Crab Cavity Efforts at CERN

Alejandro Castilla on behalf of the BE-RF-SRF section and HL-LHC Project Work Package 4, with special thanks to (but not only) Lancaster University, USLARP, ODU, Jefferson Lab, and more…

Jefferson Lab - Accelerators Seminar, December 15th 2016
Outline

- Luminosity Requirements
  - Jefferson Lab Electron-Ion Collider
  - HL-LHC
- Crab Cavity Designs
- Schedule
- Activities at CERN
- Summary
Jefferson Lab - EIC

*from F. Pilat, JLEIC Collaboration Meeting 5th – 7th Oct 2016
Jefferson Lab - EIC

• \((\sqrt{s} = 20 - 70 \, GeV)\) and \(> 10^{33} \, cm^{-2}s^{-1}\) luminosity

*from V. Morozov, JLEIC Collaboration Meeting 5\textsuperscript{th} – 7\textsuperscript{th} Oct 2016
CERN HL-LHC Upgrades
CERN HL-LHC Upgrades

- $\sim 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ peak luminosity
Comparing the Machines

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>JLEIC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Collision frequency (SRF1)</td>
<td>MHz</td>
<td>476</td>
<td>400</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>(10^{10})</td>
<td>0.98</td>
<td>3.7</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>0.75</td>
<td>2.82</td>
</tr>
<tr>
<td>Polarization (BDD1)</td>
<td></td>
<td>&gt;70%</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>Bunch length, rms</td>
<td>cm</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Norm. emittance, x/y (ECL)</td>
<td>(\mu m)</td>
<td>0.5/0.1</td>
<td>70/14</td>
</tr>
<tr>
<td>x/y (\beta^*) (BDD2)</td>
<td>cm</td>
<td>6/1.2</td>
<td>4/0.8</td>
</tr>
<tr>
<td>Vert. beam-beam param. (BDD3)</td>
<td></td>
<td>0.015</td>
<td>0.053</td>
</tr>
<tr>
<td>Lumi./IP, w/HG, (10^{33})</td>
<td>(\text{cm}^{-2}\text{s}^{-1})</td>
<td>19.5</td>
<td>59.5</td>
</tr>
</tbody>
</table>
Experimental Challenge of the EIC

\[ s = x y Q^2, \quad s = 4 E_e E_p \]

On one hand: need high beam energies to resolve partons in nucleons. 
\( Q^2 \) needs to be up to \( \sim 1000 \text{ GeV}^2 \)

On the other: need to resolve quantities \( (k_t, b_t) \) of order a few hundred MeV in the proton. Limits proton beam energy. High Lumi needed.

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high
LHC 2016 Run (about luminosity)

https://home.cern/cern-people/updates/2016/10/lhc-report-end-2016-proton-proton-operation
Luminosity in Colliders

- More events in time → better statistic/resolution of the processes

\[ \frac{dR}{dt} = \mathcal{L} \times \sigma_p \]

- \( \frac{dR}{dt} \) interactions per second,
- \( \sigma_p \) interaction cross section (machine independent),
- \( \mathcal{L} \) luminosity, relativistic invariant, independent of the interaction and very important measurable.
**Luminosity in Colliders**

- Identical Gaussian beams
  - no crossing angle
  - w/o dispersion
  - no offset

\[
\mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi \sigma_x \sigma_y}
\]

- Where at the IP

\[
\beta^*_{x,y} = \frac{\sigma^2_{x,y}}{\epsilon} \quad \text{and} \quad \epsilon = \frac{\gamma}{\epsilon_N}
\]

\[
\therefore \mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi \epsilon \sqrt{\beta^*_x \beta^*_y}}
\]
Luminosity Parameters

- Geometrical deformations at IP (hour-glass)
- Beam offsets
- Dispersion at IP
- Strong coupling, etc.
- Not head-on (crossing angle $\theta_c$)

$$\mathcal{L} = \frac{1}{4\pi} \left( nf N_b \right) \cdot \frac{n}{\epsilon_N} \cdot \frac{\gamma}{\beta^*} \cdot R(\theta_c, \epsilon, \beta^*, \sigma_s)$$

injector & beam-beam

Reduction factor: hourglass effect, crossing angle…

total beam current

energy & squeeze
Using rotated reference frames per beam
- change of coordinates
- rewrite Gaussian distributions
- compute the new Gaussian integrals
Luminosity + Crossing Angle

- Some more approximations since $\theta_c/2$ is small:

$$\sin \theta_c/2 \sim \tan \theta_c/2 \sim \theta_c/2;$$

discarding

$$\left\{ \begin{array}{l}
\sigma_x^k \sin^l \theta_c/2 \\
\chi^k \sin^l \theta_c/2
\end{array} \right.; \quad \forall \ k + l \geq 4$$

- And so the result is slightly different:

$$\mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi \epsilon \sqrt{\beta_x^* \beta_y^*}} \cdot \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x} \tan \frac{\theta_c}{2}\right)^2}}.$$
Crossing Angle w/o Correction

\[ \theta_c \]

IP

A. Castilla - CERN, Dec. 15th 2016
The Crabbing Concept

RF Transverse Deflection

\[ V_T = \int_{-\infty}^{\infty} \left[ E_x(z) \cos \frac{\omega z}{c} + cB_y(z) \sin \frac{\omega z}{c} \right] dz \]
RF Crabbing

\[ V_T = \int_{-\infty}^{\infty} \left[ E_x(z) \cos \frac{\omega Z}{c} + c B_y(z) \sin \frac{\omega Z}{c} \right] dz \]
Local Crab Crossing Correction

\[ \theta_c \]

IP
Comparing Machine Requirements

$$V_T = \frac{c E_b \tan \theta_c}{\omega \sqrt{\beta^* \beta^c}}$$

**HL-LHC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proton</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy $E_b$</td>
<td>7000</td>
<td>GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>1.1</td>
<td>A</td>
</tr>
<tr>
<td>Bunch frequency $\omega$</td>
<td>400</td>
<td>MHz</td>
</tr>
<tr>
<td>Crab crossing angle $\theta_c$</td>
<td>~0.5</td>
<td>mrad</td>
</tr>
<tr>
<td>Beta function at IP $\beta^*$</td>
<td>20</td>
<td>cm</td>
</tr>
<tr>
<td>Beta function at CC $\beta^c$</td>
<td>~3000</td>
<td>m</td>
</tr>
<tr>
<td>Integrated kicking voltage per beam per side $V_T$</td>
<td>~8.5</td>
<td>MV</td>
</tr>
</tbody>
</table>

**JLEIC**

*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electron</th>
<th>Proton</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy $E_b$</td>
<td>10</td>
<td>100</td>
<td>GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>0.72</td>
<td>5.0</td>
<td>A</td>
</tr>
<tr>
<td>Bunch frequency $\omega$</td>
<td>952.6</td>
<td>MHz</td>
<td></td>
</tr>
<tr>
<td>Crab crossing angle $\theta_c$</td>
<td>~0.5</td>
<td>mrad</td>
<td></td>
</tr>
<tr>
<td>Beta function at IP $\beta^*$</td>
<td>20</td>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>Beta function at CC $\beta^c$</td>
<td>~3000</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Integrated kicking voltage per beam per side $V_T$</td>
<td>2.8</td>
<td>14.5</td>
<td>MV</td>
</tr>
</tbody>
</table>
- 50 mrad crossing angle
  - Fast beam separation
  - No parasitic collisions
  - Improved momentum resolution for the detector
- Other advantages
  - Downstream chicane for electrons
    - spectrometry and polarimetry
  - e’s & p’s parallel and separated downstream by 1.5 m

*from V. Morozov, JLEIC Collaboration Meeting 5th – 7th Oct 2016
Reminder, Basic Parameters

- **Voltage** = \(3.4\, \text{MV/cavity}\) (2 cavities /beam /IP side) – 16 total
- **Frequency** = 400.79 MHz
- **\(Q_{ext}\)** = \(5 \times 10^5\), \(Q_0 \approx 10^{10}\)
- **RF power source** = 80 kW (SPS \(\leq 40\, \text{kW}\))
- **Cavity tuning** = \(\pm 100\, \text{kHz}\) (LFD \(\sim 0.5\, \text{kHz}\))
- **Operating temperature** = 2.0 K

![Diagram with IP, D2, Beam 1, Beam 2, Q4, and L = 6.6 m]
750 MHz-RFD Transverse Kick

\[ V_T = \int_{-\infty}^{\infty} \left[ E_x(z) \cos \frac{\omega z}{c} + c B_y(z) \sin \frac{\omega z}{c} \right] dz \]

Electric Field

Magnetic Field

\[ E_T = \frac{V_T}{\lambda / 2} \Rightarrow V_T^* = 0.2 \, \text{MV} \]

\[ E_T^* = 1 \, \text{MV/m} \]

\[ V_{T,E} = 0.4 \, \text{MV} \]

\[ V_{T,H} = -0.2 \, \text{MV} \]
750 MHz MEIC-Crab Fabrication

*Images courtesy of Niowave, Inc.*

A. Castilla - CERN, Dec. 15th 2016
952.6 MHz Cavity – Single Cell Cavity

- Single cell cavity designs with varying beam aperture radii
- RF properties
  - Peak surface fields increase
  - Shunt impedance decrease

<table>
<thead>
<tr>
<th>Frequency</th>
<th>952.6 MHz</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>70 mm</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>1st HOM</td>
<td>1411.5 MHz</td>
<td>1431.0</td>
<td>1420.4</td>
<td></td>
</tr>
<tr>
<td>$V_t^*$</td>
<td>0.157 MV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.2 MV/m</td>
<td>4.8</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>9.3 mT</td>
<td>11.3</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>$[R/Q]_t$</td>
<td>136 Ω</td>
<td>81</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>145 Ω</td>
<td>155</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>$R_sR_t$</td>
<td>2.0×10⁴ Ω²</td>
<td>1.3×10⁴</td>
<td>8.3×10³</td>
<td></td>
</tr>
</tbody>
</table>

$E_t = 1$ MV/m

*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016
952.6 MHz Cavity – Multi-Cell Cavity

- A 3-cell design study with varying beam aperture

- Low surface fields
- High shunt impedance
- Presence of lower order modes
  - Requires a notch filter in damping LOMs

<table>
<thead>
<tr>
<th></th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>952.6 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>LOM</td>
<td>790, 879</td>
<td>773, 870</td>
<td>757, 862</td>
</tr>
<tr>
<td>1st HOM</td>
<td>1409</td>
<td>1383</td>
<td>1335</td>
</tr>
<tr>
<td>$V_t^*$</td>
<td></td>
<td>0.157</td>
<td></td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.7</td>
<td>5.1</td>
<td>5.6</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>8.7</td>
<td>10.0</td>
<td>11.4</td>
</tr>
<tr>
<td>$[R/Q]_t$</td>
<td>494</td>
<td>323</td>
<td>219</td>
</tr>
<tr>
<td>$G$</td>
<td>161</td>
<td>170</td>
<td>179</td>
</tr>
<tr>
<td>$R_s$</td>
<td>8.0×10⁴</td>
<td>5.5×10⁴</td>
<td>3.9×10⁴</td>
</tr>
</tbody>
</table>

*$E_t = 1$ MV/m

*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016

A. Castilla - CERN, Dec. 15th 2016
Example Designs (400 MHz)

R. Calaga, Chamonix '12

Exotic zoo of crab cavities developed in about 4 years (BNL, CERN, CI-JLAB, FNAL, KEK, ODU/JLAB, SLAC)

Three cavities remaining after down-selection.
WP4 Planning

SPS prototype beam tests

preparation → SPS Test (CM1) → SPS Test (CM2)


Run 2 | Run 3 | Run 4

LHC pre-series
(2 Industrial Dressed Cavities)

LHC series production & Installation (8 CMs)

SPS Test Setup

LHC Installation

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

A. Castilla - CERN, Dec. 15th 2016
SPS Cavities, 2K Volume

Bulk Nb cavities, Dipolar symmetry

\[ V_T = 3.4 \text{ MV} \ (E_p, B_p \leq 40 \text{ MV/m, 70 mT}) \]

Stored energy \( \sim 10 - 12 \text{ J} \)

CERN insourced DQW production Nov 2015

*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016

A. Castilla - CERN, Dec. 15th 2016
Prototype Cryomodules

Vertical crossing for ATLAS, first one to go to SPS 2018

Horizontal crossing for CMS Cavities starting 2017

*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016
Design and Engineering of Prototypes

*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016
SPS-DQW Cavity Fabrication

- First CERN cavity frequency trimming last week

Cavity I cold test mid-Feb 2017 (Cavity 2 in early March)

*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016
Dressed Cavities (2K volume)

Main Mechanical interfaces:
- He-vessel: Bolted-welded concept
- Cold magnetic shield
- Tuner: Sym. tuning with warm actuation
- Three point support + alignment system

Main RF interfaces
- 1 FPC: Single ceramic coaxial line
- 3 HOMs: Two stage filter, coaxial
- 1 PU: Cu-Nb for field probe + HOM

*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016

Similar concept for RFD with different HOM interfaces
System architecture in SPS point 6

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

PA6 - shaft

BA6 – surface area
- RF power amplifiers
- IOT
- Cryogenic compressor
- LLRF Faraday cage
- Racks, utilities

~40m

RF power coaxials
Warm Cryo pipework

Cryo distribution line

~110m

Crab-cavity test stand

TA6 - alcove

Cold-box
Valve-box
New handling equipment

A. Castilla - CERN, Dec. 15th 2016
HL-LHC CC SPS test stand in 2016

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016
HL-LHC CC SPS test stand in 2018

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016
Beam vacuum sectorization valve

Valve-box2

Service module

RF power, loads & circulators

Helium pumps

Beam vacuum sectorization valve

Transfer table
Translation in-beam and out-of-beam by 510mm

Y-chamber

BPM

Cryo-module

BLM

Transport lane

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016
The motorized transfer table supports the CCCM and proximity ancillaries.

Table movement is interlocked by Access VETO in SPS and by Valves closed.

Table movement interlocks beam by sector valve closure.

Table position interlocks beam and extraction.

Mitigation of the risk of cryogenic hazard

SPS-ring BIS and EXTR 1 BIS

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

A. Castilla - CERN, Dec. 15th 2016
SPS Installation Master plan

**2016**
- Cavity Fabrication
- Cold tests, cavities
- CM Assembly

**2017**
- CM cold tests
- CM ready to install

**VISUALIZE**
- SRR
- DIC CS

**PREPARE**
- BA6 supports construction
- Uncabling & Cabling
- RF power cabling
- Cryo Transfer-Line
- Vacuum sectorization
- New handling equipment
- Cooling pipework

**INSTALL**
- Refrigeration
- Transfer table
- **CCCM** + Service Module
- Electrical connections
- RF connections
- Cryo connections
- Validation tests
- Commissioning

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

A. Castilla - CERN, Dec. 15th 2016
Tuner Mockup Vs Cryomodule

SPS-Series

Proof-of-Principle
DQW Proof-of-Principle

J. Swiesek and K. Artoos

- Calculations Norbert Kuder for 0.5 mm displacement on each plate. Maximum stress intensity: 289 MPa

- Elastic limit Nb with 1.5 safety factor is 320 MPa at 2 K (Material properties for mechanical and thermal analysis, EDMS 1530740)

- Since rigidification by welds are not in the model + other factors like Nb thickness variation, etc.:
  - Maximum 0.5 mm motor displacement for the DQW-PoP tuner test
SM18 Tuner Mockup Setup

- Test Stand
  - New test stand commissioned to allow the tuner test configuration
  - New user interface deployed
    - RF testing
    - Motor controls
- Diagnostics
  - Temperature mapping
  - 3 axis B-flux gauges
  - 2nd Sound detection
  - Strain gauge
Tuner Small Steps

- Moving 116 steps
  - ~256 nm displacement
  - Total freq. shift ~29 Hz
  - Average measure of 2.2 nm/step
- From large freq. excursions
  - $\frac{\Delta f}{\Delta y} \approx 180$ kHz/mm
Maximum Tuning Excursion

- After fixing end stops and motor slippage

\[ \Delta f_{max} = -102.5 \text{ kHz} \]
Following: CC LLRF + Tuner

- Design evolving from the existing Linac 4 cards/crates
  - A few firmware changes are needed:
    - Change from 352.2 MHz to 400.8 MHz, sampling, etc.
    - Change from pulsed to CW operation, etc.

P. Baudrenhien, B. Kremel, J. Simonin and N. Stapley
Clean Room Assembly (Bare Cavity)

- Clean assembly
  - Parts and pre-assemblies ready
  - Under *laminar flow*
  - Systematic sequence
Insert Installation (Bare Cavity)

- Remove from chariot
- Mechanically mount onto insert
Clean Room Assembly (Part. Dressed Cavity)

- Cavity + He tank is moved to ISO4
- Mounting of HOMs couplers and RF field antenna
  - Done by E. Montesinos’ team (see dedicated talk)
  - One-by-one with nitrogen overpressure
Part. Dressed Cavity Insert Installation

- Mounting into insert
  - Vacuum line connection and leak check procedure similar to bare cavity
Summary

- Lots of studies done and undergoing:
  - Machine Integration
  - Machine Protection
  - and some others still missing…
- Great efforts at CERN for infrastructure and tooling
- Insourcing of cavity fabrication has been an important investment for CERN
- Very tight schedule with a very promising added value
- Synergy of the CC program between JLEIC and CERN
Thank you

Jefferson Lab - EIC

- Understanding the nucleon, nuclear structure and associated dynamics
  - Probe the nucleon
    - many-body regime
      - $x \approx 0.005$ at large $Q^2$
  - Probe the nuclei
    - N-N and multi-N interaction regime
      - at large $Q^2$
  - Extend of QCD
    - Saturation
    - Jets in cold matter

*from R. Yoshida, JLEIC Collaboration Meeting 5th – 7th Oct 2016*
Jefferson Lab - EIC

- Non-Perturbative Quantum Chromodynamics (+TR)
  - Jefferson Lab 12 GeV
    - Quantitative understanding of DIS processes

- Perturbative Quantum Chromodynamics (pQCD)
  - Jefferson Lab EIC
    - Full picture of nucleons and nuclei
    - Origin of mass, spin, nuclear forces,…

*from R. Yoshida, JLEIC Collaboration Meeting 5th – 7th Oct 2016
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chamonix 16</th>
<th>Actual - July 16 - BCMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td><strong>β</strong>*(1/2/5/8) [m]</td>
<td>0.4 / 10 / 0.4 / 3</td>
<td>0.4 / 10 / 0.4 / 3</td>
</tr>
<tr>
<td>Ext. half X-angle (1/2/5/8) [μrad]</td>
<td>-185 / 200 / 185 / -250</td>
<td>-185 / 200 / 185 / -250</td>
</tr>
<tr>
<td>Number of colliding bunches (1/5)</td>
<td>2736 nominal 25 ns</td>
<td>2076</td>
</tr>
<tr>
<td>Bunch population</td>
<td>1.2e11</td>
<td>1.18e11</td>
</tr>
<tr>
<td>Emittance into Stable Beams [μm]</td>
<td>3.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Bunch length [ns] - 4 sigma</td>
<td>1.25</td>
<td>1.05</td>
</tr>
<tr>
<td>Peak Luminosity (L0) [cm-2s-1]</td>
<td>1.1e34</td>
<td>1.1e34</td>
</tr>
<tr>
<td>Peak mean pile-up (inel xsection 80 mb)</td>
<td>29</td>
<td>39</td>
</tr>
</tbody>
</table>

288 bunches per injection following TDI replacement
Tested in 2015 - 0.5 m also an option
10 sigma in 1&5 assuming 3.75 micron emittance
Limited by SPS dump to 96 bpi as of July 16

Limitation by SPS dump to 96 bpi as of July 16

BCMS could give around 1.4e34

cf. ~40 with BCMS

A. Castilla - CERN, Dec. 15th 2016
Number of crab cavities halved
HL-LHC virtual luminosity in 2016

Virtual luminosity [$10^{35}\text{cm}^{-2}\text{s}^{-1}$]

- $\sigma=7.55 \Rightarrow 8.1\text{cm}$
- $4\text{ CCs} \Rightarrow 2\text{ CCs}$
- $\beta^*=15 \Rightarrow 20\text{cm}$
- $\sigma=8.1 \Rightarrow 9\text{cm}$

TCC meetings: [https://indico.cern.ch/category/7361/](https://indico.cern.ch/category/7361/)
Luminosity: A Primer

- Per bunch crossing
  \[ \mathcal{L} = K \cdot n_1 n_2 \cdot \]

\[ \iiint_{-\infty}^{\infty} dx dy ds s_0 [\rho_1(x, y, s, -s_0) \cdot \rho_2(x, y, s, s_0)] \]

- Where \( s_0 = ct \)

- And \( K \) is the kinematic factor
  \[ \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)^2 / c^2} \]

- Head-on collisions \( (\vec{v}_1 = -\vec{v}_2) \), then \( K = 2 \)

- For uncorrelated distributions:
  \[ \rho(x, y, s, s_0) = \rho_x(x) \rho_y(y) \rho_s(s \pm s_0) \]
Luminosity: A Primer

- For two bunches with $n_1$ and $n_2$ particles respectively:

$$t = \frac{1}{f}$$

- Where $\sigma_{x/y}$ are the rms horizontal/vertical beam sizes.

- No offset and head-on collision.

https://en.wikipedia.org/wiki/Multivariate_normal_distribution
For two beams:

\[ \mathcal{L} = 2 \cdot n_1 n_2 \cdot f \cdot N_b \cdot \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dx dy ds ds_0 \]

\[ \rho_{1x}(x) \rho_{1y}(y) \rho_{1s}(s - s_0) \cdot \rho_{2x}(x) \rho_{2y}(y) \rho_{2s}(s + s_0) \]

The Gaussian distributions can be written:

\[ \rho_{iu}(u) = \frac{1}{\sigma_{iu} \sqrt{2\pi}} e^{-\frac{u^2}{2\sigma_{iu}^2}}, \quad \rho_s(s \pm s_0) = \frac{1}{\sigma_s \sqrt{2\pi}} e^{-\frac{(s \pm s_0)^2}{2\sigma_s^2}}; \]

where \( u = x, y \) and \( i = 1, 2 \) indicates the bunch number.
Crossing Angle

- Using rotated reference frames per beam
  - change of coordinates
  - rewrite Gaussian distributions
  - compute the new Gaussian integrals
\[ x_1 = x \cos \frac{\theta_c}{2} + s \sin \frac{\theta_c}{2}, \quad s_1 = s \cos \frac{\theta_c}{2} - x \sin \frac{\theta_c}{2}. \]

\[ x_2 = -x \cos \frac{\theta_c}{2} + s \sin \frac{\theta_c}{2}, \quad s_2 = -s \cos \frac{\theta_c}{2} - x \sin \frac{\theta_c}{2}. \]
Luminosity + Crossing Angle

- For two beams:

\[ \mathcal{L} = 2 \cdot n_1 n_2 \cdot f \cdot N_b \cdot \iiint_{-\infty}^{\infty} dx dy ds ds_0 [ \rho_{1x}(x_1) \rho_{1y}(y_1) \rho_{1s}(s_1 - s_0) \cdot \rho_{2x}(x_2) \rho_{2y}(y_2) \rho_{2s}(s_2 + s_0) ] \]

- Now we will use:

\[ \int_{-\infty}^{\infty} dt e^{-(at^2 + bt + c)} = \sqrt{\frac{\pi}{a}} \cdot e^{-\frac{b^2 - ac}{a}} \]
Luminosity + Crossing Angle

- Some more approximations since $\frac{\theta_c}{2}$ is small:

  \[
  \sin \frac{\theta_c}{2} \sim \tan \frac{\theta_c}{2} \sim \frac{\theta_c}{2};
  \]

  discarding

  \[
  \begin{cases}
  \sigma_x^k \sin^l \frac{\theta_c}{2} \\
  x^k \sin^l \frac{\theta_c}{2}
  \end{cases}; \quad \forall \ k + l \geq 4
  \]

- And so the result is slightly different:

  \[
  \mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi \epsilon \sqrt{\beta_x^* \beta_y^*}} \cdot \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \tan \frac{\theta_c}{2}\right)^2}}
  \]
Aspects of optimization

- Lower and balanced peak surface fields
- Stability of the design:
  - Cylindrical shape is preferred to reduce flat surfaces.
- Curved end plates for cleaning the cavity.
- Wider separation in Higher Order Mode (HOM) spectrum.
- Multipacting

(from S. De Silva, ODU-JLab 2012.)
TE-Like Transverse Kick
Accelerating to Deflecting

\[ E_x \text{ varying length} \]

\[ H_y \text{ varying length} \]
Accelerating to Deflecting (2)

Electric Field

Magnetic Field
Multipole Expansion

<table>
<thead>
<tr>
<th>750 MHz</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>1.0</td>
</tr>
<tr>
<td>$b_1$</td>
<td>3.3</td>
</tr>
<tr>
<td>$b_2$</td>
<td>0.0</td>
</tr>
<tr>
<td>$b_3$</td>
<td>1.81</td>
</tr>
<tr>
<td>$b_4$</td>
<td>0.0</td>
</tr>
<tr>
<td>$b_5$</td>
<td>-5.2</td>
</tr>
</tbody>
</table>
Field Flatness & Emittance

\[ \epsilon^2_{n,rms} \equiv \epsilon^2_{0n,rms} + \frac{x^2_{0,rms} (\Delta p_x^2 - \Delta p_x^2)}{m^2 c^2} \]

For a proton beam on axis coming with \( \epsilon_{0n,rms}(y) = 0.07 \mu m - rad \) then leaves with \( \epsilon_{n,rms}(y) = 0.13 \mu m - rad \) after 1 pass.
# 750 MHz MEIC-Crab Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MEIC RF-Dipole</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of p-mode</td>
<td>750.1</td>
<td>MHz</td>
</tr>
<tr>
<td>$\lambda/2$ of p-mode</td>
<td>200.0</td>
<td>mm</td>
</tr>
<tr>
<td>Frequency of 0-mode</td>
<td>1350.6</td>
<td>MHz</td>
</tr>
<tr>
<td>Cavity length</td>
<td>549.3</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity width</td>
<td>93.7</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity height</td>
<td>93.7</td>
<td>mm</td>
</tr>
<tr>
<td>Bars length</td>
<td>200.0</td>
<td>mm</td>
</tr>
<tr>
<td>Bar Vertical Angle</td>
<td>45</td>
<td>deg</td>
</tr>
<tr>
<td>Bar Horizontal Angle</td>
<td>10.9</td>
<td>deg</td>
</tr>
<tr>
<td>Bars height</td>
<td>63.0</td>
<td>mm</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>60.0</td>
<td>mm</td>
</tr>
<tr>
<td>Deflecting voltage $V_t*$</td>
<td>0.2</td>
<td>MV</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.45</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>9.31</td>
<td>mT</td>
</tr>
<tr>
<td>$G$</td>
<td>131.4</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_t/Q$</td>
<td>124.15</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_t R_s$</td>
<td>$1.65 \times 10^4$</td>
<td>Ω²</td>
</tr>
</tbody>
</table>

\[
E_T^* = 1 \text{MV/m} \\
B_p \approx 2.1 \text{mT} / (\text{MV/m})
\]

\[
E_T = \frac{V_T}{\lambda/2} \Rightarrow V_T^* = 0.2 \text{ MV}
\]
• Multipacting levels were easily processed at 1.99 K.
• Design requirement of <2 MV can be achieved with 1 cavity
• Achieved fields at 1.99 K
  – $E_T = 13.5$ MV/m
  – $V_T = 2.7$ MV
  – $E_P = 60.08$ MV/m
  – $B_P = 125.69$ mT
Cavity (RT, no PCB) with He vessel + pretuning device
Input force 2.5 kN

Displacement $z \ 0.53/0.6 \ mm$
Maximum eq. Stress 225 MPa
Corresponds to about 0.21 MHz (0.42 MHz pp) *

For 400 MPa/1.2= 333 MPa -> 0.31 MHz (0.62 MHz) range (linear), 3.7 kN, ±1.6 mm

Force/tuner stroke 2.2 kN/mm
199 MPa/mm

At RT for 50 MPa , 0.25 mm maximum tuner stroke for 0.5 kN
Successful pressure, vacuum & magnetic tests done

Internal magnetic shield (UK contribution)
Compatibility of CCCM with SPS Operation

**Fast extraction to LHC**
Not enough aperture for extracted beam at nominal location close to QDA.617

H. Bartosik @ SPS Test Day, I
https://indico.cern.ch/event/463435/

**Slow extraction of fixed target beam**
at 400GeV, incl. extraction bump
- purple: raw beam envelope
- red: beam envelope + tolerance

Crab cavity at QD617 is compatible with slow extraction to North Area

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016
## SPS Tests Program – Weekly Schedule

### Cavities

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Status</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity 1</td>
<td>ready</td>
<td>22/12/16</td>
</tr>
<tr>
<td>Cavity 2</td>
<td>ready</td>
<td>02/02/17</td>
</tr>
</tbody>
</table>

### Cavity Production

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Pieces Produced</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity 1</td>
<td>28/10/16</td>
<td>03/10/16</td>
</tr>
<tr>
<td>Cavity 2</td>
<td>22/12/16</td>
<td></td>
</tr>
</tbody>
</table>

### String Assembly

- **String assembled**: 27/07/17

### CM Assembly

- **CM assembled**: 06/12/17

### CM Commissioning

- **Commissioned in SPS**: 23/02/18

### Missing 12 days

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016*
Crab Cavity SPS Layout, LSS6

- 11° Y-chamber with multiple vacuum sectorization
- Movable table – 510 mm transversely (RF, Cryo, Vacuum)
- Approval from impedance working group to proceed with Y-chamber

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

A. Castilla - CERN, Dec. 15th 2016
SPS test programme Budget

- WP4 Crab programme: 86.2 MCHF
- SPS tests programme: 17.8 MCHF

**SPS PROGRAM BREAKDOWN**

- SPS Prototype cryomodules: 67%
- SM18 Infrastructure: 13%
- Cryogenics: 5%
- Vacuum: 4%
- Electricity: 2%
- Transfer Table: 1%
- SPS Test-stand: 1%
- WP4 Crab programme: 1%
- SPS tests programme: 2%

*from G. Vandoni, 2nd CERN-SRF Workshop Nov 2016*
SPS test-stand Budget

Overshoot of 4% of 2016 budget, 1% of total budget

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

A. Castilla - CERN, Dec. 15th 2016