FCC-hh injectors: scenarios

Brennan Goddard
CERN TE/ABT

W.Bartmann, E.Renner, A.Milanese, M.Solfaroli
Overview

- Recall of requirements
- Constraints and options considered
- Reuse of LHC for 3.3 TeV HEB
- Other 3.3 TeV options
- Recall of new scSPS for 1.3 TeV HEB
- Performance comparison summary
- Conclusion and baseline
Requirements

• Inject at 3.3 TeV
  - 1.3 TeV has been studied as low-energy option, but (presently) not favoured by collider

• Deliver required beam parameters (Intensity, emittance, spacing)

• Fill FCC-hh as quickly as possible
  - Asked for 10 minutes, targeted 30 minutes (LHC experience shows that this is reasonable)
Constraints and options considered

• Re-use existing CERN proton complex as far as possible
  - Assume post HL-LHC performance
  - Keep the main project effort focused on the 100 km collider(s)

• Options studied based on existing tunnels
  - SPS: 6.9 km
  - LHC: 26.7 km
  - FCC: 100 km
Injector chain in context

- Very regular progression in energy gain per step (~x15), except in new HEB if 450 GeV injection energy maintained (~x7)
HEB options at CERN: energy vs field

![Graph showing energy vs main dipole field for HEB options at CERN. The graph includes three lines representing SPS, LHC, and HEB, with different energy and field regions for NC/SF, SC Nb-Ti, and SC Nb₃-Sn.]
HEB options at CERN: SPS tunnel
HEB options at CERN: LHC tunnel

- SPS [TeV]
- LHC [TeV]
- HEB [TeV]

- NC / SF
- SC Nb-Ti
- SC Nb$_3$-Sn

- 7.7 T SC
  - 6.5 TeV

- 4.5 T SC
  - 3.8 TeV

- 2T NC/SF
  - 1.68 TeV

- 4 T SC
  - 3.3 TeV

Extraction energy [TeV]
Main dipole field [T]
HEB options: FCC collider tunnel
Reuse of LHC as 3.3 TeV HEB
• Transfer from LHC P1 and P8 (11.7 km with 7 T dipoles)

• LHC Straight sections:
  - IR1: new extraction system and beam crossing, plus decommissioning of ATLAS
  - IR2: injection to inside ring plus decommissioning of ALICE and crossing
  - IR3: no changes to momentum collimation
  - IR4: no changes to RF system
  - IR5: decommissioning of CMS, plus beam crossing
  - IR6: no changes to beam dump
  - IR7: no changes to betatron collimation
  - IR8: injection to inside ring plus new extraction plus decommissioning of LHCb and crossing
Reuse of LHC: general layout changes
• Layouts of modified LHC straight sections: IR1

• Low beta insertion removed from Q6; new extraction channel combined with a new superconducting crossing
• Layouts of modified LHC straight sections: IR2

• Low beta insertion and crossing replaced from Q5 inwards by FODO; injection moved to inner ring and downstream
• Layouts of modified LHC straight sections: IR5

• Low beta insertion replaced from Q4 inwards by FODO; crossing with superconducting dipoles; possibility for (collider) experiment
• Layouts of modified LHC straight sections: IR8

• Remove low beta insertion from Q5 inwards; move injection to inner ring; extract beam from outer ring
3.3 TeV LHC performance: faster ramping

- Present LHC ramp up to 3.3 TeV would take 8’30”, total FCC filling time >1.5 hours
- With dipole power converter upgrade and splitting of sectors in halves to ramp at 50 A/s, 3.3 TeV ramp takes 156 sec
- PPLP scheme instead of present PELP essential to fully profit from increased ramp rate (tested in 2017, being commissioned now for LHC)
- Time to ramp down from 3.3 TeV driven by one-quadrant main quadrupole power converters. With upgrade, ramp down time shortened to 100 s
- Overall FCC filling time (on paper) is then 46 minutes, for 4 LHC fills and ramps
- Full details in talk by A.Milanese
Alternative 3.3 TeV HEB options
100 km superferric HEB

- 3.3 TeV superferric 100 km HEB in FCC-hh tunnel
  - 1.1 T dipoles (for 70% filling factor)
  - Single aperture + polarity reversal, or simple twin aperture →
  - By-pass tunnels around 4 experiments - $\int 15$ km (FCC-ee)
  - Integration into FCC tunnel still to demonstrate
  - Issue of beam loss cross-talk? (collimation, slow extraction)
  - Impedance and stability at injection energy → could require magnet vertical gap ~80 mm
  - Ramp-up time 120 s (limited by RF)
  - FCC filling in 32 minutes (injectors)
  - Very high stored energy of 670 MJ

- 50 kA SC cable (100 MW peak power if resistive)
• 3.3 TeV superconducting 26.7 km HEB in LHC tunnel
  - 4 T dipoles (4 K cos \( \theta \) – RHIC, Tevatron, FAIR SIS200/300)
  - Single aperture needs polarity reversal, to avoid very long transfer lines, otherwise twin aperture (cost/complexity...)
  - Simplified LHC lattice, with insertions as per reused-LHC
  - Ramp-up time about 50 s (limited by RF system)
  - FCC filling time about 39 minutes (injectors)
Recall of 1.3 TeV SC HEB in SPS tunnel
1.3 TeV scSPS as HEB

• Transfer from SPS P3 and P5 (10 km @ 1.8 T)

• scSPS Straight sections:
  - LSS1: injection system
  - LSS2: slow extraction system to North Area
  - LSS3: fast extraction to FCC
  - LSS4: RF system
  - LSS5: fast extraction to FCC
  - LSS6: beam dump and collimation systems
1.3 TeV scSPS optics

- Linear optics design based on present SPS concept
  - 64 m cell length, missing magnet DS, 12 m, 6 T dipoles

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<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>Injection energy</td>
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<td>Extraction energy</td>
<td>GeV</td>
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<td>Number of quadrupoles</td>
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<td>Ramp rate</td>
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<td>Cycle length</td>
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<td>Number of injections into scSPS</td>
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<td>34 - 40</td>
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<td>Max stored beam energy</td>
<td>MJ</td>
<td>33</td>
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1.3 TeV scSPS performance

- Dipole ramp rate ~0.5 T/s, 12 s ramp
  - 37 minutes on paper to fill FCC, with 34 cycles of the scSPS
  - Aperture dimensioned for slow extracted fixed-target beam
  - x60 energy swing to validate

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<td>$\delta p/p$</td>
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<td>$A_x / A_y$</td>
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scSPS cycle length: 1 min
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<td>2600</td>
<td>2’600</td>
<td>11’000</td>
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<td>Stored HEB energy per beam</td>
<td>MJ</td>
<td>15</td>
<td>167</td>
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<td>7.5</td>
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<td>FCC filling time (25 ns)</td>
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<td>37</td>
<td>46</td>
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Conclusion and baseline

• Reuse of existing LHC with 5x faster ramp remains FCC-hh baseline
  - Can deliver 3.3 TeV beam, albeit with longer filling time than desired
  - Expected to be lowest capital cost (material and manpower), and existing well-known facility, without need to design, build and commission a completely new large machine
  - But: high operating cost and complexity, plus availability concerns: all to quantify

• Two other alternative ‘simpler’ scenarios to keep as options
  - replacing LHC with 4 T, 4 K single aperture HEB, or 100 km superferric HEB)
  - Costings needed for real comparison, including design, construction, operation, ...

• scSPS option only valid if 1.3 TeV FCC injection is possible
  - Presently excluded by collider dynamic aperture
1) High Energy Booster options for a Future Circular Collider at CERN, L.Stoel et al., IPAC2016-MOPOY007

2) Possible reuse of the LHC as a 3.3 TeV High Energy Booster for hadron injection into the FCC-hh, B.Goddard et al., IPAC2015-THPF094

3) Beam transfer to the FCC-hh collider from a 3.3 TeV Booster in the LHC tunnel, W.Bartmann et al., IPAC2015-THPF089

4) Faster ramp of LHC for use as an FCC High Energy hadron Booster, A.Milanese et al., CERN-ACC-2015-0133

5) Main changes to LHC layout for reuse as FCC-hh High Energy Booster, B.Goddard et al., CERN-ACC-2015-0030

6) Physics opportunities with the FCC-hh Injectors, B.Goddard et al., arXiv:1706.07667-2017

7) Concept of a hybrid (normal and superconducting) bending magnet based on iron magnetization for 80-100 km lepton/hadron colliders, A.Milanese, IPAC2014-TUO CB01