The Challenges of a Storage Ring-based Higgs Factory

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Caveat emptor

This is a zero-order pedagogical look
based on basic accelerator physics
My numbers are not CERN’s numbers,
but they are quite close (~5%)

For a more precise analysis
based on a real lattice design look at
arXiv: 1112.2518.pdf
by F. Zimmermann and A. Blondel

Scenario: LHC has discovered the Higgs

- Your HEP friends want to study its properties
  - "Monte Carlo studies show that you need ~ 25 K Higgs for a paper that can get the cover of Nature"
  - They & their students don't want to be on shift for a lifetime
- They comes to you, his favorite machine builder

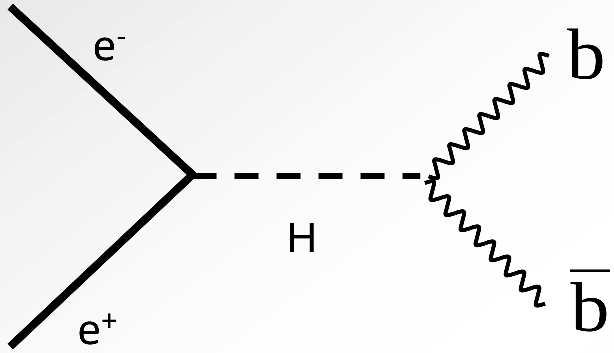
  "We *need* to build a factory to produce 6000 Higgs per year. Projected costs (€ 15 B) all but killed the ILC. Now we know that we don't need 500 GeV. What about something half that energy?"
- You reply,
  - "You don't understand about linacs. Half the energy costs you 75% of the original price."

"Let's try something different - a storage at CERN .

After all LEP 2 got up to 209 GeV."

What LEP2 might have seen

How can we produce a Higgs with e^+e^-?



They respond, "Exactly, but they did not see anything!

The cross-section ~ 2 fb. They would have had to run for decades.

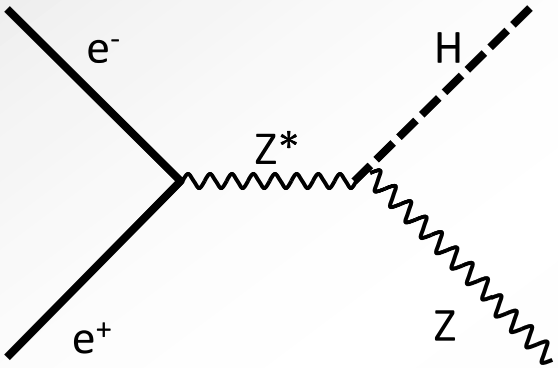
A muon collider would be ideal. The σ_H is 40,000 times larger."

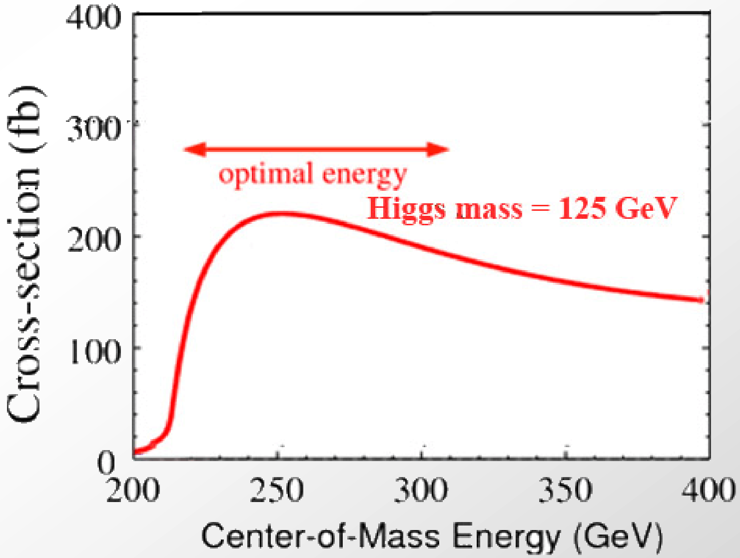
"True," you reply, "be we don't even know if it is possible.

Let's go back to storage rings. How much energy do you need?"

Dominant reaction channel with sufficient σ

- $e^+ + e^- \Longrightarrow Z^* \Longrightarrow H + Z$
- $M_H + M_Z = 125 + 91.2 = 216.2\ \mathrm{GeV}/c^2$





==> set our CM energy at the peak σ: **~240 GeV**

Physics "facts of life" of a Higgs factory
Will this fit in the LHC tunnel?

- Higgs production cross section ~ 220 fb (2.2 x 10^{-37} cm^2)
- Peak $\mathcal{L} = 10^{34}$ cm^{-1} s^{-1} ==> $< \mathcal{L} > \sim 10^{33}$ cm^{-1} s^{-1}
- ~30 fb^{-1} / year ==> 6600 Higgs / year
- Total e^+e^- cross-section is ~ 100 pb • (100GeV/E)^2
  - Will set the luminosity lifetime

We don't have any choice about these numbers

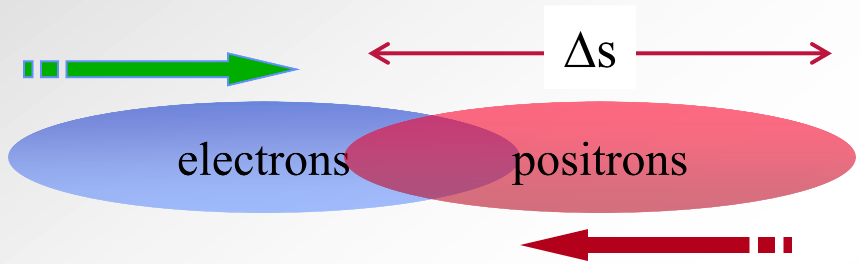
Oh, and don't use more than 200 MW of electricity

Road map for the analysis

- How do "facts of life" affect the peak luminosity
  - First some physics about beam-beam interactions

  ==> Luminosity as function of I_{beam} and E_{beam}
  - What ß* is needed?
- What is the bunch length, σ_z, of the beam?
- How does rf system give us σ_z
  - What are relevant machine parameters, α_c, f_{rev}, f_{rf}, ϕ_{synch}, etc.
  - But first, what is $\Delta E/E$
- How synchrotron radiation comes in
  - What is the rf system
  - What sets the beam size at the IP
- What are life time limitations
- Conclusions

Storage ring physics: Beam-beam tune shifts
Space charge fields at the Interaction Point



At the IP space charge cancels; but the currents add ==> the IP is a "lens"

i.e, it adds a gradient error to the lattice, ($k_{space\ charge}\Delta s$)

where ($k_{space\ charge}\Delta s$) is the kick ("spring constant') of the space charge force

Therefore the tune shift is

$$\Delta Q = -\frac{1}{4\pi}\beta^*(s)(k\Delta s)$$

For a Gaussian beam, the space charge kick gives

$$\boxed{\Delta Q \approx \frac{r_e}{2}\frac{\beta^* N}{\gamma A_{int}}}$$

Effect of tune shift on luminosity

- The luminosity is $\mathcal{L} = \dfrac{f_{coll} N_1 N_2}{4 A_{\text{int}}}$

- Write the area in terms of emittance & β at the IR (β^*)

$$A_{\text{int}} = \sigma_x \sigma_y = \sqrt{\beta_x^* \varepsilon_x} \cdot \sqrt{\beta_y^* \varepsilon_y}$$

- For simplicity assume that

$$\frac{\beta_x^*}{\beta_y^*} = \frac{\varepsilon_x}{\varepsilon_y} \Rightarrow \beta_x^* = \frac{\varepsilon_x}{\varepsilon_y}\beta_y^* \Rightarrow \beta_x^* \varepsilon_x = \frac{\varepsilon_x^2}{\varepsilon_y}\beta_y^*$$

- In that case

$$A_{\text{int}} = \varepsilon_x \beta_y^*$$

- And

$$\boxed{\mathcal{L} = \frac{f_{coll} N_1 N_2}{4 \varepsilon_x \beta_y^*} \sim \frac{I_{beam}^2}{\varepsilon_x \beta_y^*}}$$

To maximize luminosity,
Increase N to the tune shift limit

- We saw that

$$\boxed{\Delta Q_y \approx \frac{r_e}{2} \frac{\beta^* N}{\gamma A_{\text{int}}}}$$

Or, writing N in terms of the tune shift,

$$N = \Delta Q_y \frac{2\gamma A_{\text{int}}}{r_e \beta^*} = \Delta Q_y \frac{2\gamma \varepsilon_x \beta^*}{r_e \beta^*} = \frac{2}{r_e} \gamma \varepsilon_x \Delta Q_y$$

Therefore the tune shift limited luminosity is

$$\boxed{\mathcal{L} = \frac{2}{r_e} \Delta Q_y \frac{f_{coll} N_1 \gamma \varepsilon_x}{4 \varepsilon_x \beta_y^*} \sim \Delta Q_y \left(\frac{IE}{\beta_y^*} \right)}$$

Tune shift limited luminosity of the collider

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

Linear or Circular

Tune shift

In practical units for electrons

$$\boxed{\mathcal{L}_{peak} = 2.17 \circ 10^{34} \left(1 + \frac{\sigma_x}{\sigma_y} \right) \Delta Q_y \left(\frac{1 \text{ cm}}{\beta^*} \right) \left(\frac{E}{1 \text{ GeV}} \right) \left(\frac{I}{1 \text{ A}} \right)}$$

Experimentally, at the tune shift limit $\left(1 + \frac{\sigma_x}{\sigma_y} \right) \Delta Q_y \approx 0.1$ for electrons

$$\boxed{\mathcal{L}_{peak} = 2.17 \circ 10^{33} \left(\frac{1 \text{ cm}}{\beta^*} \right) \left(\frac{E}{1 \text{ GeV}} \right) \left(\frac{I}{1 \text{ A}} \right)}$$

We can only choose I(A) and ß*(cm)

- For the LHC tunnel with f_{dipole} ~ 2/3, $\rho_{curvature}$ ~ 2700 m
- Remember that

$$\rho(\mathrm{m}) = 3.34 \left(\frac{p}{1\ \mathrm{GeV/c}}\right)\left(\frac{1}{q}\right)\left(\frac{1\ \mathrm{T}}{B}\right)$$

- Therefore, B_{max} = 0.15 T
- Per turn, each beam particle loses to synchrotron radiation

$$U_o(keV) = 88.46\,\frac{E^4(GeV)}{\rho(m)}$$

or 6.54 GeV per turn

I_{beam} = 7.5 mA ==> ~100 MW of radiation (2 beams)

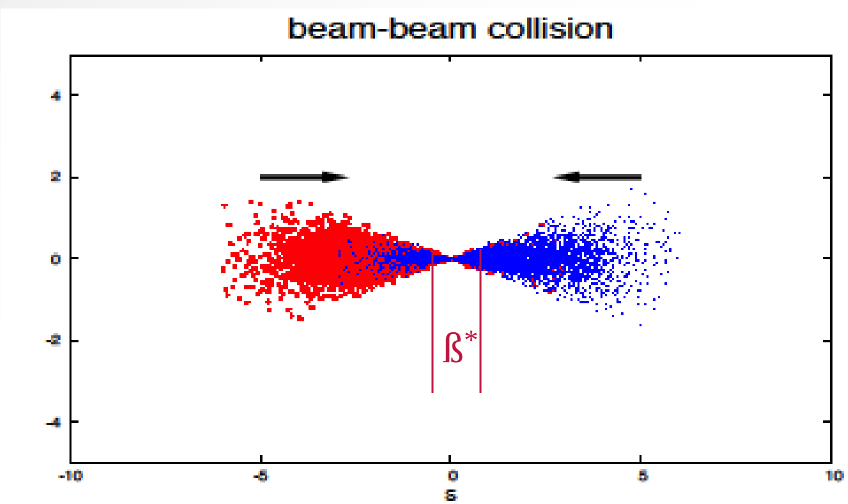
CERN management "chose" I;
That leaves β^* as the only free variable

- Then $$L_{peak} \approx 1.9 \cdot 10^{33} \left(\frac{1\ \mathrm{cm}}{b^*} \right)$$

- Therefore to meet the luminosity goal

$$\langle ß^*_x ß^*_y \rangle^{1/2} \sim 0.2\ \mathrm{cm}$$ *(10 x smaller than LEP 2)*

- Is this possible? Recall that is the depth of focus at the IP



The "hourglass effect" lowers $\mathcal{L}$

For maximum luminosity

$\Longrightarrow \sigma_z \sim \beta^* \sim 0.2$ cm

Bunch length, σ_z, is determined by ω_{rf} & V_{rf}

- The analysis of longitudinal dynamics gives

$$\boxed{\sigma_z = \frac{c\alpha_C}{\Omega_{sync}}\frac{\sigma_p}{p_0} = \sqrt{\frac{c^3}{2\pi q}\frac{p_0\beta_0\eta_C}{h\, f_0^2\,\hat{V}\cos(\varphi_S)}}\frac{\sigma_p}{p_0}}$$

where $\alpha_c = (\Delta L/L) / (\Delta p/p)$

- If the beam size is ~100 µm in most of the ring

$$\frac{\Delta L}{L} < \frac{0.01}{280000} \approx 3 \times 10^{-7}$$

for electrons to stay within $\boldsymbol{\sigma_x}$ of the design orbit

- To know bunch length & α_c we need to know $\Delta p/p \sim \Delta E/E$

Bunch length, σ_{z}, is determined by ΔE/E

- For electrons to a good approximation

$$\Delta E \approx \sqrt{E_{beam} < E_{critical,\,photon} >}$$

and

$$\boxed{\varepsilon_c[keV] = 2.218\frac{E[GeV]^3}{r[m]} = 0.665 \times E[GeV]^2 \times B[T]}$$

- So $\varepsilon_{crit} \approx 1.5$ MeV ==> ΔE/E ≈ .0035

- Therefore for electrons to remain near the design orbit

$$\alpha_c = (\Delta L/L) / (\Delta p/p) \sim 8 \times 10^{-5}$$

(was 1.8×10^{-4} for LEP2)

The rf-bucket contains ΔE/E in the beam

- As $U_o \sim 6.5$ GeV,

  $V_{rf,max} > 6.5$ GeV + "safety margin" to contain ΔE/E

- Some addition analysis

$$\left(\frac{\Delta E}{E}\right)_{\max} = \sqrt{\frac{q\widehat{V}_{\max}}{\pi h \alpha_c E_{synchronous}}\left(2\cos\varphi_s + (2\varphi_s - \pi)\sin\varphi_s\right.}$$

where h is the harmonic number (~ $C_{LEP3} / \lambda_{rf} \sim 9\text{x}10^4$)

- The greater the over-voltage, the shorter the bunch

$$\boxed{\sigma_S = \frac{c\alpha_C}{\Omega_{synch}}\left(\frac{\Delta E}{E}\right) = \sqrt{\frac{c^3}{2\pi q}\frac{p_0\beta_0\alpha_C}{h\, f_{rev}^2\, \hat{V}_{\max}\cos(\varphi_S)}}\left(\frac{\Delta E}{E}\right)}$$

For the Higgs factory…

- The maximum accelerating voltage must exceed 9 GeV
  - Also yields σ_z = 3 mm which is okay for ß* = 1 mm
- A more comfortable choice is 11 GeV (it's only money)
  - ==> CW superconducting linac for LEP 3 ==> ϕ_{synch}
- Therefore, we need a SCRF linac in 4 pieces
  - Remember that the beam loses ~ 6% of its energy in one turn

    LEP2 lost 3.4 GeV ~ 3% per turn
  - We need a higher gradient than LEP2; 6 MeV/m is not enough
  - 22 MeV/m ==> 500 m of linac *(the same as LEP 2)*
- High gradient ==> f_{rf} > 1GHz ;

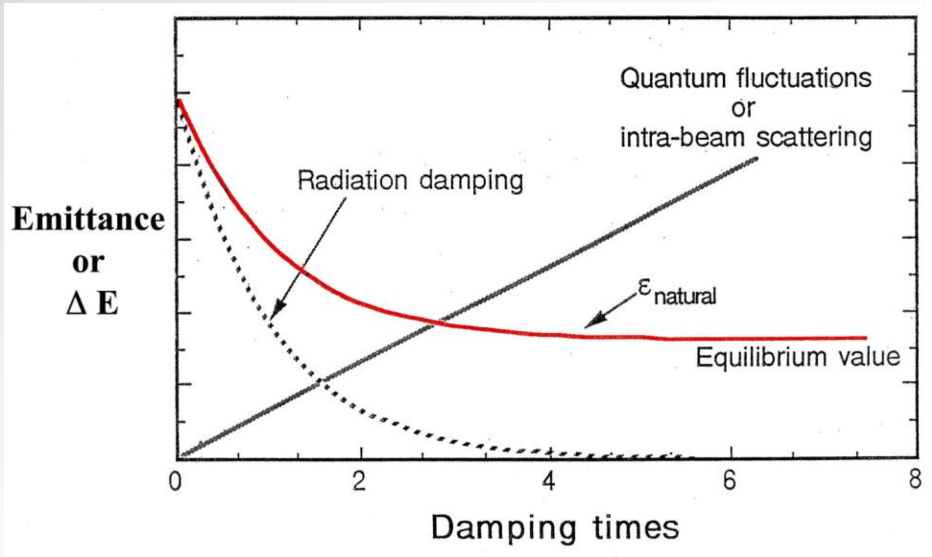
For the Higgs factory…

- The maximum accelerating voltage must exceed 9 GeV
  - Also yields σ_z = 3 mm which is okay for ß* = 1 mm
- A more comfortable choice is 11 GeV (it's only money)
  - ==> CW superconducting linac for LEP 3
  - This sets the synchronous phase
- For the next step we need to know the beam size

$$s_i^* = \sqrt{b_i^* e_i} \text{ for } i = x, y$$

- Therefore, we must estimate the natural emittance which is determined by the synchrotron radiation ΔE/E

The minimum horizontal emittance for an achromatic transport



$$\varepsilon_{x,\min} = 3.84 \times 10^{-13} \left(\frac{\gamma^2}{J_x} \right) F^{\min} \text{ meters}$$

$$\approx 3.84 \times 10^{-13} \gamma^2 \left(\frac{\theta_{achromat}^3}{4\sqrt{15}} \right) \text{meters}$$

$$\varepsilon_y \sim 0.01\ \varepsilon_x$$

Because α_c is so small, we cannot achieve the minimum emittance

- For estimation purposes we will choose 20 ε_{min} as the mean of the x & y emittances
- For the LHC tunnel a maximum practical dipole length is 15 m
  - A triple bend achromat ~ 80 meters long ==> $\theta = 2.67 \times 10^{-2}$

$$\langle \varepsilon \rangle \sim 7.6 \text{ nm-rad} \implies \sigma_{transverse} = 2.8\ \mu\text{m}$$

How many particles are in the bunch?

Or how many bunches are in the ring?

We already assumed that the luminosity is at the tune-shift limit

- We have

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

Linear or Circular

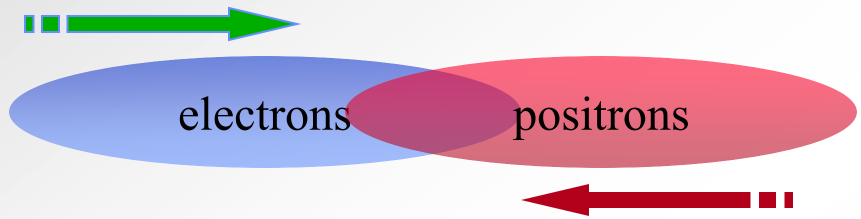
Tune shift

- Or $\quad Q = \frac{N r_e}{4\pi\varepsilon\gamma} \Rightarrow N = \frac{4\pi\varepsilon\gamma}{r_e} Q$

- So, $\quad N_e \sim 1.3 \times 10^{11}$ per bunch

- $I_{beam} = 7.5$ mA ==> there are only 3 bunches in the ring

Let’s return to
Space charge fields at the collision point



At the IP space charge cancels; currents add

==> strong beam-beam focus

- => Luminosity enhancement
- => Very strong synchrotron radiation (beamstrahlung)

Beamstrahlung is important in linear colliders

What about the beams in LEP-3?

At the collision point…with $\mathcal{L}$ =10^{34}

$$I_{peak} = N_e / 2\sigma_z \implies I_{peak} \sim 1.6 \text{ kA}$$

- Therefore, at the beam edge (σ)

$$B = I(A)/5r(cm) = 1.6 \text{ MG !}$$

- When the beams collide they emit synchrotron radiation (beamstrahlung)

$$e_{c,Beams}[keV] = 2.218 \frac{E[GeV]^3}{r[m]} = 0.665 \times E[GeV]^2 \times B[T] = 1.1 \text{ GeV}$$

- But this accumulates over a damping time

$\Delta E_{Beams} \approx (2/J_E)$*Sqrt (number of turns in damping time) $\varepsilon_{c,Beams} \approx 10$ GeV

The rf-bucket must be very large to contain such a big ΔE/E

Beamstrahlung limits beam lifetime & energy resolution of events

At $\mathcal{L}$ =2x10^{33}

- β^* ~ 1.5 cm ==> 9 GeV of linac is okay

- I_{peak} can be reduced 3 x and …

- The beam size can increase 3 x

- ==> B_{sc} is reduced ~10 x ==> ΔE_{Beams} ~ 1 GeV
  - This is < 1% of the nominal energy
  - Many fewer electrons will be lost

A much easier machine to build and operate

Yokoya has done a more careful analysis

❖ Beamstrahlung limited luminosity

$$\mathcal{L} = 4.57 \times 10^{33} \left(\frac{\rho}{1\ km}\right)\left(\frac{P_{SR}}{100\ \mathrm{MW}}\right)\sqrt{\frac{(\Delta E_{beams}/E)}{0.1\%}}\left(\frac{100\ \mathrm{GeV}}{\mathrm{E}}\right)^{4.5}\left(\frac{1\ \mathrm{nm}}{\varepsilon_{\mathrm{y}}}\right)^{1/2} \mathrm{cm}^{-2} s^{-1}$$

❖ This implies very large rings, high beam power, and small vertical emittance

Mechanisms limiting beam lifetime

- Luminosity lifetime

  Total e^+e^- cross-section is ~ 100 pb • $(100GeV/E)^2$

- Beamstrahlung lifetime

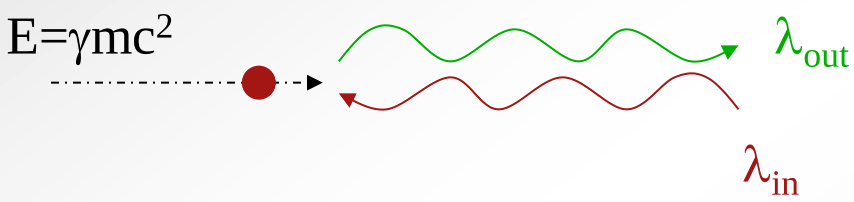
- Beam-gas scattering & bremsstrahlung

- Tousheck lifetime

- And…

And there are other problems

- Remember the Compton scattering of photons up shifts the energy by 4 γ^2



- Where are the photons?
  - The beam tube is filled with thermal photons (25 meV)

- In LEP-3 these photons can be up-shifted as much as 2.4 GeV
  - 2% of beam energy cannot be contained easily
  - We need to put in the Compton cross-section and photon density to find out how rapidly beam is lost

The bottom line:
The beam lifetime is 10 minutes

- We need a powerful injector
- Implies rapid decay of luminosity as operation shrinks away from tune shift limit

==> we need top-off operation

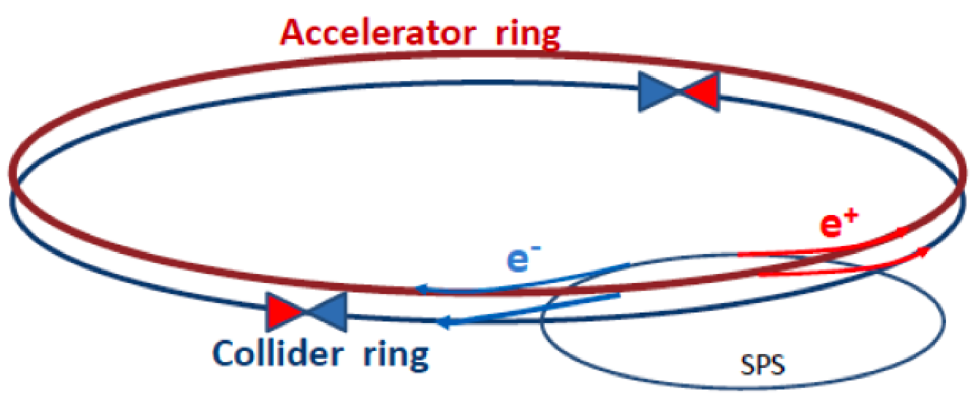


Figure 2 Possible two ring sketch for LEP3: a first ring (accelerator ring) accelerates electrons and positrons up to operating energy (120 eV) and injects them at a few minutes interval into the low emittance collider ring in which the high luminosity 10^{34}/cm^2/s interaction points are situated.

From Zimmermann & Blondel

Conclusions (for $\mathcal{L}$ =2x10^{34})

- LEP3 is a machine at the edge of physics feasibility
  - Beamstrahlung issues require more, detailed study
  - Momentum aperture must be very large
  - 240 GeV is the limit in the LHC tunnel
- The cost appears to be << a comparable linear collider
- A very big perturbation of LHC operations
- Cannot run at the same time as the LHC

The LEP3 idea might be a viable alternative as a future HEP project

Collider Physics: The Farthest Energy Frontier

Lecture 2

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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

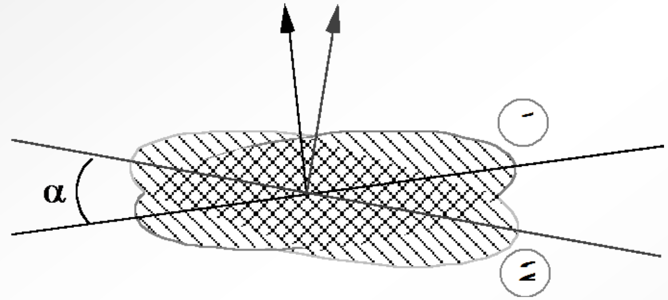
Luminosity formula exposes basic challenge of the energy frontier

Assume that $\sigma_z < \beta^*$

Neglect corrections for α

Set $N_1 = N_2 = N$

$\epsilon_x = \epsilon_y$ and $\beta_x = \beta_y$



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

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

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^*

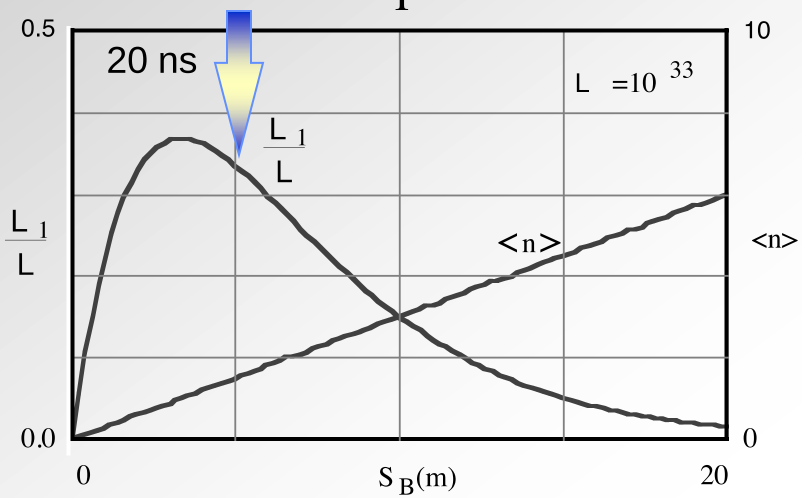
These approaches are used in the B-factories

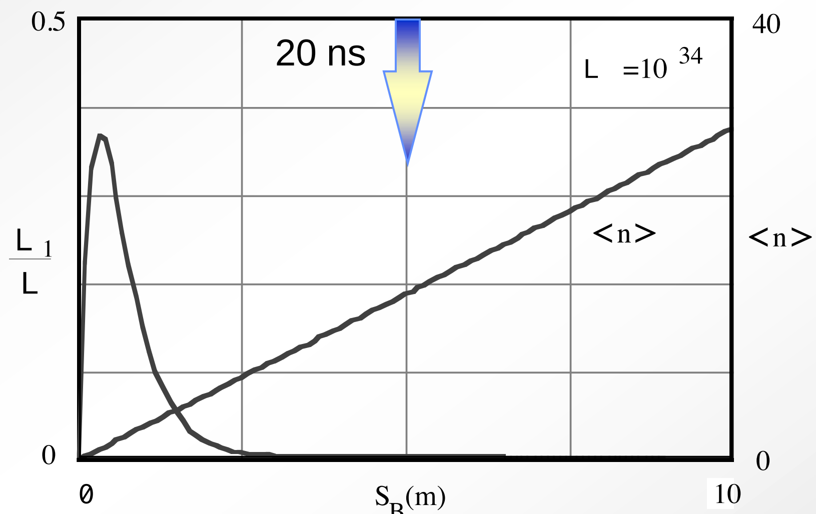
What sets parameter choices?

- How do we choose N, S_B, β^*, and ε_n as a function of energy?
  - Detector considerations
    - Near zero crossing angle
    - Electronics cycling $\geq$ 20 ns between crossings
    - Event resolution $\leq$ 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





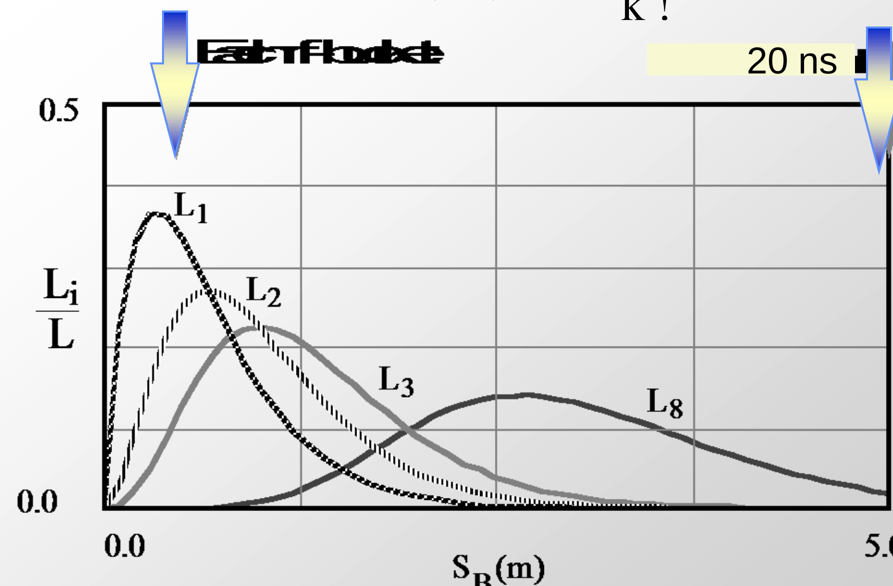
$$\sigma_{inel} \sim ln\ E_{cm}$$

Most probable # events per crossing

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

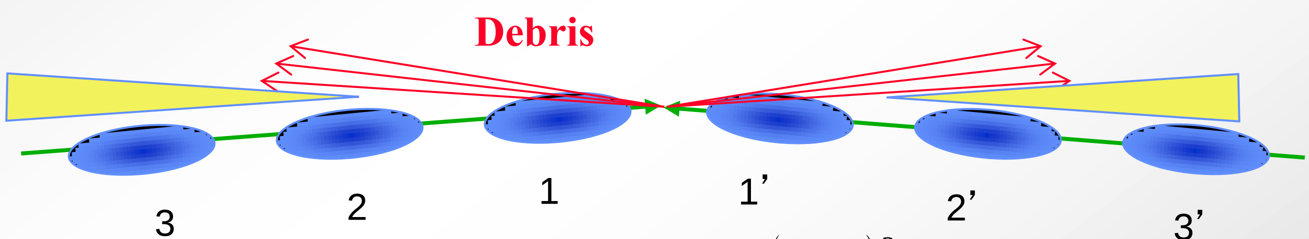
Fractional luminosity for
k events per crossing

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



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



$$\Delta n_{LR} = \Delta n_{HO}\, 2n_{LR} \left(\frac{s}{b^{*} a}\right)^{2}$$

$$\Delta n_{HO} = \frac{N_B\, r_p}{4\pi e_n}$$

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

What is the allowable tune shift ?

University of Ljubljana FACULTY OF ECONOMICS

- 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

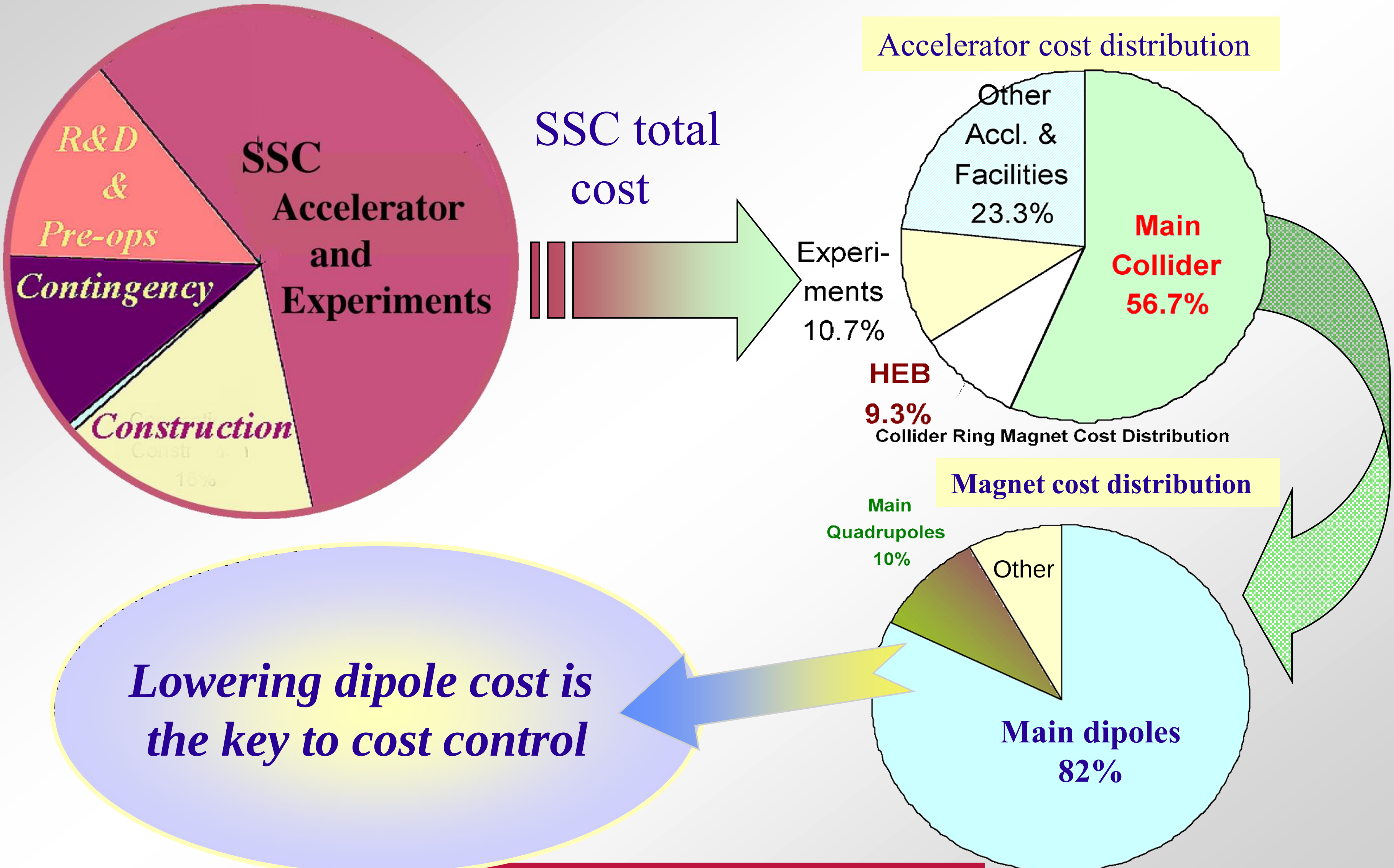
$$N_{Hi,IP} = 1 \quad \text{and} \quad N_{Hi,Med} = 0$$

  - 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

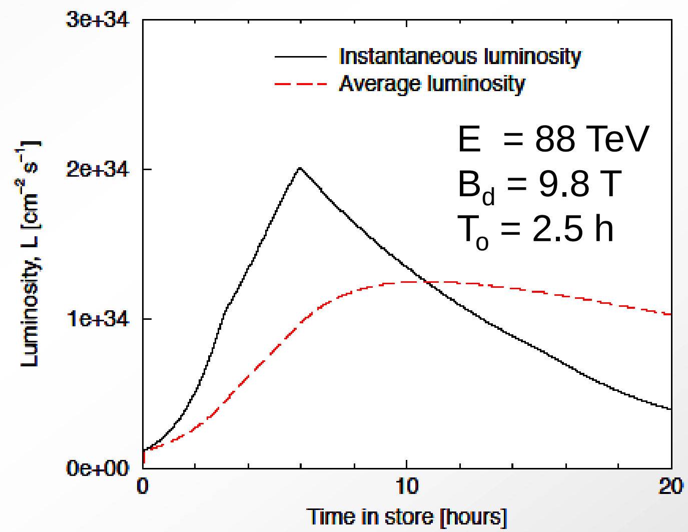
- Low field, superferric magnets
  - Large tunnel & very large stored beam energy
  - Minimal influence of synchrotron radiation
- "Medium" field design
  - Uses ductile superconductor at 4 - 8 T (RHIC-like)
  - Some luminosity enhancement from radiation damping
- High field magnets with brittle superconductor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



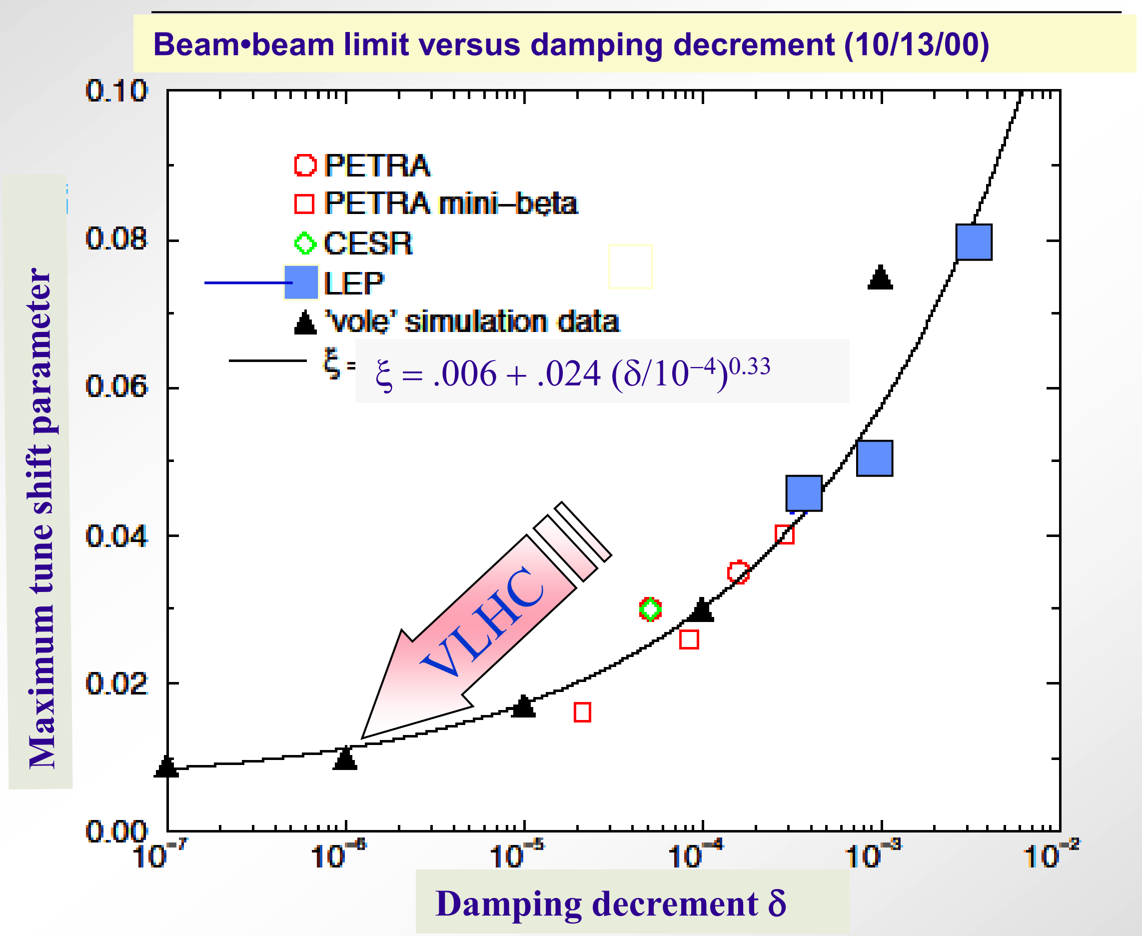
- Energy losses limit I_{beam}
  - 1 - Heating walls ==> cryogenic heat load ==> wall resistivity ==> instability
  - 2 - Indirect heating via two stream effects
  - 3 - Photo-desorption => beam-gas scattering => quench of SC magnets

    ==> Costs money

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

$N_g \sim 4pa$ per turn

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



Damping decrement fractional damping per turn

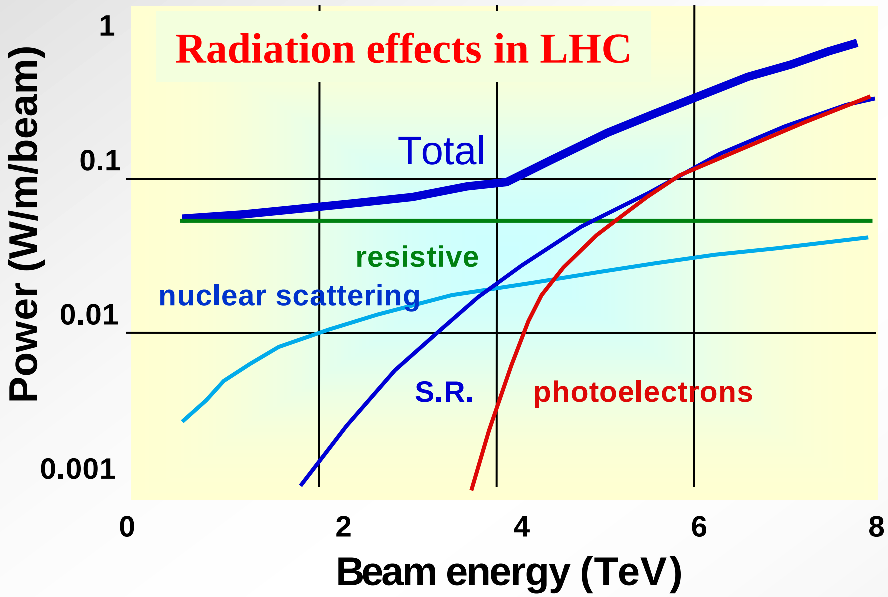
Beam dynamics of marginally damped collider needs experimental study

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:



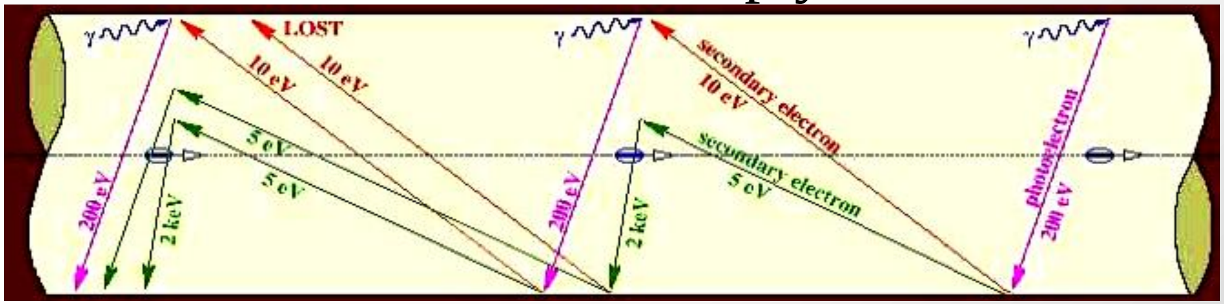
Scaling with I_b & E

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

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

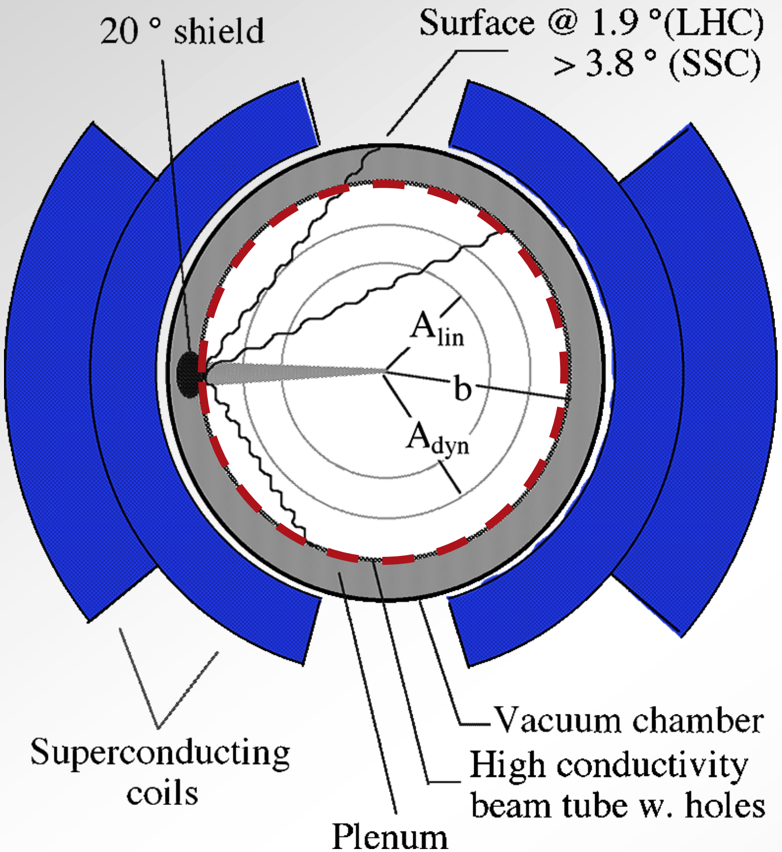
$$P(W/m) = 0.93 \frac{I(A)\ E(TeV)}{\tau(h)}$$

❖ 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

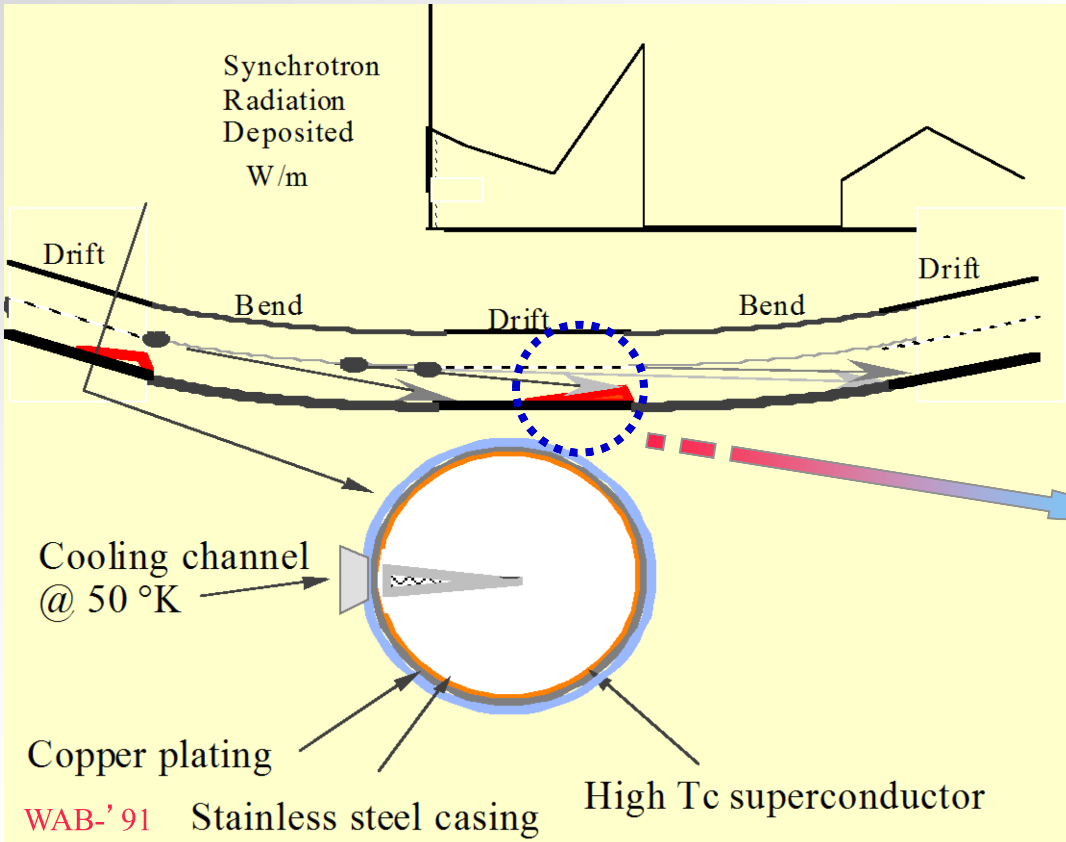
- Considerations that can limit luminosity: residual gas, instabilities
- Holes for heat removal & pumping must be consistent with low $Z(\omega)$
- As plenum gets larger & more complex cost rises rapidly

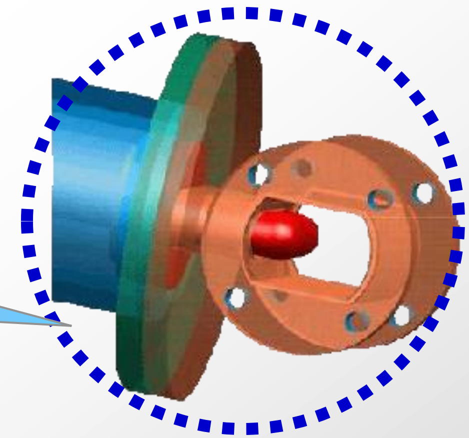
Vacuum/cryo systems: Scaling LHC is not an option

- 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.

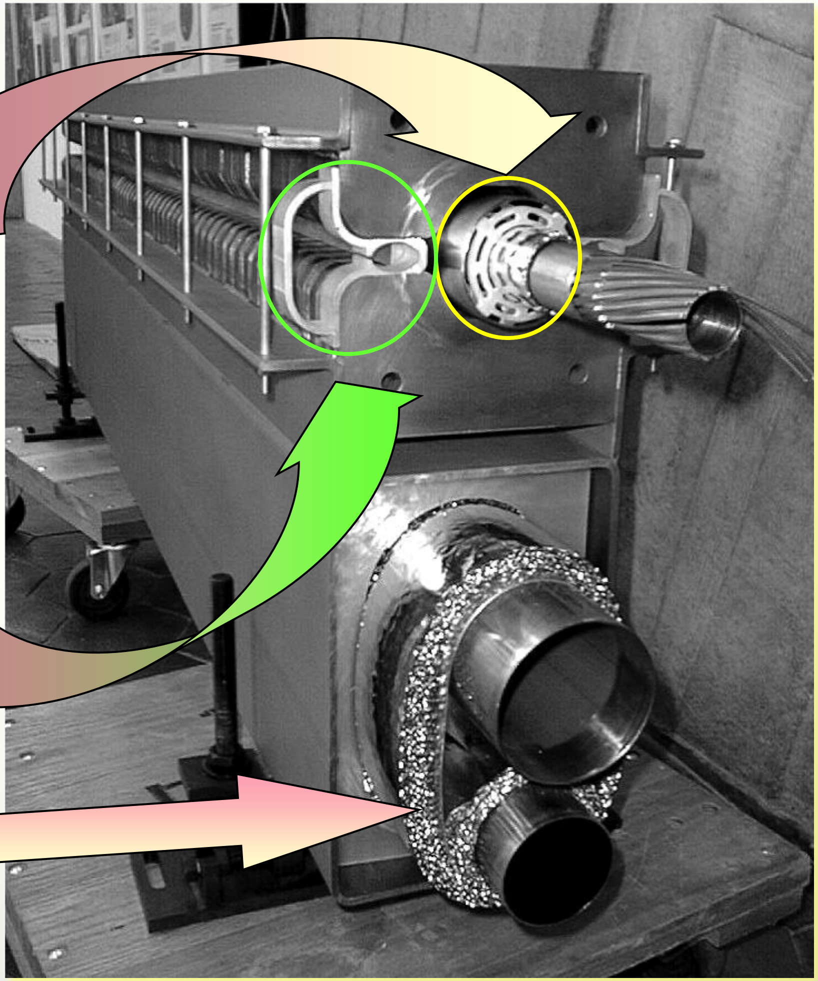
* B @ conductor ~ 1 T; NbTi has high Jc ==> low superconductor usage.

* 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}; $\approx$ 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 ($T_{multi\text{-}bunch} \approx$ 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

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

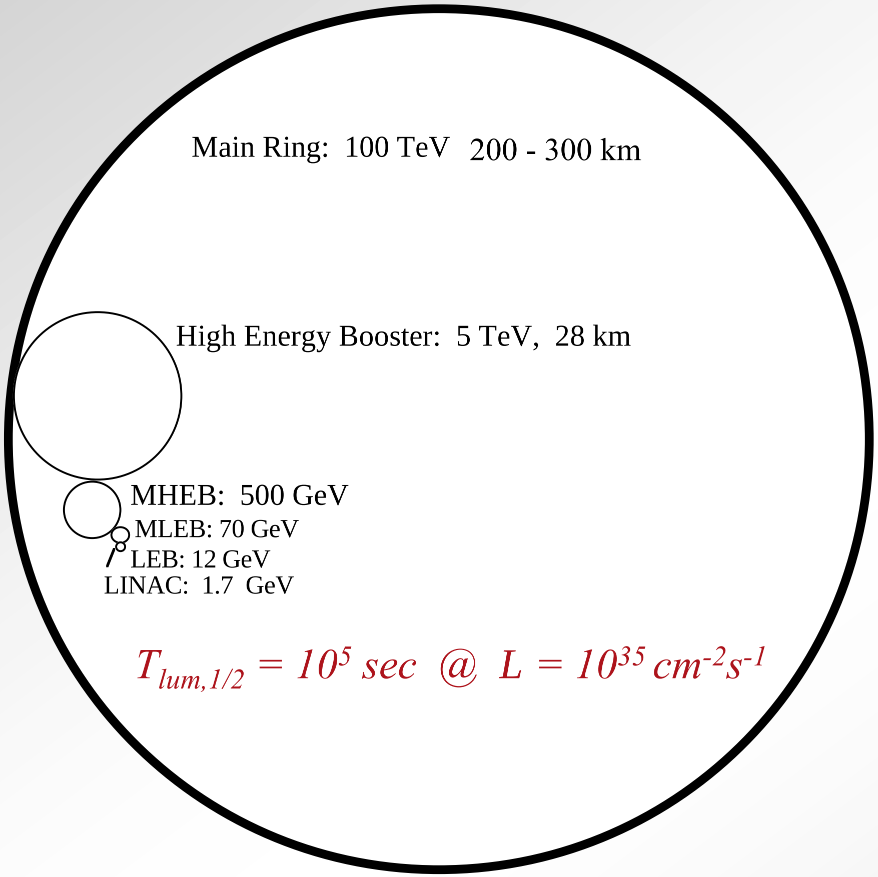
$$\tau^{-1}_{lum}(E) = \frac{1}{N_{bunch}}\frac{d\,N_{bunch}}{dt} = \frac{L\ \Sigma_{inel}(E)}{M\ N_{bunch}}$$

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

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

- 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



$T_{lum,1/2} = 10^5\ sec\ \ @\ \ L = 10^{35}\ cm^{-2}s^{-1}$

	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	Δn_{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

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

or

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

where

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

with η = psuedo-rapidity = - ln (tan θ/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 = $0.78\ s^{0.105}$
$\approx$ constant for $\eta < 6$ ($\theta > 5$ mr)
for $\eta > 6$, H(E) —> 0 linearly @ kinematic limit

$<p_{\perp}> = 0.12 \log_{10} 2E + 0.06$

$s = 4\ E^2$

Radiation damage of IR components severely limits maximum luminosity

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

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

- Let Q1 aperture = 1.5 cm ==>

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

P_{debris} = 180 kW/side

With no shielding

D (Q1) ≈ 4 x 10^8 Gy/year

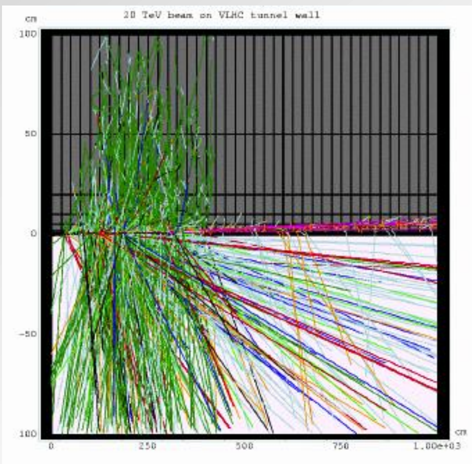
==> ≈ 45 W/kg in Q1

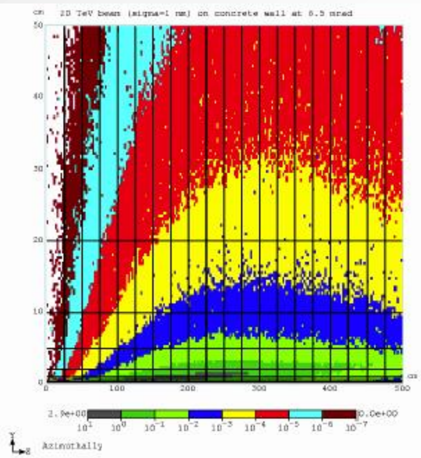
- Superconducting Q1 requires ≈ 20 kW/kg of compressor power

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

Radiation & Beam Abort: Worst- Case Accident

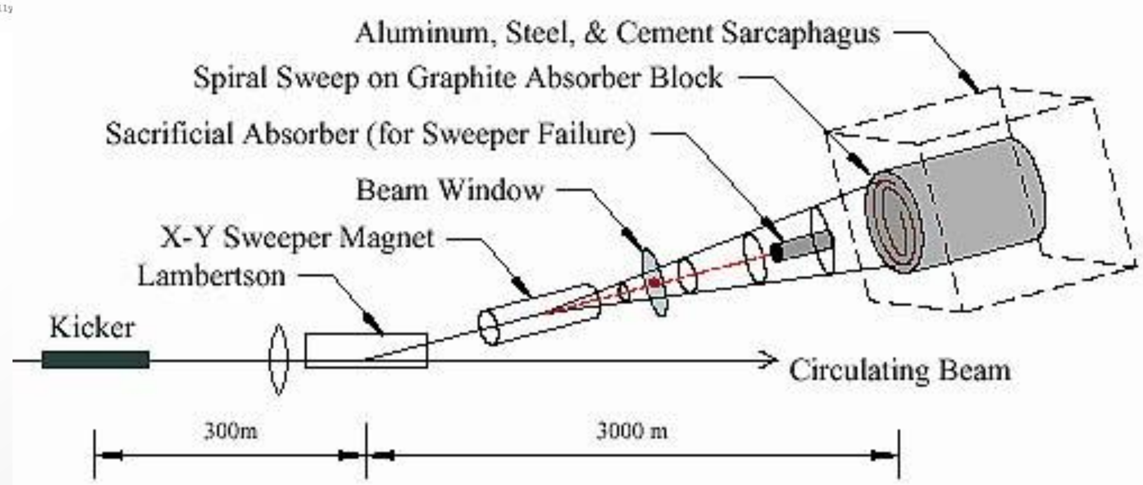
- 2. 8 GJ ~ 8 x LHC Energy (can liquify 400 liters of SS)





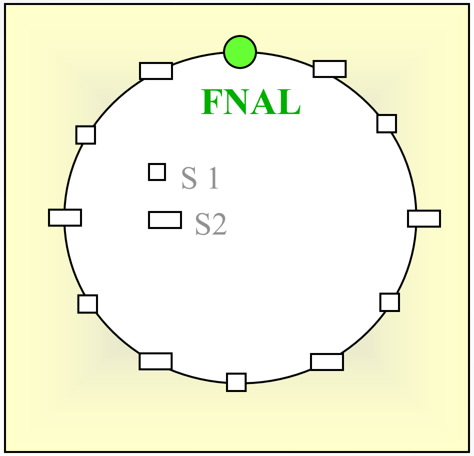
Normally extracted beam beam is swept in a spiral to spread the energy across graphite dump

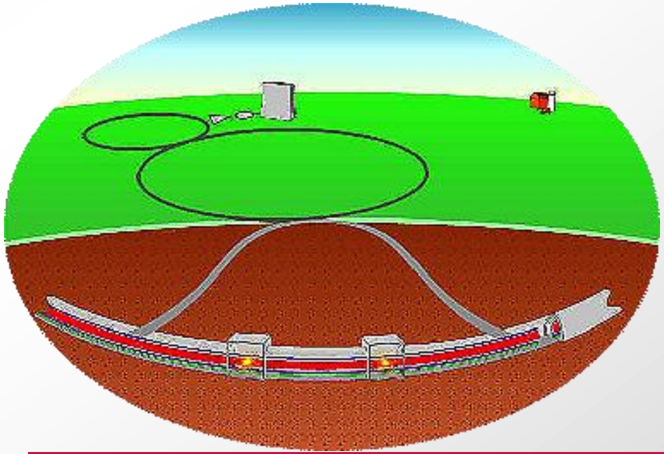
If sweeper fails, the beam travels straight ahead into a sacrificial graphite rod which takes the damage & must be replaced.
Beam window also fails.

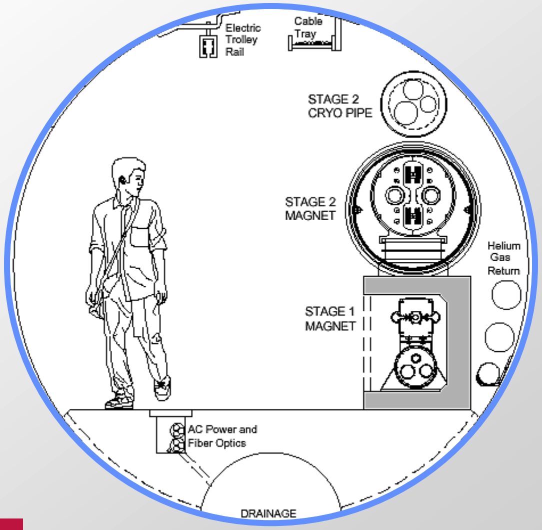


FNAL-BNL-LBNL Study: Staged approach to VLHC

- 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

Can VLHC be a linear proton collider ?

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

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

H_D is the luminosity degradation due to the pinch effect

D is the disruption parameter that measures the anti-pinch

$$D = \frac{r_p N_B s_z}{g s^2_{x,y}} = r_p N_B \left(\frac{s_z}{b^* e_n}\right)$$

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 $\sim 10^{35}$ 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