Crab Cavities
SPS MDs, Design Advancement, Plan for Production
HL-LHC WP4
SPS-DQW!
WP04 Scope

16 SC compact crab cavities to partially compensate the geometric angle (500 μrad) at ATLAS+CMS

- First protons through Crabs in SPS!

SPS-DQW CM
preparation

Tests

SPS-RFD CM
preparation

Tests

DQW* series (5 CMs)
(1 CERN, 4 UK)

Fabrication & tests
Installation + spares

RFD series (5 CMs)
(US-AUP & Canada)

Fabrication & tests
Installation + spares

* Jacketed cavities produced by RI
SPS Cavities 2K Volume

Main Mechanical interfaces:
- He-vessel: New Bolted-welded concept
- Tuner: Symmetric tuning, warm actuation
- Three point support + alignment system

Main RF interfaces
- 1 FPC: Single ceramic coaxial line
- 2-4 HOMs: Two stage filter, coaxial
- 1 PU: Cu-Nb for field probe + HOM
WP4 Highlights, 2018

- DQW-SPS prototype demonstrates with first ever crabbing with protons
- DQW-HL-LHC jacketed cavities contract with RI signed & ongoing
- DQW-HL-LHC cryostating in final stages of negotiation for building 1 at CERN and 4 at UK

- RFD-SPS cavity fabrication started at CERN, cryostating to be performed at UK and the conceptual design in an advanced stage
- RFD-HL-LHC dressed cavities in-kind contribution from US-AUP with CD1 approval
- RFD-HL-LHC cryostating is approved to be an in-kind from Canada-TRIUMF

- Discussions ongoing with Novosibirsk for an in-kind contribution of high power RF amplifiers using solid state technology
SPS-BA6 Installation

- Massive installation of a new RF & Cryo plant in BA6 in parallel to the cryomodule into the beam line

Compressor

80m long cryo distribution line

Cryo-service-box

LN2 Phase separator

Cold-box

VB1

SPS-DQW Cryomodule

Articulated vacuum Y-chamber with carbon coating

V-shaped coupling for RF waveguides
What do we Validate?

- Some critics ask, if it was necessary?
- The over-arching reason was, can we “turn-off” crab cavities if they “don’t work”

- But, reality is somewhat different – during 2018, the main struggle was not with beam but getting the cavities, cryogenics and RF controls to function as intended.

- In HL-LHC, we will have factor 8 times the same – hence the humbling experience of SPS is a lifesaver.
Expected SPS Test Sequence

<table>
<thead>
<tr>
<th>What</th>
<th>When</th>
<th>MD slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 RF commissioning (no-beam)</td>
<td>Mar-Apr</td>
<td>~ 4 weeks</td>
</tr>
<tr>
<td>1 RF-beam synchronization</td>
<td>Apr-May</td>
<td>2-4 x 10h</td>
</tr>
<tr>
<td>2 Transparency to beam</td>
<td>Jun-Jul</td>
<td>2-4 x 10h</td>
</tr>
<tr>
<td>3 Performance &amp; Stability</td>
<td>Aug-Sep</td>
<td>4 x 10h</td>
</tr>
<tr>
<td>4 High intensity RF operation</td>
<td>October</td>
<td>2 x 10h</td>
</tr>
</tbody>
</table>

- 4 main phases foreseen – 10 MDs requested
- 6 MDs have occurred. 1 MD tomorrow
- The only subject not yet quantitatively demonstrated is transparency (due to technical issues)
Cryogenic Availability

- Issues with LN$_2$ meant operation at 4.5K before the Summer
- 4.5K not ideal due to large pressure modulation, higher than 1 MV caused vacuum-thermal runaway
# MD Overview

* Operating temperature is 2K

<table>
<thead>
<tr>
<th>MD#</th>
<th>Description</th>
<th>Cav1</th>
<th>Cav2 [MV]</th>
<th>Temp [K]</th>
<th>Energy [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First crabbing, phase and voltage scan</td>
<td>0.5</td>
<td>0</td>
<td>4.5</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>270 GeV ramp with single bunch</td>
<td>1-2</td>
<td>0</td>
<td>4.5</td>
<td>26, 270</td>
</tr>
<tr>
<td>3</td>
<td>Intensity ramp up</td>
<td>1</td>
<td>~0.3</td>
<td>4.5</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>270 GeV coast setup</td>
<td>1.0</td>
<td>0.5</td>
<td>2.0</td>
<td>270</td>
</tr>
<tr>
<td>5</td>
<td>Emittance growth at 270 GeV with induced noise</td>
<td>0</td>
<td>1.0</td>
<td>2.0</td>
<td>270</td>
</tr>
<tr>
<td>6</td>
<td>Intensity ramp up to 4-batches</td>
<td>-</td>
<td>1.0-1.5</td>
<td>2.0</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>Intensity/Energy ramp up</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>26, 270, 400</td>
</tr>
</tbody>
</table>

* MD Overview table with temperature and energy details.*
Protons meet Crabs

First injection – 12:55, May 23
Cavity 1 only

Single bunch
$0.2 - 0.8 \times 10^{11}$ p/b

Crabbing reconstruction
(assuming Gaussian transversely)
How to synchronize Crab-RF?

- Crab cavity is at fixed frequency
  - Freq (400.53 – 400.78 MHz): 26 – 450 GeV
  - SPS RF ~200 MHz is rephased to crab Freq

26 GeV rephasing
Synch after ~1s after injection

270 GeV, Synchronized after ~7.4s
i.e. 0.2s after reaching flat top

Transient
Coarse rephasing
Synchronised
Synchronised

Time [ms]
Reconstruction of Crabbing using HT

# of turns for ref position along the bunch ~ 2k turns

RF re-synchronization ~ 1s after injection
Phase Scans & “Transparency”

- Nominal bunch intensities easily reached at 26 GeV and 270 GeV.
- Cavity phase manipulation goes as expected.
- Intensities up to 72b*2e10 achieved with no issues.
With cavities powered during the ramp and without BA3-BA6 synchronisation, the beam is rapidly lost due to resonant excitation at the betatron frequency.

With cavities off during the ramp the beam makes it through without losses.
Emittance Growth?

- SPS natural emittance growth at 270 GeV, $\leq 0.5 \ \mu m/hr$
- Expected growth with existing electronics (noisy!)
  - Ph. noise up to $8 \ \mu m/hr$, amp noise: $1.4 \ \mu m/hr \ (\sigma_t: 2.0 \ ns)$
  - HL-LHC we need to be below $0.05 \ \mu m/h$

See P. Baudrenghien talk

![Graph showing calculated and measured emittance growth](image)
Beam Loading & Electrical Center

- Beam induced voltage from MD6 (prelim) → See E. Yamakawa’s talk for more details
RF Multipoles, a3 Measurement

- Data analysis ongoing (M. Carla’)… skew sextupole at $2Q_H$ clearly visible that is dependent on the cavity voltage
Higher Order Modes

- Peak HOM power measured from the most dangerous HOM (960 MHz) ~100 mW
- Some deviations from expected HOM power but overall HOM power & scaling to the LHC looks reasonable (see J. Mitchell’s talk)
MD#6&7: High Intensity

- **MD#6** → 36x4 batches, 1/2 the max intensity in SPS, limited by crab bypass pressure rise
  - With moderate voltage, no beam induced failures or fast transients seen except for pressure rise

- **MD#7** → Try to push to 72x4 batches by partially conditioning the bypass in step
  - A quantitative transparency tests at 26 GeV with both cavities at 1-2 MV
  - Ramp the multi-bunches to 270-400 GeV to reach closer to LHC like bunch lengths
New WP4 Planning including collaborations, draft

**CERN+UK (SPS*)**

1-CERN + 4-UK (HL-LHC)

US-AUP + Canada

* SPS-RFD beam tests delayed till 2021
CERN-RFD Fabrication

- CERN specification drawing in final stages of approval, shaping from Cu → Nb (see M. Garlasche)
- Good progress on the US-AUP side for series production in industry
RFD (LHC-type) UK+CERN

Cryogenic update with LHC constraints

Updated vacuum vessel assembly from SPS (see T. Capelli’s talk)

New compact vacuum configuration

2nd beam pipe & transitions

New RF Bridge

New Tuner Frame
STFC Assembly of RFD Cryomodule

See E. Jordan’s Talk

CM Assembly area

Internal ISO 4 Area increased to 6m long

ISO 4 Clean Room
High Power RF

- Two 80 kW IOTs operational in SPS (see E. Montesinos’s talk)
  - Issues of linearity at very low power (< 5 kW) being addressed jointly with LLRF team
- Power couplers, HOMs and related transmissions lines also validated during operation in SPS
- For HL, discussions with Novosibirsk for SSPA prototype by 2020
Final Comments

- **SPS Crab Cavities**
  - Despite many hurdles, a monumental effort was put in to conclude 2018 beam tests a success – it a humbling experience
  - Consolidation works in LS2 is needed to have test stand through Run3. RF-Dipole cavity fabrication started and we are looking forward towards a UK built cryostat

- **HL-LHC Crab Cavities**
  - RI-DQW pre-series started off well… RFD series cavities under US-AUP progressing well
  - Canada/UK series cryostating and Amplifiers from Russia (?) will be true international challenge
Thank You!

https://videos.cern.ch/record/ (2631455, 2631454, 2630818)
Backup
# SPS Cavity Results (6 Cavities)

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

<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>4.4</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>$R_s, \text{min}$ [n$\Omega$]</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>9.5</td>
<td>11</td>
<td>7.6</td>
</tr>
<tr>
<td>$R_s, 3.4\text{MV}$ [n$\Omega$]</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 [MV]</td>
<td>3.3*</td>
<td>Not tested in VTA</td>
<td>Not tested in VTA</td>
<td>4.7</td>
<td>-</td>
<td>4.8</td>
</tr>
</tbody>
</table>

*Cashed cavity tests at CERN in VTA revealed feedthrough leaks during thermal cycling, a fix is being prepared*
Cavity Alignment

- Alignment between the 2 cavities: Radius = 130 μm
- Specification was < 500 μm
RF Feedback & Beam Induced Signal

Need to filter antenna signals better to suppress the direct beam induced signals

In parallel looking at alteration to cavity antenna to minimize effect

Input drive and voltage spikes at $F_{rev}$, due to direct beam coupling
Ramp to 270 GeV

Vertical tune: $Q_y = 0.18$

RF Freq:
- Cavity 1: 400.787 MHz (~1 MV)
- Cavity 2: 400.528 MHz (almost zero)

Resonant excitation observed as we cross the vertical tune (black dotted lines).

Kicking the beam at 270 GeV equivalent frequency, while sweeping the beam frequency from 26-270 GeV

After setting the correct cycle start voltage to 270 GeV equivalent, beam circulated w/o any issue.
Noise spectra measured in Ant CC2

Left: Phase noise PSD. Right: AM PSD. 1 kHz - 1 MHz
Top: -10 dBm excitation, bottom: 0 dBm excitation (10 times more power)
Background trace shows PSD without noise injected. The marker is on the betatron line (8 kHz)
The freq lines are generated by the beam