100 TeV hadron collider: 4.5 dipoles in a 270 km tunnel

Peter McIntyre, Saeed Assadi, James Gerity, Joshua Kellams, Tom Mann, Chris Mathewson, Al McInturff, Nate Pogue, Akhdiyor Sattarov, Klaus Smit

Texas A&M University
The FCC Collaboration has made the physics case for a large circular collider as a basis for the next generation of HEP:

Example from Mustafayev @ MWCDMP2014:
SUSY spectrum to preserve naturalness... is above LHC reach, all within reach for $\sqrt{s} = 100$ TeV.

**Summary of Natural spectrum**

- For $m_h \sim 125$ GeV and $\Delta_{EW} < 30$:
  - $\mu \sim 100$-300 GeV
  - $\text{stop}_1 \sim 1$-2 TeV, $\text{stop}_2 = \text{sbottom}_1 \sim 2$-4 TeV, highly mixed by large $A_t$
  - gluino $\sim 1$-5 TeV
  - 1st/2nd generation squarks $\sim 1$-10 TeV
  - sleptons $\sim 1$-30 TeV

- This can be realized in a simple extension of mSUGRA, NUHM2 $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\mu$, $m_A$

- Here small $m_{H_u}^2 \simeq -M_Z^2$ and lighter stops are generated by RGE evolution, hence Radiatively-driven Natural SUSY (RNS)
The FCC design studies assume a tunnel circumference of 80-100 km.

- 80 km tunnel circumference is fine for a Higgs factory, and we have one we would like to offer you...

- 80-100 km circumference is a painful choice for a 100 TeV hadron collider because it pushes magnet technology to ~16 T, and has very high synchrotron radiation into the aperture.

- Is that really the most cost-effective choice? Suppose one sought a larger circumference and lower dipole field for the ultimate hadron collider...
Tunnel cost depends strongly upon the rock in which you tunnel.

There is already an 80 km circumference tunnel in Texas – the SSC tunnel was nearly completed. The tunnel is contained in the Austin Chalk and the Taylor Marl – two of the most favorable rock types. Tunneling the SSC set world records for tunneling advance rate – 45 m/day. That record holds today!

A 270 km tunnel can be located at the same site, entirely within the Austin Chalk and Taylor Marl, tangent to the SSC tunnel as injector.

LEP tunnel cost ~$11,000/m in 1981

270 km x $3000/m = $810 million
We have explored what the FCC collider complex would be like in a 270 km tunnel

- **100 TeV hadron collider requires 4.5 T magnets**
  - RHIC dipole (3.5 T @ 4.5 K) is simple, single-shell dipole,
  - mfg. in industry, simple structure, modest forces
  - But each dipole cost 30 times more than the superconductor inside it!

- **LHC dipoles cost ~7 times more than their superconductor**
  - We need a dipole with inexpensive superconductor, simple fabrication.
We have devised a way to combine the simplicity of the low-field superferric SSC dipole with a cable-in-conduit conductor:

- 4.5 Tesla dipole field
- C-dipole: synchrotron radiation passes into a second chamber where it is absorbed at 150 K.
- Refrigeration is 100x more efficient, so heat load not a limit.
- Clearing electrode suppresses electron cloud; 25 ns bunch spacing feasible.
- Superconducting winding has 20 turns total, wound from 2 pieces of round cable-in-conduit.
The 4.5 T NbTi dipole is key to manufacturability and cost

- Each dipole winding contains a total of 20 turns of cable.
- Quench protection is provided by driving current pulse in cable sheath – quenches all turns without voltage spike.
- Total cross-section of superconducting strand in one dipole is 8 cm$^2$ NbTi.
- Compare to 39 cm$^2$ NbTi for LHC, 82 cm$^2$ of Nb$_3$Sn and 25 cm$^2$ of NbTi for 16 T dipole.
- Total mass of superconductor in double-ring is 2800 tons.
- Total cost of superconductor ~$278 million.
Everything that is tricky (cryogenics, quench protection) is contained within the cable. The dipole structure is then simple and passive. The superferric magnets can be manufactured in any medium-scale metals industry if we provide proper tooling, training, QC. That is the key to obtaining partner contributions from ~50 nations for a New World Laboratory.

LHC  superferric  16 T $\text{Nb}_3\text{Sn}/\text{NbTi}$
Manufacture of the dipole

1. Wind racetrack pancake windings for top/bottom halves - bend ends 90°.

2. Insert half-windings into one-piece lamination stack, insert wedges, compress/weld to preload and seal.

3. Vacuum-impregnate windings to lock coil geometry and preload.

4. Install winding assemblies into flux return assemblies, compress and weld.
All cryogenics are integrated with the actual windings – dipole is passive and simple.

LHe flows in series flow through the spring tubes of all turns. LHe flows in parallel through larger flow tubes near beam tube. Above is a heat transfer simulation, in which $Q = 0.4 \text{ W/m}$ is deposited in the magnet in a $1/r$ distribution w.r.t. the beam tube – simulating heat from the ionization produced by beam losses. The maximum temperature rise in the dipole windings is 0.1 K. We could tolerate $\sim 4x$ more than this without risk of quench. The dipoles are $>10x$ more robust against beam-induced heat loads than LHC dipoles.
Superconductor cross-section vs. field for example collider dipole designs
Compare the costs for two dominant cost elements of the hadron collider: tunnel and superconducting wire

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
<th>100 TeV 270 km</th>
<th>100 TeV 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating field</td>
<td>3.4 T</td>
<td>8 T</td>
<td>4.5 T</td>
<td>16 T</td>
</tr>
<tr>
<td># Bores</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td># turns per bore</td>
<td>32</td>
<td>74</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Superconductor cross section/bore</td>
<td></td>
<td></td>
<td>8 cm²</td>
<td>(82+25) cm²</td>
</tr>
<tr>
<td>Length</td>
<td>9.4 m</td>
<td>14.3 m</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Superconducting wire/bore: NbTi</td>
<td>48 kg</td>
<td>435 kg</td>
<td>140 kg</td>
<td>780 kg</td>
</tr>
<tr>
<td></td>
<td>Nb₃Sn</td>
<td></td>
<td></td>
<td>2,950 kg</td>
</tr>
<tr>
<td>Manufactured magnet cost</td>
<td>$105,000</td>
<td>$565,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of superconductor</td>
<td>$4,800</td>
<td>$87,000</td>
<td>$24,000</td>
<td>$1,260,000</td>
</tr>
<tr>
<td>Magnet cost/m/bore/T</td>
<td>$3,265</td>
<td>$2,100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superconductor cost/m/bore/T</td>
<td>$102</td>
<td>$278</td>
<td>$133</td>
<td>$31,500</td>
</tr>
<tr>
<td>Superconductor cost for collider</td>
<td></td>
<td></td>
<td>$278 million</td>
<td>$4,280 million</td>
</tr>
<tr>
<td>Tunnel cost/m: in alpine site</td>
<td></td>
<td></td>
<td>$1,323 million</td>
<td>$1,360 million</td>
</tr>
<tr>
<td></td>
<td>: in Austin Chalk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel cost:</td>
<td></td>
<td></td>
<td>$4,900</td>
<td>$17,000</td>
</tr>
</tbody>
</table>

**Challenge:** simplify manufacture so that magnet cost ~4 s.c. cost.
Multipoles are readily controlled to yield excellent dynamic aperture.

Compatible with stable high-luminosity collisions.

 Momentum acceptance $\sigma_p/p > 5 \times 10^{-4}$ sufficient for momentum stacking.
## Parameters of the lepton and hadron colliders for medium and large circumference

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^-$ ring collider</th>
<th>hadron collider</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circumference</strong></td>
<td>80</td>
<td>270</td>
</tr>
<tr>
<td><strong>Collision energy</strong></td>
<td>H: 0.24, t: 0.35</td>
<td>100, 100, 300</td>
</tr>
<tr>
<td><strong>Dipole field</strong></td>
<td>0.046, 0.066, 0.015</td>
<td>15, 4.5, 15</td>
</tr>
<tr>
<td><strong>Luminosity/I.P.</strong></td>
<td>4.8, 1.3</td>
<td>4, 5, 6, 10</td>
</tr>
<tr>
<td><strong>Luminosity lifetime</strong></td>
<td>*50x0.1, 100x0.1</td>
<td>100x0.1, 110</td>
</tr>
<tr>
<td><strong>Total synch. power</strong></td>
<td>100</td>
<td>1.0, 1.0, 44</td>
</tr>
<tr>
<td><strong>Critical energy</strong></td>
<td>430, 1350</td>
<td>330, 3.4, 34</td>
</tr>
<tr>
<td><strong>Synch power per meter</strong></td>
<td>52</td>
<td>1, 192</td>
</tr>
<tr>
<td><strong>Emittance damping</strong></td>
<td>0.5</td>
<td>4, 0.5</td>
</tr>
<tr>
<td><strong>Beam lifetime</strong></td>
<td>0.15, 0.33</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Energy loss/turn</strong></td>
<td>2100, 9300</td>
<td>2300, 3.6</td>
</tr>
<tr>
<td><strong>RF accel. voltage</strong></td>
<td>6000, 12000</td>
<td>6000, 50, 200</td>
</tr>
<tr>
<td><strong>Acceleration time</strong></td>
<td>.25, .25, .25</td>
<td></td>
</tr>
<tr>
<td><strong>Bunch spacing</strong></td>
<td>50, 50</td>
<td>50, 25, 25</td>
</tr>
<tr>
<td><strong>Beam-beam tune shift</strong></td>
<td>.01</td>
<td>.01, .01, .01</td>
</tr>
<tr>
<td><strong>Momentum acceptance</strong></td>
<td>9.4, 5.5, 6.5</td>
<td>.05, .05, %</td>
</tr>
<tr>
<td><strong># IPs</strong></td>
<td>4, 4</td>
<td>4, 2+2</td>
</tr>
<tr>
<td><strong># particles per beam</strong></td>
<td>4.1, 0.9</td>
<td>80, 220, 57</td>
</tr>
<tr>
<td><strong>Injection energy</strong></td>
<td>0.24, 0.35, 0.35</td>
<td>&gt;3, 15, 50</td>
</tr>
<tr>
<td><strong>Superconducting temp.</strong></td>
<td>4.2</td>
<td>10, 4.2</td>
</tr>
</tbody>
</table>

**Notes:**
- The table contains parameters for lepton and hadron colliders with different circumferences.
- The values for each parameter are provided in units of kilometers (km), teraelectronvolts (TeV), teslas (T), terabytes (T), cm$^{-2}$ s$^{-1}$, minutes (min), hours (h), meters (m), and others as indicated.
- The table compares the performance parameters of the $e^+e^-$ ring collider and the hadron collider for medium and large circumferences.

**Example:**
- **Circumference:** The table lists the circumference for different collider sizes, ranging from 80 km to 300 km.
- **Collision energy:** The table shows the collision energy for different collider sizes, with values ranging from 0.24 TeV to 430 TeV.
100 TeV: Synchrotron damping dominates dynamics for luminosity, stacking

- The synchrotron damping time is \( \sim 4 \text{ h} \).
- Transverse emittance damps, luminosity is a balance between shrinking emittance and depletion of protons by collisions.
- Longitudinal emittance would damp, but we heat it using rf noise to prevent instabilities.
Bottom-up stacking to deliver maximum luminosity indefinitely

- When luminosity would begin to decrease due to proton depletion, turn off rf heating, decelerate to 15 TeV, scrape tails, and momentum-stack a fresh fill of protons along with the ones in the store.

- The momentum acceptance of the superferric dipole is sufficient to perform momentum stacking at 15 TeV injection energy – this is benefit of high-energy injector in SSC tunnel.

- RF voltage ~50 MV is required to provide sufficient bucket to capture and accelerate, and to replace synch rad at full energy.

- Re-accelerate and resume collisions.

This bottom-up stacking can be used to maintain maximum luminosity indefinitely. Down-time of each cycle ~40 min every ~4 h
300 TeV: Synchrotron damping ➔ flat beams

- Synchrotron damping time \(\sim 30 \text{ m.}\)
- Synchrotron damping dominates the evolution of tune shift and luminosity.
- Beam begins \(x/y\) symmetric, and damps in \(y\) within \(\sim 30 \text{ min}\) – \(y\) tune shift increases, luminosity increases
- Program \(\beta_y\) to maintain \(\sim\)constant \(\xi_y \sim .01\)

**Very high luminosity may be possible in this regime.**
Benefits of a large-circumference hadron collider for a Hadron Collider that can actually be built...

• **pp @ 100 TeV:** industrial magnet technology

  1/3 synch rad power
  injector in separate tunnel
  $B_{\text{col}}/B_{\text{inj}} = 0.3 \Rightarrow$ no field issues at injection, stacking OK
  Luminosity $> 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ indefinitely

• **pp @ 300 TeV:** 25 years to develop 16 T magnets

  $B_{\text{col}}/B_{\text{inj}} = 0.3 \Rightarrow$ use 100 TeV collider as injector
  Luminosity $> 10^{35}$ cm$^{-2}$s$^{-1}$ indefinitely
Summary

• We have identified a candidate site that could accommodate a 270 km tunnel for a 100 TeV hadron collider (using 4.5 T dipoles).
• We have developed a design for a 4.5 T superferric dipole that is simple/low-cost to build, operates at 4.5 K.
• Operation of a 100 TeV hadron collider is dominated by the refrigeration of heat from synchrotron light. We provide a separate channel for synchrotron light, intercept it at high reservoir temp, so its heat does not dominate operating cost.
• Synchrotron radiation damps the beam in ~4 hours. We can maintain maximum luminosity indefinitely using a top-up scenario.
• The tunnel could accommodate a future 300 TeV upgrade.
• The magnets are simple:
  • Goal is magnet cost <4x superconductor cost.
  • Any industrialized nation could manufacture these magnets.
The New World Laboratory: How to build the collider in a world of finite $\$$

- Ask Texas to build the 270 km tunnel as a State contribution.
  - $\sim$1 billion
- Form scientific partnership among member states to build the lab and operate its scientific program.
  - Each country funds its own industries to build a share of the technical components for the collider.
    - $\sim$10-100 million, depending upon country – total $\sim$1 billion
- Collider staff develops designs, builds/tests prototypes, maintains quality control on all contributed hardware.
- Ask US for major funding for conventional facilities, equipment.
  - US role is as host country. This is a world laboratory, not a DOE laboratory. $\sim$1 billion
- Operating budget half DOE, half from member states.
- Lab staff half from member states.
- What is best way to coordinate design/build/funding of detectors?
Acqua alla funi...

P5 will report its findings next week. It is widely expected to recommend an ordering of priorities among the present research themes (LHC upgrade, neutrino experiments, dark matter searches) to cope with ever-shrinking US support for HEP.

<table>
<thead>
<tr>
<th>Year</th>
<th>HEP</th>
<th>Amount in FY14$</th>
<th>% decrease with inflation since FY 96</th>
<th>% of Office of Science</th>
<th>Office of Science total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>$667 M</td>
<td>$1,045 M²</td>
<td></td>
<td>26.8%</td>
<td>$2,485.2 M¹</td>
</tr>
<tr>
<td>2013</td>
<td>$776.5 M</td>
<td>$788.2 M²</td>
<td>-21.6%</td>
<td>15.5%</td>
<td>$5,001.2 M</td>
</tr>
<tr>
<td>2014</td>
<td>$796.5 M</td>
<td>$796.5 M</td>
<td>-23.8%</td>
<td>15.7%</td>
<td>$5,066.4 M</td>
</tr>
<tr>
<td>2015¹</td>
<td>$744 M</td>
<td>$733 M³</td>
<td>-29.9%</td>
<td>14.6%</td>
<td>$5,111.2 M</td>
</tr>
</tbody>
</table>

In 1995 the top quark was discovered at Fermilab. That was the last major HEP discovery in the US. There is no prospect for another, unless dark matter or a sterile neutrino were discovered here.

Without discoveries – or the prospect of discoveries – in the US it is reasonable to expect that the US support of HEP will continue to decline.

Reversing that trend requires innovation: a new lab with credible potential for new discoveries; technology to make it affordable and to share the cost and the research leadership on a global scale; potential for a future upgrade to a further generation.