Luminosity Prospects of LHeC, a Lepton Proton Collider in the LHC Tunnel

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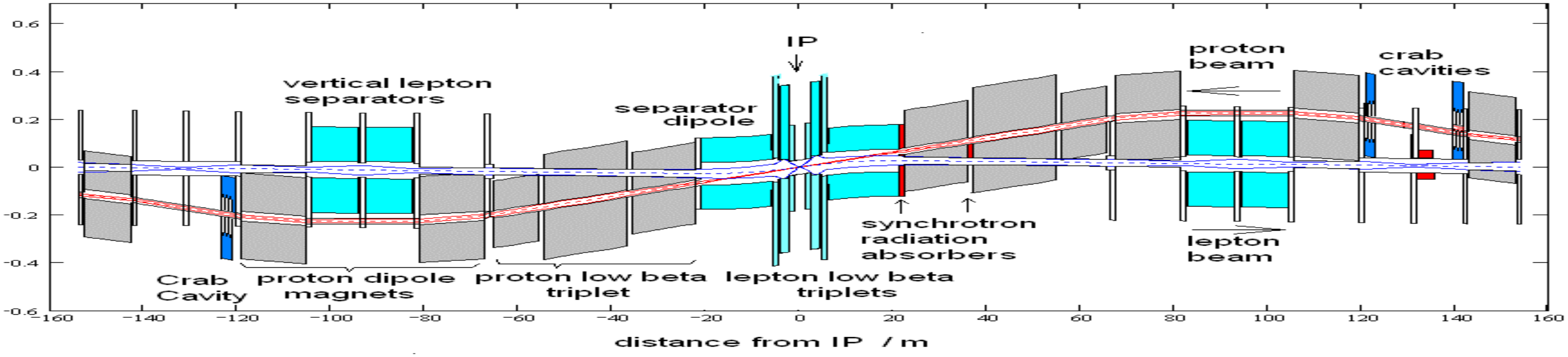


LHeC Design Goals

Luminosity $L = 1 \cdot 10^{33}\ cm^{-2}s^{-1}$

Energy $E_{cm} = 1.4\ TeV$

Design Asumptions

based on LHC Proton beam parameters

Energy	E_p = 7 TeV
Particles per Bunch	N_p = 1.68 1011
Emittance	ε_{Np} = 3.76 radμm
Bunch spacing	τ_b = 75 ns (instead of 25ns)
Bunch Length	σ_p = 7.6 cm

→ **E_e = 70 GeV**

Luminosity

$$L = \frac{N_p \cdot N_e \cdot f_{rev} \cdot n_b}{2 \cdot \pi \cdot \sqrt{\varepsilon_{xp}\beta_{xp} + \varepsilon_{xe}\beta_{xe}} \cdot \sqrt{\varepsilon_{yp}\beta_{yp} + \varepsilon_{ye}\beta_{ye}}}$$

Matched beam cross sections at IP $\sigma_{xp} = \sigma_{xe}, \quad \sigma_{yp} = \sigma_{ye}$

Lepton Beam-beam tune shift avoided

$$L = \frac{I_e \cdot N_p \cdot \gamma_p}{2\pi \cdot e \cdot \varepsilon_{Np} \cdot \sqrt{\beta_{xp} \cdot \beta_{yp}}}$$

With the proton beam brightness given by LHC, $N_p\gamma_p / \varepsilon_{Np} = 3.2 \cdot 10^{20} m^{-1}$

→

$$\frac{I_e}{\sqrt{\beta_{xp}\beta_{yp}}} = 0.063 \frac{A}{m}$$

Lepton Beam Current

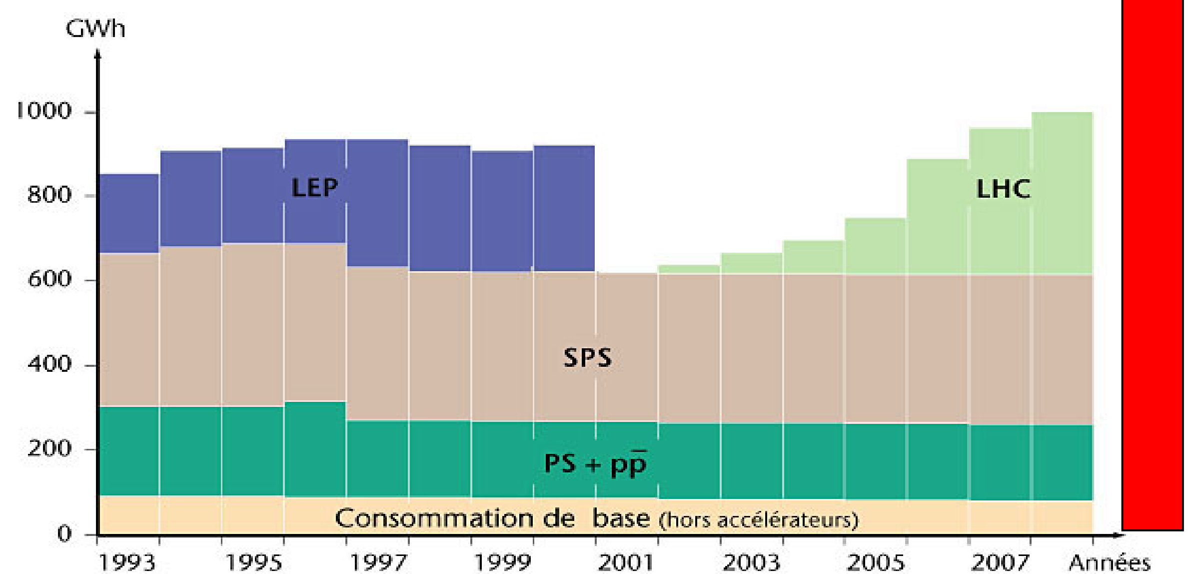
Assumptions: Limited by RF Power only

depends on Bending radius

$\rho = 80\% \cdot (C_{LHC}-8\cdot L_{straigth}) / 2\pi = 2886$ m

$eU_{loss} = C_g E_e^4 / (e\rho) = 734$ MeV

CERN Power Consumption



If 50 MW beam power considered as a limit ➔ $I_e = 68$mA $N_e = 1.3\ 10^{10}$

Design Task: e-Ring and IR Design which provides

$$\sqrt{\beta_{xp} \cdot \beta_{yp}} = 1m$$

- sufficient dynamic aperture
- With matched beams,
- Small crossing angle $\theta < \sigma_{xe} / \sigma_p$
- Small hour glass effect $\beta_{ye} \geq \sigma_p$
- tolerable synchrotron radiation background
- feasible components

Dynamic Aperture Scaling

$$n_\sigma(N,\phi) = \frac{\zeta}{ml_x(N,\phi)\cdot\sqrt{\varepsilon(N,\phi)\cdot\beta_f(N,\phi)^3}}$$

Taken from HERA: 0.2

This assumes a Plain FODO structure

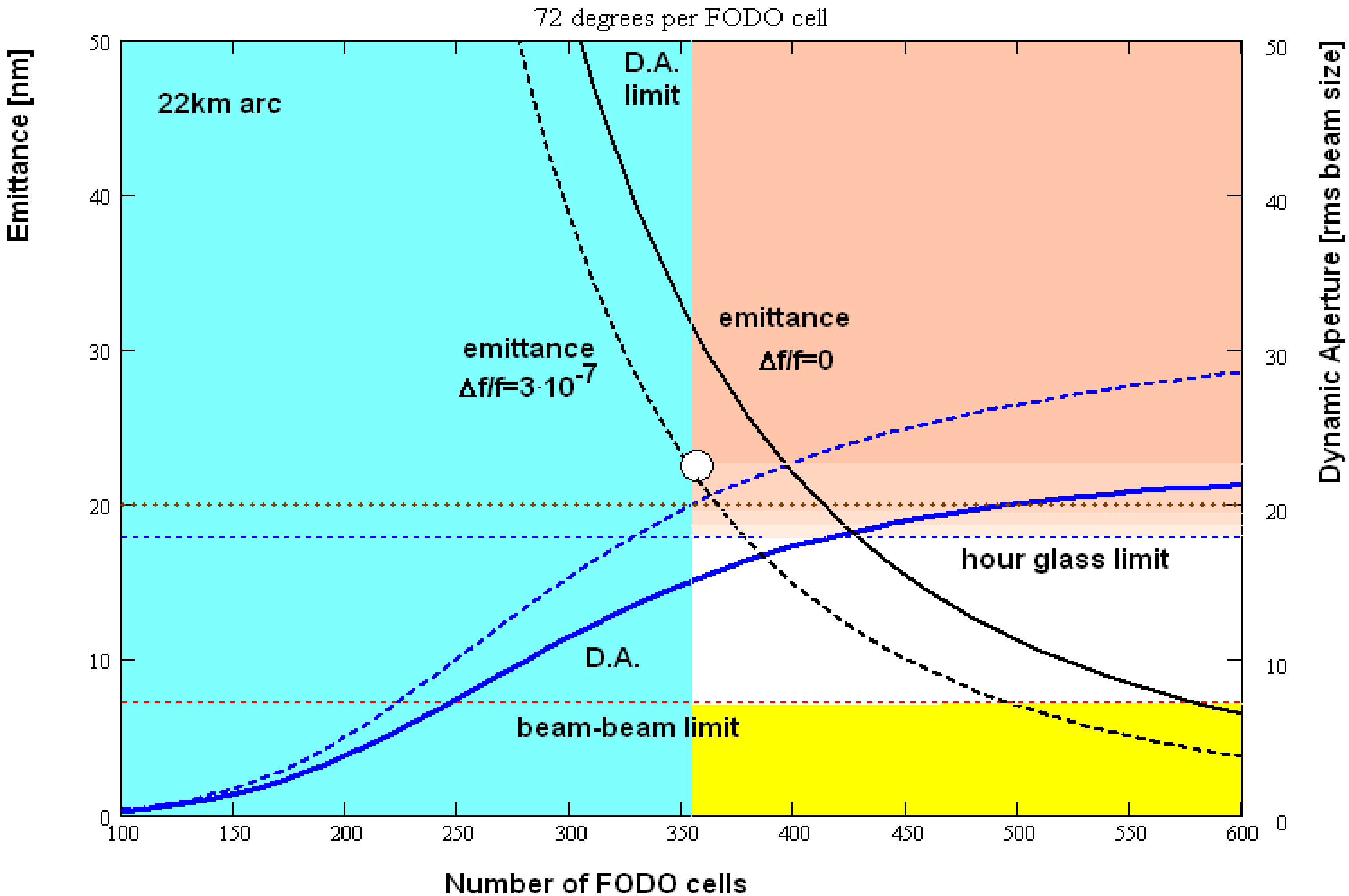
for FODO cell structure, N number of FODO Cells

$$n_\sigma(N,\phi) = \frac{\left(1+\frac{1}{2}\cdot\sin\left(\frac{\phi}{2}\right)\right)\cdot\zeta\cdot\cos\left(\frac{\phi}{2}\right)\cdot\sqrt{2\cdot\sin\left(\frac{\phi}{2}\right)^2-\frac{\pi\cdot(C-L_s)}{N^2\cdot\rho}}}{\left[\underbrace{\tan\left(\frac{1}{2}\cdot\phi\right)}_{\text{Arc chromaticity}}+\underbrace{\frac{D_{eff}\cdot\left[C_q\cdot\gamma^2\cdot\frac{(2\pi)^2}{2\cdot N^4}\cdot\frac{C-L_s}{\rho}\cdot\left(1-\frac{1}{2}\cdot\sin\left(\frac{\phi}{2}\right)^2\right)\right]}{\varepsilon_p\cdot\beta_p\cdot\sin(\phi)\cdot\left[2\cdot\sin\left(\frac{\phi}{2}\right)^2-\frac{\pi\cdot(C-L_s)}{N^2\cdot\rho}\right]}}_{\text{IR chromaticity for matched beams}}\right]\cdot\sqrt{C_q\cdot\gamma^2\cdot\frac{8}{\rho}\cdot\left(1-\frac{1}{2}\cdot\sin\left(\frac{\phi}{2}\right)^2\right)\cdot\left(1+\sin\left(\frac{\phi}{2}\right)\right)^3}}$$

Arc chromaticity

IR chromaticity for matched beams

Choosing Lepton Ring Lattice Parameters



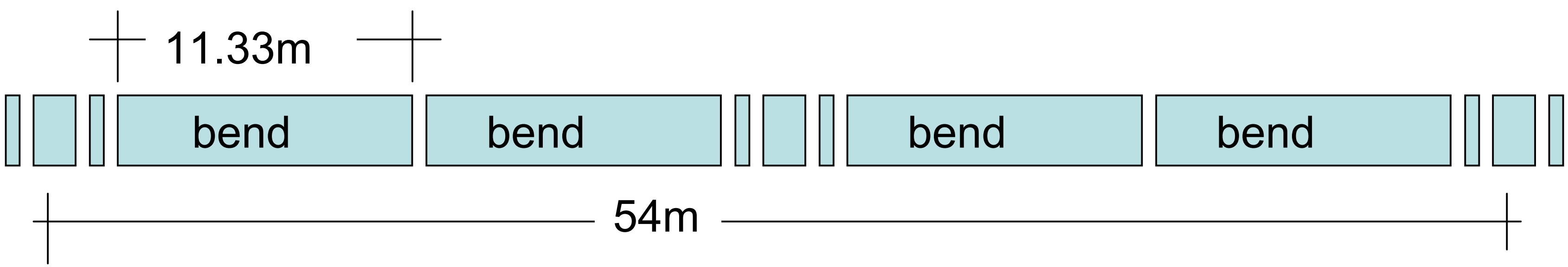
e Lattice

8 Octants with 500m Straight section

400 FODO cells, Cell length 54 m

Dipole length 2 x 11.33 m B= 780 Gauss

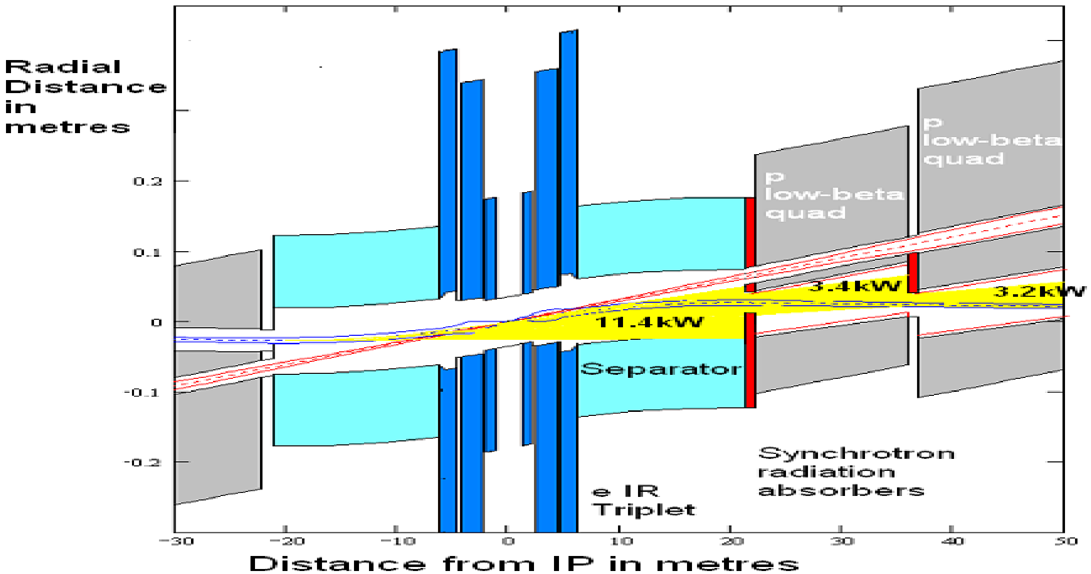
Quadrupole length 1.5 m (G = 7 T/m)



$\Delta\phi_{fodo}$ = 72 degree

ε_{xe} = 26 nm

Synchrotron Radiation

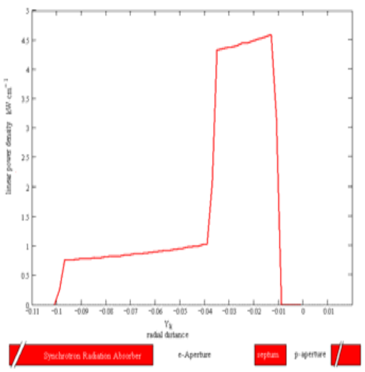


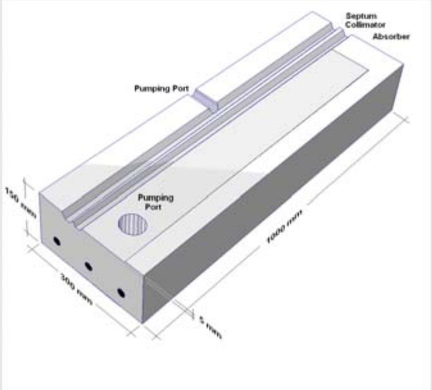
Values for IR

Instantaneous Power for one electron $$P_g(E_e, \rho_{ir}) = 3.203 \times 10^{-7}\,\text{watt}$$

Total Power $$2 \cdot P_{syn}(E_e, \rho_{ir}, \theta_{ir}, I_e) = 17.41\,\text{kW}$$

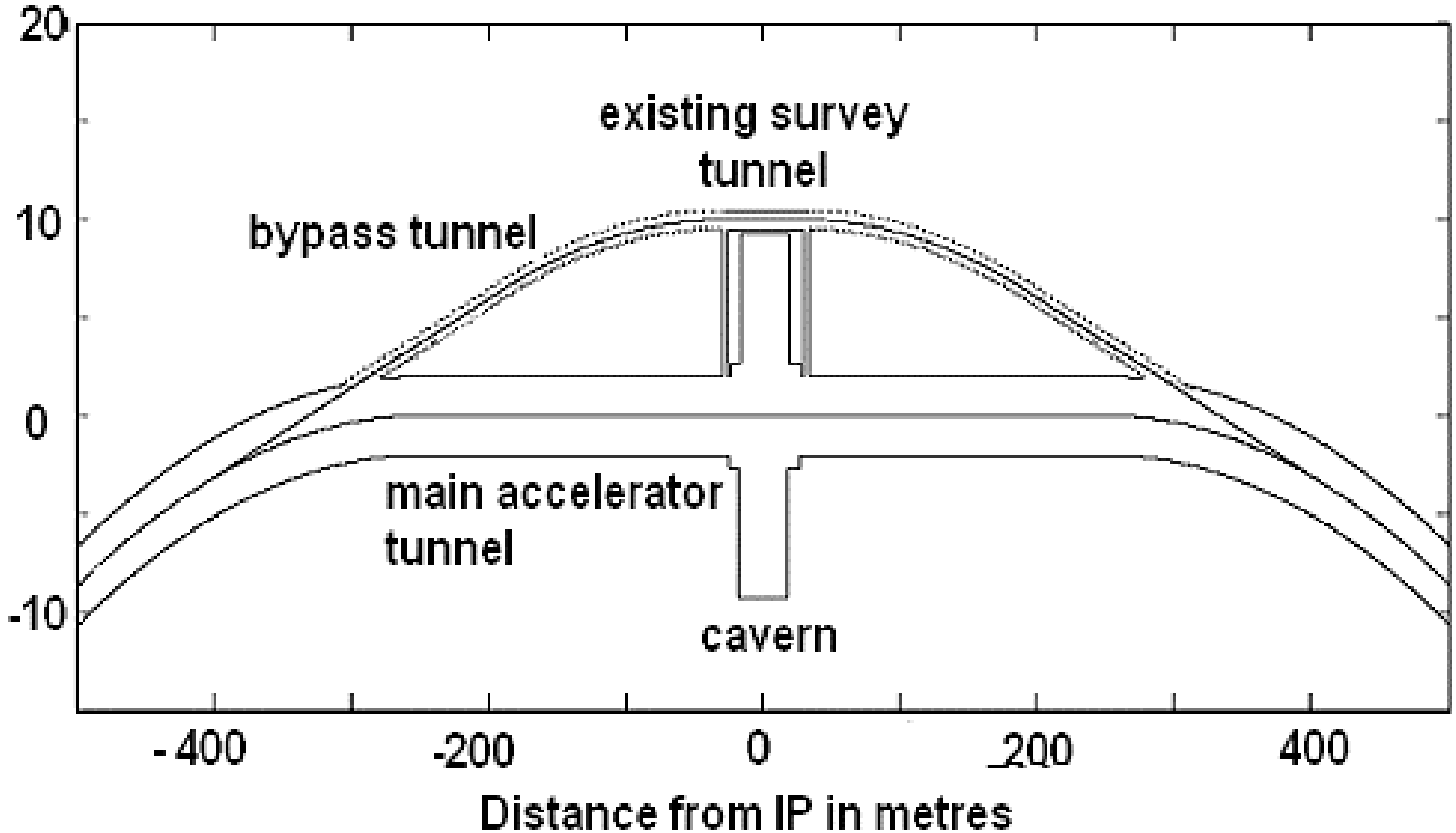
Power per unit Length $$P_s(E_e, \rho_{ir}, I_e) = 0.455\,\text{kW} \cdot \text{m}^{-1}$$



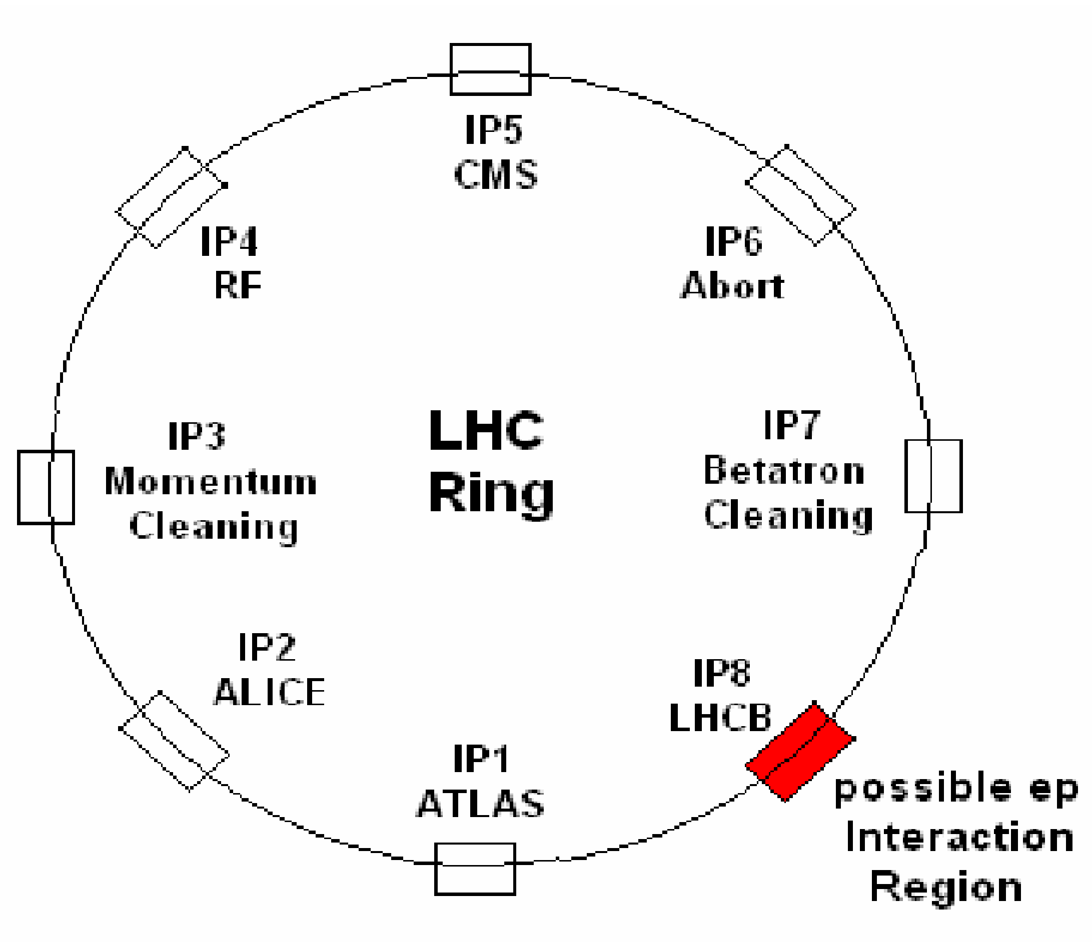


Critical Energy $$u_c(E_e, \rho_{ir}) = 107.244\,\text{keV}$$

Bypass around Atlas and CMS



Which IR?


IP5
CMS
IP4
RF
IP6
Abort
IP3
Momentum
Cleaning
LHC
Ring
IP7
Betatron
Cleaning
IP2
ALICE
IP8
LHCB
IP1
ATLAS
possible ep
Interaction
Region

IR Parameters

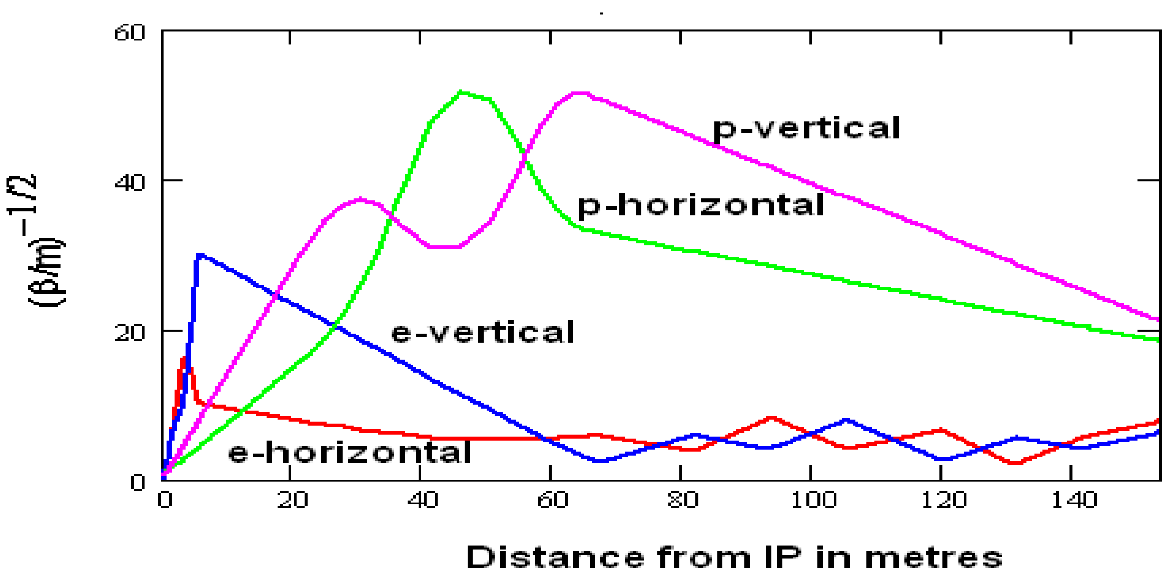
$\sigma_{xp} = \sigma_{xe}, \quad \sigma_{yp} = \sigma_{ye}$

$\varepsilon_{xp} = 0.5$ nm $\varepsilon_{xe} = 26$ nm

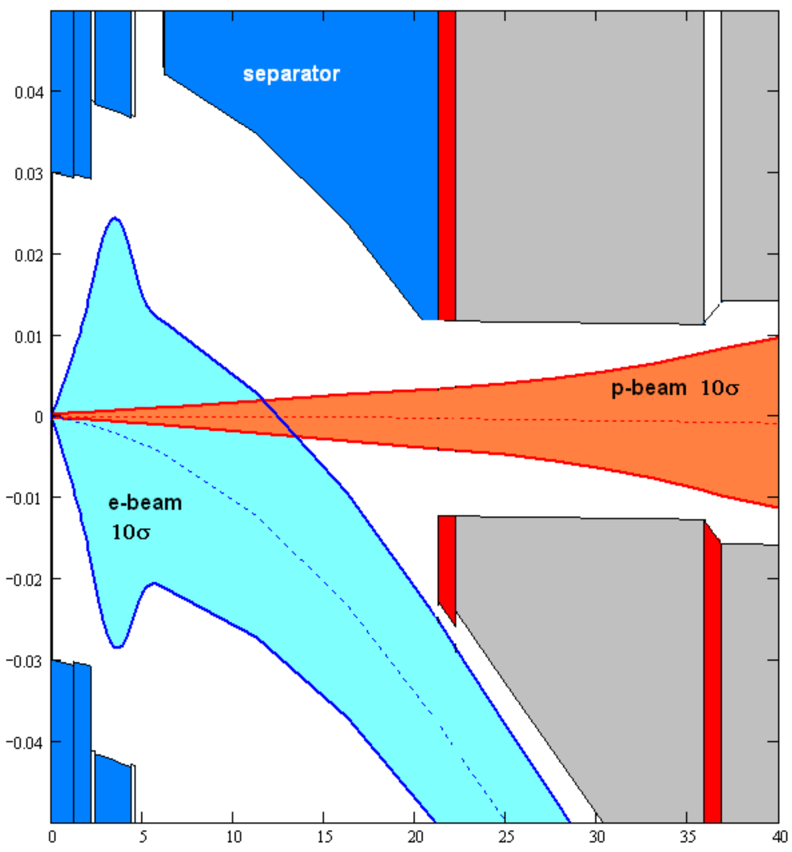
Need to match "flat" e beam with "round" p beam

$\beta_{xp}/\beta_{yp} = 4$

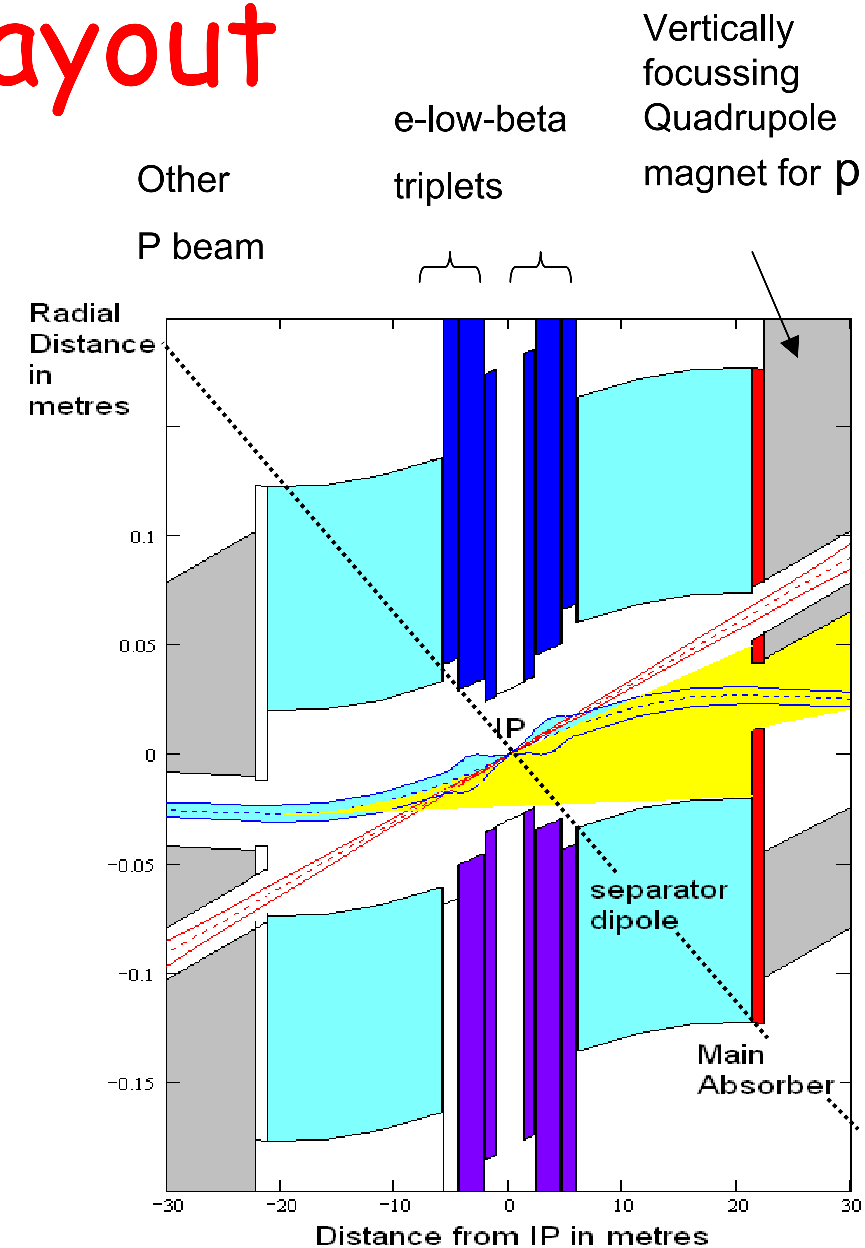
$\beta_{xp} = 2$ m
$\beta_{yp} = 50$ cm
$\beta_{xe} = 5$ cm
$\beta_{ye} = 5$ cm



IR Layout

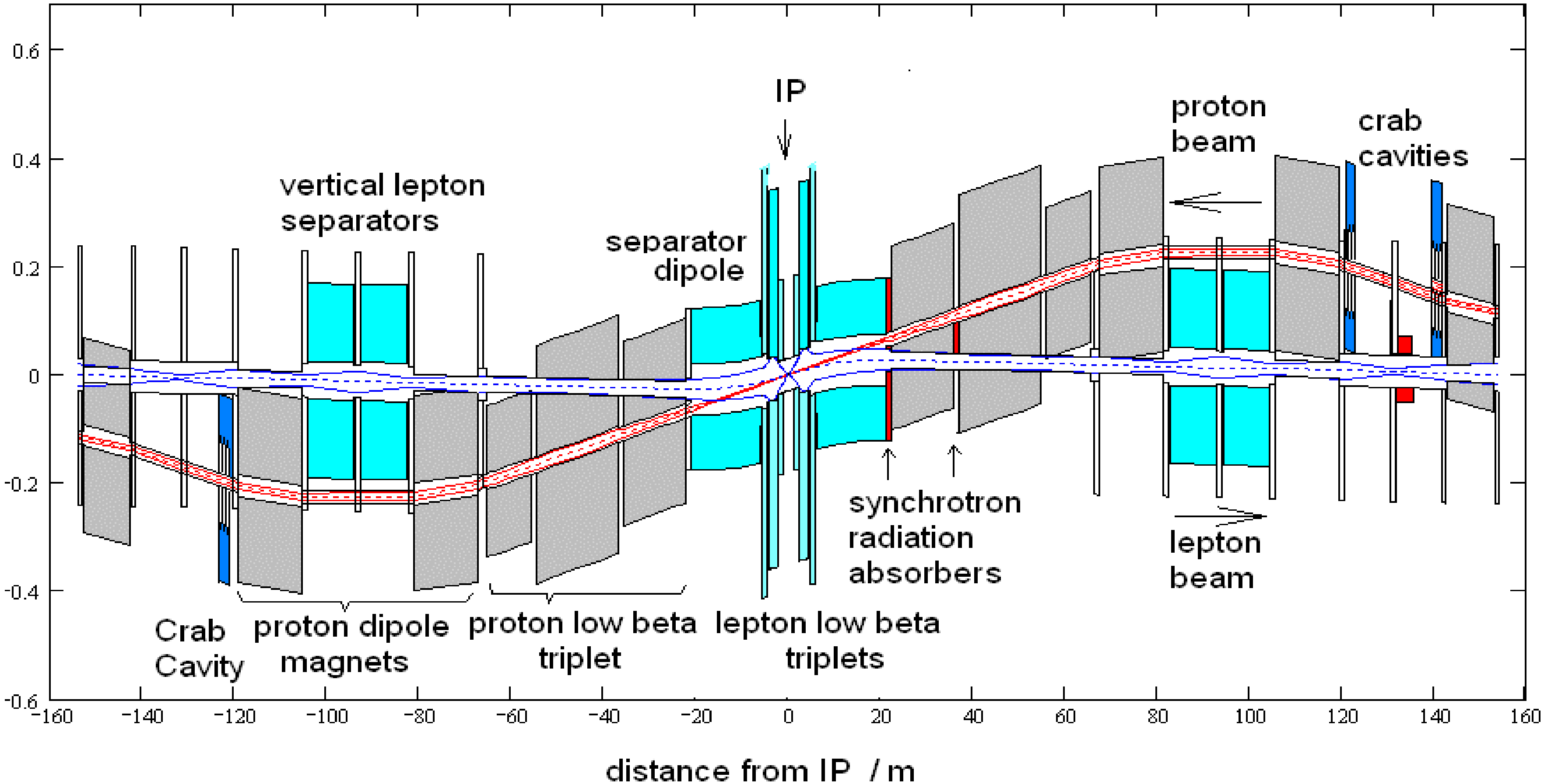


separator
p-beam 10σ
e-beam
10σ
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
5
10
15
20
25
30
35
40



Other
P beam
e-low-beta
triplets
Vertically
focussing
Quadrupole
magnet for p
Radial
Distance
in
metres
IP
separator
dipole
Main
Absorber
0.1
0.05
0
-0.05
-0.1
-0.15
-30
-20
-10
0
10
20
30
Distance from IP in metres

IR Layout



IP
proton beam
crab cavities
vertical lepton separators
separator dipole
synchrotron radiation absorbers
lepton beam
Crab Cavity
proton dipole magnets
proton low beta triplet
lepton low beta triplets
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
distance from IP / m

Luminosity

LeHC Parameter List

Beam Energies	$E_p = 7 \times 10^3\,\mathrm{GeV}$	$E_e = 70\,\mathrm{GeV}$
Center of Mass Energy	$E_s = 1.4\,\mathrm{TeV}$	
Beam Currents	$I_p = 362.667\,\mathrm{mA}$	$I_e = 70.947\,\mathrm{mA}$
Emittance	$\varepsilon_{Np} = 3.75\,\mu\mathrm{m}$	$\varepsilon_{xe} = 25.997\,\mathrm{nm}$
β^*	$\beta_{xp} = 1.8\,\mathrm{m}$	$\beta_{xe} = 0.055\,\mathrm{m}$
	$\beta_{yp} = 0.5\,\mathrm{m}$	$\beta_{ye} = 0.055\,\mathrm{m}$
p Bunch Length	$\sigma_s = 7.55\,\mathrm{cm}$	
Synchrotron Radiation Power		$P_{erf} = 50\,\mathrm{MW}$
beam-Beam Tuneshift	$\Delta\nu_{xp} = 1.24 \times 10^{-3}$	$\Delta\nu_{xe} = 0.022$
	$\Delta\nu_{yp} = 7.243 \times 10^{-4}$	$\Delta\nu_{ye} = 0.042$
Crossing Angle	$\theta_c = -0.5\,\mathrm{mr}$	
Hourglass factor	$R(\sigma_s) = 0.886$	
Peak Luminosity	$L_{peak} = 1.01 \cdot 10^{33}\,cm^{-2}\,\sec^{-1}$	

Beam-Beam Effect

Central crossing beam-beam parameters well within the HERA range

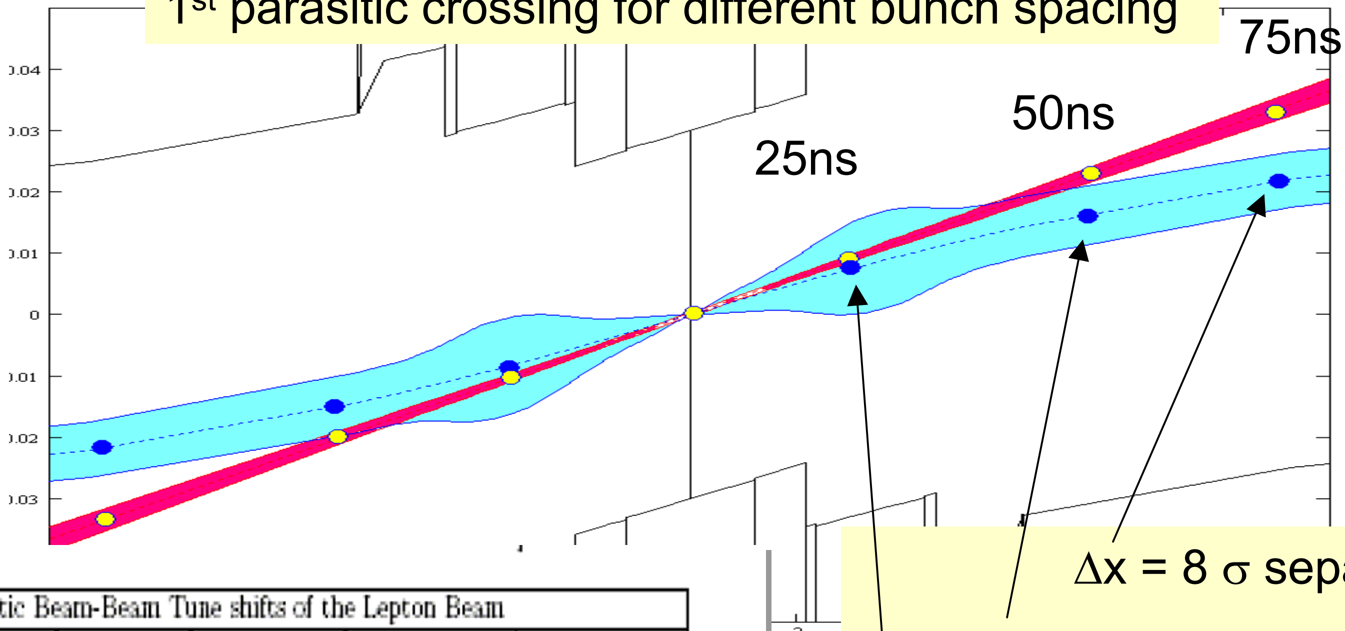
e-hor bb tuneshift $\Delta\nu_{xe} := \dfrac{r_e \cdot N_p \cdot \beta_{xe}}{2 \cdot \pi \cdot \gamma_e \cdot \sigma_{xp} \cdot \left(\sigma_{xp} + \sigma_{yp}\right)}$ $\Delta\nu_{xe} = 0.022$

e ver bb tuneshift $\Delta\nu_{ye} := \dfrac{r_e \cdot N_p \cdot \beta_{ye}}{2 \cdot \pi \cdot \gamma_e \cdot \sigma_{yp} \cdot \left(\sigma_{xp} + \sigma_{yp}\right)}$ $\Delta\nu_{ye} = 0.042$

p-hor bb tuneshift $\Delta\nu_{xp} := \dfrac{r_p \cdot N_e \cdot \beta_{xp}}{2 \cdot \pi \cdot \gamma_p \cdot \sigma_{xebb} \cdot \left(\sigma_{xebb} + \sigma_{yebb}\right)}$ $\Delta\nu_{xp} = 1.24 \times 10^{-3}$

p ver bb tuneshift $\Delta\nu_{yp} := \dfrac{r_p \cdot N_e \cdot \beta_{yp}}{2 \cdot \pi \cdot \gamma_p \cdot \sigma_{yebb} \cdot \left(\sigma_{xebb} + \sigma_{yebb}\right)}$ $\Delta\nu_{yp} = 7.243 \times 10^{-4}$

Parasitic Crossings

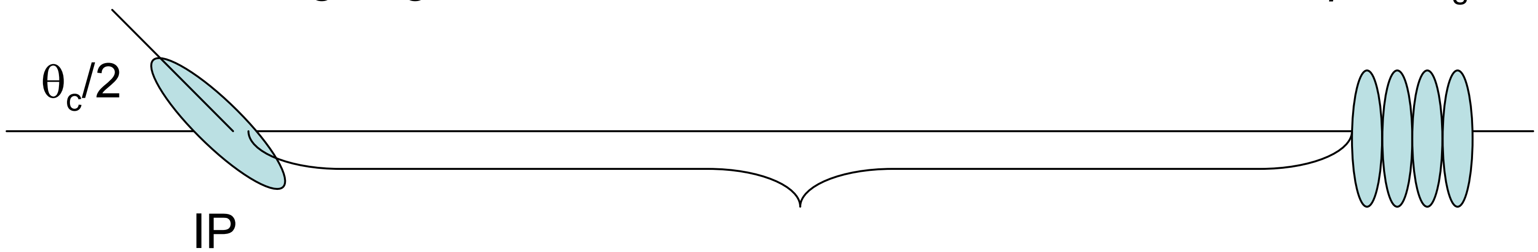


Parasitic Beam-Beam Tune shifts of the Lepton Beam				
Bunch spacing	Crossing angle	Horizontal Separation	horizontal parasitic beam-beam tune shift	vertical parasitic beam-beam tune shift
[ns]	[mrad]	[mm]		
25	0.5	2.78	0.0129	-0.0353
50	0.5	7.63	0.0088	-0.0211
75	0.5	14.47	0.0005	-0.0042
25	1	2.78	0.0053	-0.0199
50	1	7.63	0.0020	-0.0098
75	1	20.1	0.0003	-0.0022

Nominal Bunch spacing LHC not compatible with maximum LHeC luminosity !

Crab Crossing

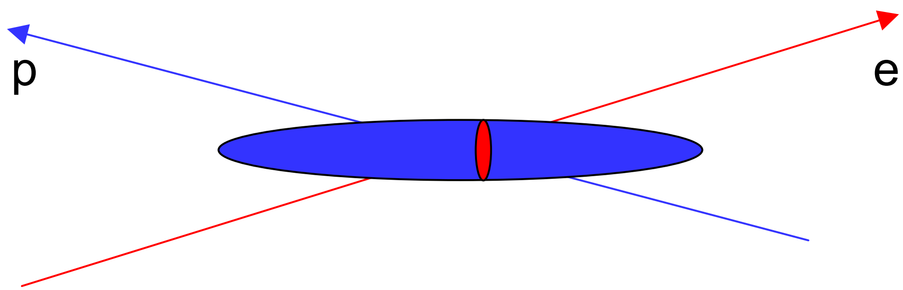
Crossing angle will enhance effective beam size $\sigma^2 = \varepsilon\beta + \theta^2\sigma_s^2$

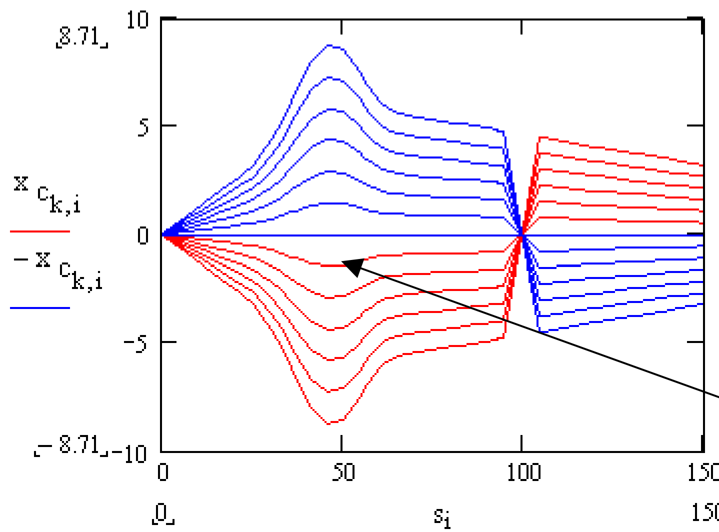


90 degree

Transverse

RF resonators

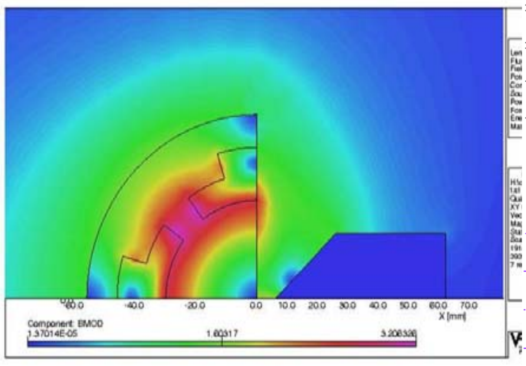


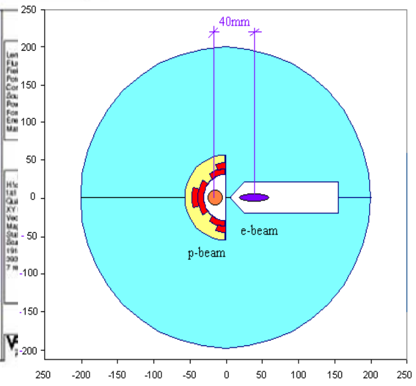


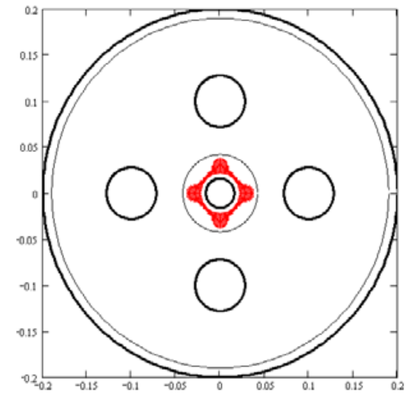
"Crabbed Trajectories

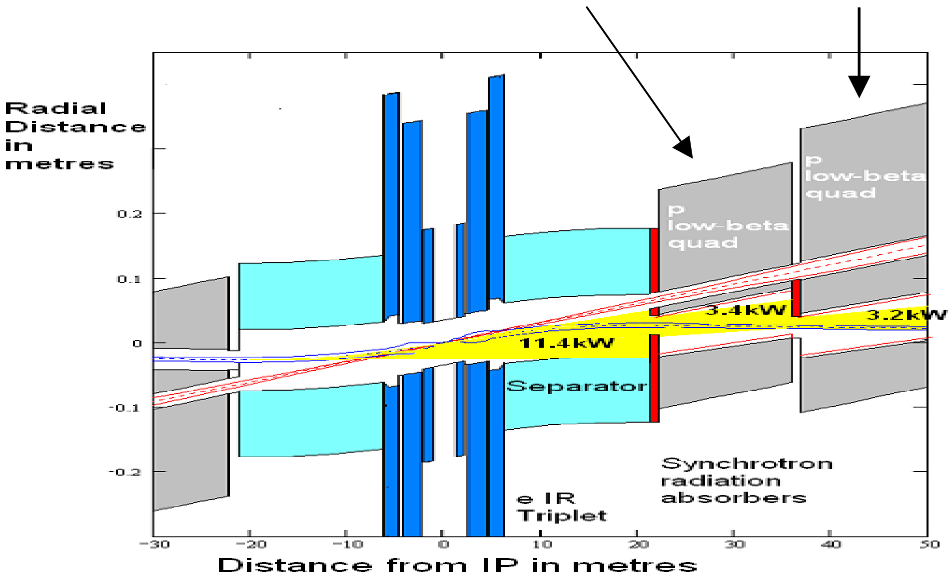
θ_c=0.5mr

Quadrupole Magnets









Conclusions

A first look at a possible lepton proton collider in the LHC tunnel with a luminosity of $10^{33}cm^{-2}s^{-1}$ appears to be technical possible

Simultaneous operation of pp and ep should be possible (however with reduced pp luminosity)

More work is needed to determine the most optimum parameters, the optimum technical choices and the cost of such a facility

A workshop to discuss this exciting option together with experimental physicists and accelerator scientists is planned in October 06