from LHC to FCC

Frank Zimmermann

thanks to Michael Benedikt, Oliver Brüning, Mirko Pojer, Stefano Redaelli

http://cern.ch/fcc

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colliders and discoveries

powerful instruments for discovery and precision measurement
many open questions remain

- Standard Model describes known matter, i.e. 5% of the universe!
- what is dark matter?
- what is dark energy?
- why is there more matter than antimatter?
- why do the masses differ by more than 13 orders of magnitude?
- do fundamental forces unify in single field theory?
- what about gravity?
- is there a “world equation – theory of everything”? ...

<table>
<thead>
<tr>
<th>Known Matter</th>
<th>Dark Matter</th>
<th>Dark Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9%</td>
<td>26.8%</td>
<td>68.3%</td>
</tr>
</tbody>
</table>

- galaxy rotation curves, 1933 - Zwicky
LHC: highest energy \textit{pp}, \textit{AA}, and \textit{pA} collider

design parameters

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

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

360 MJ/beam

g_e = 3.75 mm
b^{*} = 0.55 m
q_c = 285 mrad
s_z = 7.55 cm
s^{*} = 16.6 mm
1 PS batch (36 bunches)  
26.7 km - 1380 bunches in 2012, ~2800 in 2015

1 SPS batch (144 bunches)

Abort gap

\[ \sigma^* \propto \sqrt{\beta^*} \]

\[ \beta_{\text{max}} \sim 4.5 \text{ km} \]

John Jowett

M. Lamont
this summer LHC reached its design luminosity
integrated luminosities

2016 delivered integrated Luminosities
(update 30/08)

ATLAS: 27.2 fb⁻¹
ALICE: 9.2 pb⁻¹
CMS: 27.8 fb⁻¹
LHCb: 1.4 fb⁻¹

2016 parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>6.5 TeV</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
</tr>
<tr>
<td>Bunch population</td>
<td>~1.1-1.2e11 p/b</td>
</tr>
<tr>
<td>Max bunches/injection</td>
<td>72/96</td>
</tr>
<tr>
<td>Max. number bunches</td>
<td>2220</td>
</tr>
<tr>
<td>Nc GPDs</td>
<td>2208</td>
</tr>
<tr>
<td>Beta* GPDs</td>
<td>40 cm</td>
</tr>
<tr>
<td>Crossing angle GPDs</td>
<td>185 mrad</td>
</tr>
</tbody>
</table>
## LHC parameters – achieved versus design

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>TeV</td>
<td>7</td>
<td><strong>6.5</strong></td>
</tr>
<tr>
<td>bunch population $N_b$</td>
<td>$10^{11}$</td>
<td>1.15</td>
<td><strong>1.18</strong></td>
</tr>
<tr>
<td>bunch spacing</td>
<td>ns</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>no. bunches / beam</td>
<td>mm</td>
<td>2808</td>
<td><strong>2076</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(limited by SPS beam dump)</td>
</tr>
<tr>
<td>beam current</td>
<td>A</td>
<td>0.58</td>
<td><strong>0.44</strong></td>
</tr>
<tr>
<td>norm. rms emittance $g_{e_{x,y}}$ at start of physics</td>
<td>m</td>
<td>3.75</td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>IP beta function $b_{x,y}$ (1/2/5/8)</td>
<td>m</td>
<td>0.55 / 10 / 0.55 / 1-50</td>
<td><strong>0.4 / 10 / 0.4 / 3</strong></td>
</tr>
<tr>
<td>rms IP beam size</td>
<td>mm</td>
<td>16.6</td>
<td><strong>12.3</strong></td>
</tr>
<tr>
<td>rms bunch length</td>
<td>cm</td>
<td>7.55</td>
<td>7.88</td>
</tr>
<tr>
<td>full crossing angle (IPs 1 and 5)</td>
<td>mrad</td>
<td>285</td>
<td><strong>370</strong></td>
</tr>
<tr>
<td>luminosity</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>1.0</td>
<td><strong>1.1</strong></td>
</tr>
<tr>
<td>events / crossing (pile up)</td>
<td></td>
<td>19</td>
<td><strong>27</strong></td>
</tr>
<tr>
<td>average luminosity lifetime</td>
<td>h</td>
<td>15</td>
<td><strong>24</strong></td>
</tr>
</tbody>
</table>
Huge efforts over last months to prepare for high lumi and pile-up expected in 2012:

- Optimized trigger and offline algorithms (tracking, calorimeter 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→μμ event from 2012 data with 25 reconstructed vertices

2012: 50 ns bunch spacing

CMS Average Pileup, pp, 2012, \( \sqrt{s} = 8 \text{ TeV} \)

\( \langle \mu \rangle = 21 \)
for 25 years many experts told me LHC would never work because of this or because of that ...

but it does work beautifully!
lessons from the LHC

- combined experimental interaction and injection regions (risks & constraints) OK
- radiation to electronics → SC links and new caverns for HL-LHC
- powering in 8 separate sectors OK
- noise from klystron driven RF & from power converters OK
- field quality, magnet sorting and dynamic aperture OK
- “snap back” and dynamic magnet effects under control OK
- e-cloud conditioning works, no show stopper, but heat near limit
- emittance growth under control OK
- maximum beam-beam tune shift higher than expected OK
- UFO effects unexpected, but UFO rate decreases with time
- excellent machine reproducibility from day to day, and year to year
- first experience with crystal collimation

all these lessons are exploited in the design of future hadron colliders
first proton channeling at 6.5 TeV

S. Redaelli

(1) **angular scan**: strong reduction of local losses in channeling compared to amorphous

(2) **linear collimator scan**: measures the profile of the channeled halo.

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**Beam losses at crystal [ a.u. ]**

- **Loss rates in amorphous**
- **Reduced losses in channeling**
- **Example: scan at 450GeV**
- **~1/30**

**Losses at collimator [ a.u. ]**

- **Channeled halo**
- **Beam core**
- **Example: scan at 6.5TeV**

---

**Beam core**

**Halo**

**Crystal**

**Beam core**

**Collimator**

**Beam core**

**Collimator**

**Halo**

**Crystal**

**Beam core**

**Collimator**

---

**Important**: achieved required angular control of <1 μrad (A. Masi et al.)
time line for LHC crystal collimation

2015-2016 (start of Run II): crystal test stand on beam 1
two crystals, one per plane. Different technologies (quasi-mosaic / strip)

2017-2018 (last 2 years of Run II): New crystal test stand also on beam 2
plan an installation during this end-of-year technical stop (EYETS2016): 2 crystals
aim at testing new technology for goniometer; need better control of bending angles
want 50.0 ± 2.5 mrad, for first installation got ~40 mrad (quasi-mosaic) and ~65 mrad (strip)

EYETS2017: possible upgrade of “old” beam 1 goniometers.
if beam experience indicates need for testing the new goniometers on both beams

LHC second long shutdown (LS2): 4 new crystals for ion collimation
NOT a baseline within the HL-LHC project, but R&D funding available to prepare for this; use of 4 crystals requires production of ~10 units (including spares).

crystals for LHC fixed target experiment – larger angles above 200 mrad – waiting for feedback from recent “Physics Beyond Colliders” workshop
LHC upgrade: HL-LHC

- Peak luminosity
- Integrated luminosity

Run I
- consolidation
- energy

Run II
- injector upgrade

Run III
- 300 fb⁻¹

Luminosity [cm⁻²s⁻¹]

- 6.0E+34
- 5.0E+34
- 4.0E+34
- 3.0E+34
- 2.0E+34
- 1.0E+34
- 0.0E+00

consolidation ➔ energy

technical limits (in machine & experiments), + desire to reduce statistical halving time

cryogenic limits & radiation damage of triplet magnets

- 0.75x10^{34} cm⁻²s⁻¹
- 50 ns bunch
- high pile up ≥ 40

- 1.5x10^{34} cm⁻²s⁻¹
- 25 ns bunch
- high pile up ≥ 40

- 1.5 - 2.2x10^{34} cm⁻²s⁻¹
- 25 ns bunch
- very high pile up > 60

Y. Papaphilippou
HL-LHC Goals

- prepare machine for operation beyond 2025 and up to 2035
- beam parameters and operation scenarios for total integrated luminosity of 3000 fb\(^{-1}\)

implying an integrated luminosity of 250 fb\(^{-1}\) per year,
limit \(m \rightarrow 140\) (\(\Rightarrow\) peak luminosity \(5 \times 10^{34}\) cm\(^{-2}\) s\(^{-1}\))

\(\Rightarrow\) operation with levelled luminosity!
\(\Rightarrow\) 10 times luminosity of first 10 years of LHC operation
HL-LHC parameters with latest update

<table>
<thead>
<tr>
<th>parameter</th>
<th>nominal LHC</th>
<th>HL-LHC original</th>
<th>HL-LHC (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch population $N_b [10^{11}]$</td>
<td>1.15</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>number of bunches</td>
<td>2808</td>
<td>2748</td>
<td>2748</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.12</td>
<td>1.12</td>
</tr>
<tr>
<td>stored Beam Energy [MJ]</td>
<td>362</td>
<td>677</td>
<td>677</td>
</tr>
<tr>
<td>full crossing angle [mrad]</td>
<td>285</td>
<td>590</td>
<td>512</td>
</tr>
<tr>
<td>crossing angle with crab cavities [mrad]</td>
<td>-</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>beam separation [s]</td>
<td>9.9</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>$b^* [m]$</td>
<td>0.55</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>normalized emittance $e_n [mm]$</td>
<td>3.75</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>r.m.s. bunch length [cm]</td>
<td>7.55</td>
<td>8.1</td>
<td>8.1</td>
</tr>
<tr>
<td>virtual luminosity (w/o CC) [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]</td>
<td>1.2 (1.0)</td>
<td>21.3 (7.2)</td>
<td>13.8 (6.95)</td>
</tr>
<tr>
<td>max. luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]</td>
<td>1</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>levelled pile-up/pile-up density [evt.</td>
<td>evt./mm]</td>
<td>26/0.2</td>
<td>140/1.2</td>
</tr>
</tbody>
</table>

Y. Papaphilippou, Thessaloniki, 4 September 2016
HL-LHC projections

- **Peak luminosity**
- **Integrated luminosity**

**Luminosity [cm^{-2}s^{-1}]**

- 6.0E+34
- 5.0E+34
- 4.0E+34
- 3.0E+34
- 2.0E+34
- 1.0E+34
- 0.0E+00

**Integrated luminosity [fb^{-1}]**

- 3000 fb^{-1}
- 2500
- 2000
- 1500
- 1000
- 500
- 0

**Year**

- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20
- 21
- 22
- 23
- 24
- 25
- 26
- 27
- 28
- 29
- 30
- 31
- 32
- 33
- 34
- 35
- 36
- 37

**Splices fixed**

**Injectors upgrade**

**New Low-β* quads**

**Crab Cavity Phase2**

**LS1**

- Energy 6.5 TeV

**LS2**

- Possibly run at 7 TeV?

**LS3**

- 1.6 - 2.2 x10^{34} cm^{-2}s^{-1}
- 25 ns bunch very high pile up > 60

**LS4**

- 5x10^{34} cm^{-2}s^{-1} levelled
- 25 ns bunch very high pile up > 140

**LS5**

- 300 fb^{-1}

**HL-LHC significantly increases data rate in order to improve statistics, precision, & energy reach**
more than 100 new SC magnets, some 40 large magnets in Nb$_3$Sn, powering via SC links and HTS current leads

20 SRF crab cavities, new tunnel and surface infrastructures, new and upgraded cryoplants
Future Circular Collider Study

Frank Zimmermann

Channeling 2016, 25 September 2016

HL LHC project landmarks

Cryo@P4

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

“CRAB” CAVEITIES
10 superconducting “crab” cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

Cryo@P1-P5

N\text{b}_3\text{Sn} quads

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

LHC TUNNEL

ATLAS

MgB\text{2} links

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

LHCb

bulk Nb cavities

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

H\text{L}c\text{cavities}

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

CERN

 Nb\text{b}_3\text{Sn for the first time in a hadron accelerator (\textcolor{red}{\textbullet} 30 tons)}}
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

2016 collisions at ~design energy and design luminosity

now is the time to plan for 2040

>30 years!
beyond LHC/HL-LHC

• European Strategy for Particle Physics 2013:
  “…to propose an ambitious post-LHC accelerator project……, CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines….coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,…”

• U.S. Strategy and “P5” recommendation 2014:
  ”….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window….”

• ICFA statement 2014:
  ”…. ICFA supports studies of energy frontier circular colliders and encourages global coordination…..”
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

international FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)** → main emphasis, defining infrastructure requirements
  
  \[ \sim 16 \text{ T} \quad 100 \text{ TeV } pp \text{ in } 100 \text{ km} \]

- 80-100 km tunnel infrastructure in Geneva area, site specific

- **e^+e^- collider (FCC-ee)**, as potential first step

- **p-e (FCC-he)** option, integration one IP, FCC-hh & ERL

- HE-LHC with *FCC-hh* technology
must advance fast now to be ready for the period 2035 – 2040; goal of phase 1: CDR by end 2018 for next update of European Strategy
pp/p-pbar in the \(L-E\) plane
unravelling the universe with a sequence of hadron colliders
site investigations
• 90 – 100 km fits geological situation well
• LHC suitable as potential injector
• the 100 km version, intersecting LHC, is now being studied in more detail
injection options:

- SPS $\rightarrow$ LHC $\rightarrow$ FCC
- SPS/SPS$_{\text{upgrade}}$ $\rightarrow$ FCC
- SPS $\rightarrow$ FCC booster $\rightarrow$ FCC

current baseline:
- injection energy 3.3 TeV LHC
- confirmed by review

alternative options:
- injection around 1.5 TeV
- compatible with: SPS$_{\text{upgrade}}$, LHC, FCC booster
common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.
more detailed studies launched on

- CE: single vs. double tunnels
- CE: caverns, shafts, underground layout
- technical infrastructures
- safety, access
- transport, integration, installation
- operation aspects
## Hadron Collider Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>SPPC</th>
<th>HE-LHC*</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision energy cms [TeV]</td>
<td>100</td>
<td>71.2</td>
<td>&gt;25</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>20</td>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>100</td>
<td>54</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2</td>
<td>2 &amp; 2</td>
<td>2 &amp; 2</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.5</td>
<td>1.0</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>Bunch intensity [10^{11}]</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>Luminosity/IP [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>20 - 30</td>
<td>12</td>
<td>&gt;25</td>
</tr>
<tr>
<td>Events/bunch crossing</td>
<td>170</td>
<td>&lt;1020 (204)</td>
<td>400</td>
<td>850</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>6.6</td>
<td>1.2</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>Synchrotron. rad. [W/m/beam]</td>
<td>30</td>
<td>58</td>
<td>3.6</td>
<td>(0.35) 0.18</td>
</tr>
</tbody>
</table>
Future Circular Collider Study
Frank Zimmermann
Channeling 2016, 25 September 2016

FCC-hh luminosity phases

phase 1: $b^*=1.1 \text{ m}, DQ_{tot}=0.01, t_{ta}=5 \text{ h}, 250 \text{ fb}^{-1} / \text{ year}$

phase 2: $b^*=0.3 \text{ m}, DQ_{tot}=0.03, t_{ta}=4 \text{ h}, 1 \text{ ab}^{-1} / \text{ year}$

Transition via operational experience, no HW modification

Total integrated luminosity over 25 years operation:

$O(20) \text{ ab}^{-1}/\text{experiment}$

consistent with physics goals

PRST-AB 18, 101002 (2015)
Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1**: SM processes (238 pages)
- **Volume 2**: Higgs and EW symmetry breaking studies (175 pages)
- **Volume 3**: beyond the Standard Model phenomena (189 pages)
- **Volume 4**: physics with heavy ions (56 pages)
- **Volume 5**: physics opportunities with the FCC-hh injectors (14 pages)

- being published as CERN yellow report
FCC-hh physics perspectives

Collider Limits

- wino
- higgsino
- mixed ($\tilde{B}/\tilde{H}$)
- mixed ($\tilde{B}/\tilde{W}$)
- gluino coan.
- stop coan.
- squark coan.

$m_\chi$ [TeV]

100 TeV
14 TeV

disappearing tracks
FCC SC main magnet options and requirements

L. Bottura, B. Strauss

LHC
27 km, 8.33 T
14 TeV (c.o.m.)
1300 tons NbTi
0.3 tons HTS

HE-LHC baseline
27 km, 16 T
26 TeV (c.o.m.)
1600 tons Nb$_3$Sn
800 tons Nb-Ti

FCC-hh baseline
100 km, 16 T
100 TeV (c.o.m.)
6000 tons Nb$_3$Sn
3000 tons Nb-Ti

FCC-hh
80 km, 20 T
100 TeV (c.o.m.)
2000 tons HTS
9000 tons LTS
Nb$_3$Sn is one of the major cost & performance factors for FCC-hh and must be given highest attention.

Main development goals till 2020:

- $J_c$ increase (16T, 4.2K) > 1500 A/mm$^2$ i.e. 50% increase wrt HL/LHC wire
- Wire diameter 1 mm
- RRR > 150
- Potentials for large scale production and cost reduction
Conductor developments with regional industries:

- **CERN/KEK** – Japanese contribution. Japanese industry (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
- **CERN/Bochvar High-technology Research Inst.** – Russian contribution. Russian industry (TVEL) and laboratories
- **US DOE MDP program** – US activity with industry (OST) and labs
- **CERN/KAT** – Korean industrial contribution
- **CERN/Bruker** – European industrial contribution

Characterisation of conductor & research with universities:

- Collaboration agreement with Technical University of Vienna
- Collaboration agreement with Applied Superconductivity Centre at Florida State University
GOAL: design a 16 T accelerator-quality model dipole magnet by 2018
16 T dipole options under consideration

- Cos-theta
- Common coils

Swiss contribution via PSI

Canted Cos-theta

end 2016: down-selection of options for more detailed design work
Towards 16 T magnets

Record fields for SC “dipole” magnets

16 T “dipole” levels reached with small racetrack coils

LBNL 2004, CERN 2015
US magnet program

The U.S. Magnet Development Program Plan

Program (MDP) Goals:

GOAL 1:
Explore the performance limits of \( \text{Nb}_3\text{Sn} \) accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:
Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:
Pursue \( \text{Nb}_3\text{Sn} \) and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Under Goal 1:

16 T cos theta dipole design

16 T canted cos theta (CCT) design
FCC CDR (EuroCirCol) propose a new energy frontier accelerator

HEP & magnet time line

LHC Run-II provides results to define future HEP roadmap
(European Strategy 2018)

HL-LHC demonstrates large-scale use of Nb$_3$Sn

12 T accelerator technology

16 T magnet model(s)

20 T magnet model(s)

16 T accelerator technology

FCC construction decision

End of LHC useful life
proton synchrotron radiation: FCC beam screen prototype

high synchrotron radiation load of protons @ 50 TeV:
- \(~30 \text{ W/m/beam (}\@16 \text{ T})\) (LHC \(<0.2\text{ W/m}\))
- 5 MW total in arcs

new beam screen with ante-chamber
- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- avoids photo-electrons, helps vacuum

First FCC-hh beam screen prototype
Testing 2017 in ANKA within EuroCirCol
FCC-hh detector developments

first concepts were based on extension of LHC detector concepts:

$B=6 \text{ T, } 12 \text{ m bore, solenoid with shielding coil and 2 dipoles } 10 \text{ Tm;}$

length 64 m, diam. 30 m, magnet 7000 tons, stored energy 50 GJ
detector magnet studies

new designs for physics-enabling & cost-efficient magnet systems

today’s baseline:

- 4 T/10m bore 20m long Main Solenoid
- 4 T Side Solenoids – all unshielded
- 14 GJ stored energy, 30 kA and 2200 tons system weight

alternative challenging design:

- 4T / 4 m Ultra-thin, high-strength Main Solenoid allowing positioning inside the e-calorimeter,
- 280 MPa conductor (side solenoids not shown)
- 0.9 GJ stored energy, elegant, 25 t only, but needs R&D!
### lepton collider parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-ee (400 MHz)</th>
<th>CEPC</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics working point</td>
<td>Z</td>
<td>WW</td>
<td>ZH</td>
</tr>
<tr>
<td>energy/beam [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>30180</td>
<td>91500</td>
<td>5260</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>7.5</td>
<td>2.5</td>
<td>50</td>
</tr>
<tr>
<td>bunch population [$10^{11}$]</td>
<td>1.0</td>
<td>0.33</td>
<td>0.6</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1450</td>
<td>1450</td>
<td>152</td>
</tr>
<tr>
<td>luminosity/IP x $10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>210</td>
<td>90</td>
<td>19</td>
</tr>
<tr>
<td>energy loss/turn [GeV]</td>
<td>0.03</td>
<td>0.03</td>
<td>0.33</td>
</tr>
<tr>
<td>synchrotron power [MW]</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.4</td>
<td>0.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**identical FCC-ee baseline optics for all energies**

**FCC-ee: 2 separate rings**

**CEPC, LEP: single beam pipe**
combining successful ingredients of recent colliders → extremely high luminosity at high energies
FCC-ee luminosity per IP

**FCC**

Further increase with squeeze to $b_y^*=1\,\text{mm}, b_x^*=0.5\,\text{m}$

Mono-chromatization?

New baseline 2016, crab waist w 2 IPs $b_y^*=2\,\text{mm}, b_x^*=1\,\text{m}$

Conservative baseline with functioning optics, space for improvement, esp. at $Z$ and $W$

c.m. energy [GeV]
after 80 years
a breakthrough in klystron efficiency!

comparing simulated performances of MBIOT and HEKCW MBK

A 40-beam prototype “BAC” klystron has been built and successfully tested at VDBT, Moscow, this year!
efficient 2-in-1 arc magnets

FCC-ee 500 G dipole based on twin aperture yoke and single busbars as coils

twin 2-in-1 quadrupole

the novel arrangements of the magnetic circuit allow for considerable savings in Ampere-turns and power consumption, less units to manufacture, transport, install, align, remove,…
SuperKEKB will pave the way towards $b^* \leq 2$ mm.
FCC International Collaboration

- 87 institutes
- 28 countries + EC

Status: August, 2016
**FCC Collaboration Status**

87 collaboration members + EC + CERN as host

| ALBA/CELLS, Spain          | Goethe U Frankfurt, Germany                  | Korea U Sejong, Korea                 |
| Ankara U., Turkey          | GSI, Germany                                | U Liverpool, UK                       |
| Aydin U, Istanbul, Turkey   | GWNU, Korea                                 | U Lund, Sweden                        |
| U Belgrade, Serbia         | U. Guanajuato, Mexico                       | U Malta, Malta                        |
| U Bern, Switzerland        | Hellenic Open U, Greece                     | MAX IV, Sweden                        |
| BINP, Russia               | HEPHY, Austria                              | MEPHI, Russia                         |
| CASE (SUNY/BNL), USA       | U Houston, USA                              | UNIMI, Milan, Italy                   |
| CBPF, Brazil               | ISMAB-CSIC, Spain                           | MIT, USA                              |
| CEA Grenoble, France       | IFAE, Spain                                 | Northern Illinois U, USA              |
| CEA Saclay, France         | IFIC-CSIC, Spain                            | NC PHEP Minsk, Belarus                |
| CIEMAT, Spain              | IIT Kanpur, India                           | OIU, Turkey                           |
| CINVESTAV, Mexico          | IFJ PAN Krakow, Poland                      | Okan U, Turkey                        |
| CNRS, France               | INFN, Italy                                 | U Oxford, UK                          |
| CNR-SPIN, Italy            | INP Minsk, Belarus                          | PSI, Switzerland                      |
| Cockcroft Institute, UK    | U Iowa, USA                                 | U. Rostock, Germany                   |
| U Colima, Mexico           | IPM, Iran                                   | RTU, Riga, Latvia                     |
| UCPH Copenhagen, Denmark  | UC Irvine, USA                              | UC Santa Barbara, USA                 |
| CSIC/IFIC, Spain          | Isik U., Turkey                             | Sapienza/Roma, Italy                  |
| TU Darmstadt, Germany      | Istanbul University, Turkey                 | U Siegen, Germany                     |
| TU Delft, Netherlands      | JAI, UK                                     | U Silesia, Poland                     |
| DESY, Germany             | JINR Dubna, Russia                          | Stanford U, USA                       |
| DOE, Washington, USA       | Jefferson LAB, USA                          | U Stuttgart, Germany                  |
| TU Dresden, Germany        | FZ Jülich, Germany                          | TAU, Israel                           |
| Duke U, USA                | KAIST, Korea                                | TU Tampere, Finland                   |
| EPFL, Switzerland          | KEK, Japan                                  | TOBB, Turkey                          |
| UT Enschede, Netherlands   | KIAS, Korea                                 | U Twente, Netherlands                  |
| ESS, Sweden                | King’s College London, UK                   | TU Vienna, Austria                    |
| U Geneva, Switzerland      | KIT Karlsruhe, Germany                      | Wigner RCP, Budapest, Hungary         |
| Giresun U. Turkey          | KU, Seoul, Korea                            | Wroclaw UT, Poland                    |
summary

• LHC is running extremely well thanks to 30 years of worldwide efforts
• LHC upgrade HL-LHC will support frontier physics program till ~2035/2037
• now it is time to prepare for the post-LHC era: FCC study is developing design of large circular accelerator complex, technology developments in key areas (high-field magnets, RF, SR handling …)
• rapidly growing global FCC collaboration (now ~100 institutes), next milestone: FCC Week 2017
• what can channeling do for FCC or FCC upgrade?