Crab Cavities: CERN Program for SPS Tests

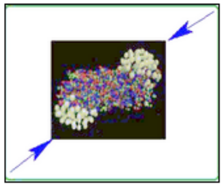
HL-LHC WP4, CERN

6th HL-LHC Collaboration Meeting, Nov 14-16

Special thanks to EN-MME/INT, RF-PM/SRF, TE-CRG/VSC, USLARP, UK-STFC

~10 Years Ago

PROCEEDINGS *LHC-LUMI-06*



Third CARE-HHH-APD Workshop

Towards a Roadmap for the Upgrade of the LHC and GSI Accelerator Complex

IR Upgrade II

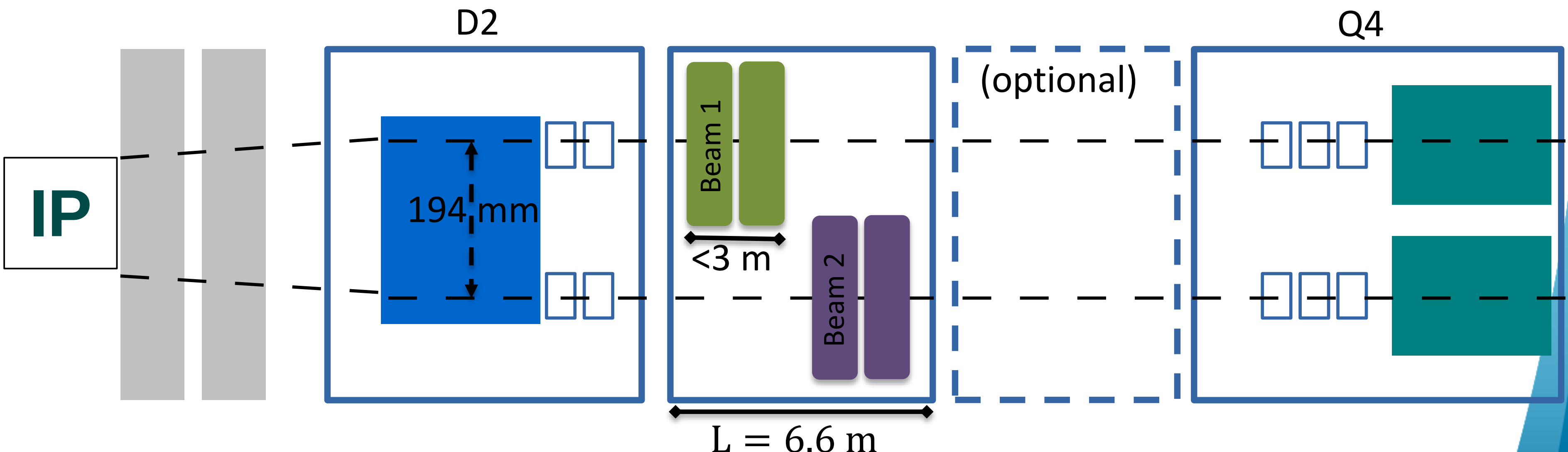
R. Tomas, Crab Cavity IR Optics Design with Q=8 mrad
R. Calaga, R. Tomas, F. Zimmermann, Crab Cavity Option for LHC IR Upgrade
J. Tuckmantel, Technological Aspects of Crab Cavities

The first ideas on LHC crab cavities emerged… at that time we were discussing about voltages & crossing angles in excess of 200 MV and 8 mrad!

Today we are a bit more humble

Reminder, Basic Parameters

- Voltage = **3.4 MV /cavity** (2 cavities /beam /IP side) – 16 total
- Frequency = 400.79 MHz
- $Q_{ext} = 5 \times 10^5$, $Q_0 \approx 10^{10}$
- RF power source = 80 kW (SPS $\leq$ 40 kW)
- Cavity tuning = $\pm$100 kHz (LFD ~ 0.5 kHz)
- Operating temperature = 2.0 K



Impact of (Cost & Schedule) Reviews

- *SPS Tests*
  - *SPS-LSS6 dedicated test stand for beam tests in 2018*
  - *Integration almost complete, installation starts in 2 months*

- *LHC*
  - *½ system (16 cavities) as a new baseline*
  - *New production strategy with industry starting 2017*
  - *UK pre-series cryostat & US contribution (10 RFD dressed Cav)*
  - *RF power infrastructure reduction to 40 kW-CW (80 kW peak)*

WP4 Planning

SPS prototype beam tests

preparation — SPS Test (CM1) — SPS Test (CM2)

2015	2016	EYETS	2017	YETS	2018	2019	2020	2021	2022	2023	2024	2025	2026

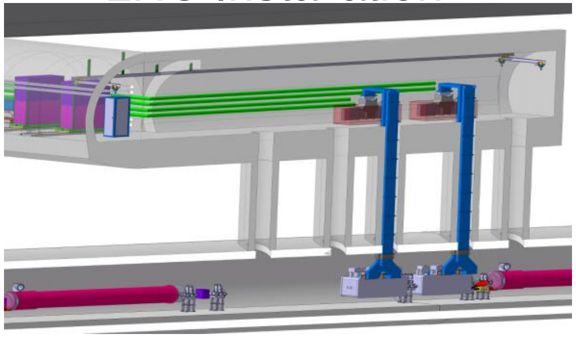
Run 2 | LS2 | Run 3 | LS3 | Run 4

LHC pre-series

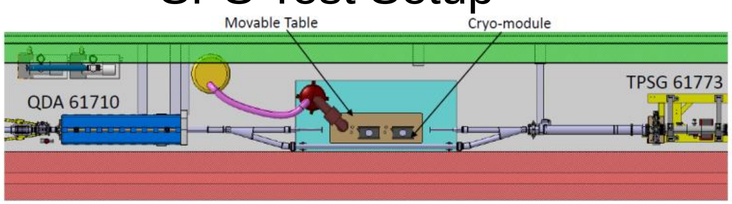
(2 Industrial Dressed Cavities)

LHC series production & Installation (8 CMs)

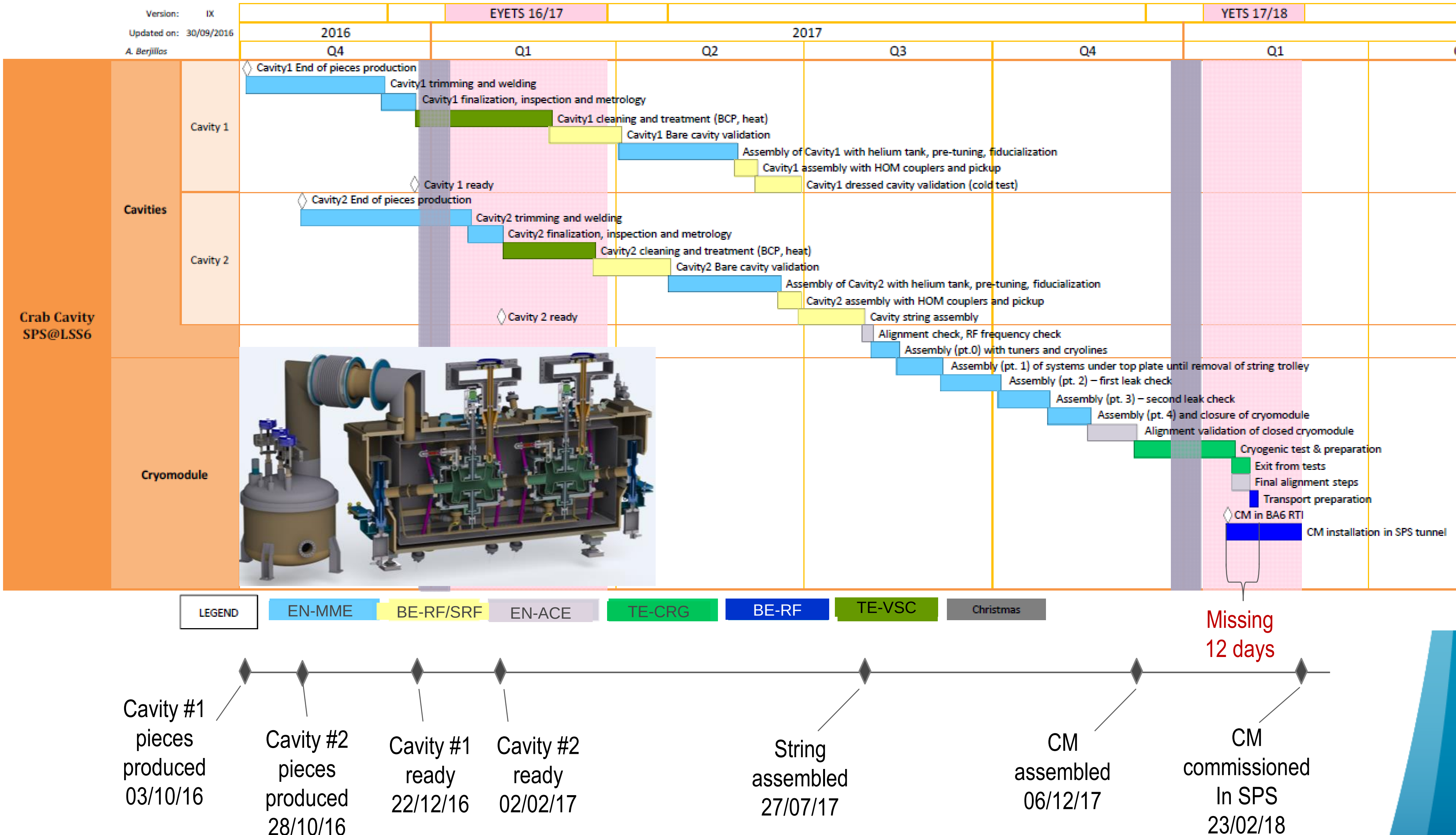
LHC Installation



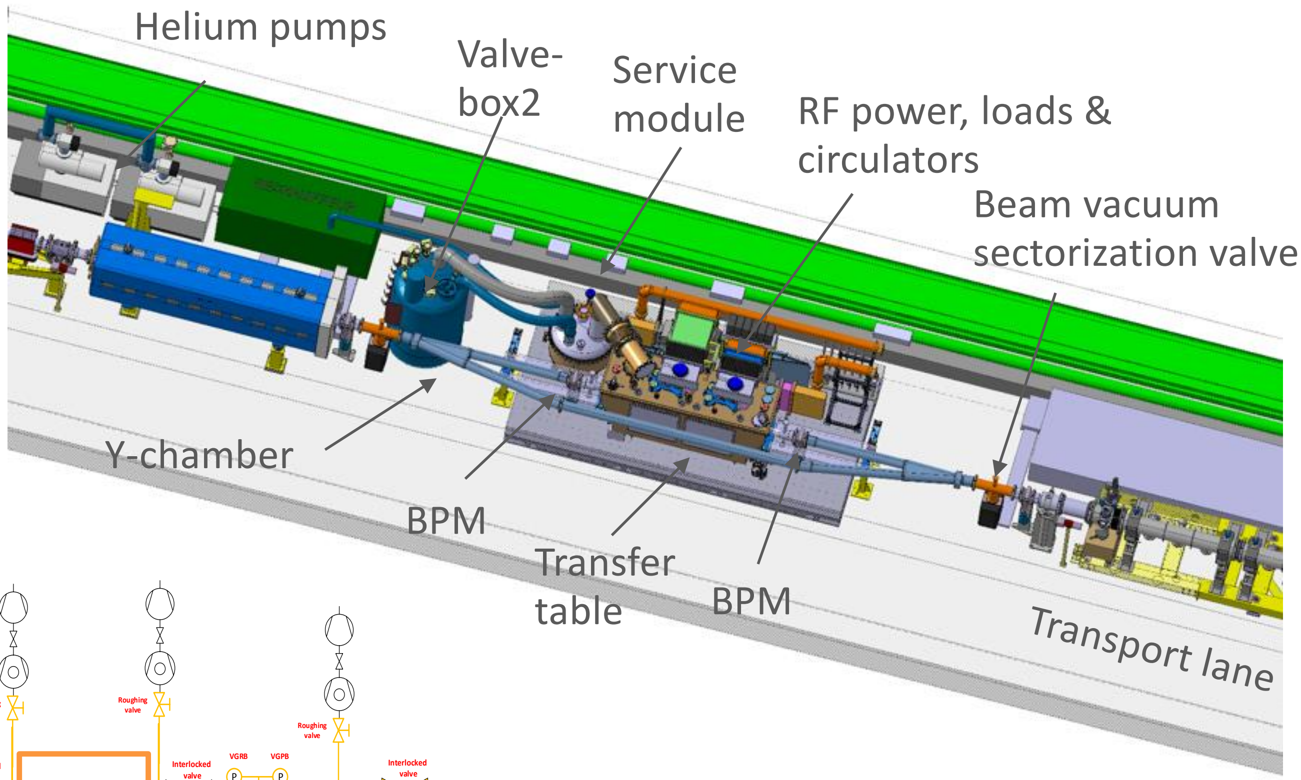
SPS Test Setup

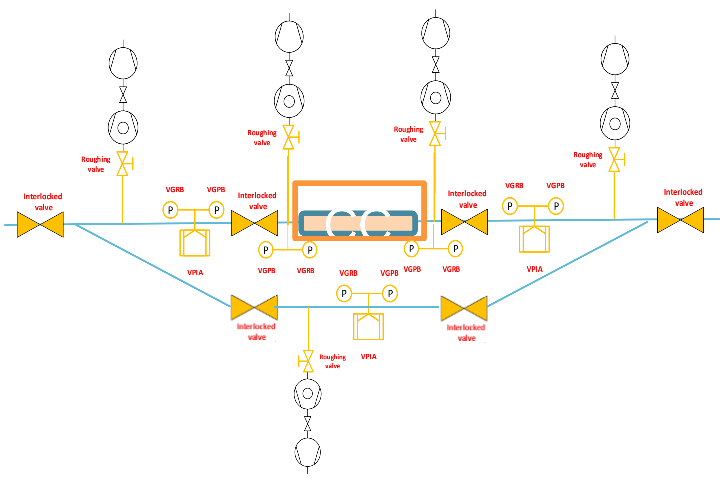


SPS Tests Program – Weekly Schedule



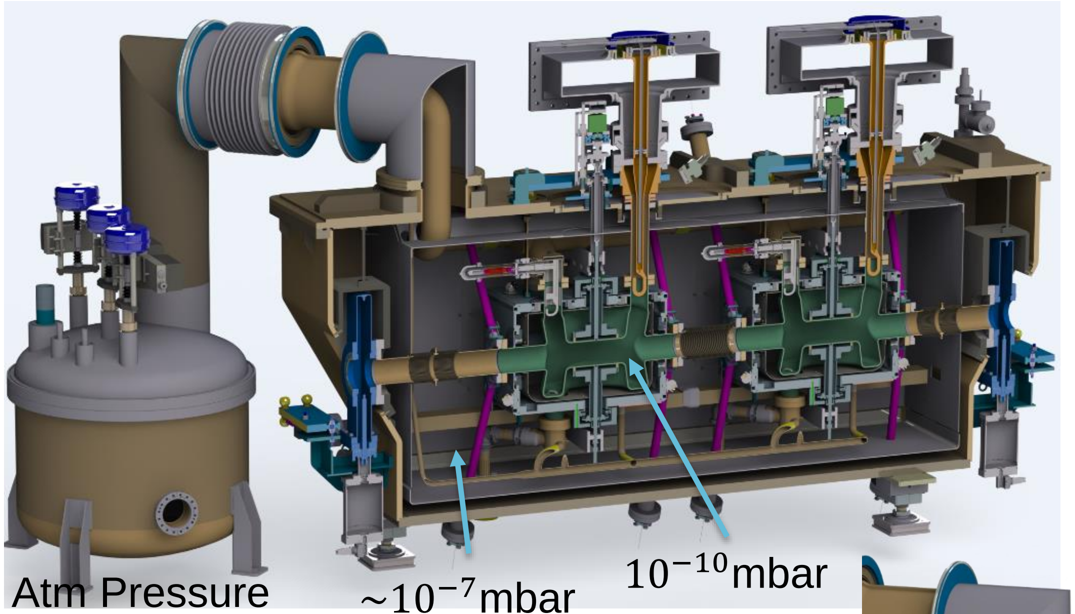
Crab Cavity SPS Layout, LSS6



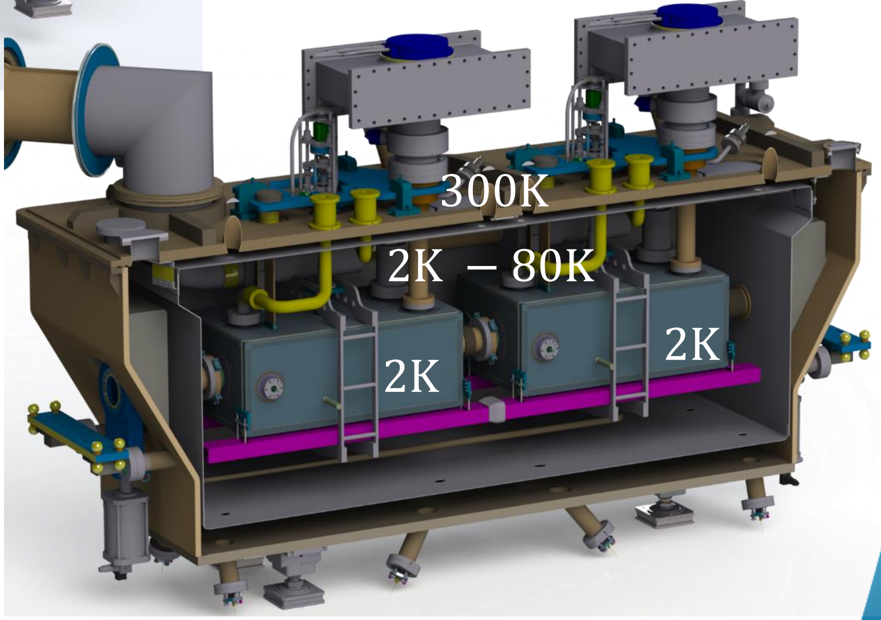


- 11^0 Y-chamber with multiple vacuum sectorization
- Movable table – 510 mm transversely (RF, Cryo, Vacuum)
- Approval from impedance working group to proceed with Y-chamber

Prototype Cryomodules



Vertical crossing for ATLAS, first one to go to SPS 2018

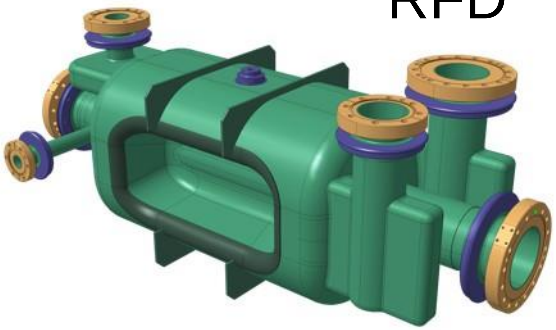


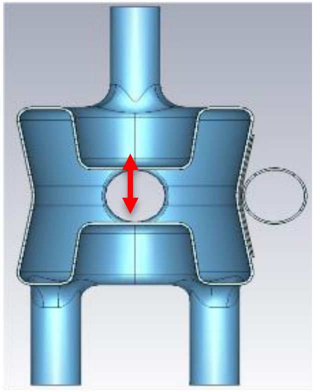
Horizontal crossing for CMS Cavities starting 2017

SPS Cavities, 2K Volume

DQW

RFD



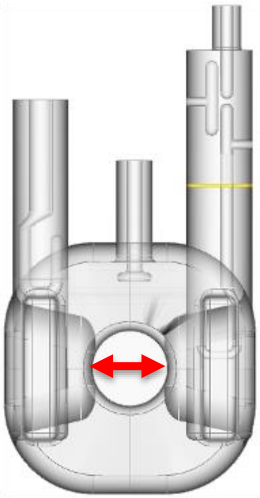


280 mm

Bulk Nb cavities, Dipolar symmetry

$V_T = 3.4 \text{ MV } (E_p, B_p \leq 40 \text{ MV/m}, 70 \text{ mT})$
Stored energy $\sim 10 - 12$ J

CERN insourced DQW production
Nov 2015



281 mm

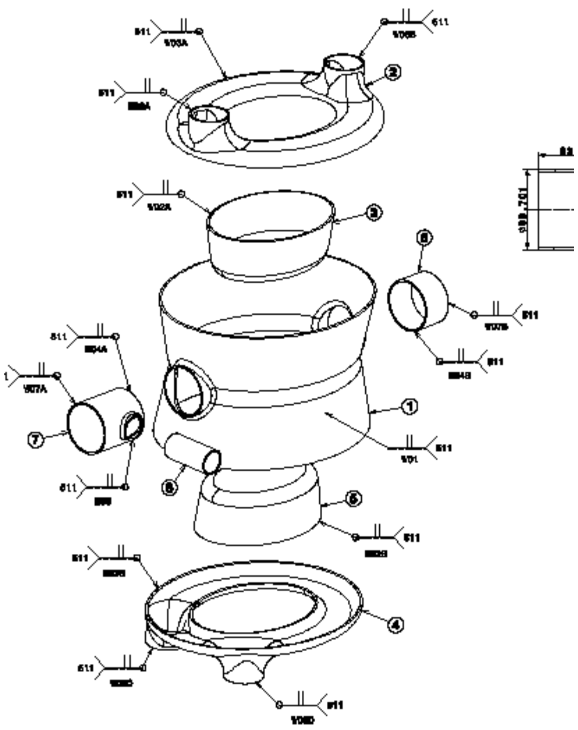
Manufacturing Status

Before starting on crabs

Today

Cavity Status

- First CERN cavity frequency trimming in 1 week

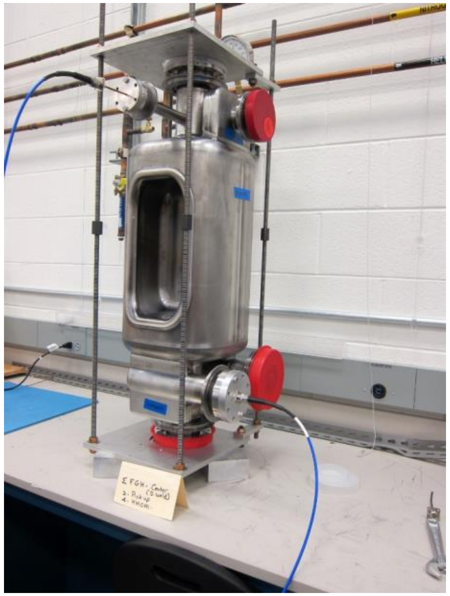


Cavity I cold test mid-Feb 2017 (Cavity 2 in early March)

USLARP & KEK Progress

3-piece assembly before surface treatment

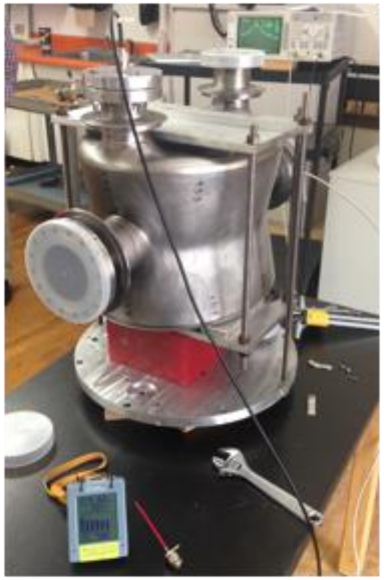
RF Dipole



Known non-conformities in fabrication not possible to test in SPS

However, wealth of information obtained from assembly

3-piece assembly during, trim tuning



DQW

KEK e-polishing setup

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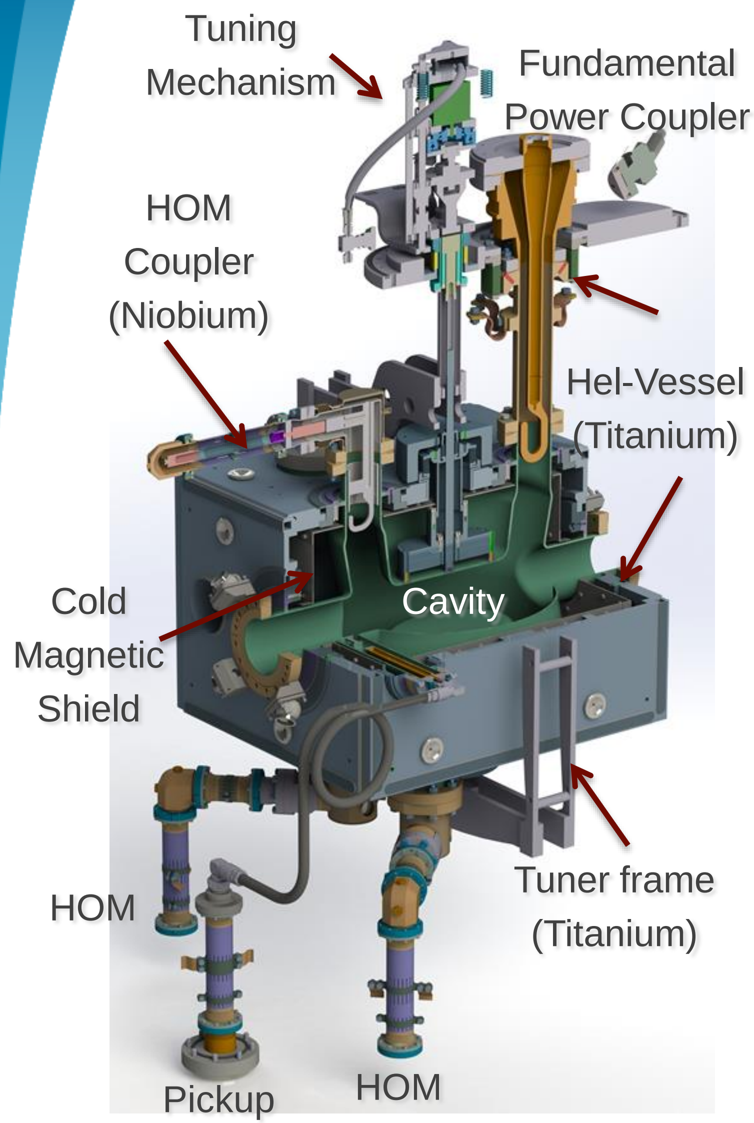
Dressed Cavities (2K volume)



Main Mechanical interfaces:

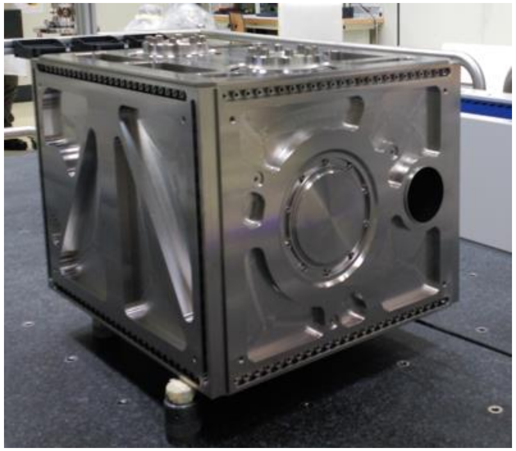
- He-vessel: Bolted-welded concept
- Cold magnetic shield
- Tuner: Sym. tuning with warm actuation
- Three point support + alignment system

Main RF interfaces

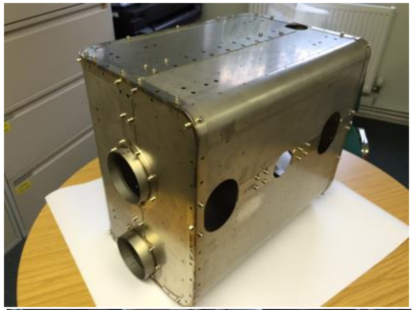
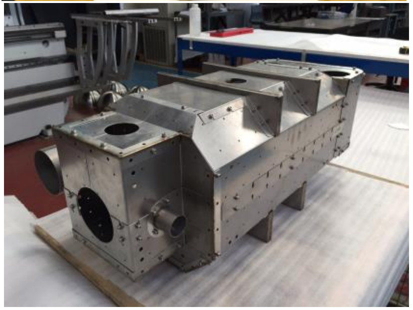
- 1 FPC: Single ceramic coaxial line
- 3 HOMs: Two stage filter, coaxial
- 1 PU: Cu-Nb for field probe + HOM

Similar concept for RFD with different HOM interfaces

Prototype He Vessel, Manufacturing R&D

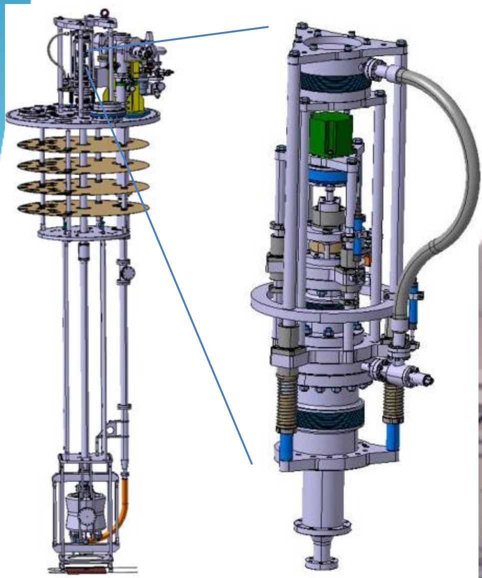


Internal magnetic shield
(UK contribution)

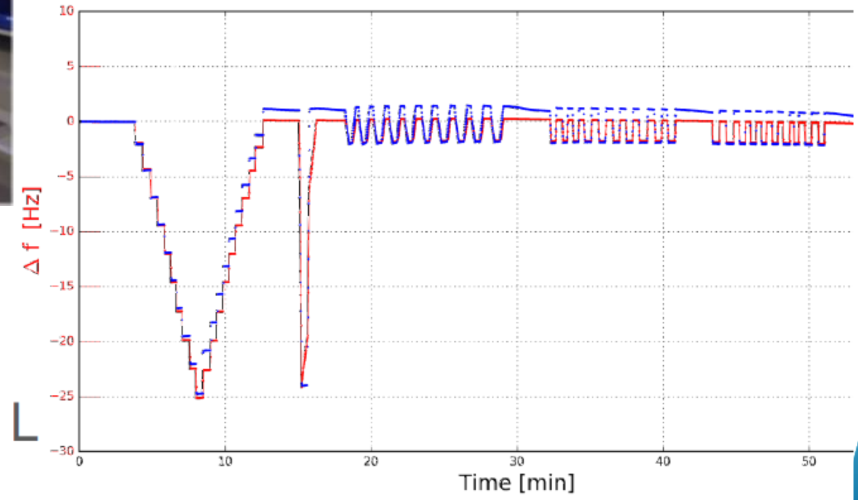
Successful pressure, vacuum & magnetic tests done

Mock-up Tuner Tests, SM18

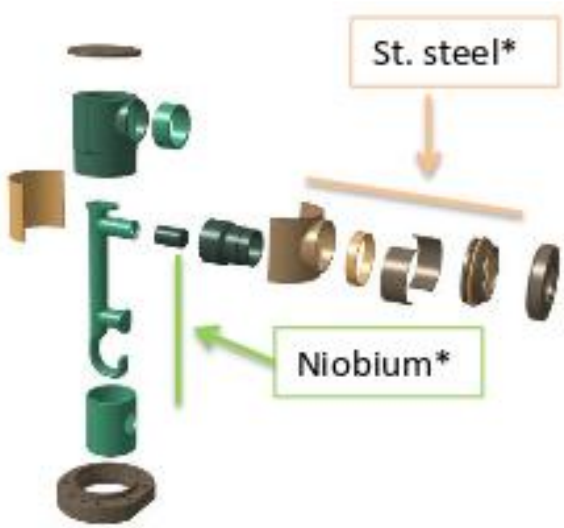


Tuner Mock up tests in performed in Jul 2016

Extremely good results from the vertical tests in SM18, frequency resolution well below the specification of 100 Hz



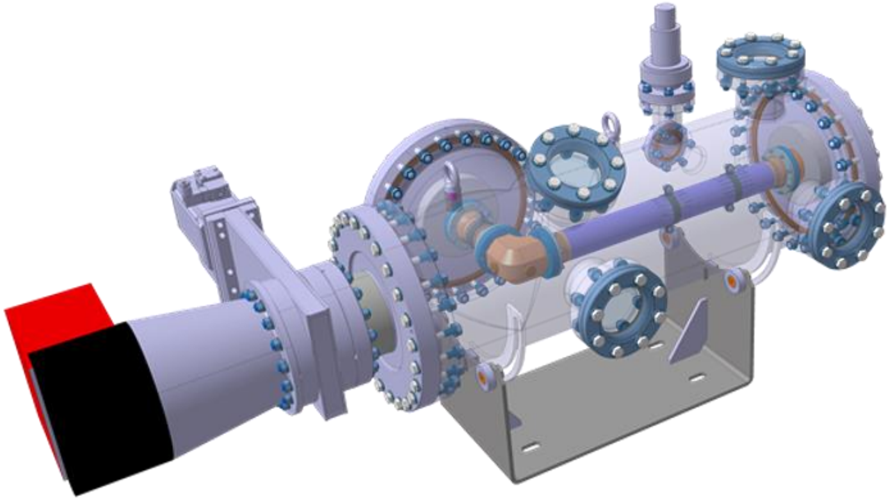
Higher Order Mode Couplers, DQW



6+2 HOM couplers machined, final welding in process
RFD couplers will follow immediately after

HOM-RF Lines

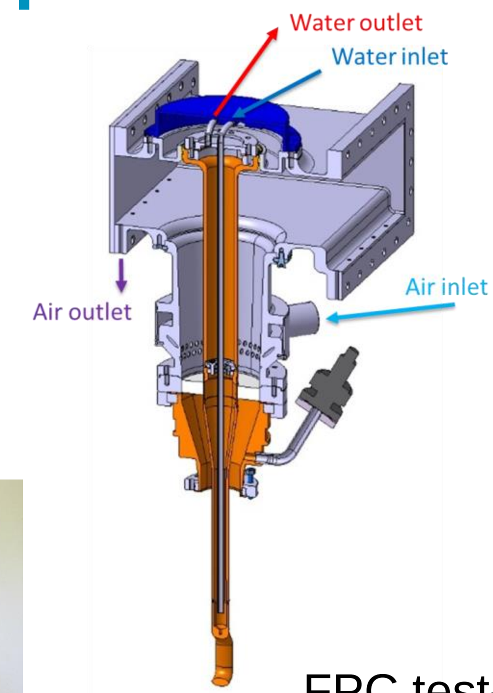
- Internal RF transmission lines for HOM extraction
- Test setup for destructive testing well beyond the 1 kW-CW specification

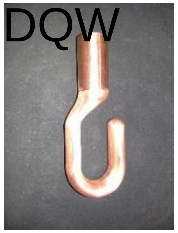


RF line high power destructive test setup

Fundamental Power Coupler

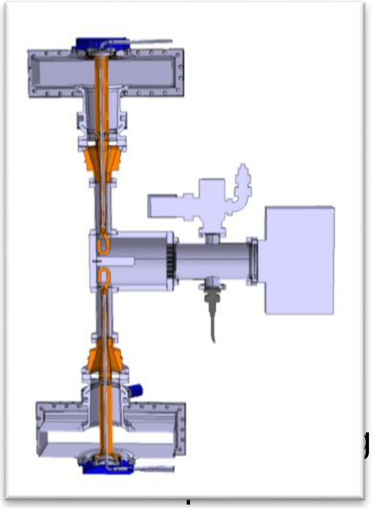
- Input power of 40 kW CW (80 kW peak)
- Four couplers fabricated and ready for testing





Cu-SS sputtering for FPC outer conductor

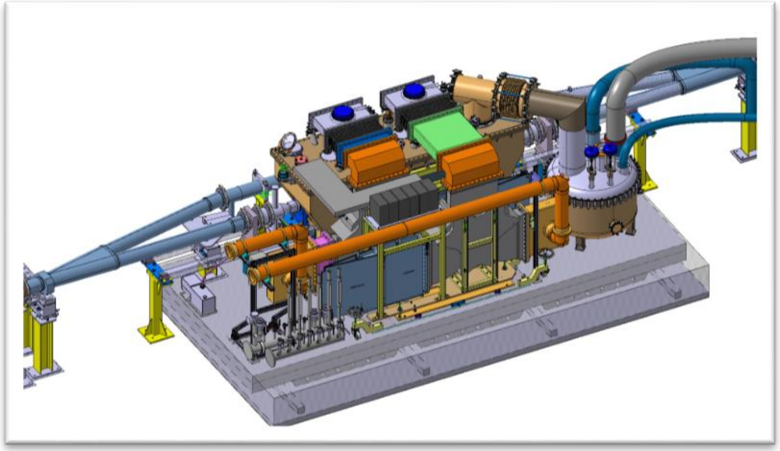
4 FPCs assembled in vacuum



FPC test-box

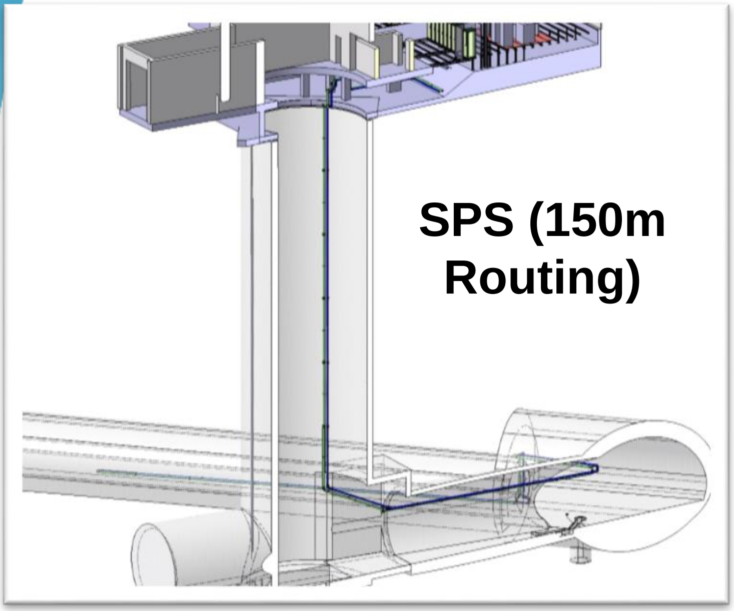
SPS RF Power

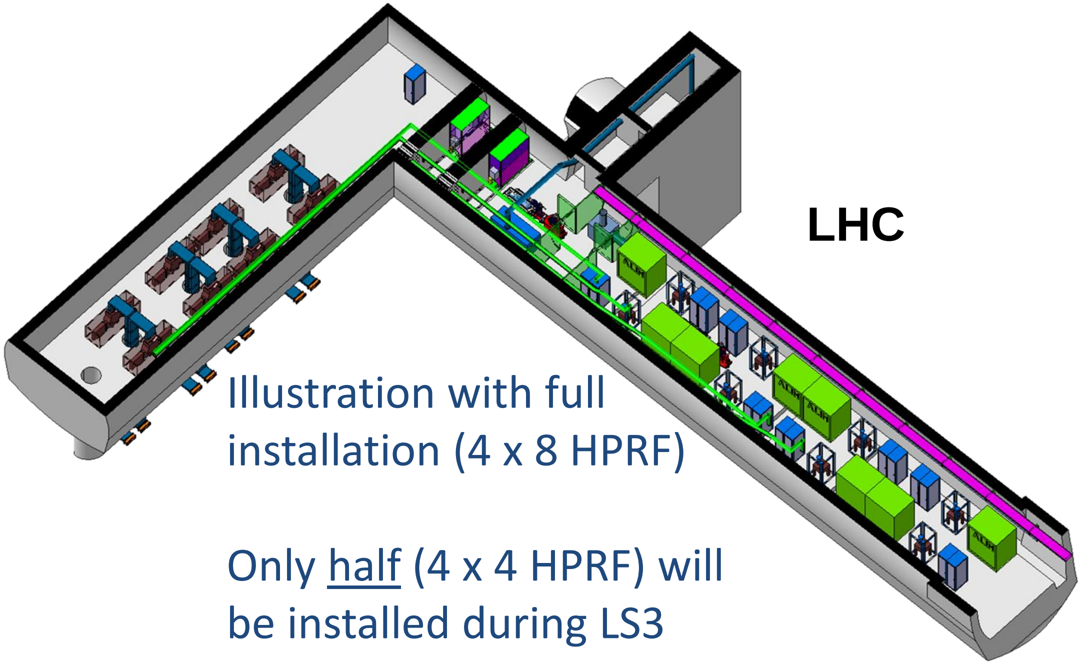
- Inductive Output Tube (IOT) as baseline solution for SPS & LHC
  - IOT Cubicle 60 kW-CW at 400 MHz validated
  - Parallel SSA solution under study as a possible compact/cheaper option in future



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

RF Integration (WP15-WP4)





The space reserved for full installation (32 HPRF)

- Cores, all built in LS3 even if not use
- Larger UA/Faraday Cage to allow space for HPRF, HV transformers and CV equipment

SPS LLRF

- Strong synergy with the Linac4 design
  - Identical VME crates (installed in SM18), Self-excited loop test early 2017 + Tuner driven tests Spring 2017
  - Re-use Linac4 modules after changing a few passive components to optimize to the new RF frequency
    - CC: RF @ 400.8 MHz, LO @ 375.75 MHz, IF @ 25.05 MHz sampled with ADC clocked @ 100.2 Msps
- Some modifications required in the firmware (CW vs. pulsed, MIMO feedback, Self-Excited Loop option) and in the FESA classes - ongoing

Standard CO-supplied CPU with timing card (CTRV/P)

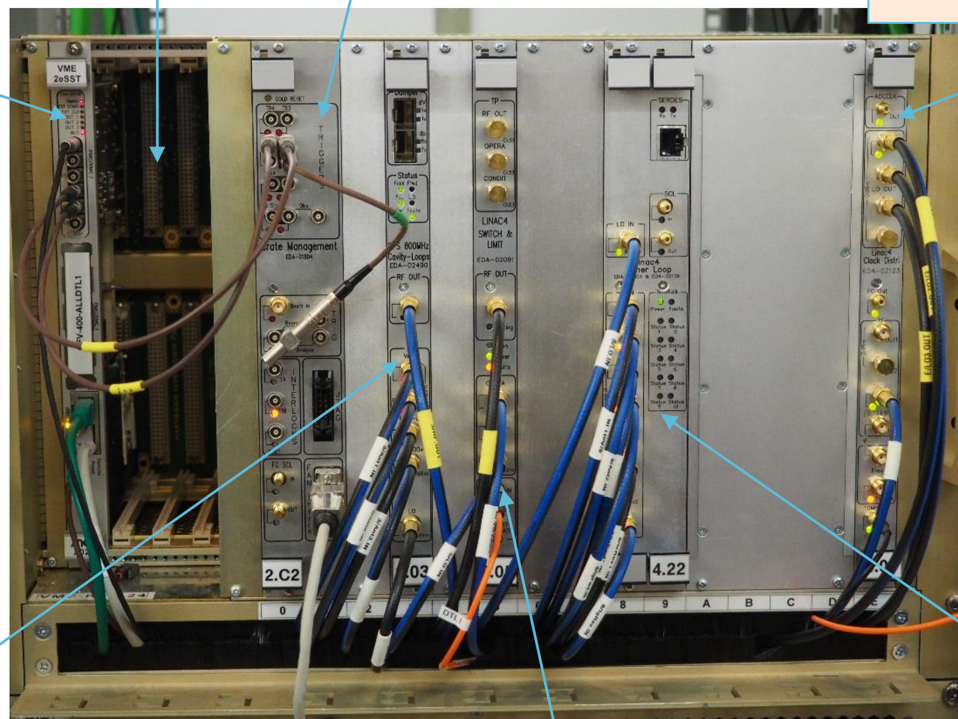
Custom-designed RF VME crate

Crate Management module (same as LHC and L4)

Clock Distributor module. Generates the harmonically related LO and ADC clocks. Adapted from L4

Color-coded Status:

- Available
- FESA class needed
- New firmware and FESA class needed



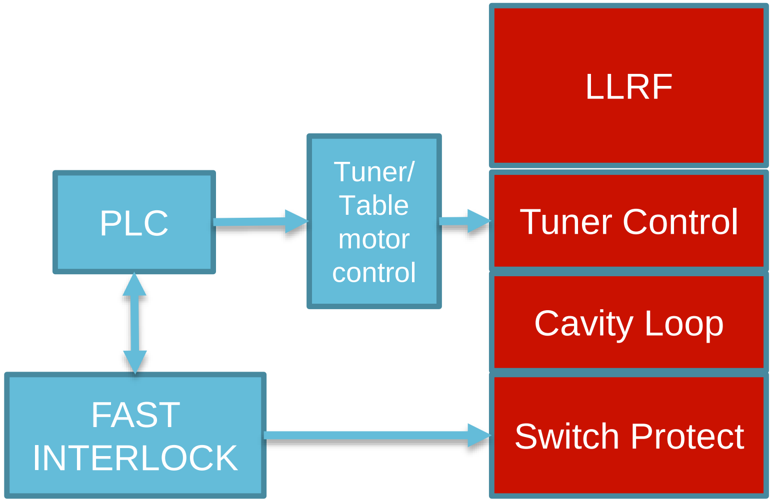
Cavity Loop module (RF feedback). Firmware being modified. Fesa class to be written

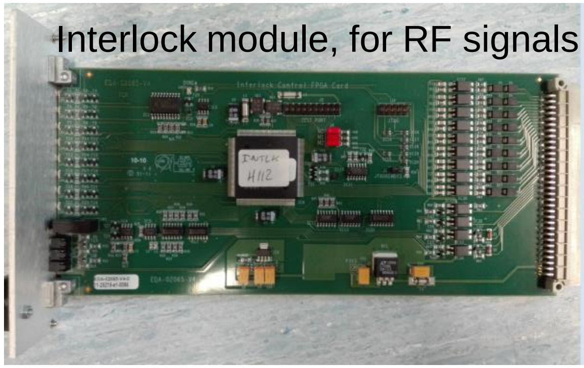
Switch and Limit module. Receives the RF power intlk. (adapted from L4)

Tuner module. Firmware ready for test in SM18. Fesa class to be written

RF “Slow” System, PLC

- RF power system & tuner/table motor control, Fast interlocks
- Expert /Operator user interfaces
- Most of the LINAC4 infrastructure is used as the basis for the SPS-Crab Cavity tests



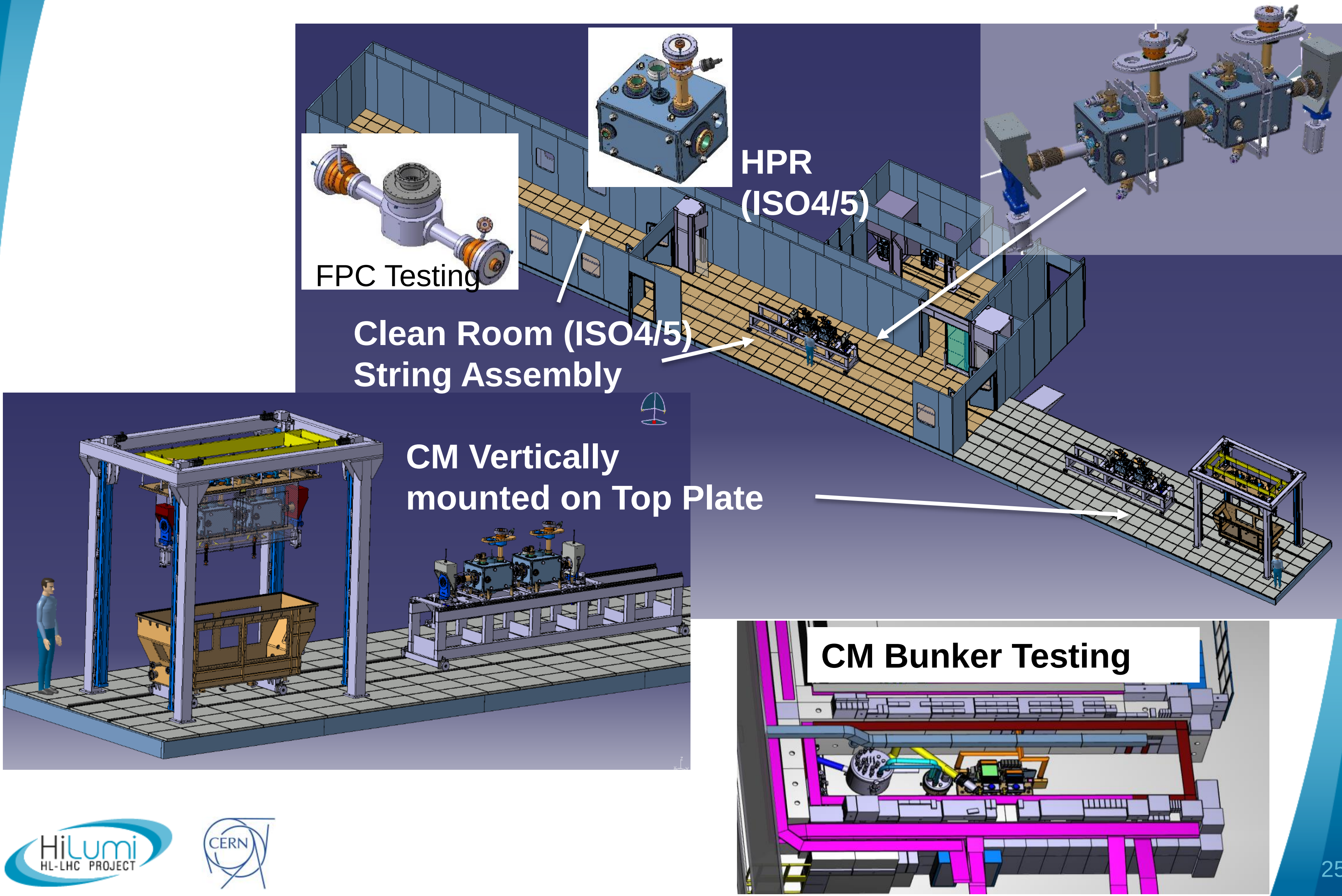

Interlock module, for RF signals

SM18 Activities

- Insourcing cavity production new tooling in SM18 for cavity preparation, treatment & assembly

HPR facility upgrade	Operational
Clean room tools & procedures (Reviewed last month)	Coherent plan and clear methodology. Review advised reinforced coordination, organisational plan, identify additional resources, bottom-up methods via training & tests on mock-ups.
Vertical cryostats for single cavity test	1 insert operational, 1 insert in assembly
LLRF & Controls	Development & test on PoP cavity Nov16
Infrastructure in M7 Bunker	New cabling & vacuum equipment
Cryo distribution	IT DO-30148 purchase procedure launched Oct16

SM18 Assembly & Testing



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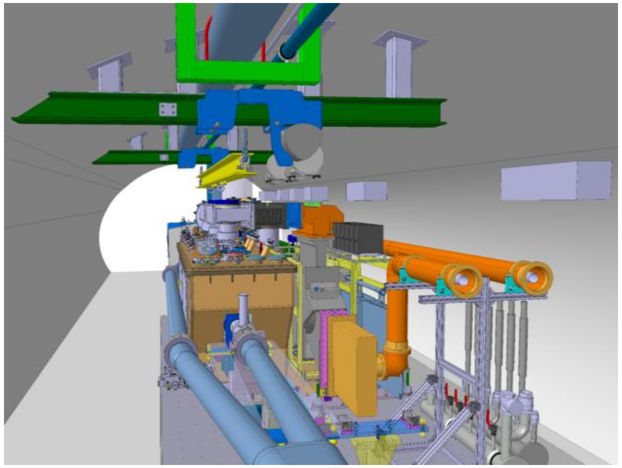
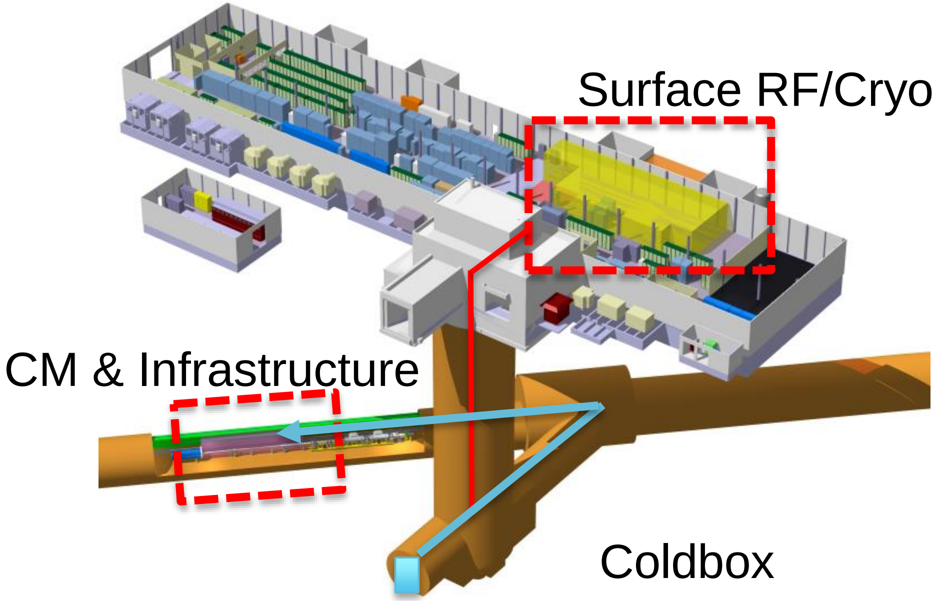
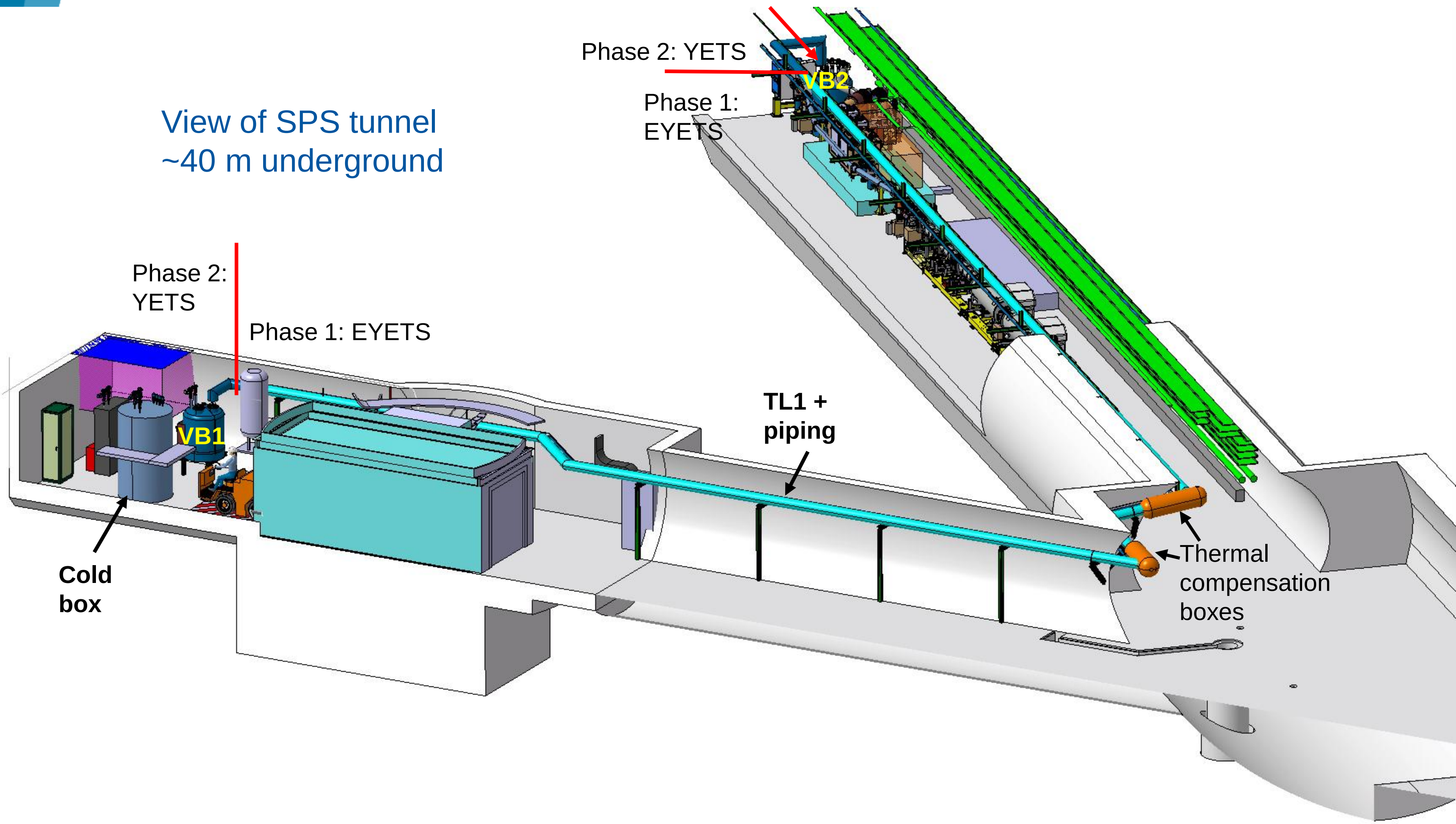
SPS infrastructure





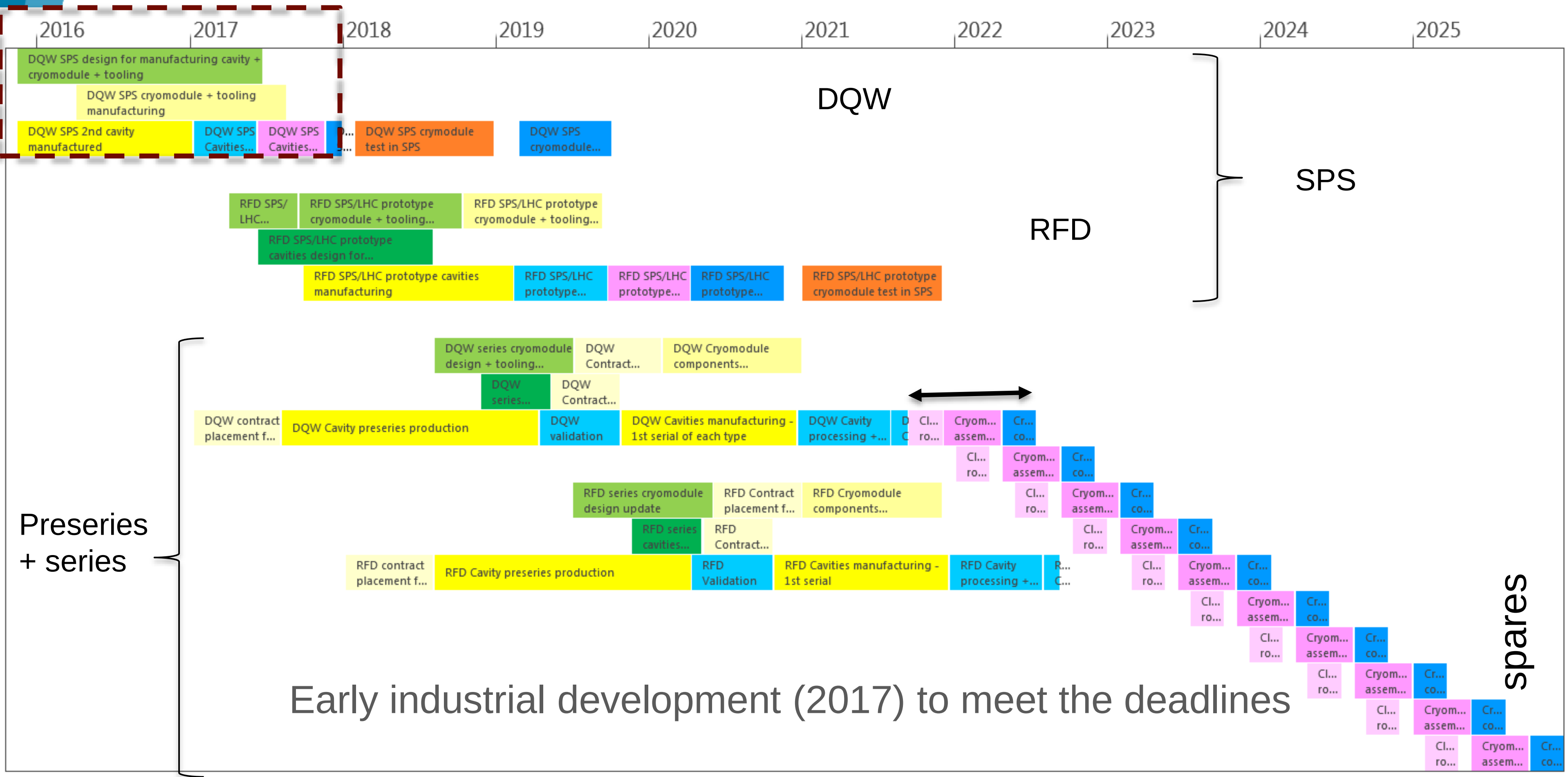
Surface Prep (YETS15-16)	BA6 cleared, uncabling tunnel
Integration	Finalized EYETS16-17,
Cryogenic distribution	Contract placed, phase1 in EYETS16-17
Infrastructure	Pipework, cables, handling rails: installation in EYETS16-17
Transfer Table	MS at Spec committee, Tech. Spec in final stages
Cryogenic Refrigeration	Offers received, LoI asked to confirm delivery end of 2017

Cryogenics architecture



TE-CRG

HL-LHC Industrial Production



The production (2021-25) assumes SM18 RF facility available

However, storage/assembly of 1 SPS-CM already challenging

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Some Final Comments

- A new paradigm on SC compact deflecting cavities will soon be validated with the highest energy protons for the first time in the world

- There is an <u>intense</u> level of activity on many fronts
  - USLARP & UK collaborations were an integral part w/o which it SPS tests be impossible

- The design choices for the CM & RF services (after many iterations) are robust. We have validated most important elements by prototyping (cavity, tuner, He-vessel…)

Thank you

(mainly to those behind the scenes)

And also to some curious visitors from Paris

Pixar Animation Studios

Need for SPS Tests

- Operation of such type of cavities in high current and high energy CW (proton) circular machines has never been done!

- Injection, capture, acceleration where the cavities are carefully counter-phased (transparency) and re-phased during collisions. Ultra-precise control of cavity voltage and phase guarantee the preservation of beam quality throughout the cycle.

- Guarantee the operation of cavities with a trip rate significantly below the LHC availability. To validate this is in SPS is pre-requisite both with and w/o beam.

- Unlike electrons, there are many aspects (emittance growth, machine protection, RF non-linearity, instabilities) where proton beam tests are the only conclusive answer.

CCTC II for SPS Preparation

- Technical CM Coordination, bi-weekly
  - **System Integration Workflow** : location, team, duration, tools, tests
  - Reviews of specific activities (clean room) and items (FPC, tuner)
- Procurement of Vessel for Cryomodule launched – on track
- Production of cavities and auxiliaries – on track

System Integration Workflow :
https://edms.cern.ch/document/1703245/9

13	Cavity inspection		112		bare cavity	Marco		NO tools	Cavity finalization, inspection and metrology	Marco	EN-MME	0	0	11
14	Leak test		112									2	0	
15	RF frequency		72		bare cavity	Rama						1	0	
16	Alternative Tuning		72		bare cavity	Marco						8	0	
17	RF frequency		72		bare cavity	Rama								
18	Metrology		72		bare cavity	Marco, Mateusz	including bead-pull measurement of the electric center, visual inspection	Visual Inspection means Endoscope? If so needs to be procured					0	
19	Mount handling frame		72		bare cavity + frame	Marco		Frame for handling	Cavity cleaning and treatment (BCP, heat)	Leonel	EN-MME	1	0	36.5
20	Cleaning + Heavy BCP		B102 + B118		bare cavity + frame	Leonel	bath etching speed vs bath speed (July to september)	PVDF/PVC flanges + Support at height to allow gravity emptying + tool for bath etching speed vs bath speed				15	1	
21	RF frequency, with antenna for cold tests		72		bare cavity + frame	Rama/ Alick?						1	1	
22	Alternative Tuning		72		bare cavity + frame	Marco						5	0	
23	RF frequency		72		bare cavity + frame	Rama								
24	Metrology		72		bare cavity + frame	Marco, Mateusz						3	0	
25	Cleaning		B102		bare cavity + frame	Leonel						1.5	0	
26	Heat treatment		B153		bare cavity	Leonel		To be defined depending on RRR tests.				3	0	
27	Light BCP		B118		bare cavity + frame	Leonel						5	0	
28	HP Water Rinsing		SM18		bare cavity + frame	Alick			Bare cavity validation	Alick	BE-RF	3	1	24
29	Assembly bare cavity		SM18	clean room	bare cavity + frame	Alick						1	0	
30	Transfer cavity to insert		SM18		bare cavity + frame	Alick		Frame for supporting the cavity during cold test				1	0	
31	Bakeout		SM18		bare cavity + frame	Alick						3	0	
32	Cold RF test		SM18		bare cavity + stiff. frame	Alick						10	0	
33	Warmup		SM18		bare cavity + stiff. frame	Alick						4	0	
34	Removal of test antenna and preparation for transport		SM18	clean room	bare cavity + frame	Alick						1	0	

Crab Cavity Technical Coordination: https://indico.cern.ch/category/8048/

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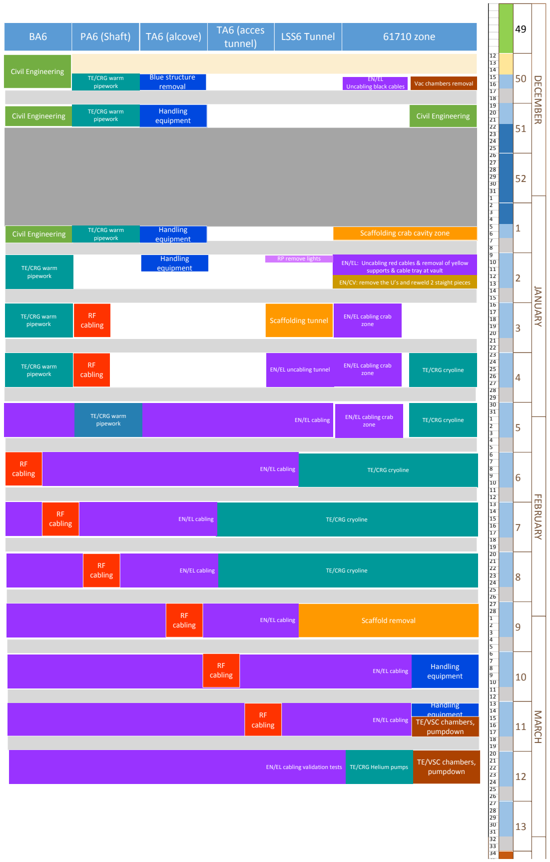
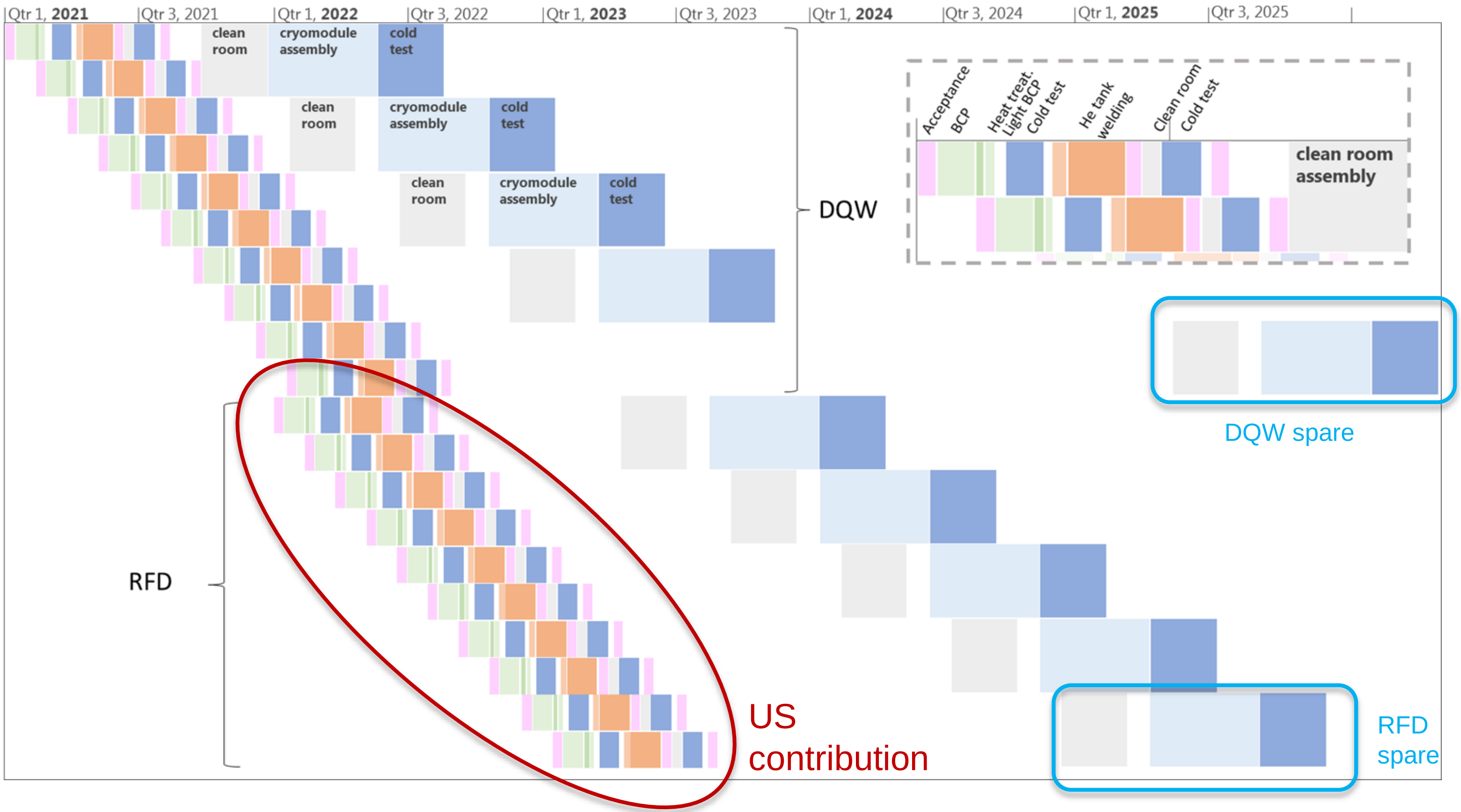
SPS Installation – EYETS planning

- Space Reservation request and description of the future test stand
- Main Activities
  - Cryogenic distribution line TL
  - Cable installation (30km purchased)
  - New vacuum layout
  - New handling equipment
  - New supporting structures in BA6
- ECR for underground areas are issued
- Safety review (Hazards & LSA), layout of the ODH and other safety alarms



Schedule series



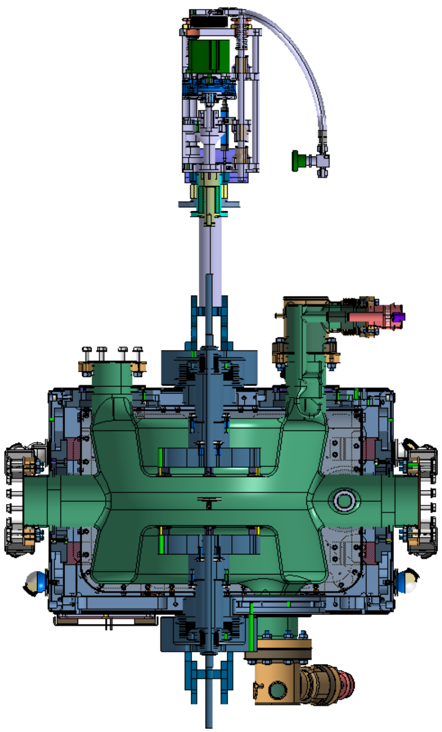
Infrastructure needed at CERN (existing):

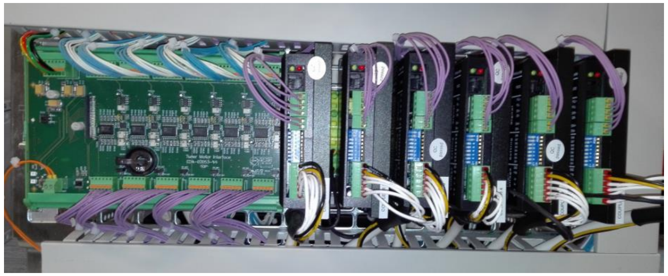
- One BCP stand
- One thermal treatment furnace
- Two vertical tests stands (one for bare and one for dressed cavities)
- One clean room string assembly zone (SM18)
- One cryomodule assembly zone (SM18)
- One cryomodule cold test stand in bunker (SM18)

Cavity Tuning & Control

- Motorized control using concentric Ti-Cylinders + tuning frame to symmetrically deform the cavity
- A CERN standard controller board driven via ethernet to adjust the position with input from LLRF.

The tuner control with LLRF feedback to be tested in Spring 2017





An example of 6 motor controller for HIE-Isolde tuning system