Towards a Very Large Hadron Collider
Issues and Progress

General features - Design Options

High field parameters/issues

Beam dynamics

Impact of synchrotron Radiation

Magnet development

Fermilab Feasibility study

Conclusions

HEACC 2001
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General Features of a 3rd generation Hadron Collider

- A discovery machine at the highest energy frontier - 100 Tev center-of-mass (or more)
- Luminosity 10^{34} -> $10^{35} cm^{-2} sec^{-1}$
- Superconducting 2-in-1 magnet technology
- Must be as cost-effective as possible (i.e. it will be expensive)
- Tunnel size starts at ~100km

The technical feasibility of the machine would not appear to be as big of an issue as other methods to achieve these very high energies - this does not mean there are no technical issues !

Potential Design Options

- 3 basic machine design options characterised by field strength:
  - Low field ~ 2T (500 km)
  - Medium field 4T - 8T
  - High Field 10T - 12.5T (100 km)
- The low field option allows superferric technology, medium field is Nb-Ti, high fields requires Nb_3Sn.
- Medium field represents a 'big' LHC which we presumably understand well enough technically and fiscally. Concentrate on low field and high field. This tends to highlight the differences. (This may be starting to change - see Palmer, Talman)

High field option - issues

- Synchrotron radiation power gives a heat load of up to 20 W/m
- Bore tube vacuum in the presence of the above e.g. photodesorption, e-cloud, beam-gas scattering
- Large beam stored energy (several GJ)
- High radiation/power load in and around the interaction points
- Sensitivity to dynamic effects in magnets (ring size)
- Beam stability at injection energies
- No accelerator magnet at these high field levels
- High costs

High field option - parameter logic

Luminosity and Energy are defined by the physics goals

Circumference determined by Energy and Dipole field

Bunch spacing negotiated between machine (big spacing - minimize beam power) and experiments (small spacing - minimize events per X-ing)

Bunch intensity determined by the number of bunches and the beam size at the IP

Hope synchrotron radiation power density, total power load, stored energy, beam-beam tune shift are O.K.

L = 2 x 10^{34}
Circumference = 241 km
Number of bunches = 41280
Damping time = 2.5 hrs

Beam Energy = 87.5 Tev
Bunch spacing = 18.8 ns
Bunch Intensity = 8 x 10^{9}
Dipole field = 10T

Radiated power = 5 W/m
Total radiated power = 1 MW

Initial stored energy = 4.6 GJ

High Field option - synchrotron radiation power

- The total SR power is $$P_{SR} = (U_0/T_0)\, NM$$
- **Most protons burn off**,
  so total number of protons is $$NM \approx L\, N_{IP}\, \sigma_{tot}\, \tau_{store}$$
- The damping time $$\tau_d = T_0 E/U_0$$
- The store time is naturally
  where $$\tau_{store} \equiv n_1 \tau_d$$ $$n_1 \sim 5$$
- **Therefore** $$P_{SR} \approx LE\,(N_{IP}\, \sigma_{tot}\, n_1)$$

$$P_{SR} \propto LE$$

The minimum synchrotron radiation power is proportional to the luminosity times the energy

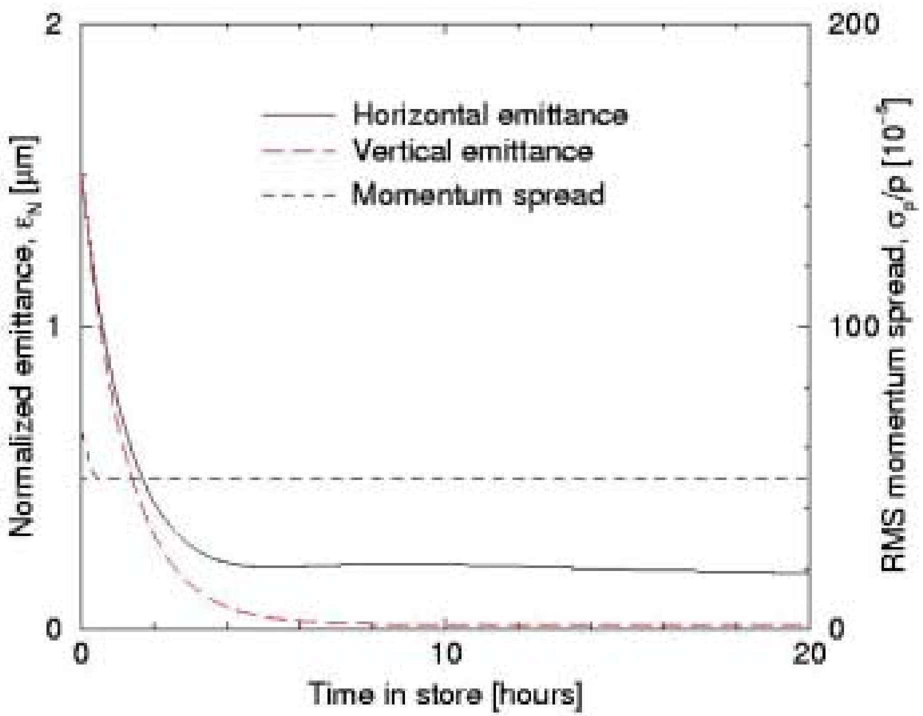
High Field option - Flat Beams

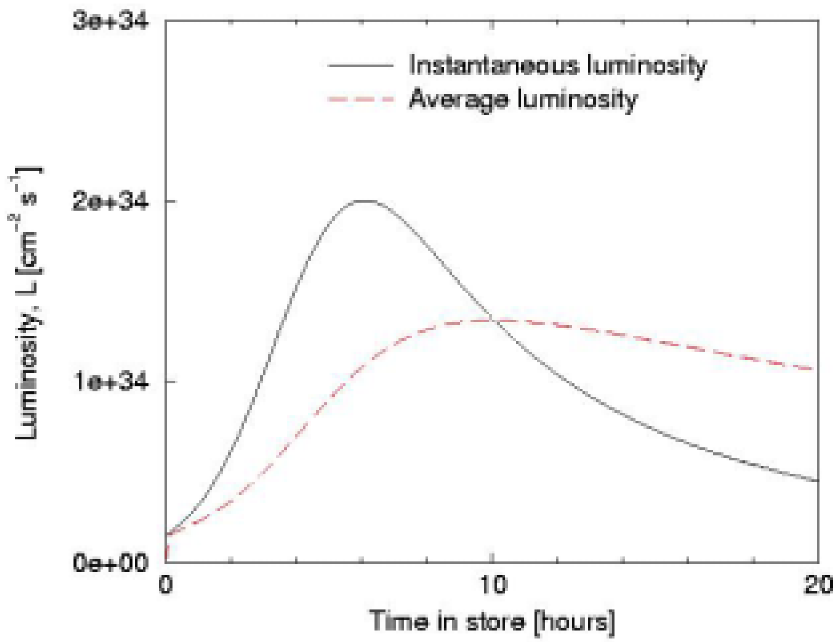
If the vertical dispersion, linear coupling and diffusion mechanisms are well controlled, the vertical emittance will damp to a value much smaller than the horizontal emittance resulting in flat beams as in an electron storage ring

Implications:

- The final focus optics can be a doublet rather than a triplet. The peak beta function is typically much smaller which relaxes field quality criteria in the final focus.
- The final focus optics must be symmetric & vertically focussing => the beams must be separated before the first quadrupole.
- Long range tune shifts (mostly vertical) occurring before the beams are fully separated tend to be smaller.

High Field Option - beam dynamics

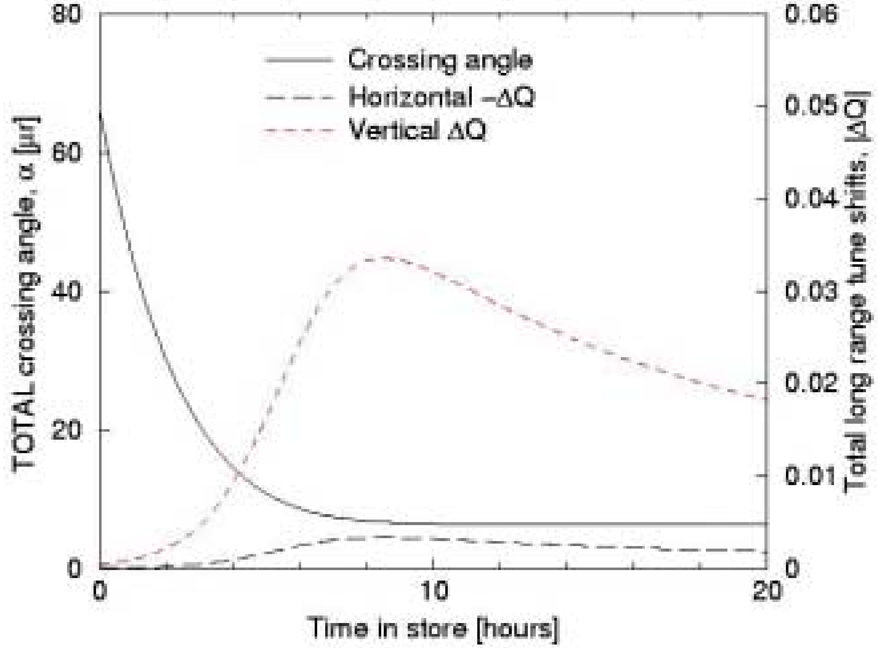




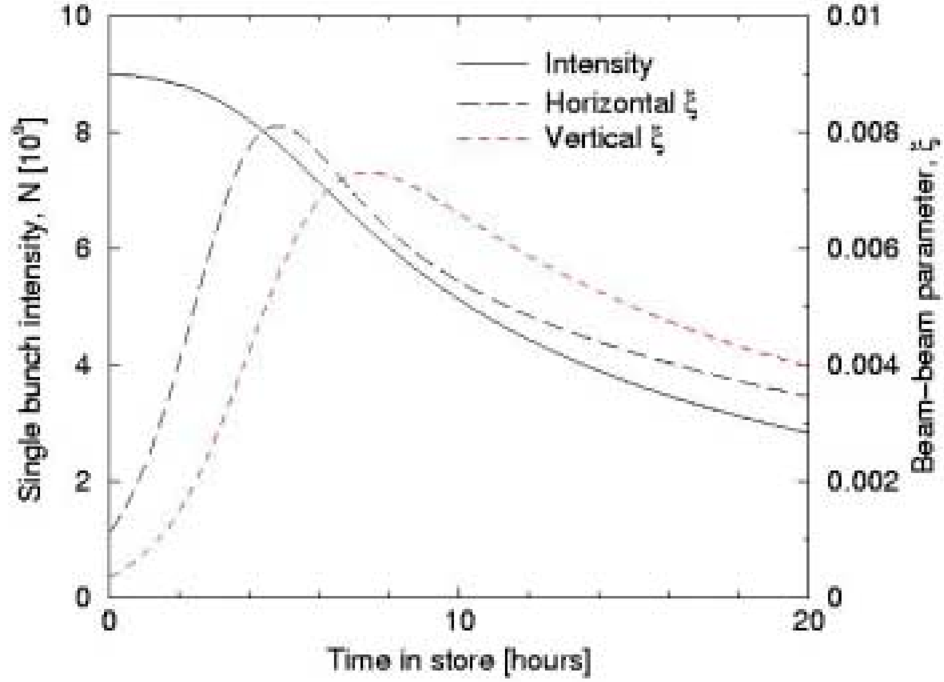
- Equilibrium emittance independent of initial emittance. Eases specifications on injector chain
- Vertical emittance assumed to be 10% of the horizontal
- Emittances determined by beam heating not equilibrium values

High Field Option - Tune shifts

Long range tune shift



Head-on tune shift/spread



X-ing angle varied during during the store

In 20 hrs 2/3 of the beam is lost from collisions (2 IP's)

Beam-beam parameter set to limiting value of 0.008 per X-ing

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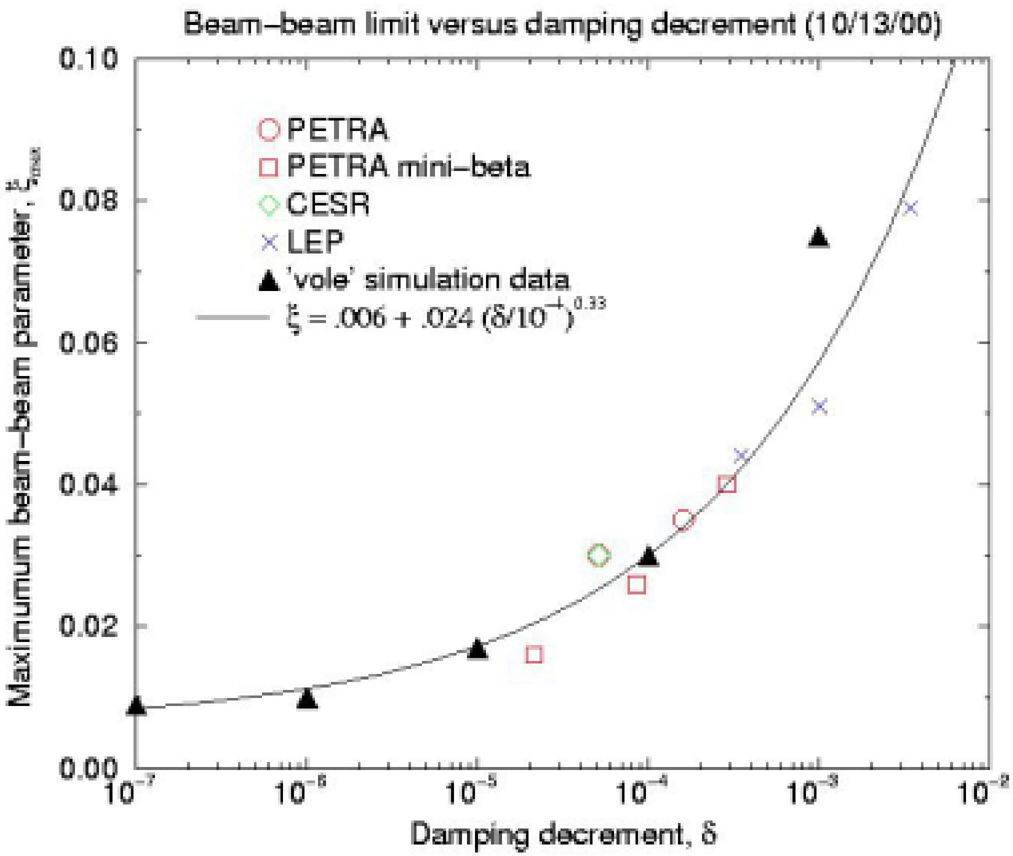
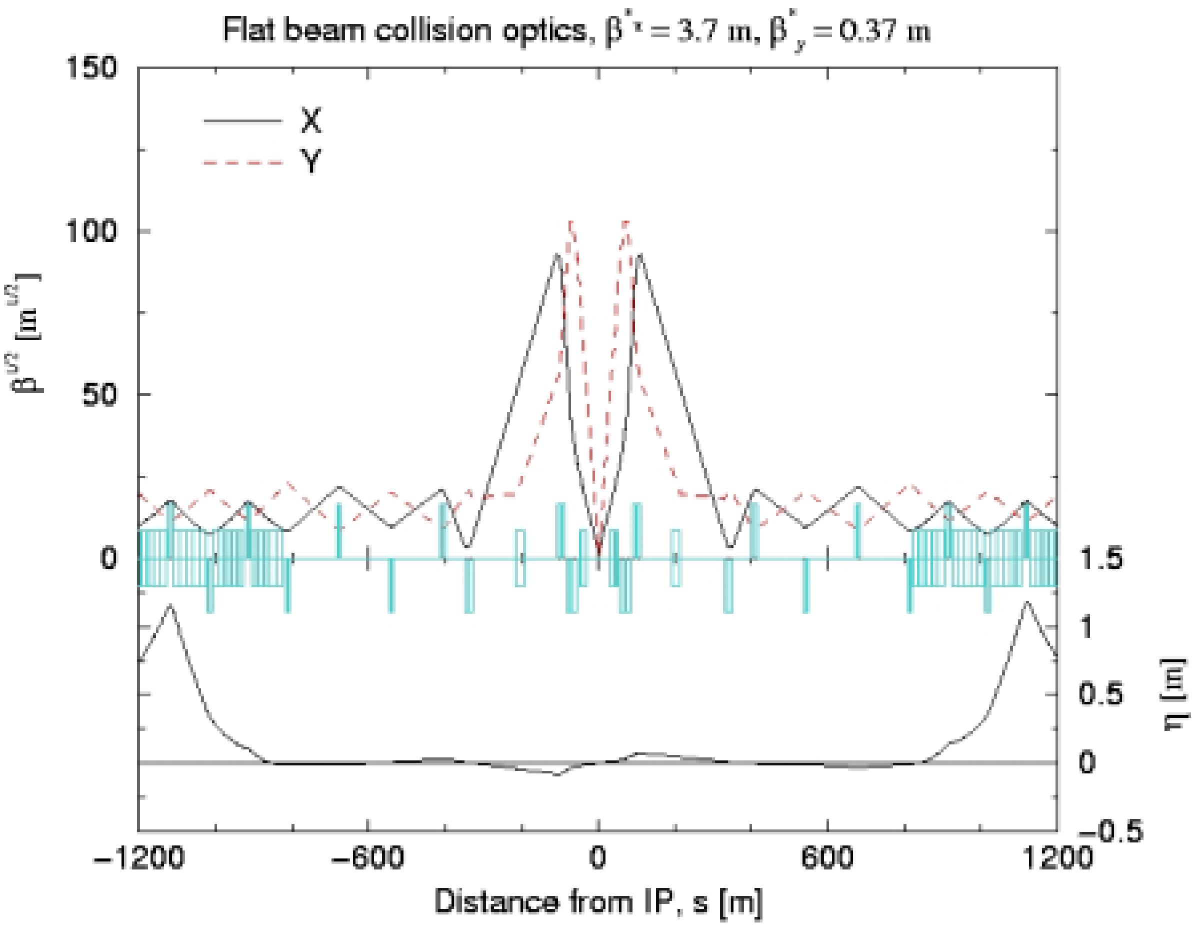
High Field option - Sustainable tune shifts



Damping decrement is the fraction of the damping time between collisions

This would indicate that the rate of damping is insufficient to allow higher tune shifts than any other hadron machine (~0.008 per X-ing)

High Field option - Lattice Design



IR β_{max} ~ 10km
Chromatic properties O.K.

- Flat beams favours unequal β*'s ($\beta_y < \beta_x$). This in turn allows the use of doublets rather than the 'normal' triplets.
- Symmetric lattice requires beam separation before the quadrupoles.
- Beam size remains 'small' in the IP magnets.
- Standard arc cell
  - Half cell length 135 m β_{max} 450 m
  - Dispersion 1.5m

High Field option - IR beam Losses

- At these extreme energies/luminosities there is significant beam power radiated from the interaction point into the IR magnets
- At 175 Tev then σ_{tot} ~ 150mb (PYTHIA) and of this the 'forward' X-section is ~ 70mb.
- At 2 x 10^{34} then estimate ~ 20kW of secondaries lie within the solid angle of the focussing quads. This is obviously a great deal of power in and around the magnets (LHC is ~800 W)
- This is an area where the use of high temperature superconductors is (at least superficially) attractive. The lack of strong temperature sensitivity would allow large operating temperature variations across the magnets

High Field option - Arc magnet Aperture

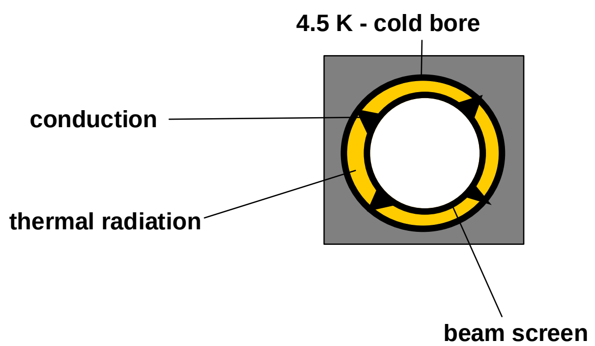
- Generally the arc magnet aperture is determined by the rms beam size at injection and a criteria such as ± 10 σ dynamic aperture
- The beam sizes at a VLHC are so small that the normal criteria will result in a necessary aperture of < ± 5mm
- Rather than dynamic aperture the magnet coil size will be determined by beam stability issues and the dimensions of the liner
- Magnet aperture is strongly correlated to cost so there is a large incentive to operate with the smallest possible aperture
- Beam stability will be determined by feedback systems
- Field quality requirements O.K.

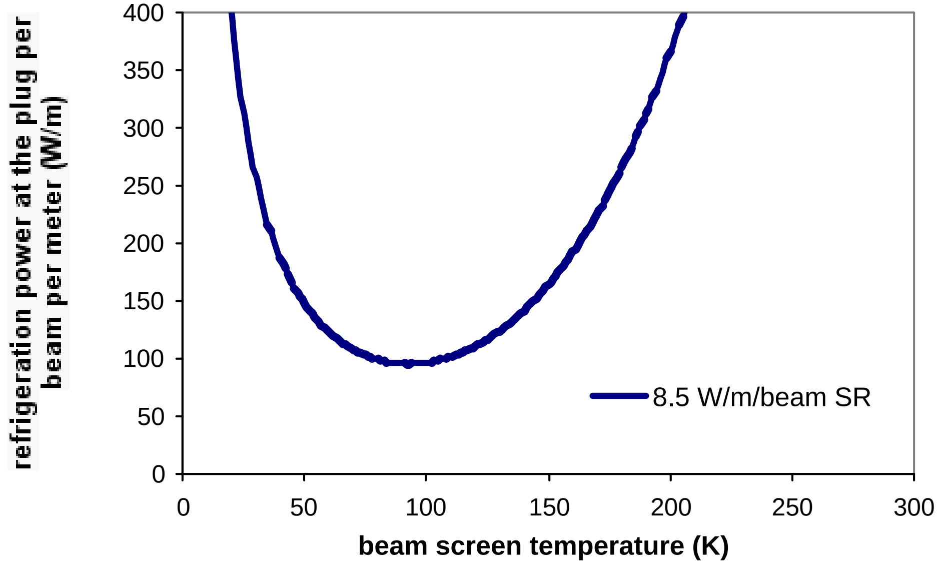
Present best guess has the beam tube liner aperture ~ 20 mm

Coil size ~ 40 mm

High Field option - Beam Screen

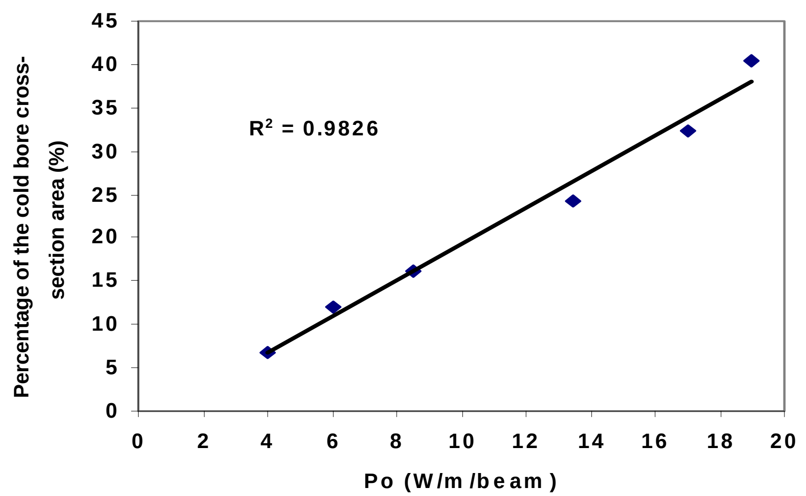
Beam screen schematic





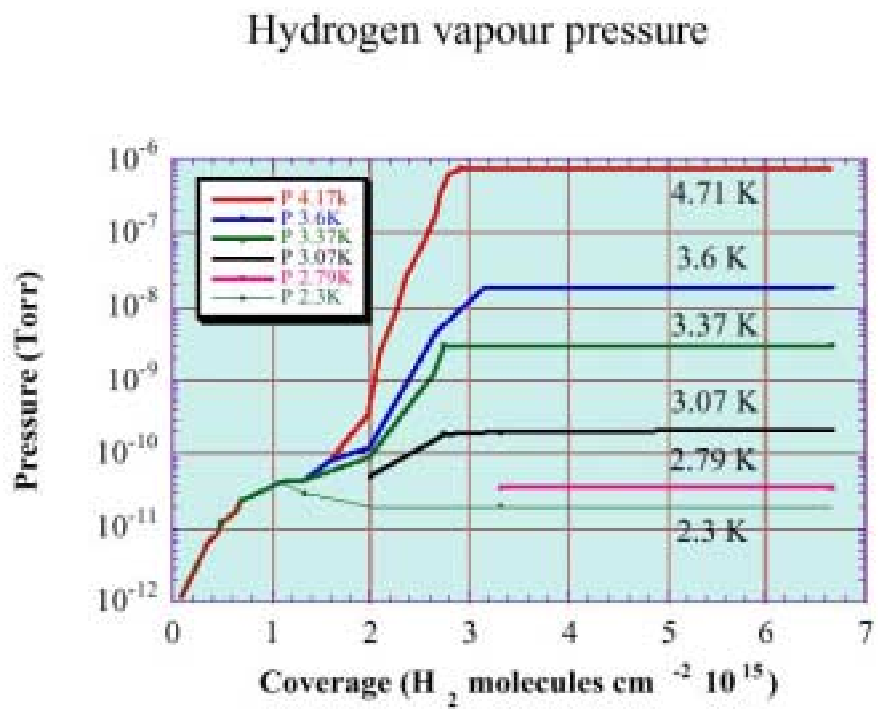
8.5 W/m of radiated power results in at least 100 W/m of wall plug power for the cryogenics system. 200 km of dipoles => 20 MW of beam screen refrigeration per beam. A large but not unreasonable number.

Sync. Rad. masks may also work given the relatively small sagitta.



High Field option - Bore tube vacuum system

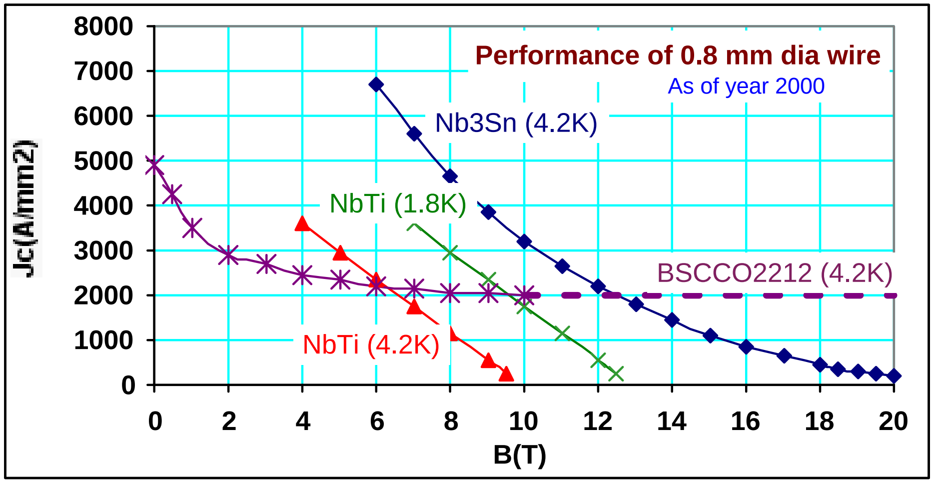
- The energy loss per particle per turn ~ 15 MeV. Photon critical energy of 8 keV (1.5 A) with 1.8 x 10^{16} photons/m/s/ produces lots of desorbed gas. Scrubbing scenarios will be needed - 100 hrs. Pumping speed ~60 l/s/m, 3% liner hole fraction.
- Residual gas background H_2 cryopumped on the cold bore with the exception of hydrogen. Bore tube vacuum specifications of ~10^{-10} torr. much smaller than H_2 vapour pressure at 4K. Some form of additional H_2 pumping necessary.

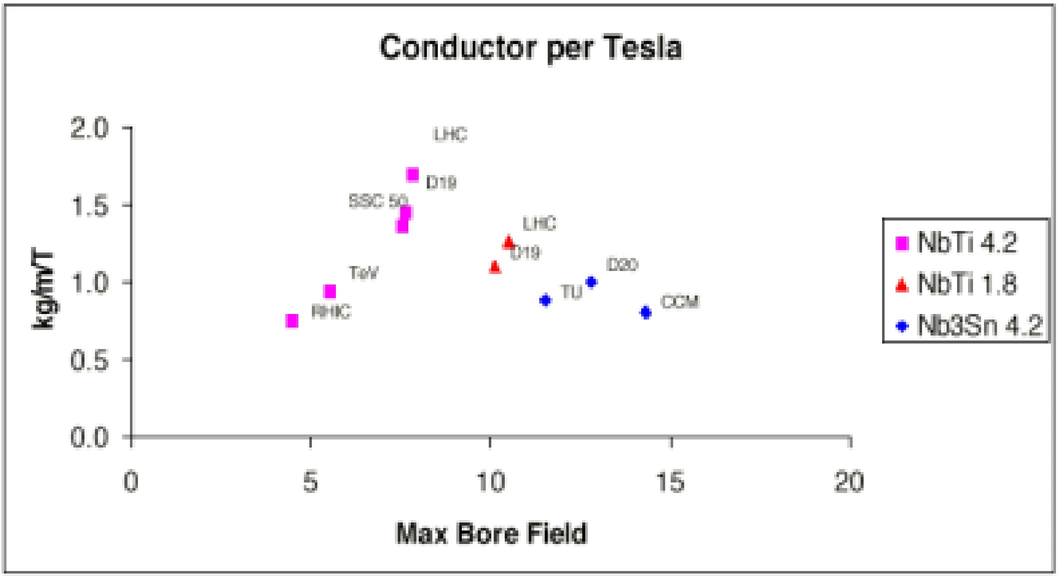


- Thermal desorbtion (from liner) small
- e-cloud estimated to be issue at higher bunch intensities than 10^{10}

High Field option - Magnet R&D

Present day superconductor performance

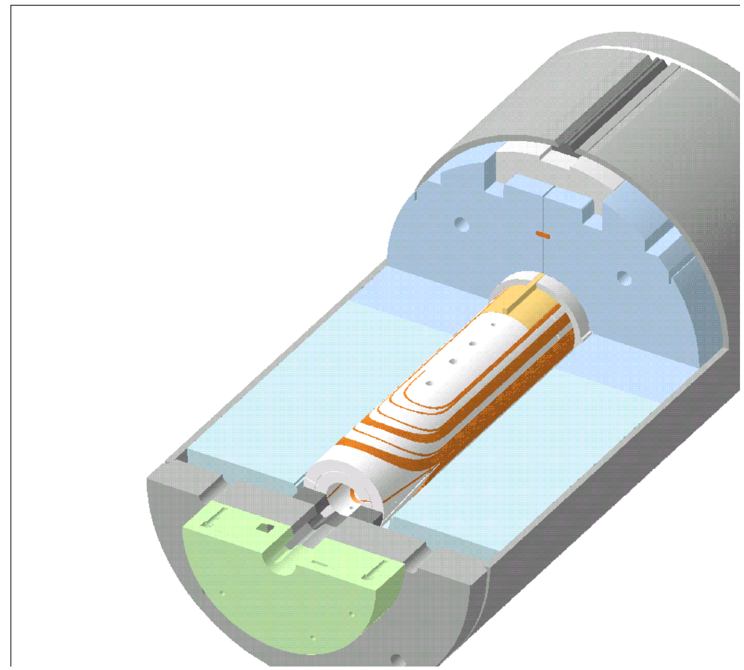




Focus on Nb_3Sn for conductor development (LBL & Fermilab). Difficult material however.

Large filament size exacerbates persistent current & magnetisation effects

High Field option - Magnet R&D



Cosine-theta test magnet with Nb3Sn coils at Fermilab

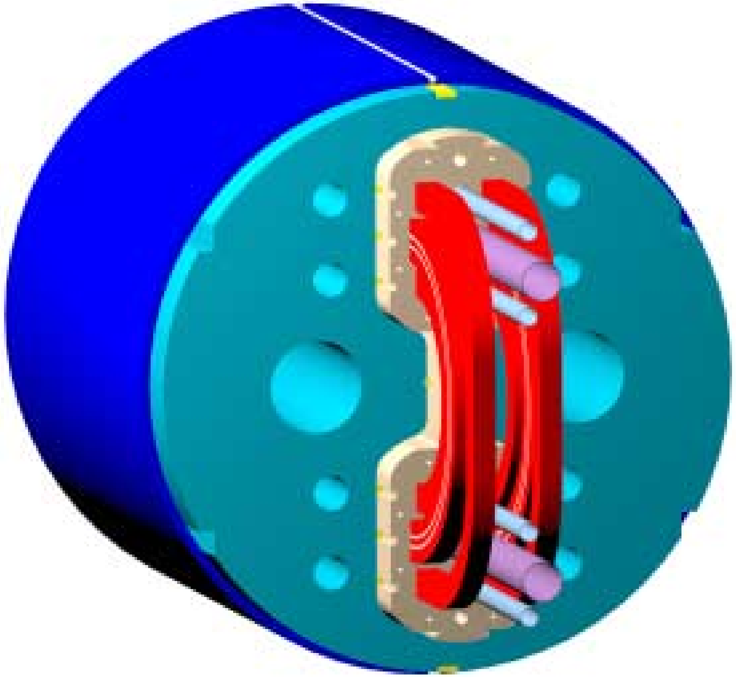
No results yet. Magnet should go to about 12T

High Field option - Magnet R&D

Fermilab

Nb3Sn

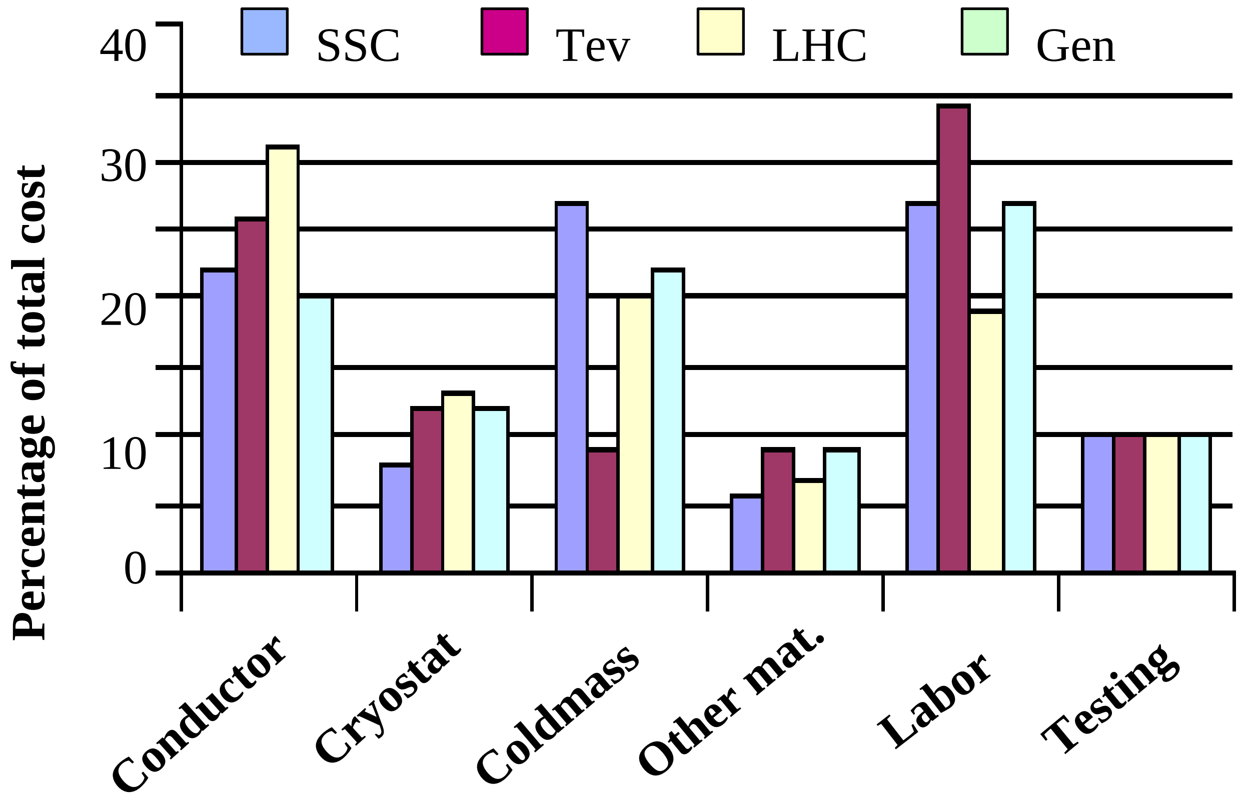
Conductor friendly coil design



Brookhaven (HTS)

High Field option - Cost

Arc dipoles - the dominant technical cost element

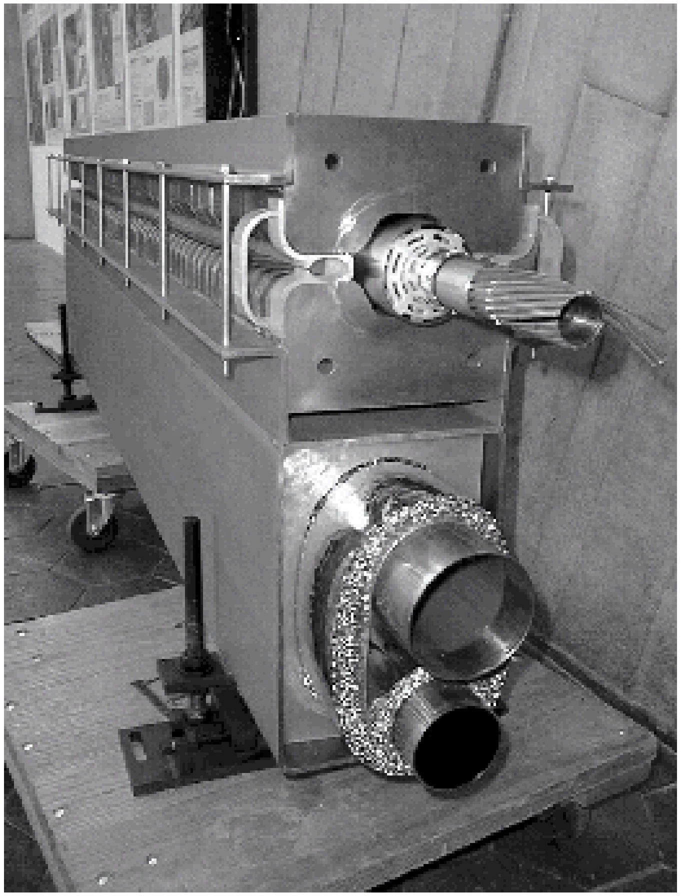


Dipole magnet cost breakdown (Gourley)

No obvious area for large cost savings

Fermilab Feasibility Study

- Attempt to see whether a staged approach starting with a large tunnel and low-field ring (2T) solves the twin problems of cost & no high field magnet.
  - Phase 1 involves a 240km tunnel and a ~2T dipole giving 40 Tev cms
  - Phase 2 installs ~10T magnets and raises energy to ~175 Tev cms
- Uses existing Fermilab accelerator complex in the injector chain.
- In principle the low field technology is understood and will be costed.
- Optimising a 2-stage approach does not result in a fully rational high field design. It does result in a very high energy stage 2.

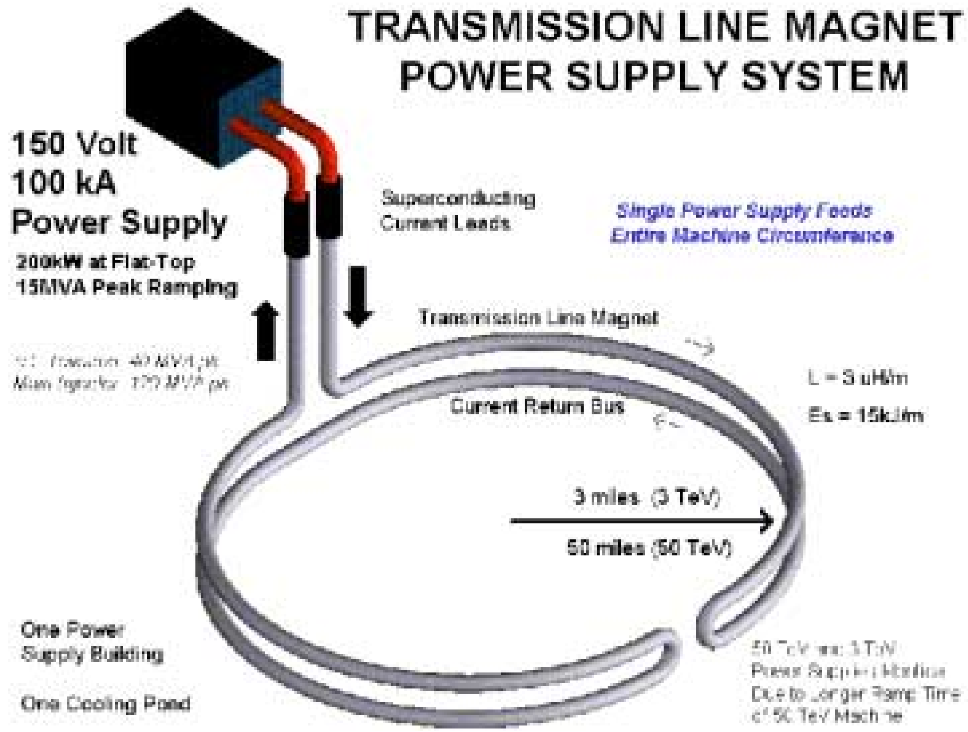


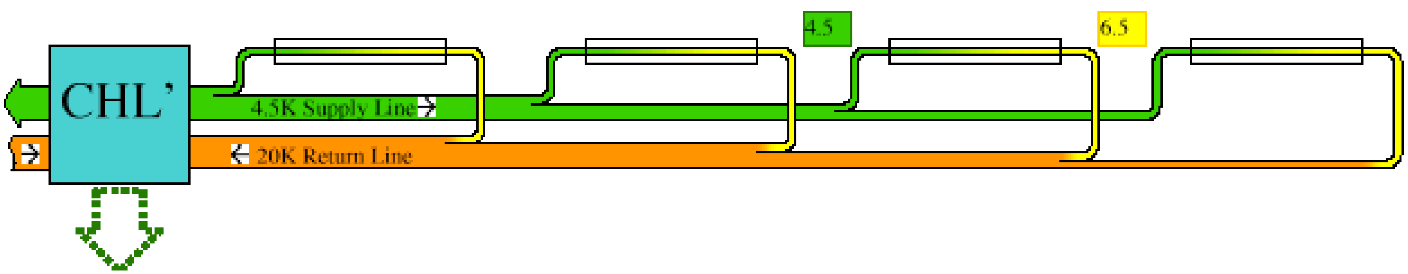
Low field superferric magnet - Fermilab

Low Field option - Simplified Systems

It is difficult to imagine anything more technically simple and cheap than something like this. Does this compensate for those elements that scale with length e.g. tunnel & infrastructure, vacuum, instrumentation ?

Beam dynamics less robust than high field option





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Conclusions

- We can envisage one more Hadron Collider after the LHC built with 'familiar techniques & technologies'.

- While technical issues tend to get more difficult with increasing energy there does not appear to be any fundamental problem precluding such a machine.

- The Fermilab feasibility study will indicate whether a phased approach is a sensible way to proceed.

- Problems at the highest energies include:

    - Beam tube environment
    - IR beam power
    - Accelerator ready high field magnet
    - Cost