e-p Collider with the VLHC

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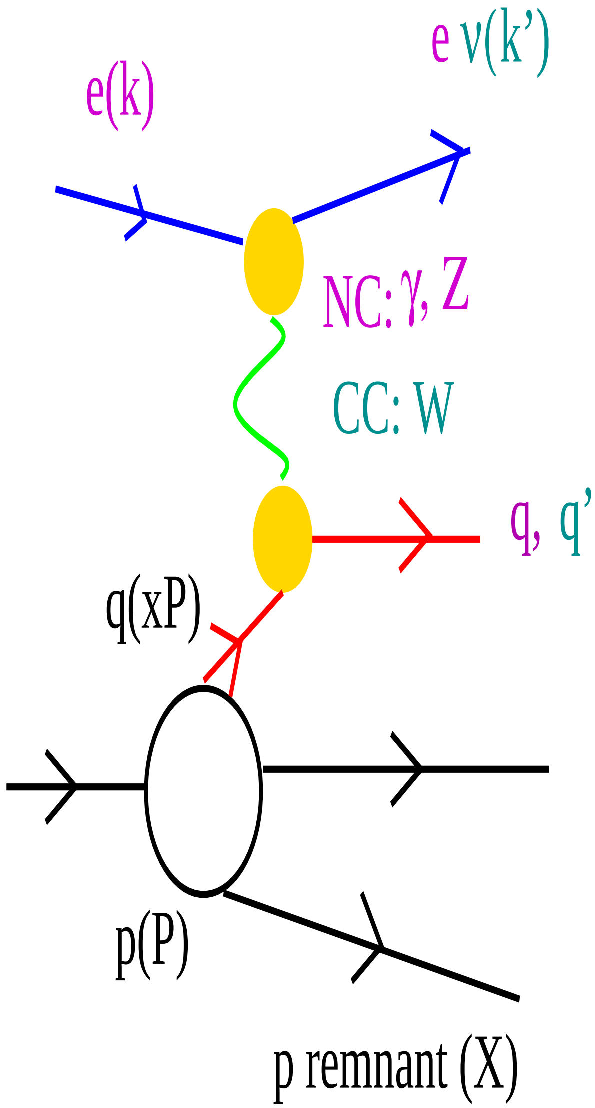
e-p PHYSICS

Deep Inelastic Scattering



$$Q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P.(k - k')}$$

$$y = \frac{P(k - k')}{P.k}$$

$$Q^2 = s\,x\,y$$

Physics Goals

Diverse physics program covering wide range of energy scales

- Low Q^2: $1\ \mathrm{GeV}^2 < Q^2 < 50\ \mathrm{GeV}^2$.
  - exploration of perturbative QCD with multiple scales.
  - explore transition of perturbative QCD to non-perturbative regime.

  This will not be covered by any other accelerator except perhaps the NLC.
- Medium Q^2: $10\ \mathrm{GeV}^2 < Q^2 < 15{\times}10^3 \mathrm{GeV}^2$.

  "Bread and butter" precision QCD physics, e.g. precision measurements of parton densities, α_S.
- High Q^2: $10^3\ \mathrm{GeV}^2 < Q^2 < 25{\times}10^4 \mathrm{GeV}^2$.

  Precision QCD and electroweak physics, e.g.
  - most precise measurement of α_S, precision measurement of M_W, $\sin^2\theta_W$.
  - confirmation of weak-radiative corrections and Higgs physics.
- Very High Q^2: $5{\times}10^4\ \mathrm{GeV}^2 < Q^2 < 10^6 \mathrm{GeV}^2$.

  Search for new and exotic physics, e.g.
  - leptoquarks up to $M_{lQ} \sim 750$GeV, SUSY particles up to $M \sim 500 - 800$GeV.
  - lepton number violating processes.

Alternatives

- CERN: LEP⊗LHC: 90GeV$e \otimes$ 7TeVp
- DESY: TESLA⊗HERA-p: 250GeV⊗ 1TeVp

	VLHC booster $e-p$	DESY	CERN
Time scale	within 10yrs	within 10yrs	after 2014
Luminosity	10	1	10
Energy	1	1	1.6

What do we want

- **Center of mass energy** $\geq$ **1 TeV**
- **Luminosity** $> 10^{32}$ **cm**$^{-2}$ **sec**$^{-1}$**.**
- **Adequate lifetime** $>$ **10 hrs**
- **Low backgrounds in detectors**
- **Operate with both** e^{+}/e^{-}**.**
- **Longitudinally polarized beams would be very desirable**.
- **Turn on around 2007**

VLHC-e Issues

Physics Goals

Lattice Design

Insertion Region

Magnets

Beam Physics

Vacuum System

RF System

Diagnostics

Tunnelling/Constr.

Alignment/Support

Cost

Lattice Design

- Arcs - FODO cell, emittance...
- Interaction Region
- Dispersion Suppressors
- RF sections
- Nonlinear chromaticity correction
- Wigglers

Beam Physics

- Luminosity.
- Lifetime.
- Instabilities.
- Beam-beam effects.
- Polarization.
- Dynamic Aperture.
- Injection and Acceleration.

Interaction Region Design

- Optics.
- Beam Separation scheme.
- Synchrotron radiation shielding.
- Backgrounds.
- Design of beam pipe, heating.
- Vacuum
- Detector size and geometry.
- Other Machine-Experiment interface issues

Luminosity

$$\mathcal{L} = \frac{1}{4\pi}\left[\frac{N_p\gamma_p}{\sqrt{\epsilon_{N,x}\epsilon_{N,y}}}\frac{\mathbf{1}}{\sqrt{\beta^*_{\mathbf{p,x}}\beta^*_{\mathbf{p,y}}}}\right]\mathbf{I_e} \tag{1}$$

assuming the beam sizes are matched at the IP.

Goal: *Maximize the luminosity within known constraints*.

The proton beam brightness factor $N_p\gamma_p/\sqrt{\epsilon_{N,x}\epsilon_{N,y}}$ is set by the injector chain and the energy of the booster.

To increase the luminosity we must

- **Make β^*_x, β^*_y as small as possible**.
- **Make the electron beam current I_e as large as possible**.

Constraints on β^*_x, β^*_y

- Maximum beam size in the IR (limited by the aperture of the IR quadrupoles) is $\propto 1/\beta^*$.
- Chromaticity(linear and non-linear) of the IR is $\propto 1/\beta^*$.
- Lowest value of β^* also depends on the distance of closest approach of the IR quads to the IP.
- $\beta^*_\perp >\sim \sigma_s$ to avoid losing luminosity due to the hourglass effect.
- Matching the electron and proton beam sizes at the IP requires

  $$\frac{\beta^*_{p,y}}{\beta^*_{p,x}} = \kappa\frac{\beta^*_{e,y}}{\beta^*_{e,x}} \tag{2}$$

  where $\kappa = \epsilon_{e,y}/\epsilon_{e,x} < 1$.
- The beam divergence at the IP is $\sigma' = \sqrt{\epsilon/\beta^*}$. The width of the synchrotron radiation fan and the resulting background increases with the electron beam divergence.

Constraints on I_e

- Primarily limited by the available RF power= 50MW.
- Should be lower than thresholds for instabilities.
- The heat load due to synchrotron radiation should be tolerable.
- Beam-beam tune shifts of the proton beam < 0.005.

FODO Cell

Given Parameters

Beam Energy	80 GeV
Arcs length	30.4km
Straight section length	3.6km

Design Criteria

- **Small emittance beam**
- **Large bending radius**

Design Choices

Length of cell	100m
Length of dipole	46m
Length of quadrupole	1.5m
Phase advance per cell	90°

Consequences

Bend angle/dipole	10.334mrad
Dipole field	600G
Quadrupole field	5.03 T/m

Beam Emittance

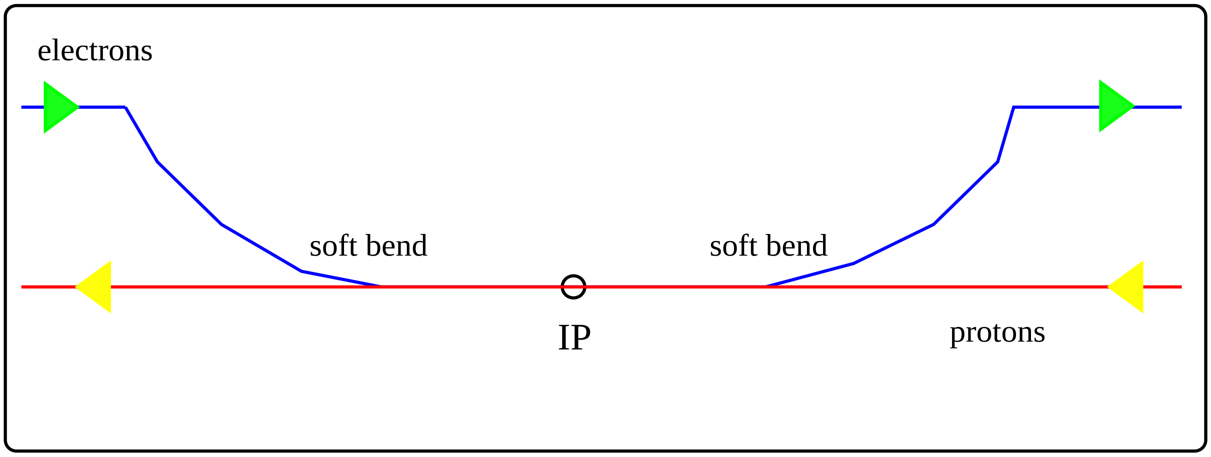
$$\begin{aligned}\epsilon &= C_q \frac{\gamma^2\theta^3}{J_x} \frac{1}{2\sin\mu_C} \frac{5+3\cos\mu_C}{1-\cos\mu_C} \frac{L_H}{L_B} \\ &= \mathbf{28.15}\ \mathrm{nm-rad}\end{aligned}$$

With $\kappa = 0.25$,

$$\epsilon_x = 22.5\mathrm{nm-rad}, \quad \epsilon_y = 5.6\mathrm{nm-rad}$$

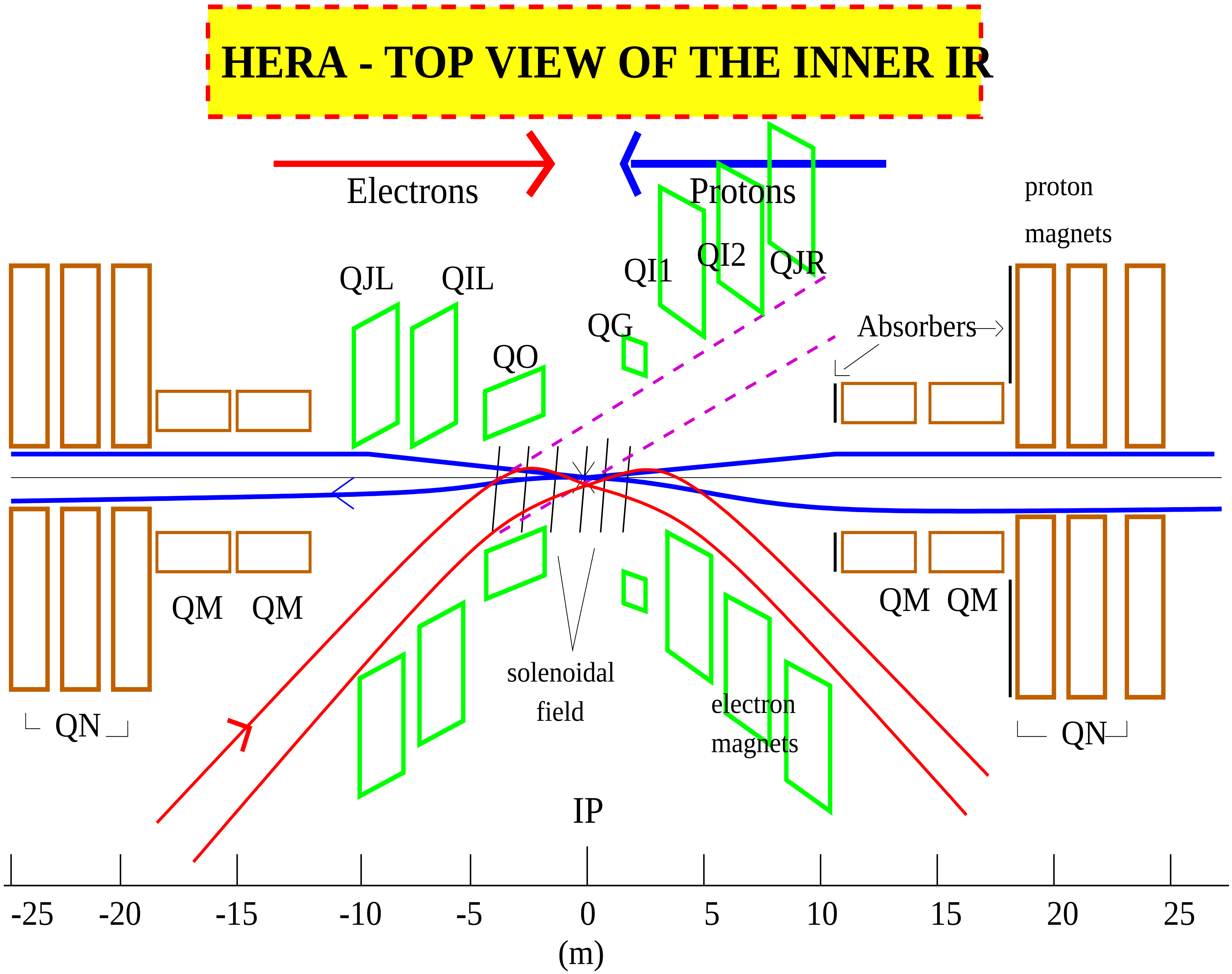
Energy spread

$$\sigma_\delta = \sqrt{\frac{C_q}{J_s\rho}\gamma} = 1.03 \times 10^{-3}$$

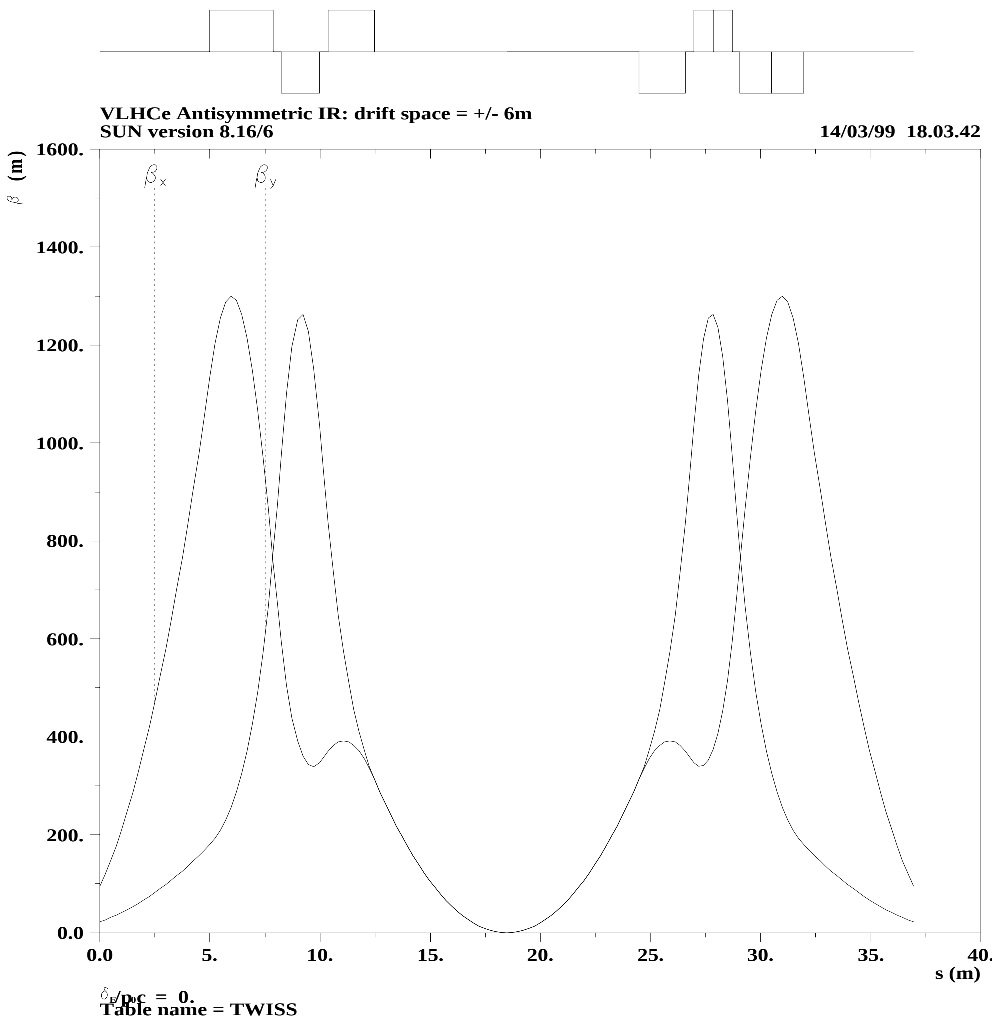


e-p IR Design

- **Minimize bend angles of electrons close to the IP.**
- **Displace quadrupoles close to the IP**, both to start the separation of the electrons early and to ensure that the synchrotron radiation fan passes through the quadrupole apertures. Quadrupoles on the downstream end have to be offset more.
- **Electrons should not be subject to the fields of the proton magnets.** The first proton quadrupoles can start either when
  - separation between the beams $d_{sep} = r_{p,BP} + r_{e,BP}$, or
  - use a half quadrupole in which the electrons go through a field free region (as in HERA). Separation can start earlier. Triplets should be used for focusing electrons to make the e-beam size small.
- **Vertical IR chromaticity should preferably be smaller.** Dispersion next to the defocusing quadrupoles is smaller.
- **Matched beam sizes** to avoid beam blow up and poor lifetime.
- **Main sources of background are the synchrotron radiation photons** emitted in the IR magnets **and electrons which have lost energy** due to collisions with the residual gas hitting the beam pipe. Require very good vacuum in the IR.



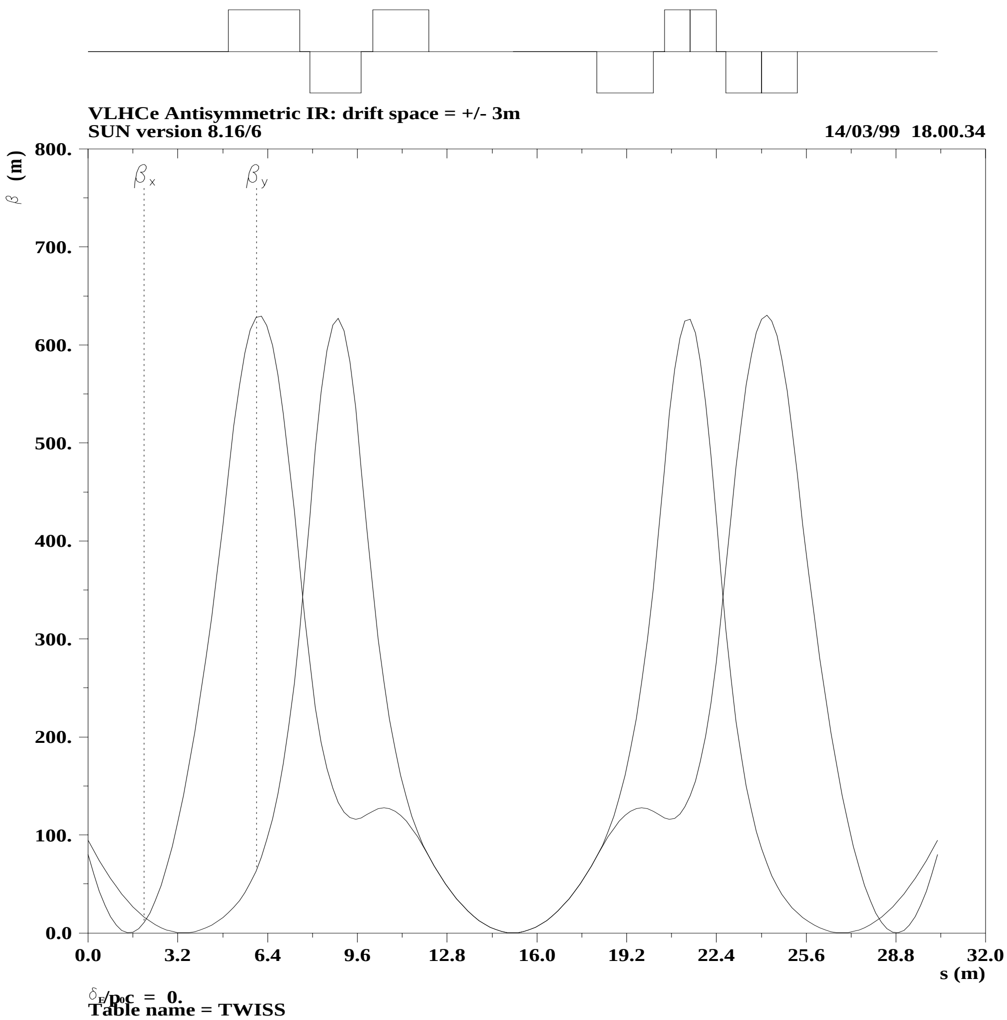
HERA - TOP VIEW OF THE INNER IR
Electrons
Protons
proton
magnets
QJL
QIL
QI1
QI2
QJR
QG
QO
Absorbers
QM
QM
QM
QM
QN
QN
solenoidal
field
electron
magnets
IP
-25
-20
-15
-10
-5
0
5
10
15
20
25
(m)



Drift space [m]	± 6
β^*_x, β^*_y[cm]	11.5
Maximum rms beam size σ_{Max}[mm]	5.96

Quadrupole parameters

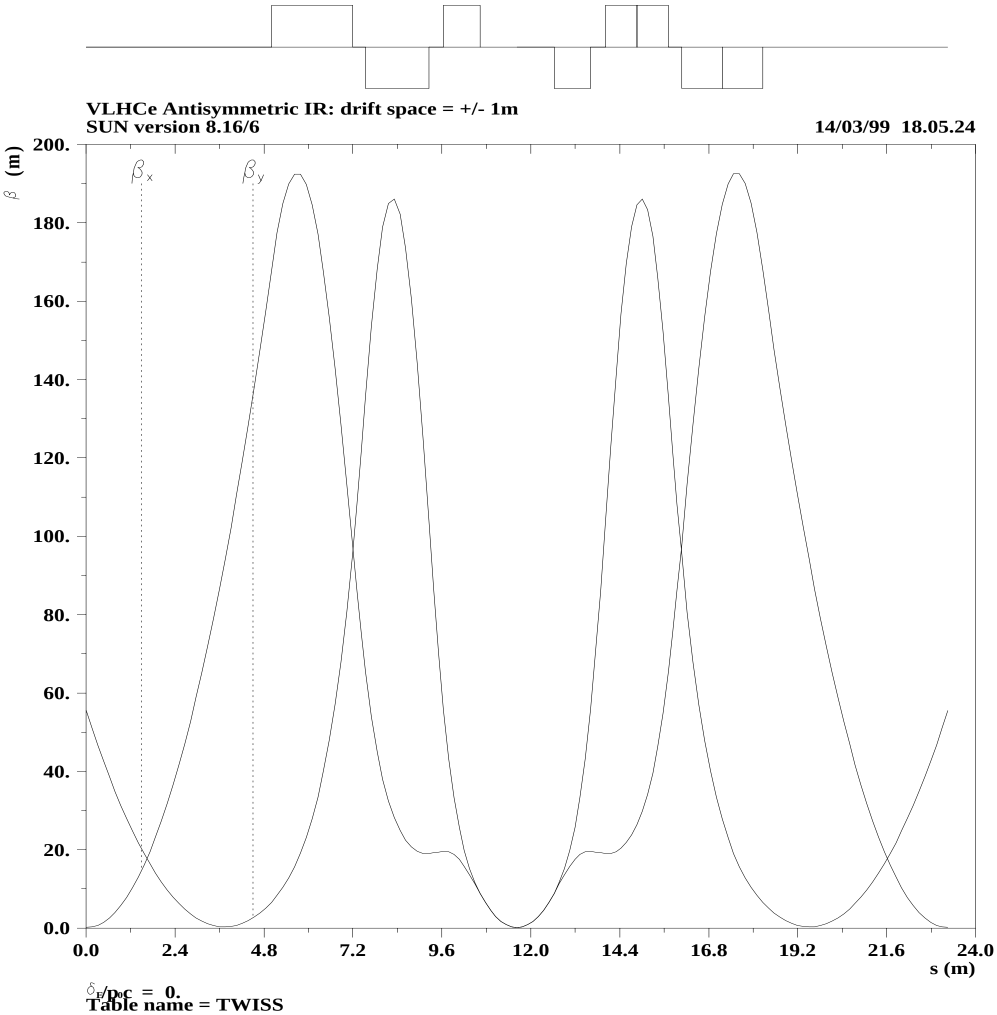
Quadrupole	Length [m]	Gradient [T/m]
Q1	2.1	29
Q2	1.7	78
Q3	2.9	37



Drift space [m]	± 3
β_x^*, β_y^*[cm]	11.5
Maximum rms beam size σ_{Max}[mm]	4.20

Quadrupole parameters

Quadrupole	Length [m]	Gradient [T/m]
Q1	2.1	47
Q2	1.7	99
Q3	2.9	62



Drift space [m]	± 1
β_x^*, β_y^*[cm]	11.5
Maximum rms beam size σ_{Max}[mm]	2.30

Quadrupole parameters

Quadrupole	Length [m]	Gradient [T/m]
Q1	1.0	213
Q2	1.7	150
Q3	2.2	73

Beam-beam parameters

Electrons		Protons	
N_e	3.26×10^{10}	N_p	1.25×10^{11}
$\epsilon_{e:x}/\epsilon_{e:y}$ [πnm-rad]	22.52/5.63	$\epsilon^N_{p:x}/\epsilon_{p:y^N}$ [πmm-rad] (95%)	25/25
$\beta^*_{e:x}/\beta^*_{e:y}$ [m]	0.115/0.115	$\beta^*_{p:x}/\beta^*_{p:y}$ [m]	2.0/0.5
$\sigma^*_{e:x}/\sigma^*_{e:y}$ [μm]	51/25.5	$\sigma^*_{p:x}/\sigma^*_{p:y}$ [μm]	51/25.5

Beam-beam tune shifts

$$\xi_{p:x} = \frac{r_p\beta^*_{p:x}}{2\pi\gamma_p}\frac{N_e}{\sigma^*_{e:x}[\sigma^*_{e:x}+\sigma^*_{e:y}]} = 0.0013$$

$$\xi_{p:y} = \frac{r_p\beta^*_{p:y}}{2\pi\gamma_p}\frac{N_e}{\sigma^*_{e:y}[\sigma^*_{e:x}+\sigma^*_{e:y}]} = 0.0065$$

$$\xi_{e:x} = \frac{r_e\beta^*_{e:x}}{2\pi\gamma_e}\frac{N_p}{\sigma^*_{p:x}[\sigma^*_{p:x}+\sigma^*_{p:y}]} = 0.011$$

$$\xi_{e:y} = \frac{r_e\beta^*_{e:y}}{2\pi\gamma_e}\frac{N_p}{\sigma^*_{p:y}[\sigma^*_{p:x}+\sigma^*_{p:y}]} = 0.021$$

The optics limit on luminosity is set by the proton β^*.

- Lowering β^*_p increases the proton beam size in quadrupoles. These are further from the IP.
- Proton bunch length $\sigma_{p:s}$ also sets the lower limit for β^*_p.

Normal RF

Scaling from the HERA parameters with conducting cavities:

	HERA	VLHC-e
Beam energy [GeV]	27.5	80
Energy lost/turn [MeV]	91	814
RF voltage [MV]	125	1090
Shunt resistance per cavity[MΩ]	~ 18	18
Peak voltage/cavity [MV]	~ 1.5	1.5
Number of cavities	82	727
Power absorbed in a single cavity [kW]	62.5	62.5
Total power absorbed in cavities [MW]	5.1	45.4
Total RF power [MW]	~10	50
Achievable current[mA]	58	6

Assuming other IR parameters and proton intensity and emittance are unchanged, $I_e = 6\text{mA} \Rightarrow$

$$\mathcal{L} = 2.8 \times 10^{31} \text{cm}^{-2}\text{sec}^{-1}$$

- **Any increase of the luminosity must come from optics manipulations and increasing proton intensity.**
- **A large number of cavities are required. Increases the machine impedance. All of them cannot be placed in low dispersion, low β locations.**
- **Bunch length $\propto 1/\sqrt{V_{rf} f_{rf}}$. Higher frequencies are preferred, reducing the power consumed.**

Scaling of Luminosity with Energy

Requirements on the RF

- RF must supply the energy lost.
- RF acceptance $\sim$ 10 Energy spread for a good quantum lifetime.

1. Higher energy with a fixed number of cavities.

$$\frac{P_{cav}(E_1)}{P_{cav}(E_0)} \propto [\frac{U_1}{U_0}]^2$$

The luminosity scales as

$$\boxed{\frac{\mathcal{L}_1}{\mathcal{L}_0} = (1 + \frac{P^0_{cav}}{P^0_{beam}}) \left[\frac{E_0}{E_1}\right]^4 - \left(\frac{\sin\phi^0_s}{\sin\phi^1_s}\right)^2 \left[\frac{E_1}{E_0}\right]^4 \frac{P^0_{cav}}{P^0_{beam}}} \qquad (3)$$

2. Higher energy with increased number of cavities, fixed peak voltage per cavity.

$$\frac{P_{cav}(E_1)}{P_{cav}(E_0)} \propto [\frac{U_1}{U_0}]$$

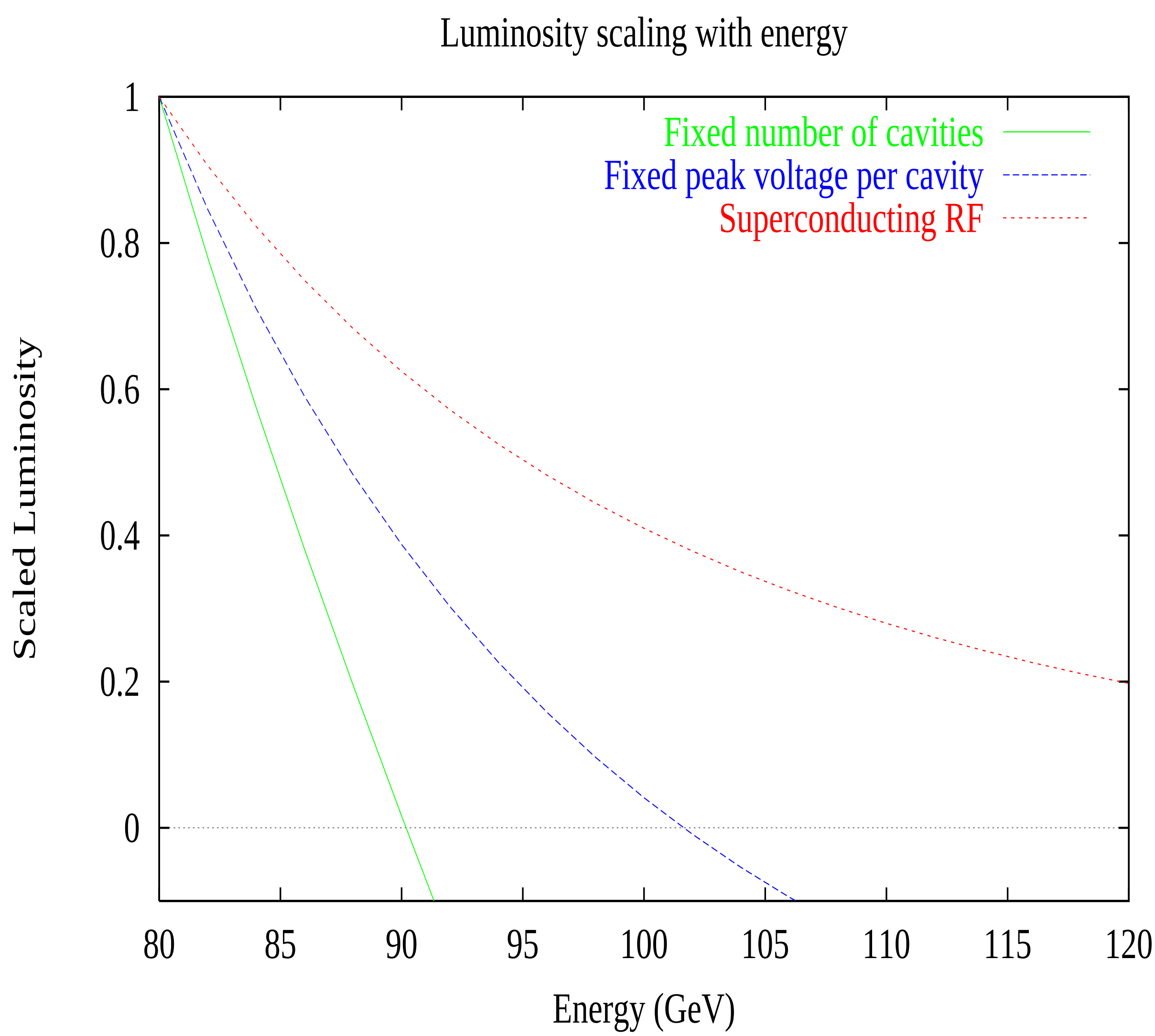
The luminosity scales as

$$\boxed{\frac{\mathcal{L}_1}{\mathcal{L}_0} = (1 + \frac{P^0_{cav}}{P^0_{beam}}) \left[\frac{E_0}{E_1}\right]^4 - \frac{\sin\phi^0_s}{\sin\phi^1_s} \frac{P^0_{cav}}{P^0_{beam}}} \qquad (4)$$

3. Superconducting cavities. Negligible power loss in the cavities.

The luminosity scales as

$$\boxed{\frac{\mathcal{L}_1}{\mathcal{L}_0} = \left[\frac{E_0}{E_1}\right]^4} \qquad (5)$$


Luminosity scaling with energy
Fixed number of cavities
Fixed peak voltage per cavity
Superconducting RF
Scaled Luminosity
Energy (GeV)
1
0.8
0.6
0.4
0.2
0
80
85
90
95
100
105
110
115
120

Parameters

BEAM PARAMETERS	
Energy [GeV]	80
Circumference [m]	34000
Luminosity [cm^{-2} s^{-1}]	2.6 $\times 10^{32}$
β_x^* / β_y^* [m]	0.115/0.115
RMS beam size at IP (H/V) [μm]	51/25.5
Beam-beam tune shifts (H/V)	0.0106/0.021
Beam Current [mA]	55.3
Bunch spacing [m]	28.33
Number of bunches	1200
Particles/bunch	3.26×10^{10}
Energy Loss/turn [MeV]	814
Damping times (τ_x, τ_y, τ_s) [msec]	(22, 22, 11)

TRANSVERSE		RF/LONGITUDINAL	
Cell Length [m]	100	Total RF power[MW]	50
Main Dipole field [T]	0.06	RF Voltage[MV]	1090
Bending radius [m]	4451.25	RF frequency[MHz]	529.046
Length of main dipole [m]	46	Harmonic Number	60,000
Number of dipoles/cell	2	Longitudinal emittance[eV-sec]	0.0067
Length of arc quadrupole [m]	1.5	Synchronous phase	48.3°
Quadrupole gradient [T/m]	5.03	Energy spread	1.03×10^{-3}
Phase advance/cell [degrees]	90	Bunch length [cm]	0.77
$\beta^{max} / \beta^{min}$ in cell [m]	171/29	Momentum compaction	0.000167
D_x^{max} / D_x^{min} in cell [m]	1.4/0.67	Synchrotron tune	0.120

Lifetime due to photo-desorption

The lifetime due to inelastic nuclear scattering alone, in the absence of intensity dependent pressure changes, is

$$\tau_0 = \frac{X_0}{W d_0 c}$$

$X_0$is the radiation length of residual gas [gm/cm^2]. $W \propto 1/\ln[\Delta E/E]$.

Usual gases present: H_2, CO, CO_2, CH_4, Ar. The lifetime (without current dependent effects) is

$$\frac{1}{\tau_0} = \frac{W c m_u P_0}{k_B T}\left[\frac{2f_{H_2}}{X_0(H_2)} + \frac{28 f_{CO}}{X_0(CO)} + \frac{44 f_{CO_2}}{X_0(CO_2)} + \frac{16 f_{CH_4}}{X_0(CH_4)} + \frac{40 f_{Ar}}{X_0(Ar)}\right]$$

With $P_0 = 10^{-9}$Torr, and reasonable assumtions on the fractional amounts of gases, the "zero-current" lifetime is

$$\tau_0 = 66 \text{ hrs}$$

At HERA, lifetime at low current is $\tau_0 = 15$hrs.

Synchrotron radiation dependent pressure.

Critical energy E_c

$$E_c = 2.218 \frac{E^3}{\rho} \quad [\text{keV}] = 255.1 [\text{keV}]$$

The linear photon flux which desorbs gases from the walls of the vacuum chamber is

$$\Phi_\gamma = \frac{N_\gamma}{2\pi\rho} = 1.28 \times 10^{17} \quad [\text{photons/m/sec}]$$

At HERA $\Phi_\gamma = 5.8 \times 10^{17}$photons/m/sec.

The flux of molecules per unit length desorbed by synchrotron radiation photons

$$\Phi_{mol} = \eta \Phi_\gamma$$

The gas load per unit length is

$$Q_\gamma = \frac{3}{2} k_B T \Phi_{mol} = 4.5 \times 10^{-20} \Phi_\gamma \eta$$

Pressure rise due to the gas load

$$\Delta P = \frac{Q_\gamma}{\langle S \rangle}$$

where $\langle S \rangle$ is the average pumping speed in litres/m/sec. The specific pressure rise is

$$\alpha_P = \frac{\Delta P}{I} = 3.64 \times 10^{-2} \frac{\eta E}{2\pi\rho\langle S \rangle} \quad [\mathrm{Torr/mA}]$$

The specific current I_α (the current at which the pressure rise due to photo-desorption equals the initial pressure)

$$I_\alpha = \frac{P_0}{\alpha_P}$$

Due to the photo-desorption, the pressure depends on the current.

$$P = P_0 + \Delta P = P_0[1 + \frac{I}{I_\alpha}]$$

Lifetime

$$\boxed{\tau = \frac{\tau_0}{1 + I/I_\alpha}}$$

Time dependent current

$$I(t) = I_0 \frac{e^{-t/\tau_0}}{1 + \frac{I_0}{I_\alpha}(1 - e^{-t/\tau_0})}$$

$$\boxed{\text{Integrated Luminosity} \propto \int I dt = \tau_0 I_\alpha \ln[1 + \frac{I_0}{I_\alpha}(1 - e^{-t/\tau_0})]}$$

Assuming $\langle S \rangle$= 100 litres/m/sec, P_0 = 10^{-9} [Torr],

	Aluminium	Copper
η [molecules/photon]	2×10^{-5}	2×10^{-6}
α_P [Torr/mA]	1.21×10^{-11}	1.21×10^{-12}
I_α [mA]	51.5	515.1
$\tau(I_0)$ [hrs]	31.7	59.4

After a 10hour run.

No.	Material	Integrated current [mA-hrs]	% decrease
0	α_P=0	513.0	-
1	Aluminum	477.7	6.9%
2	Copper	509.2	0.75%

Inelastic Electron-Proton scattering

Electrons lose energy to photons emitted in the bremmstrahlung process

$$e + p \rightarrow e + p + \gamma$$

If E_i, E_f are the initial and final energies of the electron and k is the energy of the emitted photon, the differential cross-section is

$$\frac{d\sigma}{dk} = 4\alpha r_e^2 \frac{E_f}{kE_i}\left(\frac{E_i}{E_f} + \frac{E_f}{E_i} - \frac{2}{3}\right) \ln\left[\frac{4E_pE_iE_f}{M_eM_pk} - \frac{1}{2}\right]$$

where E_p is the proton energy, $\hbar = c = 1$. The change in the proton energy is very small, so

$$E_i \approx E_f + k$$

The maximum energy k_{max} imparted to the photon occurs when the final state electron is nearly at rest, i.e.

$$k_{max} \approx E_i$$

In the scattering cross-section for events leading to the loss of an electron from the beam pipe we can set

$$k_{min} = \delta_{accept} E_i$$

where $\delta_{accept} = (\Delta E/E)_{accept}$. The total cross-section, integrating k from k_{min} to k_{max}, is

$$\sigma = \frac{16\alpha r_e^2}{3}\left[(-\ln\delta_{accept} - \frac{5}{8})\ln(\frac{4E_pE_i}{M_eM_p} + \frac{1}{2}) + \frac{1}{2}(\ln\delta_{accept})^2 - \frac{\pi^2}{6} - \frac{3}{8}\right]$$

Using $\delta_{accept} = 9.91 \times 10^{-3}$, the total cross section is

$$\sigma = 2.906 \times 10^{-25} \quad [\mathrm{cm}^2]$$

The rate $\dot{N}$ at which electrons are lost from the beam is

$$\dot{N} = N_{IP}\mathcal{L}\sigma$$

where N_{IP} is the number of interaction points in the ring. Hence the lifetime of the electron beam is

$$\tau_{p-bremm} = \frac{N_{e,tot}}{N_{IP}\mathcal{L}\sigma}$$

where $N_{e,tot}$ is the total number of electrons in the beam initially.

$I_e = 65.88$mA, $N_{e,tot} = 4.66 \times 10^{13}$, proton energy is $E_p = 3000$GeV. Assuming that there is only one interaction point in the ring, the lifetime is

$$\boxed{\tau_{p-bremm} = 142 \ \ \text{hours}}$$

Quantum Lifetime

Horizontal plane:

$$\tau_{quant;x} = \frac{1}{\sqrt{2\pi}} \frac{\exp[r_{x,\delta}]}{(2r_{x,\delta})^{3/2}} \frac{1}{(1+f)\sqrt{f(1-f)}} t_{damp,x} \tag{6}$$

where

$$r_{x,\delta} = \frac{1}{2}(\frac{x_{Apert}}{\sigma_T})^2, \quad \sigma_T^2 = \sigma_x^2 + D_x^2\sigma_\delta^2, \quad f = \frac{D_x^2\sigma_\delta^2}{\sigma_T^2} \tag{7}$$

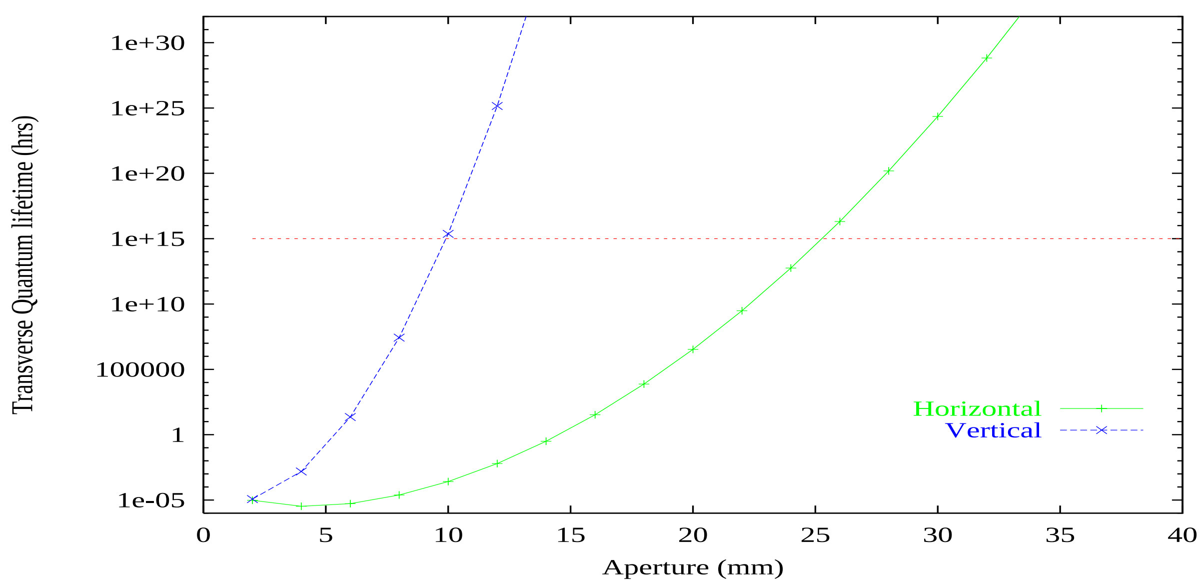
Vertical plane:

$$\tau_{quant;y} = \frac{e^{r_\beta}}{2r_y} t_{damp,y} \tag{8}$$

where

$$r_y = \frac{1}{2}(\frac{y_{Apert}}{\sigma_y})^2$$

$$\sigma_T^{max}(\text{Arcs}) = 2.43\text{mm}, \quad \sigma_y^{max}(\text{Arcs}) = 0.98\text{mm}, \quad \sigma_\delta = 1.03 \times 10^{-3}$$



Beam stay clear half-aperture

$$(A_x, A_y) = 10(\sigma_T, \sigma_y) + (X_{COD}, Y_{COD}) \tag{9}$$

Required beam chamber half-aperture

$$A_x \ \times \ A_y = 40\text{mm} \ \times \ 20\text{mm} \tag{10}$$

Beam Lifetime

Touschek lifetime

$$\tau_{Tousch} \propto \gamma^3 \frac{\sigma_x \sigma_{x'} \sigma_y \sigma_s}{N_e} (\frac{\Delta E}{E})^2_{accept}$$
$$= 5.4 \times 10^5 \text{ hrs}$$

Quantum lifetime at 10σ in each plane

$$\tau_{Qx} = 5.6 \times 10^{12} \text{ hrs}, \quad \tau_{Qy} = 2.3 \times 10^{15} \text{ hrs}, \tau_{Qs} = 3.8 \times 10^6 \text{ hrs}$$

$e - p$ bremmstrahlung lifetime

$$\tau_{e-p} = 142 \text{ hrs}$$

Synchtrotron radiation induced photo-desorption lifetime

$$\eta = 2 \times 10^{-5}; \quad \tau_{photo} = 32 \text{ hrs}$$
$$\eta = 2 \times 10^{-6}; \quad \tau_{photo} = 59 \text{ hrs}$$

Total lifetime

$$\frac{1}{\tau_T} = \frac{1}{\tau_{Tousch}} + \frac{1}{\tau_{Qx}} + \frac{1}{\tau_{Qy}} + \frac{1}{\tau_{Qs}} + \frac{1}{\tau_{ep}} + \frac{1}{\tau_{photo}}$$

$$\boxed{\tau_T = 26 \text{ hrs} \qquad [\eta = 2 \times 10^{-5}]}$$

$$\boxed{\tau_T = 42 \text{ hrs} \qquad [\eta = 2 \times 10^{-6}]}$$

Not included

- Effects of orbit distortion, larger emittances and energy spreads on the quantum lifetime.
- Ion or "dust trapping".
- Scattering of thermal photons.

Polarization

Sokolov-Ternov polarization time

$$\tau_{ST} = \frac{8}{5\sqrt{3}} \frac{m_e c^2 \rho^3}{e^2 \hbar \gamma^5} = 0.9 \text{ hrs}$$

Electrons are polarized anti-parallel to the field, positrons are polarized parallel. Closed orbit distortions lead to spin diffusion and depolarization.

Energy dependent spin tune

$$\nu_{spin} = a\gamma = 181.54$$

Depolarizing resonances

$$\nu_{spin} = k + m_x q_x + m_y q_y + m_s q_s$$

Dangerous resonances

- First order resonances: $m_x = \pm 1$, $m_y = \pm 1$, $m_s = \pm 1$
- Next, synchrotron side-band resonances of first order resonances: m_s a small integer. Modulation of spin tune by synchrotron oscillations. Measure of the strengths of these resonances

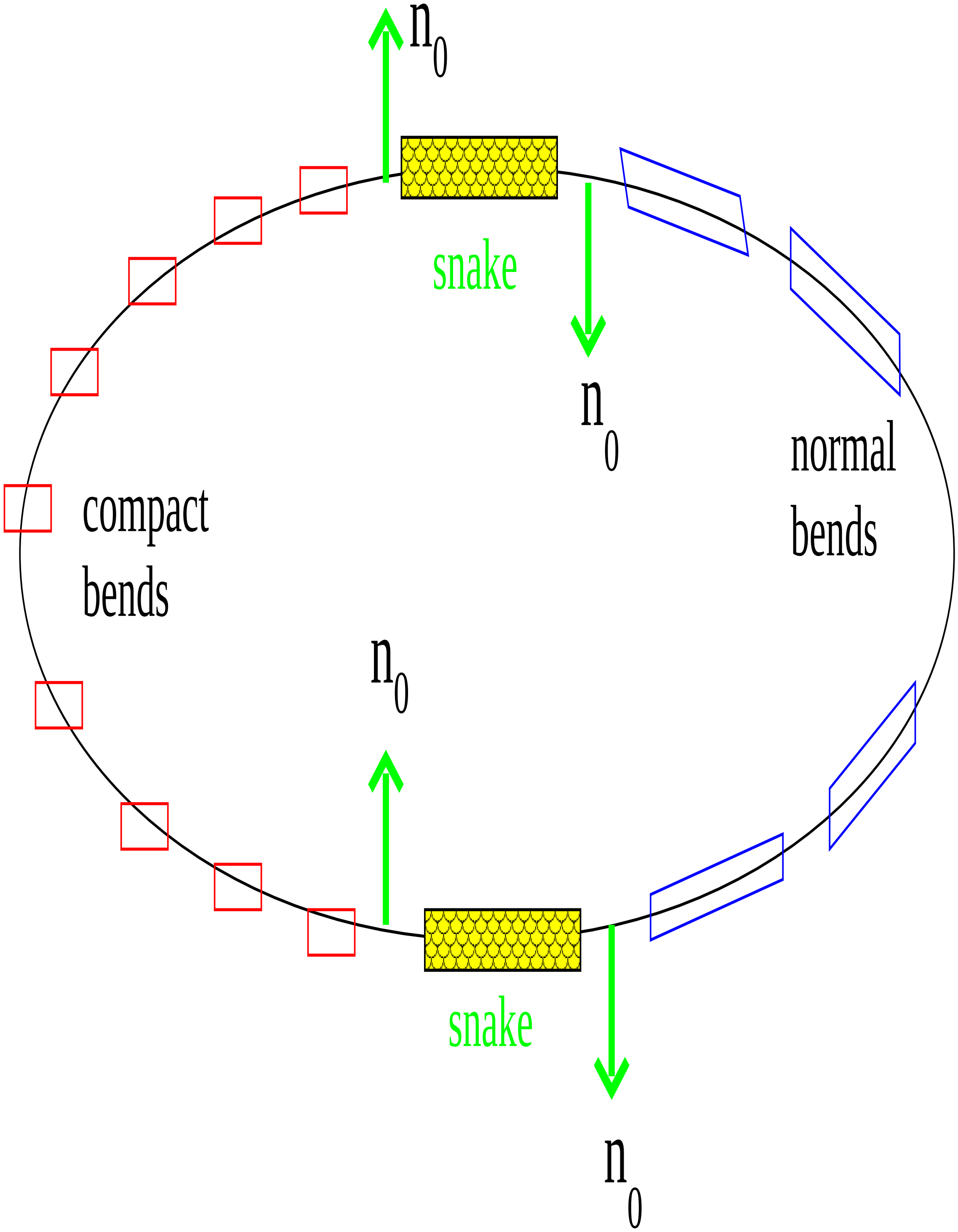
$$\kappa_{spin} = \left[\frac{a\gamma\sigma_\delta}{q_s}\right]^2 = 2.4$$

  Preferably $\kappa_{spin} \ll 1$ for depolarization to be weak.

Possible solution:

- Include polarization wigglers to enhance S-T rate. This however increases energy spread, κ_{spin} and depolarization.
- Incorporate asymmetric snakes a la Derbenev: spin tune is almost 0.5 independent of energy via a "spin echo" effect due to the two spin flips. Resonant depolarization is weak.

SNAKE DISTRIBUTION FOR POLARIZATION



Main Features

- **Low field (600 Gauss), air cooled, dipoles**.
- **Small Aluminium vacuum chambers**.
- **Ion pumps, every $\sim$ 8m section**.
- **50MW total RF power. Water cooling required.**
- **Superconducting cavities**.
- **Possibly superconducting IR quadrupoles.**
- **Low β^* (11.5 cm), head on collisions.**
- **Many bunches (1200)**
- **Feedback system for multi-bunch instabilities.**
- **Polarization must be designed in.**
- **Relatively low cost.**