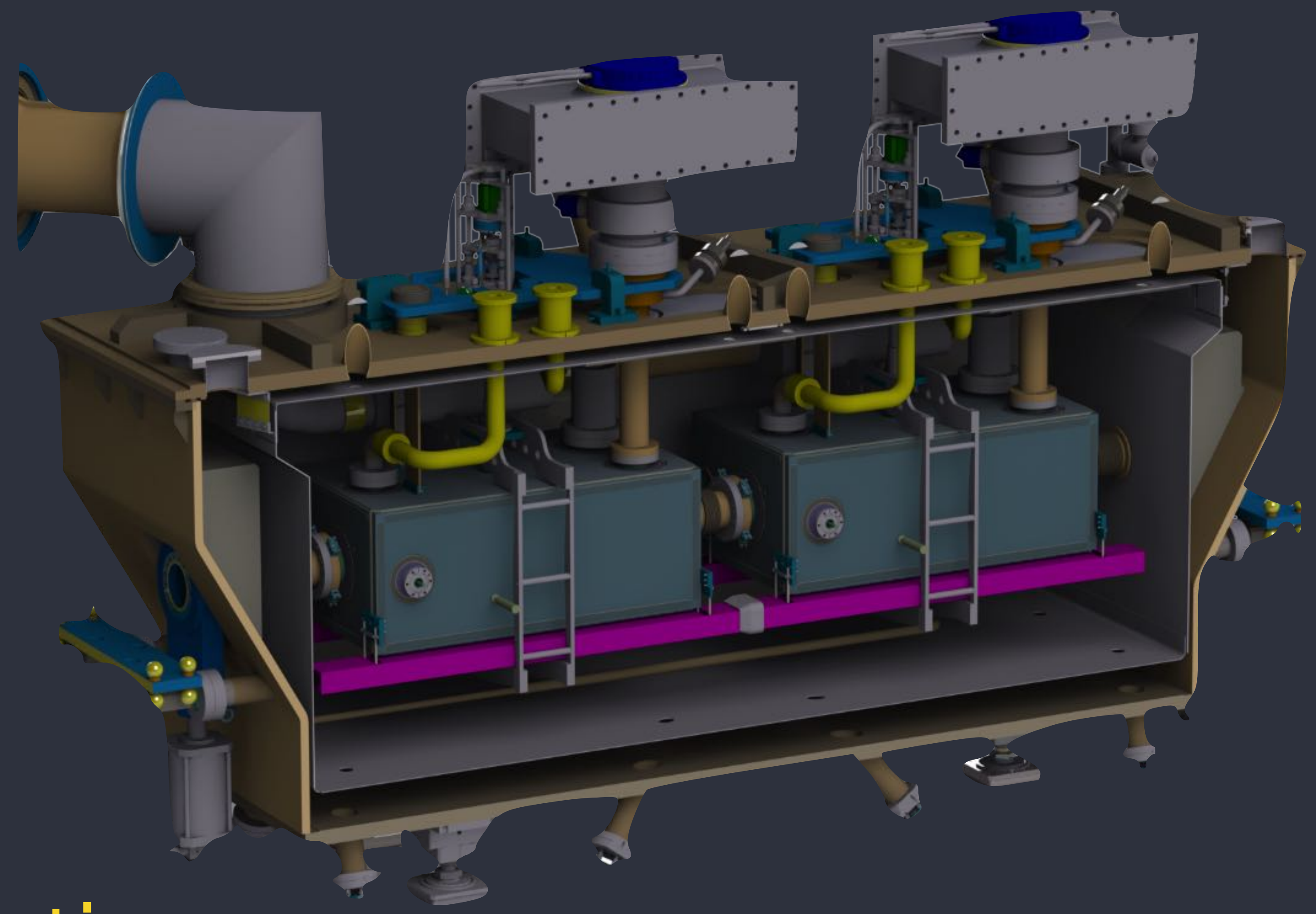
2 types of Crab cavities

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





RF Dipole
- Horizontal crossing for CMS
- SPS test in 2021

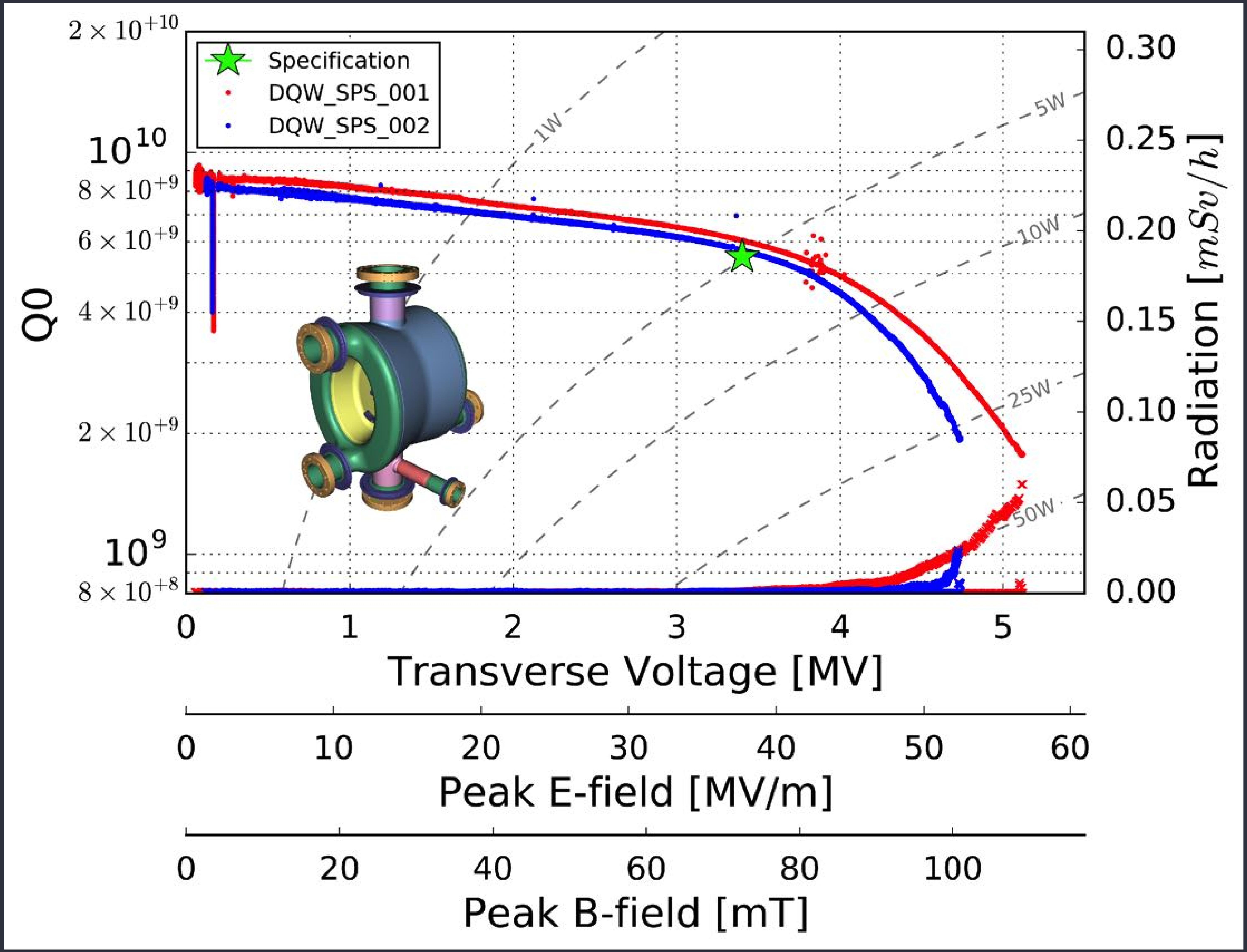


Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power (SPS)	40 kW

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

courtesy R. Calaga/O. Capatina

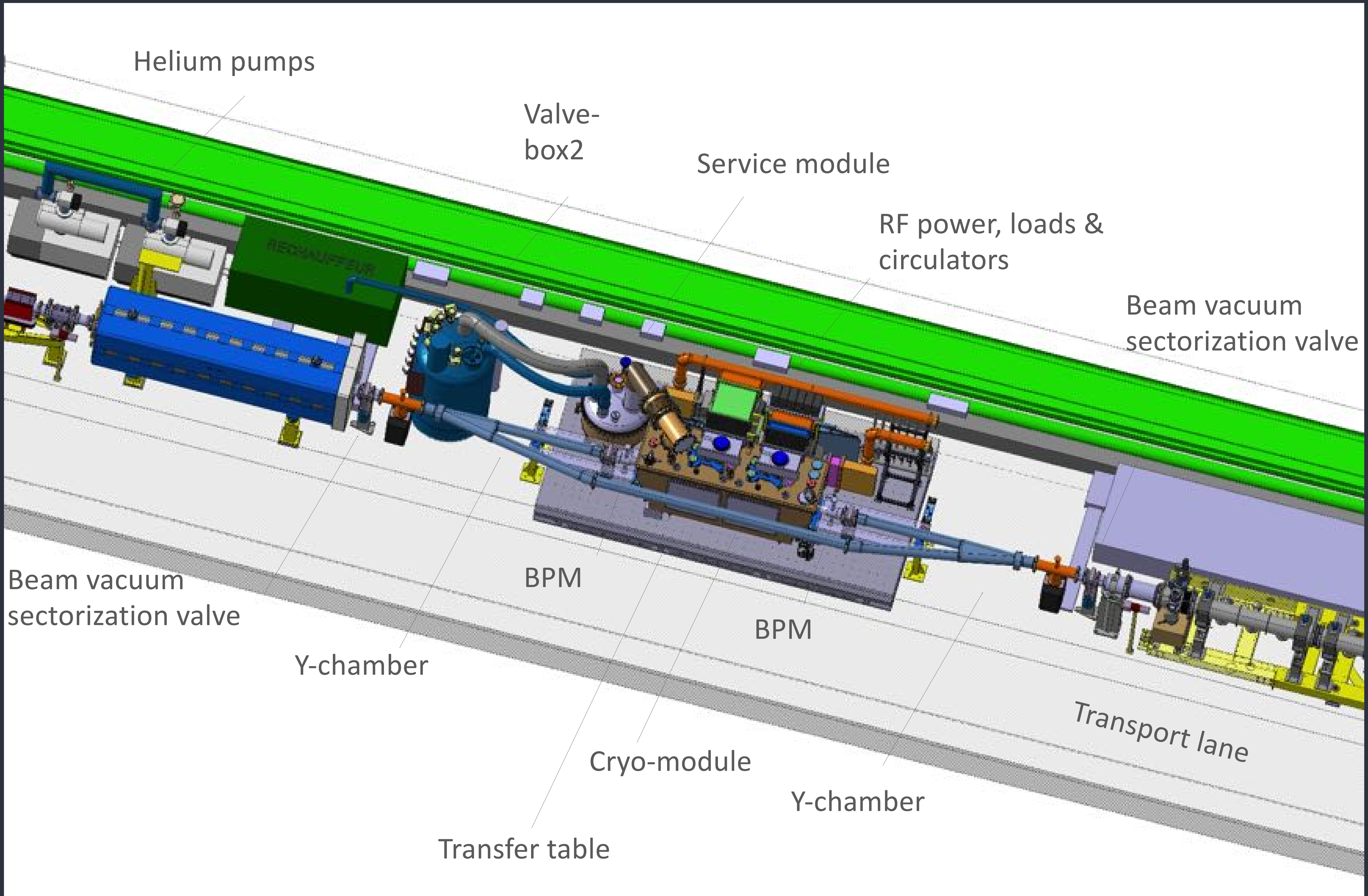
DQW cold test of bare cavities



A. Macpherson
Poster: 4LP5-17

courtesy A. Castilla/A. Macpherson

SPS test stand layout



- Moving table can move the cavity in/out of the SPS beam in ~10 min.
- Test stand is foreseen for DQW and RFD.
- In Nov 2015 CERN in-sourced the DQW production
- Test stand will remain as a unique SRF test stand with proton beams at CERN.

courtesy G. Vandoni

Crab cavities: timeline

Last test opportunity before launch of series:

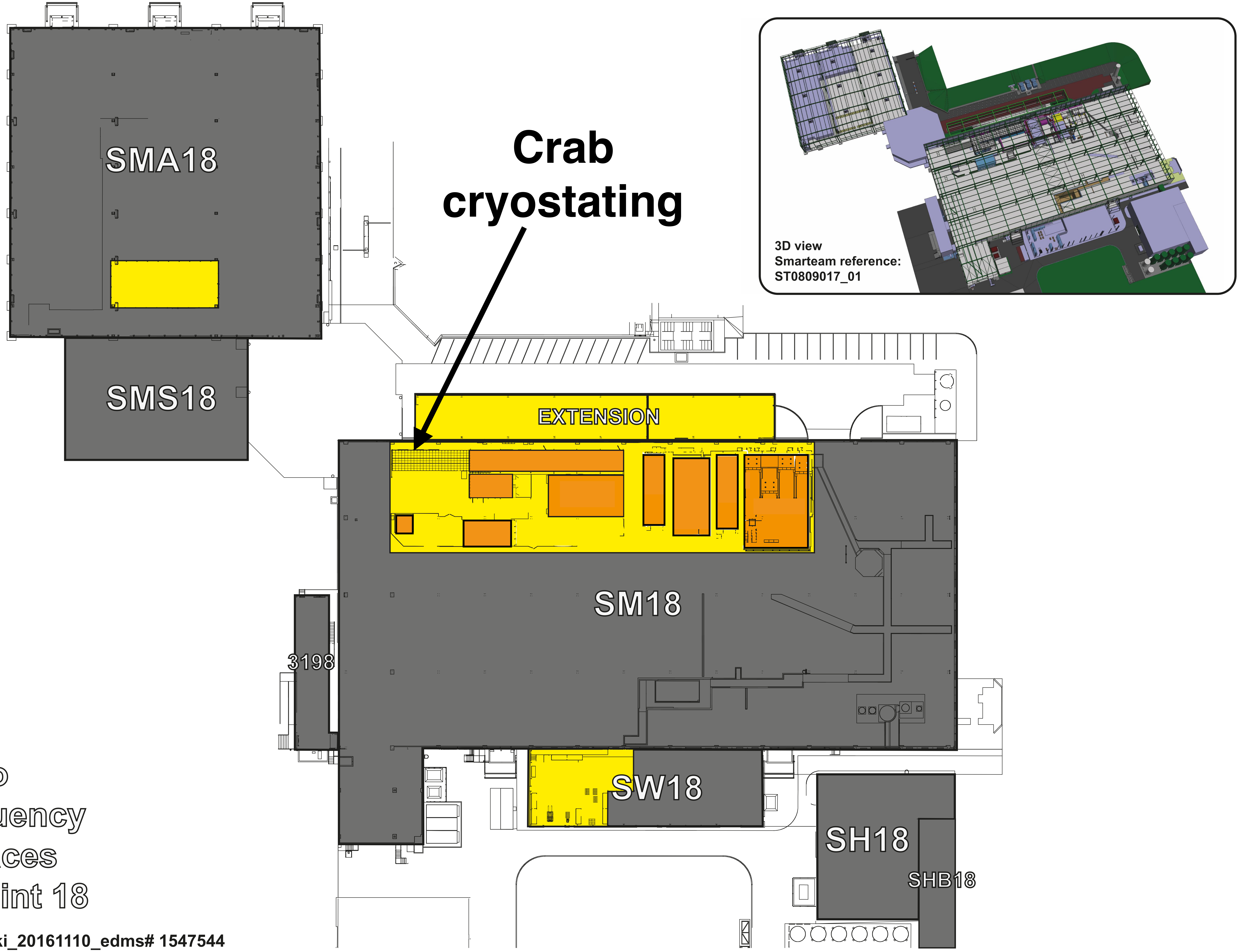
➡ First operation of crab cavities in high-current and high-energy proton machine. Mandatory test before LHC installation!

➡ Injection/capture/acceleration with crabs, can the cavities be made invincible for the beam (counter-phasing)?

➡ Precision control of voltage and phase for preservation of beam quality.

➡ Trip rate must not impact LHC availability.

➡ Emittance growth, machine protection, RF non-linearities, instabilities, ….



Radio Frequency Surfaces @ Point 18

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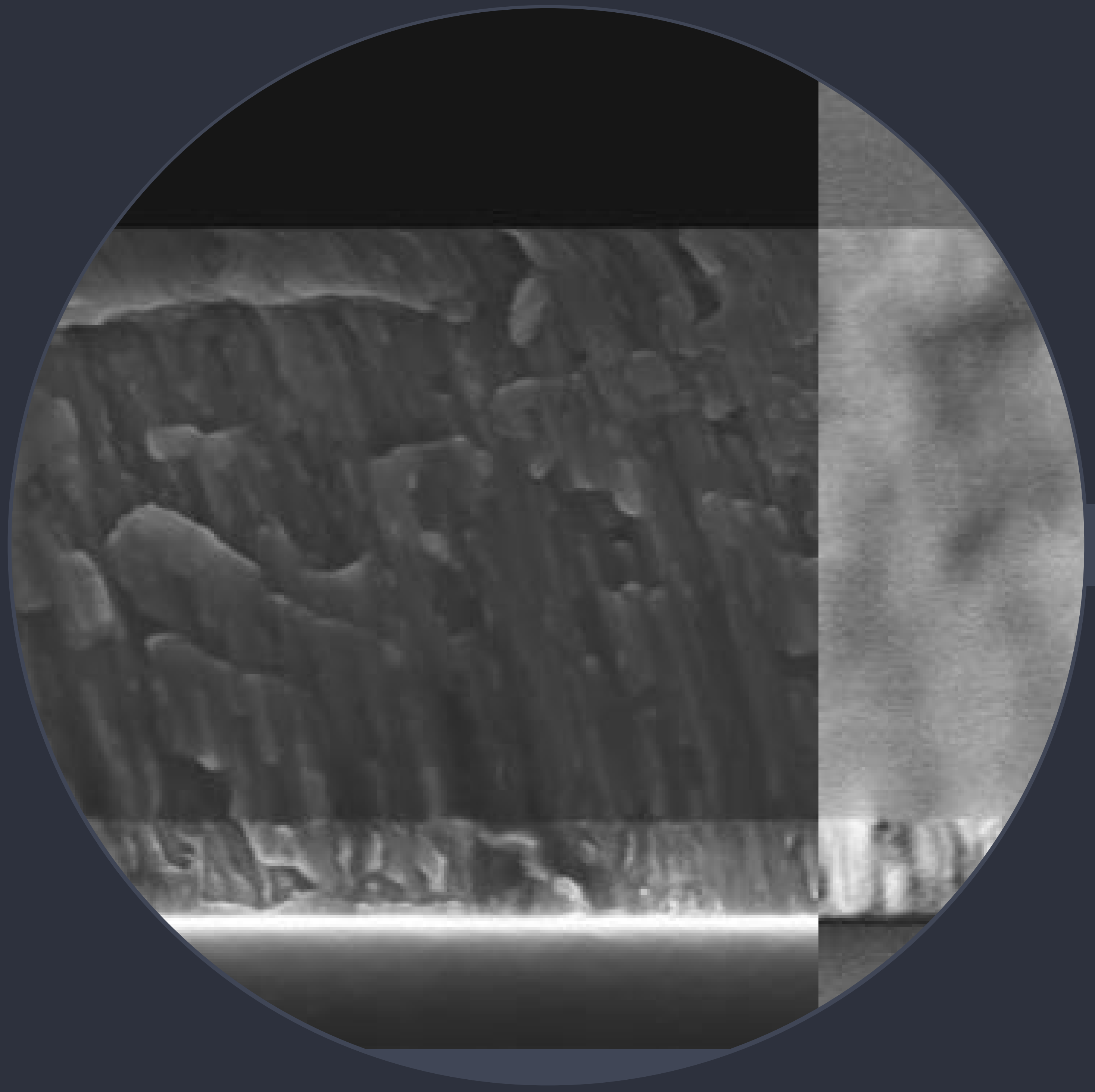
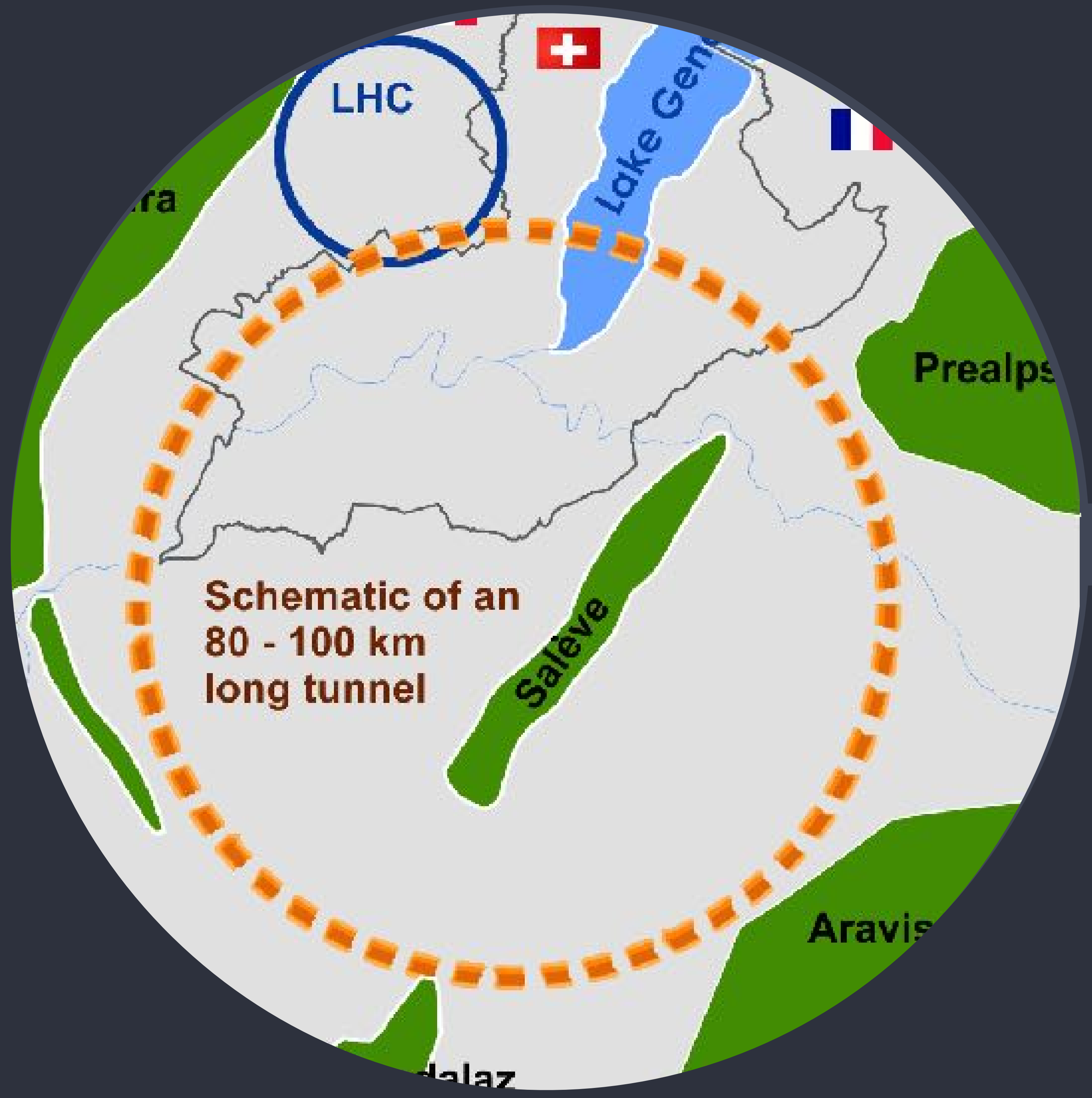


SRF R&D

some highlights



Future Circular Collider Study

selected highlights:

- Cavity development
- Thin film R&D
- Low-impedance Crab cavities
- etc.

courtesy O. Brunner

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 2-cell cavities (Z, hh)

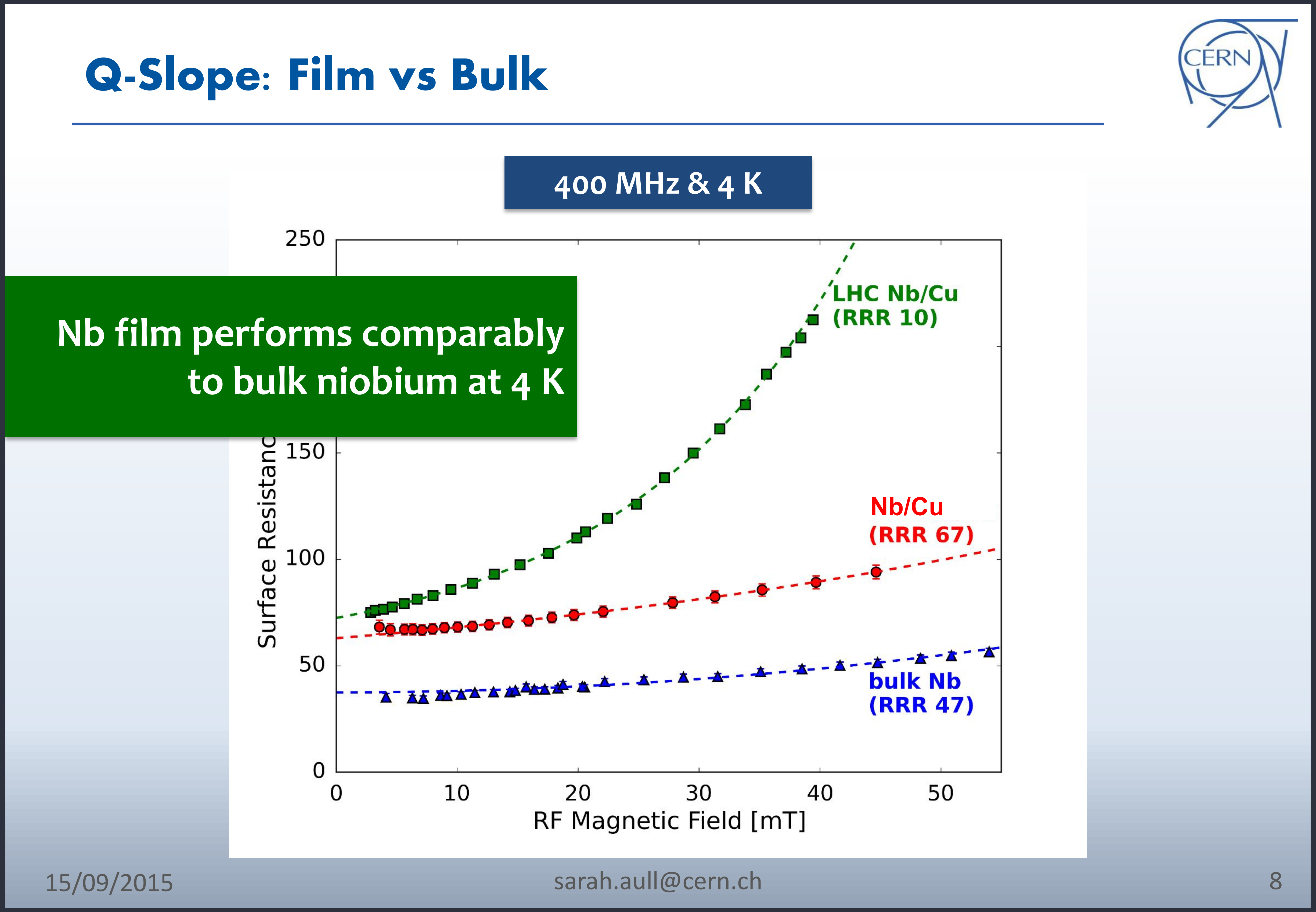
"high gradient" machine

H t

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

courtesy O. Brunner

Progress on coatings



Sarah Aull, SRF 2015

- **First Nb/Cu sample with a Q-slope comparable to bulk Nb** (ECR coating).
- Proof that the **potential of coatings is not yet fully exploited**.
- More statistics with samples and cavities needed to optimise coating process.

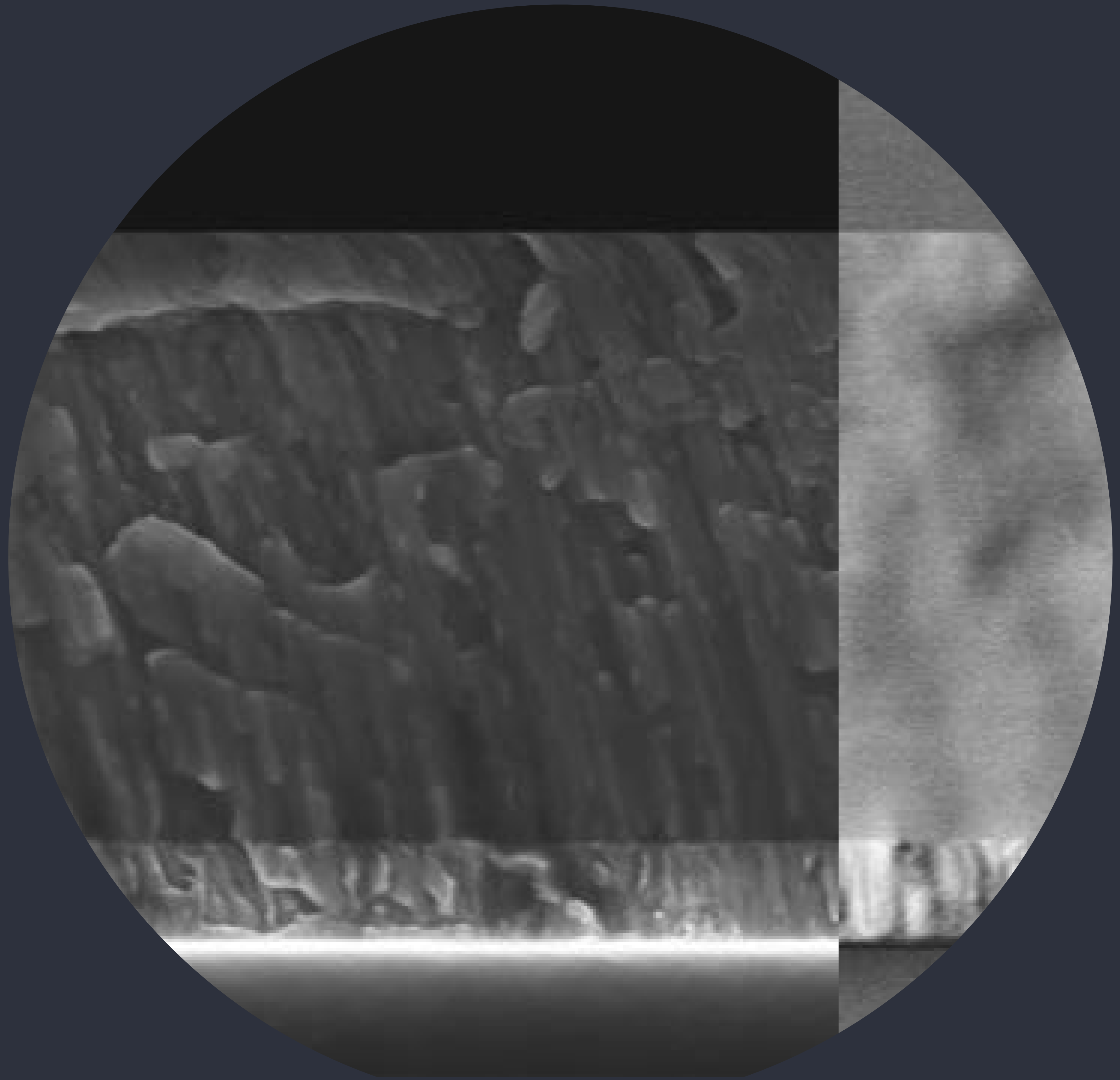
Coatings within FCC

- Diode coating with bias for HIE-ISOLDE
- Direct Current Magnetron Sputtering (DCMS) for LHC cavities.
- Improved method: Biased HiPIMS: High Power Impulse Magnetron Sputtering, more R&D needed.
- **HIPIMS coating: 10 single cell 1.3 GHz cavities (from LNL) are being prepared to test coatings with different HIPIMS parameters.**
- Upgrade of coating station (optimised for 400 MHz LHC single cell) to 800 MHz single and 2-cell.

G. Rosaz next talk

courtesy G. Rosaz, A. Sublet

Coatings within FCC



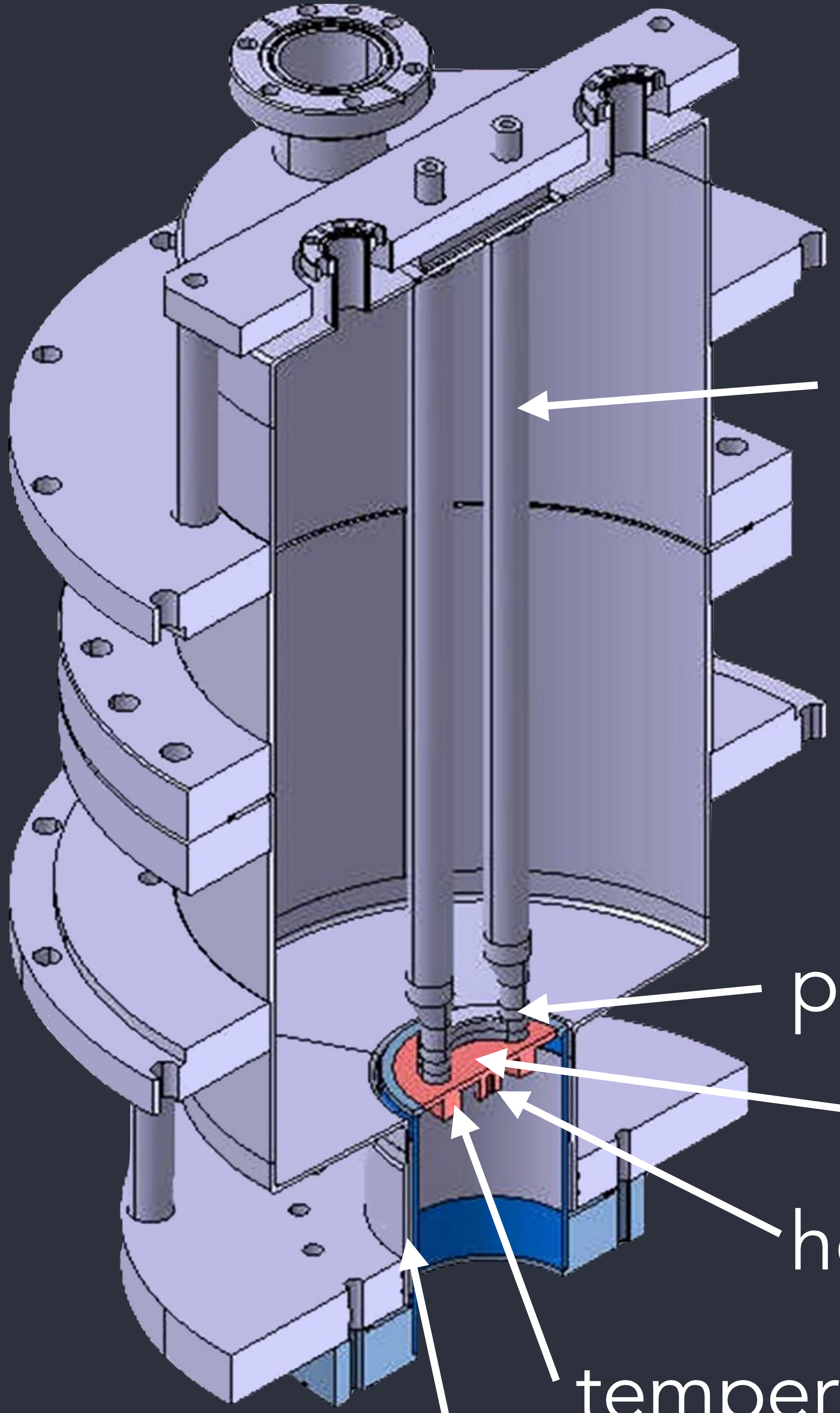
- **> 30 coatings on seamless 6 GHz cavities** at INFN, Italy.
- Microscopic and surface characterisation of samples at STFC (UK)
- **Longer term effort: A15 coatings**: Nb_3Sn at high-temperature (600-700 deg), annealed Cu, V_3Si with Ta diffusion barrier layer, so far: TC=12/12.5 K

G. Rosaz
next talk

courtesy G. Rosaz, A. Sublet

Quadrupole Resonator

our tool to qualify samples



courtesy V. Del Pozo Romano

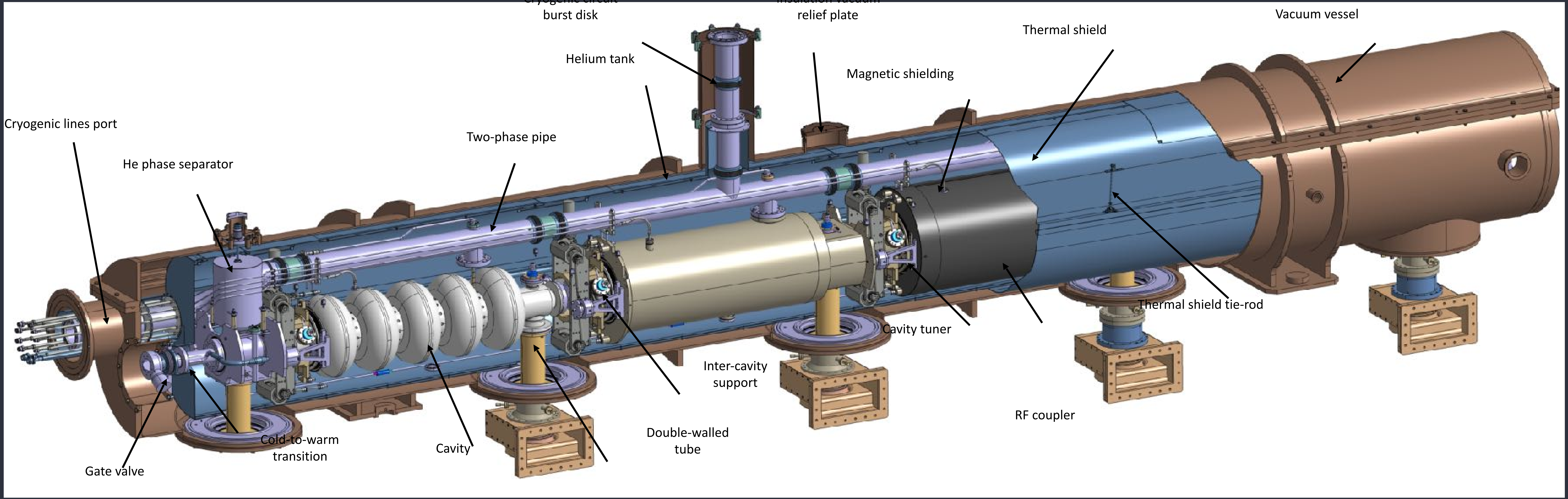
- Replacement of 20 year old QPR is under construction, ready in 2018.
- resonant frequencies: 400/800/1200 MHz
- pole shoes focus magnetic field on the sample
- thermally decoupled sample
- high-resolution calorimetric measurement of surface resistance

Bulk Nb

High Gradient Program

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

Four cavity cryomodule



Originally developed for a Superconducting Proton Linac at CERN, in collaboration with ESS and CNRS Orsay. Now proposed for the PERLE ERL facility at Orsay.
Most elements are ready, cryostating and cold testing in 2019/20.

courtesy V. Parma, L. Dassa

Innovations/developments

over almost 10 years

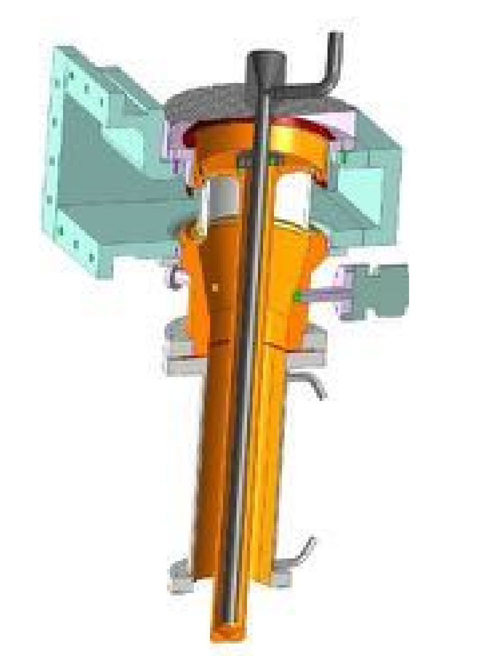
Successful development and application of **vertical Electropolishing**. Unique facility worldwide (Leonel Ferreira)

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

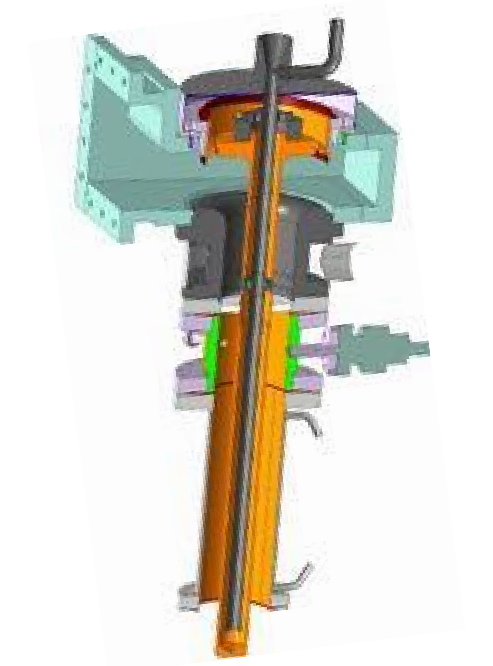
Optimised set-up for **High Pressure Water Rinsing** (A. Macpherson, K. Hernandez Chahin)

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

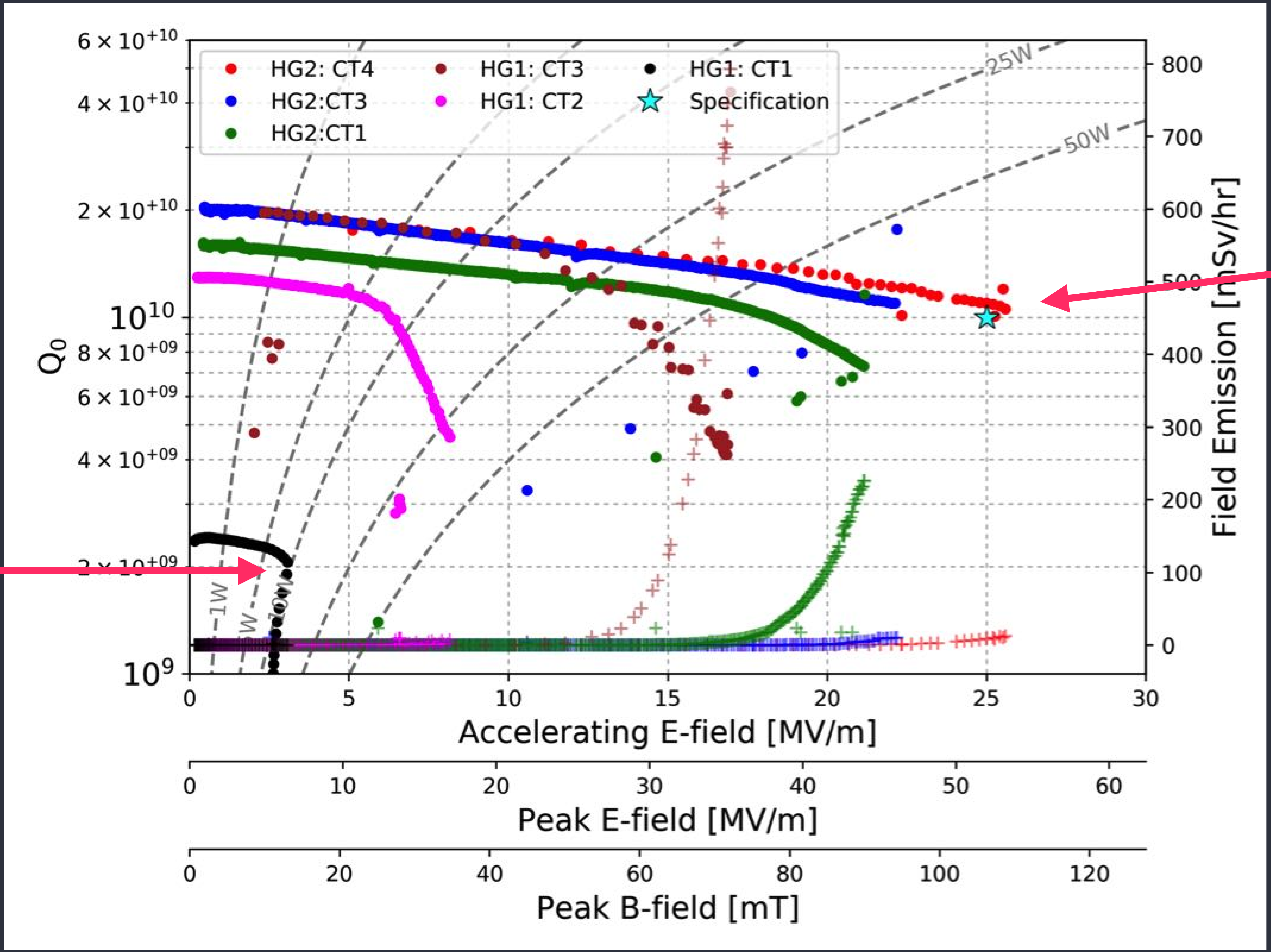


Disc type

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

Cold test results

Evolution over 10 separate cold tests



September 2014

May 2017

First cavity @25 MV/m with Q>10^{10}

A. Macpherson Poster: 4LP5-17

→ Bulk Nb testing re-established at CERN!

courtesy K. Turaj, A. Macpherson

Status & timeline

infrastructure upgrade

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
SM18 extension		definition,			Operation						
SRF operation			consolidation								
2002			refur	RATS			RATS + SRF activity				
864 coupler lab			refur	Operation							
HIE-ISOLDE	construction & commissioning			Operation (+ 5th module? REX SC front-end?)							
Crab Cavities		CM1 construction		SPS	CM2 construction		SPS				
						Series Production					
LHC spares	Design consolidation, prototyping					spare CM					
				8 spare cavities							
R&D	thin film coatings										
	QPR, coated crab, FCC, PERLE										

Summary

- During the last 5 years, the SRF infrastructure was updated to deal with HIE-ISOLDE, CRAB cavities, elliptical bulk Nb cavities & LHC cavities.
- This infrastructure will be consolidated over the next years to streamline assembly, maintenance, repair and testing for LHC, HIE, HL-LHC. LHC spare production and Crab cavities will be the main SRF projects until 2025.
- R&D focus is on coatings: extensive Nb on Cu R&D with a few towards FCC, 400/800 MHz.
- short to medium term: focus on HIPIMS Nb/Cu.
- long term: A15 coatings on Cu.
- Improved power couplers, aiming at 1 MW CW.

➜ After years of inactivity CERN SRF is again becoming “state of the art”