Collider in the Sea

ultimate-energy hadron collider to discover new gauge fields

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 14 TeV capability of LHC. 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. The cost/TeV of the superconducting magnets has a broad minimum in the window ~3-4 T, and increases steeply to the 8 T of LHC and much more steeply at the ~16 T that has been suggested for FCC-hh [1]. Tunnel cost/m depends strongly upon the stratigraphy of each site. The tunnel for the SSC in Waxahatchee, TX was bored in Austin Chalk, one of the most favorable rock strata for tunneling. The tunnel contracts for SSC were among the lowest-cost bored tunnels ever made: $3000/m cost). The LEP tunnel (now used for LHC) was bored in less favorable rock, and its cost/m was >3 times greater. Ring tunnels with 100 km circumference would typically pass through many rock strata with even higher unit cost.

Those considerations led us to propose a way to eliminate the tunnel altogether [2], and 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 [3]. Each collider detector is housed in a bathysphere the size of the CMS hall at LHC, also neutral-buoyant. Once we eliminate the tunnel cost, we are free to choose a magnetic field ~3-4 T to minimize the project cost. As will be seen, this opens the possibility to dramatically increase the collision energy, and at the same time accommodate high luminosity without strong bounds from the heat produced by synchrotron radiation.

In 2015 we presented a design for a compact dual dipole [4], utilizing NbTi cable-in-conduit (CIC) windings, as a basis for the Collider-in-the-Sea. A choice of ~3.2 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 [5], which sustains luminosity for >10 hours and supports bottoms-up injection to replace losses and sustain high luminosity indefinitely. Fig. 2a 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

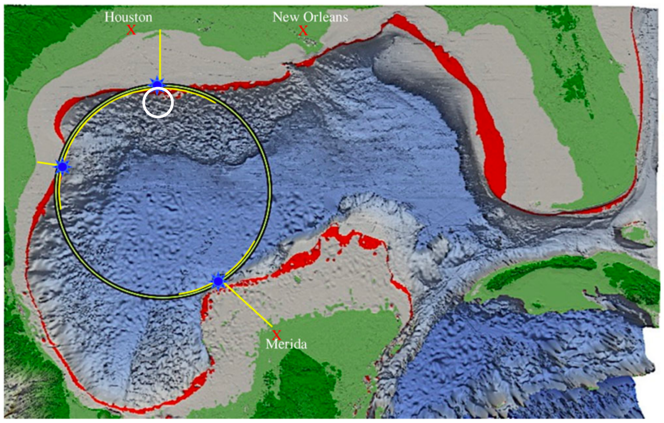

Fig. 1. Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron collider. Red=100→200 m isobaths; Gray=0–100 m isobaths; blue=detectors. The white ring shows a possible placement of a 100 TeV ring that could serve with the parameters proposed for FCC-hh and FCC-ee, and later as injector for the 500 TeV collider.

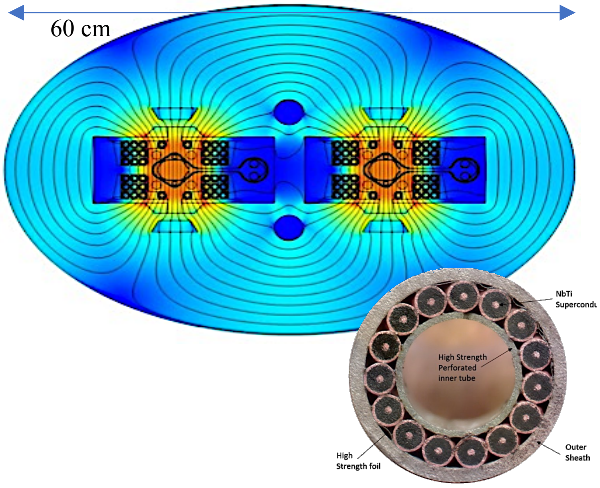

Fig. 2. a) cross-section of a 3.5 T dual block-coil C-dipole for Collider-in-the-Sea; the open slots to the right of each bore provide for capture of synchrotron radiation in a LN2-temperature channel; b) cross-section of NbTi cable-in-conduit used in the dipole.

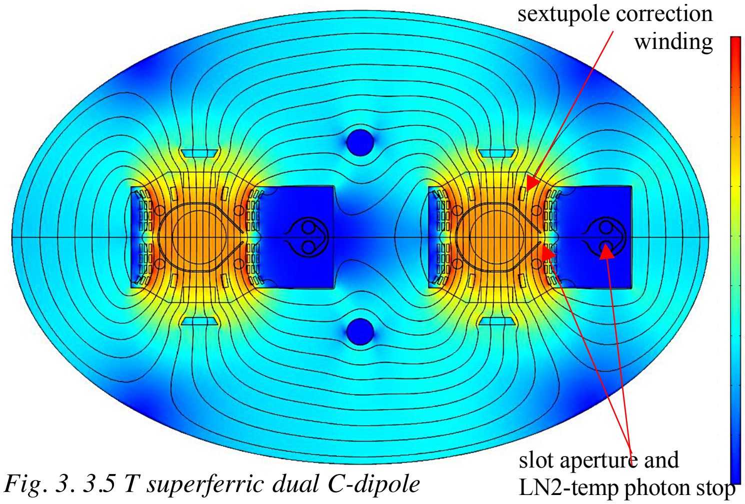

Fig. 3. 3.5 T superferric dual C-dipole using NI REBCO/Cu windings.

Table 1. Parameters for 100 and 500 TeV hadron colliders.

	LHC	100 TeV		500 TeV	
Circumference	26.7	100	270	1900	
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	0.02	
protons / beam	2.3	10	22	40	10^{14}
Injection energy	0.45	>3	15	50	TeV

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.

Fig. 2b shows a cross-section of the NbTi cable-in-conduit (SuperCIC) that we developed for its windings. The windings are cooled by a flow of super-critical helium (SCHe) through the center tube of the SuperCIC so the windings operate in the temperature range 4.5-5 K. SCHe is single-phase, and the cryogenics design provides for volumetric cooling of all turns of the winding with ample capacity for beam losses and SR albedo. Accelerator Technology Corp. has manufactured long-length segments suitable for dipole manufacture. The windings are simple to fabricate, and we have demonstrated that they can be made with the precision of registration required for collider-quality field homogeneity [6].

The distributed cryogenics to support SCHe flow with distributed heat transfer around a 1900 km pipeline is a daunting proposition. Recently we developed a novel approach for magnet windings in which a high-current cable could be fabricated from a non-insulated (NI) block of Cu-clad REBCO tapes, which could be operated at ~20 K with He gas cooling to make the refrigeration simpler and much more efficient than the 5 K required for NbTi windings. A key consideration in such an approach is the orientation angle θ of the face of each tape with respect to the vector magnetic field in which it is immersed. REBCO is a highly anisotropic superconductor – the critical current in a 6 mm-wide tape is ~2400 A at 4 T, 20 K if the tape face is parallel to field, but only 750 A if the tape face is normal to the field.

A methodology has been developed by which each turn of NI REBCO/Cu cable in a dipole winding can be oriented so that the faces of the tapes within the block are parallel to the magnetic field at that block [7]. Fig. 3 shows the configuration of NI REBCO cables for a 3.5 T dual dipole using this configuration. Innovations in the cable, the windings, and the magnetics have made it possible to control-sharing among the NI tapes within the cable and magnetization properties during ramping.

We have followed the strategy that was used in the 3 T superferric dipole for SCC [8], in which the sextupole field is nulled at all field values by separately programming the current in a correction winding located at an optimum location as shown. This provision enables control of the above effects so that the dipole could provide full dynamic aperture over the entire range of beam energies.

Table 1 summarizes the main parameters that should be feasible with the 100 TeV and 500 TeV hadron colliders. One approach would be to first build a ~100 TeV hadron collider in the sea, using superferric dipoles of ~3.5 Tesla and circumference ~270 km. The white ring shown in Fig. 1 shows such a ring located off-shore near Houston. The fabrication of the magnets for that hadron collider would drive cost reduction of REBCO/Cu tape and operating experience with both the REBCO-based magnet ring and the Collider-in-the-Sea, and so build a credible basis of costs and performance for the grand challenge to build the 500 TeV collider.

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[1] A. Abada *et al*., 'FCC-hh – the hadron collider', Eur. Phys. J. Special Topics **228**, 755–1107 (2019).

[2] P. McIntyre, *et al*., 'Large-circumference, low-field optimization of a Future Circular Collider', presented at the CERN Symposium on a Future Circular Collider, Geneva, 2014.

[3] P. McIntyre *et al*., 'Collider in the Sea: Vision for a 500 TeV world laboratory', Proc. N. American Part. Accel. Conf., Chicago, October 2016.

[4] S. Assadi *et al.,* 'Cable-in-conduit dipoles to enable a future hadron collider', IEEE Trans. Appl. Superconduct. **27**, 4, 4004005 (2017).

[5] E. Keil, 'Synchrotron radiation dominated hadron colliders', Proc. 1997 Part. Accel. Conf.

[6] J. Breitschopf *et al., '* Cable-in-Conduit dipoles for the Ion Ring of JLEIC', IEEE Trans. Appl. Superconduct. **29**, 5, 4004806 (2019). https://ieeexplore.ieee.org/document/8675432

[7] P. McIntyre *et al*., 'Optimized cable and NI REBCO/Cu windings for dipoles and solenoids', submitted to IEEE Trans. Mag. (2020).

[8] H. Bingham *et al*., 'Superferric magnet option for the SSC', IEEE Trans. Nucl. Sci. **NS32**, 3462 (1985).