The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.
New LHC / HL-LHC Plan

Run I
- 0.75 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
- 50 ns bunch
- high pile up \(\sim 40\)

Run II
- 1.5 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
- 25 ns bunch
- pile up \(\sim 40\)

Run III
- 1.7-2.2 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
- 25 ns bunch
- pile up \(\sim 60\)

Technical limits
(experiments too)
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with levelling, allowing:

An integrated luminosity of $250 \text{ fb}^{-1}$ per year, enabling the goal of $3000 \text{ fb}^{-1}$ twelve years after the upgrade. This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Concept of ultimate performance: under definition:

$L_{\text{peak}} \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and $\text{Int. } L \sim 4000 \text{ fb}^{-1}$
This goal would be reached in 2036

How do we make this jump?

M. Lamont,
at RLIUP workshop, October 2013
Luminosity increase

- Increasing the crossing angle decreases the long range effect but decreases geometric overlap
- Rotating the bunches with crab cavities before and after collision can reduce this effect

\[ L \propto \frac{N_b^2}{\sigma^2}/R_{\Phi}F_{RF} \]

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>after LS1</th>
<th>after LS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>3.5 TeV</td>
<td>4 TeV</td>
<td>7 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$\beta^*$ [cm]</td>
<td>100</td>
<td>60</td>
<td>55</td>
<td>15</td>
</tr>
<tr>
<td>$2\phi$ [\mu rad]</td>
<td>260</td>
<td>313</td>
<td>247</td>
<td>473</td>
</tr>
</tbody>
</table>

$R_\phi(\sigma_z = 7.55\text{cm})$: 0.94, 0.85, 0.82, 0.37
$R_\phi(\sigma_z = 10.1\text{cm})$: 0.76, 0.74, 0.28

Dramatic Benefit in Geometric Luminosity with CC
(Reduction Factor from RF Curvature Included, $\theta_c = 1/\beta$)
Nominal LHC with CC (10-15 % more)
HiLumi: largest HEP accelerator in construction

Dispersion Suppressor (DS)
- Modifications
  1. In IP2: new DS collimation in C.Cry.
  2. In IP7 new DS collimation with 11 T
- + Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr... extension of infrastr.

Matching Section (MS)
- Complete change and new lay-out in IP1-IP5
  1. TAN
  2. D2
  3. CC
  4. Q4
  5. All correctors
  6. Q5 (Q6 @1.9 K?)
  7. New MQ in P6
  8. New collimators

Interaction Region (ITR)
- Complete change and new lay-out in IP1-IP5
  1. TAS
  2. Q1-Q2-Q3
  3. D1
  4. All correctors
  5. Heavy shielding (W)
- > 1.2 km of LHC !!

G Burt RAL June16
But work is required all around the ring...

- **Cryo@P4**
- **Beam diagnostics BGV**
- **Cryo@P1-P5**
- **New TAS and VCX**
The critical zone around IP1 and IP5

1. Deep change in the IRs and interface to detectors; relocation of Power Supply
2. Deep change also matching section: Magnets, collimators and CC
3. For collimation we need to change also this part, DS in the continuous cryostat
4. LR BB compensation wires

1.2 km of LHC !!
The most straightforward action: reducing beam size with a «local» action

LHC has a better aperture than anticipated: however it is not possible to have $\beta^* < 40 \text{ cm}$

Smaller $\beta^* \Rightarrow$ larger aperture
Magnet progress

- LHC dipoles features 8.3 T in 56 mm (designed for 9.3 peak field)
- LHC IT Quads features 205 T/m in 70 mm with 8 T peak field
- HL-LHC
  - 11 T dipole (designed for 12.3 T peak field, 60 mm)
  - New IT Quads features 140 T/m in 150 mm > 12 T operational field, designed for 13.5 T)

![Field progress in accelerator magnets](image)
LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

LHC (USA & JP, 5-6 m)
Ø70 mm, $B_{\text{peak}} \sim 8$ T
1992-2005

LARP TQS & LQ (4m)
Ø90 mm, $B_{\text{peak}} \sim 11$ T
2004-2010

LARP HQ
Ø120 mm, $B_{\text{peak}} \sim 12$ T
2008-2014

LARP & CERN MQXF
Ø150 mm, $B_{\text{peak}} \sim 12.1$ T
2013-2020

New structure based on bladders and keys (LBNL, LARP)
Crab Cavities for fast beam rotation
Crab crossing

4 Rod Crab cavities

IR
Successful Cold Testings

HiLumi-LHC/LARP Crab Cavity System External Review, May 5-6 2014
Latest cavity designs toward accelerator

- Double ¼-wave: Coaxial couplers with hook-type antenna
- 4-rod: Coaxial couplers with different antennae types

Present baseline: 3 cavity/cryomodule
4 cavity/cryomod is under study for Crab Kissing TEST in SPS under preparation
Low impedance collimators (LS2 & LS3)

New material: MoGr
Availability: SC links \(\Rightarrow\) removal of EPCs, DFBs from tunnel to surface

1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS) – LS3
4 pairs 300 m 150 kA (IR) – LS3

tens of 6-18 kA CLs pairs in HTS
L = 20 m
(25×2) 1 kA @ 25 K, LHC Link P7

Feb 2014:
World record for HTS
Diagnostics

Precise measurement of beam parameters is essential. The LHC is equipped with an extensive array of beam diagnostics that has played a major role in commissioning, rapid intensity ramp-up and safe and reliable operation of the accelerator. The HL-LHC presents new challenges:

**Challenge 1:**
- Crab-cavities will rotate the bunches
- A method to accurately measure the bunch rotation is required.
- Conventional BPMs have insufficient bandwidth for single pass, intra-bunch measurements.
- A new technology is needed:

**Challenge 2:**
- The unprecedented stored beam energy would damage conventional diagnostics and/or disrupt the particle beam.
- Non-invasive diagnostics are required to measure the beam profile and beam halo.

**Electro-optic crystals as the BPM pickup**
The electric field of the passing bunch induces a polarization change in the crystal that is readout with <50ps time resolution to derive the transverse position along the bunch.

**Gas-jet based beam profile monitor**
A supersonic jet of neutral gas is shaped into a thin sheet and injected with a 45° tilt across the particle beam.

Ions produced accelerate toward a phosphor screen, to monitor profile.
The **Crab-kissing** (CK) scheme for **pile-up density shaping** and leveling (S. Fartoukh)

**Baseline:** CC in X-plane “only”

**Crab-kissing & variants:** CC also in ||-plane

\[ \frac{\partial \mu}{\partial z} \text{ [mm}^{-1}] \]

... Work on-going together with the machine experiments (S. Fartoukh, A. Valishev, A. Ball, B. Di Girolamo, et al.)

G Burt RAL June16
In-kind contribution and Collaboration for HW design and prototypes

Q1-Q3 : R&D, Design, Prototypes and in-kind USA
D1 : R&D, Design, Prototypes and in-kind JP
MCBX : Design and Prototype ES
HO Correctors: Design and Prototypes IT
Q4 : Design and Prototype FR
Where the UK fits into HL-LHC

High Luminosity LHC Project

HL-LHC-UK Involvement

HiLumi-LHC Leadership

HiLumi-LHC involvement

Parameter & Lay-out Committee
Technical Committee

Project Coordination Office
Steering Committee

US-LARP
JP-KEK
HL-LHC Coordination Group

WP1 Project Management & Technical Coordination
WP2 Accelerator Physics & Performance
WP3 IR Magnets
WP4 Crab Cavities & RF
WP5 Collimation
WP6 Cold Powering

WP7 Machine Protection
WP8 Collider-Experiment Interface
WP9 Cryogenics
WP10 Energy Deposition & Absorber Coordination
WP11 11 T Dipole Two-in-One for DS Collimation
WP12 Vacuum

WP13 Beam Diagnostics
WP14 Beam Transfer and Kickers
WP15 Integration & (De-)Installation
WP16 Hardware Commissioning
WP17 Infrastructure, Logistics and Civil Engineering
WP19 High Field Magnets R&D – FRESCA2

G Burt RAL June16
Manchester
Lancaster
ASTeC

Crab Cavities

Manchester
RHUL

Collimation

Manchester
Liverpool
ASTeC

Beam dynamics

Manchester
Southampton

Superconductivity and Cryogenics

Liverpool
RHUL

Diagnostics

HiLumi-LHC UK

Manchester
Liverpool
ASTeC

Machine-detector interface
What’s next?

• Energy upgrade of LHC with new Nb$_3$Sn dipoles?

• A 80/100 km tunnel as a higgs factory and then a 100 TeV pp collider (FCC)? Could CERN afford such a large machine that cannot be staged?

• Chinese Higgs factory or FCC? Could they get the international community to buy in?

• A staged linear collider going to 1 TeV (ILC) or 3 TeV (CLIC)? ILC could be built now, CLIC still has some technical challenges.

• An electron-ion collider (LHeC, ELIC, e-RHIC)? We can do it if the HEP community wants it enough.
New “Conventional” breakthrough's

- High field dipole magnets allowing projects like FCC.

- N-doped, Nb3Sn and Multilayer SRF provides higher Q, higher temperature and higher fields.

- High gradient X-band still going strong and replacing old S-band technology.
Novel or Advanced Accelerators

- Laser-Plasma-based electron and hadron accelerators:
  - Driven by lasers (for both e- and hadron) e-: Multi-GeV beams have been achieved → beam energy sufficient for applications → applications around the corner???
  - Hadrons: ion beams have been produced and transported at low energies
  - Activities at many centers in Europe (as well as US and Asia)
  - This dominates the novel acceleration arena
  - Excellent future sources of compact accelerators but can they be used for HEP?
Laser Plasma Accelerators
Efficiency and rep-rate

• Efficiency is at least one or two order of magnitude less than conventional sources (around 1% if that). For a 1 TeV collider at CERN the required power would dwarf the rest of Geneva (roughly 10 times the entire energy budget of Geneva) and would potentially require several new dedicated power stations.

• Rep-rate is limited by material heating to sub-1Hz, this would limit luminosity.

• Laser efficiency and rep-rate could be increased by
  • OPCPA but would need new pump sources that are also more efficient and can handle higher average powers, currently can demonstrate either high power, high efficiency or high rep-rate but only one at a time.
  • Combining fibre lasers but locking that many lasers is far from realisable at present. Progress has been made on locking tens of lasers (ICAN) together but millions would be required.
Staging of laser plasma

- At present a few GeV beams can be obtained, but higher energies need either
  - Higher power lasers (material heating limits are difficult to overcome)
  - Combining multiple stages.
- The laser stability coupled with the sensitivity to the laser parameters means every shot is different and most have poor beam quality. Typical variation is 1-5% energy, 5-50% charge, 1-3mrad beam pointing.
- The phase space for external injection is very small in both longitudinal (fs synchronisation) and transverse planes. We are far from a point where we can get close to staging and there are few theories on how this could be achieved.
- Also holes in the mirrors for beam injection get burnt by the laser meaning they need replaced or repositioned frequently.
- Even if we could proposals either require very high laser mean powers (GW) or very high rep rates (15 kHz)
Accelerator size

• The laser travels slower than c in the plasma while electrons travel close to c hence you lose synchronisation after a few mm. The gradient is very high (10’s GV/m) but acceleration is limited to synchronisation length

• Several items of equipment would be required around each plasma stage, the laser itself, vacuum pumps, mirrors, beam transport and diagnostics. In a conventional linear accelerator these items can be 20-50% of the accelerators length. For example a plasma FEL would be only half the size of conventional ones.

• The lasers and power supplies are very large so the gradient is often overstated. In conventional sources we have two numbers active length and total length. LPWA have a small active length but the total length is still significant. Still smaller than linacs but not by as much as implied.
Are there other options or are we stuck with conventional accelerators until we can stage plasma?

• **YES!!!!**

• Lasers could be used with dielectrics to overcome the stability issues and reach gradients up to 1 GV/m. Using THz lasers/vacuum tubes significantly increases beam quality over shorter wavelength sources in dielectrics. Efficiency still is an issue at present. Good for medical linacs and light source replacements. Good potential for higher efficiency THz vacuum tubes (harmonic gyrotrons, BWO’s) or wakefield driven could allow path to TeV colliders.

• You could drive the plasma with a proton or electron beam as opposed to a laser. The drive beam could be a highly efficient high current beam. This would be far more efficient and stable than a laser plasma accelerator. Likely the most viable option for a novel multi-TeV collider other than traditional accelerators. But luminosity is low
AWAKE project, a proton driven plasma wakefield acceleration (PDPWA) experiment is approved by CERN. The PDPWA scheme consists of a seeding laser, a drive beam and a witness beam to be accelerated. The primary goal of this experiment is to demonstrate acceleration of a 16 MeV single bunch electron beam up to 1 GeV in a 10m of plasma.
AWAKE Project

Production of a Witness Beam

Baseline specifications for AWAKE $e^{-}$ beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Range of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (MeV)</td>
<td>16</td>
<td>10-20</td>
</tr>
<tr>
<td>Energy spread ($\sigma$, %)</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Bunch length, ($\sigma$, ps)</td>
<td>4</td>
<td>0.3-10</td>
</tr>
<tr>
<td>Beam focus size, ($\sigma$, $\mu$m)</td>
<td>250</td>
<td>250-1000</td>
</tr>
<tr>
<td>Norm. emittance (rms, mm-mrad)</td>
<td>2</td>
<td>0.5-5</td>
</tr>
<tr>
<td>Bunch charge, (nC)</td>
<td>0.2</td>
<td>0.1-1</td>
</tr>
</tbody>
</table>
Towards the Future An electron-positron collider

Electron beam energy with plasma density step-up.


For this PDPWA-based $e^+e^-$ collider design, half of the LHC bunches (1404 bunches) are used for driving electron acceleration and the other half for positron acceleration. Taking into account that the ramping time of the LHC is about 20 min and assuming that the loaded electron (and positron) beams have a bunch charge of 10% of the drive proton bunch, i.e. electron (and positron) bunch charge of $N_e = 1.15 \times 10^{10}$, and the beam spot sizes at IP are the same as that of the CLIC beam, as shown in Table 1, the resulting luminosity for such an $e^+e^-$ linear collider is about $3.0 \times 10^{31}$ cm$^{-2}$ s$^{-1}$, which is about three orders of magnitude lower than that of the ILC or the CLIC.

G. Xia, O. Mete et al., NIMA Volume 740, 11 March 2014, 173–179

1 TeV $e^+/e^-$ beam in 2 km of plasma
- Via plasma step up and self modulation instability.

LHC radius, 4.3 km
- Transfer and matching of protons&plasma.
- Dedicated $e^-$ source
- 2 km plasma section (0.5 GeV m$^{-1}$).
- 2 km beam delivery and final focusing section.
- “Used” protons to be extracted, dumped or may be recycled.

Luminosity is limited by LHC filling time. However rather than use LHC we could develop a faster cycling machine with looser beam quality specs.
Issues of Proton Driven Plasma Wakefield Acceleration

- Phase slippage
- Interaction of “driver” beam with plasma
- Interaction of “witness” beam with plasma
- Positron acceleration (in case of e⁻p collider)

Production of accelerating field by using a **hollow plasma** for positron acceleration.

**Electron beam scattering by plasma electrons and ions - luminosity degradation through emittance growth**

Electrons may overrun the wakefields - no acceleration.

**Group velocity of wakefields is the same as the velocity of the driver, protons.**

**Bunch lengthening** due to energy spread and **focusing** issues of protons.

- **Phase slippage**
- Interaction of “driver” beam with plasma
- Interaction of “witness” beam with plasma
- Positron acceleration (in case of e⁻p collider)
PWFA at Cockcroft Institute

PWFA at VELA user station in 2015
*First experiment on plasma lens started in August 2015*

- E=4.8 MeV
- Q=250 pC
- σz = 3.3 mm
- σr = 0.45 mm
- focusing gradient of 10 T/m

PWFA at CLARA front end in 2016
*Demonstration of high acceleration gradient ~ GV/m*

- Two bunch acceleration for high quality beam production
- E=50-150 MeV
- Q=250 pC
- σz = 20-100 μm
- σr = 50 μm
- acc. gradient ~GV/m

Guoxing Xia et al.

PWFA at CLARA in 2020
*High beam quality preservation, ultrahigh brightness e-production, e.g. plasma photocathode*

- E=250 MeV, Q=250 pC
- E_{acc} ~ 3 GV/m

E=50-150 MeV
- Q=250 pC
- σz = 20-100 μm
- σr = 50 μm
- acc. gradient ~GV/m

Guoxing Xia et al.
Dielectric Accelerators

Types

• Photonic structures
• **Dielectric Wakefield Accelerators** (like CLIC but with dielectric)
• Dielectric RF Linacs (replace RF structure with dielectric)
• Dielectric Wall Accelerators (high voltage switches)
• **THz/Laser driven dielectric accelerators** (high frequency linacs)

Why?

• Dielectrics can have very high gradients if the right material is used (5.5 GV/m shown in experiments but not with acceleration yet)
• They can operate at high frequencies, THz or higher (smaller)
• Can potentially have lower long-range wakefields (for photonic structures)
• Simpler to manufacture (in some cases)
Laser-driven dielectric structures

- 1 GeV/m demonstrated but low absolute energies achieved so far (emerging field)
- At present led by DESY-MIT (THz) and UCLA-SLAC (optical) collaborations
- Field is excited by either a high current beam or a laser
- Wave velocity is matched to the beam velocity using a dielectric structure
- Lots of parameter space to explore still lots of opportunity for UK to get involved and lead.
- Easy to use multiple stages unlike plasma.
Stanford, SLAC, UCLA results
Terahertz driven dielectric linacs

Terahertz vs. optically driven

All particles are accelerated with THz

Shrink the size and cost of future high energy colliders

Nat. Commun. 6, 8486 (2015)
Conclusions

• The next big HEP accelerator project will be the LHC luminosity upgrade, now in the prototyping phase.

• HL-LHC-UK will develop UK accelerator contribution

• LHC results will determine what happens next

• In the far future we are looking to beam-driven plasma and dielectrics to develop higher energy colliders.