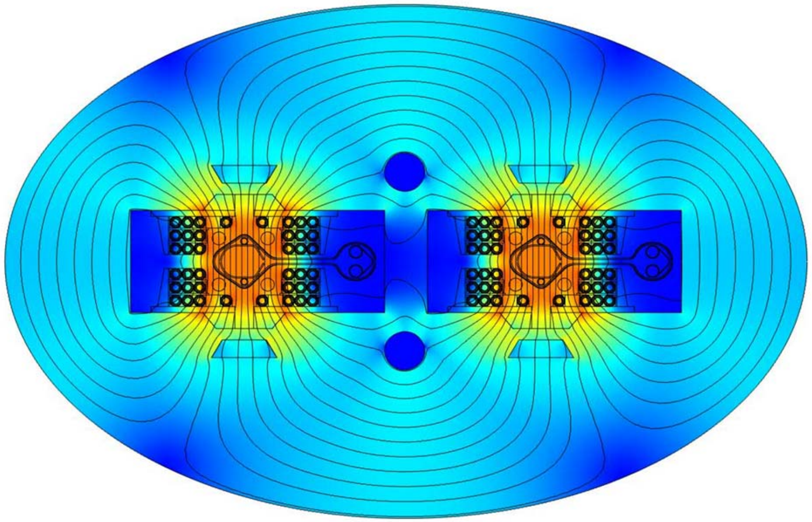
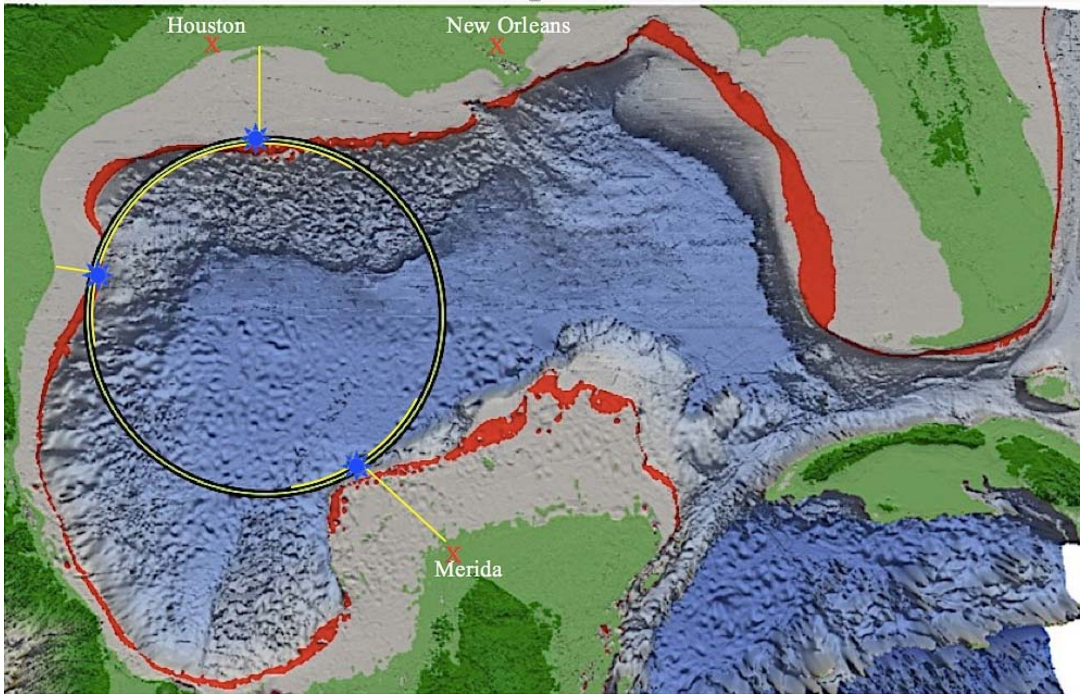
Cable-in-Conduit Dipoles to enable a Future Hadron Collider





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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

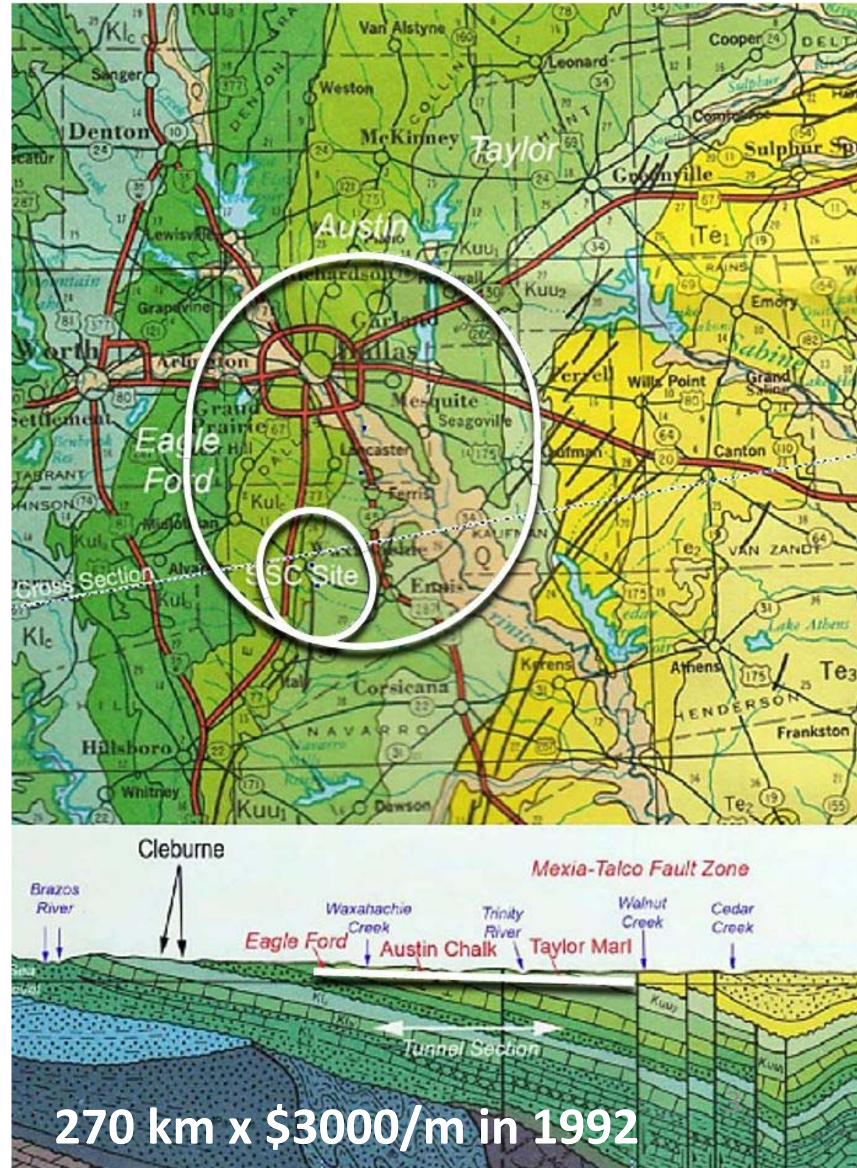
Tunnel would likely cost ~$4 Billion

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



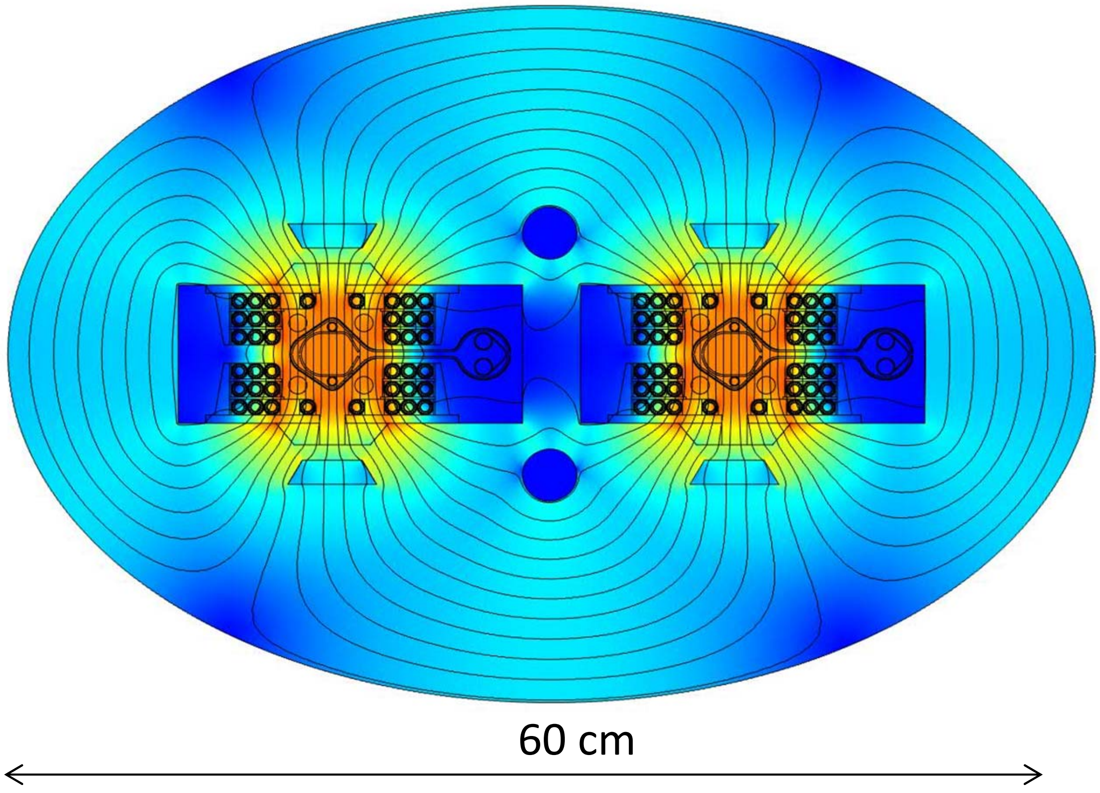
There is already an 80 km circumference tunnel in Texas – the SSC tunnel was nearly completed.

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!

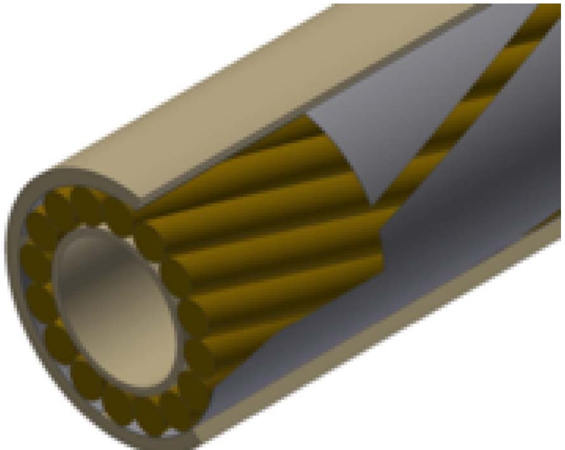
A 270 km tunnel can be located at the same site, entirely within the Austin Chalk and Taylor Marl, tangent to the SSC tunnel as injector.

We have devised a way to combine the simplicity of the low-field superferric SSC dipole with a cable-in-conduit conductor:

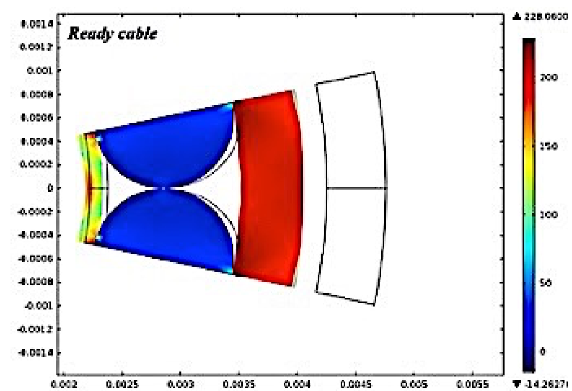


- 4.5 Tesla dipole field
- C-dipole: synchrotron radiation passes into a second chamber where it is absorbed at 150 K.
- Refrigeration is 100x more efficient, so heat load not a limit.
- Clearing electrode suppresses electron cloud; 25 ns bunch spacing feasible.
- Superconducting winding has 20 turns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

Cable-in-Conduit for an Ultimate Collider

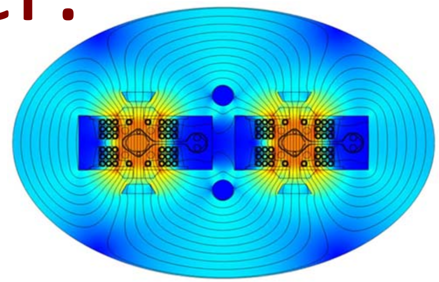


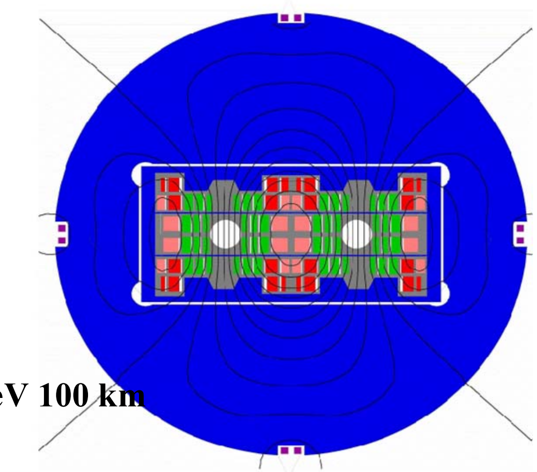
15 NbTi/Cu wires are cabled onto a perforated spring tube.



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:



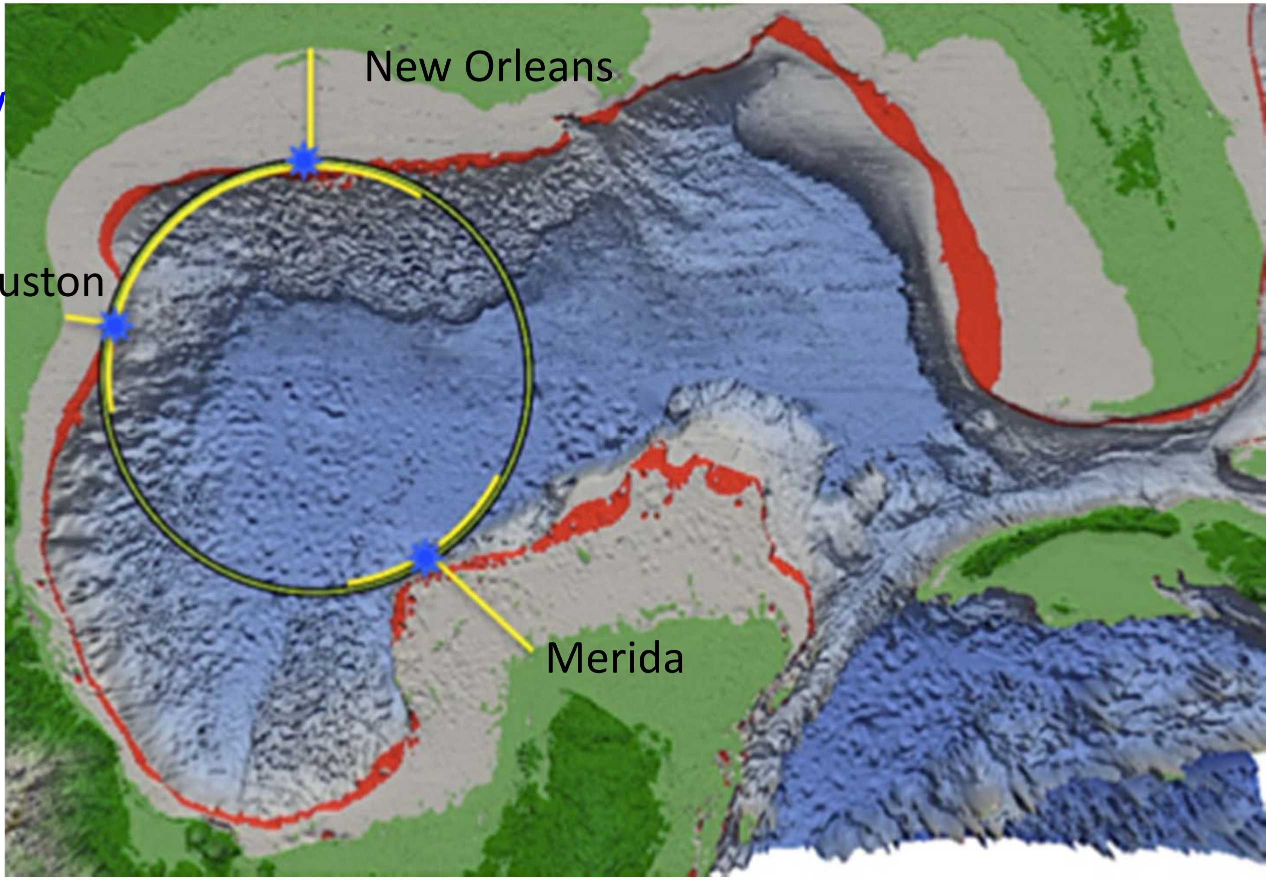


	RHIC	LHC	100 TeV 270 km	100 TeV 100 km
Operating field	3.4 T	8 T	4.5 T	16 T
# Bores	1	2	2	2
# turns per bore	32	74	20	
Length	9.4 m	14.3 m	20	20
Superconducting wire/bore: NbTi	92 kg	380 kg	124 kg	390 kg
Nb_3Sn				1,480 kg
Manufactured magnet cost/dipole	$105,000	$565,000	$185,000	?
Cost of superconductor/dipole	$23,100	$190,000	$62,000	$3,050,000
Magnet cost/m/bore/T	$3,265	$2,470	$1,028	
Superconductor cost/T/m/bore	$150	$380	$345	$4,780
Superconductor cost for collider			$720 million	$10,000 million
Magnet cost for collider			$2,150 million	
Tunnel cost/m: CERN site				$10,470
: Dallas site			$6,080	
Tunnel cost:			$1,650 million	$3,863 million

Now that we are thinking big, what is the ultimate hadron collider?

500 TeV collision energy

$5x10^{35}$ $cm^{-2}s^{-1}$ luminosity



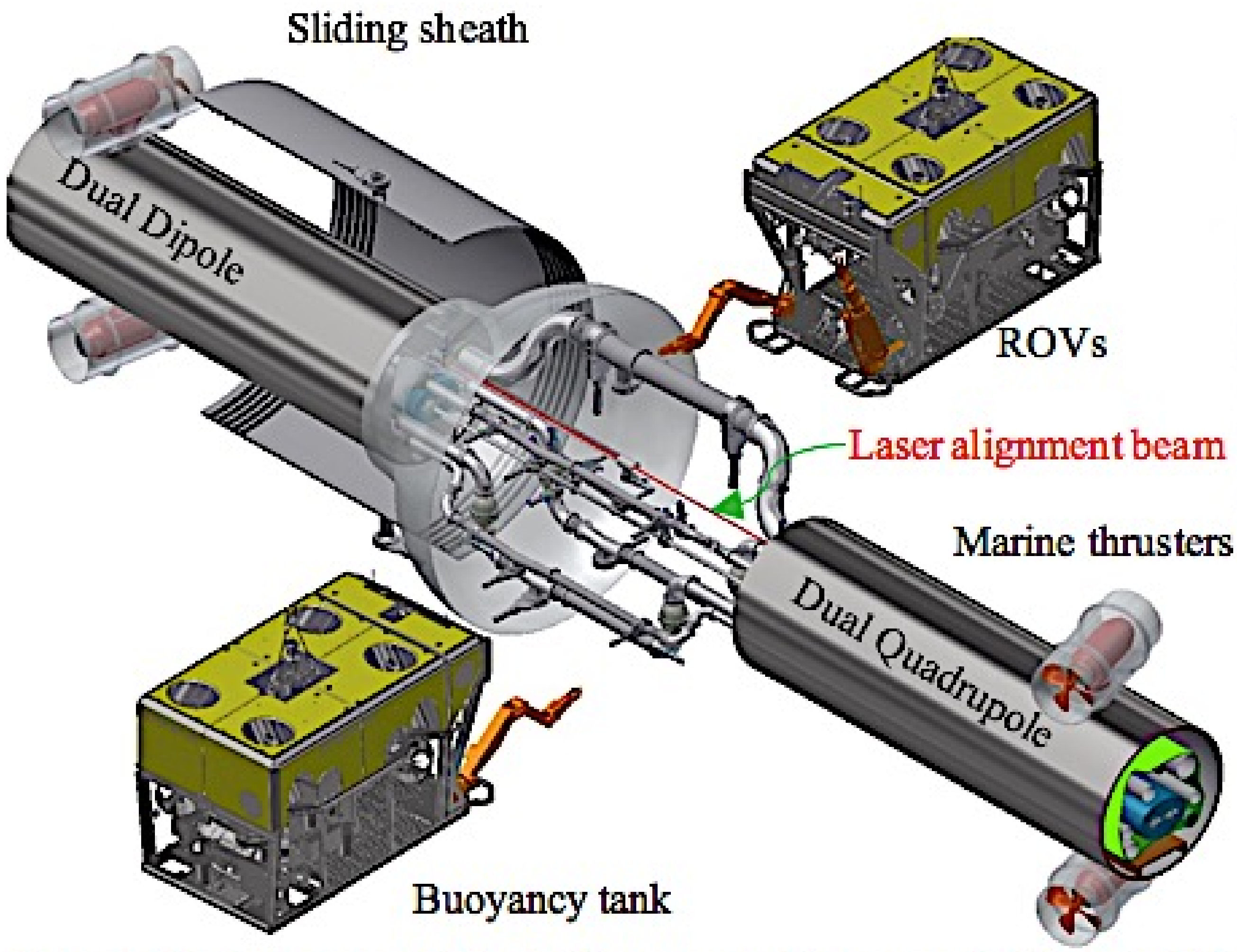
Configure collider ring from 5,000 half-cell segments: 300 m long, 1.5 m diameter

Pipeline with magnets inside = neutral buoyancy @ 100 m depth

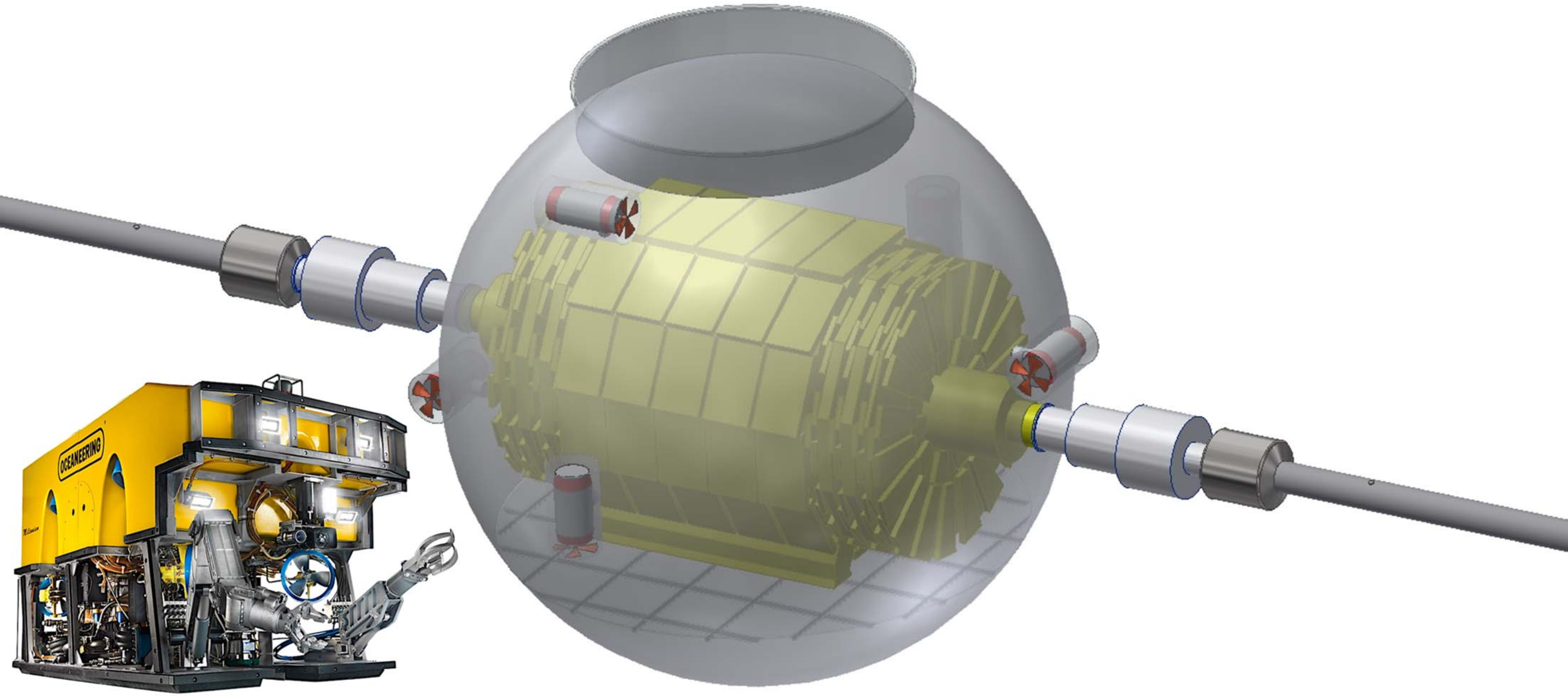
Segments connect with 3-valve interconnects

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 bathyspere would be neutral buoyancy, live at 100 m depth.

Fit out a row of saddle-cranes along the long deck of a container ship.

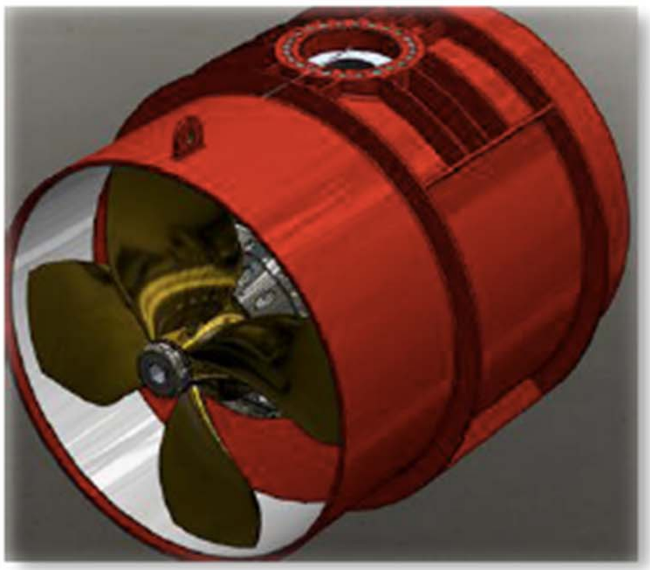
- Build the 300 m half-cell cryostat pipeline segments at a port facility.
- Load directly onto a 400 m re-fitted container ship.
- Each half-cell segment is taken by 2 ROVs to depth, connected to the last half-cell.

Comparison of parameters

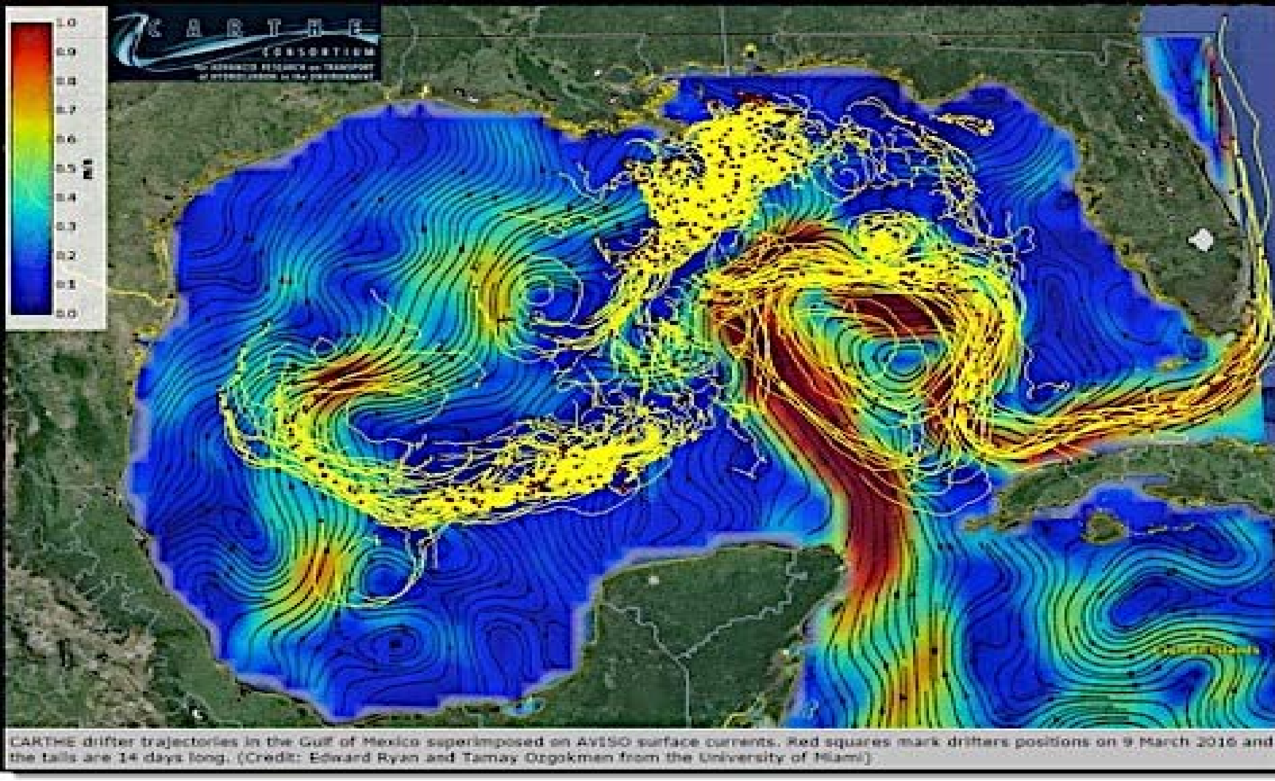
	LHC	100 TeV		500 TeV	
Circumference	26.7	100	270	1900	km
Collision energy	14	100	100	500	TeV
Dipole field	8.3	16	4.5	3.2	Tesla
Luminosity/I.P.	1.0	5	5	50	$10^{34}cm^{-2}s^{-1}$
β*	40	110	50	50	cm
Total synch. power	.004	4.2	1.0	36	MW
Critical energy	43	4.0	1.0	19	keV
Synch rad/m/bore	0.22	26	2	11	W/m
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

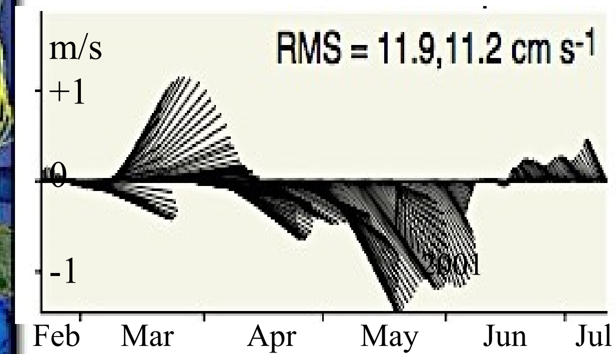
Ultimate luminosity is limited by synchrotron radiation power.

The ring is held in position and alignment in the sea using active station-keeping and terrain-following.

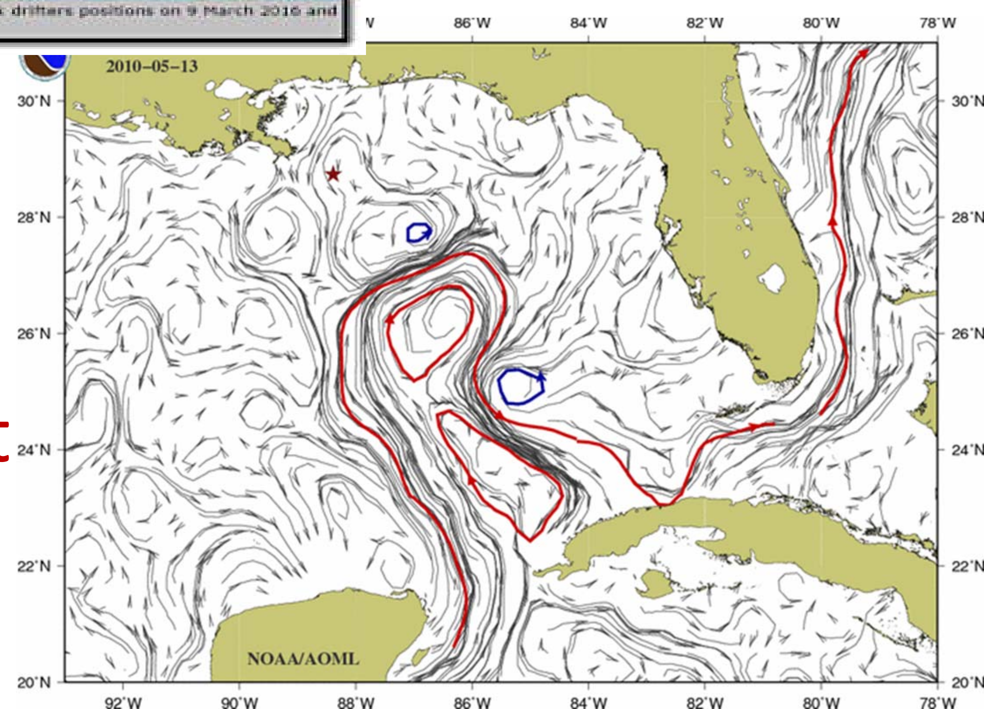


Marine thrusters are used routinely in marine power to precisely control the direction and thrust to propel or station-keep a vessel with precision.
One 50 kW thruster mounted adjacent to each half-cell hub can station-keep the position and geodesy of the ring to ~1 cm precision, even when a hurricane passes overhead.
Feedback for geodesy is provided by a ring-laser whose beam traverses the ring.



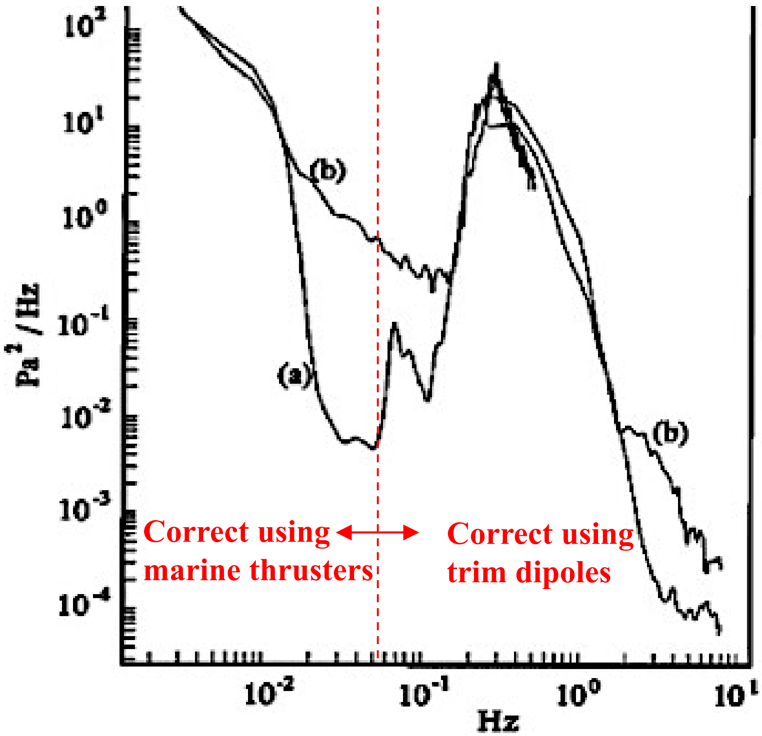


Gulf of Mexico has Loop Current in the East, eddies spin off to the West

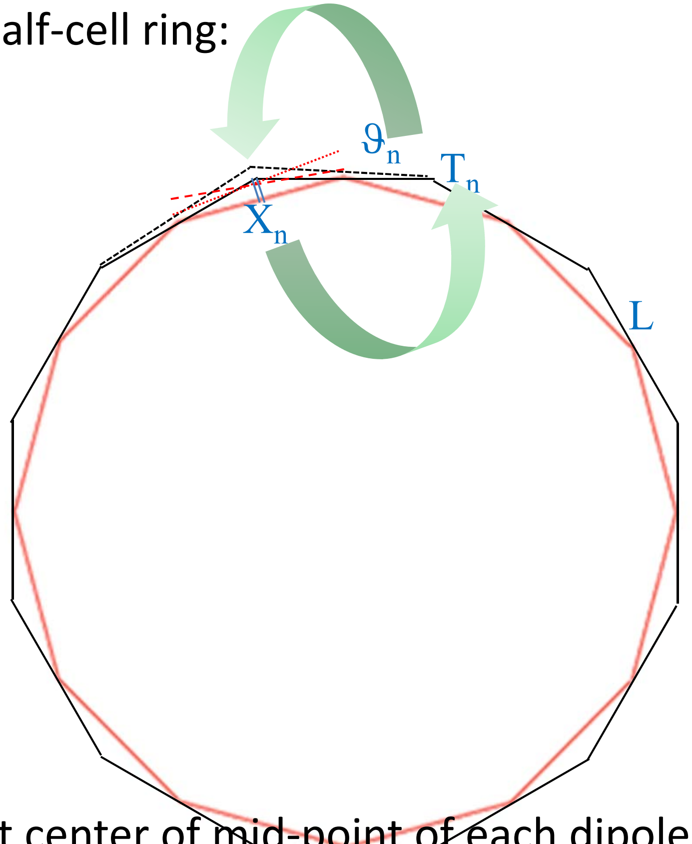


Control Deflections of Ring Alignment using Laser Geodesy

Illustration with 12 half-cell ring:



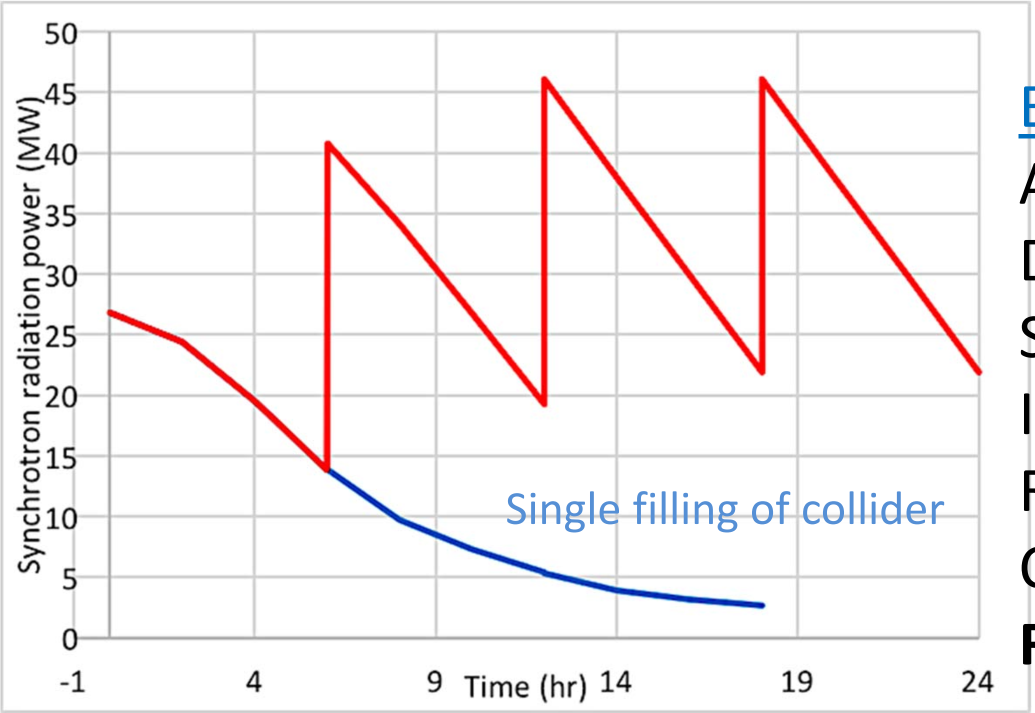
Power spectra of pressure fluctuations near the sea floor, for a) 5 cm/s and b) 30 cm/s currents.



- 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 θ,
  - 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

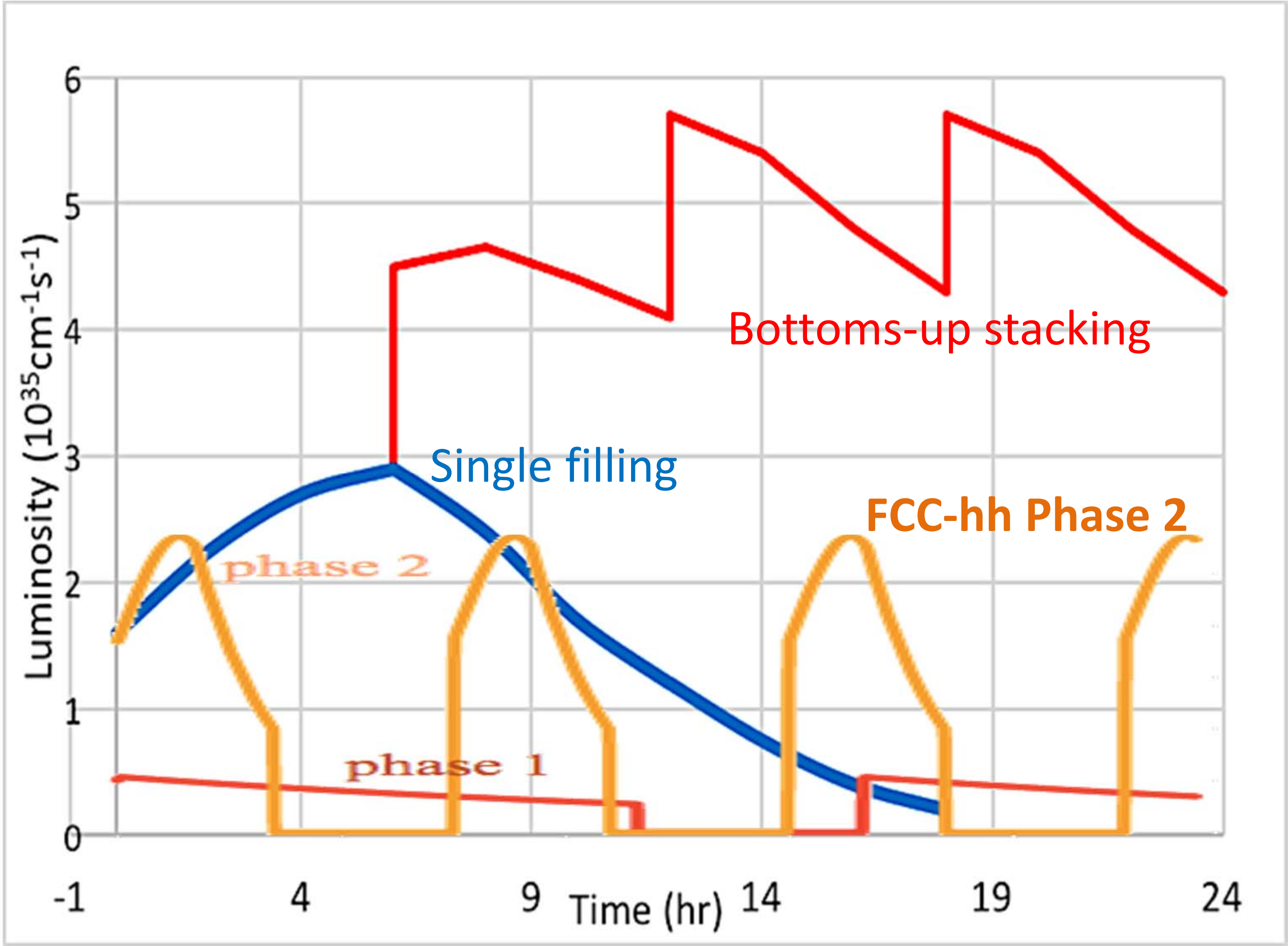
- Synchrotron damping increases the bunch brightness even as the bunch intensity decreases.
- In 6 hours of collisions:
  - *emittance decreases x6,*
  - *# protons decreases x2,*
  - *Luminosity doubles*



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: $5x10^{35}$ $cm^{-2}s^{-1}$



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.

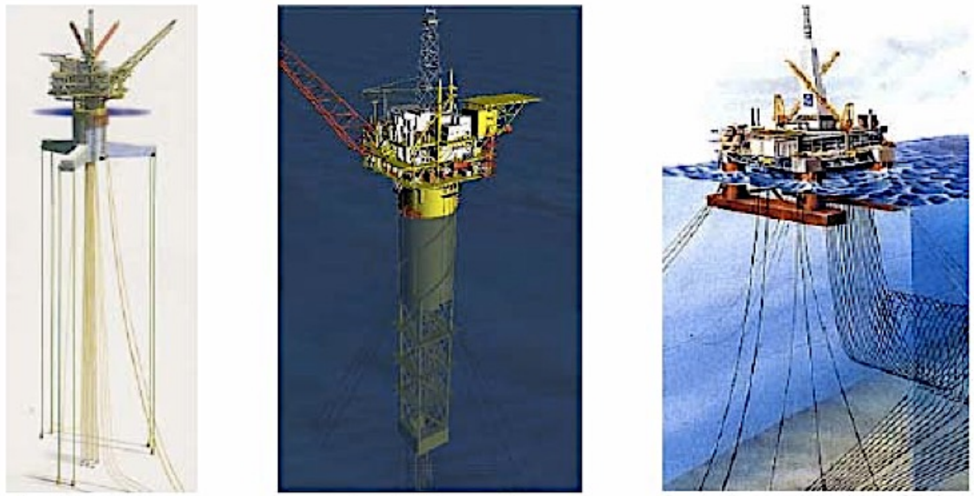
Locate 5 MW turbines on spacing of ~150 m along 1000 km arc = 35 GW capacity

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…

Horns Rev Wind Farm (Denmark) - Rated Power 160 MW – Water Depth 10-15m

Deep Water Offshore Platforms for Oil and Gas Exploration



Tension Leg Platform | Taut-Moored Spar | Catenary-Moored Semi-Submersible

5 MW Wind Turbine

Rotor Orientation	Upwind	
Control	Variable Speed, Collective Pitch	
Rotor Diameter/Hub Diameter	126 m/3 m	
Hub Height	90 m	
Max Rotor/Generator Speed	12.1 rpm/1,173.7 rpm	
Maximum Tip Speed	80 m/s	
Overhang/Shaft Tilt/Precone	5 m/ 5°/ -2.5°	
Rotor Mass	110,000 kg	Overall c.g. location: $(x,y,z)_t$ = (-.2,0,64)m
Nacelle Mass	240,000 kg	
Tower Mass	347,460 kg