short LHC history

1983 *LEP Note 440* - S. Myers and W. Schnell propose twin-ring *pp* collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle
1992 EoI, LoI of experiments
1993 SSC termination
1994 CERN Council: LHC approval
1995-98 cooperation w.Japan, India, Russia, Canada, & US
2000 LEP completion
2006 last s.c. dipole delivered
2008 first beam
2010 first collisions at 3.5 TeV beam energy
2015 collisions at ~design energy (plan)

*we are already late if we want to get a new machine by ~2040!*

>30 years!
LHC: highest energy *pp, AA, and pA* collider

design parameters

c.m. energy = 14 TeV \( (p) \)
luminosity = \( 10^{34} \) cm\(^{-2}\)s\(^{-1} \)

1.15x10\(^{11} \) p/bunch

2808 bunches/beam

360 MJ/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
integrated $pp$ luminosity 2010-12

- **2010**: 0.04 fb$^{-1}$
  - 7 TeV CoM
  - Commissioning

- **2011**: 6.1 fb$^{-1}$
  - 7 TeV CoM
  - Exploring the limits

- **2012**: 23.3 fb$^{-1}$
  - 8 TeV CoM
  - Production

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
reliable luminosity forecasts

2012 Measured vs Predicted

- Integrated Lumi 50 (pb-1)
- Measured 50ns (pb-1)
### Peak Performance through the Years

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch spacing [ns]</td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>no. of bunches</td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td>2808</td>
</tr>
<tr>
<td>beta* [m] ATLAS and CMS</td>
<td>3.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.55</td>
</tr>
<tr>
<td>max. bunch intensity [protons/bunch]</td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.45 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>normalized emittance [mm-mrad]</td>
<td>$\sim 2.0$</td>
<td>$\sim 2.4$</td>
<td>$\sim 2.5$</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$2.1 \times 10^{32}$</td>
<td>$3.7 \times 10^{33}$</td>
<td><strong>$7.7 \times 10^{33}$</strong></td>
<td>$1.0 \times 10^{34}$</td>
</tr>
</tbody>
</table>

>2x design when scaled to 7 TeV!

M. Lamont, IPAC’13
Huge efforts over last months to prepare for high lumi and pile-up expected in 2012:

- optimized trigger and offline algorithms (tracking, calo noise treatment, physics objects)
  - mitigate impact of pile-up on CPU, rates, efficiency, identification, resolution
- in spite of x2 larger CPU/event and event size
  - we do not request additional computing resources (optimized computing model, increased fraction of fast simulation, etc.)

\[ Z \rightarrow \mu\mu \text{ event from 2012 data with 25 reconstructed vertices} \]

pile up will increase at higher energy
\rightarrow experiments request 25 ns operation in 2015
$\sqrt{s} = 7$ TeV $\int L dt = 0.05$ fb$^{-1}$ Apr 24, 2011

**ATLAS** Preliminary

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel

- Light blue: Signal ($m_H = 125$ GeV)
- Red: Background ZZ$^{(*)}$
- Magenta: Background Z+jets, $t\bar{t}$
- Black: Data
LHCb

LHCb luminosity levelling at around 4e32 cm\(^{-2}\)s\(^{-1}\) via transverse separation (with a tilted crossing angle)

not completely trivial!

first evidence for the decay \(B_s \rightarrow \mu^+ \mu^-\)

M. Lamont, IPAC’13
LHC injector complex

SPS: 26 to 450 GeV

PSB: 50 MeV to 1.4 GeV

PS: 1.4 to 26 GeV
Pb-Pb

- good performance from the injectors - bunch intensity and emittance
- preparation, Lorentz’ law: impressively quick switch from protons to ions
- peak luminosity around $5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ at $3.5Z$ TeV (2011) – nearly twice design when scaled to $6.5Z$ TeV

M. Lamont, IPAC’13
proton-lead

- beautiful result in early 2013
- final integrated luminosity above experiments’ request of 30 nb\(^{-1}\)
- injectors: average number of ions per bunch was \(\sim 1.4 \times 10^8\) at start of stable beams, i.e. around twice the nominal intensity

Beam orbits at top energy with RF frequencies locked to Beam 1
Beam dump
Ramp down/precycle
Injection
Ramp
Squeeze
Collide
Stable beams

Ramp down 35 mins
Injection ~30 mins
Ramp 12 mins
Squeeze 15 mins
Collide 5 mins
Stable beams 0 – 30 hours

turn around 2 to 3 hours on a good day

M. Lamont, IPAC’13
availability

- “There are a lot of things that can go wrong – it’s always a battle”
- Pretty good availability considering the complexity and principles of operation

Cryogenics availability in 2012: 93.7%
some issues in 2011-12 operation

Beam induced heating
- Local non-conformities (design, installation)
  - injection protection devices
  - sync. Light mirrors
  - vacuum assemblies

UFOs
- 20 dumps in 2012
- time scale 50-200 µs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

Radiation to electronics
- concerted program of mitigation measures (shielding, relocation...)
- premature dump rate down from 12/fb⁻¹ in 2011 to 3/fb⁻¹ in 2012

arc UFOs at 7 TeV:
4x peak energy deposition
5x less quench margin
→ 20x signal/threshold
> 100 beam dumps?
earlier this week – “All Clear” for LHC UFOs?

UK closed UFO desk after 50yrs and no 'potential threat'

Jun 21, 2013

The British government finally shut down a special unit investigating UFO sightings after more than 50 years as it was a drain on resources and not a single report ever revealed "a potential threat to the United Kingdom," newly released government files showed Friday.
another issue in 2011-12 operation

Electron cloud
• beam induced multipactoring process, depending on secondary emission yield
• LHC strategy based on surface conditioning (scrubbing runs)
• worry about 25 ns (more conditioning needed) and 6.5 TeV (photoelectrons)

25-ns scrubbing in 2011 – decrease of SEY

25-ns scrubbing in 2012 – conditioning stop?
Long Shutdown 1 - motivation

after 2008 incident partial consolidation & related problem of imperfect Cu stabilizer continuity discovered in 2010-12 LHC operated at 7 & 8 TeV c.m. beam energy to avoid any risk presently: Long Shutdown 1 (LS1) ~2 yr to prepare LHC for 13-14 TeV c.m., detector upgrades in parallel
2008 “incident”

A faulty bus-bar (SC splice) in a magnet interconnect failed, leading to an electric arc which dissipated some 275 MJ.

This burnt through beam vacuum and cryogenic lines, rapidly releasing ~2 tons of liquid helium into the vacuum enclosure.

R. Veness
The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines
7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes
2015 – post LS1

- energy: 6.5 TeV (magnet retraining)
- bunch spacing: 25 ns
  – pile-up considerations
- injectors potentially able to offer nominal intensity with even lower emittance

<table>
<thead>
<tr>
<th>Number of bunches</th>
<th>Ib LHC FT[1e11]</th>
<th>Emit LHC [um]</th>
<th>Peak Lumi [cm^{-2}s^{-1}]</th>
<th>~Pile-up</th>
<th>Int. Lumi per year [fb^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns low emit</td>
<td>2520</td>
<td>1.15</td>
<td>1.9</td>
<td>1.7e34</td>
<td>52</td>
</tr>
</tbody>
</table>

BCMS = Batch Compression and Merging and Splitting

expected maximum luminosity from inner triplet heat load (collisions debris) $1.7 \times 10^{34}$ cm^{-2}s^{-1} ±20%
uncertainties for 2015:

- electron cloud
- UFOs

both get more difficult at 25 ns & at higher energy

- energy (limited by retraining)
draft early 2015 schedule

Re-commissioning with beam

HW tests & machine checkout

Pilot

Scrubbing

5 nb^{-1}

7.0 TeV

3.5 TeV

in red beam time requested by LHCf
example LHC time line – next ten years

- 2012: Chamonix
- 2013: LS1
- 2014: LS1
- 2015: Linac 4 ready
- 2016: PSB H-injection could be available
- 2017: LS2
- 2018: SPS e-cloud mitigation, 200 MHz power upgrade
- 2019: PSB-PS transfer 1.4 GeV → 2 GeV
- 2020: Injectors commissioned
- 2021: “Ultimate Physics”
- 2022: HL-LHC

Physics @ 6.5/7 TeV

NB: not yet fully approved
Linac4 (160 MeV $H^-$ instead of 50-MeV $p$)

Linac4 could double the beam brightness injected into the booster, but there may be other bottlenecks downstream (e.g. PS injection)
discussion elements concerning next 10 years

• next long shutdowns LS2 & LS3 – needs & dates
• regular Christmas stops (13 weeks?)
• “LS1.5” for CMS – 4.5 months in 2016/17?
• - exchange of CMS pixel tracker
• extended 3-months ion run in 2016?
• connecting Linac4 (6-7 months) during ion run
• & LS1.5?
• 400/fb by 2021?
LHC luminosity forecast

~30/fb at 3.5 & 4 TeV

~400/fb at 6.5-7 TeV

~3000/fb at 7 TeV

2012 DONE

2021 goal (?)

2035 goal (??)

to obtain 3000/fb by 2035

we need the HL-LHC
HL-LHC – modifications

IR upgrade
(detectors, low-β quad’s, crab cavities, a few high-field dipoles, etc)
~2022

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

Booster energy upgrade
1.4 → 2 GeV, ~2018

Linac4,
~2015
(HL-)LHC Time Line

Shut down for interconnects to overcome energy limitation (LHC incident of Sept. 2008) and R2E

Full upgrade

Shut down to overcome beam intensity limitation (Injectors, collimation and more...)

two reasons for HL-LHC: performance & consolidation
in LHC: 1.2 km of new equipment ...

6.5 kW@4.5K cryoplant

2 x 18 kW @4.5K cryoplants for IRs
## HL-LHC Official Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25ns</th>
<th>50ns</th>
<th>6.2 $10^{14}$ and 4.9 $10^{14}$ p/beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>3.5E+11</td>
<td></td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
<td></td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.12</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>x-ing angle [$\mu$rad]</td>
<td>300</td>
<td>590</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>beam separation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td></td>
<td>12.5</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_n$ [$\mu$m]</td>
<td>3.75</td>
<td>2.5</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_L$ [eVs]</td>
<td>2.51</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>energy spread</td>
<td>1.20E-04</td>
<td>1.20E-04</td>
<td>1.20E-04</td>
<td></td>
</tr>
<tr>
<td>bunch length [m]</td>
<td>7.50E-02</td>
<td>7.50E-02</td>
<td>7.50E-02</td>
<td></td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>106</td>
<td>20.0</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td>60</td>
<td>15.8</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.68</td>
<td>3.1</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>geom. reduction</td>
<td>0.83</td>
<td>0.35</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>beam-beam / IP</td>
<td>3.10E-03</td>
<td>3.9E-03</td>
<td>5.0E-03</td>
<td>(Leveled to 5 $10^{34}$ cm$^{-2}$ s$^{-1}$ and 2.5 $10^{34}$ cm$^{-2}$ s$^{-1}$)</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$1 \times 10^{34}$</td>
<td>$7.4 \times 10^{34}$</td>
<td>$8.5 \times 10^{34}$</td>
<td></td>
</tr>
<tr>
<td>Virtual Luminosity</td>
<td>$1.2 \times 10^{34}$</td>
<td>$21 \times 10^{34}$</td>
<td>$26 \times 10^{34}$</td>
<td></td>
</tr>
<tr>
<td>Events / crossing (peak &amp; leveled L)</td>
<td>210</td>
<td>475</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>
luminosity leveling at the HL-LHC

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

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

no leveling w peak \(2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\)

leveling at \(5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)

nominal

\(t\) [h]
luminosity leveling at the HL-LHC

example: maximum pile up 140

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

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

average no level
average level
luminosity & integrated luminosity during 30 h at the HL-LHC

example: maximum pile up 140

- 4 fb^{-1} per day, with 40% of efficiency
- \sim 250 fb^{-1} /year
final goal : 3000 fb$^{-1}$ by 2030’s...
some HL-LHC ingredients

new final quadrupole
• $Nb_3Sn$ instead of $Nb-Ti$
• larger aperture allowing smaller $\beta^*$

11-T dipoles for dispersion suppressors
• $Nb_3Sn$ instead of $Nb-Ti$
• provide space for extra collimators catching off-energy protons or ions at ALICE, collimator sections, ATLAS & CMS

SC link
• move radiation sensitive power converters away from machine
• first prototype, 20 m – 20 kA, under test at CERN!

LQS03 (90 mm ap., 3.7 m long):
208 T/m@4.6 K, 210 T/m@1.9 K

HQ02a (120 mm, 1.5 m long):
150 T/m@4.6 K, 170 T/m@1.9 K

Goal: 150 mm ap, 140 T/m

1-m model tested in April 2014, $B_{nom}=11$ T achieved!

Next: 2-m single bore, then 2-in-1
tests of novel $MgB_2$ and $HTS$ (YBCO and BSCCO) cables
HL-LHC optics

Achromatic Telescopic Squeeze (ATS), «fully proven» MDs ($\beta^* = 15$ cm «easy», room for $\beta^* \sim 10$-12 cm)

squeeze through the arcs to enhance effective sextupole strength;
tested with beam in LHC MDs of 2011 & 2012

typical ATS collision optics with IR1 & IR5 squeezed down to $\beta^*=10$ cm
luminosity reduction due to crossing angle is more pronounced at smaller $\beta^*$

"Piwinski angle"

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

eff. beam size:

\[ \sigma_{x,\text{eff}}^* \approx \sigma_x^*/R_\theta \]

luminosity reduction factor

\[ R_\theta \]

nominal LHC

crab cavities

HL-LHC

$\Theta \sim 1/\beta^*$
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, used in operation at KEKB since 2007.

Until recently plan was to vary crab cavity voltage for leveling, but this would change size of luminous region & is disliked by experiments (instead leveling by $\beta^*$ or offset?)
HL-LHC needs compact crab cavities
only 19 cm beam separation, but long bunches

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).
**breaking news** – PoP double-ridge cavity achieved 7 MV deflecting voltage cw

- **Expected**
  - $Q_0 = 6.7 \times 10^9$
  - At $R_S = 22 \, \text{nM}
  - And $R_{\text{res}} = 20 \, \text{nM}$

- **Achieved**
  - $Q_0 = 4.0 \times 10^9$

- **Achieved fields**
  - $E_T = 18.6 \, \text{MV/m}$
  - $V_T = 7.0 \, \text{MV}$
  - $E_P = 75 \, \text{MV/m}$
  - $B_P = 131 \, \text{mT}$

**better than required!**

J. Delayen, LARP CM20
HL-LHC preliminary budget estimate

<table>
<thead>
<tr>
<th></th>
<th>Improving Consolidation</th>
<th>Full performance</th>
<th>Total HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mat. (MCHF)</td>
<td>476</td>
<td>360</td>
<td>836</td>
</tr>
<tr>
<td>Pers. (MCHF)</td>
<td>182</td>
<td>31</td>
<td>213</td>
</tr>
<tr>
<td>Pers. (FTE-y)</td>
<td>910</td>
<td>160</td>
<td>1070</td>
</tr>
<tr>
<td>TOT (MCHF)</td>
<td>658</td>
<td>391</td>
<td>1,049</td>
</tr>
</tbody>
</table>
### 3 scenarios

<table>
<thead>
<tr>
<th>PICs</th>
<th>US1</th>
<th>US2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Improving Consolidations</td>
<td>+HHRF?+DS collimators?</td>
<td>+crab cavities, e-lens,...</td>
</tr>
<tr>
<td><strong>integrated luminosity by 2035</strong></td>
<td>1000-1200/fb</td>
<td>2000/fb</td>
</tr>
</tbody>
</table>

**physics needs & motivation?; also, reasons to go >3000/fb?**
beyond HL-LHC?
High-Energy LHC

HE-LHC
20-T dipole magnets

S-SPS?

ALICE

LHC 2008 (27 km)

ATLAS

TT60

2-GeV Booster

Linac4

AD 1999 (182 m)

PS 1959 (628 m)

ISOLDE 1999

LEIR 2005 (78 m)

CMS

TT10

TT40

TT41

TT18

North Area

Gran Sasso

CNGS 2006

neutrinos

n-ToF 2001

electronics

East Area

higher energy transfer lines
20-T dipole magnet

E. Todesco, L. Rossi, P. McIntyre
80-km tunnel for VHE-LHC – “best” option

the same tunnel could host an $e^+e^-$ Higgs factory “TLEP” (LAL seminar 22 March 2013) and a highest-luminosity highest-energy $e-p/A$ collider
TLEP/VHE-LHC tunnel site visit (!?) on Lake Geneva 12 June 2013
## HE-LHC & VHE-LHC parameters – 1

<table>
<thead>
<tr>
<th>parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>VHE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td>14</td>
<td>33</td>
<td>100</td>
</tr>
<tr>
<td>circumference C [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>80</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>8.33</td>
<td>8.33</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>dipole coil aperture [mm]</td>
<td>56</td>
<td>56</td>
<td>40</td>
<td>≤ 40</td>
</tr>
<tr>
<td>beam half aperture [cm]</td>
<td>~ 2</td>
<td>~ 2</td>
<td>1.3</td>
<td>≤ 1.3</td>
</tr>
<tr>
<td>injection energy [TeV]</td>
<td>0.45</td>
<td>0.45</td>
<td>&gt; 1.0</td>
<td>&gt; 3.0</td>
</tr>
<tr>
<td>no. of bunches ( n_b )</td>
<td>2808</td>
<td>2808</td>
<td>2808</td>
<td>8420</td>
</tr>
<tr>
<td>bunch population ( N_b ) ( [10^{11}] )</td>
<td>1.15</td>
<td>2.2</td>
<td>0.94</td>
<td>0.97</td>
</tr>
<tr>
<td>init. transv. norm. emit. [( \mu \text{m} )]</td>
<td>3.75</td>
<td>2.5</td>
<td>1.38</td>
<td>2.15</td>
</tr>
<tr>
<td>initial longitudinal emit. [eVs]</td>
<td>2.5</td>
<td>2.5</td>
<td>3.8</td>
<td>13.5</td>
</tr>
<tr>
<td>no. IPs contributing to tune shift</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>max. total beam-beam tune shift</td>
<td>0.01</td>
<td>0.015</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>beam circulating current [A]</td>
<td>0.584</td>
<td>1.12</td>
<td>0.478</td>
<td>0.492</td>
</tr>
<tr>
<td>rms bunch length [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>0.15 (min.)</td>
<td>0.35</td>
<td>1.1</td>
</tr>
<tr>
<td>rms IP spot size [( \mu \text{m} )]</td>
<td>16.7</td>
<td>7.1 (min.)</td>
<td>5.2</td>
<td>6.7</td>
</tr>
<tr>
<td>full crossing angle [( \mu \text{rad} )]</td>
<td>285</td>
<td>590</td>
<td>185</td>
<td>72</td>
</tr>
<tr>
<td>stored beam energy [MJ]</td>
<td>362</td>
<td>694</td>
<td>701</td>
<td>6610</td>
</tr>
</tbody>
</table>

O. Dominguez, L. Rossi, F.Z.
## HE-LHC & VHE-LHC parameters – 2

<table>
<thead>
<tr>
<th>parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>VHE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR power per ring [kW]</td>
<td>3.6</td>
<td>7.3</td>
<td>96.2</td>
<td>2900</td>
</tr>
<tr>
<td>arc SR heat load [W/m/aperture]</td>
<td>0.17</td>
<td>0.33</td>
<td>4.35</td>
<td>43.3</td>
</tr>
<tr>
<td>energy loss per turn [keV]</td>
<td>6.7</td>
<td>6.7</td>
<td>201</td>
<td>5857</td>
</tr>
<tr>
<td>critical photon energy [eV]</td>
<td>44</td>
<td>44</td>
<td>575</td>
<td>5474</td>
</tr>
<tr>
<td>photon flux ([10^{17}/\text{m/s}])</td>
<td>1.0</td>
<td>2.0</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>longit. SR emit. damping time [h]</td>
<td>12.9</td>
<td>12.9</td>
<td>1.0</td>
<td>0.32</td>
</tr>
<tr>
<td>horiz. SR emit. damping time [h]</td>
<td>25.8</td>
<td>25.8</td>
<td>2.0</td>
<td>0.64</td>
</tr>
<tr>
<td>init. longit. IBS emit. rise time [h]</td>
<td>57</td>
<td>23.3</td>
<td>40</td>
<td>396</td>
</tr>
<tr>
<td>init. horiz. IBS emit. rise time [h]</td>
<td>103</td>
<td>10.4</td>
<td>20</td>
<td>157</td>
</tr>
<tr>
<td>peak events per crossing</td>
<td>27</td>
<td>135 (lev.)</td>
<td>147</td>
<td>171</td>
</tr>
<tr>
<td>total/inelastic cross section [mb]</td>
<td>111 / 85</td>
<td>129 / 93</td>
<td>153 / 108</td>
<td></td>
</tr>
<tr>
<td>peak luminosity ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</td>
<td>1.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>beam lifetime due to burn off [h]</td>
<td>45</td>
<td>15.4</td>
<td>5.7</td>
<td>14.8</td>
</tr>
<tr>
<td>optimum run time [h]</td>
<td>15.2</td>
<td>10.2</td>
<td>5.8</td>
<td>10.7</td>
</tr>
<tr>
<td>opt. av. int. luminosity / day [fb^{-1}]</td>
<td>0.47</td>
<td>2.8</td>
<td>1.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>

O. Dominguez, L. Rossi, F.Z.
controlled blow up is applied in transverse & longitudinal planes, maintaining $\Delta Q_{x,y} = 0.01$ and constant bunch length, respectively.
HE-LHC & VHE-LHC luminosities could greatly improve for bunch spacings < 25 ns, e.g. by factor 5 for 5 ns, and make better use of strong radiation damping!

are 5 ns spacing & $2.5 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ acceptable for the (V)HE-LHC detectors?

first indications: not inconceivable for ~2040
**pp Higgs factories**

**LHC is the 1st Higgs factory!**  
\[ E_{CM} = 8-14 \text{ TeV}, \ L \sim 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

**HL-LHC (~2022-2030):**  
\[ E_{CM} = 14 \text{ TeV}, \ L \sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \text{ (leveled)} \]

**HE-LHC: in LHC tunnel (2035-?)**  
\[ E_{CM} = 33 \text{ TeV}, \ L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

**VHE-LHC in new 80-100 km tunnel (2040?)**  
\[ E_{CM} = 84-104 \text{ TeV}, L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

- 1 M Higgs produced so far – more to come!
- 15 H bosons / min – and more to come
- 10x more Higgs
- 6x higher cross section for \( H \) self coupling
- 42x higher cross section for \( H \) self coupling
**pp Higgs coupling cross sections vs c.m. energy**

<table>
<thead>
<tr>
<th>M. Mangano</th>
<th>HE-LHC</th>
<th>VHE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma(14\ \text{TeV})$</td>
<td>$R(33)$</td>
</tr>
<tr>
<td>ggH</td>
<td>50.4 pb</td>
<td>3.5</td>
</tr>
<tr>
<td>VBF</td>
<td>4.40 pb</td>
<td>3.8</td>
</tr>
<tr>
<td>WH</td>
<td>1.63 pb</td>
<td>2.9</td>
</tr>
<tr>
<td>ZH</td>
<td>0.90 pb</td>
<td>3.3</td>
</tr>
<tr>
<td>ttH</td>
<td>0.62 pb</td>
<td>7.3</td>
</tr>
<tr>
<td>HH</td>
<td>33.8 fb</td>
<td>6.1</td>
</tr>
</tbody>
</table>

- **High statistics studies of ttH**
- ... and, at long last, HHH couplings

**VHE-LHC is ultimate machine to measure Higgs self coupling!**

(\sim 2-5\% level)
TLEP - circular $e^+e^-$ colliders to study the «Higgs boson» $X(126)$

a relatively young concept (2011)
### Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) [arxiv1302:3318]

#### Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e⁺e⁻ colliders, as compiled from the Higgs Factory 2012 workshop.

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC</th>
<th>Full ILC</th>
<th>CLIC</th>
<th>TLEP3, 4 IP</th>
<th>TLEP, 4 IP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Quantity</td>
<td>300 fb⁻¹/expt</td>
<td>3000 fb⁻¹/expt</td>
<td>250 GeV</td>
<td>5 yrs</td>
<td>250+350+1000 GeV</td>
<td>5 yrs each</td>
<td>350 GeV (500 fb⁻¹)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.4 TeV (1.5 ab⁻¹)</td>
</tr>
<tr>
<td>N_H</td>
<td>1.7 × 10^7</td>
<td>1.7 × 10^8</td>
<td>6 × 10^4 ZH</td>
<td>10^5 ZH</td>
<td>7.5 × 10^5 ZH</td>
<td>4 × 10^5 ZH</td>
<td>2 × 10^6 ZH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5 × 10^4 Hvv</td>
</tr>
<tr>
<td>m_H (MeV)</td>
<td>100</td>
<td>50</td>
<td>35</td>
<td>35</td>
<td>100</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>ΔΓ_H / Γ_H</td>
<td>--</td>
<td>--</td>
<td>10%</td>
<td>3%</td>
<td>ongoing</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>ΔΓ_{inv} / Γ_H</td>
<td>Indirect (30%?)</td>
<td>Indirect (10%?)</td>
<td>1.5%</td>
<td>1.0%</td>
<td>ongoing</td>
<td>0.35%</td>
<td>0.15%</td>
</tr>
<tr>
<td>𝛿g_{Hγ} / 𝛿g_{Hγ}</td>
<td>6.5 – 5.1%</td>
<td>5.4 – 1.5%</td>
<td>--</td>
<td>5%</td>
<td>ongoing</td>
<td>3.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>𝛿g_{Hee} / 𝛿g_{Hee}</td>
<td>11 – 5.7%</td>
<td>7.5 – 2.7%</td>
<td>4.5%</td>
<td>2.5%</td>
<td>&lt; 3%</td>
<td>2.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>𝛿g_{Hww} / 𝛿g_{Hww}</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>4.3%</td>
<td>1%</td>
<td>~1%</td>
<td>1.5%</td>
<td>0.25%</td>
</tr>
<tr>
<td>𝛿g_{Hzz} / 𝛿g_{Hzz}</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>~1%</td>
<td>0.65%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Δ𝑔_{HHTT} / Δ𝑔_{HHTT}</td>
<td>&lt; 30% (2 expts)</td>
<td>&lt; 30%</td>
<td>~30% (≈11% at 3 TeV)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Δ𝑔_{HH} / Δ𝑔_{HH}</td>
<td>&lt; 30%</td>
<td>&lt; 10%</td>
<td>--</td>
<td>--</td>
<td>10%</td>
<td>14%</td>
<td>7%</td>
</tr>
<tr>
<td>Δ𝑔_{Htt} / Δ𝑔_{Htt}</td>
<td>8.5 – 5.1%</td>
<td>5.4 – 2.0%</td>
<td>3.5%</td>
<td>2.5%</td>
<td>≤ 3%</td>
<td>1.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Δ𝑔_{Hee} / Δ𝑔_{Hee}</td>
<td>--</td>
<td>--</td>
<td>3.7%</td>
<td>2%</td>
<td>2%</td>
<td>2.0%</td>
<td>0.65%</td>
</tr>
<tr>
<td>Δ𝑔_{Hbb} / Δ𝑔_{Hbb}</td>
<td>15 – 6.9%</td>
<td>11 – 2.7%</td>
<td>1.4%</td>
<td>1%</td>
<td>1%</td>
<td>0.7%</td>
<td>0.22%</td>
</tr>
<tr>
<td>Δ𝑔_{Htt} / Δ𝑔_{Htt}</td>
<td>14 – 8.7%</td>
<td>8.0 – 3.9%</td>
<td>--</td>
<td>5%</td>
<td>3%</td>
<td>--</td>
<td>30%</td>
</tr>
</tbody>
</table>

(*) The total luminosity is the sum of the integrated luminosity at all energies.

See seminar of 22 March
SuperKEKB – TLEP demonstrator!

beam commissioning will start in early 2015

- $\beta_y^* = 300 \, \mu m$ (TLEP: 1 mm)
- lifetime 5 min (TLEP: ~15 min)
- $\varepsilon_y / \varepsilon_x = 0.25\%$ (~TLEP)
- off momentum acceptance
- $e^+$ production rate

\[ L = \frac{\gamma \pm}{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \frac{I_{\pm, \pm} \varepsilon_y}{\beta_y^*} \frac{R_L}{R_y} \right) \]
VHE-LHC + TLEP

HE-LHC-LER (0.17→1.5 T)
TLEP collider (0.07 or 0.05T)
TLEP injector (0.007→0.05/7 T)

multipurpose tunnel

transmission line magnet
(B. Foster, H. Piekarz)

20 mm thick shield around cable
Gaps: 2 x V30xH60 mm

HE-LHC (20 T)

super-resistive cable

based on MgB₂ SC
only 12 MEuro/100 km!

Cable:
inner core of 40 mm Cu (700 mm²)
+ outer core: 2 layers, 150 strands of MgB₂, 1 kA each; Outer size 45 mm.
120 kA =>120 k€/km!

For electrons: Cu water cooled,
J₀ 2.5 A/mm²

For protons: 800 A/strands
120 kA (for >2.1 T); central copper acts as stabilizer
common modular detectors for $e^+e^-$ and $pp$ collisions!? 

GMS-2T (TLEP)  

GMS-4T (VHE-LHC)
conclusions - LHC

• LHC running well & predictably; 2 years 3 months from 1st collisions to Higgs; foundations for run II
• in 2015 LHC will operate close to design energy with peak luminosity likely to exceed the design
• new performance limits will be encountered (e.g. triplet cooling limit)
• baseline for 2015 is 25 ns, but uncertainties with regard to e-cloud and UFOs; backup option: 50 ns with leveling (pile up)
• plans & schedules for injector upgrade and longer shutdowns till~2022 to be reviewed this fall
conclusions – HL-LHC & beyond

• well defined, key prototypes successfully tested
• plan & goals for HL-LHC under review
  - budget considerations & LHC results
• HL-LHC develops the technology ($Nb_3Sn$ magnets, 20-kA HTS cables) for future higher energy $pp$ colliders: HE-LHC (33 TeV c.m.) and/or VHE-LHC (100 TeV c.m.)
• TLEP, in VHE-LHC tunnel, being studied as highest-luminosity $e^+e^-$ Higgs factory
  - excellent energy resolution, & superb performance at $Z$ pole, $W$ & top threshold
• glorious future ahead of us with right strategy
possible long-term strategy

TLEP (80-100 km, \(e^+e^-, \text{ up to } \sim 350 \text{ GeV c.m.}\))

VHE-LHC (\(pp, \text{ up to } 100 \text{ TeV c.m.}\))

“same” detectors!?

\& \(e^\pm (120 \text{ GeV})-p (7, 16 \& 50 \text{ TeV})\) collisions ([V)HE-]TLHeC)

\(\geq 50\) years of \(e^+e^-, pp, ep/A\) physics at highest energies
possible long-term time line
Global endeavour: collaborators from Europe, US, Japan, China,…

Next events: TLEP workshops 25-26 July 2013, Fermilab 16-18 October, CERN 

Joint VHE-LHC+ TLEP kick-off meeting in February 2014