LHeC
Considerations for a Lepton Hadron Collider Option for the LHC

F. Willeke, BNL

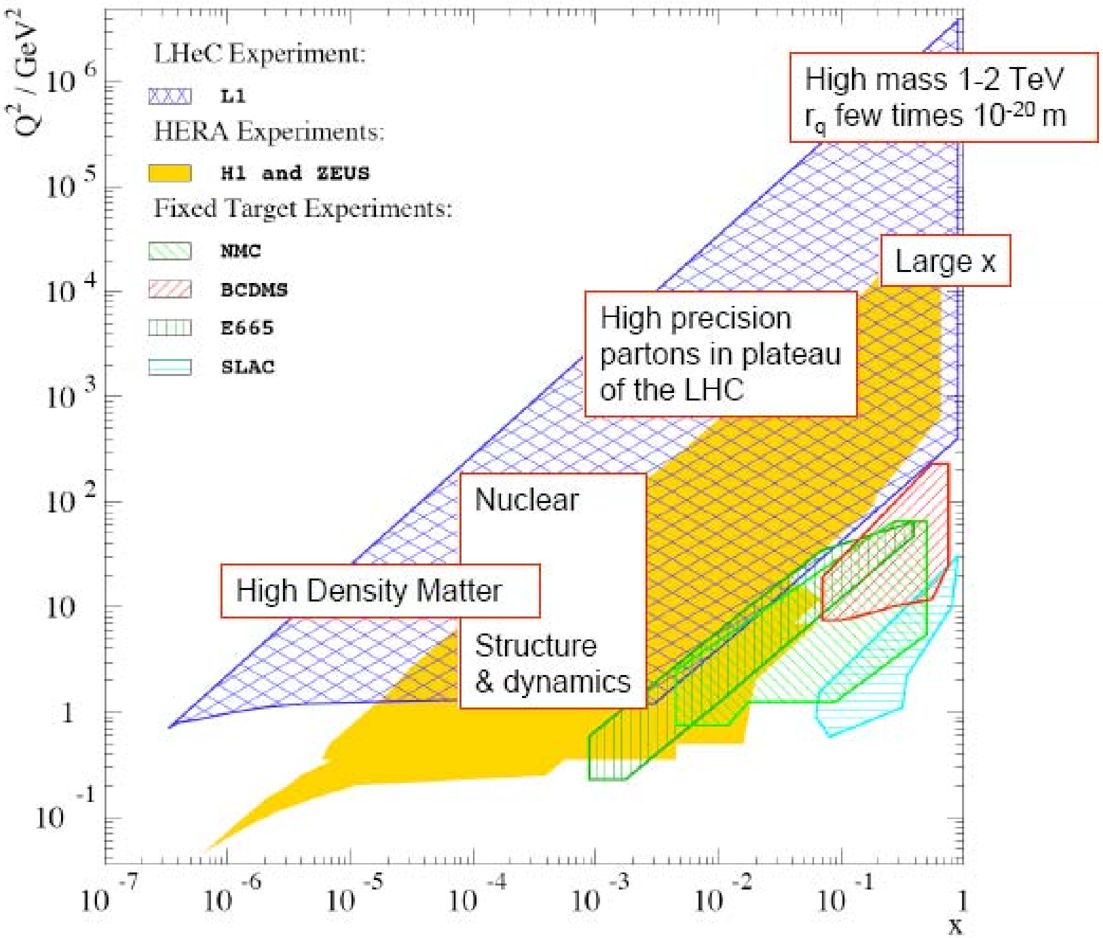
The 4th Electron Ion Collider Workshop
Hampton University, 19-23 May, 2008

Ring–Ring Option

Linac Ring Option

LHeC a physics opportunity with a Threefold physical goal:

New Physics - QCD and EW Physics – High Parton Density



Max Klein LHeC DIS08 London 11.4.08

Several Options under consideration:

- **p-Ring-e-Ring:**

“conservative”, limited in c.m. energy, luminosity limited by RF power, beam-beam limited

- **p-Ring-e-Linac:**

No energy limit (in principle), luminosity severely limited by RF power, beam-beam limit

- **ERL Option:**

very exotic, energy limited, RF power limitation and beam-beam limit reduced

Luminosity: Ring-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3\,10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

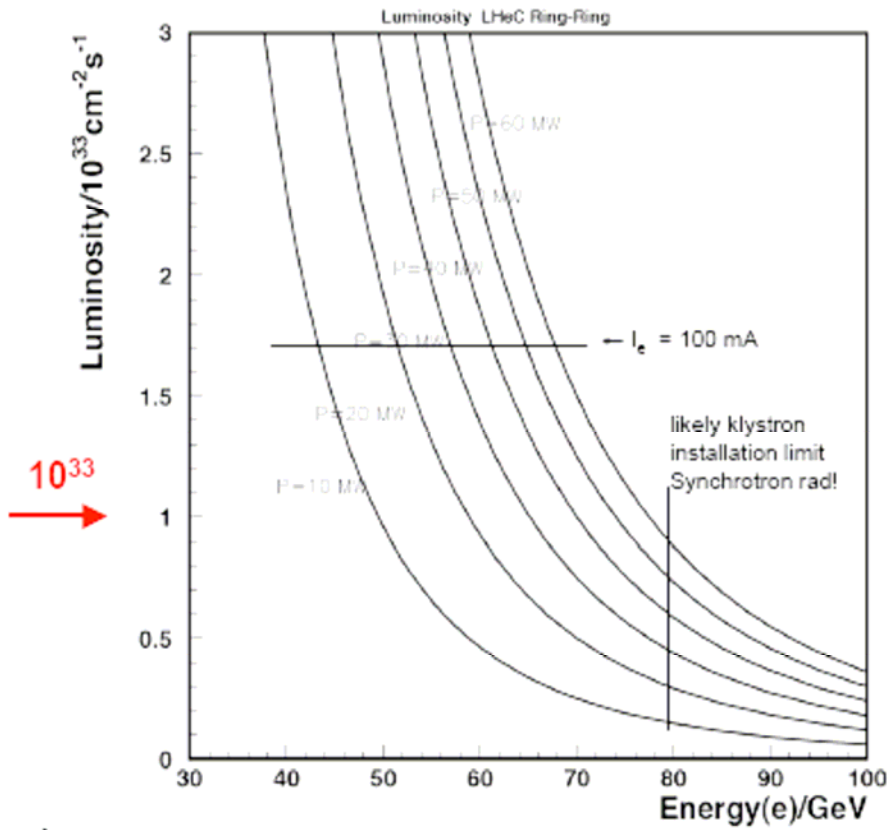
$\varepsilon_{pn} = 3.8\mu m$

$N_p = 1.7 \cdot 10^{11}$

$\sigma_{p(x,y)} = \sigma_{e(x,y)}$

$\beta_{px} = 1.8m$

$\beta_{py} = 0.5m$



$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$

10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 10^{31} cm^{-2} s^{-1}
huge gain with SLHC p beam

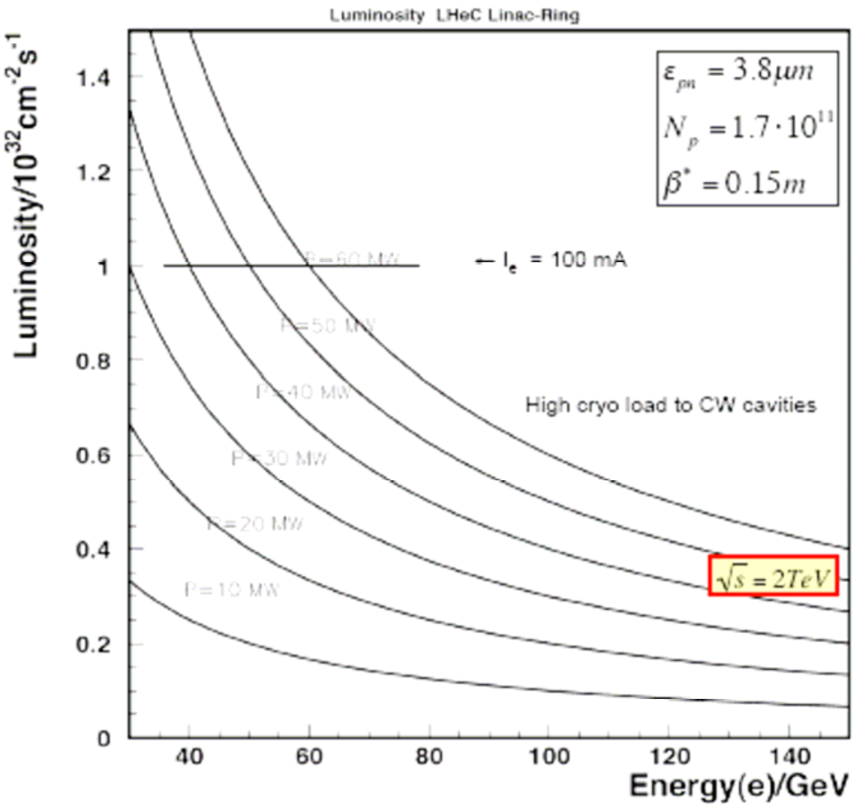
F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

Factor of 5 possible to gain with intensity and beam emittance (cf H.Braun this workshop).
May relax power requirement.

cf also A.Verdier 1990, E.Keil 1986

Luminosity: Linac-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 1 \cdot 10^{32} \cdot \frac{P/MW}{E_e/GeV} cm^{-2}s^{-1}$$



DIS08, H.Braun

$\varepsilon_{pn} = 1.9\mu m$
$N_p = 3.4 \cdot 10^{11}$
$\beta^* = 0.10m$

New p injector chain, LHC Luminosity Upgrade.

2 10^{32} may be reached with LR:
E_e = 40-140 GeV & P=20-60 MW
LR: average lumi close to peak!
-> 10 times HERA II luminosity.

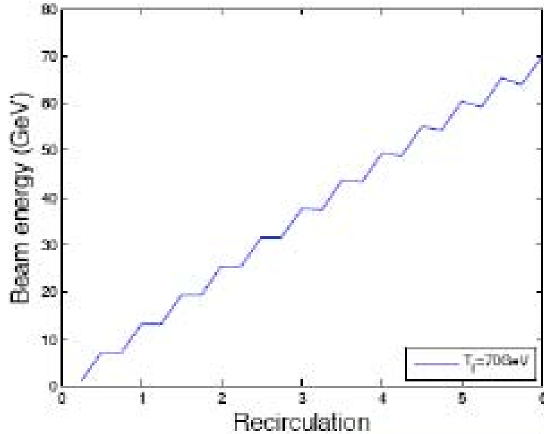
LINAC is not physics limited in energy, but cost + power limited
140 GeV at 23 MV/m: 6km +gaps

Note: positron source challenge:

SLC 10^{13} /sec
ILC 10^{14} /sec
LHeC at 10^{32} needs 10^{15} /sec

Recircularing Linac Scheme proposed by Hans Braun

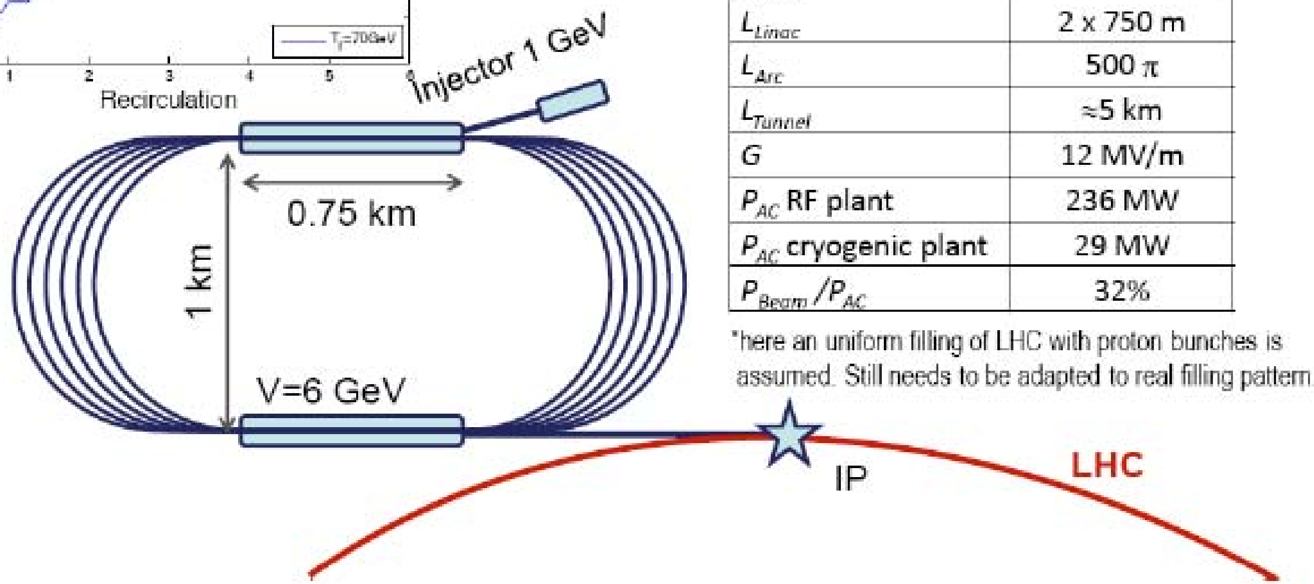
Recirculated superconducting c.w. Linac for LHeC



Tentative parameter set for $10^{33}cm^{-2}s^{-1}$

E	70 GeV
$E_{Injector}$	1 GeV
I_{Beam}	1.2mA
N_B	1.87 10^8
Bunch spacing*	25ns
P_{Beam}	84 MW
P_{SR}	5.6 MW
$N_{Recirculation}$	6
V_{Linac}	2 x 6.14 GeV
L_{Linac}	2 x 750 m
L_{Arc}	500 π
L_{Tunnel}	≈5 km
G	12 MV/m
P_{AC} RF plant	236 MW
P_{AC} cryogenic plant	29 MW
P_{Beam} / P_{AC}	32%

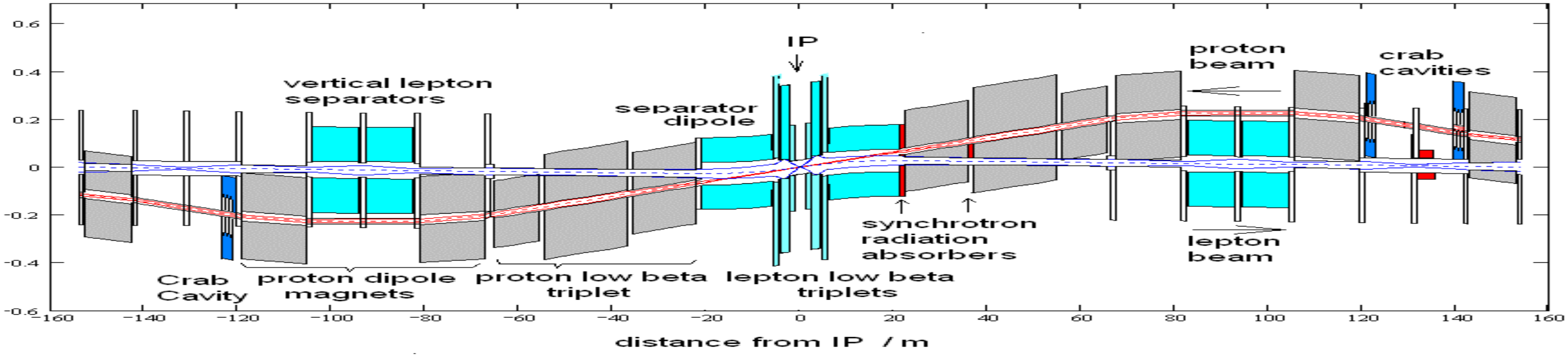
*here an uniform filling of LHC with proton bunches is assumed. Still needs to be adapted to real filling pattern.



Ring – Ring Option

Design Study J.Dainton, M.Klein, P.Newman, E.Perez, F.Willeke

A high luminosity approach based on matured accelerator technology and on experience in operating HERA.



Design Goal: $L = 10^{33} cm^{-2} sec^{-1}$

with 1.4 GeV centre of mass energy

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

*) There are more optimistic parameters under discussion for the LHC Upgrade

→ **$E_e = 70$ 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 $\sigma_{xp} = \sigma_{xe}, \quad \sigma_{yp} = \sigma_{ye}$

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, $N_p\gamma_p / \varepsilon_{Np} = 3.2 \cdot 10^{20} m^{-1}$

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

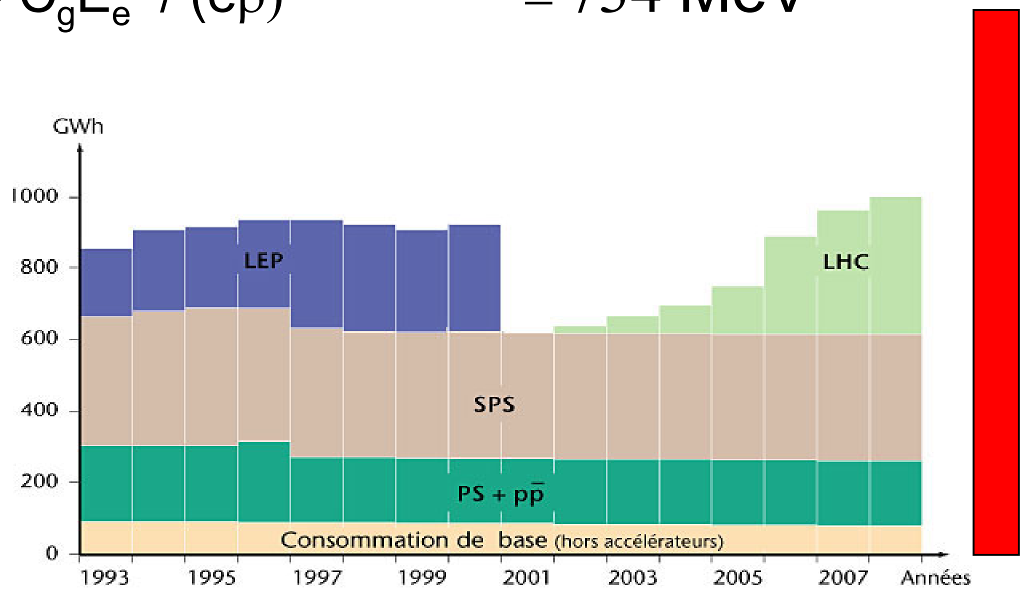
Lepton Beam Current

Assumptions: Limited by RF Power only

depends on Bending radius

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

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



If **50 MW** beam power considered as a limit 5000 h/y x 50MW x 5 = **1250 GWh/y**

➔ $\mathbf{I_e = 68mA}$ (with Δt=25ns➔ N_e=1.3 10^{10})

e-Ring Lattice Parameters

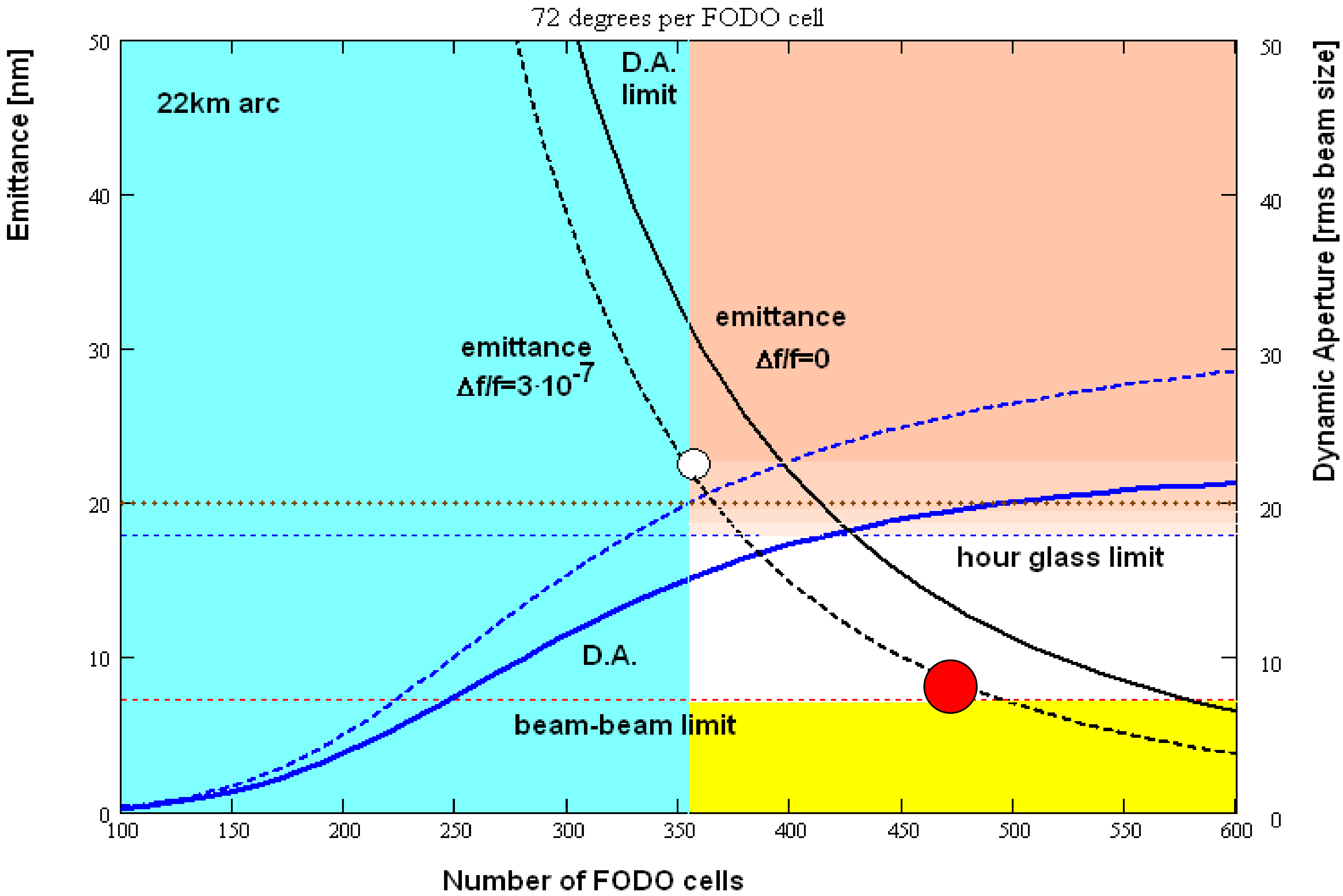
bend radius & circumference fixed by LHC effective FODO structure chosen (no alternative) the only choice to be made id the FODO cell length or the number of cell length of the arc

➔ 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

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	$10^{33}\,cm^{-2}s^{-1}$	1.1	

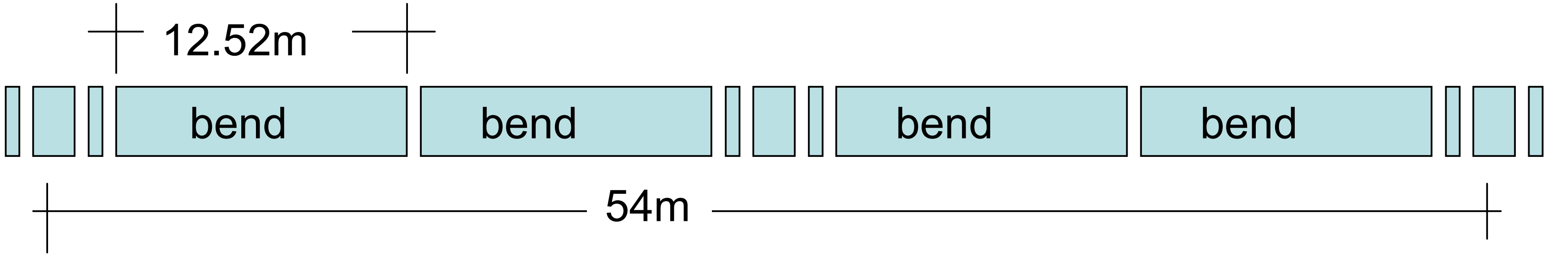
e Lattice

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)

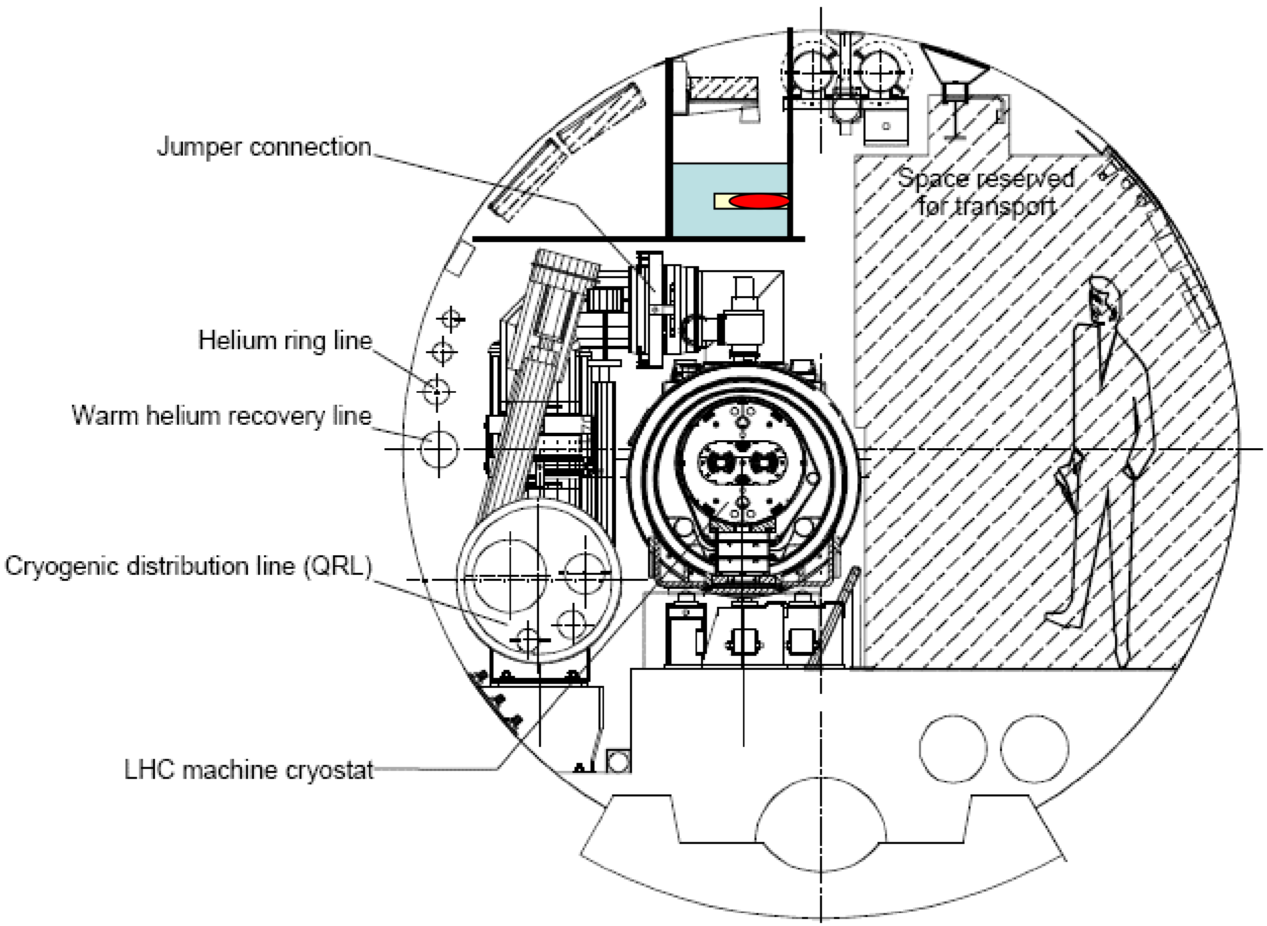


$\Delta\phi_{fodo}$ = 72 degree

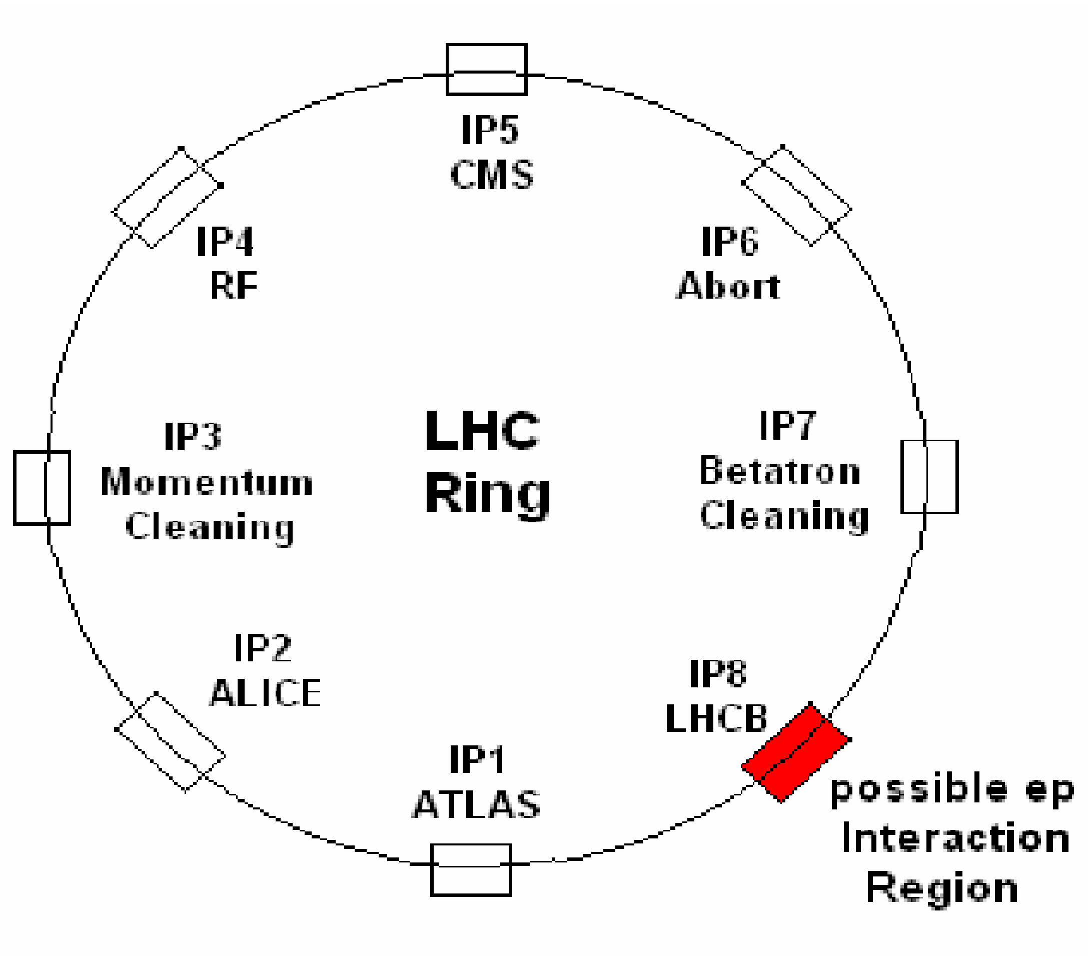
ε_{xe} = 8 nm

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

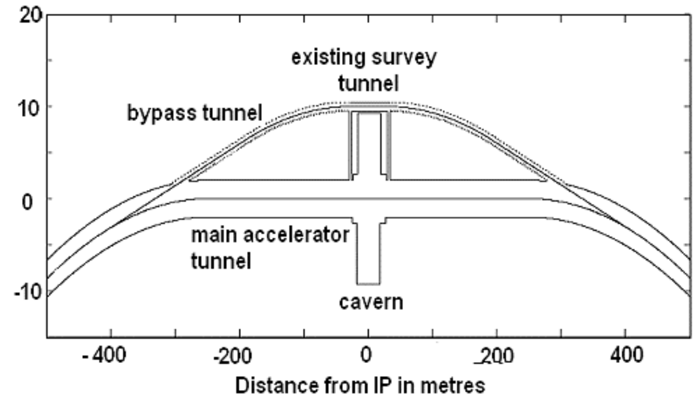
Tunnel Cross Section

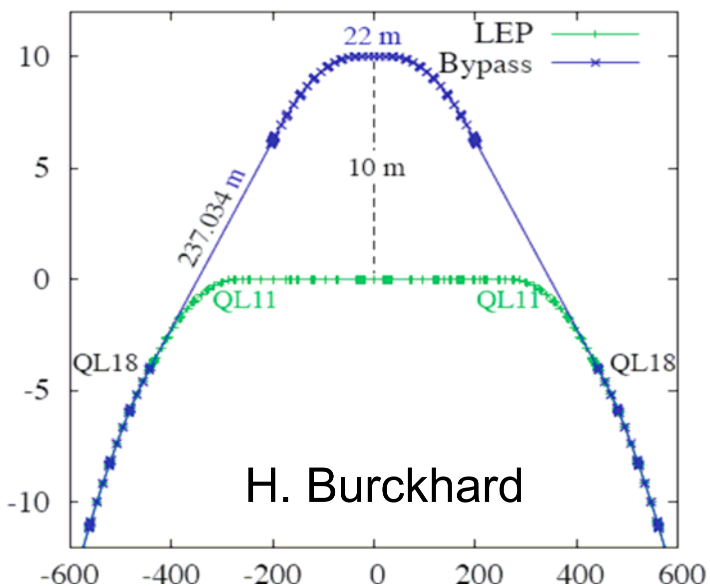


Which IR?


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

Bypass around Atlas and CMS





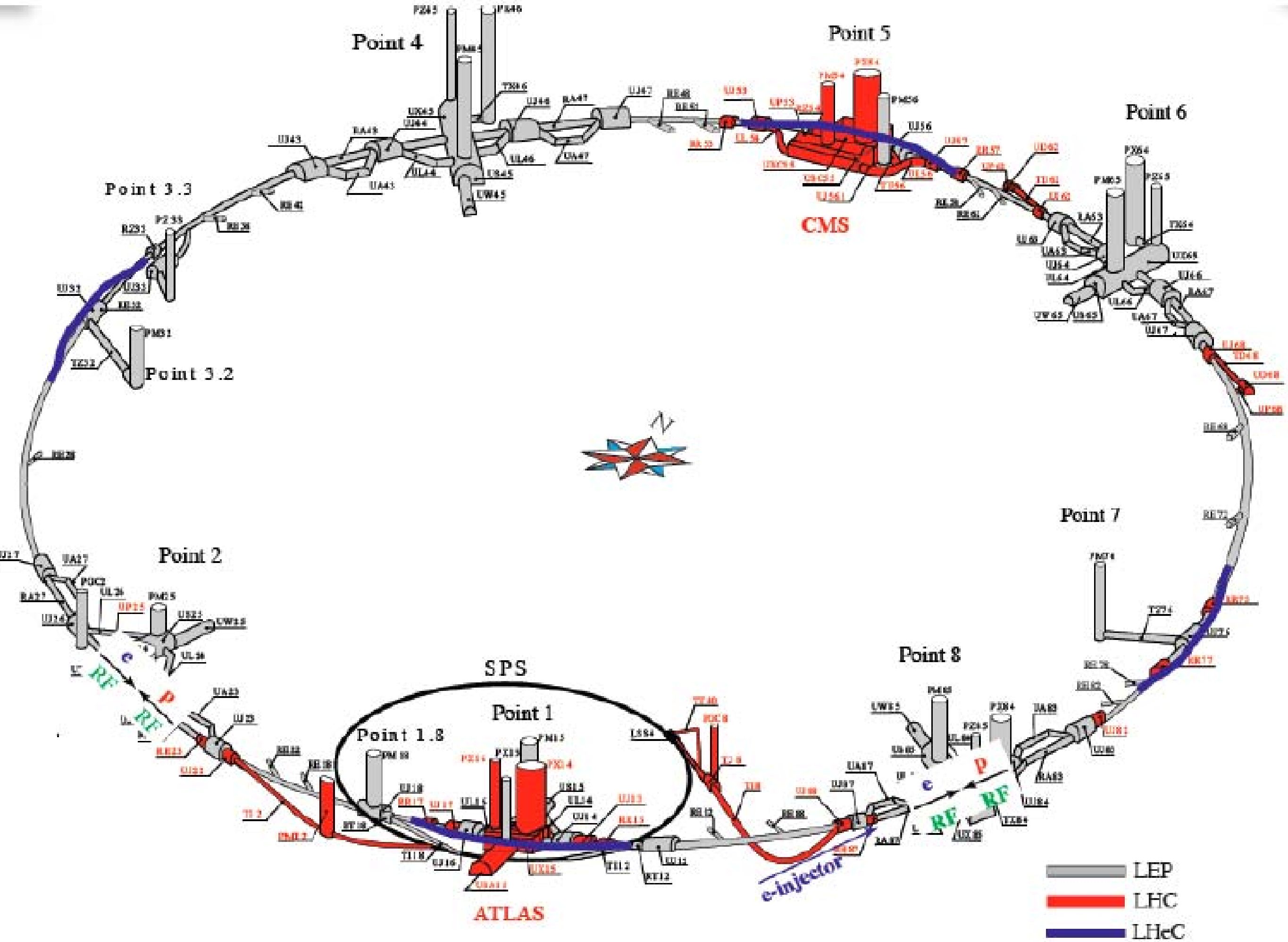
from J.A. Osborne CERN/TS

No additional radiation

Little, easy to correct influence on Circ.

But

Existing Bypass Tunnels probably not available

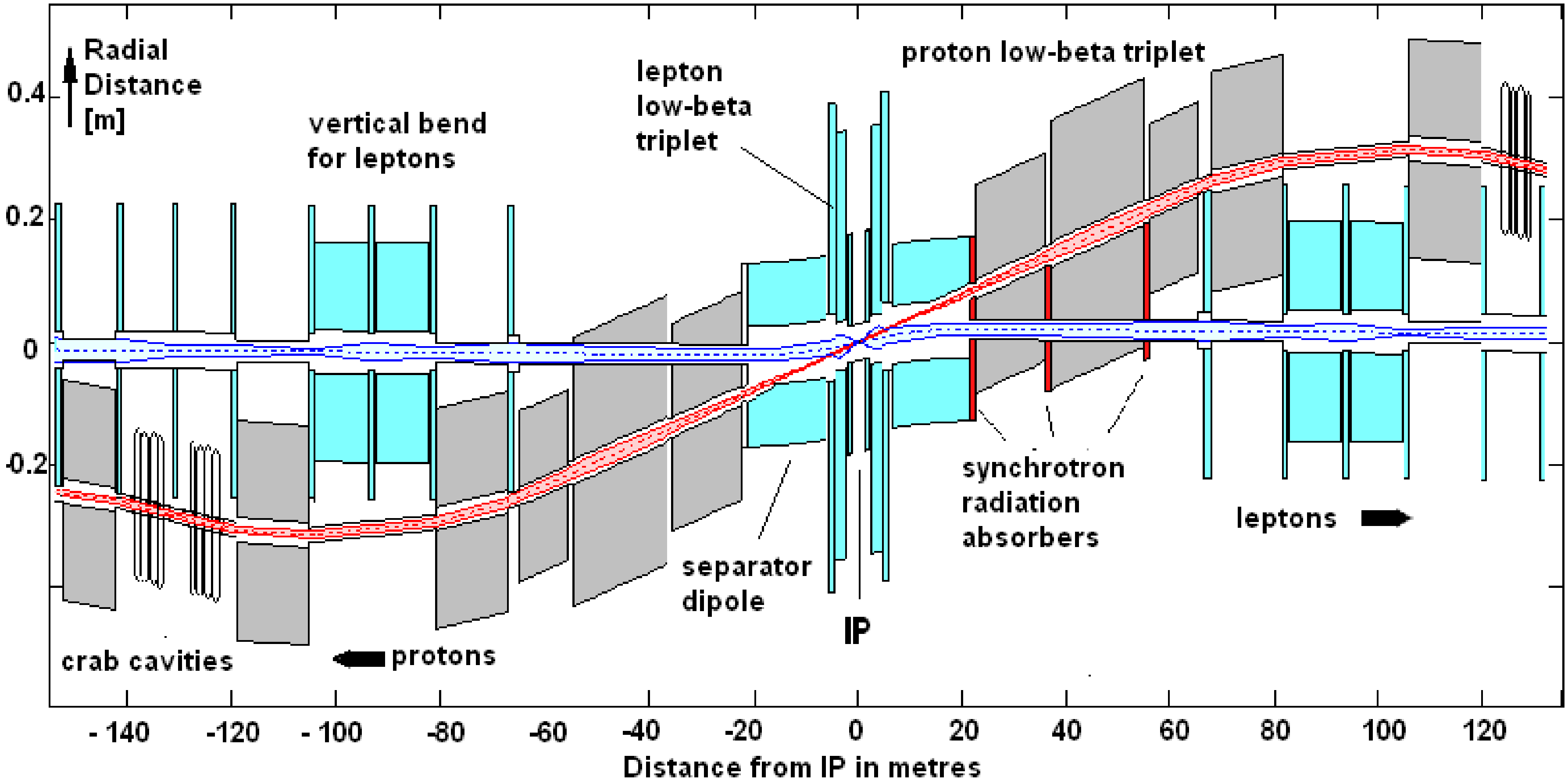

Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ATLAS
CMS
e-injector
e
p
RF
RF
LEP
LHC
LHeC

Additional Tunnels needed

	Point 1 ATLAS	Point 5 CMS	Point 2 and/or 8 RF	Point 3 Collimators	Point 7 Collimators	
Type	Bypass Experiment	Bypass Experiment	Bypass ; allow for space for e - ring RF	Bypass Collimation	Bypass Collimation	
Approximate Tunnel length	500 m	500 m	500 m	500 m	500 m	2500 m - 3000 m
Diameter	4.40 m	3.80 m	5.50 m	4.20 m	3.80 m	
Distance to p-Ring axis	10 - 13 m	10 - 13 m				

From H. Burckhard, DIS 08

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

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

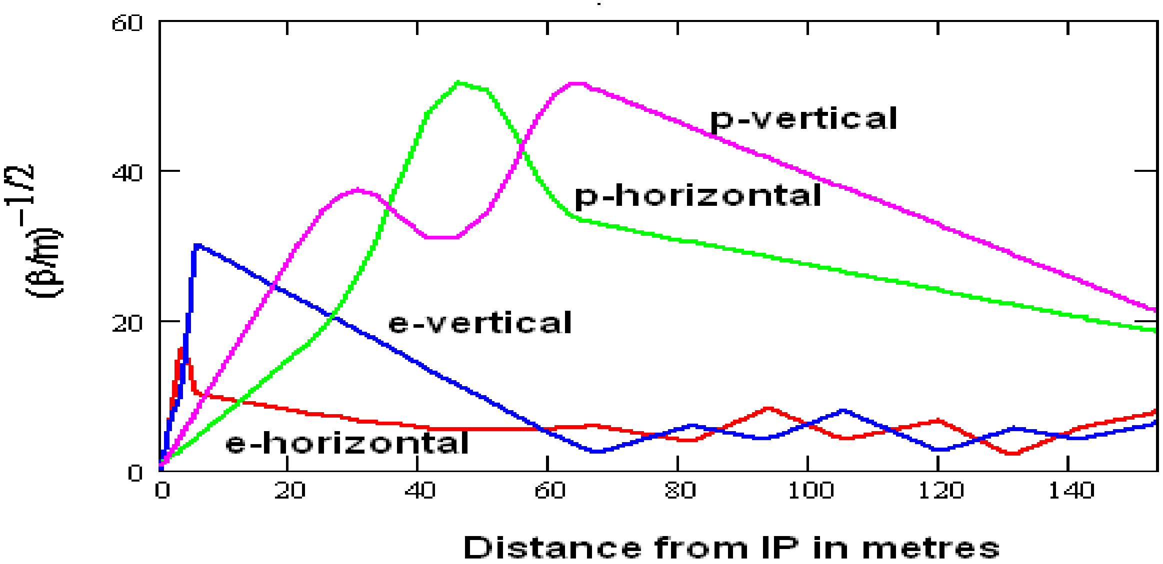
$\varepsilon_{xp} = 0.5$ nm $\varepsilon_{xe} = 7.6$ nm

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

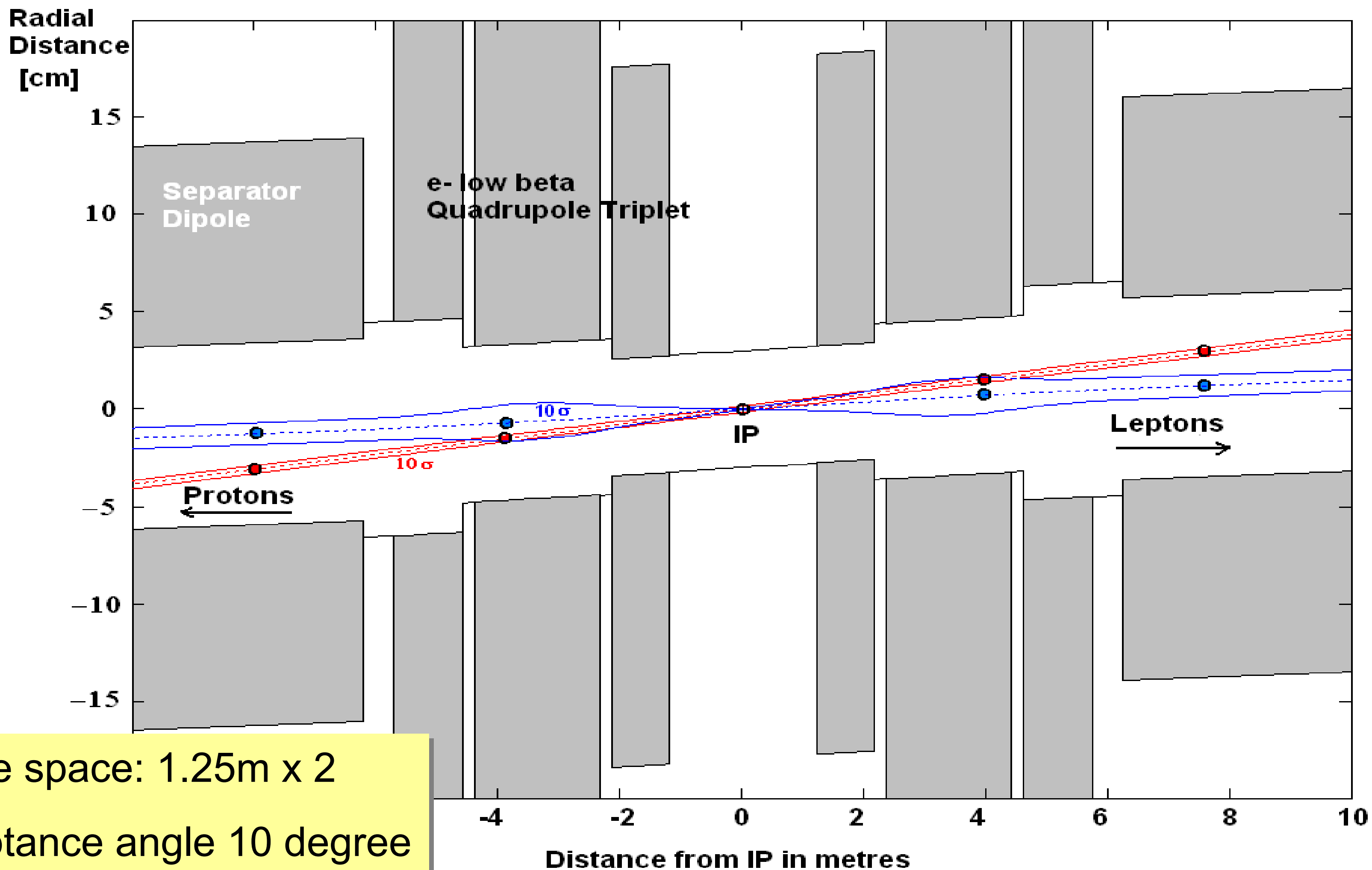
$\beta_{xp}/\beta_{yp} \approx 4$

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

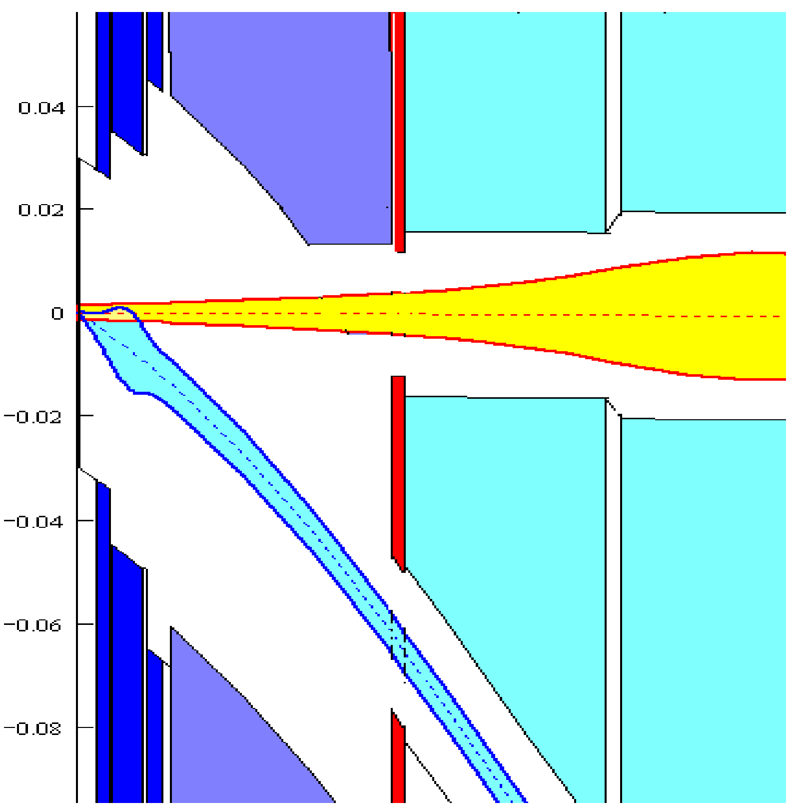
Crossing angle 2mr

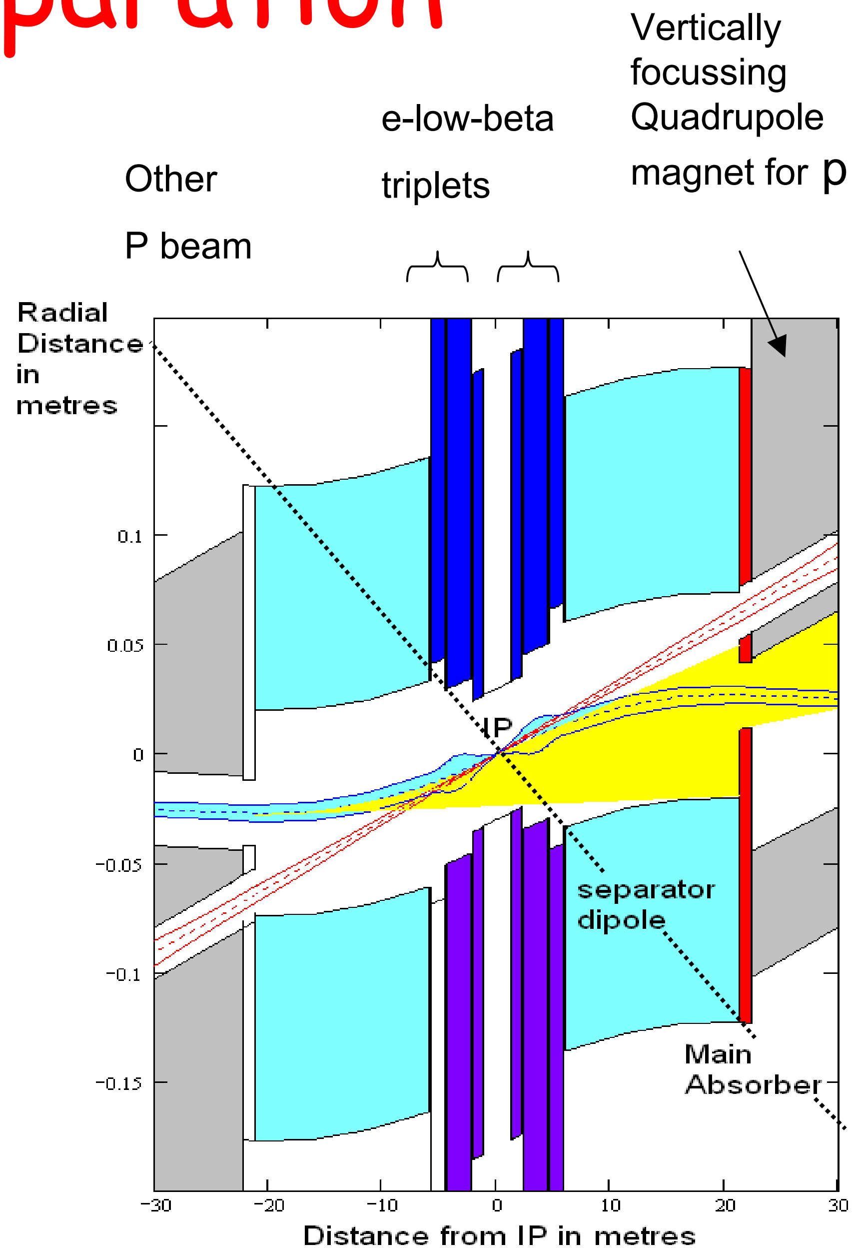
Beam Separation

Crossing angle 2mr

Magnetic separation 2mr

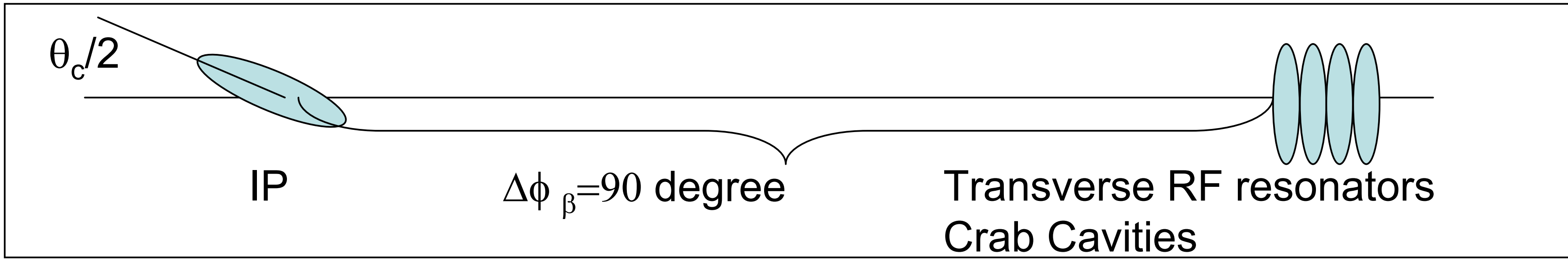
➔ 60 mm separation @20m

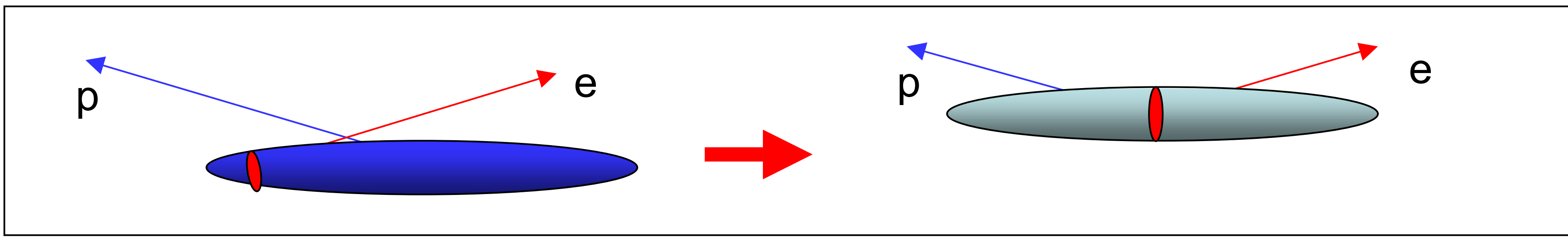




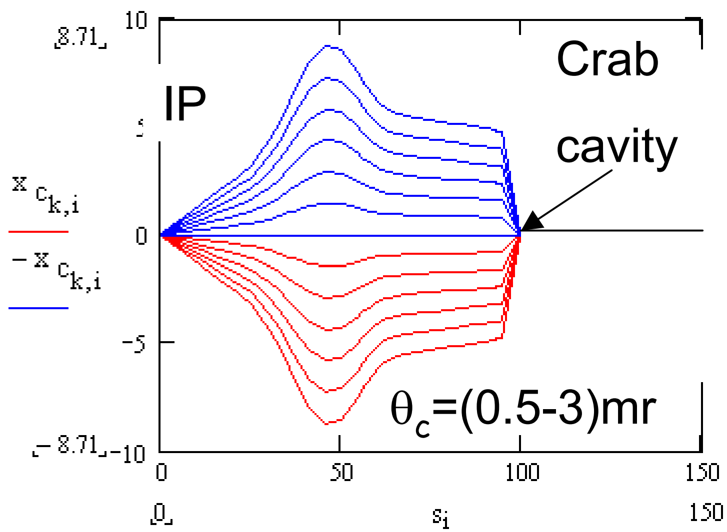
Crab Crossing

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

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

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

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

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

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

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

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

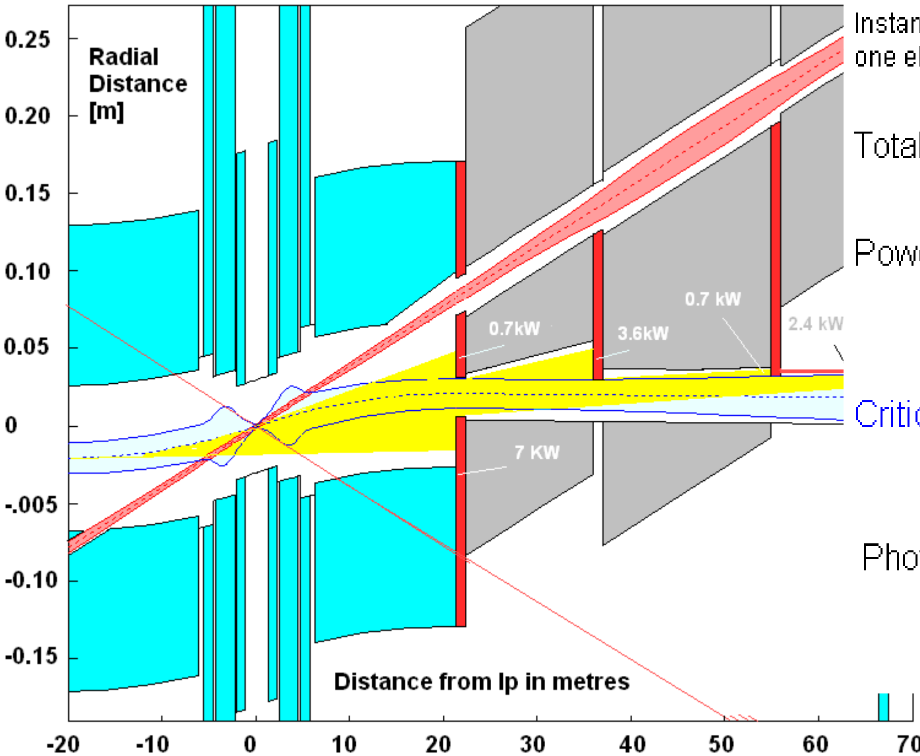
Required cavitiy voltage: $U_{cc} := \frac{\theta_{cc} \cdot E_p}{e \cdot \sin(\phi_{cc1s})}$ $U_{cc} = 20.775\,MV$

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

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

Synchrotron Radiation

$\rho_{ir} = 10000$ m



Instantaneous Power for one electron

$$P_g(E_e, \rho_{ir}) = 1.615 \times 10^{-7} \text{watt}$$

Total Power

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

Power per unit Length

$$P_s(E_e, \rho_{ir}, I_e) = 0.238 \, \text{kW} \cdot \text{m}^{-1}$$

Critical Energy

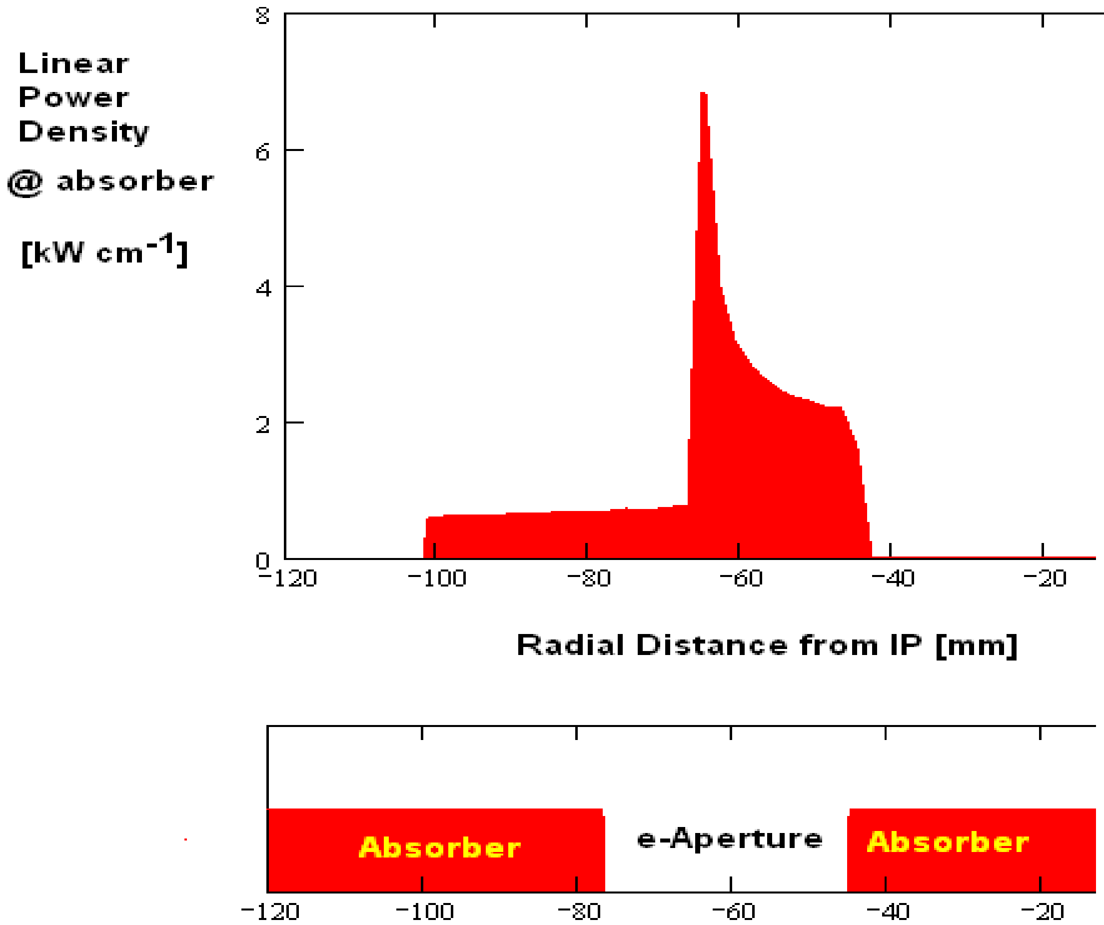
$$u_c(E_e, \rho_{ir}) = 76.137 \, \text{keV}$$

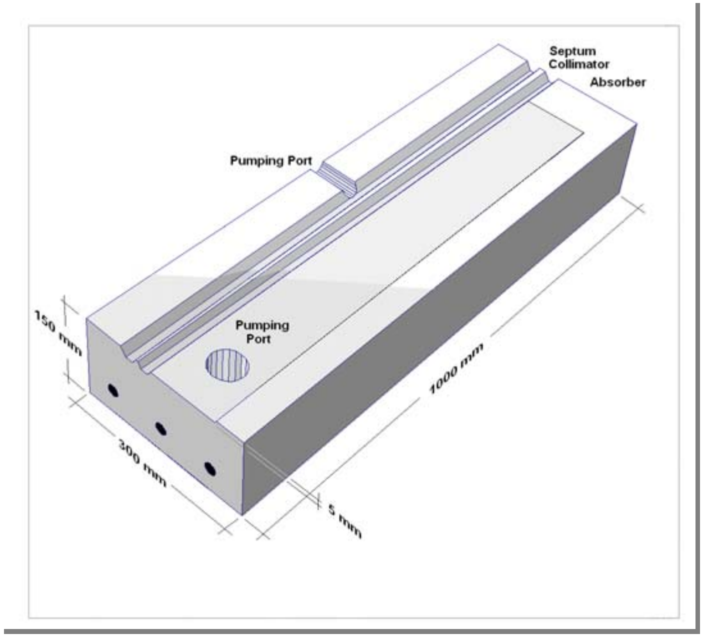
Photonflux

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

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

SR Power Density on Absorber





ep Collision Parameters and Luminosity

E	$E_p = 7 \times 10^3\,GeV$	$E_e = 70\,GeV$		
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**	$\beta_{xp} = 180\,cm$	$\beta_{xe} = 12.73\,cm$	$\max(\beta_{py}) = 2.637 \times 10^3\,m$	$\max(\beta_{ey}) = 704.454\,m$
	$\beta_{yp} = 50\,cm$	$\beta_{ye} = 7.072\,cm$	$\max(\beta_{px}) = 2.668 \times 10^3\,m$	$\max(\beta_{ex}) = 131.728\,m$
Beam size	$\sigma_{xp} = 31.066\,\mu m$	$\sigma_{xe} = 31.066\,\mu m$		
	$\sigma_{yp} = 16.373\,\mu m$	$\sigma_{ye} = 16.373\,\mu m$		
	$\sigma_s = 75\,mm$	$\sigma_{be} = 7.085\,mm$		
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	$\theta_c = -2\,mr$			
Hourglass factor	$R(\sigma_s) = 0.947$			
Peak Luminosity	$L_{peak} = 1.103 \times 10^{33}\,sec^{-1} \cdot cm^{-2}$			

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

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

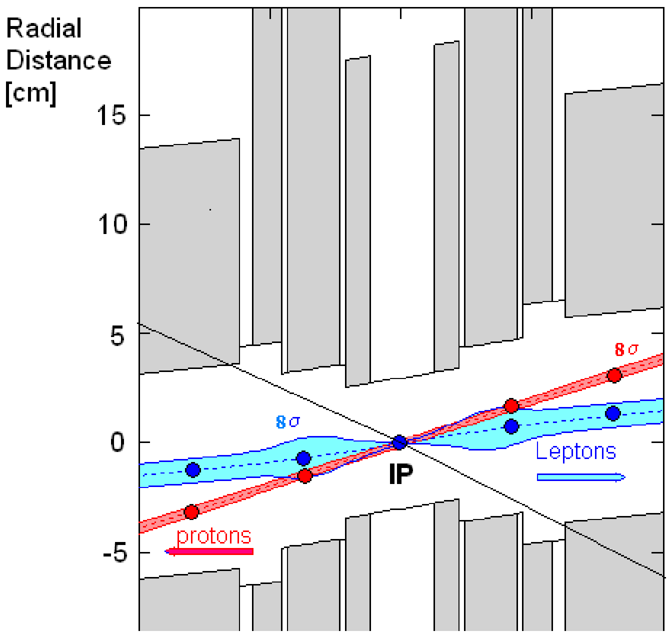
p-hor bb tuneshift

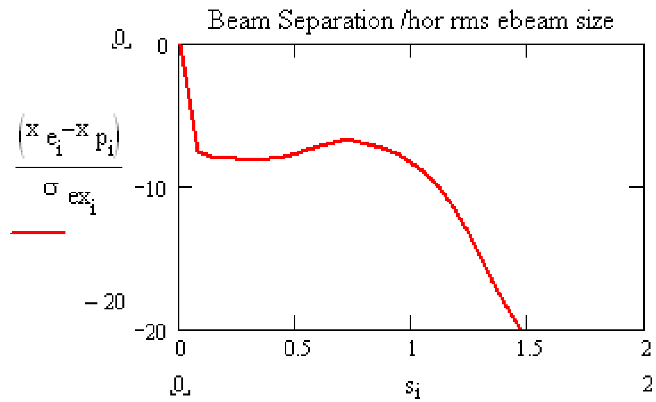
$$\Delta\nu_{xp} := \frac{r_p \cdot N_e \cdot \beta_{xp}}{2 \cdot \pi \cdot \gamma_p \cdot \sigma_{xe} \cdot \left(\sigma_{xe} + \sigma_{ye}\right)} \qquad \Delta\nu_{xp} = 5.122 \times 10^{-4}$$

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





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

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

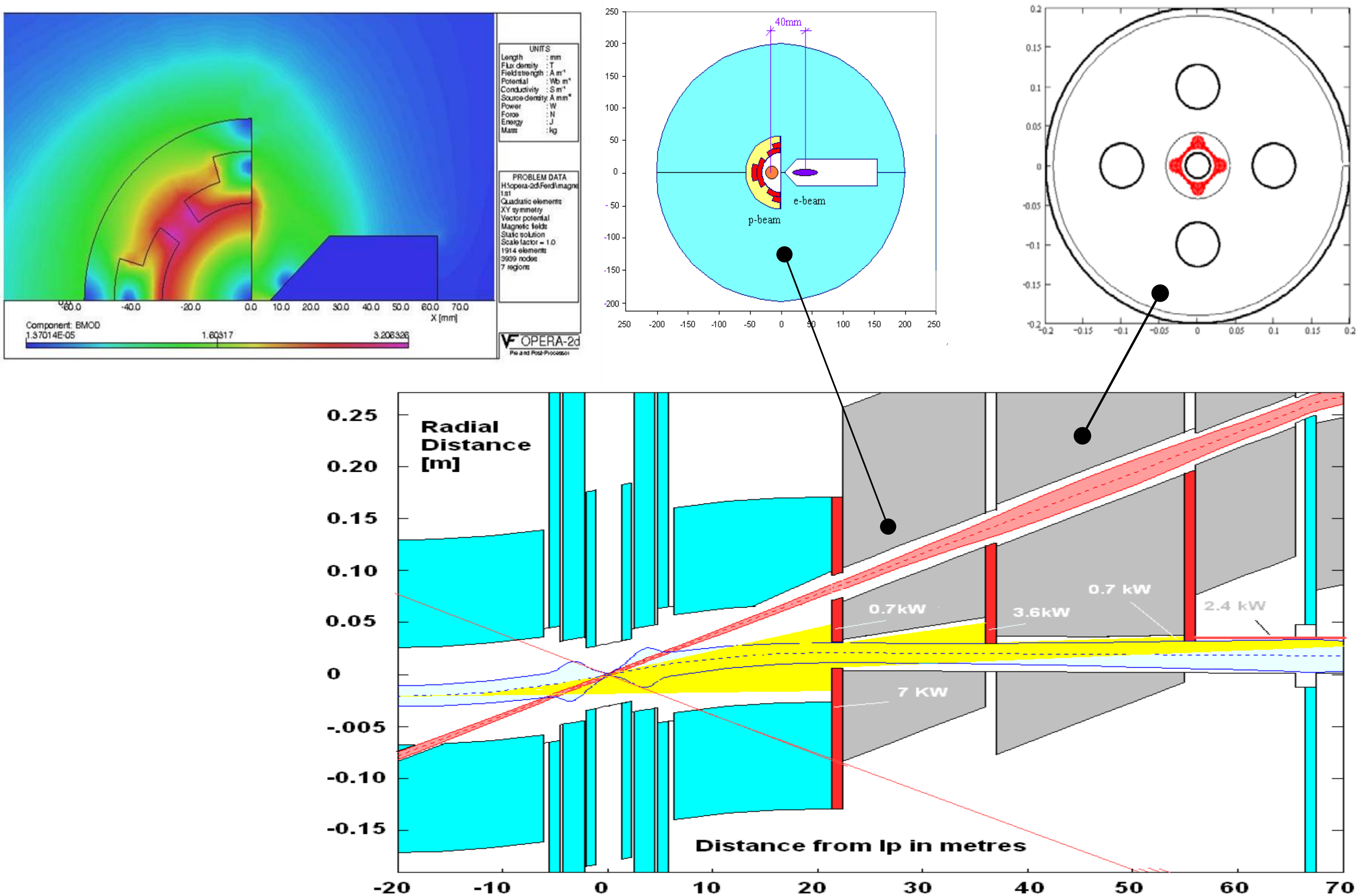
Bunch spacing	Crossing angle	Separation	Separation	Horizont. parasitic beam-beam tune shift	Vertical parasitic beam-beam tune shift
[ns]	[mrad]	[mm]	[σ_{ex}]		
25	2.0	7.7	8.3	0.0011	-0.0015
50	2.0	15	23	0.0001	-0.002
75	2.0	27	50	0.00003	-0.0004

Luminosity vs Bunch Spacing

L independent of bunch spacing
as long as I_e 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



modified ELFE as LHeC injector

ELFE@CERN

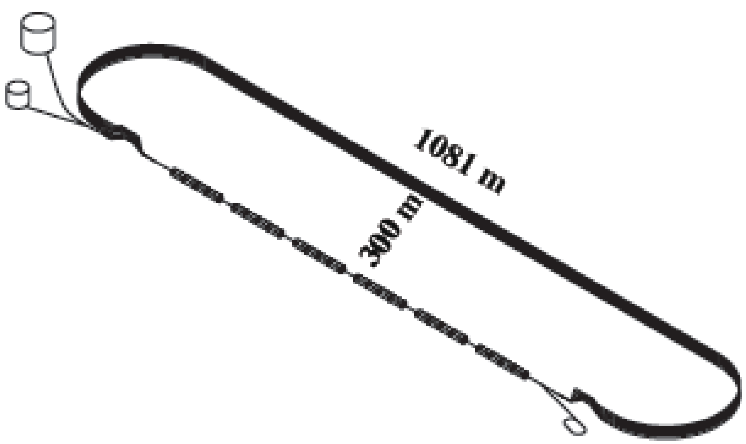
f_{rf} = 352 MHz, gradient 8 MV / m

V_{rf} = 3.5 GV, 72 rf-modules

7 passes (last at 21.5 GeV)

L = 3924 m of which Linac 1081 m

ϱ = 56.9 m



From H. Burckhard, DIS08

LHeC injector

f_{rf} ~ 1 GHz, gradient 31.5 MV/m

Linac L = 150 m 7× shorter

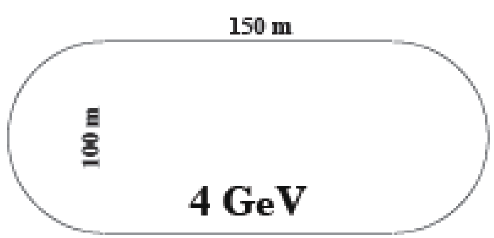
V_{rf} = 4 GV, 5 passes ; last 16 GeV

ϱ = (16/21.5)^4×56.9 m = 17.5 m

or 3.3× shorter

significantly downscaled L ≈ 600 m

and simplified (5 passes) version of ELFE@CERN



recirculating LINAC

more cost effective (?) than single LINAC

+ extra phys. potential

LHeC Activities

The first ECFA-CERN workshop on the LHeC is announced,: http://www.lhec.org.uk

The workshop takes place at Divonne, not far from CERN,
Monday-Wednesday 1.-3.9.2008.

The working group convenors are nominated and can be found on the web page.

The LHeC work will focus on the work of these groups in the preparation for the workshop and beyond.

Meeting on exchange of information on the LHeC project status and on the NuPECC long range planning. NuPECC expressed an interest in the LHeC. NuPECC has formed a study group on the future of lepton-hadron colliders, which will investigate the potential of the EIC (eRHIC/ELIC) and the LHeC as part of NuPECC's long range planning.

At the DIS08 meeting new physics studies and updates on the two machine options were presented by Helmut Burkardt (Ring-Ring) and by Hans Braun(Linac-Ring).

Conclusions

- Comparison of different options ring-ring, ring linac and ERL show specific advantages of each of the options. The final physics case, and the cost/luminosity and energy trade off will decide which option is the most favorable one.
- A first look at a ring-ring based 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 had been held, several working groups (CERN, CI, DESY) have started to work out scenarios in more detail
- Further activities on the layout of the accelerator should b coordinated with and integrated into the discussions on LHC upgrades