COLLIDER IN THE SEA: VISION FOR A 500 TeV WORLD LABORATORY

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Abstract

A design is presented for a hadron collider in which the magnetic storage ring is configured as a circular pipeline, supported in neutral buoyancy in the sea at a depth of ~100 m. Each collider detector is housed in a bathysphere the size of the CMS hall at LHC, also neutral-buoyant. Each half-cell of the collider lattice is ~300 m long, housed in a single pipeline segment. A choice of ~3.2 T dipole field, 1,900 km circumference provides a collision energy of 500 TeV. Beam dynamics is dominated by synchrotron radiation (SR) damping, which sustains luminosity for >10 hours and supports bottoms-up injection to replace losses and sustain high luminosity indefinitely. We discuss how to connect and disconnect half-cell segments of the collider at-depth using remote submersibles, and how to maintain the lattice in the required alignment.

INTRODUCTION

Several scenarios are being investigated [1,2] for a future hadron collider that would extend well beyond the 14 TeV collision energy of LHC. Keil [3] showed that the beam dynamics in a hadron collider operating at 100 TeV or greater collision energy is dominated by synchrotron damping. The choice of magnetic field strength B strongly determines the cost and performance of such a collider. The radius R of the storage ring is inversely proportional to B; the total SR power P that is radiated by the beams is proportional to B, and the achievable luminosity L is limited by P and by the beam-beam tune shift ξ:

$$L = \frac{\gamma \xi N f}{\beta_x r_p},\ P = \frac{8\pi}{3}\frac{N f e^2}{R}\gamma^4\ ,\quad L = \left(\frac{3\xi}{8\pi\gamma^3 \beta_x r_p e^2}\right) PR.$$

The lowest cost/TeV superconducting dipoles ever built were those for the 3 T superferric SSC [4] and the 4 T RHIC [5]. Thus both technology cost and performance (~L) improve with decreasing field and increasing circumference. At the other pole is the choice of 15 T that would be required to achieve 100 TeV collision energy with tunnel circumference that could be built near CERN.

It is also important to keep in view the physics motivation that drives proposals for a future hadron collider – to discover new particles and new gauge fields of nature. There is a fundamental difference between the present case and the successes of the last generation – the proposal to build proton-antiproton colliders [6] was motivated by the prediction that the weak bosons should have a mass ~100 GeV/c^2, and the proposals for SSC and LHC were motivated by the prediction that the Higgs boson should have a mass <500 GeV/c^2. *There is however no compelling prediction today of a mass scale for new gauge fields beyond the electroweak and Higgs scales.* This consideration suggests that the parameters for a new hadron collider should be chosen to achieve the highest possible collision energy for a given public investment.

In a previous paper [2] we presented the design of a cable-in-conduit (CIC) dual-dipole, shown in Fig. 1 that minimizes the cost/TeV of the superconducting magnets for a future hadron collider. In this paper we consider using that design in a hadron collider that with radius limited ultimately by the total synchrotron radiation heat P that can be sustainably pumped from an intermediate-temperature intercept in the cryogenics. Those parameters optimize with a magnetic field of ~3.2 T, a circumference of 1,900 km, and a collision energy of 500 TeV. We further consider a new option that would eliminate the tunnel: a Collider-in-the-Sea.

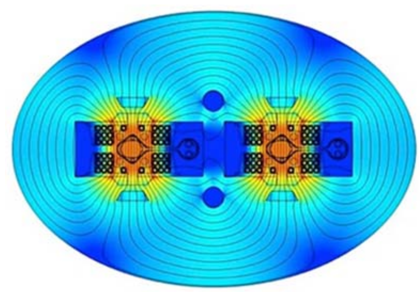

Figure 1: 4.5 Tesla C-dipole for an ultimate-energy hadron collider. Each beam tube has a side SR channel.

COLLIDER IN THE SEA

An example siting of the Collider in the Sea is shown in Fig. 2 for an example site in the Gulf of Mexico. The

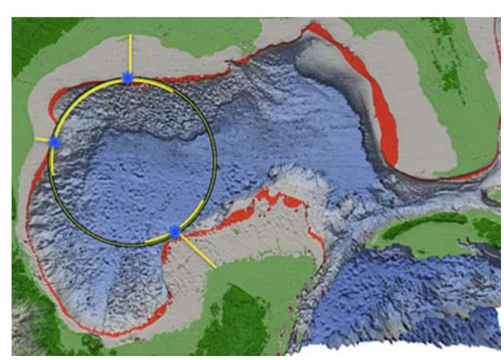

Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron collider. Red =100➔200 m isobaths; gray = 0-100 m isobaths; blue = detectors; green = surface topography.

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double-ring of superconducting magnets is housed in a circular cryostat pipeline that is supported in neutral buoyancy at a depth of ~100 m, where the population of fauna is minimum. The ring is located so that it skirts the edge of the continental slope. This criterion places the ring beyond the regions that are used for shipping oil wells, fishing, and recreation. Umbilicals to land are located at three places where buried superconducting transmission lines carry electric power, cryogens, and instrumentation connections to land-based stations. Table 1 gives its main parameters.

Table 1. Main Parameters for 500 TeV Collider in the Sea

	LHC	100 TeV		500 TeV	
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	0.004	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	0.007	4.3	1.3	117	MeV
RF energy gain/turn	0.5	100	50	2500	MeV
Acceleration time	0.4	0.20	0.40	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

This novel approach to a hadron collider naturally opens a number of strategic questions. In a previous paper [7] we discussed how the collider and its detectors could be installed and operated. The building block from which the collider ring is assembled is a 300 m half-cell, containing a single long dipole, a quadrupole, and a correction package. The half-cell is built in a factory at a nearby port, and is housed in a hermetic cryostat pipeline segment. The ends of each half-cell segment are hubs that maintain vacuum integrity within the segment. Eight umbilical stubs interconnect the segments - 2 beam tubes, 3 cryogen manifolds, process vacuum, current bus cluster, and instrumentation. Each umbilical stub extends beyond the hub and is connected to the stub from the neighboring segment through a 3-valve set that enables assembly and disassembly, filling or emptying of sea water inside each stub, and processing to working vacuum. We show in that paper that this operation can be conducted entirely using remotely operated vehicles (ROVs) that are a routinely used today in marine technology.

In the present paper we consider the issues associated with positioning and alignment of the collider, and an interesting aspect of SR damping that opens the potential for bottoms-up injection and maintaining optimum luminosity.

The ocean provides an excellent medium for the Collider in the Sea, but the geodesy of the rings must be stabilized against ocean currents, infrasound pressure waves, and local changes in bouyancy depth. Figure 3 shows the velocity field of surface currents spanning the example site. The dominant feature in the Gulf is the Loop Current, which flows between Cuba and Yucatan, loops close to Florida's West Coast, thence to the Atlantic.

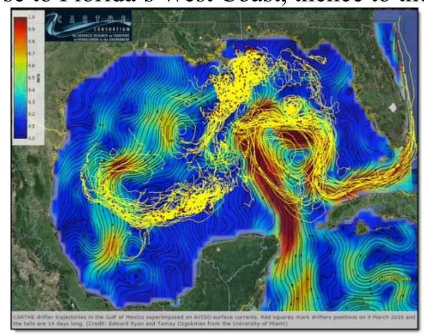

Figure 3: Velocity field of surface currents in Gulf of Mexico, March 2016. Velocity magnitudes are shown in color code, velocity directions are shown.

The western part of the Gulf has no prevailing current, and contains a slowly evolving eddies that cut off from the Loop Current, drift westwards, and dissipate. The motion of the eddies is shown in Fig. 4, the time log of surface currents at 122 m depth at a typical location [8]. The rms current speed is ~12 cm/s, the maximum speed is ~1 m/s. Figure 5 shows the fluctuation power spectra in deep water, for locations with 5 cm/s and 30 cm/s currents. These data underscore that the Collider geodesy must be stabilized in neutral bouyancy at every half-cell; and fluctuations separate into slow (<0.02 Hz) and medium (0.1-1 Hz).

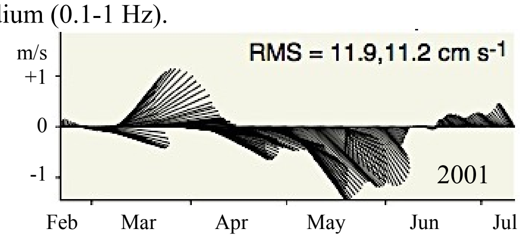

Figure 4: Velocity field history of currents at 122 m depth at an example site in Gulf of Mexico.

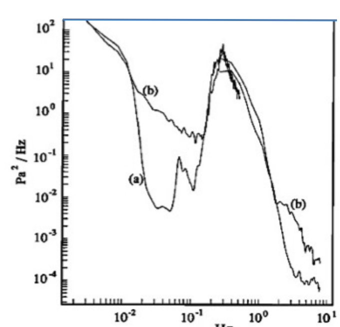

Figure 5: Power spectra of pressure fluctuations near the sea floor, for a) 5 cm/s and b) 30 cm/s currents.

Currents and slow fluctuations are stabilized using a set of marine thrusters that are located close to the end of each half-cell, as shown in Fig. 6. The thruster is a propeller that is driven by a variable-speed electric motor. Each thruster is supported on a swivel mount that permits

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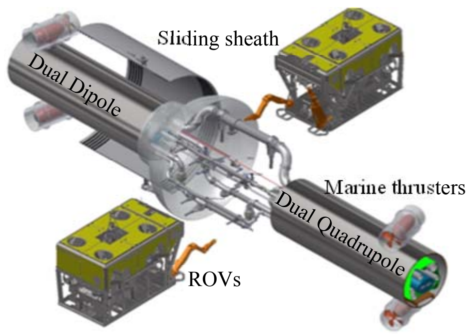

Figure 6: Demountable joint connecting half-cells of the pipeline cryostat. Shown are the valve trees for each umbilical, the retractable sheath, the marine thrusters, and two ROVs assembling joints.

it to be turned to any orientation in the horizontal plane. A second thruster is oriented to deliver vertical thrust. In that way both the ambient water current and the slow-scale fluctuations can be countered by a force from the thrusters at each quadrupole. A laser is mounted at the centerpoint of each dipole and oriented so that it emits beams in both directions parallel to the dipole axis. The transverse position of each laser beam is measured at the quadrupole, as shown in Fig. 7 for the example of a single quadrupole displaced by a local currant. The laser beams are shown in red, and the ring is shown with only 12 half-cells to make the displacement visible. The quad displacement produces symmetric angular displacements ϑ_n in the flanking dipoles.

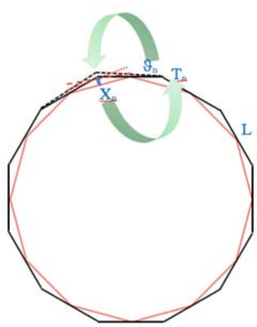

Figure 7: Schematic of detection of a local displacement ϑ_n of single quadrupole and correction using trim dipole T_n.

The deviation X_n of the laser beam at the quadrupole location is proportional to the angular deformation ϑ_n. The measured X_n can be used in feedback: in slow feedback it can be used to control the n^{th} thruster to correct the geodesy of the ring; in medium-frequency feedback it can be used to control the n^{th} trim dipole T_n to deflect the beams so that they follow the slightly deformed trajectory. This strategy is applied in both horizontal and vertical planes and enables a strategy of *dynamic terrain following* in which the fluctuation spectrum in the ocean can be counteracted locally and globally so that it need not affect beam dynamics.

BOTTOMS-UP INJECTION

SR damping dramatically reduces the transverse emittance, and opens the way for a *bottoms-up stacking* scenario to sustain a luminosity at ~5x10^{35}cm^{-1}s^{-1} indefinitely. We have used the Mathematica notebook of Syphers [9] to make a first simulation of the collider, and to balance its major parameters for roughly optimum performance. We optimized the luminosity within a limit of 35 MW of total SR power by filling 40,000 bunches with 10^{11} protons/bunch, (1/5 of the RF buckets).

The initial luminosity is 1.6x10^{34} cm^{-2}s^{-1}. Over a 6 hour period half of the protons are used in collisions, but the transverse emittance decreases a factor 5 via SR damping – the luminosity actually doubles during that time! The blue curve in Fig. 8 shows the luminosity as a function of time for a single store. Longitudinal emittance is roughly balanced between heating and cooling terms.

The emittance damping opens the prospect for bottoms-up stacking: After 6 hours of a store, the beams are decelerated to injection energy (still well above transition energy), the beams are scraped to remove tails, and a fresh fill of protons is accelerated in the injector and stacked with the old beams. The beams are re-accelerated to collision energy, squeezed to low-β, and the store is resumed. The red curve in Fig. 8 shows the SR power and the luminosity as a function of time. The luminosity is sustained at ~5x10^{35}cm^{-2}s^{-1} for as long as one continues bottoms-up stacking. This ~constant luminosity is the optimum way to operate the experiments, since many of the backgrounds and detector responses are luminosity dependent. Also shown in Fig. 8 is the luminosity *vs.* time for the high-luminosity upgrade foreseen for Phase2 FCC-h [10].

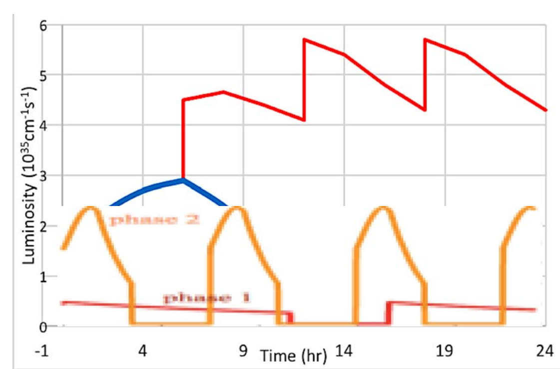

Figure 8: Instantaneous luminosity for a single filling of protons beam (blue), and for top-up stacking every 6 hours (red), and for FCC-hh in orange [10].

CONCLUSIONS

The Collider in the Sea appears to have significant promise as a strategy to optimize performance and cost for an ultimate-energy hadron collider. We are developing a next level of simulations of long-term beam dynamics in the above scenario of dynamic terrain following, and for the bottoms-up stacking scenario. We plan to build a short-model half-cell cryostat and evaluate the procedures for connecting hub umbilicals underwater.

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