US cold RF test program of DQW prototype cavities

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BNL  Ilan Ben-Zvi, Silvia Verdú-Andrés, Qiong Wu, Binping Xiao
CERN  Rama Calaga
CI / Lancaster  Graeme Burt
SLAC  Zenghai Li, Alex Ratti
In 2013, cold RF tests of a PoP DQW cavity demonstrated the possibility of delivering required crab kick (3.4 MV) reaching 4.7 MV while meeting spatial constraints from LHC.

Design reviewed to meet spatial, RF requirements (HOM damping, heat load, etc.) for testing in SPS and operation in LHC: DQW SPS-series.

- Features 11% lower peak H-field.
- Highest H-field located in cavity, not in filter.

<table>
<thead>
<tr>
<th>H-field distribution for fundamental mode (400 MHz) of DQW SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQW SPS cavity and its HOM filter</td>
</tr>
<tr>
<td>$H_p^{Max} = 81 \text{ mT at } 3.4 \text{ MV}$</td>
</tr>
<tr>
<td>$H_p^{Max} = 63 \text{ mT at } 3.4 \text{ MV}$</td>
</tr>
</tbody>
</table>
Refresher

- **Four** (4) identical **DQW SPS-series** cavities **fabricated:**
  - Two prototypes built in the US (Niowave Inc. and JLab).
  - Two cavities built at CERN, fully dressed into cryomodule, being tested in SPS.

- The DQW **prototypes** proved useful learning tools to:
  1) assist **fabrication, tuning** and
  2) in **FY2018**, investigate **limited 2K RF performances** of **DQW+filters**
     - CERN DQW SPS-series cavities with three (3) HOM filters quench at 3.4 MV
FY2017: cold RF performance of bare DQWs

- **Exceeded** nominal deflecting voltage (3.4 MV) with 40% margin; heat load < 5 W as required
- **Excellent** performance of bare cavities beyond nominal (up to 5.9 MV).
  - Large peak fields reached (~30 MV/m TESLA-type cavity)
  - FE onset at \( V_t = 4.1 \text{ MV} \) (above nominal deflecting voltage)
  - Pretty low surface resistance (9 nOhm)

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**Graphical Information:**
- **Intrinsic quality factor \( Q_0 \):**
  - **Deflecting voltage \( V_\text{d} \) (MV):**
  - **Peak surface electric field \( E_{\text{pk}} \) (MV/m):**
  - **Peak surface magnetic field \( B_{\text{pk}} \) (mT):**

- **Admin power limit:** (5.3 ± 0.4) MV
- **Radiation dose rate (mrem/h):** (5.9 ± 0.4) MV

**Legend:**
- US-DQW-001 Feb 2017
- US-DQW-002 June 2017
- US-DQW-002 Sept 2017

**Note:**
- After BCP+HPR
FY2017: cold RF perf. of bare DQW + HOM filter

- The **same HOM filter** tested with cavity #1 and cavity #2.
- **Light BCP** in HOM filter **between tests**: increased quench field from 2.8 to 3.6 MV.
- Quench for the two cavity+HOM tests at significantly **lower voltage than for bare cavity** tests.
- Sharp quench, but **no significant radiation** increase, **nor multipacting** (closest band at 2-3MV).
FY2018: high performance program

FOCUS
- Inspect ultimate RF performance of bare DQW cavity + HOM filters
  
  Goal: 3.4 MV (NOMINAL) + 20% margin = 4.1 MV

HYPOTHESIS
- HOM filter limiting RF performance due to insufficient surface treatment.
  
  [For previous tests HOM filter received 20 um BCP + manual pressure rinsing; compare to standard 150 um BCP + 600C bake + 20 um BCP + HPR + 120C bake for SRF cavities.]

TESTS
1) Effect of surface treatment on cavity + HOM filter performance
2) Retract HOM filter to discriminate if quench is coming from cavity or from filter
FY2018: high performance program

EFFECT OF SURFACE TREATMENT

- Cavity + HOM filter reached 4.7 MV (largest Vt to date in any DQW+HOM).
- No evidence of High-Field Q-Slope (HFQS).
- Lesson learned: HOM filters should receive same surface treatment as any other SRF cavity.

Oct'17 run II and Jan'18 not shown: see backup
FY2018: high performance program

EFFECT OF HOM FILTER

- **Retracted filter** using 20 mm spacer reduces Bp in hook by 50%, allows reaching Vt ~ 5.1 MV.
  Assume May18 test was limited by Bp(filter) ~ 120 mT. With spacer, the field in hook is only 60 mT, so the field in the cavity will be now the limiting factor. That is, we will expect voltages around 5.3 MV.

- **Q-switch** due to NbTi spacer becoming normal conductor: Q-switch ~ 1.7e10 ⇔ σ = 1.3e6 S/m.

Jul'18 and Sep'18 run II not shown: see backup
FY2018: high performance program

Why would the HOM filter limit the cavity performance?

- The cooling channel of the HOM filter is sized to extract 1 W heat max.
- For $V_t > 4.5 \text{ MV}$, power dissipated in the hook is larger than 1 W and filter becomes thermally unstable, what probably causes the quench at 4.8 MV.
- Retracting the HOM filter would reduce the dissipated heat in the hook.

From CST simulations using $R_{res} = 5 \text{ nOhm}$, $K = f(T)$ [G. Burt]
Quench location for bare DQW + HOM filter

THERMOMETRY (CERNOX)
- Temperature increase on filter registered for several tests (May’17, Oct’17, Sep’18).

SECOND SOUND DETECTION (OSTs) (only used in May’18 test)
- Non-conclusive: The 0.14-m-radius sphere envelope lies on high H-field region, far from filter. No signal from the other OST looking at same point but far from region.

OST signals and transmitted RF power before, during and after quench.
Multipacting bands

- The **multipacting predictions** by ACE3P and CST **matched well** the multipacting bands **found during the tests**.

- A **recurrent multipacting band**, below 0.5 MV, related to multipacting in the cavity waist as predicted by ACE3P and CST, is **found in every single test**.

- **Other** multipacting bands **processed** and never came back in following tests.

<table>
<thead>
<tr>
<th>Predicted [Z. Li, G. Burt]</th>
<th>Found during tests with or w/o filter</th>
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<tbody>
<tr>
<td>MP band [MV]</td>
<td>Region</td>
</tr>
<tr>
<td>(0.26)</td>
<td>Cavity waist</td>
</tr>
<tr>
<td>(0.1 – 0.5)</td>
<td>Cavity waist</td>
</tr>
<tr>
<td>(2.12)</td>
<td>HOM stub</td>
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<tr>
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</table>

See backup slides for complete table
Future of the DQW SPS-series prototypes

NEXT TESTS FOR PERFORMANCE VALIDATION TOWARDS LHC-SERIES

Test I: Cryogenic RF test with another HOM filter (in preparation for Test II)
Test II: Cryogenic RF test with 2 HOM filters (LHC configuration)
Test III: Cryogenic RF test with new HOM filter (available by Spring 2019)

- Use for: field mapping, multipoles, development of RF feedback control system of tuner, multipacting conditioning studies, etc.

EXPLORATION OF ULTIMATE RF PERFORMANCES (under consideration)

- Electropolishing on cavity (KEK conducted first trials on DQW PoP-series)
  
  Challenges: cathode shaping for uniform removal; bubble trapping in corners.

- N-infusion
  
  Limited impact expected: no $R_{BCS}$ inversion observed in low-frequency cavities; $R_{res}$ is main contributor to DQW surface resistance.

- Flux trapping studies
  
  Limited impact expected: $R_{res}^{(H-field)}$ is already small for low-frequency cavities.
SUMMARY

MATURE DESIGN OF DQW+HOM MEETS REQUIREMENTS

- DQW + HOMs delivers 4.7 MV before quench (38% margin). [5.9 MV w/o filter.]
- Cryogenic load <5 W (at 3.4 MV) with pretty low Rs (10 nOhm at low field).
  - ✓ Sound and adequate EM design of cavity + HOMs.
  - ✓ Demonstrated successful manufacture by industry
  - ✓ Proved sufficiency of standard SRF surface treatments
    (But note: HOMs should receive same treatment as any other SRF cavity.)

SOME MARGIN FOR IMPROVEMENT

- Large peak fields reached – at quench field (4.7 MV), max. Bp of 106 mT (cavity).
- But still not as high as values reached by other BCPed Nb cavities (see backup).

LIMITATIONS

- Quench, likely a thermal quench in HOM filter, limits CW operation.
- Recurrent multipacting band below 0.5 MV.

FUTURE

- Activities for performance improvement and understanding under discussion.
- Translate experience to LHC-series DQW, RFD and eRHIC DQW cavities.
- Promising new HOM filter coming (see J. Mitchell’s talk).
Thanks for your attention

Acknowledgements
Thanks to the JLab SRF testing team.

Funding agencies
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REFERENCES


Back-up
## SUMMARY: DQW SPS-series prototype tests

DQW SPS-series prototypes built by Niowave Inc. and JLab. HOM filter on loan from CERN. All tests performed in JLab.

<table>
<thead>
<tr>
<th>Test</th>
<th>Assembly</th>
<th>Surface preparation</th>
<th>Max Vt (MV)</th>
<th>FE (MV)</th>
<th>Q0, low</th>
<th>Q0,nom [P (W)]</th>
<th>CX</th>
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<td>Bulk BCP, 600C, light BCP, HPR, 120C</td>
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<td>4.1</td>
<td>1e10</td>
<td>6e9</td>
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<td></td>
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<td>HOM filter</td>
<td></td>
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<td></td>
<td>#B-2 #F-4</td>
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<td>DQW01+HOM01 Flange set #b</td>
<td>None</td>
<td>Flash BCP (on hook); rinse</td>
<td>2.8</td>
<td>n/a</td>
<td>1e10</td>
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<td>#B-5 #D-7 #E-8</td>
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<td>DQW02</td>
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<td>Flash BCP (on hook); rinse</td>
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<td>Rinse, 120C</td>
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<td>Jul’18 (testing anomaly)</td>
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<tr>
<td>Sep’18</td>
<td>DQW02+HOM01 20mm NbTi spacer Flange set #a</td>
<td>HPR, 120C</td>
<td>None</td>
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<td>2.7</td>
<td>9e9</td>
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<td>#E-8</td>
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SUMMARY: DQW SPS-series prototype tests

Thermosensor labels:
### Coupling evolution for test probes

<table>
<thead>
<tr>
<th>Assembly</th>
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<th>$Q_{\text{ext,IC}}$</th>
<th>$Q_{\text{ext,PC}}$</th>
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<tr>
<td>DESIGN</td>
<td>CST</td>
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<td>8e11</td>
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<td>NWV-DQW-001</td>
<td>Warm</td>
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<td>Cold Feb’17</td>
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<td>NWV-DQW-002</td>
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<td>1.93e9</td>
<td>1.21e12</td>
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<td>Cold May’18</td>
<td>2.12e9</td>
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<td>Cold Jul’18</td>
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<td>1.04e11 (anomaly)</td>
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<td>2.08e9</td>
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<td>Multipacting predicted</td>
<td>Found during tests w/o filter</td>
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<td>--------------------------------</td>
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<tr>
<td>MP band [MV]</td>
<td>Region</td>
<td>Code</td>
<td>MP voltage [MV]</td>
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<tr>
<td>(0.26)</td>
<td>Cavity waist</td>
<td>CST</td>
<td>0.17, 0.2</td>
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<td>(0.1 – 0.5)</td>
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<td>Cavity-small port</td>
<td>ACE3P</td>
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</table>

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Found during tests with or w/o filter</th>
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<tbody>
<tr>
<td>MP band [MV]</td>
<td>Region</td>
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<tr>
<td>(0.26)</td>
<td>Cavity waist</td>
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<td>(0.1 – 0.5)</td>
<td>Cavity waist</td>
</tr>
<tr>
<td>(2.12)</td>
<td>HOM stub</td>
</tr>
<tr>
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</tr>
</tbody>
</table>
Test summary: Lorentz force detuning

- Cold test frame does not fully reproduce boundary conditions of DQWs in cryomodule. Expected LFD for DQW in cryomodule is -40 Hz/(MV2)???. Measured LFD during cold tests is about 500 Hz/(MV2)??

- Removed rods fixing capacitive plates to stiffening frame for test on Jan’18.
  See further reduction of frequency, as expected, if capacitive plates are not longer fixed.
Comparison to other cavities

- Magnetic field level comparable to the highest values reached by other SRF cavities following a BCP-based surface treatment (see next slide).
### Survey – highest peak fields reached by SRF cavities

<table>
<thead>
<tr>
<th>Cavity type</th>
<th>Cavity name</th>
<th>No. cells</th>
<th>beta</th>
<th>Freq</th>
<th>Temp</th>
<th>Eacc</th>
<th>Ep/Eacc</th>
<th>Hp/Eacc</th>
<th>Ep</th>
<th>Hp</th>
<th>Note</th>
<th>Project</th>
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<tr>
<td>Spoke</td>
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<td>CAVS injector</td>
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<td>90</td>
<td>191.70</td>
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<td>ANL ATLAS intensity upgrade</td>
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<td>1</td>
<td>400</td>
<td>2.0</td>
<td>5.9</td>
<td>11.0588</td>
<td>21.4</td>
<td>65.2469</td>
<td>126.26</td>
<td>HL-LHC</td>
<td></td>
</tr>
</tbody>
</table>

- Shows peak surface electric field and peak surface magnetic field at the maximum accelerating (deflecting for the crab cavities) gradient reached by different SRF cavities.
- Only cavities with best performance found in literature (best here means highest peak fields, not highest Q0).
- Cavities following **EP-based** surface treatment are highlighted in blue. The other cavities followed a BCP-based treatment.
NWV-DQW02+CERN-HOM01 + 20mm NbTi spacer

**Temperature monitoring during test of Sep’18 at JLab**

- CERNOX thermosensors in 8 different locations.
- CX#3 signal not available during Vt sweep.
- CX#8 follows Vt until it gets lost; however, CX#7 did not registered any $\Delta T$.
- Other CERNOX do not show any significant temperature increase associated with Vt.