SRF technology for future CERN machines

Frank Gerigk, CERN, GARD-SRF Roadmap Workshop
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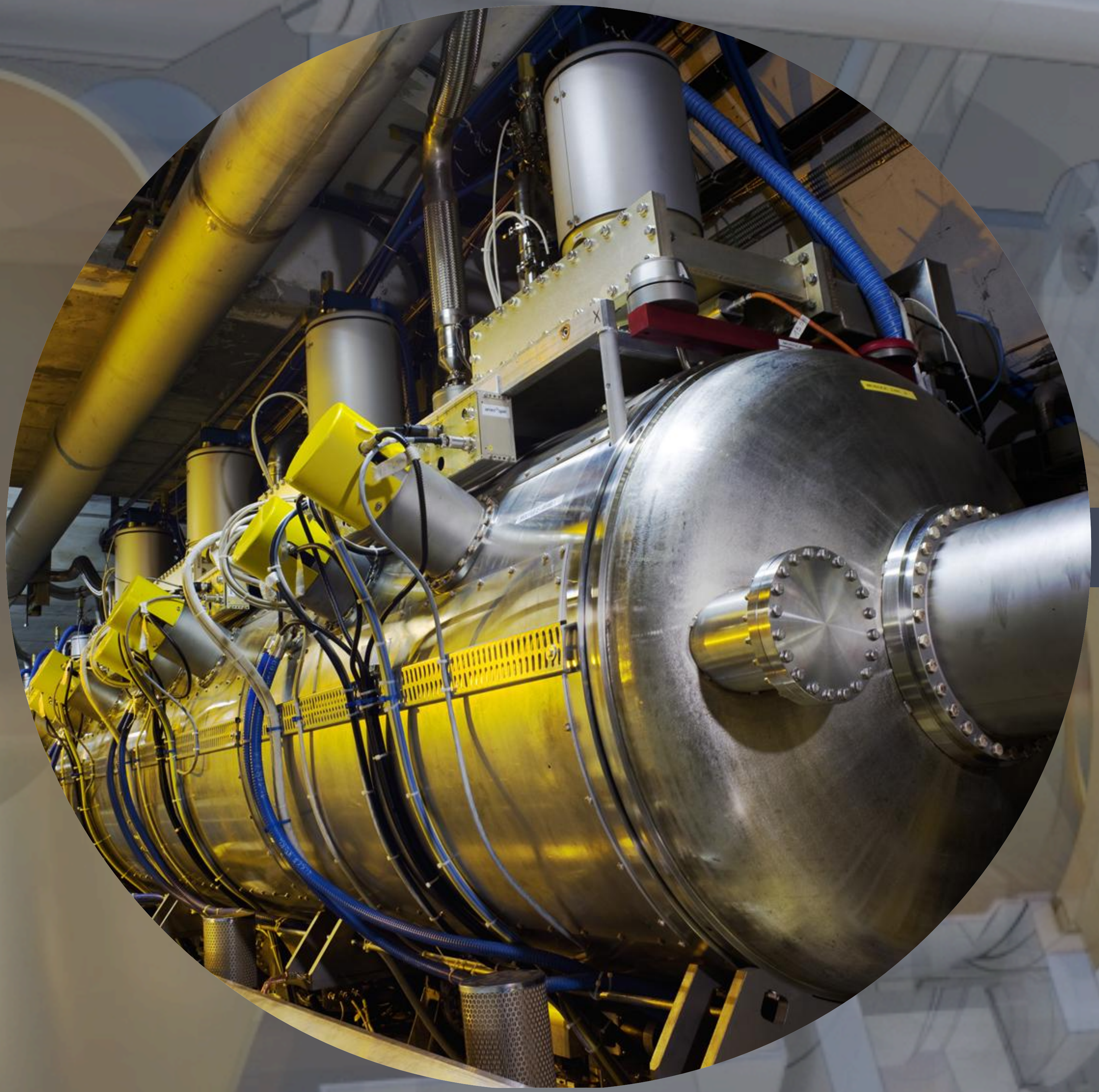


LHC cavities

LHC spare cavity program

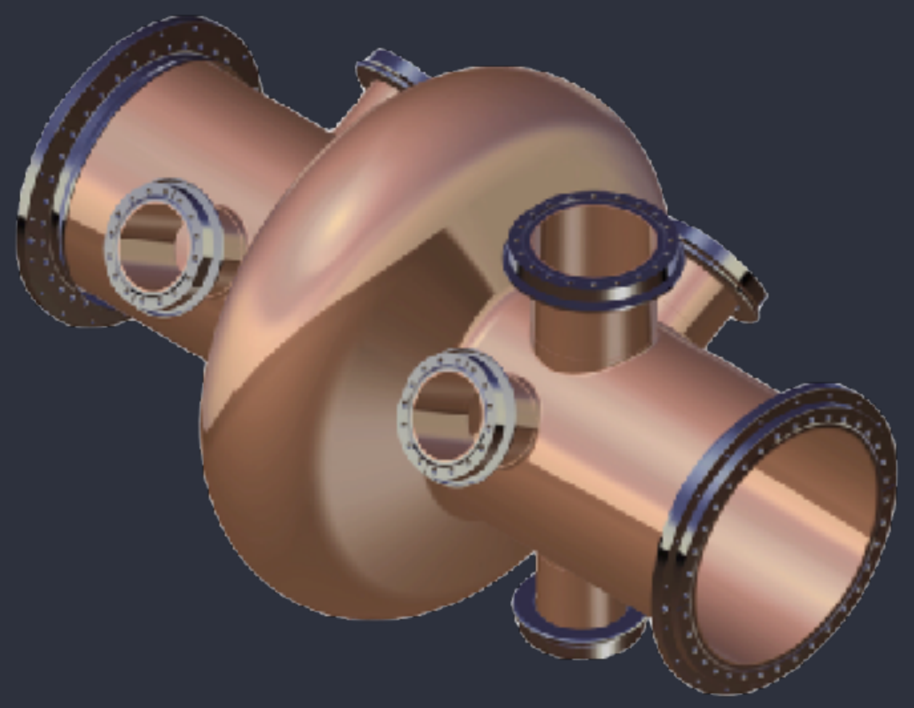
- NB-COATED Cu cavities operating at 4.5 K.
- 400.790 MHz, 8-16 MV/beam.
- 2 cryomodules of 4 cavities/beam.
- **1 spare module and one spare dressed cavity available. Many of the "old" experts have retired.**
- **LHC has a physics program until 2035 and we have no experience with ageing of LHC cryomodules.**

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

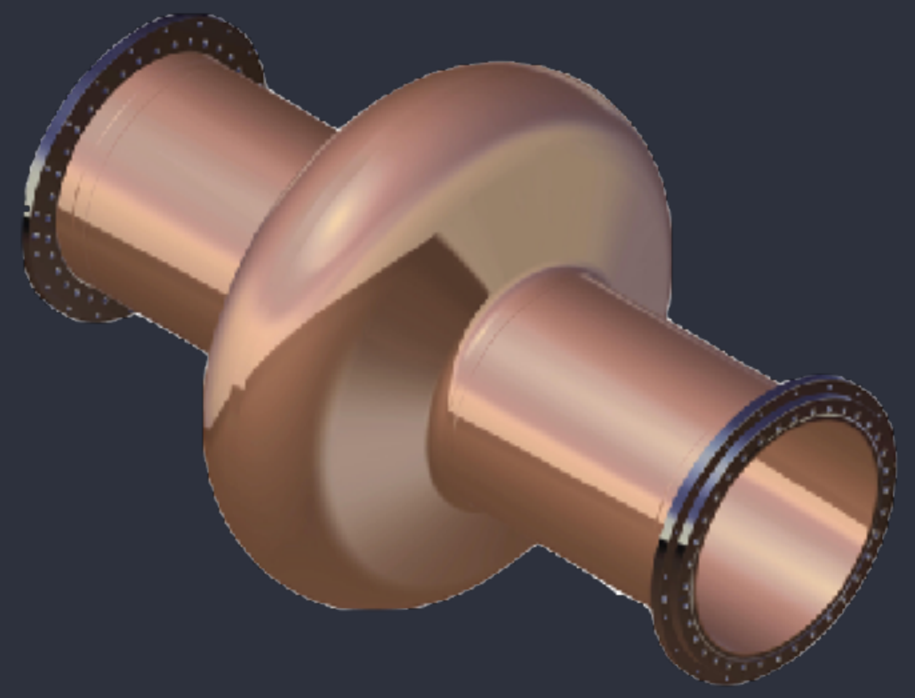
➡ industrial production of cavities and subsequent coating at CERN

LHC spare cavity program



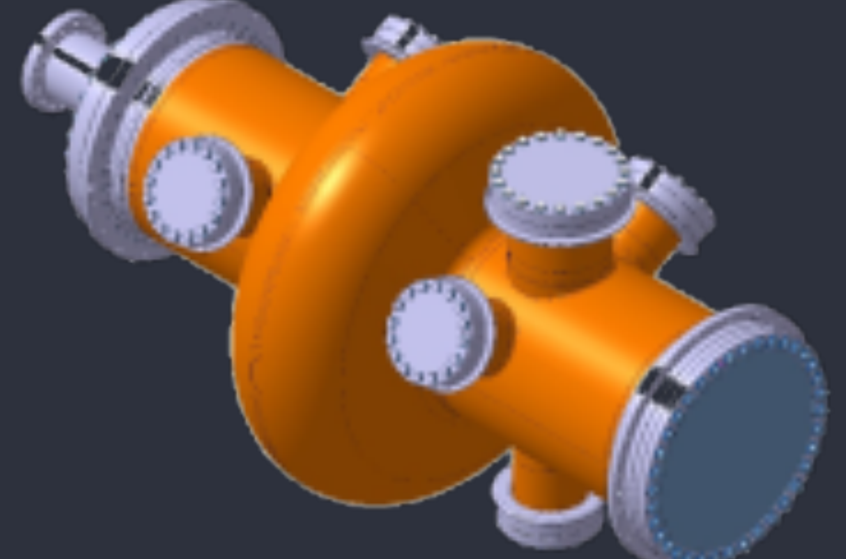
Practice cavity 1,2

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



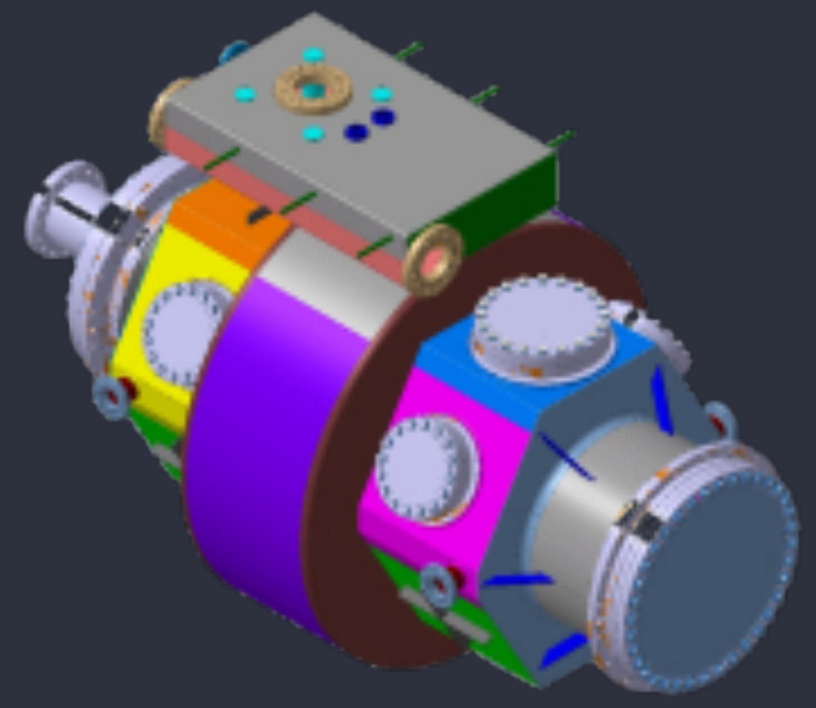
Practice cavity 3,5

- half cells by spinning and electro-hydraulic forming (EHF),
- simplified cut-off tubes,
- cold tests in May/July 2017



Model cavity

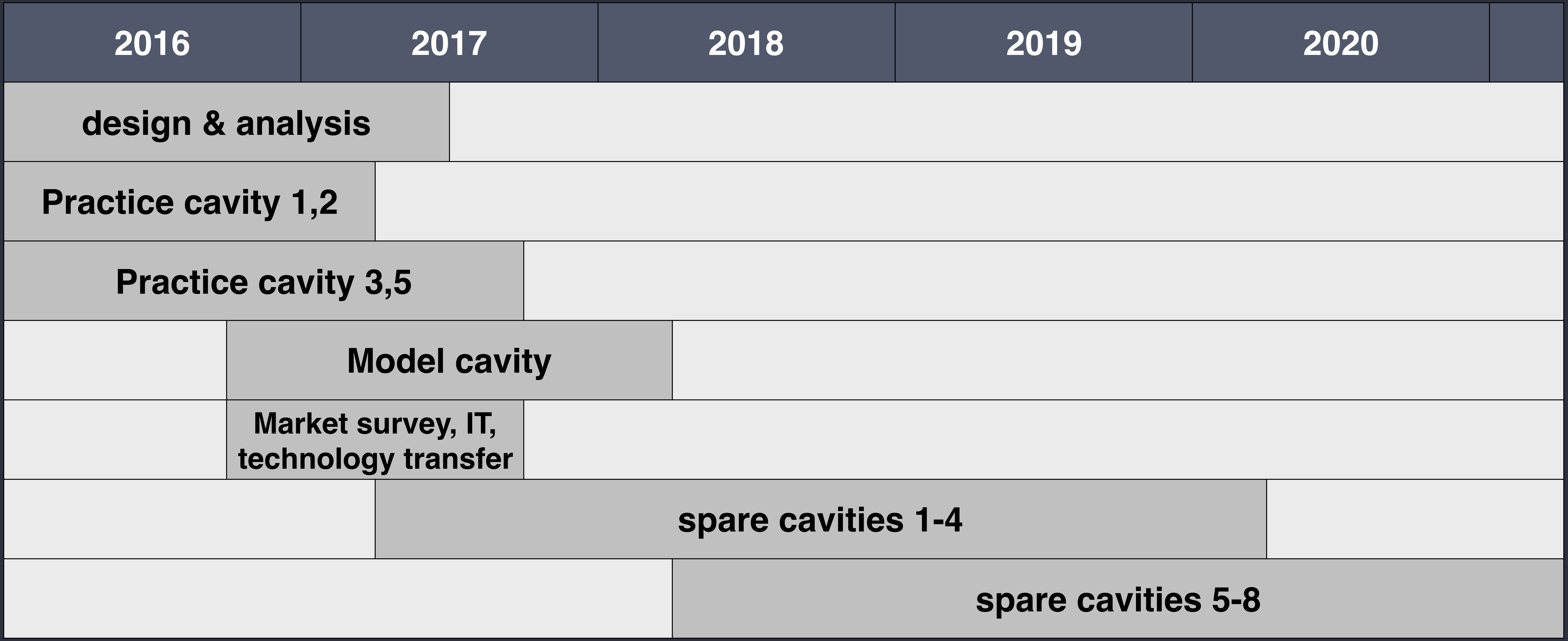
- validation of cavity design & fabrication process
- He-tank updated design,
- cold test expected August 2017
- if successful: the first spare cavity



Series production

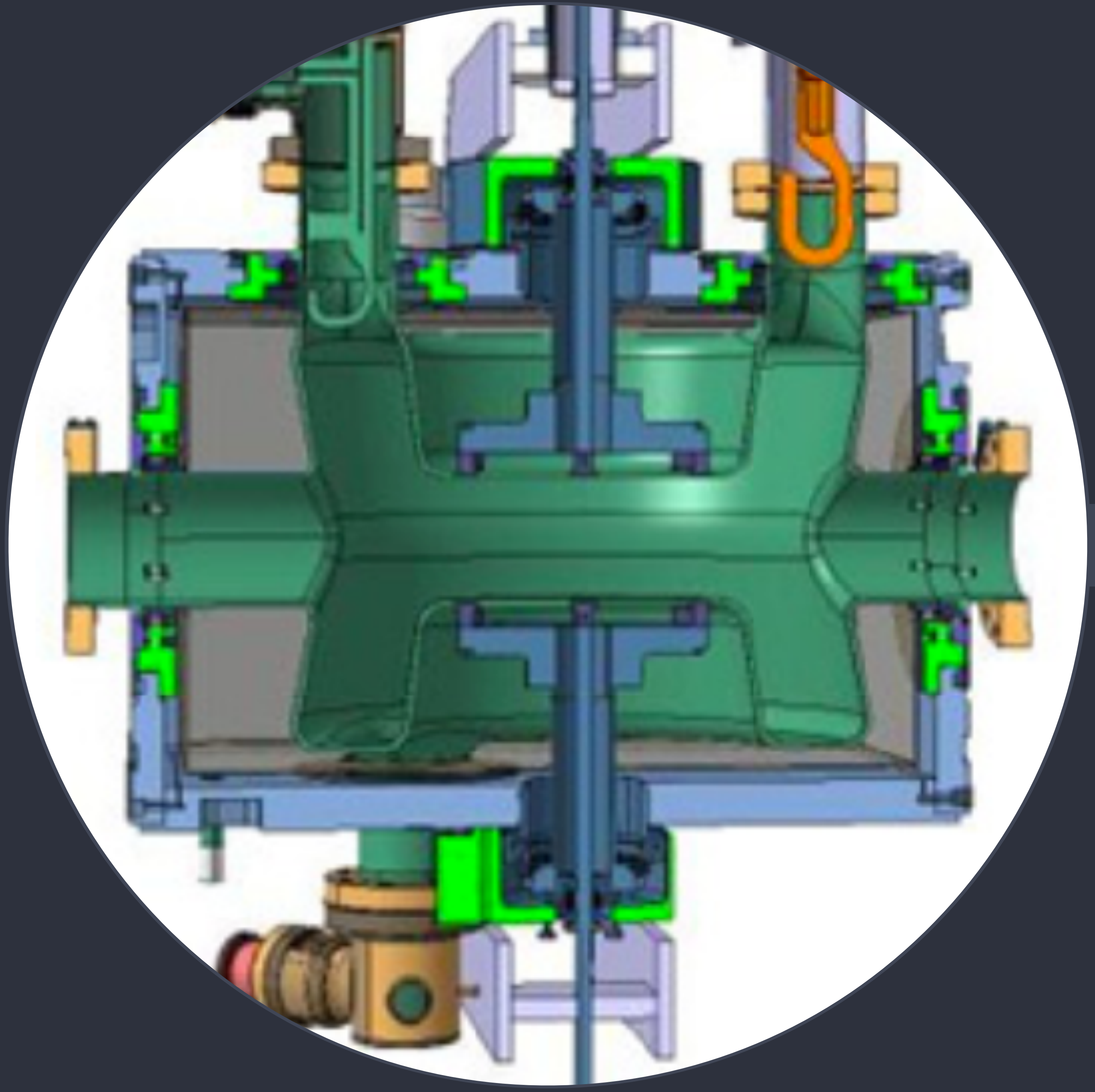
- 8 cavities + 2 spares,
- tendering for cut-off tubes early 2017,
- production of half cells (spun or EHF)
- He-tanks tendering in 2017

LHC spares: timeline



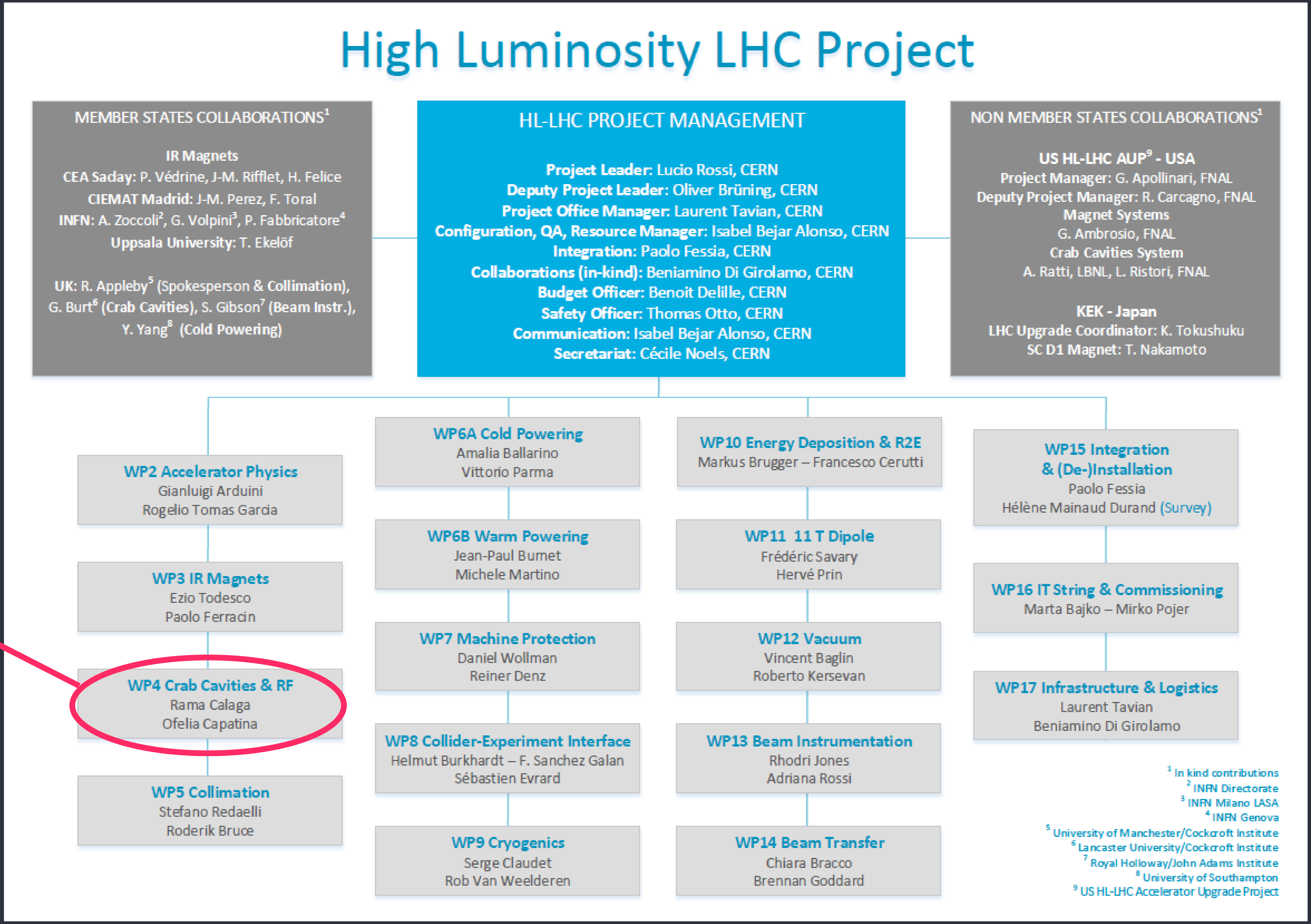
Technology dev. / R&D

- 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 instead of deep drawing.



High-luminosity LHC

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


High Luminosity LHC Project
MEMBER STATES COLLABORATIONS1
IR Magnets
CEA Saday: P. Védrine, J-M. Rifflet, H. Felice
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)
HL-LHC PROJECT MANAGEMENT
Project Leader: Lucio Rossi, CERN
Deputy Project Leader: Oliver Brüning, CERN
Project Office Manager: Laurent Tavian, CERN
Configuration, QA, Resource Manager: Isabel Bejar Alonso, CERN
Integration: Paolo Fessia, CERN
Collaborations (in-kind): Beniamino Di Girolamo, CERN
Budget Officer: Benoit Delille, CERN
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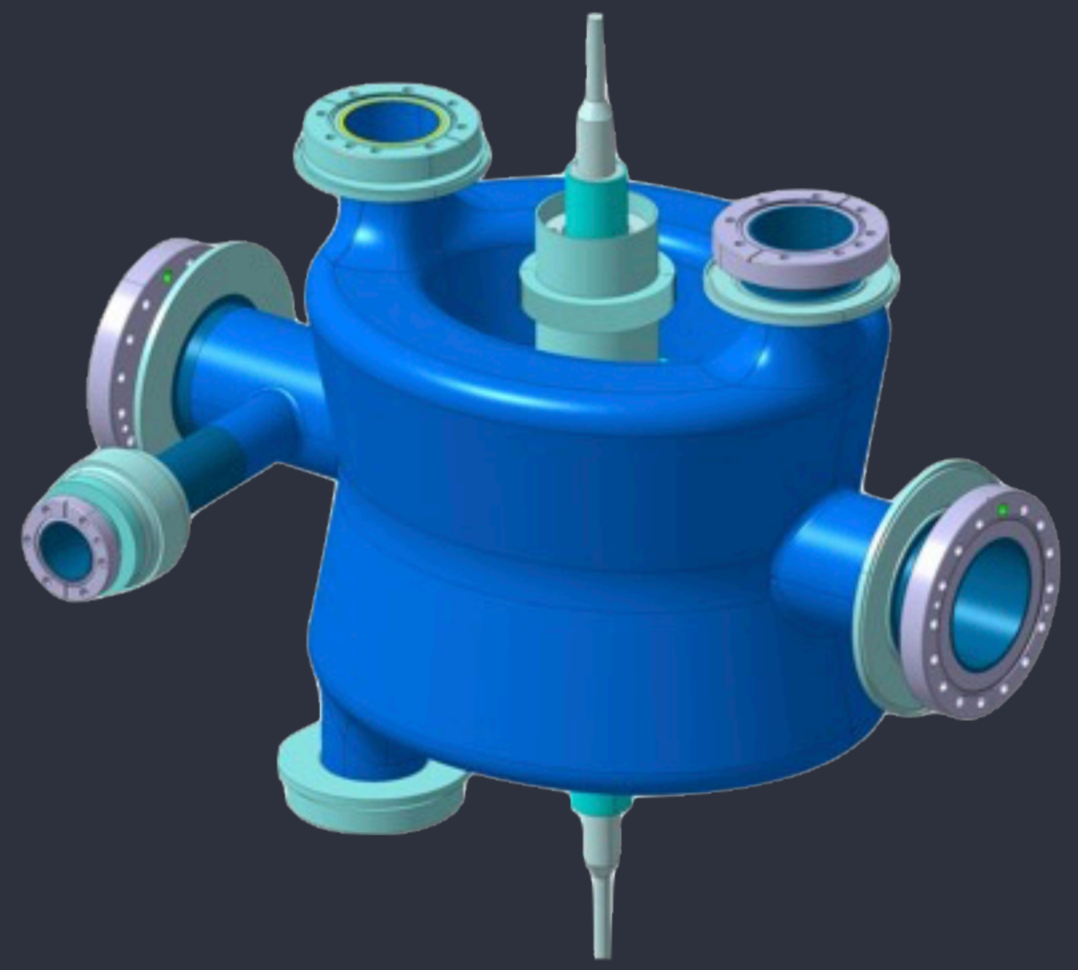
WP3 IR Magnets
Ezio Todesco
Paolo Ferracin
WP4 Crab Cavities & RF
Rama Calaga
Ofelia Capatina
WP5 Collimation
Stefano Redaelli
Roderik Bruce
WP6A Cold Powering
Amalia Ballarino
Vittorio Parma
WP6B Warm Powering
Jean-Paul Burnet
Michele Martino
WP7 Machine Protection
Daniel Wollman
Reiner Denz
WP8 Collider-Experiment Interface
Helmut Burkhardt – F. Sanchez Galan
Sébastien Evrard
WP9 Cryogenics
Serge Claudet
Rob Van Weelderen
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
Rhodri Jones
Adriana Rossi
WP14 Beam Transfer
Chiara Bracco
Brennan Goddard
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

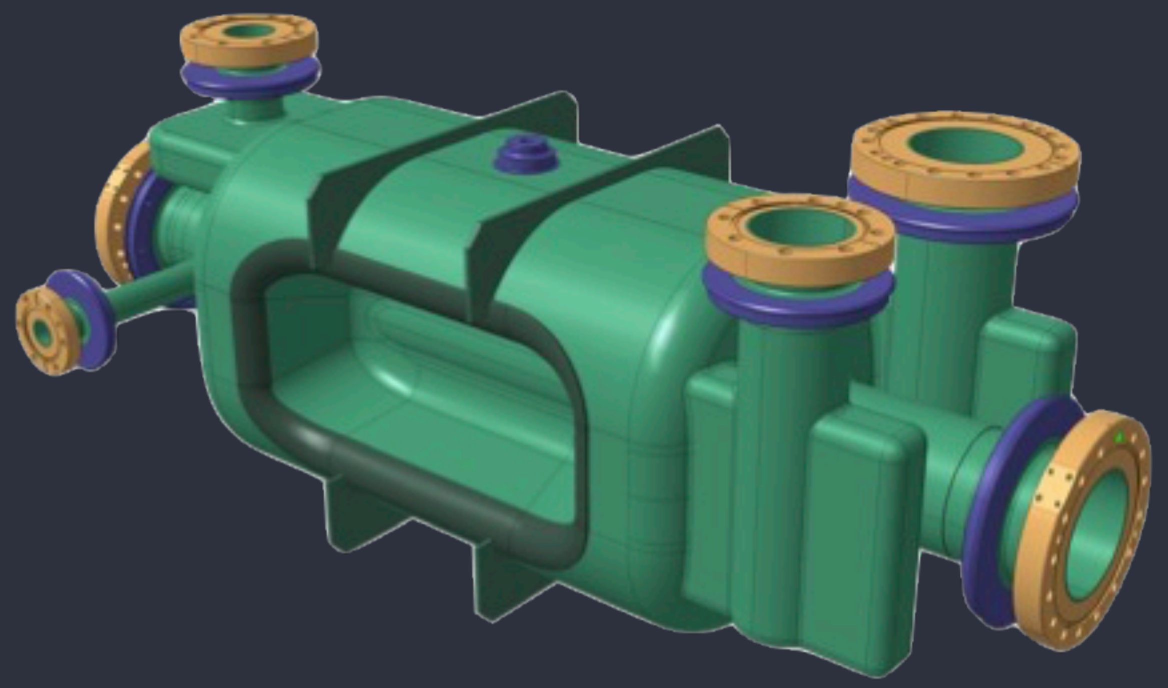
The SRF part…

2 types of Crab cavities

Double Quarter Wave



RF Dipole

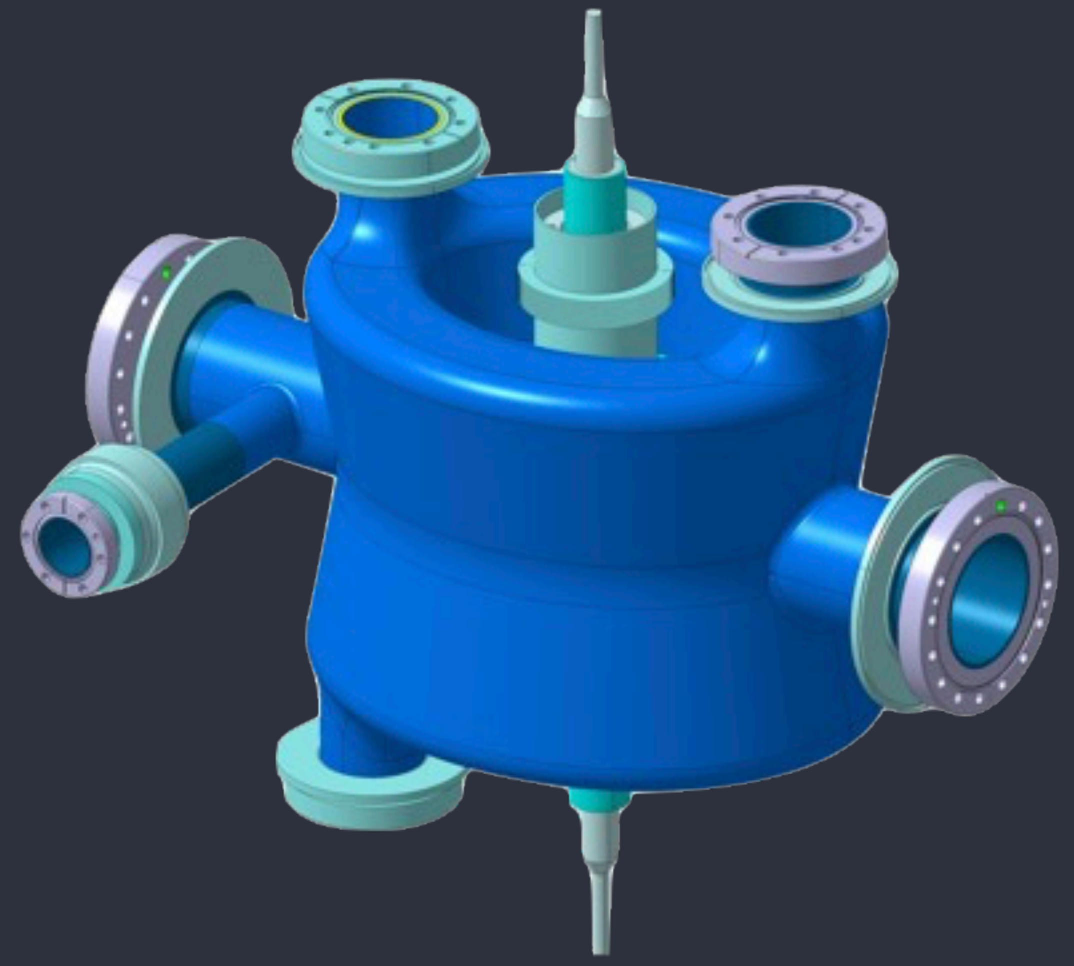


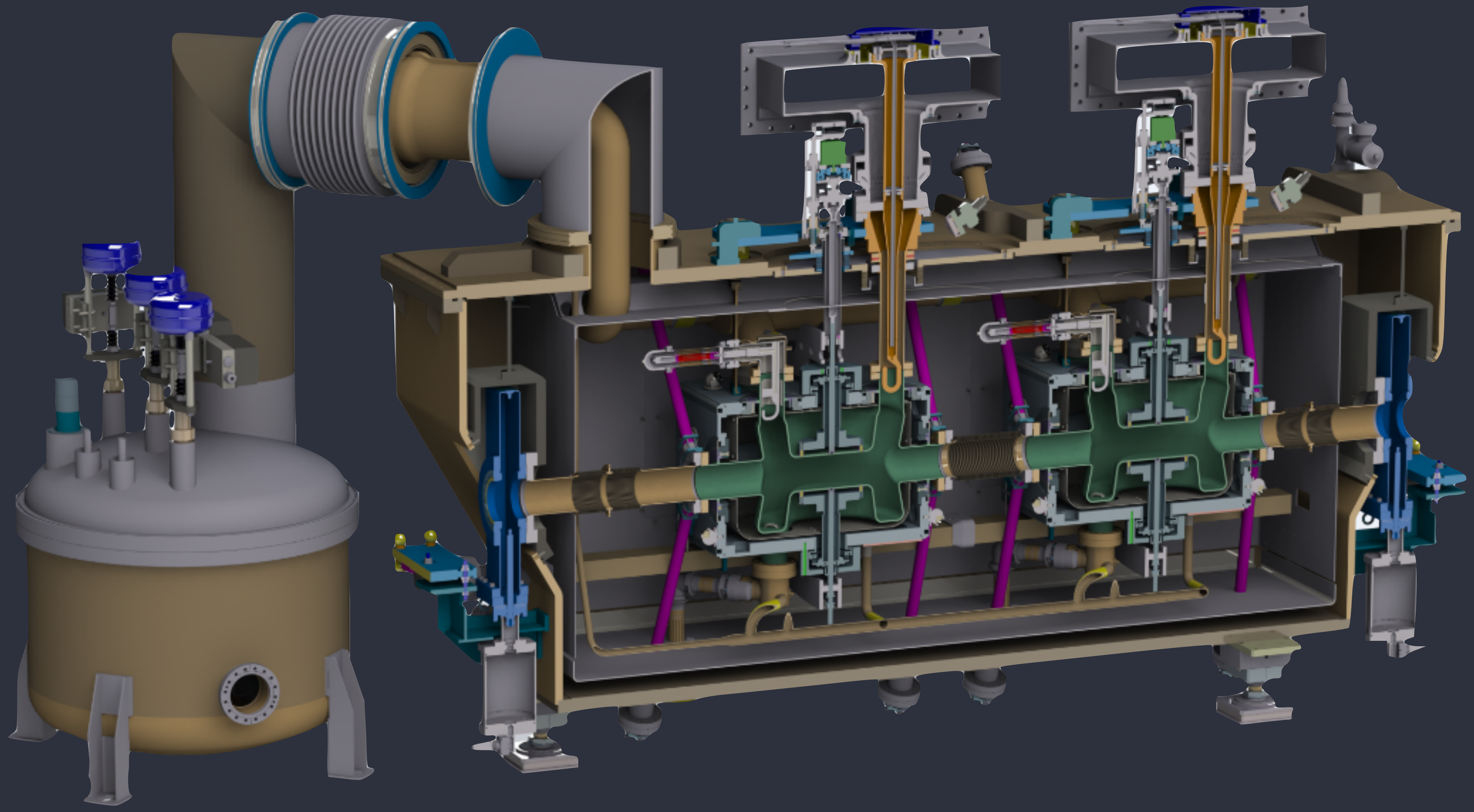
Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power (SPS)	40 kW

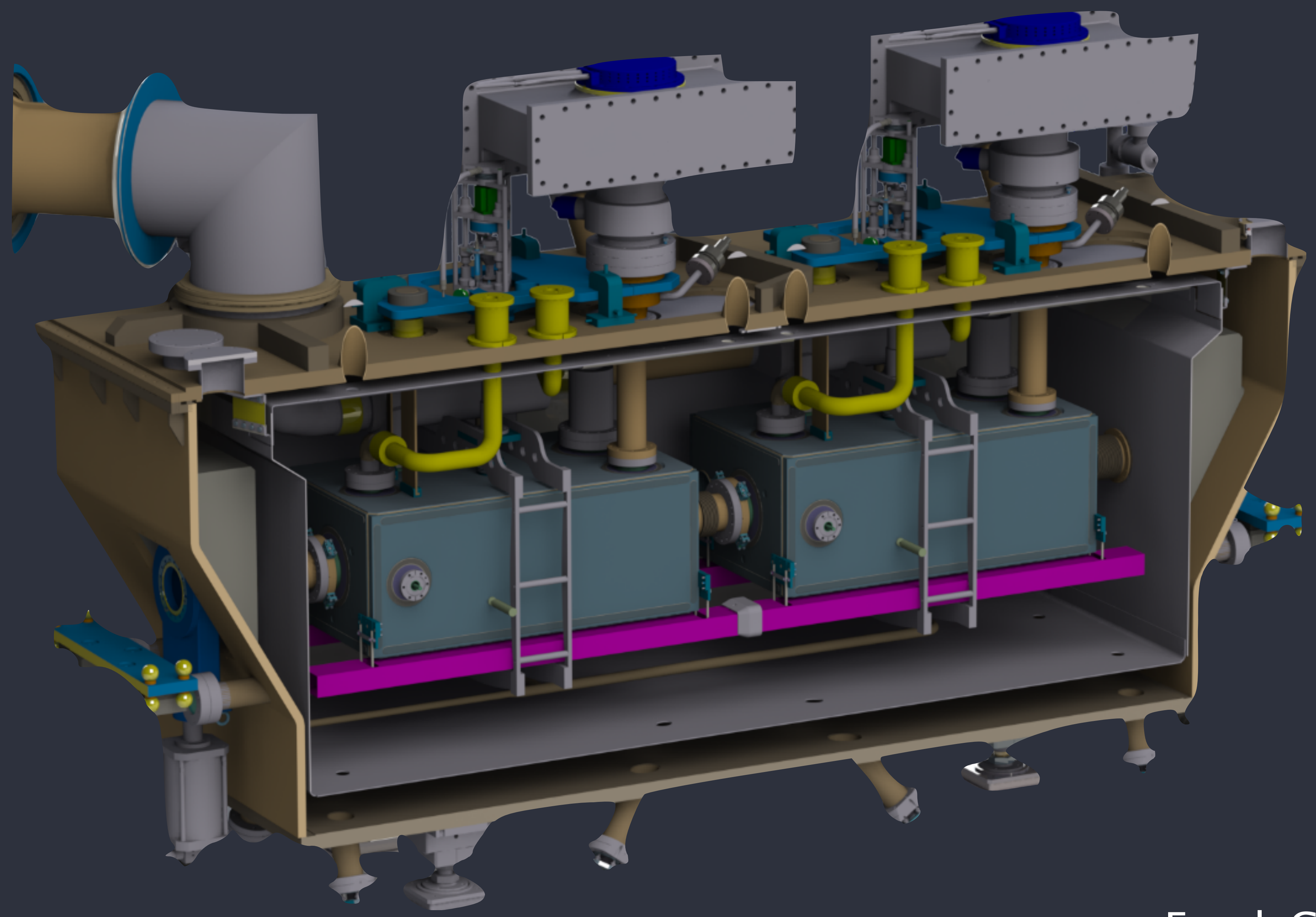
➡ 2 cavities/beam/IP side
➡ for ATLAS and CMS
➡ 16 cavities/8 CMs in total

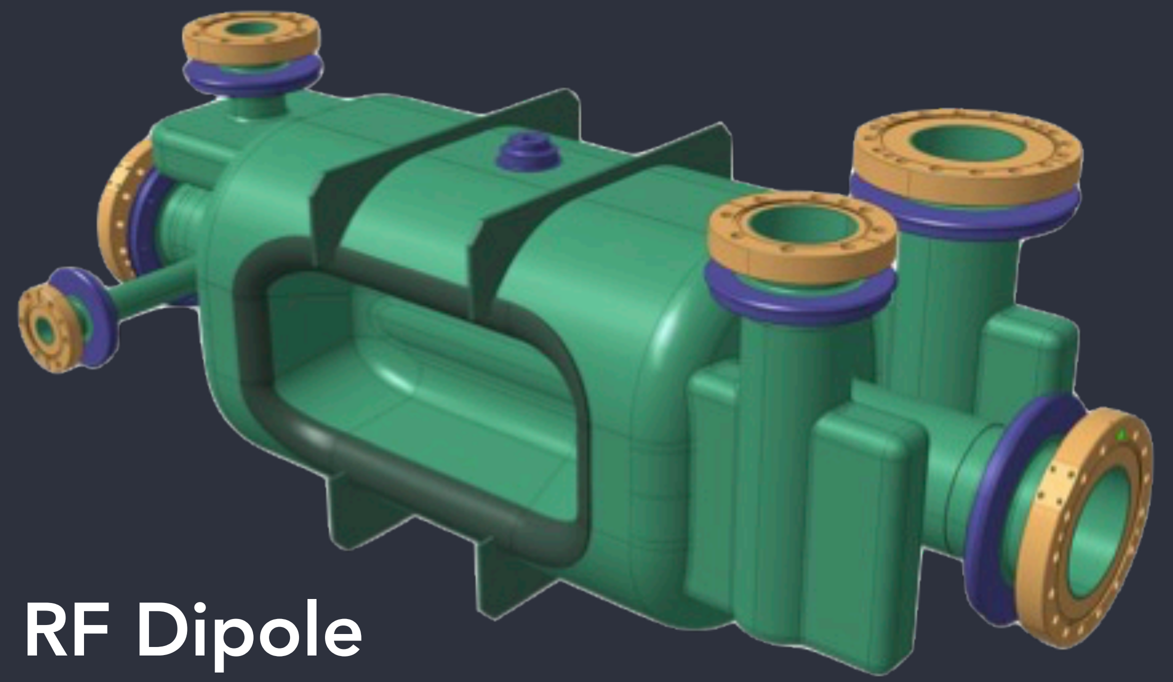
2 types of Crab cavities

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



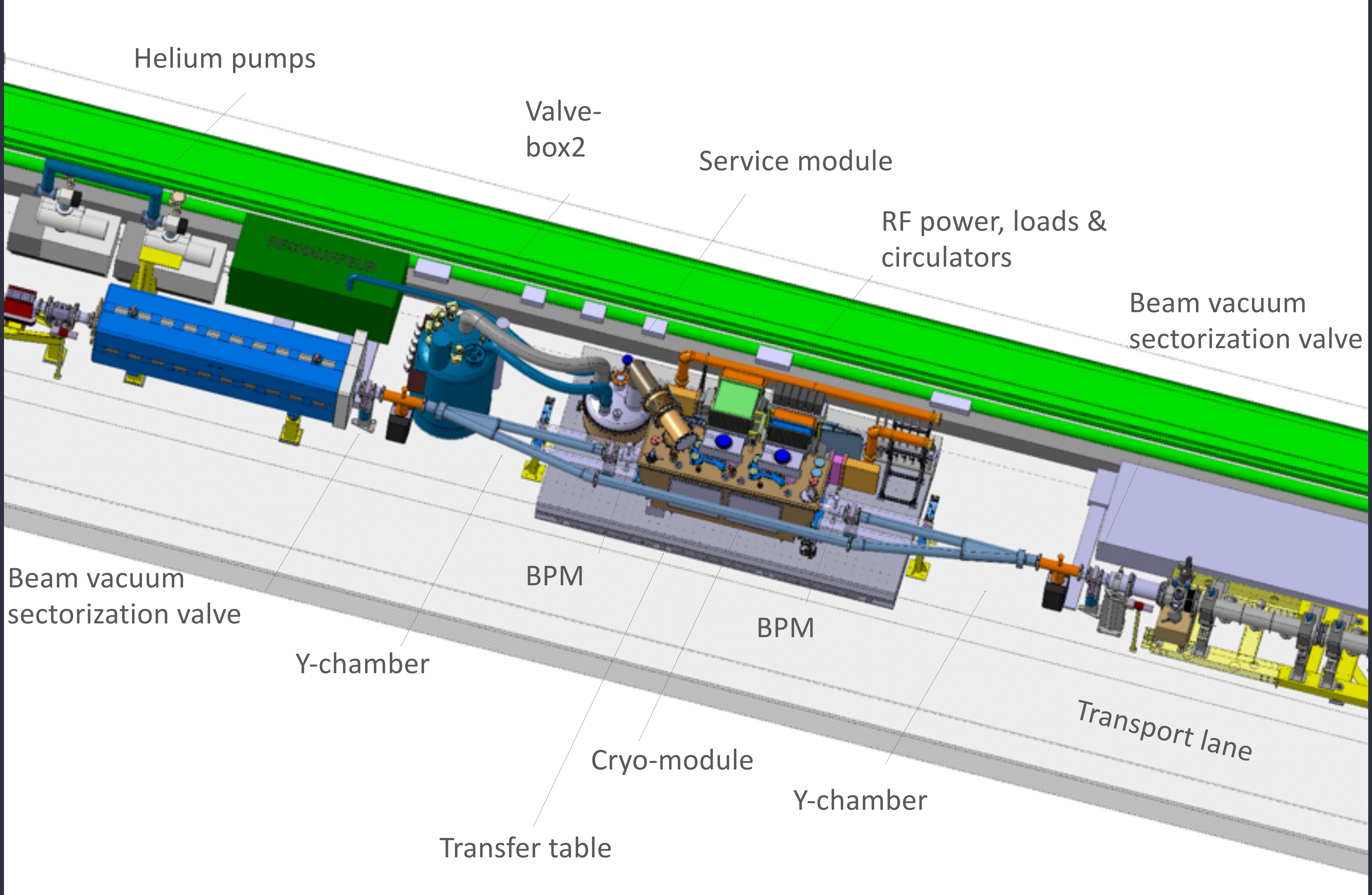






RF Dipole
- Horizontal crossing for CMS
- SPS test in 2021

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.

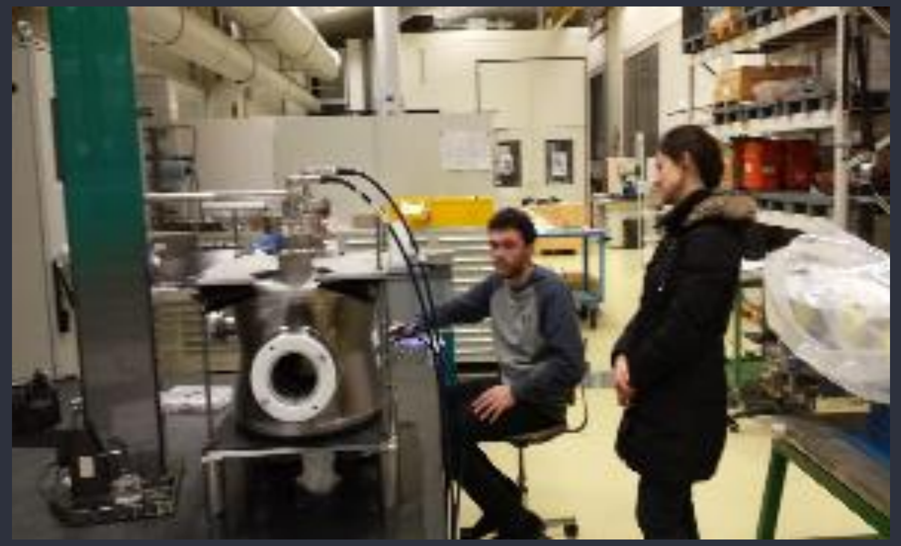
➡ Trip rate must not impact LHC availability.

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

Recent progress

Final weld on DQW #1

FPC mounting onto test box



Degreasing of DQW #1

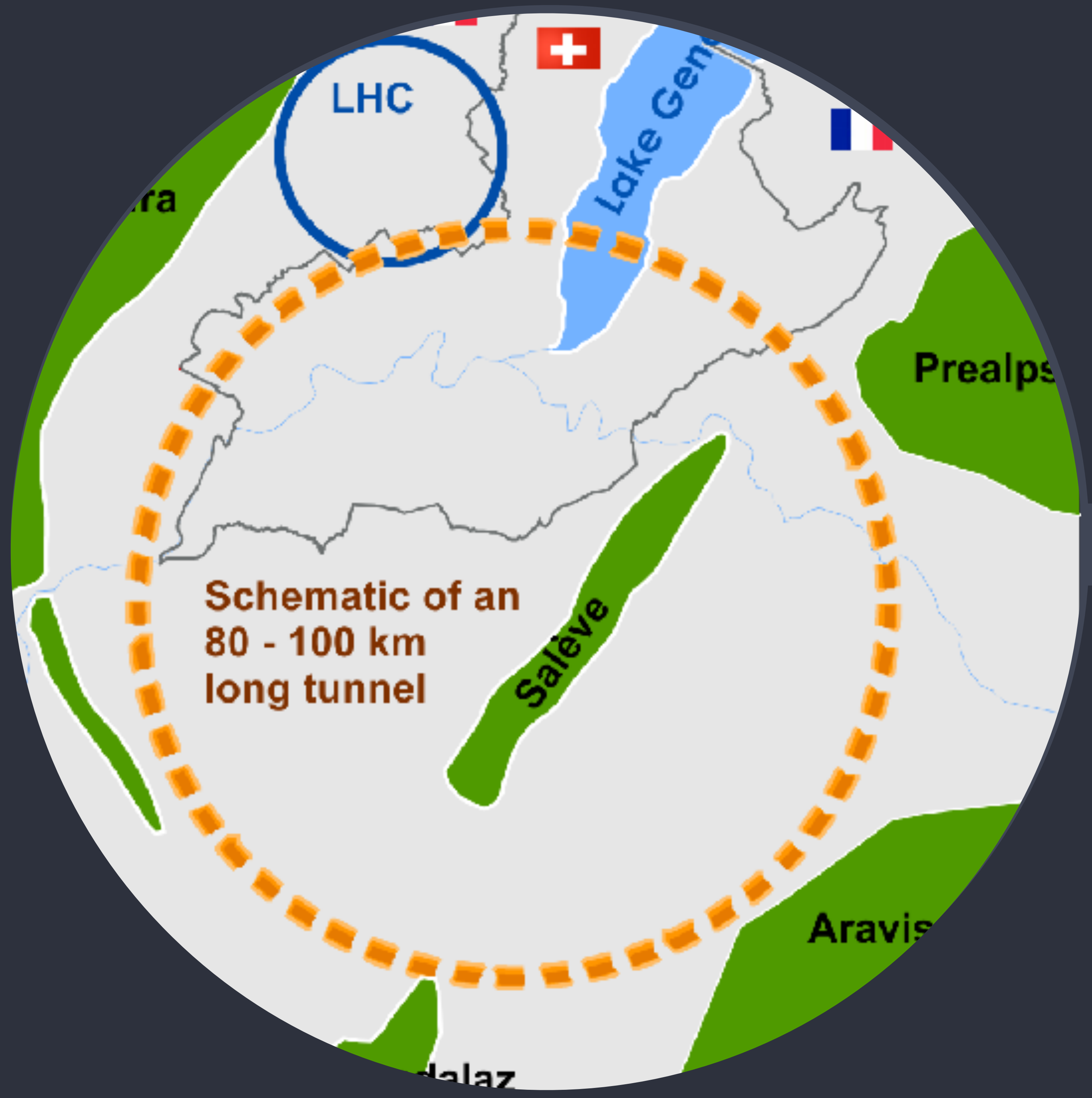
FPC conditioning

Frequency tuning successful

Chemistry of DQW #1

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 from the US, 8 tendered by CERN).



Future Circular Collider Study

- CDR until end of 2018,
- 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	0.32

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	0.32

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

"high gradient" machine

cavity options

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
beam current [mA]	**1450**	**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	53	107	107	200	160	667	533	32
cells/cavity	1	1	2	2	4	5	4	5	1
P_{cavity}	900	900	470	470	251	313	75	93	<500
	5.4375	5.4375	1.14	1.14	0.45	0.5625	0.099	0.12375	1.875

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

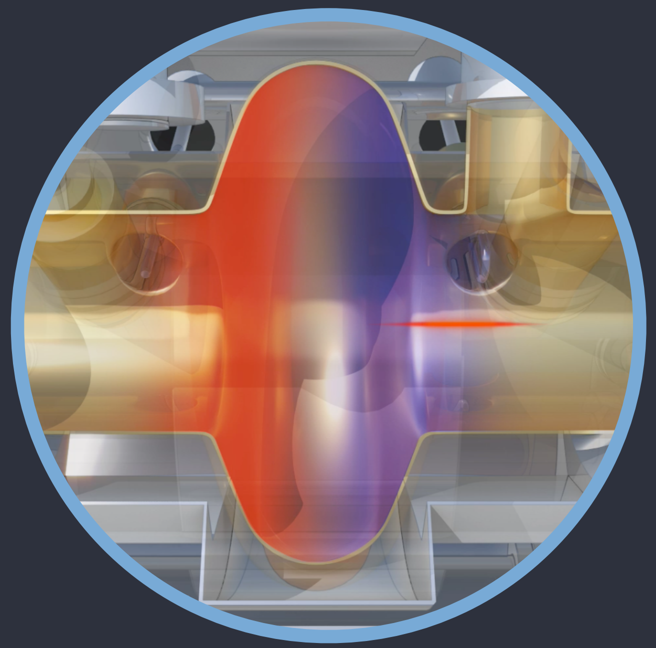
- lower frequency, low N_{cells}, low R_s
- 400 MHz, Nb/Cu, < 100 cavities
- FPC: aim at 1 MW/cavity (movable for hh, fixed for ee)
- HOM power < 1.5 kW/cavity
- 1 RF source/cavity (e.g. high efficiency klystrons)
- CM design to accommodate 1-cell (W) and 2-cell cavities (Z, hh)

"high gradient" machine

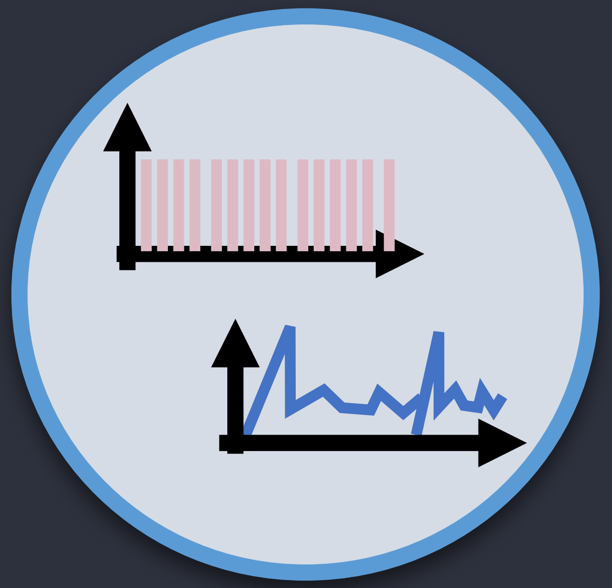
H t

- 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: SSA, IOT

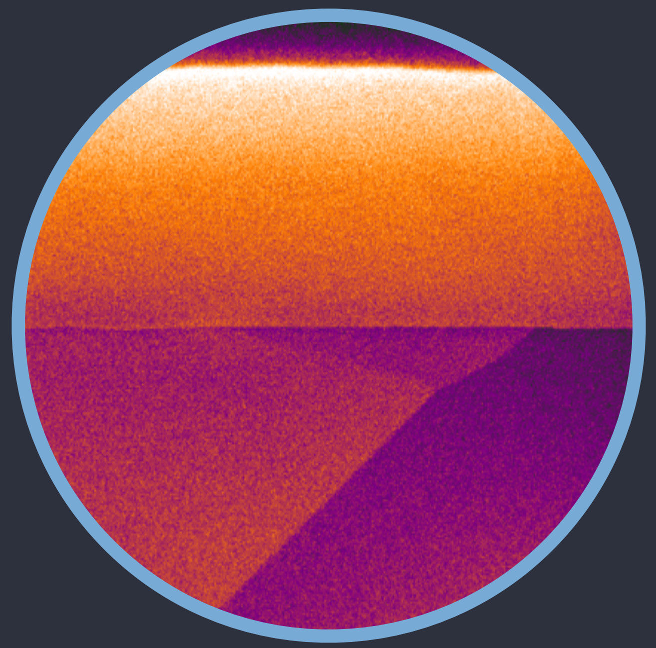
SRF R&D for FCC



optimize cell shapes

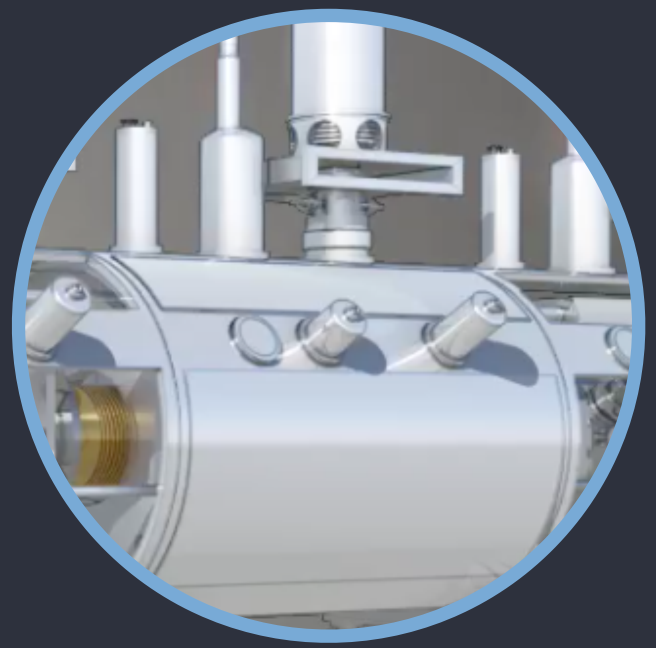


beam dynamics studies

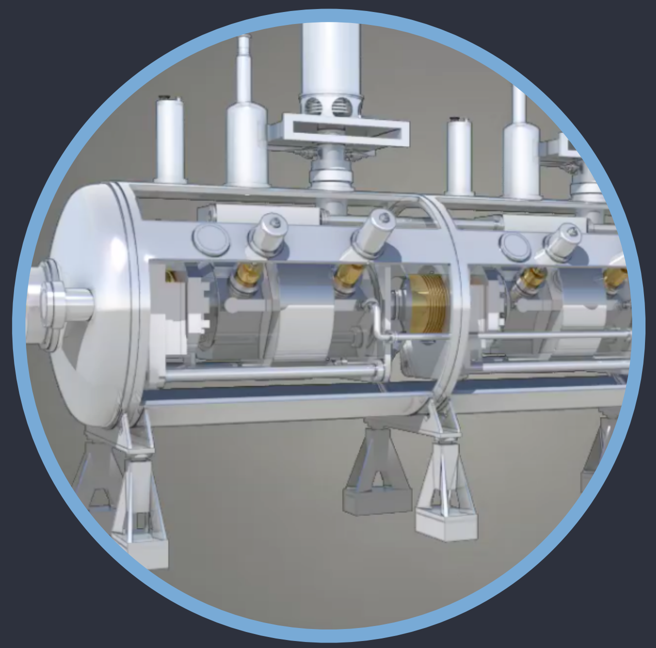


Q-slope mitigation

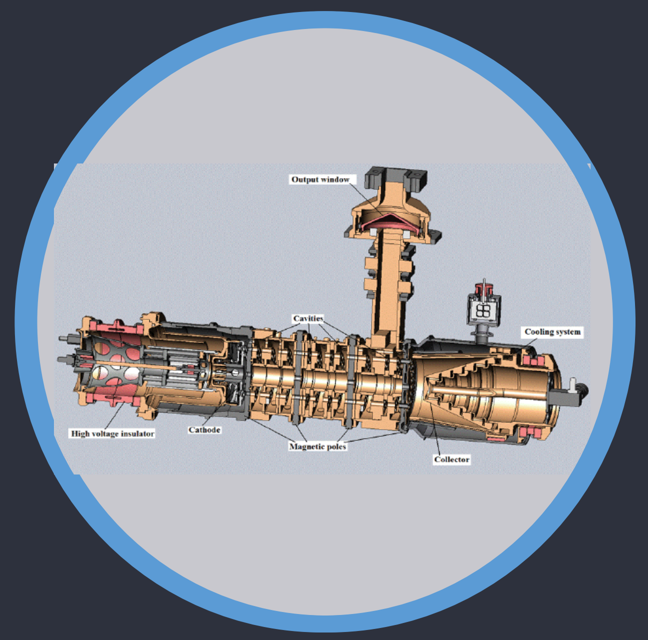
material & manufacturing



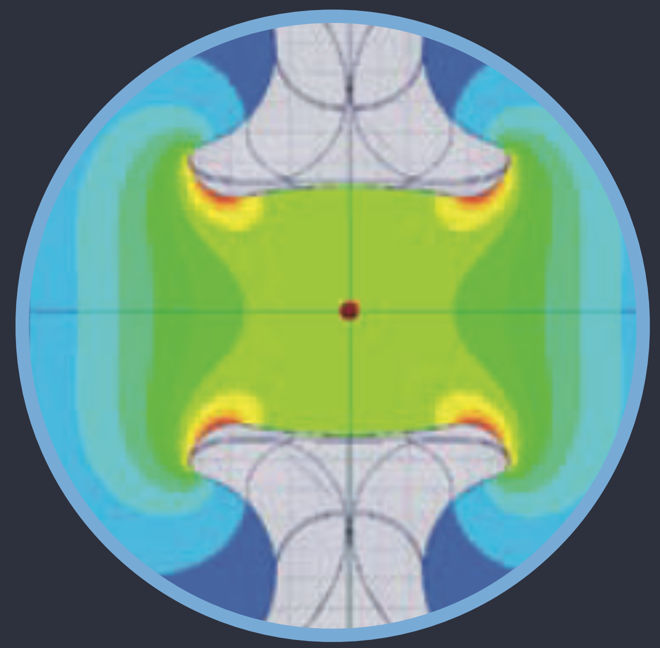
assembly & cost optimisation



ancillaries



efficient RF production



coated crab cavities

FCC

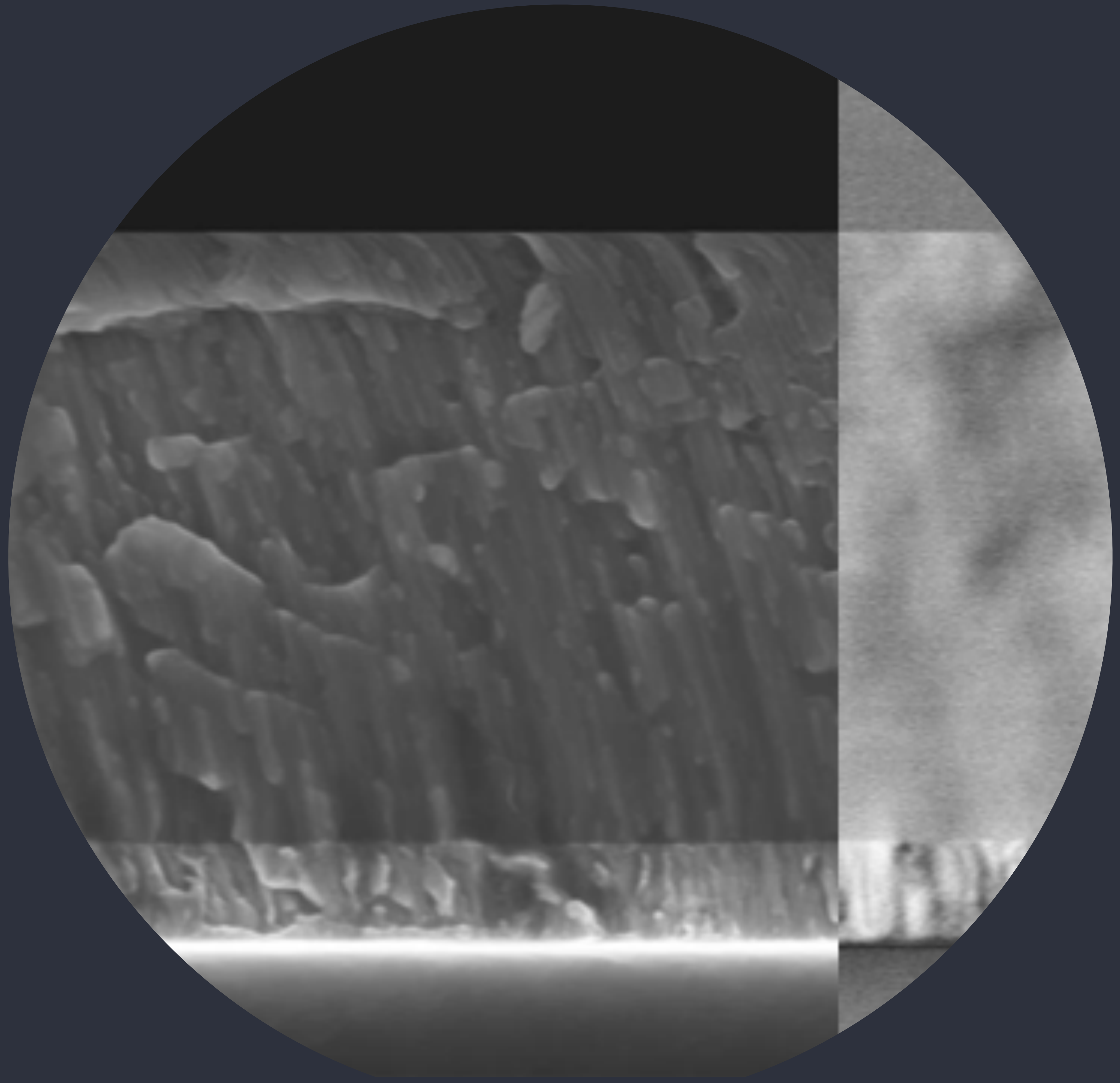
Thin film R&D

#

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.

Coatings within FCC



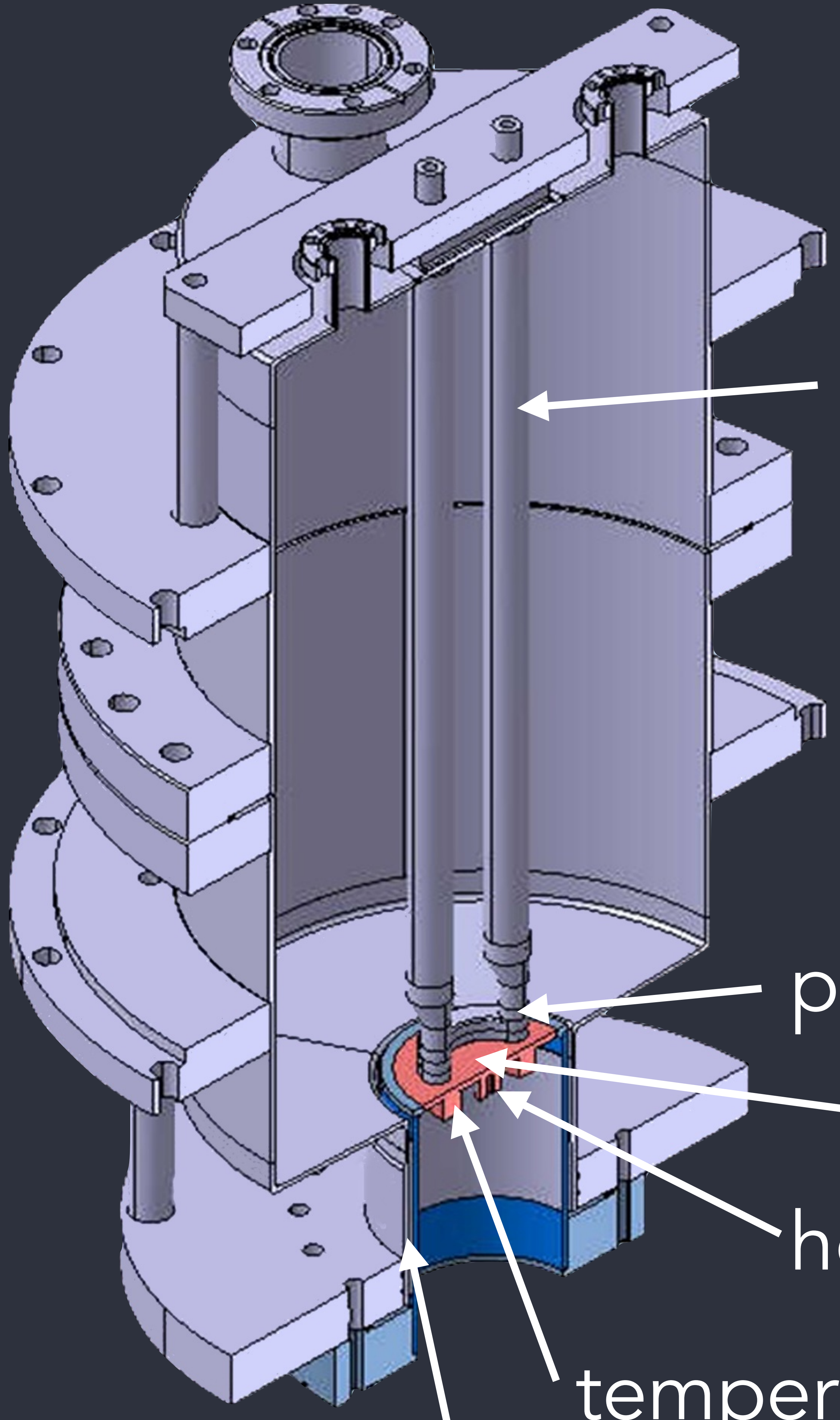
- Crucial: R&D on surface preparation of Cu and Nb surfaces.
- Full EP of substrates, upgrade existing facility for 400 and 800 MHz. 704 MHz multi-cell was already done in a vertical set-up.
- 800 MHz bulk Nb used as state of the art comparison.
- > 30 coatings on seamless 6 GHz cavities with a few for 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 with Ta diffusion barrier layer, so far: TC=12/12.5 K
- More details in session 1 & 2 by Sarah Aull.

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)

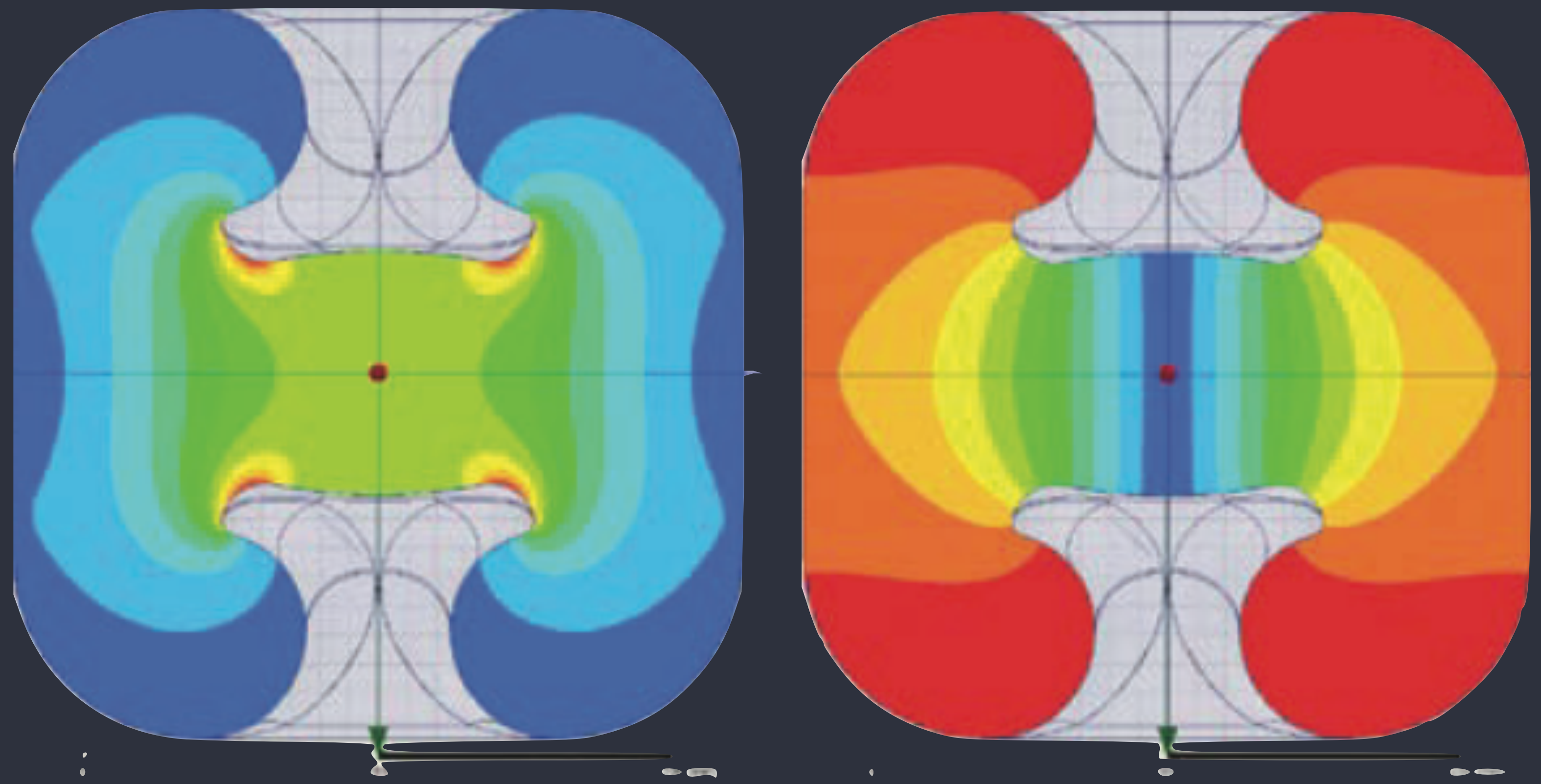
Why a Nb/Cu crab cavity?

- No thermal tun-away ("natural" quench protection).
- Crab cavity power needs are driven by off-axis beam and not by surface losses.
- Lower cavity impedance: factor 3-4 for $Z_{x,y}$ (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).
- Operation at 4.5 K.
- Mechanical stability (much lower microphonics: easier RF stabilisation).
- Structure can be cascaded.

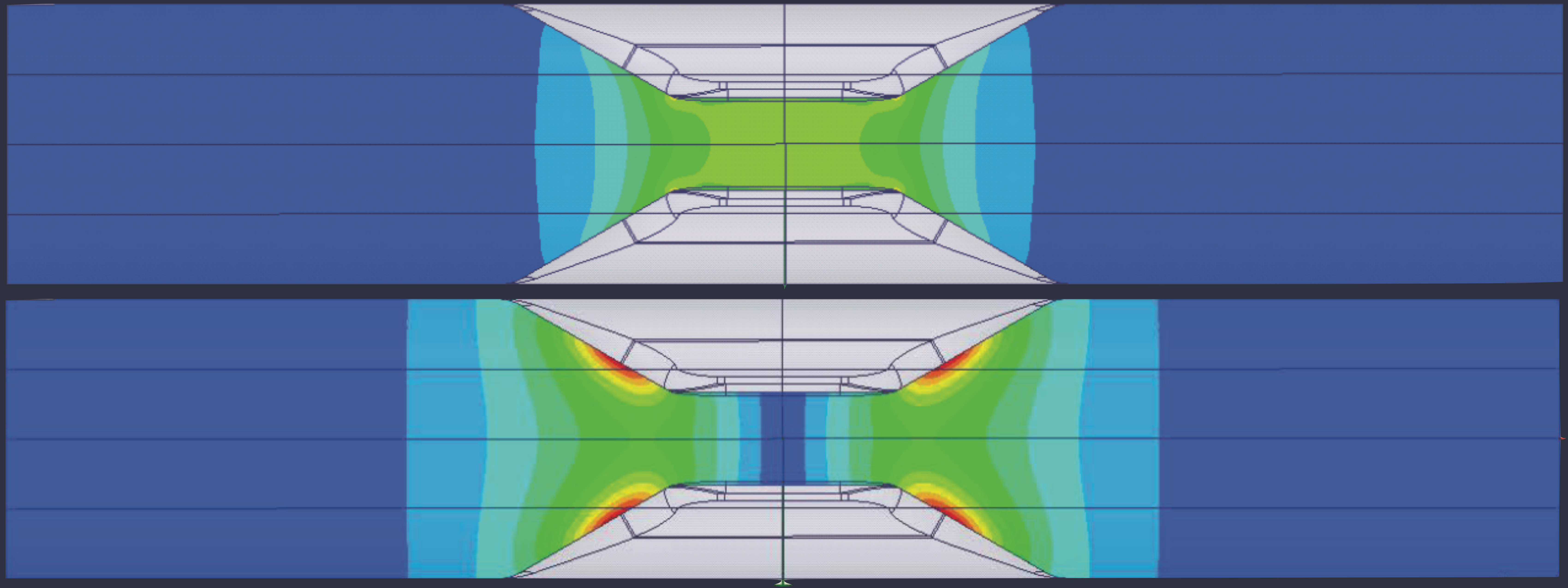
Wide Open Waveguide cavity

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



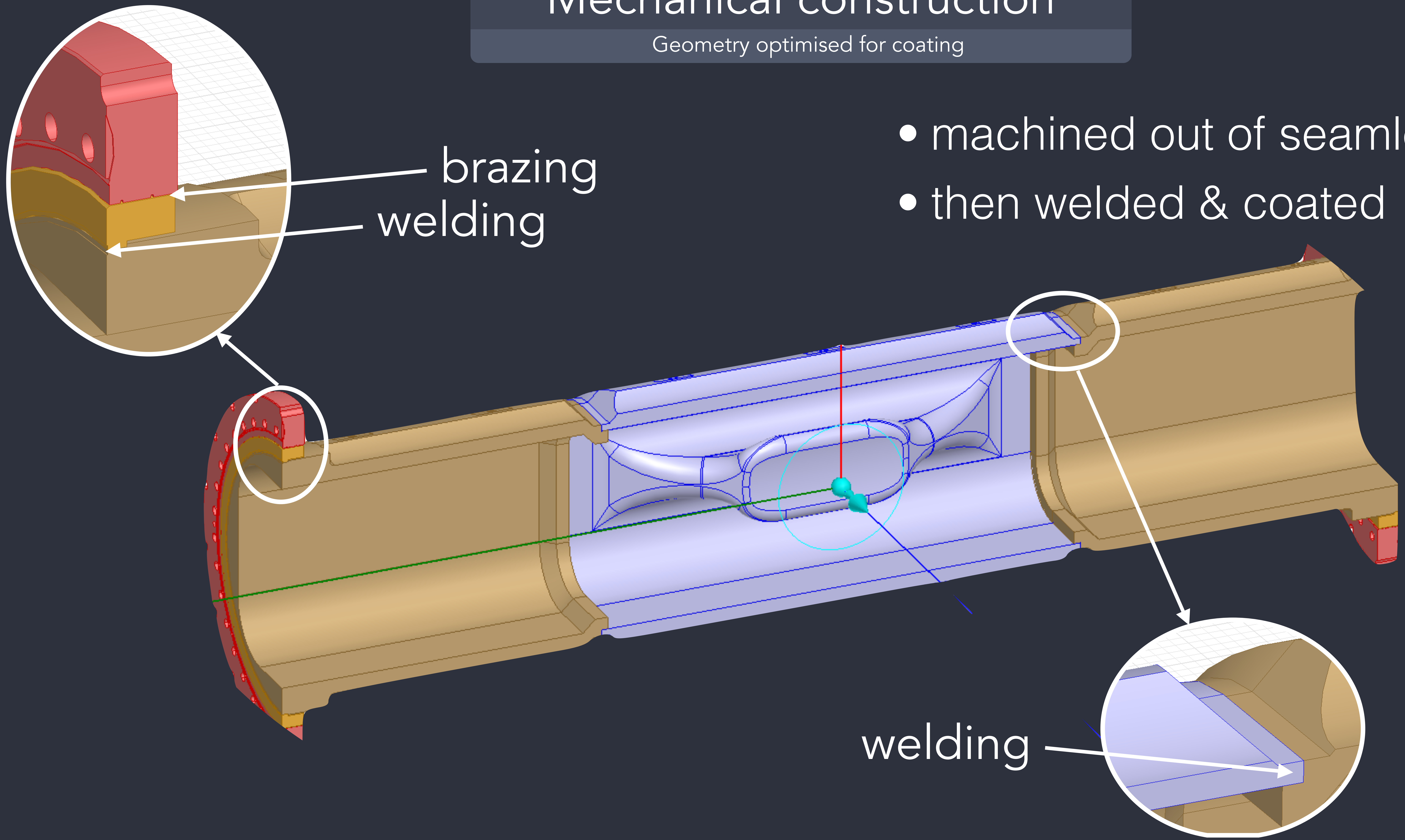
electric

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.

2016				2017				2018				2019		
material procurement, drawings				fabrication 1st prototype										
							fabrication 2nd prototype							
				coating design & construction					coating, cold testing, re-coating					

Summary

- HIE ISOLDE low-beta QWR: 2 modules installed, 2 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.
- Extensive Nb on Cu R&D with a few towards FCC, 400/800 MHz with modest gradients.
- short to medium term: focus on HIPIMS Nb/Cu.
- long term: A15 coatings on Cu.
- Work on bulk Nb crab cavities for HL-LHC and 2nd generation coated crabs for FCC.
- Improved power couplers, aiming at 1 MW CW.