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Accelerator Physics in the Collider in the Sea

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The potential for discovering new gauge fields of nature beyond the Higgs boson relies upon extending the collision of hadron colliding beams as far as possible beyond the present 14 TeV capability of LHC. A new vision for the technical design of a hadron collider has been proposed [1] that would minimize the cost for a 100 TeV collider, and set the stage for a future 500 TeV collider for which it would serve as injector. We propose a working group to examine the accelerator physics issues that attend the beam dynamics of a synchrotron-radiation-dominated 500 TeV hadron collider, staged in a ring pipeline in the sea.

The cost for a new collider is dominated by the double-ring of superconducting magnets that guide the proton beams, and the tunnel that contains the magnet rings.

We proposed a way to eliminate the tunnel altogether [2], and instead house the ring of dual dipoles in a circular pipeline, supported in neutral buoyancy in the sea at a depth of ~100 m, as shown in Fig. 1. Each collider detector is housed in a double-hull bathysphere the size of the CMS hall at LHC, also neutral-buoyant. Once we eliminate the tunnel cost, we are free to choose a dipole field ~3.5 T to minimize the project cost. This opens the possibility to dramatically increase the collision energy to 500 TeV with less project cost, and at the same time accommodate high luminosity without strong bounds from the heat produced by synchrotron radiation. Staging a HEP collider undersea is novel, but it uses proven, widely used marine technology and the performance required of that technology is within its present standards [2].

A choice of ~3.5 T dipole field, 1,900 km circumference (the yellow ring in Fig. 1) provides a collision energy of 500 TeV. Beam dynamics is dominated by synchrotron radiation (SR) damping [3], which sustains luminosity for >10 hours and supports bottoms-up injection to replace losses and sustain high luminosity indefinitely. Fig. 2 shows a cross-section of the dual dipole. Each dipole winding is configured as a C-geometry, and a slot aperture in the midplane opens into a side channel that contains a photon trap, maintained at a reservoir temperature of 80 K by a flow of liquid nitrogen (LN2). SR is emitted as a thin fan in the horizontal plane, so its copious heat can be pumped to ambient temperature with maximum efficiency.

The 18-turn magnet windings utilize a high-current cable that is fabricated from a non-insulated (NI) block of Cu-clad REBCO tapes and operated at ~25 K using either He vapor or liquid H_2 as cryogen. A key innovation is that each turn of REBCO cable is oriented parallel to the magnetic field at its location, so that each tape can carry maximum superconducting current. Evaluation of the performance of this new magnet technology is the subject of another[4] Snowmass working group (AF7).

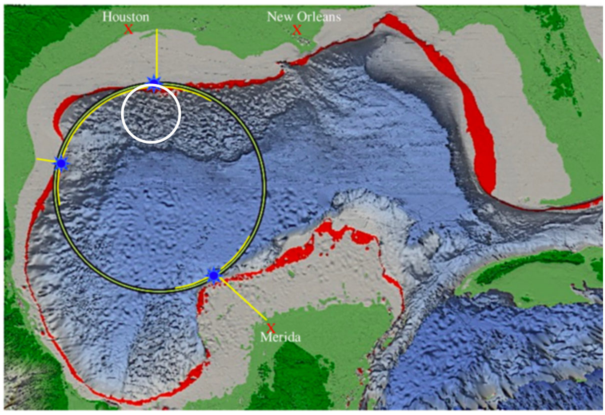

Fig. 1. Bathymetry of the Gulf of Mexico, showing one potential alignment of a 1,900 km circumference hadron collider. Red=100→200 m isobaths; Gray=0–100 m isobaths; blue=detectors. White = 300 km ring for FCC-ee, then 100 TeV FCC-hh, and later as injector for the 500 TeV collider.

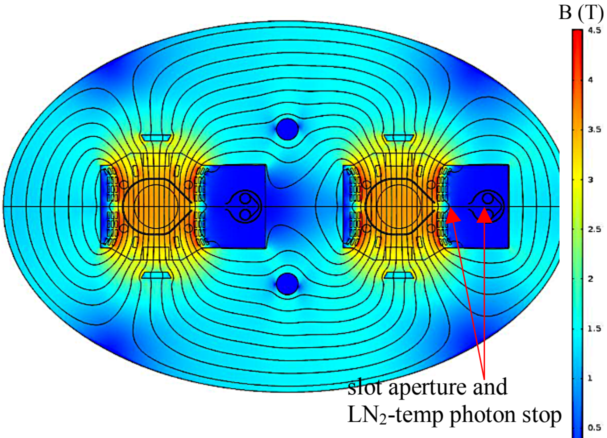

Fig. 2. 3.5 T superferric dual C-dipole using NI REBCO/Cu windings.

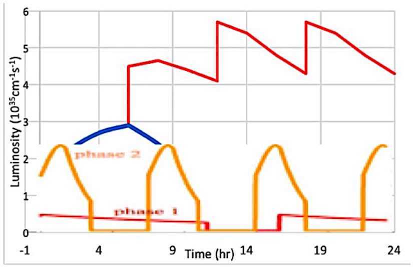

Fig. 3. Instantaneous luminosity for a single filling of protons beam (blue), and for top-up stacking every 6 hours (red), and for FCC-hh (orange).

Table 1. Parameters of LHC, FCC-hh, and C-in-S.

	LHC	FCC-hh	Collider-in-the-Sea		
Circumference	26.7	100	270	1900	km
Collision energy	14	100	100	500	TeV
Dipole field	8.3	16	4.5	3.2	Tesla
Luminosity/I.P.	1.0	5	5	50	10^{34}cm^{-2}s^{-1}
β*	40	110	50	50	cm
Total synch. power	.004	4.2	1.0	36	MW
Critical energy	43	4.0	1.0	19	keV
Synch rad/m/bore	0.22	26	2	11	W/m
Emitt. damp time	13	0.5	19	3.7	hr
Lum. lifetime	20	18	20	>24	hr
Energy loss/turn	.007	4.3	1.3	117	MeV
RF energy gain/turn	0.5	100	50	2500	MeV
Acceleration time	0.4	.20	.40	2.4	hr
Bunch spacing	25	25	25	30	ns
B-B tune shift	0.01	0.01	0.01	.02	
protons / beam	2.3	10	22	40	10^{14}
Injection energy	0.45	>3	15	50	TeV

Table 1 compares the main parameters of 100 TeV and 500 TeV versions of the Collider in the Sea with those of LHC and FCC-hh. One approach would be to first build a ~100 TeV hadron collider in the sea, using the 3.5 T superferric dipoles and circumference ~300 km. The white ring shown in Fig. 1 shows such a 100 TeV collider located off-shore near Houston. The manufacture of the magnets for that hadron collider would drive cost reduction of REBCO/Cu tape and provide operating experience with both the REBCO-based magnet ring and the Collider-in-the-Sea, and so build a credible basis of technology, costs and performance for the grand challenge to build the 500 TeV collider thereafter.

The proposed agenda for this AF4 working group is to identify and evaluate accelerator issues that could determine the performance of a 500 TeV hadron collider of the above design. Examples of such issues are:

- *Field homogeneity requirements for the magnet rings.* The conformal REBCO windings have two salient benefits for collider performance. First, every tape within the windings is optimally oriented so that the anisotropic properties of REBCO give maximum I_c. Second, the stacked tapes within each turn are loaded under compression so that current can share among the tapes, both as the field is ramped and at collision energy. The current-sharing relaxes with a favorable time constant ~ minutes, and provides for suppression of field harmonics and quench stabilization.
- *Control of perturbations to the geodesy of the ring from ocean currents*. The western part of the Gulf has no prevailing ocean current. Secular currents and slow fluctuations are stabilized using a set of swivel-mounted marine thrusters that are located close to the end of each half-cell. A geodesy monitoring system has been designed in concept to precisely monitor the position and geodesy of the collider ring in real time. It uses a ring of lasers, mounted within the circular pipeline of the collider at each quad location, to detect modulations of the geodesy. The marine thrusters can be used to correct slow modulations, and correction dipoles at the half-cells can be used to correct proton orbits for terrain-following for small-amplitude long-range perturbations.
- *Synchrotron damping and bottoms-up stacking*. At 250 TeV beam energy, phase space is damped with a time constant ~4 hours, which by our initial simulations should make it possible to overcome slow emittance growth from collisions, and open the possibility to stack new cycles of protons at injection energy to sustain high emittance indefinitely.

Read more: **Accelerator design: SR side-channels, active harmonic control, bottoms-up stacking**
Circular pipeline and detector bathyspheres, neutral-buoyant @100 m, marine thrusters
Superconducting dipoles for the Collider-in-the-Sea: NbTi CIC, Conformal REBCO
Discovery potential at 100 TeV and 500 TeV

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EF-9: HEP discovery potential at 100 TeV and 500 TeV
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AF-6: HEP meets marine engineering – how to stabilize and operate a circular pipeline