Cable-in-Conduit Dipoles to enable a Future Hadron Collider

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CERN is beginning studies for a 100 TeV hadron collider in the Rhone Valley

90 km circumference – limited by the surrounding mountains and lake
15 T magnets – no one knows how to build them successfully today
Superconducting wire for that magnetic field would cost $20 Billion today
Tunnel would likely cost ~$4 Billion
Ultimate reach for discovery of new gauge fields : 7.5 TeV ➞ 40 TeV

Today we have no credible prediction for the mass scale where a new gauge field might appear.

Strategy: Large-circumference site with low tunneling cost,
Modest field-strength magnets with low cost
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 in 1992
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.
Cable-in-Conduit for an Ultimate Collider

15 NbTi/Cu wires are cabled onto a perforated spring tube.
We are building a 1.2 m model of a 3 T CIC dipole for the Ion Ring of JLAB’s proposed Electron-Ion Collider
Compare the costs for the tunnel and superconducting wire for a 100 TeV hadron collider:

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
<th>100 TeV 270 km</th>
<th>100 TeV 100 km</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>20</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>92 kg</td>
<td>380 kg</td>
<td>124 kg</td>
<td>390 kg</td>
</tr>
<tr>
<td></td>
<td>Nb$_3$Sn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufactured magnet cost/dipole</td>
<td>$105,000</td>
<td>$565,000</td>
<td>$185,000</td>
<td>?</td>
</tr>
<tr>
<td>Cost of superconductor/dipole</td>
<td>$23,100</td>
<td>$190,000</td>
<td>$62,000</td>
<td>$3,050,000</td>
</tr>
<tr>
<td>Magnet cost/m/bore/T</td>
<td>$3,265</td>
<td>$2,470</td>
<td>$1,028</td>
<td></td>
</tr>
<tr>
<td>Superconductor cost/T/m/bore</td>
<td>$150</td>
<td>$380</td>
<td>$345</td>
<td>$4,780</td>
</tr>
<tr>
<td>Superconductor cost for collider</td>
<td></td>
<td></td>
<td>$720 million</td>
<td>$10,000 million</td>
</tr>
<tr>
<td>Magnet cost for collider</td>
<td></td>
<td></td>
<td>$2,150 million</td>
<td></td>
</tr>
<tr>
<td>Tunnel cost/m: CERN site</td>
<td></td>
<td></td>
<td>$6,080</td>
<td></td>
</tr>
<tr>
<td>: Dallas site</td>
<td></td>
<td></td>
<td></td>
<td>$10,470</td>
</tr>
<tr>
<td>Tunnel cost:</td>
<td></td>
<td></td>
<td>$1,650 million</td>
<td>$3,863 million</td>
</tr>
</tbody>
</table>
Now that we are thinking big, what is the ultimate hadron collider?

500 TeV collision energy
5x10^{35} \text{ cm}^{-2}\text{s}^{-1} \text{ luminosity}

Configure collider ring from 5,000 half-cell segments: 300 m long, 1.5 m diameter
Pipeline with magnets inside = neutral buoyancy @ 100 m depth
Segments connect with 3-valve interconnects
Install/remove segments using remotely operated submersibles (ROV)
Connect/disconnect half-cell segments at interconnect hub.
Collider detector lives in a bathysphere

CMS detector has a mass of 14,000 tons, and lives in a 30 m diameter cavern at the LHC. CMS inside a 30 m diameter double-hull spherical bathysphere would be neutral buoyancy, live at 100 m depth.
Fit out a row of saddle-crane along the long deck of a container ship.

- Build the 300 m half-cell cryostat pipeline segments at a port facility.
- Load directly onto a 400 m re-fitted container ship.
- Each half-cell segment is taken by 2 ROVs to depth, connected to the last half-cell.

No human being ever goes underwater.
Comparison of parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>100 TeV</th>
<th>500 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26.7</td>
<td>100</td>
<td>270</td>
</tr>
<tr>
<td>Collision energy</td>
<td>14</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Dipole field</td>
<td>8.3</td>
<td>16</td>
<td>4.5</td>
</tr>
<tr>
<td>Luminosity/I.P.</td>
<td>1.0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>40</td>
<td>110</td>
<td>50</td>
</tr>
<tr>
<td>Total synch. power</td>
<td>.004</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Critical energy</td>
<td>43</td>
<td>4.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Synch rad/m/bore</td>
<td>0.22</td>
<td>26</td>
<td>2</td>
</tr>
<tr>
<td>Emitt. damp time</td>
<td>13</td>
<td>0.5</td>
<td>19</td>
</tr>
<tr>
<td>Lum. lifetime</td>
<td>20</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Energy loss/turn</td>
<td>.007</td>
<td>4.3</td>
<td>1.3</td>
</tr>
<tr>
<td>RF energy gain/turn</td>
<td>0.5</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Acceleration time</td>
<td>0.4</td>
<td>.20</td>
<td>.40</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>B-B tune shift</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>protons / beam</td>
<td>2.3</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>Injection energy</td>
<td>0.45</td>
<td>&gt;3</td>
<td>15</td>
</tr>
</tbody>
</table>

Ultimate luminosity is limited by synchrotron radiation power.
The ring is held in position and alignment in the sea using active station-keeping and terrain-following.

Marine thrusters are used routinely in marine power to precisely control the direction and thrust to propel or station-keep a vessel with precision. One 50 kW thruster mounted adjacent to each half-cell hub can station-keep the position and geodesy of the ring to ~1 cm precision, even when a hurricane passes overhead. Feedback for geodesy is provided by a ring-laser whose beam traverses the ring.
Gulf of Mexico has Loop Current in the East, eddies spin off to the West.
Control Deflections of Ring Alignment using Laser Geodesy

Illustration with 12 half-cell ring:

Power spectra of pressure fluctuations near the sea floor, for a) 5 cm/s and b) 30 cm/s currents:

Correct using marine thrusters
Correct using trim dipoles

Install laser at center of mid-point of each dipole.
Align laser parallel to dipole axis, aiming both ways.

- Suppose one quad is deflected radially:
  - Flanking dipoles will deflect symmetrically by $\theta$,
  - Laser image at quad will deflect $X = L \theta/2$.
- Slow response – control thruster to re-position quad
- Fast response – control trim dipole to steer beam
Bottoms-Up Stacking

- Synchrotron damping increases the bunch brightness even as the bunch intensity decreases.
- In 6 hours of collisions:
  - \textit{emittance decreases x6},
  - \textit{# protons decreases x2},
  - \textit{Luminosity doubles}

**Bottoms-Up Stacking:**
After 6 hours of collisions,
Decelerate to injection energy,
Scrape bunches,
Inject fresh bunch with old one,
Re-accelerate, low-b squeeze,
Collider for another 6 hours,
Repeat indefinitely.
Bottoms-Up Stacking: $5 \times 10^{35}$ cm$^{-2}$s$^{-1}$
Comparison with LHC

• Each half-cell of the Collider-in-the-Sea has one 300 m dipole, with 20 turns of cable.
• There are 5,000 half-cells.
• So there are 100,000 turns of cable in one ring.
• Each dipole of LHC has 74 turns of cable.
• There are 1,300 half-cells.
• So there are 100,000 turns of cable in one ring.
• Many aspects of fabrication cost scale with the number of cable turns.
• Many aspects of reliability scale with the # of magnet ends.
Until now we have always had a credible prediction of a mass scale when we propose a new collider.

• In 1976 I proposed $p\bar{p}$ colliding beams in the existing synchrotrons.
  – We expected to find the weak bosons, and we did.

• In 1980 I proposed building the SSC to find the Higgs boson.
  – We expected it to have a mass of 125-1000 GeV, and LHC found it in Run 1.

• But so far we have no convincing signals of supersymmetry or other next gauge field.

• Mass reach grows less than linearly as we increase collision energy.

• How do we make the public case for such a huge investment? Make the mass reach as big and the price as low as our ingenuity can manage.
We have submitted a proposal for first steps in developing the concepts for the Collider-in-the-Sea

- Develop a simulation of beam dynamics with *dynamic terrain following*.
  - Beam position is measured using stripline BPMs at each quad.
  - Deviations of ring alignment from its reference are measured using the ring detectors in each half-cell.
  - Slow corrections are made as feedback to thrusters.
  - Fast fluctuations are corrected using trim dipoles at each quad to match the equilibrium orbit to the geodesic.
Build and test a short-model half-cell cryostat with hub interconnect.

• Build a model of the hub interconnect and develop its hardware and methods to put into practice the ability to make/break connections underwater without leaking to the half-cell.

• Develop and test a U-pull superconducting bus connector suitable for the current buses.

• Once it is working empty, install a short-model superferric dipole in the model cryostat and operate it with cryogenics and current.

• If we can do those things, this science fiction could become affordable reality.
Study Energy, Make Energy...

Tether a wind-turbine farm along the arc of collider offshore from TX, LA.
Locate 5 MW turbines on spacing of ~150 m along 1000 km arc = 35 GW capacity
Interconnect power along superconducting transmission line installed in tandem with collider pipeline.

*Use the deep-water siting to advantage, that is the subject of another talk...*