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 μrad) 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
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

- 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

\[ f_0 = 400 \text{ MHz} \]
\[ V_T = 3.4 \text{ MV} \]
(E\(_p\), B\(_p\) < 40 MV/m, 70 mT)
Beam aperture = 84 mm
Beam-to-beam dist = 194 mm
Common FPC = 40 kW-CW

RF Dipole
Vertical Cavity Tests (6 Cavities)

Nominal Spec $V_{\text{kick}} = 3.4$ MV

<table>
<thead>
<tr>
<th></th>
<th>DQW #1 (CERN)</th>
<th>DQW #2 (CERN)</th>
<th>DQW #1 (USLARP)</th>
<th>DQW #2 (USLARP)</th>
<th>RFD #1 (USLARP)</th>
<th>RFD #2 (USLARP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Volt</td>
<td>[MV]</td>
<td>5.04</td>
<td>4.8</td>
<td>5.8</td>
<td>5.3</td>
<td>5.0</td>
</tr>
<tr>
<td>$E_p, B_p$ [MV/m, mT]</td>
<td>56, 109</td>
<td>54, 103</td>
<td>65, 125</td>
<td>59, 114</td>
<td>42, 73</td>
<td>56, 96</td>
</tr>
<tr>
<td>$R_{s \text{ min}}$ [nΩ]</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>9.5</td>
<td>11</td>
<td>7.6</td>
</tr>
<tr>
<td>$R_{s, 3.4MV}$ [nΩ]</td>
<td>15</td>
<td>18</td>
<td>15</td>
<td>17</td>
<td>13</td>
<td>8.2</td>
</tr>
<tr>
<td>Max Volt with HOM</td>
<td>[MV]</td>
<td>3.3*</td>
<td>-</td>
<td>-</td>
<td>4.7</td>
<td>-</td>
</tr>
</tbody>
</table>

* 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 $25 \, \Omega$ 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 $\rightarrow \mu$TCA 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
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)

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

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