Crab Cavities: past, present and future

Silvia Verdú-Andrés – Toohig Fellow at Brookhaven National Laboratory
Sergey Belomestnykh, Ilan Ben-Zvi, Qiong Wu and Binping Xiao (BNL) and Rama Calaga (CERN)

The Linear Collider Problem
If head-on collisions, debris can interact with the machine

✓ Crossing angle
but decreased peak luminosity

✓ Crab crossing [R. Palmer (BNL), 1988]
reestablish head-on collision for maximal $\mathcal{L}_{\text{peak}}$

→ Deflecting kick provided by crab cavities

$\theta_c/2$
First implementation: the KEK-B complex

KEKB B-factory
- Horizontal cross angle of 22mrad

CRABS: head-on + beam-beam tune shift $\xi_y = 0.05 \rightarrow > 0.1$
- 2.8 MV defl voltage
- Global scheme: less cavities but bunch wiggles around whole ring

One crab cavity per ring (global scheme configuration)
First implementation: performances

- SRF “Squashed cell cavity” at 2.8K with crabbing mode at 500 MHz (2.8 MV defl voltage)
- ~ 3 years operation under high current
- $L_{peak} = 2.1 \times 10^{33}$ /cm$^2$/s (with crabs)

KEKB operation terminated in June 2010 for the upgrade towards SuperKEKB

---

Oide, ICFA08
Potential benefits from crab cavities:

- Luminosity increase
- Luminosity levelling
- Alleviate pile-up

4 cavities/IP/side/beam Between D2 and Q4
Crab cavities for HL-LHC: schedule

LHC crab cavity program phases:
- 2003 → 2008  Conceptual design, feasibility study and system development
- 2009 → 2014  Proof of Principle Cavities
- 2014 → 2018  Cavities and Cryomodules for a validation test in the SPS
- 2017 → 2023  HL-LHC system
# Crab cavities for HL-LHC: design criteria

<table>
<thead>
<tr>
<th>Parameters per cavity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency</td>
<td>400.790 MHz</td>
</tr>
<tr>
<td>Nominal kick voltage (CW)</td>
<td>3.3 MV</td>
</tr>
<tr>
<td>Residual resistance $R_s$</td>
<td>$\leq 10 \text{ n} \Omega$</td>
</tr>
<tr>
<td>$R_T \cdot R_s$</td>
<td>$3.7 \times 10^4$</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>$300 \Omega \ldots 900 \Omega$</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$\geq 1 \times 10^{10}$</td>
</tr>
<tr>
<td>$Q_{ext}$</td>
<td>$5 \times 10^5$</td>
</tr>
</tbody>
</table>

## Constrains

1. Adjacent beam pipe $\rightarrow$ **max cavity radial size** (warm): 145 mm
2. **10 meters available** at each crabbing site to fit in 8 cavities (4 per beam) with helium vessels and cryostats
CCs for LHC – three compact candidates

2003 → 2008 Conceptual design, feasibility study and system development

Three cavities remaining after down-selection from large exotic zoo of cavities (BNL, CERN, CI-JLAB, FNAL, KEK, ODU/JLAB, SLAC)
### Proof of Principle Cavities

Successful RF tests at 2K!

<table>
<thead>
<tr>
<th>Designed by</th>
<th>Tested at</th>
<th>$Q_0$</th>
<th>$V_{defl}^{max}$ [MV]</th>
<th>$E_{max}$ [MV/m]</th>
<th>$B_{max}$ [mT]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RF-dipole</strong></td>
<td>ODU-SLAC</td>
<td>JeffLab</td>
<td>4x$10^9$</td>
<td>7.0</td>
<td>75</td>
</tr>
<tr>
<td><strong>DQWCC</strong></td>
<td>BNL</td>
<td>BNL</td>
<td>2x$10^9$</td>
<td>4.6</td>
<td>53</td>
</tr>
<tr>
<td><strong>4-rod</strong></td>
<td>Lancaster U.</td>
<td>CERN</td>
<td>$10^9$</td>
<td>3.3</td>
<td>32</td>
</tr>
</tbody>
</table>

**Goal:**

- $\geq 3.3$ MV

As reference, 1.3 GHz single-cell cavity (ILC high-grad studies): $B_{max} \sim 200$ mT and $Q_0 \sim 4x10^9$
Compact crab cavities for HL-LHC

KEK 509 MHz crab cavity (2.8 MV def voltage at 2.8 K):

DQWCC 400 MHz crab cavity (3.4 MV def voltage at 2 K):
Testing the DQWCC with beam in SPS

2014 → 2018 Cavities and Cryomodules for a validation test in the SPS
- Crabs never tested on hadron beams → SPS test
- SPS DQWCC: collaboration BNL-CERN-UK
- Status: cavity ready for production

Cryo jumper

FPC

Ribs for additional vessel stiffening

Adjacent beam pipe through the vessel

Helium vessel and tuning system for SPS DQWCC

Cryomodule with 2 cavities for beam test in SPS
**CLIC**
- single collision point with a 20 mrad cross angle

**CRABS** increase $\mathcal{L}$ to 95% of head-on case
- $V_{\text{defl}} = 2.55\text{MV}$ at 11.9942 GHz

Currently installed at XBox2 (CERN) for high gradient testing↓

12 cell high gradient TW structure in copper
Crabs for eRHIC

eRHIC
- 250 GeV polarized protons and 16/21 GeV electron
- $\mathcal{L} \sim 1-2 \times 10^{33}$ upgrade to $10^{34}/\text{cm}^2\text{s}$

10 mrad cross angle H-plane $\rightarrow$ CRABS
- Local scheme
- Higher harmonic cavities correct non-linearity kick.

Based on DQWCC design (SRF technology):

<table>
<thead>
<tr>
<th>Crab cavities for:</th>
<th>250 GeV proton</th>
<th>21.2 GeV e-</th>
</tr>
</thead>
<tbody>
<tr>
<td>freq [MHz]</td>
<td>225</td>
<td>450</td>
</tr>
<tr>
<td>$N_{\text{cavities}}$</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$V_{\text{defl}}$ [MV]</td>
<td>6.19</td>
<td>2.79</td>
</tr>
</tbody>
</table>

B. Parker, V. Litvinenko
### PAST

- Robert Palmer proposes the crab crossing technique (1988)
- KEKB demonstrated the crabbing principle for lepton beams (2009)
- Exotic zoo of crabs developed for LHC → 3 compact candidates (2008)
- Successful cold tests of PoP crabs for LHC (2013)

### PRESENT

- Or immediate future... test of LHC crab cavities with SPS beam (2017)
- Crab cavities under consideration for eRHIC (...)

### FUTURE

- LHC performances could greatly benefit from crabs and associated beam gymnastics
- Future linear colliders envisaged crab crossing... maybe also for the FCC?
Thanks for your attention

Special thanks to
Alexei Fedotov, Vladimir Litvinenko, Robert Palmer, Dejan Trobojevic (BNL) Graeme Burt (Lancaster U.)

Long life to the crabs
LARP and the Toohig fellowship

LARP Toohig fellowship in accelerator science for recent PhDs in physics or engineering.

Four US laboratories, BNL, FNAL, LBNL, and SLAC, who collaborate with CERN for the High Luminosity LHC project.

Currently three main topics:

• Magnets
• Crab cavities
• Feedback system

Visit http://www.interactions.org/toohig/toohig.html or write to John Fox.
Outline

PAST
• First ideas: motivation and crab concept
• First implementation: KEK-B

PRESENT
• HL-LHC

FUTURE
• eRHIC
• Future linear colliders: CLIC, ILC
• ...Future Circular Collider FCC
Compact crab cavities for HL-LHC

**KEKB 500 MHz crab cavity adapted for LHC**

- KEKB 500 MHz crab cavity adapted for LHC
- Cavity wall 4 mm
- He vessel wall 3 mm
- Adjacent beam pipe wall 3 mm
- 194 mm

**SPS 400 MHz crab cavity**

- 194 mm
- 140 mm
References

Geng et al., High Gradient Studies for ILC with Single Cell Re-entrant Shape and Elliptical Shape Cavities made of Fine-grain and Large-grain Niobium, PAC07.