Future Circular Collider Study Kick Off Meeting
12-15 February, Geneva

http://indico.cern.ch/event/282344/overview

Péter Lévai
MTA WIGNER RCP

10 March 2014,
CMS Seminar, Wigner RCP, Budapest
FCC Meeting: 340 participants

CERN Indico Page contains all talks (plenary, parallel)
http://indico.cern.ch/event/282344/overview

The aim of the Meeting:

Talk of Rolf Heuer CERN DG
Future Circular Collider (FCC) Study
Why

• Push the energy frontier beyond LHC
• High Priority item within the European Strategy for Particle Physics
• Timely
  lead times for R&D very long
  LHC physics program for ~20 years
• Need for a project plan when LHC results indicate direction to go
What

• Technical/Conceptual Design Reports for linear $e^+e^-$ Colliders exist: ILC/CLIC
  Japan interested in housing ILC
  Europe and CERN: participation in both endeavours will be continued

• Need to go beyond present energy frontier $\rightarrow$ circular high energy collider
How

• Exploitation of all options for such a project (hh – ee – ep) within one study

• Global Collaboration for the Study of Future Circular Colliders (similar to the CLIC collaboration)

• Hosted by CERN
A conceptual design study of options for a future high-energy frontier circular collider at CERN for the post-LHC era shall be carried out, implementing the request in the 2013 update of the European Strategy for Particle Physics.

Many results of the study will be site independent.

The design study shall be organised on a world-wide international collaboration basis under the auspices of the European Committee for Future Accelerators (ECFA) and shall be available in time for the next update of the European Strategy for Particle Physics, foreseen by 2018.
The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies.

The conceptual design study shall also include a lepton collider and its detectors, as a potential intermediate step towards realization of the hadron facility. Potential synergies with linear collider detector designs should be considered. Options for e-p scenarios and their impact on the infrastructure shall be examined at conceptual level.

The study shall include cost and energy optimisation, industrialisation aspects and provide implementation scenarios, including schedule and cost profiles.
Proposed international organization structure

**Collaboration Board**
- 1 person/inst.

**Steering Committee**
- around 2-3 persons/region

**Advisory Committee**
- 1-2 experts/field

**Study Coordination Group**

- Hadron Collider Physics Experiments
- Lepton Collider Physics Experiments
- e-p Physics Experiments Machines
- Hadron Injectors
- Hadron Collider
- Lepton Injectors
- Lepton Collider
- Accelerator R&D Technologies
- Infrastructures Operation
- Costing Planning

**Future Circular Collider Study**
**FCC Kick-Off 2014**
Workshop Goals

- Discussion of all FCC aspects
- Refine scope of the study
- Define schedule, WBS, milestones of the study
- Establish the path towards international collaboration: Expressions of Interest, formation of collaboration, accepting new partners throughout the duration of the study
- Open process
Plenary Talks – Theoretical Background:

Nima ARKANI-HAMED:

Energy frontier after the Higgs discovery (Naturalness)

„... we will want a factory for new colored particles, 
to study how they makes higgs Natural 
[e.g. SUSY coupling relations].”

„Center for Future HEP @ IHEP, Beijing”

Christophe GROJEAN:

Precision frontier at high energies (Higgs coupling, Nat)

MLM@Aspen’14: The days of „guaranteed” discoveries or of no-lose theorems in particle physics are over, ... 
... but the big questions of our filed remain wild open 
(hierarchy problem, flavour, neutrinos, DM, BAU, ...).

This simply implies that, more than for the past 30 years, 
future HEP’s progress is to driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias.
Plenary Talks – FCC Construction:

Frederic BORDRY:
The CERN Roadmap (of LHC and Beyond)
„… to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”

Michael BENEDICT & Frank ZIMMERMANN:
Future Circular Collider (FCC) Study
Design studies and R&D at the energy frontier
Following the European Strategy Update 2013
14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

1983: First studies for the LHC project
1988: First magnet model (feasibility)
1994: Approval of the LHC by the CERN Council
1996-1999: Series production industrialisation
1998: Declaration of Public Utility & Start of civil engineering
1998-2000: Placement of the main production contracts
2004: Start of the LHC installation
2005-2007: Magnets Installation in the tunnel
2006-2008: Hardware commissioning
2008-2009: Beam commissioning and repair
2009-2035: Physics exploitation
The CERN Roadmap

Frédérick Bordry

Future Circular Collider Kick-off Meeting – Geneva. 12th February 2014

- ECFA-CERN workshop
  - One Channel
  - Time Channel
  - Magnetic Circuits
  - pp only
  - pp mainly
  - pp, pp
  - High
  - Moderate
  - B, E

- June 1994 first full scale prototype dipole

- 1994 project approved by council (1-in-2)

- June 2007 First sector cold

- April 2008 Last dipole down

- 25 years

- Main contracts signed

- 83 84 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10

- Decision for Nb-Ti

- 9T -10 m prototype

- 2002 String 2

- September 10, 2008 First beams around

- November 2006 1232 delivered

- 9T -1m single bore

- ECFA-CERN workshop
August 2008
First injection test

Sept. 10, 2008
First beams around

Repiar and Consolidation

October 2011
3.5x10^{-33}, 5.7 fb^{-1}

First Hints!!

October 14, 2010
1380 bunches

March 14th, 2012
Restart with Beam

May 2012
Ramping Performance

Nov. 2012
End of p+ Run 1

Nov. 2010
Second Ion Run

March 30, 2010
Pb^{82+} Ions

March 2009
Beam back

Sept. 2008
Incident

Sept. 19, 2008
First collisions at 3.5 TeV

November 29, 2009
The CERN Roadmap
Frédérick Bordry
Future Circular Collider Kick-off Meeting – Geneva . 12th February 2014

2010-2012: LHC integrated luminosity

CMS Integrated Luminosity, pp

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

- **2010**: 0.04 fb⁻¹
  - 7 TeV CoM Commissioning
- **2011**: 6.1 fb⁻¹
  - 7 TeV CoM ... exploring limits
- **2012**: 23.3 fb⁻¹
  - 8 TeV CoM ... production

3.5 TeV and 4 TeV in 2012
Up to 1380 bunches with \(1.5 \times 10^{11}\) protons

\[ L_{\text{peak}} = 0.77 \times 10^{34} \]
LS 1 from 16th Feb. 2013 to Dec. 2014

- Beam commissioning
- Shutdown
- Powering tests

Available for works:
- Physics
- Beam commissioning

Timeline:
- 16th Feb. 2013
- 12th February
- 2014
- 2015

LHC

SPS

PS

PS Booster

Beam to beam

The CERN Roadmap
Frédérick Bordry
Future Circular Collider Kick-off Meeting – Geneva. 12th February 2014
Expectations after Long Shutdown 1 (2015)

• Collisions at **13 TeV** c.m.
• **25 ns** bunch spacing
  Using new injector beam production scheme (BCMS), resulting in brighter beams.

• **$\beta^* \leq 0.5$ m** (was 0.6 m in 2012)
• Other conditions:
  – Similar turn around time
  – Similar machine availability
• Expected maximum luminosity: $1.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \pm 20$
  – Limited by inner triplet heat load limit, due to collisions debris

<table>
<thead>
<tr>
<th></th>
<th>Number of bunches</th>
<th>Intensity per bunch</th>
<th>Transverse emittance</th>
<th>Peak luminosity</th>
<th>Pile up</th>
<th>Int. yearly luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns BCMS</td>
<td>2508</td>
<td>$1.15 \times 10^{11}$</td>
<td>1.9 µm</td>
<td>$1.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>~43</td>
<td>~40-45 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Batch Compression and Merging and splitting (BCMS)

Courtesy of the LIU-PS project team
## LHC schedule beyond LS1

**LS2**
- Starting in **2018 (July)**
- **=> 18 months + 3 months BC**

**LS3**
- LHC: starting in **2023**
- **=> 30 months + 3 months BC**
- Injectors: in **2024**
- **=> 13 months + 3 months BC**

### 30 fb⁻¹

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>YETS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injectors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>YETS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injectors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 300 fb⁻¹

<table>
<thead>
<tr>
<th>Year</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
<th>2033</th>
<th>2034</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>YETS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injectors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**3'000 fb⁻¹**

(Extended) Year End Technical Stop: (E)YETS

---

The CERN Roadmap
Frédérick Bordry
Future Circular Collider Kick-off Meeting – Geneva . 12th February 2014

---

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)
c) Europe’s top priority should be the *exploitation of the full potential of the LHC*, including the high-luminosity upgrade of the machine and detectors with a view to collecting *ten times more data than in the initial design, by around 2030*. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

**HL-LHC from a study to a PROJECT**

300 fb$^{-1}$ → 3000 fb$^{-1}$

including LHC injectors upgrade **LIU**
(Linac 4, Booster 2GeV, PS and SPS upgrade)
“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”

d) CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.
Magnet design (20 T): very challenging but not impossible.

300 mm inter-beam multiple powering in the same magnet (and more sectioning for energy)

Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam.

Otherwise limit field to 15.5 T for 2x13 TeV

Higher INJ energy is desirable (2xSPS)

The synchrotron light is not a stopper by operating the beam screen at 60 K.

The beam stability looks «easier» than LHC thanks to dumping time.

Collimation is possibly not more difficult than HL-LHC. Reaching $2 \times 10^{34}$ appears reasonable.

**Beam handling for INJ & beam dump:**

...need more room for LHC kickers.
First studies on a new 80 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb$_3$Sn dipoles
- 100 TeV with 20 T based on HTS dipoles

HE-LHC: 33 TeV with 20T magnets
80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh) with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

**FCC (Future Circular Colliders)**

CDR and cost review for the next ESU (2018) (including injectors)

16 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km
Future Circular Collider Study - SCOPE CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- **pp-collider** (*FCC-hh*) → defining infrastructure requirements
  - $16 \, T \Rightarrow 100 \, \text{TeV} \, pp$ in 100 km
  - $20 \, T \Rightarrow 100 \, \text{TeV} \, pp$ in 80 km

- **$e^+e^-$ collider** (*FCC-ee*) as potential intermediate step

- **$p$-$e$** (*FCC-he*) option

- 80-100 km infrastructure in Geneva area
FCC motivation: pushing energy frontier

High-energy hadron collider \textit{FCC-hh} as long-term goal
- Seems only approach to get to 100 TeV range in the coming decades
- High energy and luminosity at affordable power consumption
- Lead time design & construction > 20 years (LHC study started 1983!)
  \[ \rightarrow \text{Must start studying now to be ready for 2035/2040} \]

Lepton collider \textit{FCC-ee} as potential intermediate step
- Would provide/share part of infrastructure
- Important precision measurements indicating the energy scale at which new physics is expected
- Search for new physics in rare decays of Z, W, H, t and rare processes

Lepton-hadron collider \textit{FCC-he} as option
- High precision deep inelastic scattering and Higgs physics

Most aspects of collider designs and R&D non-site specific. Tunnel and site study in Geneva area as ESU requests.
## Main areas of FCC design study

<table>
<thead>
<tr>
<th>Accelerators and infrastructure conceptual designs</th>
<th>Technologies R&amp;D activities planning</th>
<th>Physics experiments detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron collider conceptual design</td>
<td>High-field magnets</td>
<td>Hadron coll. physics experiments interface, integration</td>
</tr>
<tr>
<td>Lepton collider conceptual design</td>
<td>Superconducting RF systems</td>
<td>e⁺ e⁻ coll. physics experiments interface, integration</td>
</tr>
<tr>
<td>Hadron and lepton injectors</td>
<td>Cryogenics</td>
<td>e⁻ - p physics, experiments, Interface, integration</td>
</tr>
<tr>
<td>Safety, operation, energy management, environmental aspects</td>
<td>Specific technologies</td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Planning</td>
<td></td>
</tr>
</tbody>
</table>
**FCC-****hh** parameters – starting point

**Energy**
- 100 TeV c.m.
- ~ 16 T (Nb\textsubscript{3}Sn), [20 T option HTS]
- ~ 100 km

**Dipole field**
- ~ 16 T (Nb\textsubscript{3}Sn), [20 T option HTS]

**Circumference**
- ~ 100 km

**#IPs**
- 2 main (tune shift) + 2

**Luminosity/IP\textsubscript{main}**
- 5x10\textsuperscript{34} cm\textsuperscript{-2}s\textsuperscript{-1}

**Stored beam energy**
- 8.2 GJ/beam

**Synchrotron radiation**
- 26 W/m/aperture (filling fact. ~78% in arc)

**Long. emit damping time**
- 0.5 h

**Bunch spacing**
- 25 ns [5 ns option]

**Bunch population (25 ns)**
- 1x10\textsuperscript{11} p

**Transverse emittance**
- 2.2 micron normalized

**#bunches**
- 10500

**Beam-beam tune shift**
- 0.01 (total)
- 1.1 m (HL-LHC: 0.15 m)

---

already available from SPS for 25 ns
**FCC-hh design challenges**

**Optics and beam dynamics**
- IR design, dynamic aperture studies, SC magnet field quality

**Impedances, instabilities, feedbacks**
- Beam-beam, e-cloud, resistive wall, feedback systems design

**Synchrotron radiation damping**
- controlled blow up, luminosity levelling, etc…

**Energy in beam & magnets → dump, collimation, quench protection**
- **Stored beam energy critical:** 8 GJ/beam (0.4 GJ LHC)
- Beam losses, radiation effects → collimation, shielding
- Synergies intensity frontier (SNS, J-PARC, PSI, PIP, FRIB, ESS, FAIR)

**High synchrotron radiation load on beam pipe**
- **Up to 26 W/m/apererture in arcs, total of ~5 MW for FCC-hh**
- (LHC has a total of 1W/m/apererture from different sources)
- Heat extraction: photon stop, beam screen temperature, cryo load,
- Synergies with SSC, VLHC, LHC, light sources, SppC, …
High-field magnet R&D targets

**FCC-hh baseline 16T Nb$_3$Sn technology for ~100 TeV c.m. in ~100 km**

Develop Nb$_3$Sn-based 16 T dipole technology,
- with sufficient aperture (~40 mm) and
- accelerator features (field quality, protectability, cycled operation).
- In parallel conductor developments

Possible goal:
- 16T short dipole models by 2018 (America, Asia, Europe)

In parallel HTS development targeting 20 T:
- HTS insert, generating $O(5 \text{ T})$ additional field
- in large aperture $O(100 \text{ mm, 15 T})$

Possible goal:
**demonstrate HTS/LTS 20 T technology in two steps**
- a field record attempt to break the 20 T barrier (no aperture), and
- a 5 T insert, with sufficient aperture (40 mm) and accel. features
FCC-ee parameters – starting point

Design choice: max. synchrotron radiation power set to 50 MW/beam

- Defines the maximum beam current at each energy
- 4 physics operation points (energies) foreseen $Z$, $WW$, $H$, $ttbar$
- Optimization at each operation point, mainly via bunch number and arc cell length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$Z$</th>
<th>$WW$</th>
<th>$H$</th>
<th>$ttbar$</th>
<th>$LEP2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E/beam (GeV)</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>105</td>
</tr>
<tr>
<td>L ($10^{34}$ cm$^{-2}$s$^{-1}$)/IP</td>
<td>28.0</td>
<td>12.0</td>
<td>5.9</td>
<td>1.8</td>
<td>0.012</td>
</tr>
<tr>
<td>Bunches/beam</td>
<td>16700</td>
<td>4490</td>
<td>1330</td>
<td>98</td>
<td>4</td>
</tr>
<tr>
<td>I (mA)</td>
<td>1450</td>
<td>152</td>
<td>30</td>
<td>6.6</td>
<td>3</td>
</tr>
<tr>
<td>Bunch popul. $[10^{11}]$</td>
<td>1.8</td>
<td>0.7</td>
<td>0.47</td>
<td>1.40</td>
<td>4.2</td>
</tr>
<tr>
<td>Cell length [m]</td>
<td>300</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>79</td>
</tr>
<tr>
<td>Tune shift / IP</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
<td>0.09</td>
<td>0.07</td>
</tr>
</tbody>
</table>
**FCC-ee design challenges**

Short beam lifetime from high luminosity (radiative Bhabha scattering)
- **Top-up injection** (single injector booster in collider tunnel)

Additional lifetime limit from beamstrahlung at top operation energy
- Flat beams (small vertical emittance, small vertical $\beta^* \sim 1$ mm)
- Final focus with large (~2%) energy acceptance to reduce losses

Machine layout for high currents, large #bunches at $Z$ pole, $WW$, $H$
- Two ring layout and configuration of the RF system.

Polarization for high precision energy calibration at $Z$ pole and $WW$ with long natural polarization times ($WW$: ~10 hours, $Z$: ~200 hours)

Important expertise available worldwide and potential synergies:
- IR design, experimental insertions, machine detector interface, (transverse) polarization
  - RHIC, VEPP-2000, BEPC-II, SLC, LEP, $B$- and Super-$B$ factories, CEPC, ILC, CLIC
SC-RF main R&D areas

SC cavity R&D
- Large $Q_0$ at high gradient and acceptable cryogenic power
  - Recent results at 4 K with Nb$_3$Sn coating on Nb at Cornell
  - 800 °C ÷ 1400 °C heat treatment at JLAB
  - Beneficial effect of impurities observed at FNAL
- Relevant for many other accelerator applications

High efficiency RF power generation from grid to beam
- Power converter technology
- Klystron efficiencies beyond 65%, alternative RF sources as Solid State Power Amplifier or multi-beam IOT (inductive output tube), etc.
- Relevant for all high power accelerators, intensity frontier (drivers): J-PARC, SNS, νstorm, LBNE, XFEL, µcoll, ESS, MYRRHA, …

Overall RF system reliability $\rightarrow$ relevant for FCC-hh and FCC-ee

R&D Goal is optimization of overall efficiency, reliability and cost!
- Power source efficiency, low-loss high-gradient SC cavities, operation temperature vs. cryogenic load, total system cost and dimension.
Following ESU in May 2013, creation of a small preparation group in autumn 2013 to prepare on a short time scale:

- preliminary **draft baseline parameter sets** for all options
- a possible work breakdown structure and study organisation
- an **international kick-off meeting** (*now!*)

**Kick-off event should start process of internat. collaboration**

- presenting **preparatory work** as basis for discussion
  
  → **draft parameter sets & WBS documents available**

- inviting **feedback and suggestions**
- working towards **formation of a**

  **global design study collaboration integrating all aspects of machines, physics and detectors**

Reflected in kick-off meeting programme.
International collaboration process in 2014

Proposal for next steps:

- Suggestions and comments from international community and discussion on study contents, organisation and resources
- Invitation of non-committing expressions of interest for contributions from worldwide institutes by end May 2014
- Prepare for formation of International Collaboration Board (ICB); proposed date first meeting 9-11 September 2014, to start FCC study

Process can be moderated by preparation group (possibly extended – following EOI) until global collaboration is formed and an international team is put in place to conduct the further study

Process remains open, further joining possible …
## FCC Kick-Off & Study Preparation Team

### Future Circular Colliders - Conceptual Design Study

Study coordination, **M. Benedikt, F. Zimmermann**

<table>
<thead>
<tr>
<th>Hadron collider</th>
<th>Hadron injectors</th>
<th>e+ e- collider and injectors</th>
<th>Infrastructure, cost estimates</th>
<th>Technology</th>
<th>Physics and experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Schulte</td>
<td>B. Goddard</td>
<td>J. Wenninger</td>
<td>P. Lebrun</td>
<td>High Field Magnets</td>
<td>Hadrons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L. Bottura</td>
<td>A. Ball, F. Gianotti, M. Mangano</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Superconducting RF</td>
<td>e+ e-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E. Jensen</td>
<td>A. Blondel, J. Ellis, P. Janot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cryogenics</td>
<td>e- p</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L. Tavian</td>
<td>M. Klein</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific Technologies</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JM. Jimenez</td>
<td></td>
</tr>
</tbody>
</table>

**e- p option**

Integration aspects **O. Brüning**

**Operation aspects,**

energy efficiency, safety, environment **P. Collier**

**Planning (Implementation roadmap, financial planning, reporting)**

**F. Sonnemann, J. Gutleber**
Proposal for FCC WBS top level

preliminary
## Draft work packages and units

### Lepton injectors

#### Functional machine design
- LEP chain performance and gaps
- LEP chain compatibility with hadron injectors
- New injector chain baseline

#### Technical systems
- Low energy beam transfer lines
- LIL/EPA re-installation feasibility
- Existing injectors to be decommissioned for lepton operation
- Technologies that require R&D
- SuperKEKB-type injector option
- CTF3 option usability
- Planned LHeC test facility usability
- Electron and positron sources

### Lepton collider

#### Functional machine design
- Beam dynamics and collective effects
- Collimation concepts
- Injection and extraction concepts and designs
- Interaction region and final focus design
- Booster ring conceptual design and integration
- Lattice design and single particle dynamics
- Polarization and energy calibration
- Machine detector interface
- Machine protection concepts
- Radiation effects

#### Technical systems
- Beam diagnostics requirements and conceptual design
- Beam transfer elements requirements and conceptual design
- Collimation systems and absorber requirements and conceptual design
- Dump and stopper requirements and conceptual design
- Element support and alignment requirements and conceptual design
- Machine detector integration
- Machine protection system requirements and conceptual design
- Normal magnet requirements and element conceptual design
- Power converter requirements and conceptual design
- Quench protection and stored energy management requirements and concepts
- RF system requirements and conceptual design
- Superconducting magnet and cryostat requirements and conceptual design
- Proximity cryogenics for RF and magnets
- Vacuum system requirements and conceptual design
- Shielding

---

**International contributors and convenors needed for technical areas and study organisation**
Proposed international organization structure

- **CERN DG**
- **Steering Committee**
  - 2-3 persons/region
- **Advisory Committee**
  - 1-2 experts/field
- **FCC Study Coordination**

**Collaboration Board**
- 1 person/inst.

**Steering Committee**

**Advisory Committee**
- 1-2 experts/field

**FCC Study Coordination**

**Institutes and Groups**
- Hadron Collider Physics Experiments
- Lepton Collider Physics Experiments
- e-p Physics Experiments Accelerators
- Hadron Injectors
- Hadron Collider
- Lepton Injectors
- Lepton Collider
- Accelerator R&D Technologies
- Infrastructure Operation
- Costing Planning
# Proposal for FCC Study Time Line

<table>
<thead>
<tr>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Prepare</strong></td>
<td>Kick-off, collaboration forming, study plan and organisation</td>
<td><strong>Ph 1: Explore options “weak interaction”</strong></td>
<td>Workshop &amp; Review → identification of baseline</td>
<td><strong>Ph 2: Conceptual study of baseline “strong interact.”</strong></td>
</tr>
</tbody>
</table>

- **4 large FCC Workshops distributed over participating regions**
- **Report**

---

*Future Circular Collider Study*
*Michael Benedikt*
*FCC Kick-Off 2014*
Possible FCC Study Phases

Phase 1: Explore options, now – spring 2015:
- Investigate **different options** in all technical areas, **taking a broad view**
- Deliverables: description and comparison of options with relative merits/cost
- FCC workshop to converge to common baseline with small number of options
- **Proposed WS date 23 – 27 March 2015** (presently no known collisions…)
- Followed by review ~2 months later, begin June 2015

Phase 2: Conceptual design: spring 2015 – autumn 2016
- Conceptual study of baseline and remaining options with iterations between all areas
- Deliverable: description of baseline with first cost model, identification of critical areas, cost drivers, performance limitations
- FCC workshop to discuss conceptual design, performance and cost figures
- Proposed date autumn 2016.
- Followed by review 2 months later to take into account LHC results and do re-scoping of study for phase 3

Phase 3: Study consolidation: winter 2016 – winter 2017
- Detailed conceptual design of re-scoped baseline
- Deliverables: description of re-scoped baseline with cost model, identification of critical areas, cost drivers, performance limitations, planning for further R&D activities
- FCC workshop to discuss conceptual design, performance and cost figures and contents for CDR editing.
- Proposed date autumn 2017.
- Followed by review 2 months later to confirm CDR contents

Phase 4: Editing conceptual design report: winter 2017 – summer 2018
FCC EU Design Study (DS) Proposal

Horizon2020 call – design study, deadline 02.09.2014
Prepare proposal parallel to FCC collaboration setup

Goals for EU DS: conceptual design, prototypes, cost estimates, …
From FP7 HiLumi LHC DS → positive experience:
- 5-6 work packages as sub-set of FCC study
- ~10-15 beneficiaries (signatories of the contract with EC)

Time line

kick-off event discussions input from interested partners, end of May complete draft proposal, end of June iteration, agreements, signatures submission of EU FCC DS proposal, 2 Sept.

March April May June July August September 2014

Non-EU partners can join as beneficiary – signatory with or w/o EC contribution (contractual commitment) or as associated partner – non-signatory (in-kind contribution with own funding, no contractual commitment)
• In line with the European Strategy, CERN is launching a 5-year international design study for Future Circular Colliders;

• Worldwide collaboration in all areas - physics, experiments and accelerators – is essential to reach CDR level by 2018.

• FCC R&D areas e.g. SC high-field magnets and SC RF are of general interest & relevant for many other applications.

• Significant R&D investments have been made over last decade(s), e.g. in the framework of LHC and HL-LHC; further continuation will ensure efficient use of past investments.

• Goals of kick-off meeting: Introducing FCC study, discussing study scope and organization, preparing and establishing collaboration! Invitation to join!
Material R&D towards superconductors for the 16 T horizon and 20 T horizon

A. Ballarino, CERN, Geneva
Large Scale Production

**LHC**

~ 1200 tons of Nb-Ti
~ 200 kg of HTS (Bi-2223)

**ITER**

PF and CC coils
~ 200 tons of Nb-Ti
TF and CS coils
~ 500 tons Nb$_3$Sn

**Hi-Lumi LHC**

11 T Dipoles, IR Quadrupoles
~ 25 T tons Nb$_3$Sn
+ ~ 5 tons for CERN development program
+ ~ 5 tons for LARP development program*

*A. Ballarino, CERN

* Arup Ghosh, BNL
**Nb$_3$Sn Electrical Performance**

**ITER - Nb$_3$Sn**

Non-Cu $J_c \geq 800 \text{ A/mm}^2$  
(12 T, 4.2 K)

**Hi-Lumi LHC - Nb$_3$Sn**

Non-Cu $J_c \geq 1340 \text{ A/mm}^2$  
(15 T, 4.2 K)

Non-Cu $J_c \geq 2500 \text{ A/mm}^2$  
(12 T, 4.2 K)

Critical current density versus field

A. Ballarino, CERN
16 T for 100 TeV in 100 km

Cosine theta type magnet, **Nb-Ti** and **Nb$_3$Sn**. Bore $\Phi = 40$ mm

<table>
<thead>
<tr>
<th>16 T magnet in 100 km tunnel</th>
<th>Width (mm)</th>
<th>Average radius (mm)</th>
<th>Overall Jc (A/mm$^2$)</th>
<th>Strand Jc (eng) (A/mm$^2$)</th>
<th>Conductor mass (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb$_3$Sn layer 1</td>
<td>20</td>
<td>30</td>
<td>193</td>
<td>386</td>
<td>1690</td>
</tr>
<tr>
<td>Nb$_3$Sn layer 2</td>
<td>20</td>
<td>50</td>
<td>385</td>
<td>770</td>
<td>2710</td>
</tr>
<tr>
<td>20 mm collar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb-Ti layer 1</td>
<td>15</td>
<td>87.5</td>
<td>337</td>
<td>523</td>
<td>4710</td>
</tr>
<tr>
<td>Nb-Ti layer 2</td>
<td>15</td>
<td>102.5</td>
<td>433</td>
<td>672</td>
<td>5520</td>
</tr>
</tbody>
</table>

4300 tons Nb$_3$Sn + 10200 tons of Nb-Ti

~9 times Nb$_3$Sn for ITER and Nb-Ti for LHC

A. Ballarino, CERN
20 T for 100 TeV in 80 km

Cosine theta type magnet, **Nb-Ti** and **Nb₃Sn** and **HTS** insert. Bore $\Phi = 40$ mm

<table>
<thead>
<tr>
<th>20 T magnet in 80 km tunnel</th>
<th>Width (mm)</th>
<th>Average radius (mm)</th>
<th>Overall Jc (A/mm²)</th>
<th>Strand Jc (eng) (A/mm²)</th>
<th>Conductor mass (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS layer</td>
<td>25</td>
<td>32.5</td>
<td>231</td>
<td>600</td>
<td>1409</td>
</tr>
<tr>
<td>10 mm collar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb₃Sn layer 1</td>
<td>20</td>
<td>65</td>
<td>193</td>
<td>386</td>
<td>2930</td>
</tr>
<tr>
<td>Nb₃Sn layer 2</td>
<td>20</td>
<td>85</td>
<td>385</td>
<td>770</td>
<td>3685</td>
</tr>
<tr>
<td>20 mm collar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb-Ti layer 1</td>
<td>15</td>
<td>122.5</td>
<td>337</td>
<td>523</td>
<td>5275</td>
</tr>
<tr>
<td>Nb-Ti layer 2</td>
<td>15</td>
<td>137.5</td>
<td>433</td>
<td>672</td>
<td>5925</td>
</tr>
</tbody>
</table>

1400 tons of HTS + 6600 tons Nb₃Sn + 11300 tons of Nb-Ti

~13 times Nb₃Sn for ITER  
~10 times Nb-Ti for LHC
By adopting a graded block design it may be possible to **better optimize the use of the different conductors**. This will change the numbers in the tables, but the order of magnitude will remain. Also, **higher Jc will decrease conductor total quantity**. The final distribution will depend on further optimization.

A. Ballarino, CERN
$\textbf{Nb}_3\text{Sn Electrical Performance}$

$B_{op} = 16-20 \text{ T} + 20\% \text{ margin} \Rightarrow B_{des} = 19-24 \text{ T at } 4.5 \text{ K}$

$\textbf{Nb}_3\text{Sn for HE}: \text{ Jeng } \sim 386 \text{ A/mm}^2$

$\Rightarrow J_c \sim 900-1000 \text{ A/mm}^2 \text{ at } 19 \text{ T and } 4.5 \text{ K}$

$\textit{New generation of Nb}_3\text{Sn conductor}$

A. Ballarino, CERN
HTS Electrical Performance

$B_{op} = 16-20 \ T + 20\% \ margin \Rightarrow B_{des} = 19-24 \ T \ at \ 4.5 \ K$

HTS $\Rightarrow$ Hirr (4.2 K) $> 30 \ T$

HTS for HE: Jeng $\sim 600 \ A/mm^2$ at 24 T and 4.5 K

REBCO tape:

Jeng today up to $\sim 300-350 \ A/mm^2$ at 20 T and 4.5 K (B//c)

Factor 2 in Jeng

BSnCCO 2212 round wire:

Demonstrated Jeng up to $\sim 550 \ A/mm^2$ at 20 T and 4.5 K

New generation of HTS conductors

A. Ballarino, CERN
There is more than $J_c$...

B. Bordini and D. Richter, CERN

L. Oberli and A. Bonasia, CERN

R. Flukiger and T. Spina, CERN

A. Ballarino, CERN
To get there....

**Nb₃Sn (16 T magnets)**
- **Increase** $J_c$ in high fields
- Develop **wire architectures** that meet the characteristics required for accelerator quality magnets (reduce **filaments size for field quality**, assure stability requirements (**RRR**), guarantee **mechanical properties** as needed for cabling, winding and operation in a magnet assembly)

**HTS (20 T magnets)**
- **Increase** $J_c$ at 4.5 K and in high fields
- **Reduce** (or cope with...) **conductor anisotropy** (**REBCO** tape)
- Develop and demonstrate high current **HTS cables**
- Understand and handle **quench performance and quench protection** (first on strands and cables and **after** on magnets)
- Study and demonstrate **field quality** - for tape and wire geometry. Improve conductor geometry as needed – striation for tape, smaller filament size for wire ....

---

A. Ballarino, CERN
To get there:

Production of conductor of a sufficiently robust quality for large scale production \(\Rightarrow\) good yield (low cost Euro/\(\text{kA} \cdot \text{m}\))

A. Ballarino, CERN
In order to make a 100 TeV superconducting machine possible, conductors need to undergo a sustained and intensive **program of R&D** including:

(i) *development of materials* that meet the desired characteristics for accelerator quality magnets;

(ii) *work with conductor manufacturers* to ensure that the developed strands are also of a sufficiently robust quality for large scale production (i.e. good yield)

A. Ballarino, CERN
Conclusions (2/2)

- Whereas the annual production of $\text{Nb}_3\text{Sn}$ was in the past about 15 t, for ITER the producers increased this to about 100 tons in order to achieve the total required delivery of about 500 tons. **Scaling of production rate** should be feasible – once we know what we want.

  **N.B.** the required performance of $\text{Nb}_3\text{Sn}$ is beyond the ITER current levels

- The **quantity of HTS required** is many times the present production capacity. It is too early to discuss this (and *a fortiori* to hazard a guess of cost)
One final theoretical comment on the BSM physics:
Facts: After the analysis of LHC data: No SUSY particles, yet!
Standard Model: at least 3 pieces are still missing!

Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom

⇒ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV),
nearly impossible to find.

.... but could perhaps explain all: Dark Matter,
Baryon Asymmetry in the Universe + ν-masses
FCC will be fun for the next 30 years !!!