LHC Crab Cavities, LARP Review
R. Calaga, July 13, 2009
Ack: LHC-CC Collaboration

- Framework & Status
- Feasibility test & Challenges
- Milestones & Schedule
- Crab Project
Framework

LARP & CARE

LUMI-05 (Arcidosso), LARP (FNAL)
First Crab Cavity Ideas for LHC
KEK-B Not Started Yet

LUMI-06 (Valencia)
LHC Crab Crossing Proposed
KEK-B Not Started Yet

PAC07, CM8, ..., LHC-CC08
Small Angle Crab Scheme
KEK-B CCs Successfully Commissioned

FY08 – LHC-CC08
Global Collaboration
US-LARP/EUCARD-CT-DE/KEK CERN

FY09 – FY13
Cryomodule R&D, Simulations, Fabrication
Testing, Installation, Beam Testing

KEK-B CCs observes
less gain than expected
More MDs planned
CERN/LARP Participation

Future
LHeC, Super KEK-B, LC, ...
Using Crab Cavities, KEKB Breaks Luminosity World Record

A team of accelerator physicists at the KEK High Energy Physics Laboratory in Tsukuba, Japan, has broken the world's luminosity record by utilizing new accelerator devices called "crab cavities." The team at the KEKB electron-positron collider, home to the world's highest luminosity particle accelerator, installed the first pair of these futuristic superconducting radio-frequency cavities over two years ago.
Why crab the LHC

Proposed by Palmer, 1988

Finite crossing angle due to parasitic interactions
Luminosity reduction → Recover from crab crossing
Luminosity Leveling

Crab Cavity

Crab Cavity

Crab Cavity

Crab Cavity

KEK-B

+20 yr

LHC
Two Phase approach

+5 yr?
Real Motivation, Phase II

Upgrade scenarios aim at x10 Lumi increase ($\beta^* \downarrow$, Current $\uparrow$)

- D0 in detector (Experiments prefer not, may requires crab cavities)
- LPA scheme (requires x5 increase in intensity, problem in injector chain)
- Crab crossing (experiments favor, lumi-leveling, technological challenge)
- Low emittance (machine protection & stability issues ?)
- Large emittance (under study)

For crab crossing: The proposal is to do two-phase approach
Crab Crossing, Phase I

Prototype Tests (5-7 TeV):
- Feasibility
- Luminosity gain (15-21%)
- Luminosity leveling

\[ \beta^* \leq 30 \text{ cm} \]
- Bunch length: 7.55 cm
- IR4 beam-line Separation: 42 cm

Crab RF frequency: 800 MHz
- 1 cavity/beam: 2.5 MV kick
Crab Crossing, Phase II

Full Crossing Scheme
Luminosity gain: 43-62%
Leveling on

\[ \beta^* \leq 25 \text{ cm} \]
Crab Freq: 800 (or 400) MHz
Kick Voltage: \( \sim 5 \) MV
\# cavities/IP: 4-8
What has been done

https://twiki.cern.ch/twiki/bin/view/Main/LHCCrabCavities

• Layout
  • Several layout schemes were explored & final solution in place
  • Crab optics for Phase I & II are available and evolve with LHC needs

• Beam simulations
  • Detailed collimations simulations done, no show stopper (Y. Sun, PRST-AB)
  • Detailed beam-beam & noise simulations and experiments (KEK-B) done. Specifications are set and more detailed studies underway
  • Impedance budget laid out (PAC09)

• Cryomodule
  • Cavity-coupler designs almost at final stages, well under impedance budget, multipacting, thermal and mechanical studies ongoing
  • Cryostat design advancing & will be ready for 2011 construction phase

• Operational Scenarios
  • Procedures for crab cavity and safe beam commissioning is well advanced, different scenarios for lumi gain and leveling for prototype tests are proposed, failure scenarios are laid out with possible remedies

• LHC Integration
  • Layout, cryogenics, RF power, transmission lines, instrumentation, water cooling, controls & additional items are advancing for both phase I & II
Cavity & Cryomodule

- 2 cell SRF cavity @800 MHz
- 3 aggressive damping schemes
- Down selection

Multipacting, thermal, mechanical etc...

Cryostat development underway (FNAL), interfaces, RF-cryogenic-mechanical constraints
5-6 yr Proposal

- LARP deliverable: Cryomodule TDR FY10-11
- Assist in fabrication & testing
  - “Crab Project”: Project Engineer?
LHC-CC09: “Prelim Review”

Dates: September 16-18, 2009
Venue: CERN

Format:

  Advisory board – 12 Members (7 Institutes)
  Scientific program committee – 17 Members (10 Institutes)

9 Sessions (2.5 days)

  Introduction, layout & design, cavity design, cryomodule design, cavity integration,
  Cryomodule construction, phase I validation, phase II validation, planning & milestones

1 Long discussion session + 1 Closed AB session (day 3)

Advisory board Summary & Recommendations

AB: I. Ben-Zvi, S. Chattopadhyay, G. Hoffstaetter, E. Jensen, S. Myers (Chair), M. Nessi, T. Raubenheimer, E. Tsesmelis, J. Virdee, A. Yamamoto

Program: [http://indico.cern.ch/conferenceDisplay.py?confId=55309](http://indico.cern.ch/conferenceDisplay.py?confId=55309)
SBIR & Warm Models, FY10-11

• Cavity SBIR of the proposed four was accepted for phase I

• Based on LHC-CC09 outcome:
  • AES will move towards detailed engineering design and development
  • Detailed cost estimate

• 2-cell cavity model (more than one design ?)

• Coupler Model(s) & Mock-up Cryostat ?

• Engineering design and fabrication
  • Sort all possible difficulties (by LHC-CC11)
  • Benchmark RF simulations
Construction Proposal

To DOE: Separate crab cavity project for the construction of 2-cryomodules (suggested during a meeting with Kovar @CERN)

- LARP studies and cavity SBIR will ideally place the start around FY11
- Identify host U.S. Lab & project engineer (follow LHC triplet construction example)
- Additional help from KEK & Europe maybe available (cavity treatment, testing...)

<table>
<thead>
<tr>
<th></th>
<th>Module I</th>
<th>Module II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>$4.0 M</td>
<td>$2.0 M</td>
</tr>
<tr>
<td><strong>Contingency</strong></td>
<td>40%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td>38%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>38%</td>
<td>61%</td>
</tr>
<tr>
<td><strong>Fabrication</strong></td>
<td>20%</td>
<td>32%</td>
</tr>
<tr>
<td><strong>Integration &amp; Support</strong></td>
<td>4%</td>
<td>7%</td>
</tr>
</tbody>
</table>
Conclusions

• Very detailed crab-crossing schemes (Phase I/II) is in place

• Tremendous progress in a short time, due to large interest in community

• Continue the momentum into FY10/11 (700 k/yr, 0.5 FTE/lab)
  • “TDR”: cryomodule, integration, OP procedures, simulations
  • More detailed studies on LHC beams and safe operation
  • Continue with KEK-B experiments and any other if relevant

• Beyond FY10-11: LARP to play an assisting “physics” role

• Positive outcome of 2010 Review → “Crab Project”
Backup: Lab Contributions

- BNL
  - Overall coordination, layout, optics, cryomodule development

- FNAL
  - Cryostat design & development, multipacting, compact structures (phase II)

- LBNL
  - LLRF, Cavity development, Beam-beam simulations

- SLAC
  - LARP baseline cavity-coupler, compact structures (phase II)

- Jlab/Argonne/Others:
  - General input and interest in crab cavities
Backup: Multipacting

Excellent progress on multipacting and cures to overcome. Continue the effort towards LHC-CC09.
Compact Structures, Phase II

SLAC ½ Wave & Spoke Structures

FNAL Mushroom Cavity

UK-JLAb Rod Structure

BNL TM010, BP Offset

KEK Kota Cavity
Backup: KEK-B Experiments

Artificial modulated noise (inside and outside betatron spectrum)

HER Ring

KEKB measured crab dispersive orbit

1st measurement of crab-dispersion

R. Tomas et al., PRST-AB to be submitted
Backup: Impedance Estimates

Longitudinal criteria:

Narrow band impedance threshold, $R_{sh} < 200 \text{ k}\Omega$

Inductive low freq & broadband $\rightarrow \text{Im}\{Z/n\} < 0.15\Omega$ (loss of landau damping)

Landau damped for $\geq 2 \text{ GHz}$ (synchrotron freq. spread)

Transverse criteria:

Landau octupoles, chromaticity, feedback (Landau damped $\geq 2 \text{ GHz}$)

$\text{Re, Im}\{\Delta Q\} < 10^{-4}$ Coupled bunch $(\beta_\perp/\sqrt{\beta_\perp}) R_\perp/Q << 1 \text{ G}\Omega/\text{m}$

<table>
<thead>
<tr>
<th></th>
<th>Freq [GHz]</th>
<th>$R/Q [\Omega]$</th>
<th>$Q_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopole</td>
<td>0.54</td>
<td>35.17</td>
<td>$\sim 10^2$</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>194.52</td>
<td></td>
</tr>
<tr>
<td>Dipole</td>
<td>0.80</td>
<td>117.26</td>
<td>$10^6$</td>
</tr>
<tr>
<td></td>
<td>0.81</td>
<td>0.46</td>
<td>$\sim 10^2$</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
<td>93.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>6.79</td>
<td></td>
</tr>
</tbody>
</table>

** Main RF cavities, $Q_{ext} \sim 10^2 - 10^3$
Backup: Crab Noise, Tolerances

Modulated noise (measured, ex: 32 kHz)
- Strong-strong BB $\leq 0.01\sigma$ (1%/hr)
- Weak-strong BB $\leq 0.01-0.1\sigma$

White noise (pessimistic)
- Strong-strong BB $\leq 0.002\sigma.(\tau)$

KEK-B crab spectrum
K. Akai et al.
Backup: Collimation Studies

- Loss maps with crabs similar to nominal LHC
- Hierarchy preserved, impact parameter investigation
- Not a serious concern for prototype tests
- Fine tuning with crabs-collimator setup maybe needed

<table>
<thead>
<tr>
<th></th>
<th>Nominal $2\sigma_z$</th>
<th>Crab Cavity $2\sigma_z$</th>
<th>Nominal $3\sigma_z$</th>
<th>Crab Cavity $3\sigma_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>First turn ($\mu m$)</td>
<td>0.78</td>
<td>3.84</td>
<td>0.78</td>
<td>3.84</td>
</tr>
<tr>
<td>All turns ($\mu m$)</td>
<td>0.153</td>
<td>0.147</td>
<td>0.154</td>
<td>0.147</td>
</tr>
<tr>
<td>Part. absorbed</td>
<td>70.2%</td>
<td>68.5%</td>
<td>70.2%</td>
<td>68.5%</td>
</tr>
<tr>
<td>First turn ($\mu m$)</td>
<td>50.61</td>
<td>76.16</td>
<td>59.82</td>
<td>79.03</td>
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<tr>
<td>All turns ($\mu m$)</td>
<td>36.1</td>
<td>66.47</td>
<td>40.44</td>
<td>67.03</td>
</tr>
<tr>
<td>Part. absorbed</td>
<td>96.5%</td>
<td>99.56%</td>
<td>97%</td>
<td>99.56%</td>
</tr>
</tbody>
</table>

\[
\delta p/p = 0
\]

\[
\delta p/p \neq 0
\]

Y. Sun et al.
Prototype test scenarios are proposed and being studied

Adapt to various LHC configurations while maintaining safe operation

Identifying all failures scenarios and corresponding remedies

<table>
<thead>
<tr>
<th>{E, \max \beta, \min \beta_{\alpha\beta}}</th>
<th>3 TeV, 1 km</th>
<th>5 TeV, 2 km</th>
<th>7 TeV, 3 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>\beta^* = 25 cm</td>
<td>Reduce Emittance</td>
<td></td>
<td>56%</td>
</tr>
<tr>
<td></td>
<td>Increase X-Angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Artificial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>\beta^* = 30 cm</td>
<td>Enhancement</td>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>\beta^* = 55 cm</td>
<td></td>
<td></td>
<td>10%</td>
</tr>
</tbody>
</table>