Collider Physics: The Farthest Energy Frontier
Lecture 2

William Barletta

United States Particle Accelerator School

Dept. of Physics, MIT

VLHC/ELN: Offers decades of forefront particle physics

- A large advance beyond LHC
  - The last big tunnel
  - Multi-step scenarios are the most realistic
  - Eventually 50 to >100 TeV per beam
- Discovery potential of VLHC far surpasses that of lepton colliders
  - Much higher energy plus high luminosity
  - The only sure way to the next energy scale

Could this really be done?

Let's work backward from the collision point

Luminosity formula exposes basic challenge of the energy frontier

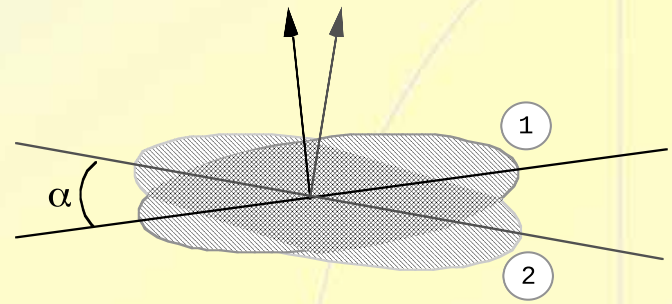
Assume that $\sigma_z < \beta^*$

Neglect corrections for α

Set $N_1 = N_2 = N$

$\varepsilon_x = \varepsilon_y$ and $\beta_x = \beta_y$

Collision frequency is $(\Delta t_{coll})^{-1} = c/S_{Bunch}$



$$L = \frac{N^2 c\gamma}{4\pi\varepsilon_n \beta^* S_B} = \frac{1}{e r_i m_i c^2}\frac{N r_i}{4\pi\varepsilon_n}\left(\frac{EI}{\beta^*}\right) = \frac{1}{e r_i m_i c^2}\frac{N r_i}{4\pi\varepsilon_n}\left(\frac{P_{beam}}{\beta^*}\right) \qquad i = e, p$$

Linear or Circular

Other parameters remaining equal

$\mathbf{L_{nat} \propto Energy}$ but $\mathbf{L_{required} \propto (Energy)^2}$

"Pain" associated with going to higher energy grows non-linearly

Most "pain" is associated with increasing beam currents.

Potential strategies to increase luminosity

- 1) Increase the charge per bunch, N
- 2) Increase the number of bunches, to raise I
- 3) Increase the crossing angle to allow more rapid bunch separation,
- 4) Tilt bunches with respect to the direction of motion at IP ("crab crossing") *(will not present this)*
- 5) Shorten bunches to minimize β^*

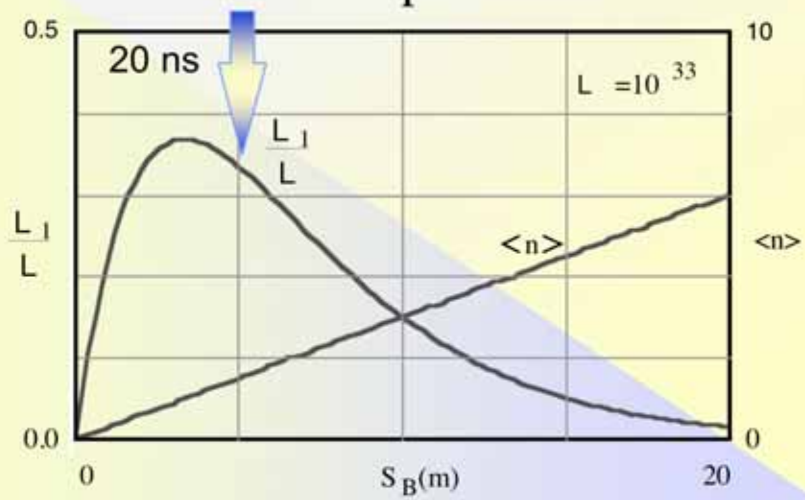
These approaches are used in the B-factories

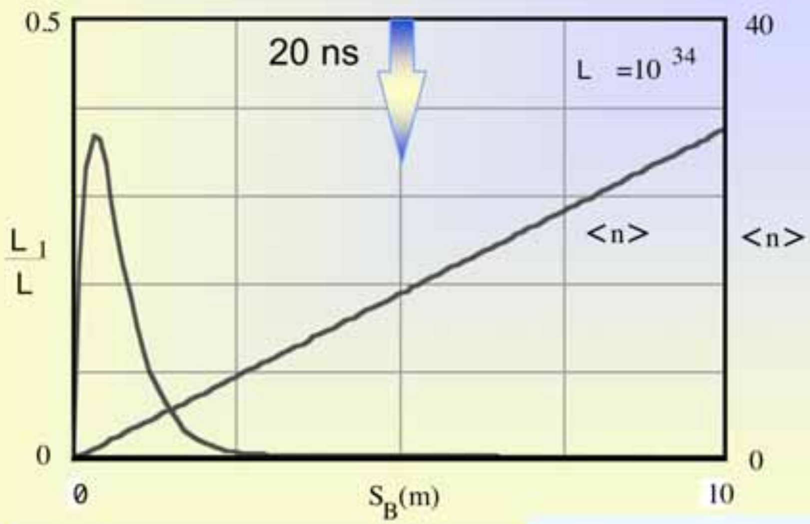
What sets parameter choices?

- How do we choose N, S_B, β^*, and ε_n as a function of energy?
  - → Detector considerations
    - ◆ Near zero crossing angle
    - ◆ Electronics cycling ≥ 20 ns between crossings
    - ◆ Event resolution ≤ 1 event/crossing
    - ◆ Distinguish routine vs. peak luminosity running
  - → Accelerator physics
    - ◆ Tune shifts
    - ◆ Luminosity lifetimes
    - ◆ Emittance control
  - → Accelerator technologies
    - ◆ Synchrotron radiation handling
    - ◆ Impedance control
    - ◆ Radiation damage
    - ◆ Magnet technologies

Bunch spacing: Crucial detector issue

20 TeV per beam





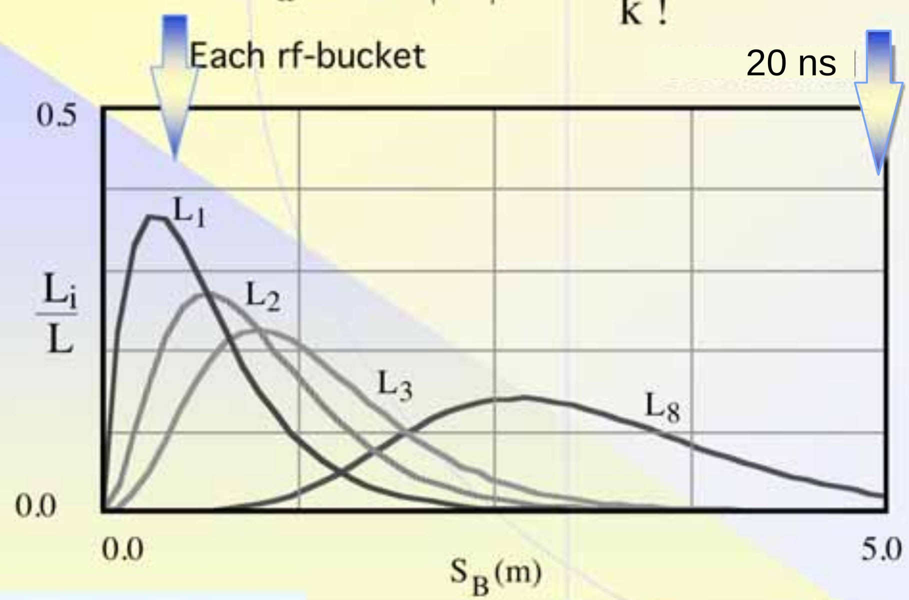
$$\sigma_{inel} \sim \ln E_{cm}$$

Most probable # events per crossing

$$\langle n \rangle = \frac{L \ \sigma_{inel} S_B}{c}$$

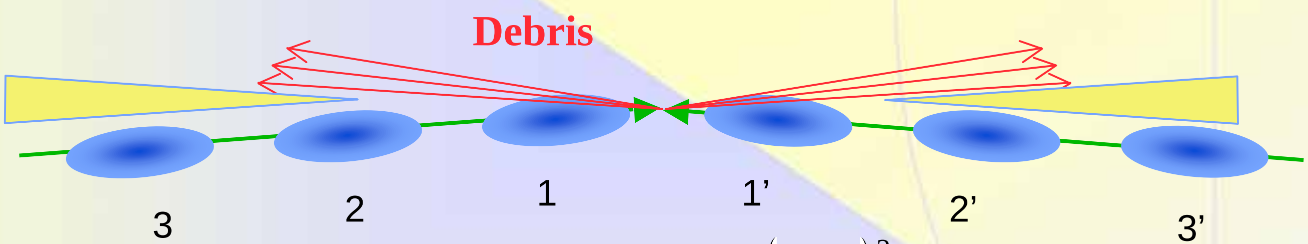
Fractional luminosity for k events per crossing

$$L_k = L \ \langle n \rangle^k \frac{\exp(-\langle n \rangle)}{k\,!}$$



If you could reset electronics every 5 ns…

- Minimum bunch spacing is set by filling every rf-bucket
  - → High radio frequencies are preferred, but
    - ◆ 1) must control impedances ==> superconducting rf
      - ❖ Go to high V_{rf} per cavity
      - ❖ requires powerful wideband feedback system
    - ◆ 2) avoid excessive long rang tune shift, $\Delta\nu_{LR}$
      - ❖ ==> larger crossing angle



$$\Delta\nu_{LR} = \Delta\nu_{HO}\, 2n_{LR} \left(\frac{\sigma}{\beta^* \alpha}\right)^2$$

$$\Delta\nu_{HO} = \frac{N_B\, r_p}{4\pi\,\varepsilon_n}$$

$$\Delta\nu_{tot} = \left(N_{Hi,IP} + N_{Med,IP}\right)\Delta\nu_{HO} + N_{Hi,IP}\,\Delta\nu_{LR}$$

What is the allowable tune shift ?

- From experience at $S\bar{p}pS$ and the Tevatron

$$\Delta\nu_{tot} \leq 0.024$$

- Luminosity is maximized for a fixed tune spread when 3/4 of $\Delta\nu_{tot}$ is allocated to $\Delta\nu_{HO}$ and 1/4 to $\Delta\nu_{LR}$
- Suggests that ultimate luminosity can be reached for

$$N_{Hi,IP} = 1 \quad \text{and} \quad N_{Hi,Med} = 0$$

→ However, validity of extrapolation is unknown

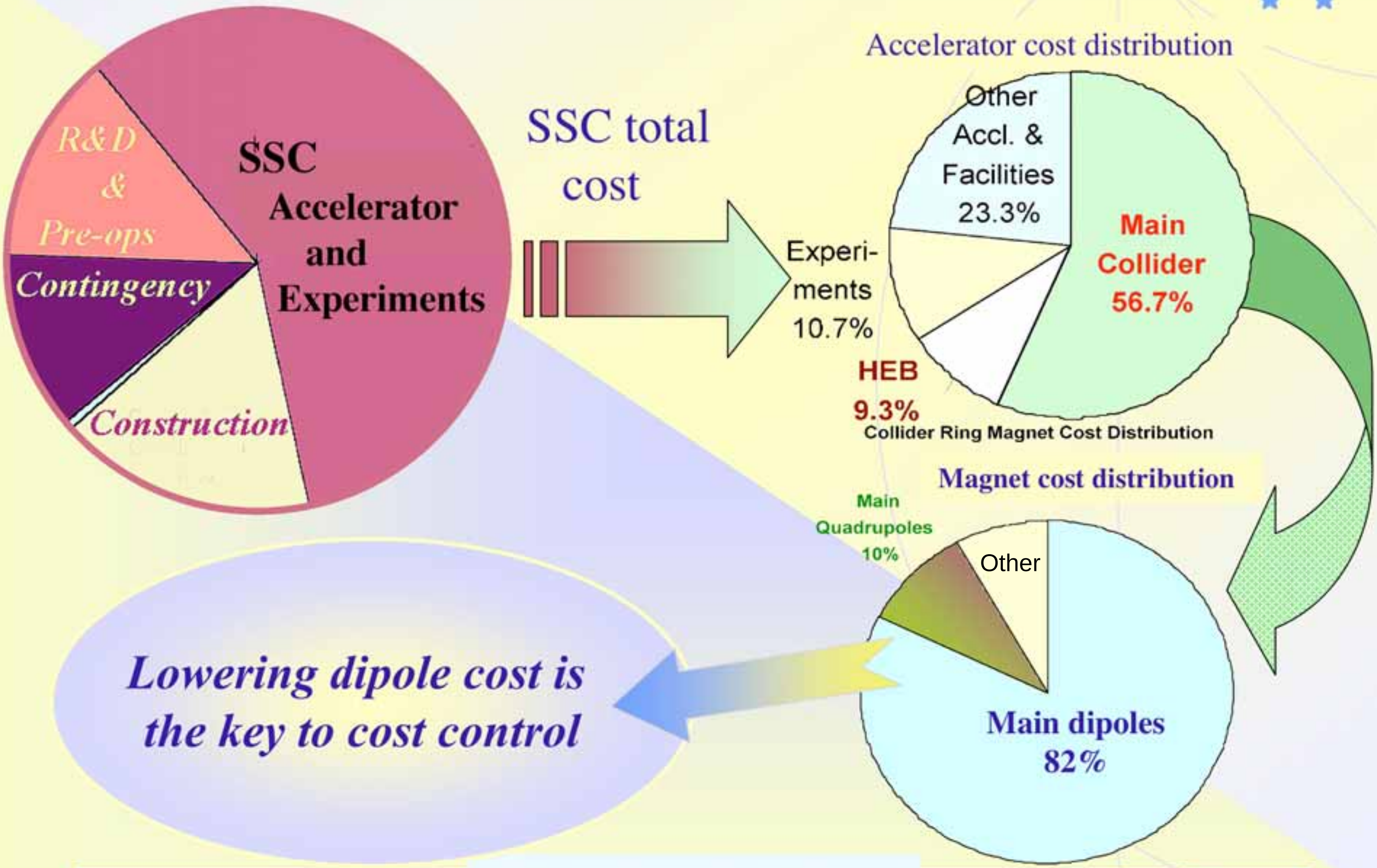
- may depend on radial distribution of particles in bunch.

- Assume maximum $\Delta\nu_{HO}$ per IP is ~0.01
- In $e^+ e^-$ colliders $\Delta\nu_{tot} = 0.07$ achieved at LEP

Supercollider components that affect energy & luminosity limits

- Injector chain
  - Linac
  - Lower energy booster synchrotrons
- Main ring
  - Dipoles - bend beam in “circle”
  - Quadrupoles - focus beam
  - RF cavities - accelerate beam, provide longitudinal focusing
  - Feedback - stabilizes beam against instabilities
  - Vacuum chamber - keeps atmosphere out
  - Cooling - removes waste heat
  - Beam dumps & aborts - protects machine and detectors
- Interaction Regions and detectors
  - Quadrupoles to focus beam
  - Septa to decouple beams electromagnetically
  - Detector to do particle physics

SSC experience indicates cost drivers



Dipole magnet type distinguishes strategies for VLHC design

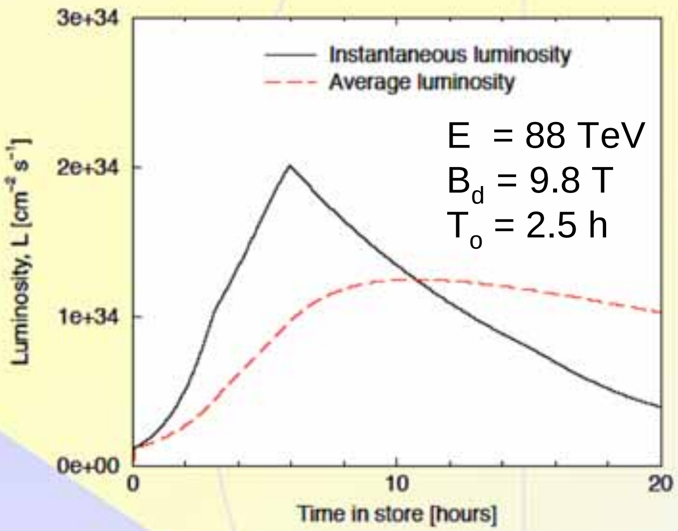
- Low field, superferric magnets
  - → Large tunnel & very large stored beam energy
  - → Minimal influence of synchrotron radiation
- "Medium" field design
  - → Uses ductile superconductor at 4 - 8 T (RHIC-like)
  - → Some luminosity enhancement from radiation damping
- High field magnets with brittle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

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

Dominant beam physics @ 50 TeV/beam: synchrotron radiation

- Radiation alters beam distribution & allowed $\Delta\nu$ at acceptable backgrounds
- Radiation damping of emittance increases luminosity
  - → Limited by
    - ◆ Quantum fluctuations
    - ◆ Beam-beam effects
    - ◆ Gas scattering
    - ◆ Intra-beam scattering
  - → Maybe eases injection
  - → Maybe loosen tolerances

  ==> Saves money ?

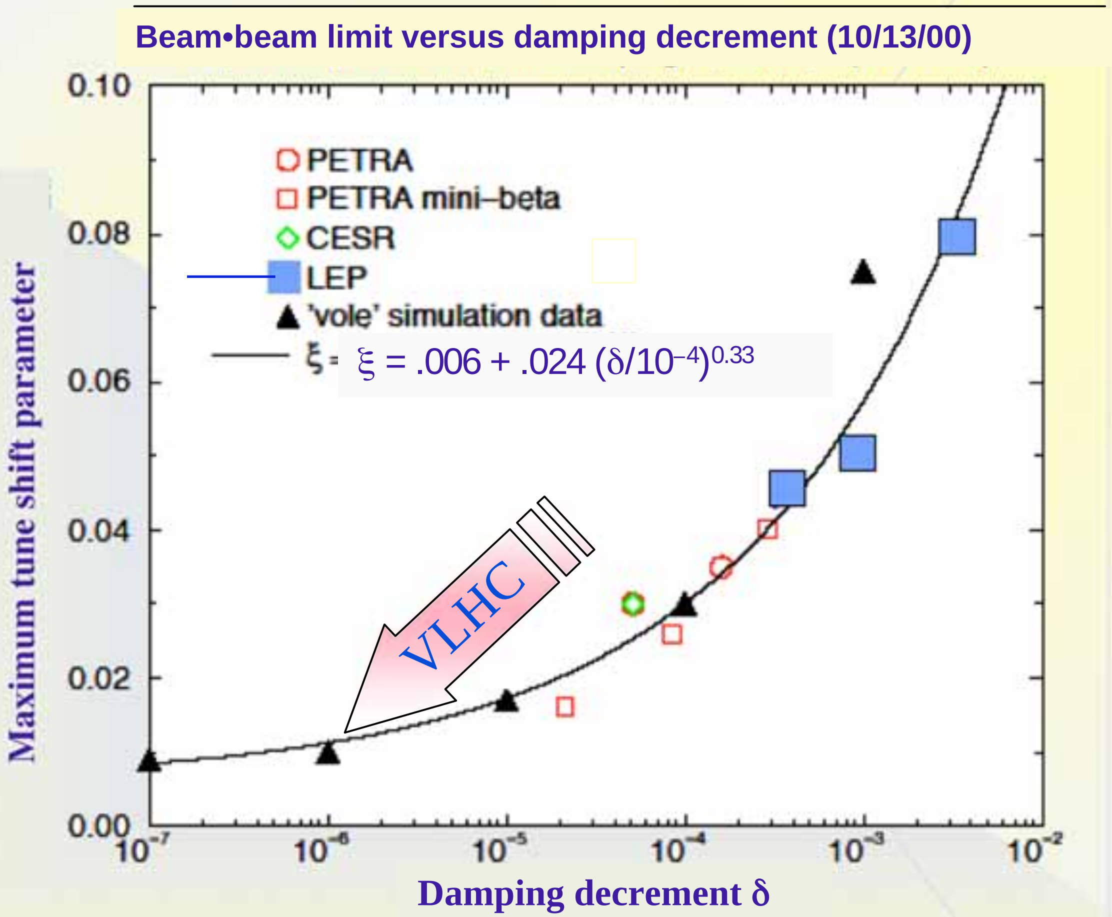


- Energy losses limit I_{beam}
  - → 1 - Heating walls ==> cryogenic heat load ==> wall resistivity ==> instability
  - → 2 - Indirect heating via two stream effects
  - → 3 - Photo-desorption => beam-gas scattering => quench of SC magnets

  ==> Costs money

$$U_o = \frac{4\pi r_p m_p c^2}{3} \frac{\gamma^4}{\rho} = 6.03 \times 10^{-18} \frac{\gamma^4}{\rho\,(m)} \text{ GeV}$$

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



Damping decrement fractional damping per turn

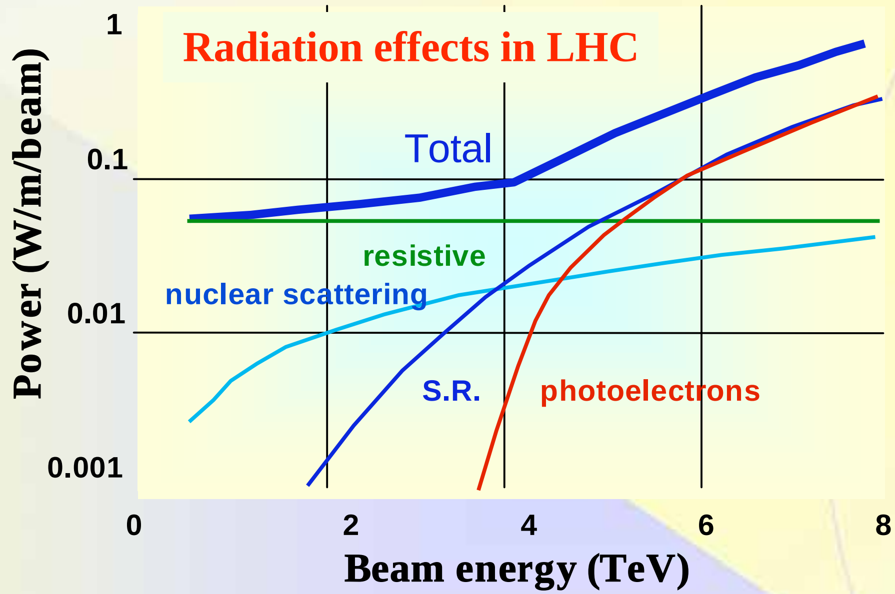
Beam dynamics of marginally damped collider needs experimental study

Comparison of SR characteristics

		LEP200	LHC	SSC	HERA	VLHC
Beam particle		e+ e-	p	p	p	p
Circumference	km	26.7	26.7	82.9	6.45	95
Beam energy	TeV	0.1	7	20	0.82	50
Beam current	A	0.006	0.54	0.072	0.05	0.125
Critical energy of SR	eV	$7\ 10^5$	44	284	0.34	3000
SR power (total)	kW	$1.7\ 10^4$	7.5	8.8	$3\ 10^{-4}$	800
Linear power density	W/m	882	0.22	0.14	$8\ 10^{-5}$	4
Desorbing photons	$s^{-1}\ m^{-1}$	$2.4\ 10^{16}$	$1\ 10^{17}$	$6.6\ 10^{15}$	none	$3\ 10^{16}$

Thermal loads constrain current in high field designs

- Direct thermal effects of synchrotron radiation:



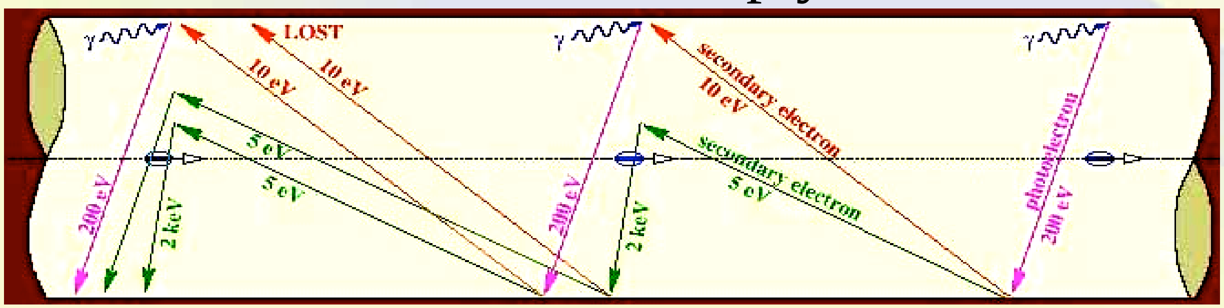
Scaling with I_b & E

$$P \propto \rho_w I^2 \leq 0.05 (W/m)$$

$$P(W/m) = 1.24 \cdot 10^3 \frac{E^4(TeV)\ I(A)}{\rho^2(m)}$$

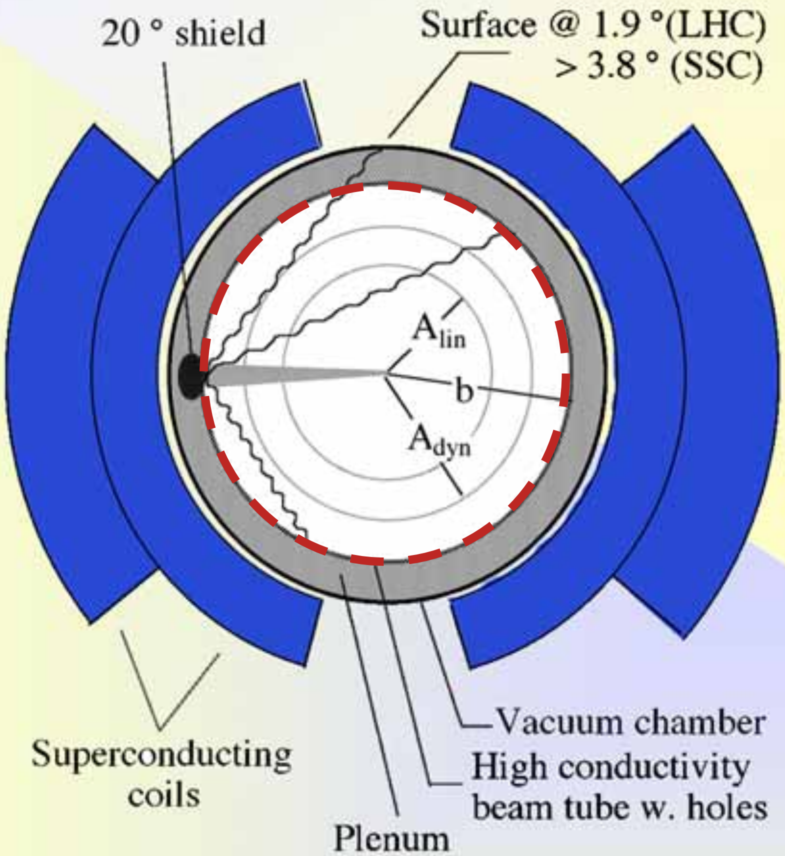
$$P(W/m) = 0.93 \frac{I(A)\ E(TeV)}{\tau(h)}$$

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



Scales with photon number ~ IE

Physics & technology of vacuum chamber in arcs seriously limits collider performance



$$P_{compress} \approx 5.4 \left(\frac{300\,°K - T_{wall}}{T_{wall}} \right) P_{synch}$$

Major determinant of operating costs

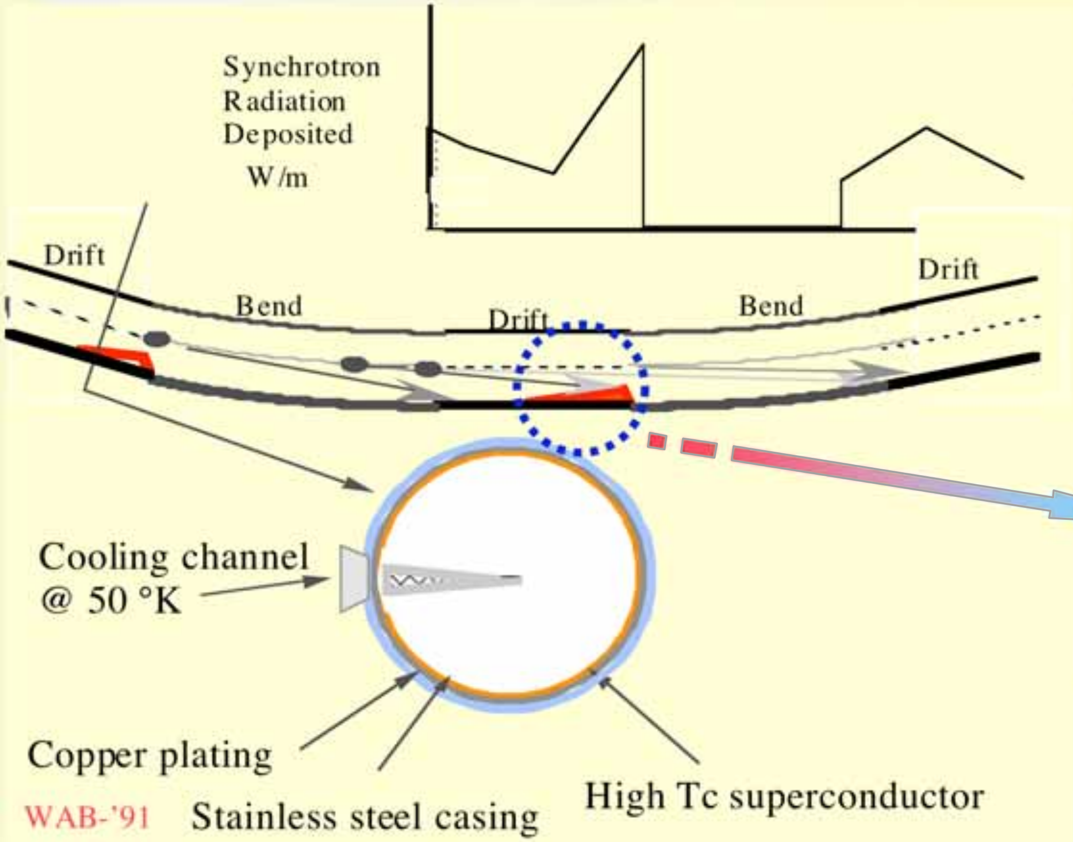
- Considerations that can limit luminosity: residual gas, instabilities
- Holes for heat removal & pumping must be consistent with low Z(ω)
- As plenum gets larger & more complex cost rises rapidly

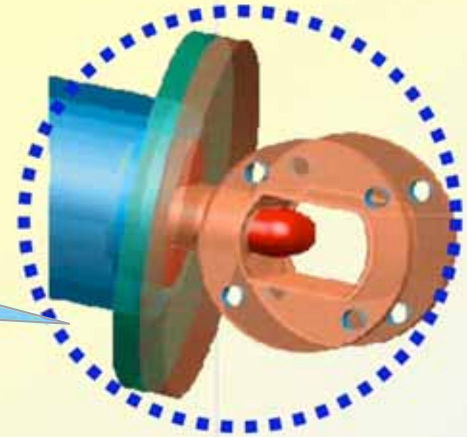
Vacuum/cryo systems: Scaling LHC is not an option

- 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.

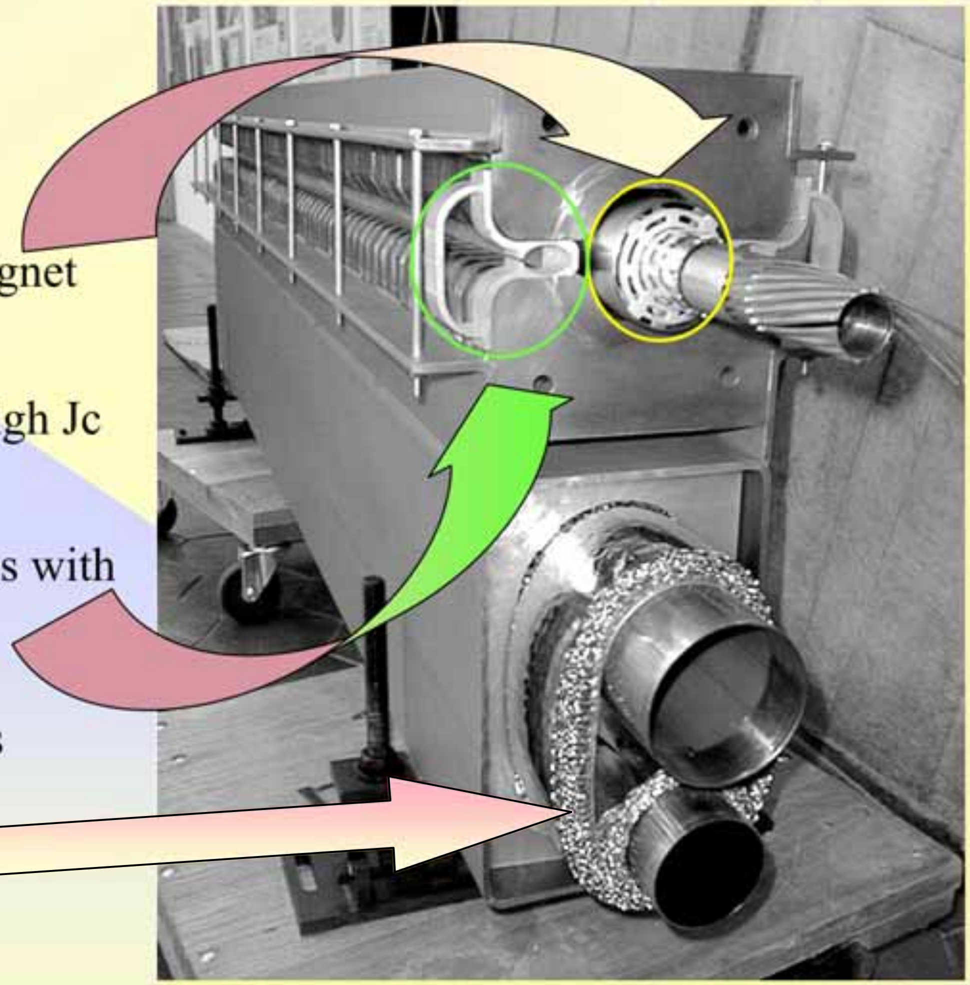
* B @ conductor ~ 1 T; NbTi has high Jc ==> low superconductor usage.

* 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.



Technical challenges for RF System

- Provide large power for synchrotron radiation losses
  - → (5.5 MW in B factory HER @ L_{des}; ≈ 2 MW in VLHC)
- Provide large voltage for short bunches (easier with SC rf)
- Minimize Higher Order Mode (HOM) impedance
- Options:
  - → 1) Fundamental mode frequency (*200 - 600 MHz)*
  - → 2) Room temperature v. SC rf-cavities (Need fewer cavities)
  - → 3) Time domain or frequency domain feedback
- Design approach (B factories):
  - → Minimize number of cavities with high gradient
  - → 500 kW/window ==> >120 kW_{therm}/cavity => difficult engineering
  - → Shape cavity to reduce HOMs
  - → High power, bunch by bunch feedback system ($T_{multi\text{-}bunch}$ ≈ 1 - 5 ms)

Short luminosity lifetime at maximum L requires powerful injection chain

- Beam loss by collisions at L_{max} limits minimum I_{beam} at injection

$$\frac{1}{L}\frac{dL}{dt} = \frac{2}{N_{bunch}}\frac{dN_{bunch}}{dt} - \frac{1}{\varepsilon}\frac{d\varepsilon}{dt}$$

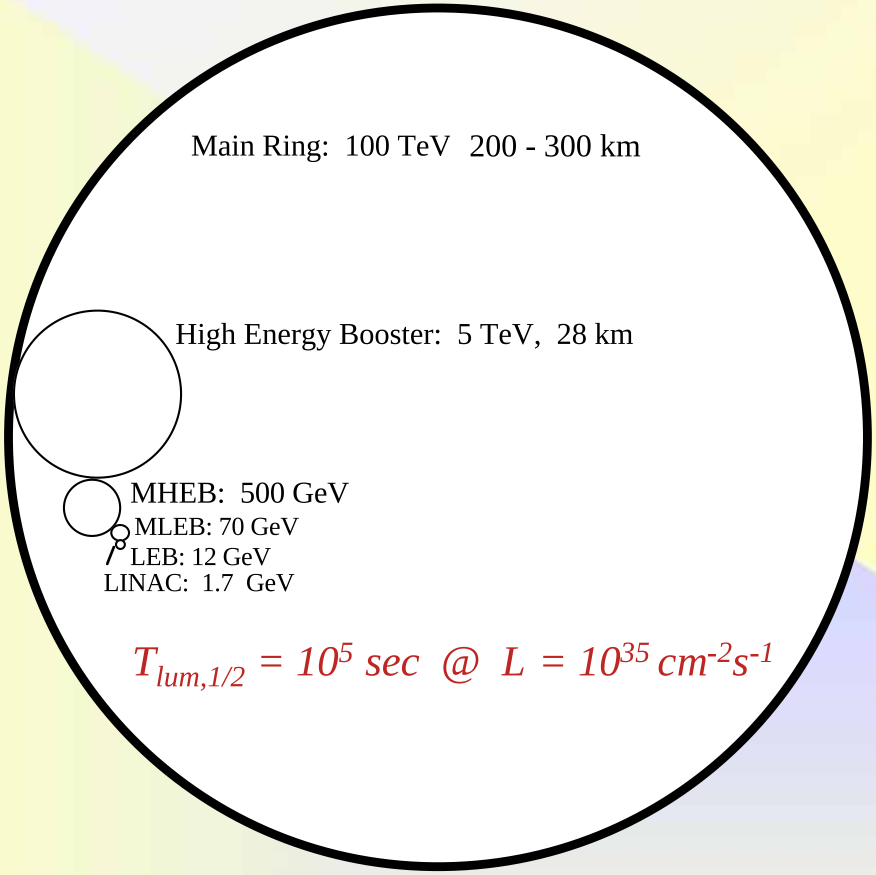
$$\tau^{-1}_{lum}(E) = \frac{1}{N_{bunch}}\frac{dN_{bunch}}{dt} = \frac{L\ \Sigma_{inel}(E)}{M\ N_{bunch}}$$

$$T_{1/2,\,lum} \approx 0.41\ \tau_{lum}(E)$$

$$T_{inj} < 0.1\ T_{1/2,lum}$$

- For large I_{beam} & N_{bunch} : resistive wall instability sets minimum injection energy for main ring
- Space charge tune spread sets energy of linac & boosters

Example: Loading 500,000 bunches for high L



	Circum (km)	Max E	Min E
Main Ring	270	100 TeV	5 TeV
HEB	28	5 TeV	0.5 TeV
MHEB	2.9	500 GeV	70 GeV
MLEB	0.35	70 GeV	12 GeV
LEB	0.1	12 GeV	1.7 GeV
LINAC	0.1	1.7 GeV	—

	Bunches	$\Delta\nu_{SC}$	Cycle T (s)
Main Ring	500000	1.60E-04	1000
HEB	50000	1.60E-03	300
MHEB	5000	7.97E-03	30
MLEB	200	9.61E-03	1.2
LEB	10	1.23E-02	0.06
LINAC	5	—	0.03

Total loading time 3000 sec / main ring (1.5 nC/bunch)

Total acceleration time 1000 sec / main ring ==> Total fill at 100 TeV = 8000 sec

Radiation from IP at high L

- From hadronic shower

$$\text{Dose} \propto N_{collision} \times \sigma_{inel} \times \text{Charged multiplicity/event} \times \frac{dE}{dx}$$

or

$$\text{Dose} \propto N_{collision} \frac{d^2 N_{charged}}{d\eta\, dp_\perp} \frac{dE}{dx}$$

where

$$\frac{d^2 N_{charged}}{d\eta\, dp_\perp} \approx H f(p_\perp)$$

with η = psuedo-rapidity = - ln (tan $\theta/2$)

H = height of psuedo-rapidity plateau

- Detailed studies show that dose is insensitive to form of $f(p_\perp)$; use $f(p_\perp) = \delta(p_\perp - \langle p_\perp \rangle)$
- Approximately half as many π^o's are produced

Scaling of radiation from hadronic shower

- Power in charged particle debris (per side)

$$P_{debris} = 350\ \mathrm{W}\left(\frac{L}{10^{33}}\right)\left(\frac{\sigma_{inel}}{90\ \mathrm{mb}}\right)\left(\frac{E}{20\ \mathrm{TeV}}\right)$$

- Radiation dose from hadron shower

$$D(E,r) = 26.1\,\frac{\mathrm{Gy}}{\mathrm{yr}}\left(\frac{L}{10^{33}}\right)\left(\frac{\sigma_{inel}}{90\ \mathrm{mb}}\right)\left(\frac{H(E)}{7.5}\right)\left(\frac{\langle p_\perp\rangle}{0.6\ \mathrm{GeV}}\right)^{0.9}\frac{\cosh^{2.9}\eta}{r^2}$$

where

r = distance from IP in meters

η = psuedo-rapidity = - ln (tan $\theta/2$)

H = height of rapidity plateau = 0.78 $s^{0.105}$
≈ constant for $\eta < 6$ ($\theta > 5$ mr)
for $\eta > 6$, H(E) —> 0 linearly @ kinematic limit

$\langle p_\perp \rangle = 0.12 \log_{10} 2E + 0.06$

$s = 4 E^2$

Radiation damage of IR components severely limits maximum luminosity

- Distance to first quad, Q1: $l^* \propto \beta^* \propto (\gamma / G)^{1/2}$

$$l^* = 20\text{ m}\left(\frac{E}{20\text{ TeV}}\right)^{1/2}$$

- Let Q1 aperture = 1.5 cm ==>

At 100 TeV & $L = 10^{35}$ cm^{-2}s^{-1}

P_{debris} = 180 kW/side

With no shielding

D (Q1) ≈ 4 x 10^8 Gy/year

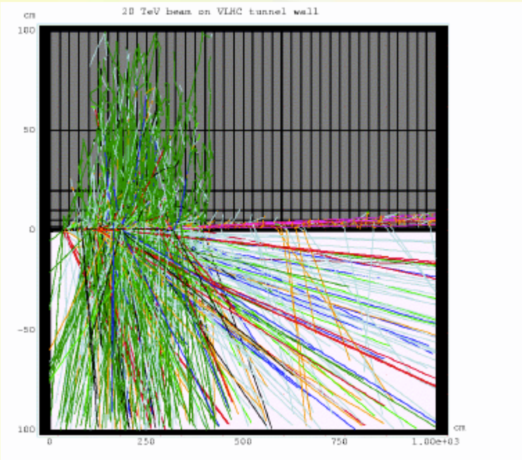
==> ≈ 45 W/kg in Q1

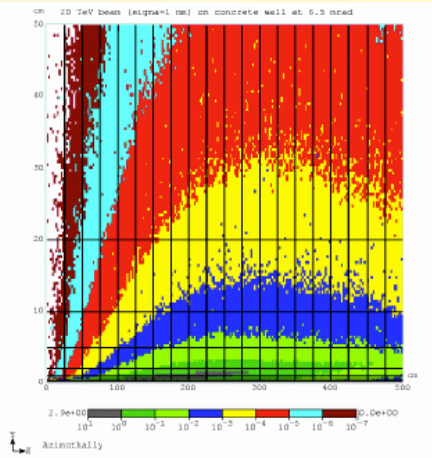
- Superconducting Q1 requires ≈ 20 kW/kg of compressor power

At $L = 10^{35}$ cm^{-2}s^{-1} Q1requires extensive protection with collimators

Radiation & Beam Abort: Worst- Case Accident

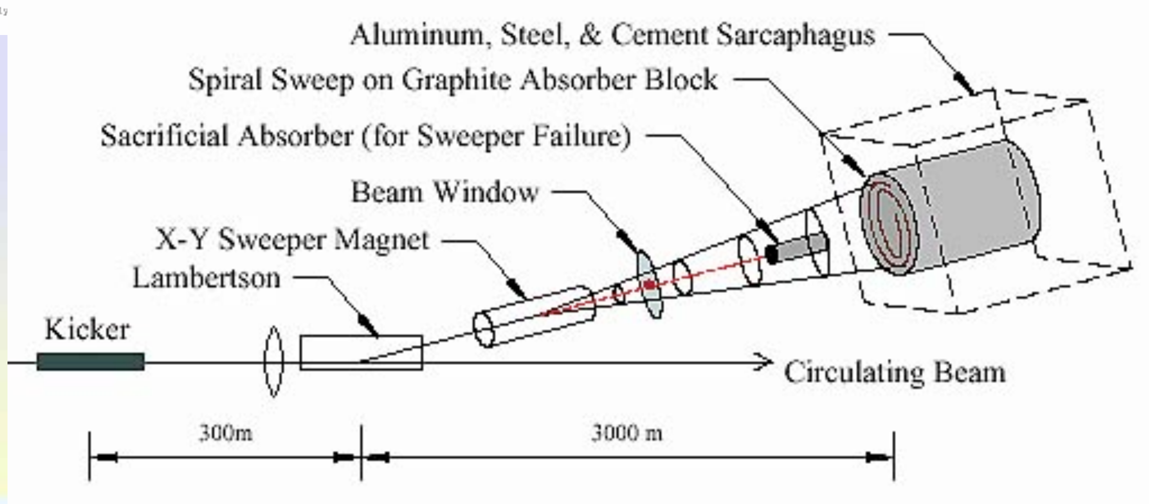
- 2. 8 GJ ~ 8 x LHC Energy (can liquify 400 liters of SS)





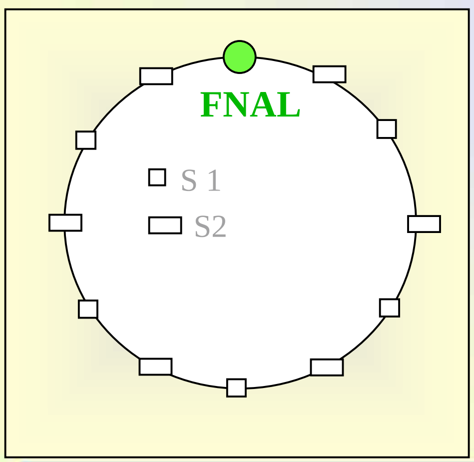
Normally extracted beam beam is swept in a spiral to spread the energy across graphite dump

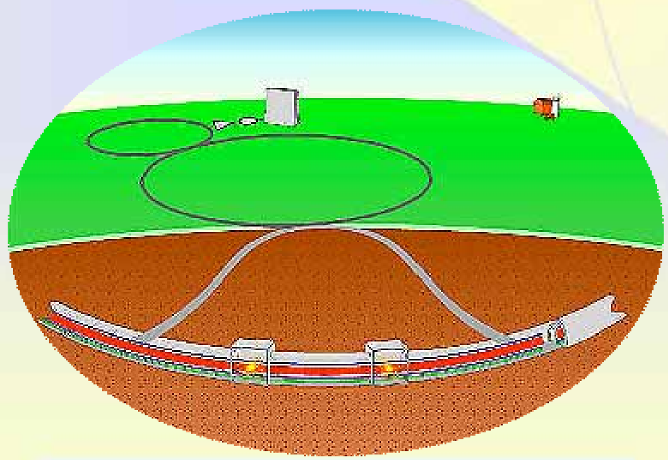
If sweeper fails, the beam travels straight ahead into a sacrificial graphite rod which takes the damage & must be replaced.
Beam window also fails.

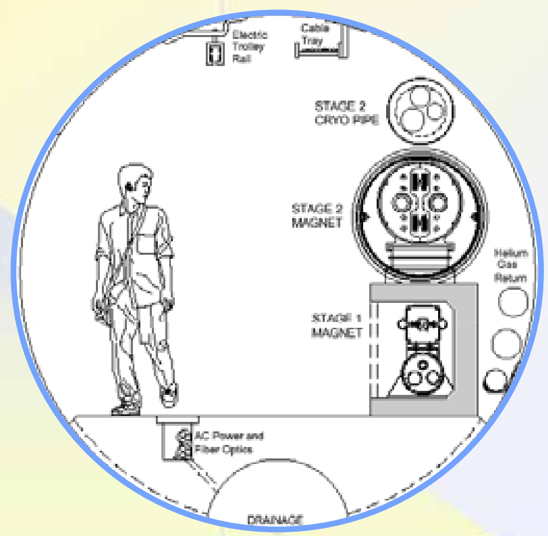


FNAL-BNL-LBNL Study: Staged approach to VLHC

- 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







Parameter list for VLHC study

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity (10^{34} cm -2 s -1)	1	2
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial Protons per Bunch (10^{10})	2.6	0.8
Bunch Spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	133
Interactions per bunch crossing at L_{peak}	21	58
P_{synch} (W/m/beam)	0.03	4.7
Average power (MW) for collider	20	100
Total installed power (MW) for collider	30	250

R&D will reduce technical risk & cost & 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

Can VLHC be a linear proton collider ?

- Say $L_{coll} < 250$ km ==> $E_{acc} \sim 1$ GeV/m ==> $f_{rf} \approx 100$ GHz

$$L\ (10^{33}\ cm^{-2}\ s^{-1}) = \frac{D\ H_D}{30}\left(\frac{1\ mm}{\sigma_z}\right)\left(\frac{P_{beam}}{1\ MW}\right)$$

H_D is the luminosity degradation due to the pinch effect

D is the disruption parameter that measures the anti-pinch

$$D = \frac{r_p N_B \sigma_z}{\gamma\, \sigma^2_{x,y}} = r_p N_B \left(\frac{\sigma_z}{\beta^* \varepsilon_n}\right)$$

For $D < 2$, the value of $H_D \approx 1$.

At 100 TeV/beam, $\beta^* \sim 1$ m & $\varepsilon_n \sim 10^{-6}$ m-rad

- For $f_{rf} = 100$ GHz, $\sigma_z \sim 10^{-6}$ m ==> $\sigma_z/\beta^*\varepsilon_n \approx 1\ m^{-1}$
- Assume we can

  1) generate bunches of 100 nC & 2) preserve emittance in the linac

$$r_p N_B \sim 10^{-6}\ m$$

- Hence $10^{33}\ cm^{-2}\ s^{-1}$ ==> $P \approx 30$ GW per beam

  ==> the ultimate supercollider should be a synchrotron

Conclusions

- No insurmountable technical difficulties preclude VLHC at ~10^{35} cm^{-2} s^{-1} with present technologies
  - → Radiation damage to detectors & IR components is a serious issue
- At the energy scale >10 TeV the collider must recirculate all the beam power (must be a synchrotron)
- Proton synchrotrons could reach up to 1 PeV c.m. energy
  - → One must find a way to remove the synchrotron radiation from the cryo-environment
  - → Even given the money, big question is whether the management and sociology of such a project (~1000 km ring) is feasible