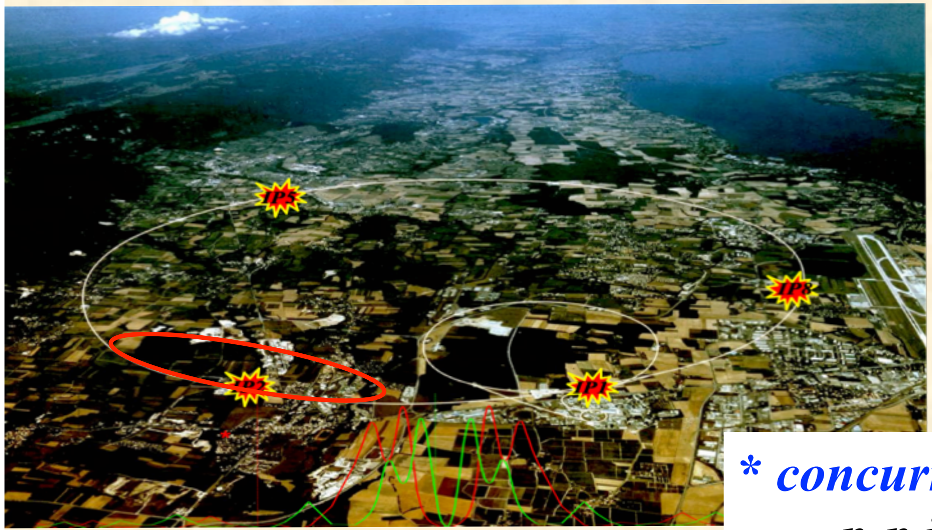
LHeC Performance Limits

Bernhard Holzer



Definitions

** concurrent:*

p-p in IP 1,5,8

and e-p … or p-p in IP2

one electron beam & two proton beams separated in common IR

** run alone*

one electron beam and one hadron beam in IP2

or standard HL-LHC operation with two hadron beams

** stand alone*

e-p in e.g. IP 2

second proton beam in sep lattice,

p-p in IP1,5,8

The Challenges: Boundary Conditions

Many ingredients, that have to be considered:

keep separation scheme soft … to limit E_{crit} & P_{γ}

$$P_{syn} = \frac{e^2 c}{6\pi\varepsilon_0} \frac{\gamma^4}{\rho^2}$$

keep L^* as large as possible (—> LHC Design)

β^* is determined by L^*

$$\beta(s) = \beta^* + \frac{(L^*)^2}{\beta^*}$$

$\varepsilon_{electrons}$ is determined by synchrotron light

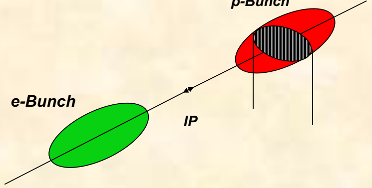
—> determines circumference and beam energy

keep the beams matched at IP

$$\sigma_x^*(e) = \sigma_x^*(p) \qquad \sigma_y^*(e) = \sigma_y^*(p)$$

and finally … optimise luminosity

Luminosity and its Limitations:



$$L = \frac{N_e \cdot N_p \cdot n_b \cdot f_{rev}}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \cdot \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} \Pi_i H_i$$

Correction factors

- hourglass factor $H1 \simeq 0.9$
- the pinch $H2 \simeq 1.3$
- filling factor $H3 \simeq 0.8$
- *crossing angle* $H4 = 1.0$

$$\Pi_i H_i \approx 1$$

"Free" Parameters & Limits:

bunch intensity p: $N_p, \quad n_b, \quad f_{rev} \approx const$ ***LHC Design / beam-beam***

bunch intensity e: $N_e \to I_e$ ***Impedance / Budget (P_γ)***

emittance p: $\varepsilon = 3.3 \cdot 10^{-10}\ rad\ m$ ***LIU Design***

β -function: $\beta^* \approx 15\ cm\ \ldots\ 30\ cm$

$$\sigma_{px} = \sigma_{ex} \quad \leftrightarrow \quad \sigma_{py} = \sigma_{ey}$$

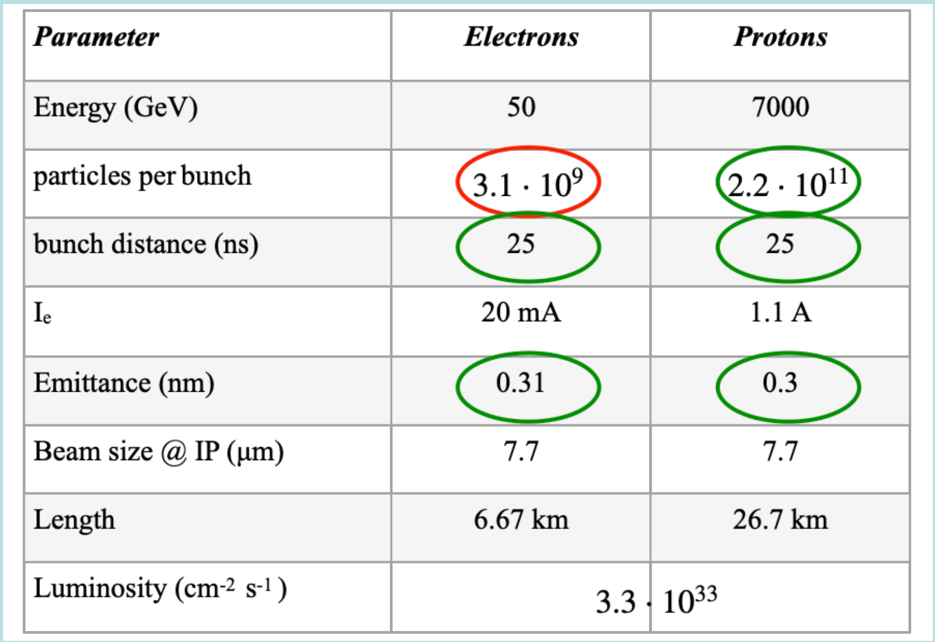
ATS $\beta^* = 15\ cm$, LHC design $\beta^* = 55\ cm$

Q'-Limit / Aperture

Synchrotron Radiation: $P_s = \frac{2}{3}\alpha\hbar c^2 \frac{\gamma^4}{\rho^2}$

Beam Separation Scheme

example : $\beta^* = 20\ cm$

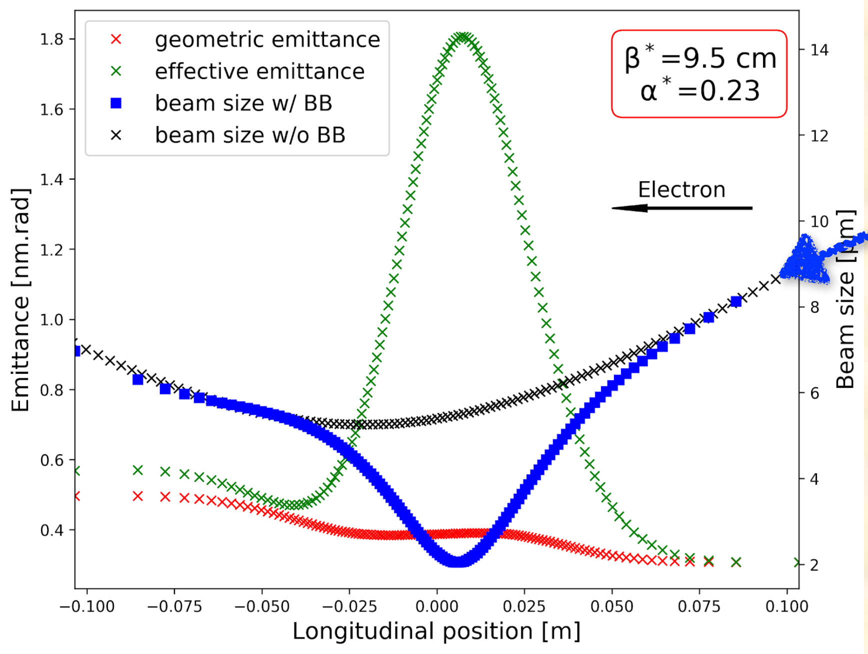


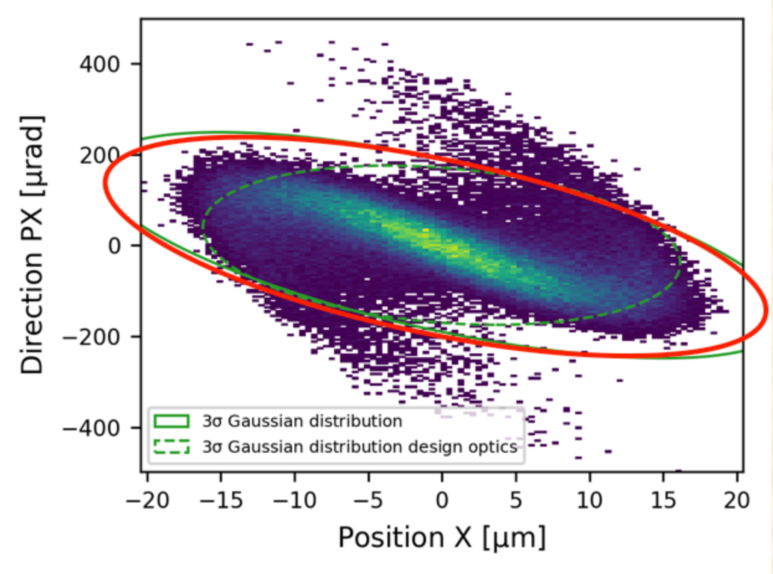
Parameter	*Electrons*	*Protons*
Energy (GeV)	50	7000
particles per bunch	$3.1 \cdot 10^9$	$2.2 \cdot 10^{11}$
bunch distance (ns)	25	25
I_e	20 mA	1.1 A
Emittance (nm)	0.31	0.3
Beam size @ IP (µm)	7.7	7.7
Length	6.67 km	26.7 km
Luminosity ($cm^{-2}\ s^{-1}$)	$3.3 \cdot 10^{33}$	

Beam Beam Effect —> Electron Emittance

Optimise optics: Rematch including the beam-beam focusing

IR Optics for minimum
Optics mismatch





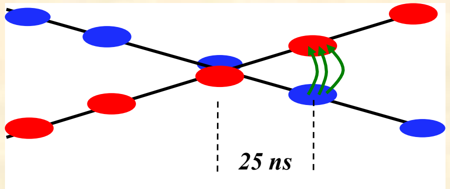
details —> Kevin André

Performance Limit: Beam disruption

development of tails due to non-linear beam beam force

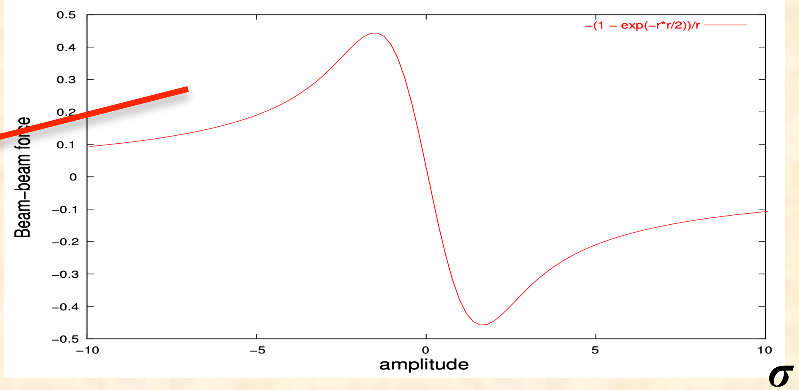
==> ok up to HL-LHC proton currents ✓

Beam Beam Effect —> Proton Emittance



… the ultimate limit of any collider
space charge of the colliding bunch has a detrimental effect on the opposing bunch

Beam Beam Force (round beams)



in linear approximation:
tune shift (LHC)

$$\Delta Q_{x,y} = \frac{N_e \, r_0 \, \beta^*_{x,y}}{2\pi\gamma \, \sigma_{x,y} \, (\sigma_x + \sigma_y)}$$

✓

$$N_e \approx 3 \cdot 10^9 \;\leftrightarrow\; N_p \approx 2.2 \cdot 10^{11}$$

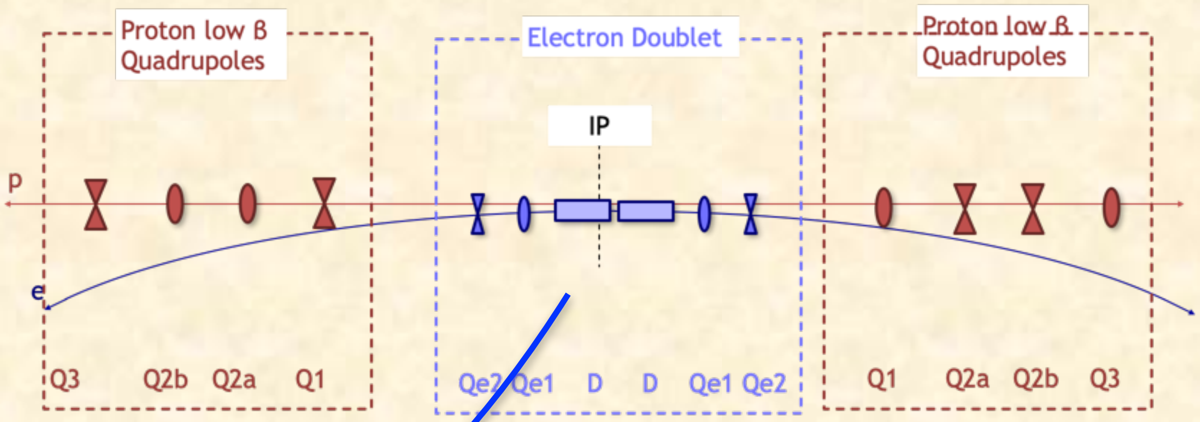
LHeC adds to the tune shift
on the percent level
tbc via tracking Monte Carlo

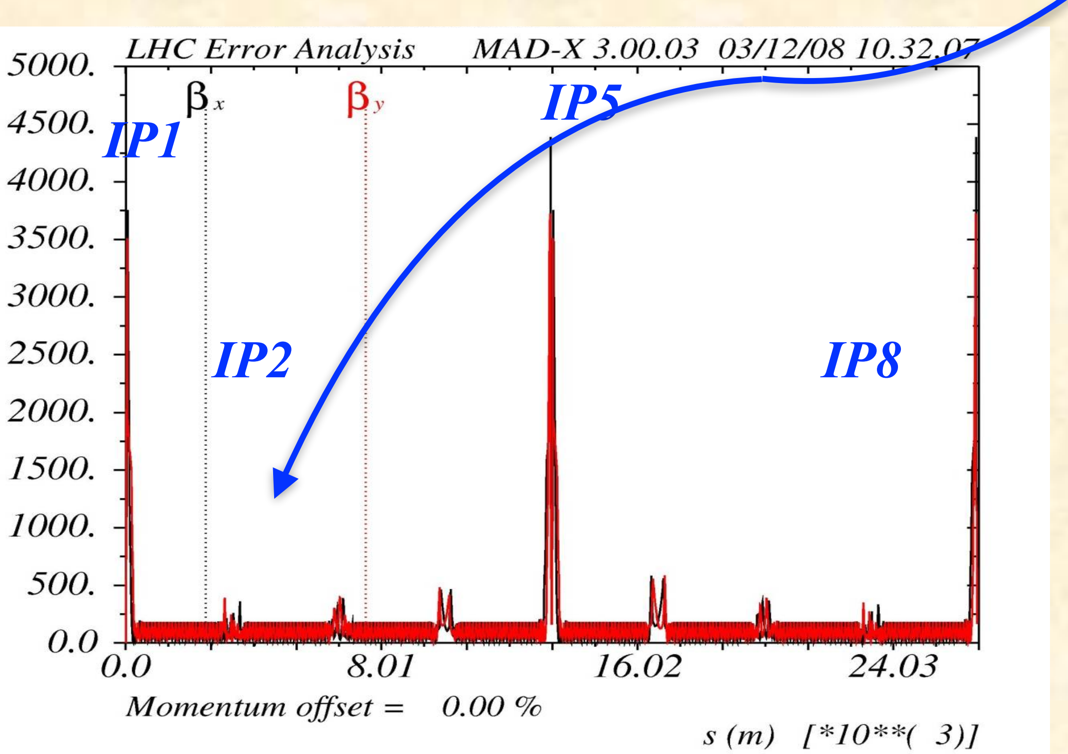
$\Delta Q_{\underline{p,p}} \approx -3.1 \cdot 10^{-3}$ *per IP* *for* $\underline{N_p = 1.5 \cdot 10^{11}}$

$\Delta Q_{\underline{e,p}} \approx +6.4 \cdot 10^{-5}$ *for* $\underline{N_e = 3.1 \cdot 10^9}$

e-p Interaction Region: Proton Optics & Orbit

Double Mini-Beta Insertion
imbedded e-p collisions in LHC standard structure





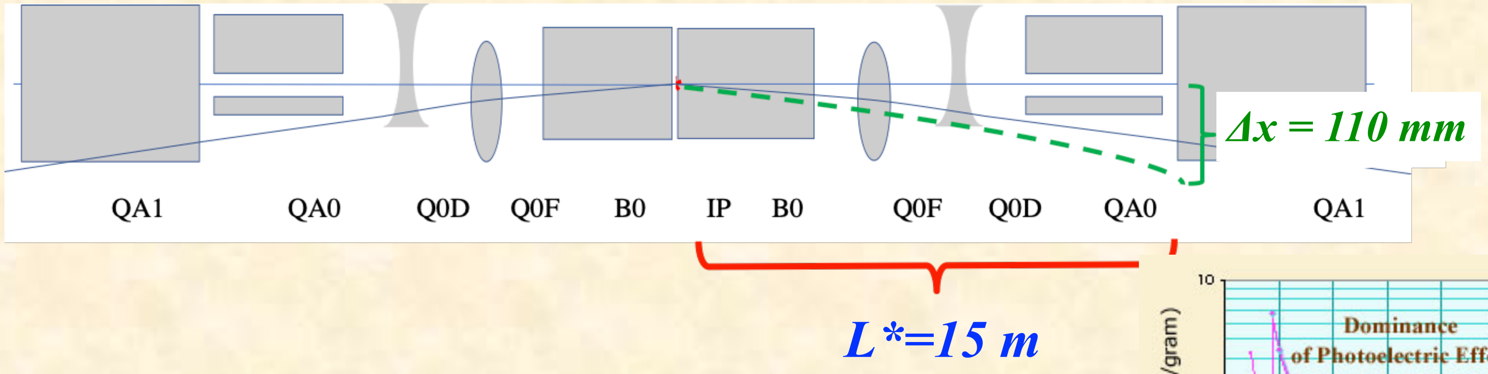
we need 110mm within $L^*=23m$
—> "soft" separation by detector dipole
& e-mini-beta quadrupoles

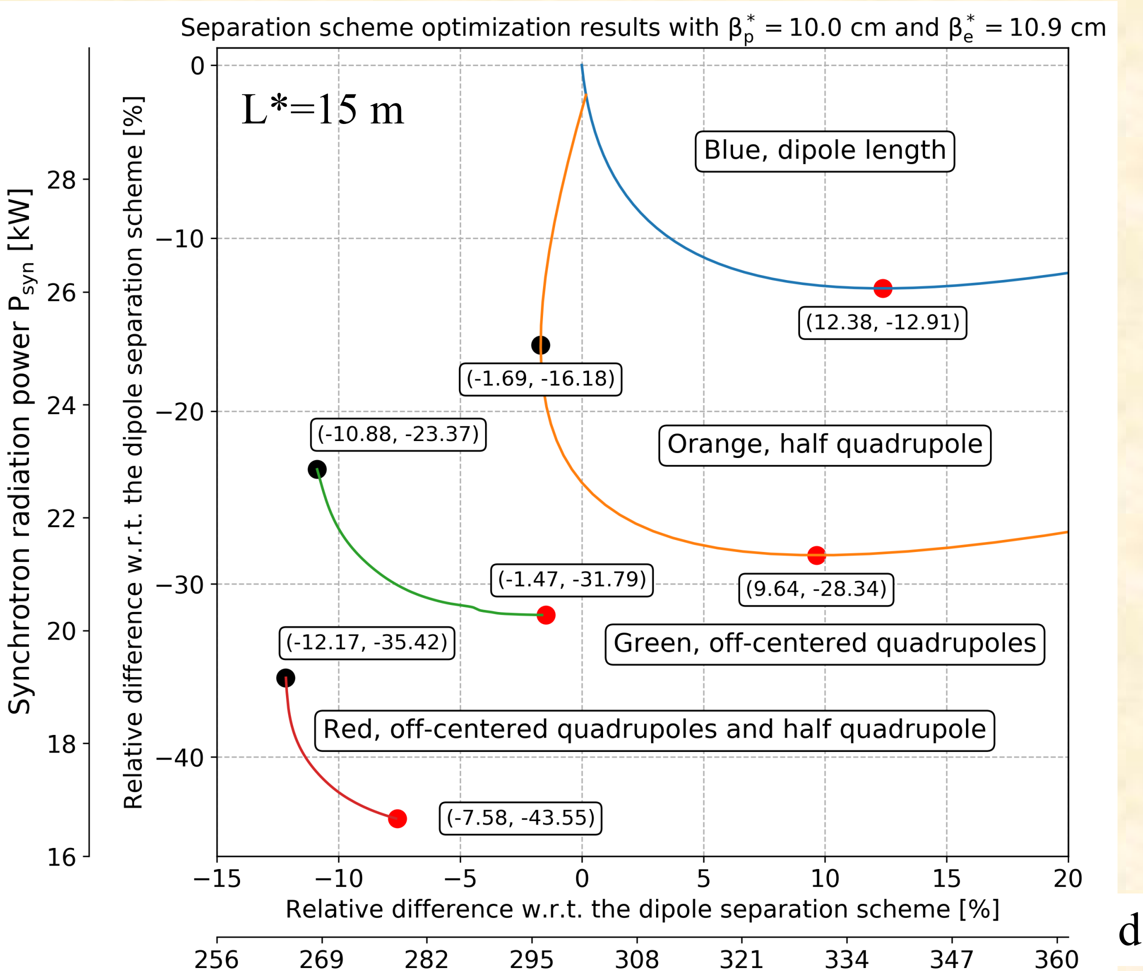
effect on p-orbit & p-optics compensated

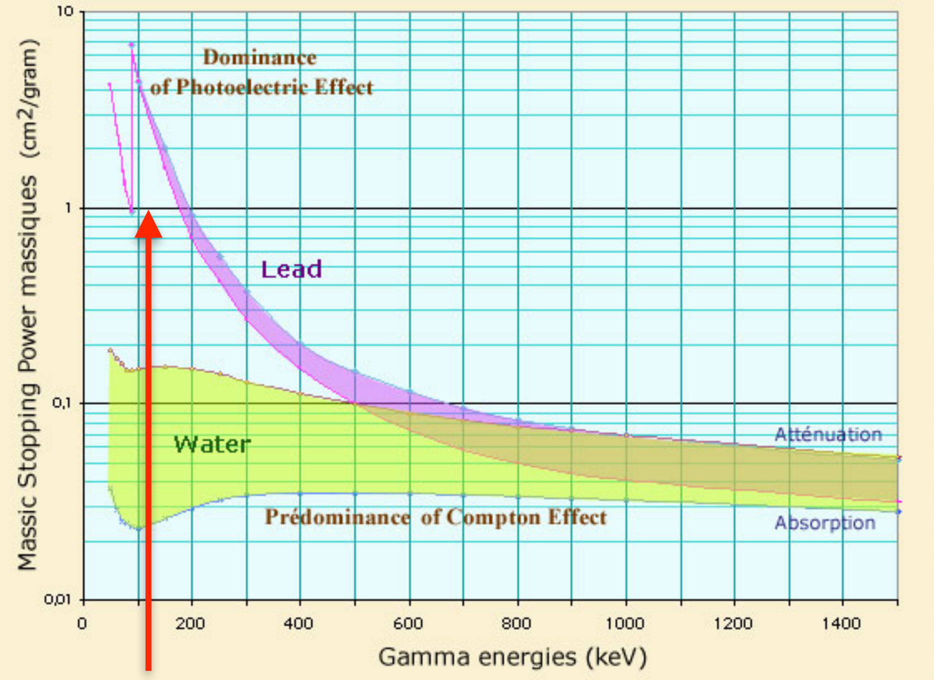
✓

The Interaction Region: Synchrotron Light L= 15 m*

keep separation fields as low as possible







Absorption of photons in Pb

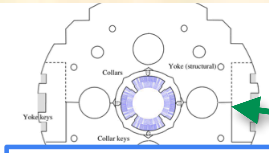
Goal: $E_c \approx 100\ keV$

details —> Kevin André

The Interaction Region: New Magnets, scaling for L*= 23 m

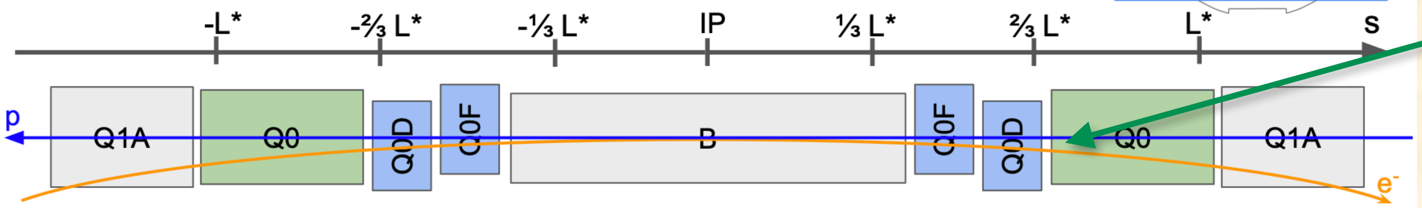
e-p beam separation scheme optimisation

Based on the difference in beam rigidities of the colliding beams.

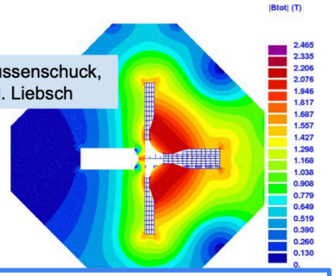


Q1A magnet design

110 mm

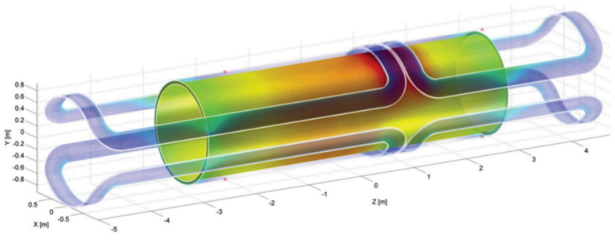


Kevin André

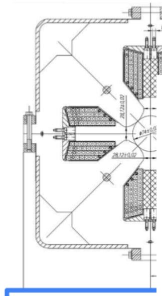


S. Russenschuck, M. Liebsch

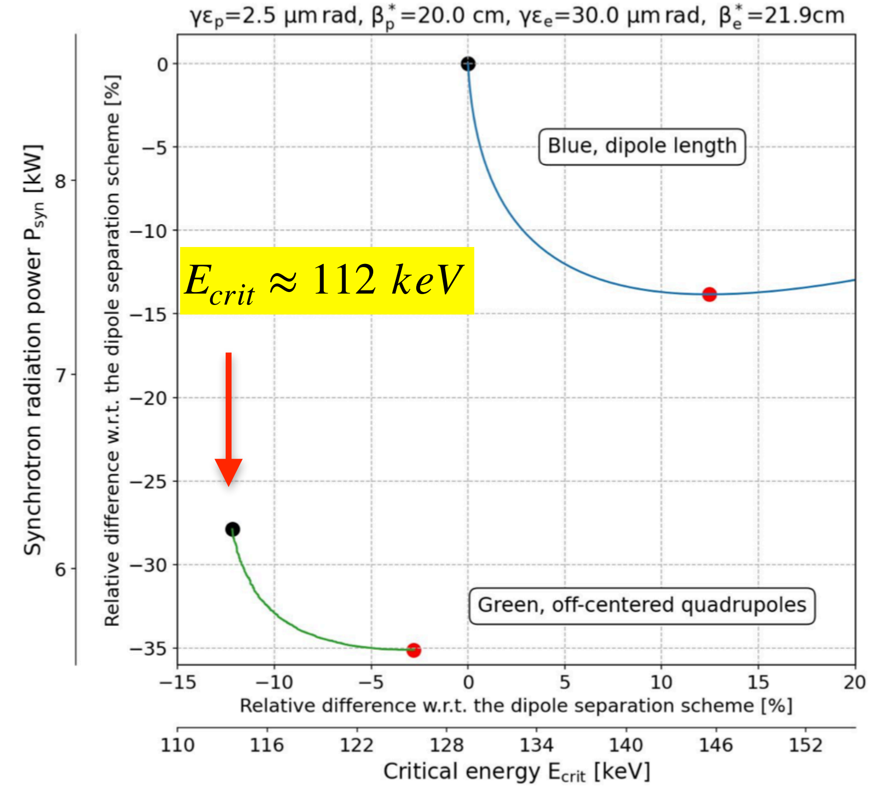
Q0 magnet design



Solenoid + Dipole superconducrting magnet



QI HERA r



$E_{crit} \approx 112\ keV$

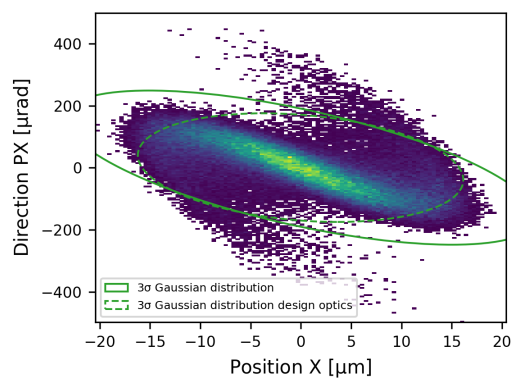
—> *following LHC Design / softening synchr. radiation*

$$E_{crit} = \frac{3hc}{2}\frac{\gamma^3}{\rho} \qquad P_{syn} = \frac{e^2c}{6\pi\varepsilon_0}\frac{\gamma^4}{\rho^2}$$

B. J. Holzer, CERN

Focusing of the electron beam before Q1A.
Pole tip field of quadrupoles below 1T.

ERL Performance:



front-to-end tracking, including

… emittance blow up (radiation in arcs, spreader, bypass)
beam separation scheme
energy gain in linacs
energy loss in arcs
beam-beam effects

particle distribution after IP
as starting conditions for the deceleration & energy recovery

✓

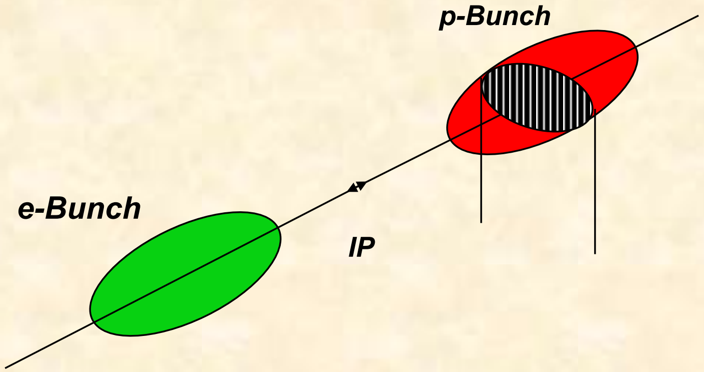
ERL performance: ≈ 98 %

1/3	unit	Injection	Until IP	Post IP	Dump	Energy recovery
εx, εy	um.rad	25.4, 29.4	30.0, 30.0	47.7, 45.2	89.6, 202.6	
dpp	%	0.02	0.0210	0.0210	4.174	97.9 %
Transmission	%	-	100	100	99.93	

Pushing the Luminosity Limit:

==> It's the β -function <==*

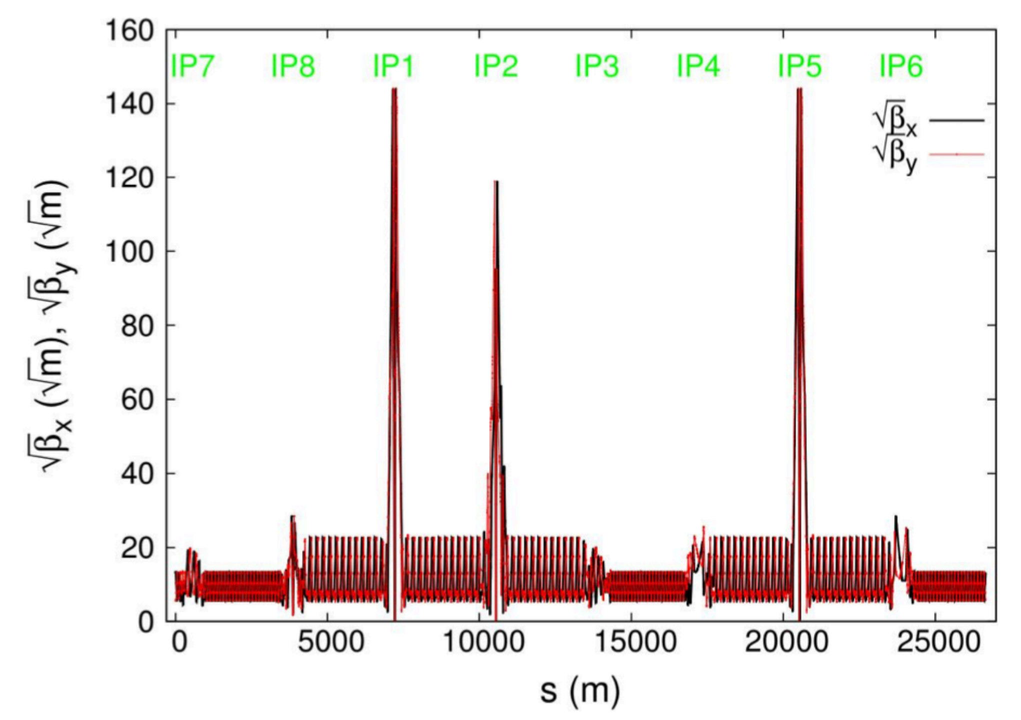
… of the protons !!



$$L = \frac{N_e \cdot N_p \cdot n_b \cdot f_{rev}}{4\pi\ \varepsilon_p \cdot \beta_p^*}$$

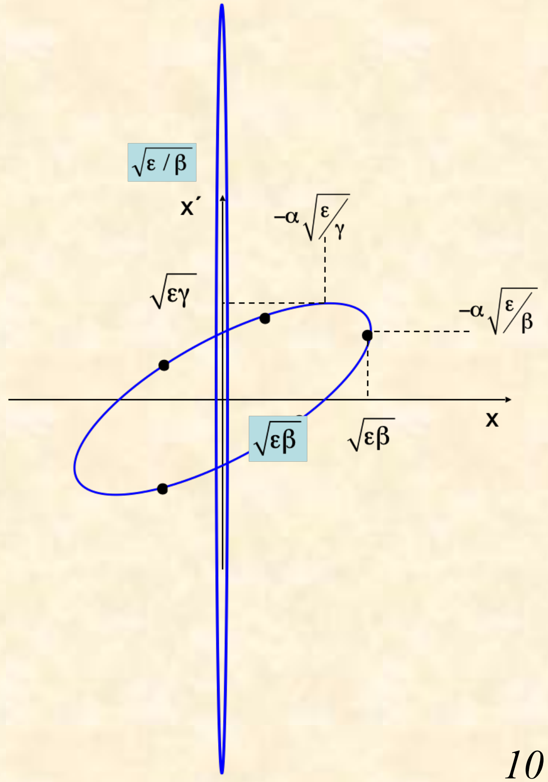
$$\beta^* \approx 15\ cm\ \ \ldots\ \ 35\ cm$$

ATS, Q'-Limit / Aperture



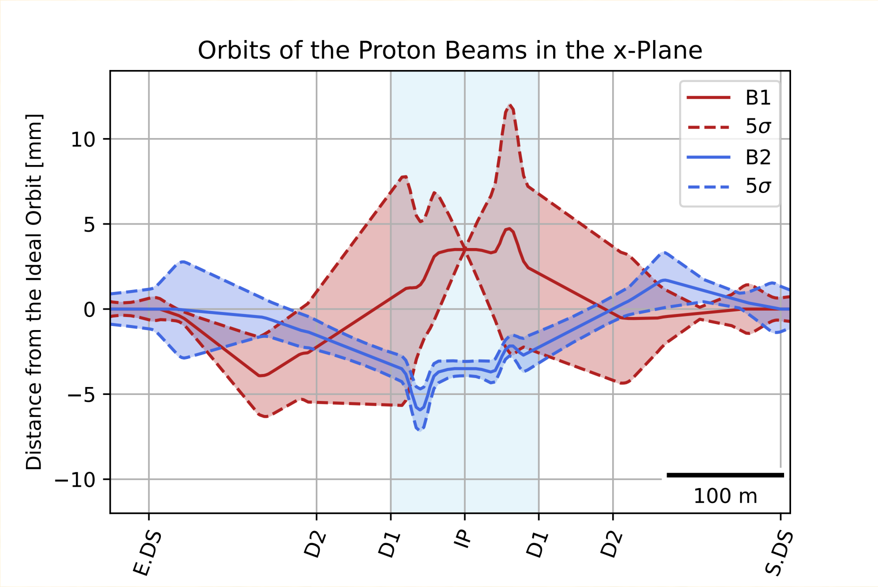
Liouville:

Phase Space Conservation



Proton Beam Performance

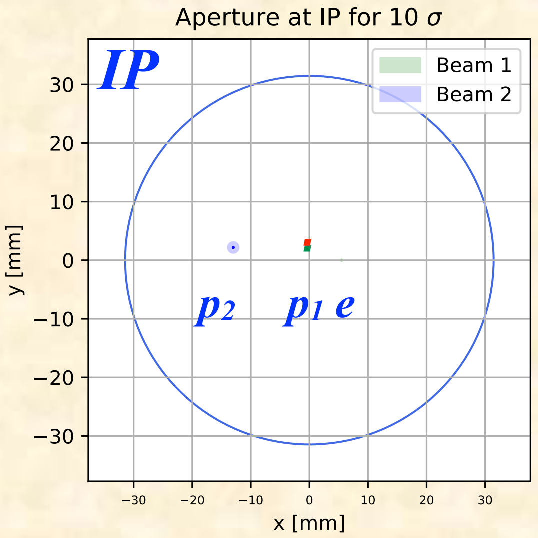
Design Orbits & Aperture Need



Details Tiziana vWitzleben

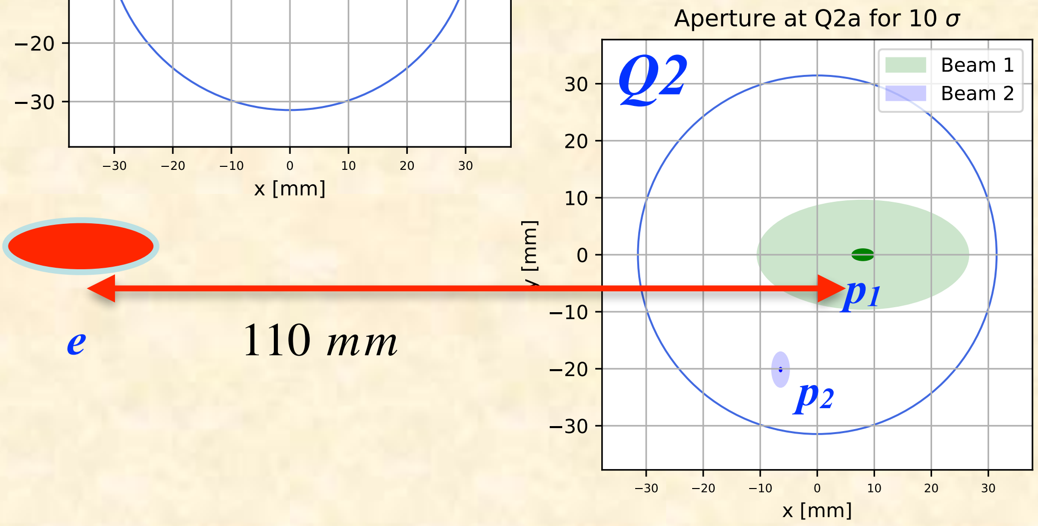
concurrent operation IP1,5 / IP2:

- ***colliding beam***
- ***non-colliding beam***



$$\sigma_{coll} = \sqrt{\varepsilon\beta} = 7.7\mu m$$

$$\sigma_{non-coll} = \sqrt{\varepsilon\beta} = 73\mu m$$



Luminosity limited by aperture of Mini-β quadrupoles

Required: 15 σ

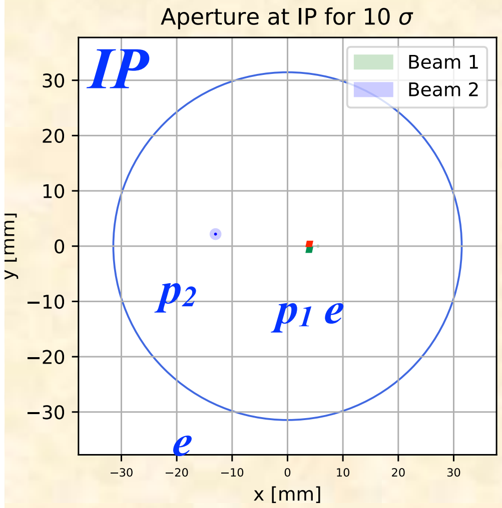
$$\beta_1{}^* = 15cm$$
$$\beta_2{}^* = 24m$$

… for Nb_3Sn technology

B. J. Holzer, CERN

Proton Beam Performance

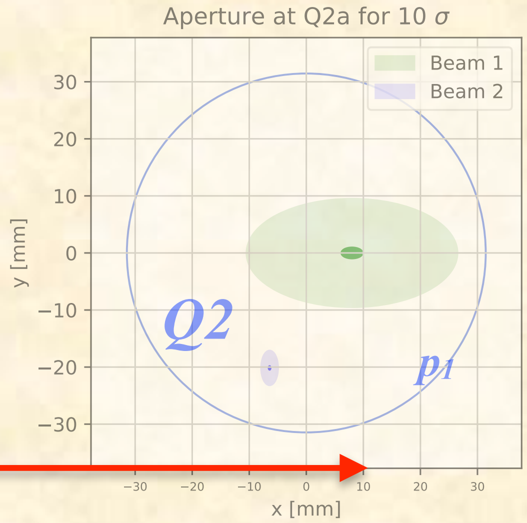
Luminosity limited by aperture of Mini-β quadrupoles

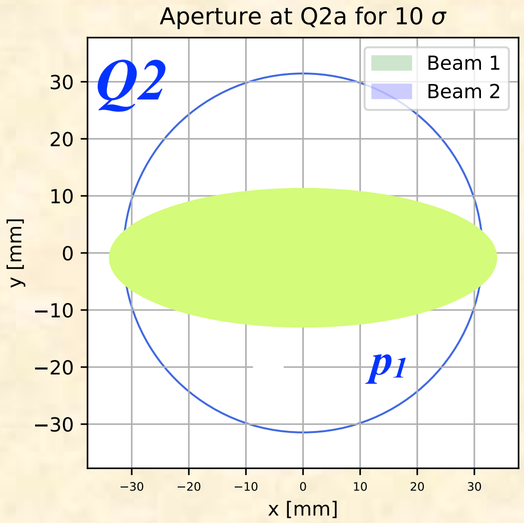


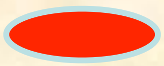
$$\sigma_{coll} = \sqrt{\varepsilon\beta} = 7.7\mu m$$

$$\sigma_{non-coll} = \sqrt{\varepsilon\beta} = 73\mu m$$

stand alone operation IP2: one colliding proton beam







$110\ mm$

qualitativ not to scale !!

$$\beta^* \approx 20cm$$

$$\beta^* \approx 10cm$$

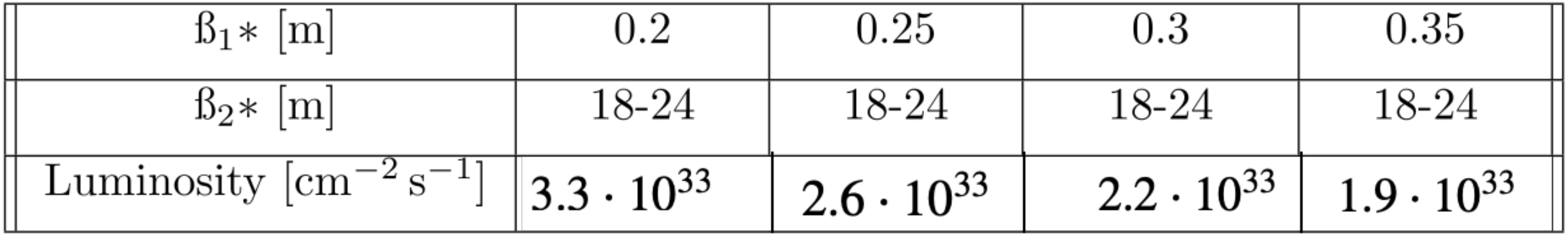
small β needs Nb_3Sn

Parameter	Unit	Value HL-LHC	LHC IR1/5 Q1/Q2/Q3
Magnetic field gradient	T/m	132.6	200/205
Magnetic length	m	4.20/7.15	6.3/5.5/6.3
Aperture radius	mm	75	22.2/28.95
Number of turns per pole		50	
Conductor material		Nb_3Sn	NbTi

B. J. Holzer, CERN

LHeC Luminosity Performance Limits:

—> it's a Proton Problem



ß$_1*$ [m]	0.2	0.25	0.3	0.35
ß$_2*$ [m]	18-24	18-24	18-24	18-24
Luminosity [cm^{-2} s^{-1}]	$3.3 \cdot 10^{33}$	$2.6 \cdot 10^{33}$	$2.2 \cdot 10^{33}$	$1.9 \cdot 10^{33}$

Nb_3Sn Nb_3Sn **NbTi … ?** **NbTi**

concurrent

HL-LHC design
or
NbTi stand alone

stand alone *concurrent*

LHC established

with optimism …

Nb_3Sn ***concurrent for*** $\beta^* = 15\ cm$

stand alone for $\beta^* = 10\ cm$ $\Longrightarrow L \approx 5 \cdot 10^{33} cm^{-2} s^{-1}$

Performance Limit = dyn. Aperture

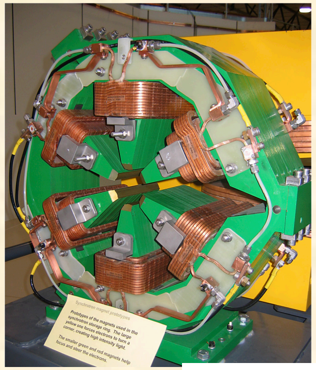
LHeC Wish List:

establish scenario for

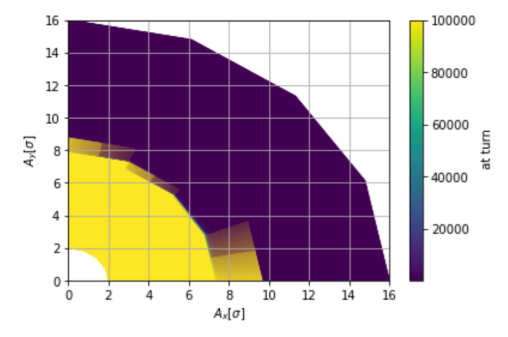
stand alone $\beta^* = 10\ cm$

aperture check & feasibility of Nb_3Sn ***mini-β quadrupole***

dynamic aperture for an ATS type Q' correction scheme



sextupole correction scheme



dynamic aperture

B. J. Holzer, CERN