The High Gradient Program & Other SRF activities at CERN

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Content

High gradient program

…history and status

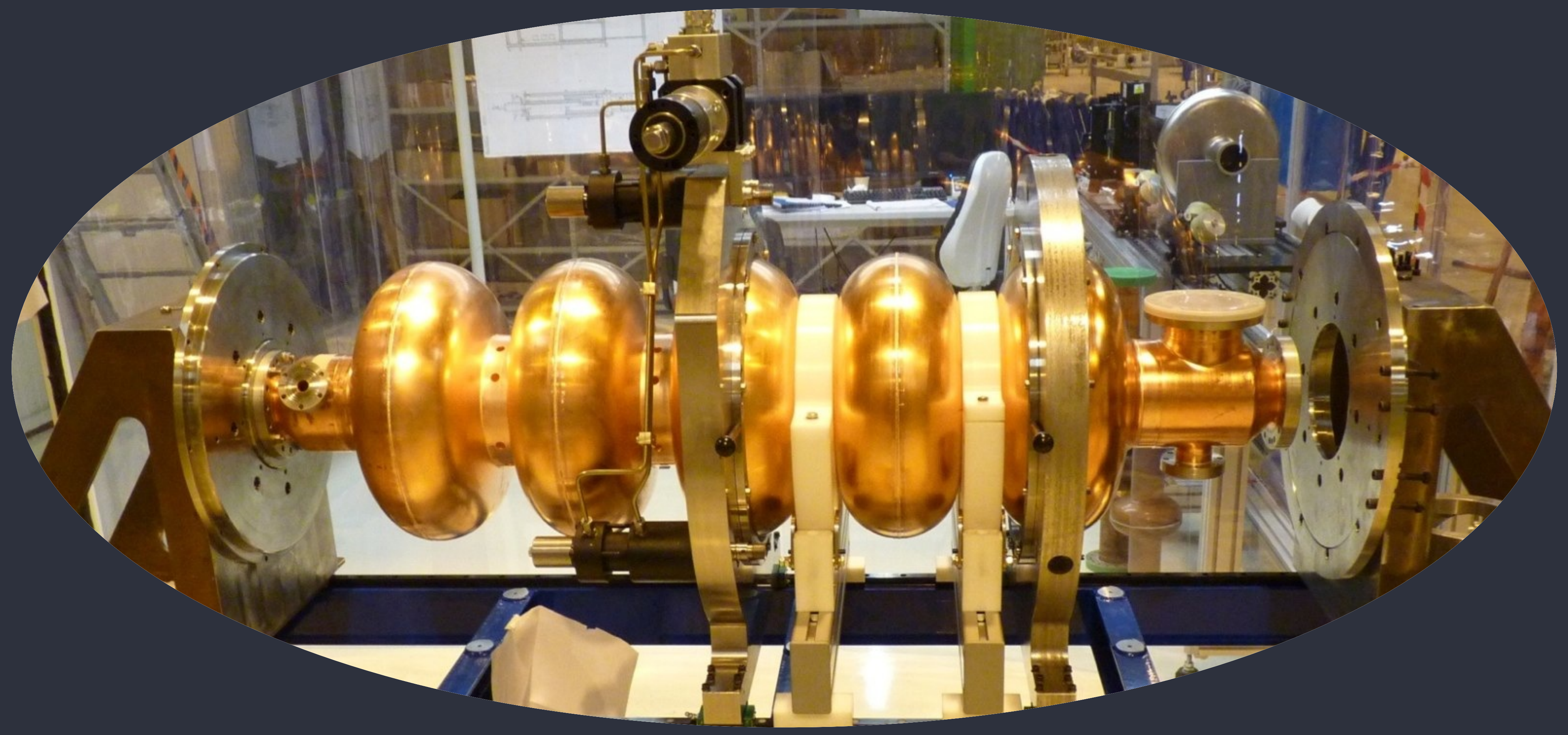
The SPL/High Gradient Program

2000 - 2017

2000	First SPL conceptual design report (re-using LEP SC cavities), CERN 2000-012
2006	2nd SPL conceptual design report (bulk Nb 5-cell cavities), CERN-2006-006
12/2007	Council approval for “new initiatives”: preparation of a SPL technical design report and cost estimate.
12/2008	1st SPL collaboration meeting: need to build SC Nb cavities and upgrade SM18 infrastructure (clean rooms, 704 MHz RF, vertical bunkers, etc.), ground breaking of Linac4,
2009	•SPL & Linac4 are part of sLHC, planned date for Linac4 beam + PSB modifications: April 2014 •SPL construction start foreseen for Jan 2013, •ESS will be build in Lund •ESS/SPL looking for synergy and cost sharing, planning for an 8-cavity cryo module at CERN to transform XFEL/TESLA technology to 704 MHz and to demonstrate 25 MV/m, start of infrastructure upgrade at CERN, start of coupler work
2010	Decision not to build SPL but to upgrade PSB, decision to build 4-cavity cryomodule for first half of 2013, 8-cavity cryomodule for first half of 2015: SPL becomes an R&D program with the goals: i) preserve potential for alternative physics programs, ii) preserve possibility of new injectors for the long term, iii) update CERN competences in SRF
2017	4-cavity module assembly is now foreseen only for 2019 as the assembly space is blocked by the CRAB and LHC spare program. SPL is suggested as a potential part of the FCC injector chain to enable 5 ns bunch spacing (see FCC week, Elena Chaposhnikova).

Cavity fabrication, tuning, warm testing

EN-MME



2 Cu cavities + 4 Nb cavities (RI) + 1 Nb cavity (CERN)

- development of 1/2 cell f-measurement
- development of cell-by-cell tuning bench (picture)
- CERN's first optical bench for cavity inspection from Kyoto Univ./KEK
- technology transfer of port extrusion from CERN to RI
- automated bead-pull measurements to record HOM spectrum

Electrohydroforming

- collaboration with BMAX started for HG cavities,
- first developments done on 704 MHz HG Cu shells,
- further developed for 704 MHz Nb,
- today being developed for 400 MHz LHC/FCC Cu substrates,

Cavity chemistry & cleaning

TE-VSC

Vertical Electroposlishing

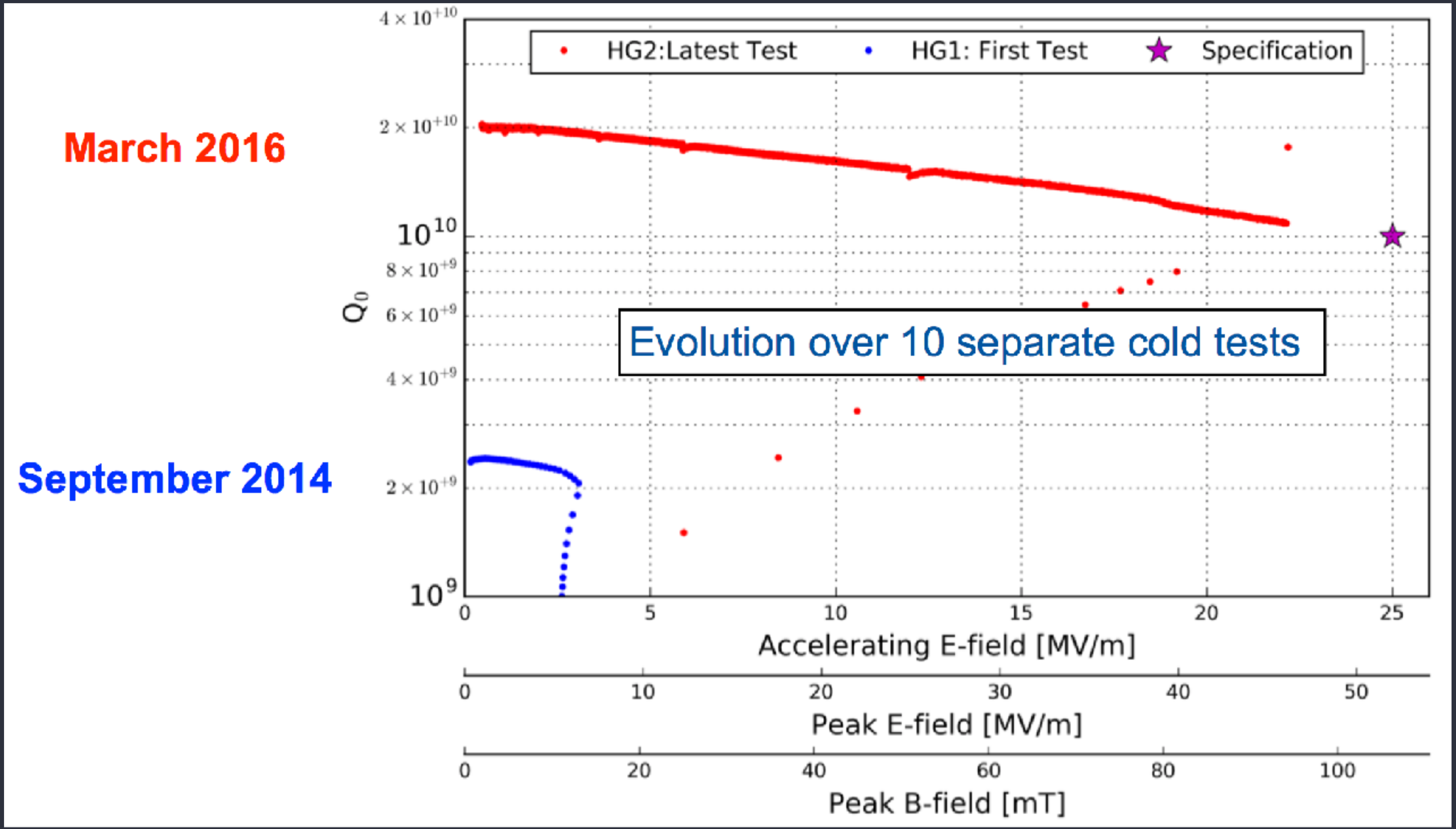
- Development of vertical EP process.
- No moving parts, less risk, but more difficult flow dynamics.
- 3 iterations of cathodes led to an optimised process giving excellent surface quality.
- 3 cavities processed so far.
- Unique facility in the SRF world!

High Pressure Water Rinsing

- Installation and commissioning of HPR station with direct access to clean room.
- On site water cleaning station and particle counting of waste water.
- Development of HPR process using HG cavities as test objects (time, particle counting, handling, outside surfaces, nozzle, …)
- HPR accounts for 90% of the re-treatments done on XFEL cavities, crucial technology
- Was then adapted for the CRAB cavities.

Cold testing

BE-RF

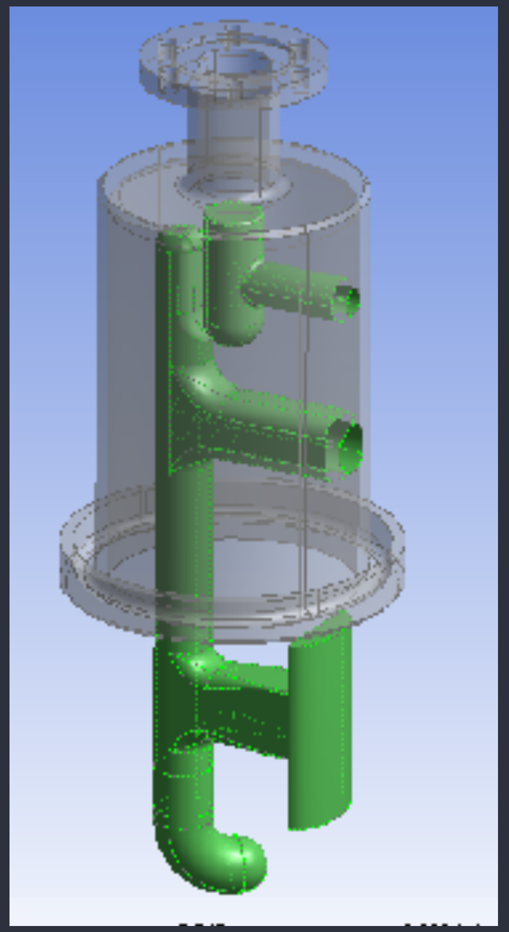


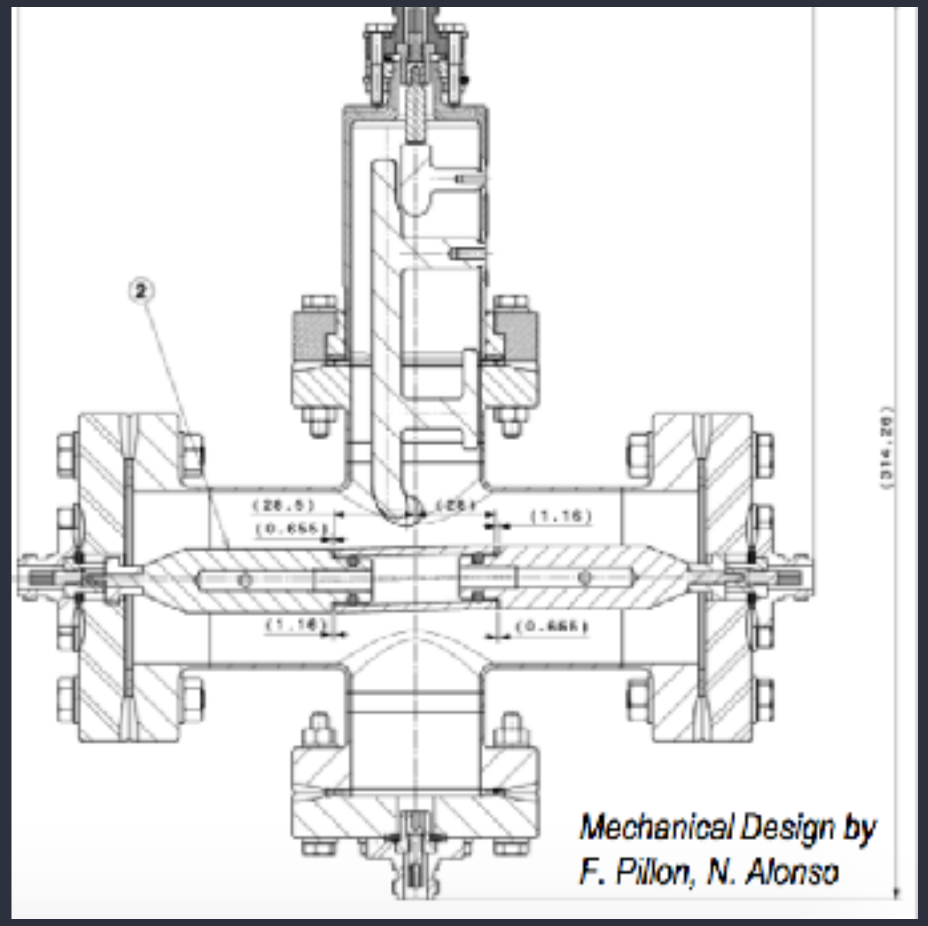
Last year we presented 22 MV/m. This year's results will be presented by Katarzyna Turaj

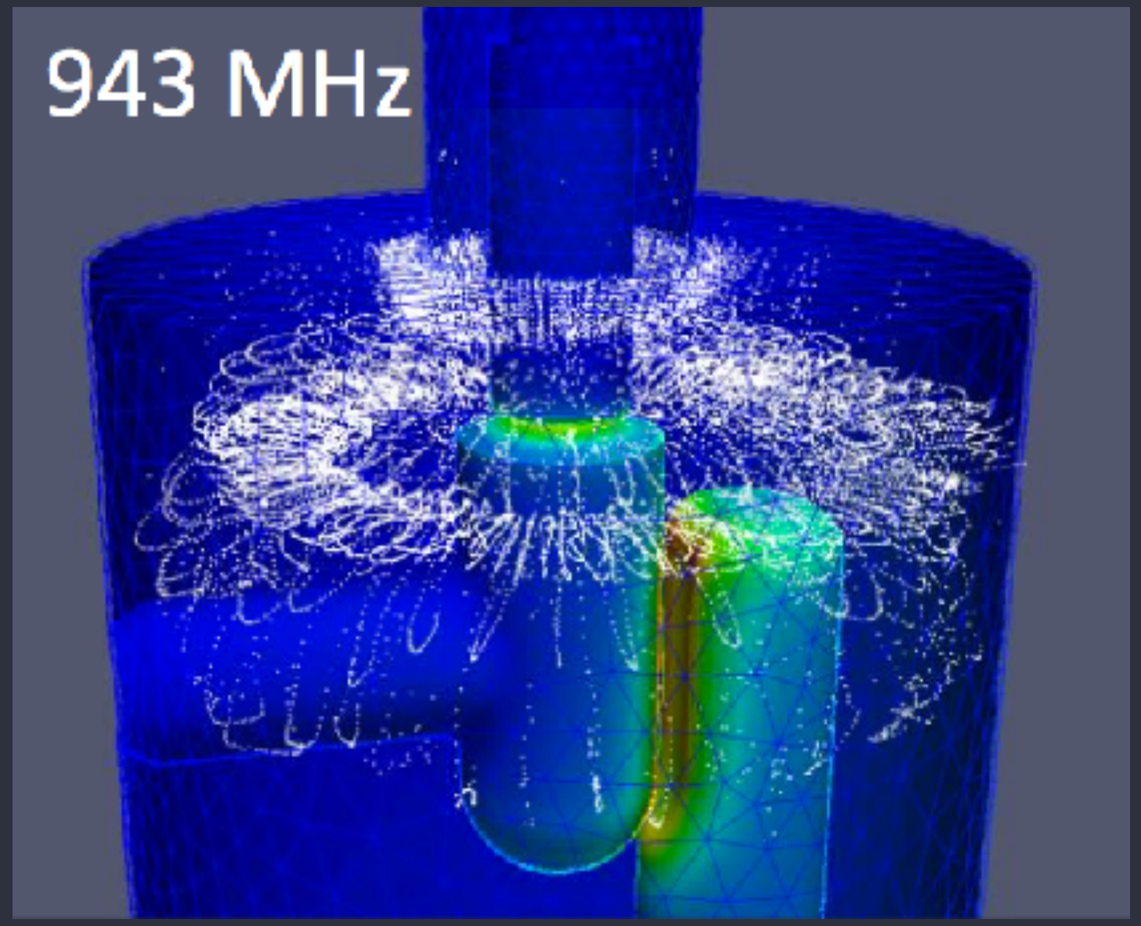
HOMs

2 doctoral thesis

- On J. Tückmantel's advice HOM's in the SPL machine were studied in depth.
- Marcel Schuh made his thesis on finding the conditions under which there could be beam destabilising HOMs in the SPL: if one wants to keep open all possible chopping and pulsing schemes, then one cannot exclude that dangerous HOMs appear.
- Kai Papke is finalising his thesis on defining and building appropriate HOM dampers.
- Nb HOM dampers under construction, one damper shall be installed in the module.







CM integration and assembly

CEA, CNRS, TE-MSC, EN-MME

The High-Gradient 4-cavity cryo-module

- Started as a French in-kind contribution, drawings + vessel (2010 - 2015, followed by V. Parma)
- Vittorio developed the concept of supporting the cavities with the power coupler,
- Principle was experimentally validated with a cryo-mock-up (V. Parma + R. Bonomi)
- In 2015 the design and integration effort was taken over by MME (Luca Dassa).
- Since then: large effort on drawings, safety documentation, specifications, re-design of magnetic shield, etc…

High-Gradient status

Design update & general progress:

- ~520 hours to modify IN2P3 design and to transfer CAD data (3D model, 2D dossier).
- ~2300 hours of mechanical design for updating the design & drawings, tools for clean room assembly & cryostating, tooling design for tuning, cold-test, welding, half-cell manufacturing
- Redesigned magnetic shielding: cold shield + warm shield + active compensation coils.
- 3 cavities are EP treated, 2 are high-power tested (more news in Katarzyna's talk).
- CERN cavity is ready for welding. Presently waiting for a slot in the welding schedule.
- All CM components (incl. instrumentation, alignment, etc.) have been defined, specified, and integrated. Many components are ordered.
- A valve box for SM18 (compatible with Crabs) has been ordered.
- MB IOT test stand was established and commissioned, Thales/CPI tube was tested (see Eric's talk).
- High power coupler development (Eric).
- Transition Edge Sensors for quench location (Hernan)
- **Loan of high-power test stand to ESS (addendum 26): can continue until autumn 2018.**

High-Gradient planning

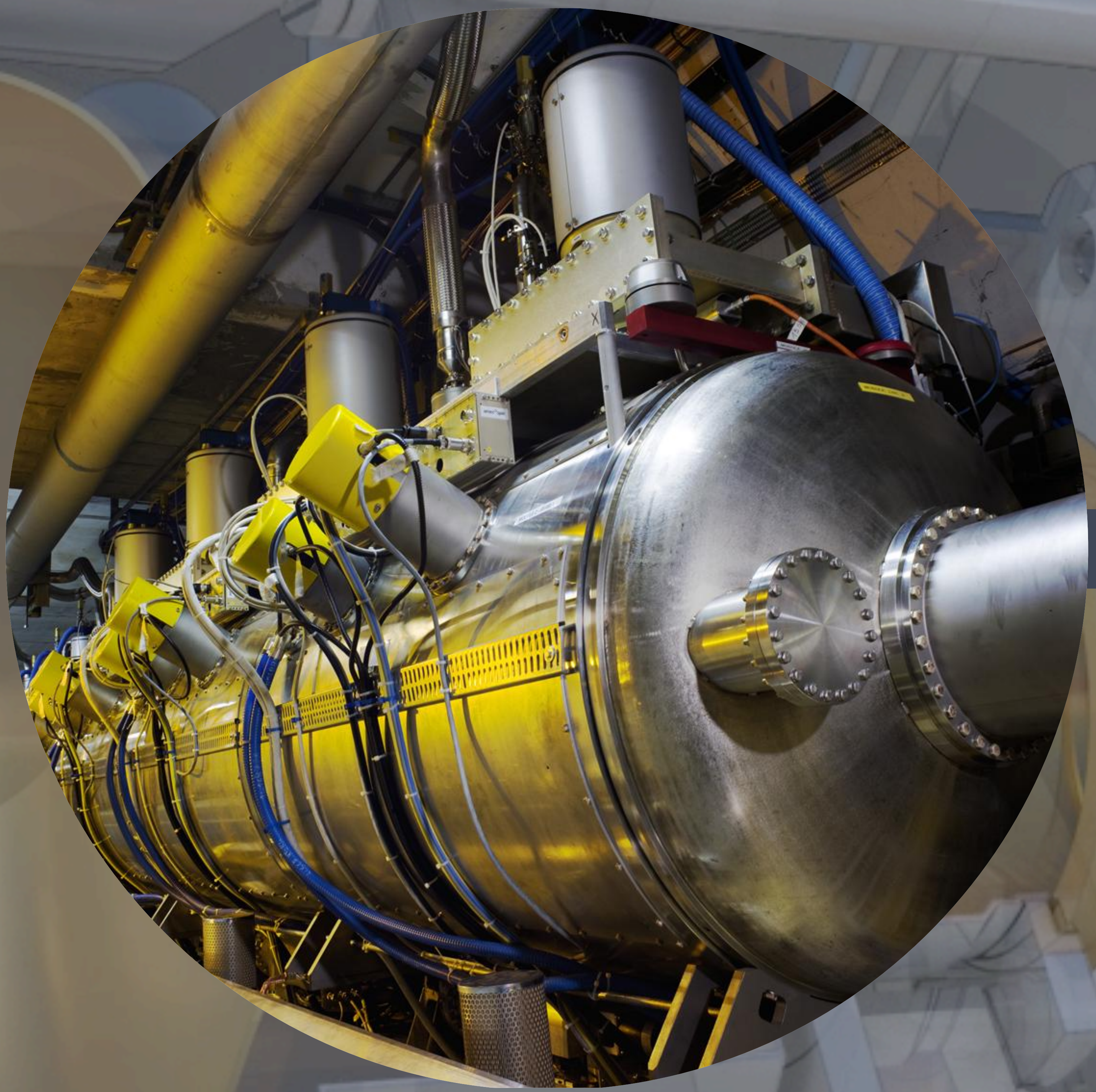
Until the completion of the SM18 extension, we do not have a space to assembly the HG module (occupied by Crab cavity program) —> updated schedule.

2017			2018				2019			
Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Cavity testing & He tank welding, tooling, cryogenic piping, material orders										
					clean room string assembly					
					cryostating					
								SM18 shut down	cold testing	

Summary HG

A RICH R&D PROGRAM

- started in the SPL context and was supported by ESS,
- was the reason to establish and upgrade substantially the CERN SRF infrastructure (clean rooms, HPR, EP, optical bench, tuning, vertical test stands, high-power RF,…)
- It drove some key SRF developments, which are today beneficial for other SRF activities: HPR procedures, cold test preparation procedures, clean handling, having 2 K in the SM18 bunkers, SRF coupler development, fundamental work on HOMs in linacs, new CM concept (couplers supporting cavities),
- today we have accumulated 6 years of delay on the original 3-year plan, because the priorities were shifted to HIE-ISOLDE, CRABs, and LHC spares,
- the experience (and infrastructure) gained with HG program, helps us to succeed with the CRAB cavity program for the SPS test.



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.**

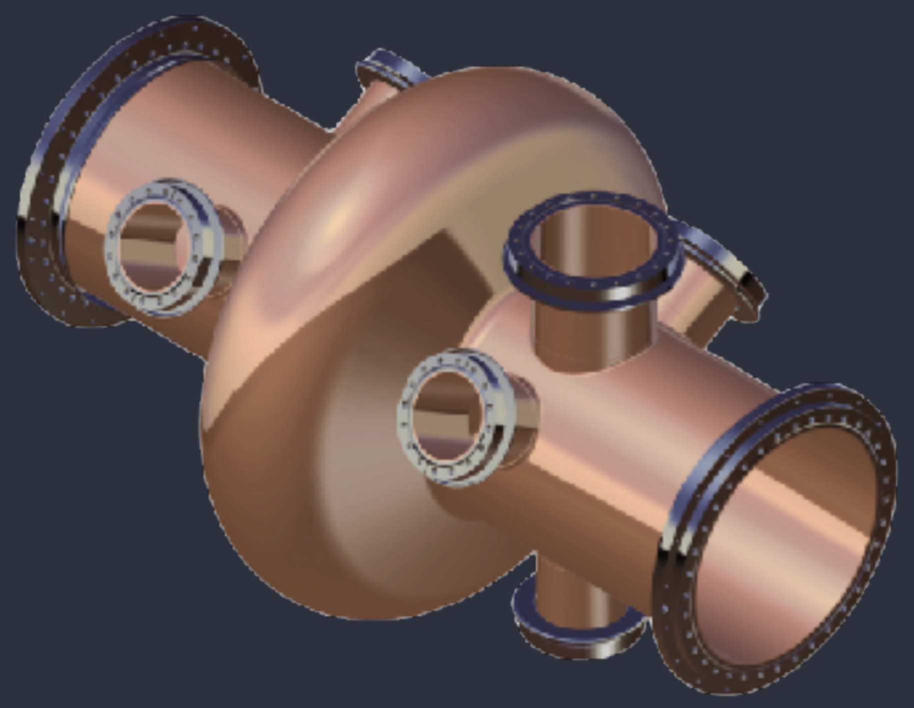
The LHC spare cavity program aims at producing 1 complete cryomodule and one spare cavity train (4 cavities).

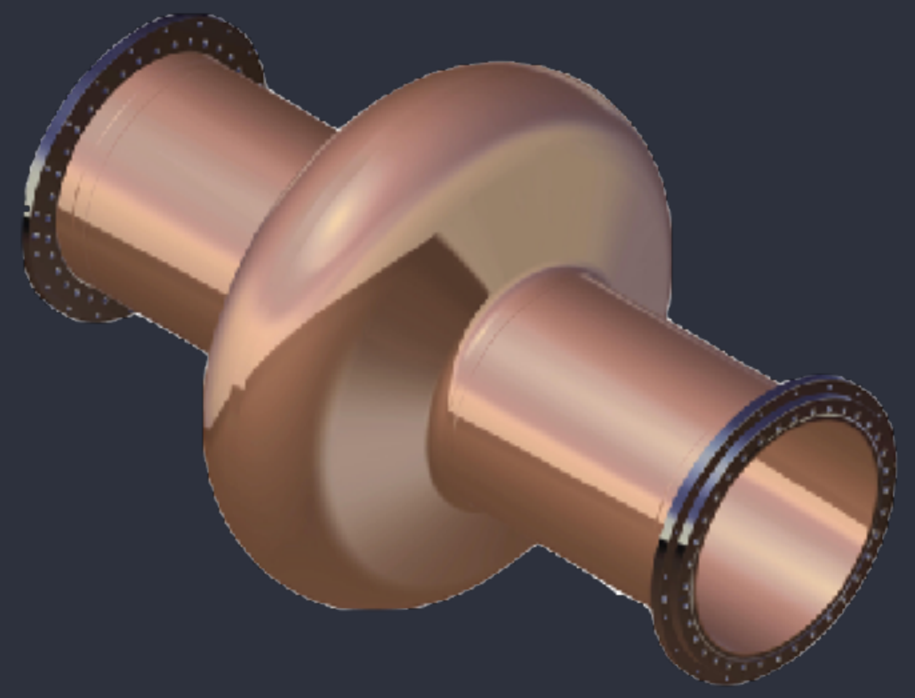
➡ re-establishment of engineering folder, welding, tuning, assembly, and coating procedures

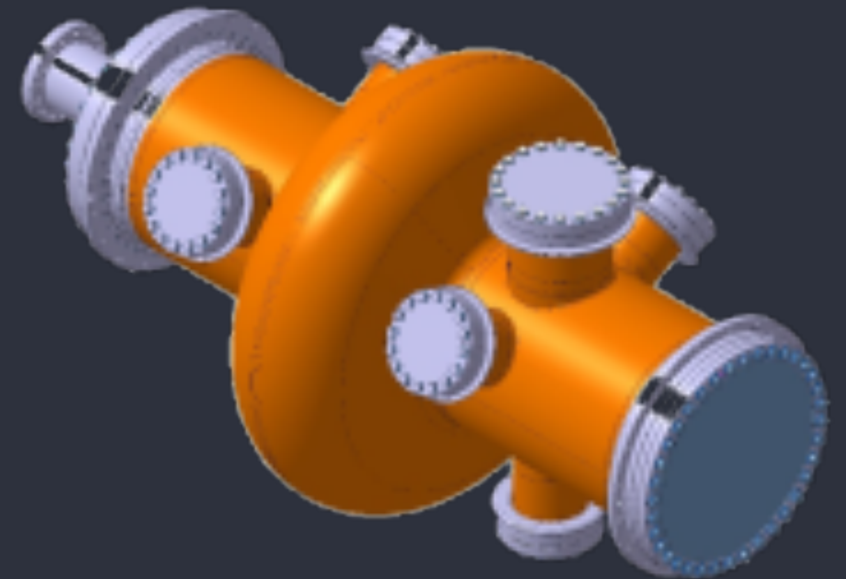
➡ industrial production of cavities and subsequent coating at CERN

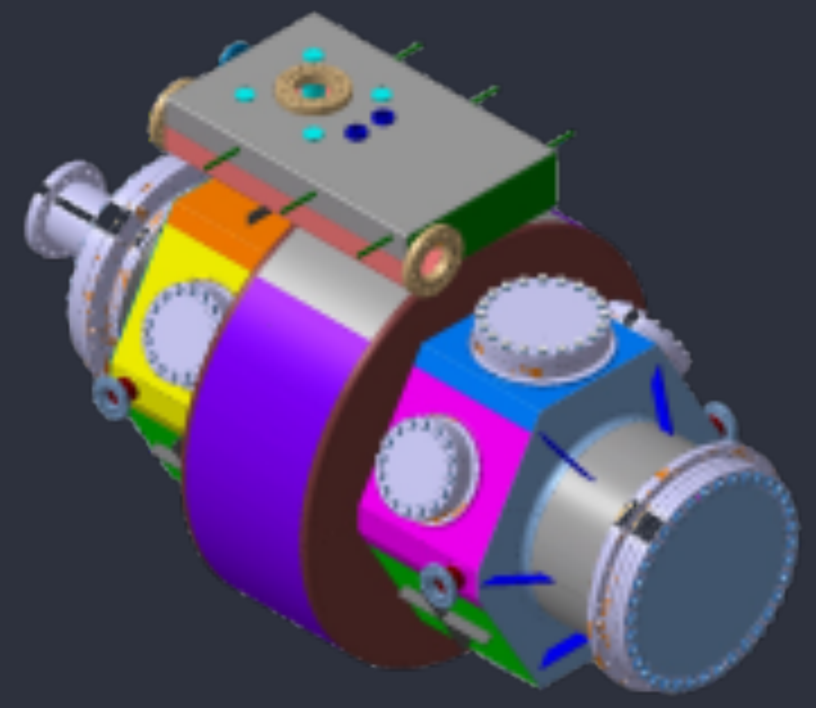
➡ collaboration with BINP on production of cut-off tubes started

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),
- several re-coatings

➡ **coating and cold testing validated**

Practice cavity 3,5

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

➡ **forming validated, coating consolidated**

Model cavity

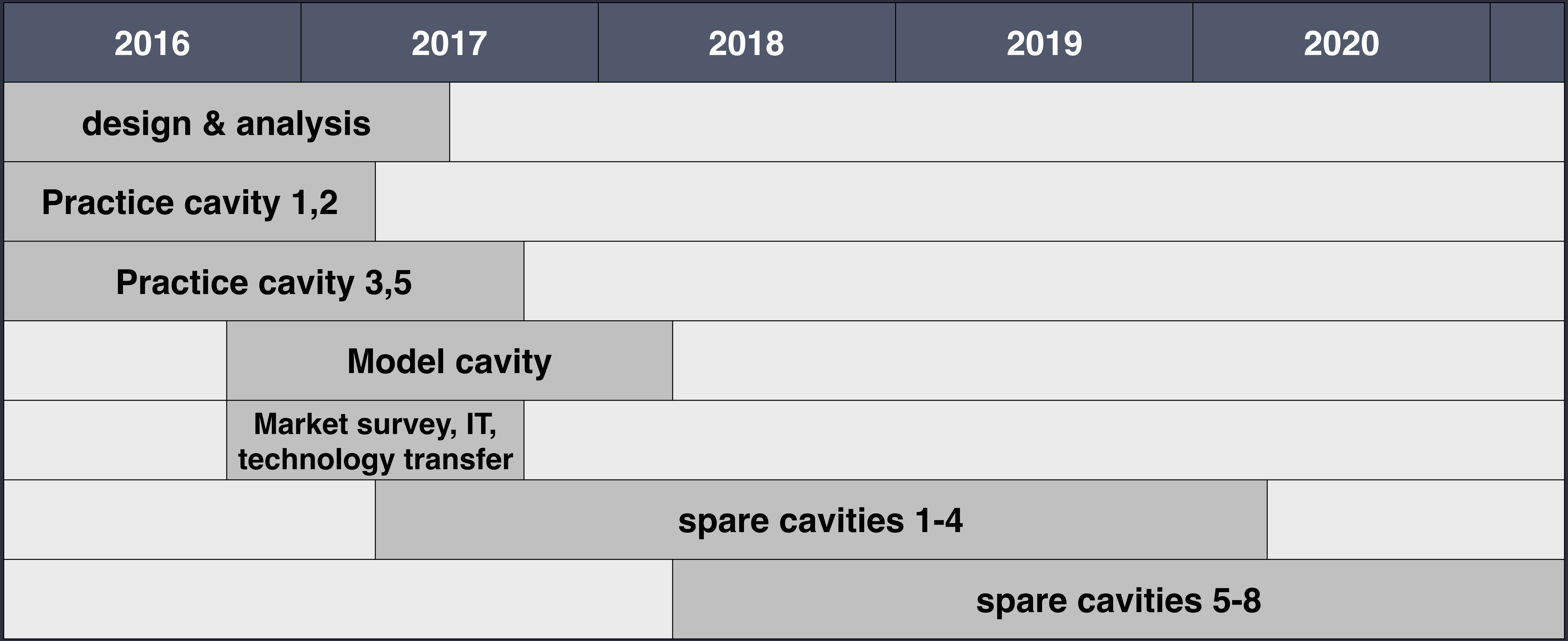
- He-tank updated design,
- cold test expected August 2017
- if successful: the first spare cavity

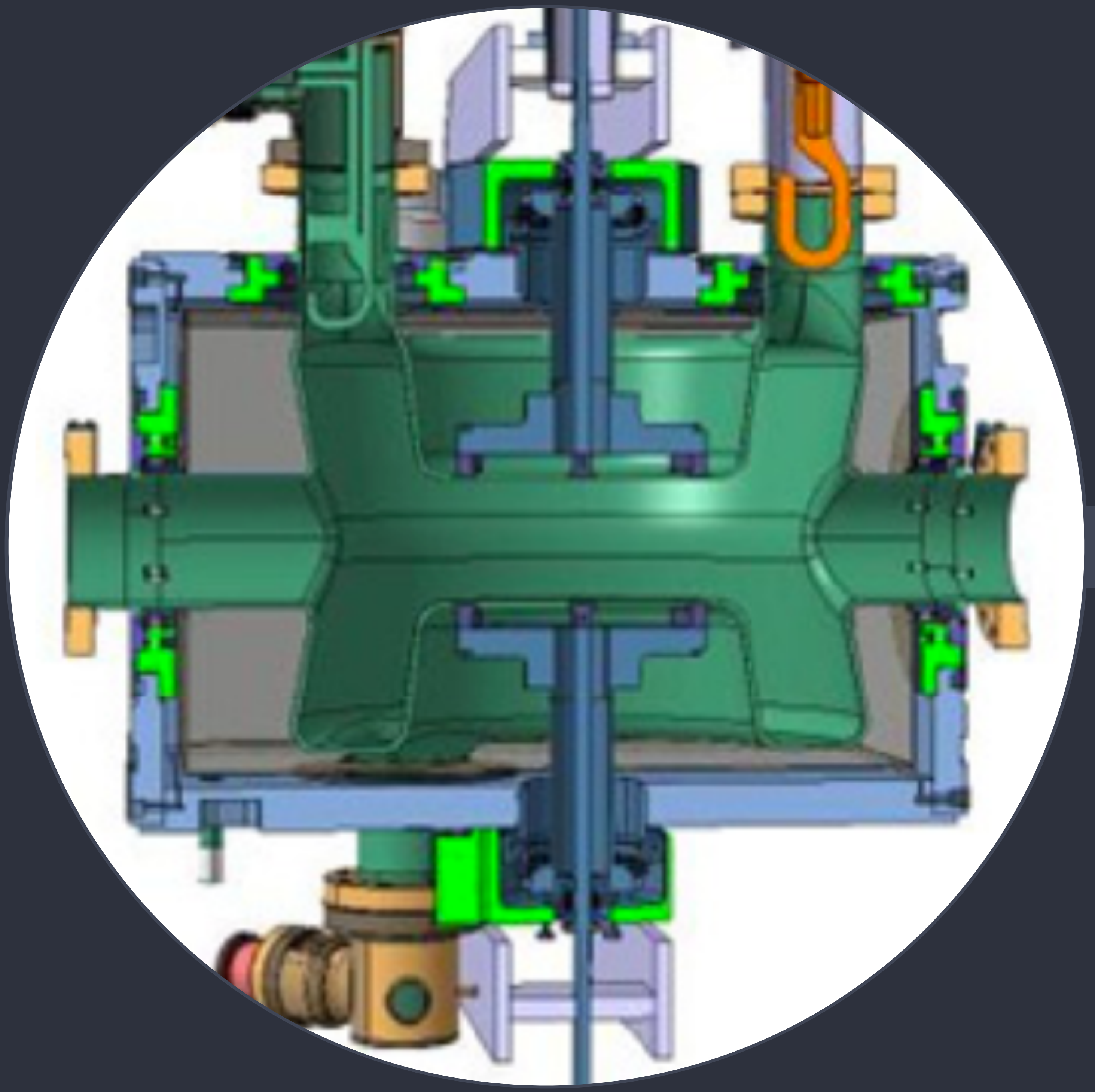
➡ **validation of cavity design & fabrication process**

Series production

- 8 cavities + 2 spares,
- technology transfer to BINP for cut-off tube production,
- production of half cells (spun or EHF)
- He-tanks tendering in 2017

LHC spares: timeline



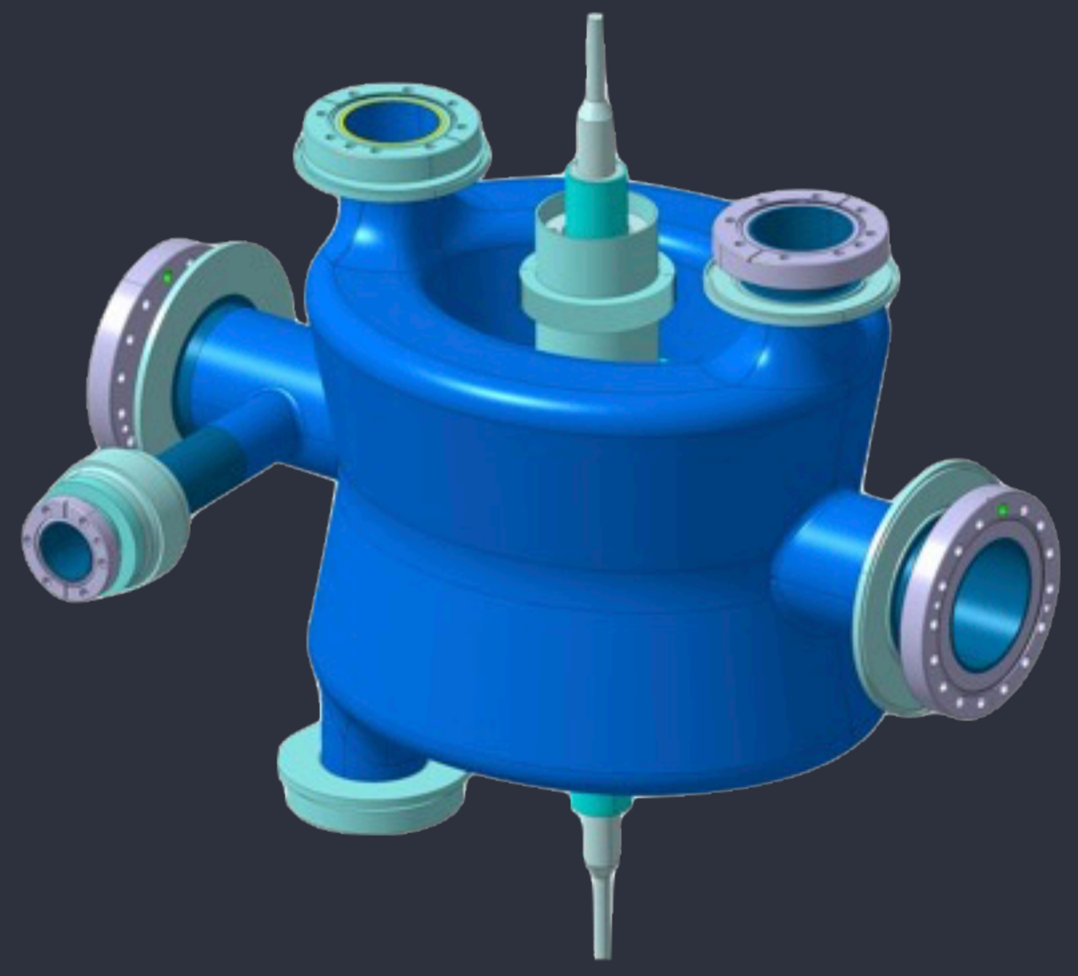


High-luminosity LHC

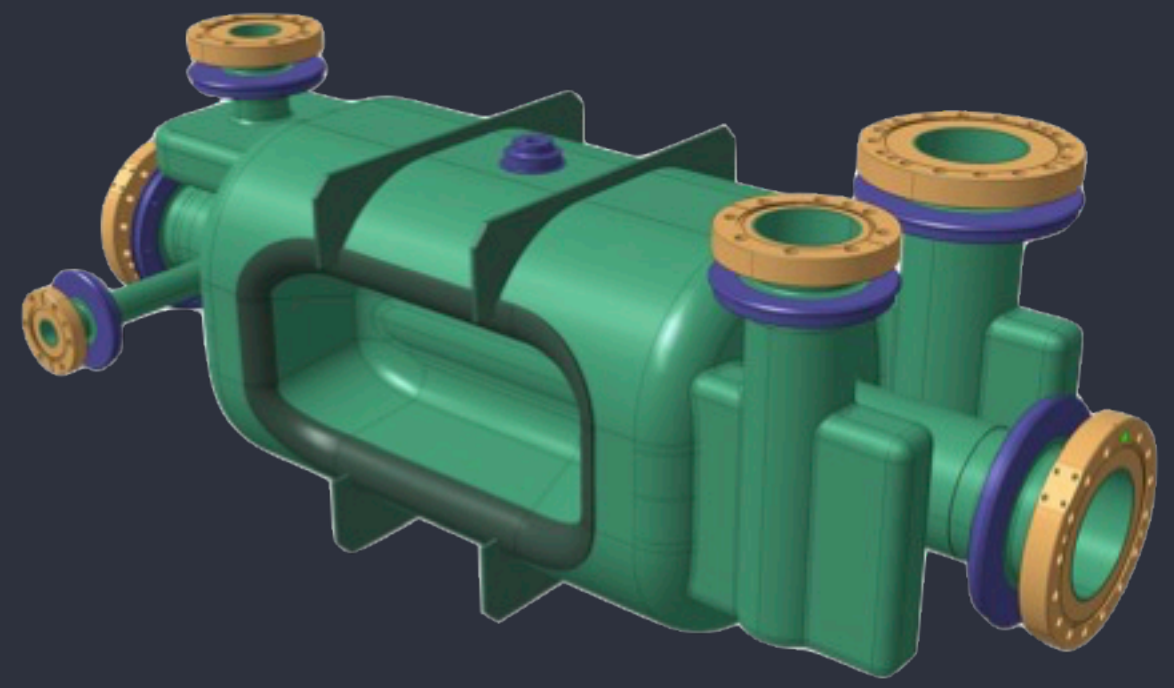
the largest HEP accelerator in construction (1.2 km of LHC!)

2 types of Crab cavities

Double Quarter Wave



RF Dipole



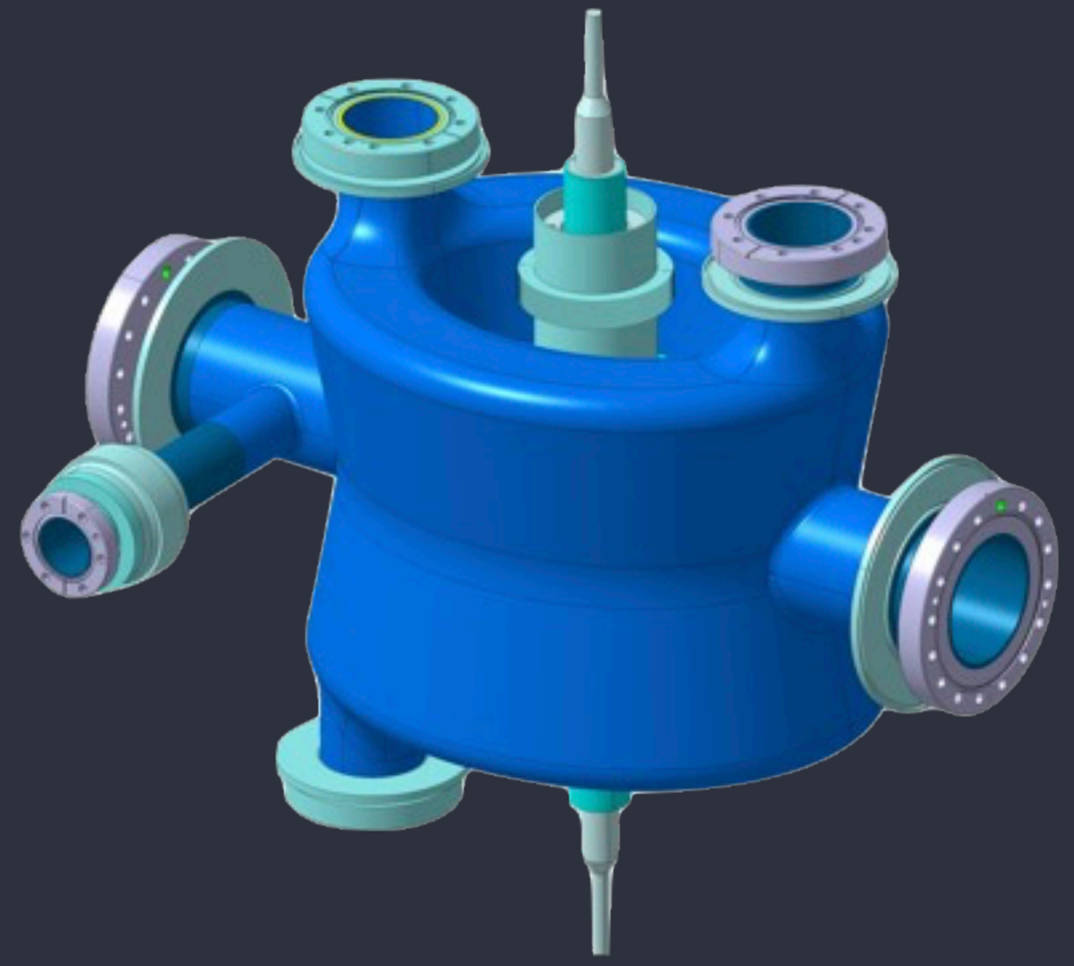
Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power (SPS)	40 kW

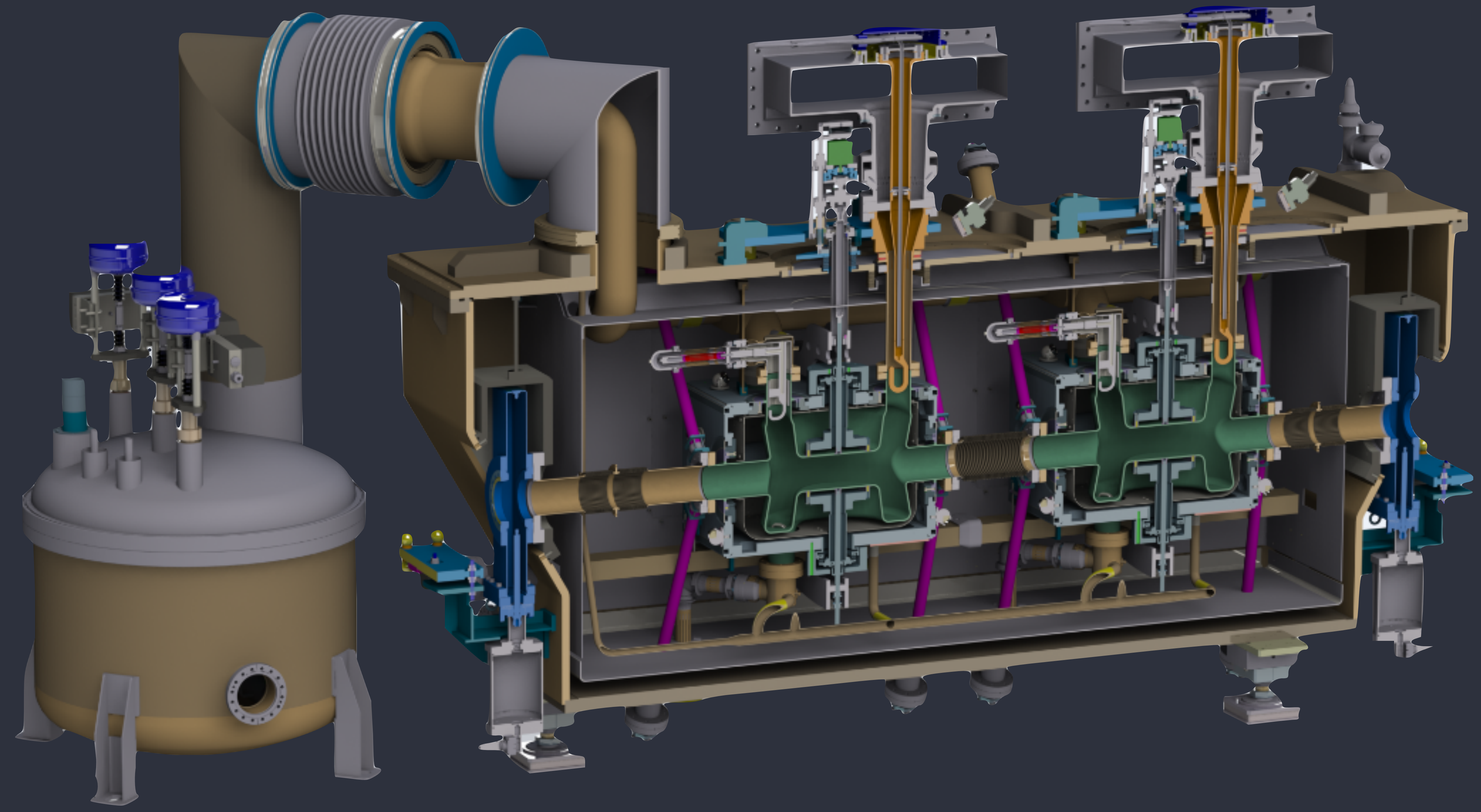
➡ 2 cavities/beam/IP side
➡ for ATLAS and CMS
➡ 16 cavities/8 CMs in total

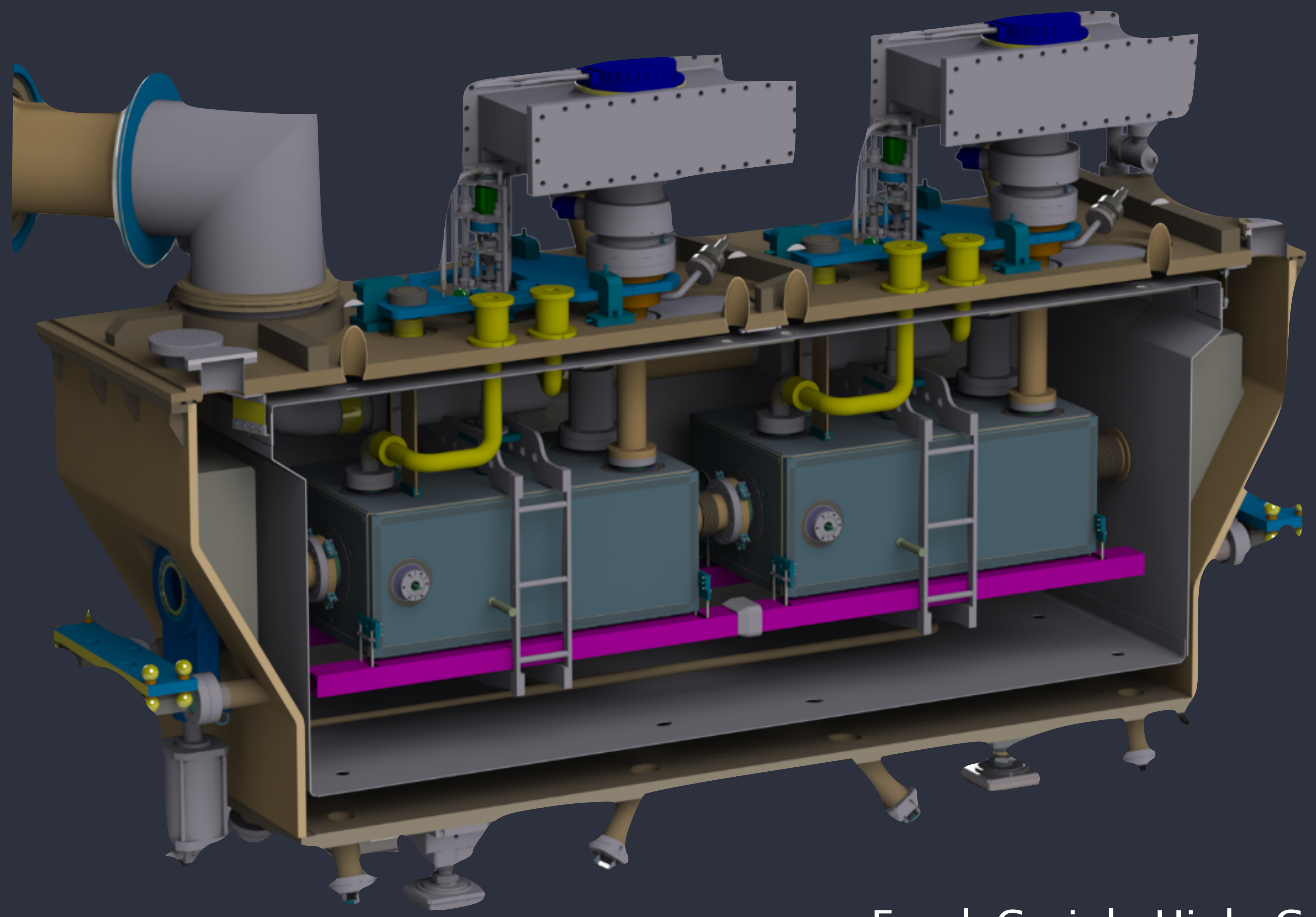
2 types of Crab cavities

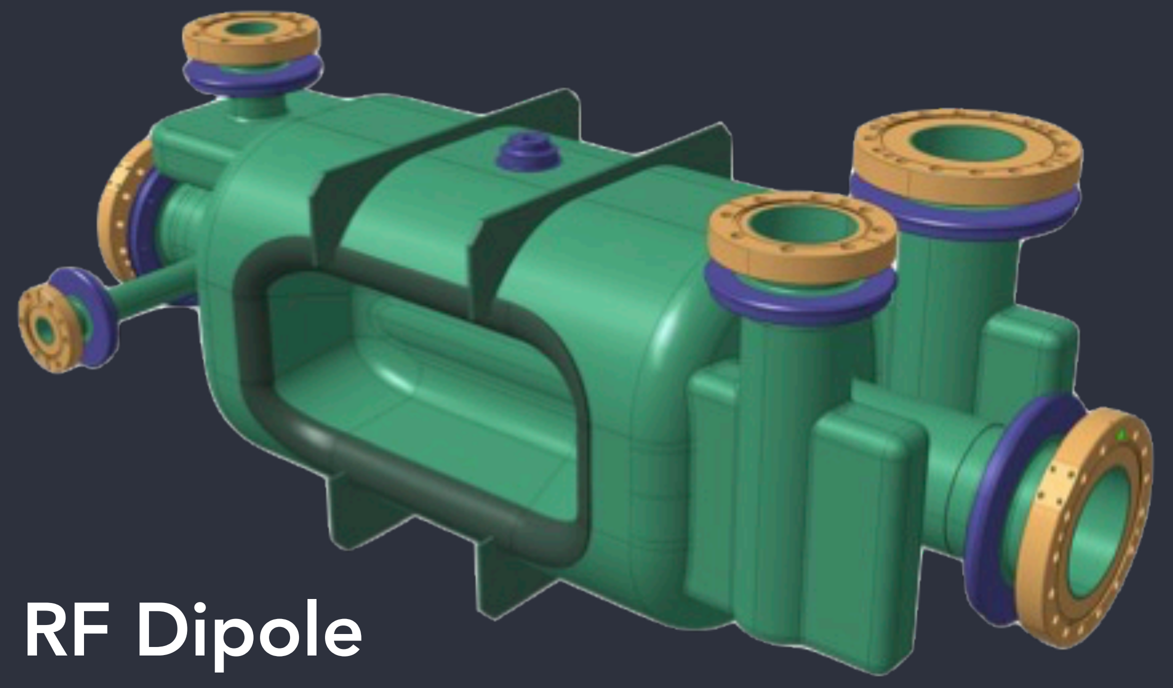
Double Quarter Wave

- Vertical crossing for Atlas
- SPS test in 2018





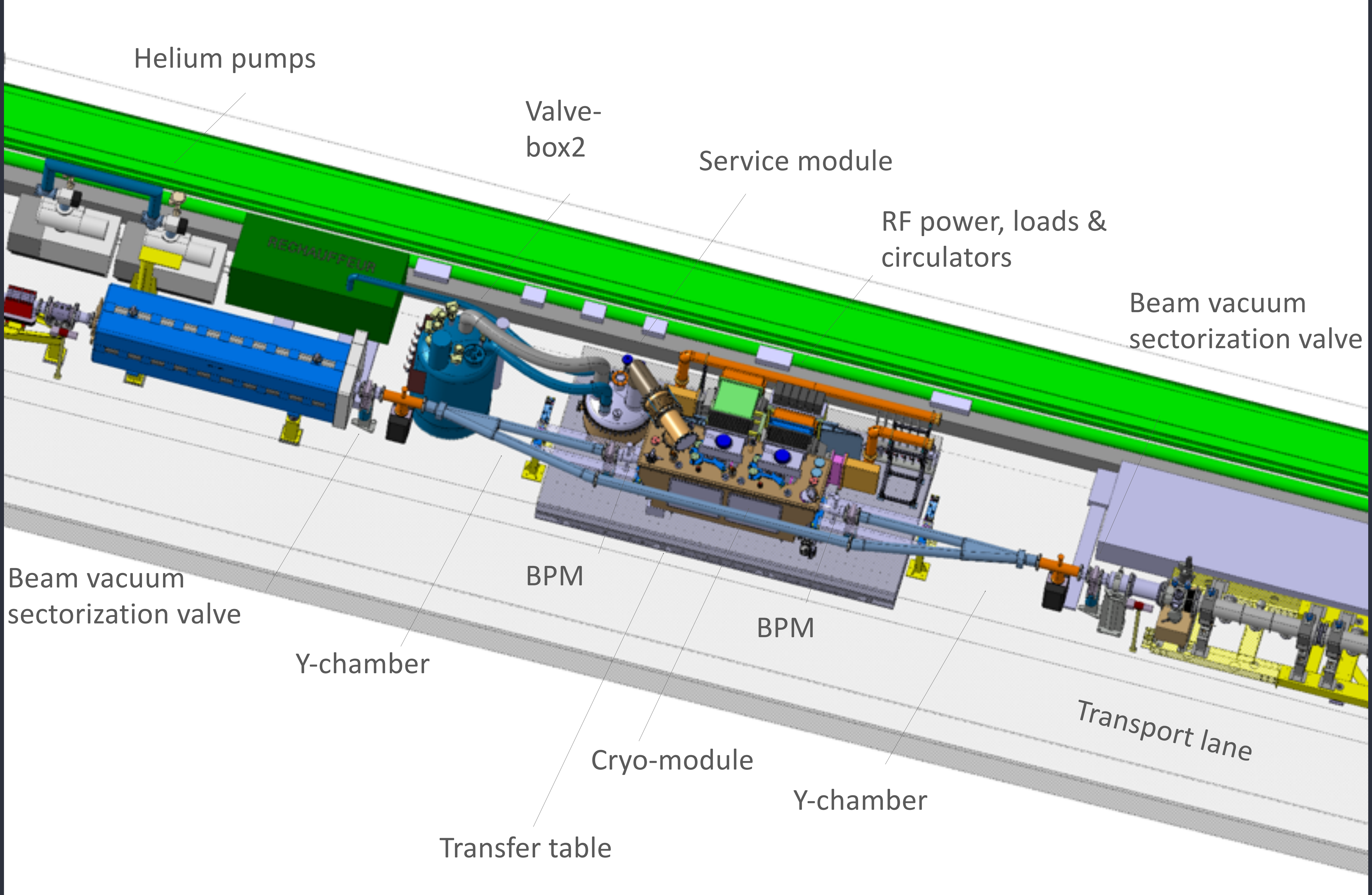




RF Dipole

- 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. Beam test mandatory before LHC installation!

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

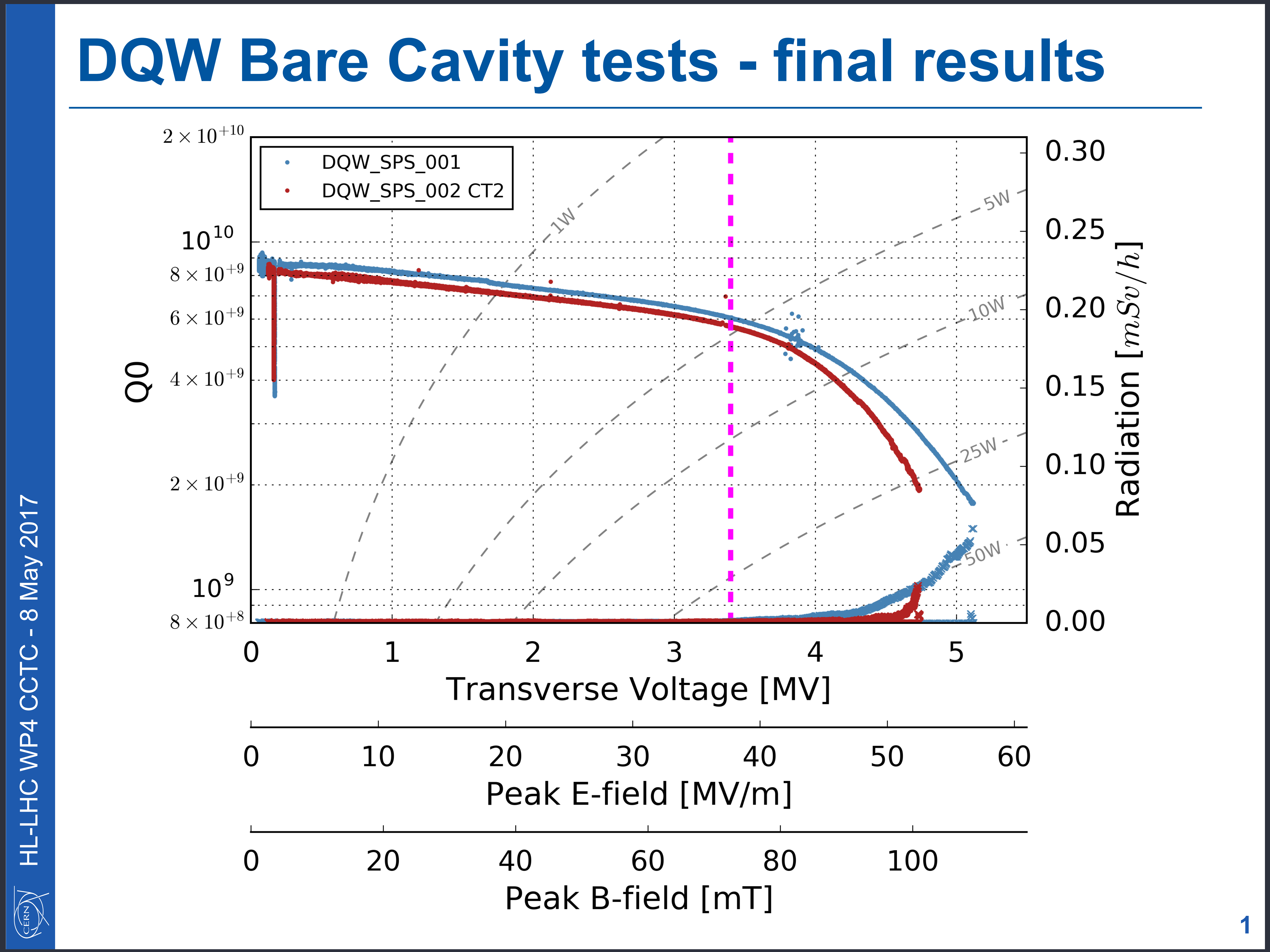
➡ Precision control of voltage and phase for preservation of beam quality.

➡ Trip rate must not impact LHC availability.

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

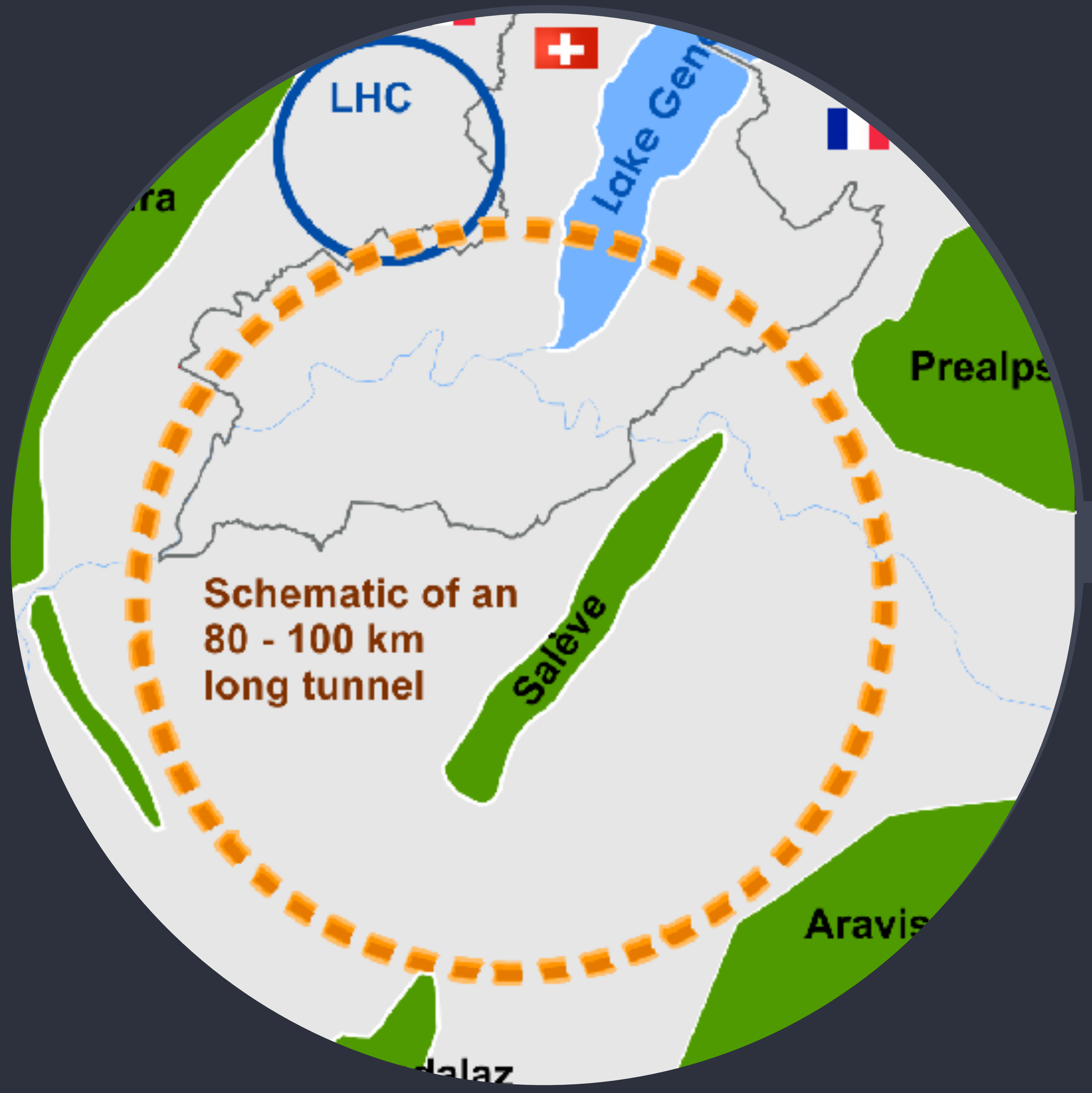
Summary HL-LHC

- The 2 bare DQW cavities were tested and performed above specs.
- One DQW and one RFD tested in the US above specs
- First dressed cavity is under test (He leak at one flange).
- First US dressed cavity quenched at 2.8 MV.
- 8 cavities from the US (AUP, LARP successor), 8 tendered by CERN.
- Going forward towards SPS installation during 2017/18 break without any slack..



HIE ISOLDE

- CM4 is under assembly and will be finished after summer.
- Cryo losses in transfer line were reduced to nominal.
- All 15 cavities (3 CMs) operate above specs due to optimised cool-down procedure.
- Helium processing works and provides a mechanism to save declining (dirty) cavities. However, it will be used as little as possible due to associated risks.
- First beam through 3 CMs this week.



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

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
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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, staging is foreseen: install more cavities in each shut-down

"high current" machine

Z **W** **hh**

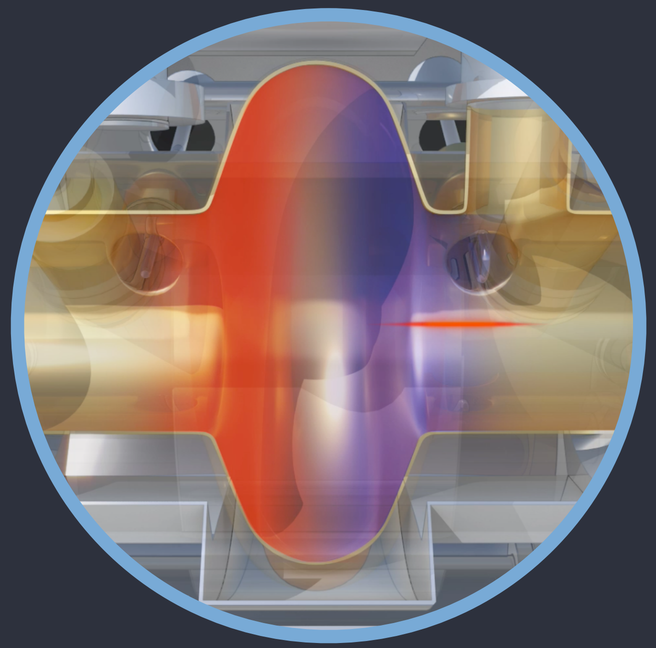
- lower frequency, low N_{cells}, low R_S
- 400 MHz, Nb/Cu, < 100 cavities
- FPC: aim at 1 MW/cavity (movable for hh, fixed for ee)
- HOM power < 1.5 kW/cavity
- 1 RF source/cavity (e.g. high efficiency klystrons)
- CM design to accommodate 1-cell (W) and 2-cell cavities (Z, hh)

"high gradient" machine

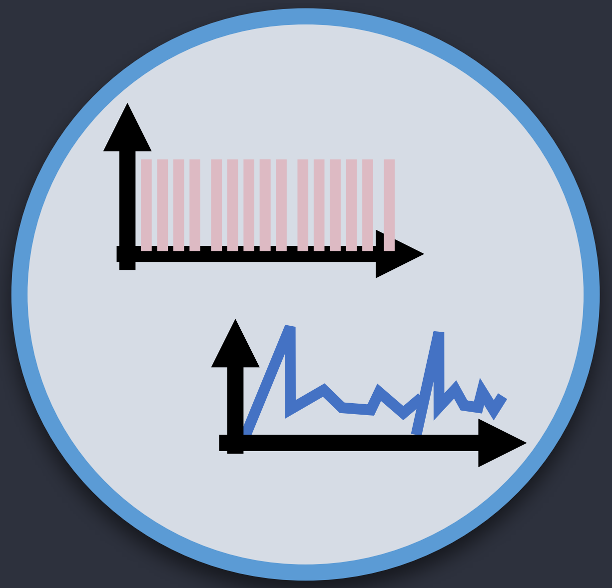
H **t**

- 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

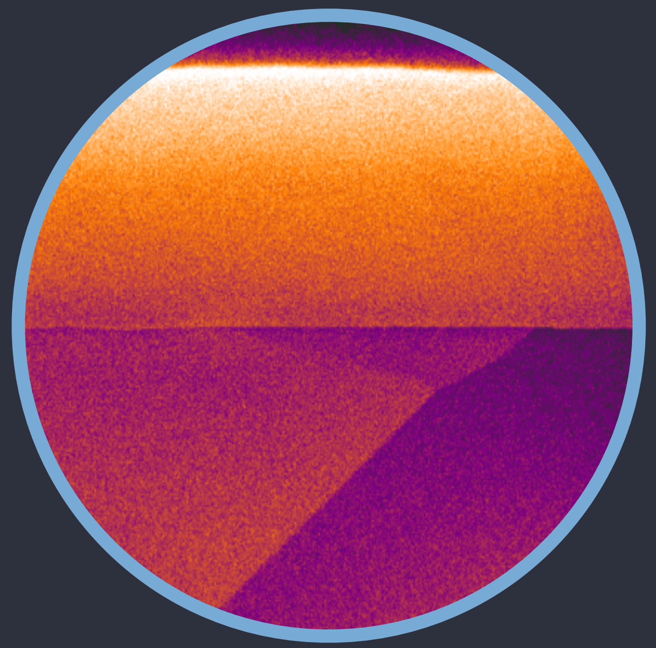
SRF R&D for FCC



optimize cell shapes

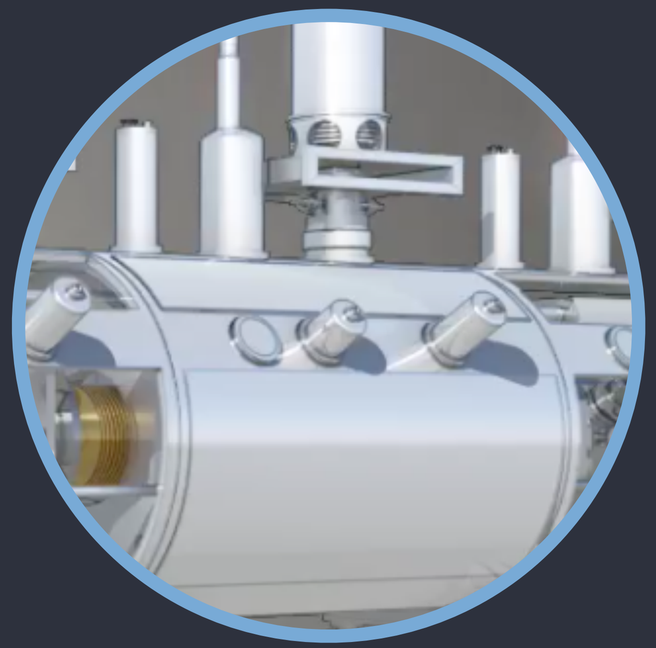


beam dynamics studies

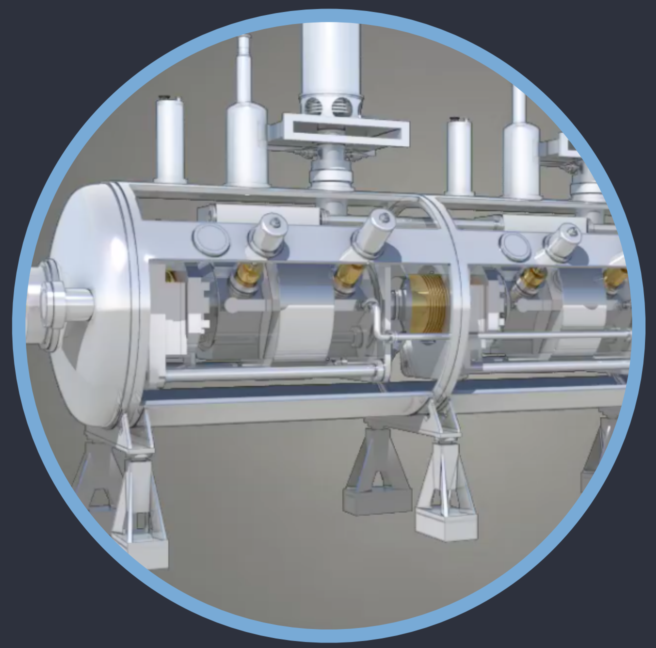


Q-slope mitigation

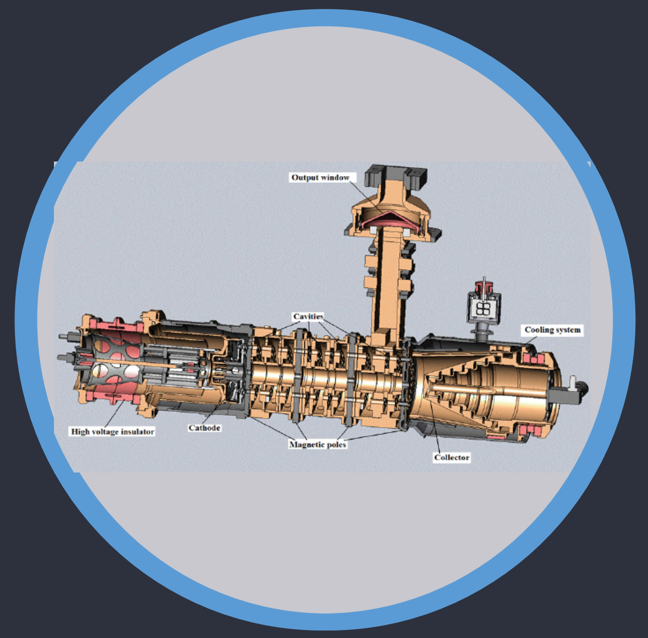
material & manufacturing



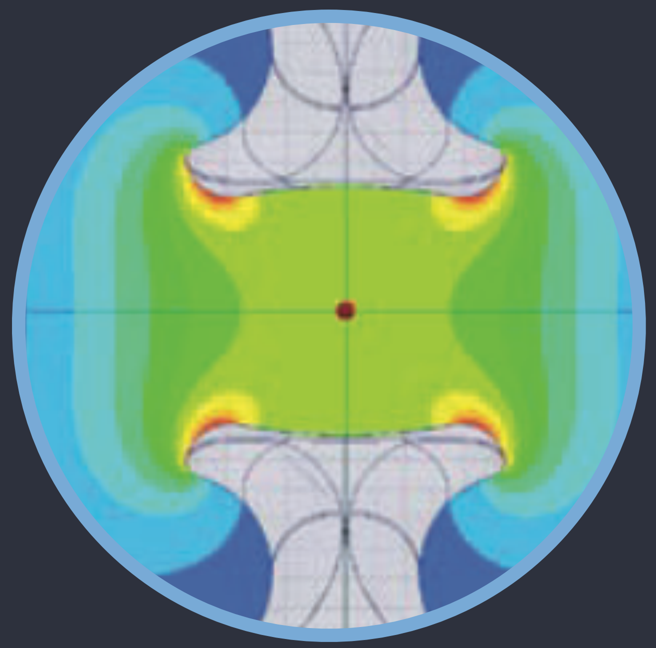
assembly & cost optimisation



ancillaries



efficient RF production



coated crab cavities

FCC

Next generation Crab Cavity

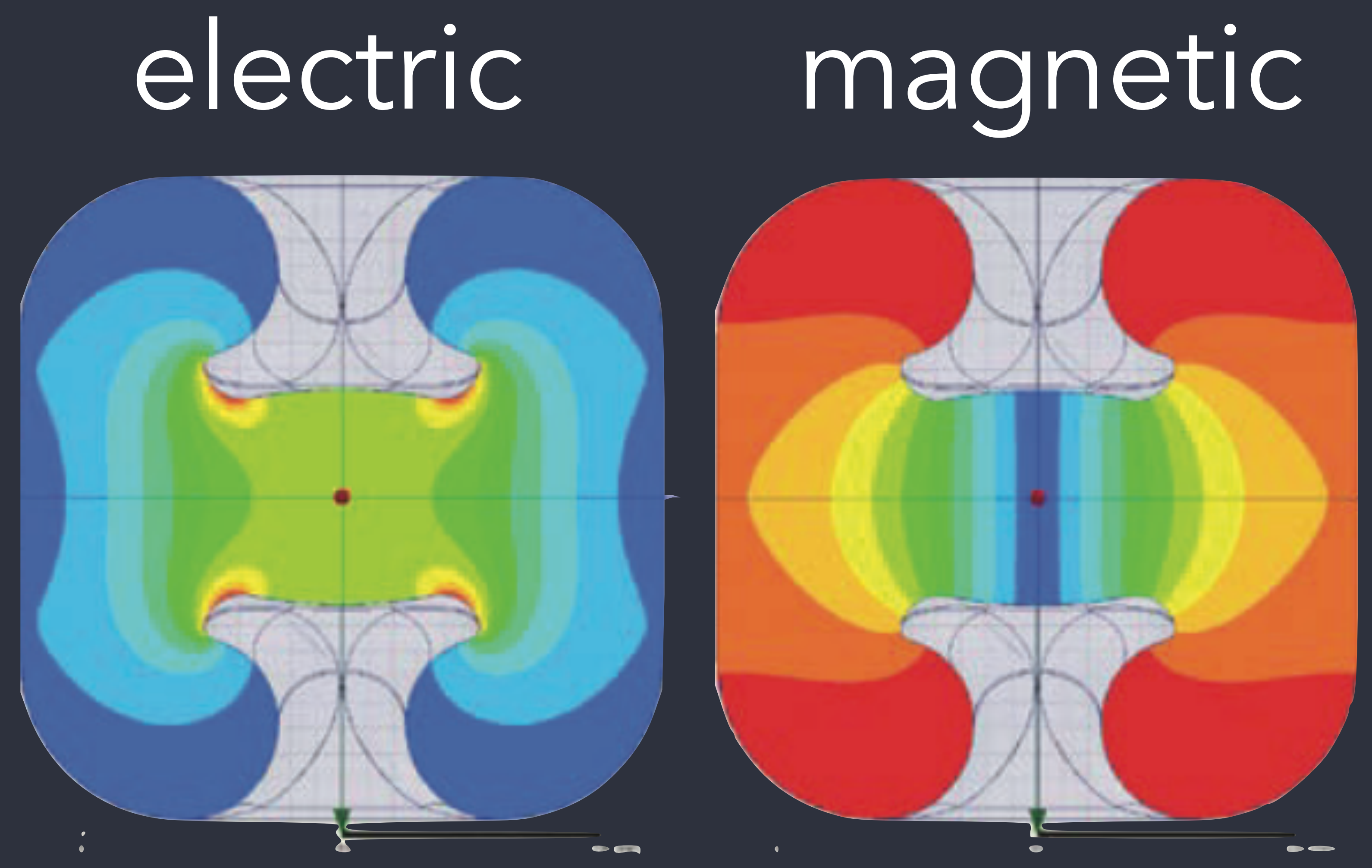
Wide Open Waveguide cavity (WOW)

Why a Nb/Cu crab cavity?

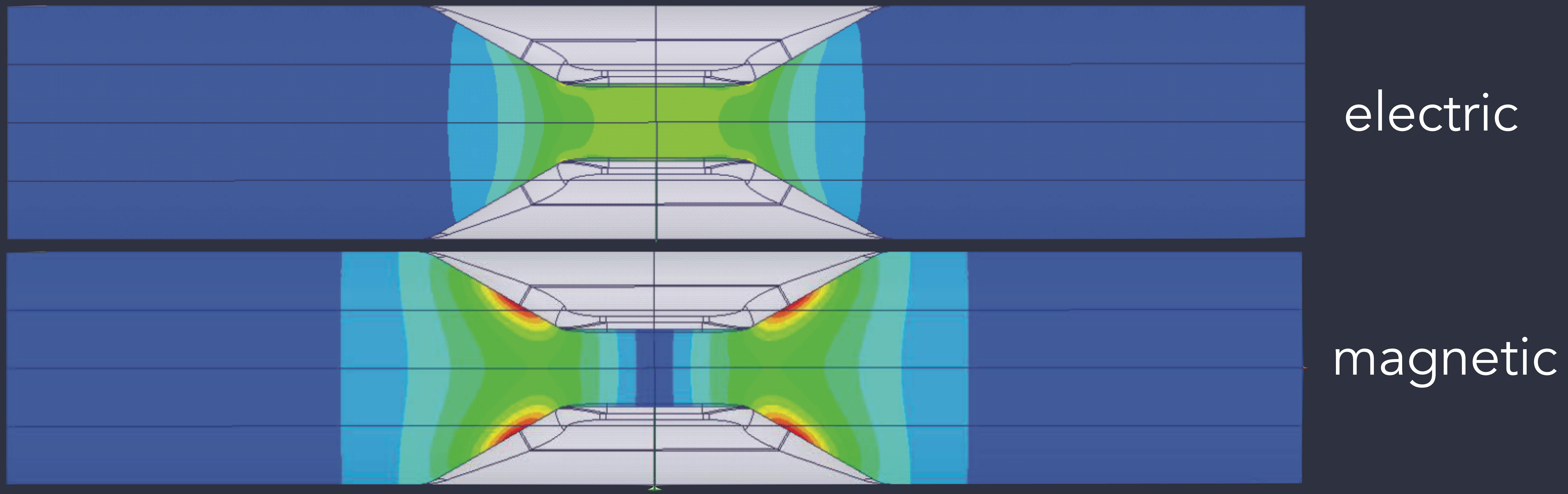
- No thermal tun-away ("natural" quench protection).
- Crab cavity power needs are driven by off-axis beam and not by surface losses.
- **Lower cavity impedance**: factor 3-4 for $Z_{x,y}$ (mandatory for FCC).
- No magnetic shield (cost, simplicity).
- Power coupler and HOM dampers can be outside of 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



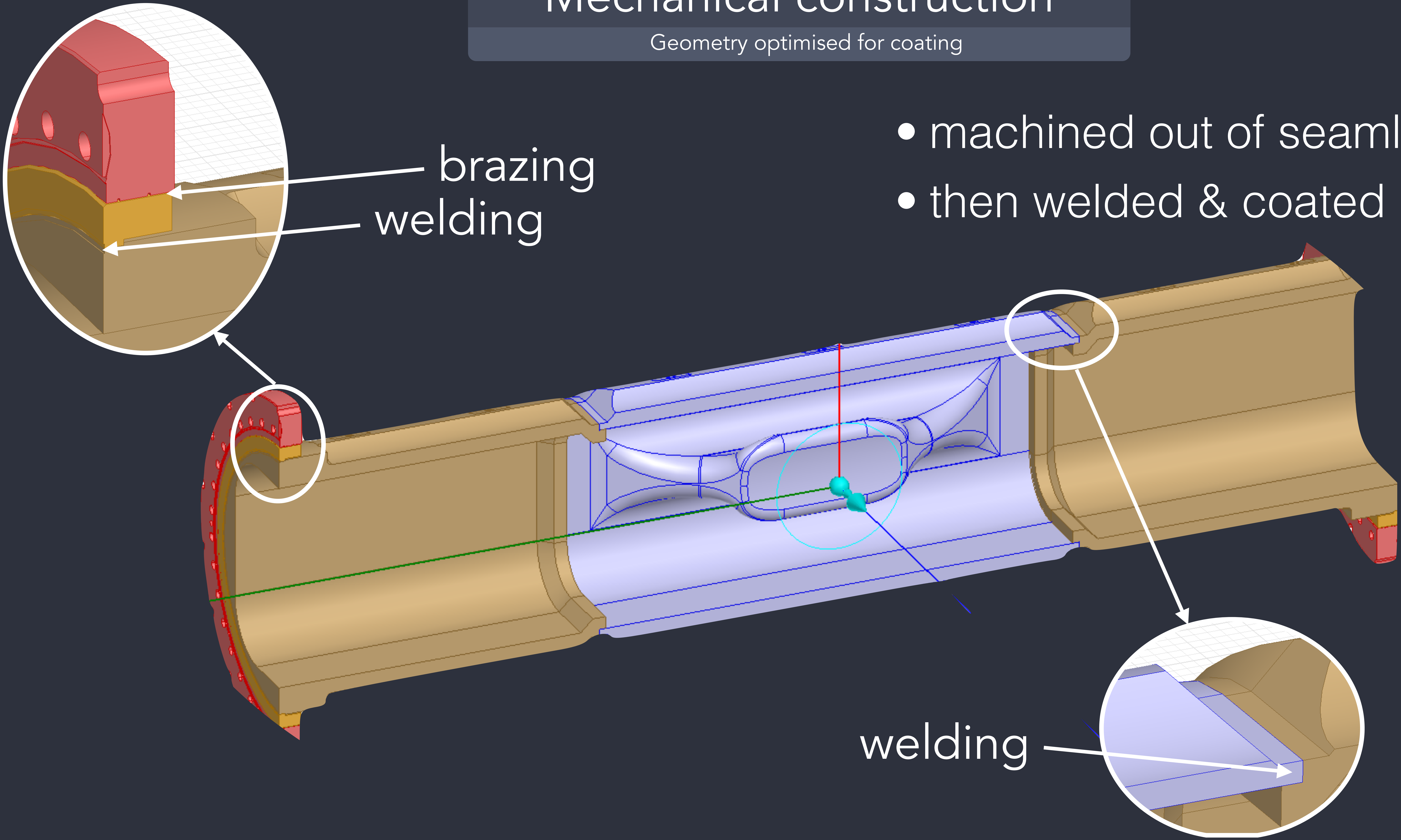
Voltage	2.7 MV/cavity	80% of bulk Nb CC
E_{peak}	40.5 MV/m	same as bulk Nb CC
B_{peak}	70 mT	same as bulk Nb CC
Frequency	400.79 MHz	
Temperature	4.5 K	
P_{diss}	< 50 W	for LHC quality coating



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.
- Pieces for prototype 1 are ready for welding.
- Preliminary coupler design for vertical testing.
- LHC-style coating set-up (coating electrodes inserted in cavity) was chosen. Modifications on existing set-up is needed.

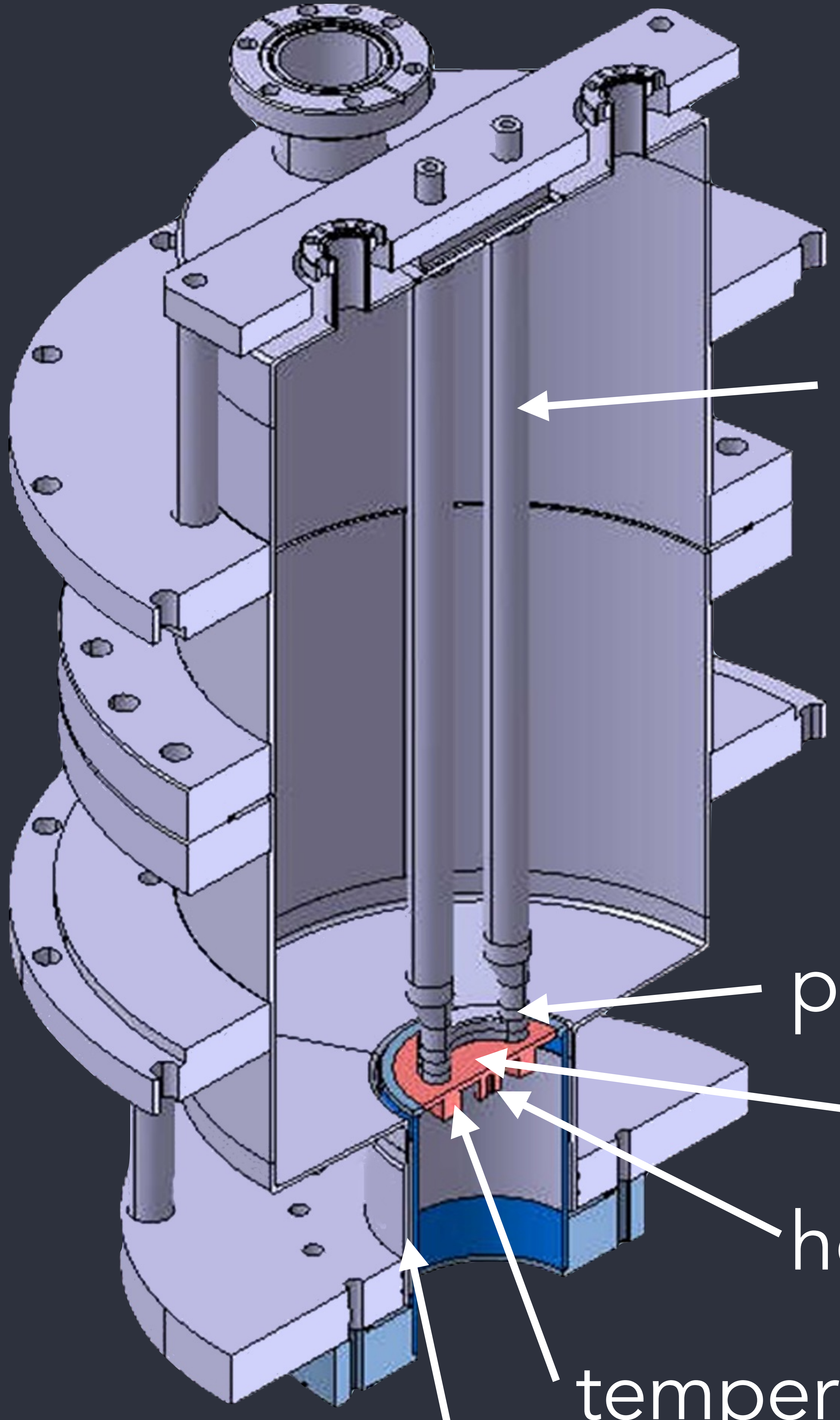
2016				2017				2018				2019		
material procurement, drawings				fabrication 1st prototype										
							fabrication 2nd prototype							
				coating design & construction					coating, cold testing, re-coating					

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

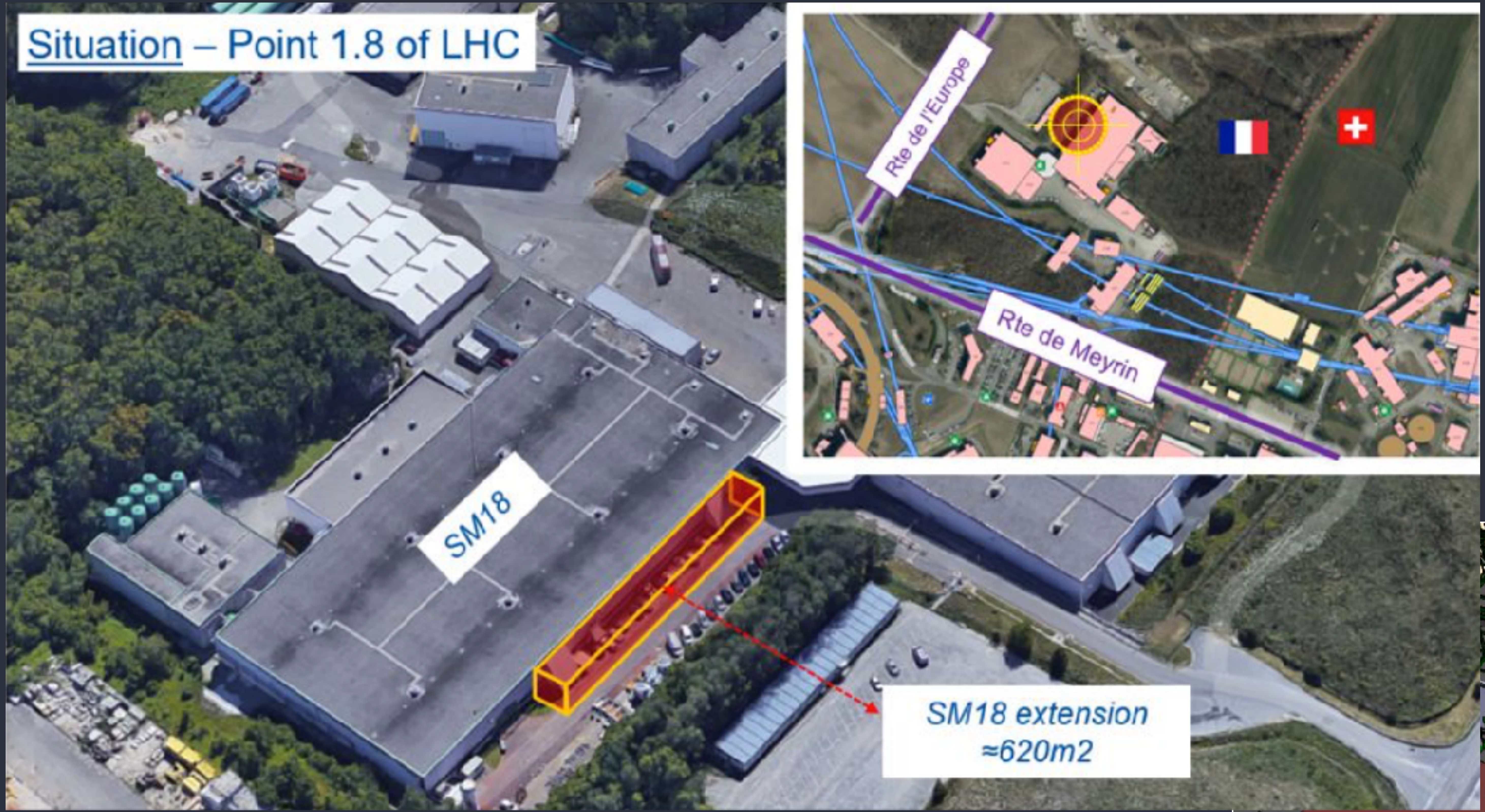
Activity

- 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 in October/November 2017, first tests foreseen in 2018.

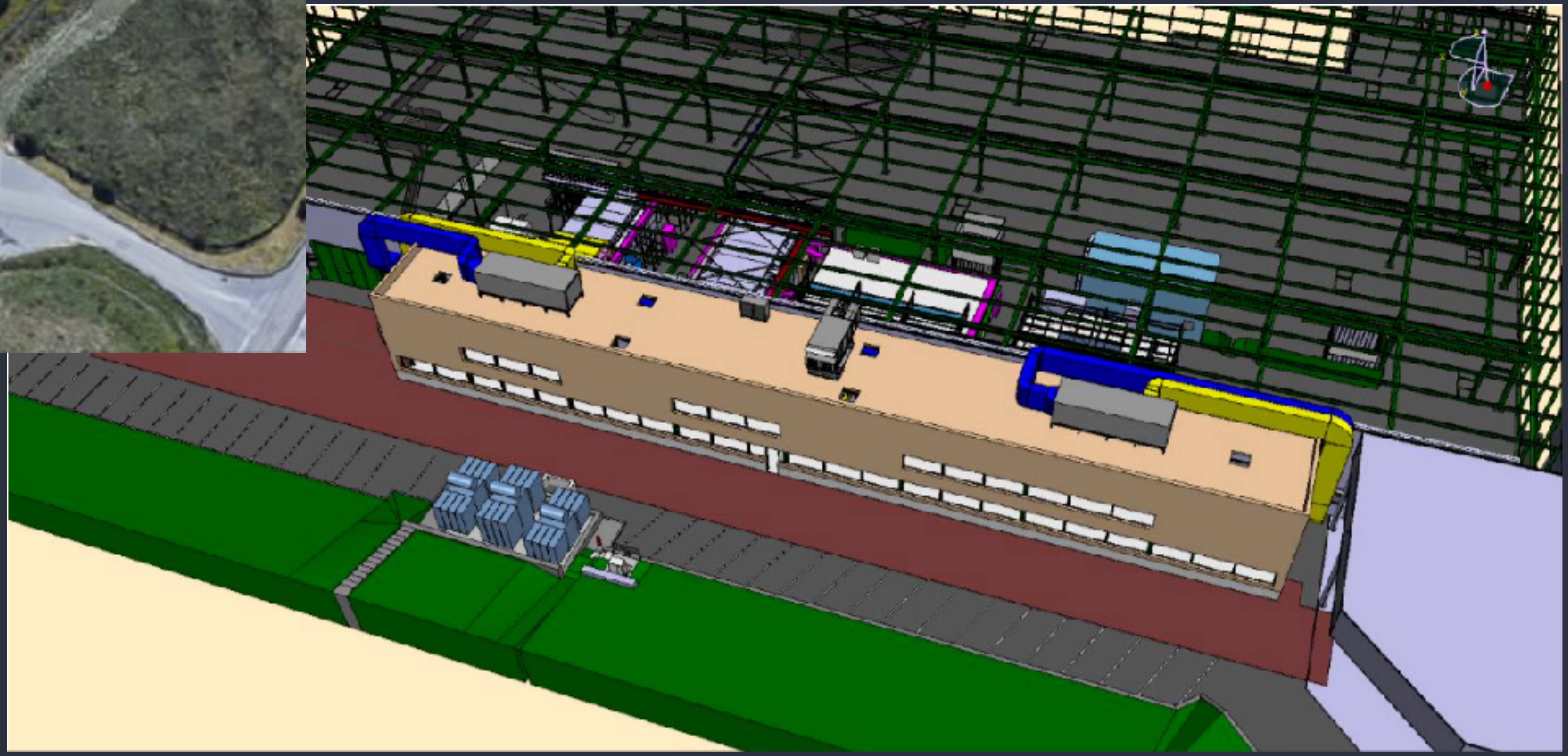
infrastructure

space, space, space…

SM18 extension



- Civil engineering consultant is hired.
- Final cost estimate in preparation.
- Assumed start of construction: beginning 2018 (duratioin: 8 months)



- Trying to acquire an additional 400 m^2 on the Meyrin site (existing building)

THANKS

FOR

Listening