SPS Tests of Crab Cavities & Lessons Learned

HL-LHC WP4, CERN

14 October 2019, HL-LHC Annual Meeting, FNAL
Dressed Cavity Geometries

Double Quarter Wave

\[ f_0 = 400 \text{ MHz} \]
\[ V_T = 3.4 \text{ MV/cavity} \]
\[ (E_p, B_p < 40 \text{ MV/m, 70 mT}) \]
Beam aperture = 84 mm
Beam-to-beam dist = 194 mm
Common FPC = 40 kW-CW
Operating Temp = 2 K

RF Dipole
Super Proton Synchrotron, SPS

LSS6-BA6 is the highest energy superconducting test facility in the world!

DQW cavities successfully installed & tested in 2018

<table>
<thead>
<tr>
<th>Circumference</th>
<th>7 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection-Extraction energy</td>
<td>26-450 GeV</td>
</tr>
<tr>
<td>Main RF Frequency</td>
<td>200 MHz, TW</td>
</tr>
<tr>
<td>CC Operating Freq Range</td>
<td>400.528 – 400.788 MHz</td>
</tr>
</tbody>
</table>
SPS-LSS6 – Crab Cavity Module
1: We can Crab Protons!

We can crab the proton beams of 3 ns, with predicted crabbing agrees with measured angles within 10%

No noticeable effect on beam in variety of conditions including strong RF curvature
2: Transparency

- We can regulate the intra-cavity phase in a precise and stable manner. In next run, we need to understand timescale of phase drifts.
3: Voltage Ramp-Up

- Long RF conditioning to go beyond 1 MV stable operation. Maximum reached was 2.5 MV
4: Freq Tuning

- Maximum range of > 300 kHz achieved with resolution of few 10’s Hz (cavity BW 800 Hz)
- But observed sudden increase in stiffness and motor gear slippage towards end of 2018 – new mechanism warm part will be replaced in LS2
5: Alignment

- Intra-cavity alignment tolerances < 500 \( \mu m \) in the transverse plane required.
- Achieved successfully during SPS test including validation of FSI system

radius \( \sim 130 \mu m \)
Beam Loading & Electrical Center

- Electrical center from beam induced voltage to validate mechanical alignment
- Test static re-alignment of $\sim 150 \, \mu m$ in LS2 and re-measure with beam in 2021
6: Field Antenna

- Strong coupling of the field antenna (like a BPM) to the beam passage instead of just measuring cavity field variation.
Direct Beam Coupling Mitigation

- Design change for field antenna adopted for HL-LHC to minimize this effect by approx. $\times 10$

Approx $x5-10$ reduction
7: RF Feedthroughs

- Vacuum leaks at 2K experience during SPS solved with re-design for window brazing
- Feedthrough impedance used for SPS 38 Ω! Ideally 50 Ω, decision to go for 25 Ω for robustness & standardized feedthroughs for all couplers
Electro-acoustic Instabilities > 1MV

- Electro-acoustic instabilities above 1 MV (LFD is \(~400\) Hz which is \(1/2\) the cavity BW)
- Self excited loop essential for setup. Now in place but not the case in 2018 MDs

800kV

1.9 MV
9: Microphonics

- Microphonics, non-issue due small detuning & sufficient RF bandwidth
- Choice of bandwidth appropriate

<table>
<thead>
<tr>
<th></th>
<th>Cav 1 [Hz]</th>
<th>Cav 2 [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps ?</td>
<td>20-30</td>
<td>20-30</td>
</tr>
<tr>
<td>TX HV ripple + Tuner mode</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>Mech. mode</td>
<td>74</td>
<td>73</td>
</tr>
<tr>
<td>Harmonics of TX ripple</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Not Identified</td>
<td>171</td>
<td>172</td>
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<tr>
<td>Harmonics of TX ripple ?</td>
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<td>195</td>
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<tr>
<td>Mechanical Mode</td>
<td>210</td>
<td>212</td>
</tr>
<tr>
<td>Not identified</td>
<td>342</td>
<td>342</td>
</tr>
</tbody>
</table>
10: Voltage Program, Ramp

- The easiest way (almost “brute force”) was to run cavities off to circulate beam in the SPS
- Could be new operational scenario for HL-LHC where we turn on cavities at flattop. Easier than counter-phasing with low voltage, although the latter is baseline for HL-LHC

Cav1 ~1MV (400.787 MHZ), Cav2 off (400.528 MHz)
11: Emittance Growth

- Measured emittance growth is lower by $\times2$-4 compared to predicted values
- Not fully understood – appears like a systematic error, but positive outcome for HL-LHC

![Graph showing emittance growth](image)
12: Impedance

- Integrated max HOM power measured < 3 W. More than 75% from ~960 MHz as expected
- Overall HOM power & scaling to the HL-LHC looks reasonable, some deviations related to lack of accurate beam profile
12: Vacuum Dynamics

- High intensity limited by pressure rise in bypass (2 × 60 nominal bunches). No obvious problems with cavities or intensity related failure scenarios ($V = 1\text{MV}$)
- Scrubbing needed post LS2 to fill max current
13: Cryogenics

- Cav1 ~15 W & Cav2 ~8 W (at ~2.1 MV)
- Much higher than vertical tests (5 W). Better estimates needed post-LS2 after improved conditioning.
14: RF Power

- Only notable issue with RF power was linearity at low power (< 5 kW). Added to specification for HL-LHC amplifiers (now SSPA)
- Rest of the RF chain validated
Final Comments

- SPS tests with Crab Cavities
  - SPS-DQW experience was invaluable for beam & hardware validation in an “almost” LHC like environment
  - Several operational aspects will be fine-tuned during 2021-24. Scrubbing needed before MDs
  - The next prototype module (RFD) fabrication on track for installation in 2021-22. Series for HL-LHC is now launched

- The SCRF infrastructure in SPS-LSS6 is unique can could serve for future SRF studies

- Special thanks to our collaborations (UK & US) who played a critical part in the SPS success
Thank You!

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