Evaluation of RF pickup antennas for crab cavity (DQW and RFD) LHC-series

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Some background

- **Each crab cavity** equipped with **one RF pickup** (field probe) to monitor fundamental mode field in the cavity. The signal:
  - provides **indirect measure of deflecting kick** \( V_t \) delivered by cavity:
    \[
    V_t = \sqrt{P_t \times Q_t \times R_t/Q}
    \]
  - used as primary **input for field** (amplitude and phase) **control** in the cavities via RF feedback

- For LHC crab cavities, pickup should **extract about 1 W fundamental mode power** \( P_t \) when cavity delivers **3.4 MV deflecting kick** \( Q_t = 2.8e10; R_t/Q \approx 430 \text{ Ohm} \) for both DQW and RFD cavities.

- This pickup **already** implemented in DQW and RFD **SPS-series** cavities.
Some background: **DQW SPS-series pickup**

- The pickup of DQW SPS-series cavities is **dual-purpose**; combines:
  - a **hook** to extract **fundamental mode** power for **monitoring** purposes
  - a ‘**mushroom**’ for **coupling and damping** of the **1754 MHz** mode

  ![Diagram of E-field for 400 MHz and 1754 MHz](image)

- The **pickup tip** exposed to large currents, made of **Nb** to **reduce heat load**; **the rest** fabricated in **Cu**, for better **heat extraction**.

  ![Diagram of niobium and copper](image)
The pickup revisited: Motivation

- SPS beam tests of DQWs evidence direct coupling of beam to pickup, with consequent impact on the RF feedback (see P. Baudreghien’s talk).

*Cavity 1 antenna signal, MD#02 (30 May 2018), 1 MHz span; about 41.538 kHz (SPS rev. freq. = 43.450 kHz) from beam-induced voltage.*
**The pickup revisited: Motivation**

- SPS beam tests of DQWs evidence **direct coupling** of beam to pickup, with consequent **impact on the RF feedback**.

- CST simulations reveal ‘**mushroom**’ to be **responsible** for **direct coupling**.

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Voltage signal at pickup output from direct coupling of pickup to beam (single bunch, sigma = 30 mm, charge = 1 nC) [R. Calaga]

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84 mm
The pickup revisited: Proposal, design goals

- Equip the DQW LHC-series cavity with **two horizontal tubes**, each connected to one of the beam pipes and **revisit pickup** design [R. Calaga]:

  1) Adopting **simple hook** to extract **1 W fundamental mode** at $V_t = 3.4$ MV
     - **Requirements**: reduced beam coupling, adequate $Q_e$ (2.8e10), high $Q_0$ (reduced dissipation, copper preferred), consider machining.

  2) Opening **another** port for damping of **1.754 GHz** mode (also **backup pickup**)
     - see J. Mitchell’s talk

- **Second port integration validated** (LHCACFHT0258) [P. Marcillac, R. Leuxe]

![Diagram of DQW LHC-series cavity equipped with two horizontal tubes integrated into its helium vessel.](image)
The pickup revisited: DQW LHC-series pickup

- DQW SPS-series pickup w/o ’mushroom’ provides insufficient coupling ($Q_e = 5.5 \times 10^{10}$). Models below provide adequate field coupling ($Q_e \approx 2.8 \times 10^{10}$).

<table>
<thead>
<tr>
<th>Penetration (mm)</th>
<th>Clearance (mm)</th>
<th>Heat loss (mW, Cu)</th>
<th>Max. beam coupling (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQW SPS-series</td>
<td>0</td>
<td>6.8</td>
<td>&lt;1 (Cu part)</td>
</tr>
<tr>
<td>C</td>
<td>-25</td>
<td>6.5</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>-19.5</td>
<td>10.8</td>
<td>22</td>
</tr>
</tbody>
</table>

Assumed $R_s$ (Cu, 2K) = 1 mOhm for heat loss calculation (anomalous skin effect + 30% extra to account for surface roughness …)

About 4 W/m² dissipated power density localized in hook section.
The pickup revisited: **DQW LHC-series pickup**

**CST SIMULATION SETTINGS**
Non-iterative (thermal properties of materials not updated with temperature)

*Pickup model: D*

\[ V_t = 3.4 \text{ MV} \]

\[ T_0 = 2.1 \text{ K} \]

\[ \sigma(Cu) = 5.8e7 \text{ S/m} \]

\[ K(Cu) = \text{ W/K/m} \]

**PRELIMINARY RESULTS**
Most penetrating, thinnest wall hook leads to $\Delta T \sim 0.14 \text{ K}$, in principle, acceptable.

**CONCLUSION**
- Found a possible pickup with reduced beam coupling, heat loss, adequate field coupling. Can be made in copper. Good clearance to ease insertion.
- Repeat RF and thermal simulations incl. RF feedthrough, T-dependent material properties; compare with other software.
The pickup revisited: **What about the RFD?**

**From the PDR (2018) ➔ see also Z. Li’s talk**

The **field pickup** is placed on the VHOM side of the cavity using straight probe coupling […]. The designed power extraction by the field pickup is **1.5 W** at the **3.34 MV** deflection voltage, which corresponds to a **$Q_{ext}$ value of $1.7 \times 10^{10}$**. […] has a **negligible effect on the field symmetry**.

![Voltage signal from RFD pickup coupling to beam is not negligible](image-url)
The pickup revisited: **RFD LHC-series pickup**

All below provide 1 W fundamental mode power at 3.4 MV deflecting kick.

<table>
<thead>
<tr>
<th>Penetration (mm)</th>
<th>-7.6</th>
<th>-9.8</th>
<th>-20.5</th>
<th>-15.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat loss (mW, Cu)</td>
<td>13</td>
<td>22</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Max. beam coupling (V)</td>
<td>2.2 (30% DQW)</td>
<td>1.5 (20% DQW)</td>
<td>0.6 (8% DQW)</td>
<td>0.6 (8% DQW)</td>
</tr>
</tbody>
</table>

**Conclusion:** a hook into vertical tube provides adequate field coupling, reduced beam coupling and reduced heat dissipation to be made in copper.
Summary and outlook

- Each crab cavity equipped with one pickup to monitor field in the cavity.

- SPS beam tests of DQW cryomodule evidence direct coupling of beam to pickup. Simulations also predict beam coupling to SPS-series RFD pickup.

- Investigated alternative pickup locations and designs; found possible solutions for DQW and RFD LHC-series that show small coupling to beam.

- The proposed DQW LHC-series pickup provides adequate Qe (2.8e10), reduced beam coupling and reduced heat dissipation to be made in Cu.

- Pickup tube orientation and antenna type of RFD cavity may need to change (vertical tube, hook coupler) to limit coupling to beam (to be discussed).

- Possibility to use the same pickup design for both DQW and RFD cavities (check length difference). Further studies needed (RF, thermal, including RF feedthrough).
Thanks for your attention

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Back-up
The pickup revisited: DQW LHC-series pickup

Observations:
- P0 varies greatly with antenna length (penetration).
- Qe mainly given by antenna length and hook width.
- Could further reduce P0 at expenses of clearance (\(wi = 20\) leaves 6.5 mm distance between hook and tube wall; \(wi = 16\) leaves 8.5).

Selection criteria – select...
1) parameter sets providing required Qe.
2) length to meet P0 budget (<10 mW).
3) hook width and thickness as per required Qe; thicker preferred for robustness and cooling.

The wider and the thicker, the shorter to reach required Qe.
For 3 mm minor diameter section, pu2l0 ~ 89 mm provides 1 W fundamental mode power and 20 mW dissipated in hook. About 4 W/m2 dissipated power density localized in hook section (actually power density calculated using power dissipated in the whole pickup, but using only surface area in the hook section).

- Increased **minor diameter of ellipse** from 3 mm to **4.4 mm** to ease manufacturing. Tried to keep **hook within envelope** of stem section (see blue-dashed line below).

- Evaluated Qe for different values of minor radius ellipse (pu2r2 = 1.5%2.2 mm) and stem length (pu2l0 = 85%115 mm). Observations: coupling barely changes with pu2r2 but does change dramatically with pu2l0. As required Qe is 2.75e10 to extract 1 W fundamental mode power, then it is convenient to choose the hook model with **thicker section (pu2r2 = 2.2 mm)** for expected improved heat extraction (however, it will lead to **higher dissipated power of 21 mW** with pu2l0 = 87.2 mm and qe = 2.86e10).
The pickup revisited: **DQW LHC-series pickup**

**DQW SPS-series**

**C**

**D**

![Graph showing signal voltage over time for different series](image)

- Red: DQW SPS-series
- Blue: DQW SPS-series (w/o T)
- Black: DQW LHC-series (C)
- Purple: DQW LHC-series (D)

**Signal voltage (V)**

**Time (ns)**

0 1 2 3 4 5

-10 -5 0 5 10
The pickup revisited: *RFD LHC-series pickup*

- RFD SPS pickup, more retracted
- RFD SPS pickup, tube close to cavity, further retracted
- Hook, vertical tube
- Contained hook, vertical tube

![Diagram of pickup configurations]

![Graph showing signal voltage over time for different pickup configurations]
Preliminary results: the widest hook provides the lowest temperature increase because it needs to penetrate less into the high field region.

To be done: repeat simulation including RF feedthrough, temperature-dependent material properties and possibly compare with other software’s results.