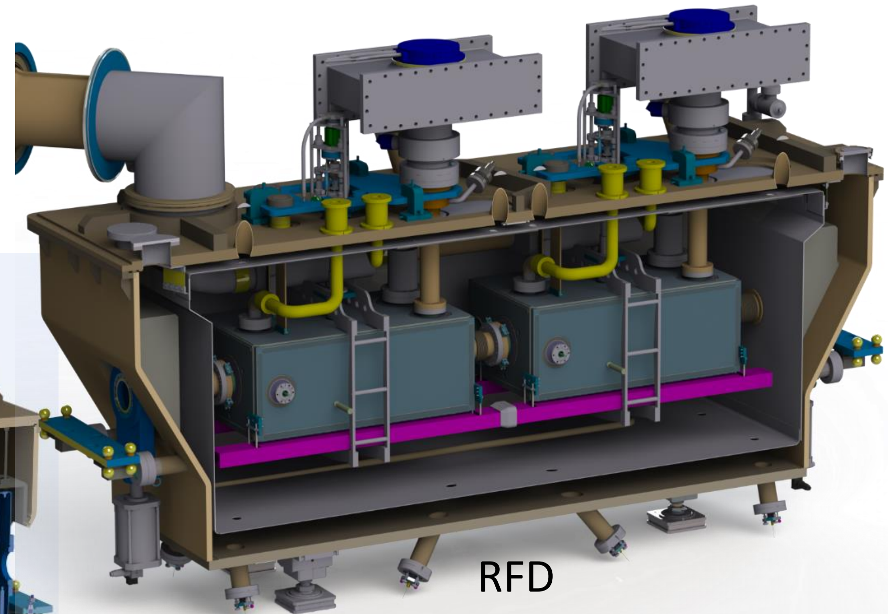
Status of the Crab Cavity Effort
May 18, 2016

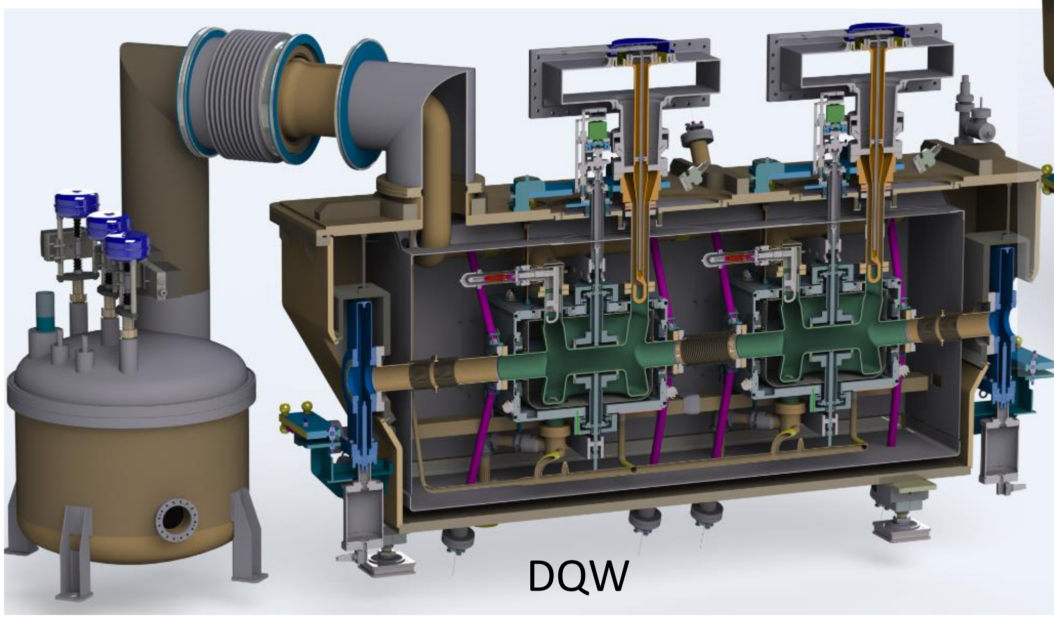
On behalf of WP4

Joint USLARP CM26/Hi-Lumi Meeting, SLAC

Outline

- *Update on the Cavity + CM production*
- *SPS Test preparation*





Cost & Schedule Review (New Baseline)
CM Review, Nov 2015 (Basic design choices approved)
SPS Test Day I

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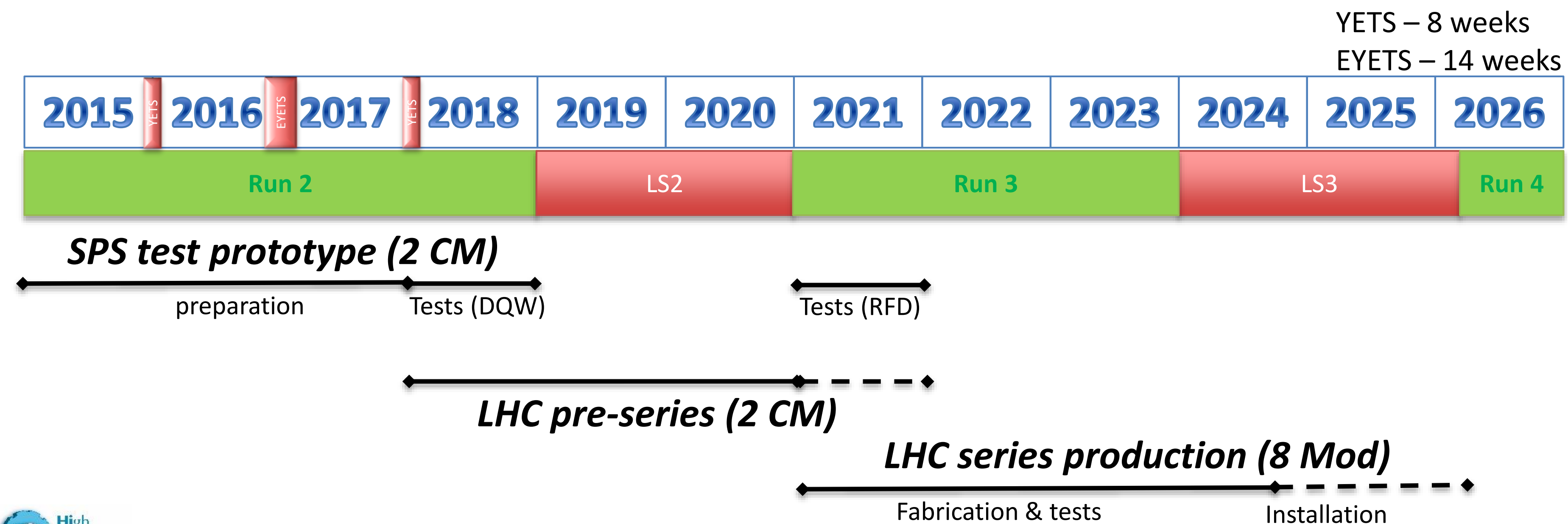
Revised Planning

- *First Re-Baselining after C&S Review I*
  - *US cavities delayed (+ unresolved “conformity standards”)*
  - *CERN cavity production (DQW) for SPS is adopted as baseline*
- *Impact on SPS is significant*



SPS Revised Planning

	2016				2017				2018
	Qtr1	Qtr2	Qtr3	Qtr4	Qtr1	Qtr2	Qtr3	Qtr4	Jan
RF Power	2 IOTs SM18 2 IOTs in BA6 (FPC Conditioning)								
LLRF/Controls	SM18-Vertical Tests Setup			Deploy for VTA	BA6-SM18 Setup High Power & deployment				
Dressed Cavities	Cavity 1 Fabrication (Treatment + Cleanroom tooling)				Cav 2 Fabrication + Cav 1 & 2 Treatment/Testing + Clean room assembly				
FPCs	2xFPCs in SM18 Cleanroom				FPC Conditioning (TB)				
Cryomodule	Cryostat & Tooling Design/Procurement			Cryomodule/Tooling Preparation			CM Assembly	Cold Tests	SPS
Cryogenics	Cryogenic Distribution & Valve Box SM18/SPS							CM + VB	
Movable Table	Design & Manufacturing						Tests at CERN		

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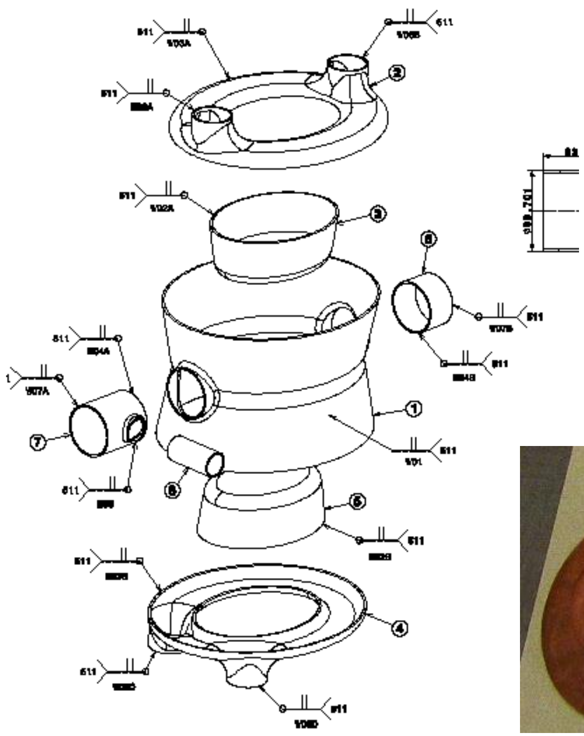
CM-Review Recommendations (A. Yamamoto et.al)

- Clarify “the minimum functional requirement/goal” for the SPS test
  - Draft acceptance criteria prepared, being revised/approved
- A decision/action on the ordering/implantation of the refrigerator
  - Done
- The system integration workflow, including tooling, fixtures, and intermediate tests must be studied in greater detail
  - Now coordinated under a new WG
- The critical components such as FPCs and tuners shall be individually reviewed (in 2016)
- Cryogenic-safety and failure-mode analyses should be performed
  - 1st safety analysis approved by HSE, will review again in Fall 2016
- Reinforce the supporting system & limiting forces on the FPCs.
  - Blade type supporting system was optimized

DQW Production, Circular Trials

(Lunette, Cuvette, Extrusion)

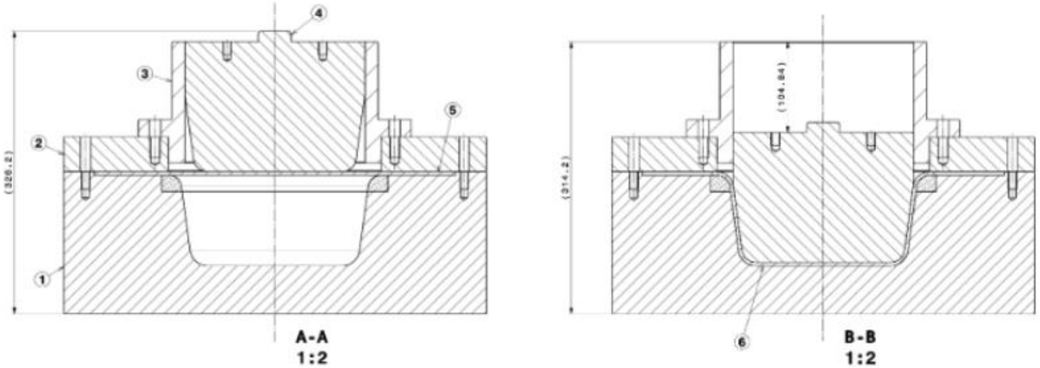
See Talk: M. Garlasche



Cu tests performed to explore shaping techniques & tooling (very systematic analysis)
Circular samples show very good shape and thickness accuracies

Example Shaping Simulations

See Talk: M. Garlasche



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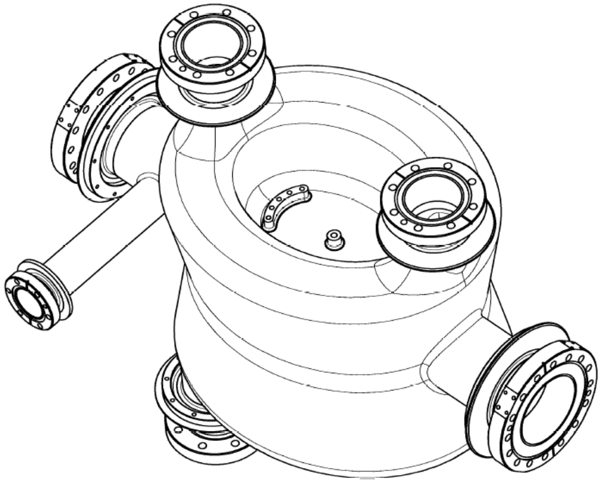

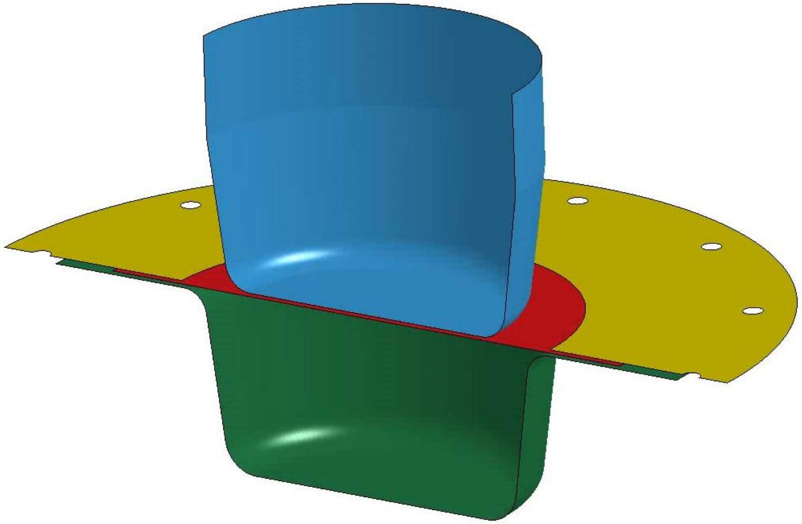

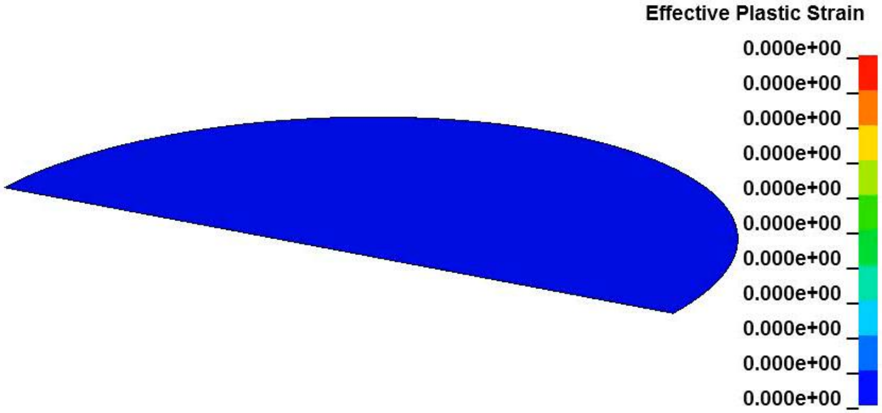

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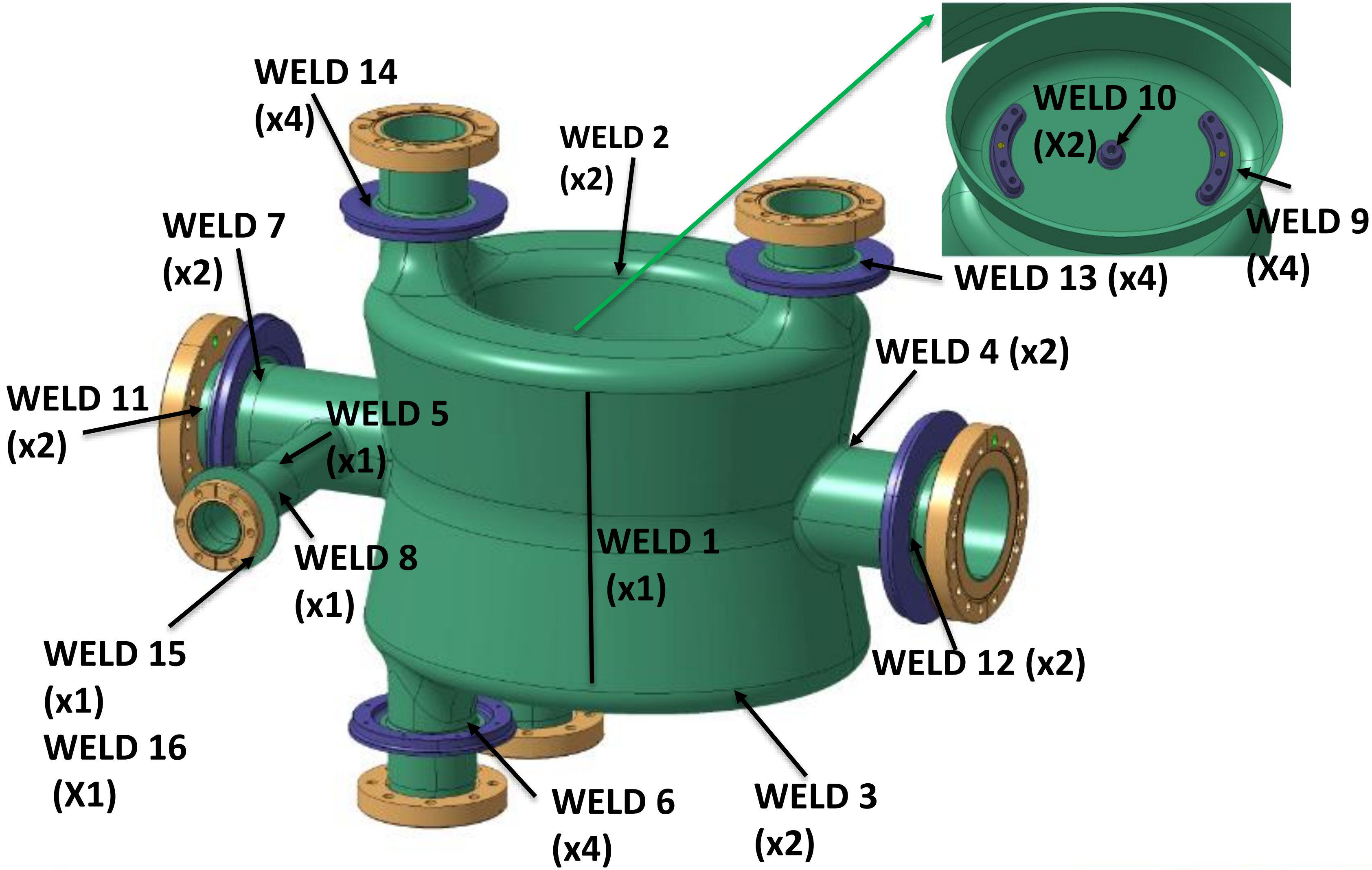
Weld Map

16 complex welds to qualify & perform
(with tight tolerances)



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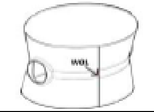
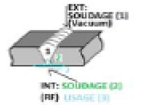
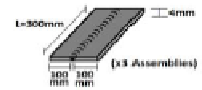
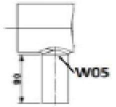
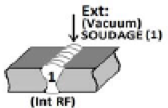
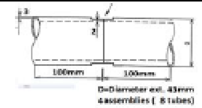
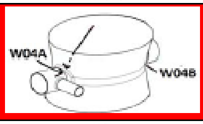
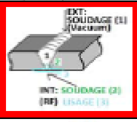
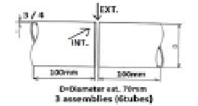
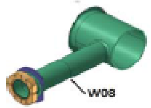
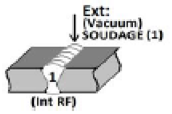
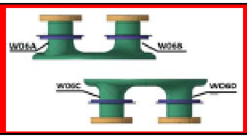
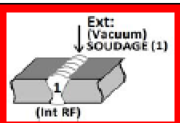
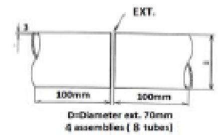
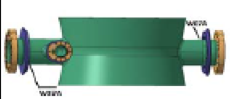
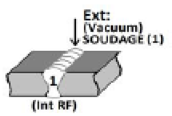
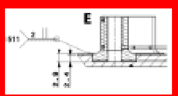
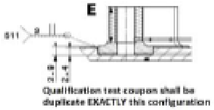
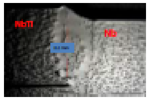
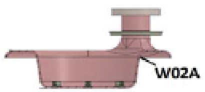
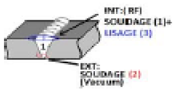
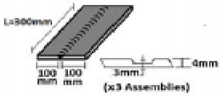
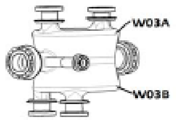
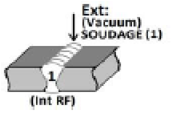
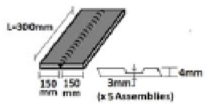
Welding Test Qualification Flow Chart

WELDING TESTS & QUALIFICATIONS - CRAB CAVITY — DATE: 30/10/15 — Issued/Réalise: P.Freijedo & T.Tardy

Weld N, / N° soudure & SEQUENCE	Joint identification	Joint configuration	PASS	Dwg's reference / Références plans de détail	Joint Type / Type de joint	Dimension Øint (mm)	Esp. (mm)	Esp.Estimé (mm)	Process / Procédé	Sample for Welding tests & Qualification (EN-15614-11) (Configuration & Dimensions)	MATERIAL NEEDED	pWPS /pDMOS Preliminaire Descriptif de Mode	REMARKS
W01			Par l'extérieur cavité: 1er pass: Soudage Par l'interieur cavité : 2nd pass- Soudage 3th pass- Lissage	LHCACFCA0023	BW with full penetration	-	4	4	511-EBW		PLATE 520X520X4 (1 Unit)		
W05			Par l'extérieur cavité: Soudage	LHCACFCA0023	BW with full penetration	37,63	3	2	511-EBW		PLATE 520X520X3 (1 Unit)		Thickness to be defined
W04A W04B			Par l'extérieur cavité: 1er pass: Soudage en deux cycles Par l'interieur cavité : 2nd pass- Lissage local interieur	LHCACFCA0023	BW with full penetration	83,7	3		511-EBW		PLATE 520X520X4 (1 Unit)		Thickness to be defined
W08			Par l'extérieur cavité: Soudage	LHCACFCA0023	BW with full penetration	37,63	3	3	511-EBW	Already qualified with circular sample for W05	-		
W06A W06B W06C W06D			Par l'exterieur cavite: Soudage	LHCACFCA0023	BW with full penetration	61,67	3		511-EBW		PLATE 520X520X4 (1 Unit)		Thickness to be defined
W07A W07B			Par l'exterieur cavite: Soudage			83,7	3	3	511-EBW				
W09A W09B W09C W09D W10A W10B			Par l'exterieur cavite: Soudage	LHCACFCA0001	BW with partial penetration		2		511-EBW		NbTi/Nb		Preliminary test performed: 
W02A W02B			Par l'interieur cavité : 1er pass-Soudage 3-Lissage Par l'extérieur cavité: 2-Soudage	LHCACFCA0023	BW with full penetration	238	4	4-3	511-EBW		PLATE 520X520X4 (3 Units)		Thickness to be defined
W03A W03B			Par l'exterieur cavite: Soudage	LHCACFCA0023	BW with full penetration	398	4	4-3	511-EBW				

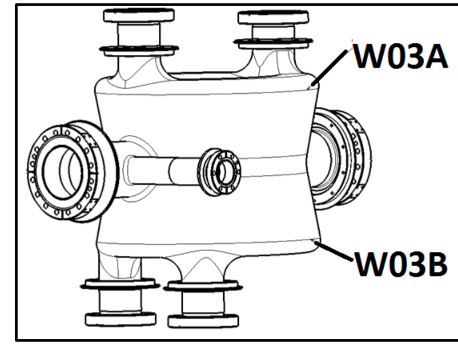
Difficult Weld

A Sample Weld

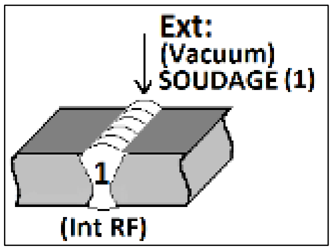
<u>Nb-Nb: W03A/B Final ellipsoidal welds :</u>

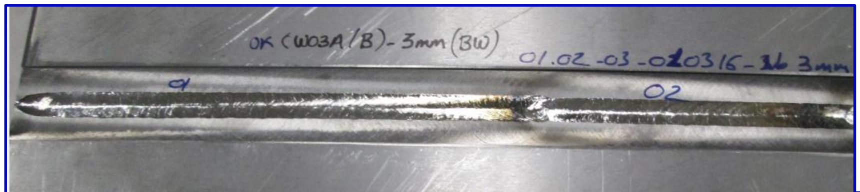
Welding in 3mm of thickness performed on 1 side.

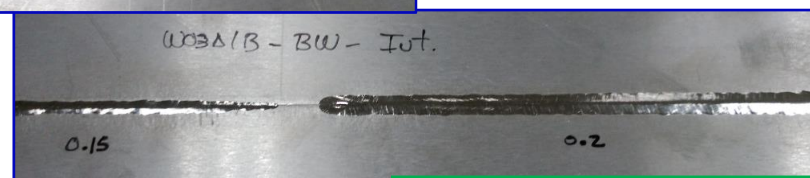
Two configurations tested: Key (Clé) and BW (Bords droits)



BW

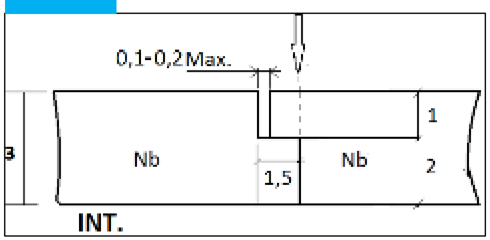


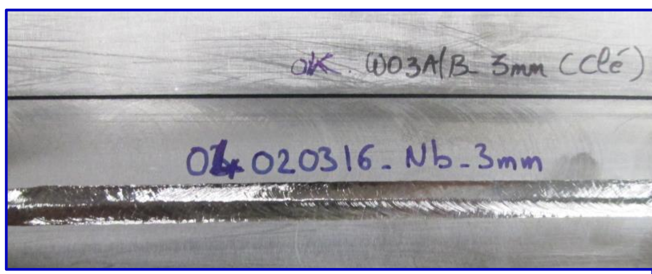


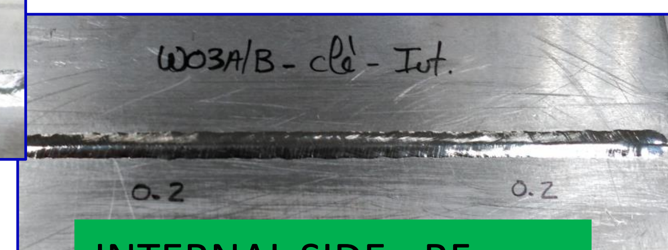


INTERNAL SIDE - RF

KEY



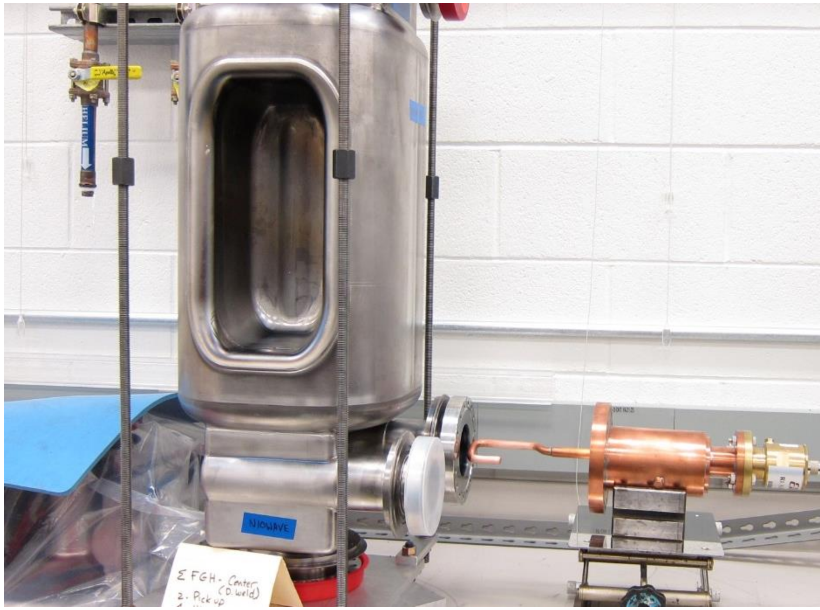


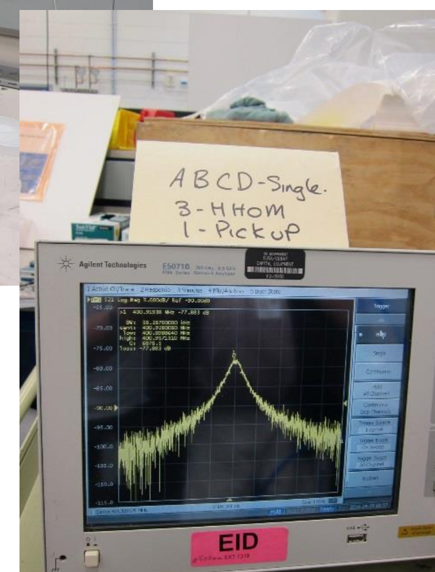


INTERNAL SIDE - RF

BOTH CONFIGURATIONS WITH SATISFACTORY RESULTS

Status of US Cavities from Niowave

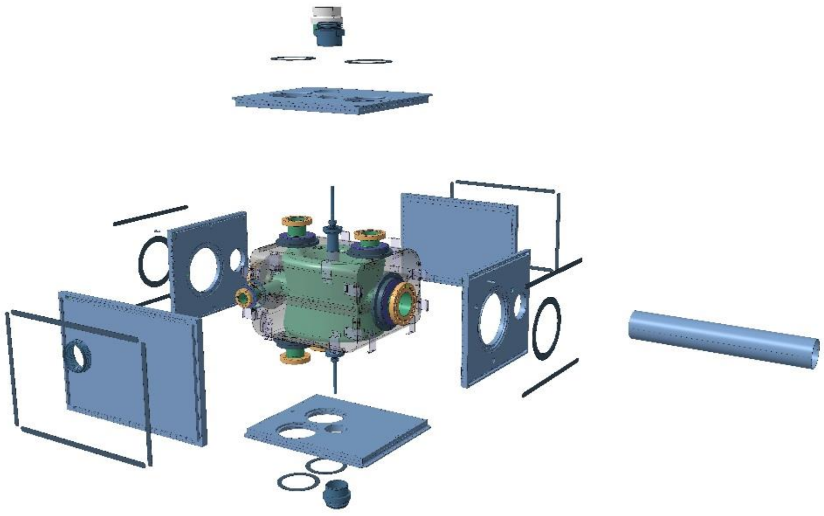




Three welded assemblies of an 2-RFDs at Jlab
RF, CMM, Radiography etc.. started
Expect 1-RFD qualified and sent to CERN Mar 2017

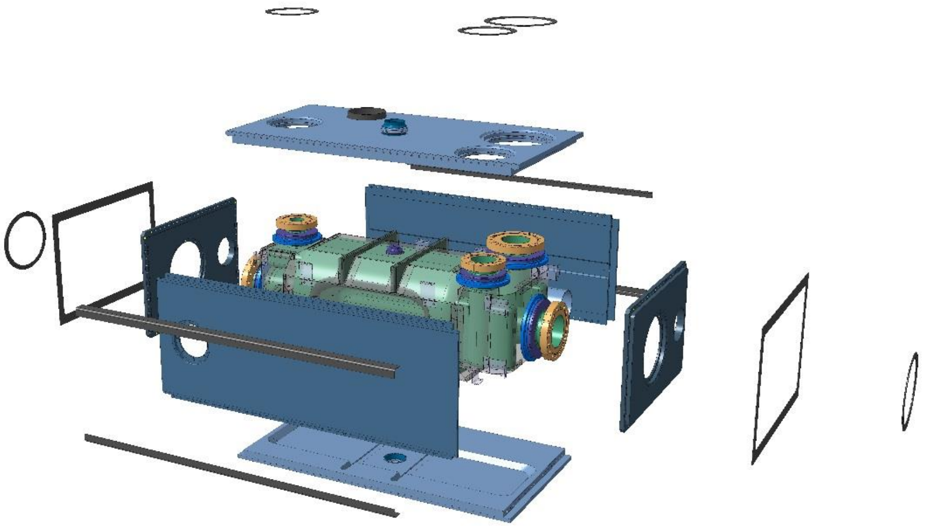
DQWs parts being re-stamped and in a similar configuration to be sent to Jlab

Helium Vessel



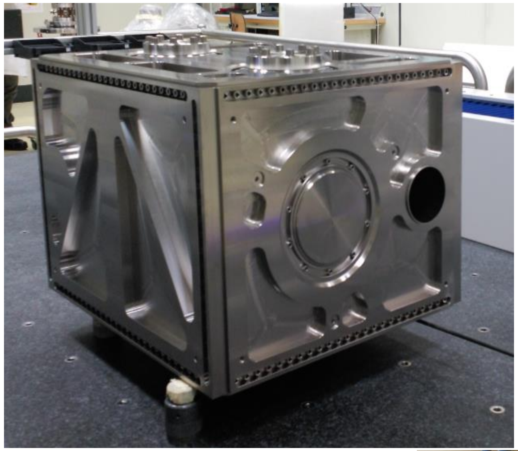
Bolted/welded concept was chosen for structural integrity & minimal stress to cavity

A dummy prototype was launched for experimental verification of assembly procedure, stress, vacuum integrity and other aspects.



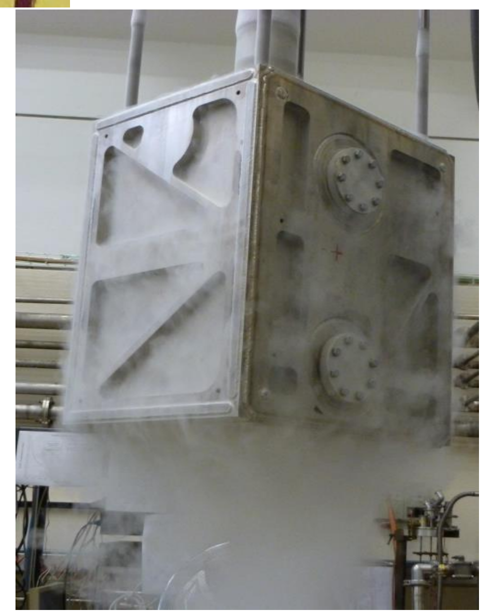
They are now verified

Prototype Helium Vessel



WELDING STEPS
1- Vertical welds
2- Welds around the top/bottom plate
3- Longitudinal Covers
4- Circular Covers & Beam pipe

Pressure tests (2.6 bar)



The vacuum levels remained at $\leq 10^{-9}$ mbar (5 thermal cycles)

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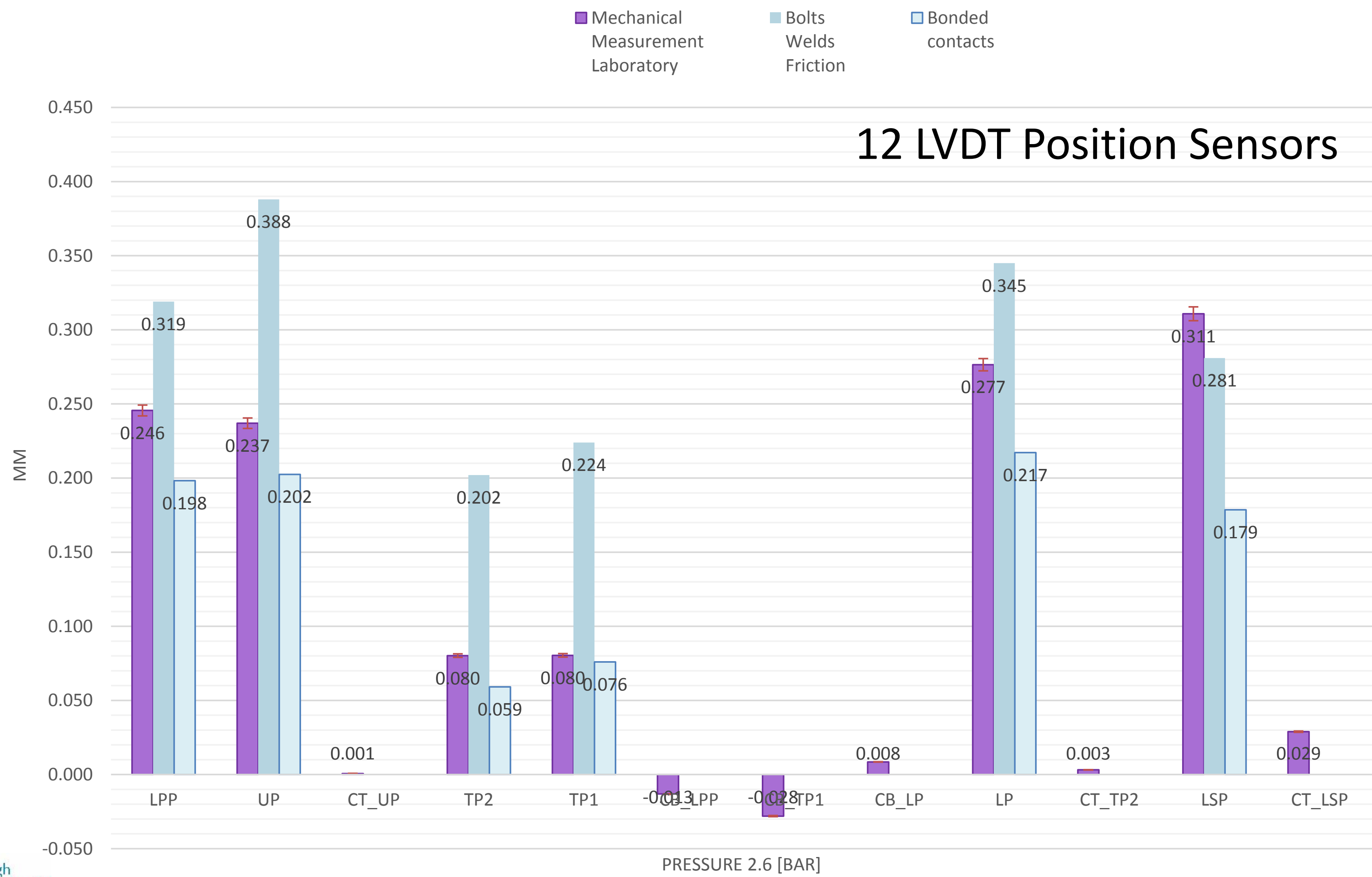
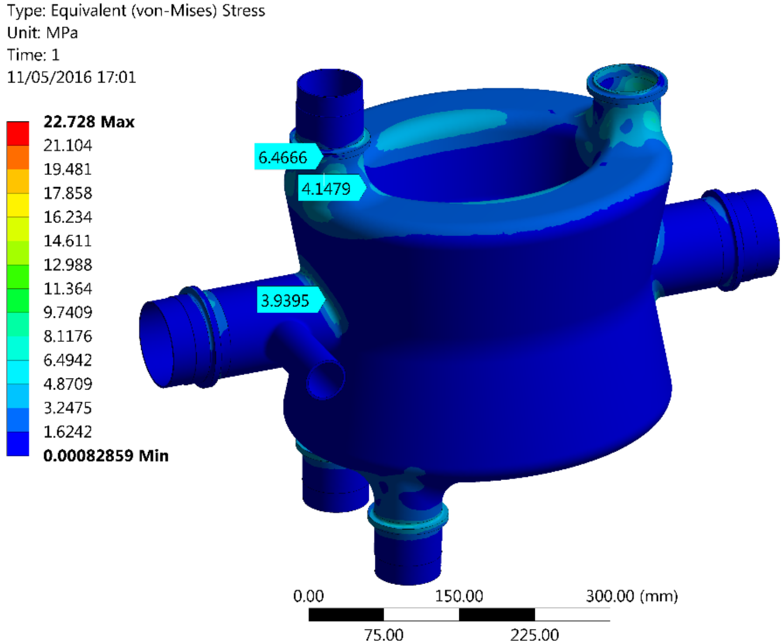
Tests vs. Simulations

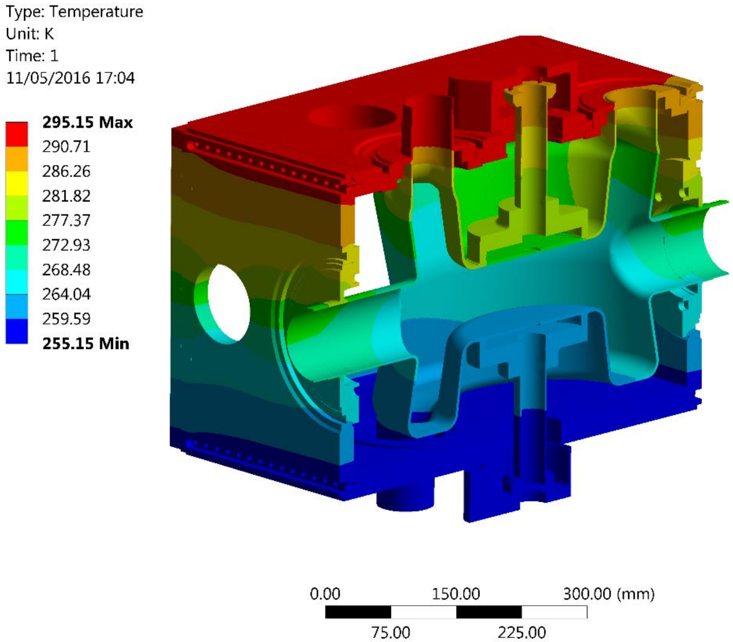


High Luminosity LHC

Cavity Stress, cool down

- $\Delta T_{max} = 40$ K top/bottom of tank (input constraint)

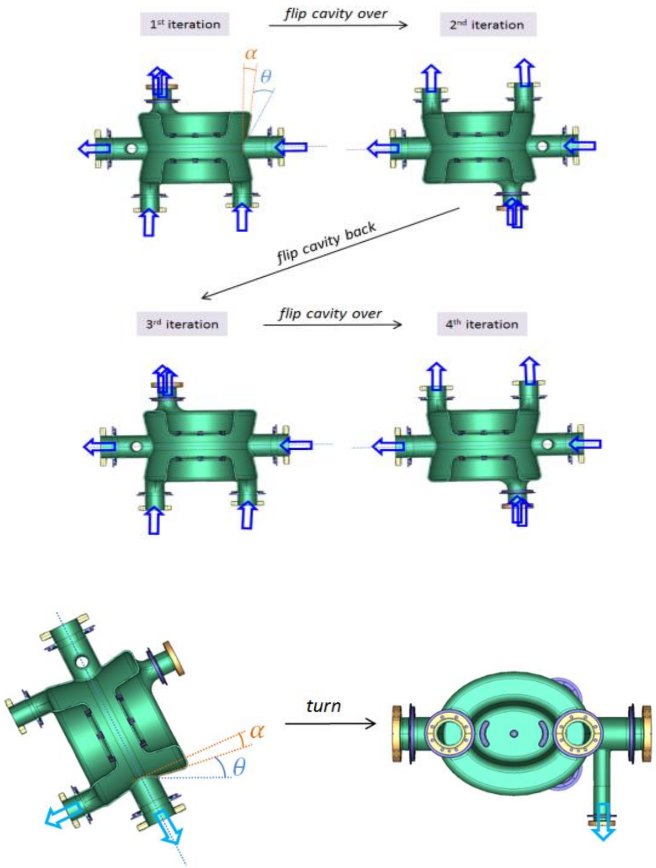




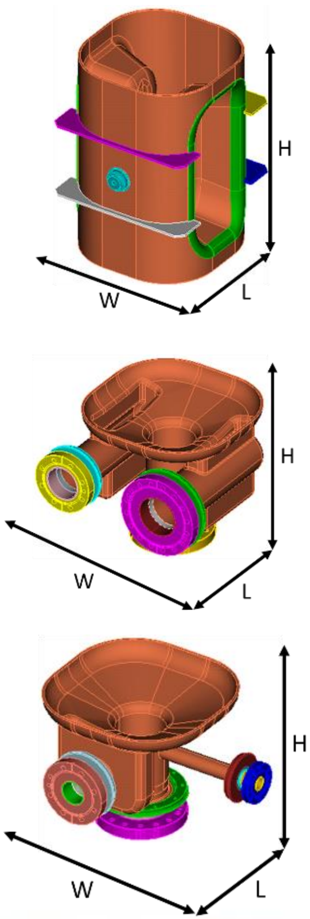
- Stress on cavity is low ($\leq 10\%$ of allowable)
- Slower cool-down rate can further reduce if necessary

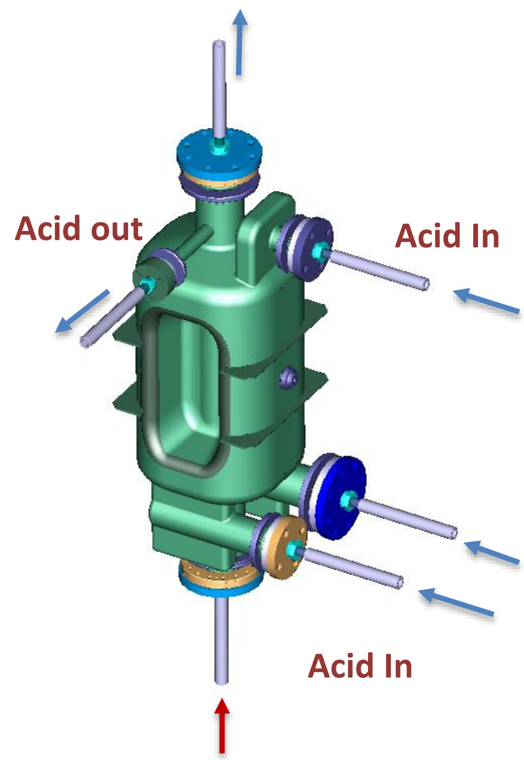
Cavity Chemistry, DQW & RFD

DQW: Very light chemistry on Parts & Bulk Chemistry on assembled cavity

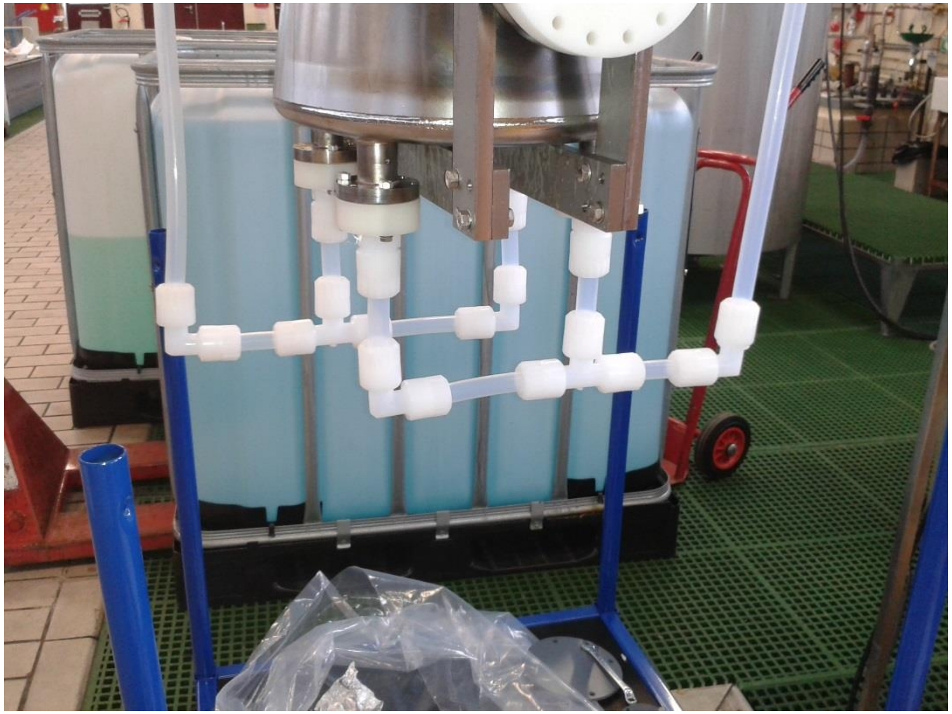


RFD: Bulk Chemistry on Parts & Light Chemistry on assembled cavity





CERN Setup, Cavity Chemistry (PoP)

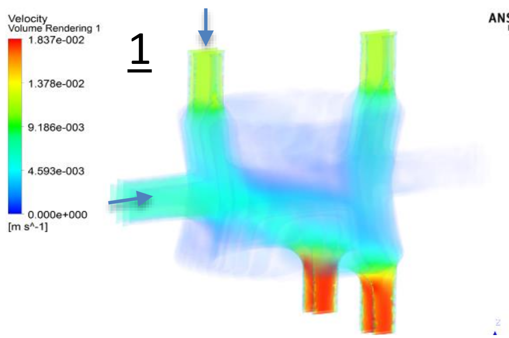


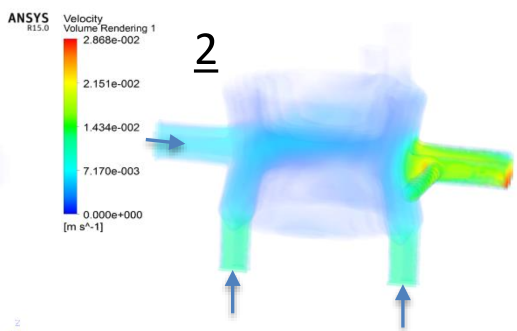
General procedure uses acid circulation between $10 - 15^{0}$ C (~ 40 min, indicative)

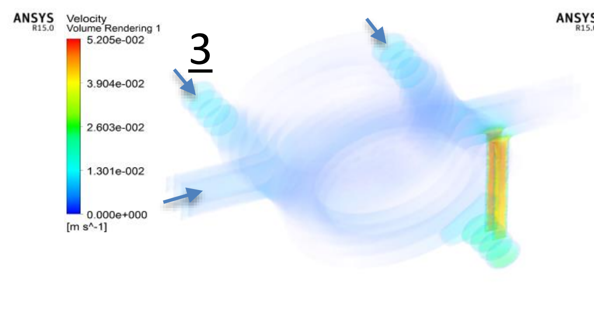
Small tilting for trapped gas removal

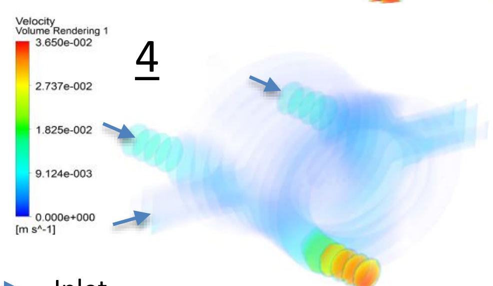
Fluid Dynamics for Chemistry

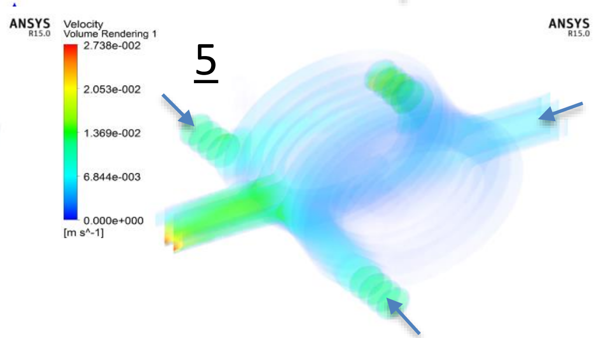
See Talk: T. Jones

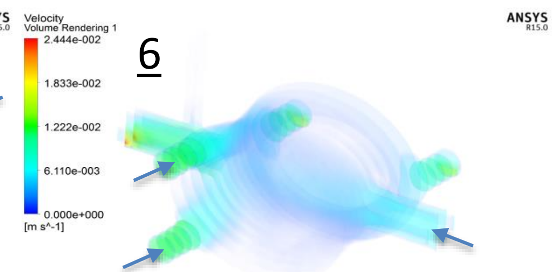












→ = Inlet
All other ports outlets
Gravity acts down as shown in images

Analysis	1	2	3	4	5	6
Range (cm/s)	0.63	1.82	0.90	0.65	1.23	0.92
Standard Deviation (cm/s)	0.21	0.40	0.24	0.21	0.26	0.23
Av. Velocity (cm/s)	0.29	0.38	0.33	0.31	0.36	0.28

High Luminosity LHC

Data taken for 21 points throughout the cavity for each orientation

KEK Electro-polishing Status

EP apparatus ready waiting for the cavity

Transparent dummy chamber


Transparent dummy chamber


Set up at our EP station


Central electrode inserted


The cavity can be tilted to extract trapped air in the crab cavity during electrolyte filling

Frequency Tracking

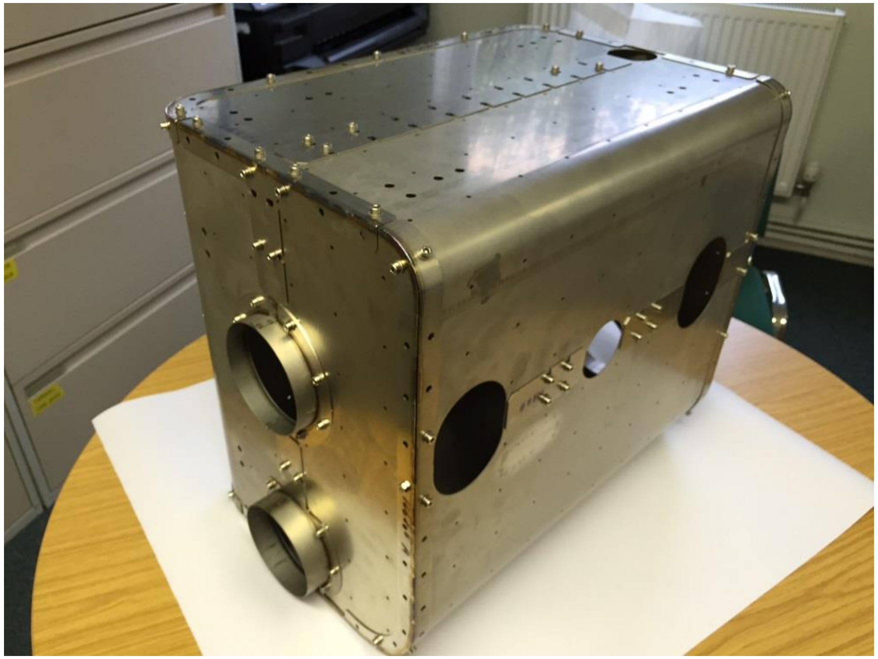
See Talk: S. De Silva, S. Verdu

FREQUENCY SHIFTS Target: 400.79 MHz (-60 kHz)

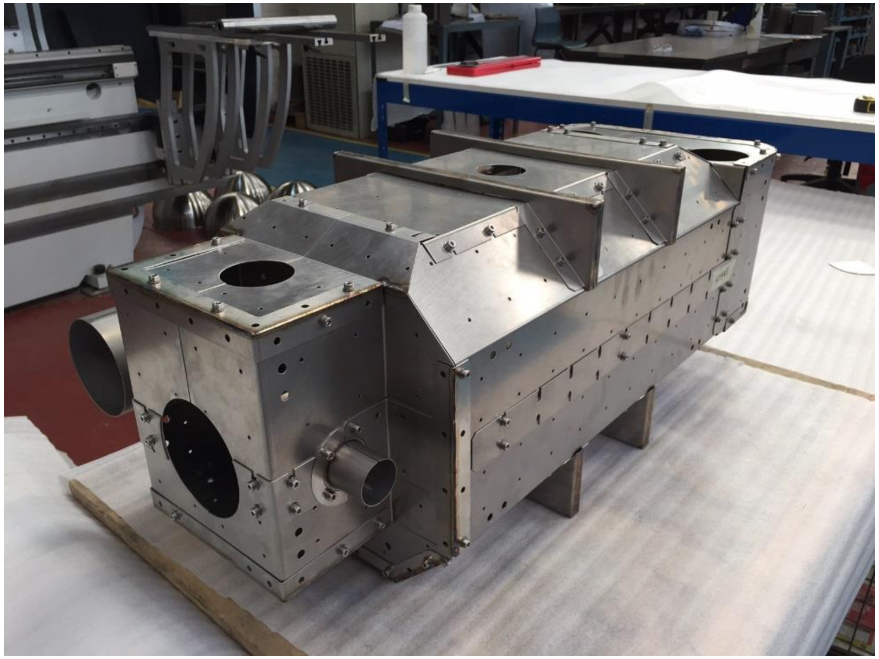
	Effect	Magnitude		Uncertainty		Unit	Premises under which value was calculated	
Fabrication	*Last weld-A shrinkage (assumed ~1 mm)*	$\Delta f_{ShrinkWeldA}$	980	-490	+980	kHz	Freq shift calculated as expected shrinkage times trim sensitivity.	Cumulative freq shift from both shrinkage and sagging of last weld-A will be known after welding the "next-to-last" weld.
	Last weld-A sagging (assumed 0.5mm-deep, 5mm-thick bead)	$\Delta f_{SaggWeldA}$	-70	-50	+70	kHz	From simulations.	
	High-T baking	$\Delta f_{High\text{-}T}$	0			kHz		
	Low-T baking	$\Delta f_{Low\text{-}T}$	0			kHz		
	BCP (210 μm)	Δf_{BCP}	-170	-50	+50	kHz	Models prepared for CST simulations.	Take about ~30% for error due to thickness removal uncertainty and unhomogenenity. Error may be reduced if BCP performed in several iterations and in rotating facility.
Assembly	*Couplers and ports (bare cavity --> baseline aseembly of cavity with couplers)*	Δf_C	-89	??	??	kHz		Estimate uncertainty coming from assembly error that will turn into penetration error.
	Test couplers out --> in	Δf_{TestC}	0			kHz		
	Helium vessel mounting and magnetic shield assembly	Δf_{Mount}	0			kHz		
	Welding of helium vessel	$\Delta f_{TankWeld}$	-150	-116	+416	kHz	Magnitude: form measurement of displacements in dummy tank after welding used as input for ACE3P simulations. Uncertainty: worst-case scenario for tolerance error of $\pm$0.1 mm.	
Setup	*Frequency change from air to vacuum*	Δf_ε	133.3			kHz	Formula	
	Frequency sensitivity to pressure	$\Delta f_P/P$	-0.103			Hz/mbar	ANSYS-APDL	
	Frequency change from 300 K to 2 K	Δf_T	573			kHz	ANSYS-APDL	
Operation	*Lorentz detuning coefficient*	$\Delta f_U/(Vt)^2$	-40			Hz/(MV)^2	CST simulation for model including tuning system and vessel.	
	LF detuning: RF power off --> on	Δf_{LD}	-0.4			kHz		
	Beam loading	Δf_{BL}	0			kHz	Formula	

2K Internal Magnetic Shields

Double QW

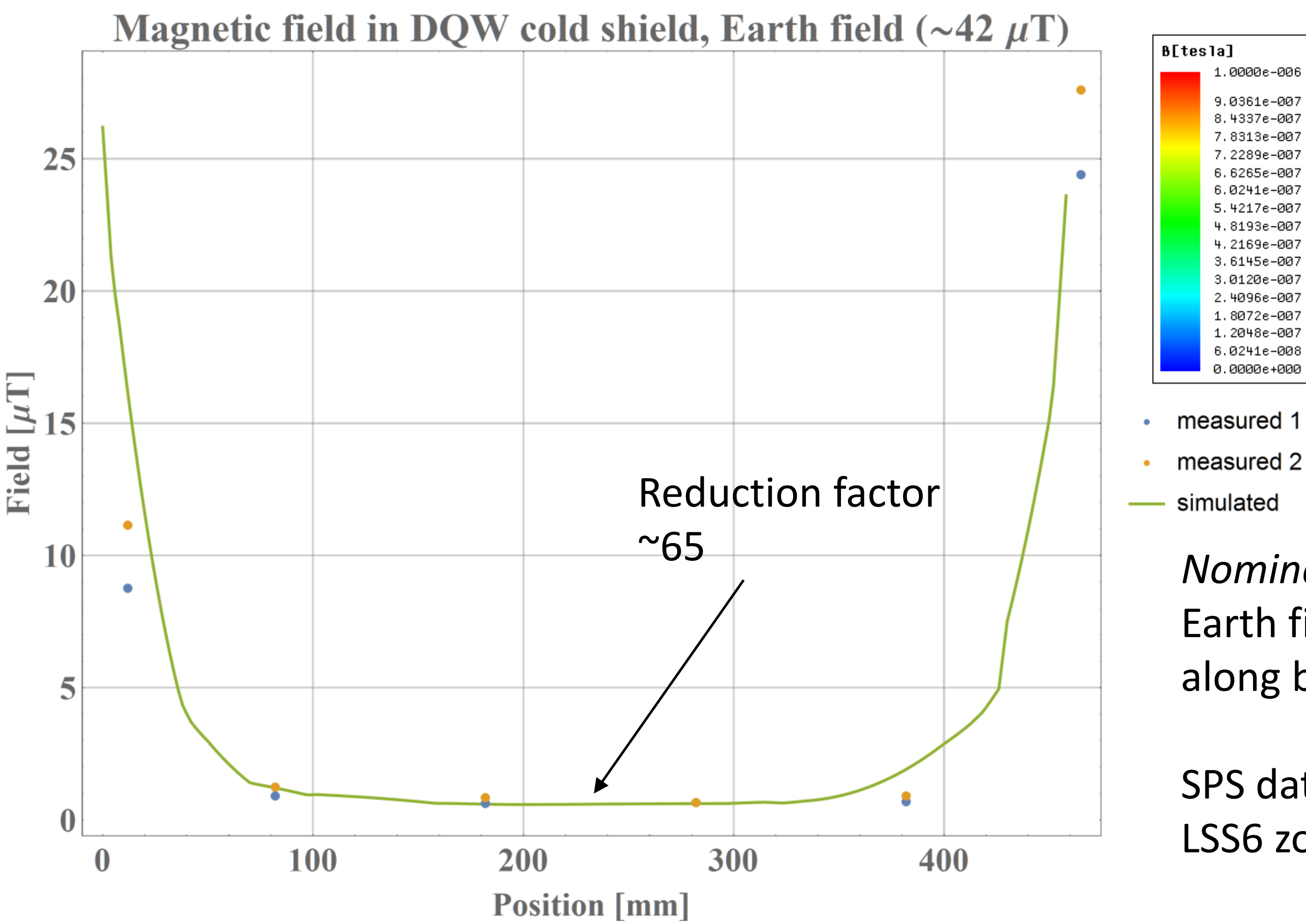


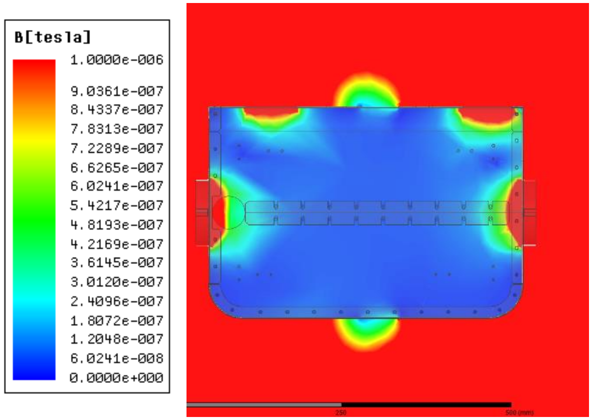
RF Dipole



- *Internal magnetic shields already integrated by STFC-UK !!*
  - *1 mm Cryophy, annealed after shaping, supported by Ti brakets*
  - *Controls done: dimensions, shielding reduction factor*
  - *At CERN waiting for cavities…*

Comparison of Data and Simulations



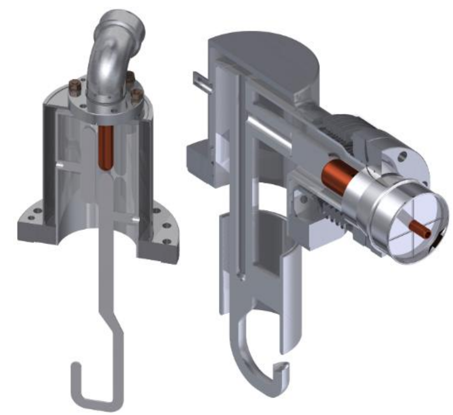


Nominal input:
Earth field ($\sim$ 42 μT) along beam axis

SPS data taken in LSS6 zone from YETS

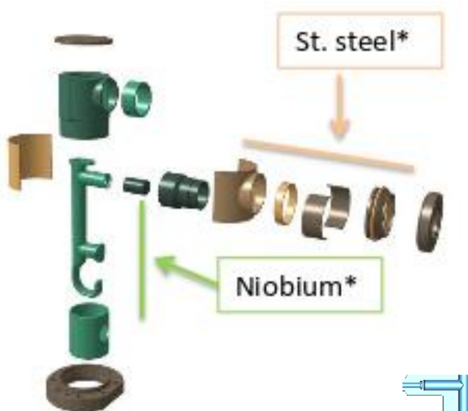
HOM Couplers

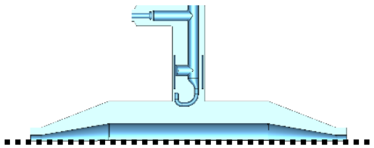
See Talk: M. Garlasche



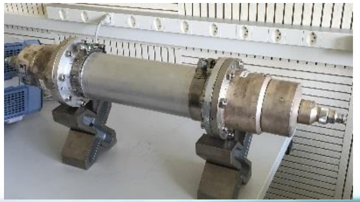
DQW Status
- Niobium pieces & other ancillaries produced
- Final metrology & welding tests ongoing before assembly

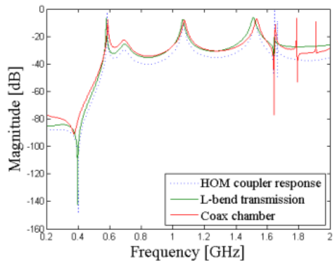
RFD material at CERN, fabrication in 2016



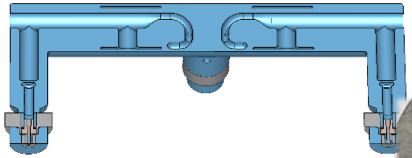


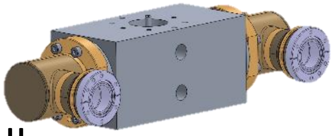
HOM Testbox





See Talk: J. Mitchell

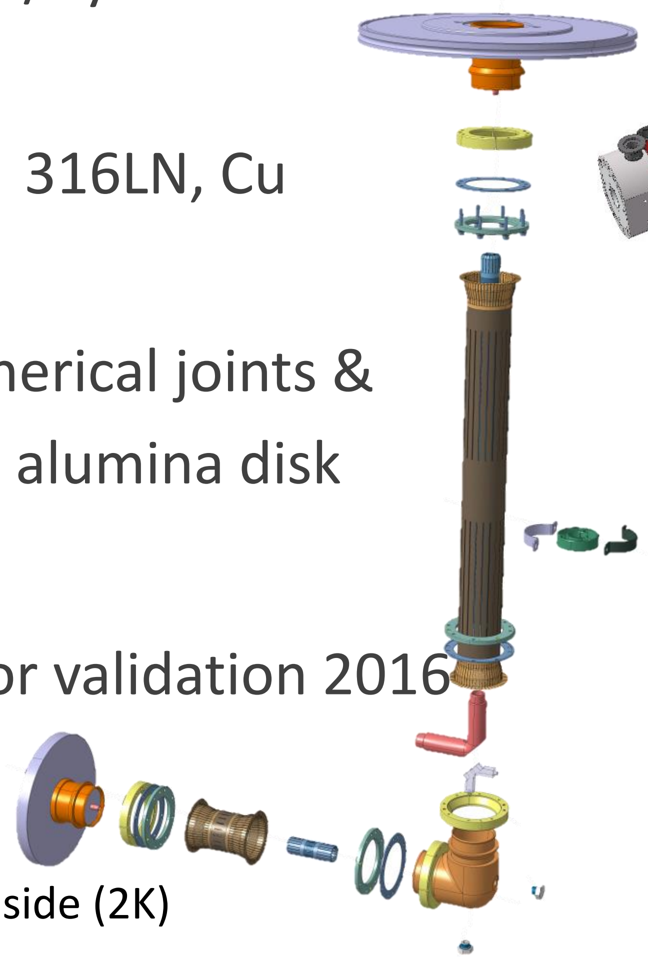


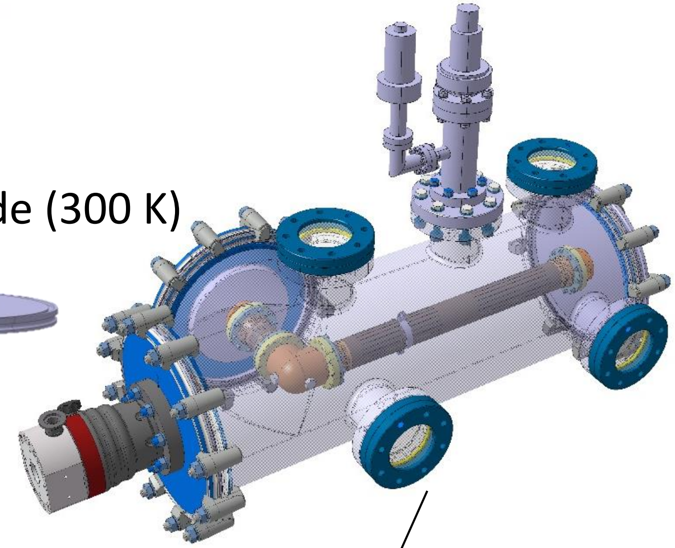


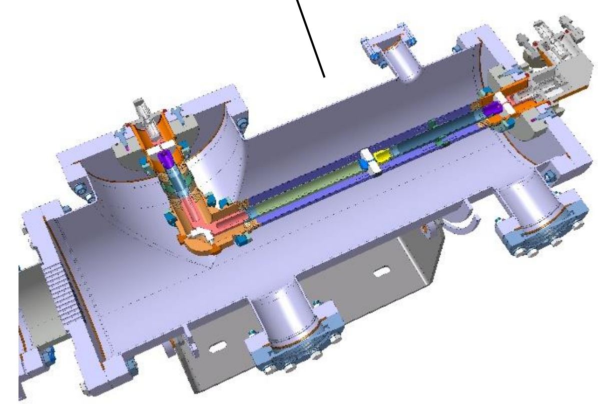
High Luminosity LHC

HOM Lines

- Optimized for static/dynamic heat loads to 2K
- Coax line for 1 kW, 316LN, Cu sputtered ($5\mu\mathrm{m}$)
- Flexibility using spherical joints & themalization with alumina disk
- Destructive tests for validation 2016

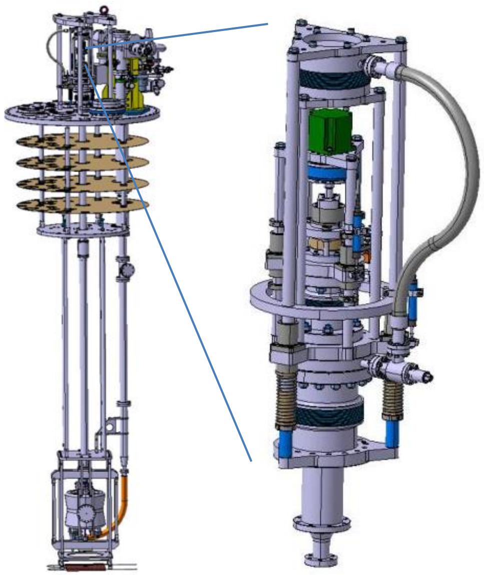






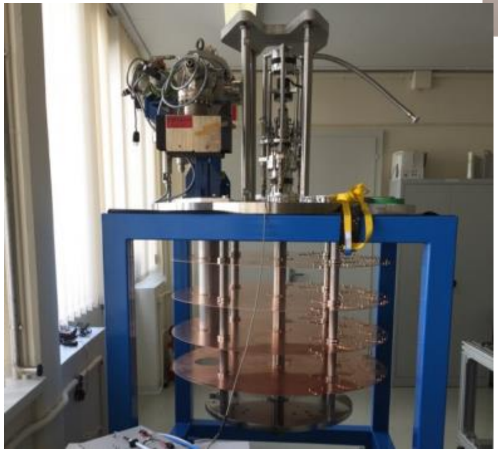
Tuner Tests (on PoP)

See Talk: A. Castilla

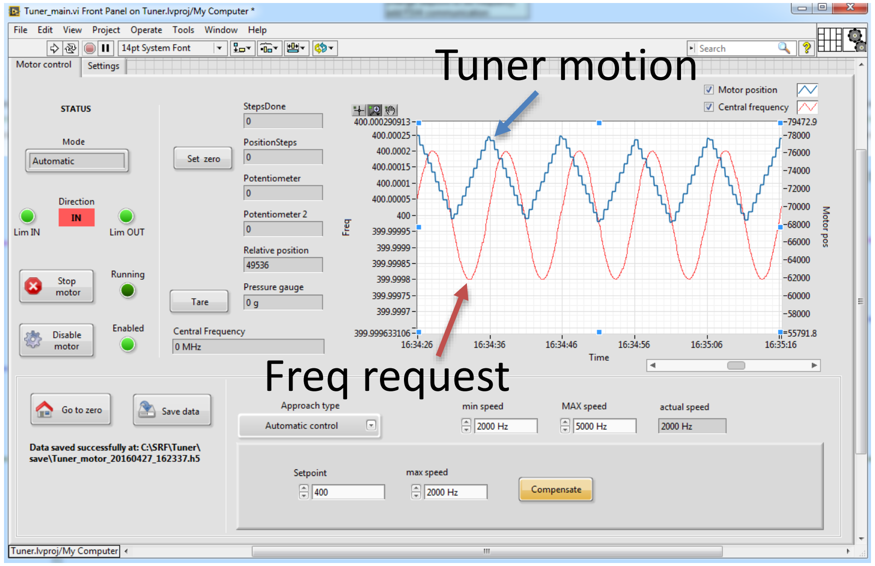


Tuner preparation for Cold Tests planned during Jun 2016

- Assembly into SM18_V3 & protection for cooldown actions ongoing
- PLC based control system successfully tested in a feedback loop

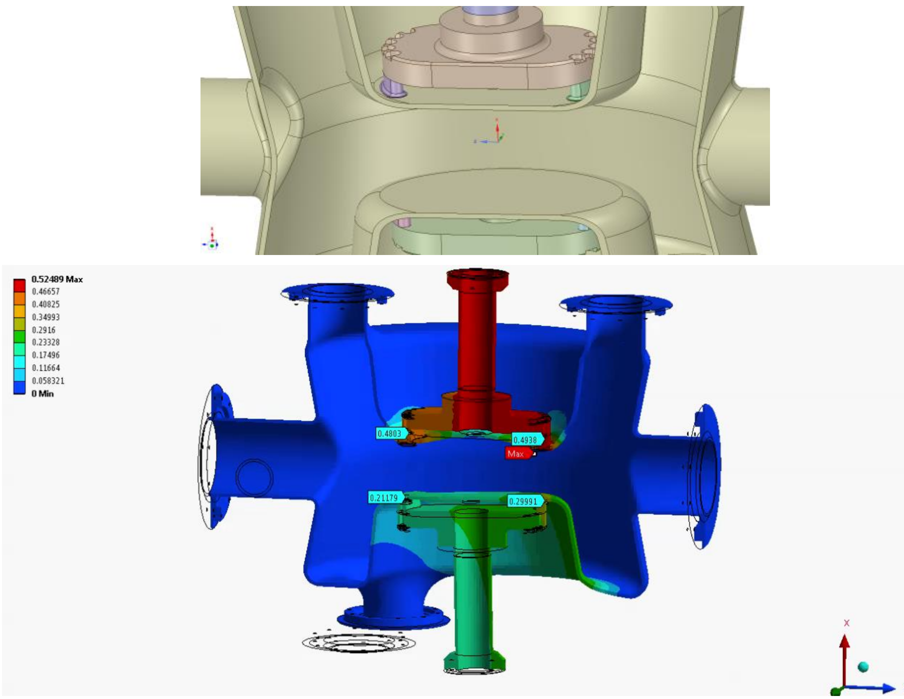


Repeatability preceision ~0.5 µm ~ 100 Hz

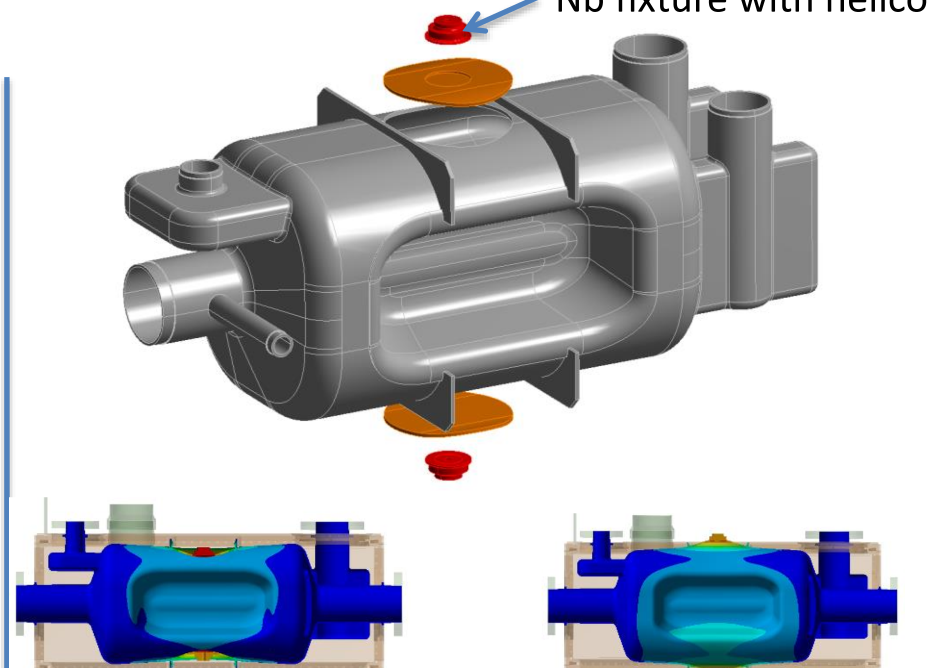


Tuning Fixtures

- Warm frequency tuning limited by tuning fixture
- Limiting factor is the strength of NbTi fixture and weld
  - CERN (NbTi), USLARP (Nb with reinforced shape)



DQW Pre-tuning: $\geq$ 0.3 mm permanent deformation

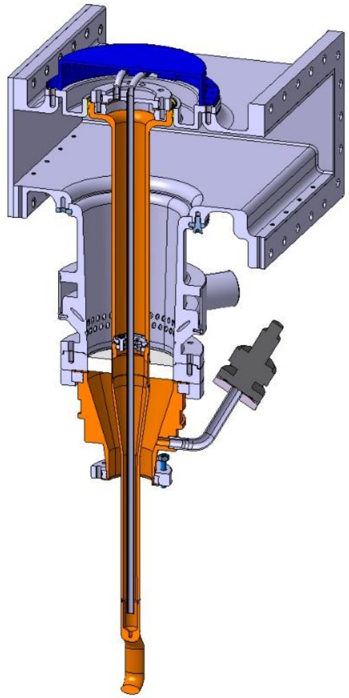


RFD: ~ 1.4 mm (7000 kN elastic limit)

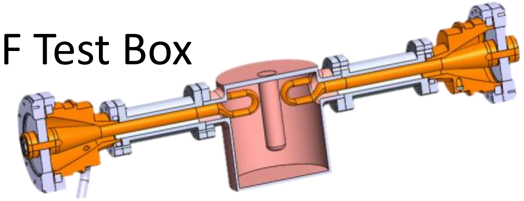
High Luminosity LHC

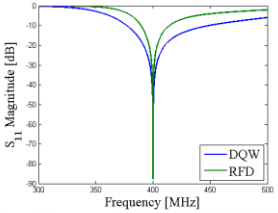
Power Coupler

Most FPC parts (+spares) completed



RF Test Box





2 DQW + 2 RFD Couplers by end of May (spares in Oct)

RF Test box ready by Sept. → Clean room assembly in Oct
Two DQW couplers ready April 2017

RF Amplifier

2016: Important decision to adopt IOT as baseline for SPS

Modification of the existing IOT station to $400\ \mathrm{MHz}$

- New output cavities & new coupling elements (designed at CERN)
- Validation will establish IOTs as baseline for LHC (streamline integration)

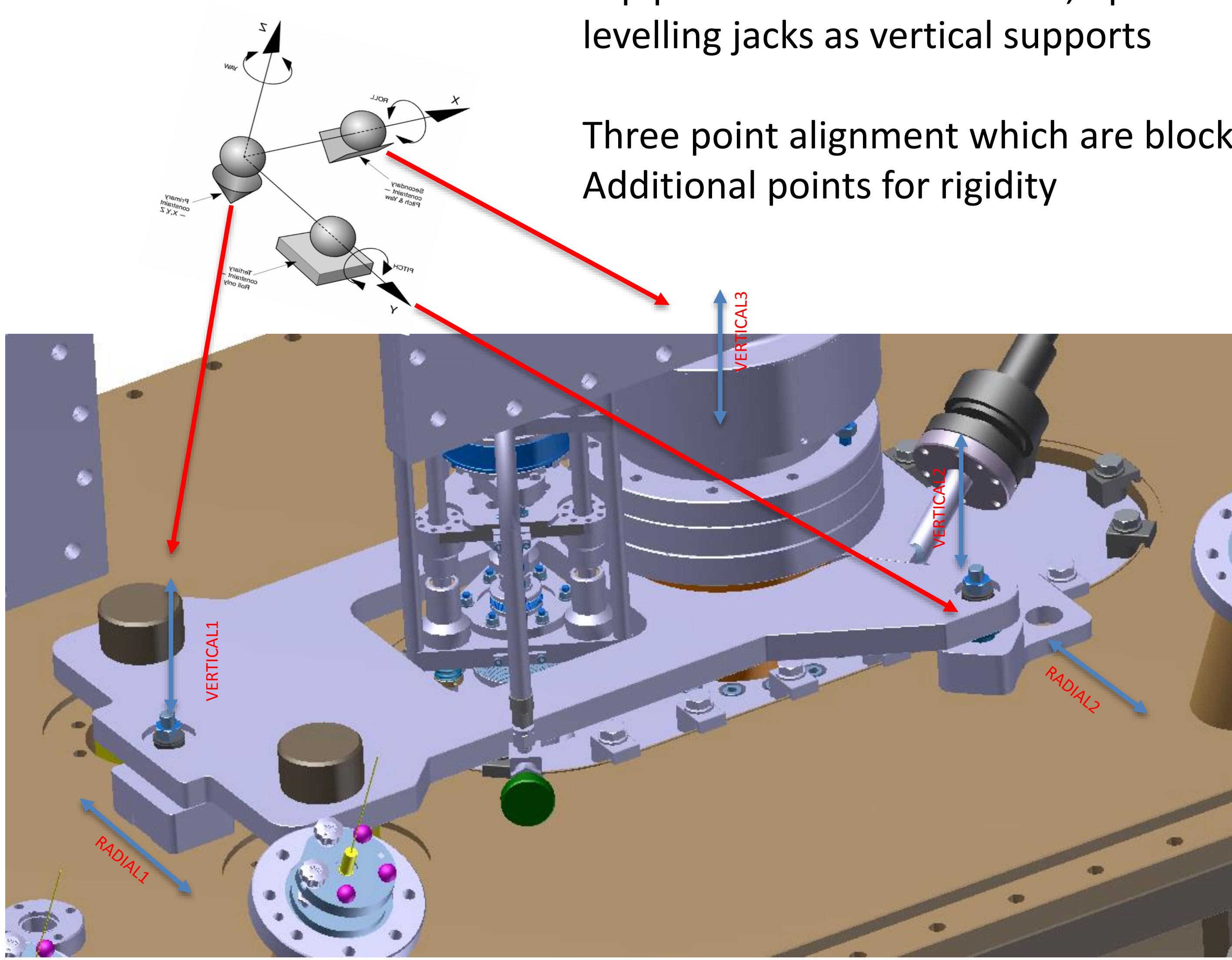
Reached 60 kW last Friday, limited by the exiting power supplies !

High Luminosity LHC

Cavity Supports & Alignment

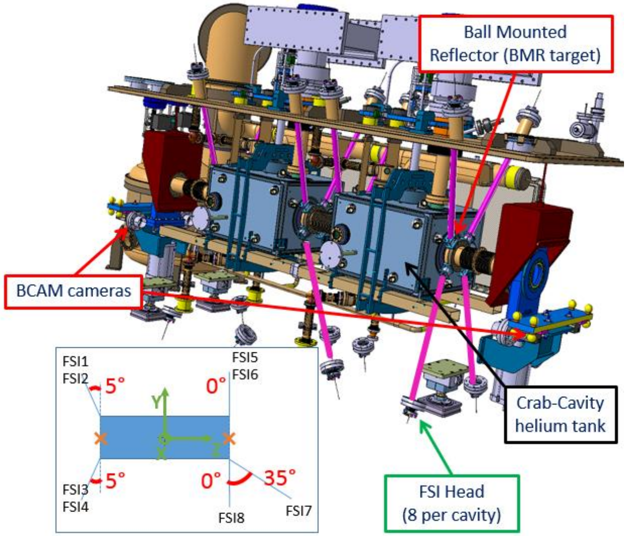
Top plate – kinematic mount, option with levelling jacks as vertical supports

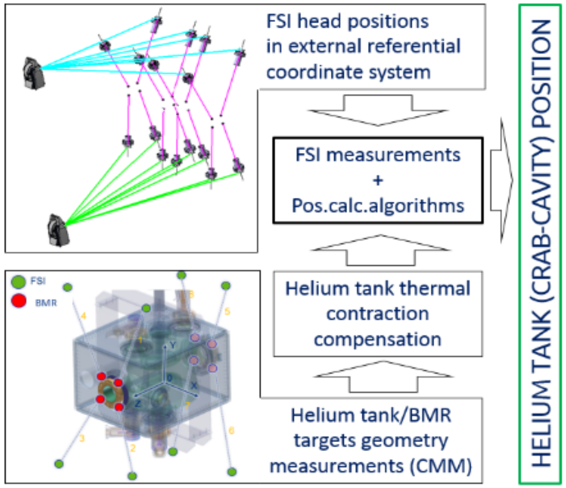
Three point alignment which are blocked after
Additional points for rigidity



Position monitoring system (BCAM + FSI)

- BCAM + FSI (1:1) full system mock-up under construction
- Irradiation campaign of reflective targets and collimators finished
- FSI head prototypes designed and under manufacturing
- BCAM → System performance initially validated on the mock-up. Tests and calibration of camera vacuum viewports pending
- Cryogenic tests of reflective targets planned in the next 2 months



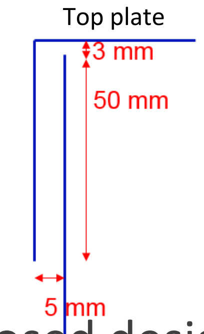


- Fiducialisation of the helium tank mock-up on CMM and laboratory verification of full system performance
- FSI head test in operation conditions (vacuum, reflector at 4K)
- Irradiation campaign of FSI heads assemblies
- SM18, SPS - DAQ and data processing software development
- Measurements in SM18 – validation of the final system

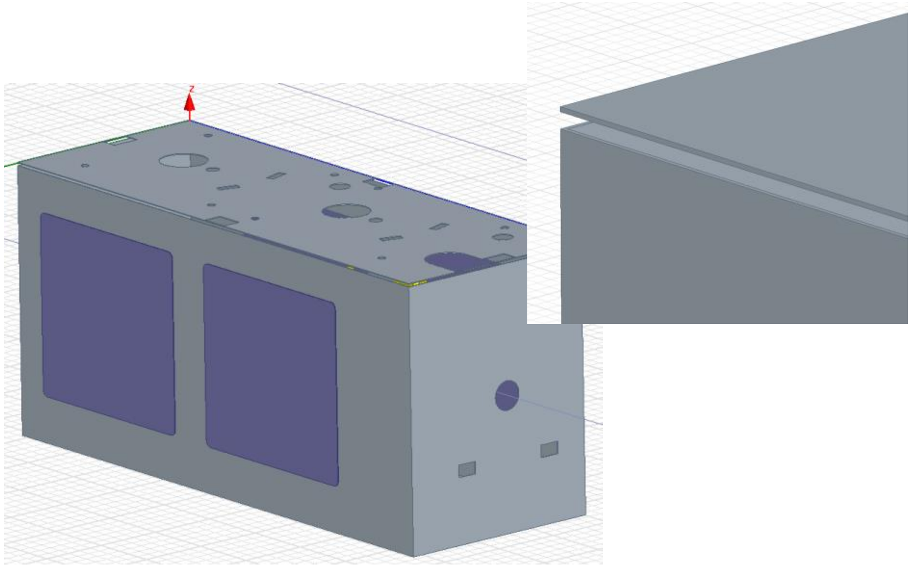
High Luminosity LHC

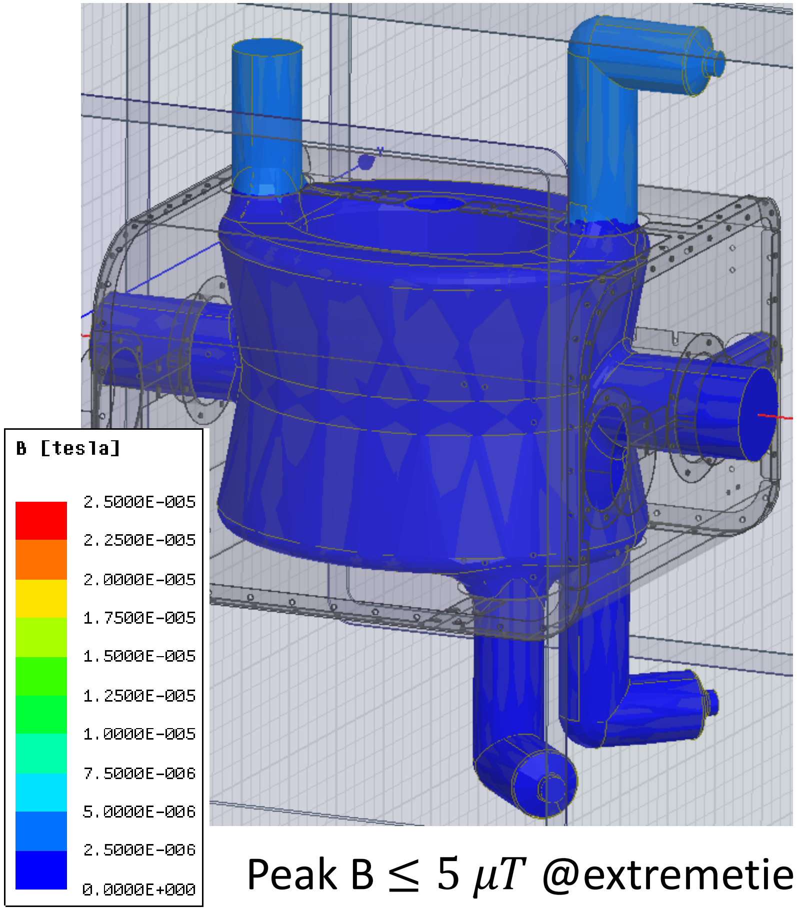
Warm Magnetic Shield

- Field measured in SPS and applied to Warm Magnetic Shield
- Gaps between plates induces field leaks, fine tuning



Results with optimal proposed design

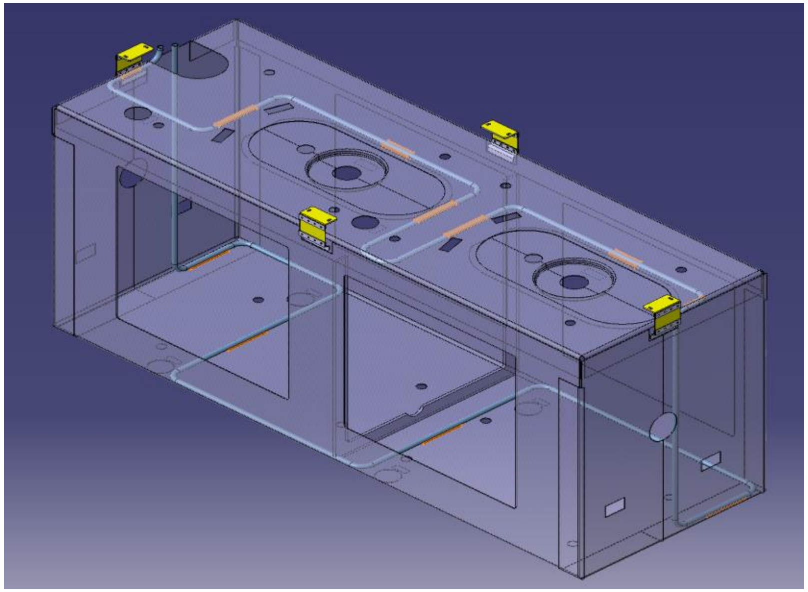


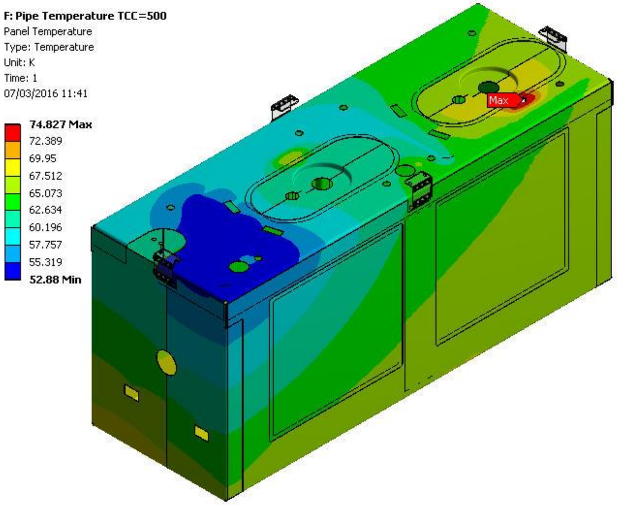


Peak B $\leq 5\ \mu T$ @extremeties

CM Thermal Shields

- After several studies, Cu chosen as baseline
- Connection between cooling pipe and plates under study
- Design & integration finishing

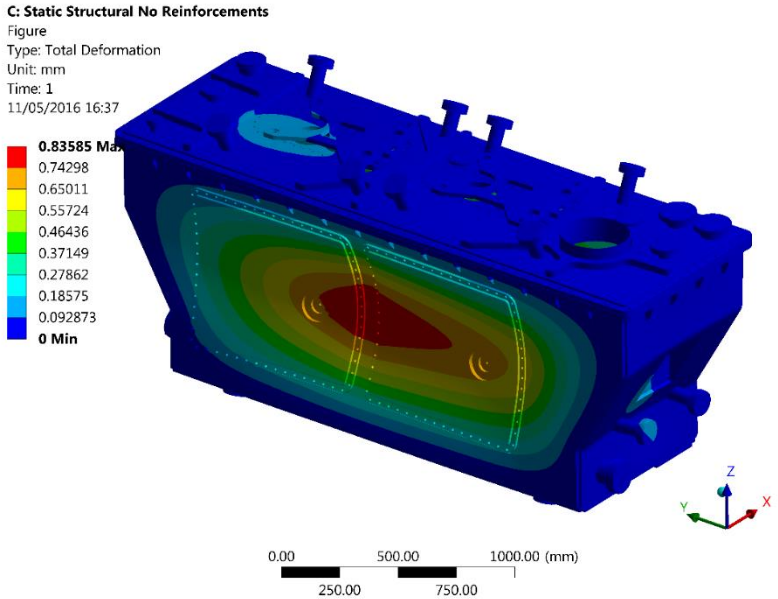


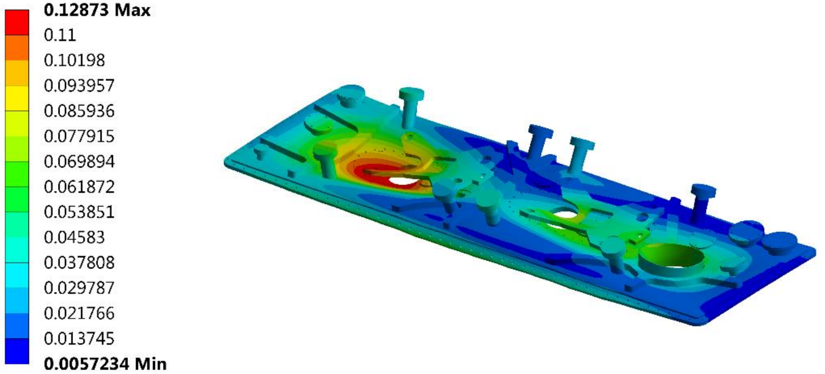


Result Summary		Pipe Temperature		Pipe Convection	
		T_{min} (K)	T_{max} (K)	T_{min} (K)	T_{max} (K)
Al/SS	Panels	64	81	70	87
	Pipe	50	105	50	139
Cu	Panels	53	75	55	84
	Pipe	50	70	50	75

Vacuum Vessel

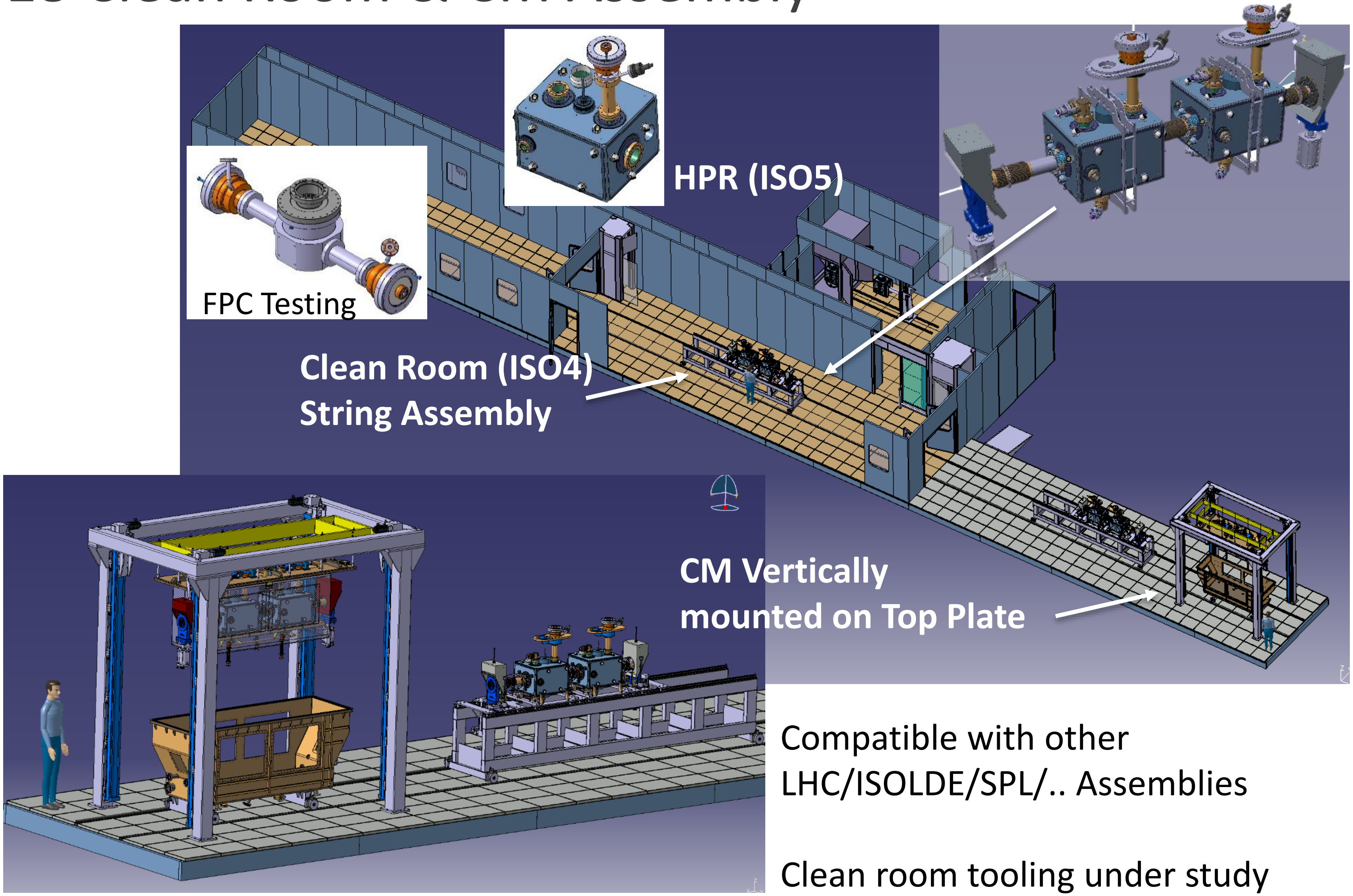
- Trapezoidal design for assembly (adopted from Triumph)
- Stainless steel with Al lateral windows (max access)
- Deformation on top must be limited to mitigate misalignments
- Deformation to be limited for vacuum integrity





High Luminosity LHC

SM18 Clean Room & CM Assembly

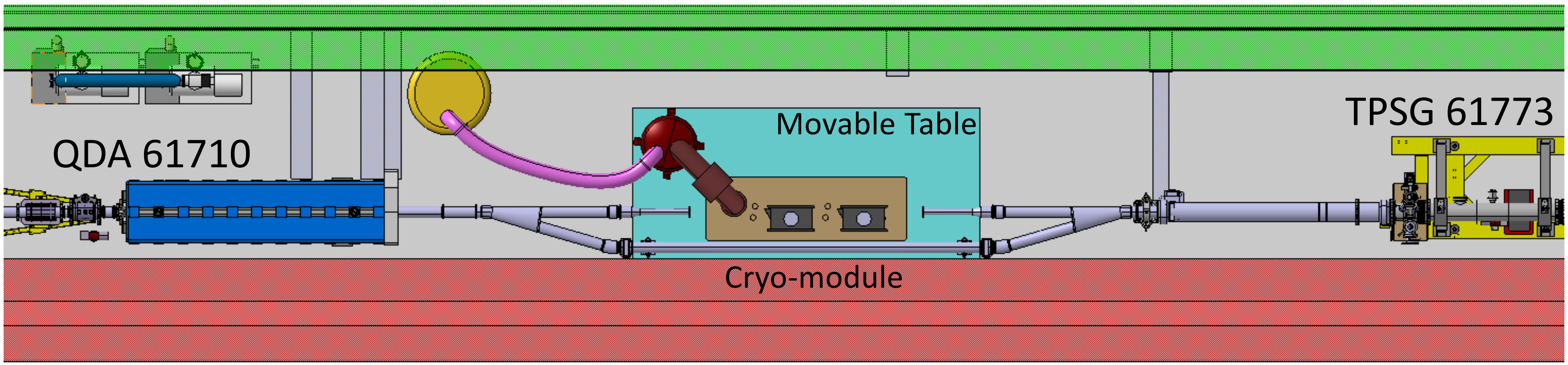


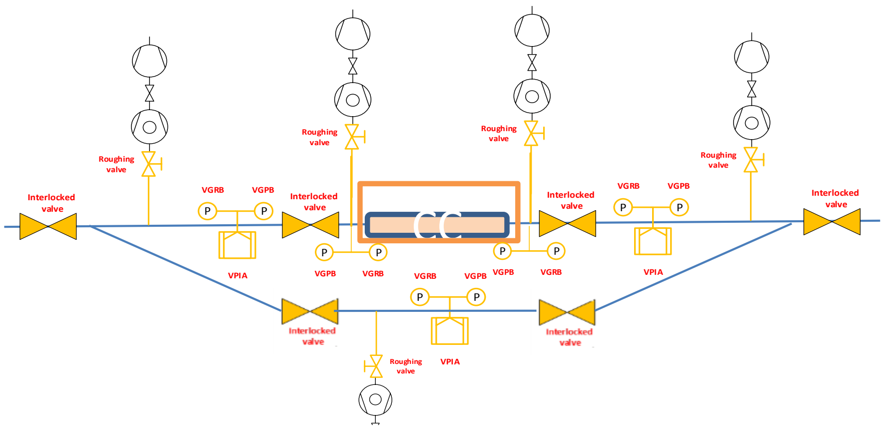
Compatible with other LHC/ISOLDE/SPL/.. Assemblies

Clean room tooling under study

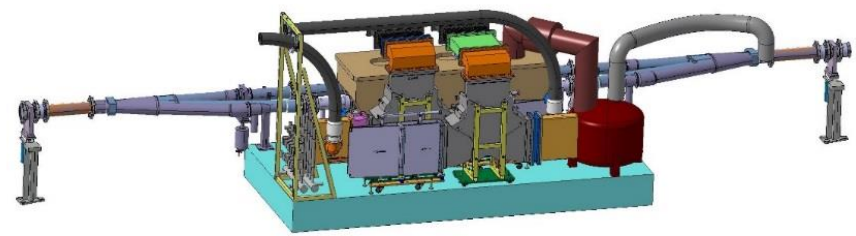
SPS-LSS6 Implantation

11.5m overall space, CM installed in a by-pass & motorized transfer table





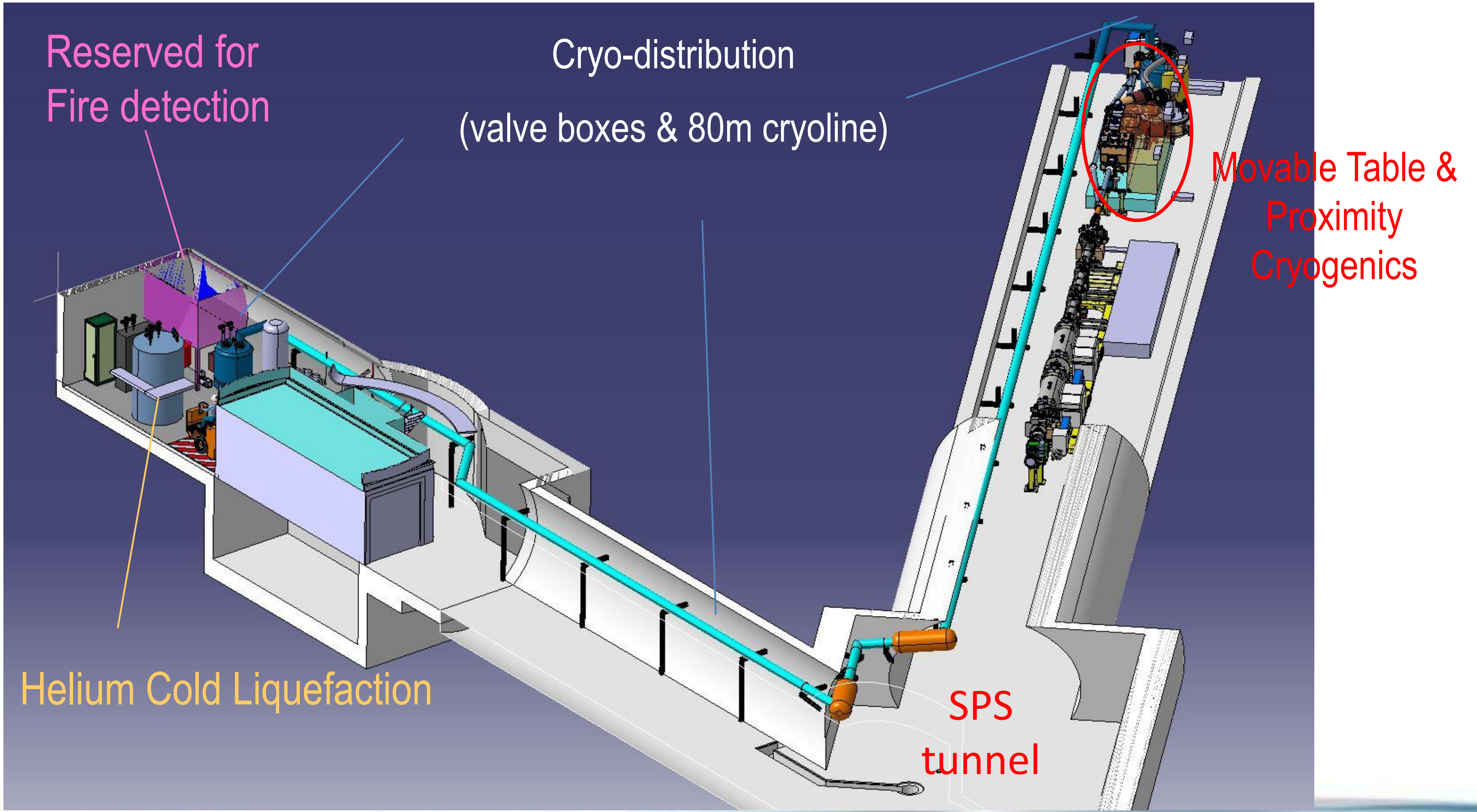
Multiple Vacuum sectorization to
accommodate bypass & module replacement



RF & Cryo on movable table
with liquid Helium

Cryogenics

- Decision for refrigerator and ancillaries to go underground
- Procurement for cryo-distri, refrigerator & proximity cryogenics launched

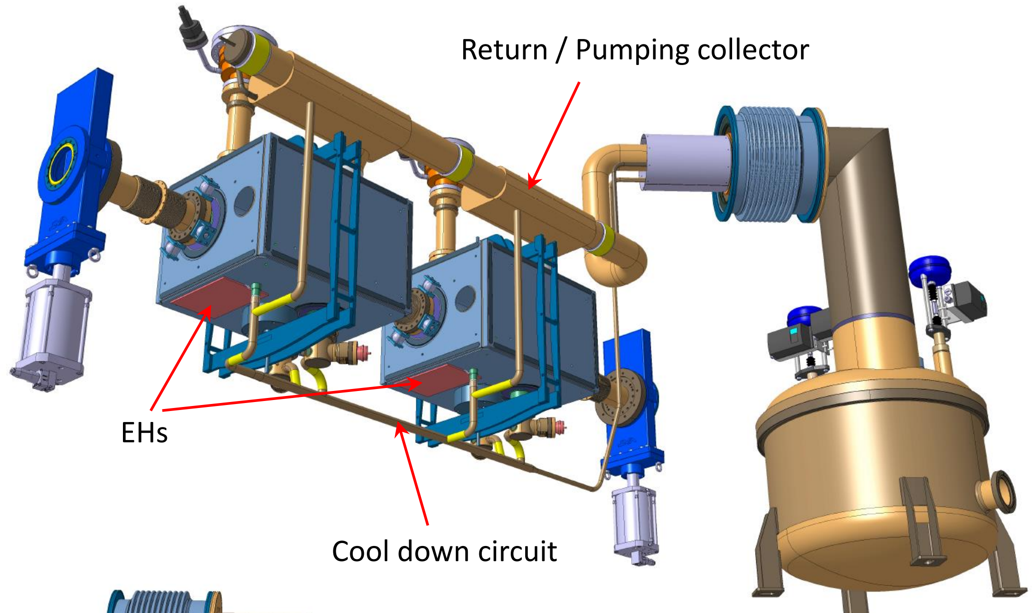


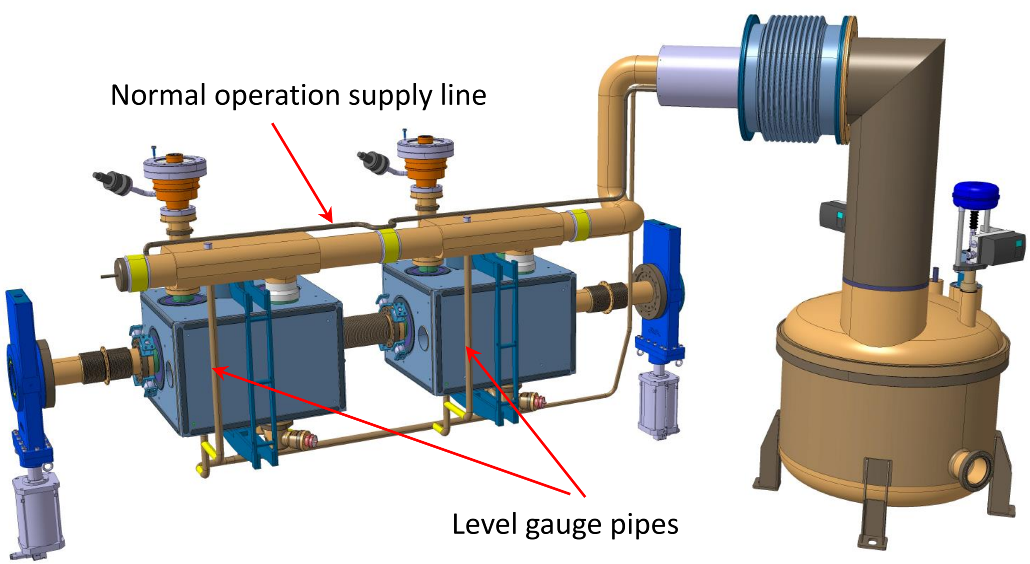
CM Cryo-Circuits

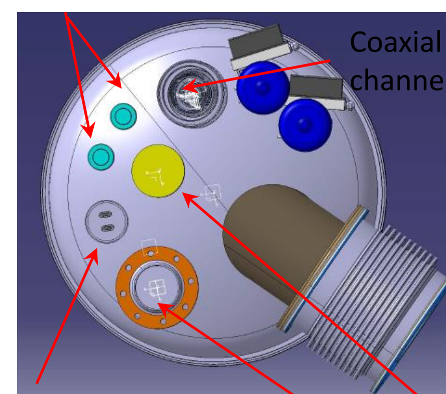
Cool down and 2 K normal operation

DQW static HL: 12.5 W
RFD static HL: 12 W

DQW dynamic HL: 18.1 W
RFD dynamic HL: 15.9 W



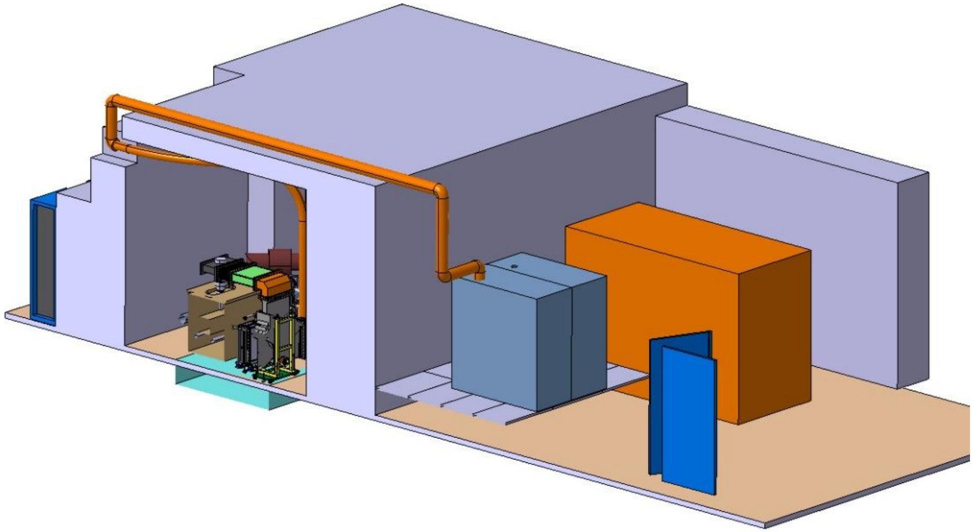




BA6/SM18 (Surface) Integration

Integration in BA6 area has started

Integration in SM18 bunker and RF power area ongoing



High Luminosity LHC

SPS Test Program Summary

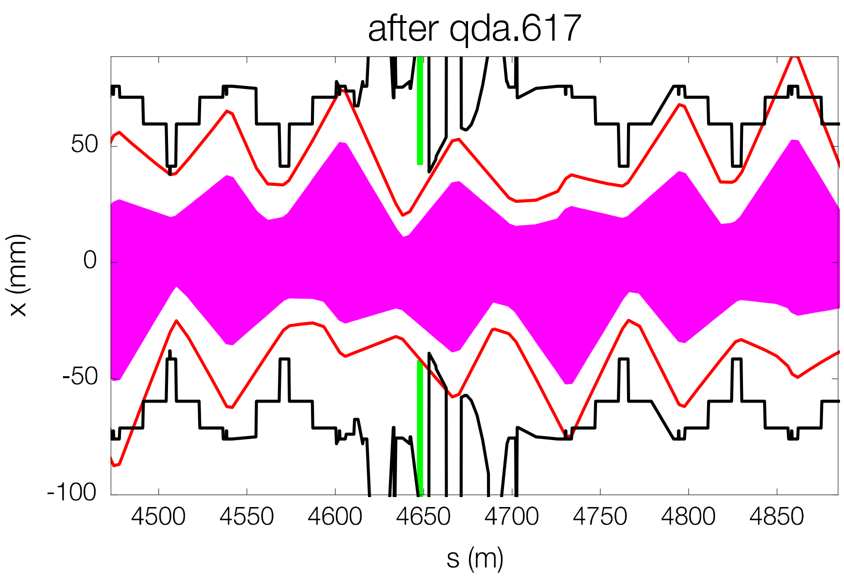
- **In-situ cryomodule RF commissioning/testing** in park position
- **RF commissioning** with low-intensity beam, 1-12 bunches
- **High intensity** single bunch up to 4x72 trains
- **Long-term behavior** of coasting beams in the SPS with 1-bunch

½ -day Meeting in Jan 2016 to discuss potential MDs
(ABP, BI, OP, RF & others)

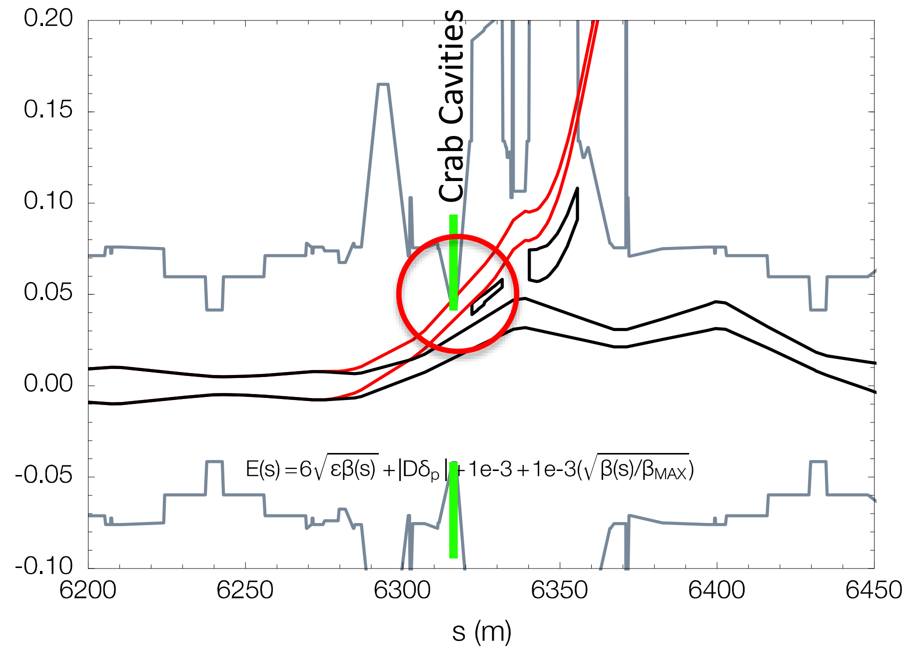
High Luminosity LHC

Compatibility with SPS Operation

Fixed Target Beam



LHC beam extraction



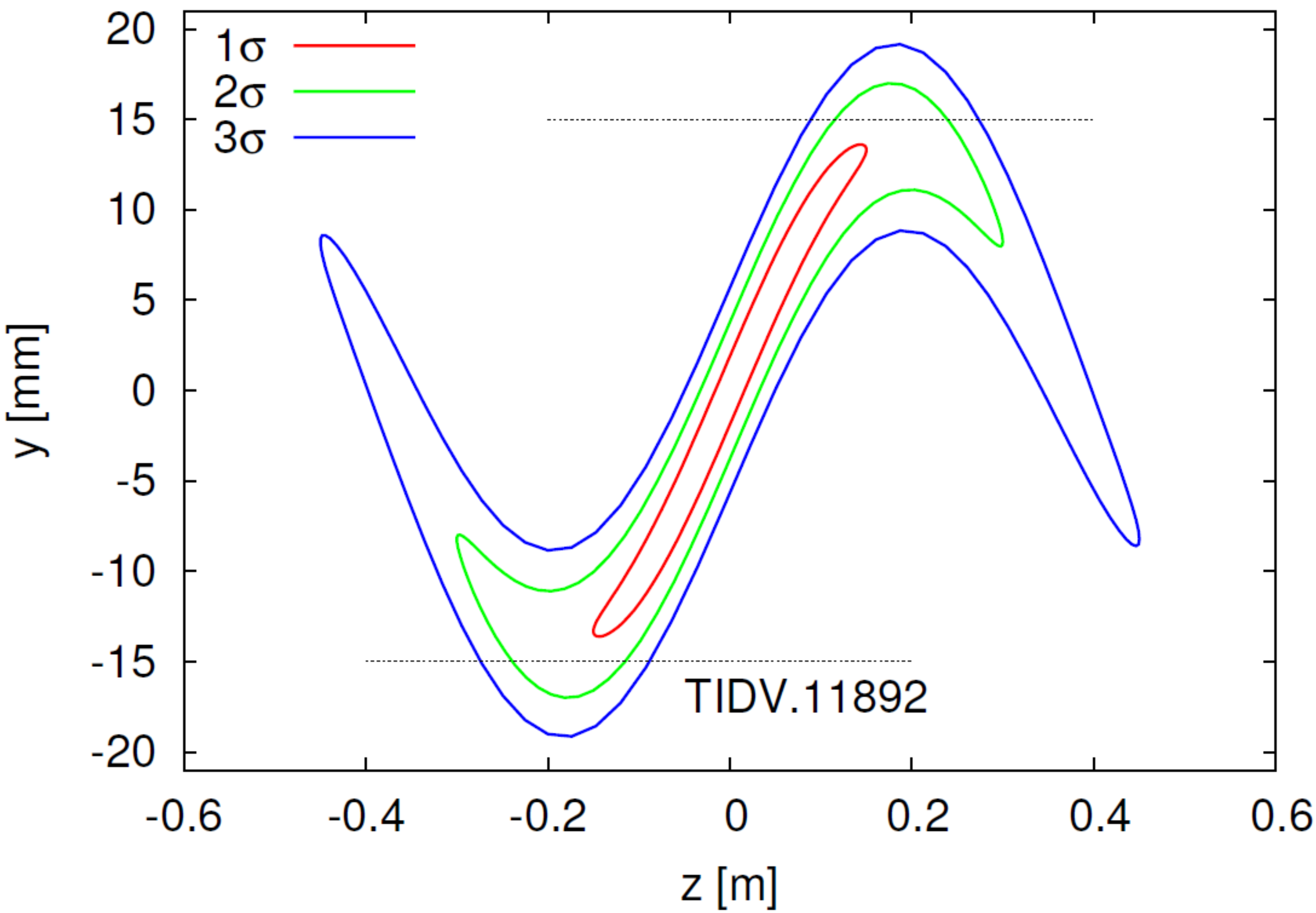
- Compatible with slow extraction to Fixed target beam
- Aperture not enough LHC extraction

Measurements considered here

- ★ Beam crabbing (Head Tail Monitor)
- ★ Crab dispersion (BPMs around the ring)
- ★ Longitudinal collimation (bunch length)
- ★ Emittance growth (wire scanners)
- ★ Crab Cavity phase noise (Turn-by-Turn BPM)
- ★ Crab Cavity b_3 RF multipole (TbT or tune)
- ★ Dynamic aperture (on-going simulations)

Motivation is twofold: Test CCs in view of HL-LHC but also develop techniques for beam-based CC qualification in HL-LHC.

Crabbed beam (vertical, 26 GeV)



Longitudinal collimation: reduce bunch to 7.5cm?

High Luminosity LHC

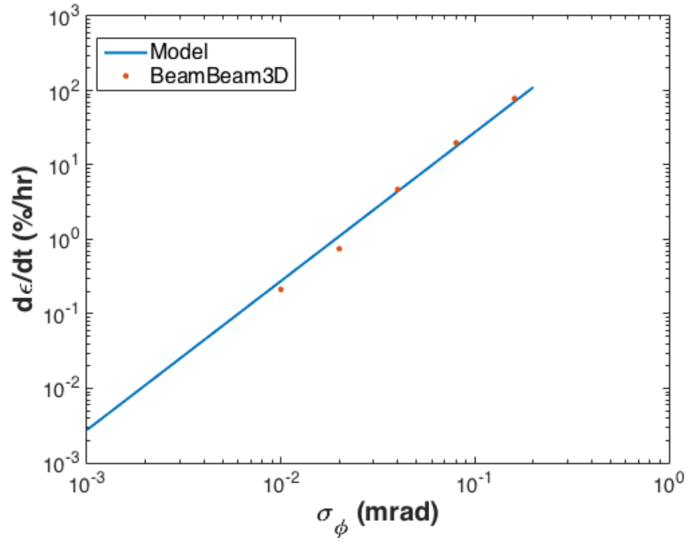
Test Program, LLRF

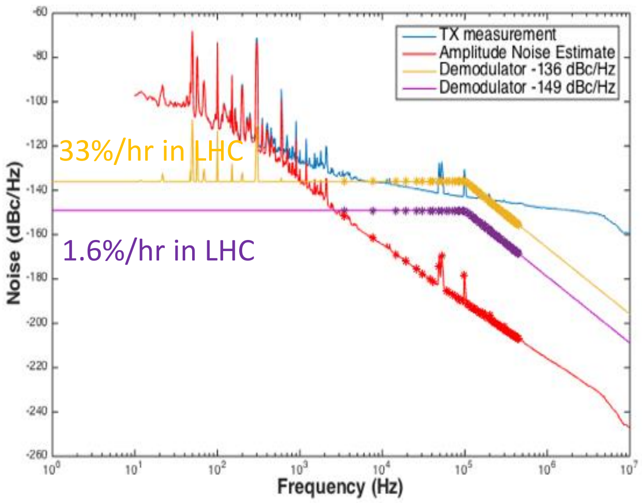
See Talk: T. Mastoridis

- **Long-term behavior** of coasting beams
  - *Validate the calcs/simulations, and mitigation by damper*

$$\frac{d\varepsilon}{dt} = \beta_{CC}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta\phi}(\pm f_b - n f_{rev}) + \beta_{CC}\left(\frac{eV_o \sigma_\varphi f_{rev}}{2E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta A}(\pm f_b \pm f_s - n f_{rev})$$

  - *The SPS CC emittance growth will be much larger than the final LHC system (noisy LLRF, lower energy, smaller f_{rev} - but smaller β_{cc}) -> probably **no need to boost the noise to see an effect** …*





- Calculated and simulated transverse emittance growth vs. CC RF phase noise (left)
- Goal is to **derive the exact specification for the LHC**

High Luminosity LHC

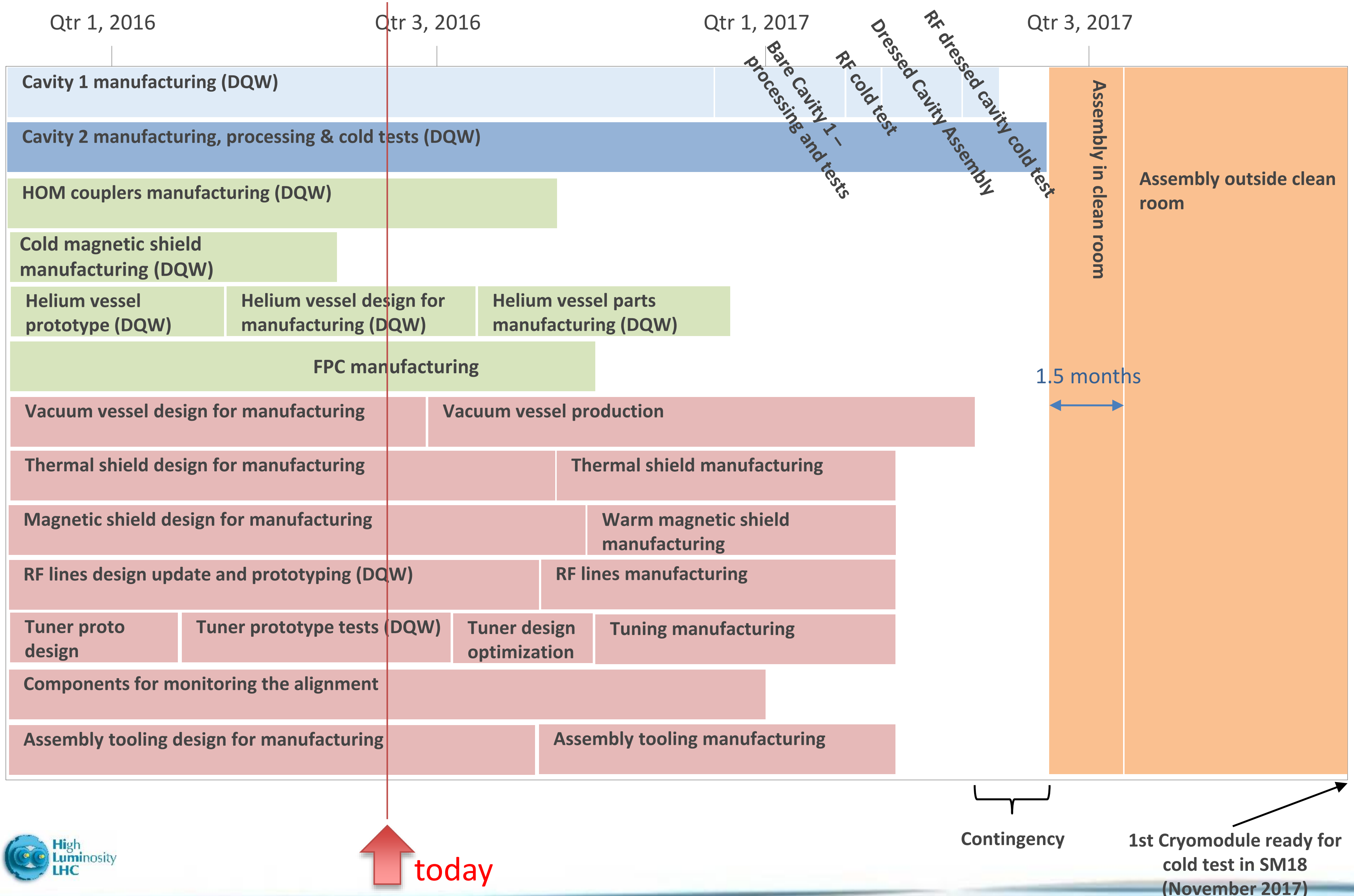
Summary

- Intense & exciting 2015-16
  - Highly motivated team, but no shortage of crisis meetings
  - Keeps us on our toes

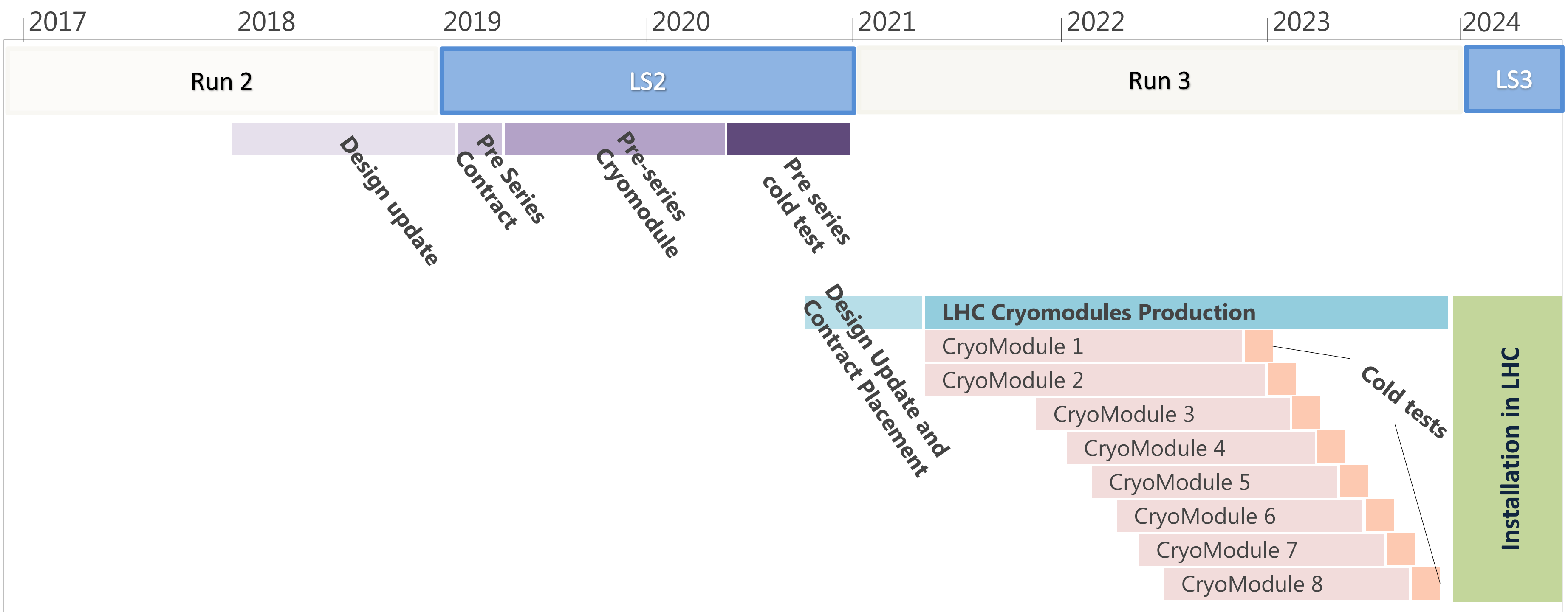
- In approx. 1-yr we should be in final assembly phase & in 2-yrs in the SPS

High Luminosity LHC

CERN Plans for SPS-CM

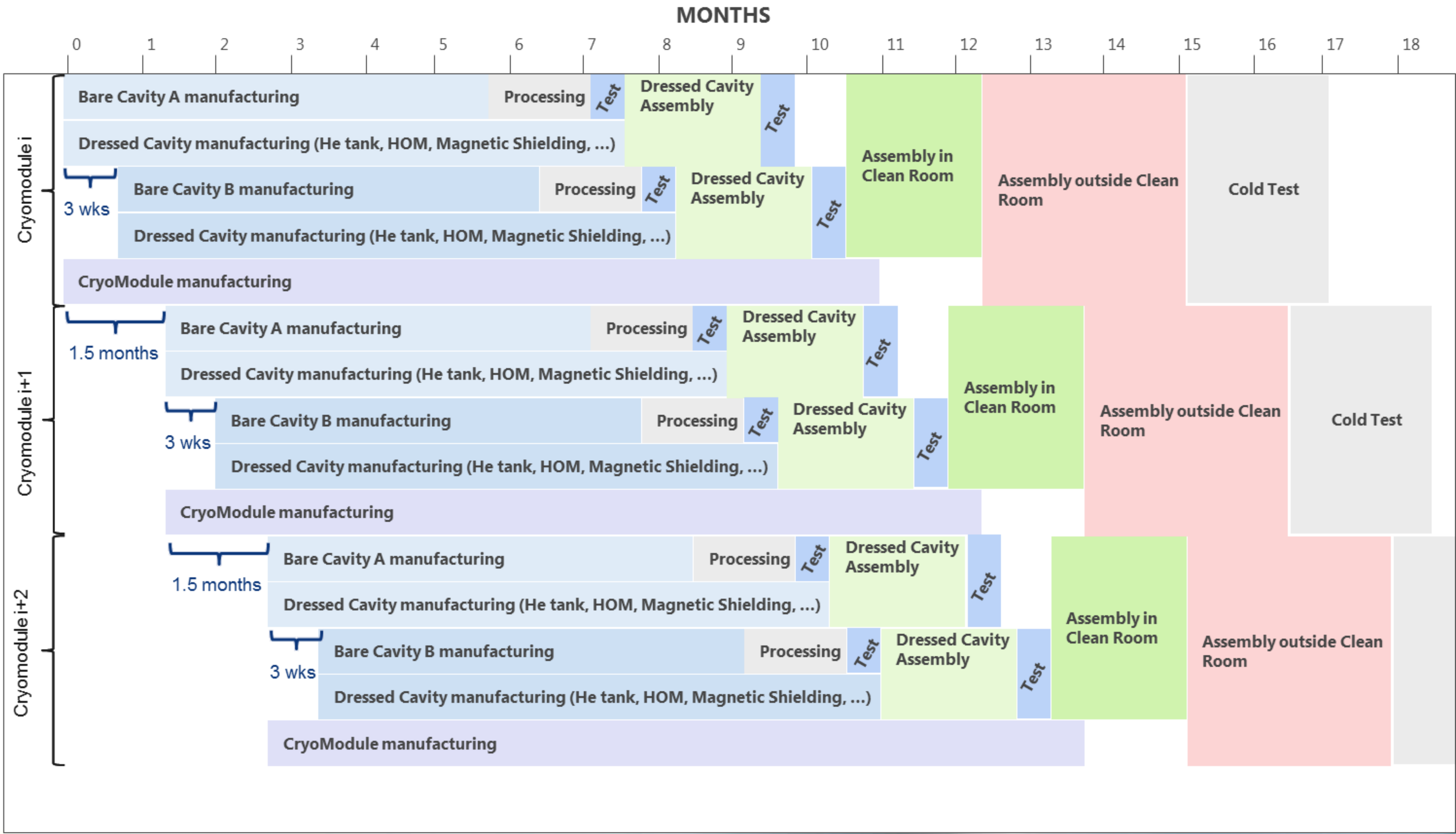


Revised Plan, LHC Series

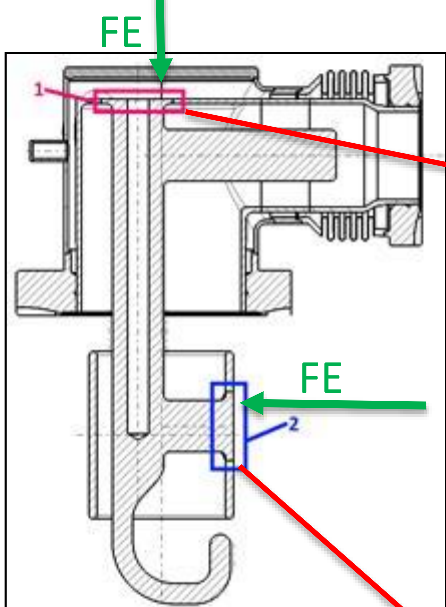


High Luminosity LHC

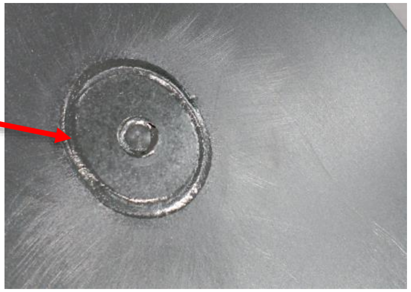
Revised Plan, LHC Series

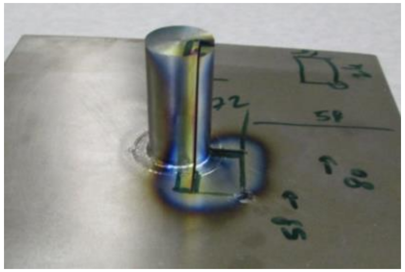


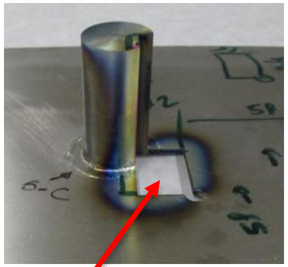
Welding tests, HOMs



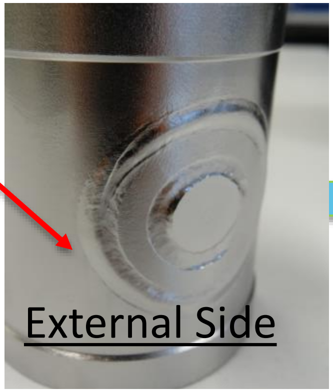
- **W050:** Niobium thickness 2mm. Welding from external side

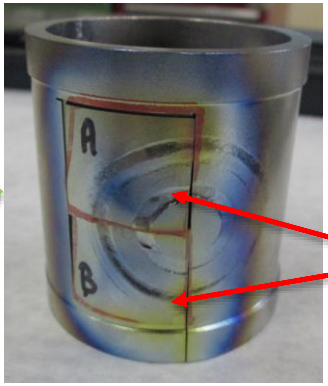

External side


Internal Side


Sample for testing

- **W010**: Niobium thickness 3.6 & 4.2mm. Welding from external side


External Side



A/B Samples for testing

- Welding parameters for both welds: OK
- Visual inspection according to ISO 13919-2 level B
- Qualification according to EN-15613: Metallographic and Hardness Test