The Global Future Circular Colliders Effort

Benedikt, Michael (CERN) et al.

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The research leading to this document is part of the Future Circular Collider Study

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The Global Future Circular Colliders Effort

P5 Workshop, BNL Brookhaven – 16th December 2013

Michael Benedikt
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• Main challenges and R&D areas for hadron collider
• Main challenges and R&D areas for lepton collider
• Conclusions
Overview Global FCC activities

  - Focus on lepton collider, long-term potential hadron machine.

  International Workshop on Future High Energy Circular Colliders
  chaired by Xinchou Lou (IHEP, Beijing)
  from Monday, December 16, 2013 at 08:30 to Tuesday, December 17, 2013 at 19:20 (Asia/Shanghai)
  at IHEP (A214) Main Building

  Description: The workshop will bring together people interested in circular high energy e+e- colliders as a Higgs factory as well as a future circular high energy pp collider beyond the Higgs factory, and will discuss critical issues in accelerator technology, detector design and in theory on the precision measurement of the Higgs and the physics with pp collision at 50-100 TeV.

- America/U.S: Presently seems no considerations for FCC in US.
  - Very relevant expertise from VLHC Design Study and US DOE Labs

- Europe: European Strategy suggests FCC design studies

  - Strong arguments for common design studies since conceptual machine designs are to a large extent of non-site specific nature.
    - Many R&D subject are of fundamental nature also relevant for other accelerator areas e.g. intensity frontier, etc.
• We are looking for a machine after BEPCII
• A circular Higgs factory fits our strategic needs in terms of timing, science goal, technological & economical scale, manpower reality, etc.
• Its life can be extended to a pp collider: great for the future

➢ Circular Higgs factory is complementary to ILC
  ➢ Push-pull option
  ➢ Low energy vs high energy

We hope to collaborate with anyone who is willing to host this machine. Even if the machine is not built in China, the process will help us to build the HEP in China
“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.
The Global FCC Effort
Michael Benedikt
P5 workshop BNL 16
December 2013

• 80-100 km tunnel infrastructure in Geneva area
• pp-collider (VHE-LHC) defining the infrastructure requirements
• e+e- collider (TLEP) as potential intermed. step and p-e (VLHeC) option
• CERN-hosted study performed in international collaboration

FCC Study (Future Circular Colliders)
CDR and cost review for the next ESU (2018)

~15 T ⇒ 100 TeV in 100 km
~20 T ⇒ 100 TeV in 80 km
• To prepare international collaborations, discuss study scope/topics. A Kick-off meeting will be held at Geneva University 12-15. Feb. 2014.

• Invitation to participate!
### Main areas for design study

#### Machines and infrastructure conceptual designs
- **Infrastructure**  
  P. Lebrun
- **Hadron collider conceptual design**  
  D. Schulte
- **Hadron injectors**  
  B Goddard
- **Lepton collider conceptual design**  
  J. Wenninger
- **Safety, operation, energy efficiency, environment**  
  P. Collier

#### Technologies R&D activities Planning
- **High-field magnets**  
  L. Bottura
- **SC RF systems**  
  E. Jensen
- **Cryogenics**  
  L. Tavian
- **Specific technologies**  
  JM. Jimenez
- **Planning**  
  F. Sonnemann

#### Physics experiments detectors
- **Hadron physics experiments interface, integration**  
  A. Ball, F. Gianotti, M. Mangano
- **e⁺ e⁻ coll. physics experiments interface, integration**  
  A. Blondel, J. Ellis, P. Janot
- **e⁻ - p physics, experiments, integration aspects**  
  O. Bruning, M. Klein

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**Preparatory group for a kick-off meeting**
Main parameters for FHC (VHE-LHC)

**PRELIMINARY**

- **Energy**: 100 TeV c.m.
- **Dipole field**: ~ 15 T (design limit) [20 T option]
- **Circumference**: ~ 100 km
- **#IPs**: 2 main (tune shift) + 2
- **Beam-beam tune shift**: 0.01 (total)
- **Bunch spacing**: 25 ns [5 ns option]
- **Bunch population (25 ns)**: 1x10^{11} p
- **#bunches**: 10500
- **Stored beam energy**: 8.2 GJ/beam
- **Emittance normalised**: 2.15x10^{-6} m, normalised
- **Luminosity**: 5x10^{34} cm^{-2}s^{-1}
- **β***: 1.1 m [2 m conservative option]
- **Synchroton radiation arc**: 26 W/m/aperture (filling fact. 78% in arc)
- **Longitudinal emit damping time**: 0.5 h
FHC - some machine design challenges

- **Optics and beam dynamics**
  - Optimum lattice design
  - IR design & length (&#) of straight section
  - Maximise filling factor of arcs
  - Dynamic aperture studies

- **Impedances, instabilities, feedbacks**
  - Beam-beam, e-cloud, etc.
  - Feedback simulation & system conception

- **Synchrotron radiation damping**
  - Controlled blow up? Shorter bunch spacing?, etc.

- **Already many collaborations for LHC and HL-LHC (LARP programme) with U.S. DOE laboratories**

- **Strong expertise in the U.S. in all these areas and U.S. contributions would be very welcome!**
FHC - Synchrotron Radiation Heat Load

- High synchrotron radiation load on beam pipe
  - Up to 26 W/m/aperture in arcs, total of ~5 MW for the collider
  - (LHC has a total of 1W/m/aperture from different sources)

- Three strategies to deal with this
  - **LHC-type beam screen**
    - Cooling efficiency depends on screen temperature, higher temperature creates larger impedance
  - **Open midplane magnets**
    - Synergies with muon collider developments
  - **Photon stops**
    - dedicated warm photon stops for efficient cooling between dipoles
    - as developed by FNAL for VLHC

http://inspirehep.net/record/628096/files/fermilab-conf-03-244.pdf

Also P. Bauer et al., "Report on the First Cryogenic Photon Stop Experiment," FNAL TD-03-021, May 2003
FHC - Machine Protection and Collimation

• Energy in beam & magnets, dump, collimation; quench protection
• Stored beam energy and losses critical: 8 GJ/beam (0.4 GJ LHC)

• Collimating low-emittance, high-energy-density beam challenging
  • higher energy density: even more robust materials?
  • smaller beam sizes and collimator gaps (gaps of 1 mm or less, requires higher precision in collimator control, setup, reproducibility)
  • New approaches like hollow electron beam, rotating collimators, crystal collimation

• Losses and radiation effects
  • Loss and shielding studies
  • IR quadrupoles, interplay of magnet design, loss and shielding simul.

• Synergies to intensity frontier machines (SNS, FRIB)
  • Important U.S. expertise in collimation and loss-studies, magnet design (HL-LHC IR quads), LARP
FHC high-field magnet targets

- FHC baseline is 16T Nb$_3$Sn technology for $\sim 100$ TeV c.m. in $\sim 100$ km

  Goal: 16T dipole model(s) by 2018

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

- In parallel HTS development targeting 20 T.
- HTS insert, generating $\mathcal{O}(5$ T) additional field, in an outsert of large aperture $\mathcal{O}(100$ mm)

  Goal: Demonstrate HTS/LTS 20 T dipole 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
# The running programs – LTS (\(\text{Nb}_3\text{Sn}\))

<table>
<thead>
<tr>
<th>Program</th>
<th>Goals</th>
<th>Main partners</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-base program</td>
<td>High field (\text{Nb}_3\text{Sn}) dipoles as technology demonstrators</td>
<td>DOE (BNL, FNAL, LBNL)</td>
<td>D20 reached 13.5 T (50 mm) in 1997, HD1 reached 16 T (0 mm) in 2004. LD1 shell and conductor procured</td>
</tr>
<tr>
<td>EuCARD FReSCa2</td>
<td>13 T (100 mm) (\text{Nb}_3\text{Sn}) dipole</td>
<td>EuCARD collaboration (CEA, CERN)</td>
<td>SMC reached 13.5 T (0 mm) in 2013, RMC in construction, FReSCa2 structure procured and tested at CERN, coils in fabrication at CEA</td>
</tr>
<tr>
<td>US-LARP</td>
<td>140 T/m (150 mm) (\text{Nb}_3\text{Sn}) quadrupoles for the LHC IR upgrade</td>
<td>DOE US-LARP (BNL, FNAL, LBNL), CERN</td>
<td>Short HQ models (120 mm), long LQ prototype (90 mm) tested, QXF (150 mm) models in production (US-LARP and CERN)</td>
</tr>
<tr>
<td>11 T</td>
<td>11 T (60 mm) (\text{Nb}_3\text{Sn}) dipoles for the LHC DS collimators</td>
<td>FNAL, CERN</td>
<td>2 short models tested, 1 mirror in test at FNAL, first model in production at CERN</td>
</tr>
</tbody>
</table>

NOTE: program at TAMU not reported
## The running programs – HTS

<table>
<thead>
<tr>
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<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-base program</td>
<td>High field HTS small models as technology demonstrators</td>
<td>DOE (BNL, FNAL, LBNL)</td>
<td>BSCCO racetracks produced and tested (self field) at LBNL. CCT design and prototyping work, first model (NbTi) reached 2.5 T in 2013</td>
</tr>
<tr>
<td>EuCARD HTS insert</td>
<td>6 T (0 mm) HTS dipole insert for FReSCa2 (19 T)</td>
<td>EuCARD collaboration (INPG, CEA)</td>
<td>Short racetrack coils in test at INPG</td>
</tr>
<tr>
<td>EuCARD2</td>
<td>5 T (40 mm) HTS short dipole (also as insert for FReSCa2 (18 T)</td>
<td>EuCARD2 collaboration (CERN, CEA), S-Innovation, US-BSCCo</td>
<td>Superconductor material studies in progress, conceptual designs</td>
</tr>
<tr>
<td>US-BSSCo</td>
<td>Increase ( J_e ) of BSCCO-2212 to 600 A/mm(^2) for high B physics (30 T all SC user facility)</td>
<td>DOE (BNL, FNAL, LBNL), NHMFL</td>
<td>BSCCO-2212 production restarted at OST in collaboration with CERN, OPHT furnaces, cabling R&amp;D</td>
</tr>
<tr>
<td>S-Innovation</td>
<td>HTS-based compact accelerator systems</td>
<td>Kyoto University, KEK</td>
<td>Conceptual design studies, test of a racetrack HTS at 77 K (self field) to determine field quality</td>
</tr>
</tbody>
</table>

NOTE: program at Carolina University not reported.
Summary on high-field magnets

• U.S. research has been leading superconducting high-field magnet technology:
  • Highest field achieved in dipole configuration (LBNL, 16 T)
  • Hosting the industrial superconductor production with highest critical current density (OST RRP, 3300 A/mm\(^2\) at 12 T and 4.2 K)
  • Vigorous program for the industrial production of a BSCCO-2212 round wire with the characteristics required by high-field applications

• CERN has a record of very fruitful collaborations with US-DOE Laboratories and Universities. E.g.
  • US-LARP collaboration for HL-LHC quadrupole production of approximately half of the triplet magnets, as required for LHC LS3
  • FNAL/CERN collaboration for the 11 T LHC dipole design and demonstration of the technology required for a for the LHC
  • CERN/NHMFL collaboration agreement on the study of LTS / HTS materials.

• These are excellent pre-requisites for a strong participation of the U.S. to the high-field magnet R&D that will be essential for FCC studies.
Lepton collider parameters – preliminary

- Design choice: max. synchrotron radiation power set to 50 MW/beam
  - Defines the max. beam current at each energy.
  - Different optimization at each energy (bunch current, emittance, etc).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TLEP-Z</th>
<th>TLEP-WW</th>
<th>TLEP-H</th>
<th>TLEP-(t)(_{\text{bar}})</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GeV)</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>104</td>
</tr>
<tr>
<td>I (mA)</td>
<td>1400</td>
<td>150</td>
<td>30</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>(\beta^*_{x/y}) (mm)</td>
<td>500 / 1</td>
<td>200 / 1</td>
<td>500 / 1</td>
<td>1000 / 1</td>
<td>1500 / 50</td>
</tr>
<tr>
<td>(\varepsilon_x) (nm)</td>
<td>30</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>30-50</td>
</tr>
<tr>
<td>(\varepsilon_y) (pm)</td>
<td>60</td>
<td>17</td>
<td>15</td>
<td>2</td>
<td>~250</td>
</tr>
<tr>
<td>L (10(^{32}) cm(^{-2})s(^{-1}))</td>
<td>5800</td>
<td>1600</td>
<td>500</td>
<td>120</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- For TLEP-H and TLEP-\(t\) the beam lifetime of \(~\)few minutes is dominated by Beamstrahlung (momentum acceptance of 2\%).
Some machine design challenges

• Short beam lifetime from Bhabha scattering and high luminosity
  • Top-up injection
• Lifetime limits from Beamstrahlung
  • Flat beams (very small vertical emittance, $\beta^* \sim 1$ mm)
  • Final focus with large (~2%) energy acceptance
• Machine layout for high currents and large #bunches at the Z pole.
  • Number of rings and size of the RF system.
• Polarization and continuous high precision energy calibration at Z pole and WW, where natural polarization times are ~ 15 hours.
• Important expertise in the U.S. and potential synergies:
  • Beam optics, experimental insertions, machine detector interface ⇔ ILC, B-factories, SLAC, BNL
• Transverse Polarization ⇔ RHIC, SLC:
  • Polarization optimization, snakes for physics with polarized beams.
Lepton collider RF - relevant parameters

Main RF parameters
• Synchrotron radiation power: 50 MW per beam
• Energy loss per turn: $7.5 \text{ GeV}$ (at $175 \text{ GeV}$, $t$)
• Beam current up to $1.4 \text{ A}$ (at $45 \text{ GeV}$, $Z$)
• Up to 7500 bunches of up to $4 \times 10^{11} \text{ e per ring.}$
• CW operation with top-up operation, injectors and top-up booster pulsed

First look on basic choices and RF system dimension
• Frequency range ($200 \ldots 800$) MHz with ~400 MHz as starting point
  • Initial choice based on present frequencies (harmonics of 200 MHz FHC)
  • Disadvantage lower frequency: mechanical stability, He amount for cooling, size …
  • Disadvantage higher frequency: denser HOM spectrum (multi-cell), BBU limit, larger impedance, smaller coupler dimensions
• System dimension compared to LHC:
  • LHC $400 \text{ MHz} \rightarrow 2 \text{ MV and } \sim 250 \text{ kW per cavity, (8 cavities per beam)}$
  • Lepton collider $\sim 600 \text{ cavities } 20 \text{ MV / 180 kW RF } \rightarrow 12 \text{ GV / 100 MW}$
RF main R&D areas

**SC cavity R&D**
- Large $Q_0$ at high gradient and acceptable cryogenic power!
- E.g.: Recent promising 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**
- Amplifier technologies
- Klystron efficiencies beyond 65%
- Alternatives: RF sources as Solid State Power Amplifier or multi-beam IOT, e.g. ESS solution developed with industry (CPI in U.S.)
- Relevant for all high power accelerators, intensity frontier (drivers), (e.g. νstorm, LBNE, DAEδALUS, μcoll.)

**Goal is optimization of overall system efficiency and cost!**
- Power source efficiency, low loss high gradient SC cavities, operation temperature vs. cryogenic load, total system cost and dimension.
RF R&D potential contributions

- Over the last decade(s) the U.S. have invested substantially in the field of superconducting RF R&D and technology. At present U.S. has a world leading role in the field of SCRF technology.

- A large scale U.S. program on SCRF R&D for international FCC studies looks like a logical continuation of the program.

- Goal for RF related R&D:
  - Significantly advance SCRF technology;
  - by 2018 propose a valid, cost/performance/efficiency optimized solution for a ~100 MW CW, ~10 GV RF System.
Summary

• There are strongly rising activities in energy-frontier circular colliders worldwide. CERN is offering to help and coordinate international studies for the design of Future Circular Colliders (FCC).

• U.S. participation in all study areas, i.e. physics, experiments and accelerators will be very important for the field of HE physics.

• Particularly in the main R&D areas of high-field magnets, SC RF, high-power beam handling and advanced machine design, a strong U.S. contribution is essential to reach conceptual design level by 2018.

• A strong U.S. contribution will also be a natural continuation of ongoing collaborations in the framework of LHC and HL-LHC, strengthen areas of U.S. core competency and ensure efficient use of past investments.

• FCC kick-off meeting 12-15 February 2014 in Geneva University
  - Establish collaborations, define WPs and set-up study groups
  - Looking forward to welcoming you!