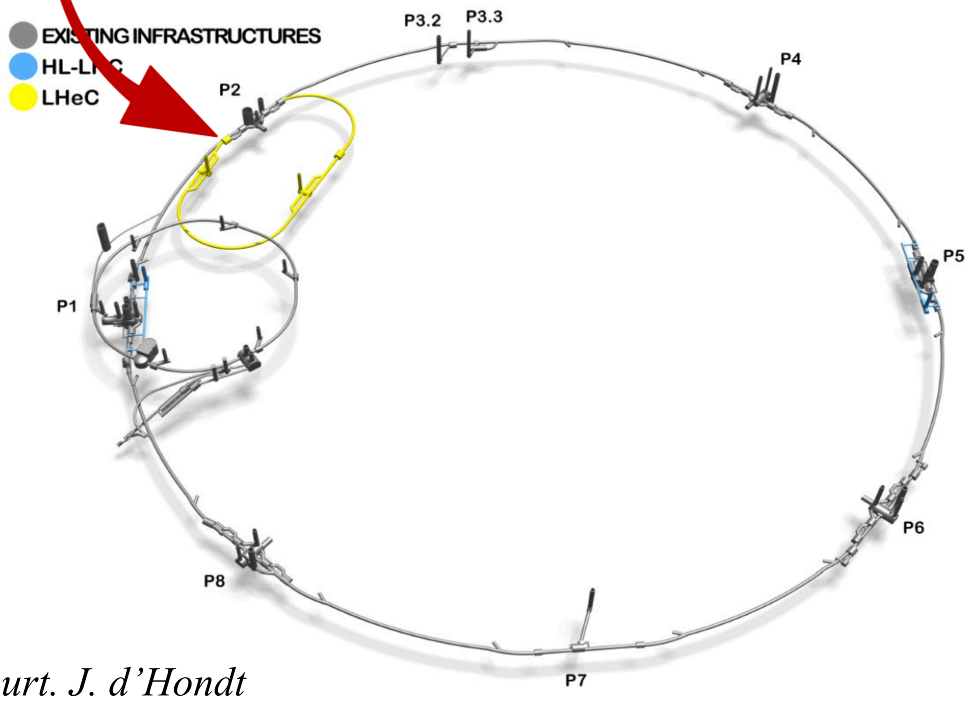
LHeC

Basic Concepts and Layout of the Machine

Bernhard Holzer, CERN
for the LHeC study group

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)

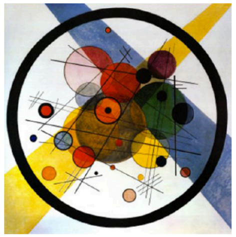


court. J. d'Hondt

LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC Study Group



Published in J.Phys. G

Main Components & Challenges,

… what is needed to provide e-p Collisions at LHC ??

Electron Acceleration:

compact, efficient, "green" —> ERL

IR-region: *Electron mini-beta*
Beam separation
Proton mini beta

Individual optics *for p-p collisions*
and e-p collisions

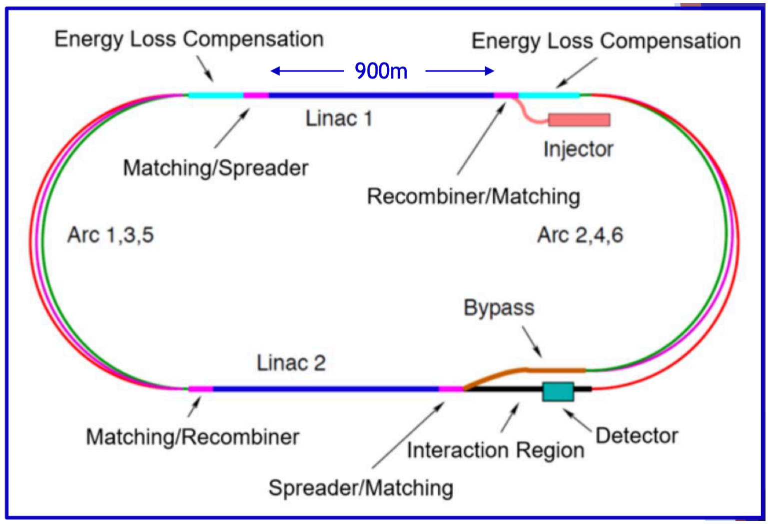
—> colliding p-beam
—> non-colliding proton beam

concurrent
&
alternating
e-p /p-p Operation

Beam-Beam Effect & Luminosity: *limits & impact for p & e beam*

Synchrotron Radiation & MDI

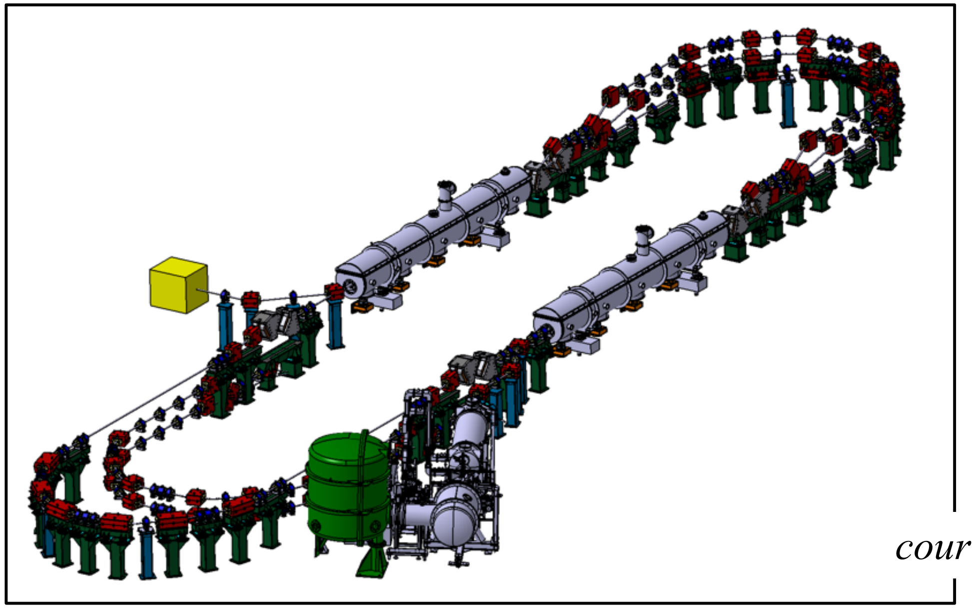
LHeC: The ERL



Design of an ERL based Linac to accelerate electrons and collide with one LHC proton beam

- ***limited size** of the electron "ring"*
- ***beam-beam limit pushed far up***
- ***synchrotron radiation limited** to "one turn"*
- ***beam energy recovered** in the deceleration branch*

Prototype Design: PERLE / Orsay



court. A. Stocchi

Parameter	***Electrons***
Energy (GeV)	50
N_p /bunch (10^{11})	2.2
N_e /bunch (10^{9})	3.1
bunch distance (ns)	25
I_e (mA)	20
Emittance (nm)	0.31
Beam size @ IP (µm)	8 / 8
Length (m)	6665
Luminosity (cm^{-2} s^{-1})	3*10^{33}
wall plug power	100 MW

ERL: Energy Recovery Linac

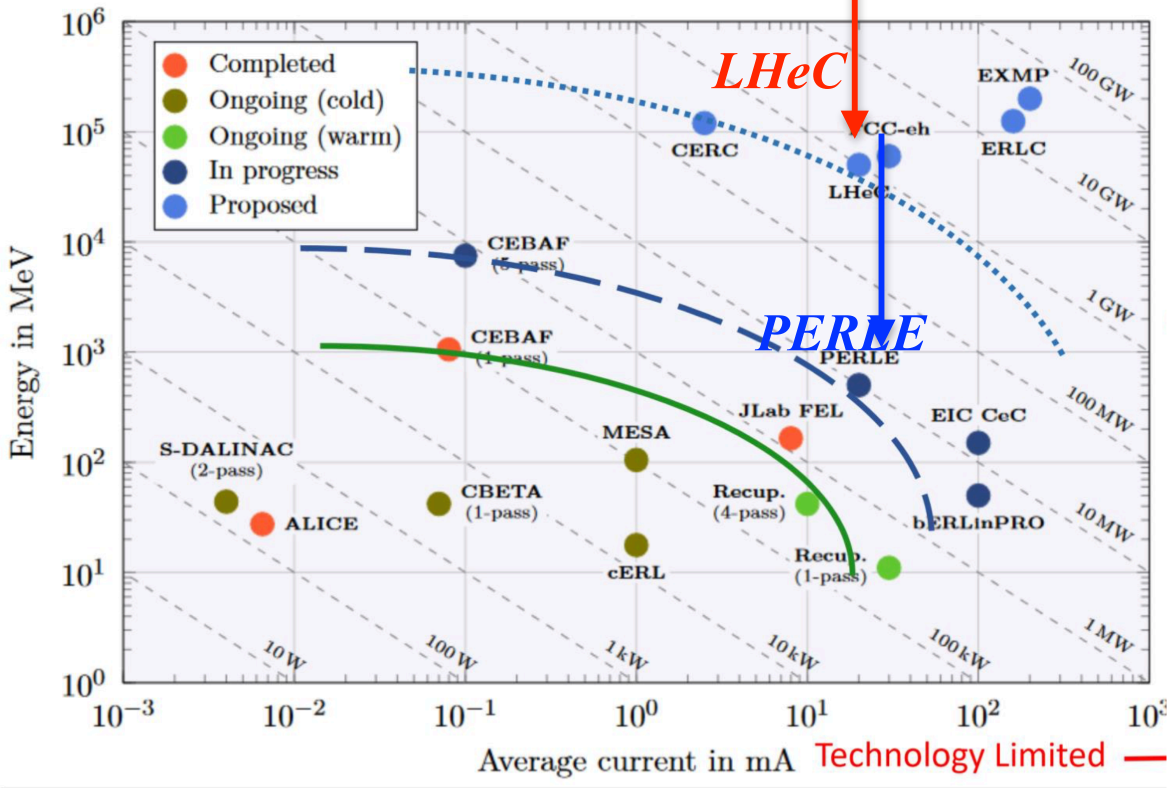
> The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.
>
> ***A detailed plan for the […] <u>saving and re-use of energy</u> should be part of the approval process for any major project.***
>
> *European Strategy for Particle Physics 2020*

Instead of recirculating the electron beam (Storage Ring) (loosing brightness & energy) …

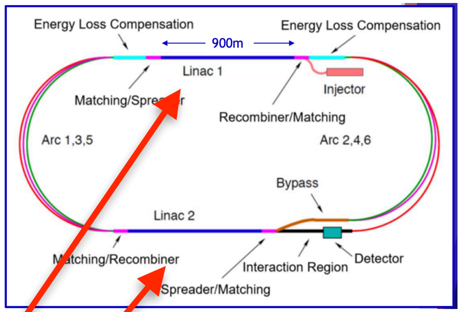
… recirculating the beam energy for new acceleration (high brightness, low radiation losses, high efficiency)

LHeC: Where are we ?

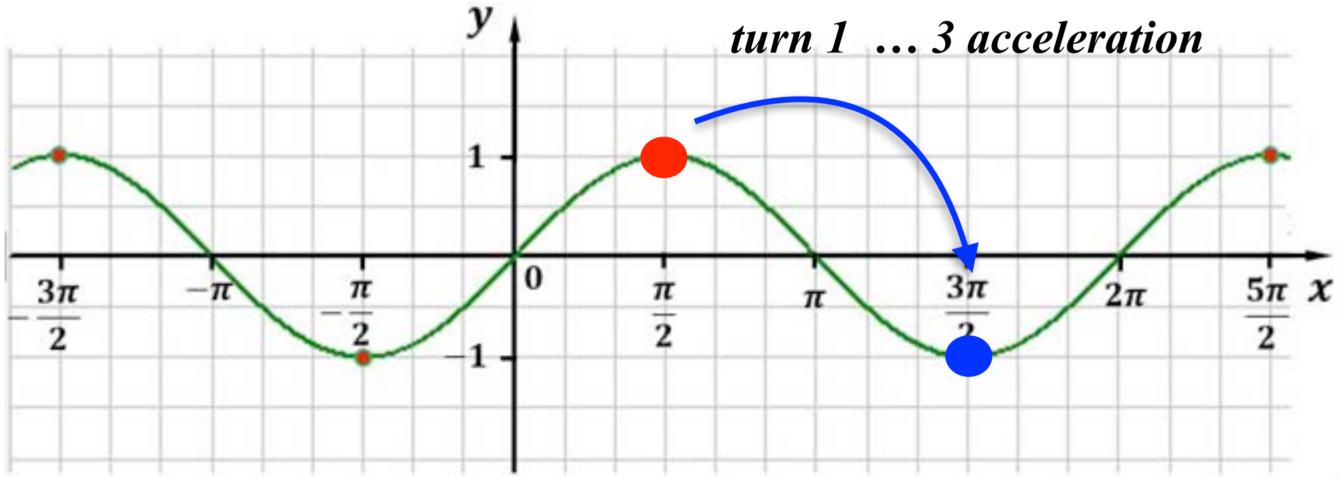
ESPP R&D Accelerator RoadMap:
https://arxiv.org/ftp/arxiv/papers/2201/2201.07895.pdf



LHeC Main Components: sc. RF System



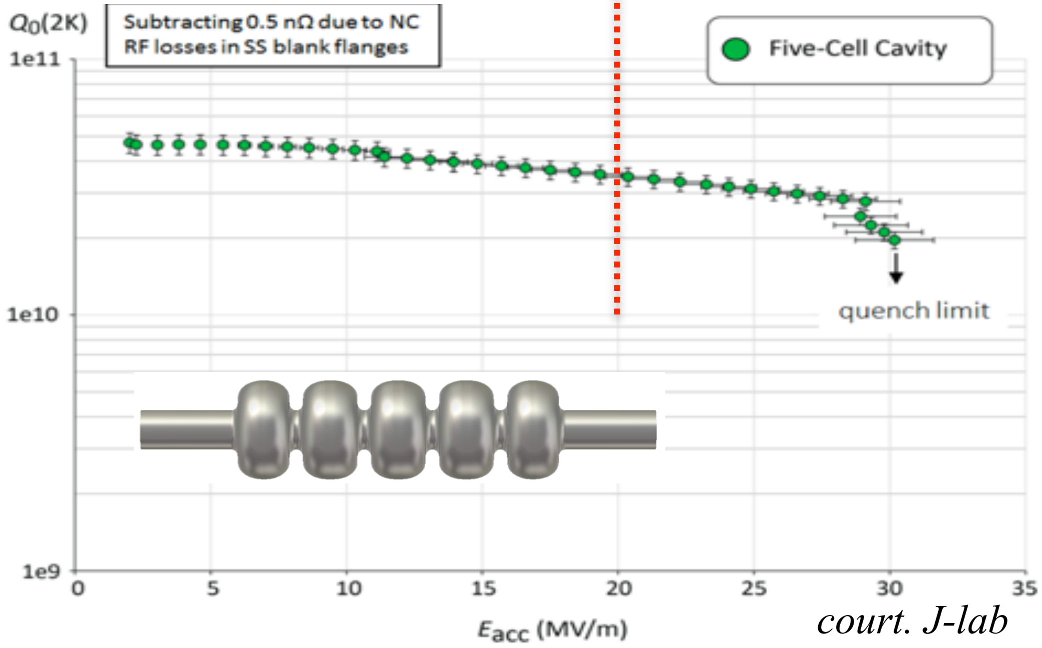
turn 1 … 3 acceleration



phase shift after collision
- via path length of arc 6 -

turn 4 … 6 de-acceleration
& energy recovery

High Q sc. RF system



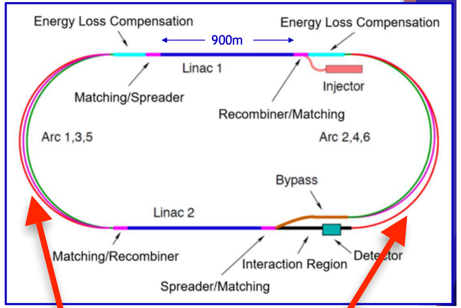
court. J-lab

ERL operation as
“built-in” concept
in the Accelerator Design

Prototype design of 5 cell sc. cavity (J-lab)

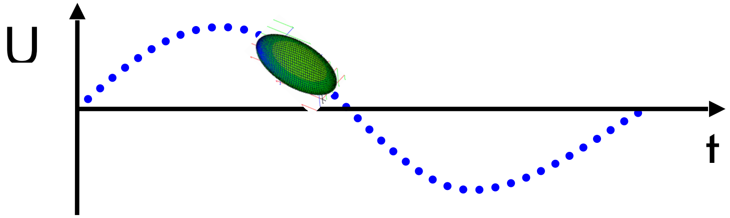
Required Acc Gradient: 20 MV/m
Frequency: 801.58MHz

Return Arcs: … a piece of Art *court. A. Bogacz*

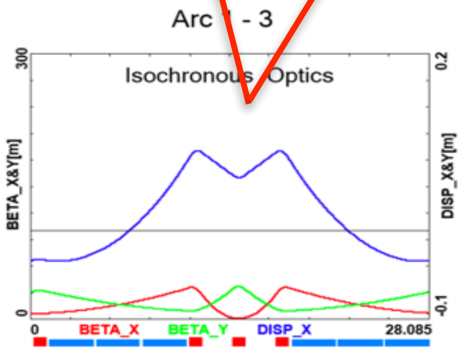


FMC cell to optimise for low / high energy arcs:

**** low energy: keep bunches short for optimum phase "spread"***



isochronous optics arc 1,2,3



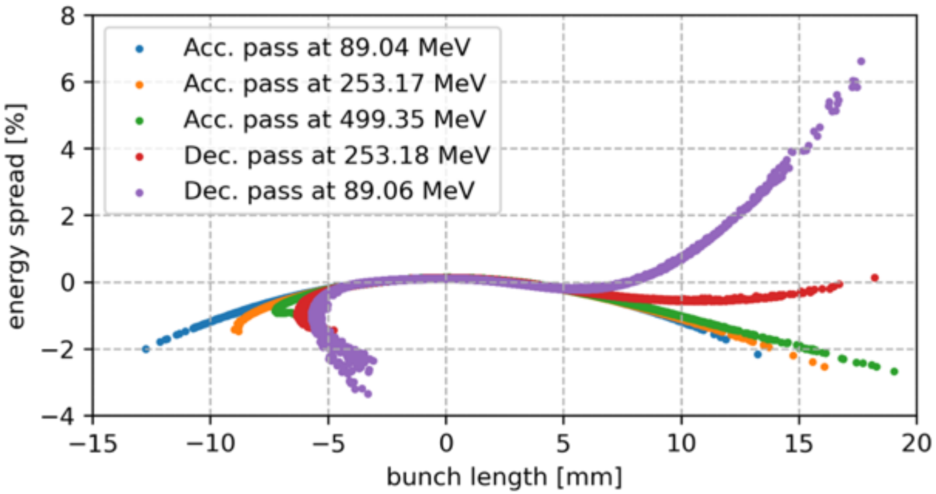
$< H > = 3.62 \times 10^{-3}$ m

Develop a focusing structure for constant revolution time, independent of the particle energy

—> keep the bunch length short

Simulation for the PERLE-ERL

long bunches "see" the non-linear rf field and distort in phase space



Return Arcs & Spreaders

FMC cell to optimise for low / high energy arcs:

**** high energy: v = const, keep radiation effects small***

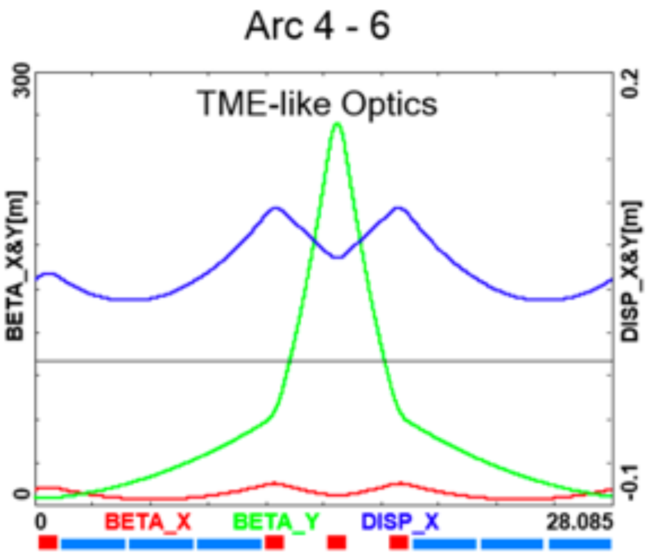
$$\varepsilon_0 = C_q \frac{\gamma^2}{j_x} \frac{I_5}{I_2}$$

$$I_2 = \oint \frac{1}{\rho^2} ds \approx \frac{2\pi}{\rho}$$

$$I_5 = \oint \frac{\mathcal{H}_x}{\rho^3} ds$$

$$\mathcal{H}_x = \gamma_x(\eta_x)^2 + 2\alpha_x\eta_x\eta_x' + \beta_x(\eta_x')^2$$

low emittance
optics arc 4,5,6



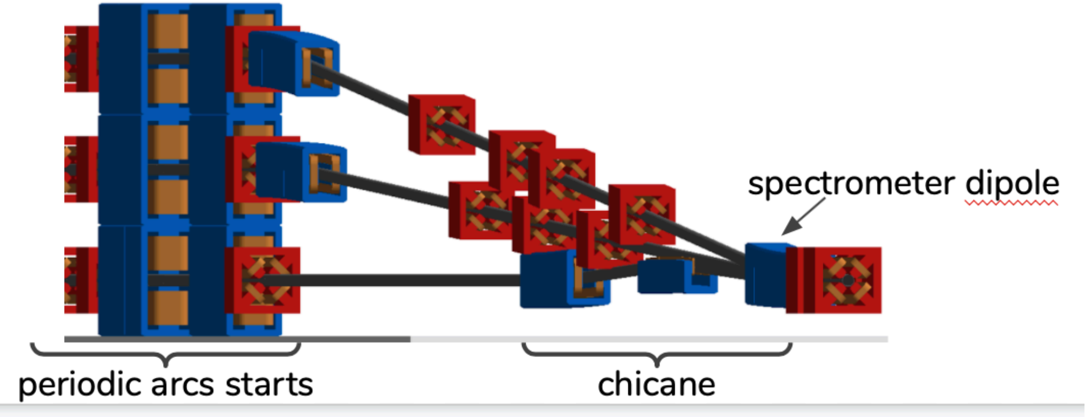
$< H > = 0.59 \times 10^{-3}$ m

Between Arcs and RF structure: Beam Spreader / Re-Combiner

Distribute / re-combine the beam before / after each linac to the corresponding arc structure

Challenge: minimise emittance dilution … in the vertical plane —> H_y

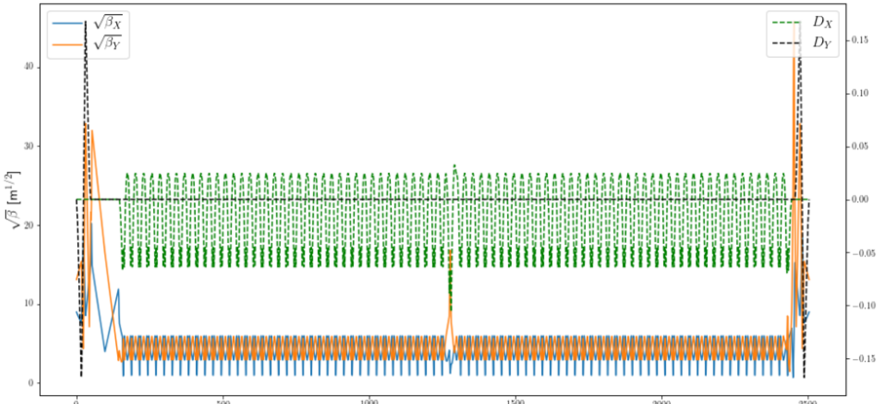
- ***Non-dispersive (i.e. "achromatic") vertical deflection system***
- ***Gently matched beam optics between Linacs and Arcs***
- ***Optimised for smallest impact on ε_y***



$$\mathscr{H}_x = \gamma_x(\eta_x)^2 + 2\alpha_x\eta_x\eta_x' + \beta_x(\eta_x')^2$$

court. A. Bogacz, K. André

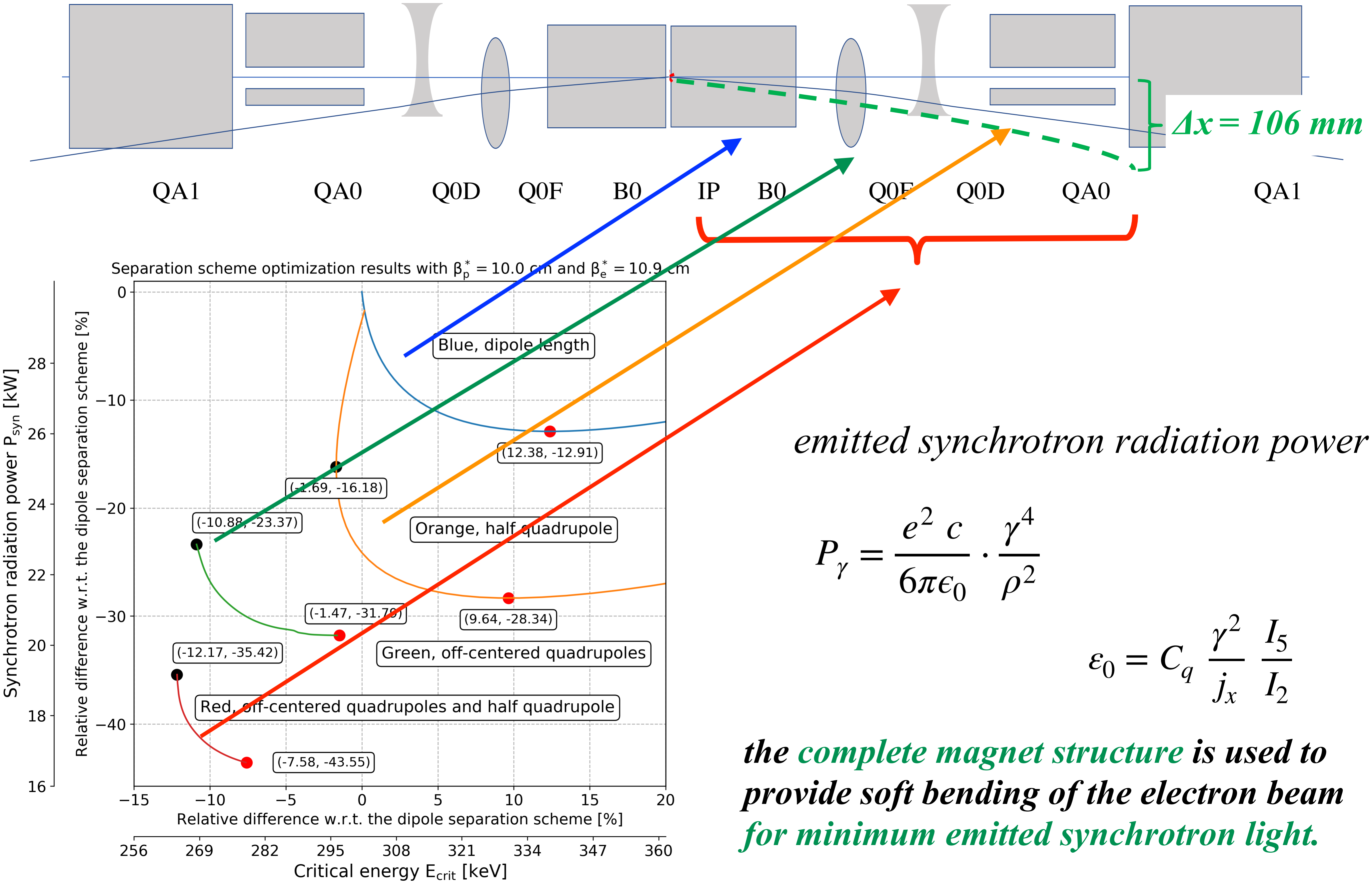
ERL beam optics: spreader,
dispersion suppressor
arc structure & re-combiner



The Interaction Region

court. Kevin André

Separation Scheme of the Electrons



emitted synchrotron radiation power

$$P_\gamma = \frac{e^2\, c}{6\pi\epsilon_0} \cdot \frac{\gamma^4}{\rho^2}$$

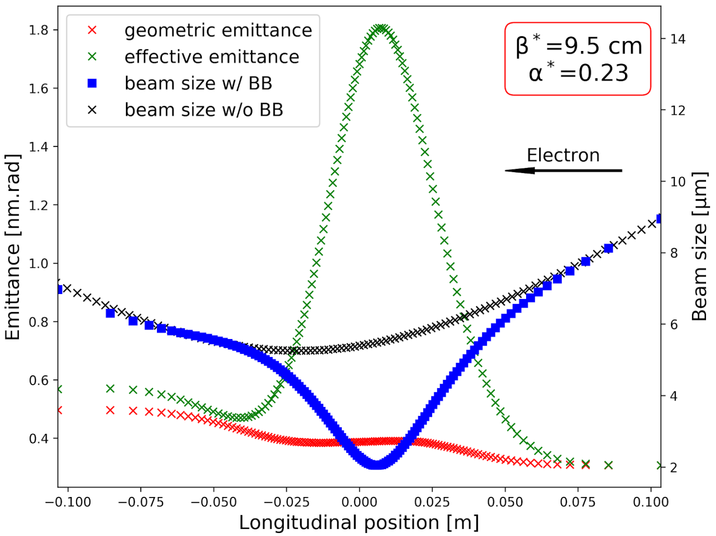
$$\varepsilon_0 = C_q \, \frac{\gamma^2}{j_x} \, \frac{I_5}{I_2}$$

the complete magnet structure is used to provide soft bending of the electron beam for minimum emitted synchrotron light.

Electron Emittance & Beam Beam Effect

court. K. André

Optimise optics: Rematch including the beam-beam focusing

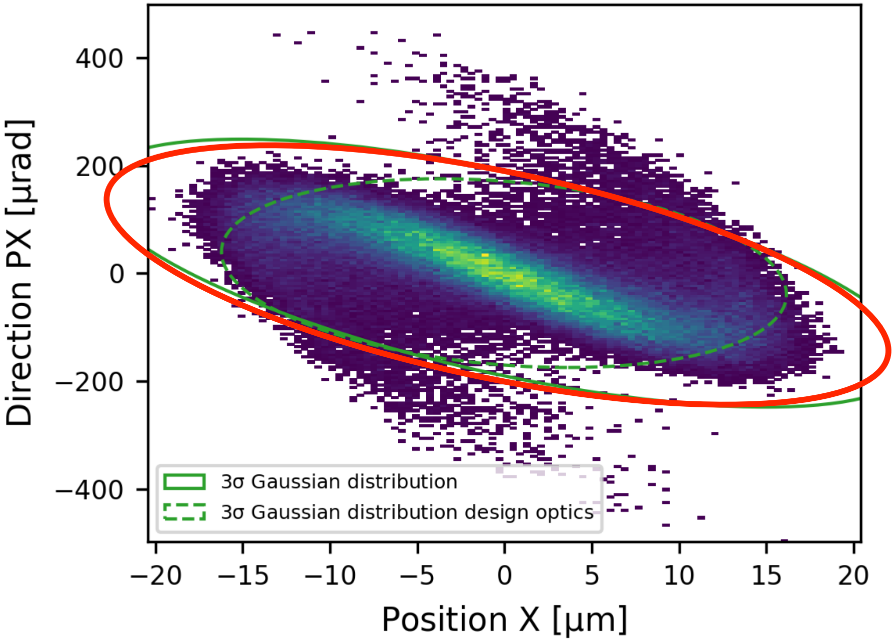


IR Optics for minimum
Optics mismatch

Performance Limit: Beam disruption

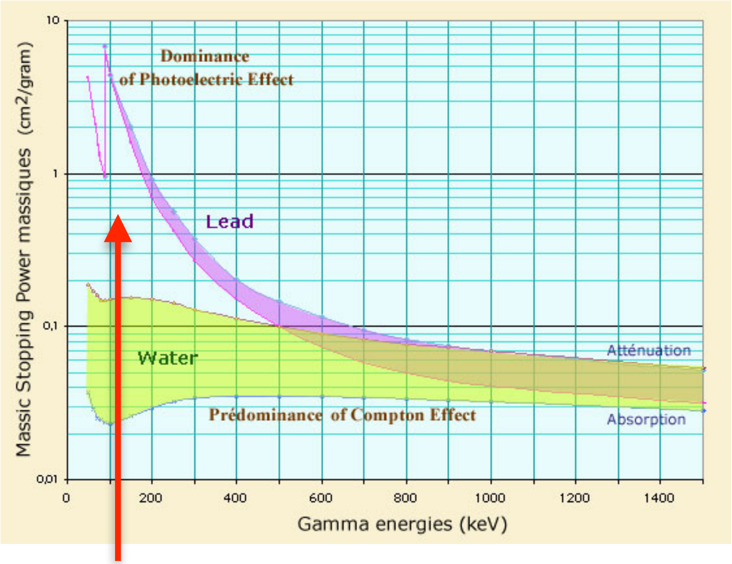
development of tails due to
non-linear beam beam force

$$D_{x,y} = \frac{2\,\boxed{N}\,r_0\,\sigma_z}{\gamma\,\boxed{\sigma_{x,y}\,(\sigma_x+\sigma_y)}}$$



The Interaction Region:

Synchrotron Light & Emittances

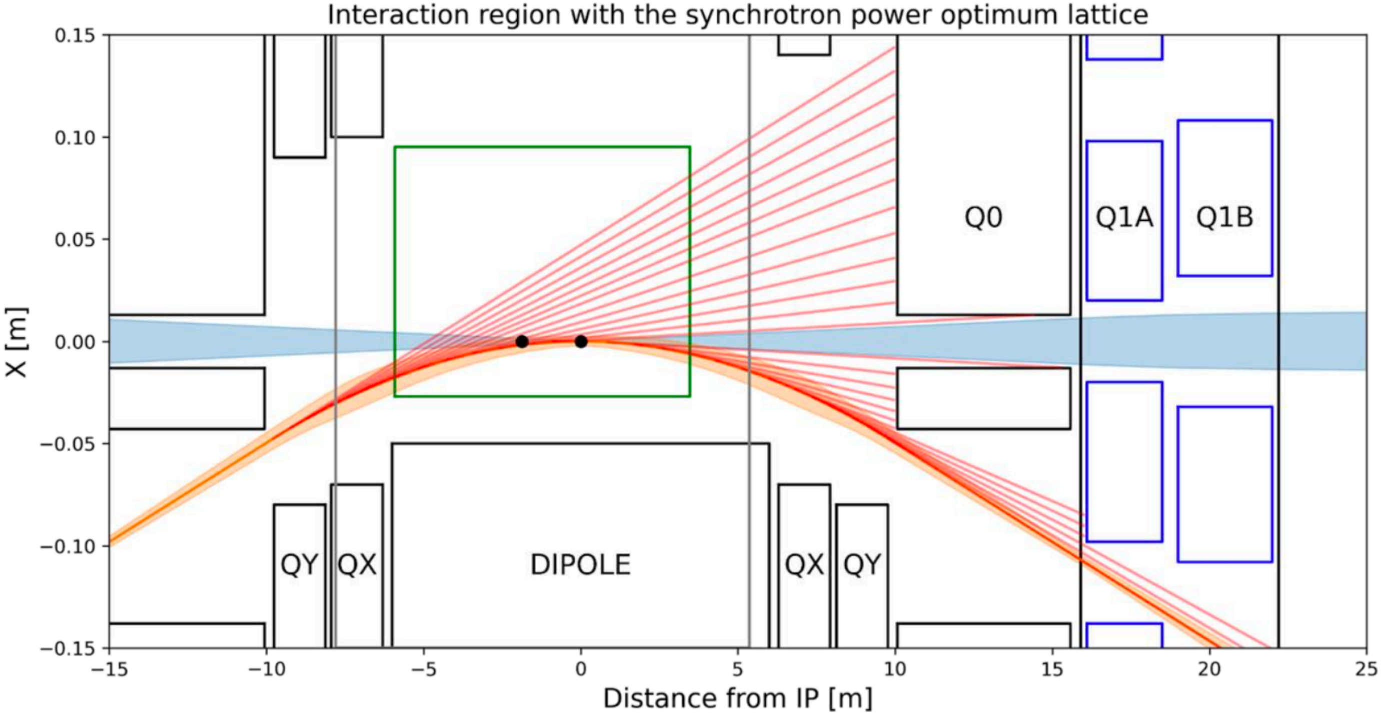


critical energy $$E_{crit} = \frac{3hc}{2}\boxed{\frac{\gamma^3}{\rho}}$$

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

emitted synchrotron radiation
during beam separation

Shielding of Detector
& sc Magnets

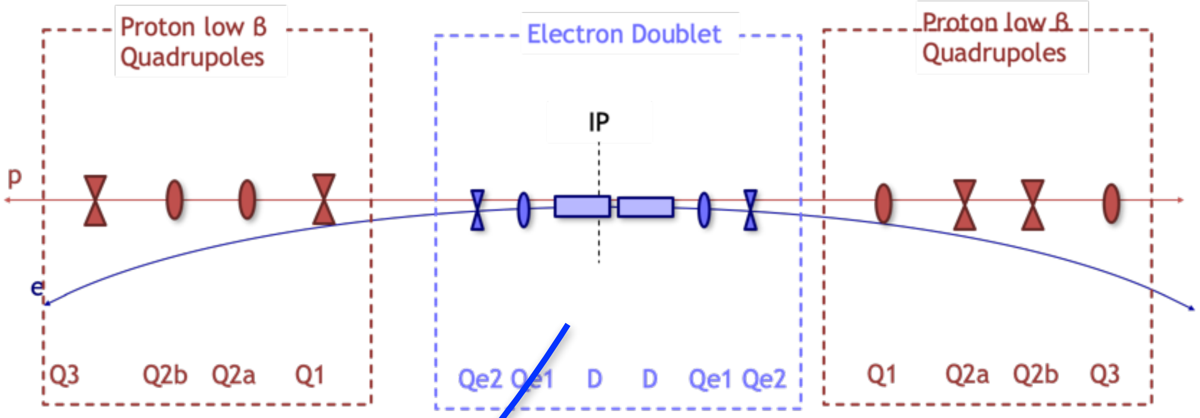


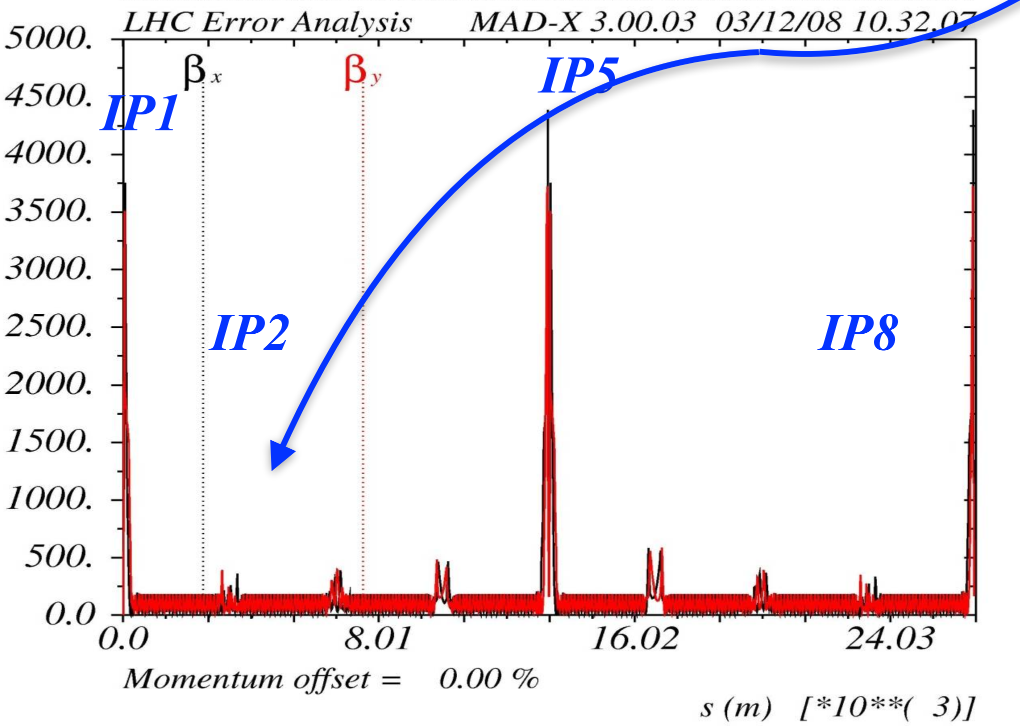
court. Dan Hanstock
Laurent Forthomme

Main Systems: Interaction Region

court. T. vonWitzleben

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





***proton optics* "modular"**
within the LHC periodic
arc structure

***electron optics* insertion**
within the p-final focusing

early beam separation scheme

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

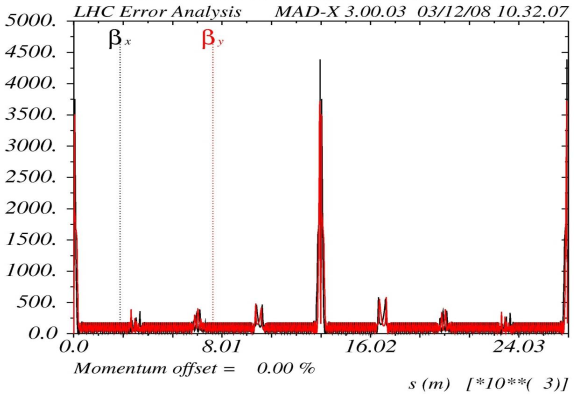
Proton Beam Performance: two fold operation mode

Create a three beam optics, with e-p collisions and one - relaxed - proton beam passing by

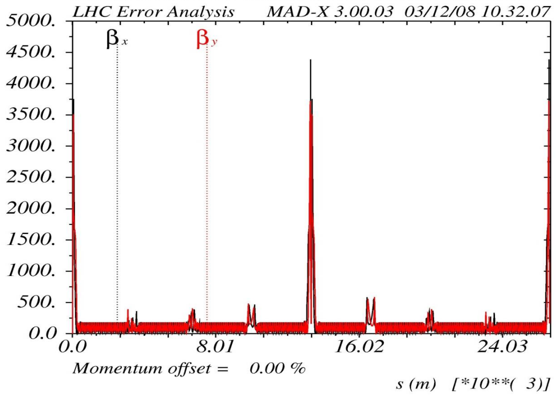
h-h operation:

standard LHC collision optics

p-beam 1

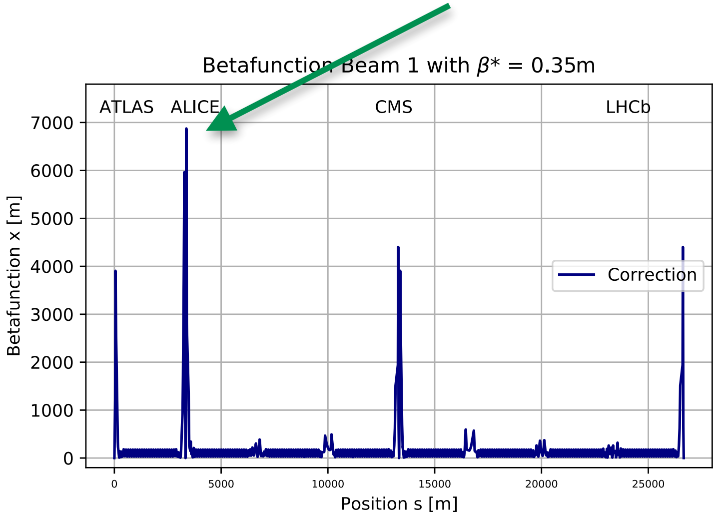


p-beam 2

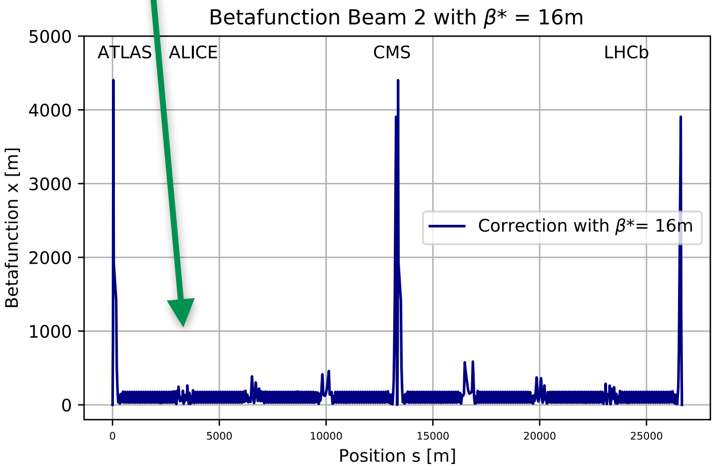


e-p operation:

p-beam 1
—> high luminosity optics



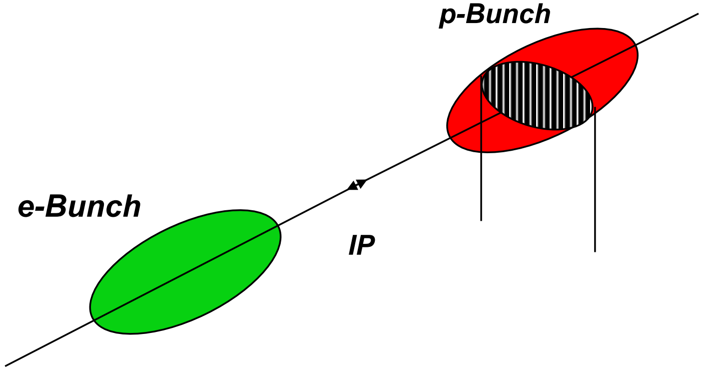
p-beam 2
—> relaxed optics
max aperture margin



court. T. vonWitzleben

Finally the Luminosity:

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



Correction factors

$$\Sigma_i H_i \approx 1$$

matched beam sizes

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

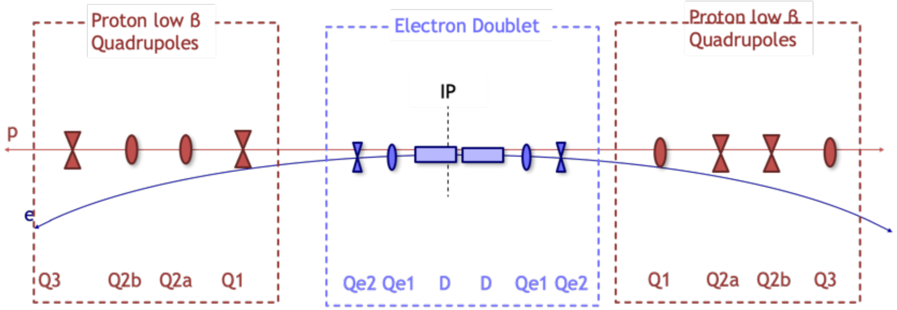
$$L = \frac{N_e \cdot N_p \cdot n_b \cdot f_{rev}}{4\pi \ \varepsilon_p \ \boxed{\beta_p^*}}$$

	Electrons	Protons
Energy (GeV)	50	7000
N /bunch	$3.1\ 10^{9}$	$2.2\ 10^{11}$
bunch distance (ns)	25	
I (mA)	20	1100
Emittance (nm)	0.31	0.33
Beam size @ IP (μm)	8 / 8	
Luminosity ($cm^{-2}\ s^{-1}$)	$3*10^{33}$	

$$\boxed{\beta_p^* \approx 20\ cm \ldots 55\ cm}$$

wall plug power: 100 MW

Status & Next Steps:

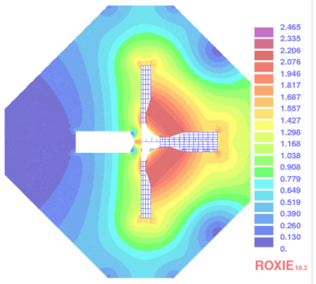


Design of ERL, Proton Optics

- *beam separation scheme* ✓

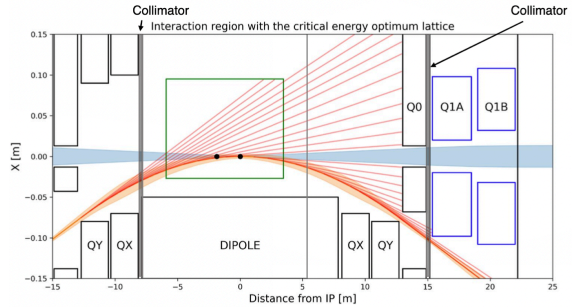
Design for prototypes of special magnet Q1:

- *sc. "field free" quadrupole* ✓



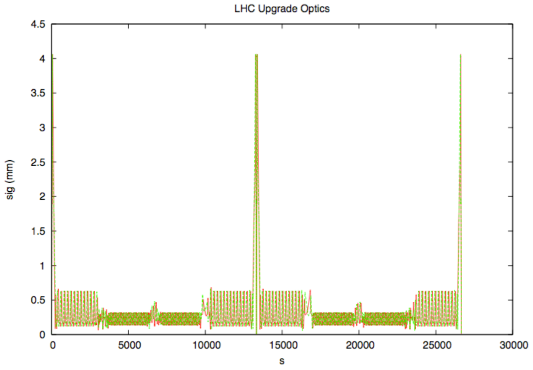
Synchrotron Radiation & Shielding

- *MDI - inner detector* ✓
- *sc. Quadrupoles down-stream IP*



Optimise e-p Performance ✓

- *HL-LHC optics*
  —> ATS for extreme p-optics



Long Term stability ✓

- *tracking calculations, bb effect*

Merci

Appendix

Return Arcs: … a piece of Art

High Energy Arcs: Arc 4 … 6

v = const, keep radiation effects small
well known problem in synchrotron light sources

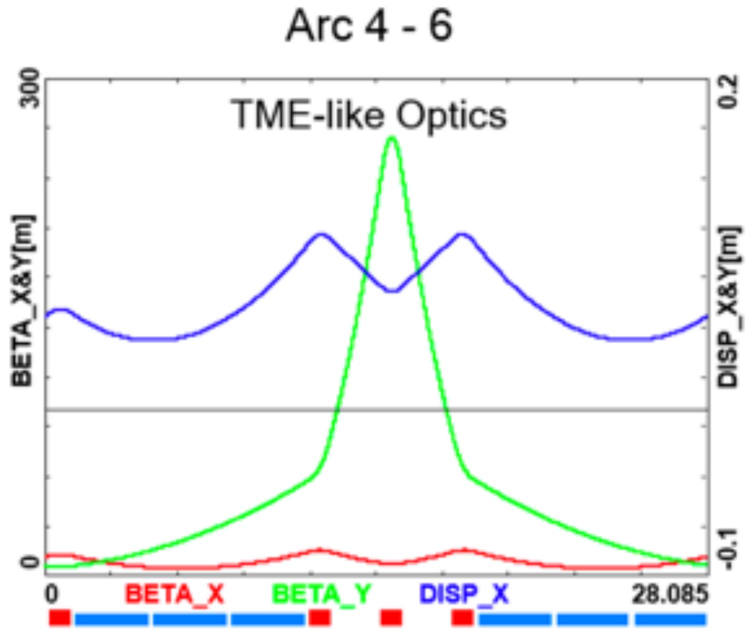
$$\varepsilon_0 = C_q \frac{\gamma^2}{j_x} \frac{I_5}{I_2}$$

$$I_2 = \oint \frac{1}{\rho^2} ds \approx \frac{2\pi}{\rho}$$

$$I_5 = \oint \frac{\mathscr{H}_x}{\rho^3} ds$$

$$\mathscr{H}_x = \gamma_x(\eta_x)^2 + 2\alpha_x\eta_x\eta_x' + \beta_x(\eta_x')^2$$

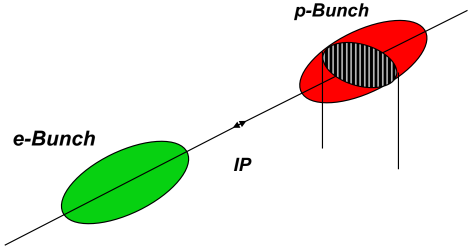
low emittance
optics arc 4,5,6



$$< H > = 0.59 \times 10^{-3}\ \mathrm{m}$$

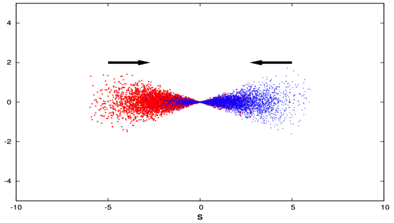
and … the Luminosity Limits:

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



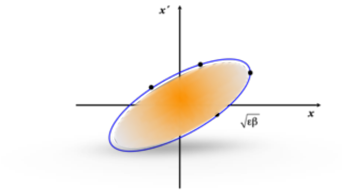
Liouville & Aperture

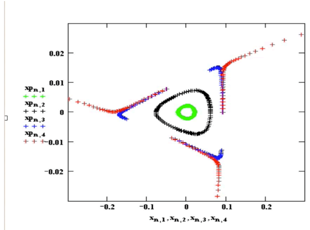
$$\beta(L) = \beta_0 + \frac{L^2}{\beta_0} \quad , \quad \sigma = \sqrt{\varepsilon\beta}$$



Beam Beam Tuneshift

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





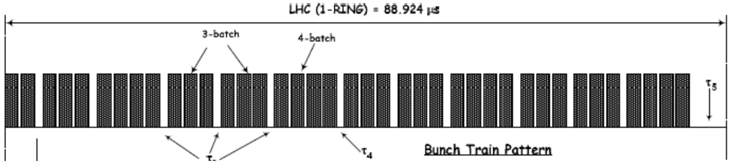
Chromaticity & sextupole strength

$$Q' = -\frac{1}{4\pi}\oint k(s)\beta(s)ds$$

$$S = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}} \approx \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}} .$$

Crossing Angle

Bunch Fill Factor H3 ≃ 0.8



Hourglass Factor, H1 ≃ 0.9

$$A = \frac{\sin^2\frac{\phi}{2}}{(\sigma_x^*)^2[1 + (\frac{s}{\beta^*})^2]} + \frac{\cos^2\frac{\phi}{2}}{\sigma_s^2} .$$

$\beta^* = 35\ cm/10\ m$