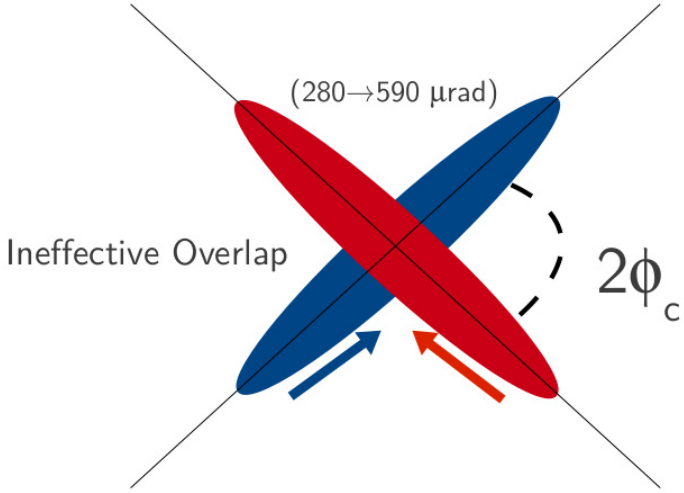
Crab Cavities for the LHC Luminosity Upgrade

Rama Calaga, CERN

SRF2017, 20 Jul 2017, Lanzhou

Crab Crossing in the LHC

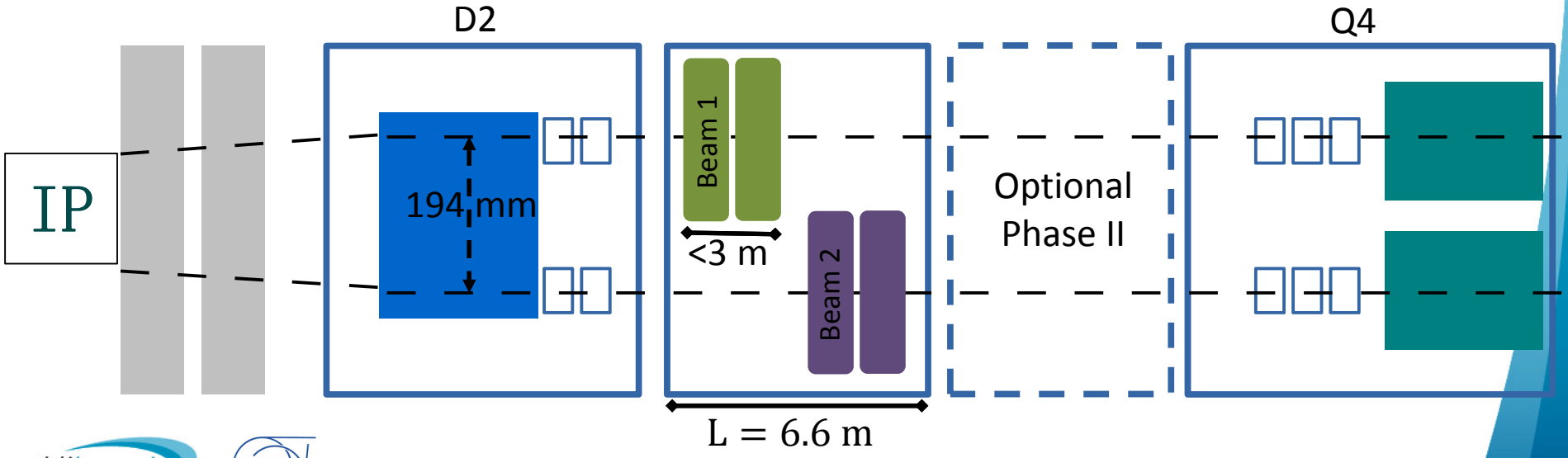


$$\Phi = \frac{\sigma_z}{\sigma_x}\varphi_c$$

7.55cm

~7 μm

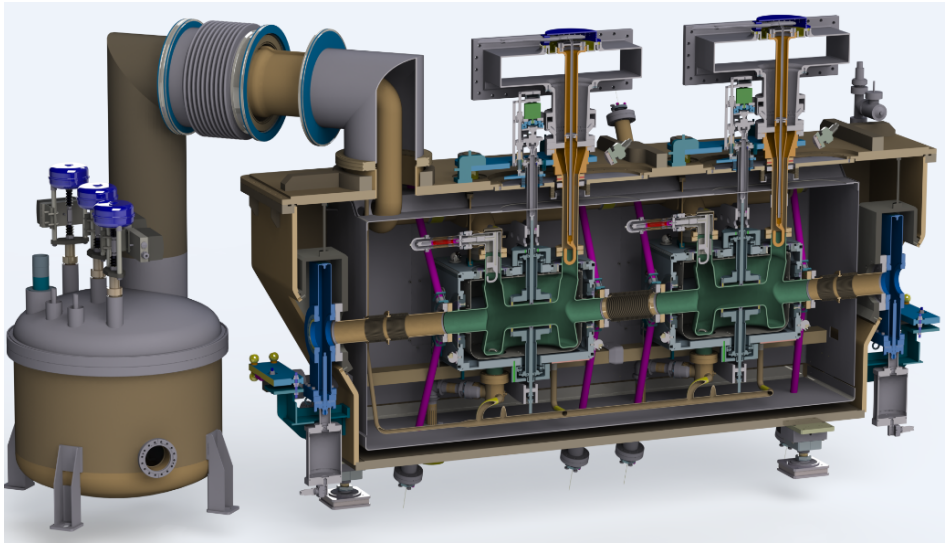
$$L = \frac{L_{HO}}{\sqrt{1+\Phi^2}}$$



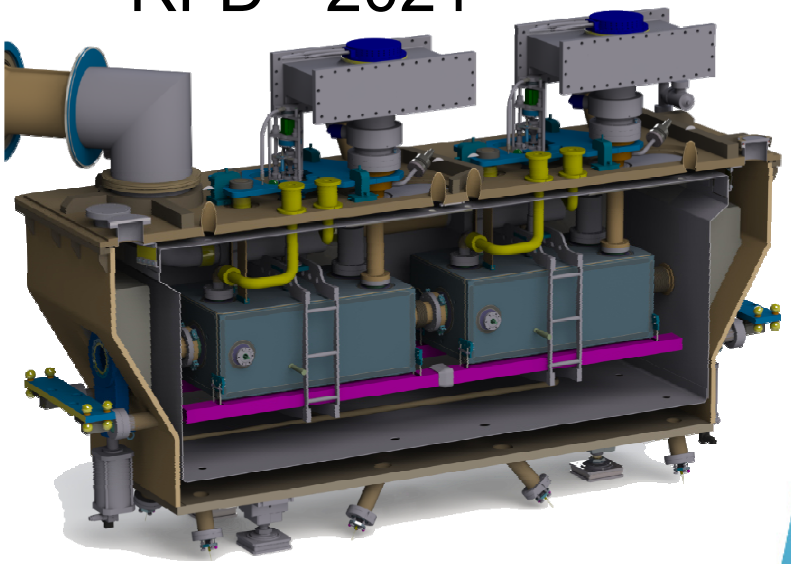
Outline

- *Update on the Cavities + CM production*
- *SPS beam test preparation*

DQW - 2018



RFD - 2021

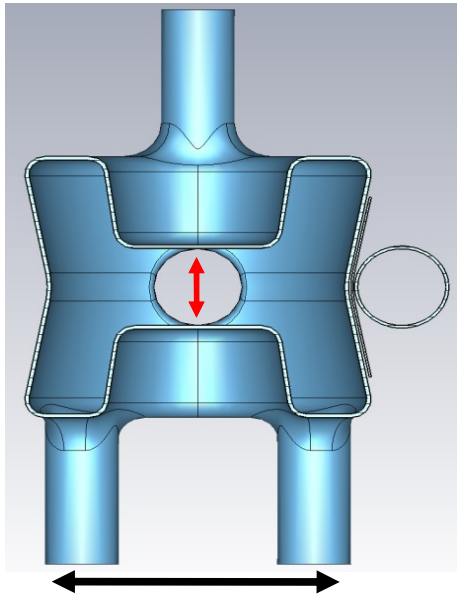


LHC installation, 8 Modules by 2025

Crab Cavity Geometries

- Two geometries for Ver/Hor Crossing

Double Quarter Wave



280 mm

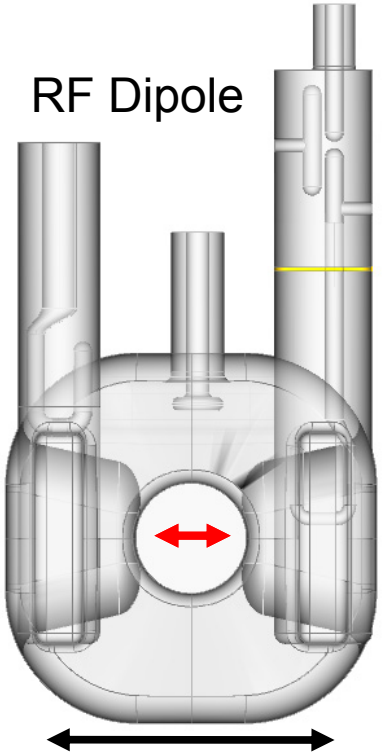
$400\ \mathrm{MHz}$, HL-LHC

$V_T = 3.4\ \mathrm{MV}$

$(E_p, B_p < 40\ \mathrm{MV/m}, 70\ \mathrm{mT})$

Dynamic load ~ 5W/cavity

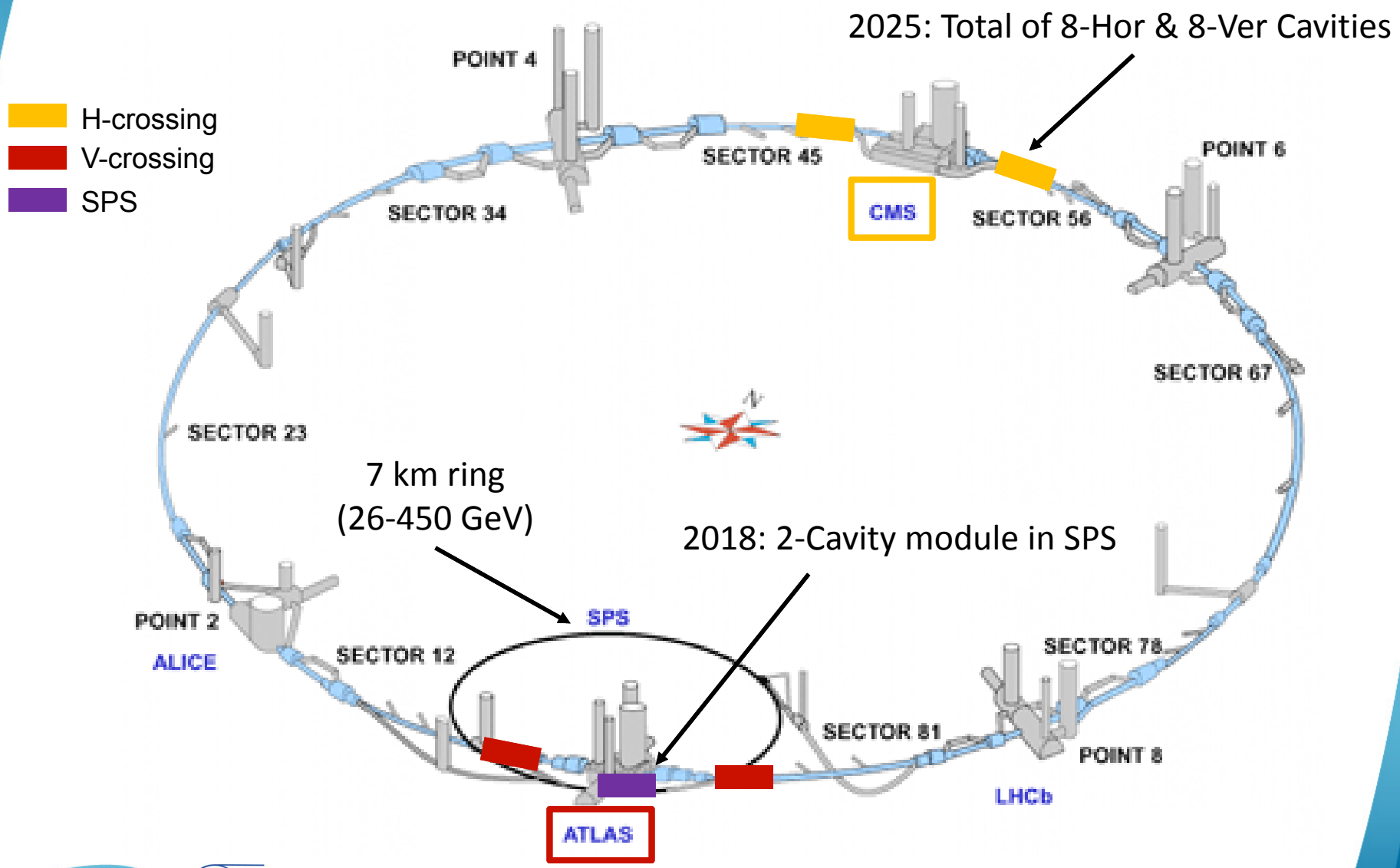
RF Dipole



281 mm

*The voltage limit is to operate ~ 30% below the quench limit to minimize RF trips for machine protection

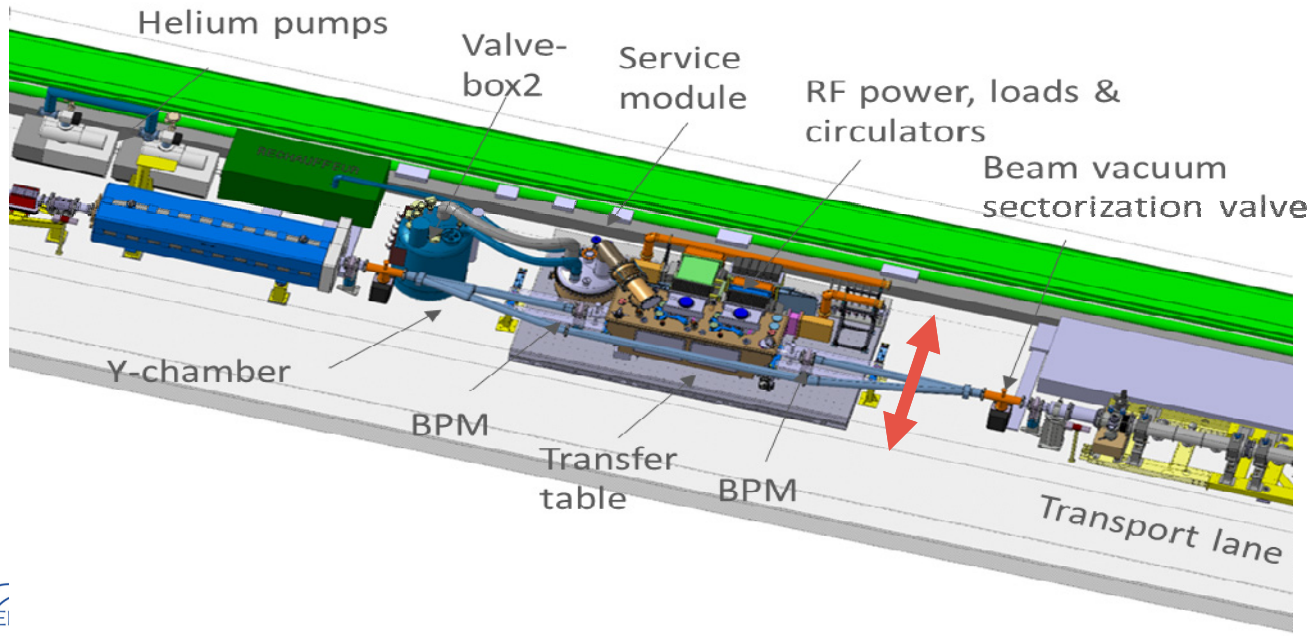
HL-LHC & SPS


2025: Total of 8-Hor & 8-Ver Cavities
H-crossing
V-crossing
SPS
POINT 4
SECTOR 45
CMS
SECTOR 56
POINT 6
SECTOR 34
SECTOR 67
SECTOR 23
7 km ring
(26-450 GeV)
2018: 2-Cavity module in SPS
SPS
POINT 2
ALICE
SECTOR 12
SECTOR 78
SECTOR 81
POINT 8
LHCb
ATLAS

Why Test in the SPS

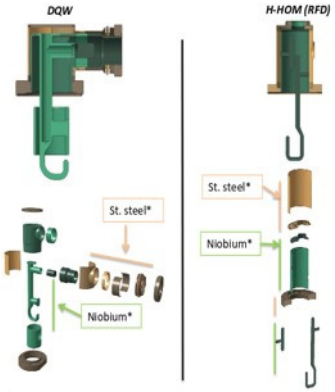
- Demonstrate ‘transparency’ (counter-phased)
- Failure scenarios & machine protection for the HL-LHC
- Operational cycle (injection/ramp, collisions, RF stability)
- Beam measurements with protons

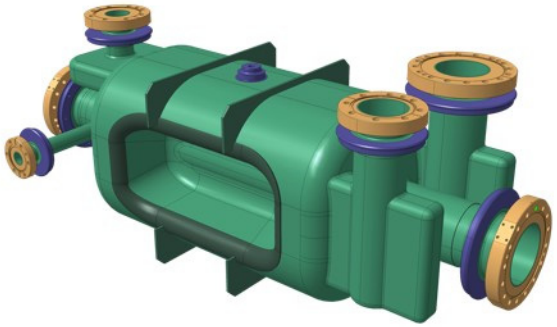
Mechanical Bypass in SPS for Crabs

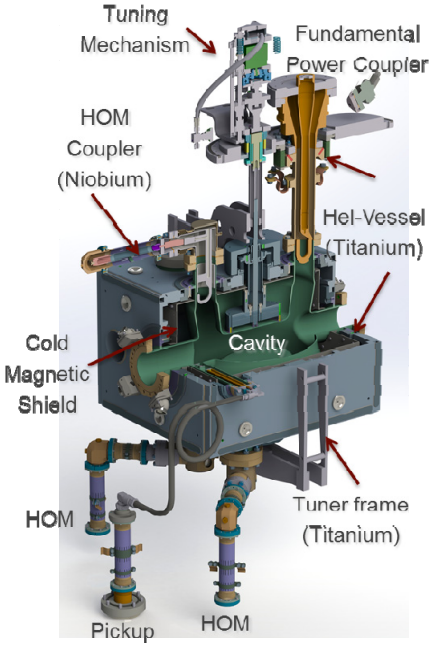


SPS Cavities 2K Volume

TUPB013
TUPB053
TUPB100





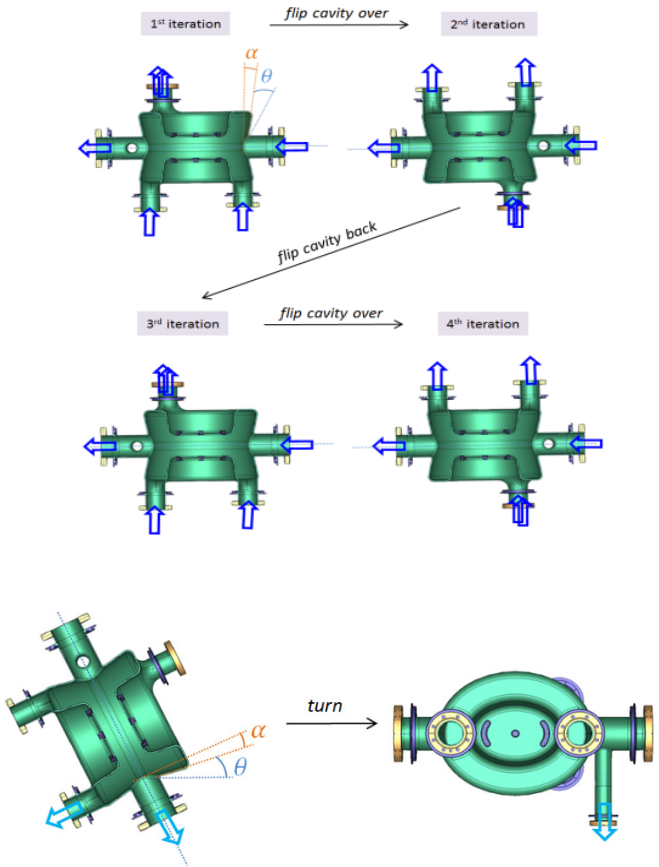


- Main Mechanical interfaces:
  - He-vessel: New Bolted-welded concept
  - Tuner: Symmetric tuning with warm actuation
  - Three point support + alignment system
- Main RF interfaces
  - 1 FPC: Single ceramic coaxial line
  - 3 HOMs: Two stage filter, coaxial
  - 1 PU: Cu-Nb for field probe + HOM

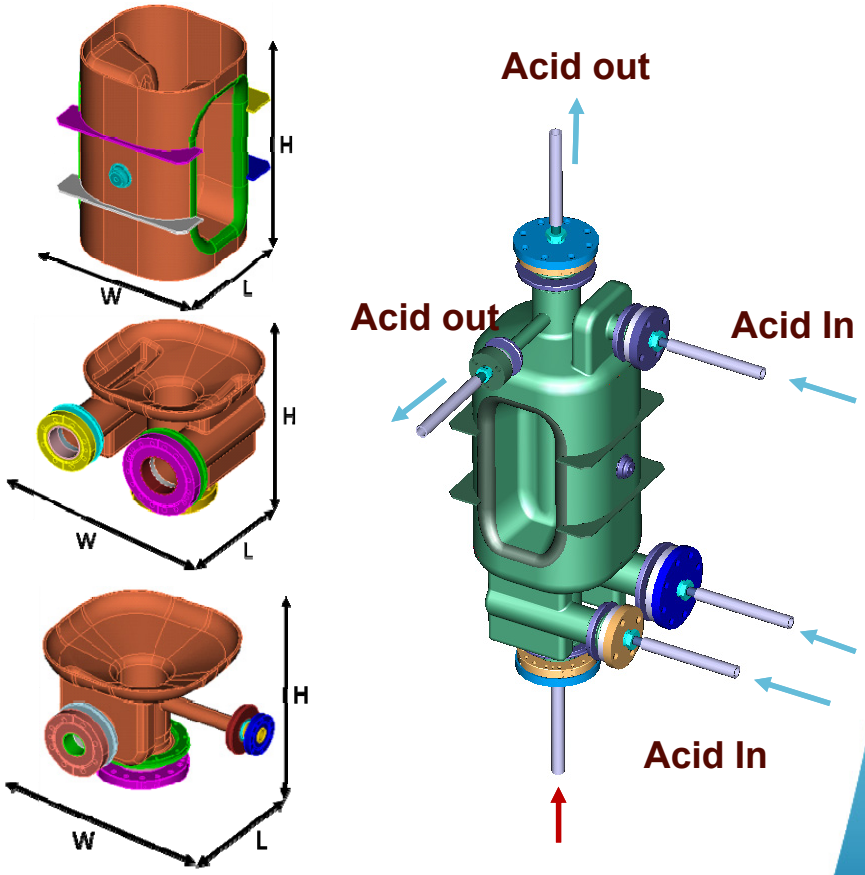
Similar concept for RFD with 2 HOM interfaces

Cavity Chemistry, DQW & RFD

DQW: Very light chemistry on Parts & Bulk Chemistry in 4-cycles



RFD: Initial Chemistry on Parts & Light Chemistry on assembled cavity



Now adopted bulk chemistry on fully assembled cavity after prototype

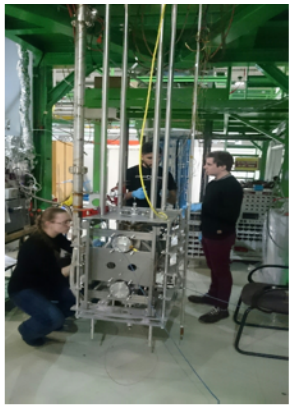
SPS Cavity Results (6 Cavities)

Nominal Spec $V_{kick} = 3.4$ MV, $R_s = 10\ n\Omega$

		DQW #1 (CERN)	DQW #2 (CERN)	DQW #1 (USLARP)	DQW #2 (USLARP)	RFD #1 (USLARP)	RFD #2 (USLARP)
Max Volt	[MV]	5.04	4.8	5.8	5.3	4.4	5.75
E_p, B_p [MV/m, mT]		56, 109	54, 103	65, 125	59, 114	42, 73	56, 96
R_s min	[nΩ]	10	10	9	9.5	11	7.6
R_s, 3.4MV	[nΩ]	15	18	15	17	13	8.2
FE onset	[MV]	4.0	4.4	4.5	3.4	-	4.5

Quench field reduced to ~3.2 MV with HOM coupler – under investigation

CERN DQW



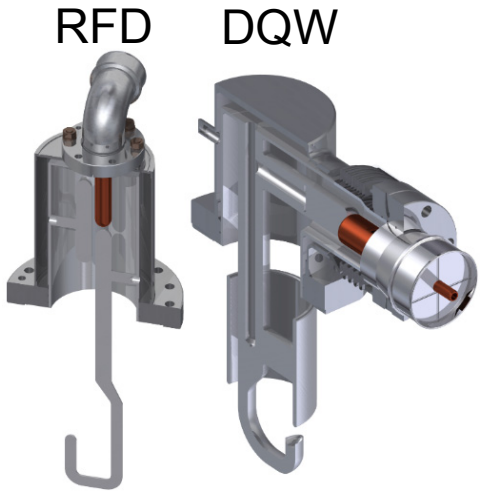
USLARP DQW & RFD

RF Power & Coupler Conditioning

- 4 FPC Couplers fabricated and conditioned to 30 kW CW on a load (limited by thermal load on test box)

- FPC couplers ready for installation 2nd week of May. Amplifiers for SPS-BA6 delivered and tested in Sept

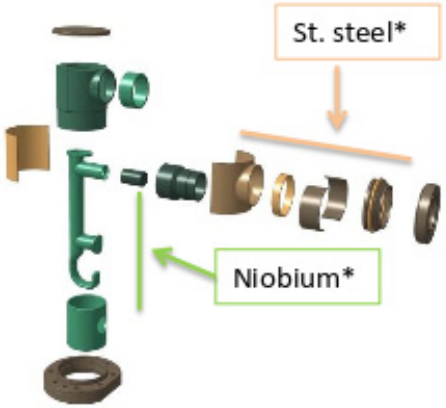
HOM Couplers



DQW HOM couplers

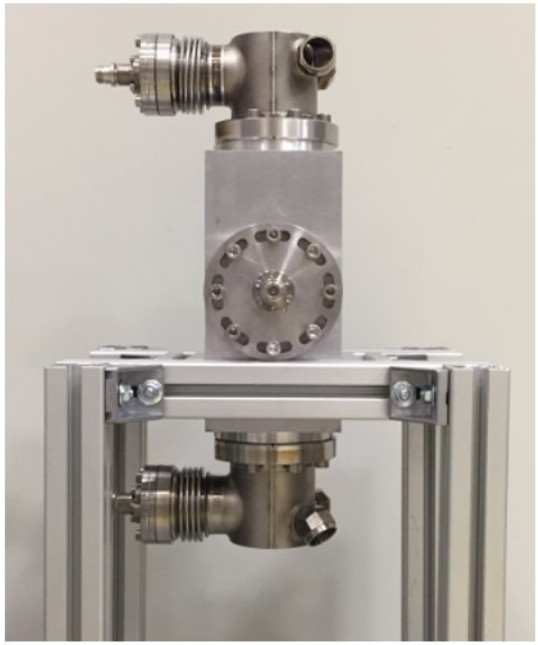
- 8 couplers fabricated, 6 needed for the SPS-DQW cavities
- All couplers now mounted on the SPS-DQW cavities

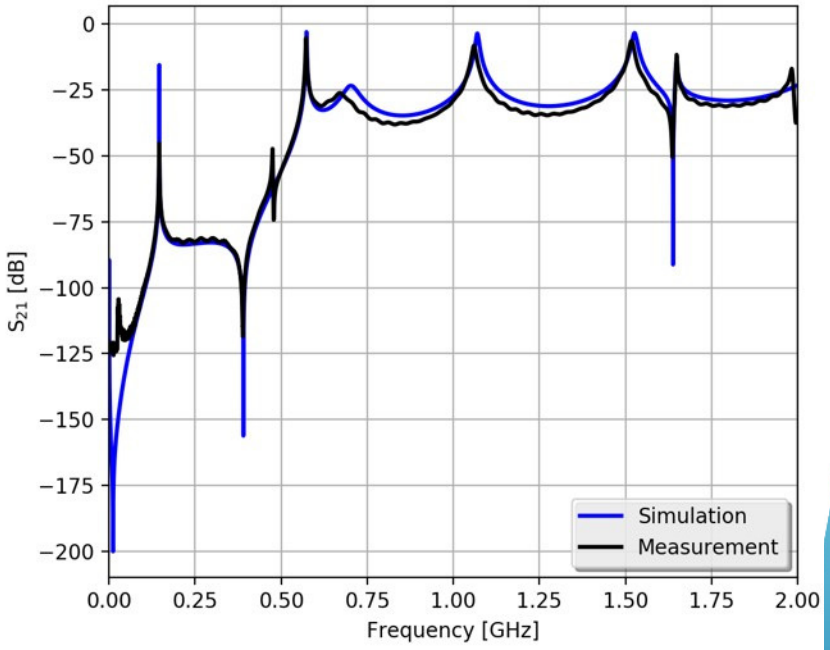
RFD HOM couplers to be fabricated in 2018



HOM Coupler Validation

- Dedicated HOM test box for warm qualification tests of the HOMs (total 6 + 2 spares)

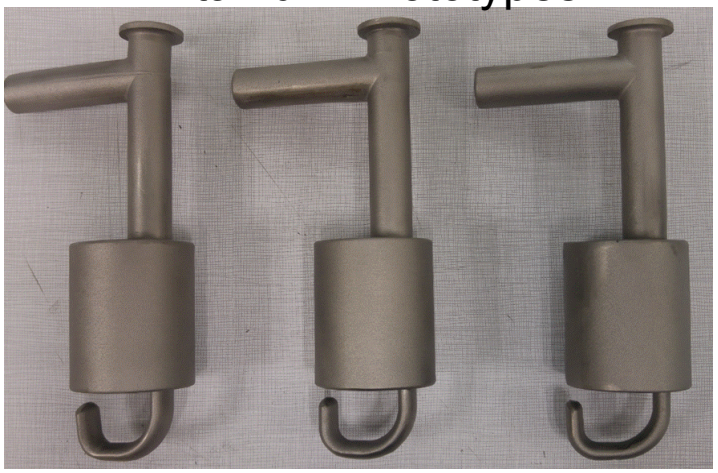




3D Printing: HOM Prototypes & Assembly

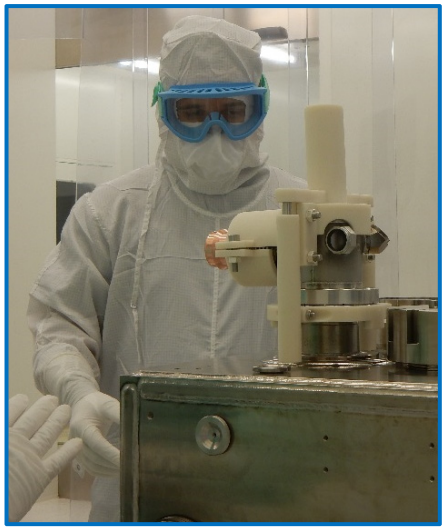
Polymer + Cu Coating

Titanium Prototypes

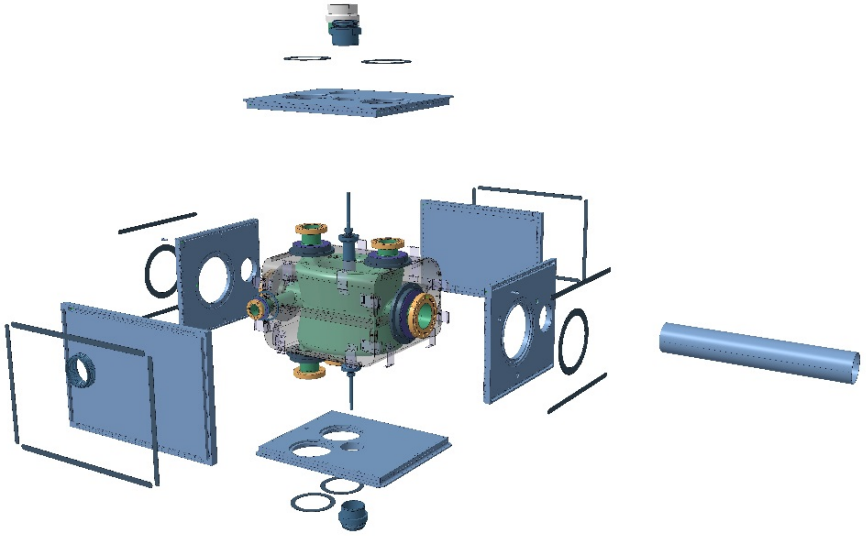


FPC Mock Up Assembly

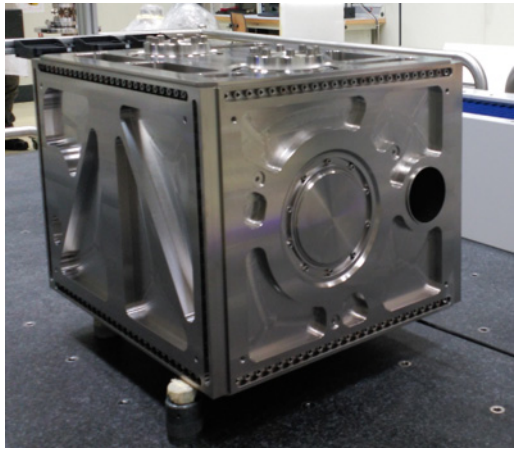
HOM Assembly Tool in ISO4



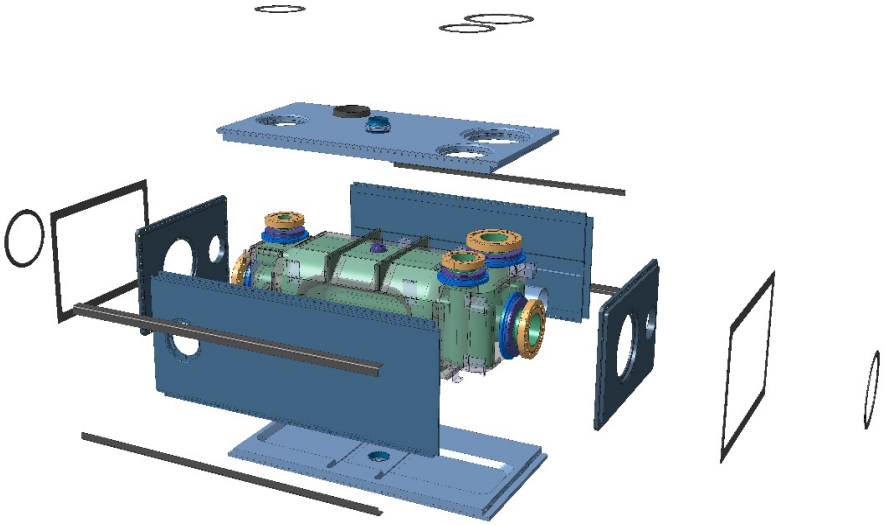
Helium Vessel



Prototype for concept validation

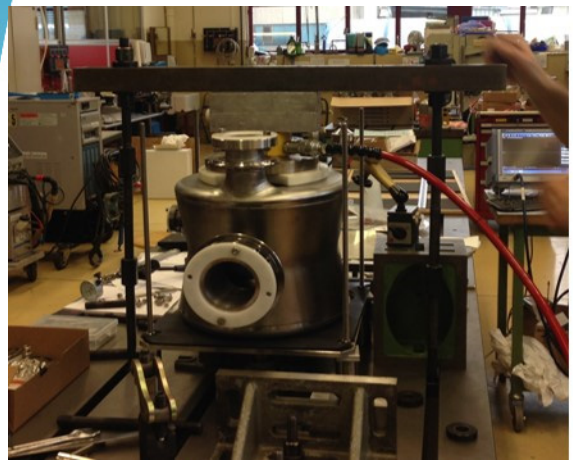


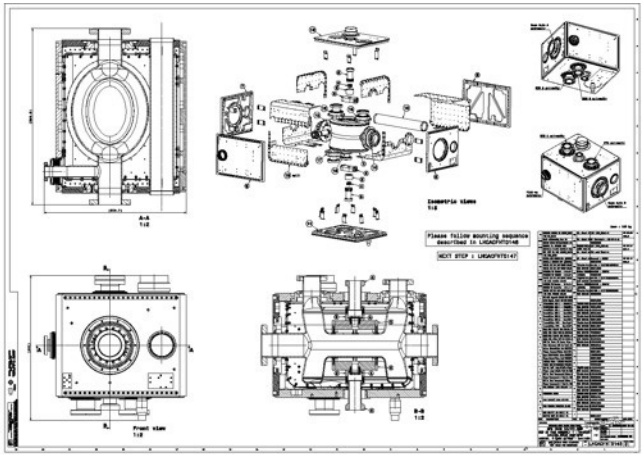
Novel bolted/welded concept was chosen for structural integrity & minimal stress to cavity including internal magnetic shield and the adjacent beam pipe

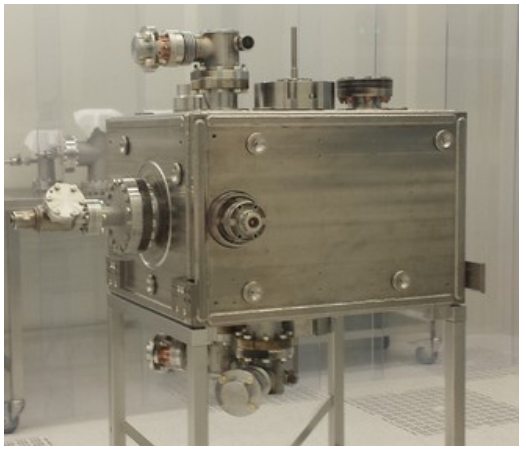


Dressing of CERN-DQW #1 & #2

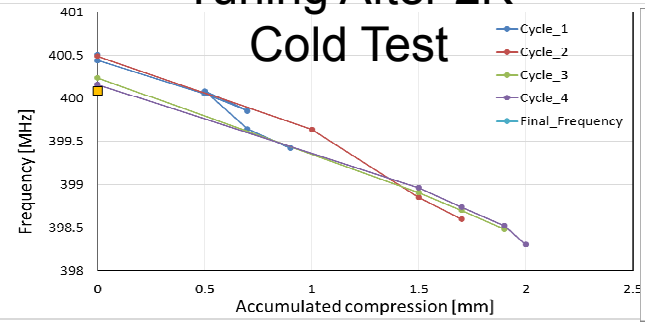
MOPB089
MOPB104



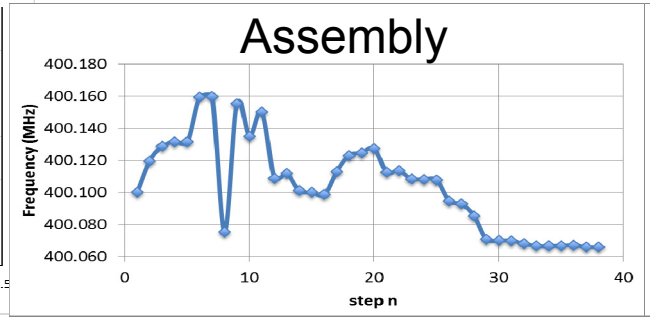




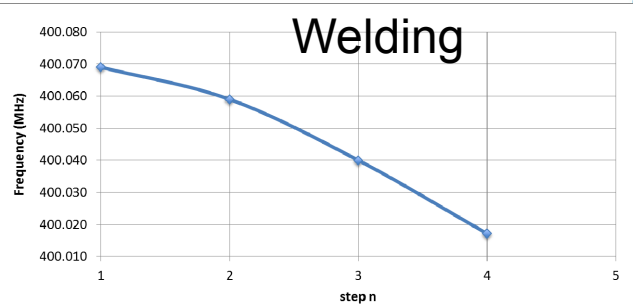
Tuning After 2K Cold Test



Helium Vessel Assembly



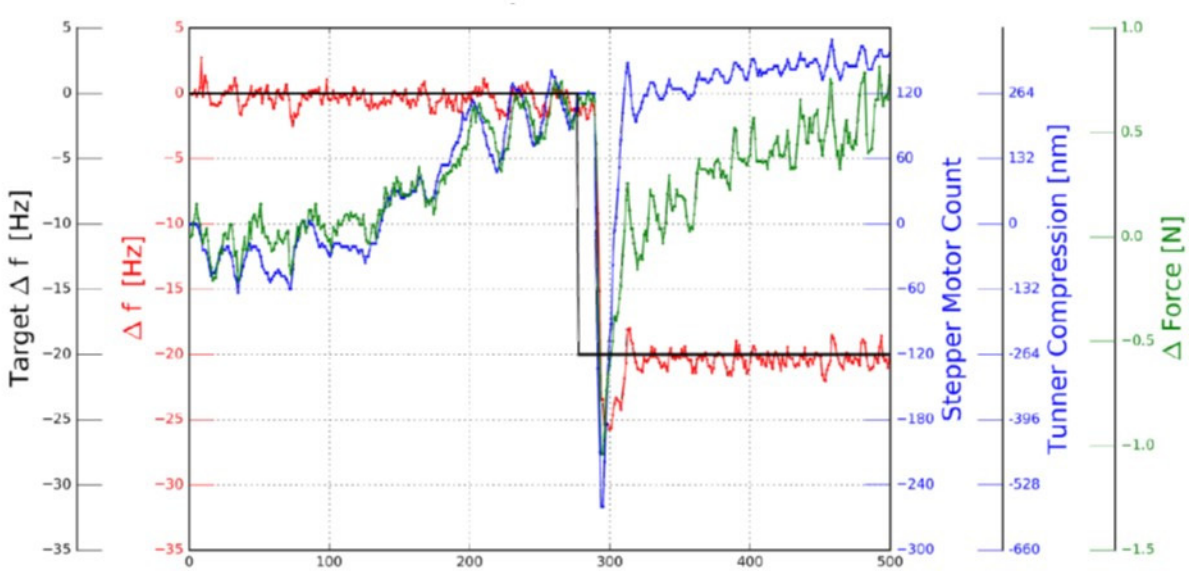
Helium Vessel Welding



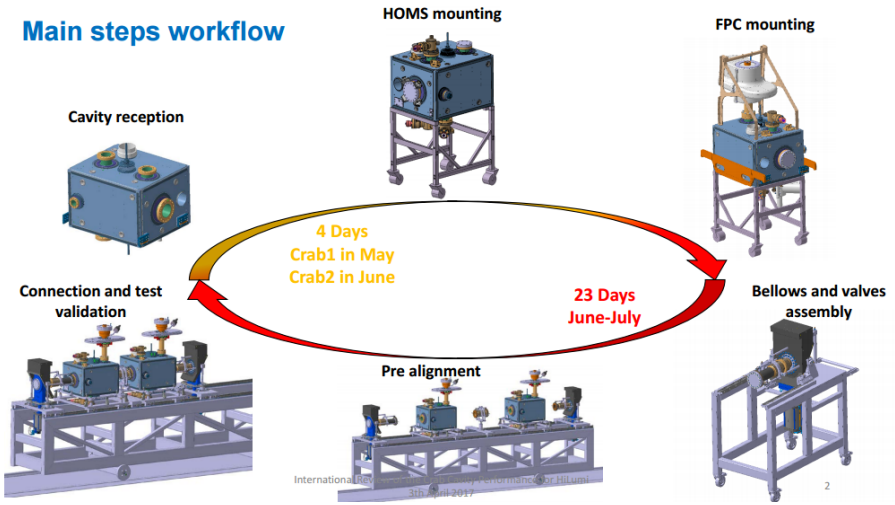
Target frequency achieved with a few kHz @2K

Frequency Tuning System

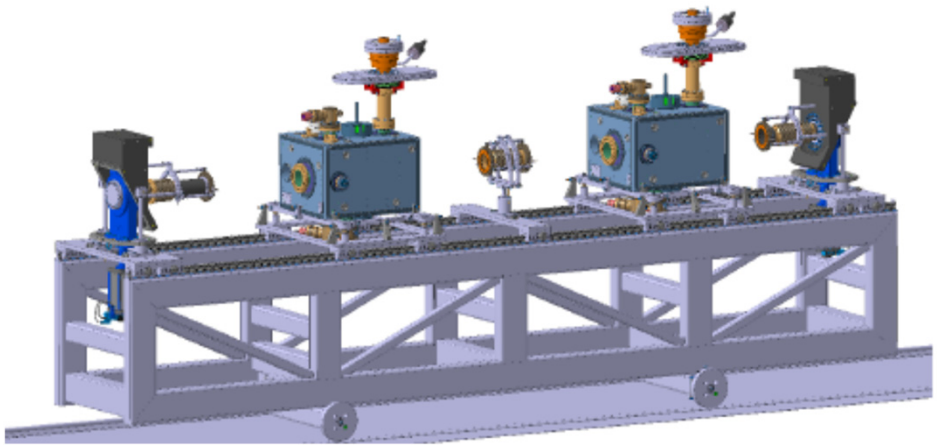
- Mockup tests in a vertical test performed.
- Better results in range ($> 100\ KHz$) and resolution ($\ll 80\ Hz$) than spec.



String Assembly in ISO4

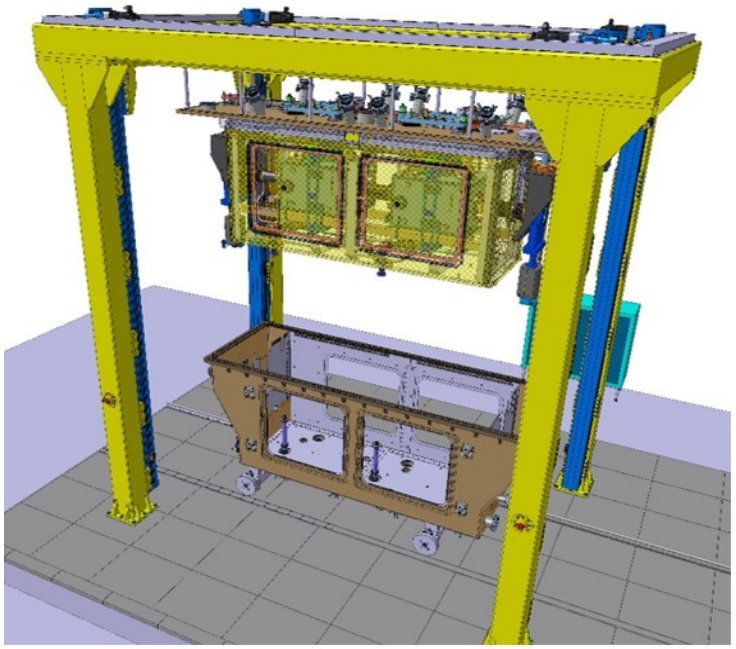


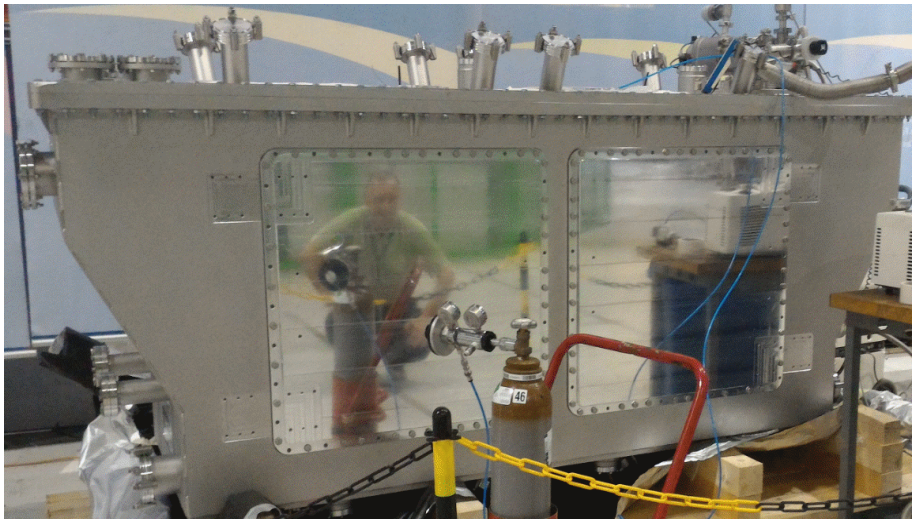
- First two steps of string assembly completed (but not w/o some problems*)
- FPCs to be mounted and string will be closed with the gate valves beginning of August



*Degradation of Q0 & quench field after dressing, feed-through leaks

Cryostat Assembly & Tooling



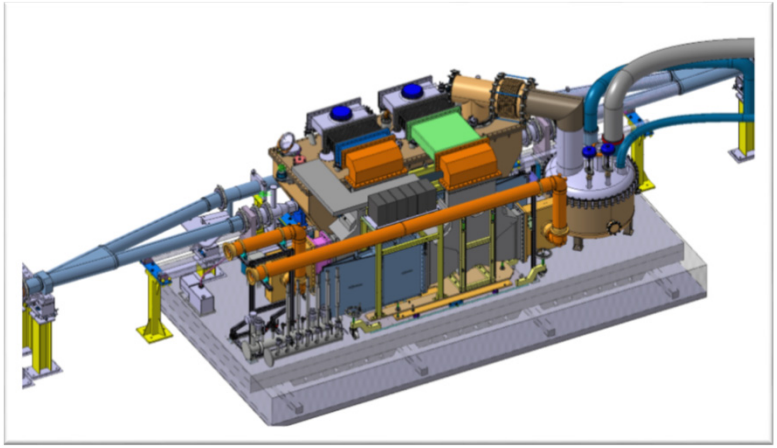


Cryostating preparation and tooling moving well

Vacuum vessel under pressure validation

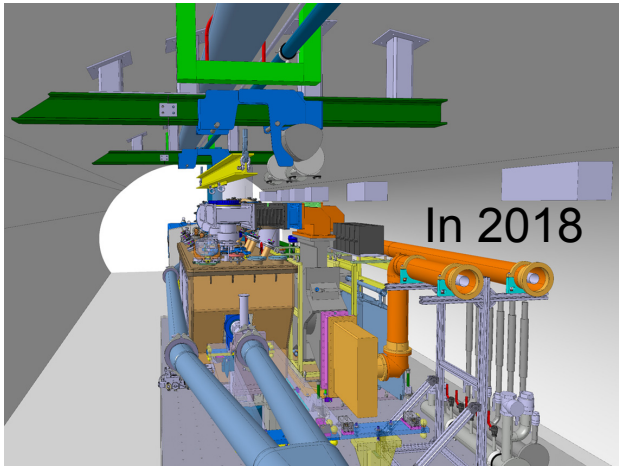
SPS RF Power

- Inductive Output Tube (IOT) as baseline solution for SPS & LHC
  - IOT Cubicle 60 kW-CW at 400 MHz validated
  - Parallel SSA solution under study as a possible compact/cheaper option in future

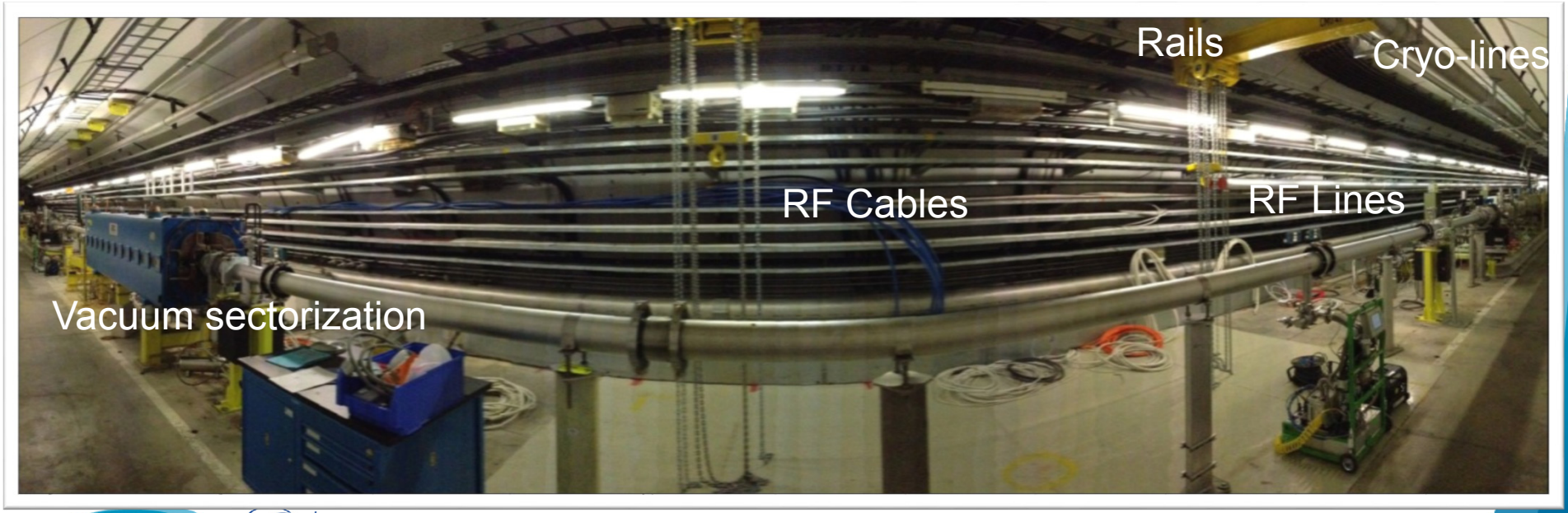


- Integration of the LHC type circulators & loads completed and procured.
  - Will also serve as spares for LHC

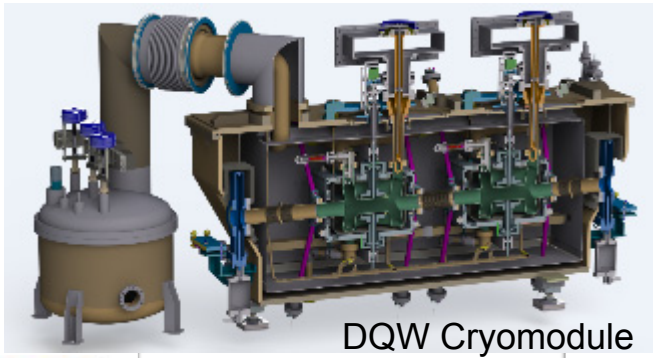
SPS Tunnel Infrastructure

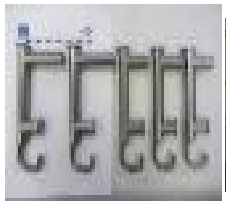


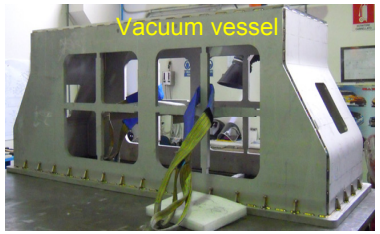
- Approx $10\ \mathrm{m}$ mechanical bypass with independent vacuum sectorization, RF cryogenics and services
- Starting 2018 it will be the highest energy and high current SRF test stand (26-450 GeV) in the world



Big Thanks to the Dedicated Teams
(CERN RF/MME/VSC/CRG, USLARP, UK-STFC)

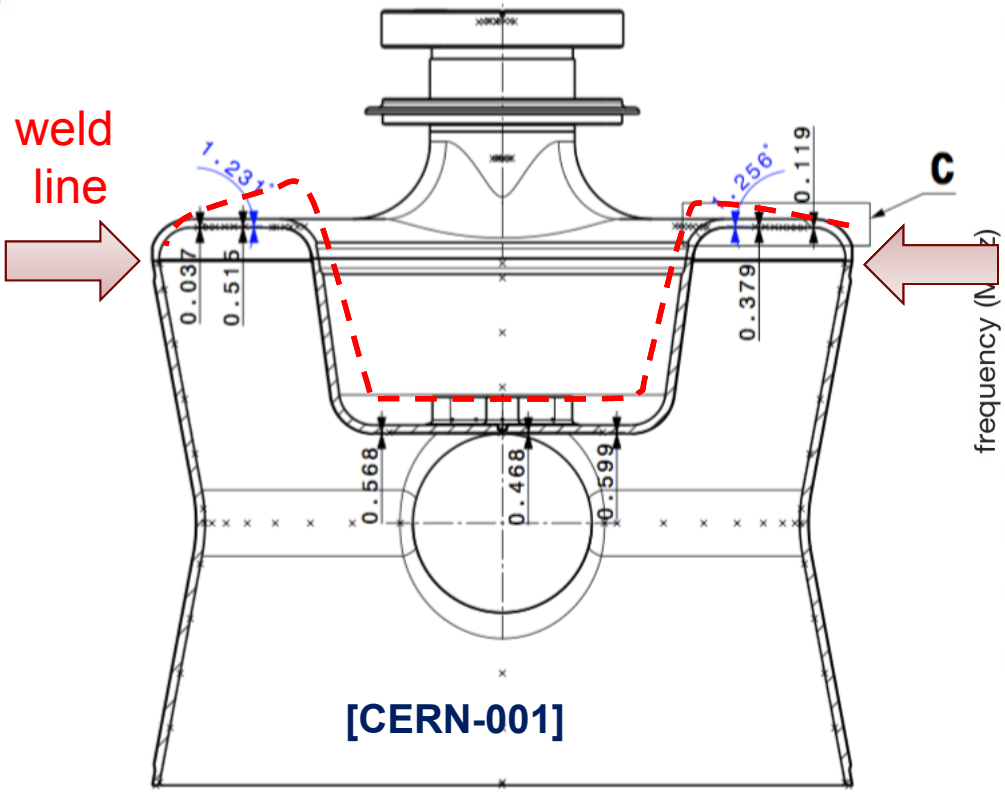






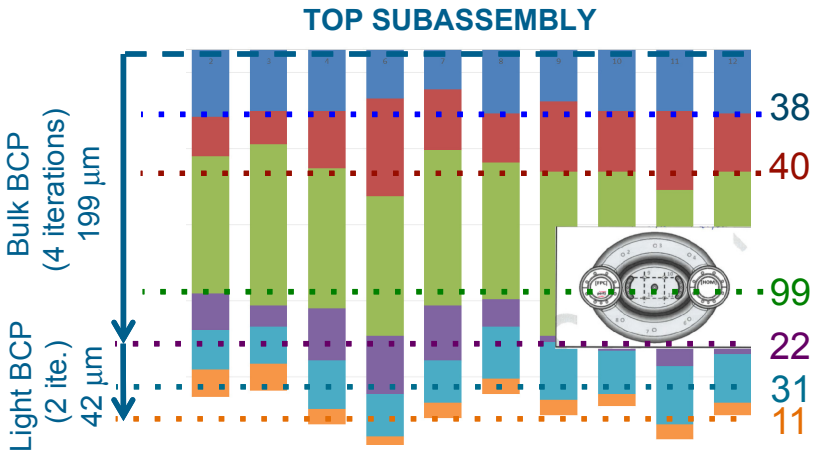
Important Finding, Fabrication

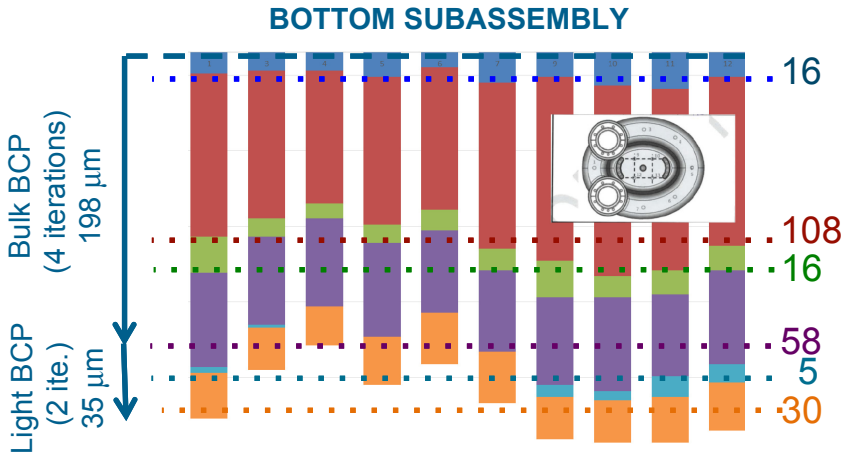
- **Trim tuning** allowed **controlled, reproducible tuning** of cavity
- The two **last welds shifted** the cavity **frequency in unexpected direction**.
- Dedicated **metrology** at CERN showed that **cavity** assembly had **deformed** as shown.

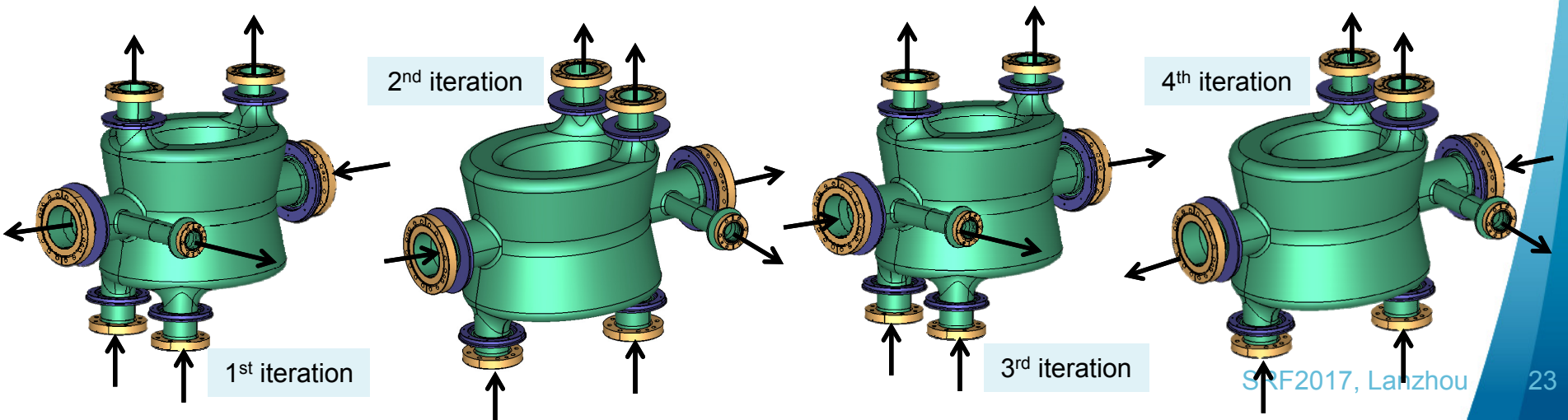


Important Finding, Cavity Chemistry

- Uniform surface etching possible only with multiple iterations. 2% deviation after 4 steps







KEK Electro-Polishing R&D

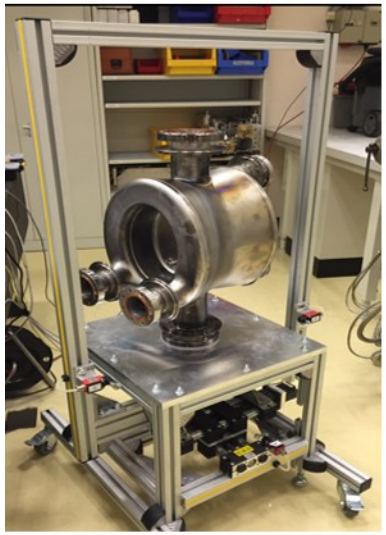
- Joint KEK-CERN proposal to develop EP for the complicated shape of crab cavities (2015-19)
- The EP system was built in 2016 and ready to be applied (Apr/May, 2017)
- If successful, the goal is to adopt it for the future production

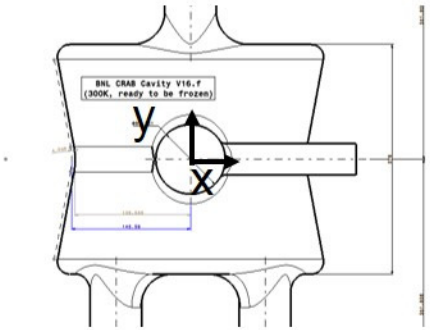
EP apparatus preparation at KEK

PoP-DQW Testing at KEK

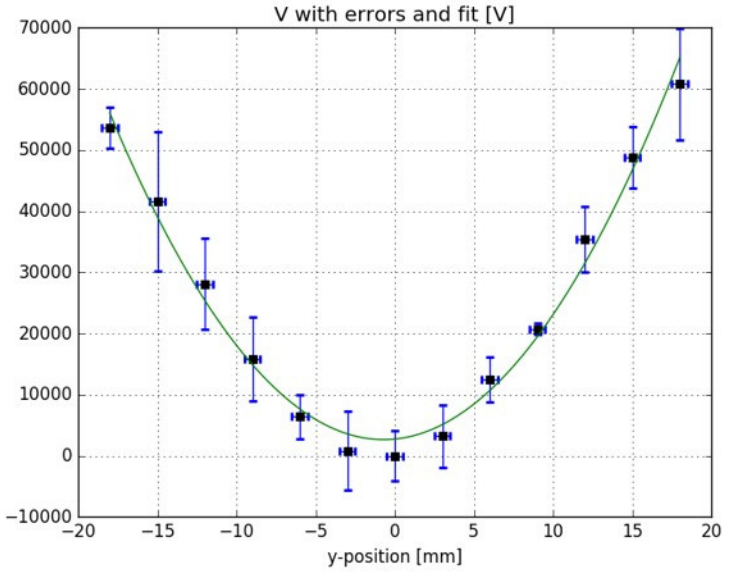
Beadpull Measurements

- 3-axis bead-pull test stand at CERN
- Electrical centre measurement and azimuthal analysis for RF multipoles
- Symmetry of the poles very good and within the measurement accuracy

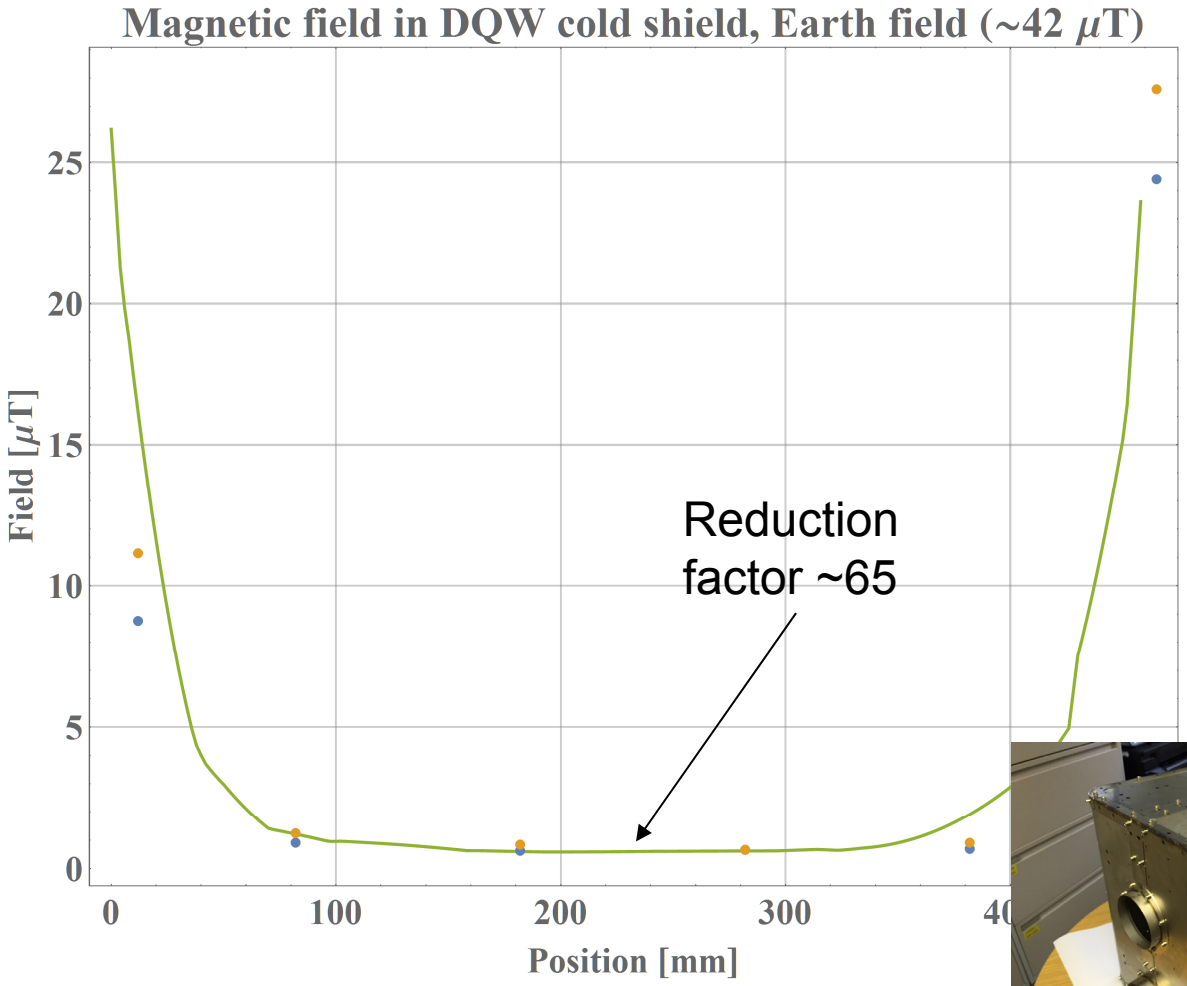


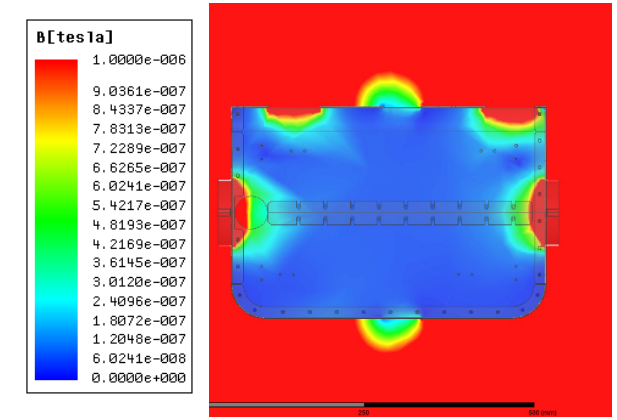


Multi-axis bead-pull test stand



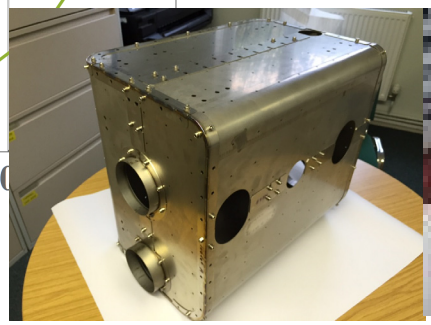
Internal Cold Magnetic Shield





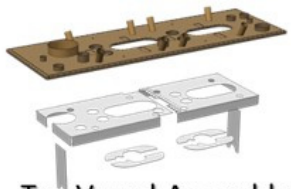
measured 1
measured 2
simulated

DQW

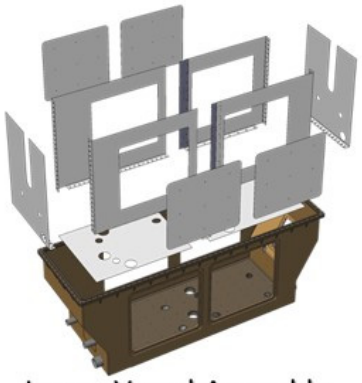


RFD

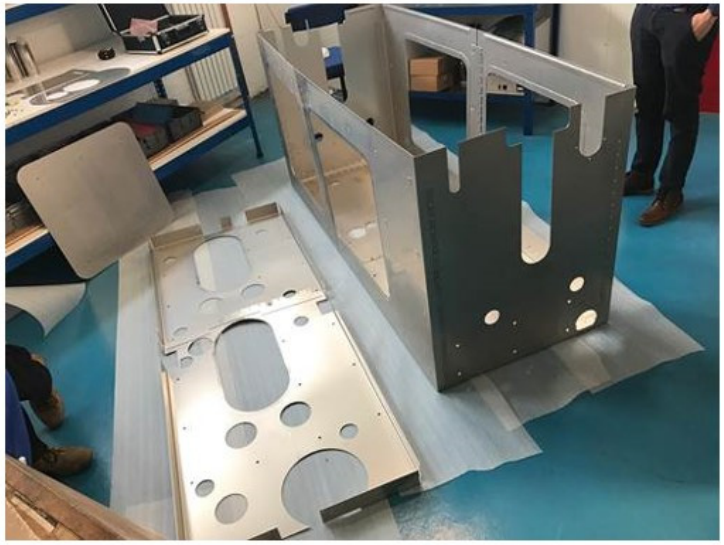
Warm Magnetic & Thermal Shielding



Top Vessel Assembly

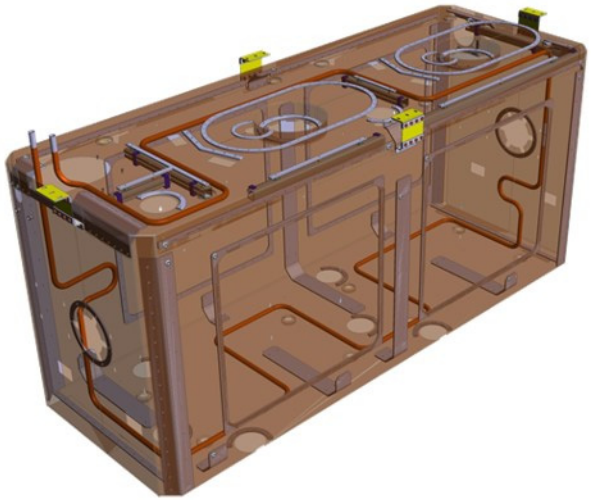


Lower Vessel Assembly



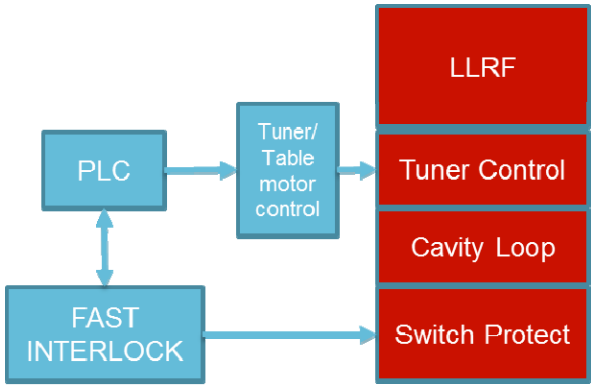
Warm magnetic shields for the SPS cryomodule ready for assembly into cryostat

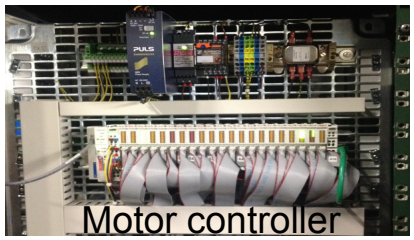
Copper shield with copper tubing brazed to stainless steel transitions, fabrication in its final stages



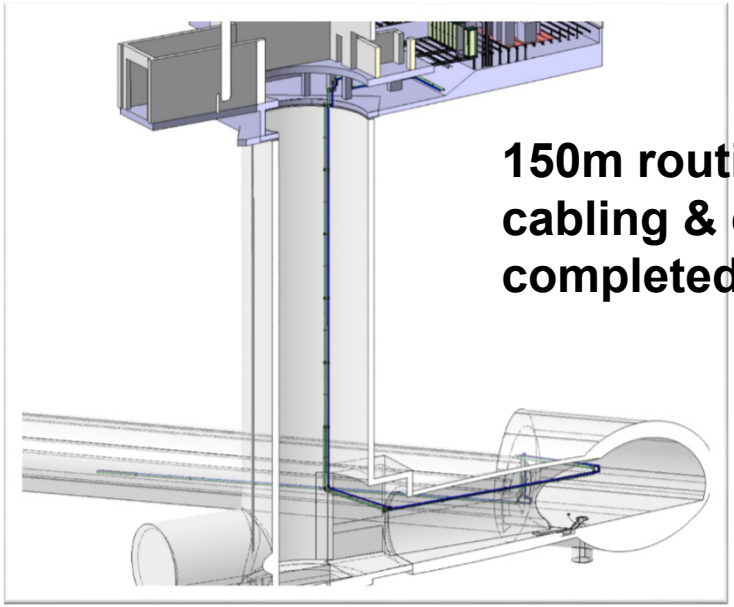
SPS CC-RF Fast/Slow Controls

- Strong synergy with the Linac4 design, that was an evolution of the LHC design (VME based)
  - Identical VME crates (installed in SM18), Self-excited loop test early 2017 + Tuner driven tests Spring 2017
  - PLC based RF power system, tuning, table control & fast interlocks, also LINAC4 based
  - Amplitude/phase stability with realistic loop delays to derive the specs for the LHC





RF Lines from BA6-SPS Tunnel



150m routing for RF lines, RF cabling & cryogenic lines completed Jan 2017

SPS RF/Cryo Routing (150 m)