Title: Ultimate Hadron Colliders: What is feasible? What is affordable? How to maximize reach for new gauge fields?

Speakers: Peter McIntyre

Series: Particle Physics

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Abstract: The potential for discovering new gauge fields of nature relies upon extending the collision energy of hadron colliding beams as far as possible beyond the present 14 TeV capability of LHC.  We must seek a balance of minimum cost/TeV for the ring of superconducting magnets, feasibility and cost of a tunnel to contain the ring, and balancing the luminosity against synchrotron radiation.  Balancing feasibility, technology, and cost is crucial if there is to be a high-energy frontier for discovery of new gauge fields. Three design cases exhibit the tricky balance among these parameters:

FCC-hh:                                100 TeV,              ~100 km tunnel around Geneva,               ~16 T magnets using Nb3Sn

SuperCIC:            100 TeV,              270 km tunnel around Dallas,                      4.5 T magnets using NbTi

Collider-in-the-Sea:         500 TeV,              1900 km pipeline in the Gulf of Mexico,  3.5 T magnets using REBCO

# How to build a hadron collider

Peter McIntyre
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The potential for discovering new gauge fields of nature relies upon extending the collision energy of hadron colliding beams as far as possible beyond the present 14 TeV capability of LHC. We must seek a balance of minimum cost/TeV for the ring of superconducting magnets, feasibility and cost of a tunnel to contain the ring, and balancing the luminosity against synchrotron radiation. Balancing feasibility, technology, and cost is crucial if there is to be a high-energy frontier for discovery of new gauge fields. Three design cases exhibit the tricky balance among these parameters:

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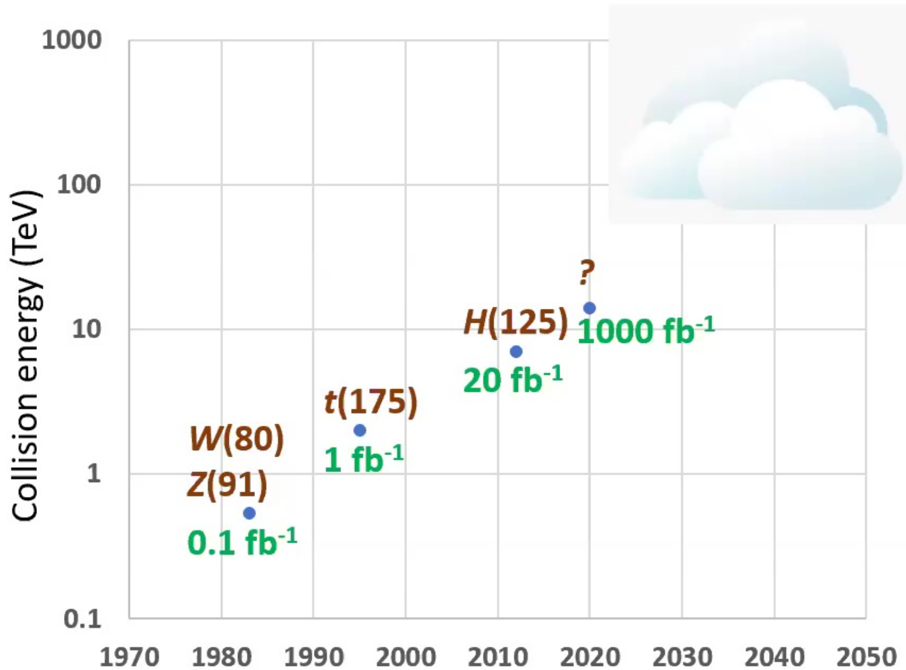
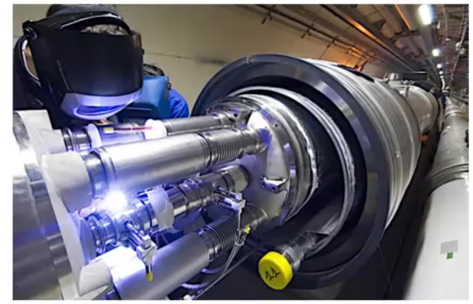
# Hadron colliders have been the primary engines for discovery of the particles and gauge fields of nature

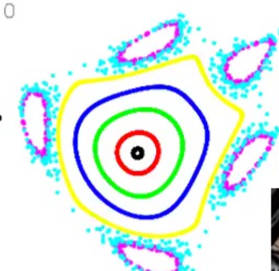


# You need four things to make a hadron collider:

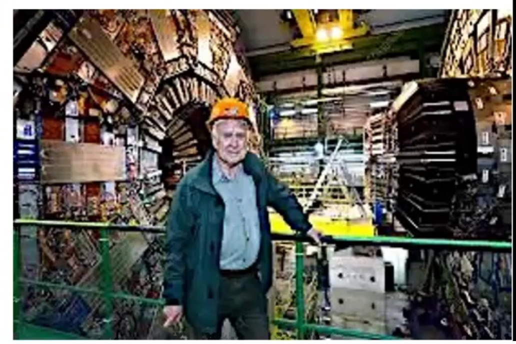


- A ring of superconducting magnets to guide the beams in circular orbits

- A tunnel to safely contain the magnet. ring and provide access



- Control of beam dynamics to. sustain high-luminosity



- Detectors to identify interesting events and record all possible data for them.

# 1974: We knew what should be the mass of the weak bosons if the weak interaction was to work as a gauge theory

- The coupling of weak interactions is proportional to energy for neutrino scattering:
- $$\frac{d\sigma}{dq^2} = \frac{\sqrt{2mE_\nu}}{q^2 - M_W^2}$$
- Weak interactions would become strong unless
- $M_W$ = 80 GeV,      $M_Z$ = 100 GeV
- Exact values were predicted from the absence of weak neutral currents

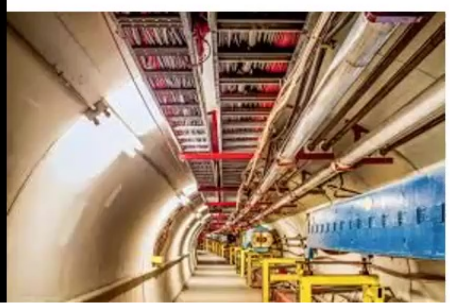
No accelerator then extant had enough energy to make them.

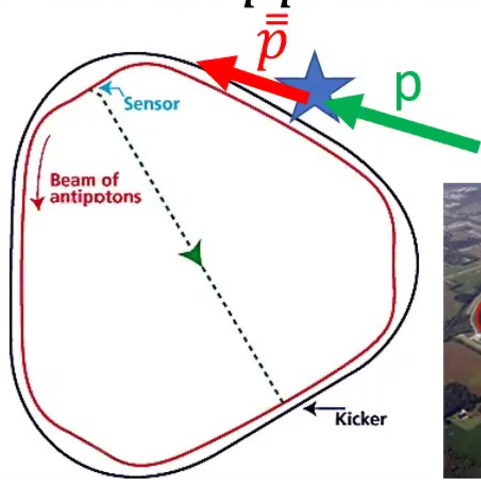
# We transformed the existing proton accelerators (400 GeV, 1 TeV) into proton-antiproton colliders

Center-of mass energy is gamma-boosted:

$\sqrt{s} = \sqrt{2mE}$ = 45 GeV for Tevatron beam on fixed target

$\sqrt{s} = 2E$ = 2000 GeV for $p\bar{p}$ colliding beams in Tevatron

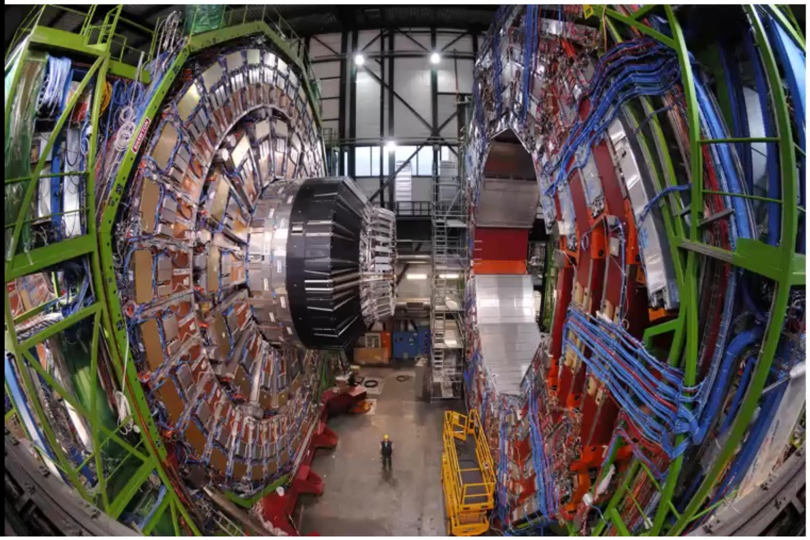


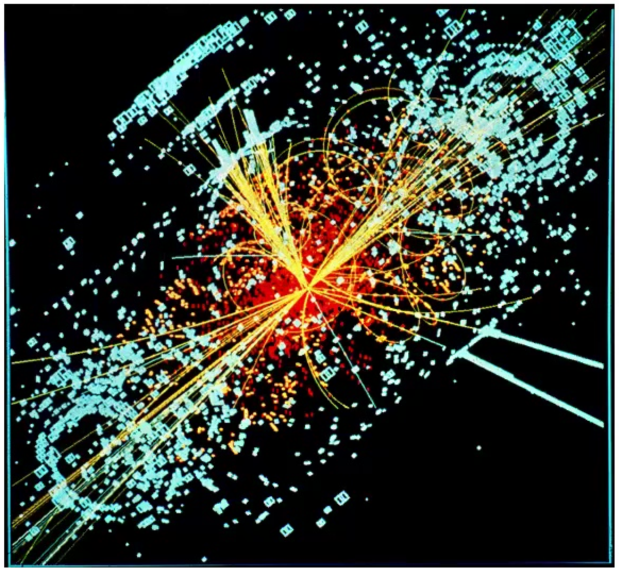



# 2000: We knew the electroweak interaction required another gauge field to give mass to particles – the Higgs boson at LHC

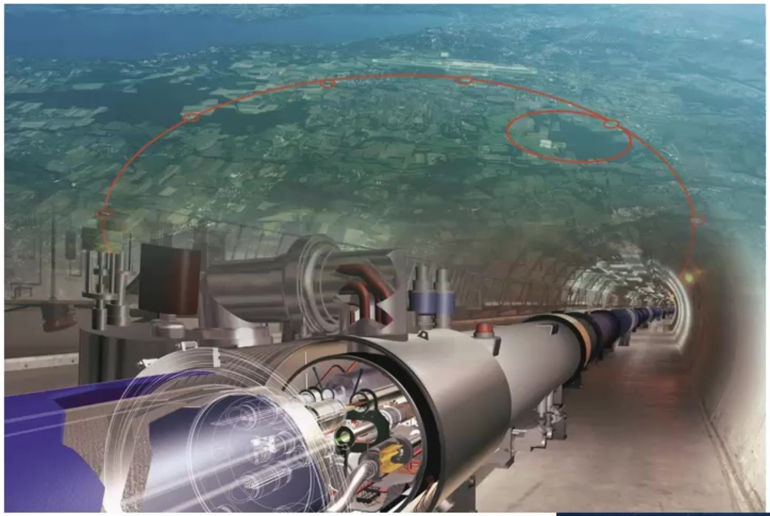
6 TeV collisions to discover~1 TeV.

Mass reach with 14 TeV ~few TeV.





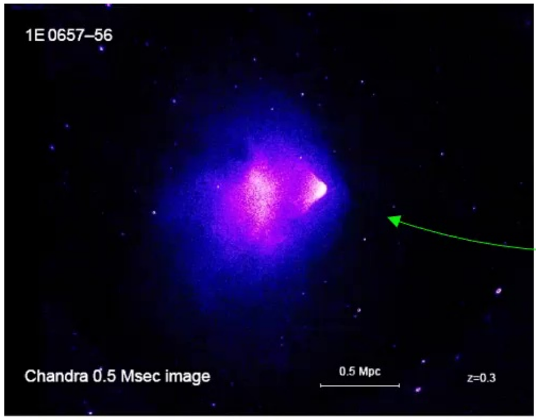
# LHC pushed NbTi superconducting magnet technology to its limit, cost ~$5 B

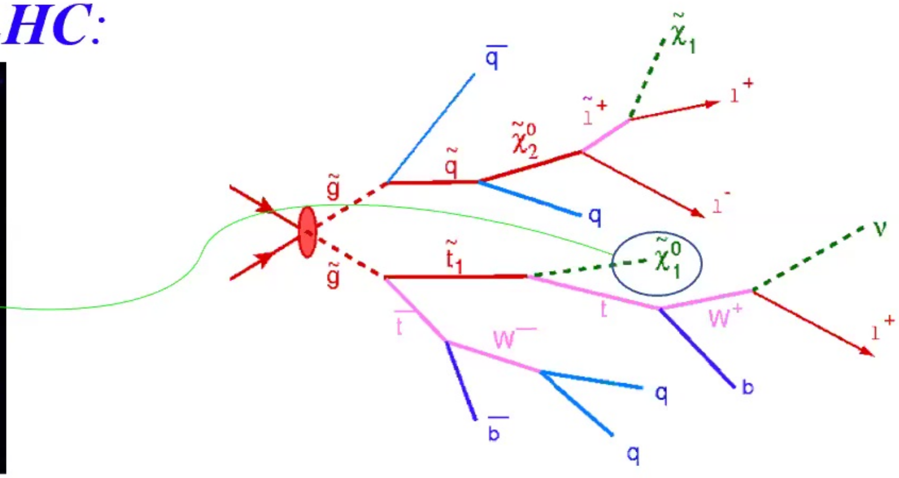


27 km circumference
8 T dipole field
Superfluid He cooling

# Which brings us to 2020:

- ***Puzzle**: Why are bosons and fermions so different?*
  - Could the same symmetry-breaking picture be extended to break the strong force at much higher energy? Could the three interactions be unified at a single higher energy scale for Einstein's dream?
- ***Old/new ideas**: Supersymmetry/supergravity*
  - A new gauge field couples the fermions and bosons to superpartners by exchange of new *sparticles*.
- ***Hope for discovery at LHC**:*

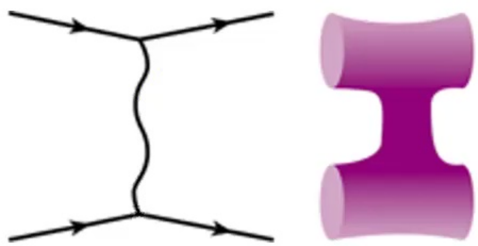


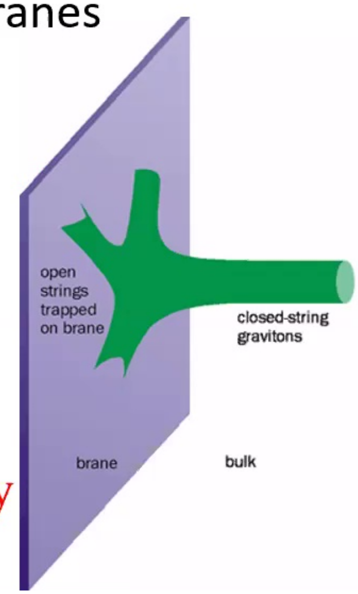



# Sparticles should have been discovered at LHC, unless…

The flood of precise data from astrophysics suggests that the gauge fields of nature may be more complex than the picture of the Standard Model + Higgs + Supergravity

*Example*: large extra dimensions from strings and branes






We need to seek ways to extend the reach for discovery to the highest feasible mass scales.

# Hadron colliders are the only tools that can discover gauge particles beyond TeV scale

- But predicting the energy for discovery is perilous.
- <u>Example</u>: after discovery of the *b* quark in 1977, we 'knew' there should be a companion *t* quark. But we couldn't predict its mass. Predictions grew dueing the 80's (with the limits) 20 $\rightarrow$40 $\rightarrow$80 $\rightarrow$120 GeV
- 4 $e^+e^-$ colliders were built with top discovery as a goal.
- Finally top was discovered at Tevatron – 175 GeV!
- In the search for new gauge fields, will history repeat?

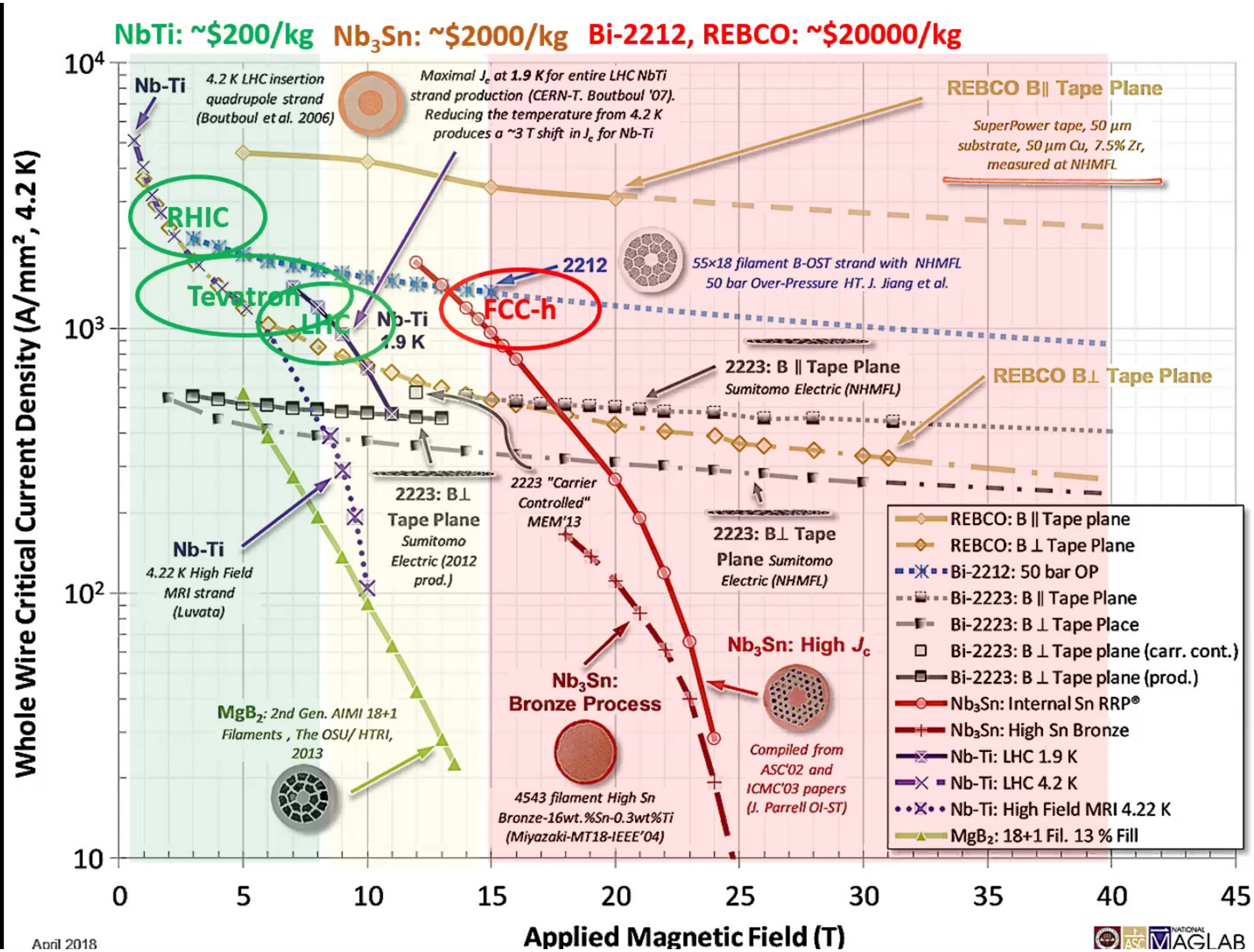
# The cost of a hadron collider is driven by two parameters

- The ring of superconducting dipoles that circulates the beams.
  - Choice of superconductor that can operate with high current at the design field
  - *In situ* heat treatment of windings for high-field s.c.
  - Control of the immense Lorentz forces ($\sim B^2$) that act on the windings

- The tunnel that safely contains the collider ring.
  - Strata of rock are layered, with layer thickness ~10-20 m and transitions from one rock type to another every few km.
  - Some rock types enable good tunneling (e.g. soft limestone)
  - Some rock types are expensive and dangerous to tunnel.

# So let's examine options for how to maximize the physics and minimize the cost of a hadron collider

- What is the minimum cost/TeV for superconducting dipoles?
- Can we identify tunnel sites where the entire tunnel could be bored in favorable rock types?
- Could we push to yet further with collision energy and luminosity *without a tunnel*?


NbTi: ~$200/kg Nb3Sn: ~$2000/kg Bi-2212, REBCO: ~$20000/kg
Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Maximal Jc at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in Jc for Nb-Ti
REBCO B∥ Tape Plane
SuperPower tape, 50 μm substrate, 50 μm Cu, 7.5% Zr, measured at NHMFL
RHIC
Tevatron
LHC
Nb-Ti 1.9 K
FCC-h
2212
55×18 filament B-OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al.
2223: B ∥ Tape Plane Sumitomo Electric (NHMFL)
REBCO B⊥ Tape Plane
2223: B⊥ Tape Plane Sumitomo Electric (2012 prod.)
2223 "Carrier Controlled" MEM'13
2223: B⊥ Tape Plane Sumitomo Electric (NHMFL)
Nb-Ti 4.22 K High Field MRI strand (Luvata)
Nb3Sn: High Jc
Nb3Sn: Bronze Process
MgB2: 2nd Gen. AIMI 18+1 Filaments, The OSU/ HTRI, 2013
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B ∥ Tape plane
REBCO: B ⊥ Tape Plane
Bi-2212: 50 bar OP
Bi-2223: B ∥ Tape Plane
Bi-2223: B ⊥ Tape Place
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Nb3Sn: Internal Sn RRP®
Nb3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
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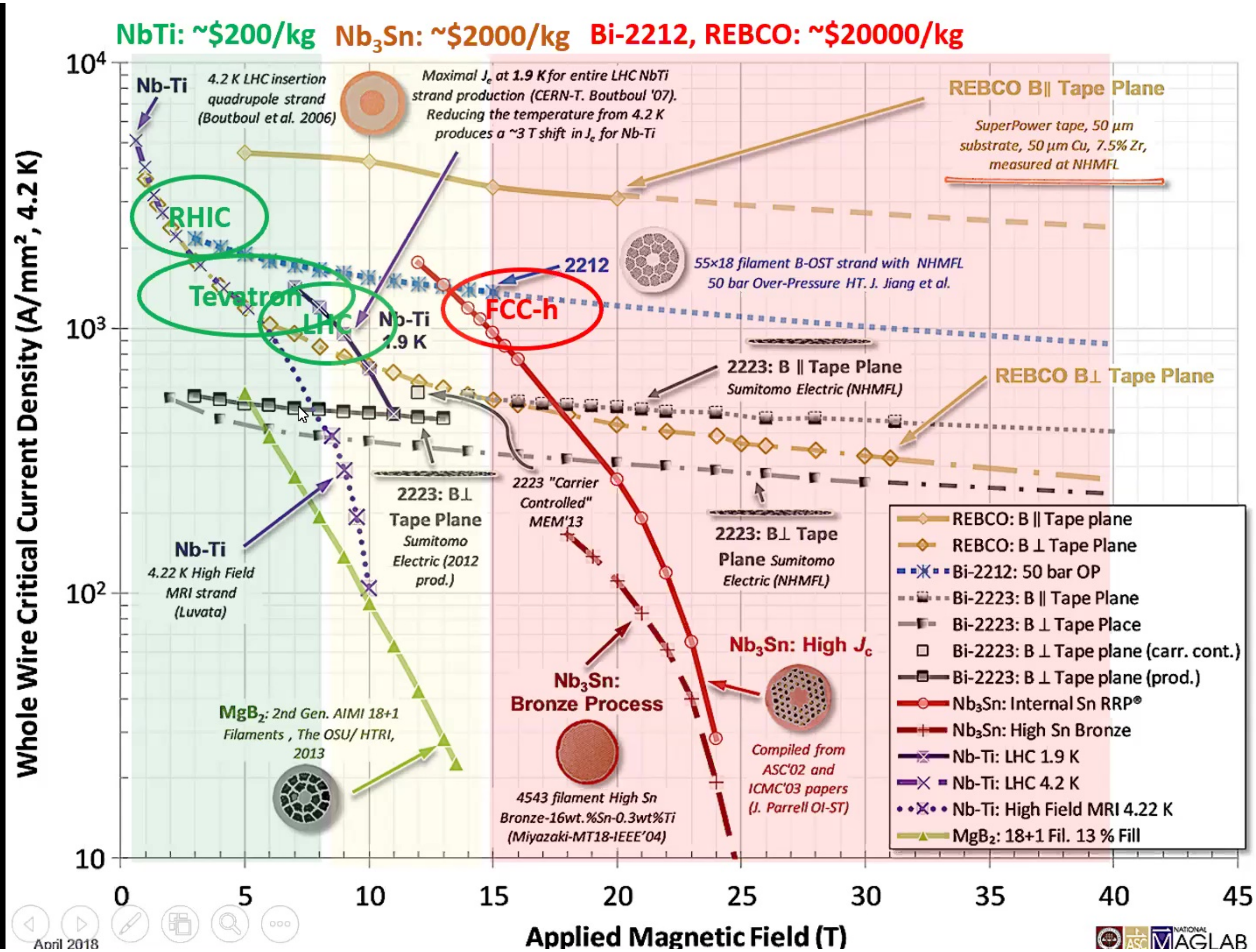
Nb-Ti: High Field MRI 4.22 K
MgB2: 18+1 Fil. 13 % Fill
April 2018
MAGLAB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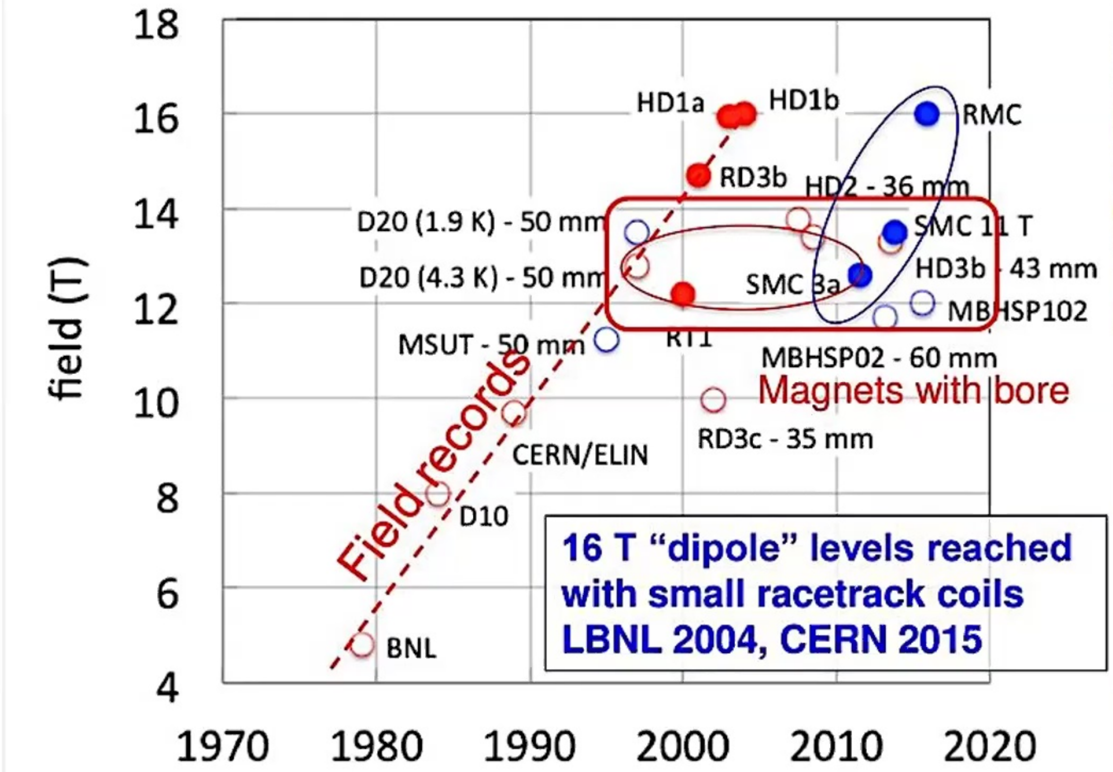
# Developments of 16 T dipoles to date




LBNL HD1

CERN RMC

No dipole with open end apertures (to pass beams) has yet been fabricated for 16 T.
Key challenges:
*cost of superconductor; immense Lorentz stress; bending compact end windings*

# CERN is beginning studies for a 100 TeV hadron collider in the Rhone Valley

100 km circumference – limited by the surrounding mountains and lake

16 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

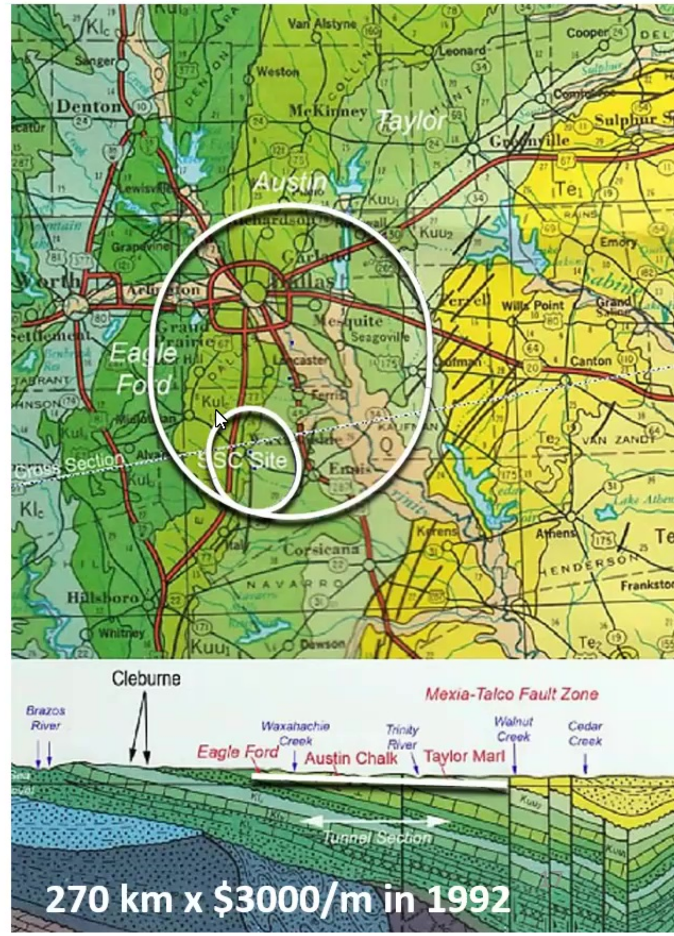
Ultimate reach for discovery of new gauge fields : 7.5 TeV → 40 TeV

***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

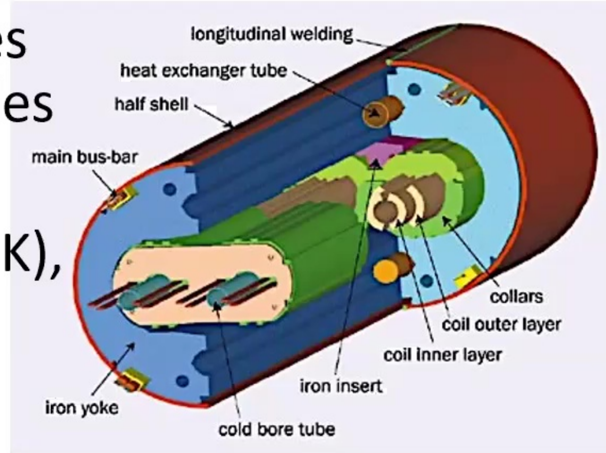
# Tunnel cost depends strongly upon the rock in which you tunnel

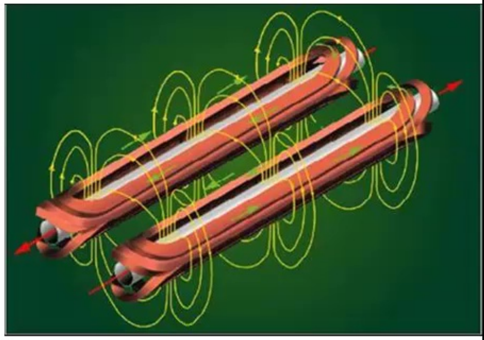

**There is already an 80 km circumference tunnel in Texas – the SSC tunnel was ~35% completed.**
The tunnel is contained in the Austin Chalk and the Taylor Marl – two of the most favorable rock types.
**Tunneling the SSC set world records for tunneling advance rate – 45 m/day. That record holds today!**
**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.**



# The ultimate NbTi dipole: LHC

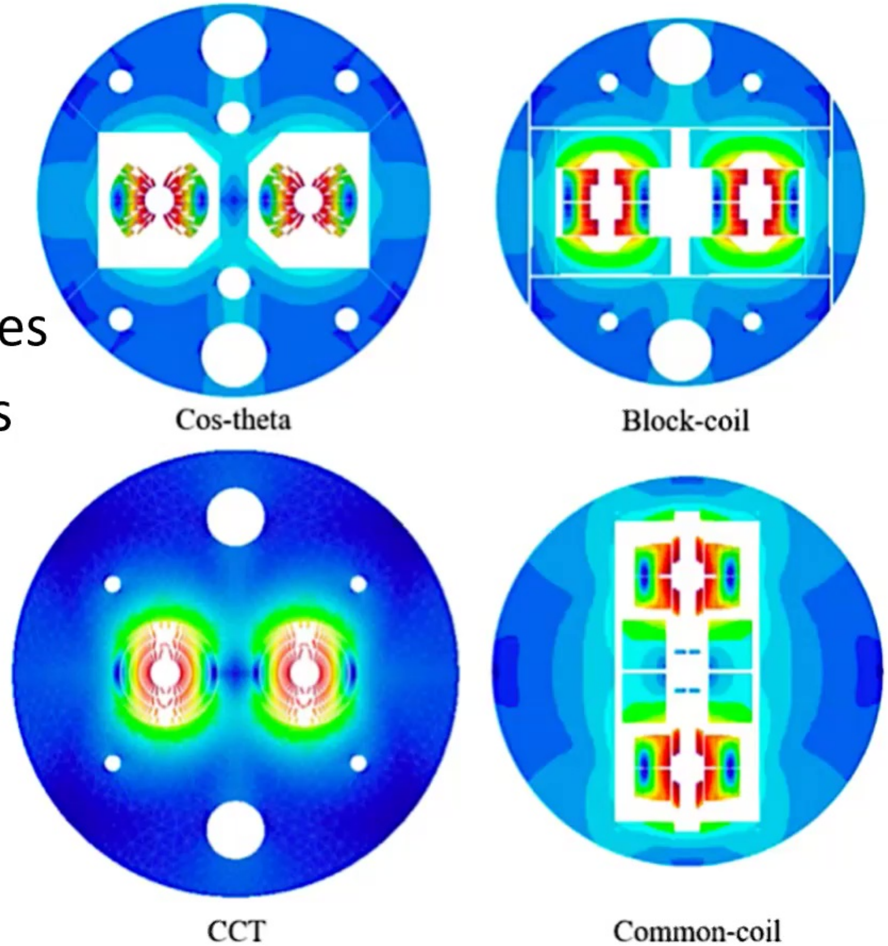
- The critical current of NbTi decreases with field, and is not useful for dipoles beyond ~6.5 T @ 4.2 K.
- By operating it in superfluid He (1.8 K), it can perform to ~8 T.
- But at a price: the superfluid He complex for LHC cost as much as the ring of superconducting magnets.



# R&D paths toward 16 T

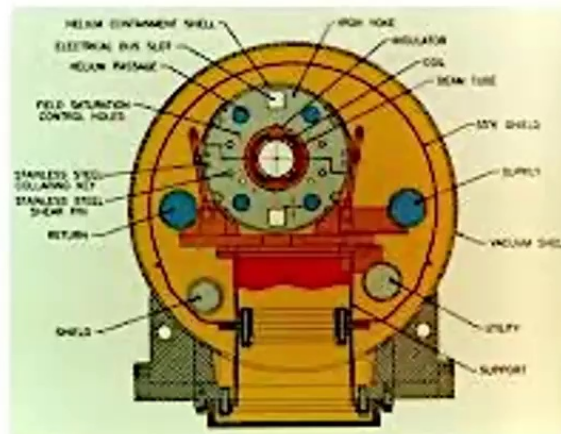
- Many winding geometries
- Many layers, many turns in the windings
- High stresses on fragile superconductor



# Optimum cost/TeV for a hadron collider: RHIC

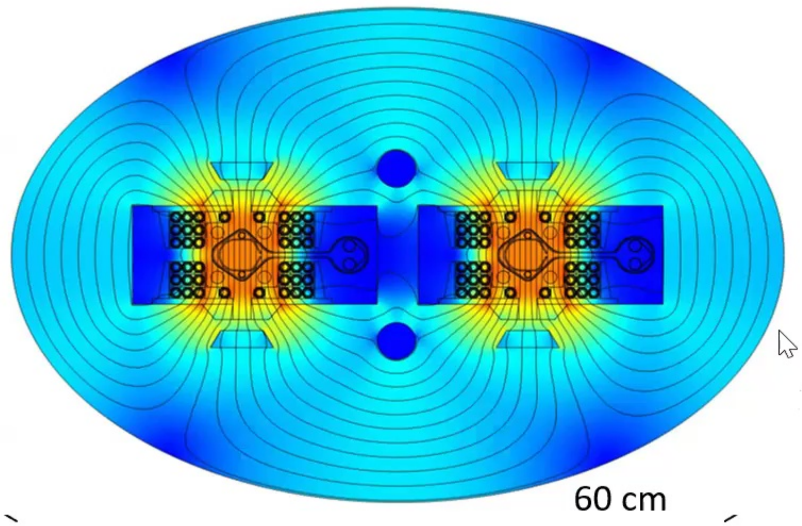
Cost drivers for superconducting dipoles:

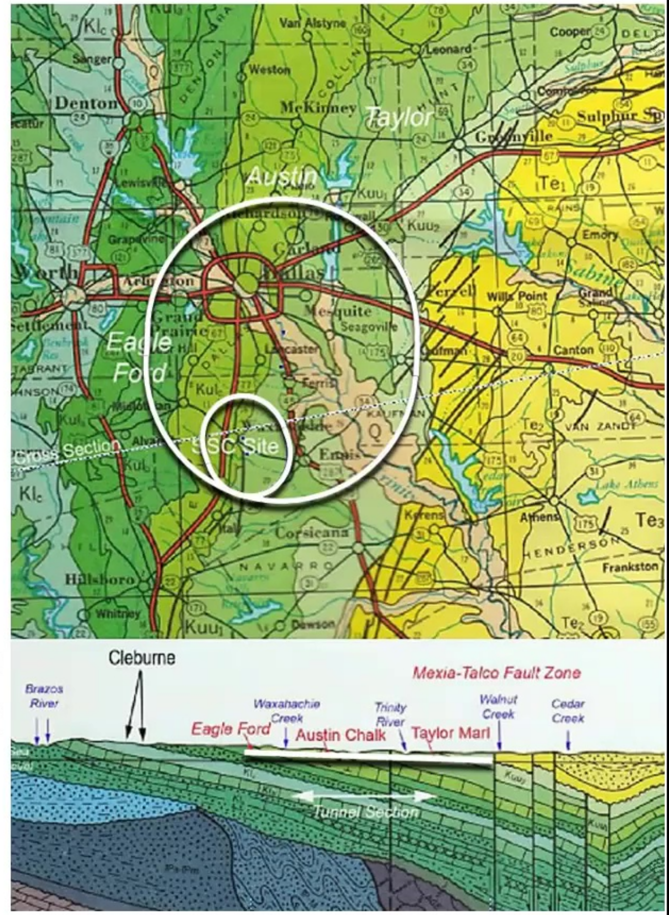
- # of turns of superconducting cable – touch labor
- Cost of superconductor




| | RHIC | LHC | FCC-h | Super-CIC |
|---|---|---|---|---|
| B (T) | 4 | 8 | 16 | 4.5 |
| #turns | 32 | 74 | ? | 20 |
| s.c. area ($cm^2$) | 6.3 | 39 | ? | 4.3 |
| TeV/100km | 30 | 60 | 120 | 34 |

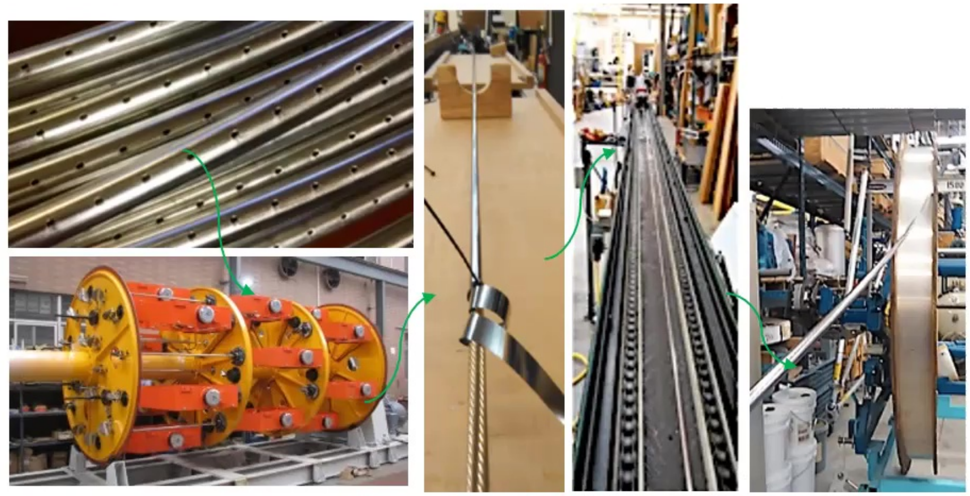
# Minimum-cost option for 100 TeV



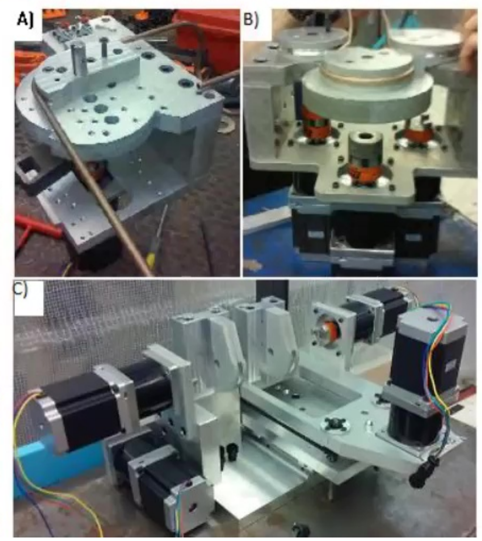




- 4.5 T dipole, NbTi cable-in-conduit windings
- 20 turns total, ends formed like bending a tube
- Side channel for synchrotron light stop @ 100K
- 270 km tunnel entirely within the Austin Chalk and Taylor Marl, tangent to the SSC tunnel as injector.

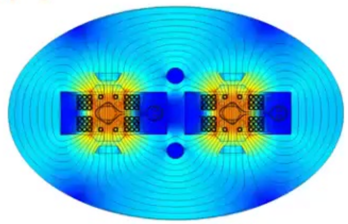
# Cable-in-Conduit makes the dipoles feasible and affordable

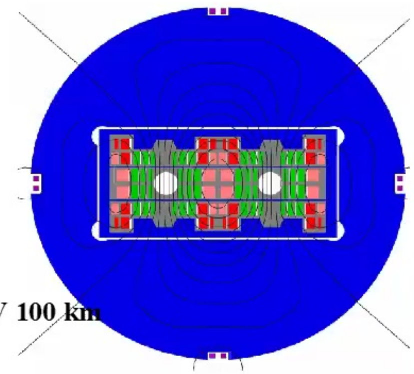


NbTi CIC cable is manufactured in industry in 150 m lengths.



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



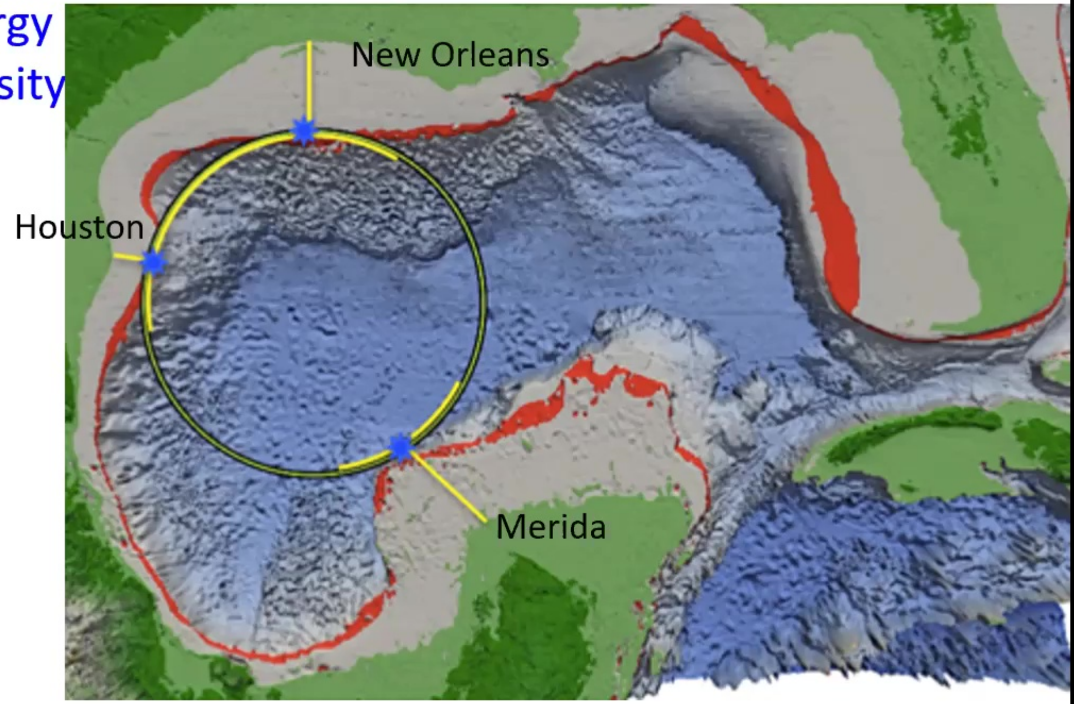


| | RHIC | LHC | 100 TeV 270 km | 100 TeV 100 km |
|---|---|---|---|---|
| Operating field | 3.4 T | 8 T | 4.5 T | 16 T |
| # Bores | 1 | 2 | 2 | 2 |
| # turns per bore | 32 | 74 | 20 | |
| Length | 9.4 m | 14.3 m | 20 | 20 |
| Superconducting wire/bore: NbTi | 92 kg | 380 kg | 124 kg | 390 kg |
| $Nb_3Sn$ | | | | 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



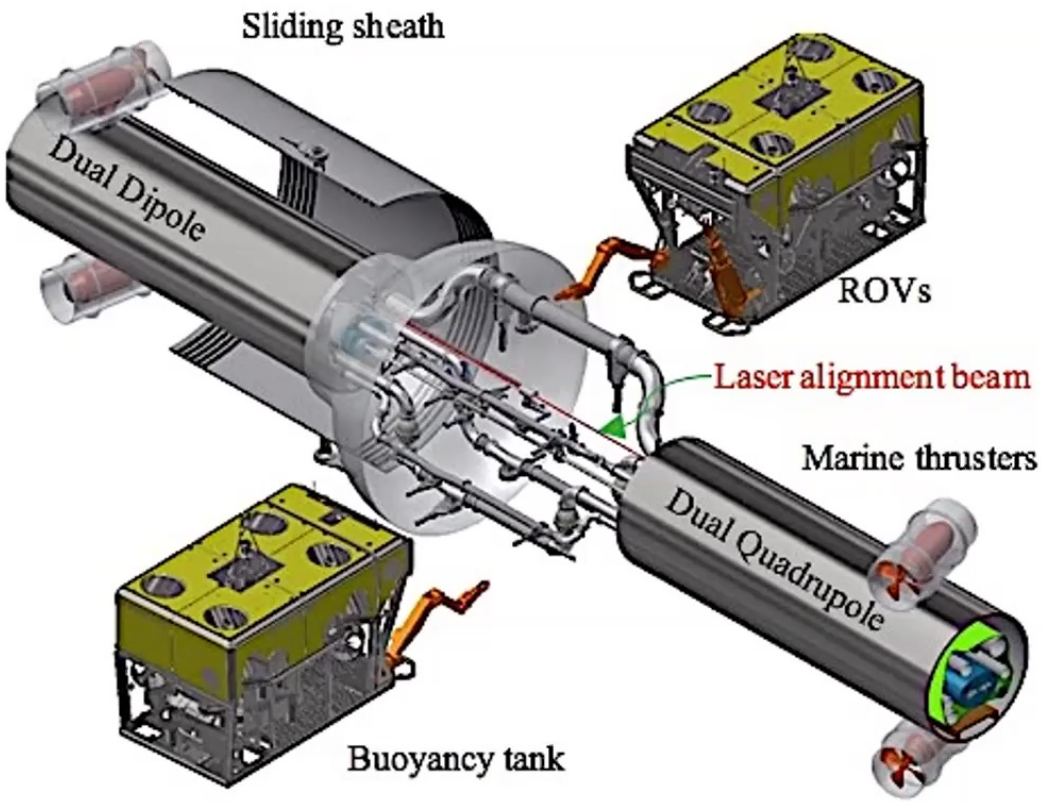

Configure collider ring from 5,000 half-cell segments: 300 m long, 1.5 m diameter

Pipeline with magnets inside = neutral buoyancy @ 100 m depth

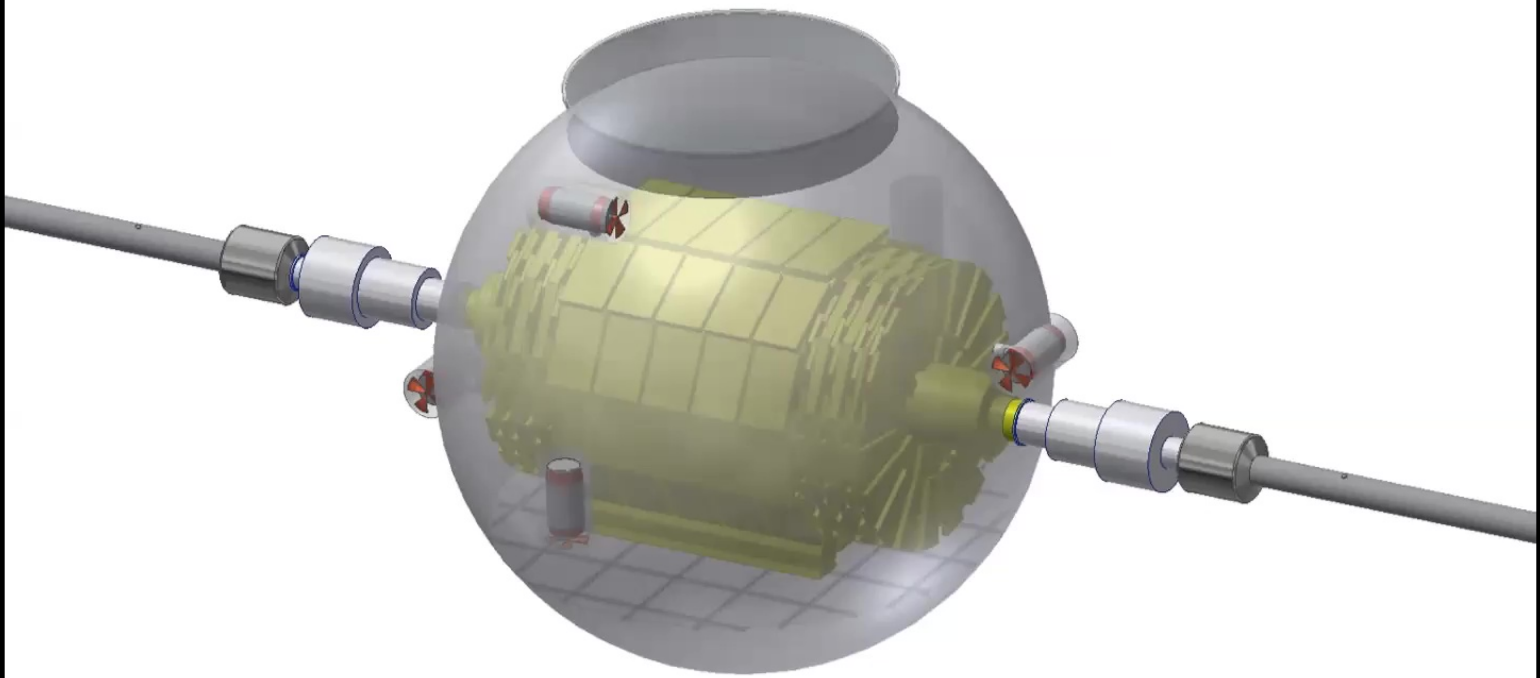
Segments connect with 3-valve interconnects

Install/remove segments using remotely operated submersibles (ROV)

# Connect/disconnect half-cell segments at interconnect hub



# Collider detector lives in a bathysphere

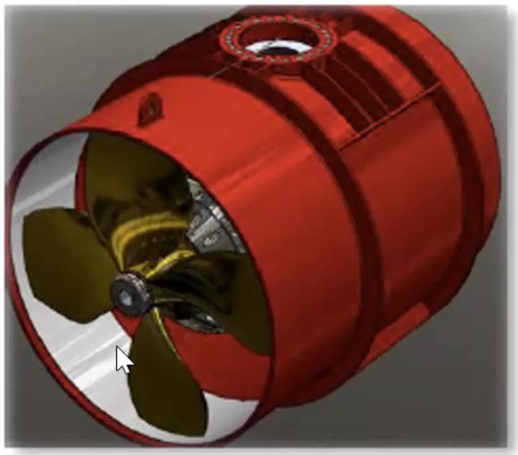


CMS detector has a mass of 14,000 tons, and lives in a 30 m diameter cavern at the LHC.
CMS inside a 30 m diameter double-hull spherical bathyspere would be neutral buoyancy, live at 100 m depth.

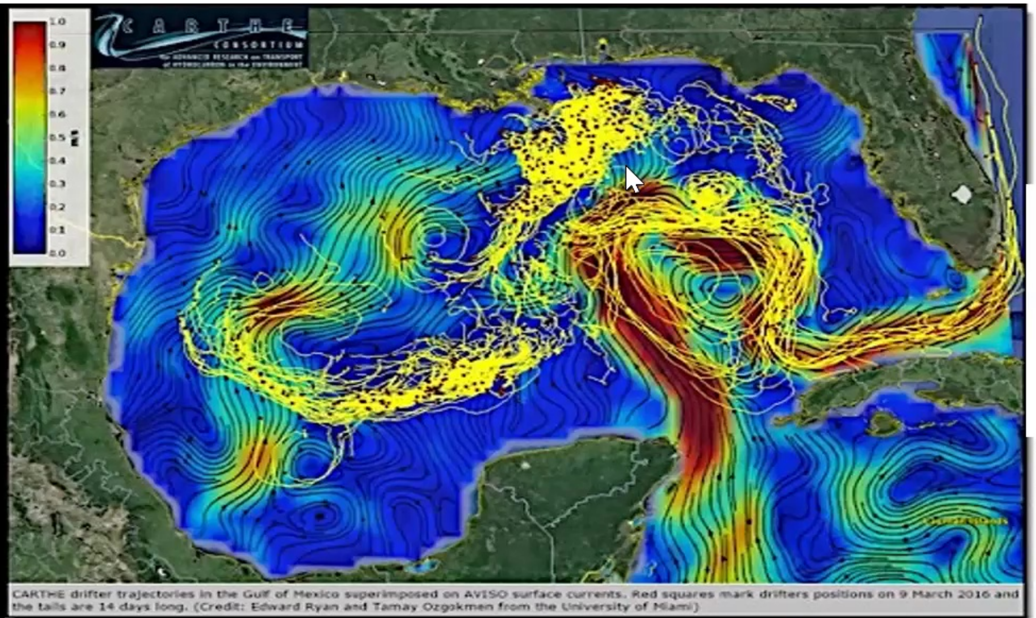
# Fit out a row of saddle-cranes along the long deck of a container ship.

- 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.

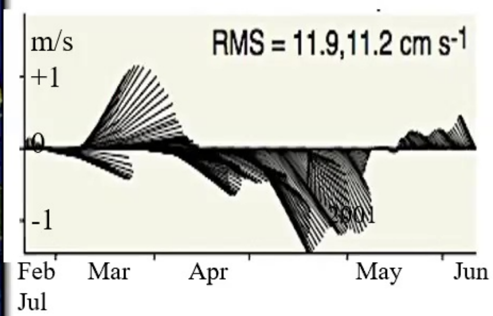
# The ring is held in position and alignment in the sea using active station-keeping and terrain-following.



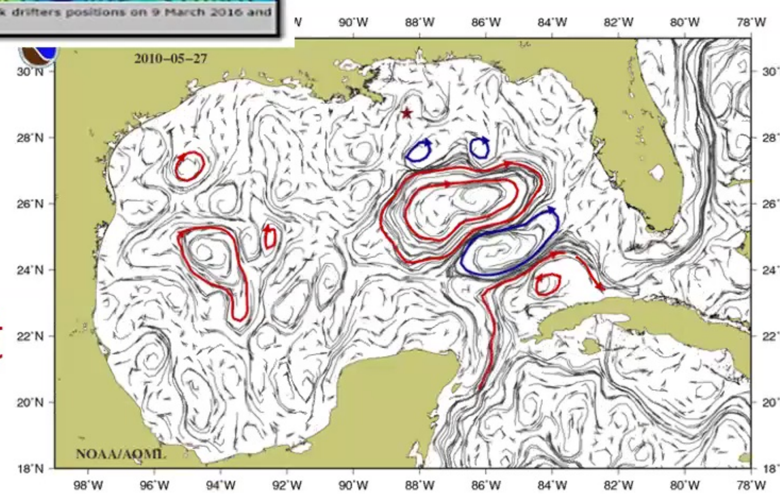
Marine thrusters are used routinely in marine power to precisely control the direction and thrust to propel or station-keep a vessel with precision.
One 50 kW thruster mounted adjacent to each half-cell hub can station-keep the position and geodesy of the ring to ~1 cm precision, even when a hurricane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

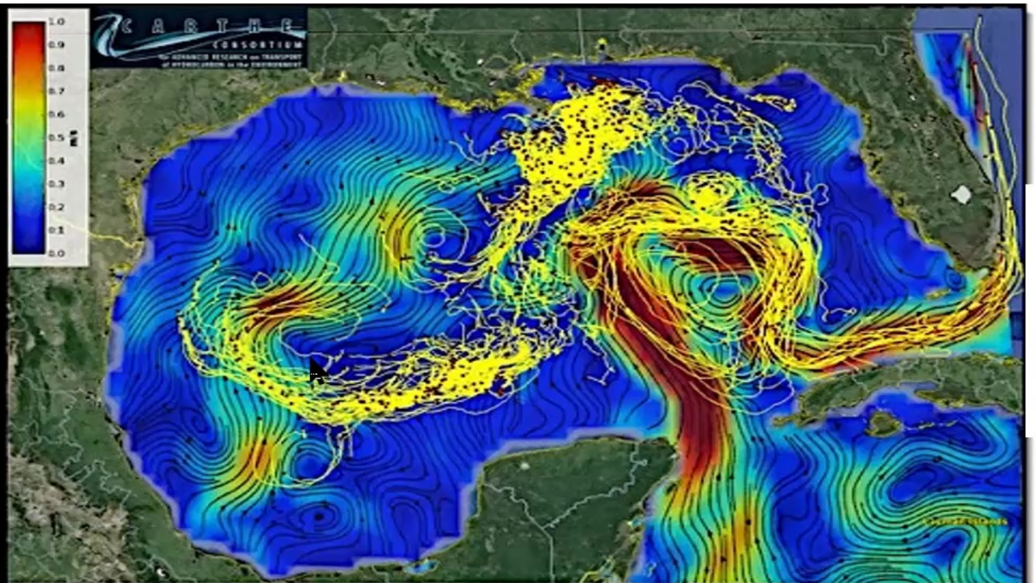


CARTHE drifter trajectories in the Gulf of Mexico superimposed on AVISO surface currents. Red squares mark drifters positions on 9 March 2016 and the tails are 14 days long. (Credit: Edward Ryan and Tamay Ozgokmen from the University of Miami)

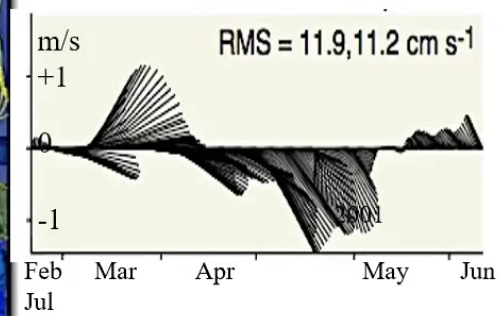



Gulf of Mexico has
Loop Current in the East,
eddies spin off to the West

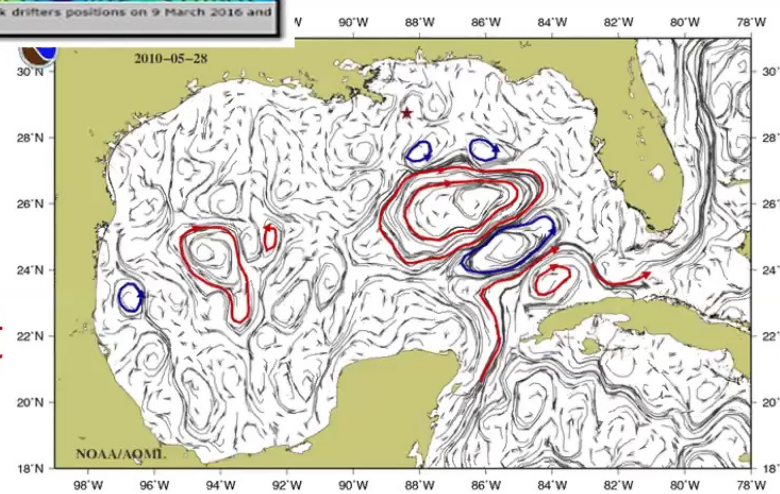




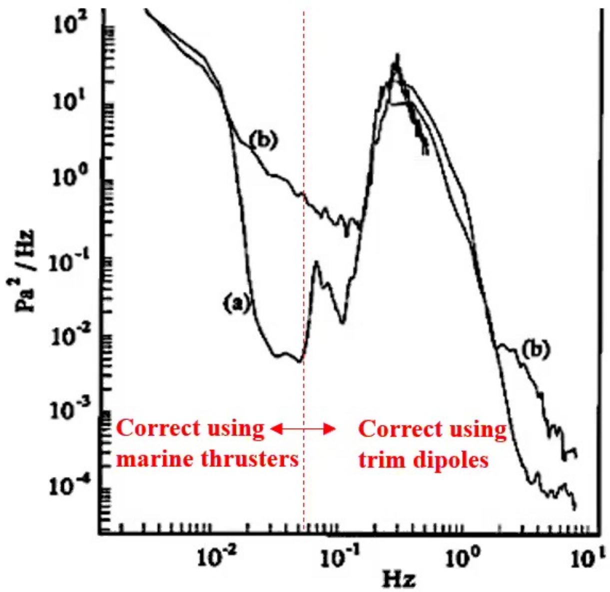

CARTHE drifter trajectories in the Gulf of Mexico superimposed on AVISO surface currents. Red squares mark drifters positions on 9 March 2016 and the tails are 14 days long. (Credit: Edward Ryan and Tamay Ozgokmen from the University of Miami)




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

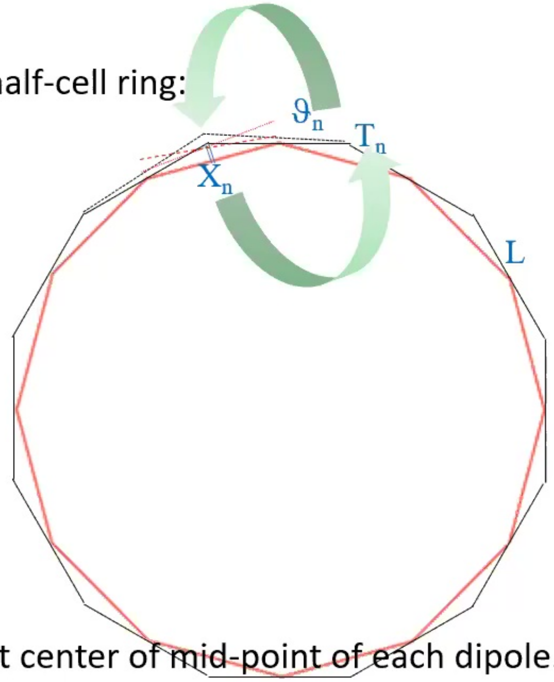


# Control Deflections of Ring Alignment using Laser Geodesy




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

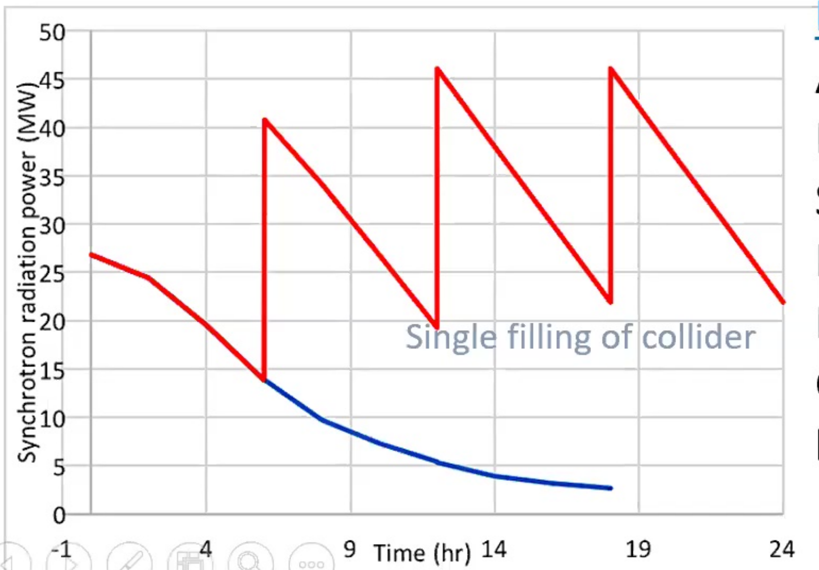
Illustration with 12 half-cell ring:




- 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 $\theta$,
  - 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

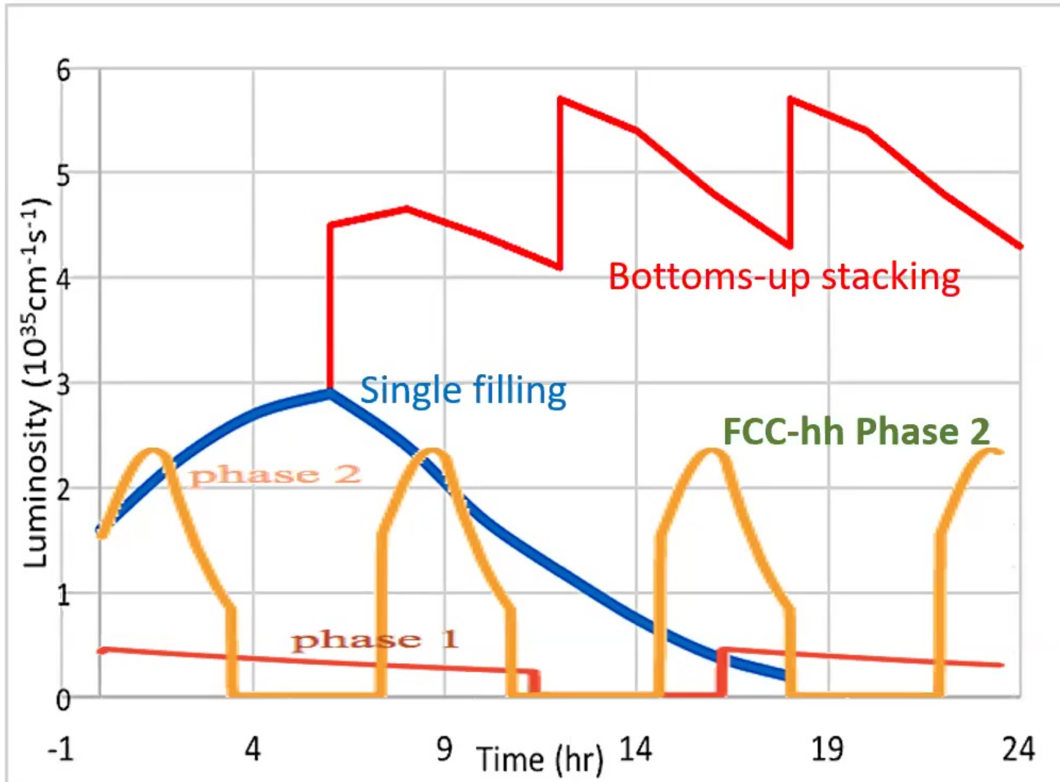
- Synchrotron damping increases the bunch brightness even as the bunch intensity decreases.
- In 6 hours of collisions:
  - *emittance decreases x6,*
  - *# protons decreases x2,*
  - *Luminosity doubles*




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.

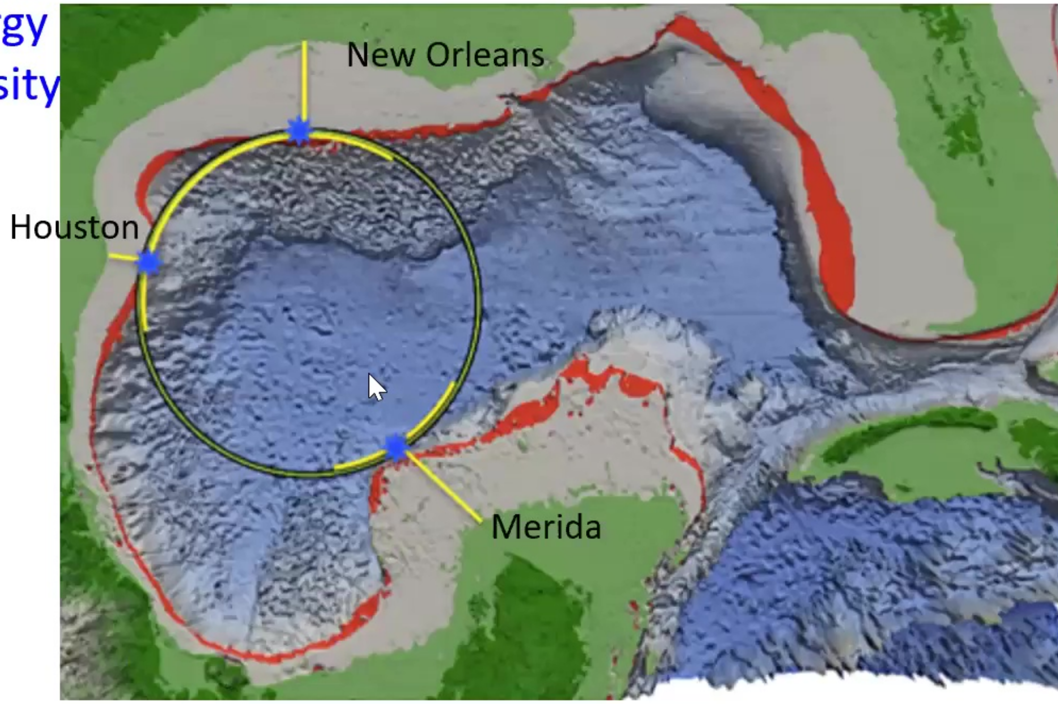
# Until now we have always had a credible prediction of a mass scale when we propose a new collider.

- 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.

# 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



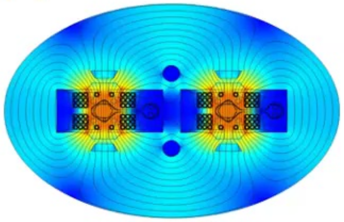

Configure collider ring from 5,000 half-cell segments: 300 m long, 1.5 m diameter

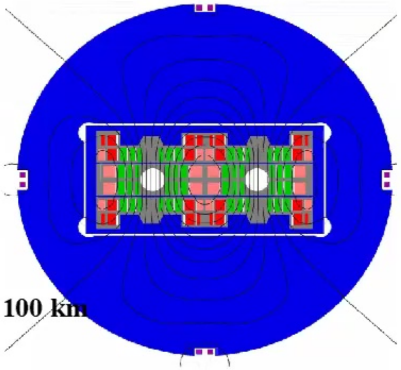
Pipeline with magnets inside = neutral buoyancy @ 100 m depth

Segments connect with 3-valve interconnects

Install/remove segments using remotely operated submersibles (ROV)

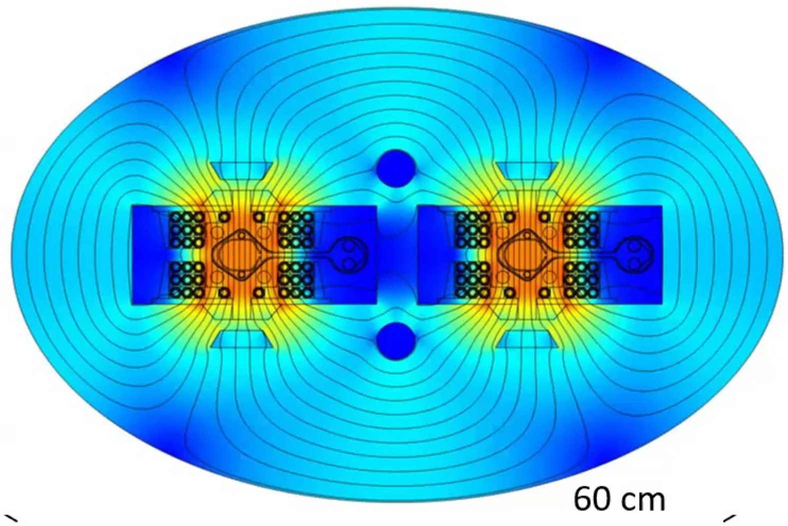
# Compare the costs for the tunnel and superconducting wire for a 100 TeV hadron collider:

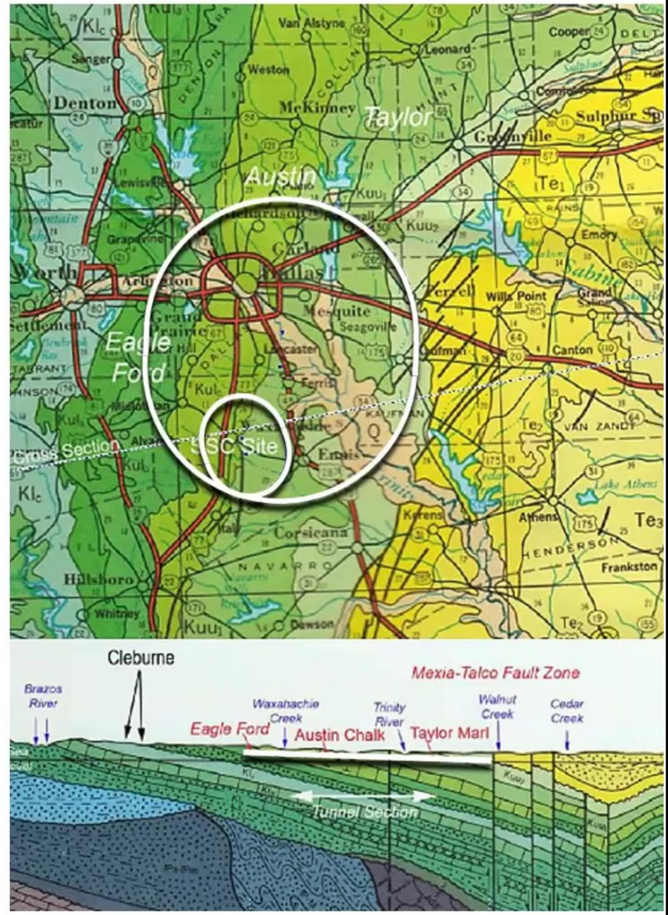




| | RHIC | LHC | 100 TeV 270 km | 100 TeV 100 km |
|---|---|---|---|---|
| Operating field | 3.4 T | 8 T | 4.5 T | 16 T |
| # Bores | 1 | 2 | 2 | 2 |
| # turns per bore | 32 | 74 | 20 | |
| Length | 9.4 m | 14.3 m | 20 | 20 |
| Superconducting wire/bore: NbTi | 92 kg | 380 kg | 124 kg | 390 kg |
| $Nb_3Sn$ | | | | 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 |

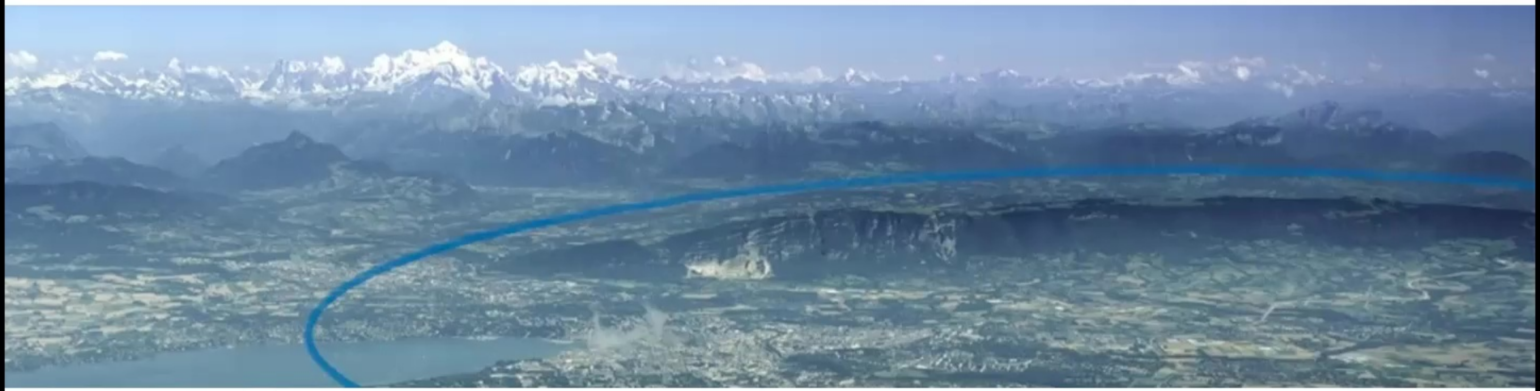
# Minimum-cost option for 100 TeV




- 4.5 T dipole, NbTi cable-in-conduit windings
- 20 turns total, ends formed like bending a tube
- Side channel for synchrotron light stop @ 100K
- 270 km tunnel entirely within the Austin Chalk and Taylor Marl, tangent to the SSC tunnel as injector.

# CERN is beginning studies for a 100 TeV hadron collider in the Rhone Valley



100 km circumference – limited by the surrounding mountains and lake

16 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