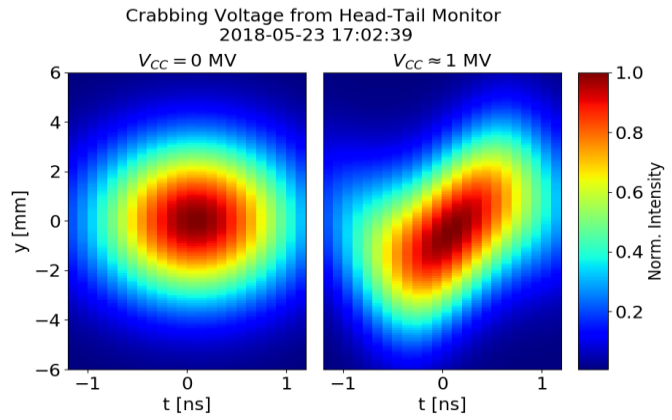
Protons see Crabs



Overview of Crab Cavities for HL-LHC

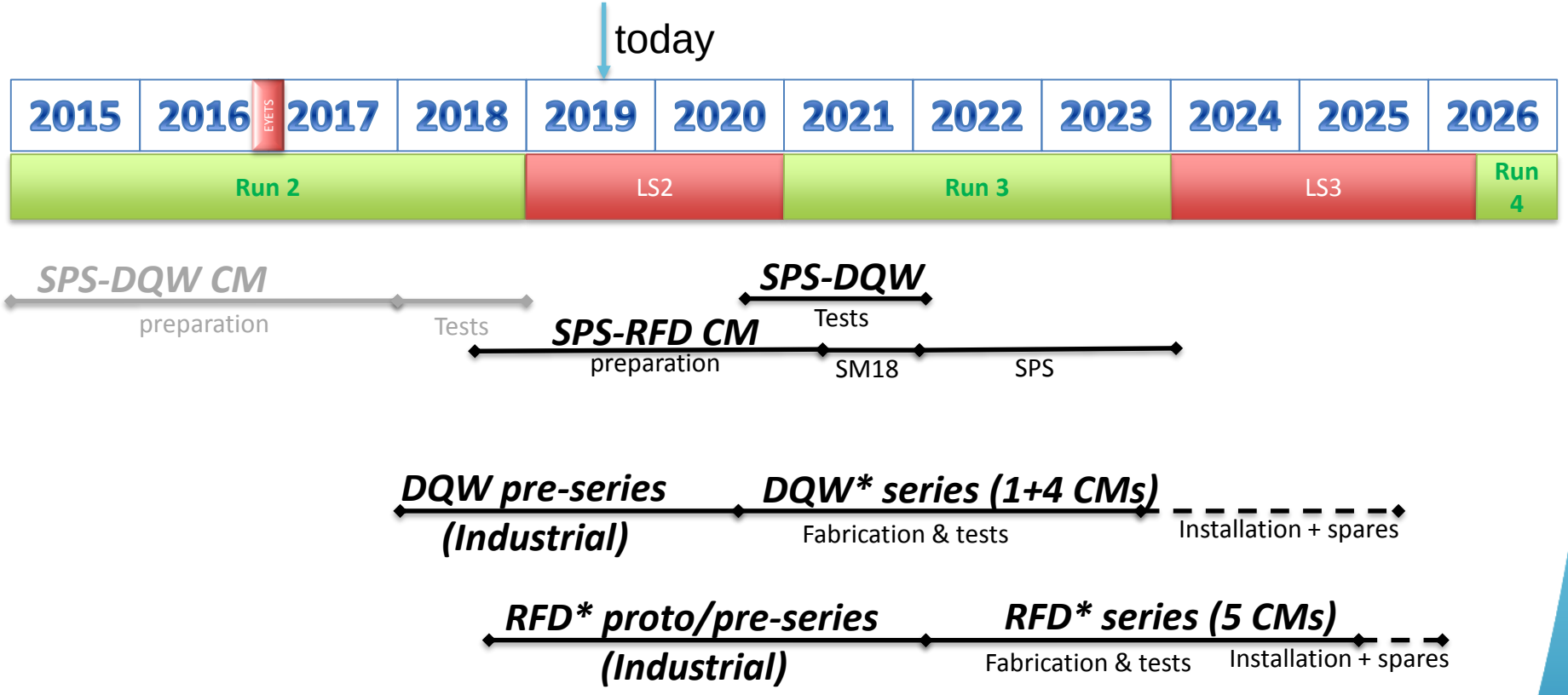
HL-LHC WP4, CERN

International Review of the Crab Cavity system design and production plan for the HL-LHC

Big thanks to BE, EN, TE, HSE, IPT departments
& Canada, UK, US collaborations and all involved

WP04-CC Scope

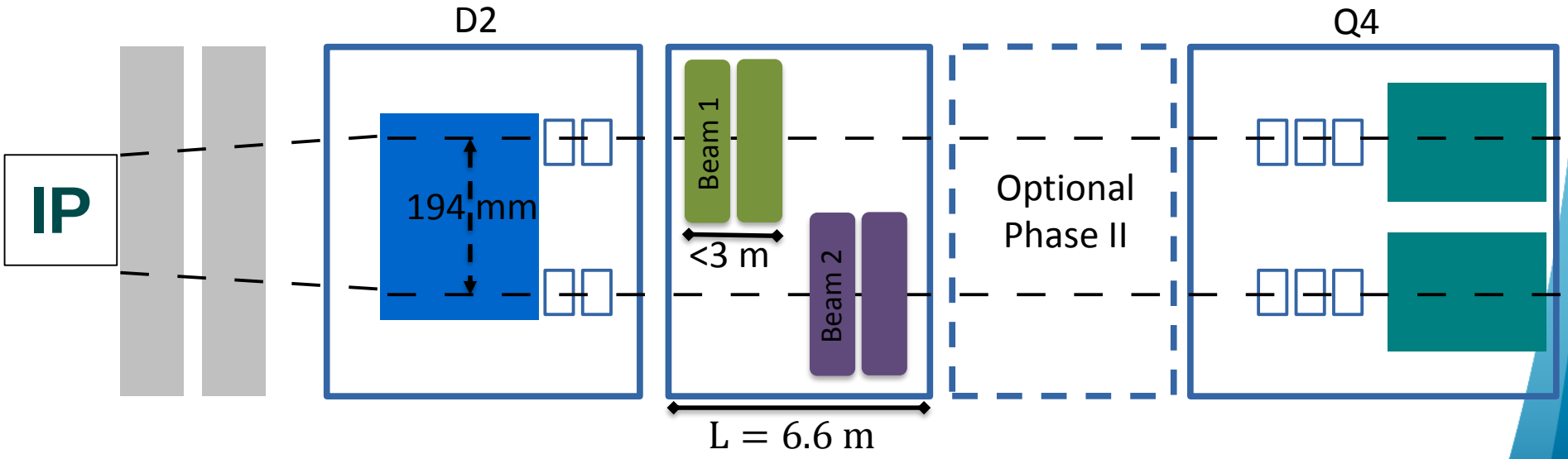
16 SC compact crab cavities to partially compensate the geometric angle ($500\ \mu rad$) at ATLAS+CMS.
Beam tests in the SPS protons



*DQW: 4 CMs by UK-STFC
*RFD: DCs by US-AUP, 5 CMs by TRIUMF

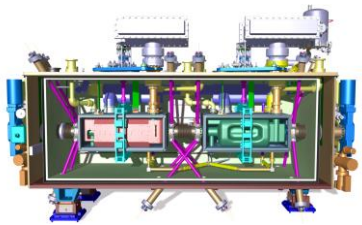
TDR-Basic Parameters

- Frequency = 400.79 MHz
- Aperture = 84 mm
- Voltage = 3.4 MV /cavity (2 cavities /beam /IP side – 16 total*)
- Frequency tuning = ±150 kHz
- $Q_{ext} = 5 \times 10^5$, RF power to cavity = 40 kW (80 kW peak)
- $P_{static} = 18$ W, $P_{dyn} \leq 30$ W (per module)
- Operating temperature = 2.0 K



*For full compensation, 4 cavities /beam /IP side

Workpackage Structure



- RF systems and crab cavities (WP4)
  - RF superconducting crab cavities
    - LHC Cavities (**ACF**)
      - Cryomodule (**ACFGA**)
        - Cryomodule Assembly (**ACF_A**)
          - Cryomodule components (**ACFCC**)
            - Cryogenic circuits (**ACFQC**)
            - Thermal shield & MLI (**ACFTS**)
            - Vacuum Vessel (**ACFVT**)
            - Warm Magnetic shield (**ACFWM**)
            - Alignment Monitoring System (**ACFAM**)
            - Support and Alignment System (**ACFAH**)
            - RF internal lines (**ACFRL**)
          - Dressed cavities (**ACFDC**)
            - Bare cavities (**ACFCA**)
            - Helium vessel (**ACFHT**)
            - Tuning system (**ACFTU**)
            - HOM couplers (**ACFHC**)
            - Cold magnetic shield (**ACFCM**)
            - Pick-up antenna (**ACFPU**)
          - Instrumentation (**ACFIS**)
          - *Beam Axis (XYZ)*
            - Vacuum valves (**VVG**)
            - Cold –Warm Transitions (**ACFVW**)
            - Inter Cavity Chamber (**ACFVC**)
            - Beam Screen (**ACFVS**)
      - External supports (**HACF**)
      - General Tooling (**ACF_T**)
        - Forming Tooling (**ACFFT**)
        - Machining Tooling (**ACFMT**)
        - Welding Tooling (**ACFWT**)
        - Clean Room Tooling (**ACFCT**)
      - RF services (**ACFSV**)
        - LLRF & Fast Controls (**ALL**)
        - RF racks (**AY**)
        - Slow controls (**AS**)
        - Transmission lines (**ACFWG**)
        - Main coupler - FPC (**ACFMC**)
        - RF Pick-ups (**APW**)
        - Amplifiers (**ACFA**)
          - Amplifier Tetrode (**ACFAA**)
          - Amplifier IOT (**ACFAB**)
          - Amplifier Solid State (**ACFAC**)
          - Amplifier 2nd Generation IOT (**ACFAD**)
          - Amplifier 2nd Generation SSPA (**ACFAE**)

- LHC
  - Harmonic system
    - 200 MHz
    - 800 MHz
  - Wide-band feedback system

HiLumi HL-LHC PROJECT

CERN

Past Reviews & Outcome

- **May 2014**: Cavity design review
  - Led to down selection to 2 cavities (DQW, RFD) for SPS-test/LHC

- Feb 2015: 1st HOM coupler review
- Mar 2015: Cost & Schedule review I
  - Study the effect of only ½ of system (16 instead of 32)
- May 2015: CERN-STFC Helium vessel review
- **Nov 2015**: SPS Cryomodule review
  - Develop minimum goal for SPS tests, review individual critical components, integrated production/test planning including infrastructure

- Oct 2016: Clean room assembly review
- Oct 2016: Cost & Schedule review II
  - Reduction to ½ system, HPRF 40 kW-CW
- Nov 2016: Operational safety review in SPS

- **April 2017**: Crab cavity performance review for HL-LHC
  - Perform SM18 tests prior to SPS installation with minimum success criteria, establish formal agreements, specifications, acceptance criteria and interfaces
- Mar 2018: Cost & Schedule review III
  - Endorsed with new strategy (UK, US-AUP, Canada)

Note: 2 SPS tests days jointly with WPs concerned for MD preparation

Mandate for 2019 Review

Full Mandate

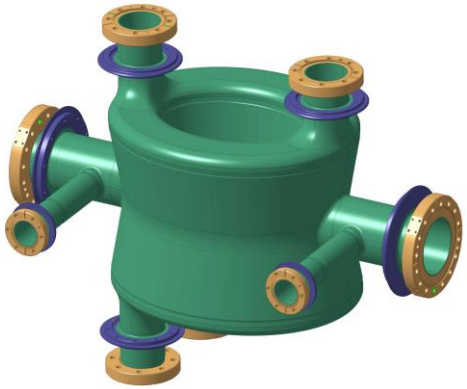
- CQ1: SPS-CC experience & lessons learned to be implemented into HL-LHC CC
- CQ2: SPS beam tests & extrapolation to HL-LHC, open questions ? Readiness of RFD pre-series cryomodule?
- CQ3: Readiness for series production? Open points being addressed implying changes
- CQ4: Status of HPRF, LLRF and other auxiliary components, do we need further attention over the coming years?
- CQ5: Baseline schedule including collaborations w.r.t HL-LHC schedule? Management of in-kind and preparations for work framework – risks for production/testing ?
- CQ6: Is CERN ready to finalize the agreements (status of acceptance criteria & procedures of different sub-components)
- CQ7: QA/QC and risks for deliverables between partner labs

Agenda of this Review

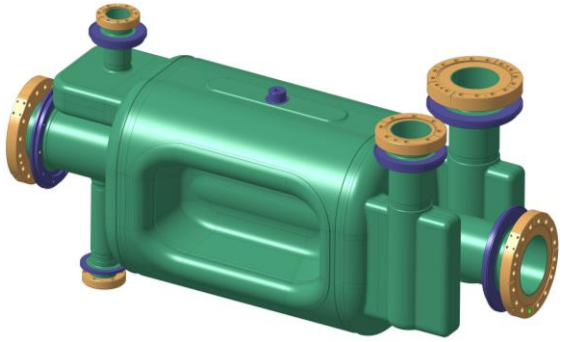
- Introduction
  - Overview of main systems + integration/interfaces
- SPS-tests Hardware & Beam Experience
- HL-LHC Pre-Series status & Series preparation
- HL-LHC main interfaces & integration
- Specifications, norms, conformity & safety

Reminder: Dressed Cavity Geometries

Double Quarter Wave



RF Dipole



$$f_0 = 400\ \text{MHz}$$

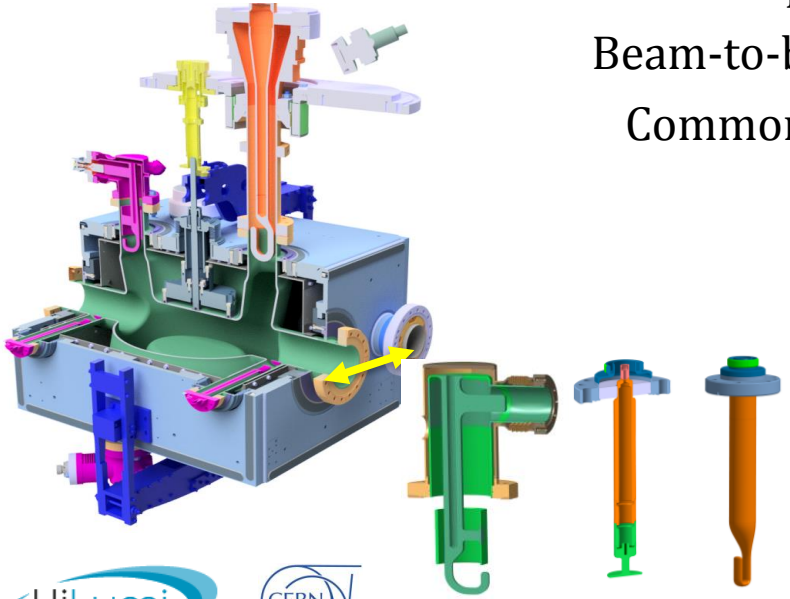
$$V_T = 3.4\ \text{MV}$$

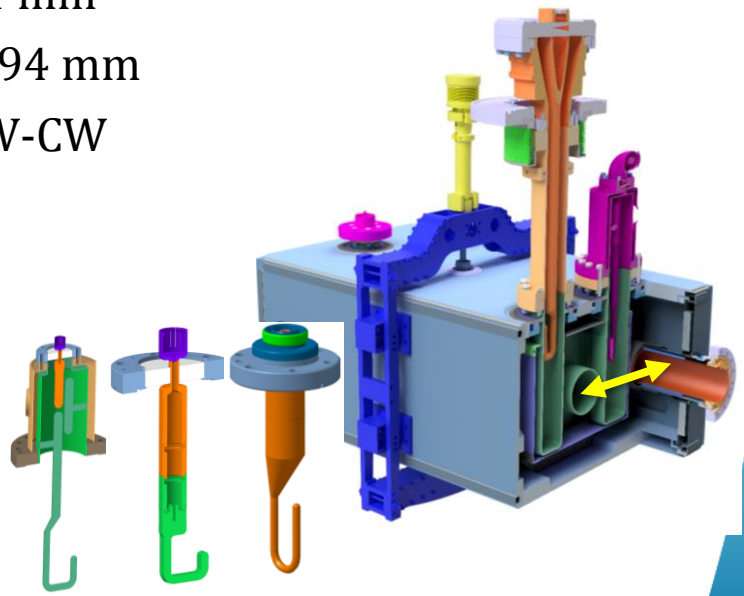
$$(E_p, B_p < 40\ \text{MV/m}, 70\ \text{mT})$$

Beam aperture = 84 mm

Beam-to-beam dist = 194 mm

Common FPC = 40 kW-CW



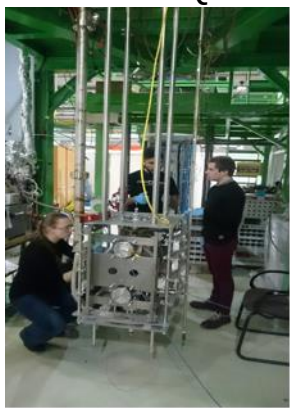


Vertical Cavity Tests (6 Cavities)

Nominal Spec $V_{kick} = 3.4$ MV

		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**	**5.0**	**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
Max Volt with HOM	[MV]	**3.3***	-	-	**4.7**	**-**	**5.5**

CERN DQW



USLARP DQW & RFD

* Voltage limit for SPS-DQW with HOMs due to inadequate BCP of HOMs

Summary of SPS-test Experience

- Bare cavity performance is +50% of the nominal voltage
  - In SM18 dressed cavities exhibited limit ~3MV, now understood
  - Performance of the SPS-test module limited to 1MV for machine developments, 2MV stable
- First crabbing of protons demonstrated. Main aspects such as transparency, beam loading, emittance growth, crab dispersion and other aspects studied – no show stopper
- Several hardware limitations: direct beam coupling, pondermotive instabilities, RF non-linearity at low power, RF/Cryo/Vacuum stability beyond 2MV..
- Consolidation of SPS test stand underway during LS2 with 2021 operation of DQW and 2022 RFD

Main Modifications since SPS-test

- Cavity design evolution
  - RFD cavity design updated for reduction in HOM power from most dangerous HOM at 760 MHz, DQW HOM coupler improved for better damping
  - DQW & RFD field antenna design change to reduce direct beam coupling, including modification to 25 Ω for all RF feedthroughs
- RFD-Cryomodule prototype fully compatible HL-LHC (Cryogenics, Vacuum & RF interfaces)
- Strong effort towards solid state for HPRF
- LLRF improvements for faster RF setup & migration from VME→ μTCA beyond LS2

Highlights, since last review

- DQW-SPS prototype demonstrates with first ever crabbing with protons, transparency & high intensity demonstrated. Detailed studies will continue in 2021

- DQW-HL-LHC jacketed cavities contract with RI signed & ongoing
- DQW-HL-LHC cryostating in final stages of negotiation for building 1-CERN and 4-UK

- RFD-SPS test cavity fabrication started at CERN, cryostating to be performed at UK and the conceptual design is almost complete
- RFD-HL-LHC dressed cavities in-kind contribution from US-AUP with CD2 approval & progressing well
- RFD-HL-LHC cryostating as in-kind from Canada-TRIUMF, detailed agreement in preparation

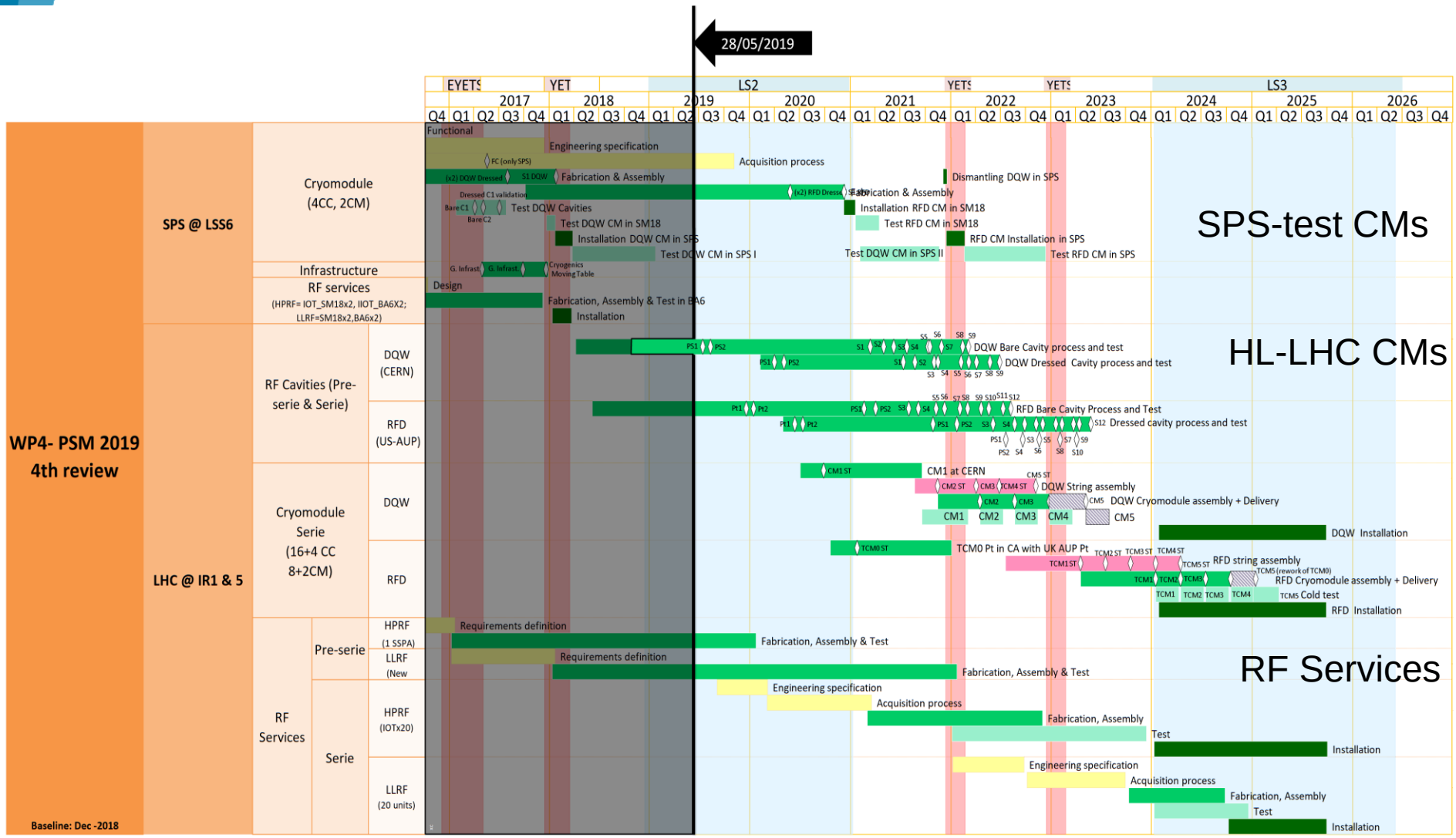
- Discussions ongoing with Novosibirsk for an in-kind contribution of high power RF amplifiers using solid state technology

- Big effort on integration for HL-LHC, including design adapted for left/right IP symmetry and IR1/5 swappable option

WP4 Planning & Collaborations

- Update strategy & planning in place since last review including 3+ collaborations
- In-kind contributions
  - UK1 – RFD-Cryomodule prototype with CERN providing dressed cavities & partial components
  - US-AUP – 10 RFD dressed cavities (He-tank, HOMs, Field Ant, Cold B-shields)
  - UK2 – 4-DQW cryomodules with CERN providing dressed cavities & partial components
  - TRIUMF – 5-RFD cryomodules with US-AUP providing dressed cavities and CERN with partial components
  - Novosibirsk – Proposal to provide SSPA amplifiers jointly with Russian industrial partner – pending final approval

Masterplan WP4-CC



WP4, Documentation QA/QC

- EDMS/MTF WP4 - CERN-0000096385
  - Centrally managed (specifications, drawings, manufacturing inspection plans, test procedures, results, quality control)
- Strategy for compliance: An engineering specification along with specification drawing (where applicable) for each main component. Also includes acceptance criteria
- Safety folder (SPS-test & HL-LHC)

Specification Documents	Document Number	Status
Dressed cavities	EDMS 1389669	V2.49 *final editing*
Cryomodule	EDMS 2043014	V0.1 for WP4 internal circulation
SSA System Safety Assessment	EDMS 2010001	V0.13 Engineering check
Guidelines for compliance with CERN safety rules	EDMS 2058183	V0.2 Eng. Check + Memo from HSE to WP4

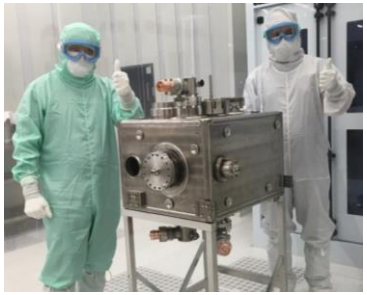
HL-LHC WP4: https://espace.cern.ch/HiLumi/WP4/default.aspx

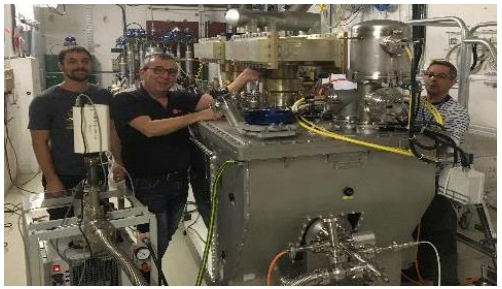
Summing Up

- SPS-test Crab Cavities
  - Despite many hurdles, a monumental effort was put in to conclude 2018 beam tests a success – hunt for higher voltage and beam current in 2021
  - Many lessons learned are being implemented for RFD-prototype jointly with UK & US, it is on schedule for 2022 SPS tests

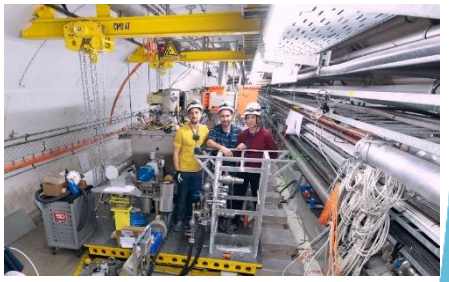
- HL-LHC Crab Cavities
  - RI-DQW pre-series contract progressing well, RFD industrial prototypes under US-AUP progressing well. SSPA with Novosibirsk looks very promising
  - Challenging year to consolidate the detailed specifications, responsibilities between CERN and external partners and adapt planning
  - Communication between CERN & external partners has ramped up significantly in 2019 – very healthy sign

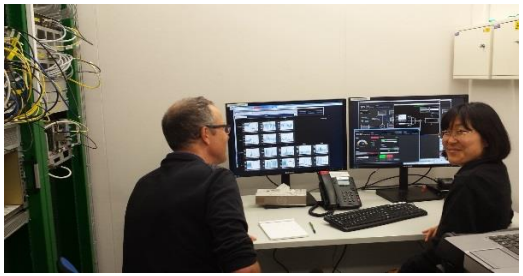
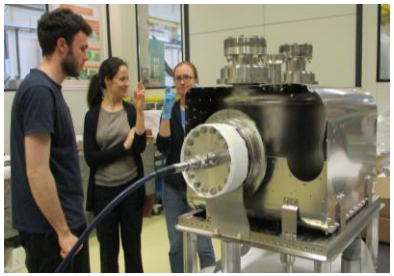
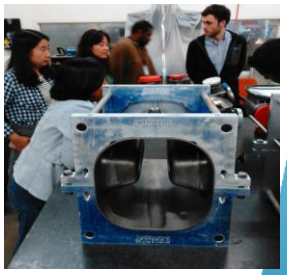
Thank You !





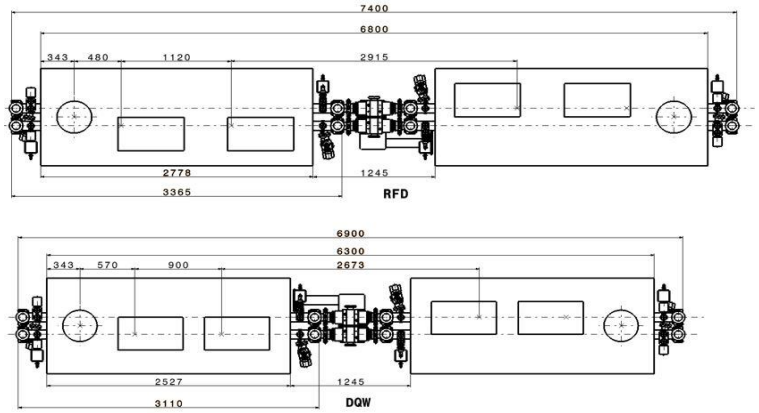


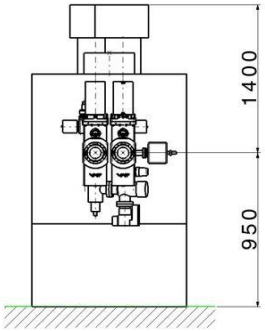




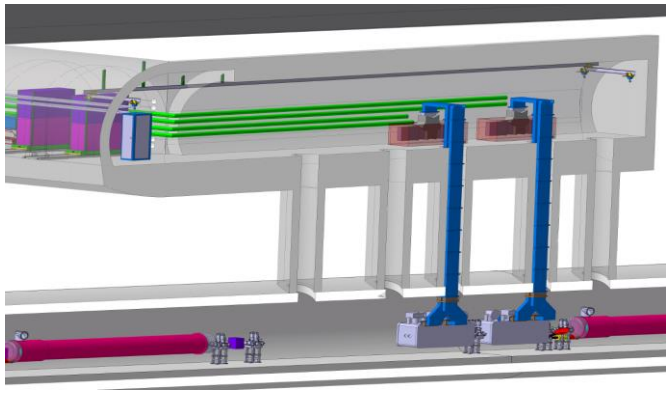
https://videos.cern.ch/record/ (2631455, 2631454, 2630818)

HL-LHC Cryomodule Layout

- RFD-proto already HL-LHC type
- Both types of cryomodules integrated in the IR
- 1-spare module per type (or IR) with left/right symmetry. Also swappable between IRs
- Integration & interfaces with all services in advanced stage







P. Fessia et al