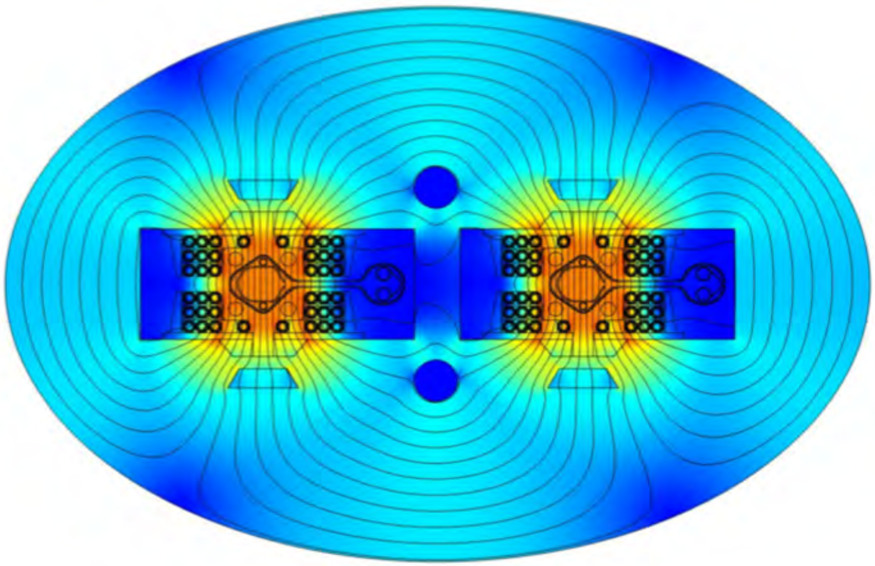
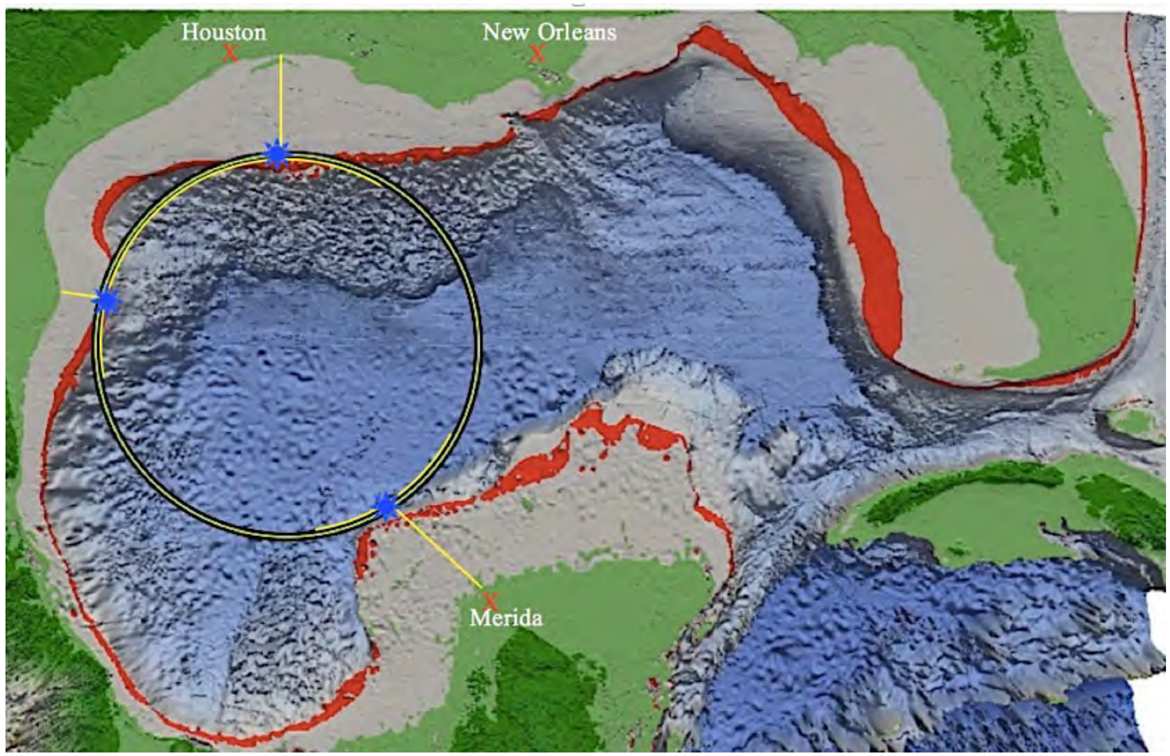
Cable-in-Conduit Dipoles to enable a Future Hadron Collider





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CERN is developing a design for a 100 TeV hadron collider in the Rhone Valley

90 km circumference – limited by the surrounding mountains and the lake

16 T magnets – no one has yet built a successful collider dipole at that field strength

Superconducting wire for that magnetic field would cost >$20 Billion today

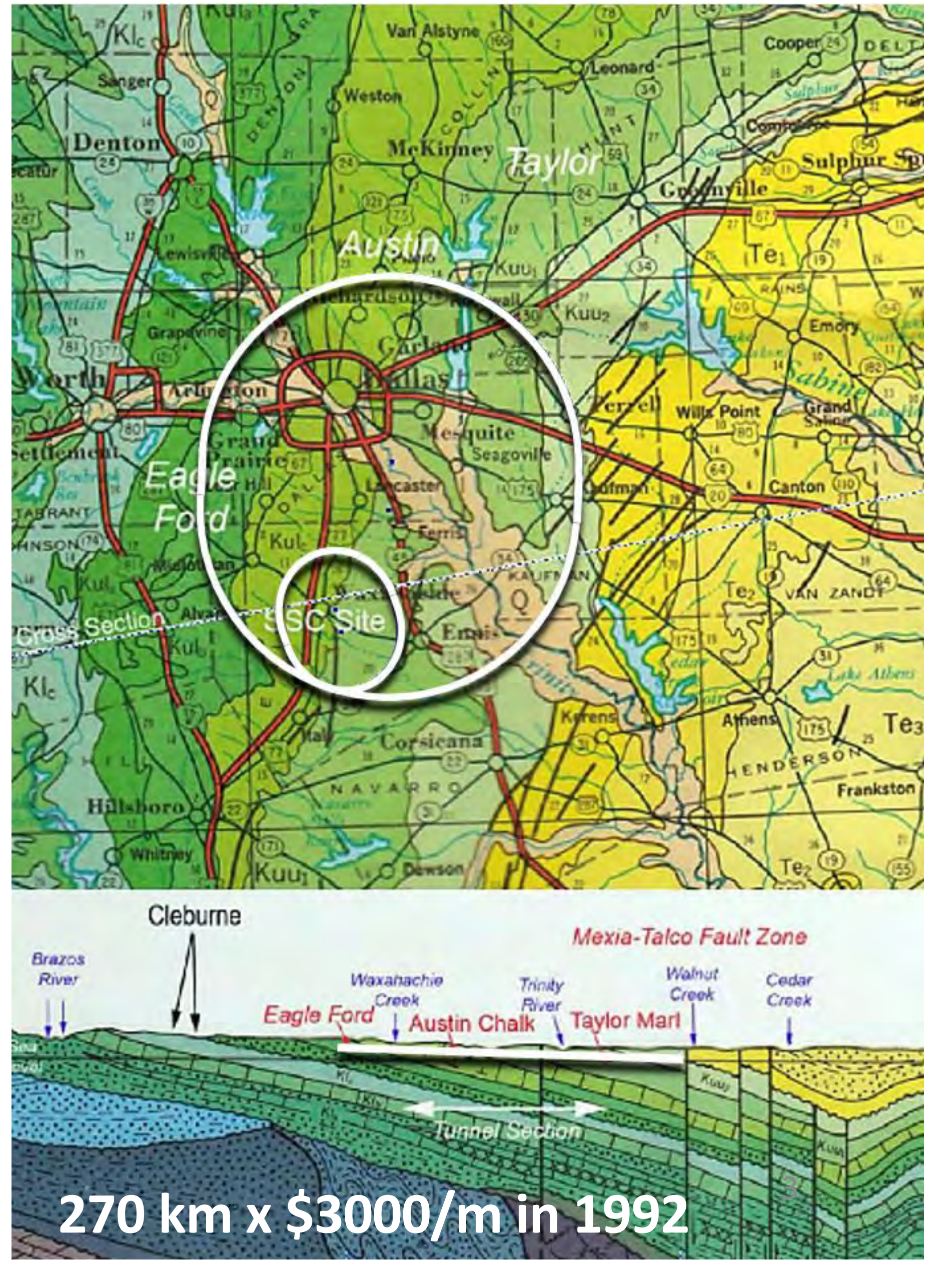
Tunnel would likely cost >$4 Billion

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 minimum tunneling cost,
Modest field-strength magnets with low cost

Tunnel cost depends strongly upon the rock in which you tunnel



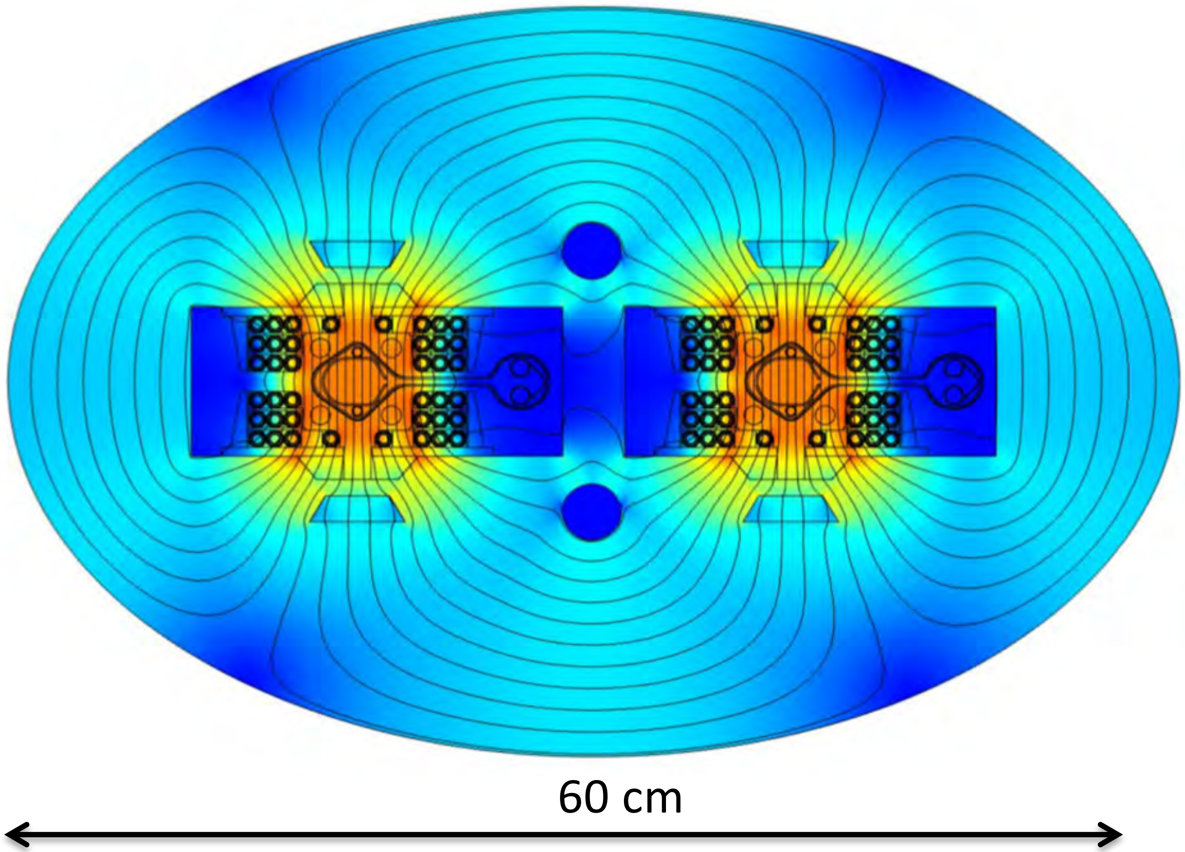
There is already an 80 km circumference tunnel in Texas – the SSC tunnel was nearly completed.

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!

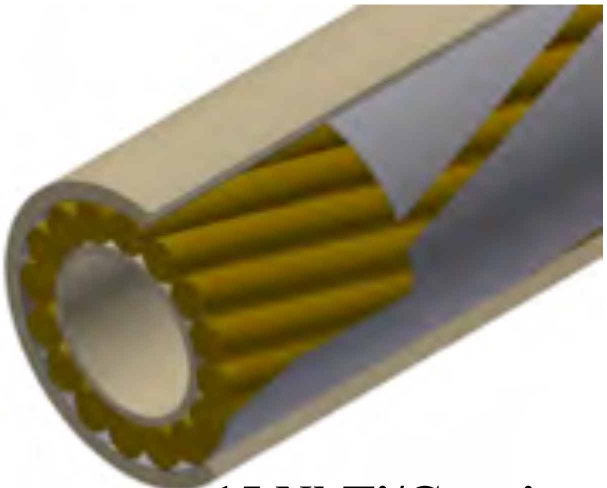
A 270 km tunnel (100 TeV @ 4.5 T) can be located at the same site, entirely within the Austin Chalk and Taylor Marl, tangent to the SSC tunnel as injector.

We combine the simplicity of the low-field superferric SSC dipole with a cable-in-conduit conductor to make reliable flared ends:

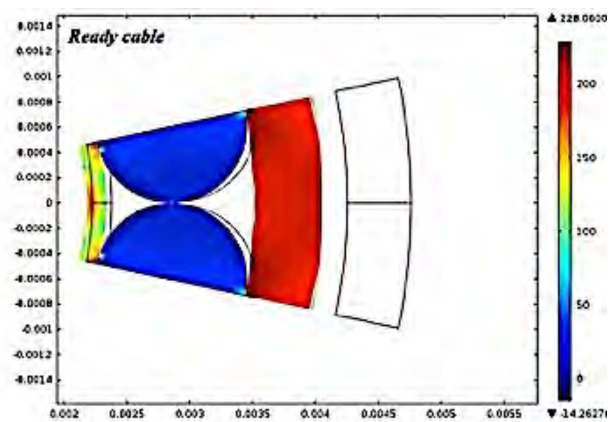


- 4.5 Tesla dipole field
- C-dipole: synchrotron radiation passes into a second chamber where it is absorbed at 80 K.
- Refrigeration is 100x more efficient, so heat load is less of a limit.
- Clearing electrode suppresses electron cloud; 25 ns bunch spacing feasible.
- Superconducting winding has 20 turns total, wound from 2 pieces of round cable-in-conduit.

Cable-in-Conduit for an Ultimate Collider

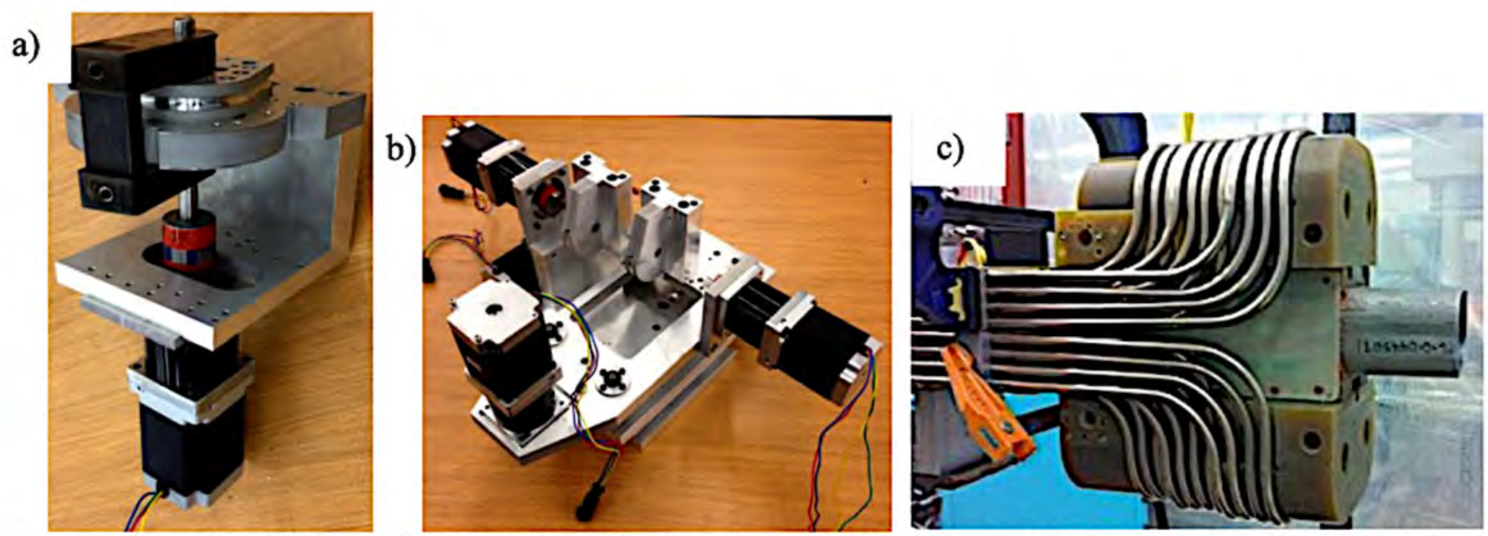


15 NbTi/Cu wires are cabled onto a perforated spring tube.



Cable-in-Conduit brings major benefits for dipole fabrication

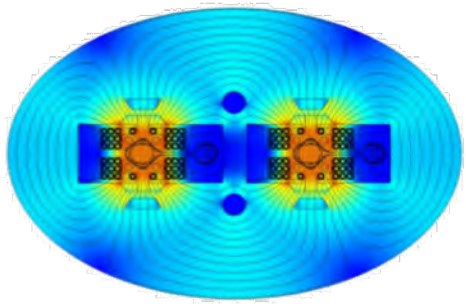
- CIC provides stress management at the cable level.
- CIC supports each wire, bathes all wires in cryogen.
- We have developed robotic bend tools that can make small-radius flared ends while preserving the internal registration of the wires.

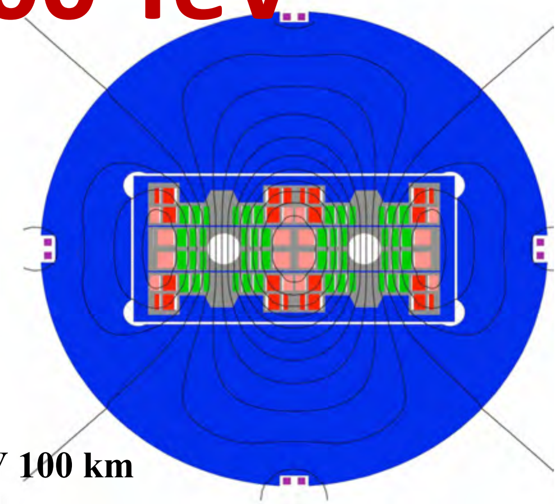


Bending CIC conductor to form the flared ends of the dipole winding: a) motorized tool for forming 180° bend; b) motorized tool for bending the 180 loop to form c) the 90° flare end region of completed dipole winding.

We built a 1.2 m model of a 3 T CIC dipole for the Ion Ring of JLAB's proposal for EIC

Compare the costs for the tunnel and superconducting wire for a 100 TeV hadron collider:

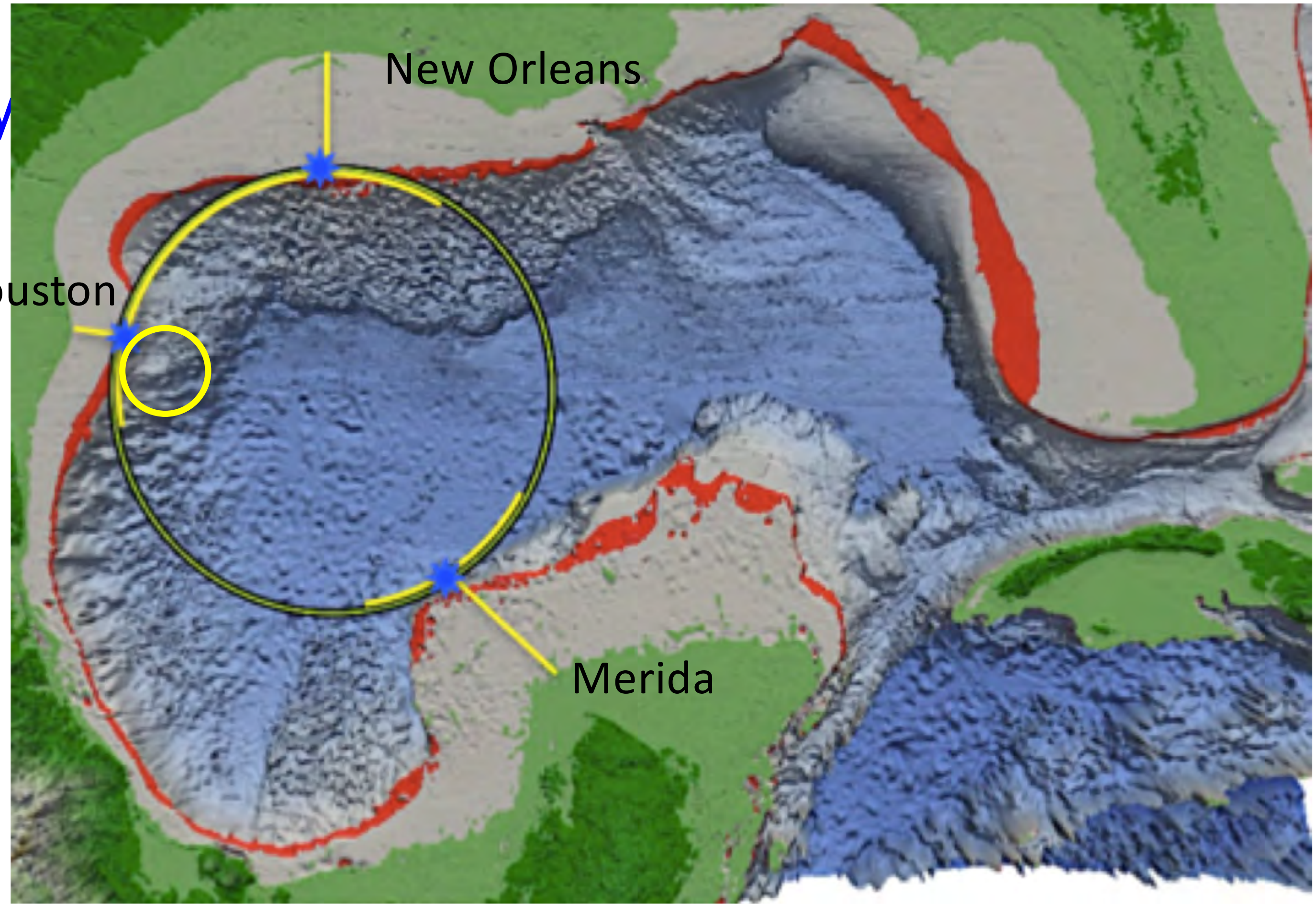




	RHIC	LHC	100 TeV 270 km	100 TeV 100 km
Operating field	3.4 T	8 T	4.5 T	16 T
# Bores	1	2	2	2
# turns per bore	32	74	20	
Length	9.4 m	14.3 m	20	20
Superconducting wire/bore: NbTi	92 kg	380 kg	124 kg	390 kg
Nb_3Sn				1,480 kg
Manufactured magnet cost/dipole	$105,000	$565,000	$185,000	?
Cost of superconductor/dipole	$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
$5 \times 10^{35}\ cm^{-2}s^{-1}$ luminosity



Configure collider ring from 5,000 half-cell segments: 300 m long dipoles.

Circular 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

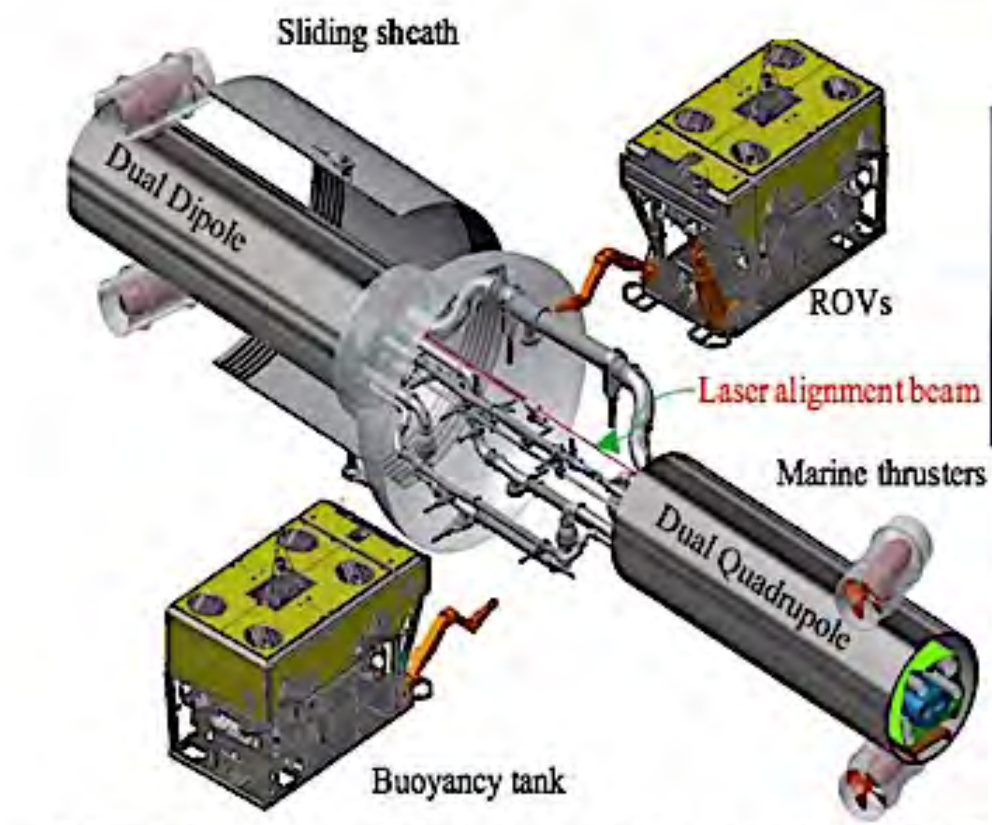
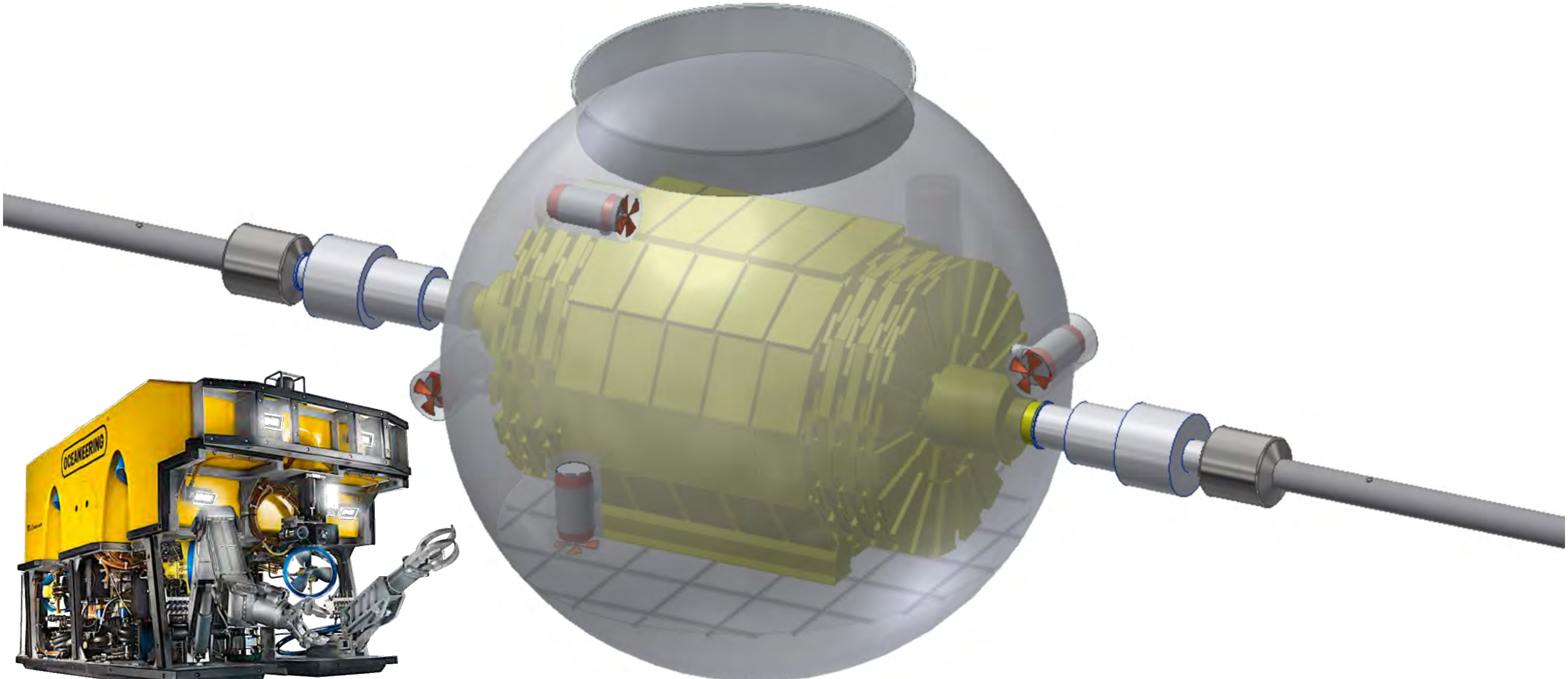


Figure 3. Demountable hub connecting two 300 m half-cells of the pipeline cryostat.

Figure 4. Cutaway showing the umbilical connections completed, the sheath in place, and vacuum restored within the connection hub. (MLI not shown for clarity).

Collider detector lives in a bathysphere



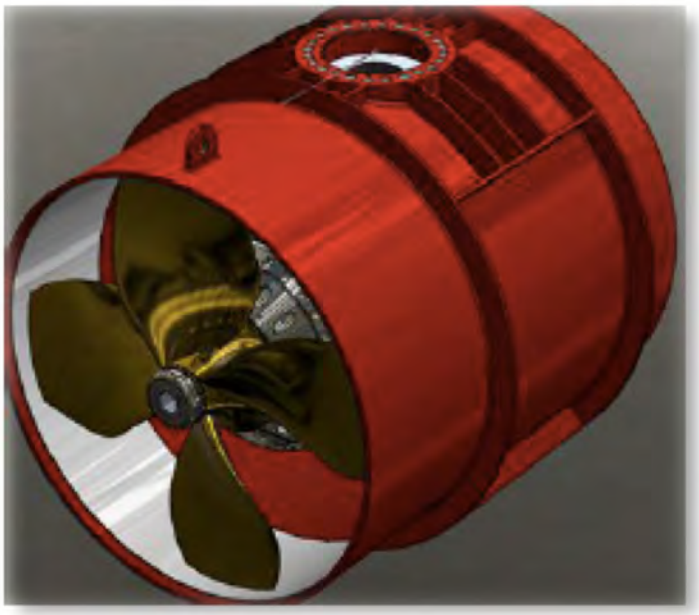
CMS detector has a mass of 14,000 tons, and lives in a 30 m diameter cavern at the LHC.

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-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.

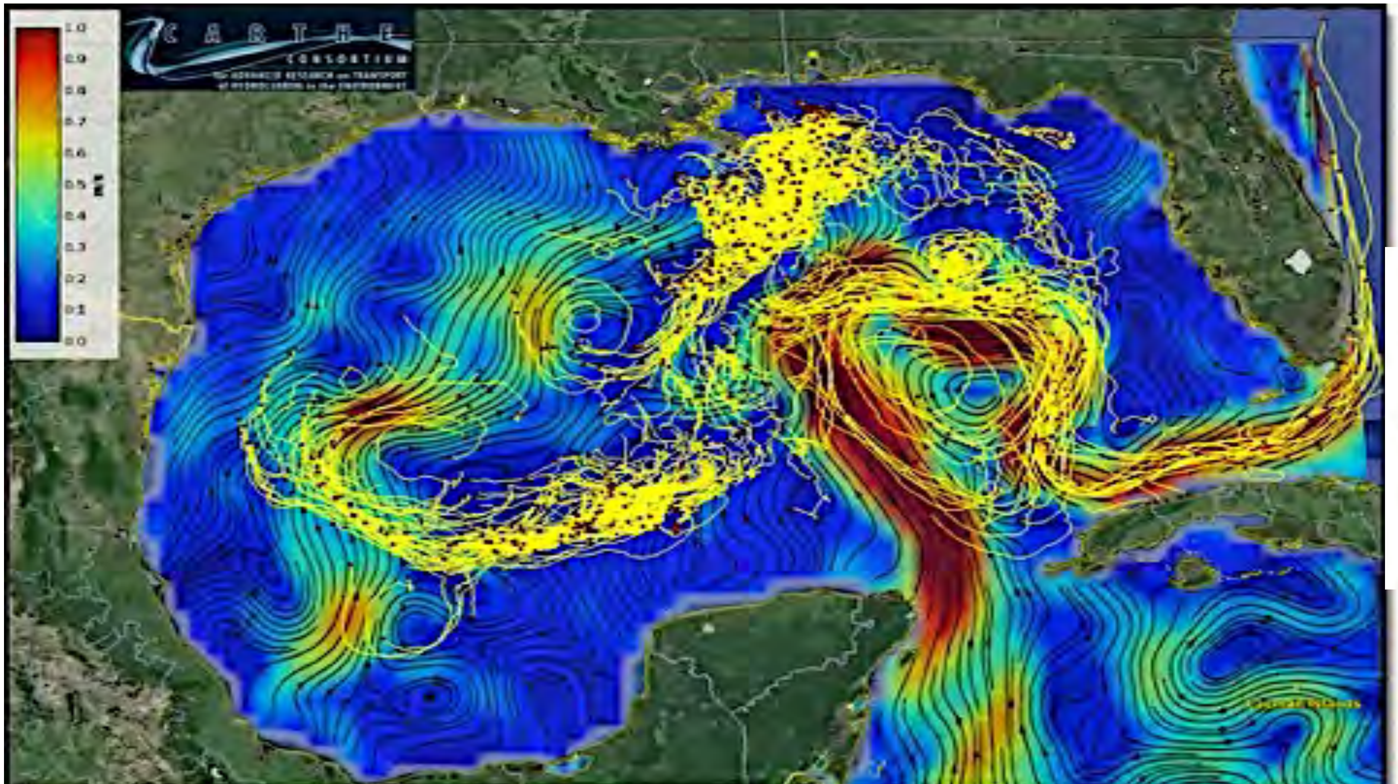
The ring is held in position and alignment in the sea using active station-keeping and terrain-following.



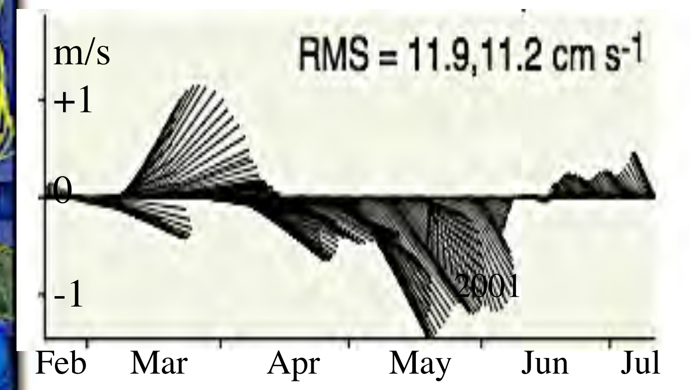
Marine thrusters are used routinely in marine power to precisely control the direction and thrust to propel or station-keep a vessel with precision.

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.

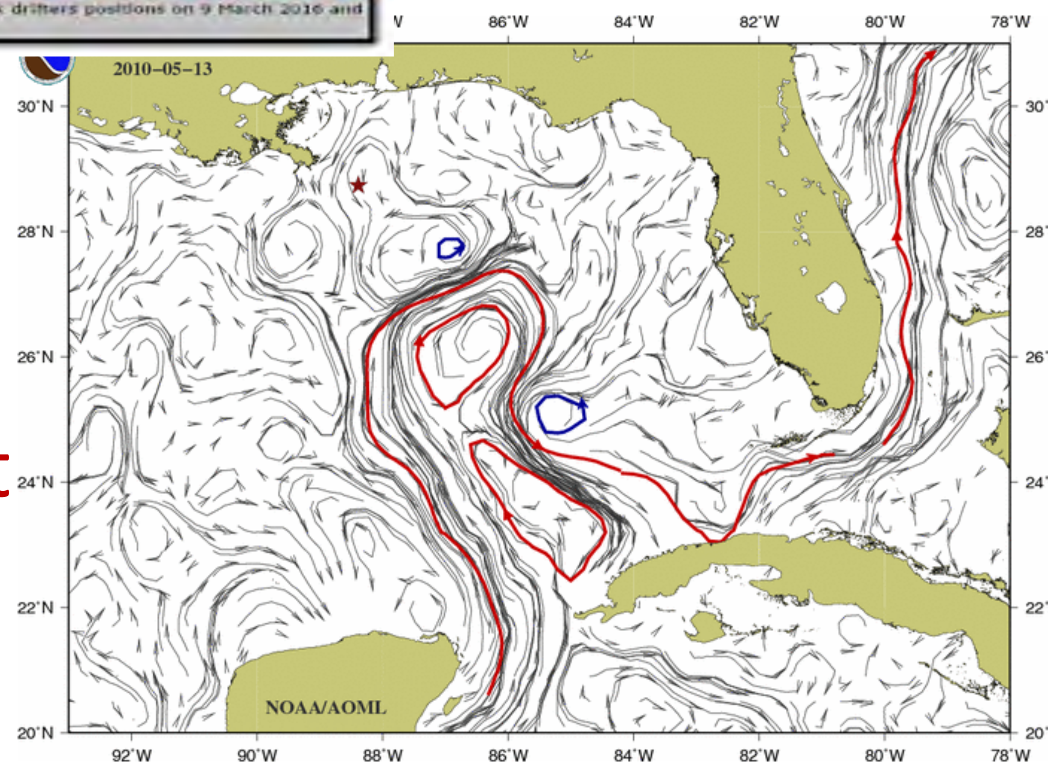
Feedback for geodesy is provided by a ring-laser whose beam traverses the ring.



CARTHE drifter trajectories in the Gulf of Mexico superimposed on AVISO surface currents. Red squares mark drifters positions on 9 March 2016 and the tails are 14 days long. (Credit: Edward Ryan and Tamay Ozgokmen from the University of Miami)



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

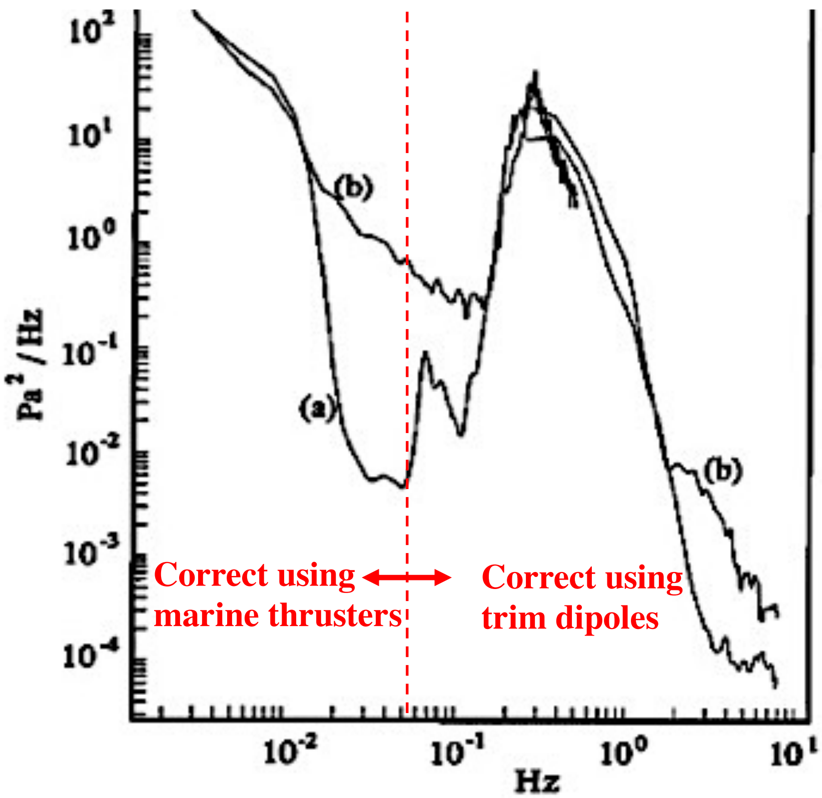


Comparison of parameters

	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

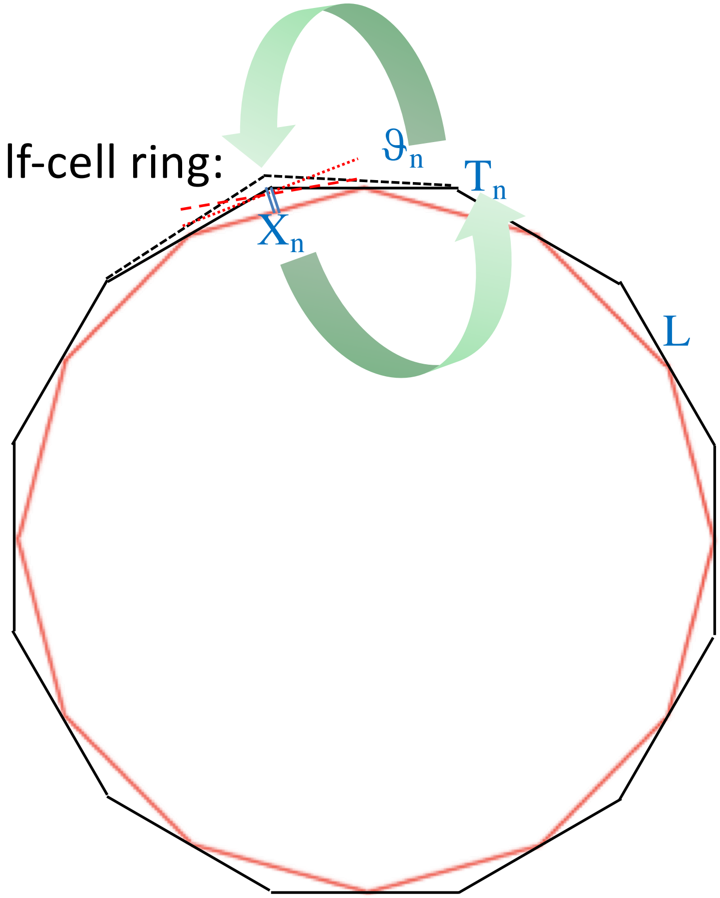
Ultimate luminosity is limited by synchrotron radiation power.

Control Deflections of Ring Alignment using Laser Geodesy



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

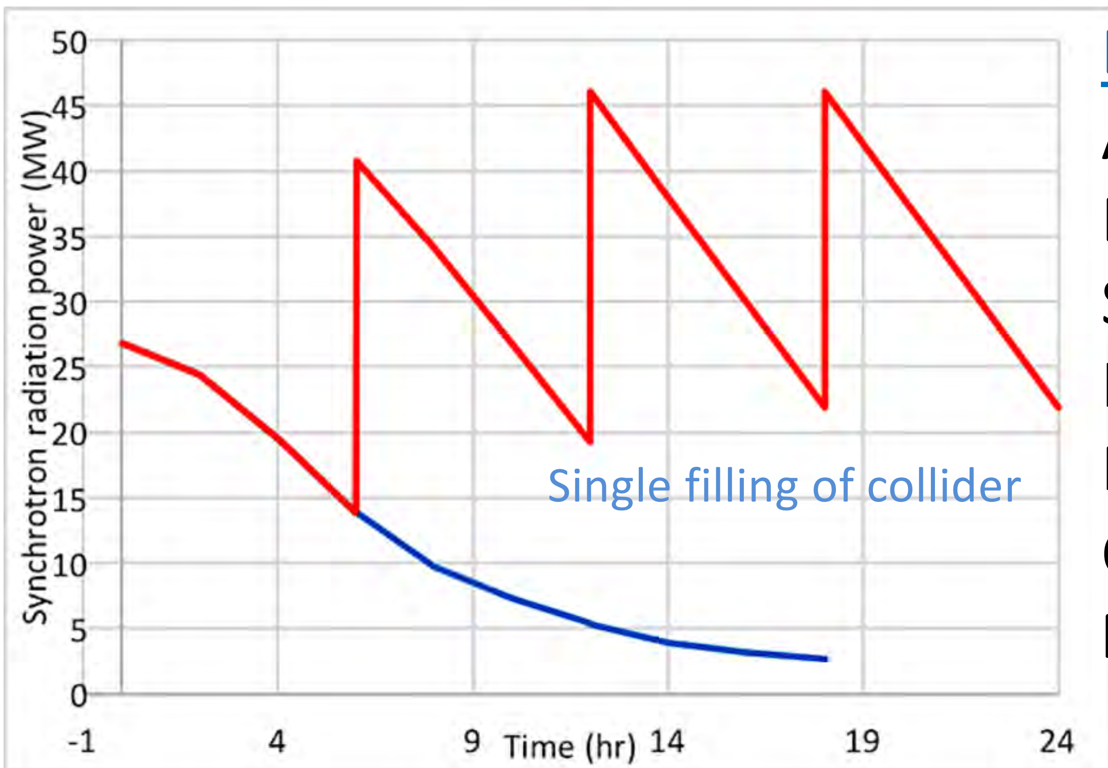
Illustration with 12 half-cell ring:



- 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 along the perturbed geodesy.

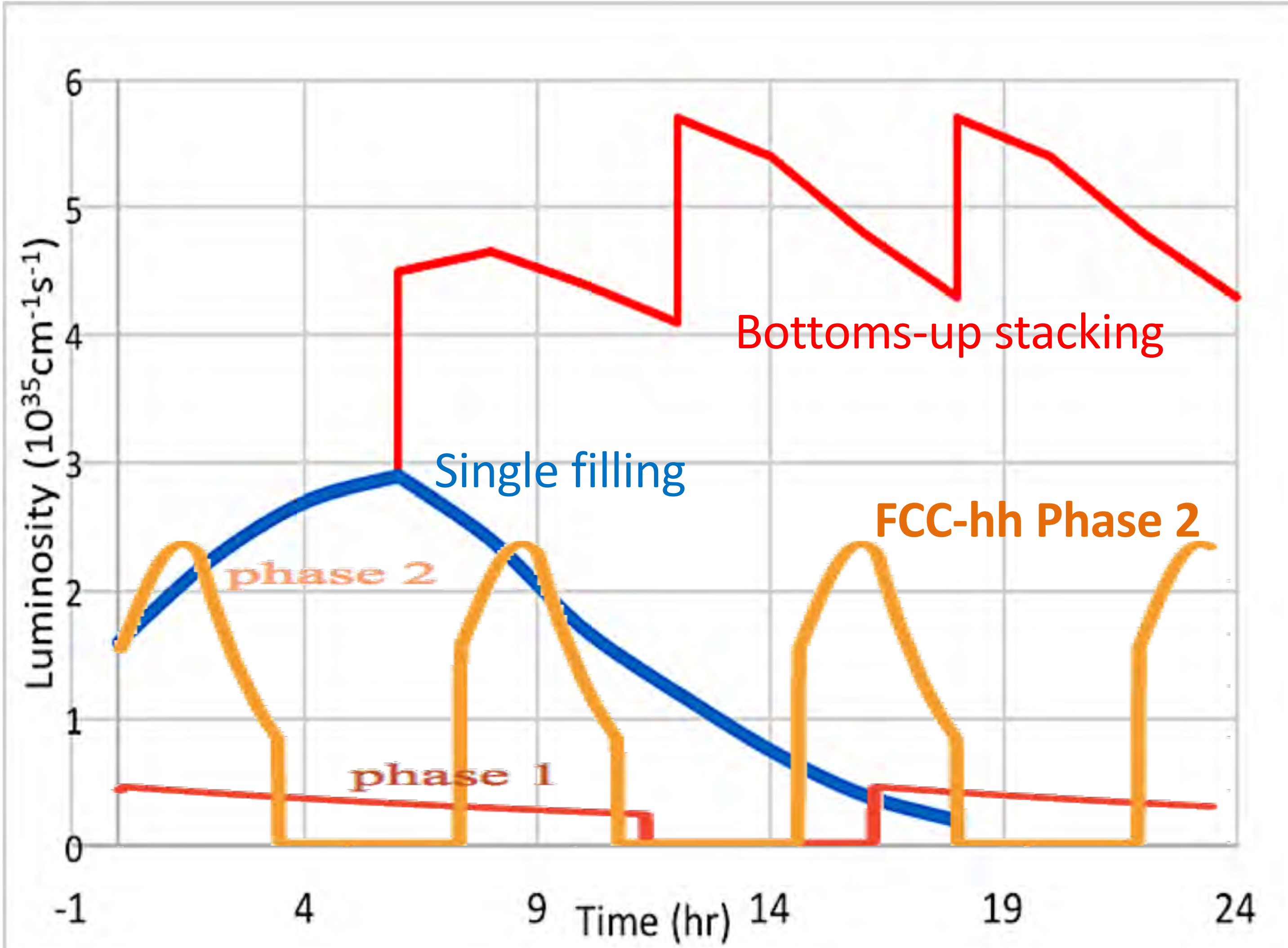
Bottoms-Up Stacking

- For proton beams at 250 TeV is a 3.2 T dipole field, 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*



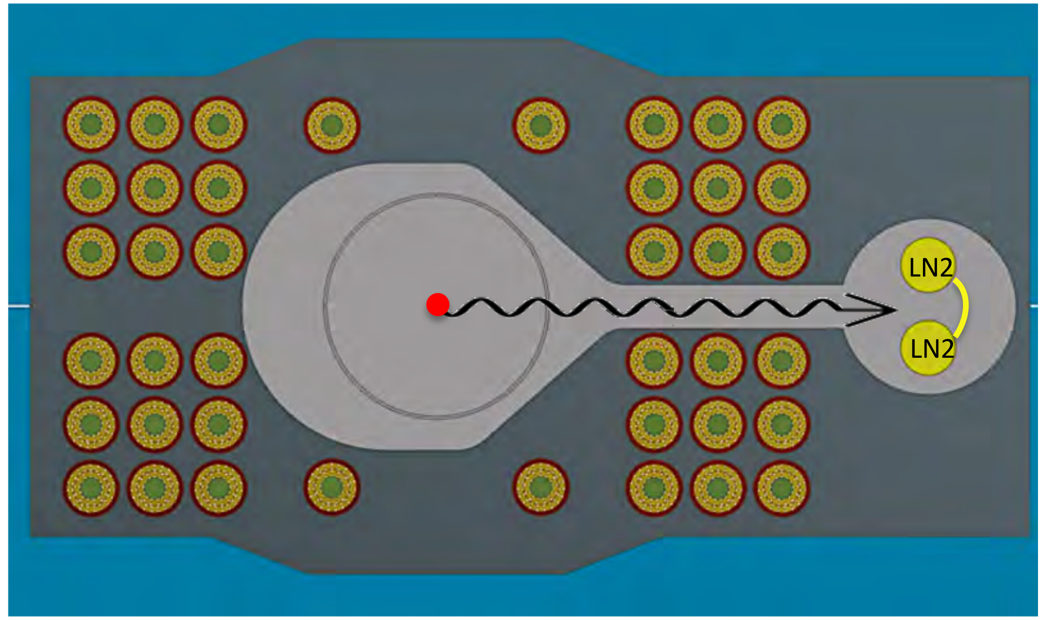
Bottoms-Up Stacking:
After 6 hours of collisions,
Decelerate to injection energy,
Scrape bunches,
Inject fresh bunch with old one,
Re-accelerate, low-b squeeze,
Collider for another 6 hours,
Repeat indefinitely.

Bottoms-Up Stacking: Sustain 5×10^{35} $cm^{-2}s^{-1}$ indefinitely



Taking 36 MW of synchrotron radiation at 80 K so it doesn't load the 20 K cryogenics

The 500 TeV CIS should sustain a luminosity of $5 \times 10^{35} cm^{-2}s^{-1}$.
The proton beams radiate 36 MW of synchrotron radiation in a narrow fan – 7 kW/dipole.



We have designed the CIS dipole with a mid-plane slot on the outer side of each dipole. The fan of SR passes through the slot and is absorbed onto a photon stop that is cooled by a continuous flow of liquid nitrogen.

The LN2 is cooled within each dipole using high-efficiency cryocoolers. Sumitomo CH-110 cools 200 W @ 80K, costs $50K

Compare 500 TeV CIS with LHC

CIS:

- The lattice contains 5,000 half-cells.
- Each half-cell has one 300 m dipole and one quadrupole.
- Each dipole has 20 turns of Cable-in-Conduit.
- So there are 5,000 dipoles, 100,000 turns of cable in the collider.

LHC:

- The lattice contains 360 half-cells.
- Each half-cell has three 14 m dipoles and one quadrupole.
- Each dipole has 74 turns of cable.
- So there are 1,100 dipoles, 80,000 turns of cable in the collider.

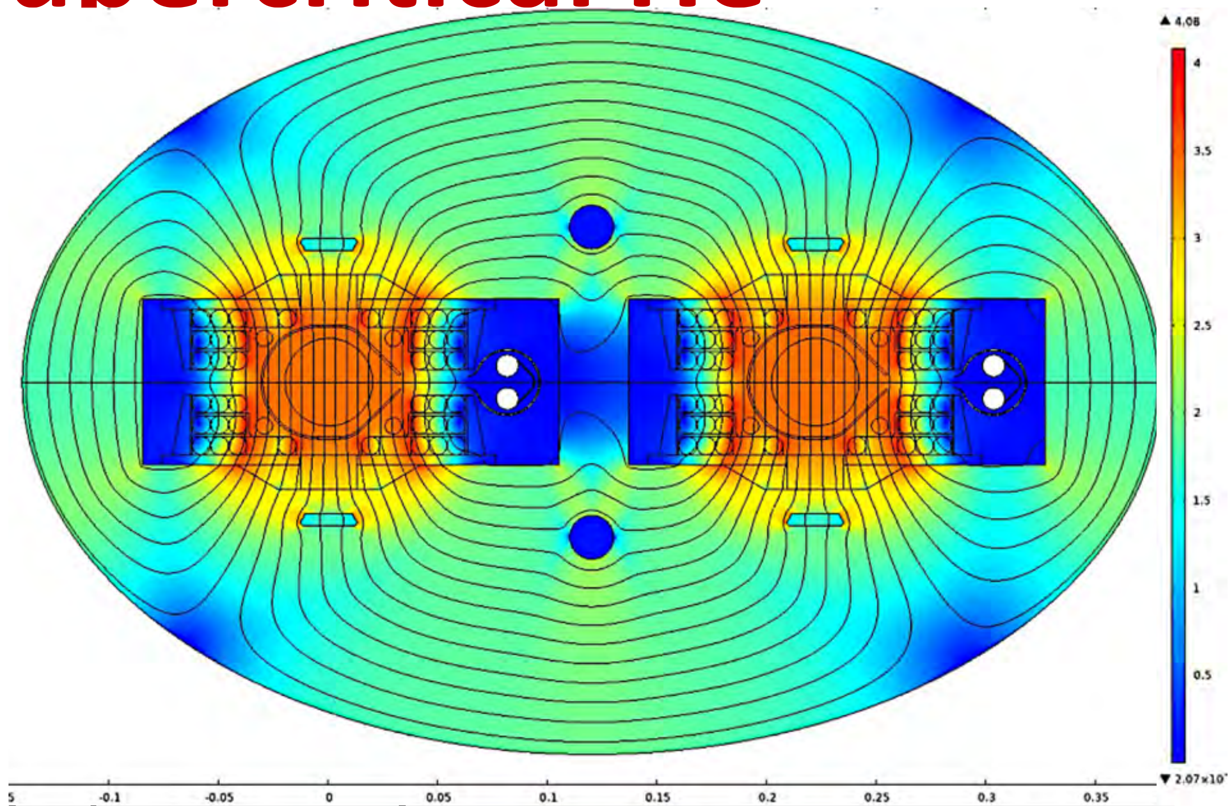
- Many aspects of fabrication cost scale with the number of cable turns.
- Many aspects of reliability scale with the # of magnet ends.

Three options for the superconductor, cryogenics of 3.2 T dipoles for 500 TeV

- **NbTi superconductor; 5 K supercritical He**
  - Lowest superconductor cost – $1.1 B
  - Requires distributed flow of supercritical He around 2000 km pipeline, heat exchange at each dipole.
- **MgB_2 superconductor; 20 K**
  - Medium superconductor cost - $28 Billion
  - Cryocoolers remove heat from 20 K windings, 80 K synchrotron light locally at every dipole.
- **REBCO superconductor; conformal windings; 20 K**
  - Highest superconductor cost - $74 B
  - Cryocoolers remove heat from 20 K windings, 80 K synchrotron light locally at every dipole

NbTi CIC; 5 K supercritical He

20 turns/dipole
12.9 kA cable current



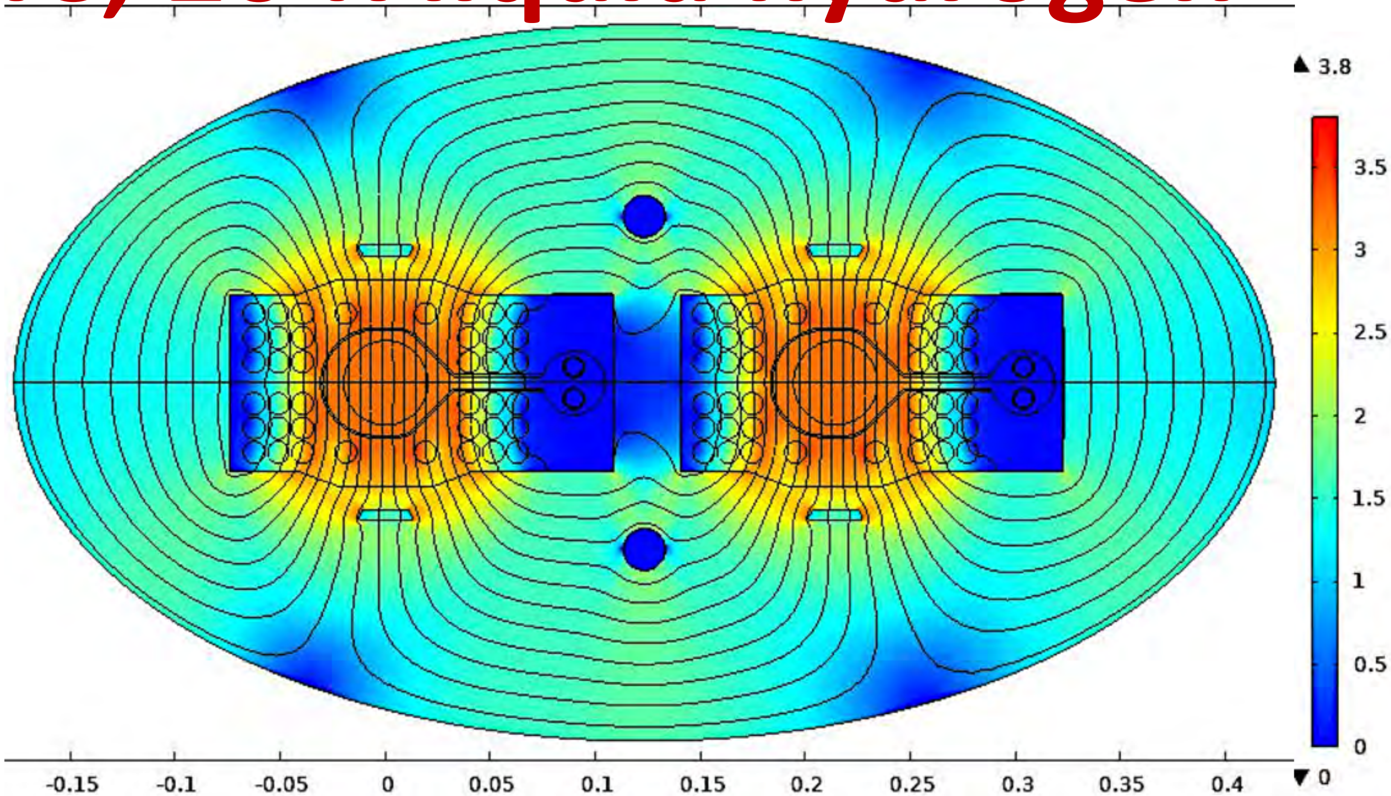
The big challenge for NbTi is the cryogenics:

Supercritical He flows through the center tube of the CIC, provides intimate heat transfer to all wires (for stability), heat is exchanged to 2-phase LHe as the SCHe flows from one dipole to the next, and refrigerators must be located in sectors around the ring. That was the cryogenic design planned for SSC.

But this is a 2000 km ring pipeline, and satellite refrigerators must be located every ~20 km…

MgB_2 CIC; 20 K liquid hydrogen

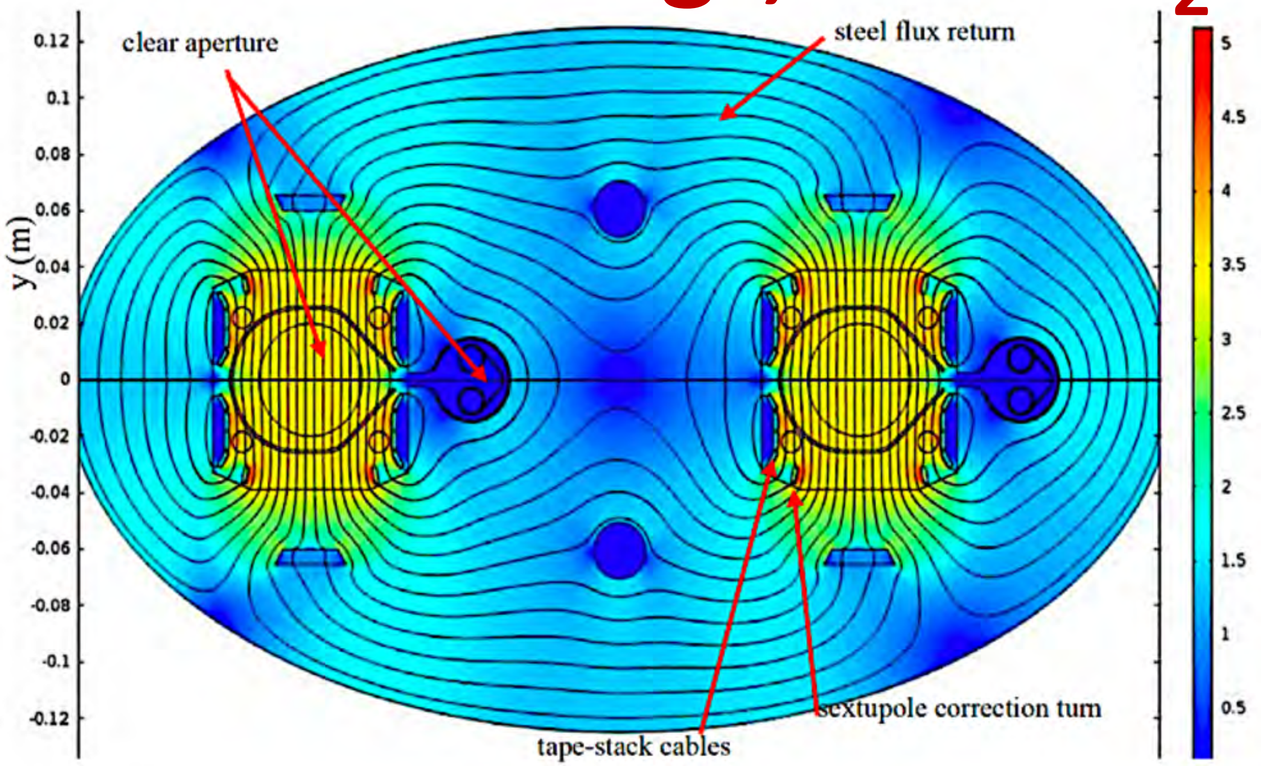
20 turns/dipole
13.6 kA cable current



- HyperTech has developed a 2nd-generation MgB_2 wire that provides 500 A/mm^2 at 20 K, 3.5 T.
- That opens the capability to operate at 20 K with 2-phase liquid hydrogen, remove heat locally in each dipole using inexpensive cryocoolers.
- Sumitomo RDK-500B cools 40 W at 20 K, costs $40K.
- *Refrigeration is local to each dipole, flow provides redundancy.*

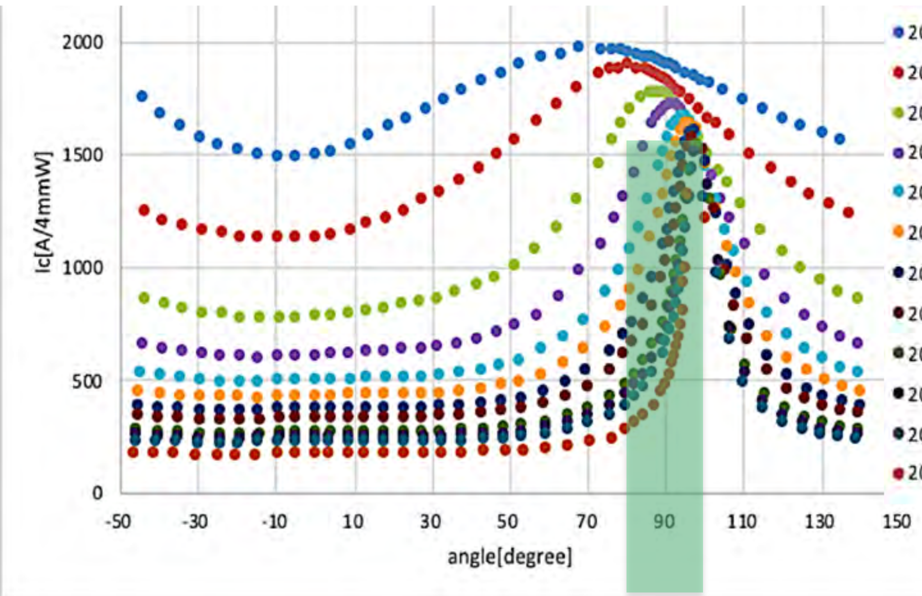
REBCO conformal windings; 20 K LH_2

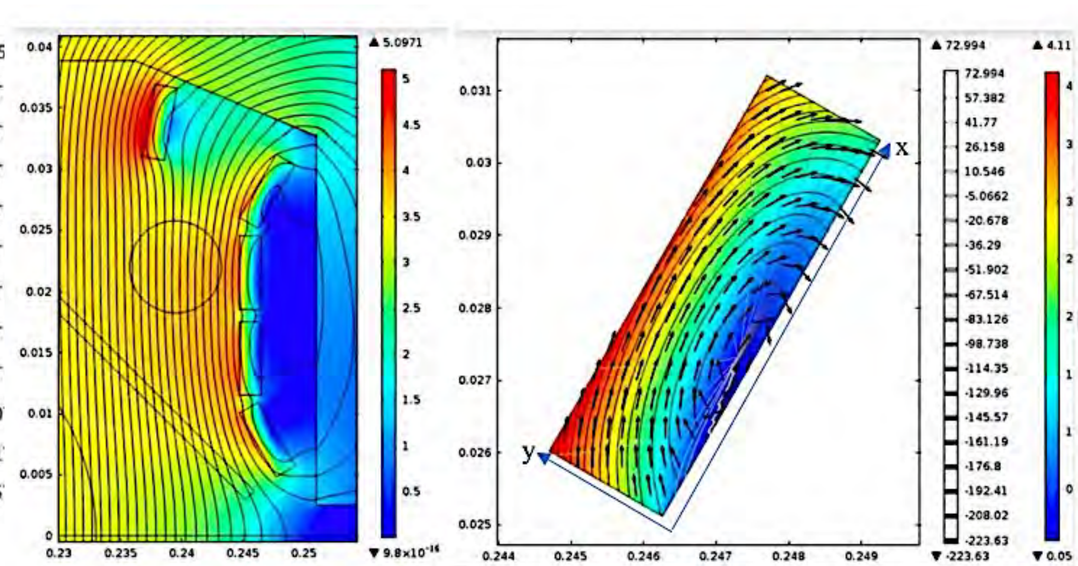
10 turns/dipole
22 kA cable current



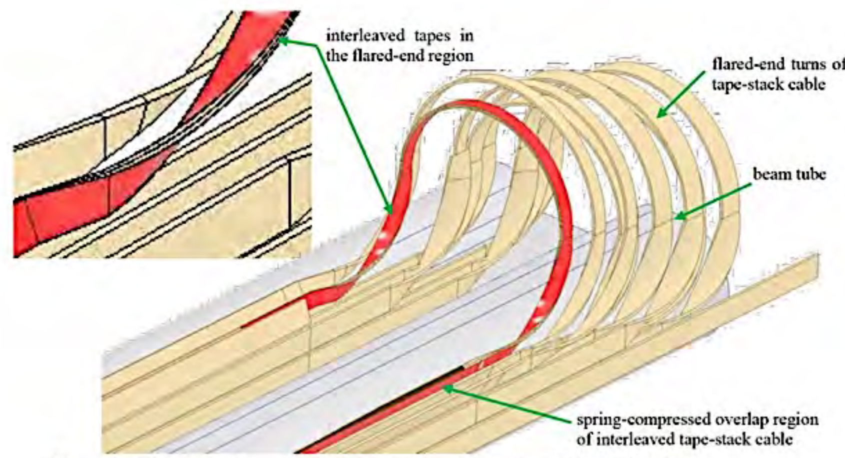
- REBCO tape has great current capacity at 20 K, but its performance is strongly anisotropic – if $\vec{B}$ is more than $10°$ out of the tape plane, current capacity drops x3!
- We configure tape stack cables of REBCO tapes so that every cable is closely parallel to the local $\vec{B}$.
- The tapes are spring-loaded within each tape-stack cable. Current-sharing provides stability and best use of each tape's capacity.

Conformal windings get full performance from REBCO





Commonwealth Fusion has adopted REBCO for their compact tokamak.
They successfully tested the first prototype SPARC.
They are now building a first actual prototype ARC, using tons of REBCO.



CF targets a large-volume price for REBCO of \$5/kA-m. That would bring the conductor cost for a 500 TeV collider down from \$74 B to \$10 B!

Until now we have always had a credible prediction of a mass scale when we propose a new collider.

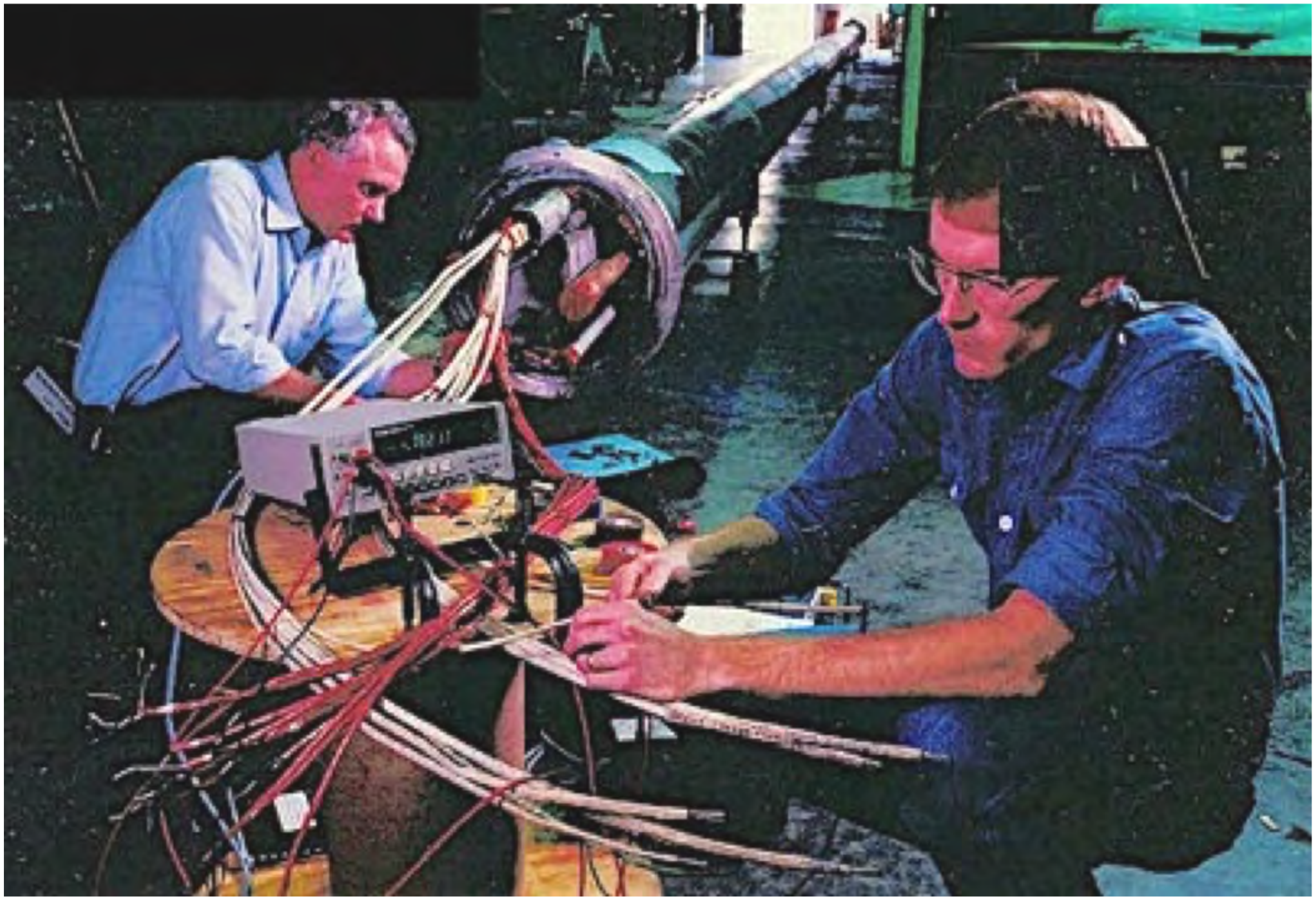
- In 1976 I proposed $p\bar{p}$ colliding beams in the existing synchrotrons.
  - We expected to find the weak bosons, and we did.
- In 1980 I proposed building the SSC to find the Higgs boson.
  - We expected it to have a mass of 125-1000 GeV, and LHC found it in Run 1.
- But so far we have no convincing 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?

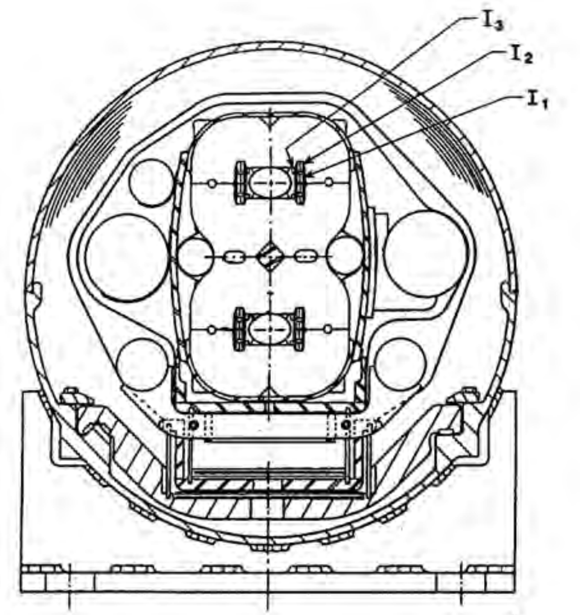
Make the mass reach as big and the price as low as our ingenuity can manage.

Technology R&D to make a future for hadron colliders

- Develop long-length Generation-2 MgB_2 wire, with target performance 500 A/mm^2 @ 20K, 3.5 T
- Develop 15 kA Cable-in-Conduit using 2-G MgB_2
- Build/test a 3.2 T short-model dipole.
- Build/test a 300 m long 3.2 T dipole.
- Support the 300 m dipole in a pipeline cryostat with interconnect hub, put it in the sea,
- Submerge to 100 m, power it up!
  - Texas A&M operates a fleet of oceanographic vessels capable of supporting such a test.

Superferric Dipole for SSC:
Still the best answer for the future of HEP





In 1983, Russ Huson and Peter McIntyre proposed a superferric dipole as the basis for the SSC. In just. 2 years, we built 3 full-length 35 m dual dipoles – the longest superconducting magnets ever made. The full-length dipoles were fabricated at General Dynamics in San Diego and trucked to Texas without incident. All three tested to spec.

Build a 100 TeV Collider-in-the-Sea, make a next generation of HEP.

- Dipole length ~80 m, assembled at the port.
- MgB_2 wire cost (today's price for 2G wire): $5.4 B
- Cryocooler cost for 20K, 80K cryogenics: $2.0 B

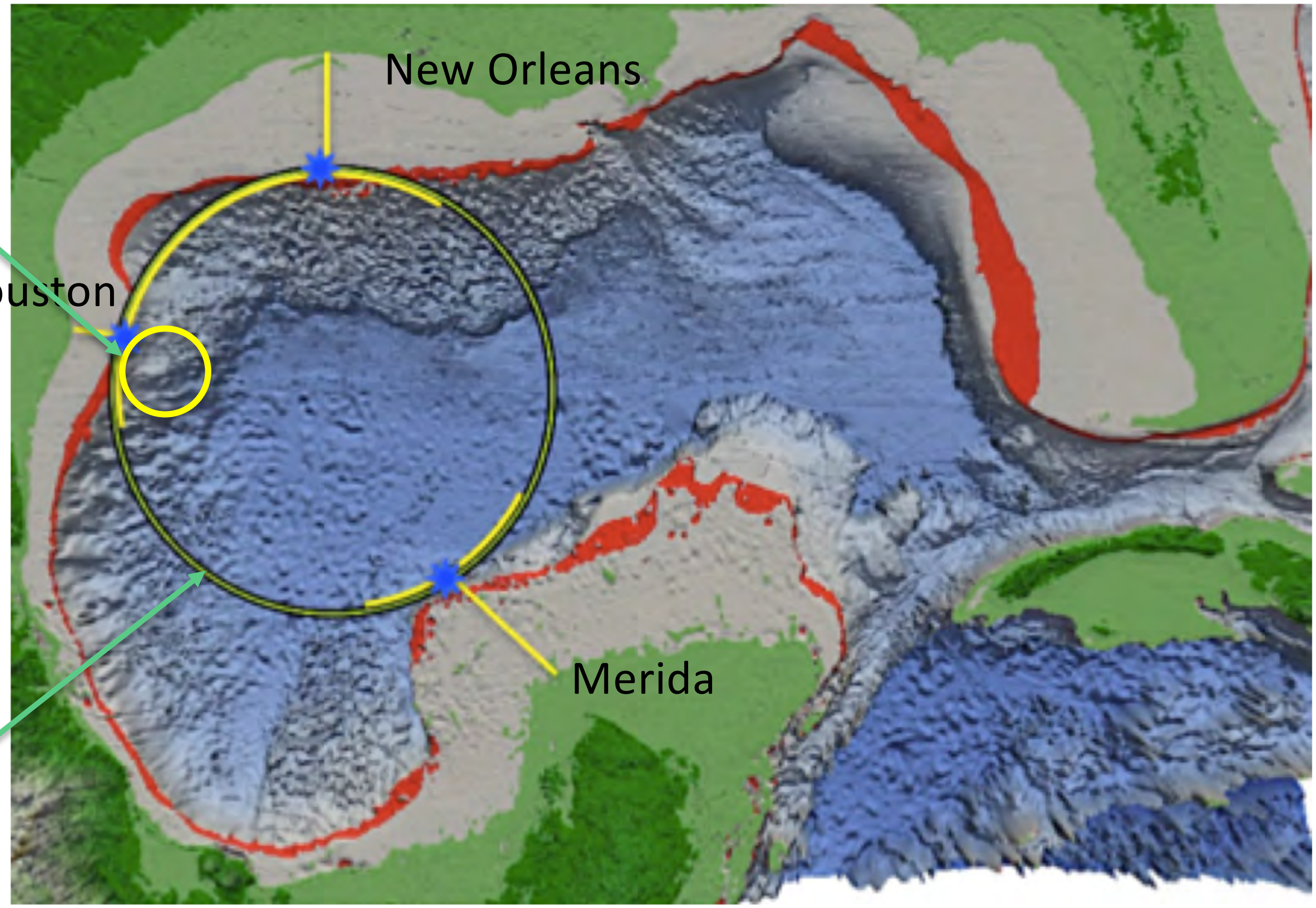
The project cost is in-scale to previous major next steps to open a new energy frontier.

The 100 TeV collider would enable us to prove (and improve) the many aspects of this new paradigm for a hadron collider: superconductor, collider, marine pipeline installation, on-site magnet fab, install/control/align at 100 m depth, dynamic terrain-following beam dynamics,..

- The day would come when we would want 500 TeV for a new generation, and we would be ready!

So in the coming decade, we would do the technology R&D, then build

Phase 1: 100 TeV collision energy; ~10^{35} $cm^{-2}s^{-1}$ luminosity



We would use it as an engine for discovery, then use it as injector for

Phase 2: 500 TeV collision energy; $5x10^{35}$ $cm^{-2}s^{-1}$ luminosity

Conclusion

- The conventional paradigm of locating high-field magnets in an underground tunnel is not cost-effective as a path to even 100 TeV.
- A new paradigm is proposed: a circular pipeline, located with neutral buoyancy at 100 m in the sea, with dipole field ~3.2 T. Dipoles would utilize either MgB_2 or REBCO, and accommodate photon trapping.
- It is technically feasible to make ultra-high-luminosity p-p colliding beams at 500 TeV.
- Emittance damping from synchrotron radiation enables bottoms-up stacking to sustain $5x10^{35} cm^{-2} s^{-1}$ indefinitely.

To learn more: p-mcintyre@tamu.edu

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

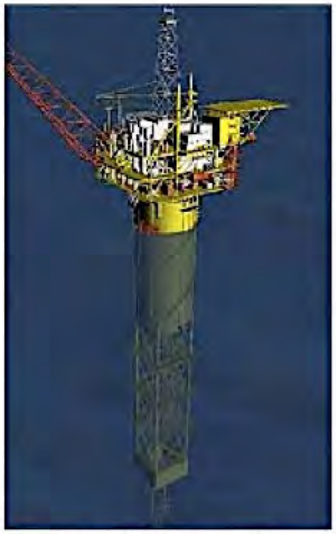
Interconnect power along superconducting transmission line installed in tandem with collider pipeline.

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