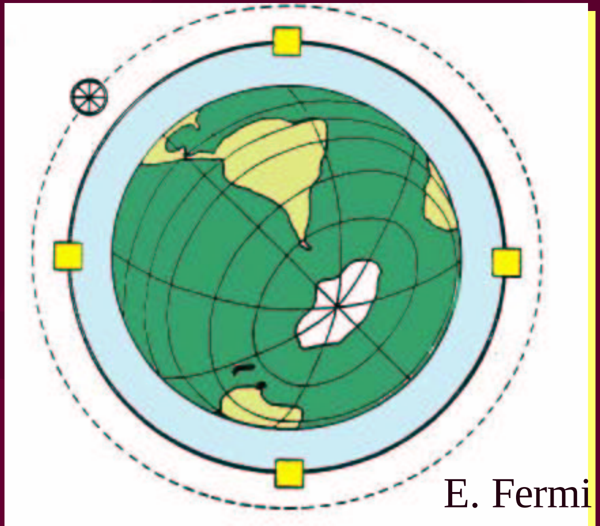
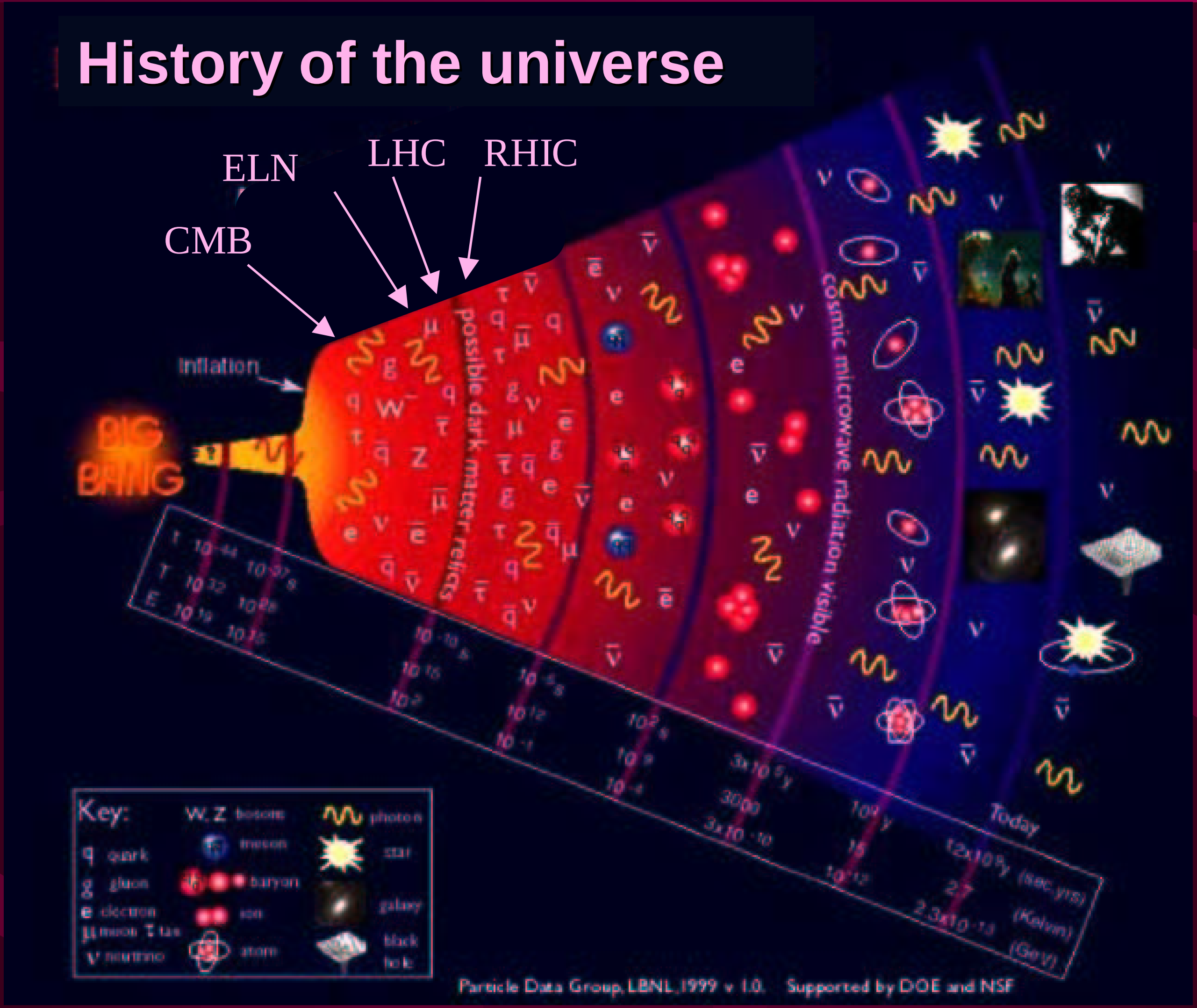
Future Hadron Colliders:
The Farthest Energy Frontier


E. Fermi

William Barletta
42nd Eloisatron Workshop
Erice, 29 September 2003

The Big Picture: ELN explores the first 100 fs



Particle Data Group, LBNL, 1999 v 1.0. Supported by DOE and NSF

ELN = A program for 50 years of forefront high energy physics

- A large advance beyond LHC
  - Multi-step scenarios are the most realistic
  - Eventually 50 to >100 TeV per beam
- No extraordinary technical difficulties preclude ELN at 10^{35} cm^{-2} s^{-1} with present technologies
  - Radiation damage to detectors is a serious issue
  - Proton synchrotrons could reach up to 1 PeV c.m. energy
- Discovery potential of ELN far surpasses that of lepton colliders
  - Much higher energy plus high luminosity
  - The only sure way to the next energy scale

Three strategies for VLHC / ELN design

- Low field, superferric magnets
  - Large tunnel & very large stored beam energy
  - Minimal influence of synchrotron radiation
- Medium field design
  - Uses ductile superconductor at 4 - 8 T (RHIC-like)
  - Some luminosity enhancement from radiation damping
- High field magnets with brittle superconductor (>10 T)
  - Maximizes effects of synchrotron radiation

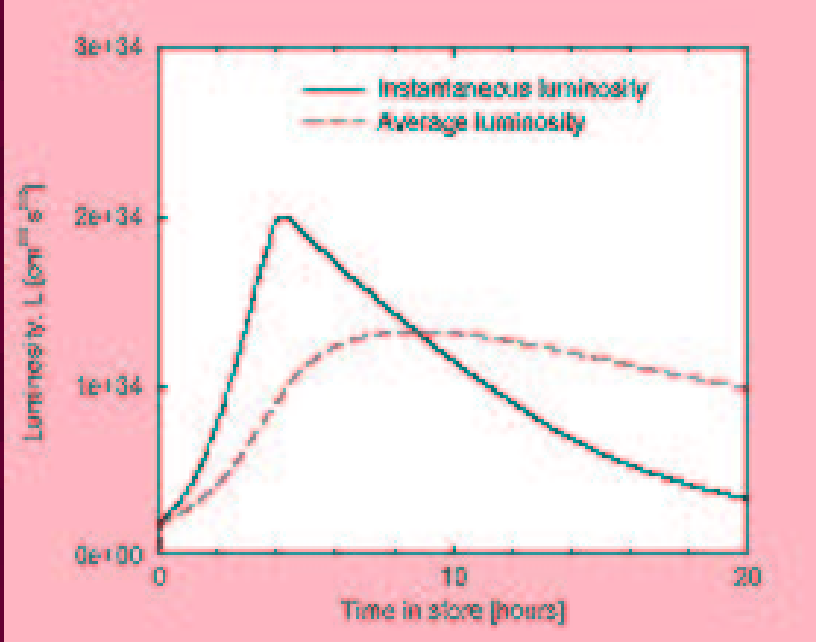
Does synchrotron radiation raise or lower the collider $/TeV?

VLHC Instability Workshop (Mar. ‘01) found no showstoppers

- Transverse mode coupling instability
  - Safety factor N_{thr} / N_b : LF ~ 0.5, HF ~ 8
- Resistive wall multi- bunch instability
  - Increments: LF ~ 1 turn, HF ~ 5 turns
- Incoherent and coherent tune shifts
  - $\Delta Q_{LF} = -0.3$, $\Delta Q_{HF} = -0.02$
- Not expected to be serious:
  - Electron cloud instability
    - LF – 0.25 s, HF – 0.5((10?) s
  - Longitudinal microwave instability: safety factor 20
  - Coherent synchrotron tune-shift: safety factor 10
  - Ground motion & ΔB/B effects suppressed by feedback
- http: / / www. slac. stanford. edu/ ~ achao/ VLHCWorkshop. html

Dominant beam physics is synchrotron radiation

- Radiation alters beam distribution & allowed tune shift at acceptable backgrounds



- Radiation damping of emittance increases luminosity
  - Maybe eases injection
  - Maybe loosen tolerances

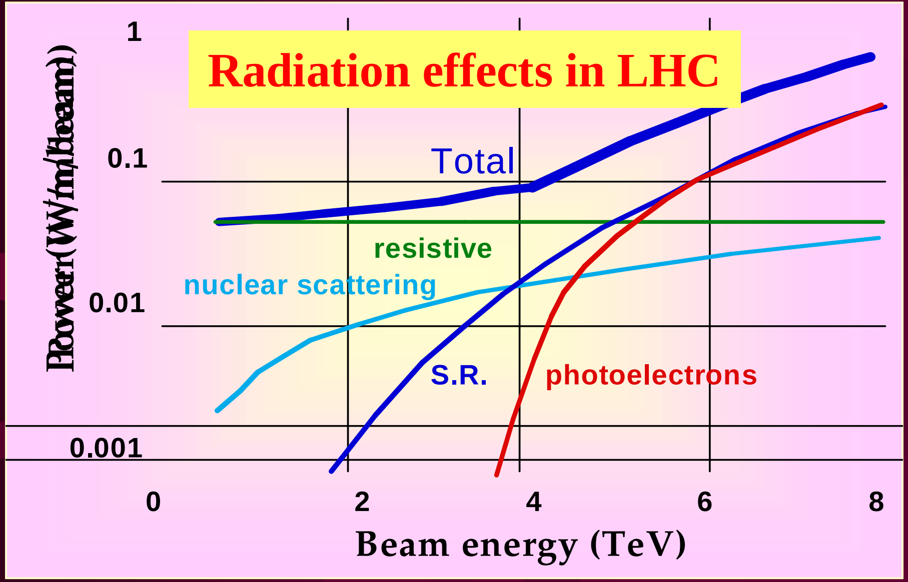
  ==> Saves money ???

- Energy losses limit I_{beam}
  - 1 - Heating walls ==> cryogenic heat load ==> wall resistivity
  - 2 - Indirect heating via two stream effects
  - 3 - Photo-desorption —> beam-gas scattering —> quench

  ==> Costs money

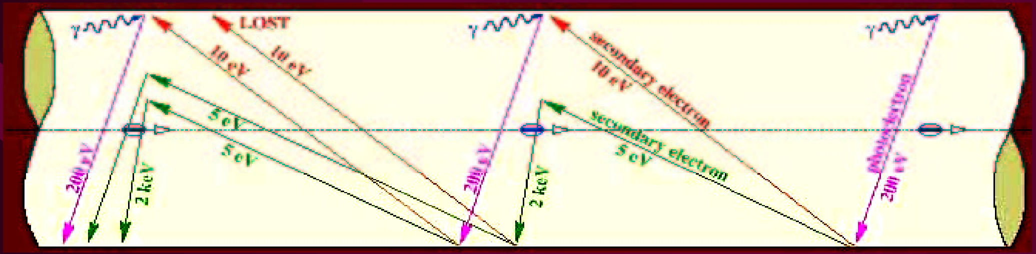
Thermal loads constrain current in high field designs

- Direct thermal effects of synchrotron radiation:



Scales with
radiation power

- 2-stream effects can multiply thermal loads - requires study



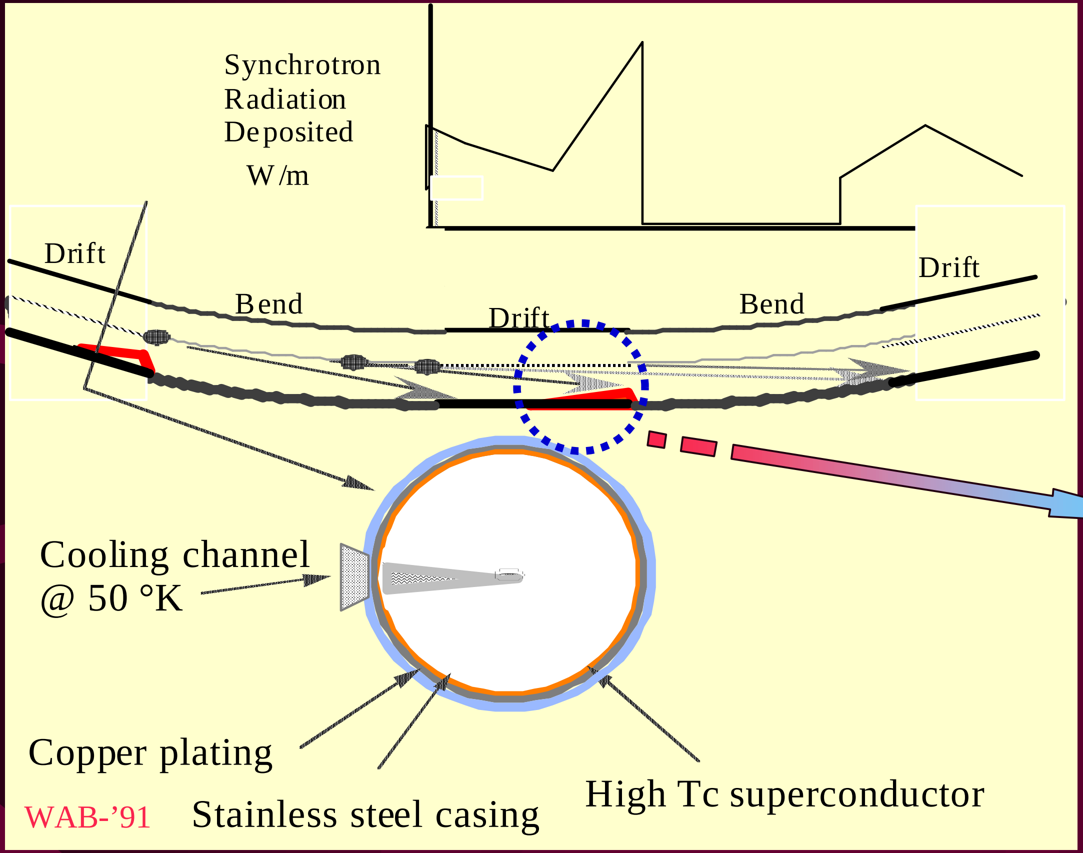
Scales with
photon number

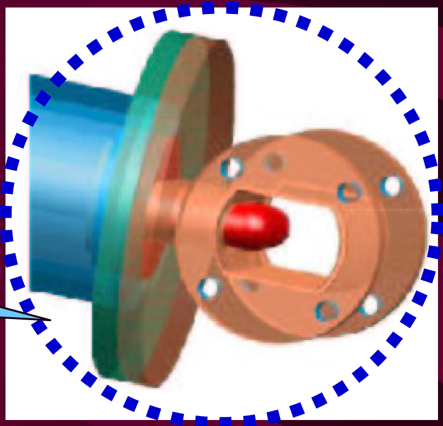
Vacuum/cryo systems: Scaling LHC is not an option

- Beam screen (requires aperture)
  1. Physical absorption
     - a) shield & absorber are required
     - b) regeneration @ 20 K tri-monthly
  2. Chemical absorption
     - a) finite life
     - b) regeneration at 450 - 600 K annually
  3. “Let my photons go”
     - a) Not-so-cold fingers
     - b) Warm bore / ante-chambers

- Cryogenics
  – sensible heat v. latent heat systems
  – LHC tunnel cryogenics have more than 1 valve per magnet average
  – Superfuild systems are impractical at this scale

Synchrotron masks and novel materials may enhance performance





Synchrotron
Radiation mask

BUT, masks work best in sparse lattices & with ante-chambers

2-in-1 transmission line magnet lets photons escape in a warm vacuum system

Radiation power is low,
but number of photons is large

* Width 20 cm.

* 2-in-1 Warm-Iron "Double-C" Magnet has small cold mass.

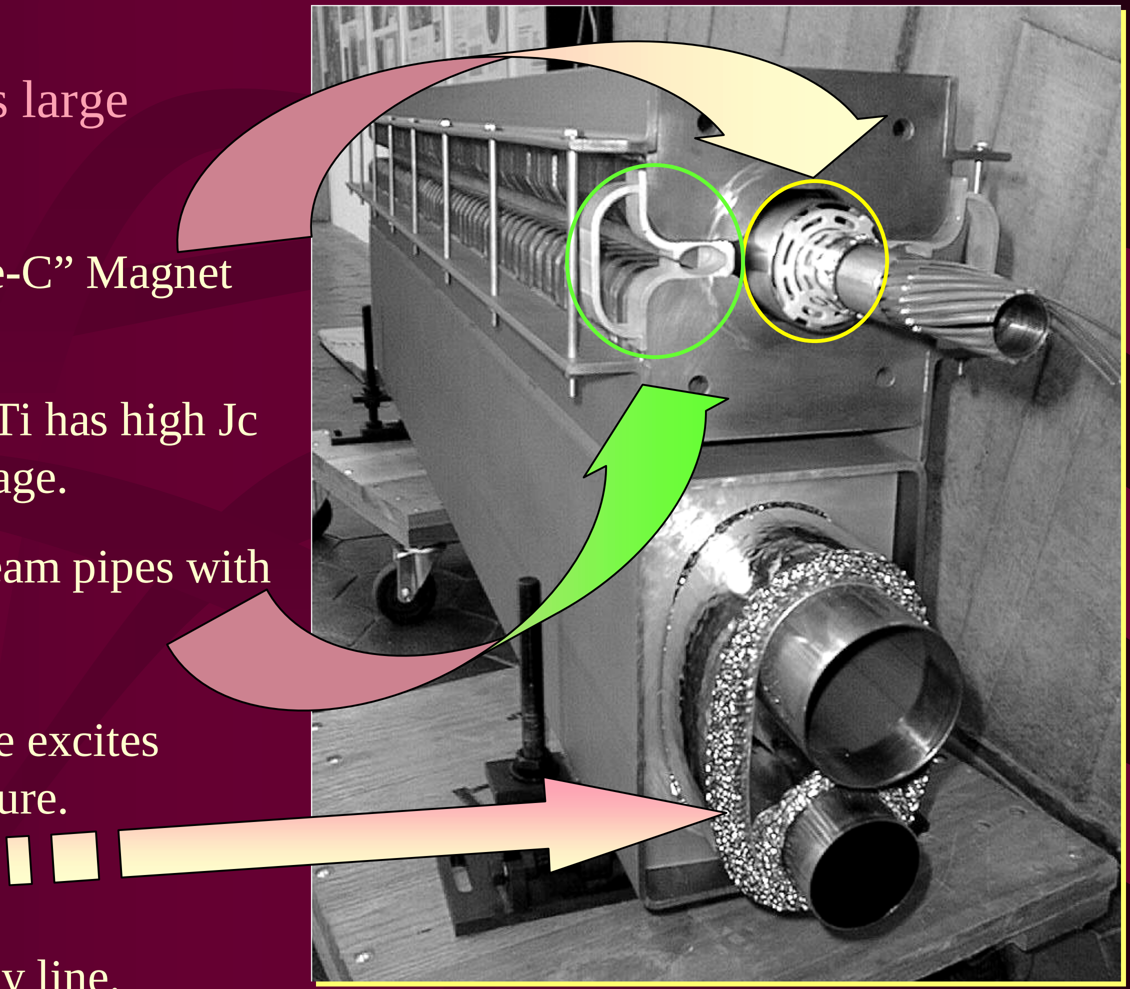
* B @ conductor ~ 1 T; NbTi has high Jc ==> low superconductor usage.

* Extruded Al warm-bore beam pipes with antechambers.

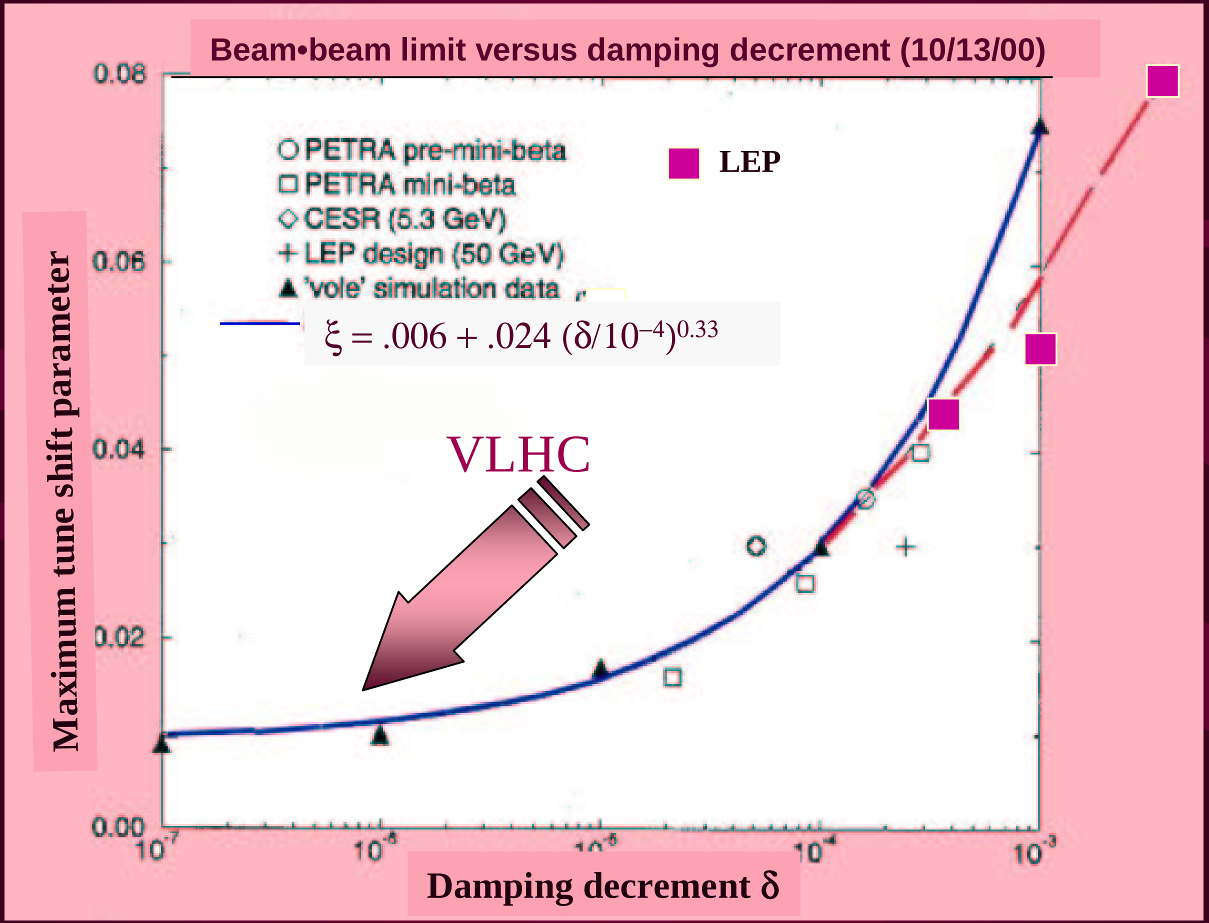
* 75 kA SC transmission line excites magnet; low heat-leak structure.

Simple cryogenic system.

Current return is in He supply line.

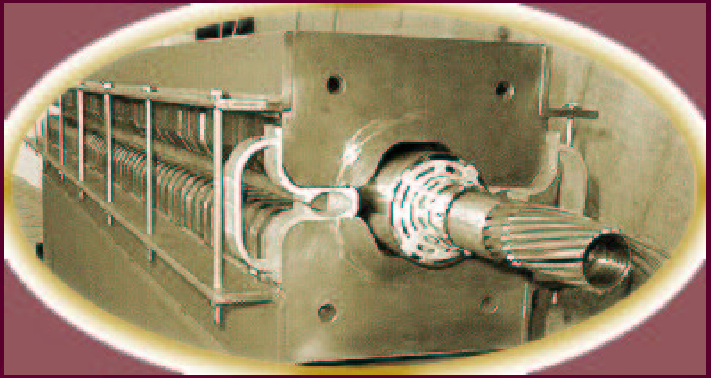


Beam distribution may change $\Delta\nu_{max}$ consistent with acceptable backgrounds



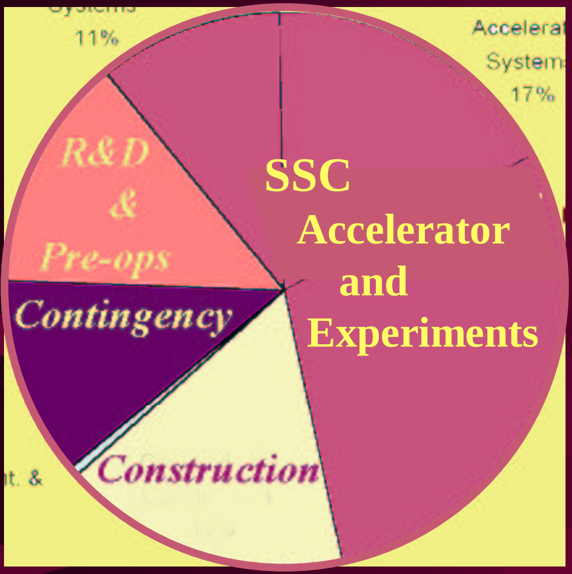
Beam dynamics of marginally damped collider needs experimental study

Controlling



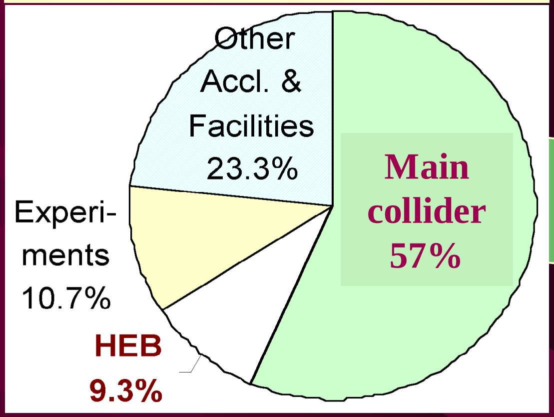
collider costs

SSC experience shows us VLHC cost drivers

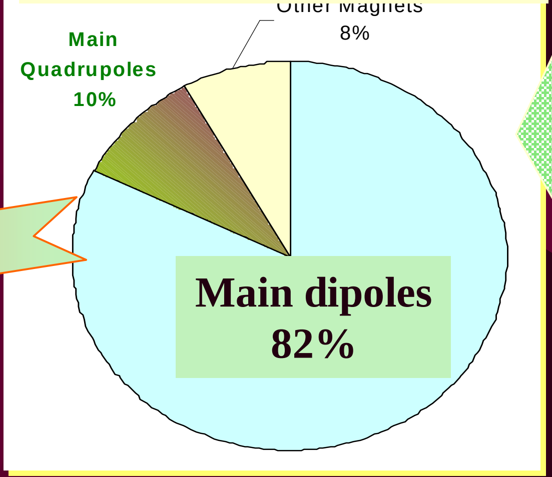


SSC total cost

Accelerator cost distribution



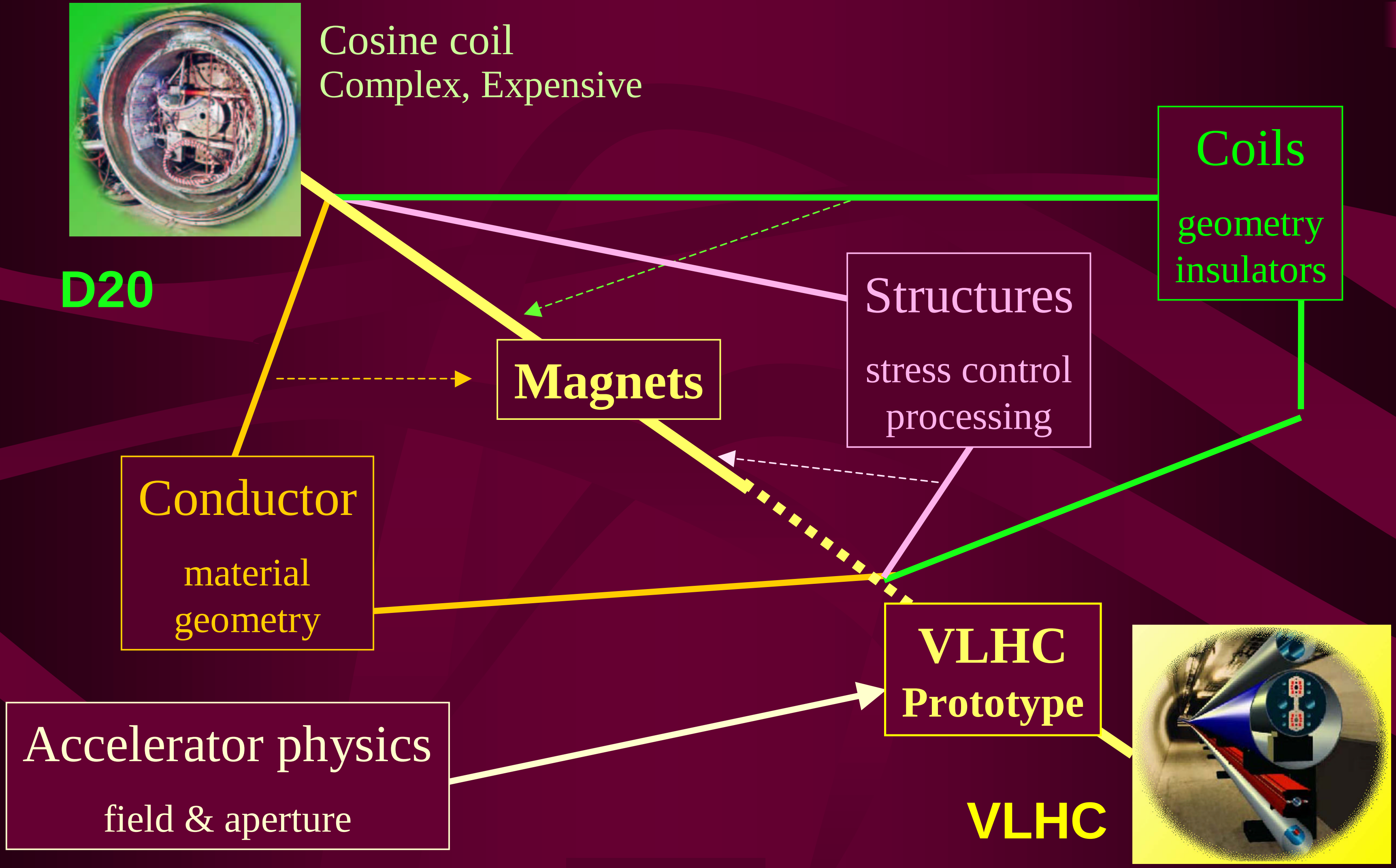
Magnet cost distribution



Lowering dipole cost is the key to cost control

2nd order reductions:
Eliminate HEB,
Main Quads

Magnet development to control dipole costs



Cosine coil
Complex, Expensive

D20

Magnets

Coils

geometry
insulators

Structures

stress control
processing

Conductor

material
geometry

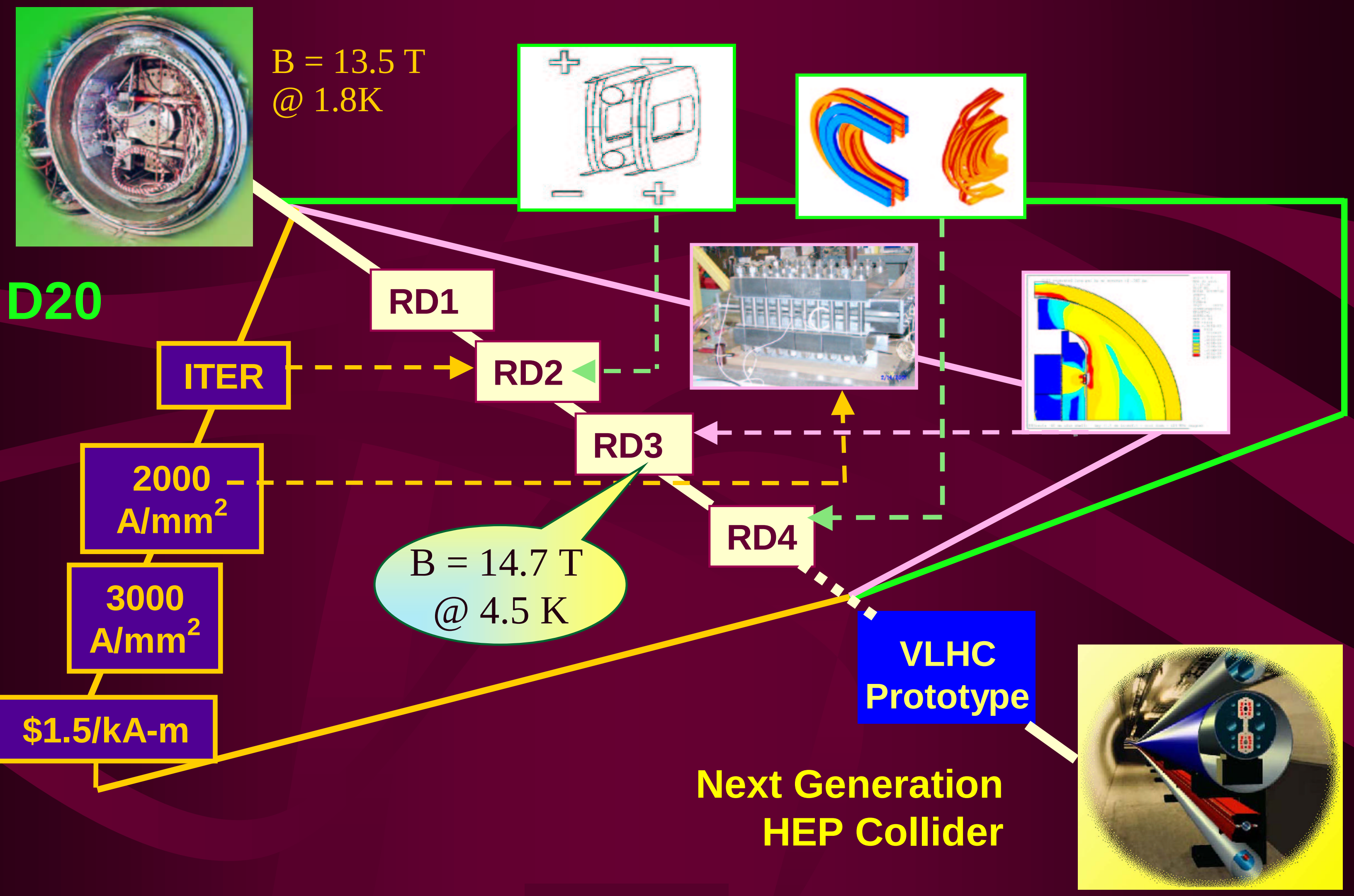
VLHC
Prototype

Accelerator physics

field & aperture

VLHC

LBNL example of magnet development



B = 13.5 T
@ 1.8K

D20

ITER

RD1

RD2

RD3

RD4

2000 A/mm^2

3000 A/mm^2

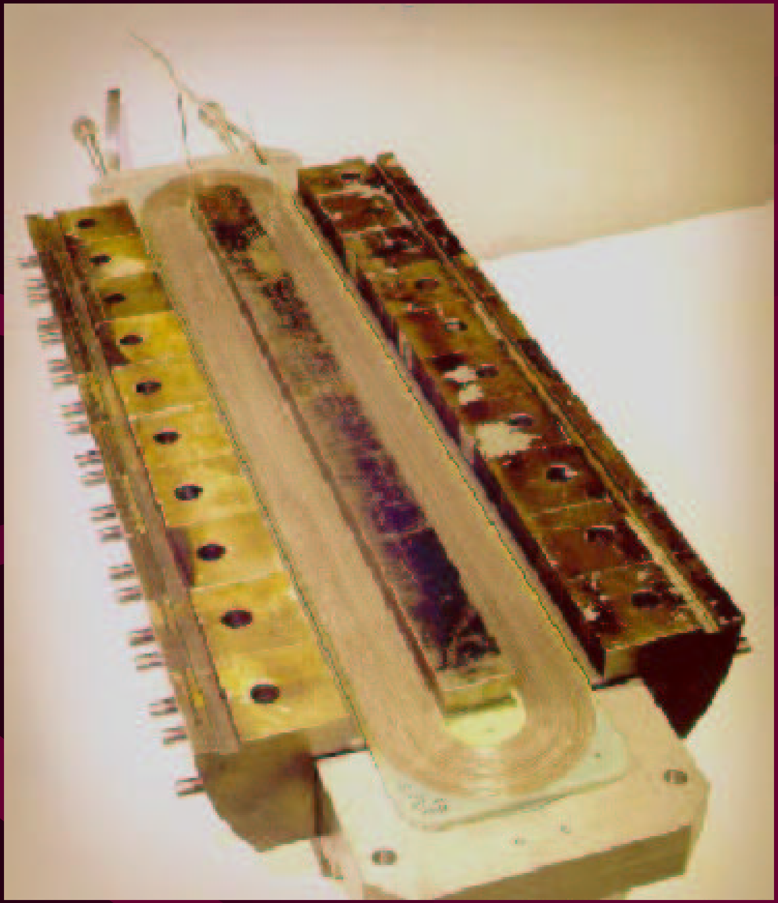
$1.5/kA-m

B = 14.7 T
@ 4.5 K

VLHC
Prototype

Next Generation
HEP Collider

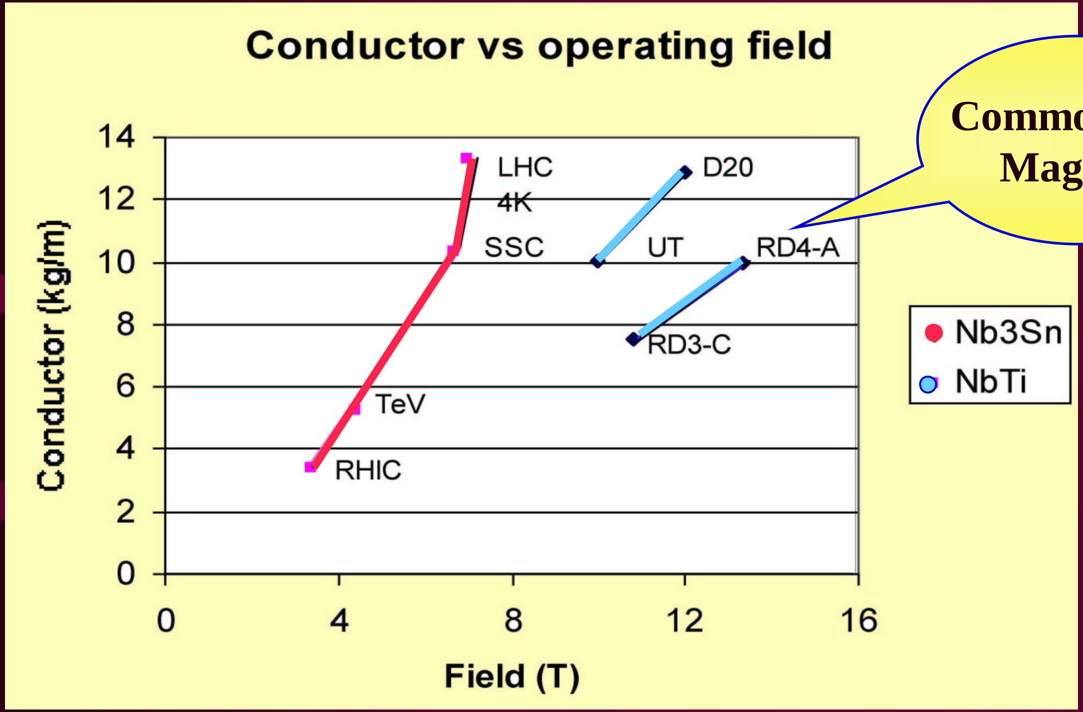
Complementary high-field magnet programs at BNL & FNAL



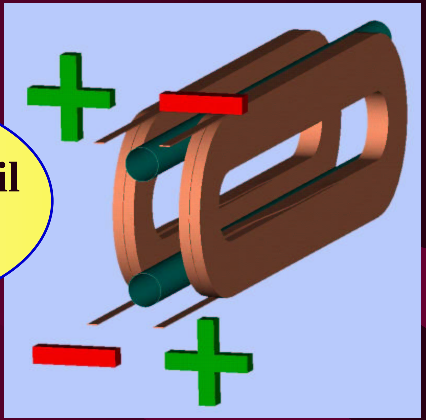
Apparatus used at BNL for testing HTS coils in a common- coil configuration

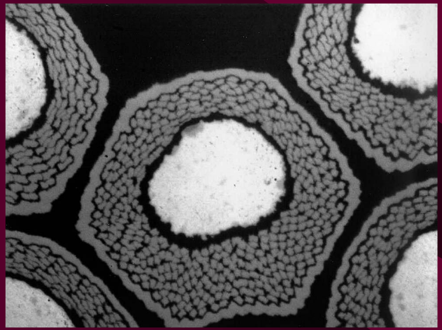
Coils for a mechanical model of a cosine θ magnet at FNAL. The Nb_3 Sn cable is insulated in ceramic cloth (left).

Better materials + simpler coil geometry can reduce magnet cost



Common Coil Magnets

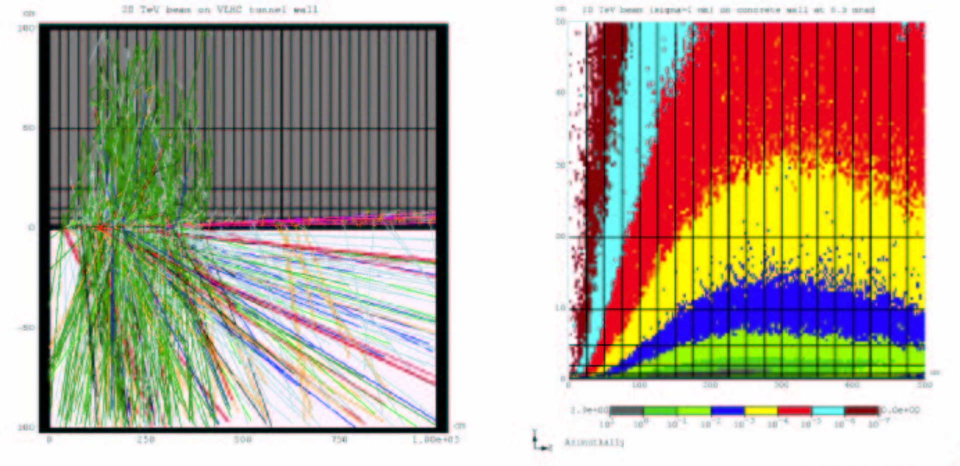




The National Conductor Program is already producing superior A15 conductor in industrial quantities @ lower $/kg

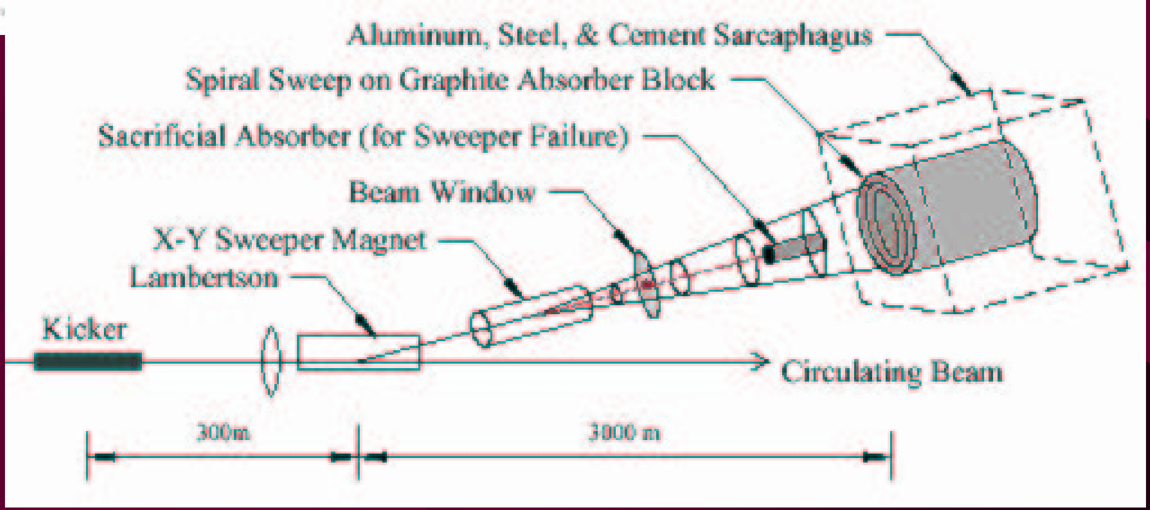
Radiation & Beam Abort: Worst- Case Accident

- 2. 8 GJ ~ 8 x LHC Energy (can liquify 400 liters of SS)



Normally extracted beam beam is swept in a spiral to spread the energy across graphite dump

If sweeper fails, the beam travels straight ahead into a sacrificial graphite rod which takes the damage & must be replaced.
Beam window also fails.



The next tunnel may be the last: Cost management through phased scenarios

C (km)	Magnet type	B-d (T)	fill factor	pp E(cm) TeV	ee E (cm) GeV	L (10^{34})
Single Tunnel scenarios						
120	Transmission Line	2.00	0.860	20		1
120	cos theta	11.20	0.780	100		1
228	Transmission Line	2.00	0.910	40		1
228	RHIC type	5.75	0.800	100		1
228	high field	12.00	0.765	200		1

FNAL’s VLH□C study has elaborated one such scenario

VLHC Study

www.vlhc.org

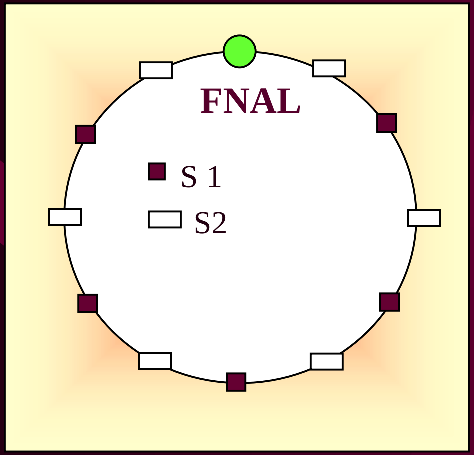
Study Leader - Peter Limon

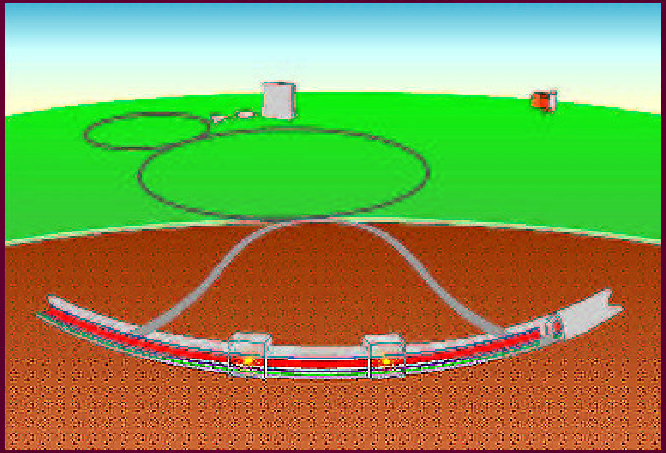
Charge to FNAL VLHC Study

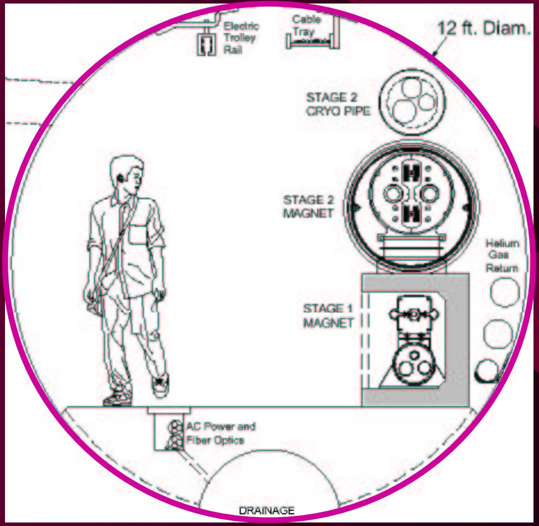
- Determine characteristics of post-LHC proton collider
  - Initial operation $E_{cm} > 30$ TeV & $L > 10^{34}$ cm^{-2} s^{-1}
  - Option for $E_{cm} > 150$ TeV collider in the same tunnel
- Identify major challenges:
  - technology & construction
  - important accelerator physics issues,
  - unusual operational, ES&H requirements
- Estimate present construction costs of major cost drivers
  - Assume Fermilab is the injector
- Identify areas of significant R&D to establish the technical basis for the facility.

Staged approach to VLHC

- Each stage promises new & exciting particle physics
  - Build a **BIG** tunnel, the biggest reasonable for the site
  - E = 40 TeV ==> C = 233 km for superferric design
- First stage assists in realizing the next stage
  - Choose large diameter tunnel
- Each stage is a reasonable-cost step across energy frontier
  - Use FNAL as injector & infrastructure base



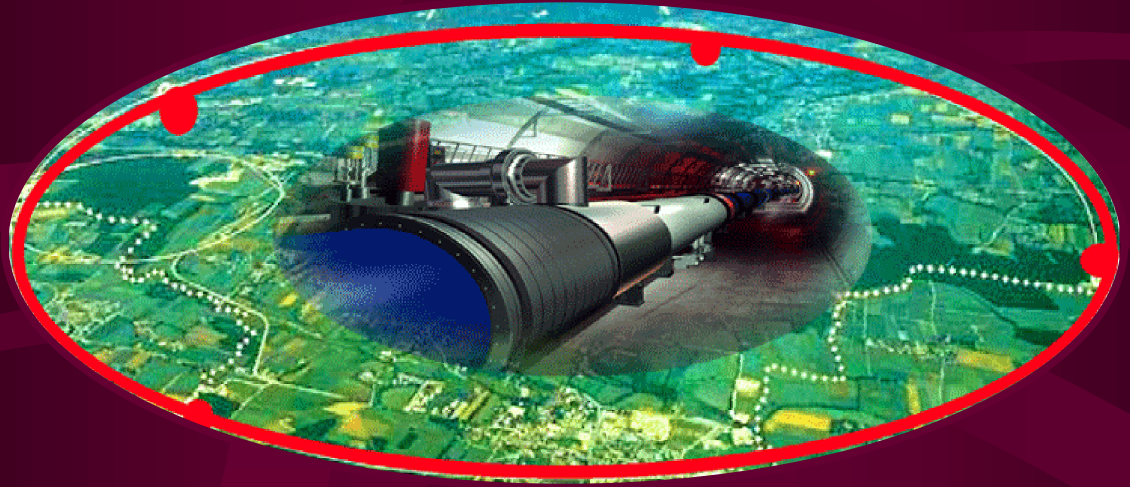




R&D is needed to reduce technical risk & cost, and to improve performance (Stage 1)

- Tunneling is the most expensive single part
  - Automation to reduce labor component and make it safer
- Beam instabilities & feedback: the largest risk factor
  - A combination of calculation, simulation & experiments
- Magnet field quality at injection and collision energy
  - This does not appear to be an issue, but needs more study
- Magnet production & handling; long magnets reduce cost
  - Reduce cost of steel yokes and assembly time & labor
- Installation requires complicated, interleaved procedure
  - Handling long magnets is tricky
- Vacuum & cryogenics: surprisingly expensive
  - Develop getters that work for methane, or cryopumps
  - Possible cryogenic instabilities due to long lines

LHC



Upgrades

See web site: http://cern.ch/lhc-proj-IR-upgrade

Committee considered 10 key questions

- **Minimum acceptable number of future experiments**
  - *ATLAS, CMS & ALICE can improve physics reach with detector upgrades*
- **Maximum events / crossing that detectors can swallow**
  - *At present ATLAS, CMS could accept L ~ 3 – 5 x* 10^{34} cm^{-2} s^{-1}
  - *Repositioning quadrupoles closer than 23 m probably requires redesign of calorimeters, muon detectors, shielding*
- **Maximum crossing angle & minimum acceptable beam separation at parasitic collision points**
  - *Depends on beam brilliance x number of parasitic collisions*
  - *Requires larger crossing angle*
- **Maximum aperture and gradient of future IR quads**
  - *A maximum gradient of ~350 T/m in ~55 mm aperture is possible*

Key questions for upgrade (cont’d)

- **Maximum field (energy) swing of LHC dipoles**
  - *Dipoles with 15 T and 2 T margin may be achievable*
  - *Present record dipole field is 14.7 T @ 4.2 K*
  - *Challenge is keeping cost/T-m same as present LHC dioles*
  - *Ideal energy swing is 3 x*
- **Magnet quench limit for higher LHC energy**
  - *Depends on magnet safety margin*
- **Maximum beam intensity on dumps at 7 TeV & 14 TeV**
  - *Increasing* I_b *from 0.56 A to 0.85 A okay with present dumps. Within present tunnels current could be raised to 2 A*
  - *Increasing energy to 14 GeV raises temperature by ~ 3 x*

Detectors: General Considerations

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
L	10^{34}	10^{35}
Bunch spacing Δt	25 ns	12.5 ns *
σ_{pp} (inelastic)	~ 80 mb	~ 80 mb
N. interactions/x-ing	~ 20	~ 100
($N = L \, \sigma_{pp} \, \Delta t$)		
$dN_{ch}/d\eta$ per x-ing	~ 150	~ 750
$\langle E_T \rangle$ charg. particles	~ 450 MeV	~ 450 MeV
Tracker occupancy	1	10
Pile-up noise in calo	1	~3
Dose central region	1	10

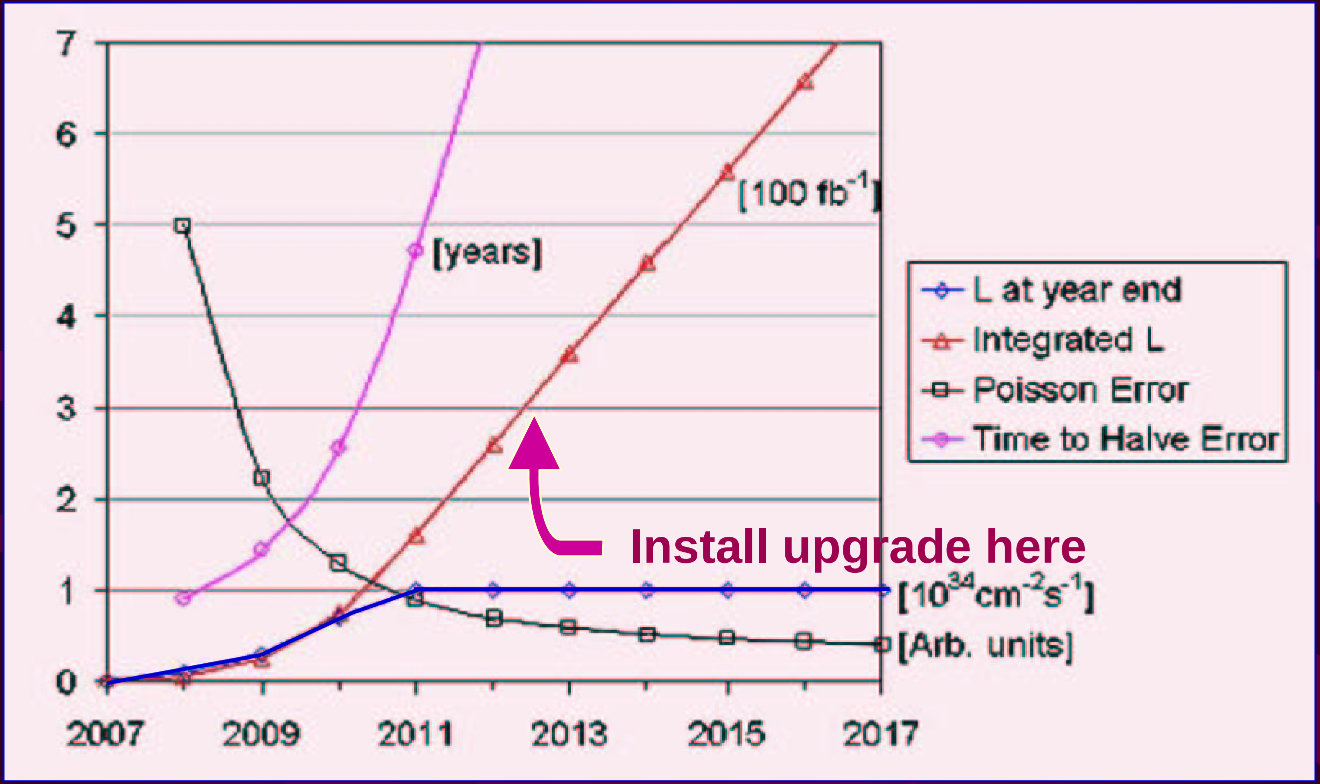
Normalised to LHC values

10^4 Gy/year R=25 cm

In a cone of radius = 0.5 there is E_T ~ 80GeV.

This will make low E_t jet triggering and reconstruction difficult.

Prepare for extending the energy frontier with LHC accelerator & detector luminosity upgrades now!



CERN task force considered several scenarios:

a) alternate IR-upgrades, injector chain upgrades, increase I_{beam}, superbunches

b) An energy doubler

LHC Phase 1: Luminosity Upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following baseline scheme:

or smaller!

1. modify insertion quadrupoles and/or layout → $\beta^* = 0.25\,\mathrm{m}$
2. increase crossing angle by $\sqrt{2} \to \theta_c = 445\,\mu\mathrm{rad}$
3. increase N_b up to ultimate intensity → $L = 3.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
4. halve σ_z with high harmonic RF system → $L = 4.6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
5. double number of bunches (and increase θ_c!) → $L = 9.2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
   excluded by electron cloud?

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$.

A 10x luminosity upgrade requires upgrading several accelerator and detector systems

- Interaction regions

  => smaller ß*, larger crossing angle, fewer parasitic collisions.

  => shorter bunches or crab cavities or superbunches

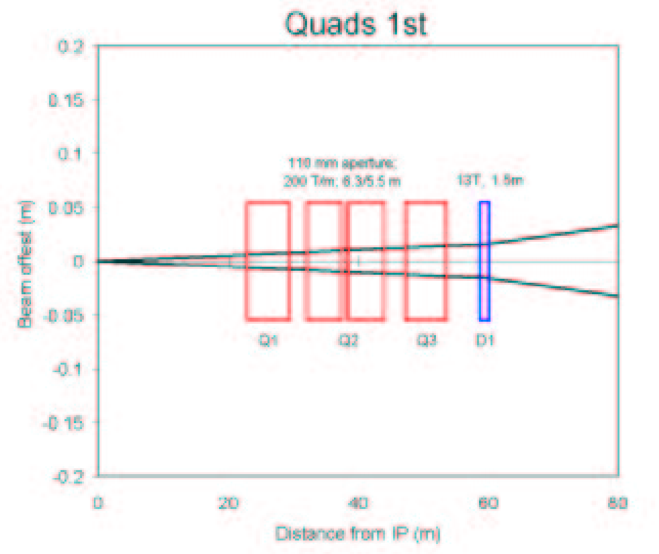
- Instrumentation, diagnostics, feedback systems

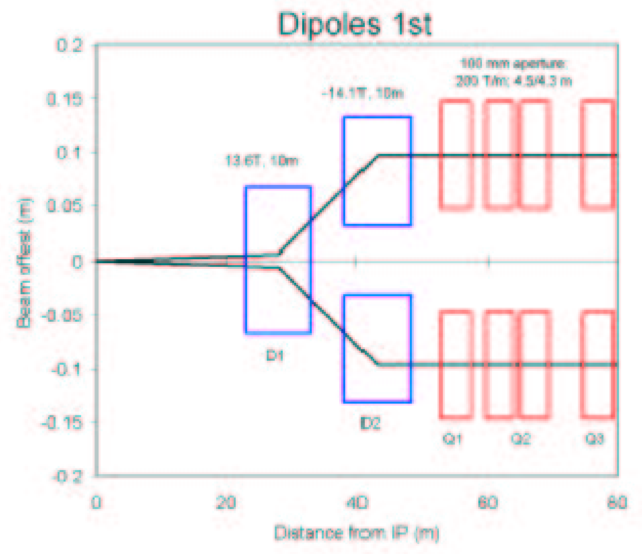
  => understand & deal with instabilities limiting beam current

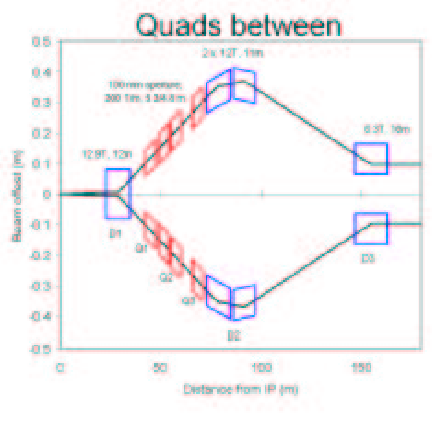
- For detectors trackers must be rebuilt, mons systems, calorimeters, triggers, DAQ need redevelopment

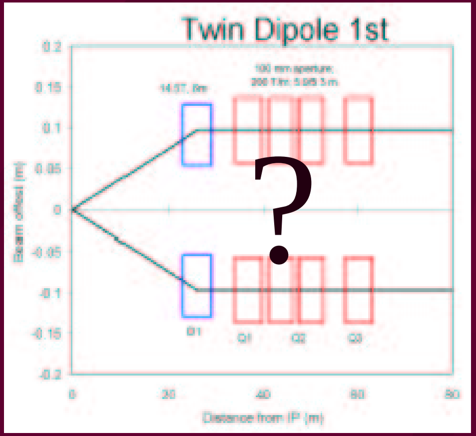
  => 8 - 10 year program…. Start now

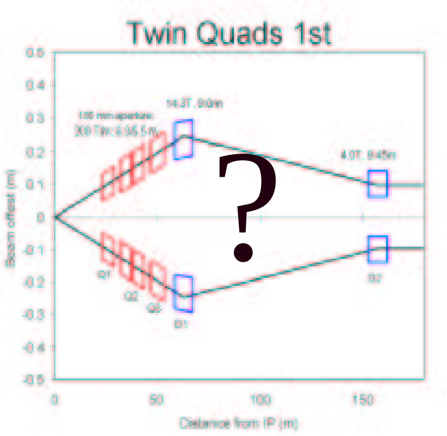
IR layouts for luminosity upgrade



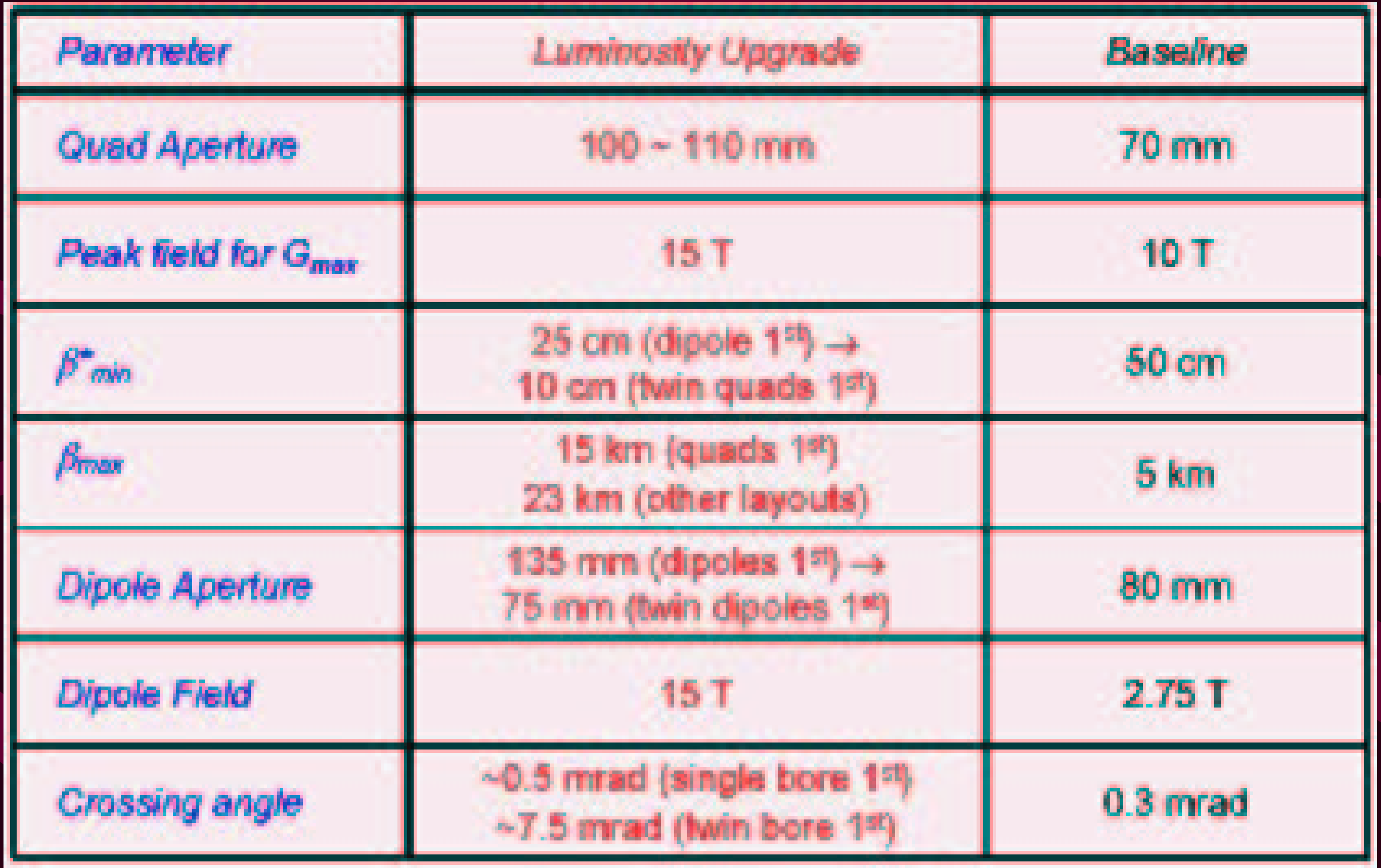








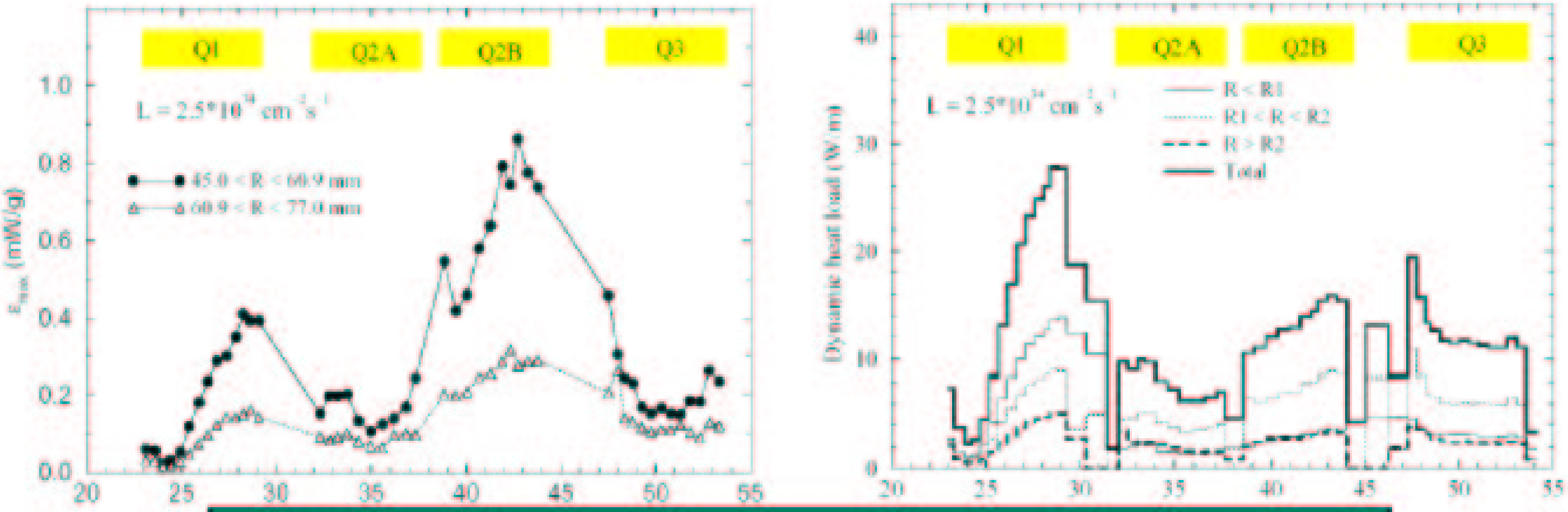
Interaction Region Upgrades



Parameter	*Luminosity Upgrade*	*Baseline*
Quad Aperture	100 ~ 110 mm	70 mm
Peak field for G_{max}	15 T	10 T
β^*_{min}	25 cm (dipole 1st) → 10 cm (twin quads 1st)	50 cm
β_{max}	15 km (quads 1st) 23 km (other layouts)	5 km
Dipole Aperture	135 mm (dipoles 1st) → 75 mm (twin dipoles 1st)	80 mm
Dipole Field	15 T	2.75 T
Crossing angle	~0.5 mrad (single bore 1st) ~7.5 mrad (twin bore 1st)	0.3 mrad

Radiation damage of IR magnets is a major issue for luminosity upgrade

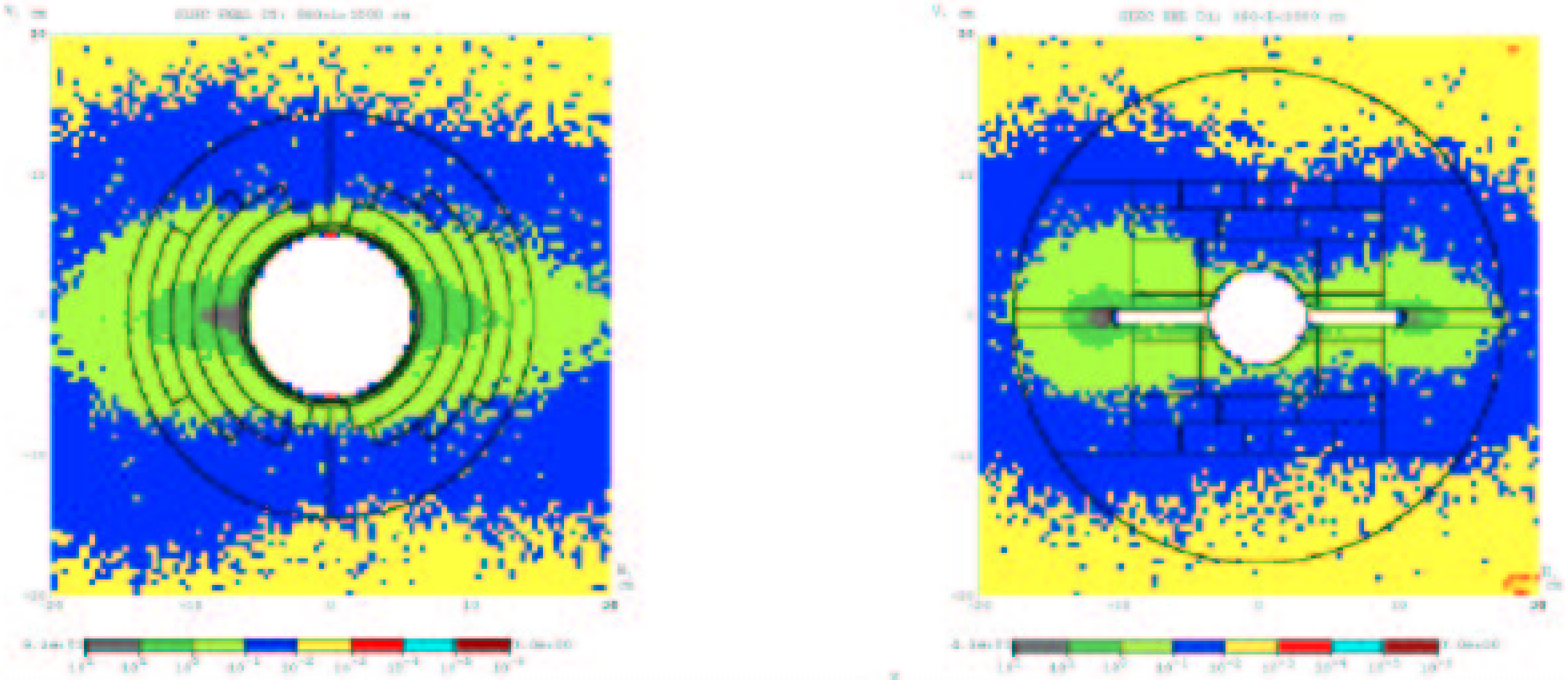
- In quad-first IR, E_{dep} increases both with L and with quad aperture.
  - $\varepsilon_{max} > 4$ mW/g, $(P/L)_{max} > 120$ W/m, $P_{triplet} > 1.6$ kW for $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.
  - Radiation lifetime for G11CR < 6 months at hottest spots.



T. Sen, et al., Beam Physics Issues for a Possible 2nd Generation LHC IR, EPAC 2002.

Problem is even more severe for dipole-first IR.

- ε_{max} on mid-plane ~ 50 mW/g; P_{dipole} ~3.5 kW for $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.
- "Exotic" magnet designs may be required, whose feasibility is not known.



N.V. Mokhov, et al., Energy Dep.Limits in a Separation Dipole in Front of the LHC High-L Inner Triplet, PAC 2003.

Magnet R&D for a Luminosity Upgrade

- Magnet R&D will be the largest part of the US LARP
    - Quads with largest possible aperture with G_{op} > 200 T/m for any new IR
    - Large-aperture dipoles for extreme radiation environment of a dipole-first IR
    - Vigorous program to develop Nb_3Sn magnet technology is required

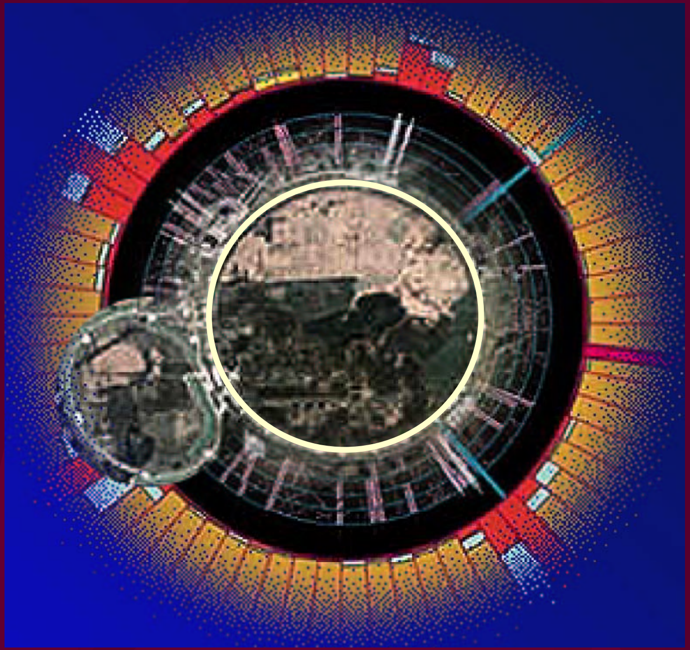
- Goal: magnet design(s) ready for production on the time scale of luminosity upgrade

- This work is a stepping stone to the magnets required for the next, higher energy hadron collider.

Energy Upgrade for LHC?

- We epect science requires a higher energy hadron collider beyond LHC
    - A higher energy machine in the same tunnel is one option.
    - Virtue of an “energy doubled” LHC: Uses CERN infrastructure.
- Concerns:
    - It will be expensive and require a long shutdown.
    - Nb3Sn fundamental properties limit energy step to only < x1.8
    - Requires multi-year shutdown

Summary comments



If we can afford a linear collider, we can afford ELN