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

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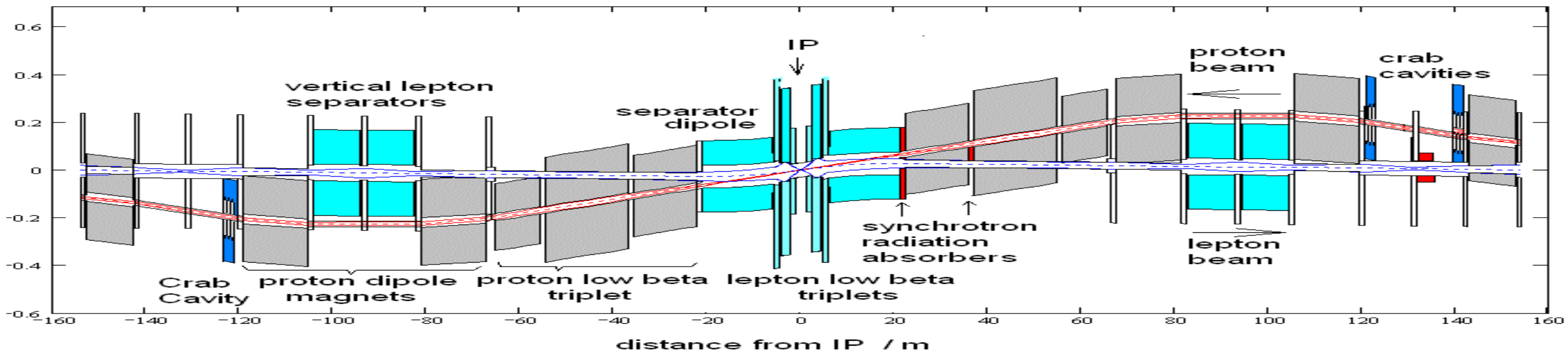


LHeC Design Goals

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

Energy $E_{cm} = 1.4\ TeV$

These input parameters are subject to be altered by further iterations

But this study assumes these parameters to be fixed

Design Asumptions

based on LHC Proton beam parameters

Energy	$E_p = 7$ TeV
Particles per Bunch	$N_p = 1.68\ 10^{11}$
Emittance	$\varepsilon_{Np} = 3.75$ radμm
Bunch spacing	$\tau_b = 25$ ns
Bunch Length	$\sigma_p = 7.55$ cm

→ **$E_e = 70$ GeV**

Circumference = 26658.883 m

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

Lepton Beam-beam tune shift limit to be 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, $N_p\gamma_p / \varepsilon_{Np} = 3.2 \cdot 10^{20} m^{-1}$

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

Lepton Beam Current

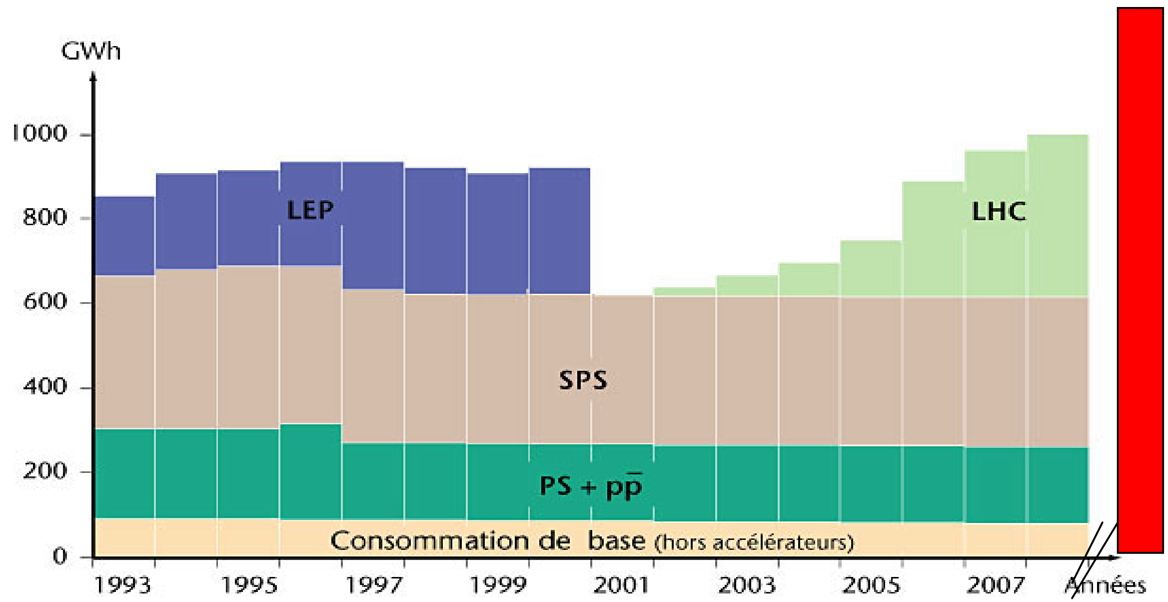
Assumptions: Limited by RF Power only

depends on Bending radius

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

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

CERN Power Consumption



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

5000 h/y x 50MW x 10 = 250 GWh/y

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

e-Ring Lattice Parameters

bend radius & circumference fixed by LHC effective FODO structure chosen (no alternative) the only choice to be made id the FODO cell length or the number of cell length of the arc

➔ This determines the lepton beam emittance and the dynamic aperture

Constraints under the assumption of matched beam sizes at the IP:

Small emittance ➔ large β^* ➔ strong beam-beam effect➔ no stability
large emittance ➔ small β^* ➔ strong hourglass effect effect➔ less lumi
Long cells ➔large emittance➔ reduced dynamic aperture ➔ no stability
Short cell➔small emittance, high cost

Dynamic Aperture Scaling

$$n_{\sigma}(N,\phi) := \frac{\zeta}{ml_{x}(N,\phi)\cdot\sqrt{\varepsilon(N,\phi)\cdot\beta_{f}(N,\phi)^{3}}}$$

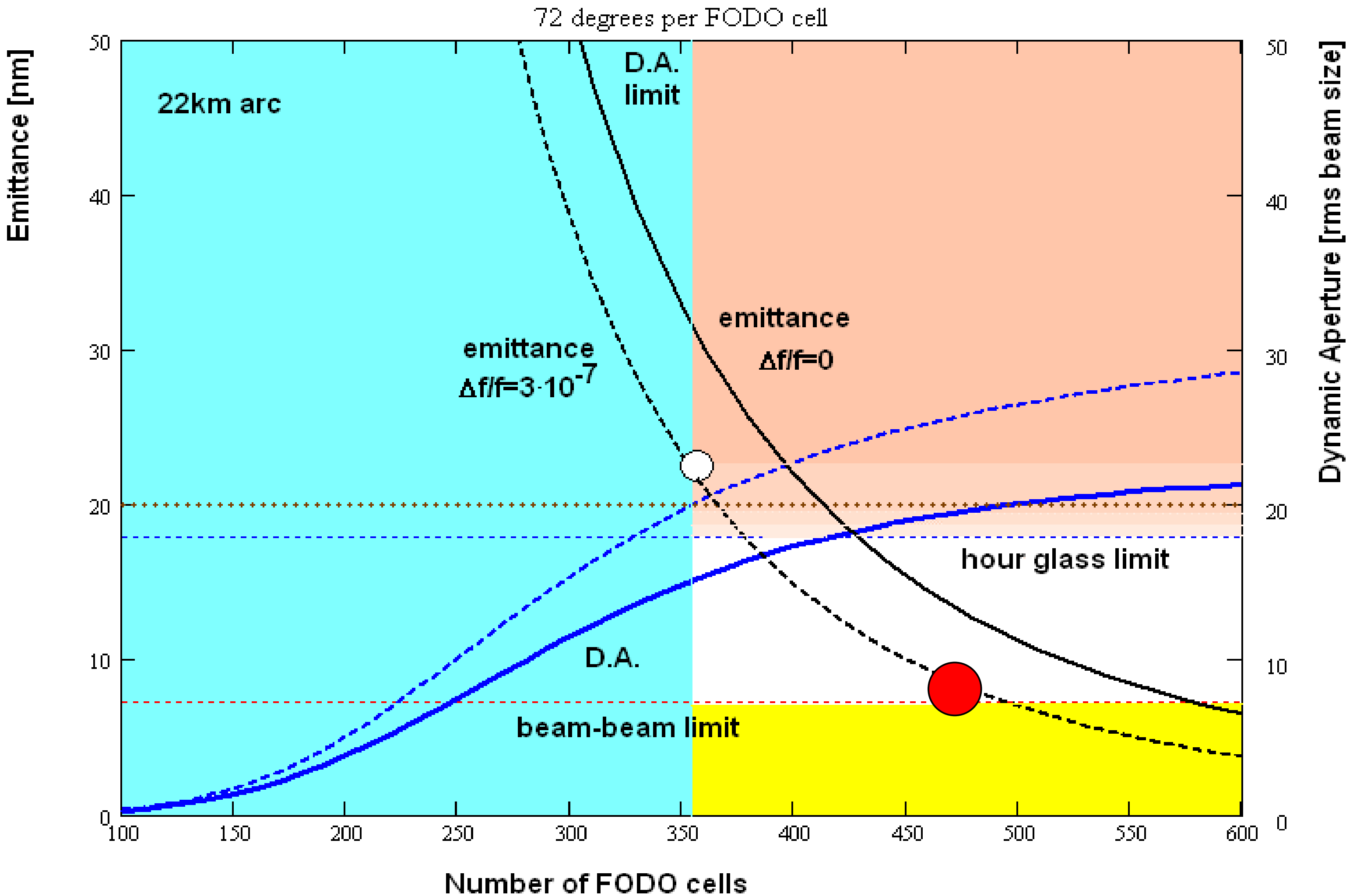
Taken from HERA: 0.2

This assumes a Plain FODO structure

for FODO cell structure, N number of FODO Cells

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

Choosing Lepton Ring Lattice Parameters



Main Parameters of LeHC

Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	7.6	0.501
Vertical Beam Emittance	nm	3.8	0.501
Horizontal β-functions at IP	cm	12.7	180
Vertical β-function at the IP	cm	7.1	50
Energy loss per turn	GeV	0.707	$6 \cdot 10^{-6}$
Radiated Energy	MW	50	0.003
Bunch frequency / bunch spacing	MHz / ns	40 / 25	
Center of Mass Energy	GeV	1400	
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.1	

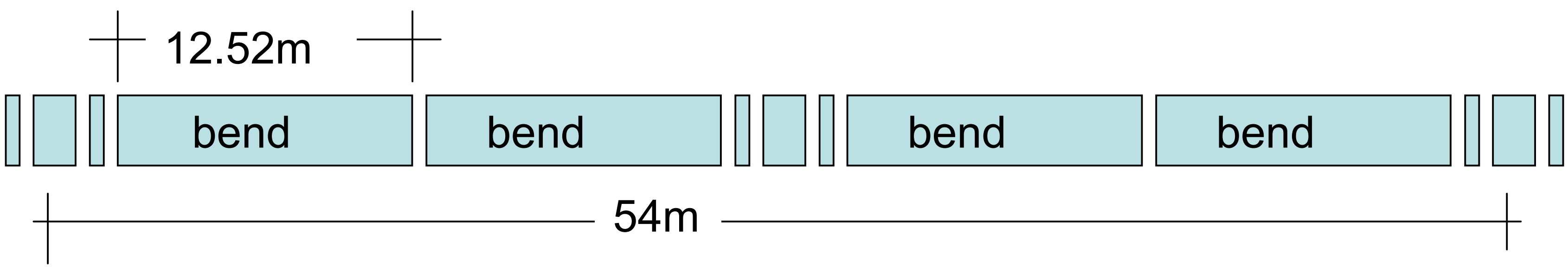
e Lattice

8 Octants with 500m Straight section each

376 FODO cells, Cell length 60.3 m

Dipole length 2 x 12.52 m B= 810 Gauss

Quadrupole length 1.5 m (G = 8 T/m)

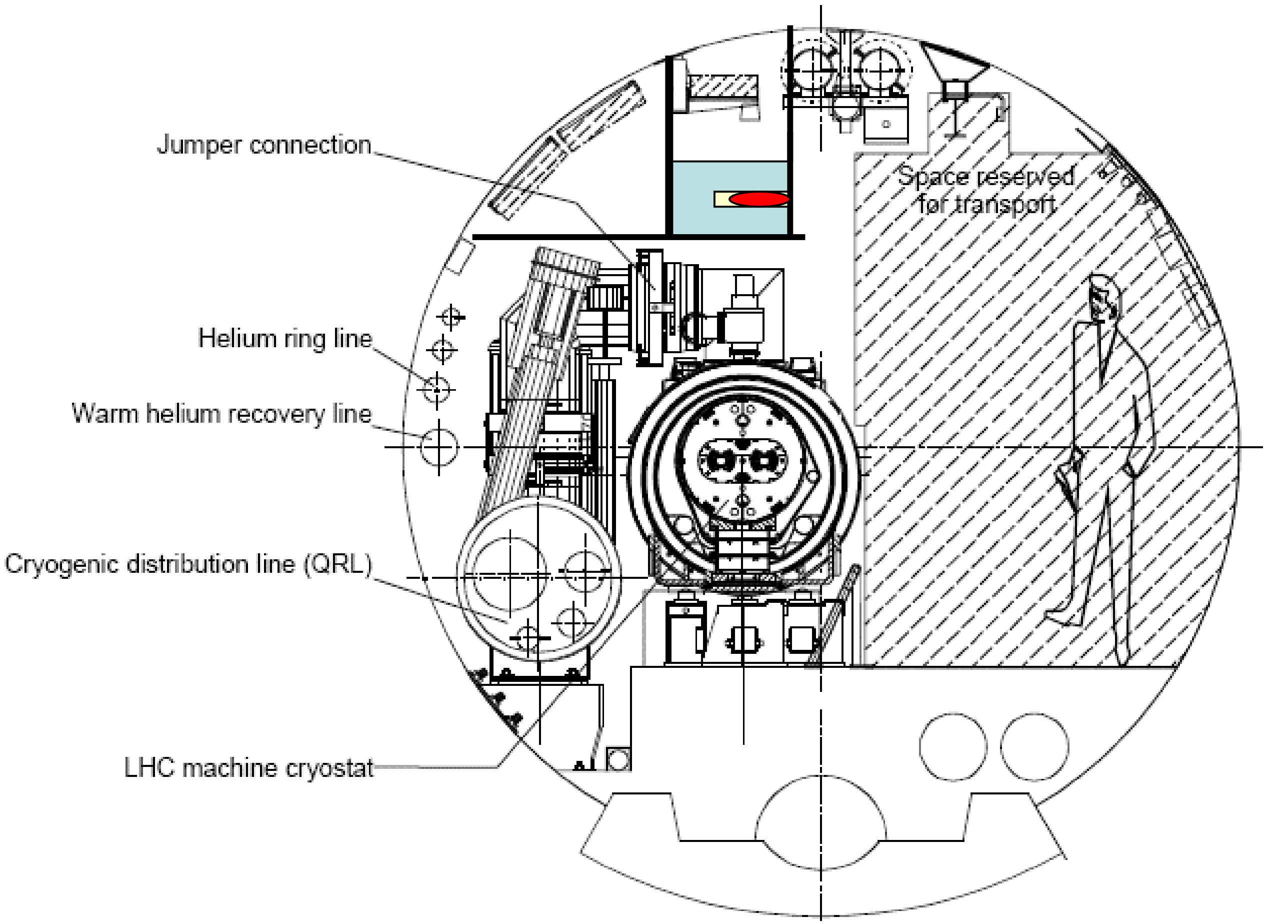


$\Delta\phi_{fodo}$ = 72 degree

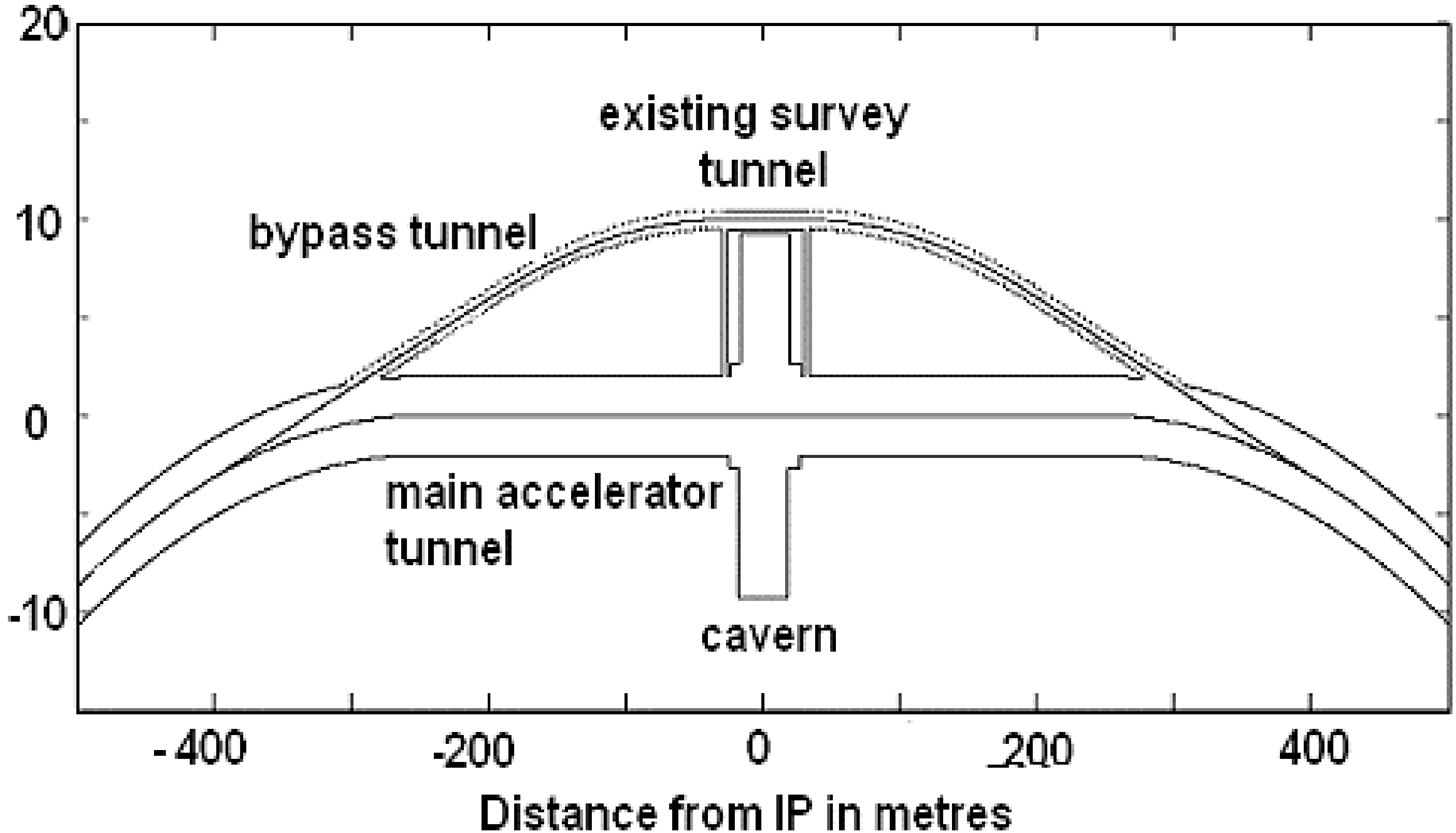
$\boldsymbol{\varepsilon_{xe}}$ **= 8 nm**

Electron Ring Parameters		
Parameter	Unit	Value
Circumference C	m	26658.86
Beam Energy E_e	GeV	70
Arc Focusing		FODO
Cell length L_c	m	60.3
Bending radius ρ	m	2997
Horizontal betatron Phase Adv./cell $\Delta\phi_x$	degree	72
Vertical betatron Phase Adv./cell $\Delta\phi_y$	degree	72
Number of FODO cells in the Arcs N_{cell}		376
Arc Chromaticity (hor/vert.) $\xi_{x,y}$		94/120
Beam Current I_e	mA	70.7
Bunch spacing τ_b	ns	25
Number of bunches n_b		2800
Number of particles per bunch N_e	10^{10}	1.4
Momentum compaction factor α	10^{-4}	1.34
Horizontal beam emittance ε_{xe}	nm	7.6
Vertical beam emittance ε_{ye}	nm	3.8
RMS energy spread σ_e	10^{-3}	2.4
RMS bunch length	mm	7.1
Particle Radiation energy loss per turn eU_{loss}	MeV/turn	706.8
Beam Power loss P_{loss}	MW	50
Circumferencial Voltage U	MV	1521
Synchronous Phase ϕ_{synch}	degree	27
RF frequency f_{rf}	MHz	1000
Bucket height h_b	σ_e	8.4
RF frequency shift	Hz	250
Synchrotron frequency f_s	f_{rev}	0.191

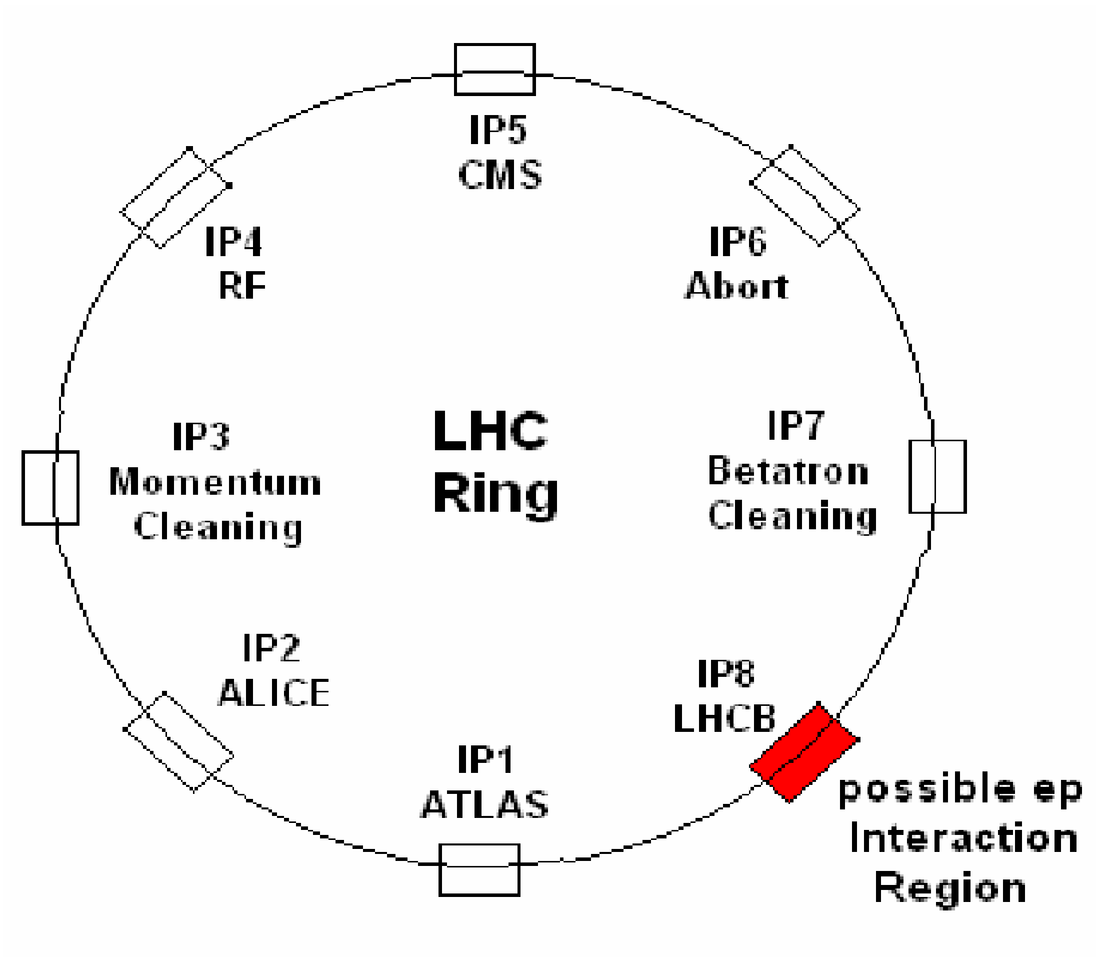
Tunnel Cross Section



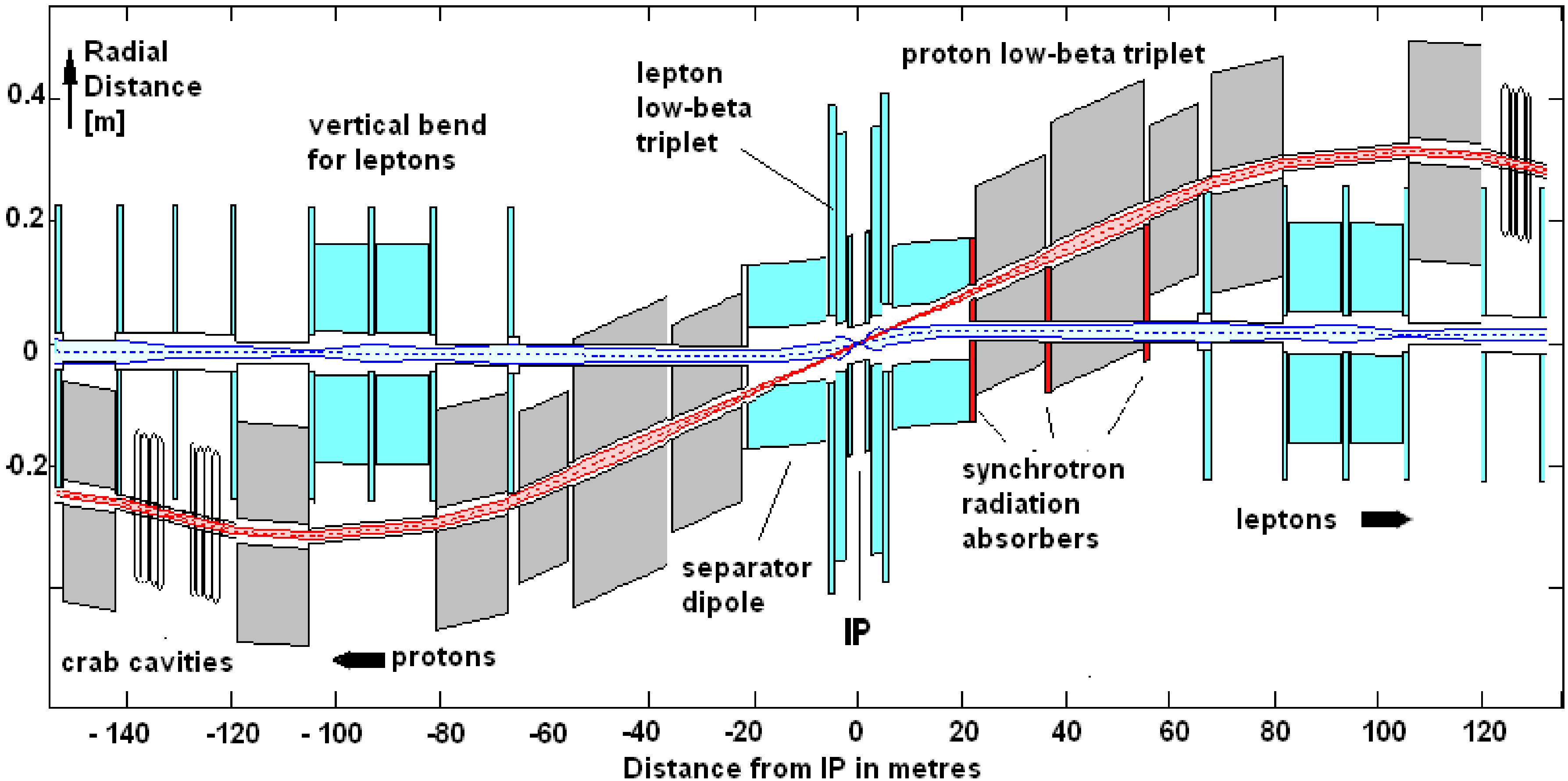
Bypass around Atlas and CMS



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 Layout



Radial Distance [m]
0.4
0.2
0
-0.2
vertical bend for leptons
lepton low-beta triplet
proton low-beta triplet
synchrotron radiation absorbers
leptons
separator dipole
IP
crab cavities
protons
- 140
-120
- 100
-80
-60
-40
-20
0
20
40
60
80
100
120
Distance from IP in metres

Interaction region parameters			
property	**unit**	**leptons**	**protons**
Horizontal Beta function at IP	cm	12.7	180
Vertical beta function at IP	cm	7.07	50
Horizontal IR Chromaticity		-7.5	-7.9
Vertical IR chromaticity		-29.7	-7.7
Maximum horizontal Beta	m	131.7	2279
Maximum vertical Beta	m	704.4	2161
Minimum of available Aperture	σ_x	16	13.5
Low beta quadrupole gradient	T/m	93.3	115
Separation dipole field	T	0.033	-
Sychrotron Radiation Power	kW	9.1	-
Low beta quadrupole length	m	.96/2.43/1.14	16.5/18.6/11
Low beta quadrupole apertures	mm	30/40/50	12/15/15
Distance of first quadruple from IP	m	1.2	22
Detector Acceptance Polar Angle	degree	9.4	
Crossing Angle	mrad	2	

IR Parameters

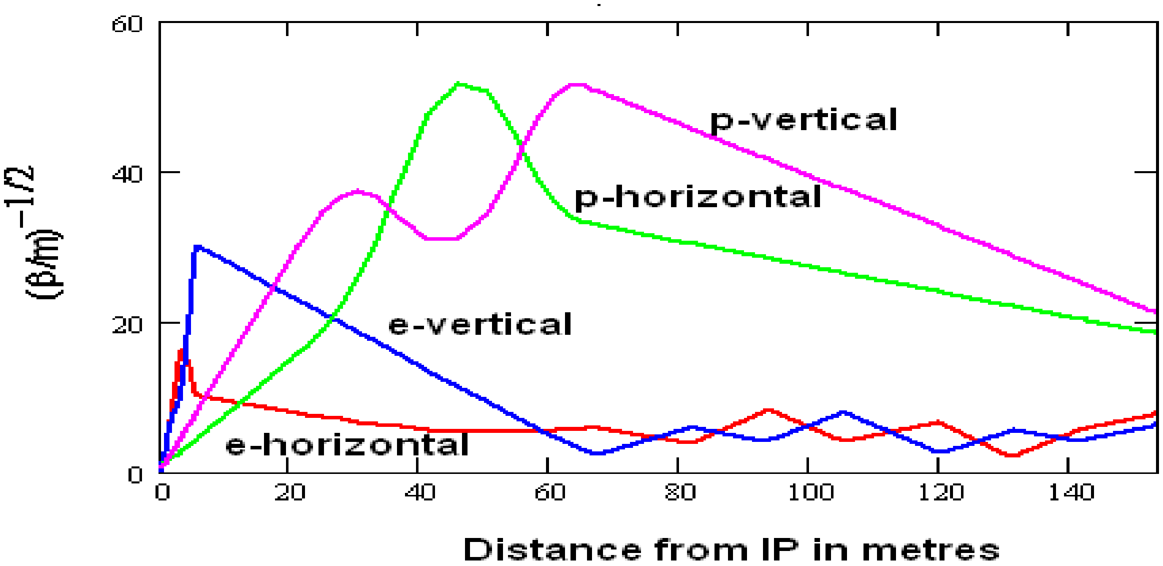
$\sigma_{xp} = \sigma_{xe}$, $\sigma_{yp} = \sigma_{ye}$

ε_{xp} = 0.5 nm ε_{xe} = 7.6 nm

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

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

IR optics with low-beta tripletts for both e and p beams



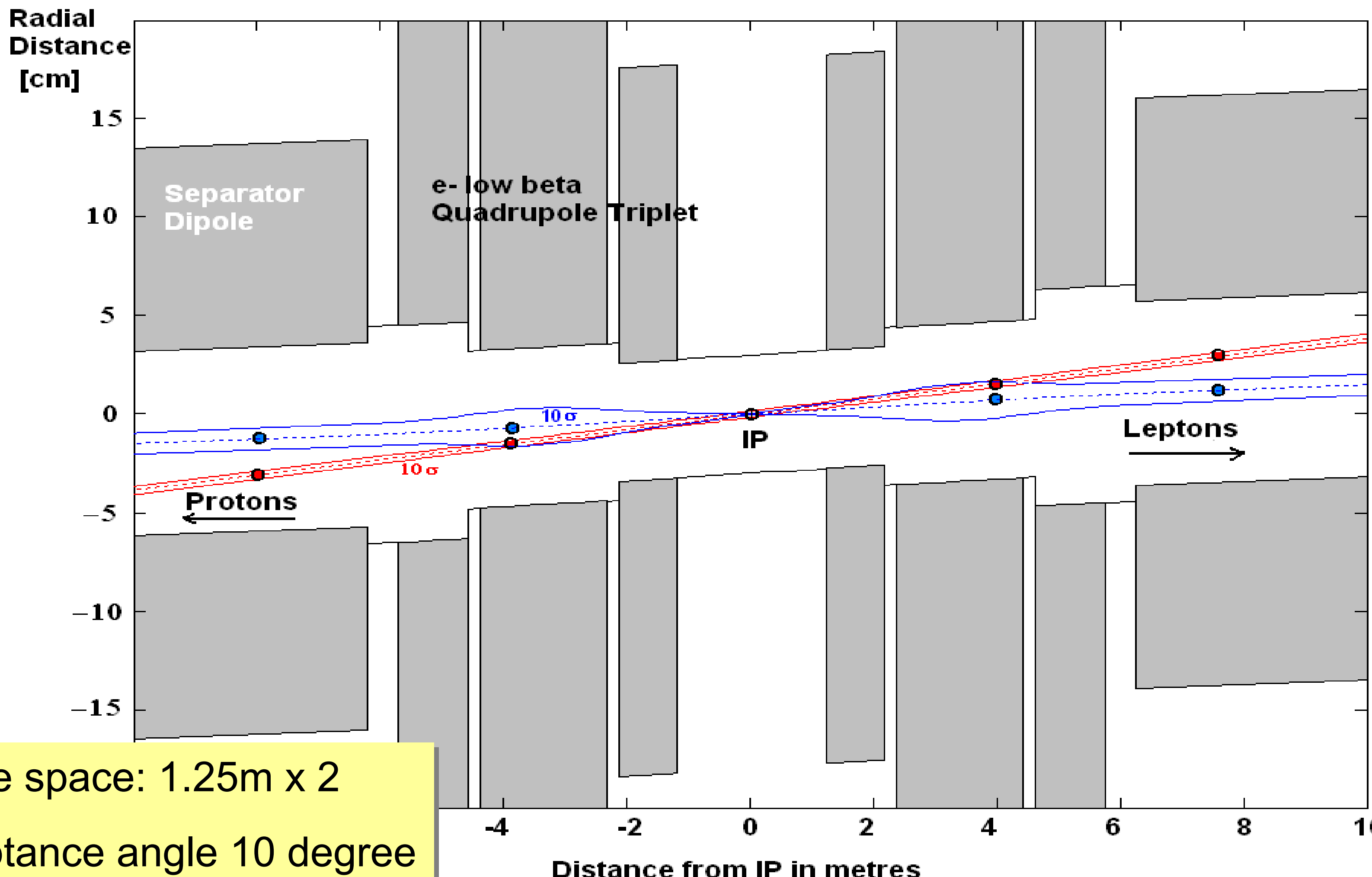
β_{xp} = 1.8 m

β_{yp} = 0.5 m

β_{xe} = 12.7 cm

β_{ye} = 7.1 cm

IR Layout



IR free space: 1.25m x 2

Acceptance angle 10 degree

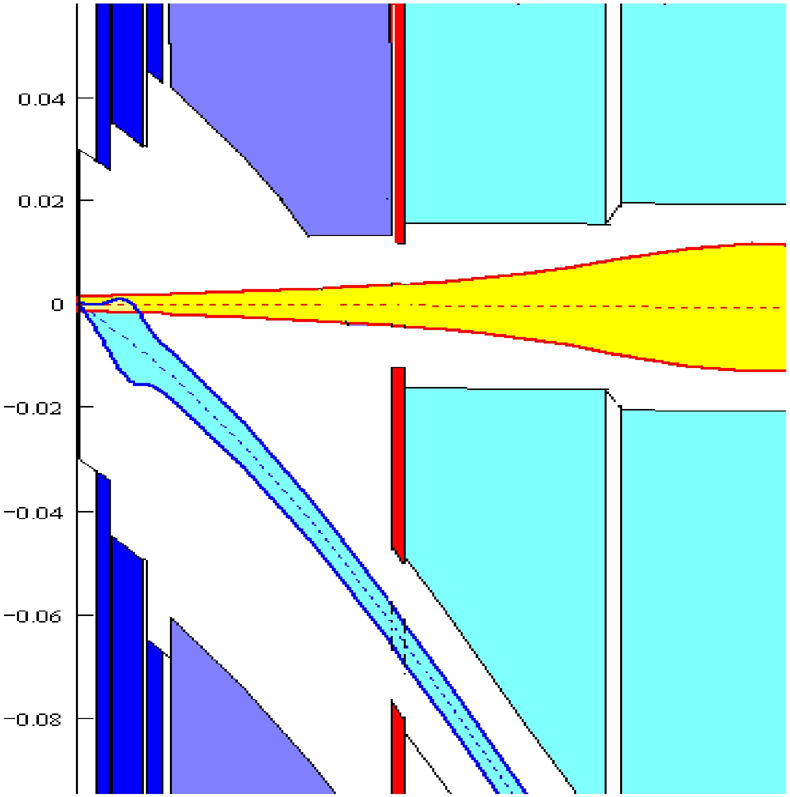
Crossing angle 2mr

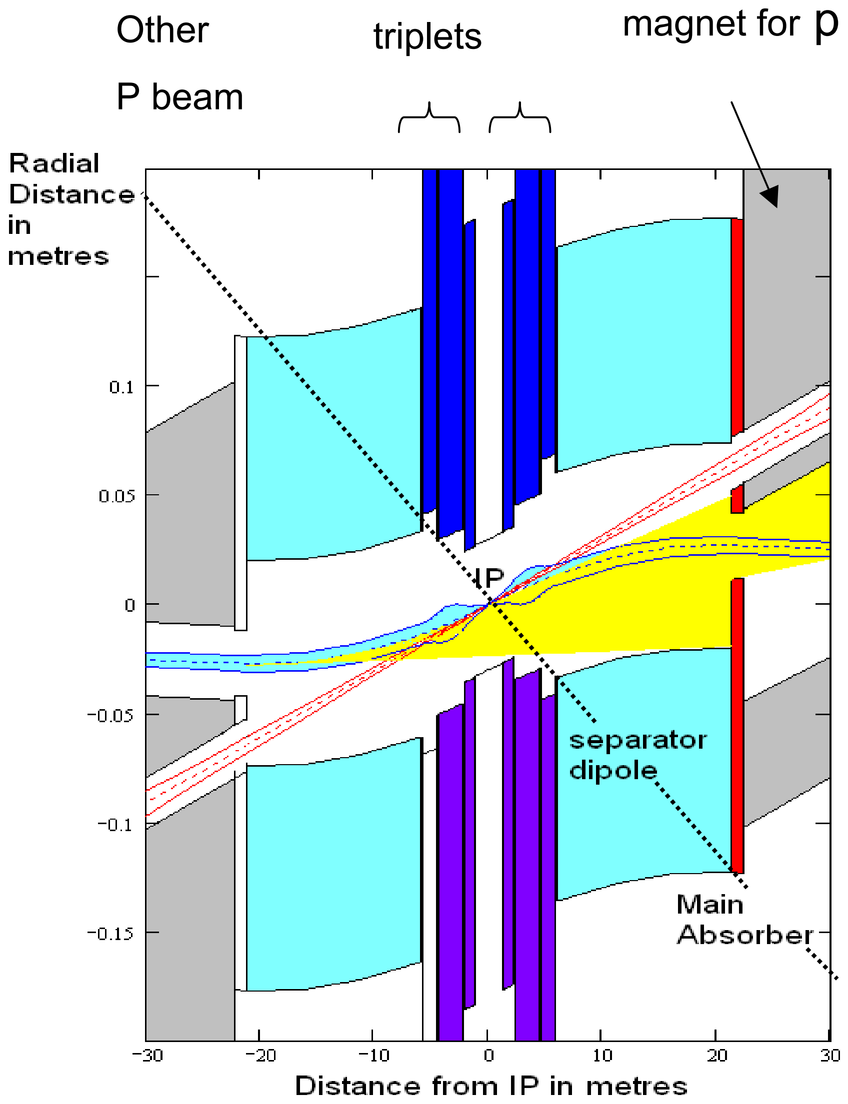
Beam Separation

Crossing angle 2mr

Magnetic separation 2mr

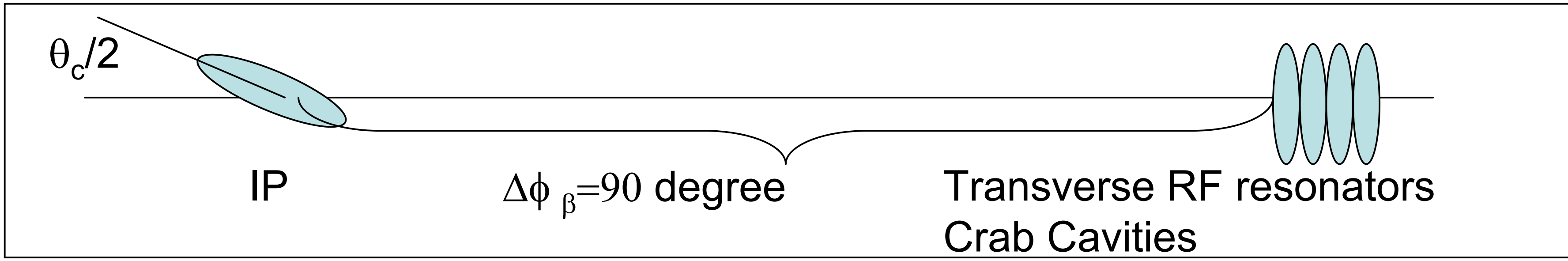
➔ 60 mm separation @20m

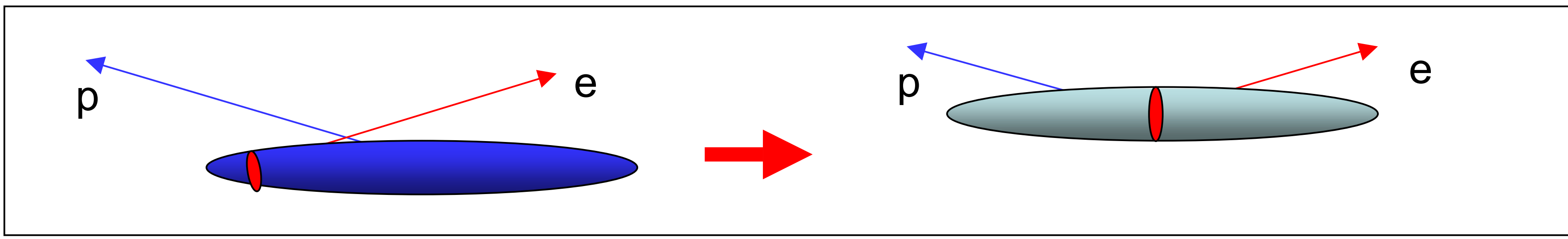




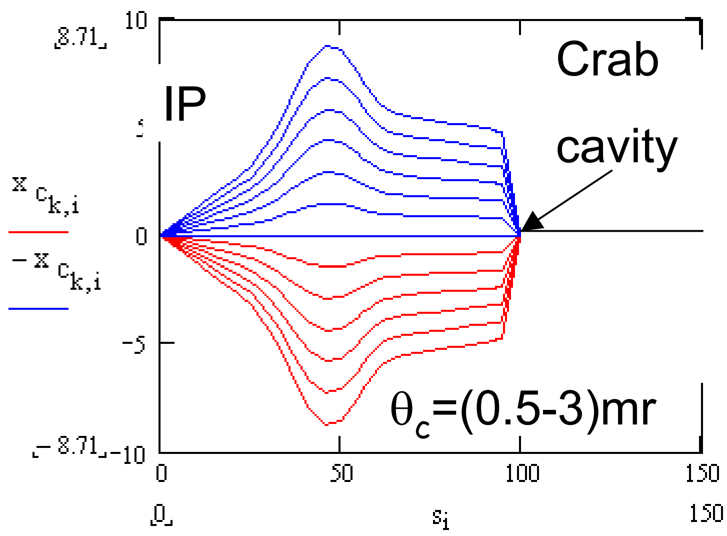
Crab Crossing

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





“Crabbed Trajectories



Crab Cavitiy Calculations

Required Crossing Angle $k_s := 42$

ep Separation $x_{p_{k_s}} - x_{e_{k_s}} = 65.571\,\mathrm{mm}$ $s_{k_s} = 22.232\,\mathrm{m}$

$\Delta x_{sep} := x_{p_{k_s}} - x_{e_{k_s}}$ $\theta_r := \theta_c$ $\theta_r = -2\,\mathrm{mrad}$

required crab cavitiy orbit kick for 1σ $\Delta\sigma/\sigma$ particles

$x_r := \frac{\theta_r}{2} \cdot \sigma_s$ $\beta_{px_0} = 1.8\,\mathrm{m}$ $\beta_{px_{82}} = 708.766\,\mathrm{m}$

$$\theta_{cc} := \frac{-x_r}{\sqrt{\beta_{px_0} \cdot \beta_{px_{82}}}} \qquad \theta_{cc} = 2.1\,\mu\mathrm{rad}$$

crac cavitiy frequency $f_{cc} := 0.5 \cdot \mathrm{GHz}$

$\lambda_{cc} := \frac{c}{f_{cc}}$ $\lambda_{cc} = 599.585\,\mathrm{mm}$ $\sigma_s = 75\,\mathrm{mm}$

crabcavity phase of one sigma particle $\phi_{cc1s} := \frac{2 \cdot \pi \cdot \sigma_s}{\lambda_{cc}}$ $\phi_{cc1s} \cdot \frac{180}{\pi} = 45.031$

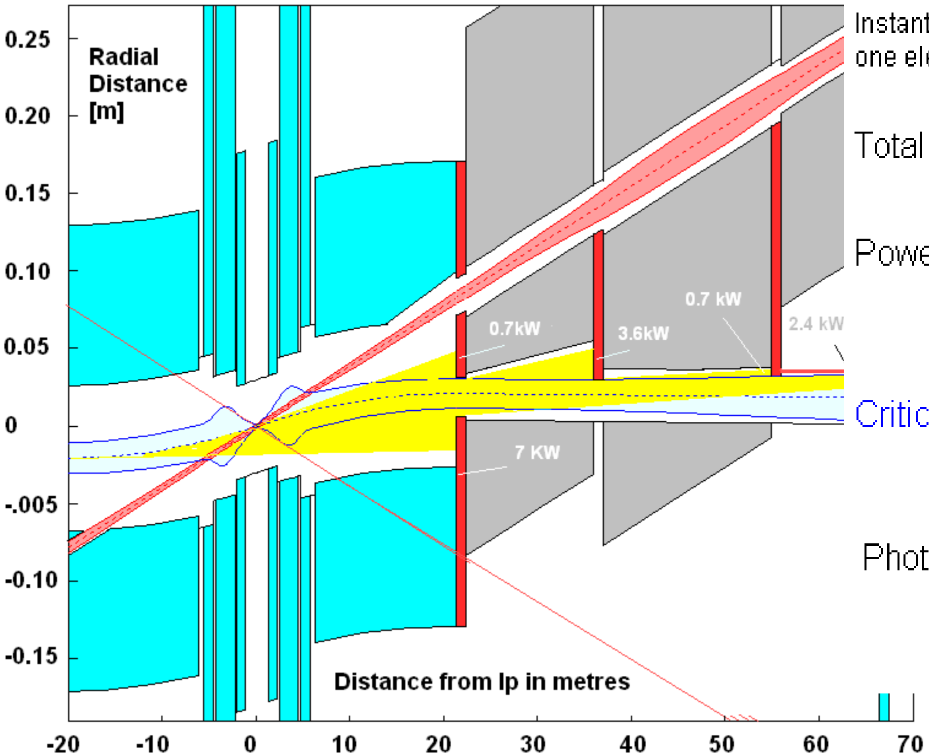
Required cavitiy voltage: $U_{cc} := \frac{\theta_{cc} \cdot E_p}{e \cdot \sin(\phi_{cc1s})}$ $U_{cc} = 20.775\,\mathrm{MV}$

achievable gradient: $G_{cc} := 3.4 \cdot \mathrm{MV} \cdot \mathrm{m}^{-1}$

Length of the cc structure: $L_{cc} := \frac{U_{cc}}{G_{cc}}$ $L_{cc} = 6.11\,\mathrm{m}$

Synchrotron Radiation

ρ_{ir} = 10000 m



Instantaneous Power for one electron $P_g(E_e, \rho_{ir}) = 1.615 \times 10^{-7}\,\mathrm{watt}$

Total Power $2 \cdot P_{syn}(E_e, \rho_{ir}, \theta_{ir}, I_e) = -9.111\,\mathrm{kW}$

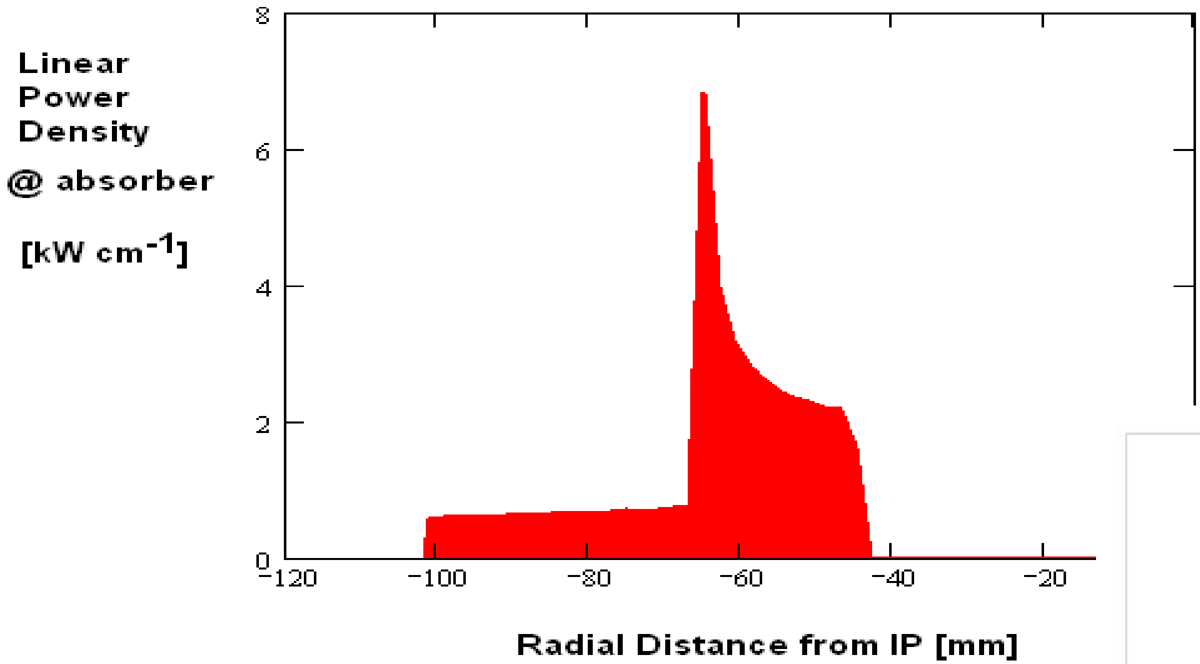
Power per unit Length $P_s(E_e, \rho_{ir}, I_e) = 0.238\,\mathrm{kW \cdot m^{-1}}$

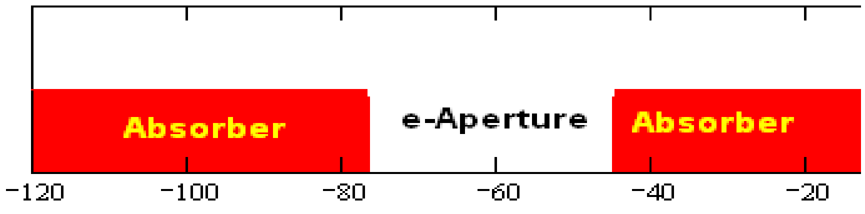
Critical Energy $u_c(E_e, \rho_{ir}) = 76.137\,\mathrm{keV}$

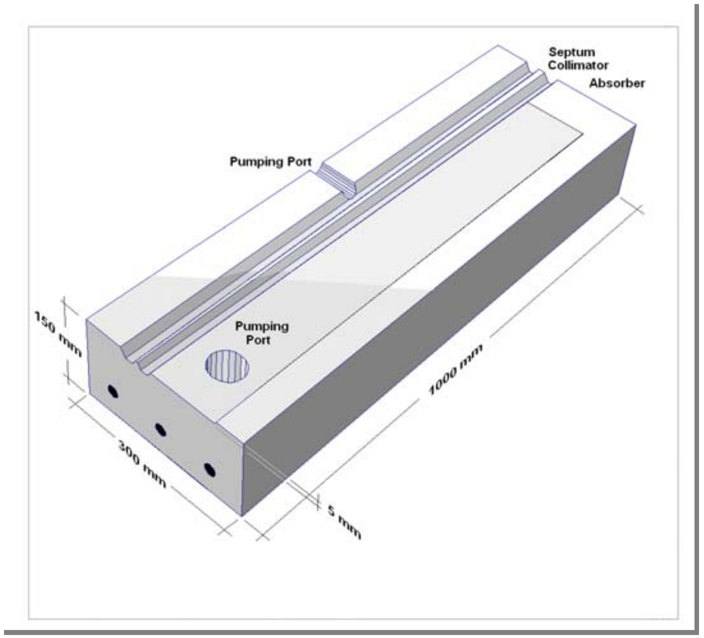
Photonflux $\Phi_{ph}(E_e, \rho_{ir}, I) = 2.957 \times 10^{19}\,\frac{1}{\mathrm{m\,s\,A}}$

$\rho_{ir} = -1.001 \times 10^{4}\,\mathrm{m}$ $L_{ir} = 19.132\,\mathrm{m}$

SR Power Density on Absorber







ep Collision Parameters and Luminosity

E	$E_p = 7 \times 10^3\,\text{GeV}$	$E_e = 70\,\text{GeV}$		
I	$I_p = 0.856\,A$	$I_e = 0.071\,A$		
N	$N_p = 1.7 \times 10^{11}$	$N_e = 1.404 \times 10^{10}$		
β^*	$\beta_{xp} = 180\,\text{cm}$	$\beta_{xe} = 12.73\,\text{cm}$	$\max(\beta_{py}) = 2.637 \times 10^3\,\text{m}$	$\max(\beta_{ey}) = 704.454\,\text{m}$
	$\beta_{yp} = 50\,\text{cm}$	$\beta_{ye} = 7.072\,\text{cm}$	$\max(\beta_{px}) = 2.668 \times 10^3\,\text{m}$	$\max(\beta_{ex}) = 131.728\,\text{m}$
Beam size	$\sigma_{xp} = 31.066\,\mu\text{m}$	$\sigma_{xe} = 31.066\,\mu\text{m}$		
	$\sigma_{yp} = 16.373\,\mu\text{m}$	$\sigma_{ye} = 16.373\,\mu\text{m}$		
	$\sigma_s = 75\,\text{mm}$	$\sigma_{be} = 7.085\,\text{mm}$		
IR Chromaticiy	$\xi_{pxIR} = -7.969$	$\xi_{exIR} = -7.517$		
	$\xi_{pyIR} = -7.74$	$\xi_{eyIR} = -29.757$		
beam-Beam Tuneshift	$\Delta\nu_{xp} = 8.318 \times 10^{-4}$	$\Delta\nu_{xe} = 0.048$	$\Delta\nu_{xpar} = 0.029\,10^{-3}$	
	$\Delta\nu_{yp} = 3.177 \times 10^{-4}$	$\Delta\nu_{ye} = 0.051$	$\Delta\nu_{ypar} = -0.444\,10^{-3}$	
Crossing Angle	$\theta_c = -2\,\text{mr}$			
Hourglass factor	$R(\sigma_s) = 0.947$			
Peak Luminosity	$L_{peak} = 1.103 \times 10^{33}\,\text{sec}^{-1} \cdot \text{cm}^{-2}$			

Beam-Beam Effect

Central crossing beam-beam parameters well within the HERA range

e-hor bb tuneshift

$$\Delta\nu_{xe} := \frac{r_e \cdot N_p \cdot \beta_{xe}}{2 \cdot \pi \cdot \gamma_e \cdot \sigma_{xp} \cdot \left(\sigma_{xp} + \sigma_{yp}\right)} \qquad \Delta\nu_{xe} = 0.048$$

e ver bb tuneshift

$$\Delta\nu_{ye} := \frac{r_e \cdot N_p \cdot \beta_{ye}}{2 \cdot \pi \cdot \gamma_e \cdot \sigma_{yp} \cdot \left(\sigma_{xp} + \sigma_{yp}\right)} \qquad \Delta\nu_{ye} = 0.051$$

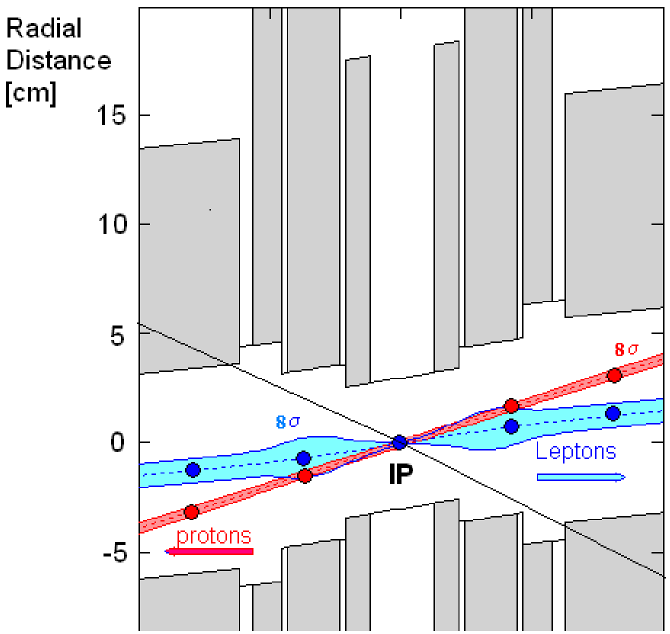
p-hor bb tuneshift

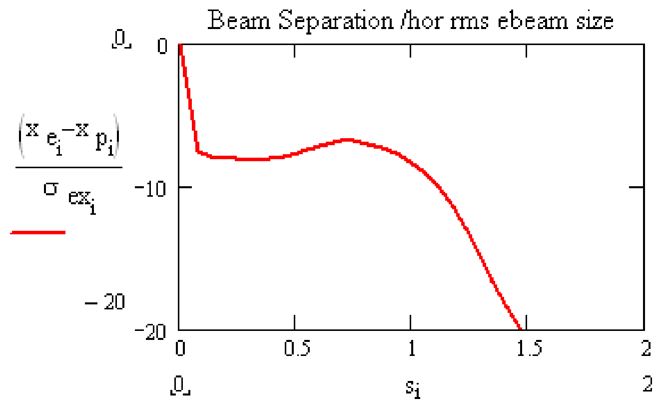
$$\Delta\nu_{xp} := \frac{r_p \cdot N_e \cdot \beta_{xp}}{2 \cdot \pi \cdot \gamma_p \cdot \sigma_{xe} \cdot \left(\sigma_{xe} + \sigma_{ye}\right)} \qquad \Delta\nu_{xp} = 5.122 \times 10^{-4}$$

p ver bb tuneshift

$$\Delta\nu_{yp} := \frac{r_p \cdot N_e \cdot \beta_{yp}}{2 \cdot \pi \cdot \gamma_p \cdot \sigma_{ye} \cdot \left(\sigma_{xe} + \sigma_{ye}\right)} \qquad \Delta\nu_{yp} = 2.7 \times 10^{-4}$$

Parasitic Crossings





$$\Delta \nu_x^{par} = \frac{N_p r_0 \beta_x^{par}}{2\pi \gamma_e \Delta x^2}$$

$$\Delta \nu_y^{par} = \frac{-N_p r_0 \beta_y^{par}}{2\pi \gamma_e \Delta x^2}$$

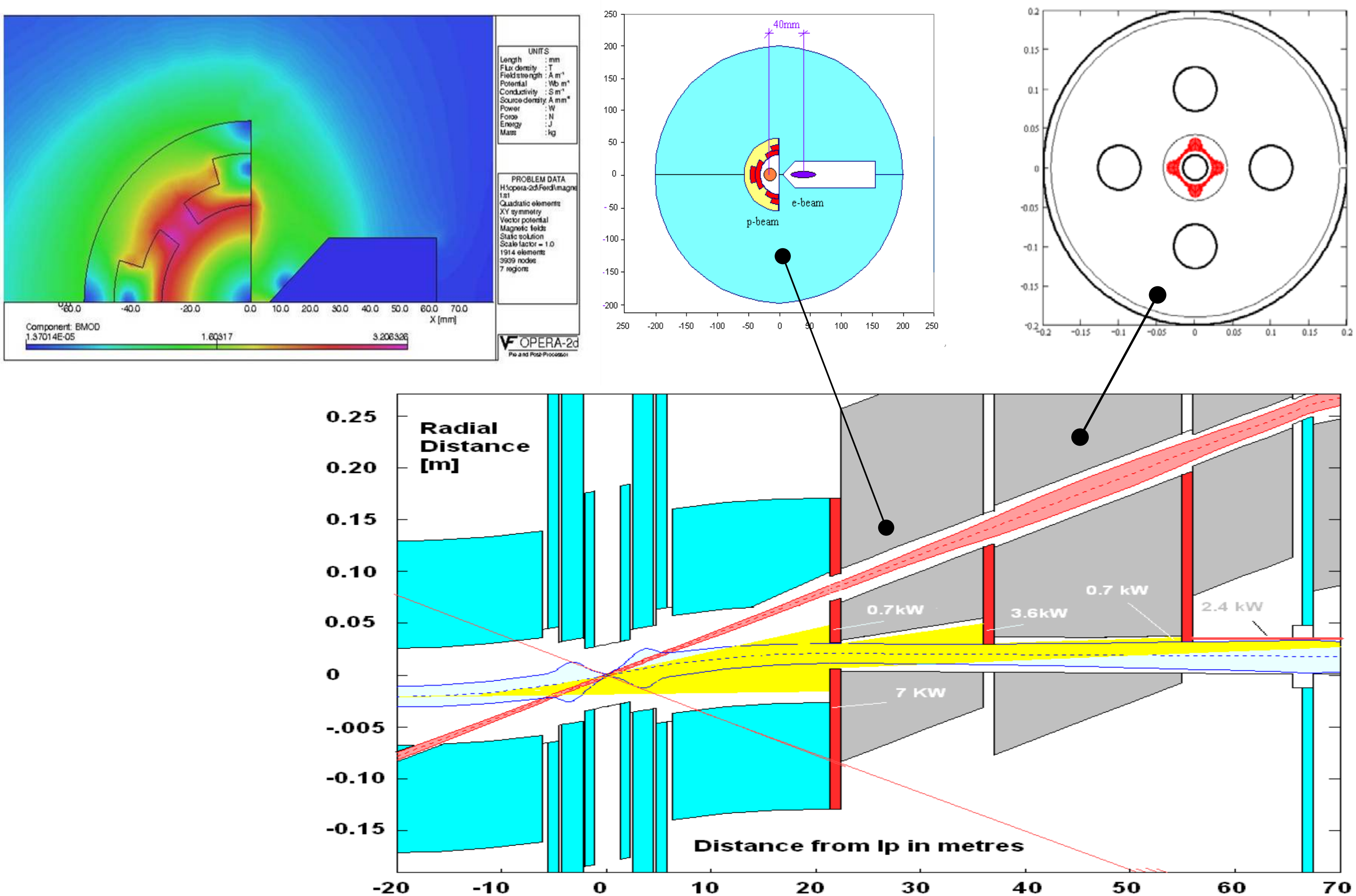
Bunch spacing	Crossing angle	Separation	Separation	Horizont. parasitic beam-beam tune shift	Vertical parasitic beam-beam tune shift
[ns]	[mrad]	[mm]	[σ_{ex}]		
25	2.0	7.7	8.3	0.0011	-0.0015
50	2.0	15	23	0.0001	-0.002
75	2.0	27	50	0.00003	-0.0004

Luminosity vs Bunch Spacing

L independent of bunch spacing
As long as Ie total can be maintained
At very large bunch spacings limitations by
Proton beam-beam effect
Single bunch instabilities of e-beam

up to 75ns bunch spacing far from becoming a problem

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 envisioned

Further activities on the layout of the accelerator should be coordinated with and integrated into the discussions on LHC upgrades