LHC Machine Upgrades

Roger Bailey, CERN, Geneva

The plans for increasing the integrated luminosity of the LHC beyond its nominal parameters are well under way. The first upgrade is based on improvement of the collimation system, probably the most limiting factor at present. This will allow to reach and to pass the nominal $10^{34}$ cm$^{-2}$ s$^{-1}$. Other improvements in the injector chain (Linac4, PSB at 2 GeV, SPS upgrade) and in the LHC ring (a new cryo-plant for cooling of SC RF cavities, removal of radiation limitation in electronic equipment, etc.) should be able to bring us around 1.7-2 $10^{34}$ cm$^{-2}$s$^{-1}$. Then, in the longer term a major upgrade involving:

- New Inner Triplets and insertion magnets
- A revision of the matching region and of the corrector system
- Crab Cavities to allow full exploitation of the low $\beta^*$ of the new triplets
- New cryoplants dedicated to the cooling of the new magnets and cavities

The implementation of this new scheme accompanied by other possible improvements under consideration (shorter bunches, etc.) should allow a peak luminosity of $\sim 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ and improved luminosity lifetime by “luminosity leveling”. Finally, the very preliminary outcome of first discussions and studies on a LHC energy upgrade to around 28-33 TeV cm will be presented.
Instantaneous luminosity

\[ L = \frac{N^2 k_b f}{4\pi\sigma_x \sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n \beta^*} F \]

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

- Nearly all the parameters are variable (and not independent)
  - Number of bunches per beam \( k_b \)
  - Number of particles per bunch \( N \)
  - Normalised emittance \( \varepsilon_n \)
  - Relativistic factor \( \gamma \)
  - Beta function at the IP \( \beta^* \)
  - Crossing angle factor
    - Full crossing angle \( \theta_c \)
    - Bunch length \( \sigma_z \)
    - Transverse beam size at the IP \( \sigma^* \)

\[ F = \frac{1}{\sqrt{1 + \left( \frac{\theta_c \sigma_z}{2\sigma^*} \right)^2}} \]
# LHC nominal performance

## Nominal settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (TeV)</td>
<td>7.0</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>2808</td>
</tr>
<tr>
<td>Crossing angle ($\mu$rad)</td>
<td>285</td>
</tr>
<tr>
<td>Norm transverse emittance ($\mu$m rad)</td>
<td>3.75</td>
</tr>
<tr>
<td>Bunch length (cm)</td>
<td>7.55</td>
</tr>
<tr>
<td>Beta function at IP 1, 2, 5, 8 (m)</td>
<td>0.55, 10, 0.55, 10</td>
</tr>
</tbody>
</table>

## Derived parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity in IP 1 &amp; 5 (cm$^{-2}$ s$^{-1}$)</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>Luminosity in IP 2 &amp; 8 (cm$^{-2}$ s$^{-1}$)*</td>
<td>$\sim 5 \times 10^{32}$</td>
</tr>
<tr>
<td>Transverse beam size at IP 1 &amp; 5 ($\mu$m)</td>
<td>16.7</td>
</tr>
<tr>
<td>Transverse beam size at IP 2 &amp; 8 ($\mu$m)</td>
<td>70.9</td>
</tr>
<tr>
<td>Stored energy per beam (MJ)</td>
<td>362</td>
</tr>
</tbody>
</table>

* Luminosity in IP 2 and 8 optimized as needed
LHC performance drivers

- Total Intensity
- Beam Brightness
- Interaction region ($\beta^*, F$)
- Aperture
- Optics
- Energy
- Interconnects
- Training
- Machine protection
Evolution of target energy during commissioning

- All main magnets commissioned for 7 TeV operation before installation
  - 7 TeV, 2002-2007, Design

- Detraining found when hardware commissioning sectors in 2008
  - Easy to get to 5 TeV
  - Harder to get to 6 TeV or higher
  - Summer 2008, 5 TeV, Detraining

- Machine wide investigations following S34 incident showed problem with splices
  - Late 2008, 9 kA, Splices

- Machine wide investigations following S34 incident showed problem with stabilizers
  - Summer 2009, 3.5 TeV, Stabilizers

- Commissioning of new QPS system
  - Breakdown at operational voltage
    - Connector quality
  - Obliged to run at lower voltage
    - OK for 2 kA
    - Need to change connectors
  - October 2009, 1.18 TeV, nQPS

- 450 GeV
Train magnets
  – Should be easy to get to 6 TeV
  – 6.5 TeV should be in reach
  – 7 TeV will take time

Fix stabilizers for 12 kA

Complete pressure relief system

Fix connectors

Commission nQPS system

Commission circuits to 6 kA

The way back

<table>
<thead>
<tr>
<th>When</th>
<th>What</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>2 kA</td>
</tr>
<tr>
<td>2009</td>
<td>1.18 TeV</td>
</tr>
<tr>
<td>2010</td>
<td>6 kA</td>
</tr>
<tr>
<td>2010</td>
<td>nQPS</td>
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<tr>
<td>2011</td>
<td>3.5 TeV</td>
</tr>
<tr>
<td>2013</td>
<td>Stabilizers</td>
</tr>
<tr>
<td>2014?</td>
<td>Training</td>
</tr>
<tr>
<td>2014?</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

450 GeV
LHC Intensity limits 2010 2011

- Collimation system conceived as a staged system
  - First stage installed and allows 40% of nominal intensity at 7TeV
    - Under certain assumptions
      - LHC lifetimes and loss rates
      - 0.1%/s assumed (0.2h lifetime)
      - Ideal cleaning
    - Imperfections bring this down
      - Deformed jaws
      - Tilt & offset & gap errors
      - Machine alignment
    - Machine stability
      - Tight settings a challenge early
      - Intermediate settings make use of aperture to relax tolerances
  - Under certain assumptions
    - LHC lifetimes and loss rates
    - 0.1%/s assumed (0.2h lifetime)
    - Ideal cleaning
  - Imperfections bring this down
    - Deformed jaws
    - Tilt & offset & gap errors
    - Machine alignment
  - Machine stability
    - Tight settings a challenge early
    - Intermediate settings make use of aperture to relax tolerances
  - Fix $I_{\text{max}}$ to $6 \times 10^{13}$ protons per beam at 3.5TeV (about 20% nominal intensity)
  - 30MJ stored beam energy
- At higher energies cleaning gets harder !!!
Higher intensities

• With experience assume that we can
  – Move to tight settings
  – Achieve 0.1% loss rates
  – Get the imperfection factor down
    • Should allow to push to higher intensities at 3.5 TeV
    • Still have the 40% limit expected at 7 TeV

• Then need to install something more
  – Collimators in the cold regions of the machine in 2012
    • Using “missing magnet” space in the dispersion suppressors
    • Requires moving magnets in LSS3 and LSS7 (24 magnets each)
    • Being pursued with high priority
β* and F in 2010 2011

• Lower energy means bigger beams
  – Less aperture margin around the IP
  – Higher β* helps in this

• > 150 bunches requires crossing angle
  – Requires more aperture
  – Higher β* again helps

• Targets for 3.5TeV
  – 2m no crossing angle
  – 3m with crossing angle
β* evolution

• The squeeze is always going to be challenging
  – Changing optics with dangerous beams
  – Follow / anticipate with collimators
  – Particularly tricky below 1m

• With experience, should be easier, but still …
Early beam operation

- Energy limited to 3.5 TeV
- 2010
  - Intensity carefully increased to collimation limit
  - $\beta^*$ pushed as low as possible
  - Target luminosity $10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- 2011
  - Run at established limits
  - Target integrated luminosity 1 fb$^{-1}$

40% efficiency for physics $\rightarrow$ 10$^6$ seconds collisions per month

10$^6$ seconds @ $\langle L \rangle$ of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ $\rightarrow$ 100 pb$^{-1}$
## Getting to nominal (dates indicative)

### Energy

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>3.5</td>
</tr>
<tr>
<td>2011</td>
<td>3.5</td>
</tr>
<tr>
<td>2012</td>
<td>3.5</td>
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<tr>
<td>2013</td>
<td>3.5</td>
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<tr>
<td>2014</td>
<td>3.5</td>
</tr>
<tr>
<td>2015</td>
<td>3.5</td>
</tr>
<tr>
<td>2016</td>
<td>3.5</td>
</tr>
</tbody>
</table>

### Splices, Collimators in IR3

- β⁺ of 2m
- 20% of $I_{\text{nom}}$
- Initial
  - $10^{32}$
  - $1 \text{ fb}^{-1}$

### Increase Beam Energy to 7TeV

- Decrease β⁺ to 0.55m
- Increase $k_b$ to 2808

### Nominal

- $10^{34}$
- $\leq 50 \text{ fb}^{-1}/\text{yr}$

### LHC Performance Drivers

- Total intensity
- Beam brightness
- Injection chain
- Machine stability
- Machine protection
## Overall strategy beyond 2016 (dates indicative)

### Increase Beam Energy to 16.5 TeV

- **New interaction region**
  - ($\beta^* \text{to } 0.2 \text{m}, \text{luminosity leveling}$)

### Increase beam brightness

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<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>$2.3 \times 10^{34}$</td>
<td>$5 \times 10^{34}$</td>
<td>$\leq 100 \text{ fb}^{-1}/\text{yr}$</td>
<td>$\leq 200 \text{ fb}^{-1}/\text{yr}$</td>
<td>$\leq 100 \text{ fb}^{-1}/\text{yr}$</td>
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<td></td>
</tr>
<tr>
<td>HE-LHC</td>
<td>$2 \times 10^{34}$</td>
<td>$\leq 100 \text{ fb}^{-1}/\text{yr}$</td>
<td>$\leq 100 \text{ fb}^{-1}/\text{yr}$</td>
<td>$\leq 100 \text{ fb}^{-1}/\text{yr}$</td>
<td>$\leq 100 \text{ fb}^{-1}/\text{yr}$</td>
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</tbody>
</table>

### LHC performance drivers

- Total intensity
- Beam Brightness
- Injection chain
- Machine imperfections
- Machine protection
- Energy
- Intercollimation

### LHC Performance Equation

$$L = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$
Present accelerator complex

LHC beam route:
- LINAC2
- BOOSTER (PSB)
- PS
- SPS
The present accelerators are getting old (PS is 50 years old...) and they operate far beyond their initial design parameters.

- Luminosity depends directly upon beam brightness $N/\varepsilon^*$

- Brightness is limited by space charge at low energy in the injectors

$\Rightarrow$ Need to increase the injection energy in the injection synchrotrons
Injector chain

- **Scenario 1 (pre 2010)**
  - Replace old machines
  - Consolidate SPS
  - **Realistic planning 2020**

- **Scenario 2 (2010)**
  - Consolidate all machines
  - Upgrade PSB energy
  - **Realistic planning 2015**
## Intensity Limits

Reminder design = 1.15 (for $10^{34}$); Ultimate = 1.7 (for $2.3 \times 10^{34}$)

### Intensity Limitations ($10^{11}$ protons per bunch)

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>SPL-PS2</th>
<th>2GeV in PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac2/LINAC4</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>PSB or SPL</td>
<td>3.6</td>
<td>4.0</td>
<td>3.6</td>
</tr>
<tr>
<td>PS or PS2</td>
<td>1.7</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>SPS</td>
<td>1.2</td>
<td>&gt;1.7?</td>
<td>&gt;1.7?</td>
</tr>
<tr>
<td>LHC</td>
<td>1.7-2.3?</td>
<td>1.7-2.3?</td>
<td>1.7-2.3?</td>
</tr>
</tbody>
</table>

### Conclusion from (or just after) Chamonix workshop in February 2010:
- We continue (as planned) and finish the study for LP-SPL/PS2
- Study in parallel the PS Booster energy upgrade
- Decision can be taken when we have the results of these studies
High Luminosity Interaction Regions

Goals of Phase I of the original upgrade project:

- flexibility & performance
- improve spares count
- cope with radiation damage
- enable focusing of the beams to $\beta^* = 0.3 \text{ m}$ in IP1 and IP5

Scope of the project:

1. Upgrade of ATLAS and CMS interaction regions: Interfaces between LHC and experiments remain unchanged.
2. Cryogenic cooling capacity and other infrastructure in IR1 and IR5 remain unchanged and will be used to full potential.
3. Replace present triplets with wide aperture quadrupoles based on the LHC dipole (Nb-Ti) cables cooled at 1.9 K.
4. Upgrade D1 separation dipole, TAS and other beam-line equipment (also TAN) so as to be compatible with the inner triplets.
5. Modify matching sections (D2-Q4, Q5, Q6) to improve optics flexibility, and introduce other equipment to the extent possible.
Reconsidered at Chamonix 2010

1. Will the phase 1 upgrade produce an increase in useful integrated luminosity?
2. Do we have the resources to complete on a time scale which is reasonable with respect to phase 2?

• Key preliminary findings (report forthcoming)
  – Can expect 1.2 to 1.35 better luminosity with present limitations
    • 30 cm $\beta^*$ is more difficult than 55 cm of the present LHC. Better solution found with $\beta^* = 40$ cm offering a 3 sigma margin per beam (which was part of the initial goal) but only 1.2 gain in lumi over nominal. Today we are limited by a single element. IR upgrade will use all the margins in the whole ring.
  – Radiation damage not an issue till 2020 with evolution now expected
  – In any case the Triplet cannot be built before 2016 at best (resources)
New study underway

- **High Gradient/Large Aperture Quads, with** \( B_{\text{peak}} \) **13-15 T.** US-LARP engaged to produce proof using Nb3Sn by 2013. Construction is 1 year more than Nb-Ti: 2018 is a reasonable assumption. Nb-Ti remains as a backup solution.

- Higher field quadrupoles translate into
  - higher gradient/shorter length
  - larger aperture/same length
  - or a mix of the two

- \( \beta^* \) as small as 22 cm are possible with a **factor \( \sim 2.5 \)** in luminosity by itself, **if coupled with a mechanism to compensate the geometrical reduction**

- **Crab Cavities:** this is the best candidate for exploiting small \( \beta^* \) (for \( \beta^* \) around nominal only +15%). However, it should be underlined that today Crab Cavities are not validated for LHC, not even conceptually: **the issue of machine protection should be addressed with priority**

- **SC links** to replace at the surface electronic equipment today in the tunnel and exposed to high radiation

- **New Cryoplants** in IP1 & IP5: for power AND to make independent Arc-IR: 2.8 kW @ 1.8 K scales as 5.2 kW @ 2 K (for 1 set of cold compressor)
Crab cavities for exploiting low $\beta^*$

![Graph showing luminosity vs. $\beta^*$ for different scenarios: Nominal crossing, No crossing angle, CC 800MHz.](graph.png)

- Upgrade with CC (40-63% more)
- Nominal with CC (10-15% more)
- No Crabs

![Diagram illustrating crab cavities and crossing angle $\theta_c$.](diagram.png)
Provisional route to achieving all this

**Shutdowns**

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2016</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHC machine</strong></td>
<td>Splices for 7 TeV Collimators in IR3 R2E driven modifications</td>
<td>Collimation phase II Prepare for crab cavities</td>
<td>New Triplets Crab cavities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>New RF cryogenic system</td>
<td></td>
</tr>
<tr>
<td><strong>LHC experiments</strong></td>
<td>ALICE – TID and calorimeter ATLAS – forward beam pipes CMS – infrastructure LHCb – conical beam pipe</td>
<td>Assuming 30 to 50 fb$^{-1}$ ALICE – new vertex detector</td>
<td>Assuming 300 to 600 fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ATLAS – pixel detector + upgrades CMS – many improvements</td>
<td>ALICE – vertex detector upgrade</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LHCb – full trigger upgrade, new vertex detector</td>
<td>ATLAS – new inner detector</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CMS – new inner detector</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LHCb –</td>
</tr>
<tr>
<td><strong>Injectors</strong></td>
<td>In two 3-4 month shutdowns • Preparations for PSB energy upgrade</td>
<td>Linac 4 connection to PSB Completion of PSB energy</td>
<td>Consolidation of all machines</td>
</tr>
<tr>
<td></td>
<td>• SPS upgrade</td>
<td>upgrade for 2 GeV operation PS and SPS consolidation</td>
<td>in 3-4 month injector shutdowns</td>
</tr>
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<td></td>
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</table>
“First Thoughts on a Higher-Energy LHC”

Ralph Assmann, Roger Bailey, Oliver Brüning, Octavio Dominguez Sanchez, Gijs de Rijk, Miguel Jimenez, Steve Myers, Lucio Rossi, Laurent Tavian, Ezio Todesco, Frank Zimmermann

Abstract:
We report preliminary considerations for a higher-energy LHC (“HE-LHC”) with about 16.5 TeV beam energy and 20-T dipole magnets. In particular we sketch the proposed principal parameters, luminosity optimization schemes, the new HE-LHC injector, the magnets required, cryogenics system, collimation issues, and requirements from the vacuum system.

Table of Contents:
1. Parameters
2. Luminosity optimization
3. Injector
4. Magnets
5. Cryogenics studies
6. Vacuum system
7. Collimation issues

7/22/2010
HE-LHC

Provisional parameter list for LHC energy upgrade at 33 TeV centre-of-mass energy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal LHC</th>
<th>LHC energy upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [TeV]</td>
<td>7</td>
<td>16.5</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>8.33</td>
<td>20</td>
</tr>
<tr>
<td>dipole coil aperture [mm]</td>
<td>56</td>
<td>40</td>
</tr>
<tr>
<td>beam half aperture [cm]</td>
<td>2.2 (x), 1.8 (y)</td>
<td>1.3</td>
</tr>
<tr>
<td>#bunches</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>bunch population [$10^{11}$]</td>
<td>1.15</td>
<td>1.29</td>
</tr>
<tr>
<td>initial transverse normalized emittance [μm]</td>
<td>3.75</td>
<td>3.75, 1.84</td>
</tr>
<tr>
<td>initial longitudinal emittance [eVs]</td>
<td>2.5</td>
<td>4.0</td>
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<tr>
<td>number of IPs contributing to tune shift</td>
<td>3</td>
<td>2</td>
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<tr>
<td>initial total beam-beam tune shift</td>
<td>0.01</td>
<td>0.01 (x &amp; y)</td>
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<tr>
<td>maximum total beam-beam tune shift</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>RF voltage [MV]</td>
<td>16</td>
<td>32</td>
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<tr>
<td>rms bunch length [cm]</td>
<td>7.55</td>
<td>6.5</td>
</tr>
<tr>
<td>rms momentum spread [$10^{-4}$]</td>
<td>1.13</td>
<td>0.9</td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>1 (x), 0.43 (y)</td>
</tr>
<tr>
<td>initial rms IP spot size [μm]</td>
<td>16.7</td>
<td>14.6 (x), 6.3 (y)</td>
</tr>
<tr>
<td>full crossing angle [μrad]</td>
<td>285 (9.5 σₓᵧ)</td>
<td>175 (12 σₓ₀)</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>0.65</td>
<td>0.39</td>
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<tr>
<td>geometric luminosity loss from crossing</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>stored beam energy [MJ]</td>
<td>362</td>
<td>478.5</td>
</tr>
</tbody>
</table>
LHeC

• 2 options on the table
  – Ring-Ring
    • e-p and e-A (A=Pb, Ar, ...) collisions, limited possibilities for polarized e
    • More “conventional” solution, like HERA, no difficulties of principle at first sight but constrained by existing LHC in tunnel
    • Steady progress with detailed design
  – Linac-Ring
    • e-p and e-A (A=Pb, Ar, ...) collisions, polarized e from source, poorer Luminosity/Power
    • No previous collider like this (at present)
    • Comparisons of layouts
• No interference with LHC
• Meets design parameters
• Synchrotron radiation energy loss < 50 MW (maximum dipole filling)
• 2 quadrupoles families
• Reasonable sextupole strength and length
• Dedicated injector at 10 GeV

$10^{33} \text{cm}^{-2} \text{s}^{-1}, \int L = 100 \text{fb}^{-1}, E_e = 60 \text{GeV}$
Table 4: Lepton beam parameters and luminosity.

<table>
<thead>
<tr>
<th></th>
<th>p-60</th>
<th>erl</th>
<th>p-140</th>
</tr>
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<tbody>
<tr>
<td>e⁻ energy at IP [GeV]</td>
<td>60</td>
<td>60</td>
<td>140</td>
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<tr>
<td>luminosity [10⁻²² cm⁻² s⁻¹]</td>
<td>1.1</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>polarization [%]</td>
<td>90</td>
<td>90</td>
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<td>bunch population [10⁹]</td>
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<td>1.6</td>
</tr>
<tr>
<td>e⁻ bunch length [μm]</td>
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<td>300</td>
<td>300</td>
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<tr>
<td>bunch interval [ns]</td>
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<td>50</td>
<td>50</td>
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<tr>
<td>transv. emit. γₑₓ,ᵧ</td>
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<td>50</td>
<td>100</td>
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<tr>
<td>rms IP beam size [μm]</td>
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<td>7</td>
</tr>
<tr>
<td>hourglass reduction H₉₉</td>
<td>0.91</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>crossing angle θₑ</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>repetition rate [Hz]</td>
<td>10</td>
<td>CW</td>
<td>10</td>
</tr>
<tr>
<td>bunches/pulse [10⁵]</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>pulse current [mA]</td>
<td>16</td>
<td>10</td>
<td>6.6</td>
</tr>
<tr>
<td>beam pulse length [μs]</td>
<td>5</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>ER efficiency η</td>
<td>0</td>
<td>94%</td>
<td>0</td>
</tr>
<tr>
<td>total wall plug power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Arc Radius = 120 m

Length = 1.5 + 4 * 0.12 + 0.3 (IR?) = 2.3 km

Arc Radius = 700 m

30 or 70 GeV Bypass

Length = 3.9 + 0.3 + 0.3 (IR?) = 4.5 km
Summary

• Clear goals for 2010 and 2011
• Route to nominal pretty clear \((E, k_b, \beta^*)\)
  – Needs collimation upgrade in 2012
• Pragmatic upgrade of the injectors for around 2016
  – Linac 4, upgraded booster
• Single upgrade of the HL IRs around 2020
• Planning will be finalised during second half of 2010
  – Ongoing HL-LHC task force (Chamonix 2011 if not before)
  – Ongoing HE-LHC study group (Chamonix 2011 if not before)
  – Ongoing LHeC machine study group (CDR Q4 2010)