LHC: The Machine

SLAC Summer Institute 2012
26 July 2012

Frank Zimmermann
CERN, Beams Department

thanks to
Mike Lamont, Steve Myers, Ralph Steinhagen
“how well LHC has done and what we can expect next”

• basics
• recent performance
• near and long term prospects
basics
Superconducting Proton Accelerator and Collider installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985
LHC design parameters

c.m. energy = 14 TeV
luminosity = $10^{34}$ cm$^{-2}$s$^{-1}$

1.15x$10^{11}$ p/bunch
2808 bunches/beam

$\gamma\varepsilon=3.75$ $\mu$m
$\beta^*=0.55$ m
$\theta_c=285$ $\mu$rad
$\sigma_z=7.55$ cm
$\sigma^*=16.6$ $\mu$m (IP1 & 5)
## LHC: Some of the Technical Challenges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (km)</td>
<td>26.7</td>
<td>100-150 m underground</td>
</tr>
<tr>
<td>Number of Dipoles</td>
<td>1232</td>
<td>Cable Nb-Ti, cold mass 37 million kg</td>
</tr>
<tr>
<td>Length of Dipole (m)</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>Dipole Field Strength (Tesla)</td>
<td>8.4</td>
<td>Results from the high beam energy needed</td>
</tr>
<tr>
<td>Operating Temperature (K)</td>
<td>1.9</td>
<td>Superconducting magnets needed for the high magnetic field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Super-fluid helium</td>
</tr>
<tr>
<td>Current in dipole sc coils (A)</td>
<td>13000</td>
<td>Results from the high magnetic field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1ppm resolution</td>
</tr>
<tr>
<td>Beam Intensity (A)</td>
<td>0.5</td>
<td>2.2 $10^{-6}$ loss causes quench</td>
</tr>
<tr>
<td>Beam Stored Energy (MJoules)</td>
<td>362</td>
<td>Results from high beam energy and high beam current (1MJ melts 2kg Cu)</td>
</tr>
<tr>
<td>Magnet Stored Energy (MJoules)/octant</td>
<td>1100</td>
<td>Results from the high magnetic field</td>
</tr>
<tr>
<td>Sectors of Powering Circuits</td>
<td>8</td>
<td>1612 different electrical circuits</td>
</tr>
</tbody>
</table>

Steve Myers, IPAC12, New Orleans
LHC: First collisions at 7 TeV on 30 March 2010

ALICE

Collision Event at 7 TeV

ATLAS EXPERIMENT
2010-03-30, 12:53 CEST
Run 152166, Event 316199

LHCb Event Display

LHCb

CMS

Peak Luminosity for First Run $10^{27}$ cm$^{-2}$ s$^{-1}$

Steve Myers, IPAC12, New Orleans
luminosity

\[ R = \sigma L \]

reaction rate

luminosity

cross section


\( \sigma_{\text{tot}} \approx 100 \text{ mbarn} \approx 10^{-25} \text{ cm}^2 \)

from cosmic rays

LHC

\( P_{\text{lab}} \text{ GeV/c} \)
TOTEM measurement at LHC (1 h in 2011)

Elastic Scattering and Total Cross-Section in p+p reactions, arXiv:1204.5689

\[ \sigma_{\text{inelastic}} \approx 85 \text{ mbarn} \approx 8.5 \times 10^{-26} \text{ cm}^2 \text{ at 14 TeV CoM} \]
events / crossing ("pile up")

bunch collision rate
= #bunches/beam x revolution frequency

#events per bunch crossing
= cross section x luminosity / bunch collision rate

nominal #events/crossing in the detector
= 8.5x10^{-26} \text{ cm}^2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} / (32 \times 10^6 \text{ s}^{-1})
= 27
event pile up in detector

$p_t > 1$ GeV/c cut, i.e. all soft tracks removed

historical simulation
I. Osborne
maximizing luminosity

luminosity for round beams:

\[ L = \frac{f_{\text{rev}} n_b N_b^2}{4\pi \sigma_x^* \sigma_y^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z) \]

\[ L = \frac{1}{4\pi} \left( f_{\text{rev}} n_b N_b \right) \frac{N_b}{\varepsilon_N} \frac{\gamma}{\beta^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z) \]

- maximize total beam current
- maximize brightness (injectors & beam-beam limit)
- compensate reduction factor \( R \)
- crossing angle
- hourglass effect
- maximize energy & minimize \( \beta^* \)
limits on LHC beam current (7 TeV)

Ideal scenario: no imperfections included!

Note: Some assumptions and conditions apply…
\( Q \) & \( \beta^* \): schematic of betatron oscillation in storage ring

tune \( Q_{x,y} \) = number of \((x,y)\) oscillations per turn

\[
Q = \frac{\phi\beta(C)}{2\pi} = \frac{1}{2\pi} \int_C \frac{ds}{\beta(s)}
\]

focusing elements: quadrupole magnets

\[
\sigma(s) = \sqrt{\frac{\beta(s)\varepsilon_N}{\gamma}} \quad \text{beam size at point } s
\]

\[
\sigma^* = \sqrt{\frac{\beta^*\varepsilon_N}{\gamma}} \quad \text{beam size at collision point}
\]
emittance $\varepsilon$

“area in phase space” occupied by the beam

$= \pi \times \varepsilon$

rms emittance $\varepsilon_{\text{rms}} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$

for Gaussian distribution

$\varepsilon_{\text{rms}}$ contains 39% of the beam
limits on $\beta^*$

to decrease the beam size at the collision point we can reduce either $\beta^*$ or $\epsilon$

$\beta^*$: - must remain larger than $\sigma_z$ - quadrupole aperture must be respected reducing $\epsilon$ decreases $\sigma$ at IP and at quadrupole!
limits on beam “brightness”

\[ B \equiv \frac{N_b}{\varepsilon_N} \]

\[ \Delta Q_{x,y;\text{beam-beam}} \propto \frac{N_b}{\varepsilon_N} \] head-on beam-beam limit in the LHC → not as severe as expected

\[ \Delta Q_{x,y;\text{space charge}} \propto \frac{N_b}{\varepsilon_N} \frac{1}{\beta^2 \gamma^2} \] space charge tune shift in the injectors → present limitation; will be removed by LHC Injector Upgrade in ~2018
(nonlinear) beam-beam force

beam-beam force, round beams

W. Herr

Force varies strongly with amplitude

Exponential function:

Contains many high order multipoles

at small amplitude similar to effect of defocusing quadrupole

for pure head-on collision

\[ \Delta Q_{x,y;\text{max}} = \xi_{x,y} = \frac{2 N_b r_0 \beta^*}{4 \pi \gamma (2 \sigma^*)^2} = \frac{N_b}{\epsilon_N} \frac{r_0}{4 \pi} \]

for single collision (nominal LHC \( \sim 0.0033 \))
vertical tune $Q_y$

beam-beam tune spread from head-on collision

maximum acceptable tune spread is limited by resonances

$nQ_x + mQ_y = p$

up to resonance order $|n| + |m| \approx 13$

horizontal tune $Q_x$
vertical tune $Q_y$

- particles at the center of the bunch
- particles in the transverse tail

- tune spread $\Delta Q_y$
- 1 collision / turn
- 2 collisions / turn

horizontal tune $Q_x$
beam parameters investigated **beyond nominal LHC** ($N_b = 1.8-1.95 \times 10^{11}$, $\varepsilon = 1.2-1.4 \mu m$); no significant beam losses nor emittance effects observed with linear head-on parameter of $\xi_{bb} \sim 0.017/IP$ and $\xi_{bb} = 0.034$ (total) – more than 3x above LHC design!
luminosity and lifetime

W. Herr et al, June 2011

beam-beam MD #2: still no beam-beam limit found

twice nominal bunch intensity, half nominal emittance!
geometric reduction factor

formula for combined effect of crossing angle and hourglass

\[ R = \frac{\cos\left(\frac{\theta_c}{2}\right)}{\sqrt{\pi} \sigma_z} \int_{-\infty}^{\infty} \frac{e^{-As^2}}{1 + \left(\frac{s}{\beta^*}\right)^2} ds \]

\[ A = \frac{\sin^2\left(\frac{\theta_c}{2}\right)}{\sigma_x^2 \left(1 + \frac{s^2}{\beta^{*2}}\right)} + \frac{\cos^2\left(\frac{\theta_c}{2}\right)}{\sigma_z^2} \]
crossing angle

\[ R_\phi = \frac{1}{\sqrt{1 + \phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \]

“Piwinski angle”

\[ R_\phi \] luminosity reduction factor

nominal LHC

HL-LHC?
hourglass effect

important if \( \sigma_z \geq \beta^* \)

\[
\beta(s) = \beta^* + s^2/\beta^*
\]

\( R_{hg} \)

\( \sigma_z = 0.0755 \text{ m} \)

HL-LHC?

nominal LHC
performance 2010-2012
Peak Luminosity 2010

Peak Luminosity 2.2E32

Goal for 2010 : 1E32
Integrated Luminosity in 2010

ATLAS Online Luminosity $\sqrt{s} = 7$ TeV

- LHC Delivered All
- LHC Delivered Stable
- ATLAS Ready Recorded

45 pb$^{-1}$ recorded
Brief History of the Standard Model

Original discovery


2006 Dec 2009 Jan 2010 Feb Mar Apr May Jun Jul 2010

"Rediscovery" in CMS (dates approximate)
“Luminosity leveling” first tested 15 April 2011
Introduced luminosity leveling for LHCb \( \rightarrow \) can run at optimal \( \mu \) and \( L_{\text{max}} \)

\( \rightarrow \) Since end of May running at constant \( L \sim 3-3.5 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) with \( \mu \sim 1.5 \)

\( \rightarrow \) LHCb wants maximum time in physics and not an increase in peak performance
History of 2011 Peak Luminosity

- **Atlas Peak Luminosity**
- **LHCb Peak Luminosity**
- **Number of Bunches**

**Peak Luminosity** / $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

- **MD, technical stop**
- **Mini-Chamonix**
- **β* = 1m**

**Intensity Ramp Up**

- **75 ns**
- **50 ns**

**Emittance Reduction and intensity increase**

**Number of Bunches**
LHC peak luminosity in 2011
### LHC Instantaneous Luminosity: September 2011

<table>
<thead>
<tr>
<th>Experiment Status</th>
<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous Lumi (ub.s)^{-1}</td>
<td>3299.941</td>
<td>0.000</td>
<td>3194.219</td>
<td>66.763</td>
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<tr>
<td>BRAN Luminosity (ub.s)^{-1}</td>
<td>4064.439</td>
<td>8.672</td>
<td>5687.963</td>
<td>73.411</td>
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<tr>
<td>Fill Luminosity (nb)^{-1}</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
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<tr>
<td>BKGD 1</td>
<td>0.461</td>
<td>0.933</td>
<td>4.409</td>
<td>0.376</td>
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<tr>
<td>BKGD 2</td>
<td>96.851</td>
<td>0.000</td>
<td>12.909</td>
<td>8.319</td>
</tr>
<tr>
<td>BKGD 3</td>
<td>20.438</td>
<td>7.419</td>
<td>5.839</td>
<td>0.333</td>
</tr>
</tbody>
</table>

**LHCb VELO Position**: OUT, Gap: 58.0 mm

**STABLE BEAMS**

**TOTEM**: STANDBY

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**Record Lumi > 3.3e33 cm^{-2} s^{-1}**

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**Comments 30-09-2011 21:04:44**

So long Tevatron. We'll miss you. Thanks for everything.

**BIS status and SMP flags**

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<thead>
<tr>
<th></th>
<th>B1</th>
<th>B2</th>
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<tr>
<td>Link Status of Beam Permits</td>
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<td>Global Beam Permit</td>
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<tr>
<td>Setup Beam</td>
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<tr>
<td>Beam Presence</td>
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<tr>
<td>Moveable Devices Allowed In Stable Beams</td>
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<td>false</td>
</tr>
</tbody>
</table>

**AFS: Single_2b+12small_13_1_1bp14inj**

**PM Status B1**: ENABLED

**PM Status B2**: ENABLED

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R. Assmann, 19.09.2011

J. Uythoven, 03.10.2011
Protons

2011 Luminosity Production

Proton-Proton: $\sqrt{s} = 7$ TeV
All Experiments: $L_{\text{del}} = 12.517$ fb$^{-1}$

~ 6000 pb$^{-1}$

Goal 2011

Integrated Luminosity (pb$^{-1}$)
Heavy Ion Operation

Lead ion injector chain

- **ECR ion source (2005)**
  - Provide highest possible intensity of Pb$^{29+}$
- **RFQ + Linac 3**
  - Adapt to LEIR injection energy
  - Strip to Pb$^{54+}$
- **LEIR (2005)**
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS
- **PS (2006)**
  - Define LHC bunch structure
  - Strip to Pb$^{82+}$
- **SPS (2007)**
In 2010:
Peak ~$18\times 10^{24}$; Integrated ~$18\text{ub}^{-1}$
Max 137 bunches, larger $\beta^*$, smaller bunch intensities

Peak & Integrated Pb-Pb luminosity in 2011

356 bunches
### 2012 – canonical (long) year

<table>
<thead>
<tr>
<th>Activity</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine check-out</td>
<td>2</td>
</tr>
<tr>
<td>Commissioning with beam</td>
<td>21</td>
</tr>
<tr>
<td>Machine development</td>
<td>22</td>
</tr>
<tr>
<td>Technical stops</td>
<td>20</td>
</tr>
<tr>
<td>Scrubbing (25 ns)</td>
<td>3</td>
</tr>
<tr>
<td>Technical stop recovery</td>
<td>6</td>
</tr>
<tr>
<td>Initial intensity ramp-up</td>
<td>~21</td>
</tr>
<tr>
<td>Proton running</td>
<td>~126</td>
</tr>
<tr>
<td>Special runs</td>
<td>~8</td>
</tr>
<tr>
<td>Ion setup</td>
<td>4</td>
</tr>
<tr>
<td>Ion run</td>
<td>24</td>
</tr>
</tbody>
</table>

~150 days
2012 Run Configuration

• beam energy – 4 TeV
  - assuming low number of quenches
  - extra luminosity
    & higher cross sections
• bunch spacing 50 ns kept
• tight collimator settings
  - operationally proven
• ATLAS and CMS - $\beta^* = 60 \text{ cm}$
• ALICE and LHCb - $\beta^* = 3 \text{ m}$
  – natural satellites versus main bunches in ALICE
  – tilted crossing and offset luminosity leveling in LHCb

Real Challenge
2 high luminosity experiments (ATLAS, CMS)
1 mid-luminosity (LHCb)
  x20 lower
1 low-luminosity (ALICE)
  x10,000 lower!
also TOTEM and ALFA

S. Myers, IPAC12, New Orleans; R. Steinhagen, ICHEP 2012
2012 Achieved vs. Target Luminosity Estimates from Moriond (Mike Lamont & Steve Myers)

Assumptions:

- 4 TeV, 50 ns, 1380 bunches, 1.6e11, 2.5 um, pile-up ~ 35
- 150 days of proton physics (assuming similar efficiencies to 2011)
Achieved Peak Luminosity in 2012

LHC 2012 RUN (4 TeV/beam)

Peak luminosity ($10^{32}$ cm$^{-2}$ s$^{-1}$)

Month in 2012

Peak value predicted in February
Integrated Luminosity in 2012 so far

2012 integrated luminosities:
- ALICE: 1.64 pb\(^{-1}\)
- ATLAS: 8.49 fb\(^{-1}\)
- CMS: 8.47 fb\(^{-1}\)
- LHCb: 855 pb\(^{-1}\)
# LHC actual versus design parameters

<table>
<thead>
<tr>
<th></th>
<th>design</th>
<th>June 2012</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>7 TeV</td>
<td><strong>4 TeV</strong></td>
<td>&gt;1/2 design</td>
</tr>
<tr>
<td>transv. norm. emittance</td>
<td>3.75 µm</td>
<td><strong>2.6 µm</strong></td>
<td>0.7x design!</td>
</tr>
<tr>
<td>beta*</td>
<td>0.55 m</td>
<td>0.6 m</td>
<td>~ design for 7 TeV</td>
</tr>
<tr>
<td>IP beam size</td>
<td>16.7 µm</td>
<td>19 µm</td>
<td>~ design</td>
</tr>
<tr>
<td>bunch intensity</td>
<td>1.15x10^{11}</td>
<td><strong>1.48x10^{11}</strong></td>
<td>1.3xdesign!</td>
</tr>
<tr>
<td>luminosity / bunch</td>
<td>3.6x10^{30} cm^{-2}s^{-1}</td>
<td>1.1x10^{30} cm^{-2}s^{-1}</td>
<td>only factor 3 away (x4 from energy!)</td>
</tr>
<tr>
<td># bunches</td>
<td>2808</td>
<td>1380</td>
<td>~ ½ design</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>25 ns</td>
<td><strong>50 ns</strong></td>
<td></td>
</tr>
<tr>
<td>beam current</td>
<td>0.582 A</td>
<td>0.369 A</td>
<td>~60% design</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>7.55 cm</td>
<td>≥9 cm</td>
<td></td>
</tr>
<tr>
<td>crossing angle</td>
<td>285 µrad</td>
<td>290 µrad</td>
<td></td>
</tr>
<tr>
<td>“Piwinski angle”</td>
<td>0.64</td>
<td>≥0.69</td>
<td></td>
</tr>
<tr>
<td>luminosity</td>
<td>10^{34} cm^{-2}s^{-1}</td>
<td>6.8x10^{33} cm^{-2}s^{-1}</td>
<td>~design at 7 TeV</td>
</tr>
</tbody>
</table>
LHC magnetic cycle

- Preparation and access
- Injection phase
- Beam dump
- Energy ramp
- Coast

- Start of the ramp
- Turnaround time

- Time from start of injection (s)
- Dipole current (A)

L.Bottura, R.Schmidt
Performance Comparison 2011-2012

2011 Proton Run: Luminosity Production

- 19.3%
- 23.6%
- 18.9%
- 2.0%
- 3.5%
- 32.6%

SB Time: 26.6 days  Total Time: 81.4 days

2012

- Mode: Proton Physics
- Number of Fills: 236
- Time in SB: 23 days 21 hrs 55 mins

- 37.5%

Percentage of time in NO BEAM and SETUP is ~same

- NB
- Ramp
- SetUp
- FTSQAD
- Inj
- SB

- Access - No beam : 13.75%
- Machine setup : 27.03%
- Beam in : 14.84%
- Ramp + squeeze : 6.87%
- Stable beams: 37.5%

A. Mcpherson, June 2012
Intensities & Lumi over one week in June

Stable performance

Mixed bag

2e14

6e33

M. Lamont, 18 June 2012
### Overview of fills in the week of 11-18 June

<table>
<thead>
<tr>
<th>Fill</th>
<th>Duration</th>
<th>Ibeam [(e30 \text{ cm}^{-2}\text{s}^{-1})]</th>
<th>Lpeak [(\text{pb}^{-1})]</th>
<th>Lint [(\text{pb}^{-1})]</th>
<th>Dump</th>
</tr>
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<tbody>
<tr>
<td>2723</td>
<td>2:26</td>
<td>2.03E+14</td>
<td>6406</td>
<td>46.06</td>
<td>Trip of ROD.A81B1, SEU?</td>
</tr>
<tr>
<td>2724</td>
<td>1:13</td>
<td>2.03E+14</td>
<td>6329</td>
<td>25.905</td>
<td>Electrical perturbation</td>
</tr>
<tr>
<td>2725</td>
<td>7:04</td>
<td>2.05E+14</td>
<td>6520</td>
<td>115.5</td>
<td>Trip of S81</td>
</tr>
<tr>
<td>2726</td>
<td>8:58</td>
<td>2.05E+14</td>
<td>6499</td>
<td>142.5</td>
<td>Electrical perturbation, FMCM</td>
</tr>
<tr>
<td>2728</td>
<td>11:41</td>
<td>2.06E+14</td>
<td>6525</td>
<td>171.5</td>
<td><strong>Operator dump</strong></td>
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<tr>
<td>2729</td>
<td>3:28</td>
<td>2.06E+14</td>
<td>6502</td>
<td>67.7</td>
<td>BLM self trigger</td>
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<tr>
<td>2732</td>
<td>1:52</td>
<td>2.06E+14</td>
<td>6592.5</td>
<td>40</td>
<td>QPS trigger RQX.R1, SEU?</td>
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<tr>
<td>2733</td>
<td>12:34</td>
<td>2.06E+14</td>
<td>6674</td>
<td>183</td>
<td>Triplet RQX.L2 tripped.</td>
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<td>2734</td>
<td>15:33</td>
<td>2.01E+14</td>
<td>6257.5</td>
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<td>2737</td>
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<td>1.99E+14</td>
<td>6021</td>
<td>66.1</td>
<td>RF Trip 2B2</td>
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<tr>
<td>Tot</td>
<td>51.1%</td>
<td>1.99E+14</td>
<td>6021</td>
<td>66.1</td>
<td>1301</td>
</tr>
</tbody>
</table>

51% of time in stable beams; total **1.3 \(\text{fb}^{-1}\)** in one week

M. Lamont, 18 June 2012
# LHC 2012 Q3/Q4 – updated schedule

## July

<table>
<thead>
<tr>
<th>Wk</th>
<th>27</th>
<th>28</th>
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**Place holders**

**Scrubbing run (date tbc)**

**J. Genevois**

**MD**

**Xmas**

**Christmas technical stop**
LHC 2012 schedule - details

- TS3 moved to W38 17th September
- Lost TS4 (effectively moved to Xmas)
- End of proton run – 06:00 Monday 17th December

<table>
<thead>
<tr>
<th>Mode</th>
<th>Days left</th>
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<td>Technical stop</td>
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<td>Recovery from TS</td>
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<tr>
<td>Scrubbing - 25 ns</td>
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<tr>
<td>Proton running</td>
<td>~131</td>
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<tr>
<td>Special runs</td>
<td>~5</td>
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<tr>
<td>Ion setup</td>
<td>4</td>
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<tr>
<td>Ion run</td>
<td>24</td>
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</tbody>
</table>

we could get additional ~20/fb from now until 17 December
• Minimum interventions before and during Xmas stop
• Need both protons and lead (i.e. ion source, LINAC3, LEIR in addition...)
• Non-LHC physics is not foreseen – flat line complex when beam not needed
• Should foresee doing maximum p-A preparation before Christmas (pilot run, aperture measurements, test squeeze...)

End ion run 06:00
p-Pb lead collisions in 2013

Feasibility controversial

Beams of unequal revolution frequencies, moving long-range beam-beam encounters at injection and in ramp

RHIC abandoned equal rigidity acceleration

LHC 1st feasibility test on 31 October 2011:
Established new RF rephasing and cogging procedure
Stored 4 Pb bunches in presence of 304 p bunches (~10% nominal intensity) at injection; lifetime and emittance growth no worse for presence of p bunches
Ramped 2 Pb and 2 p bunches, good lifetime, cogging by 9 km w/o losses

LHC 2nd feasibility test planned for September 2012:
Ramp many p and some Pb bunches
Pilot physics fill with moderate no. of bunches
Indeed our work inspired an unknown artist working for the CERN Bulletin to create this moving depiction of an LHC proton discussing behavioural competenc(i)es with his supervisor.

Now the proton’s nightmare is coming true.
LHC beam dynamics
2011/12 Lessons for the Future

- Head-on beam-beam effect not a limitation
- **Long range beam-beam** to be taken seriously
  - Need sufficient separation (otherwise bad lifetime & beam loss) of $10^{-12} \sigma$ separation as expected
- Established $\beta^*$ reach (aperture, collimation, optics)
- *Lumi*-leveling via offset tested – works fine in LHCb!
- Alternative *Lumi*-leveling with $\beta^*$ tested during last MDs

- High-intensity operation close to beam instability limits
  - **Transverse instabilities for small IP beam offsets while going into collisions**, impedances (kicker, collimator heating)
  - **Electron cloud effects**, especially for 25 ns bunch spacing
  - Longitudinal instabilities controlled by longitudinal blow up

- Availability issues (SEUs, vacuum, **UFOs**, cryogenics, ...) – vigorous follow-up and consolidation

R. Steinhagen, ICHEP2012
Without beam cleaning (collimators):
Quasi immediate **quench of superconducting magnets** (for higher intensities) and stop of physics.
Required very good cleaning efficiency
Collimator Settings in 2012

Collimation hierarchy has to be respected to achieve satisfactory protection and cleaning.

Aperture plus tight settings allow us to squeeze to 0.6 m.
How tight?

Tight settings (2012):
~2.2 mm gap at primary collimator

Nose of George Washington on US quarter
LHC – measured cleaning at 3.5 TeV

Almost all protons losses in warm regions and not in cold SC arcs.

(it works!)

almost all protons losses in warm regions and not in cold SC arcs.
LHC interaction-region layout

- **final triplet quadrupoles**
- **separation dipole**

~59 m

nominal bunch spacing = 7.5 m
nominal collision spacing = 3.75 m → **about 2x15 collisions between IP and separation dipole!**
tune shift would increase 30 times!
solution: crossing angle
30 long-range collisions per IP, 120 in total
LR-BB: Losses per Bunch, August 2011

half crossing angle
100% = 120 µrad

HD 1-2-5
Strong LR

HD 8
Tiny LR

HD 1-5
Strong LR

HD 2-8
Small LR

W. Herr et al
LHC beam-beam tune footprint

nominal tune footprint up to $6\sigma$ with 4 IPs & nom. intensity $N_b=1.15\times10^{11}$

LHC design criterion: nominal total tune spread (up to $6\sigma$ in x&y) from all IPs and over all bunches, including long-range effects, should be less than 0.01 (experience at SPS collider)

$L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$
tune footprint when bringing LHC beams into collisions

w/o octupole magnets

w actual octupole magnet settings

shrinking footprint and octupole settings related to instabilities

Stephane Fartoukh, 3 July 2012
electron cloud

schematic of e-cloud build up in LHC beam pipe, due to photoemission and secondary emission

→ heat load (→ quenches), instabilities, emittance growth, poor beam lifetime

also synchrotron radiation & beam image currents add to heat load
Electron cloud: $\delta_{\text{max}}$ in the arcs: results (25ns) G. Rumolo

Three snapshots from the 25ns MDs to try disentangling aperture of Beam1 from Beam2
Electron cloud: $\delta_{\text{max}}$ in the arcs: results

$\delta_{\text{max}}$ has decreased from the initial 2.1 to 1.52 in the arcs!

2011 scrubbing history of LHC arcs

25ns threshold @450 GeV

25ns threshold @3.5 TeV
Electron-cloud beam observable: energy loss

Measurements $\rightarrow$ the energy loss per bunch is obtained from the stable phase shift

Simulations $\rightarrow$ We use as test case the last fill on 25 October

G. Rumolo, O. Boine-Frankenheim, F. Petrov, J. Esteban, E. Shaposhnikova, G. Iadarola
Electron-cloud beam observable: emittance growth

G. Rumolo

25-10-2011_25ns_F2251_B1

Normalized Emittance [µm]

Bunch position [µs]

Bunch intensity [ppb]

Bunch #

Electron-cloud beam observable: emittance growth

G. Rumolo
fully self-consistent simulation of e-cloud effects: build-up & beam dynamics

CERN SPS at injection (26 GeV): 3 trains of 72 bunches each passing 1000 turns around the entire ring, simulated with WARP-POSINST code using 9,600 CPUs on Franklin supercomputer (NERSC, U.S.A.)

LHC – longitudinal instability

1.1x10^{11}
1.05 ns – 0.35 eVs
(450 GeV, 5 MV)

loss of longit. Landau damping
during the ramp (1.8 TeV)

Z/n=0.06 Ohm

E. Shaposhnikova, G. Papotti

main cure: controlled longitudinal
blow up on LHC ramp

feedback on bunch length measurement modulates
noise amplitude to control blow-up rate;
bunch lengths converge correctly to target 1.5 ns
(now ~1.25 ns)
UFOs in the LHC
Since July 2010, **35 beam dumps** due to (un)identified **Falling Objects** (17 in 2011).

*Loss duration: about 10 turns.  
Often unconventional loss locations (e.g. in the arc).*

In 2011: **16,000 candidate UFOs** below BLM dump thresholds found.

$\frac{1}{x}$ distribution of BLM signal is well explained by dust particle size distribution measured in SM12. *(T. Baer et al., Evian Workshop 2011)*
- UFOs occur all around the LHC
- Many UFOs around injection kickers (MKIs)
- Some arc cells with significantly increased number of UFOs:
  - 25R3 B2: 144 UFOs
  - 19R3 B1: 126 UFOs.
  - 28R7 B2: 118 UFOs.
- No correlation with sector 34 repairs has been identified.
The rate of **5957 arc UFO events** during stable beam operation at top energy (stable beams) for all proton fills with at least one hour of stable beams between April 2011 and May 2012. During 2011, the rate decreased from about 10 events per hour to about 2 events per hour. The rate is reduced during the low intensity fills directly after the technical stops (TS).
UFOs: “dust” particles falling into the LHC beam?

**trajectory in x-y space**

design beam current, \( N_{\text{tot}} = 3.2 \times 10^{14} \)

- even particles of mass \( A = 10^{18} \) proton masses are charging up to be repelled upwards

present beam current, \( N_{\text{tot}} = 2.3 \times 10^{12} \)

- particles heavier than \( A = 10^{16} \) proton masses continue to fall down

macro-particle model including gravity, beam electric field, image force, charging, & beam loss

**resulting loss rates** (compare with quench threshold \(~a few 10^7 \text{ p/s}\))

design beam current

- longer and higher losses for present beam current!

present beam current

- total loss duration \(~a few \text{ ms}\)
asymmetric UFO shape indeed observed
UFO - Extrapolation to 7 TeV

T. Baer

arc UFOs at 7 TeV:
4x peak energy deposition
5x less quench margin
→ 20x signal/threshold
> 100 beam dumps?

Expected number of UFO related beam dumps and the expected scaling of arc BLM signal/threshold with energy
LHC – next years
LHC time line

- **Chamonix 2012**
- **LS1**
- **2012**
- **LS2**
- **2016**
- **Linac 4 ready**
- **2015**
- **PSB H-injection could be available**
- **2014**
- **2017**
- **2018**
- **2019**
- **2020**
- **2021**
- **2022**
- **SPS e-cloud mitigation, 200 MHz power upgrade**
- **PSB-PS transfer**
- **1.4 GeV → 2 GeV**
- **Injectors commissioned**
- **“Ultimate Physics”**
- **Physics @ 6.5/7 TeV**

NB: not yet fully approved
Long Shutdown 1 (LS1): 2013 to end ’14; afterwards operation around 7TeV/beam

LS1 Work

- repair defect interconnects
- consolidate all interconnects with new design
- complete installation of pressure release valves
- bring all necessary equipment up to the level needed for 7TeV/beam

S. Myers, IPAC12, New Orleans
LHC MB circuit splice consolidation proposal

Phase I
Surfacing of bus bar and installation of redundant shunts by soldering

Phase II
Application of clamp and reinforcement of nearby bus bar insulation

Phase III
Insulation between bus bar and to ground, Lorentz force clamping
Long Shutdown 2 (LS2): 2018; afterwards operation w higher brightness

LS2 Work (mainly)

- connect new Linac4 to PSB (50→160 GeV)
- set up H- injection into PSB
- increase extraction energy of PSB (1.4→2 GeV)
- SPS anti e-cloud coatings (?)
- PS & SPS RF improvements
- …
LHC and its injector chain

- Duoplasmatron = Source ● 90 keV (kinetic energy)
- LINAC2 = Linear accelerator ● 50 MeV
- PSBooster = Proton Synchrotron Booster ● 1.4 GeV
- PS = Proton Synchrotron ● 25 GeV
- SPS = Super Proton Synchrotron ● 450 GeV
- LHC = Large Hadron Collider ● 7 TeV
### 25 ns vs. 50 ns Bunch Spacing in 2012

#### Operational performance from injectors:

<table>
<thead>
<tr>
<th>Bunch spacing</th>
<th>From Booster</th>
<th>Protons per bunch (ppb)</th>
<th>Emittance H&amp;V [mm.mrad]</th>
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<td>150</td>
<td>Single batch</td>
<td>1.1 x 10^{11}</td>
<td>1.6</td>
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<td>75</td>
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<td>1.2 x 10^{11}</td>
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<td>Single batch</td>
<td>1.45 x 10^{11}</td>
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<td><strong>50</strong></td>
<td><strong>Double batch</strong></td>
<td><strong>1.7 x 10^{11}</strong></td>
<td><strong>2.1</strong></td>
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<tr>
<td>25</td>
<td>Double batch</td>
<td>1.15 x 10^{11}</td>
<td>2.8</td>
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\[ L_{\text{peak}} \approx \frac{f_{\text{rev}} k_b N_b^2}{4\pi \sigma_x \sigma_y} R = \frac{f_{\text{rev}} \gamma k_b N_b^2}{4\pi \beta^* \varepsilon_n} R \]

At the same total beam current 50 ns gives >2x more luminosity!
intermediate injector improvements
(2012, 2015)

SPS “Q20” optics
- increases bunch intensity limit up to 3x

batch compression in the PS
- 30-50% gain in brightness
New SPS optics Q26 $\rightarrow$ Q20

- **Low $\gamma_t$ optics by reducing (integer) tunes**
  - $\eta=(1/\gamma_t^2-1/\gamma^2)$ increased by factor 2.85 at injection and 1.6 at top energy by changing $\gamma_t$ from 22.8 ($Q_x\sim26$, nominal optics “Q26 optics”) to 18 ($Q_x\sim20 \rightarrow “Q20$ optics”)
    - Significantly increased dispersion in the arcs $\rightarrow$ lower $\gamma_t$
    - No increase of maximal $\beta$-function values; minima increased from 20m to 30m

- **Dispersion in long straight sections similar to nominal optics**
  - By choosing phase advance of $\mu\sim3\times2\pi$ per arc (instead of $\mu\sim4\times2\pi$)
SPS Q20 test (June 2012):
Emittances of **3e+11 bunch** in the LHC

\[ \varepsilon \sim 2 \, \mu m \text{ (both planes)} \]

H. Bartosik, C. Bracco, V. Kain, Y. Papaphilippou, et al
The desired final harmonic is achieved by additive steps (compression) and not just by multiplicative ones (splitting) so less PSB intensity is needed for the same final intensity per bunch.

Double batch 4+4b, $h=9 \rightarrow 10 \rightarrow 20 \rightarrow 21$, 16b

Double batch 4+2b, $h=7 \rightarrow 7+14+21 \rightarrow 21$, 18b
Transverse emittances at SPS exit have been measured at $\varepsilon_H = \varepsilon_V = 1.0\mu$m. Although this was only for 1.2E11ppb and hence represents a 30% gain in brightness rather than the 50% expected on paper, it was nevertheless readily achieved in a single brief parasitic MD.
25 ns limited by space charge in PS, PSB. SPS; SPS RF power & SPS longit. instabilities
50 ns limited by PS longitudinal instabilities & SPS space charge, and SPS TMCI
50 ns looks less favorable for the upgraded injectors…

Brennan Goddard, HL-LHC / LIU Joint Workshop (30 March 2012)
(my) forecast to 2021 (25 & 50 ns)

- total integrated luminosity \(\sim 500/fb\) by 2021
- by 2018 \(\sim 50\%\) more integrated luminosity with 50 ns
- peak luminosity reaching \(2-3\times10^{34}\, \text{cm}^{-2}\text{s}^{-1}\)
- little gain from LIU for 50 ns spacing ?!
(my) forecast to 2021 (25 & 50 ns)

- pile up high (80-120) in 2015-2017 with 50 ns spacing
  (50-ns pile up >2x more than for 25 ns spacing)
conclusion

switch to 25 ns bunch spacing in 2014/2015

keep 50 ns as backup in case of problems
(electron cloud, total intensity limit, …)
beyond 2021: LHC upgrades & extensions
High-Luminosity LHC (HL-LHC)

goals:

leveled peak luminosity: $L = 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
(detector pile up $\sim 140$)

“virtual peak luminosity”: $L \geq 20 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

integrated luminosity: 200 - 300 fb$^{-1}$/yr

total integrated luminosity: ca. 3000 fb$^{-1}$ by $\sim 2030$
HL-LHC – LHC modifications

Booster energy upgrade
1.4 $\rightarrow$ 2 GeV, ~2018

Linac4, ~2014

IR upgrade (detectors, low-$\beta$ quad’s, crab cavities, etc)
~2022

SPS enhancements (anti e-cloud coating, RF, impedance), 2012-2022

Booster energy upgrade
1.4 $\rightarrow$ 2 GeV, ~2018
luminosity leveling at the HL-LHC

example: maximum pile up 140 (σ_{inel} \sim 85 \text{ mbarn})

\[ L \left[ 10^{34} \text{ cm}^{-2}\text{s}^{-1} \right] \]

- no leveling w peak 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}
- leveling at 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}

\[ t \left[ \text{h} \right] \]
luminosity leveling at the HL-LHC

example: maximum pile up 140

$L \left[10^{34} \text{ cm}^{-2}\text{s}^{-1}\right]$
luminosity & integrated luminosity during 30 h at the HL-LHC

example: maximum pile up 140
## HL-LHC parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>HL-LHC 25 ns</th>
<th>HL-LHC 50 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>$E_b$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_b$ $[10^{11}]$</td>
<td>1.15</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>#bunches per beam</td>
<td>$n_b$</td>
<td>2808</td>
<td>1404</td>
<td>2808</td>
</tr>
<tr>
<td>beam current</td>
<td>$I$ [A]</td>
<td>0.58</td>
<td>1.01</td>
<td>0.83</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z$ [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
</tr>
<tr>
<td>beta* at IP1&amp;5</td>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>full crossing angle</td>
<td>$\theta_c$ [$\mu$rad]</td>
<td>285 ($9.5\sigma$)</td>
<td>590 ($12.5\sigma$)</td>
<td>590 ($11.4\sigma$)</td>
</tr>
<tr>
<td>normalized emittance</td>
<td>$\gamma\epsilon$ [$\mu$m]</td>
<td>3.75</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>IBS $\epsilon$ rise time ($z, x$)</td>
<td>$\tau_{IBS,z/x}$ [h]</td>
<td>57, 103</td>
<td>24, 17 (ATS)</td>
<td>17, 15 (ATS)</td>
</tr>
<tr>
<td>max. total b-b tune shift</td>
<td>$\Delta Q_{tot}$</td>
<td>0.011</td>
<td>0.013</td>
<td>0.017</td>
</tr>
<tr>
<td>potential pk luminosity</td>
<td>$L$ $[10^{34}$ cm$^{-2}$s$^{-1}]$</td>
<td>1</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>actual leveled pk luminosity</td>
<td>$L_{lev}$ $[10^{34}$ cm$^{-2}$s$^{-1}]$</td>
<td>1</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>max. #events / #ing (pile up)</td>
<td></td>
<td>19</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>effective beam lifetime</td>
<td>$\tau_{\text{eff}}$ [h]</td>
<td>44.9</td>
<td>15.6</td>
<td>25.7</td>
</tr>
<tr>
<td>level time, run time</td>
<td>$t_{\text{level}}$ [h], $t_{\text{run}}$ [h]</td>
<td>0, 15.2</td>
<td>7.8, 11.5</td>
<td>17.2, 20.1</td>
</tr>
<tr>
<td>needed availability</td>
<td>$A$ [%]</td>
<td>(50)</td>
<td>59</td>
<td>78</td>
</tr>
<tr>
<td>needed efficiency</td>
<td>$E$ [%]</td>
<td>(38)</td>
<td>41</td>
<td>63</td>
</tr>
<tr>
<td>annual integrated luminosity</td>
<td>$L_{int}$ [fb$^{-1}$]</td>
<td>(37)</td>
<td>250</td>
<td>200</td>
</tr>
</tbody>
</table>
schematic of crab crossing at HL-LHC

- RF crab cavity deflects head and tail in opposite direction so that collision is effectively “head on” for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, in operation at KEKB since 2007
Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), $\lambda/4$ TEM cavity by BNL (centre), and double-ridge $\lambda/2$ TEM cavity by SLAC & ODU (right).

Prototype compact Nb-Ti crab cavities for the LHC: 4-rod cavity (left) and double-ridge cavity (right).
LR LHeC: recirculating linac with energy recovery

RR LHeC: new ring in LHC tunnel, with bypasses around experiments

e-/e+ injector 10 GeV, 10 min. filling time
A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

Submitted to J.Phys. G

The CDR is submitted to the arXiv and to J.Phys.G
High-Energy LHC

HE-LHC
20-T dipole magnets

S-SPS?

2-GeV Booster

higher energy transfer lines

Linac4
time line of CERN HEP projects


LEP
Constr.  Physics  Upgr.

LHC
Design, R&D  Proto.  Constr.  Physics

HL-LHC
Design, R&D  Constr.  Physics

LHeC
Design, R&D  Constr.  Physics

HE-LHC
Design, R&D  Constr.  Physics

runs in parallel to HL-LHC; tight R&D schedule
follows HL-LHC; R&D & protot. time < for LHC

Source: L. Rossi. LMC 2011 (modified)
A first ring accelerates electrons and positrons up to operating energy (120 GeV) and injects them at a few minutes interval into the low-emittance collider ring, with two high luminosity $10^{34}$ cm$^{-2}$ s$^{-1}$ interaction points.
two LEP3 scenarios

• installation in the LHC tunnel “LEP3”
  + inexpensive
  + tunnel exists
  + reusing ATLAS and CMS detectors
  + reusing LHC cryoplants
  - interference with LHC and HL-LHC

• new larger tunnel “DLEP” or “TLEP”
  + higher energy reach
  + decoupled from LHC and HL-LHC operation and construction
  + tunnel can later serve for HE-LHC (factor ~3 in energy from tunnel alone) with LHC remaining as injector; also HE-LHeC
  - 3-4x more expensive (new tunnel, cryoplants, detectors?)
80-km tunnel for LEP3, LHeC & HE-LHC?

• New Ring of about 80km, connected to the existing LHC

• Two possible alignments considered:
  – 80km tunnel in the plain (option 1)
    • Passing under the Lake of Geneva
    • Passing behind the Salève mountain
    • Partially in limestones
    • Located both in France and Switzerland
    • Shafts every 10km (or inclined/double tunnel if shafts are not possible)
  – 80km tunnel in the Jura Mountain chain (option 2)
    • Vast majority in the Jura limestones
    • Fully located in France
    • Shafts every 10km (or inclined/double tunnel if shafts are not possible)

• The ring should be ‘connected’ to the LHC
• For this study only looking at the tunnel & shaft components.
80km tunnel project

Shaft locations are only indicative not permanent

Options:

- Option 1
- Option 2
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEP2</th>
<th>LHeC</th>
<th>LEP3</th>
<th>DLEP</th>
<th>TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy $E_b$ [GeV]</td>
<td>104.5</td>
<td>60</td>
<td><strong>120</strong></td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>26.7</td>
<td>26.7</td>
<td><strong>26.7</strong></td>
<td>53.4</td>
<td>80</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>4</td>
<td>100</td>
<td>7.2</td>
<td>14.4</td>
<td>5.4</td>
</tr>
<tr>
<td># bunches/beam</td>
<td>4</td>
<td>2808</td>
<td>4</td>
<td>60</td>
<td>12</td>
</tr>
<tr>
<td>#e-/beam [$10^{12}$]</td>
<td>2.3</td>
<td>56</td>
<td>4.0</td>
<td>16.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Horizontal emittance [nm]</td>
<td>48</td>
<td>5</td>
<td>25</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Vertical emittance [nm]</td>
<td>0.25</td>
<td>2.5</td>
<td>0.10</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>Bending radius [km]</td>
<td>3.1</td>
<td>2.6</td>
<td>2.6</td>
<td>5.2</td>
<td>9.0</td>
</tr>
<tr>
<td>Partition number $J_\epsilon$</td>
<td>1.1</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
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<tr>
<td>Momentum comp. $\alpha_c$ [$10^{-5}$]</td>
<td>18.5</td>
<td>8.1</td>
<td>8.1</td>
<td>2.0</td>
<td>1.0</td>
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<tr>
<td>SR power/beam [MW]</td>
<td>11</td>
<td>44</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$\beta_x$ [m]</td>
<td>1.5</td>
<td>0.18</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\beta_y$ [cm]</td>
<td>5</td>
<td>10</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$\sigma_x$ [$\mu$m]</td>
<td>270</td>
<td>30</td>
<td>71</td>
<td>45</td>
<td>63</td>
</tr>
<tr>
<td>$\sigma_y$ [$\mu$m]</td>
<td>3.5</td>
<td>16</td>
<td>0.32</td>
<td>0.22</td>
<td>0.32</td>
</tr>
<tr>
<td>Hourglass $F_{hg}$</td>
<td>0.98</td>
<td>0.99</td>
<td>0.67</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>$\Delta E_{SR, \text{loss/turn}}$ [GeV]</td>
<td>3.41</td>
<td>0.44</td>
<td>6.99</td>
<td>3.5</td>
<td>9.3</td>
</tr>
<tr>
<td>Parameter</td>
<td>LEP2</td>
<td>LHeC</td>
<td>LEP3</td>
<td>DLEP</td>
<td>TLEP</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>$V_{RF,tot}$ [GV]</td>
<td>3.64</td>
<td>0.5</td>
<td>12.0</td>
<td>6.0</td>
<td>12.0</td>
</tr>
<tr>
<td>$\delta_{max,RF}$ [%]</td>
<td>0.77</td>
<td>0.66</td>
<td>4.2</td>
<td>4.2</td>
<td>4.9</td>
</tr>
<tr>
<td>$\xi_x/IP$</td>
<td>0.025</td>
<td>N/A</td>
<td>0.09</td>
<td>0.05</td>
<td>N/A</td>
</tr>
<tr>
<td>$\xi_y/IP$</td>
<td>0.065</td>
<td>N/A</td>
<td>0.08</td>
<td>0.05</td>
<td>N/A</td>
</tr>
<tr>
<td>$f_s$ [kHz]</td>
<td>1.6</td>
<td>0.65</td>
<td>3.91</td>
<td>0.97</td>
<td>0.43</td>
</tr>
<tr>
<td>$E_{acc}$ [MV/m]</td>
<td>7.5</td>
<td>11.9</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>eff. RF length [m]</td>
<td>485</td>
<td>42</td>
<td>600</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>$f_{RF}$ [MHz]</td>
<td>352</td>
<td>721</td>
<td>1300</td>
<td>1300</td>
<td>700</td>
</tr>
<tr>
<td>$\delta_{SR}^{rms}$ [%]</td>
<td>0.22</td>
<td>0.12</td>
<td>0.23</td>
<td>0.16</td>
<td>0.22</td>
</tr>
<tr>
<td>$\sigma_{SR,z,rms}$ [cm]</td>
<td>1.61</td>
<td>0.69</td>
<td>0.23</td>
<td>0.16</td>
<td>0.25</td>
</tr>
<tr>
<td>$L/IP[10^{32}cm^{-2}s^{-1}]$</td>
<td>1.25</td>
<td>N/A</td>
<td>107</td>
<td>144</td>
<td>65</td>
</tr>
<tr>
<td>number of IPs</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rad.Bhabha b.lifetime [min]</td>
<td>360</td>
<td>N/A</td>
<td>16</td>
<td>42</td>
<td>54</td>
</tr>
<tr>
<td>$\gamma_{BS} [10^{-4}]$</td>
<td>0.2</td>
<td>0.05</td>
<td>10</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>$n_y$ / collision</td>
<td>0.08</td>
<td>0.16</td>
<td>0.60</td>
<td>0.25</td>
<td>0.51</td>
</tr>
<tr>
<td>$\Delta\delta_{BS}$/collision [MeV]</td>
<td>0.1</td>
<td>0.02</td>
<td>33</td>
<td>12</td>
<td>61</td>
</tr>
<tr>
<td>$\Delta\delta_{BS,rms}$/collision [MeV]</td>
<td>0.3</td>
<td>0.07</td>
<td>48</td>
<td>26</td>
<td>95</td>
</tr>
</tbody>
</table>
thank you!