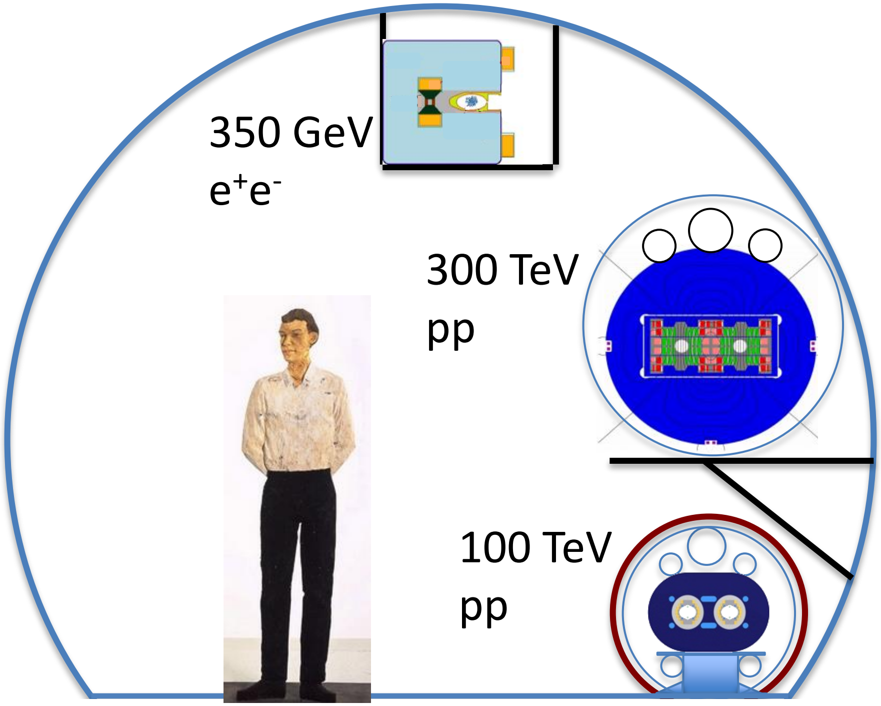
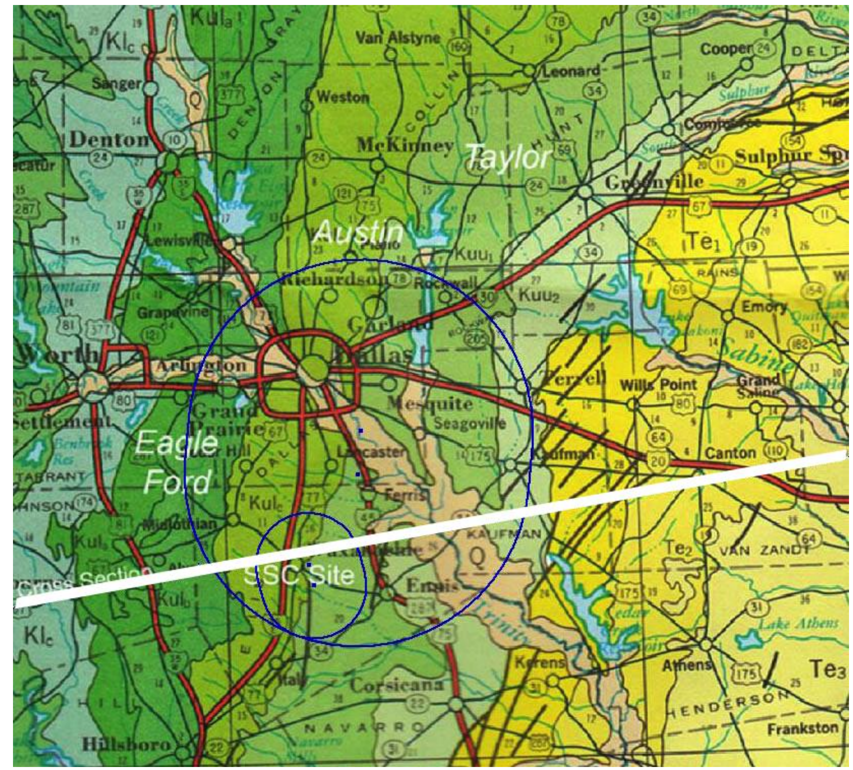
Large-circumference, Low-field Optimization of a Future Circular Collider





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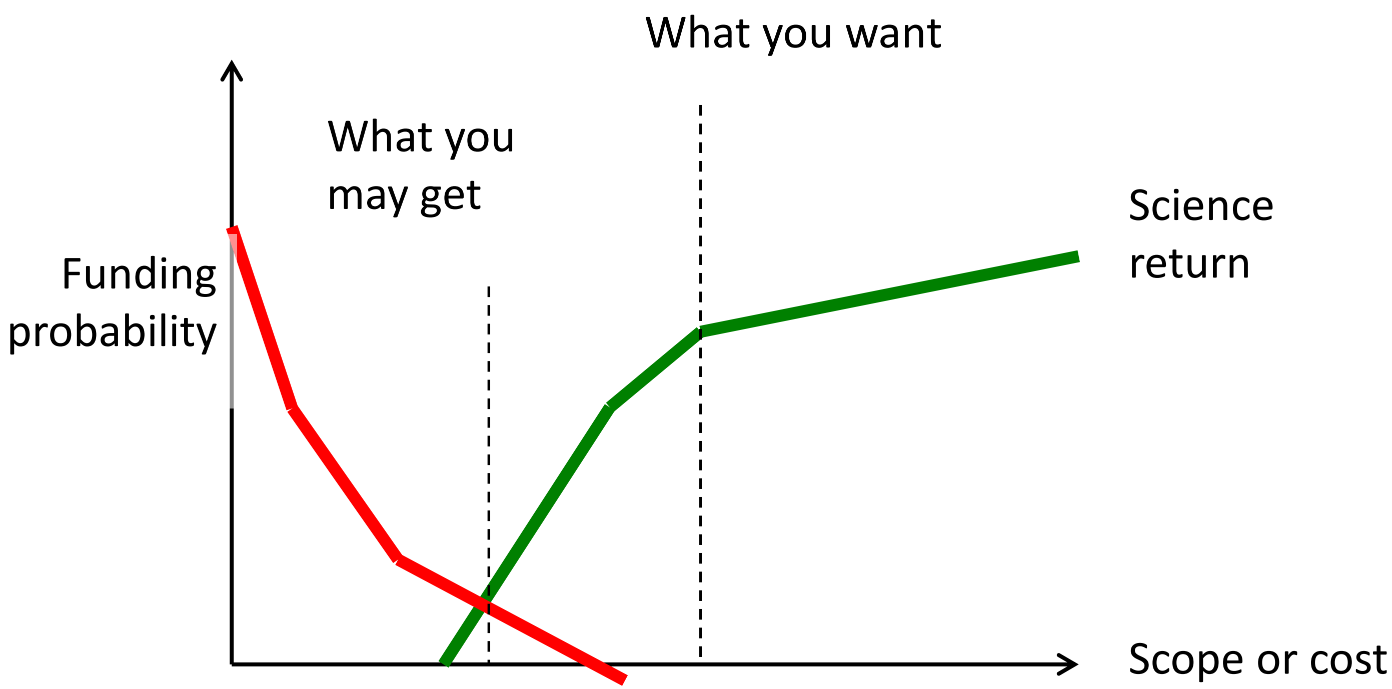
Present FCC design studies assume a tunnel circumference of 80-100 km.

- 80 km tunnel circumference is fine for a Higgs factory, and we have one we would like to offer you…
- 80-100 km circumference is a painful choice for a 100 TeV hadron collider because it pushes magnet technology to 15 T, and has very high synchrotron radiation into the aperture.
- **Is that really the most cost-effective choice? Suppose one proceeded with an 80 km Higgs factory, and sought a larger circumference for the next step to an ultimate hadron collider…**

One final word of warning:



It is imperative that the project be optimized for maximum benefit and minimum cost…

Cultural, Economic and Societal Impacts of big science projects

John Womersley

Cost drivers for FCC-hh

Capital cost:

Superconducting magnets **M(R)**

strong function of radius R

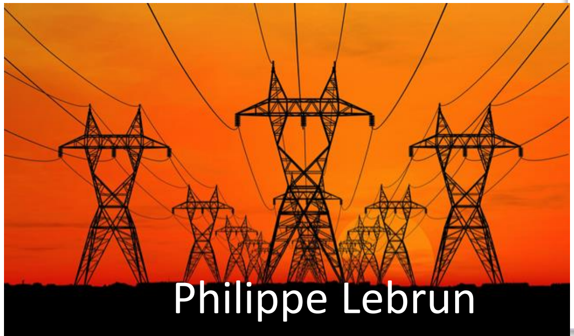
Tunnel **T(R)**

very high if it goes beyond geographic bounds, otherwise T(R) depends upon geology ~G/R

Operating cost:

Electricity dominated by refrigeration

of heat load **Q(R)**



Electrical power consumption

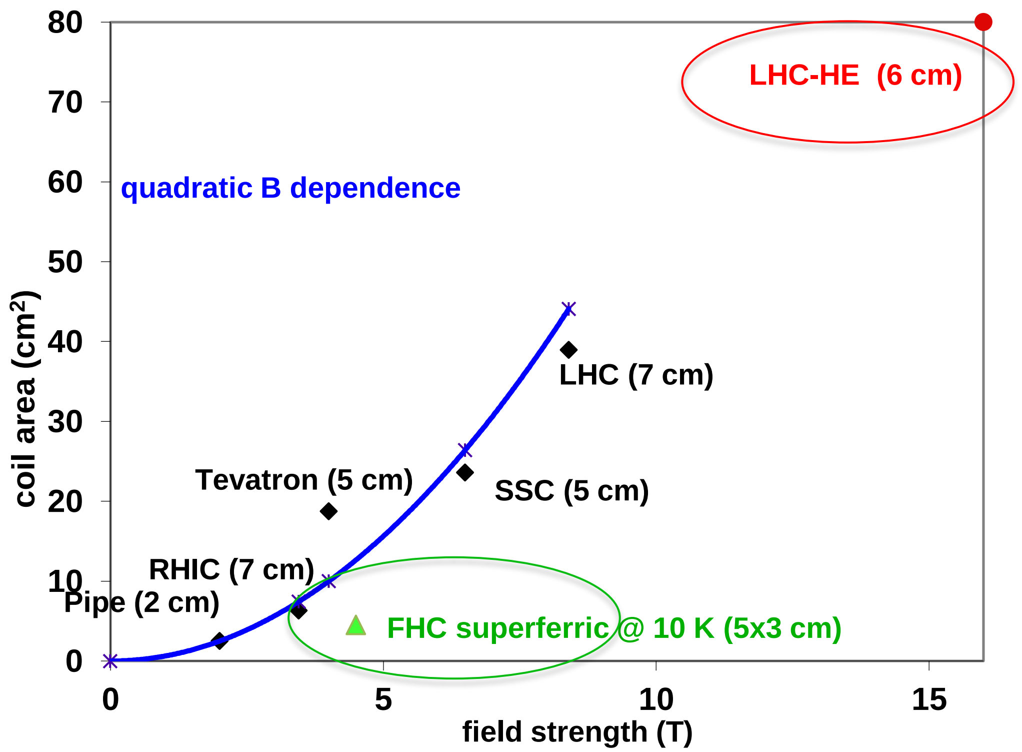
	Nominal [MW]	Standby [MW]
LHC	122	89
HL-LHC	141	101
CLIC 500 GeV	235	167
CLIC 1.5 TeV	364	190
FCC e+e-	**300?**	**100?**
FCC pp	**250?**	**150?**

Performance

- **Collision energy E(R)** -- providing we have enough luminosity to do the physics…

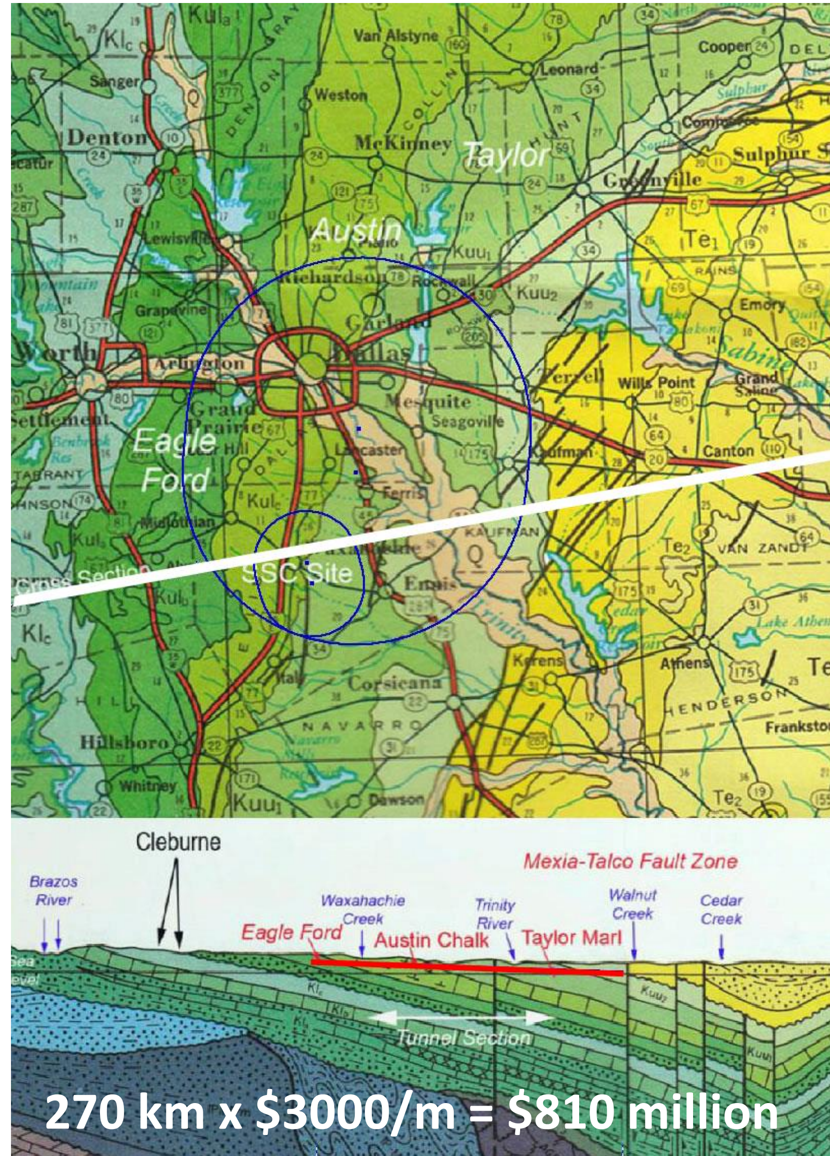
The cost and performance drivers all couple to the choice of radius R for the collider, which in turn is determined by the choice of magnetic field **R = E/B**

I am going to show you how the project cost and performance can be strongly driven by these parameters



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.



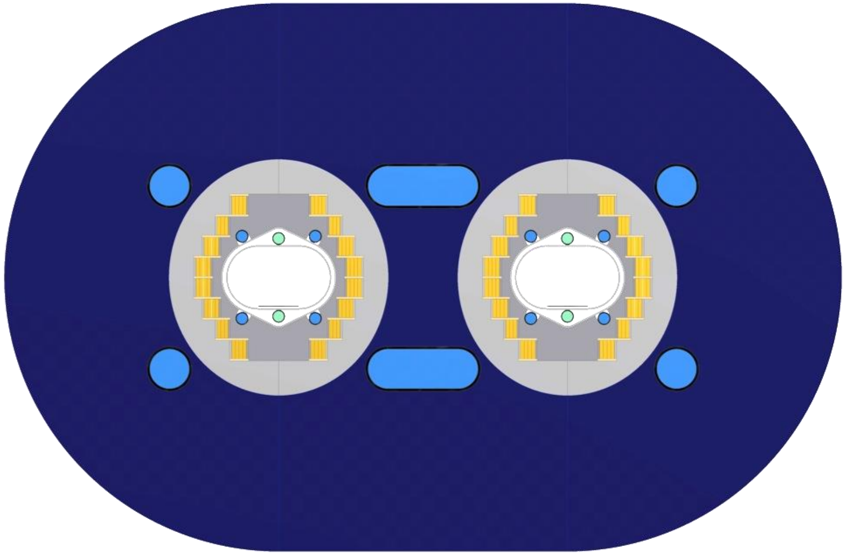
We have explored what the FCC collider complex would be like in a 270 km tunnel

100 TeV hadron collider requires 4.5 T magnets

- RHIC dipole (3.5 T @ 4.5 K) is simple, single-shell cos θ,
- We have designed block-coil cos θ for simple fabrication.

Option: Use Nb_3Sn, operate at 8-10 K

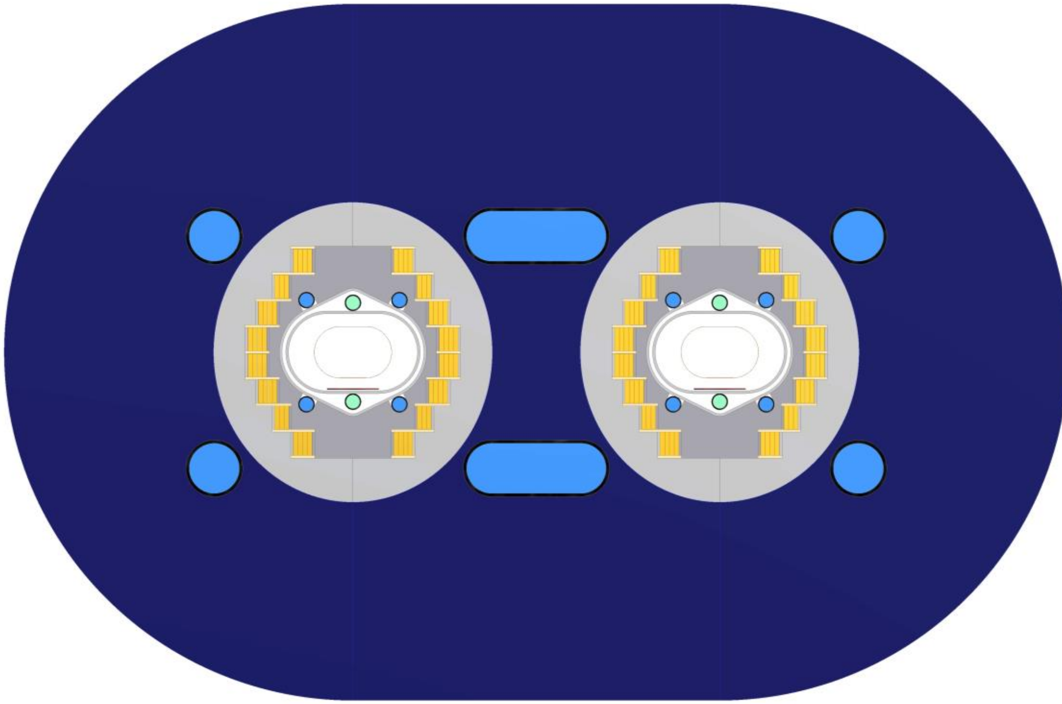
- eliminate liquid He from tunnel
- reduce helium inventory x7
- Reduce refrigeration power x2

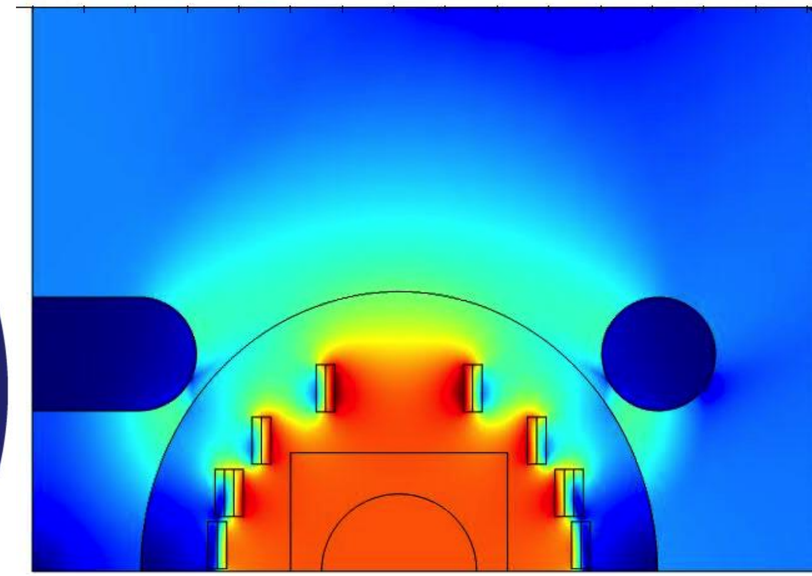


We have devised a way to combine the simplicity of the superferric block-coil dipole with the superconductor efficiency of cos θ.

- It uses 18 turns of 21 kA cable.
- It is a block-coil dipole, it is a cos θ dipole.
- Nb_3Sn version operates at 8 K
  - 2x less refrigeration, 7x less He, 7x more stability
  - But 3x conductor $
- Total cross-section of superconducting strand in one dipole is 4.5 cm^2. Compare to 40 cm^2 for LHC, >80 cm^2 for 15 T.
- 2300 tons of superconductor for 270 km double-ring.

Block-coil cos θ Collider Dipole





All multipoles are ~10^{-4} cm^{-n} for 1-4.5 T.

Dipole field	5.8	T
Operating temp	8	K
Number of turns	18	
Bore Field	4.5	T
Cable current	20.6	kA
J_c @ 5.8T 8K	3423	A/mm^2
Strand diameter	1.0	mm
Strands/cable	16	
Stored Energy	45.6	kJ/m
Inductance	0.215	mH/m

It is a block-coil dipole:

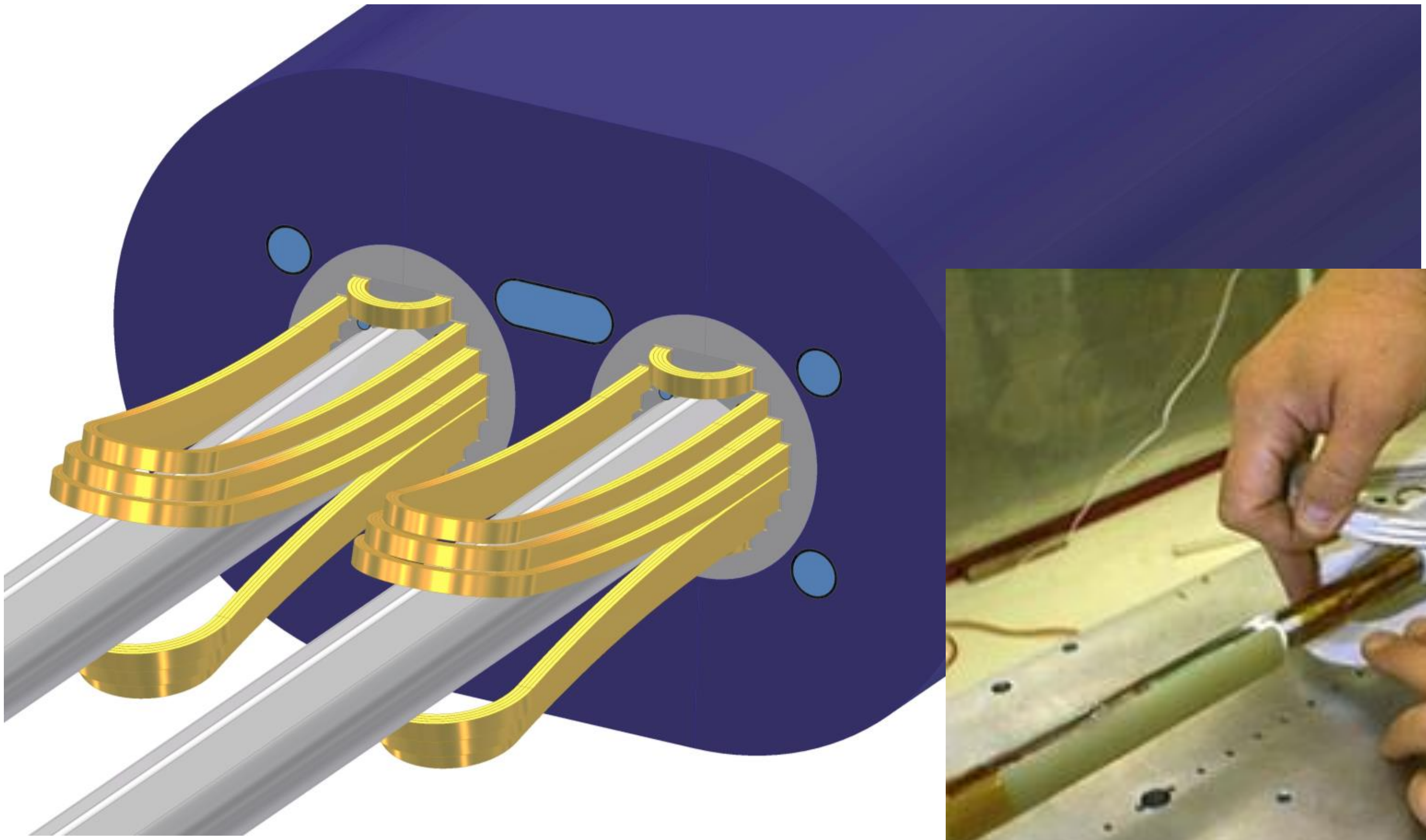
all layers wound as racetrack pancakes
low AC losses – fast ramping

It is a cos θ dipole:

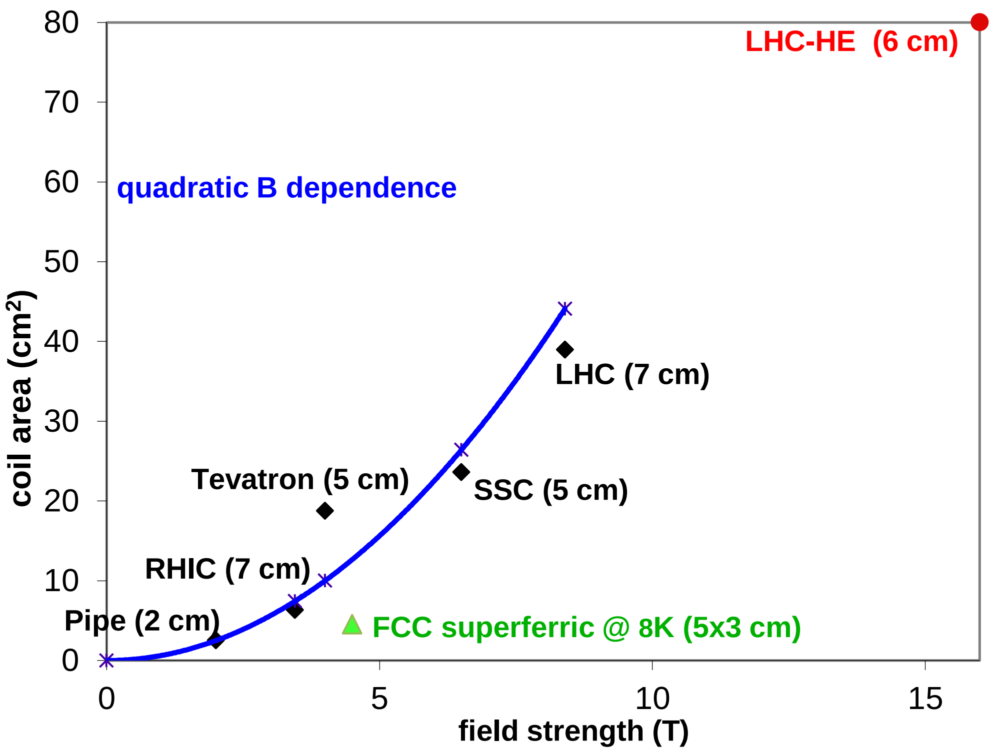
minimum quantity of superconductor

The superferric dipole coils can be wound as flat pancake racetracks, then flare the ends

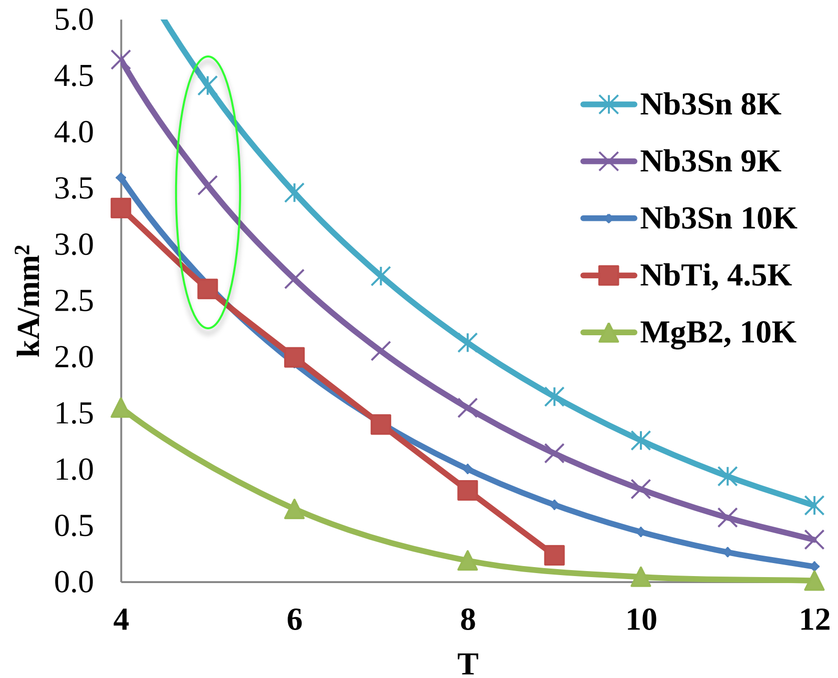
Simple to fixture, Simple to build.



Superconductor cross-section vs. field for example collider dipole designs



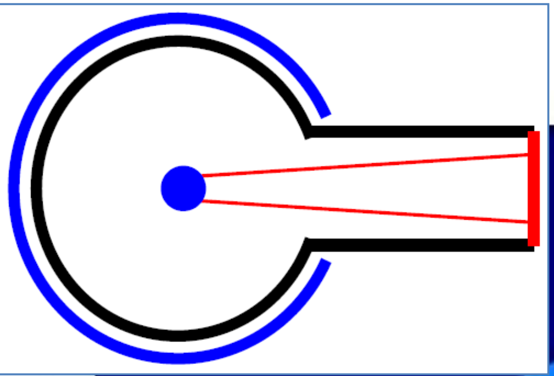
Nb$_3$Sn@8K ≅ 1.8x NbTi@4.5K

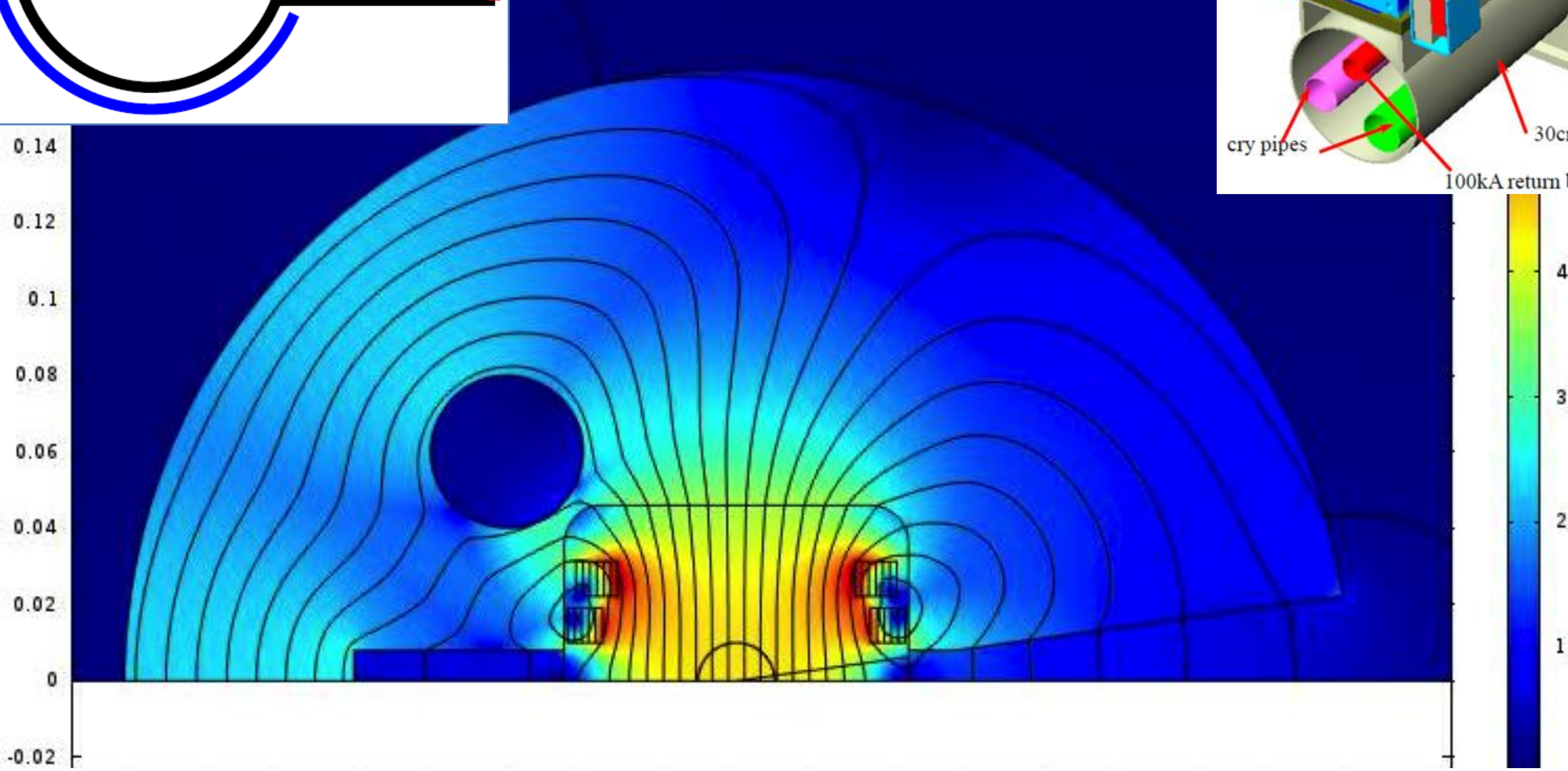


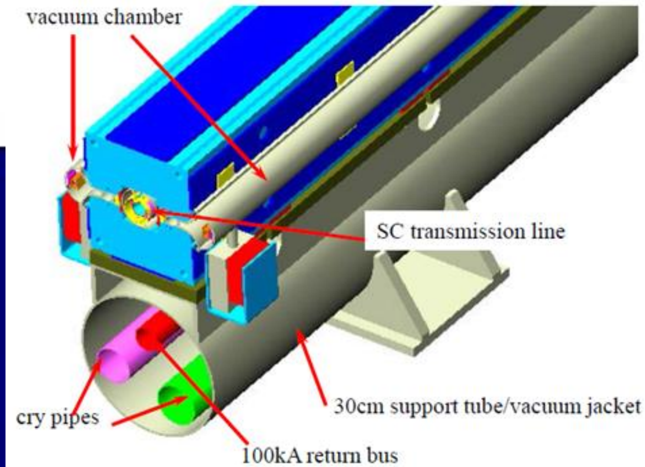
The dipole can be built with either NbTi@4.5K, or Nb$_3$Sn@10K with 8 cm^2 superconductor, or Nb$_3$Sn@8K with 4.5 cm^2 superconductor.

Choice will balance issues of coil fabrication (heat treat vs. none, stability, refrigeration costs.

Superferric 4.5 Tesla dipole can be opened to a C geometry to let the heat out…



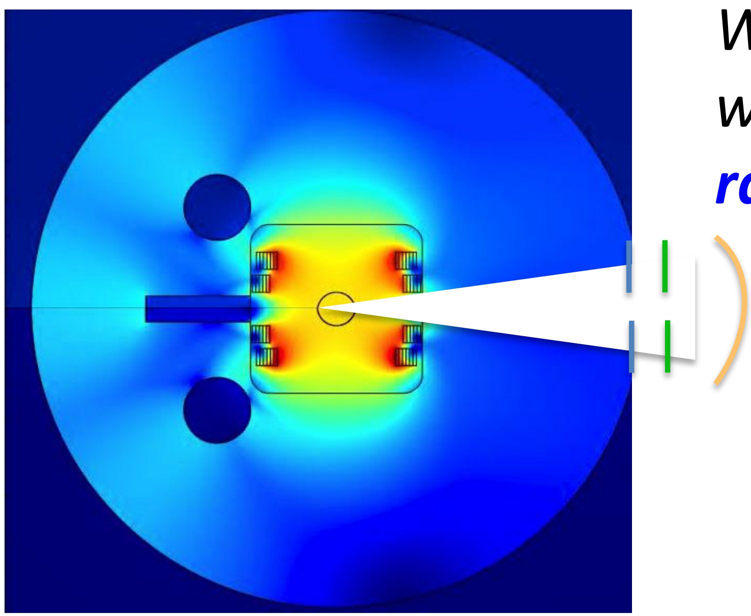




The C geometry requires 5.5 cm^2 superconductor vs. 4.5 cm^2 for block $\cos\theta$.

Refrigeration power depends strongly upon the Carnot efficiency: $Q(T) = (300/T)^n$

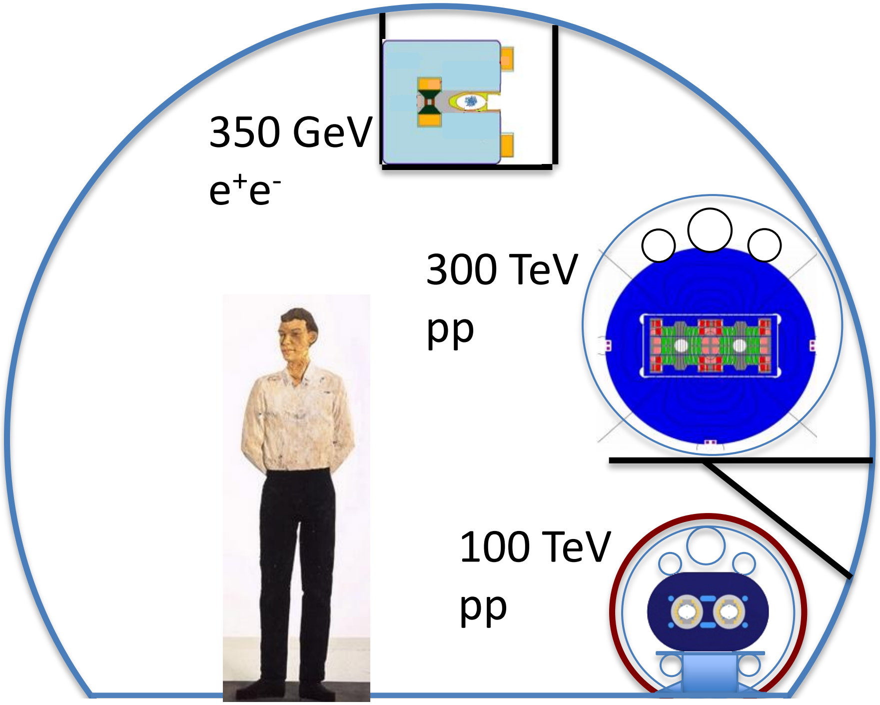
- Refrigeration removes synchrotron radiation heat at an intermediate temp T_S ~ 60K,
- Cold mass heat at T_C = 2K, 4K, 8K
- **The choices of T_S, T_C determine Q…**



*With B = 5 T, we can make a C dipole, in which **we can bring the synchrotron radiation out and capture at ~room temp.***

Parameters of the hadron colliders for medium and large circumference

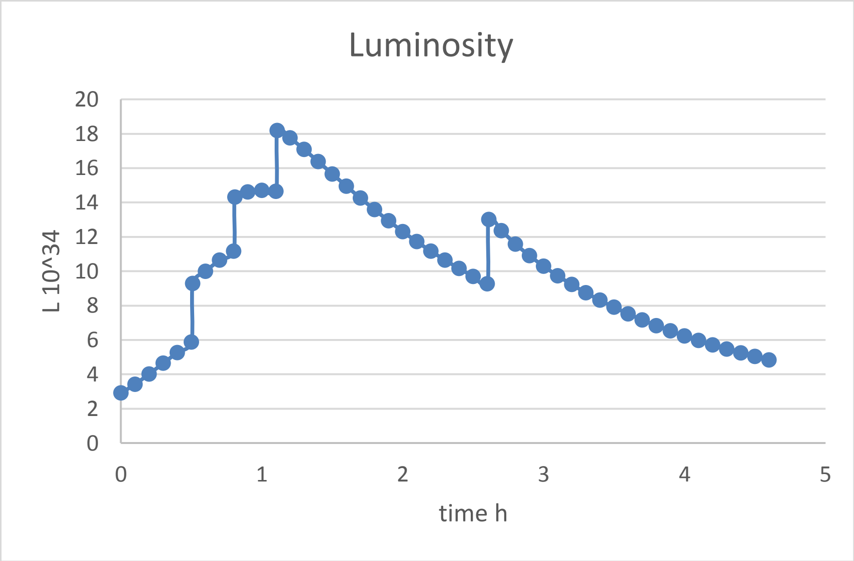
	hadron collider			
Circumference	**100**	**270**		km
Collision energy	**100**	**100**	**300**	TeV
Dipole field	15	4.5	14.5	T
Luminosity/I.P.	5	5	10	10^{34} cm^{-2}s^{-1}
b*	110	50	100, 10	cm
Total synch. power	4.2	1.0	34	MW
Critical energy	4.0	1.0	28	keV
Synch power/meter/bore	26	2	80	W/m
Emittance damping t	1	19	.66	h
Luminosity lifetime	18	20	3.7	hr
Energy loss/turn	4.3	1.3	114	MeV
RF accel. voltage:	100	50	250	MV
Acceleration time		.42	.25	h
Bunch spacing	50	25	25	ns
Beam-beam tune shift	.01	.01	.01	
# IPs	2+2	2+2	2+2	
# particles per beam	100	220	86	10^{13}
Injection energy	>3	15	50	TeV
Superconducting temp.	4.2	10	4.2	K

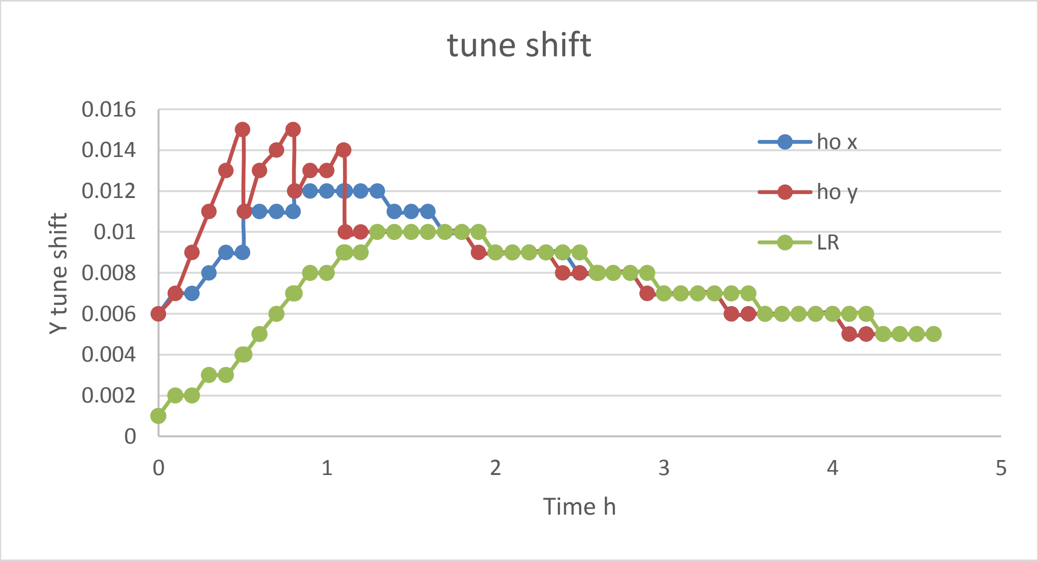


- For 100 km circumference, luminosity will be limited by refrigeration of synchrotron heat.
- For 270 km circumference, synchrotron radiation power is reduced x3.
- **If we use magnets with Nb_3Sn@10K, refrigeration power will not limit luminosity…**

Luminosity leveling for 300 TeV FHC

- Synchrotron damping dominates the evolution of tune shift and luminosity for the 300 TeV case.
- Beam begins x/y symmetric, and damps in y within ~30 min – y tune shift increases, luminosity increases
- Program β_y to maintain ~constant ξ_y ~ .01





So let's return to cost:

	5 Tesla		15 Tesla	
	Block - $\cos\theta$	Block - C	Block coil	
Magnets - superconductor	4.5	5.5	80	cm^2
Tunnel	270	270	100	km
Synchrotron rad. heat	100	300	60	K

and performance:

R = 270 km:

FCC-hh1: 5 Tesla: 100 TeV $5\times10^{34}\ cm^{-2}s^{-1}$

and for our children…

FCC-hh2: 15 Tesla: 300 TeV $10^{35}\ cm^{-2}s^{-1}$

For a cost/performance optimization, it is unwise to lock the ring circumference

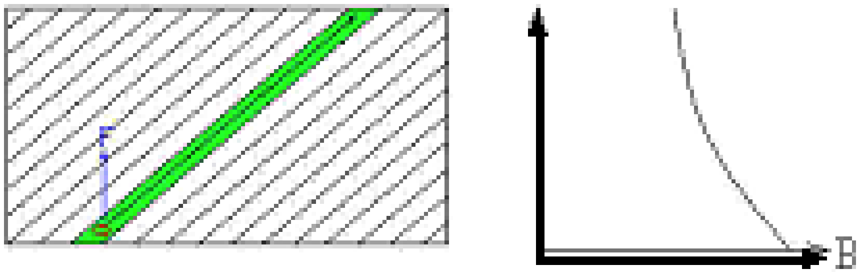
- I have presented a quantitative example that there is a site where a 270 km circumference can stay in favorable rock for world-mimimum tunnel cost.
- I have shown that 4.5 Tesla dipoles can provide ample aperture and open geometry for synch rad, with an amount of superconductor that is 15 times less than 15 T.
- I have shown that the 4.5 T dipole can operate at T_C = 8 K, doubling its Carnot efficiency,
- I have shown that the C geometry can remove synch rad at T_S ~ 200 K, tripling its Carnot efficiency.
- And the larger circumference will enable our children to bring 15 Tesla to triple the energy for a new generation…

We need to truly optimize cost and performance.

The 100 TeV hadron collider needs a rapid-cycling injector.
The 5 T 10 K dipole is an excellent candidate.
Example: 5 TeV injector in LHC tunnel

Induced coupling currents between adjacent strands in cable when it is oriented face on to time-changing flux.

Cos θ dipole:
Flux is face-on to cables



Block-coil dipole:
Flux is edge-on to cables

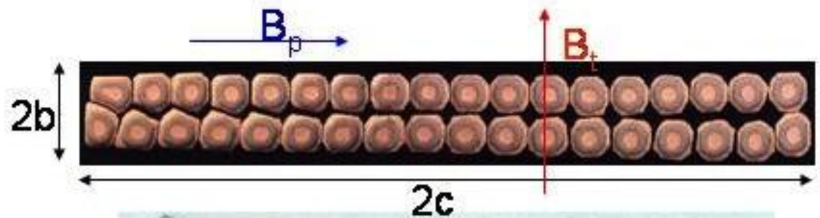
Gradient force acting on a magnetization current loop (red) in a sub-element of a) a face-on cable in a cos θ or common-coil dipole; b) an edge-on cable in a block-coil dipole.

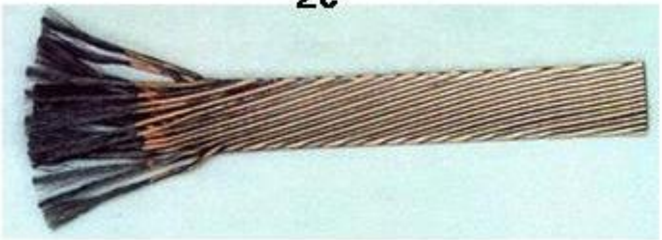
Coupling currents can be controlled by orienting cable ⎸⎸ field, coring cable

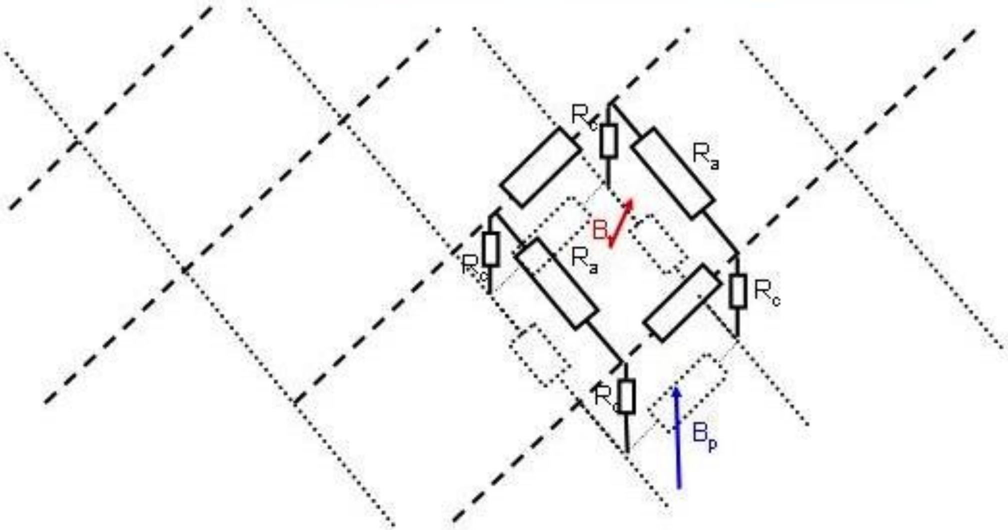
$$P_{tc} = \frac{N(N-1)}{120R_c} \cdot \dot{B}_t^2 \cdot p \cdot \frac{c}{b}$$

$$P_{pa} = \frac{1}{8R_a} \cdot \dot{B}_p^2 \cdot p \cdot \frac{b}{c}$$

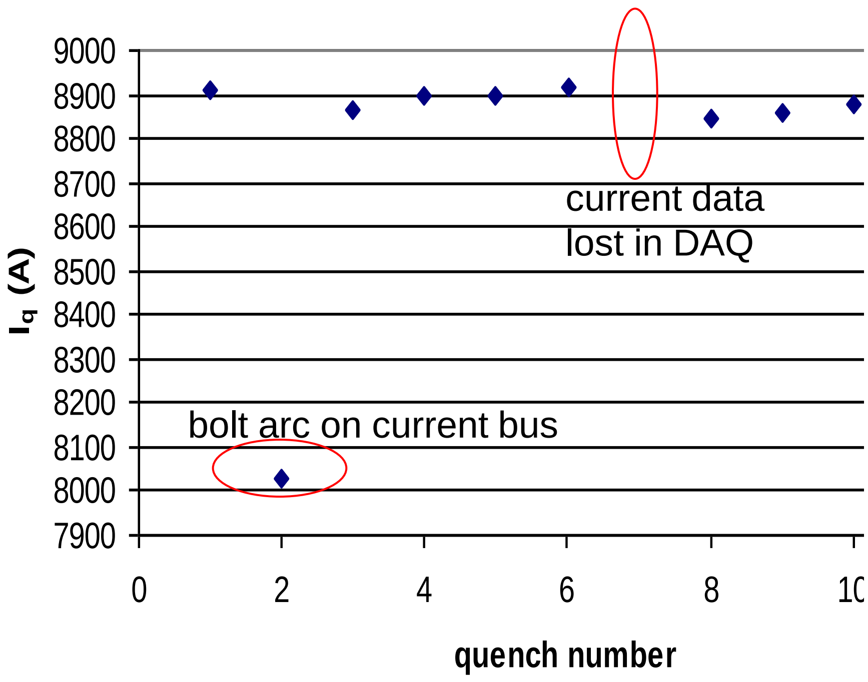
$$P_{ta} = \frac{1}{6R_a} \cdot \dot{B}_t^2 \cdot p \cdot \frac{c}{b}$$

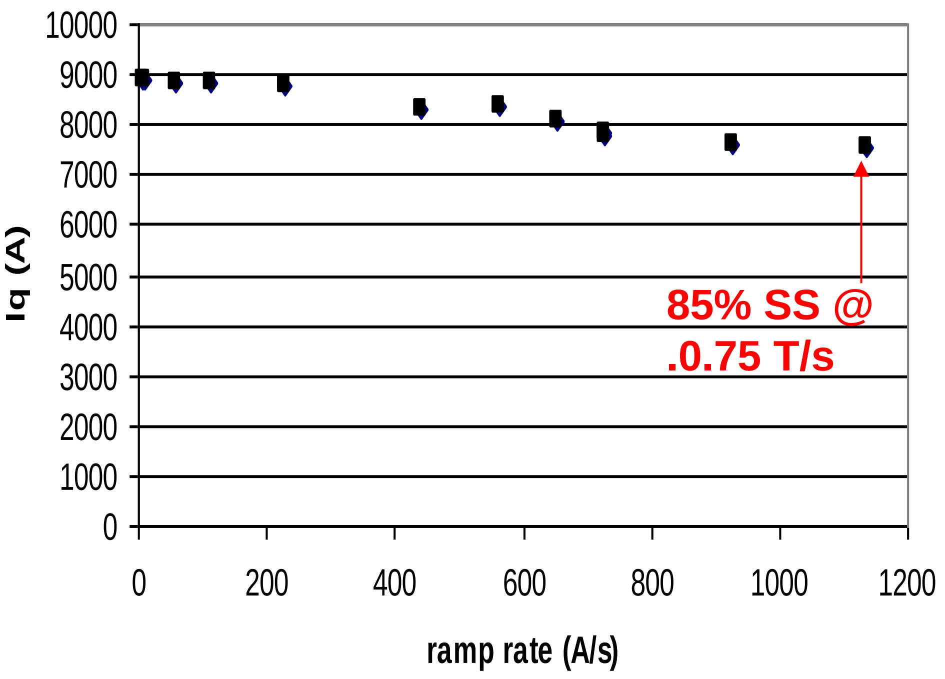






A first taste of the benefits: TAMU2 ramped to 0.75 T/s





Conductor, cabling not optimized to minimize ac losses… or was it?

Let's see what could be done to optimize for rapid cycling.

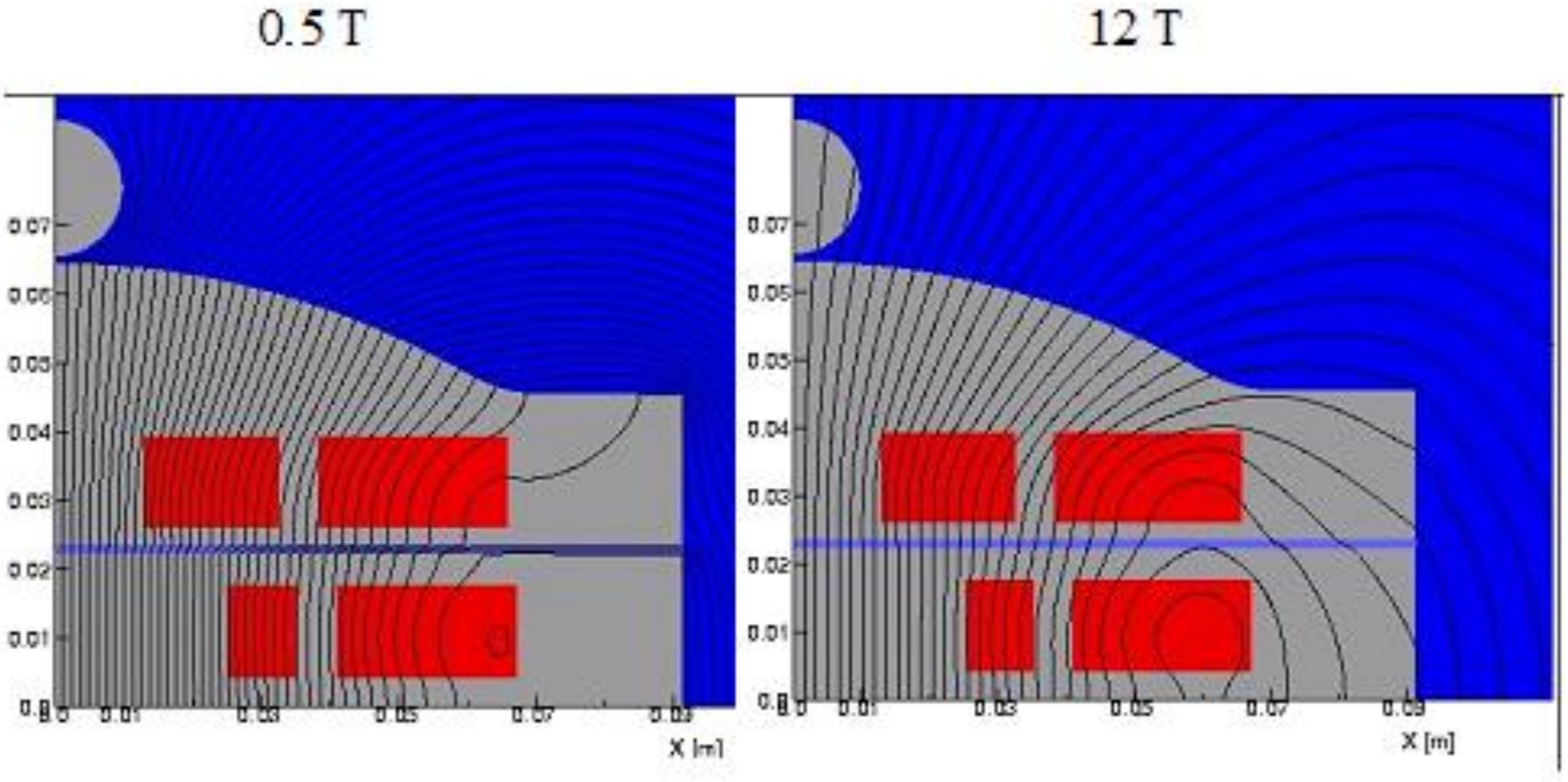
AC losses arise from several sources

- Coupling currents between strands in cable
  - *Block-coil configuration + cored cable can control coupling currents between strands*
- Hysteresis within subelements:
  - *need small subelement size*
- Coupling between subelements:
  - *need optimum matrix resistance*

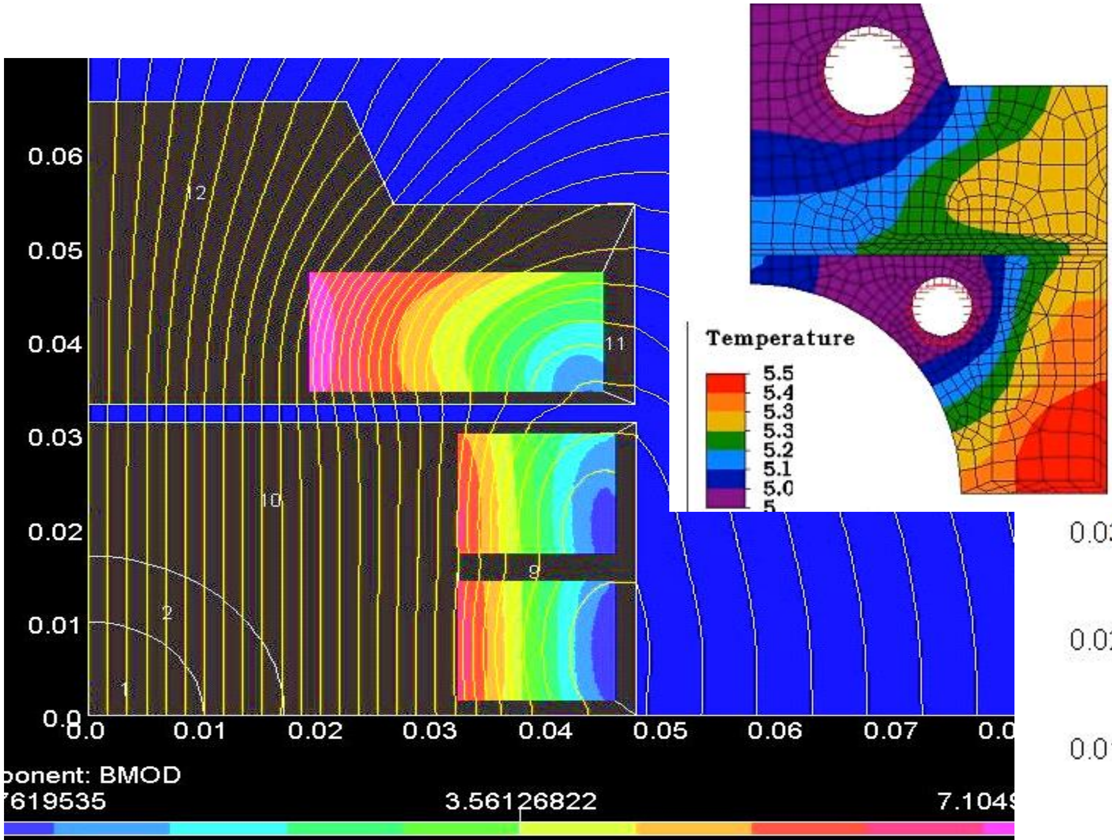
Comparison of losses @ 1 T/s

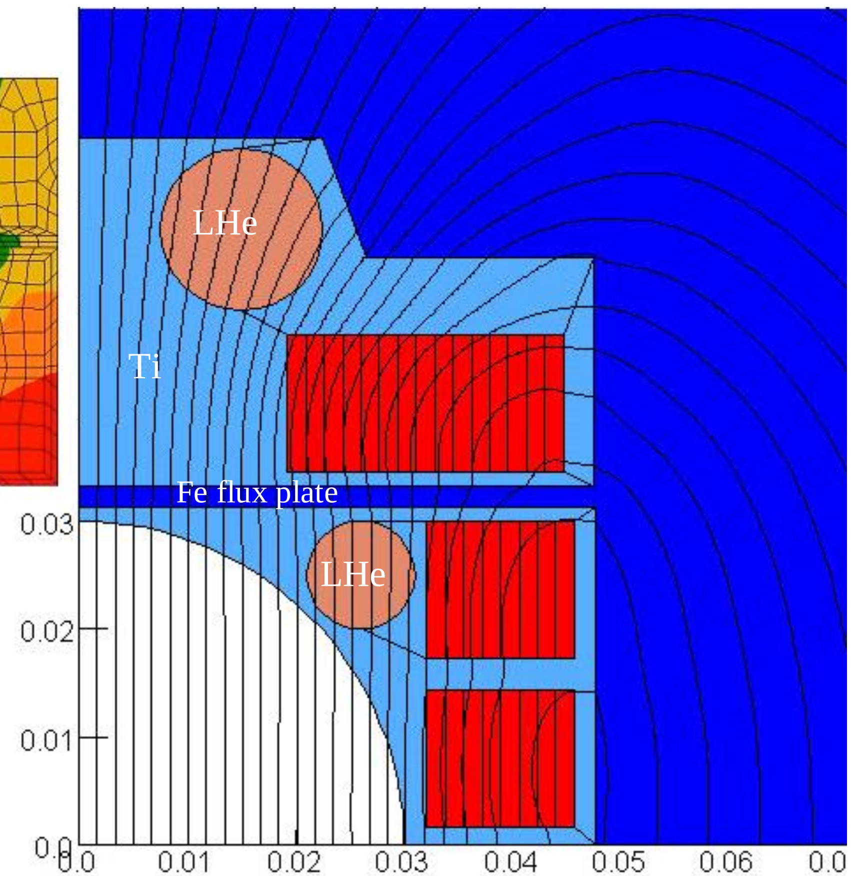
Dipole design	B_{max} (T)	A_{sc} (cm^2)	Bore dia.	AC loss (J/m/cycle)	Operating temp (K)
RHIC-type cos θ	4	13	80	58	4.5
Tkachenko cos θ	6	55	100	58	4.5
Simple block-coil	6	43	100	40	4.5
TAMU block-coil					
- NbTi	6	19	60	34	4.5
- Nb_3Sn bronze	6	19	60	20	10

Flux plate redistributes flux to suppress multipoles from persistent currents, snap-back



Optimum design using block-coil Nb_3Sn fine-filament supercritical He cooling channels





6 T Nb_3Sn 60 mm bore diam.

7.6 T/s with ΔT = 0.5 K, 48 W/m

Summary

- We have devoted a decade of magnet R&D toward high-field dipoles for hadron colliders.
- We have identified a candidate site that could accommodate a 270 km tunnel for a 100 TeV hadron collider (using 5 T dipoles).
- That tunnel could accommodate a 300 TeV upgrade.
- We have developed a design for a 5 T block-coil cos θ dipole that is simple/low-cost to build, operates at 10 K, rapid-cycles.
- We are asking Texas to offer to complete the tunnels for FCC.
- If we succeed we would like to solicit the FCC team to take a leadership role in developing the design and doing the R&D
- If we fail we would like to develop our 5 T dipole as a candidate rapid-cycling dipole for your injector.
- Either way we want to join the FCC team, and we request your endorsement to DOE that they fund us for our roles.

First we must dig out the shafts and recover the existing tunnel

- 20 years ago Congress ordered the shafts to be filled with crushed rock.
- The tunnel has filled with water.

- But the rock of these tunnels is stable, the tunnel should be the same today as when it was built, and we know how to dig rock from a hole and pump water…