SRF technology for future CERN machines

Frank Gerigk, CERN, GARD-SRF Roadmap Workshop
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Material from:

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Content

LHC cavities

LHC spare cavity program

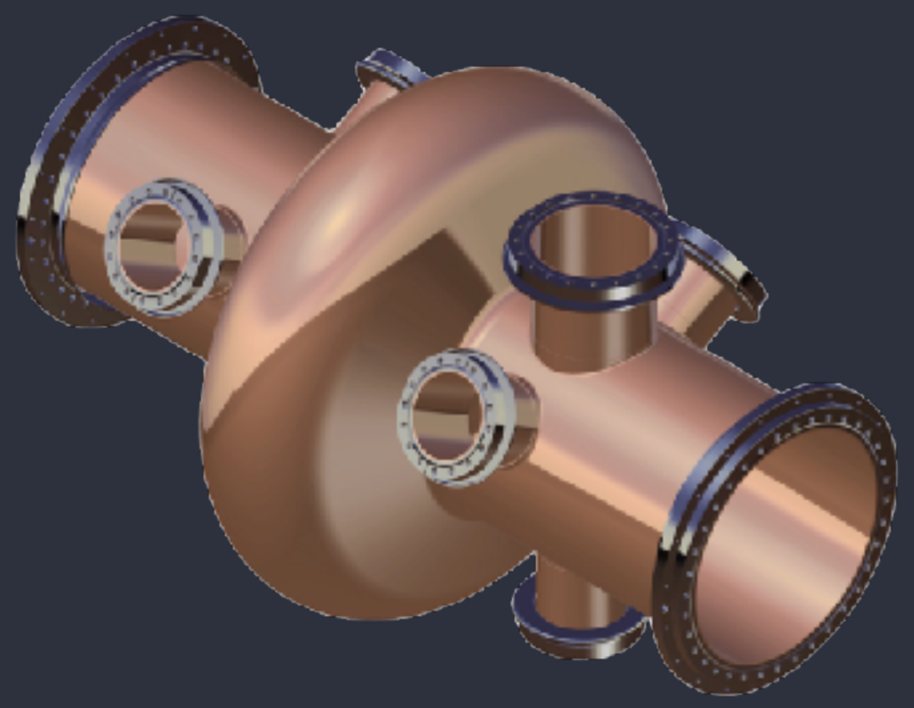
- NB-COATED Cu single cell cavities operating at 4.5 K.
- 400.790 MHz, 2 MV/cavity.
- 2 cryomodules of 4 cavities/beam.
- **1 spare module and one spare dressed cavity available. Many of the "old" experts have retired.**
- **LHC has a physics program until 2035 and we have no experience with ageing of LHC cryomodules.**

The LHC spare cavity program aims at producing 2 spare cavity trains (4 cavities), which may become potentially 2 complete cryomodules.

➡ re-establishment of engineering folder, welding, tuning, assembly, and coating procedures

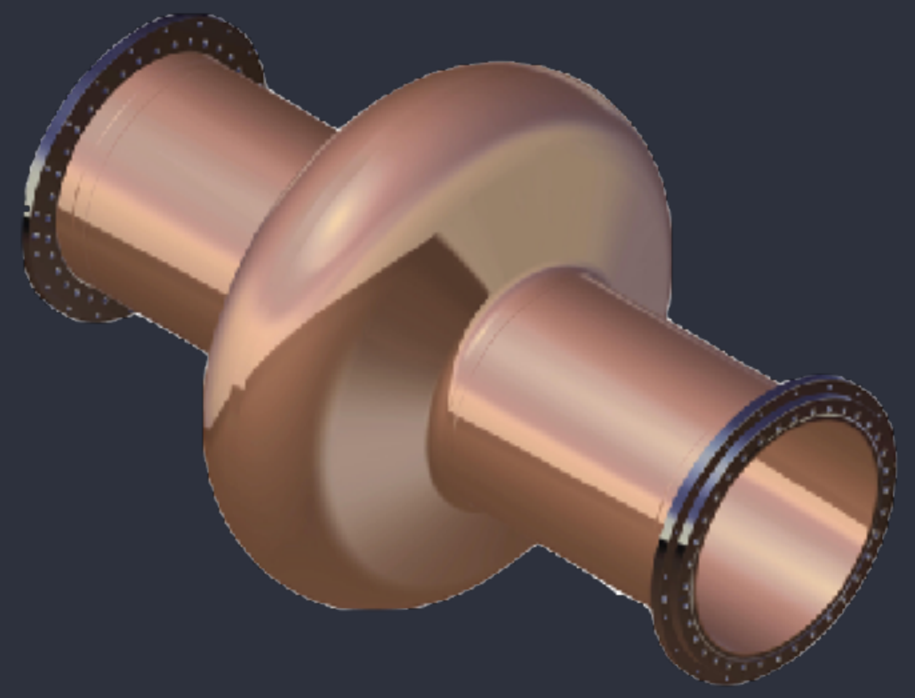
➡ industrial production of cavities and subsequent coating at CERN

LHC spare cavity program



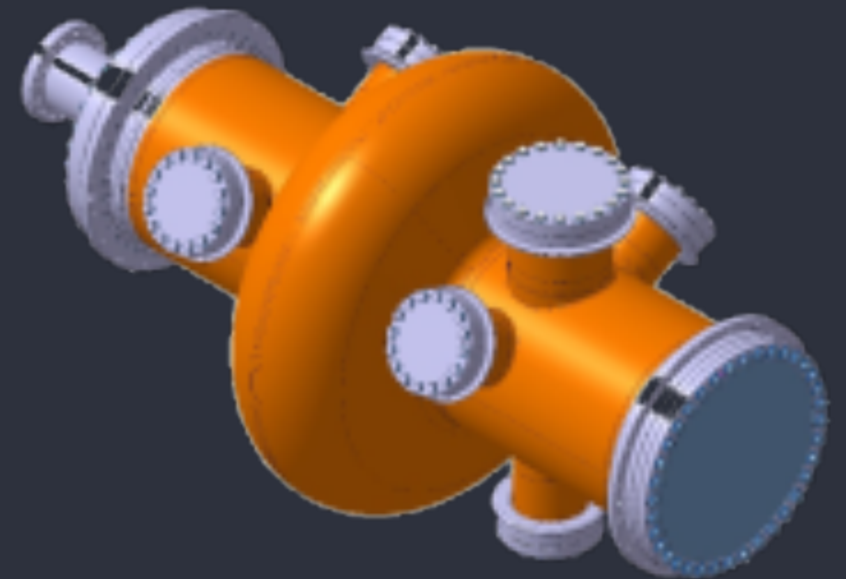
Practice cavity 1,2

- full cut-off tubes,
- cavity fabrication tools & process,
- rinsing, chemistry
- Nb-coating (magnetron sputtering),
- qualification & cold tests
- several re-coatings
- not intended as spare



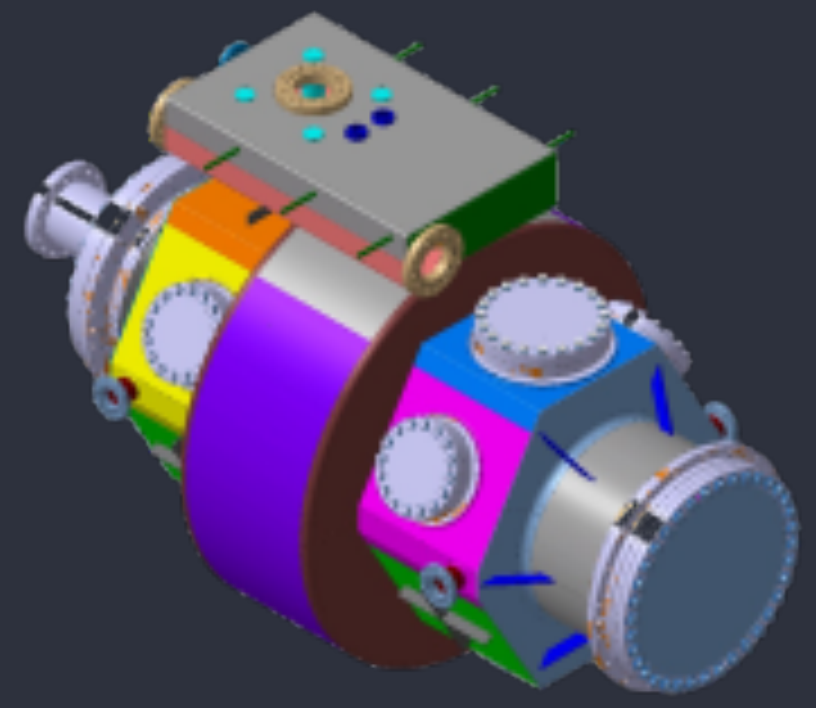
Practice cavity 3,5

- half cells by spinning and electro-hydraulic forming (EHF),
- simplified cut-off tubes,
- cold tests in May/July 2017
- not intended as spare



Model cavity

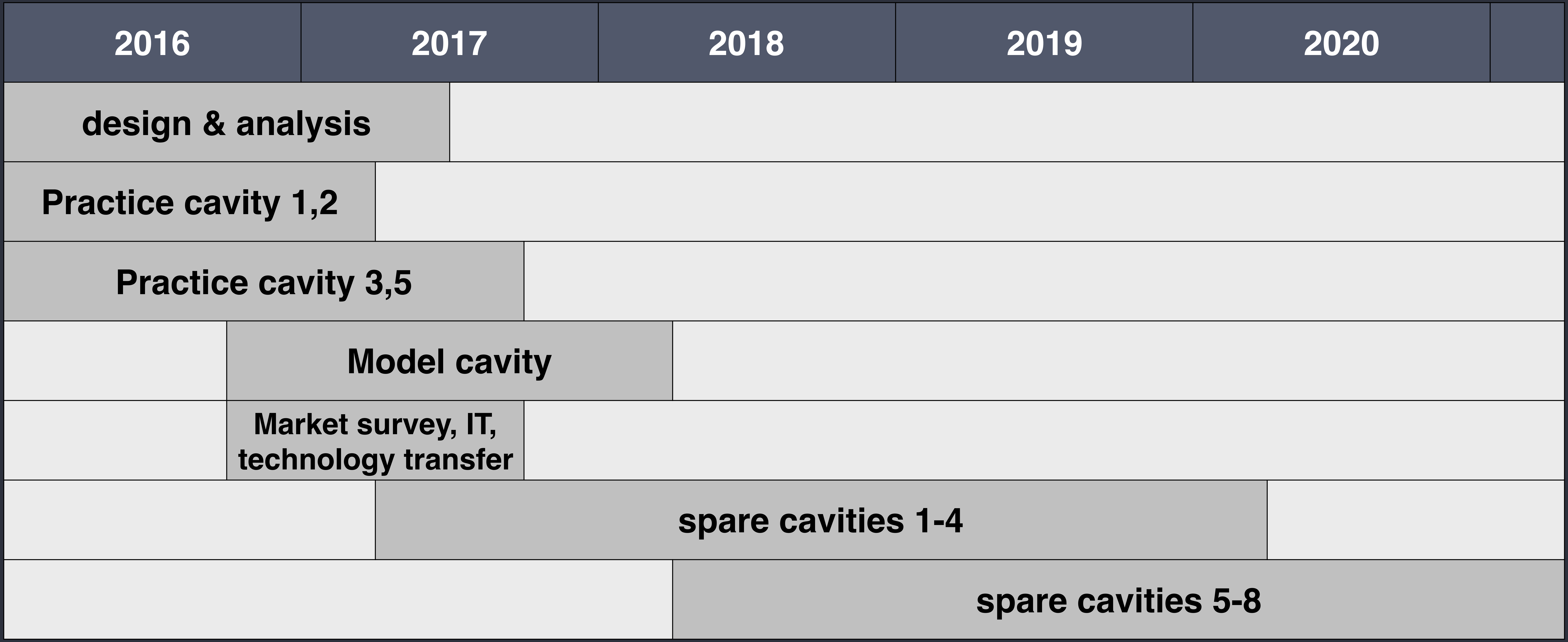
- validation of cavity design & fabrication process
- He-tank updated design,
- cold test expected August 2017
- if successful: the first spare cavity



Series production

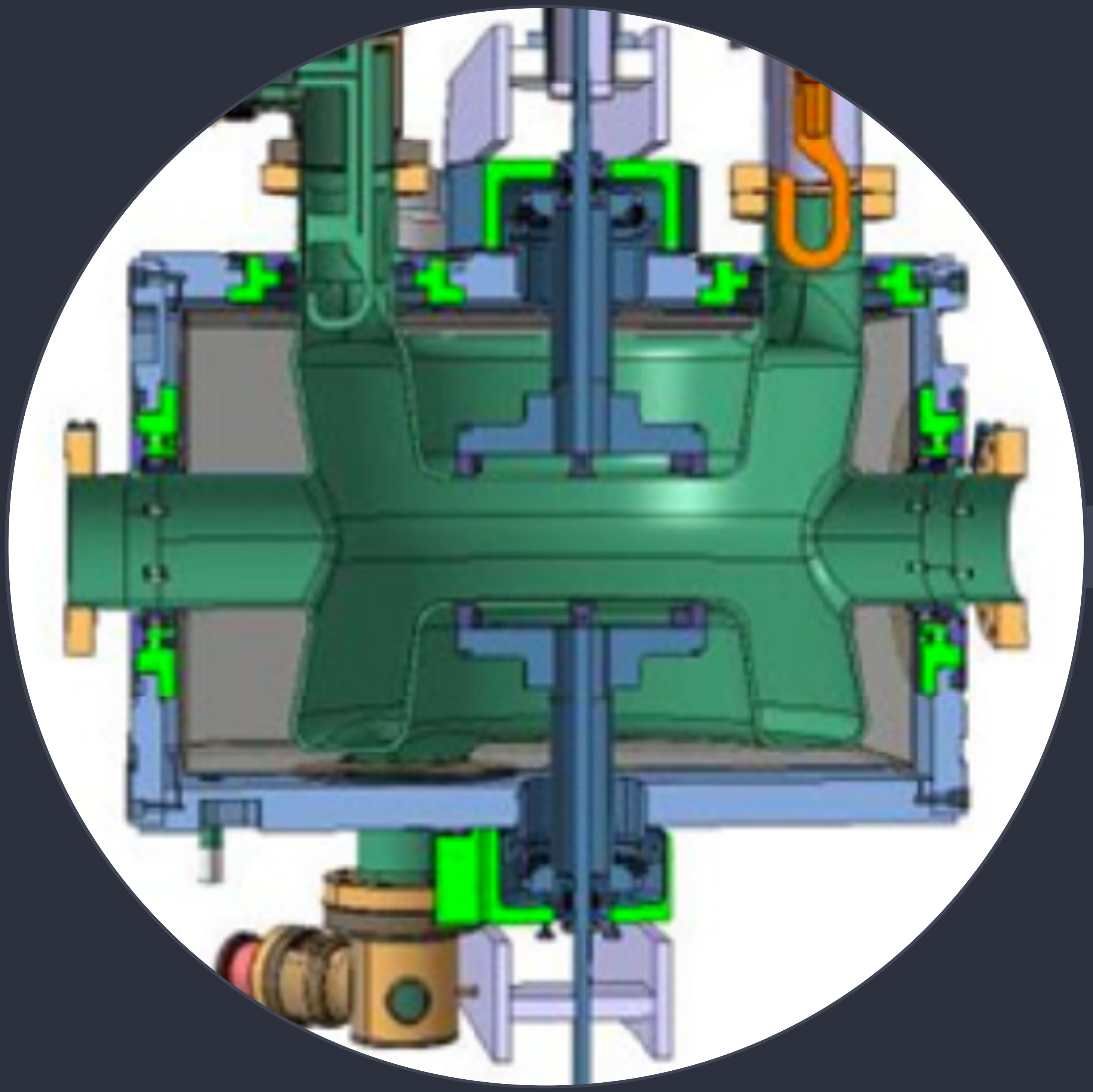
- 8 cavities + 2 spares,
- tendering for cut-off tubes early 2017,
- production of half cells (spun or EHF)
- He-tanks tendering in 2017

LHC spares: timeline



Technology dev. / R&D

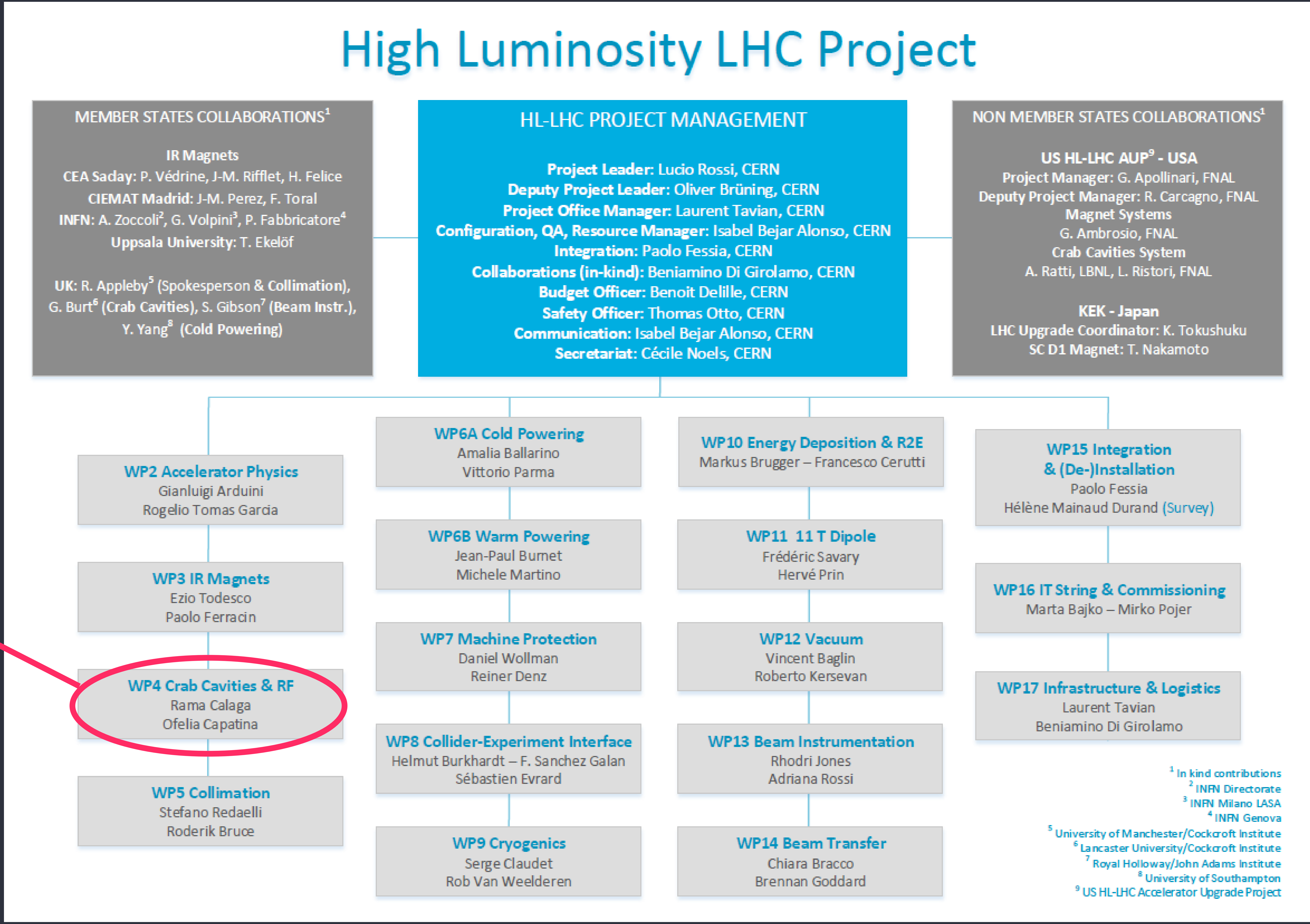
- Don't change a working system…
- Trying to replicate the original design as good as possible (with very little documentation). Only then do we get derogation from the pressure vessel tests…
- Reverse engineering effort.
- Inside welding no longer feasible, now welding from the outside.
- Calculations on material stresses, which were not possible in the original design stage.
- 40 companies contacted in market survey for cut-off tubes and potentially cavity welding: 2 replied.
- Quality of coating to be re-established.
- Tuning machine corroded in the fields. New machine to be developed.
- Using spinning or electro-hydro-forming (originals were spun).



High-luminosity LHC

the largest HEP accelerator in construction (1.2 km of LHC!)

The SRF part…



High Luminosity LHC Project
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CIEMAT Madrid: J-M. Perez, F. Toral
INFN: A. Zoccoli2, G. Volpini3, P. Fabbricatore4
Uppsala University: T. Ekelöf
UK: R. Appleby5 (Spokesperson & Collimation),
G. Burt6 (Crab Cavities), S. Gibson7 (Beam Instr.),
Y. Yang8 (Cold Powering)
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Deputy Project Leader: Oliver Brüning, CERN
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WP4 Crab Cavities & RF
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WP5 Collimation
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WP6A Cold Powering
Amalia Ballarino
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WP6B Warm Powering
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WP8 Collider-Experiment Interface
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WP9 Cryogenics
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WP10 Energy Deposition & R2E
Markus Brugger – Francesco Cerutti
WP11 11 T Dipole
Frédéric Savary
Hervé Prin
WP12 Vacuum
Vincent Baglin
Roberto Kersevan
WP13 Beam Instrumentation
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WP14 Beam Transfer
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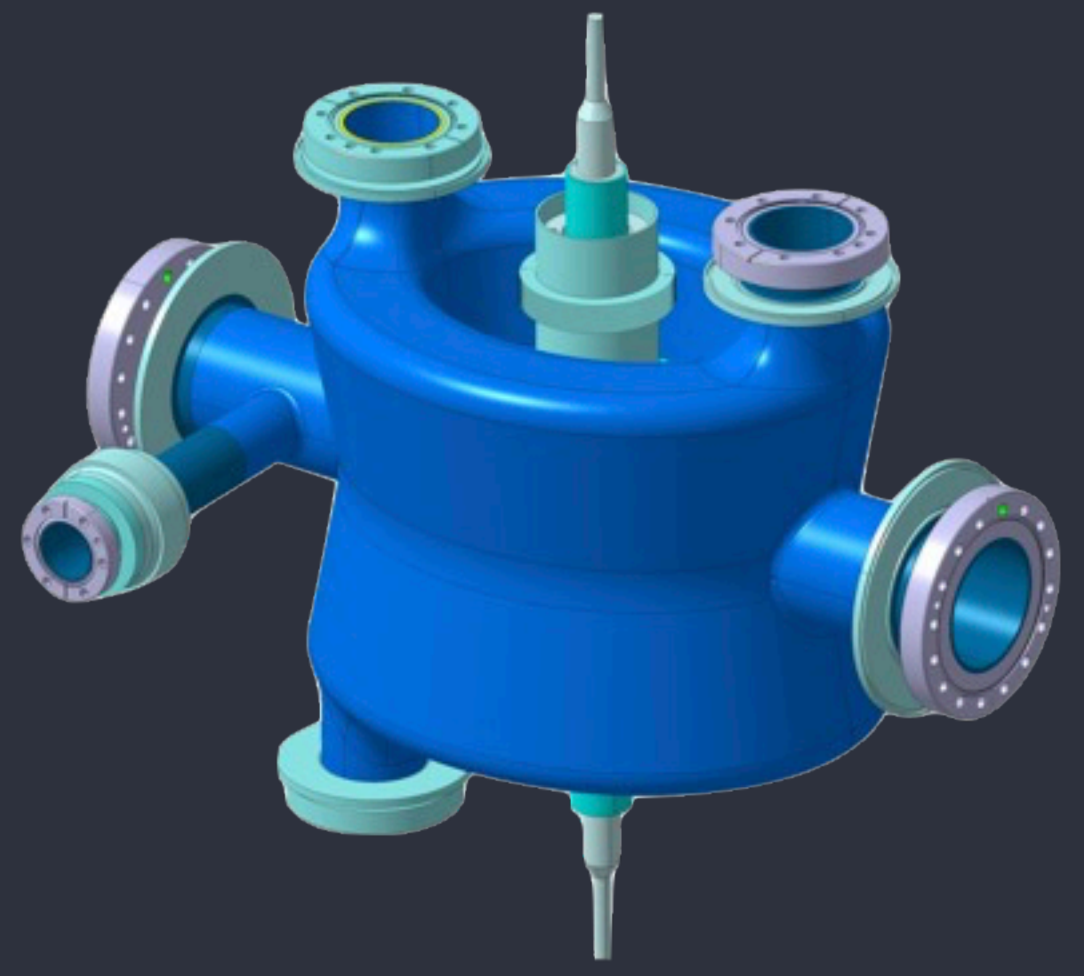
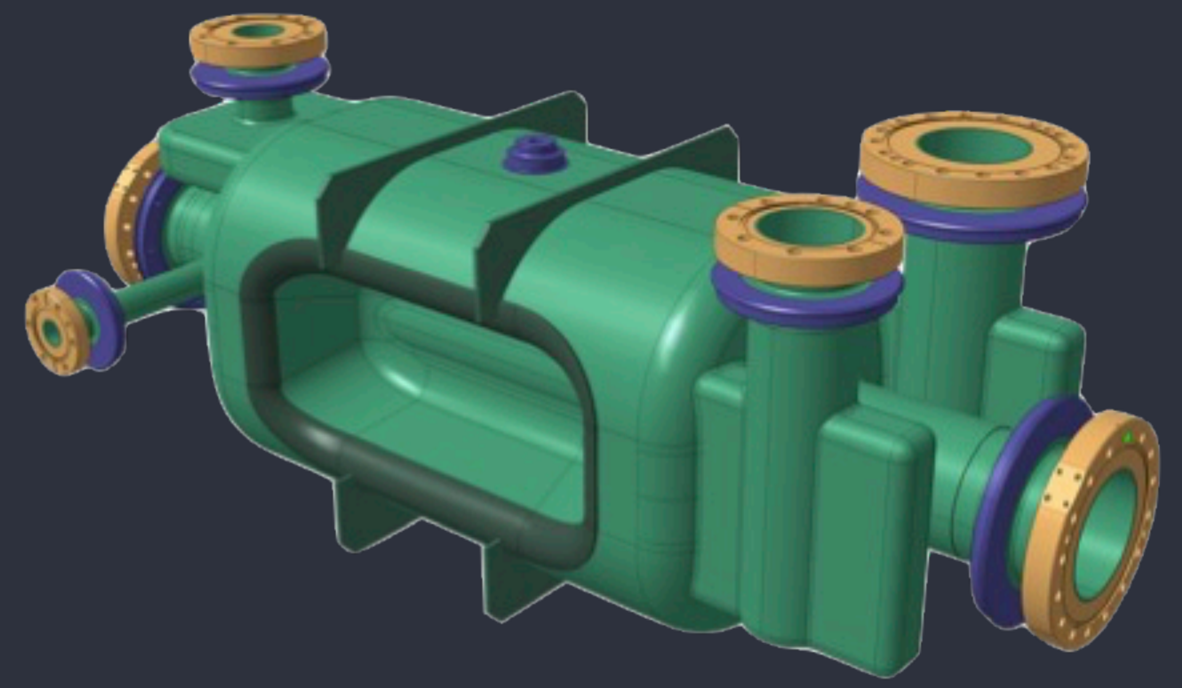
WP15 Integration
& (De-)Installation
Paolo Fessia
Hélène Mainaud Durand (Survey)
WP16 IT String & Commissioning
Marta Bajko – Mirko Pojer
WP17 Infrastructure & Logistics
Laurent Tavian
Beniamino Di Girolamo
1 In kind contributions
2 INFN Directorate
3 INFN Milano LASA
4 INFN Genova
5 University of Manchester/Cockcroft Institute
6 Lancaster University/Cockcroft Institute
7 Royal Holloway/John Adams Institute
8 University of Southampton
9 US HL-LHC Accelerator Upgrade Project

2 types of Crab cavities

Double Quarter Wave



RF Dipole

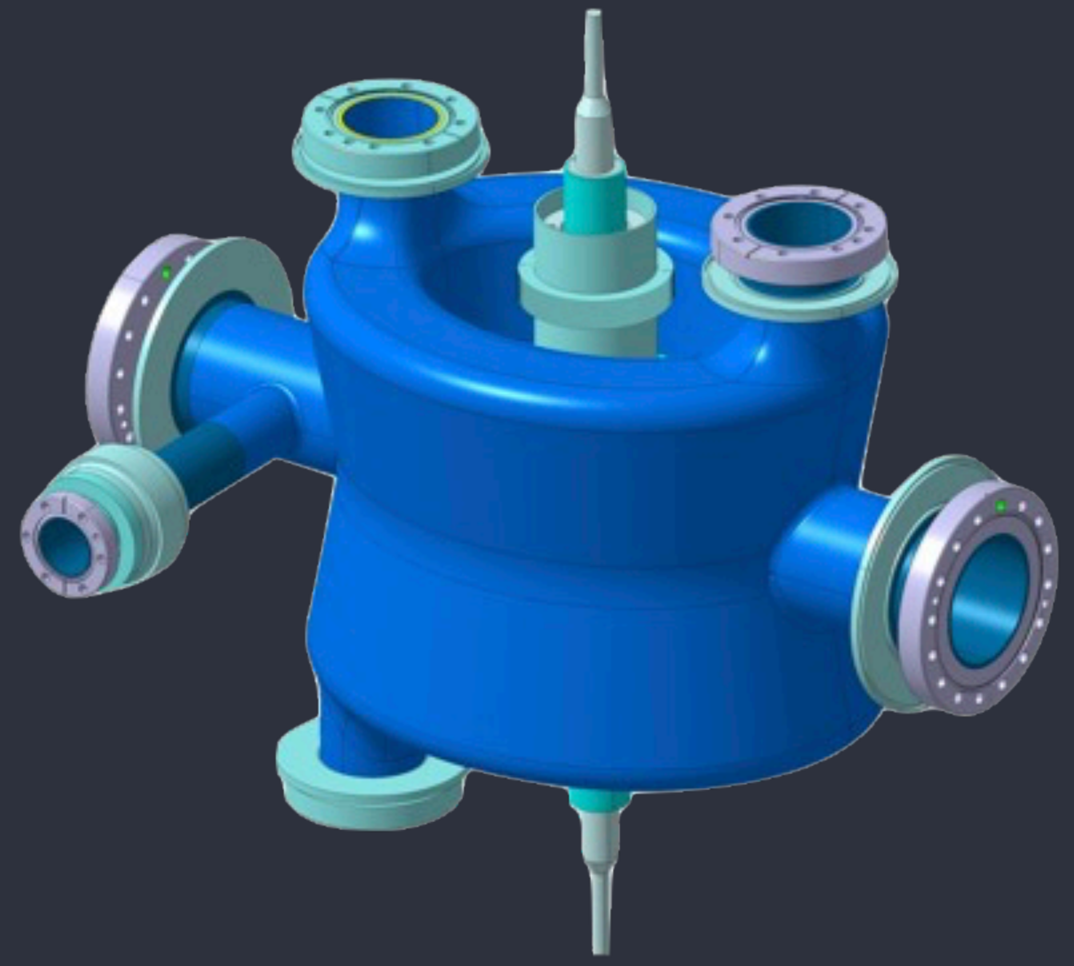


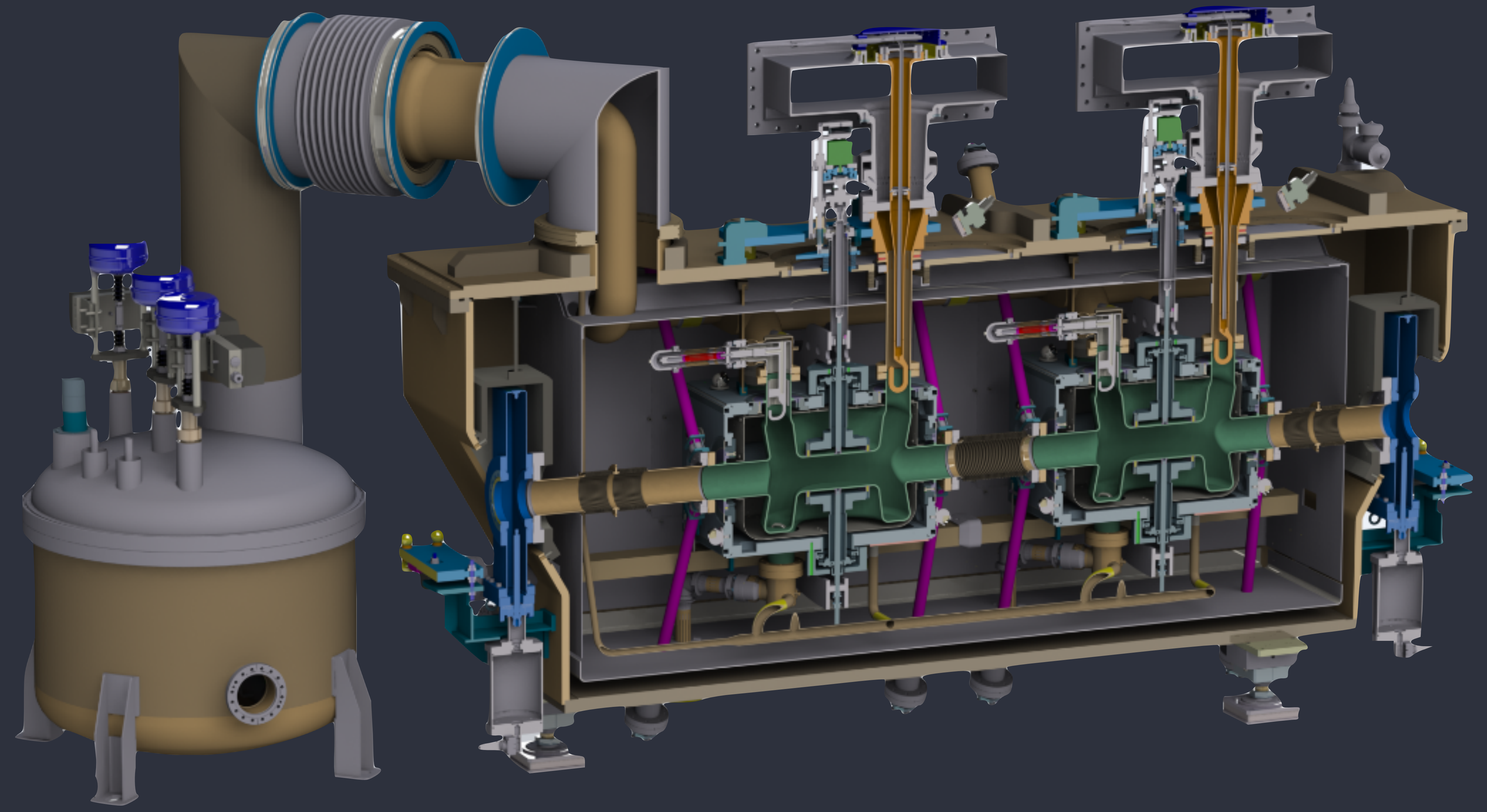
Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power	40 kW

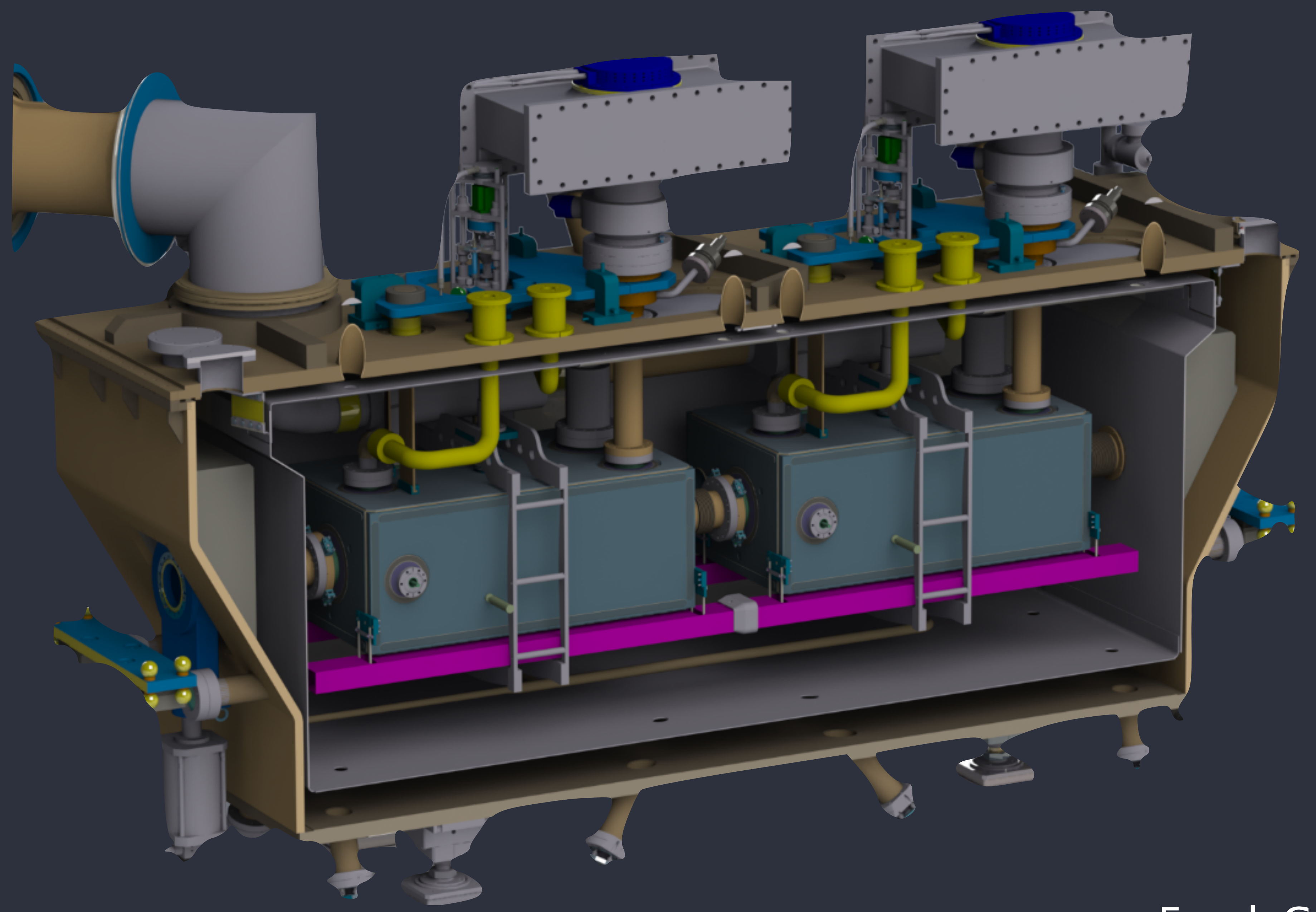
➡ 2 cavities/beam/IP side
➡ for ATLAS and CMS
➡ 16 cavities/8 CMs in total

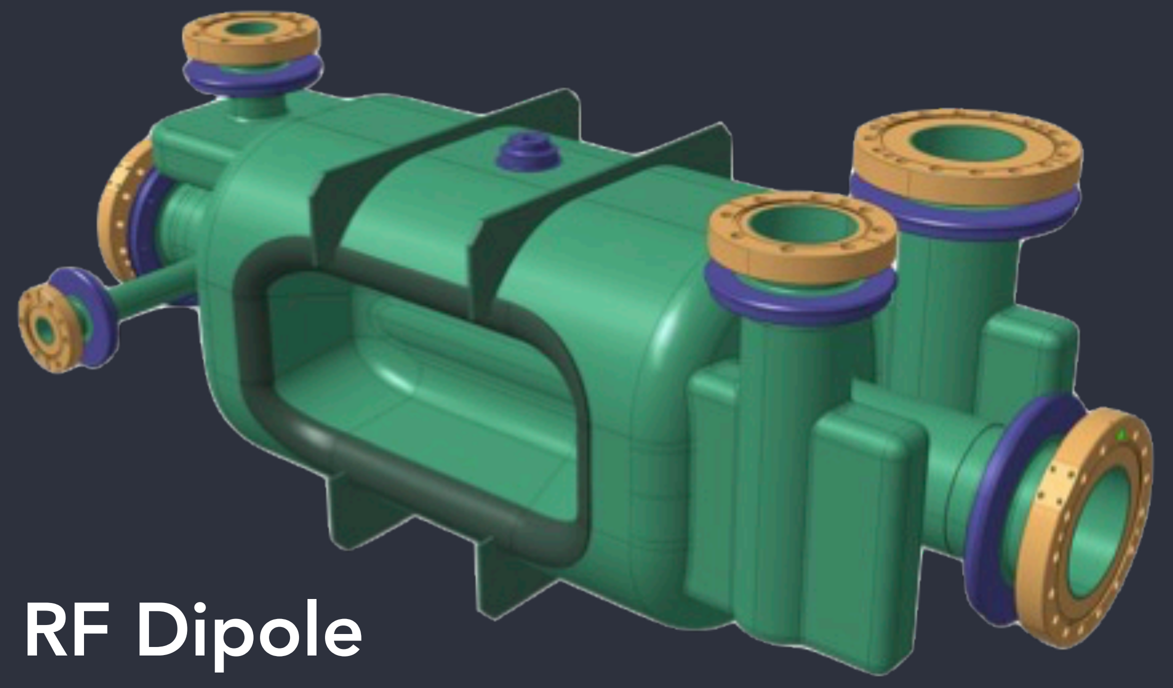
2 types of Crab cavities

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



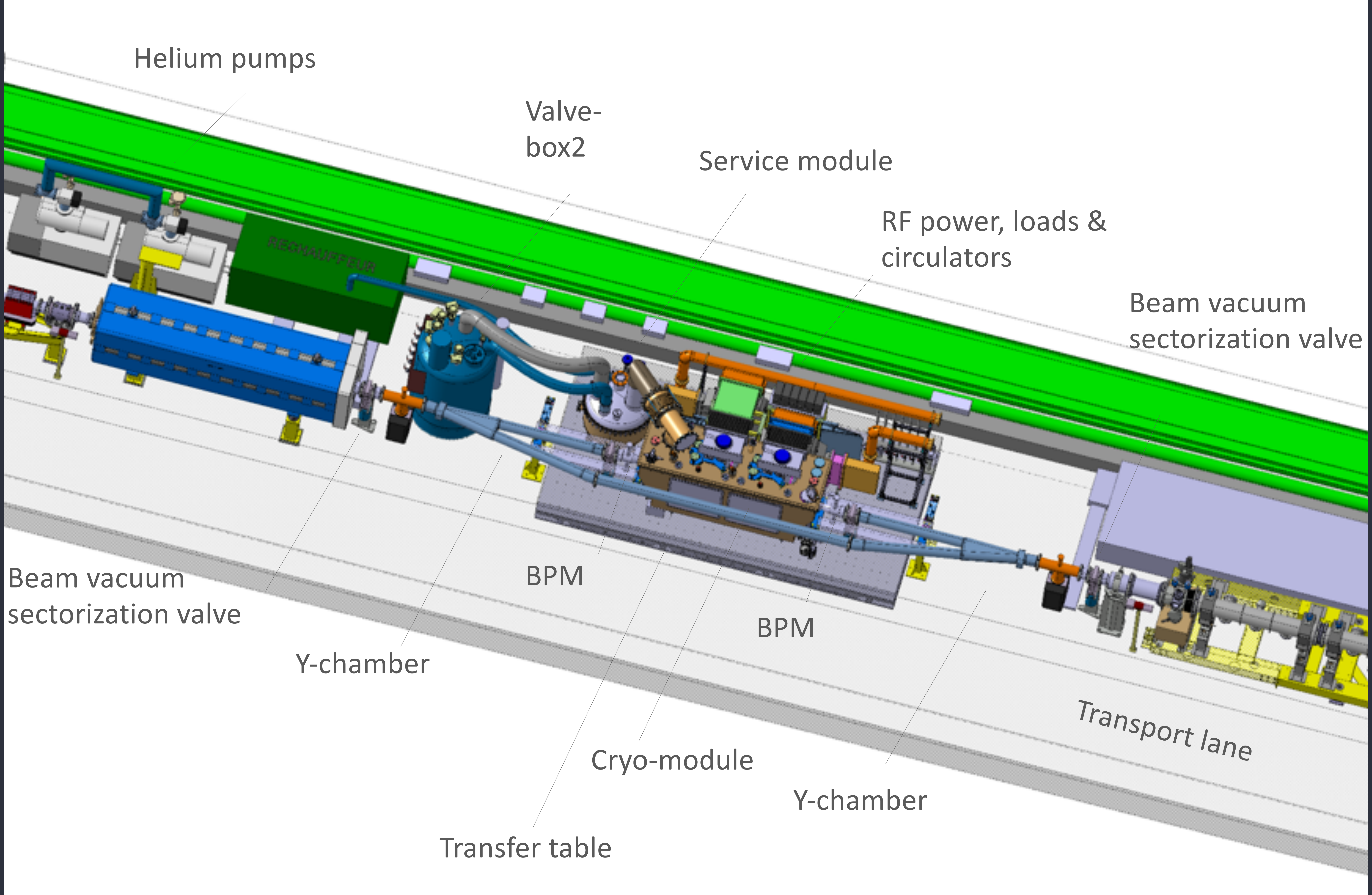






RF Dipole
- Horizontal crossing for CMS
- SPS test in 2021

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.

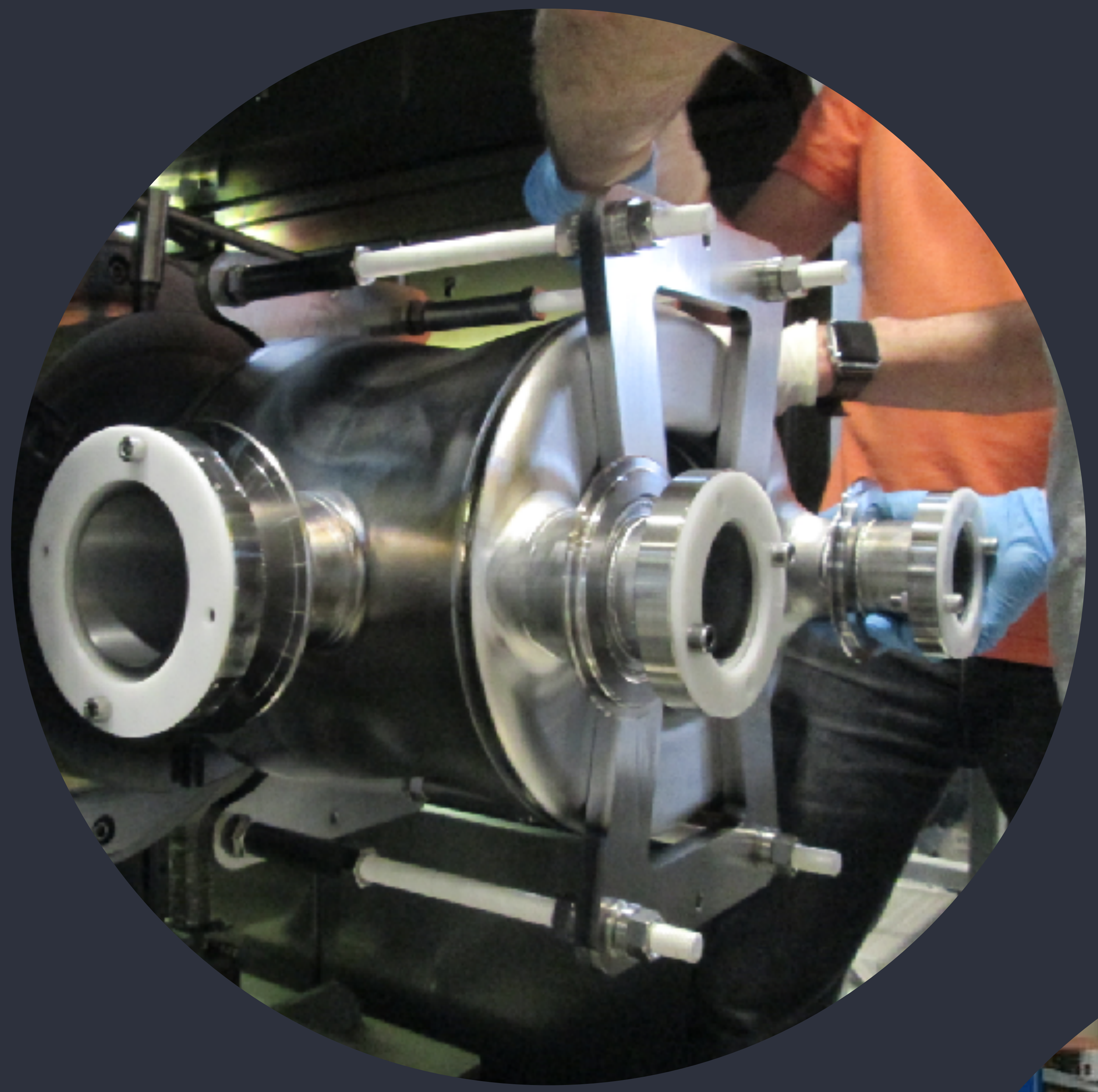
Crab cavities: timeline

Last test opportunity before launch of series:

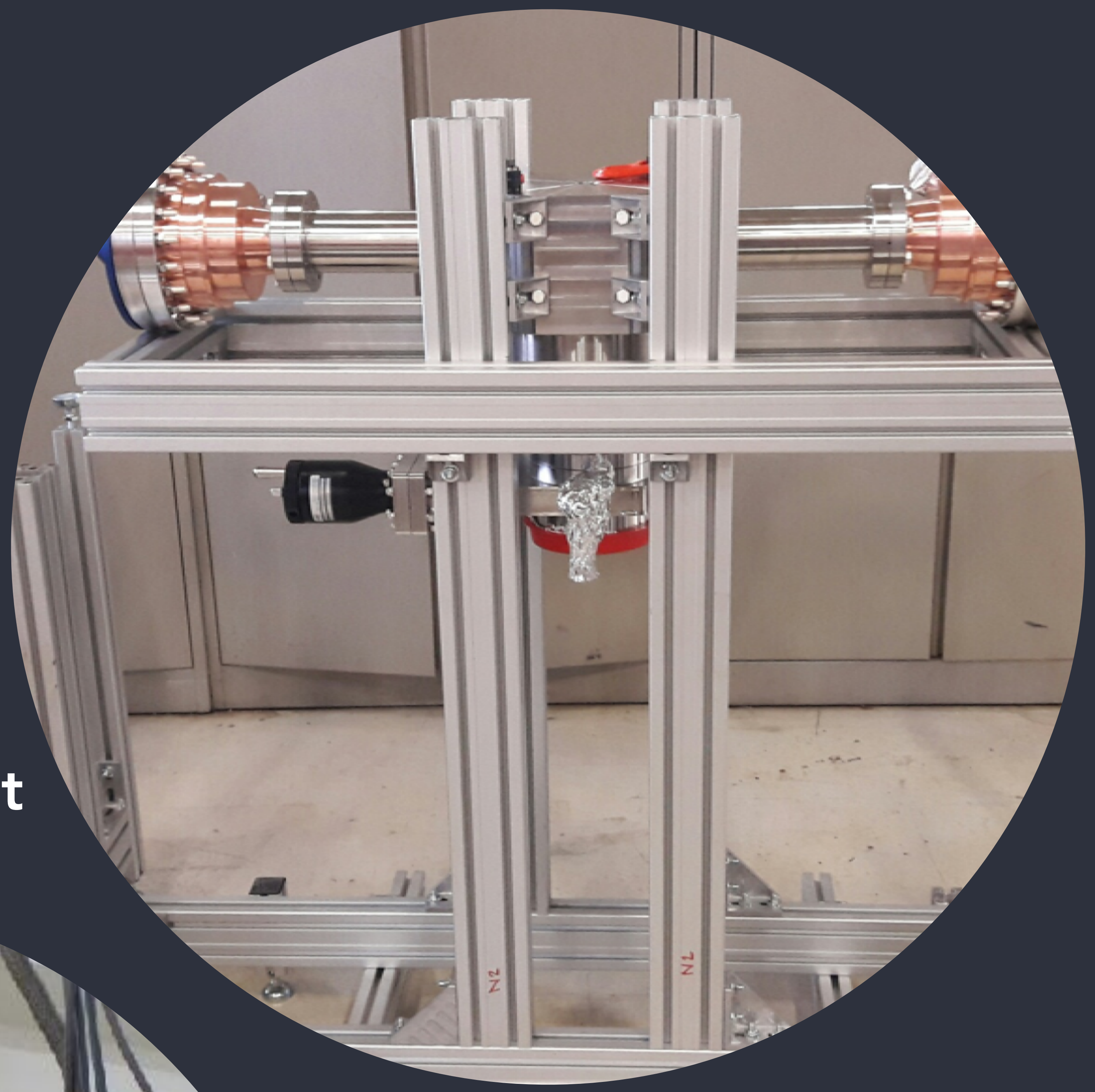
- ➡ First operation of crab cavities in high-current and high-energy proton machine. Mandatory test before LHC installation!
- ➡ Injection/capture/acceleration with crabs, can the cavities be made invincible for the beam (counter-phasing)?
- ➡ Precision control of voltage and phase for preservation of beam quality.
- ➡ Trip rate must not impact LHC availability.
- ➡ Emittance growth, machine protection, RF non-linearities, instabilities, ….

Recent progress

Final weld on DQW #1



Power coupler test box

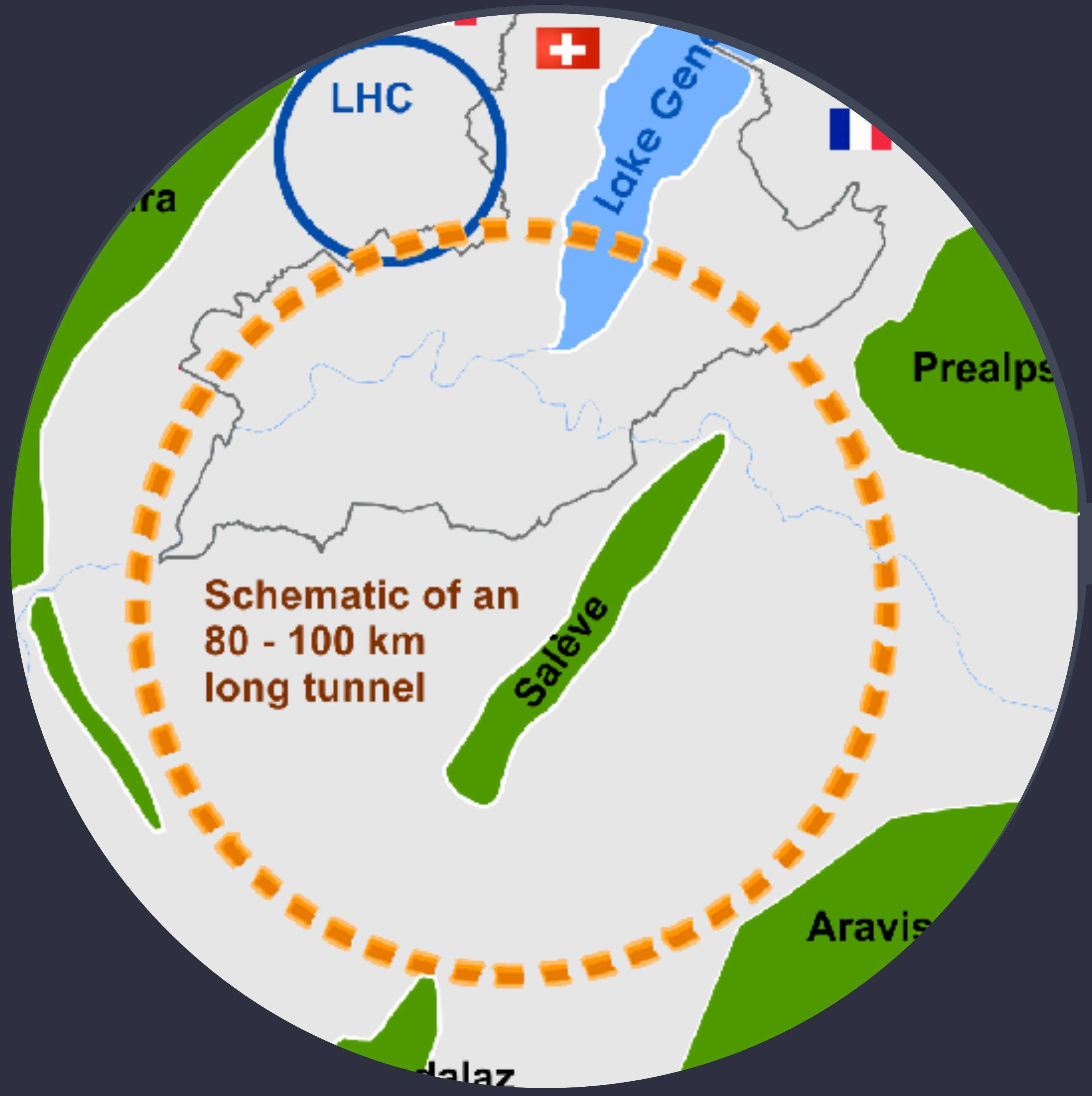


Frequency tuning successful

He-tank thermal shock test

Technology dev. / R&D

- Bulk 400 MHz Nb crab cavities & their cryomodules.
- Power couplers, HOM couplers, cavity control, operation with high-energy proton beam.
- Low trip rate mandatory!
- Industrialisation for small series (8 cavities intended from the US, 8 to be tendered by CERN).



Future Circular Collider Study

- CDR until 2019,
- In 2020 assessment by the European Strategy Group on the future physics roadmap.
- FCC-ee as potential first step
- FCC-he as option
- FCC-hh 100 TeV pp in 100 km
- Potential construction: 2025-2035

FCC options

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	**0.032**

timeline: Z → W → H → t → FCC-hh

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	**0.032**

timeline: **Z** → **W** → **H** → **t** → **FCC-hh**

"high gradient" machine

cavity options (per beam)

parameter	FCC-ee								FCC-hh
physics	**Z**		**W**		**H**		**t**		**hh**
RF voltage [GV]	0.4	0.2	0.8		3.0		10		0.32
Energy loss/turn [GeV]	0.03		0.33		1.67		7.5		
beam current [mA]	1450		152		30		6.6		500
cavity technology	Nb/Cu		Nb/Cu	Nb	Nb/Cu	Nb	Nb/Cu	Nb	Nb/Cu
E_{acc} [MV/m]	**10**		**10**	**20**	**10**	**20**	**10**	**20**	**10**
frequency [MHz]	400		400	800	400	800	400	800	400
temperature [K]	4.5	4.5	4.5	2.0	4.5	2.0	4.5	2.0	4.5
Nb cavities	107	54	107	107	200	200	667	667	32
cells/cavity	1	1	2	2	4	4	4	4	1
P_{cavity}	462	924	470	470	251	251	75	75	<500

same cryomodule

both beams in same cavities

cavity options II

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

"high current" machine

Z **W** **hh**

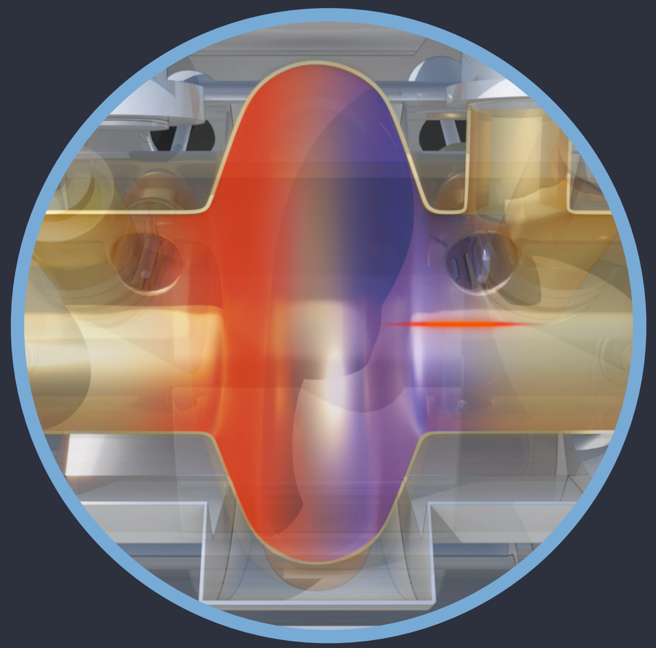
- lower frequency, low N_{cells}, low R_s
- 400 MHz, Nb/Cu, < 100 cavities
- FPC: aim at 1 MW/cavity (movable for hh, fixed for ee)
- HOM power < 1.5 kW/cavity
- 1 RF source/cavity (e.g. high efficiency klystrons)
- CM design to accommodate 1-cell (W) and 2-cell cavities (Z, hh)

"high gradient" machine

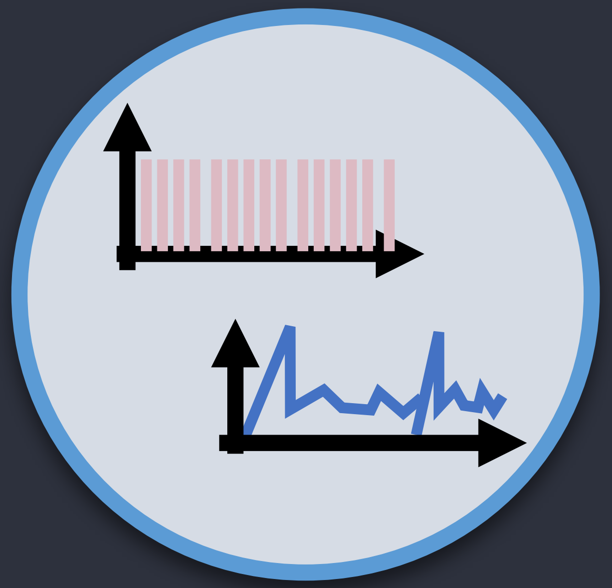
H **t**

- 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
- 1 RF source/cavity: SSPA, IOT

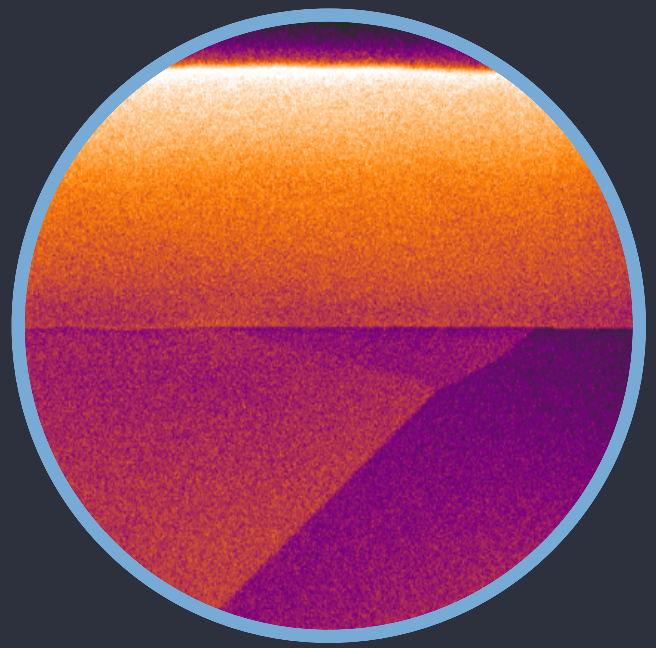
SRF R&D for FCC



optimize cell shapes

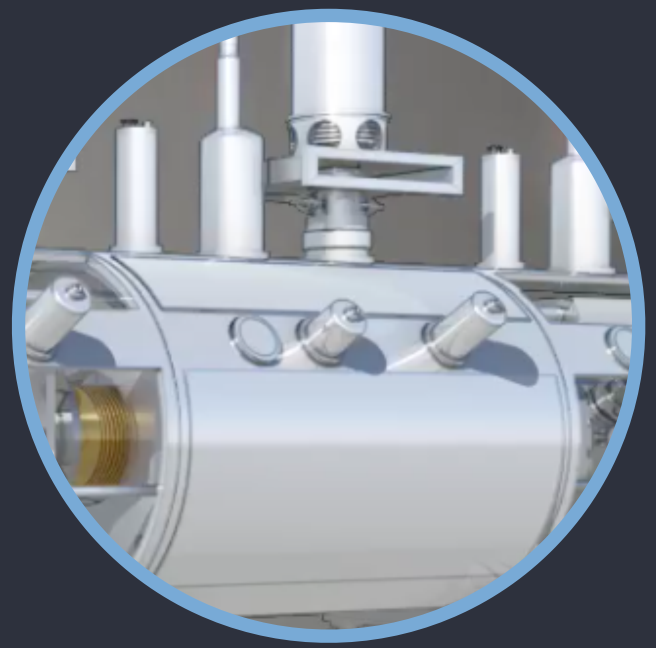


beam dynamics studies

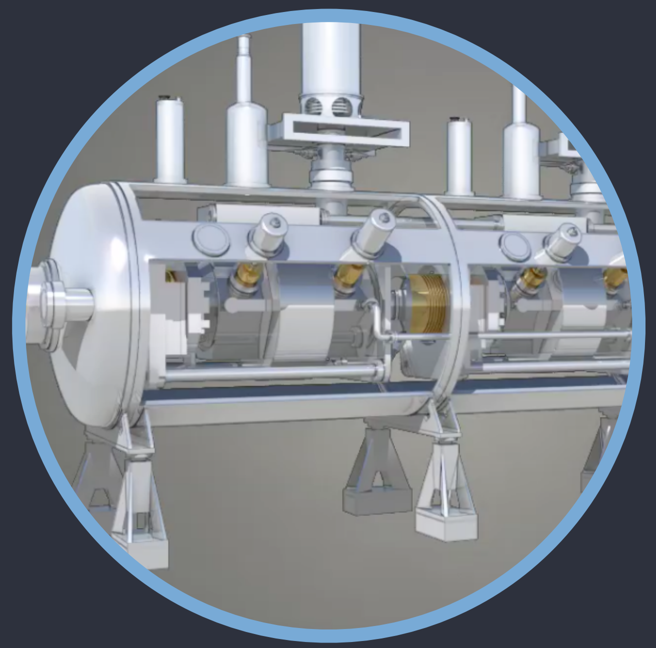


Q-slope mitigation

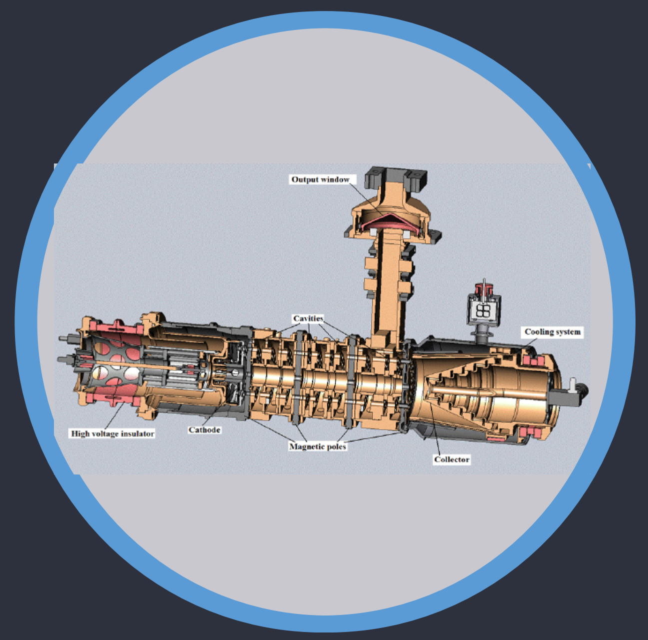
material & manufacturing



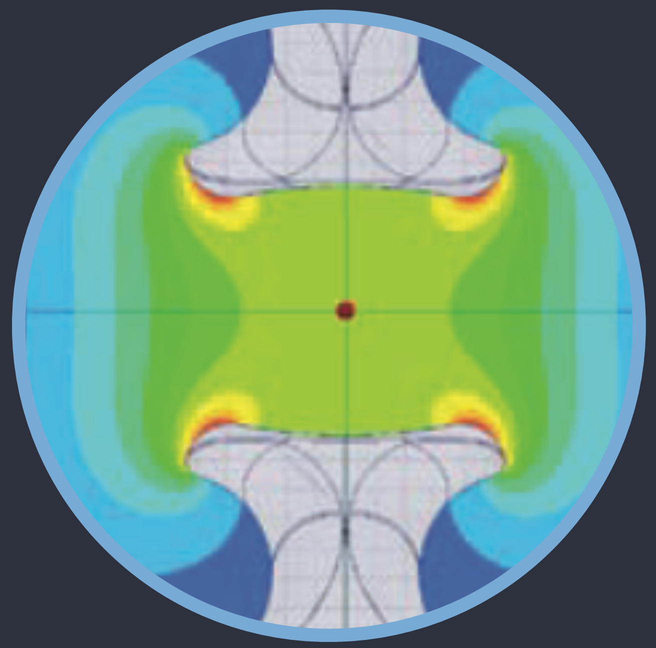
assembly & cost optimisation



ancillaries:
1 MW CW coupler!



efficient RF production



coated crab cavities

FCC

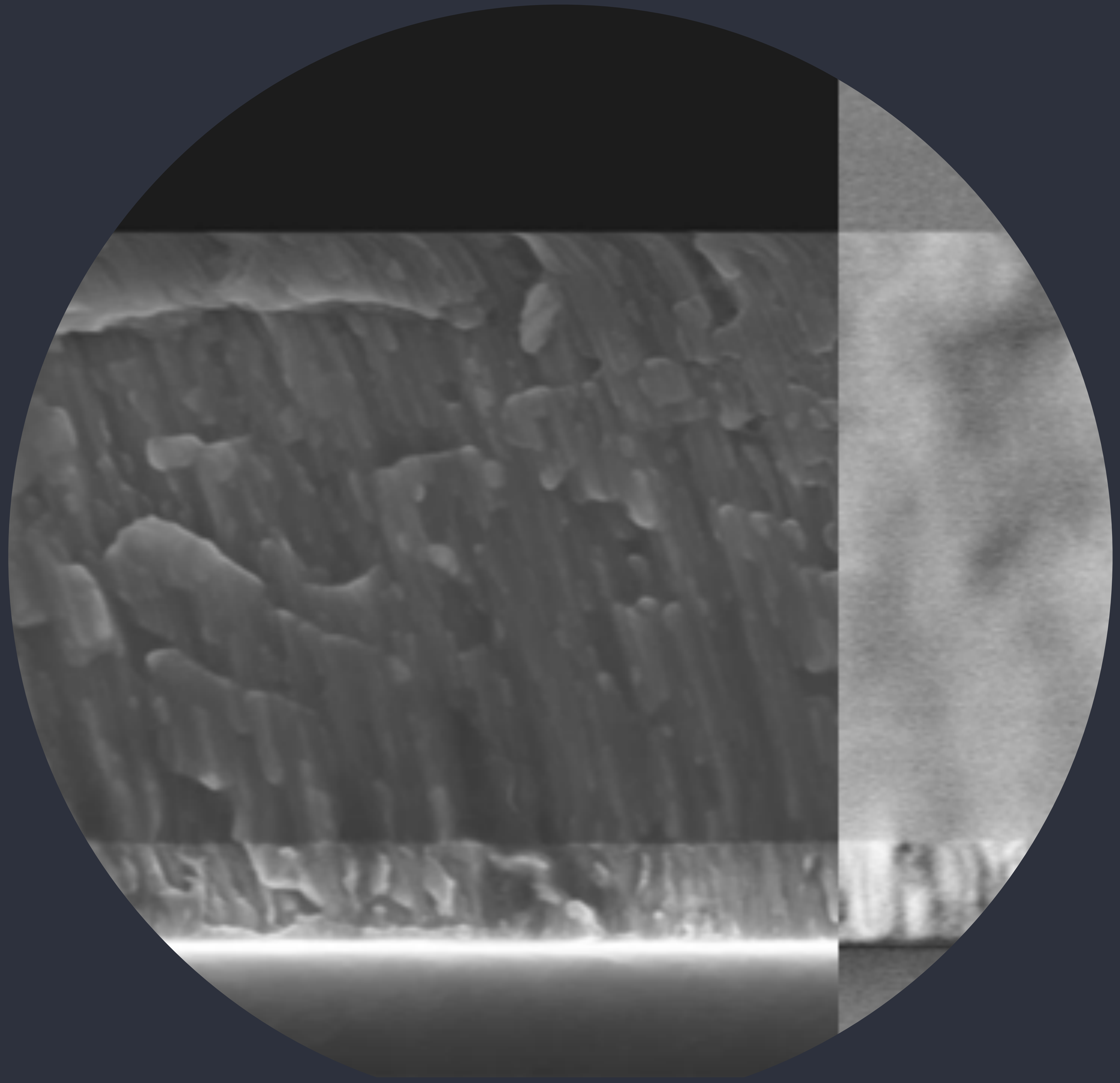
Thin film R&D

Overview

Coating methods

- **Diode coating** with bias for HIE-ISOLDE
- **Direct Current Magnetron Sputtering** (DCMS) for LHC cavities.
- Improved method: **Biased High Power Impulse Magnetron Sputtering** (HiPIMS), 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.
- R&D on new coating cathodes (400 and 800 MHz).

Coatings types



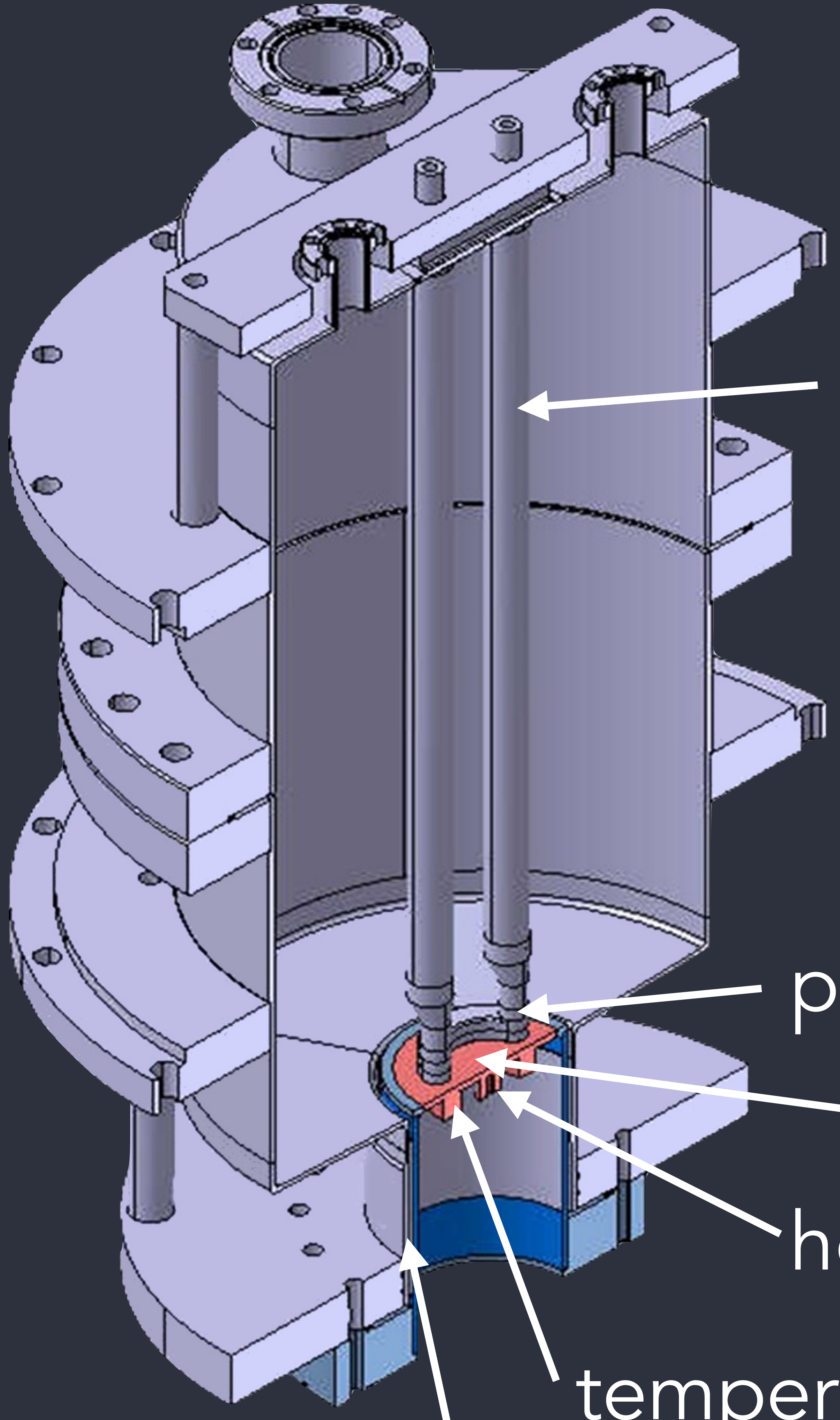
- Crucial: R&D on **surface preparation** of Cu and Nb surfaces.
- Full **EP** of substrates, upgrade existing facility for 400 and 800 MHz Cu. 704 MHz multi-cell Nb was already done in a vertical set-up.
- > 30 coatings on seamless 6 GHz cavities with a few for application at 800 MHz (INFN, Italy).
- 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
- More details in session 1 & 2 by Sarah Aull.
- 800 MHz bulk Nb used as state of the art comparison (JLAB collaboration).
- Collaboration agreement with FNAL in preparation on prospects of Nb_3Sn and nitrogen doping for bulk Nb 400-800 MHz cavities.

Thin film R&D

Quadrupole resonator

Our tool to qualify SRF surfaces

Principle



- 4 rod transmission line half-wave resonator
- resonant frequencies: 400/800/1200 MHz
- pole shoes focus magnetic field on the sample
- thermally decoupled sample
- high-resolution calorimetric measurement of surface resistance

Activity

- Original QPR was built 20 years ago to measure samples for the LHC cavities.
- Since then it became a work-horse for CERN's coating qualification.
- HZB Berlin recently optimised and re-built the QPR (Niowave) and achieved 120 mT on the sample surface (see SRF 2015) for 433, 867, and 1300 MHz.
- CERN has further optimised the pole shoes and is building another device for 400, 800, and 1200.
- Machining starts early 2017, first tests foreseen in 2018.

FCC

Next generation Crab Cavity

Wide Open Waveguide cavity (WOW)

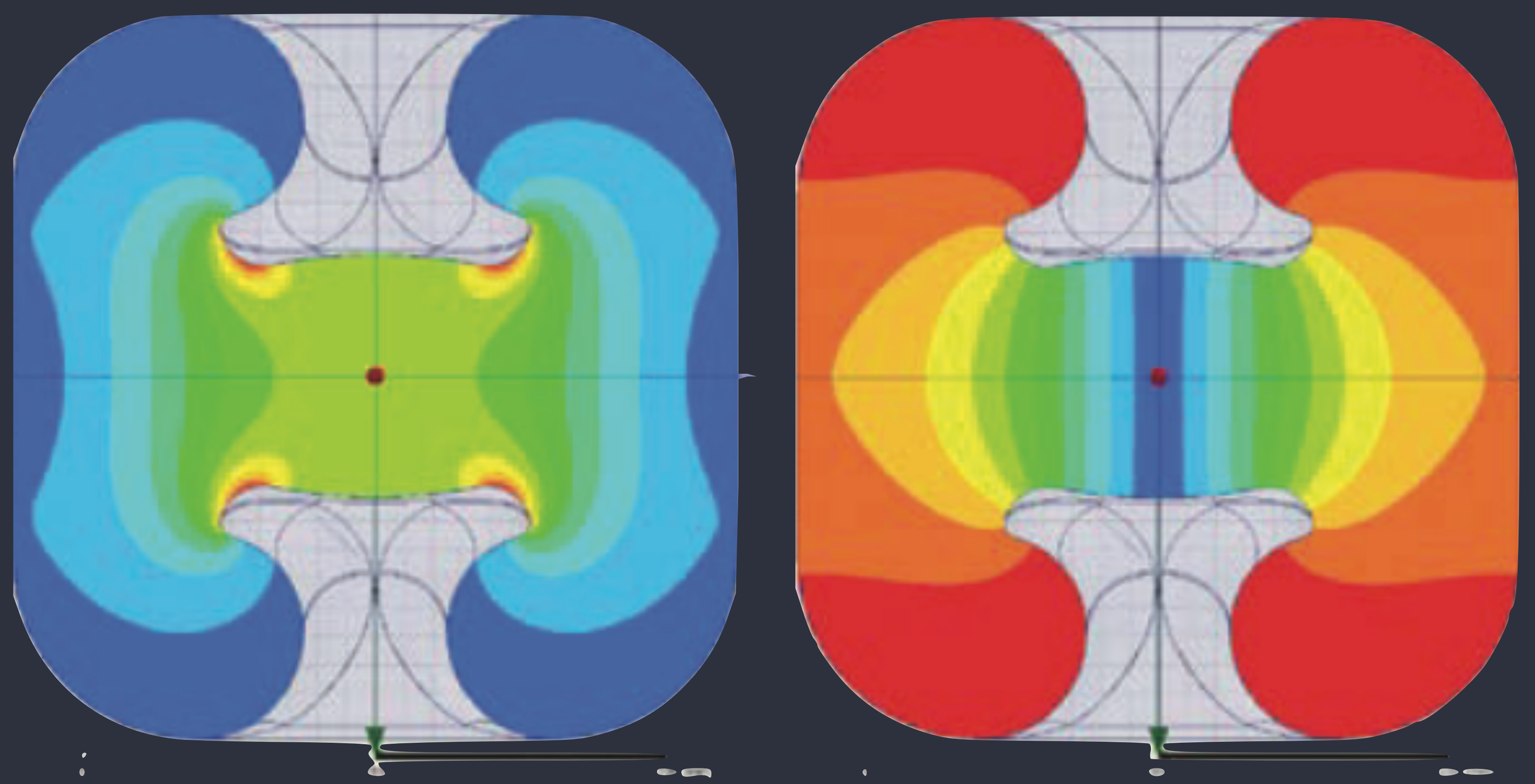
Why a Nb/Cu crab cavity?

- No thermal run-away ("natural" quench protection).
- Crab cavity power needs are driven by off-axis beam and not by surface losses.
- Lower cavity impedance (mandatory for FCC).
- No magnetic shield (cost, simplicity).
- Power coupler and HOM dampers can be outside of the helium tank (no feedthroughs).
- Cheaper base material (Cu), easier welds,
- Operation at 4.5 K.
- Mechanical stability (lower microphonics, easier RF stabilisation).
- Structure can be cascaded.

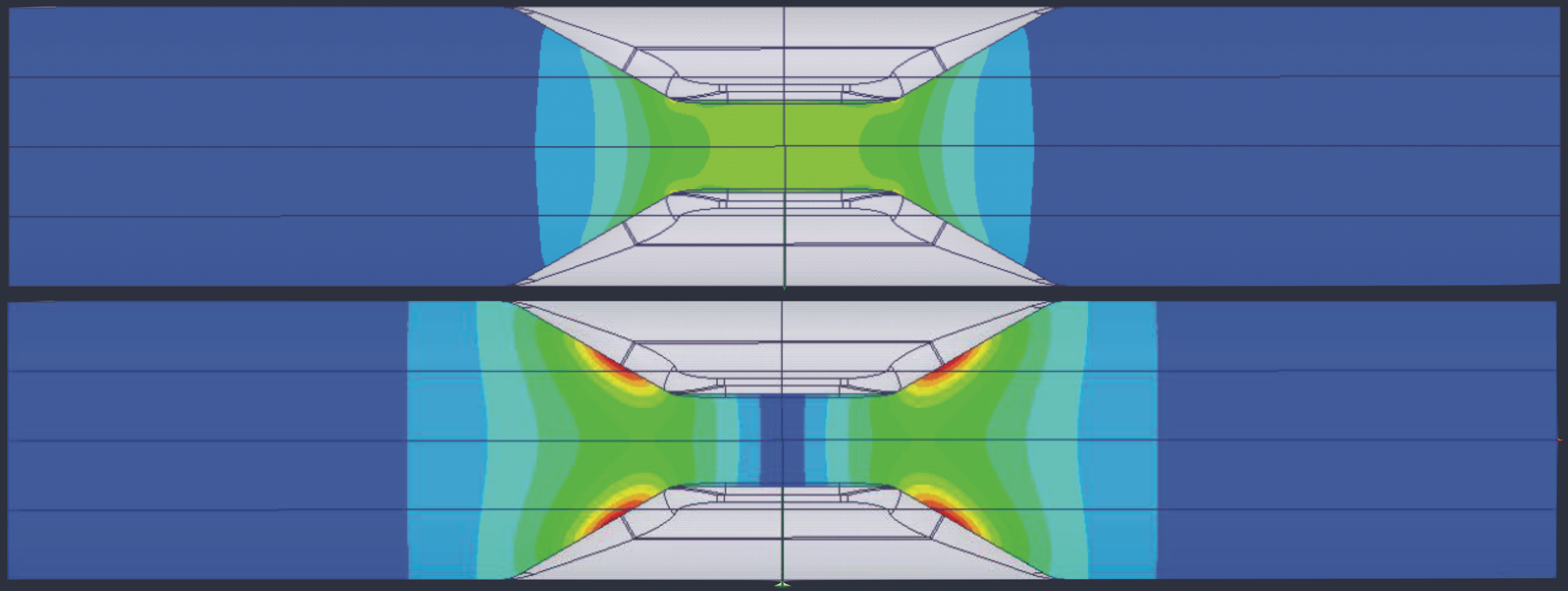
Wide Open Waveguide cavity

Basic parameters

electric magnetic



Voltage	2.7 MV/cavity	80% of bulk Nb CC
E_{peak}	40.5 MV/m	same as bulk Nb CC
B_{peak}	70 mT	same as bulk Nb CC
Frequency	400.79 MHz	
Temperature	4.5 K	
P_{diss}	< 50 W	for LHC quality coating



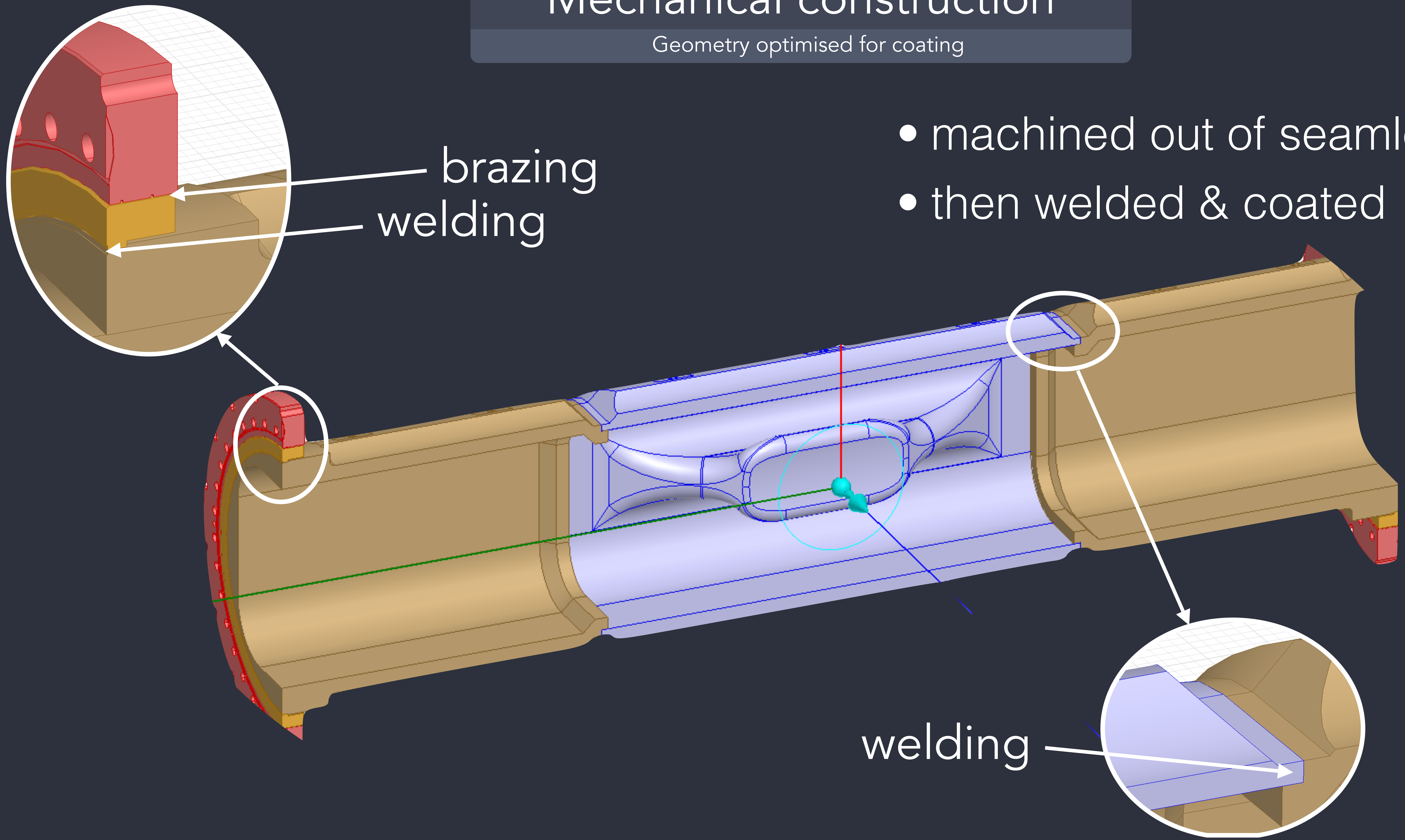
electric

magnetic

Mechanical construction

Geometry optimised for coating

- machined out of seamless tubes
- then welded & coated



Status & timeline

- Copper is at CERN and qualified, welding tests done, handling and tooling concept is defined.
- Mechanical drawings ready, machining of prototype 1 is starting.
- Preliminary coupler design for vertical testing.
- LHC-style coating set-up (coating electrodes inserted in cavity) was chosen. Small modifications on existing set-up is needed.

<table>
<tr><th colspan="4">2016</th><th colspan="4">2017</th><th colspan="4">2018</th><th colspan="3">2019</th></tr>
<tr><td colspan="4">material procurement, drawings</td><td colspan="4">fabrication 1st prototype</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">fabrication 2nd prototype</td><td colspan="4"></td></tr>
<tr><td colspan="3"></td><td></td><td colspan="5">coating design & construction</td><td colspan="6">coating, cold testing, re-coating</td></tr>
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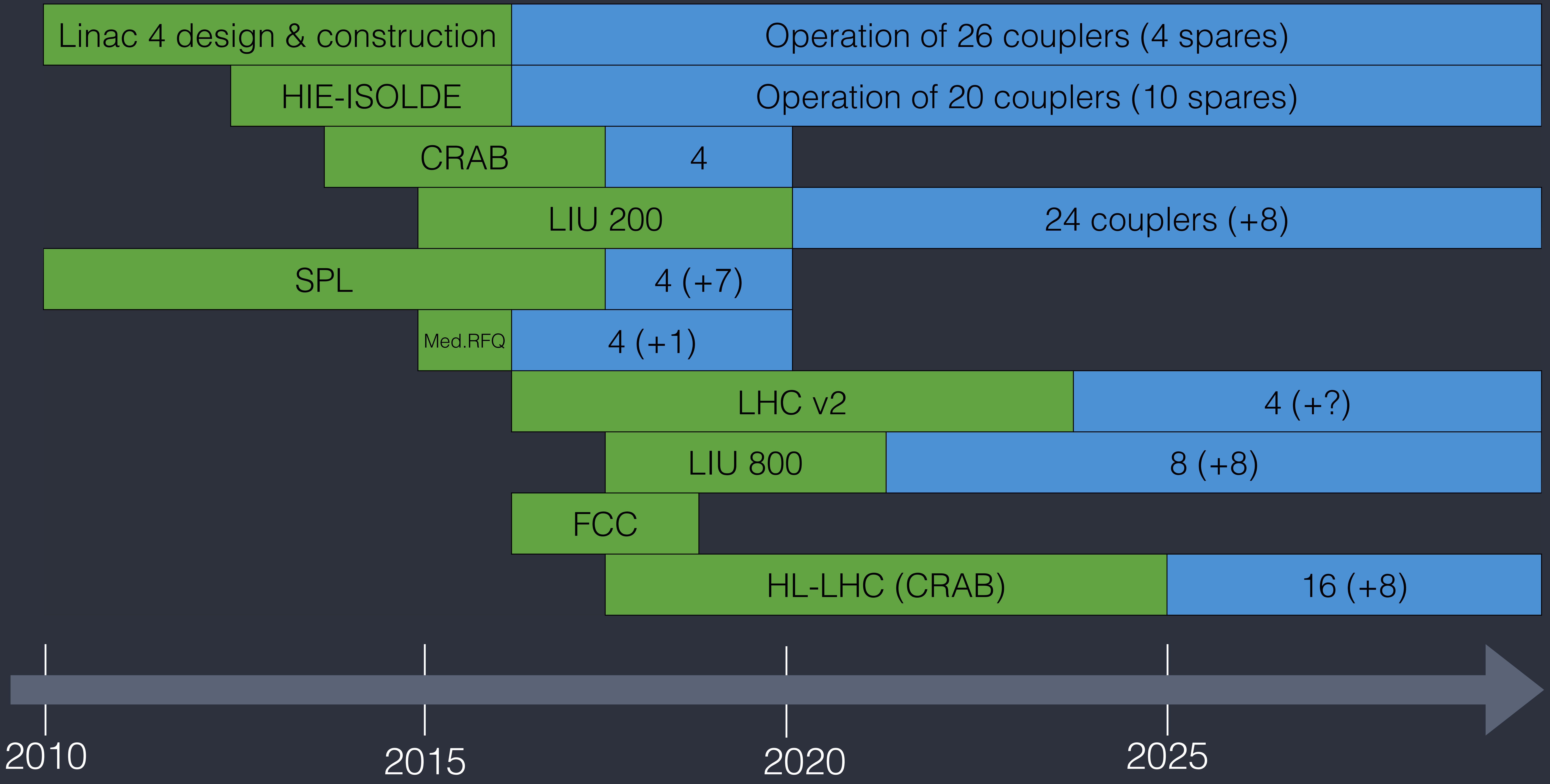
Active power coupler R&D



HIE ISOLDE

- 4 CM with 5 low-beta QWR in each. 6 MV/m, $Q_{0,nom}=5x10^8$
- Crisis in 2015, no one understood why linear indications ("microcracks") appeared on the cavities and spoiled the performance.
- Strategy: i) shrink-fit and weld at CERN, ii) work on the welding parameters (already succeeded), iii) seamless cavities (under test).
- CM3 needs 70 W instead of 50 W, and there are good hopes that CM4 will be at nominal, allowing full-spec operation!
- In-situ helium processing works and provides a mechanism to save declining (dirty) cavities.
- First 2 physics runs successful.

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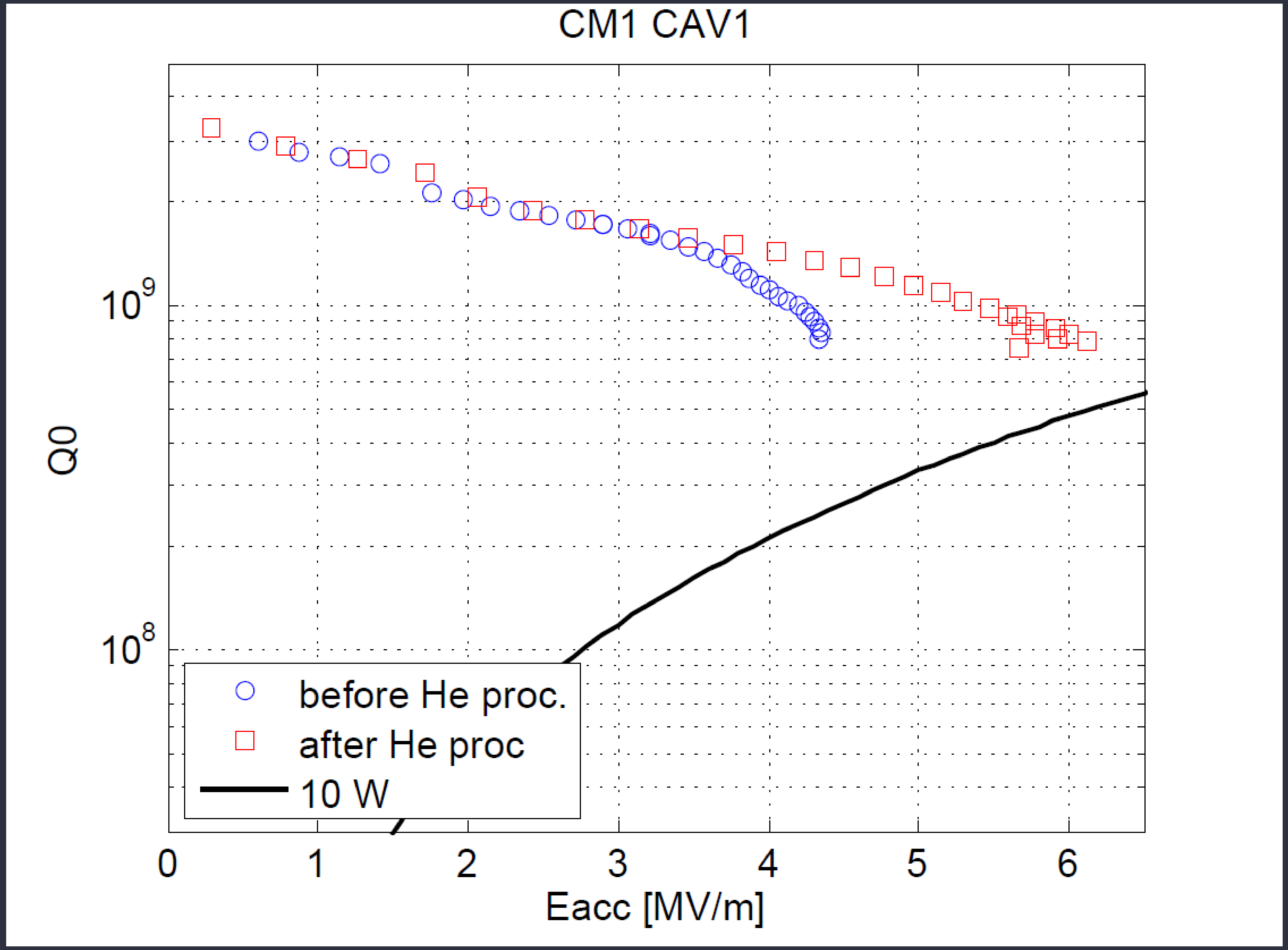
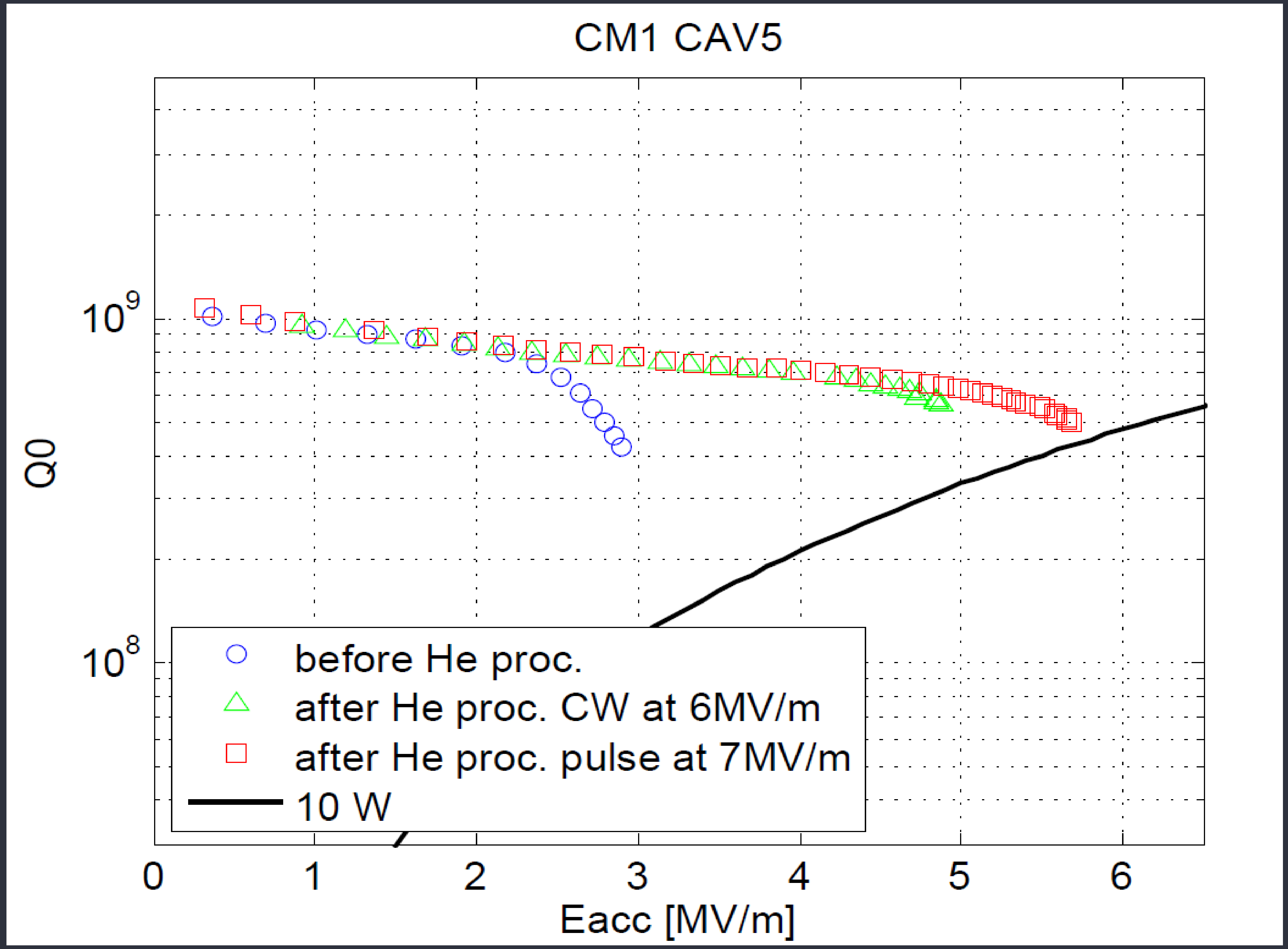
in-situ Helium processing





Summary

- HIE ISOLDE low-beta QWR: 3 modules installed, 1 more to come. Potential to replace NC front-end with SC cavities in HIE-ISOLDE phase 3 (not funded/agreed today).
- LHC spare cavities.
- Crab cavities for HL-LHC.
- Focus on coated Cu cavities (not many alternatives for <=400 MHz): Extensive Nb on Cu R&D program towards FCC, 400/800 MHz with modest gradients.
- Coated crab cavity for FCC.
- Short to medium term: focus on HIPIMS Nb/Cu. Construction of new QPR.
- Long term: A15 coatings on Cu.
- Bulk Nb: crab cavities for HL-LHC, modest effort on 704 MHz 4-cavity (5-cell) CM, 800 MHz for FCC (but also trials with Nb/Cu at 800 MHz). Reference for comparison coated cavities.
- Improved power couplers, aiming at 1 MW CW.