FCC-hh and Magnets: Summary

Vladimir Shiltsev
Fermilab
FCC-Week, June 9, 2023 9:50am-10:10am
10:30 AM | Future magnet developments
Convener: Mike Lamont (CERN)

10:30 AM | Future HFM R&D directions
Speaker: Bernhard Auchmann (PSI/CERN)

11:00 AM | US high-field magnet program
Speaker: Soren Prestemon

11:30 AM | HTS developments
Speaker: Dr Amalia Ballarino (CERN)

10:30 AM | FCC-hh accelerator
Convener: Vladimir Shiltsev

10:30 AM | FCC-hh ring: overview of the new layout
Since the publication of the CDR, much progress has been made on the layout of the FCC-hh ring. Driven by the recent result of the ring placement studies and updates of the FCC-eu layout, major changes have been implemented in the FCC-hh ring layout. In this talk, I review the main features of the new layout, and I also provide an outlook of future studies and activities.
Speaker: Massimo Giovannozzi (CERN)

10:55 AM | New FCC-hh ring layout: arc and insertion optics
We present the latest developments in the optics design of the FCC-hh particle collider. The main change with respect to previous designs is the change of the arc cells from 12 to a 16-dipole FODO scheme which makes full use of the available aperture and increases the dipole filling factor. The updated design of insertions is also discussed, adapting the changes in the layout requirements from the placement study and are made compatible with the new arcs and their dispersion suppressors.
Speaker: Gustavo Perez Segurana (CERN)

11:15 AM | Collimation in FCC-hh
Speaker: Dr Roderik Bruce (CERN)

11:35 AM | Transfer lines for injection from LHC or scSFS, and comparison of injector options
Speaker: Wolfgang Bartmann (CERN)
1\textsuperscript{st} stage collider, FCC-ee: electron-positron collisions 90-360 GeV
Construction: 2033-2045 → Physics operation: 2048-2063

2\textsuperscript{nd} stage collider, FCC-hh: proton-proton collisions at ≥ 100 TeV
Construction: 2058-2070 → Physics operation: ~ 2070-2095

Assuming... FCC-ee will not happen, we may go directly to FCC-hh via the fastest path (Nb$_3$Sn). Timescale ~ 2060 : dictated by R&D and industrialisation of magnet technology, and cost
Challenges: Timeline

—**Nb3Sn, 12~14 T**: 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start.

—**Nb3Sn, 14~16 T**: 10-15 years for short-model R&D, and the following 10 ~ 15 years for prototype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start.

—**NbTi, 8~9 T**: proven by LHC and **Nb3Sn, 10 ~ 11 T** being demonstrated. It may be feasible for the construction to begin in **> ~ 5 years**.
Challenges: Cost

Cost of a magnet (rough, LHC):
- ~1/3 Cost of conductor
- ~1/3 Cost of structure
- ~1/3 Cost of assembly

Snowmass’21 Implementation Task Force Report:

<table>
<thead>
<tr>
<th>FCChh-100</th>
<th>CME (TeV)</th>
<th>Lumi per IP (10^34)</th>
<th>Years, pre-project R&amp;D</th>
<th>Years to 1st Physics</th>
<th>Cost Range (2021 B$)</th>
<th>Electric Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>30</td>
<td>&gt;10</td>
<td>&gt;25</td>
<td>30-50</td>
<td>~560</td>
<td></td>
</tr>
</tbody>
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### FCC-hh – Goals *(Now Updated)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>80-116</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>14 (Nb$_3$Sn) – 20 (HTS/Hybrid)</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>90.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>1020-4250</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>13-54</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.77-0.26</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>normalized emittance [$\mu$m]</td>
<td>2.2</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>5</td>
<td>30</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>132</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>6.1-8.9</td>
<td>0.7</td>
<td>0.36</td>
</tr>
<tr>
<td>integrated luminosity [fb$^{-1}$]</td>
<td>20000</td>
<td>3000</td>
<td>300</td>
</tr>
</tbody>
</table>

FCChh is part of the Feasibility Study funded from CERN budget: 100 MCHF total over 5 years; in addition: ~ 20 MCHF/year for high-field magnet R&D. Additional funding from the European Commission and collaborating institutes (e.g., CHART collaboration with Switzerland).
High Field Magnet (HFM) Program - Europe

- 12 partners (labs, univ.)
- Three focused areas & goals →
  - Robust 12 T Nb3Sn magnets (Genova and CERN)
  - 16T common coil (15 T in 2025?)
  - Current density >1.5kA/mm2
  - HTS conductors and HFM
- Cross cutting topics:
  Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc
- Recent advances eg wax impregnation = no training! (slide)
  - Of course, there still questions remaining: will it be as good at very high fields? Is it rad-hard enough? etc
Feedback to Magnet Programs

PSI’s BigBOX: a 13-turn stress-managed racetrack.
- No training with 12.3 T coil field, 150 MPa coil stress at BNL’s DCC17 facility.

LBNL’s wax impregnated sub-scale (5 T) CCT.
- First Nb$_3$Sn CCT without training.
- Follow-up magnet and test planned.

Wigner Inst. / CERN collaboration on SuShi septum for FCC-hh
- Wax impregnated CCT required no training to nominal current.

[Courtesy D. Araujo et al]
Magnet Development Program (MDP) - US

- Three labs and University… FCChh and MuCollider
- Focus on stress management 14-16 T Nb3Sn
  - 120 mm aperture to fit 5T HTS insert
- Goal: in 3-4 years 16-17 T hybrid (Nb3Sn+REBCO) dipole
- Recent advances:
  - 14.5T FNAL 4-layer Nb3Sn → 2 layers
  - 1st Nb₃Sn CCT coil wax impregnated had no quenches!
  - Diagnostics! E.g.:
    - Rayleigh backscatter fiber optics for area-level strain monitoring
  - Significant promise of REBCO
- Challenges: total USHFM funding ~1/3-1/4 of that in Europe
**FCChh Optics Update**

In the FCCee footsteps: shorter $C$, less space for technical insertions, 4 IPs symmetry
Baseline change: **longer cells**
- 12 dipoles $\rightarrow$ 16 per FODO, 213 $\rightarrow$ 276m
- packing factor 80% $\rightarrow$ 84%

A non-baseline, alternative design of arcs and dispersion suppressors based on combined-function (CF) magnets
- has pros and cons
- needs further study
Beam Screen Changes

Longer cells $\rightarrow$ weaker focusing $\rightarrow$ larger beams

**REBCO (HTS strips) - Cu coating to improve conductivity at high(er) temperature**

A series of magnetic measurements are planned for October 2023 at CERN (SM18 facility) to probe the impact of the BS on the field quality.
FCChh Collimation

- LHC 0.36GJ beams → 8 GJ in FCChh
  - 11MW of losses to intercept
  - LHC gives assurance
  - Quench limits of “future magnets” - ?
- Still, some changes (wrt CDR):
  - Shorter C → 30% less space for collimators
  - New optics (12→16 dipoles/cell)
- Simulations show that:
  - No serious issues
  - Not 100% happy so far (old optics)
  - Need to redo calc’s for new optics
- Some concern:
  - Aperture bottlenecks in new optics moved
    - from IRs to arcs/disp.suppressors – effect?
Two energies/Three options (TBD later):

- 1.3 scSPS (cheaper but - good enough for collider field quality?)
- 3.3 TeV (good but expensive?)
  - Either make LHC magnets ramp faster (now ~1000 s)
  - Or new 4T ring in LHC tunnel

Reuse FCCee tunnels:

- ~2 km each, ~8 T magnets
- then ~10 km in collider 0.5-1T

The latter can be PMs:

- Smaller/cheaper (slide)
- Lower power consumption
- Experience at FNAL RR/CBETA

Lot of other inj/dumps topics:

- SUSHI (slide)
In the FCChh tunnel: Space consideration

Normal conducting solution

Permanent magnet solution

Courtesy F. Valchkova-Georgieva
SUSHI (Superconducting Shield) Dump Septum

Passive SC shield

Custom CCT winding

Zero field

High field (3 T)

Budapest/CERN

CCT magnet without shield was tested.
Thank you for your attention!