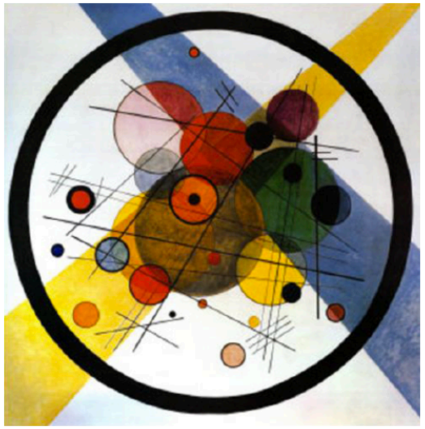
IR Design of the FCC-eh

B.J. Holzer for the LHeC and FCC-he Study Group

Update of the 2012 CDR on arXiv !

The Large Hadron-Electron Collider at the HL-LHC

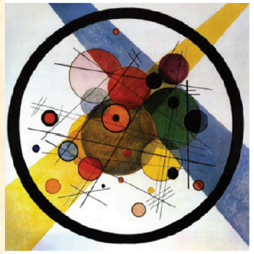
LHeC Study Group



CERN-ACC-Note-2020-0002
Version v1.0
Geneva, April 29, 2020

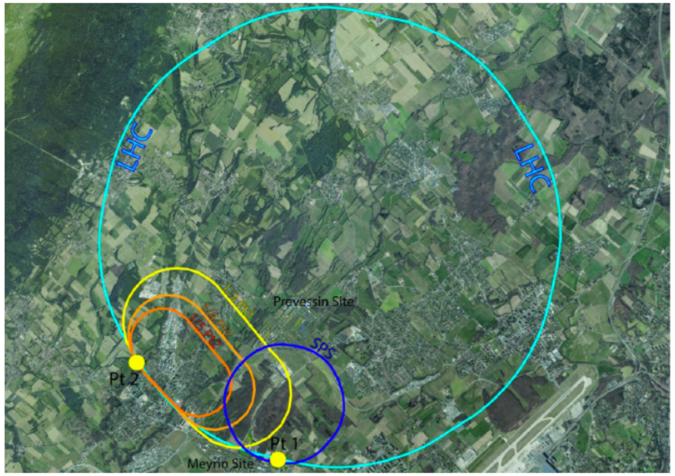
Published in J.Phys. G

LHeC / FCC-eh / PERLE
Energy Recovery Linacs towards high resolution DIS



LHeC

M Klein, O Bruening on LoIs for future ep:
Snowmass Meeting on TeV Colliders
8 July 2020, for the LHeC+PERLE+FCCeh



50 x 7000 GeV^2: 1.2 TeV ep collider

Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

CERN-ACC-Note-2020-0002 →arXiv (July)

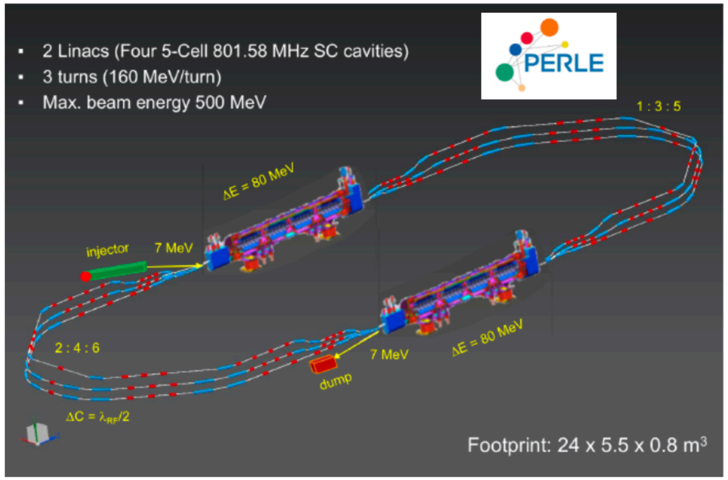
PERLE

Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

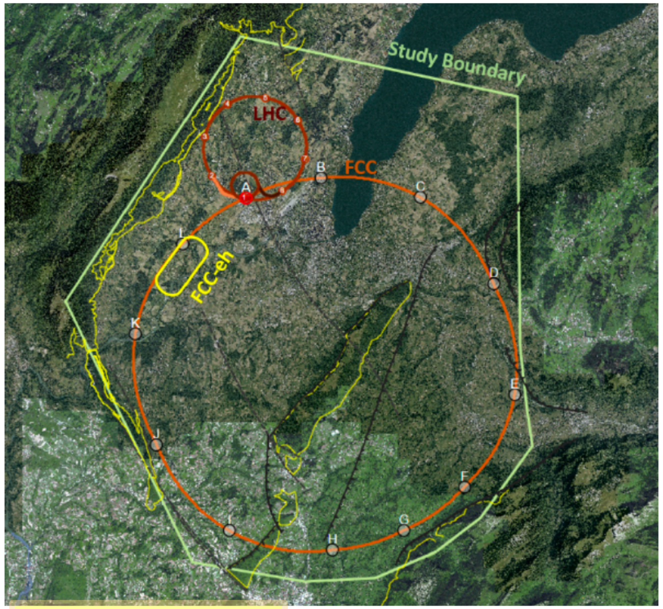
Operation: 2025+, Cost: O(20) MEuro

LHeC ERL Parameters and Configuration
I_e=20mA, 802 MHz SRF, 3 turns →
E_e=500 MeV → first 10 MW ERL facility

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (IJC), +



FCC-eh



60 x 50000 GeV^2: 3.5 TeV ep collider

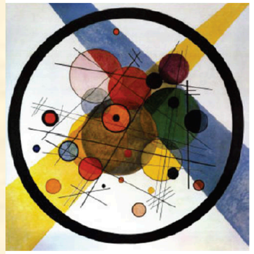
Operation: 2050+, Cost (of ep) O(1-2) BCHF

Concurrent Operation with FCC-hh

FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

ERL Circumference:

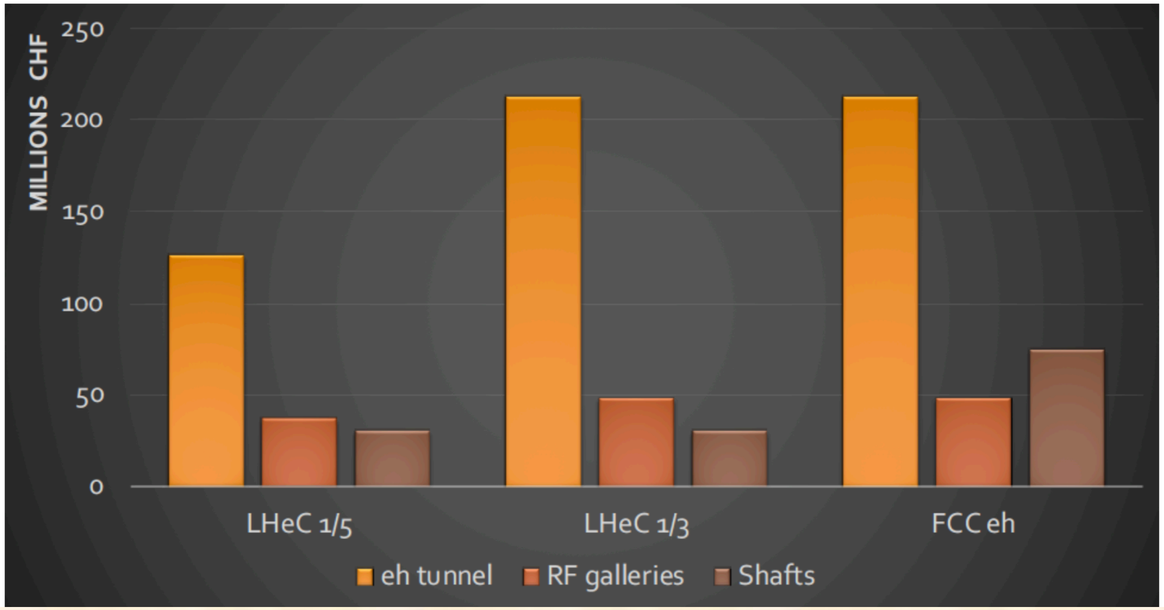


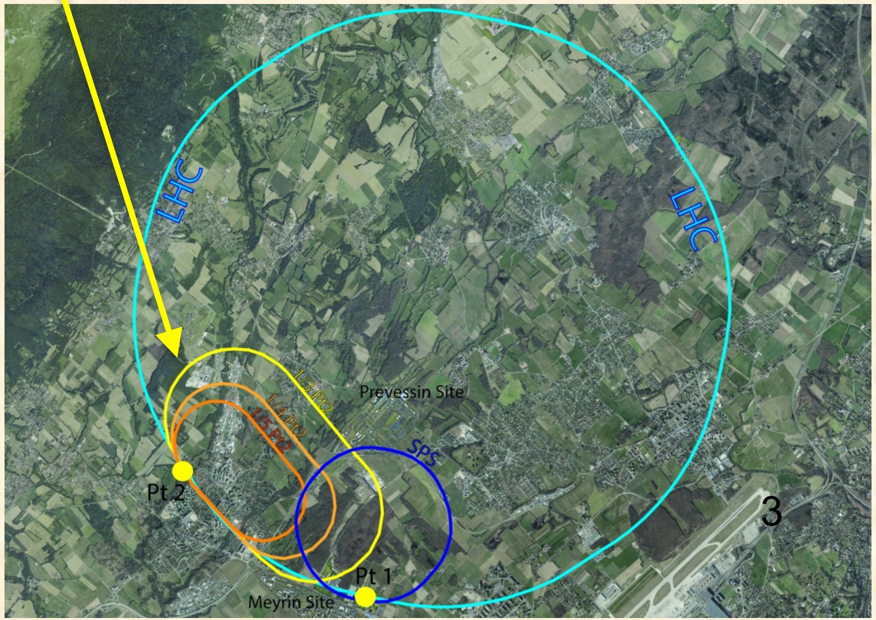
court. Kandinsky, “Circles in a Circle”, 1923 Philadelphia Museum of Art

Challenge: find balance between …

- *construction cost*
- *synchrotron light —> operational cost*
- *energy reach … up to 60 GeV electron energy*

Parameter	Unit	LHeC option			
		1/3 LHC	1/4 LHC	1/5 LHC	1/6 LHC
Circumference	m	9000	6750	5332	4500
Arc radius	$m \cdot 2\pi$	1058	737	536	427
Linac length	$m \cdot 2$	1025	909	829	758
Spreader and recombiner length	$m \cdot 4$	76	76	76	76
Electron energy	GeV	61.1	54.2	49.1	45.2



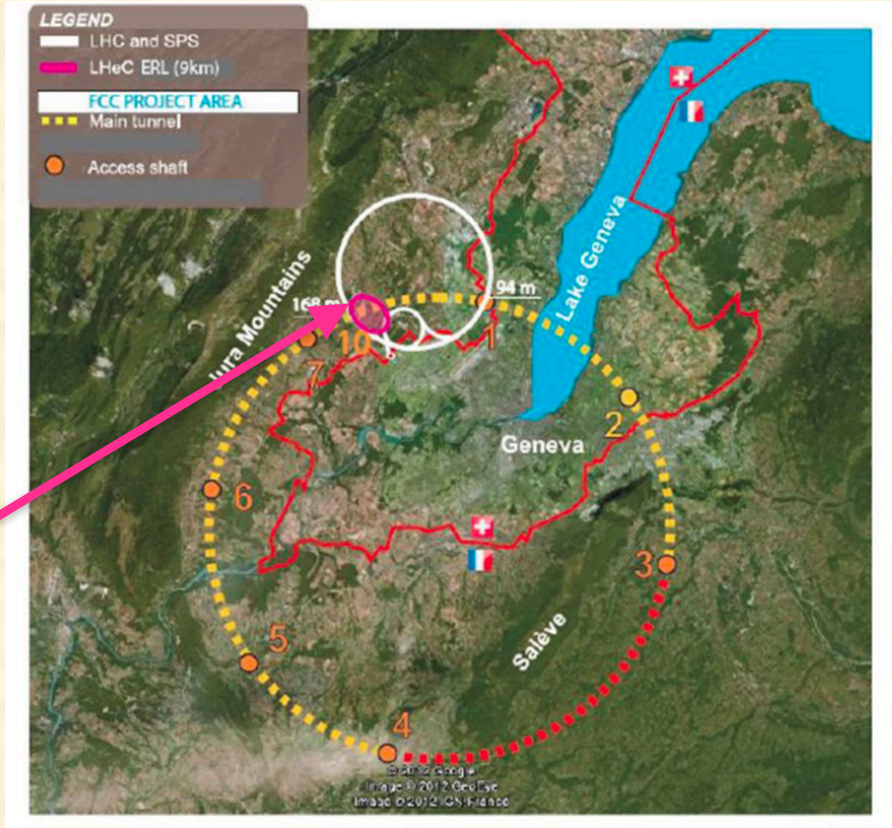


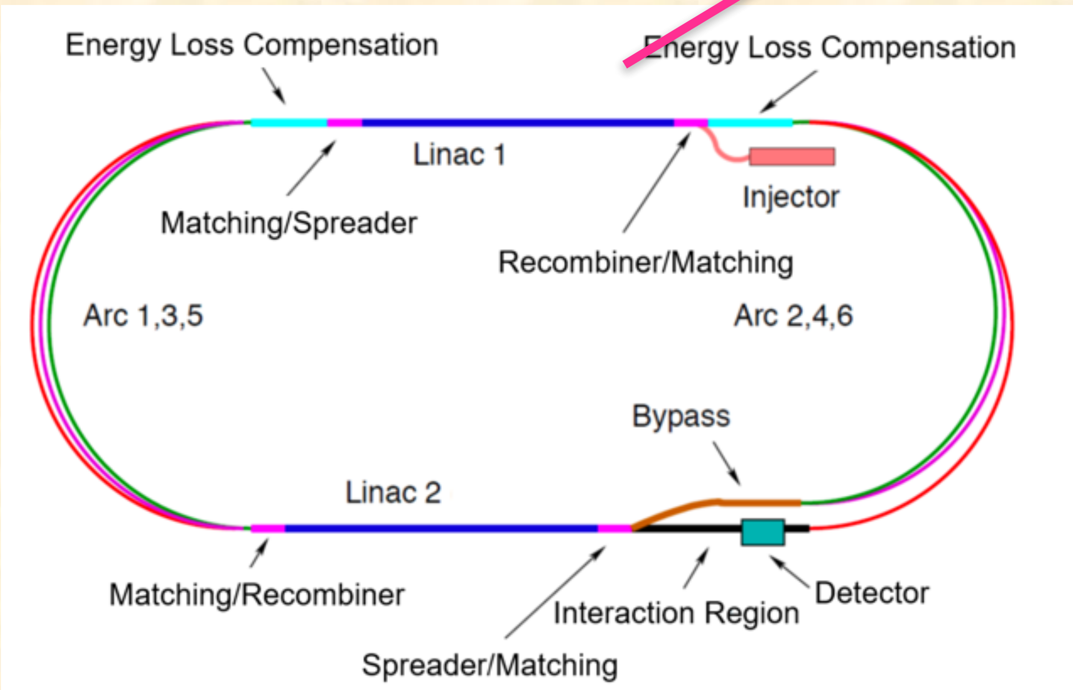
The FCC-eh Interaction Region:

— *Point L* — *(geological reasons)*

— *Unlike to the LHeC concept, we have more freedom in the IR layout.*

— *… and a larger straight section $L^*=23m$.*



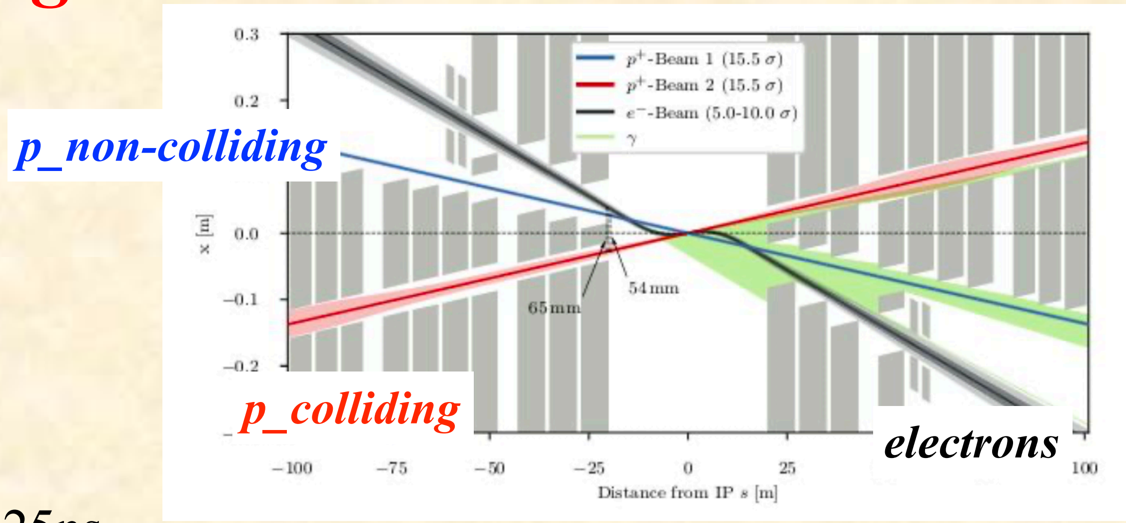


ERL

three turn racetrack Linac
800 MHz sc. Cavities
Circumference 9 km
Electron Energy 60 GeV

The FCC-eh Interaction Region:

It is a three beam problem



E. Cruz-Alaniz, FCC-week 2019

—> non colliding protons:

IP shifted wrt FCC by 1/4 * 25ns

—> 1.875 m

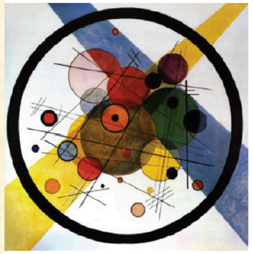
—> electron proton collisions:

optimised beam separation design for smallest synchrotron radiation load

protect / shield the particle detector
protect / shield the s.c. proton magnets

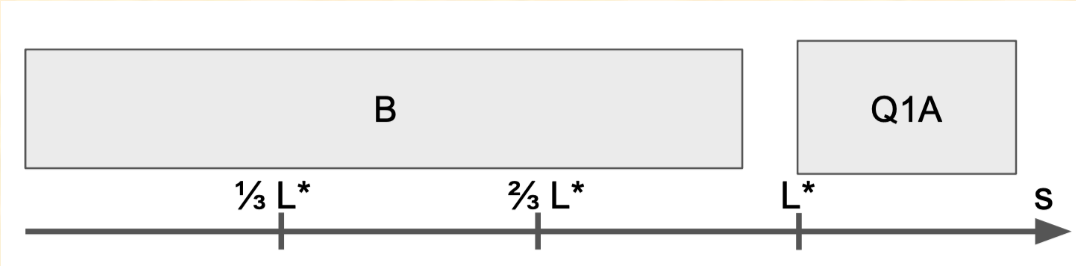
- combine mini-beta focusing & beam separation scheme
- reduce separation need
- optimise for smallest sy-light power & crit. energy

The Interaction Region:
beam separation via beam rigidity

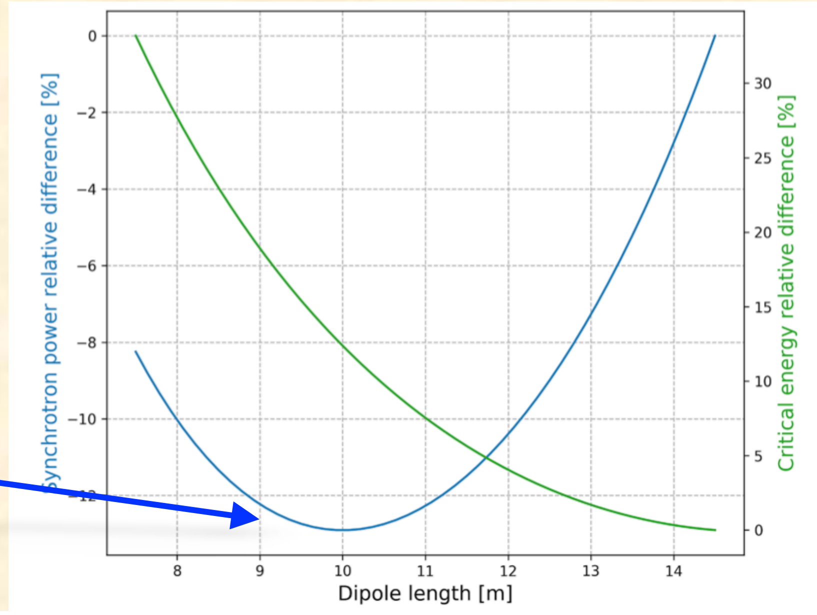


Optimisation for CDR of the LHeC

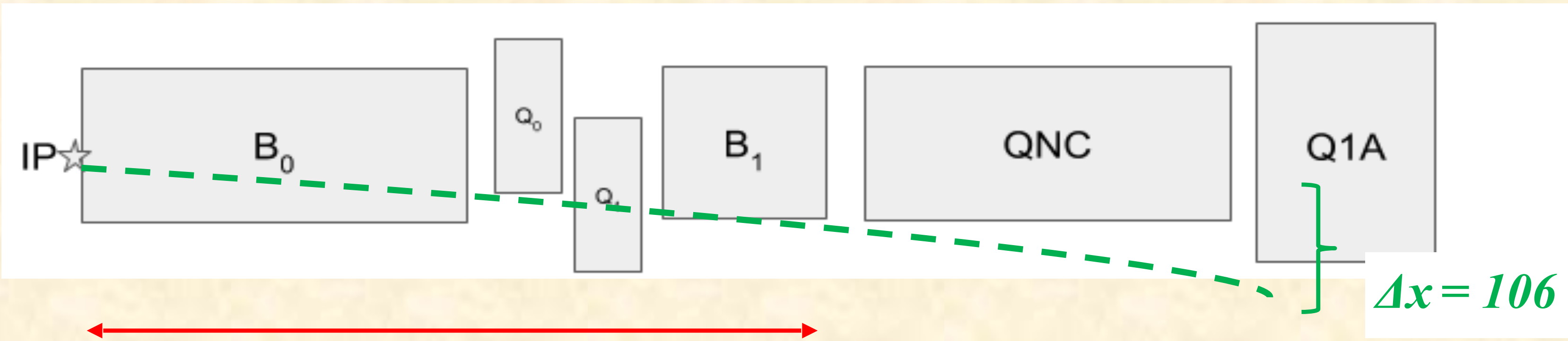
optimisation of separator dipole (R. Martin)



Minimum for Synchrotron Light power



Combining separation and mini-beta focusing scheme (K. André)

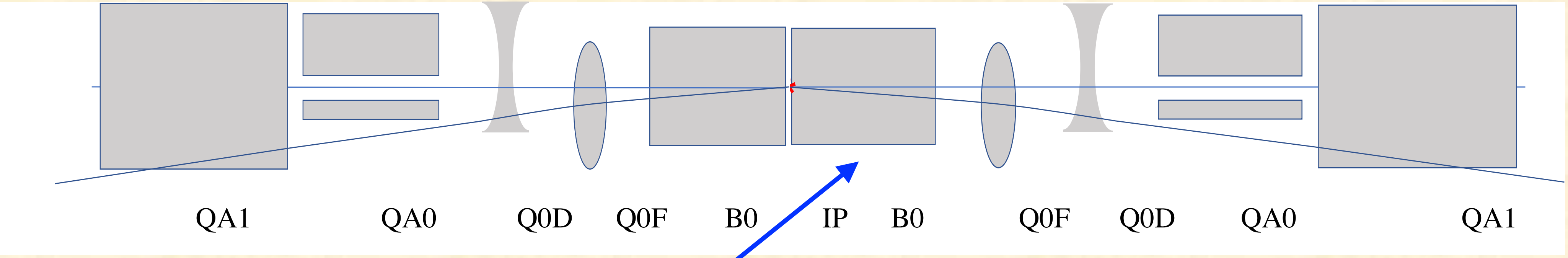


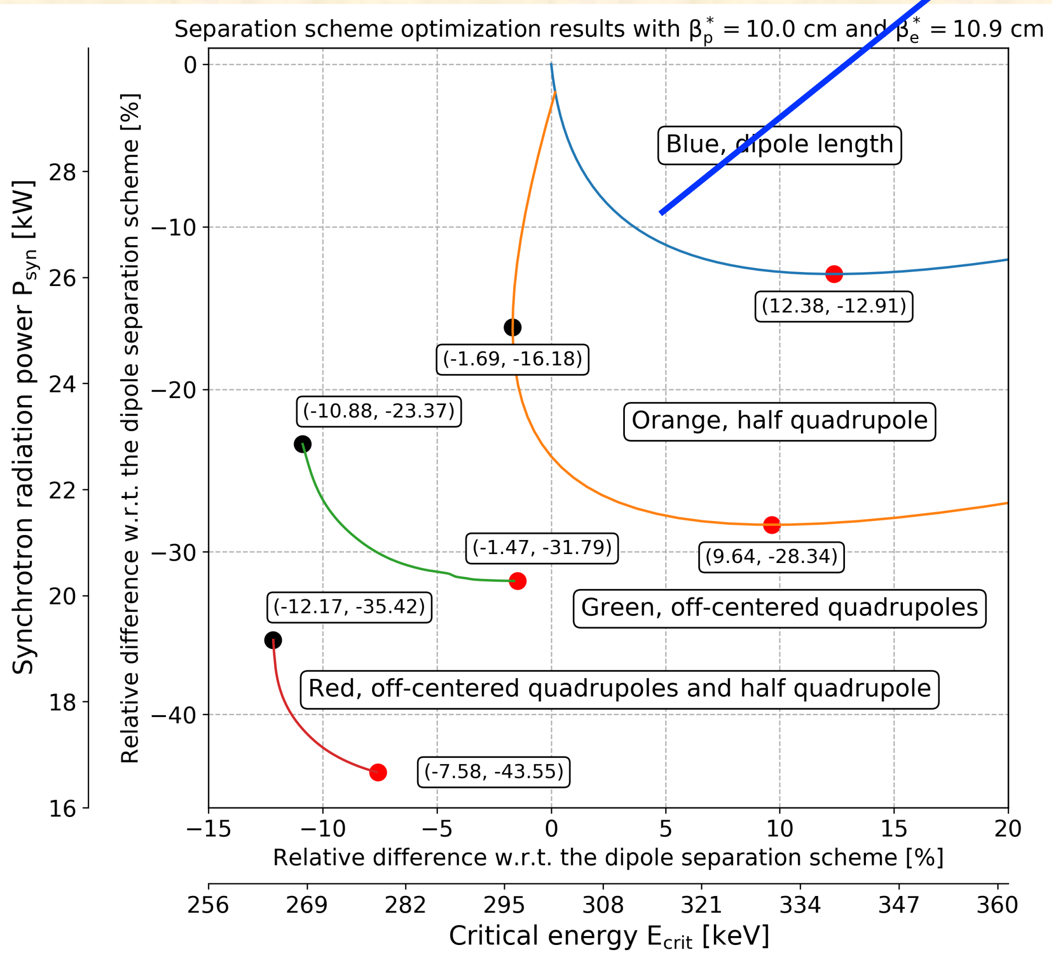
$\Delta x = 106$ mm

$L_B = 10$ m (B₀ & off-centre mini β quads)

The Interaction Region

Optimisation for CDR of the LHeC



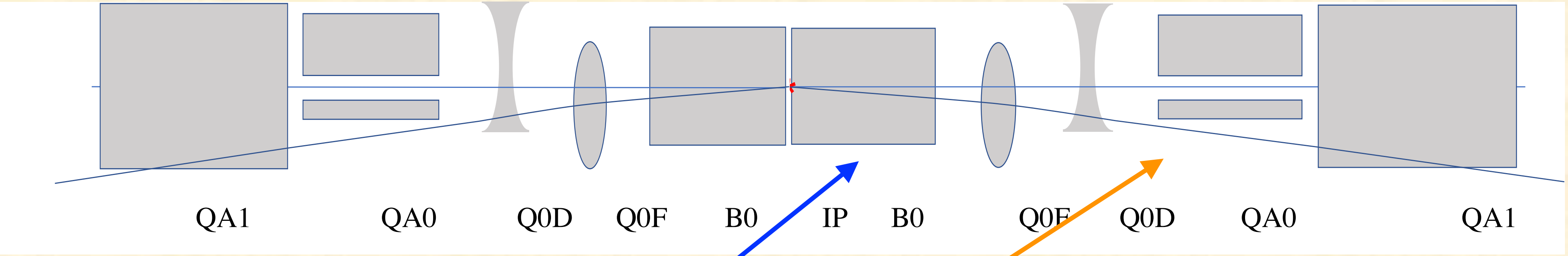


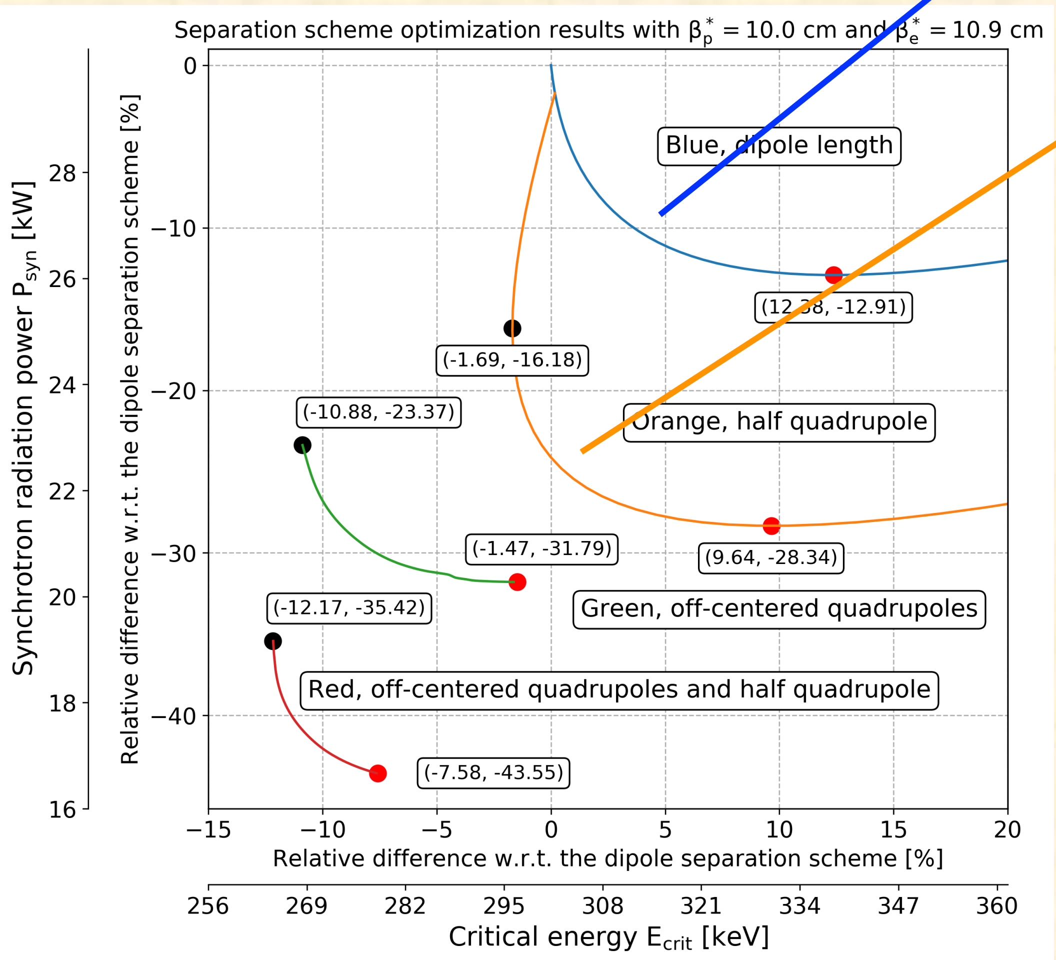
pure dipole separator
—> straight forward scheme

Kevin André

The Interaction Region

Optimisation for CDR of the LHeC





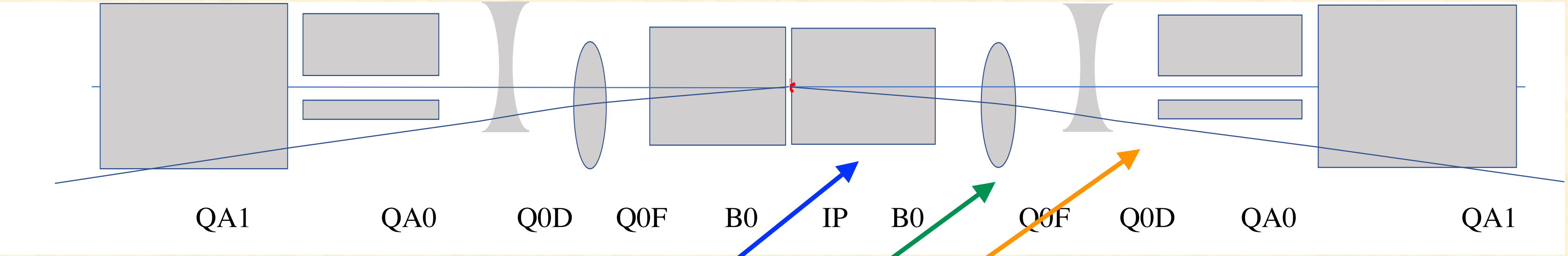
pure dipole separator
—> straight forward scheme

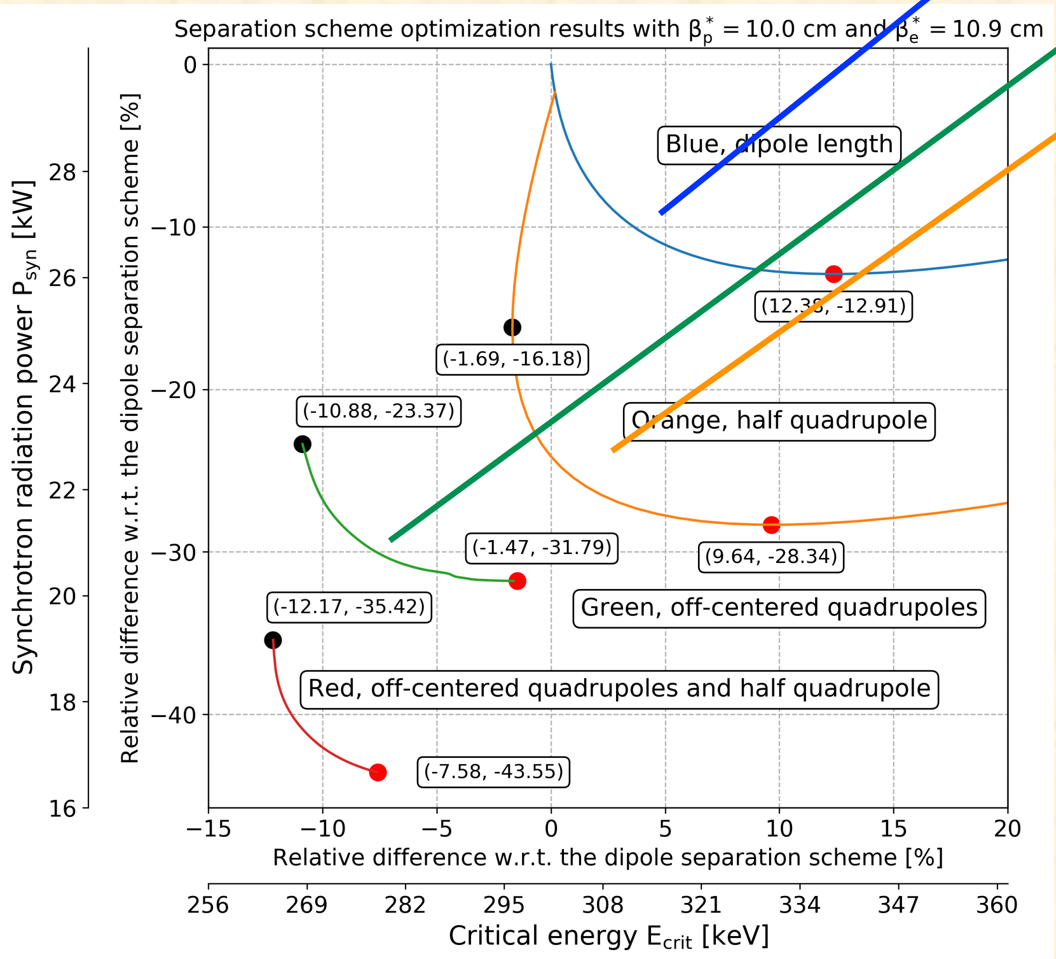
nc. half quadrupole
—> reduce separation need

Kevin André

The Interaction Region

Optimisation for CDR of the LHeC





pure dipole separator
—> straight forward scheme

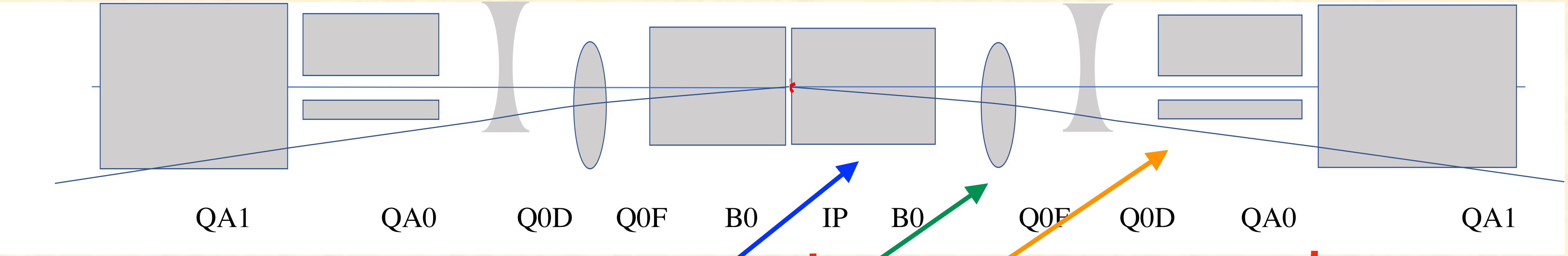
nc. half quadrupole
—> reduce separation need

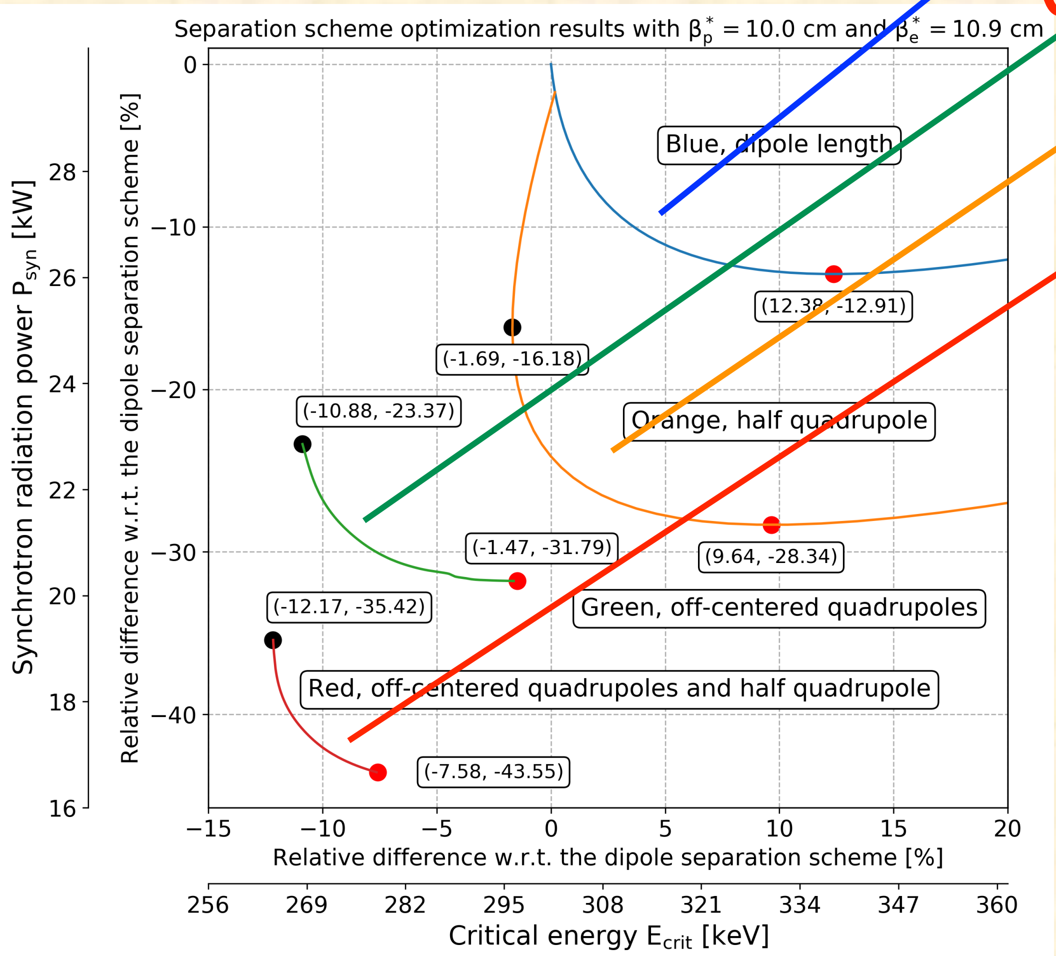
early focusing scheme for the electrons
—> reduce size of e-beam at L*

Kevin André

The Interaction Region

Optimisation for CDR of the LHeC





pure dipole separator
—> straight forward scheme

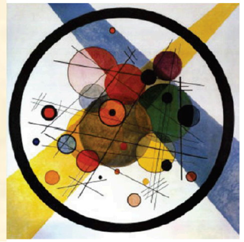
nc. half quadrupole
—> reduce separation need

early focusing scheme for the electrons
—> reduce size of e-beam at L*

off centre quads for early beam separation
—> keep 1/ρ = const.

Kevin André

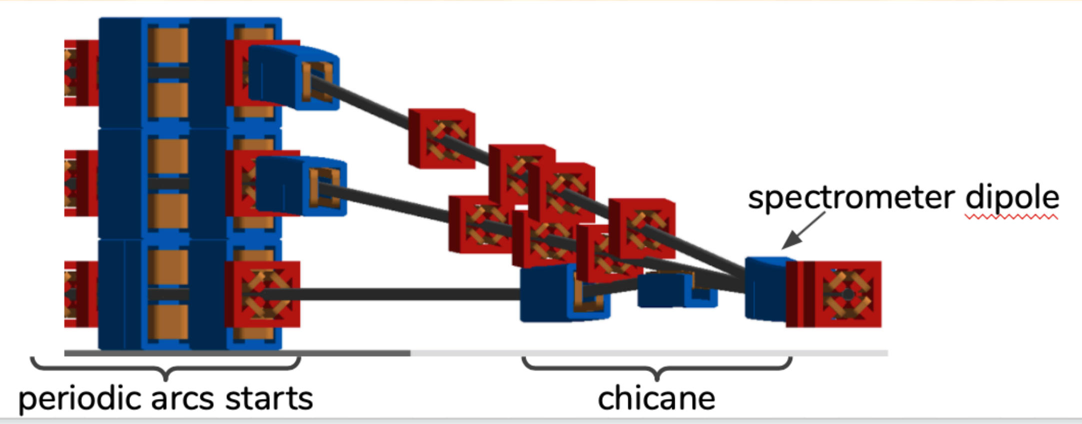
The Interaction Region: Electron Beam Spreader / Re-Combiner



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

***Challenge:* minimise emittance dilution … in the vertical plane** —> $\mathcal{H}_y$

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

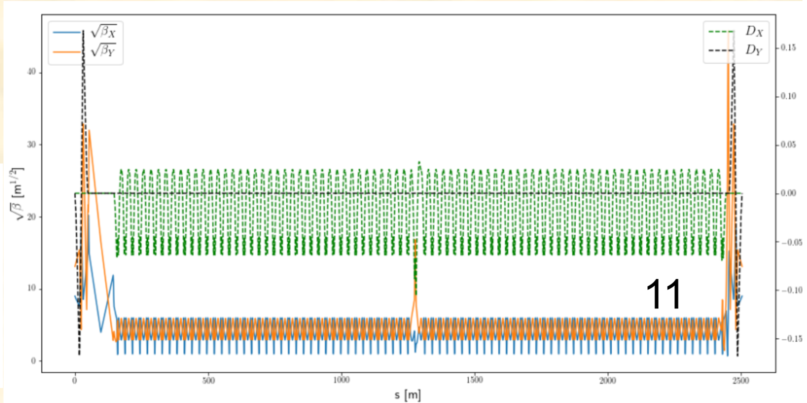


$$\Delta\epsilon = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^5}{\rho^2}$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}$$

$$H = \gamma \cdot D^2 + 2\alpha\, DD' + \beta \cdot D'^2$$

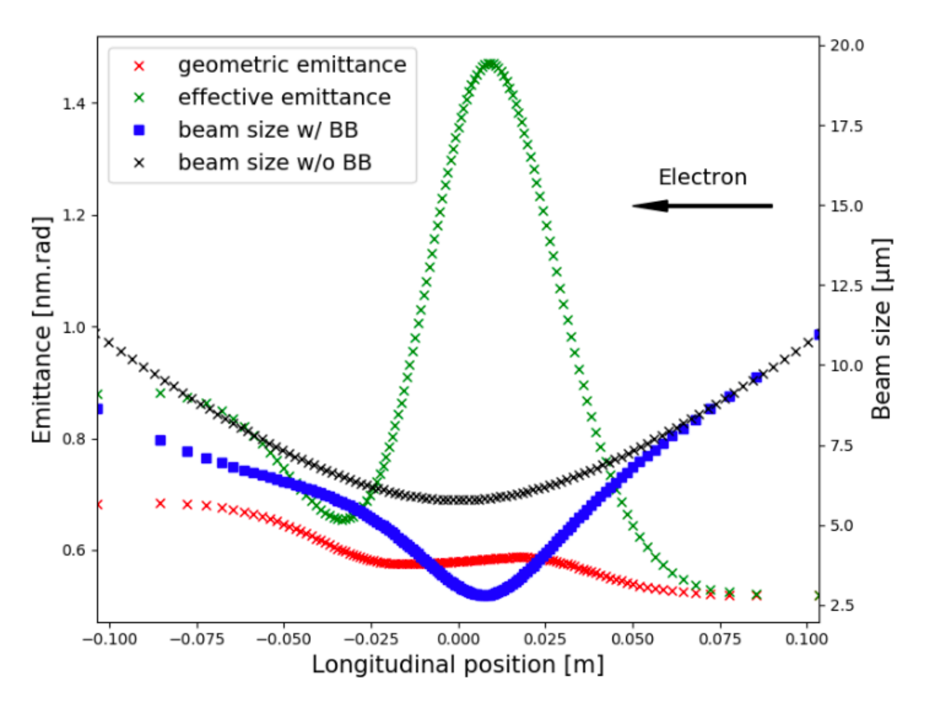
ERL beam optics: spreader, dispersion suppressor arc structure & re-combiner



Beam-Beam Interaction:

defines the initial conditions for the ERL front-to-end tracking

Beam Beam Force: Optimisation of Optics Parameters (Kevin André)

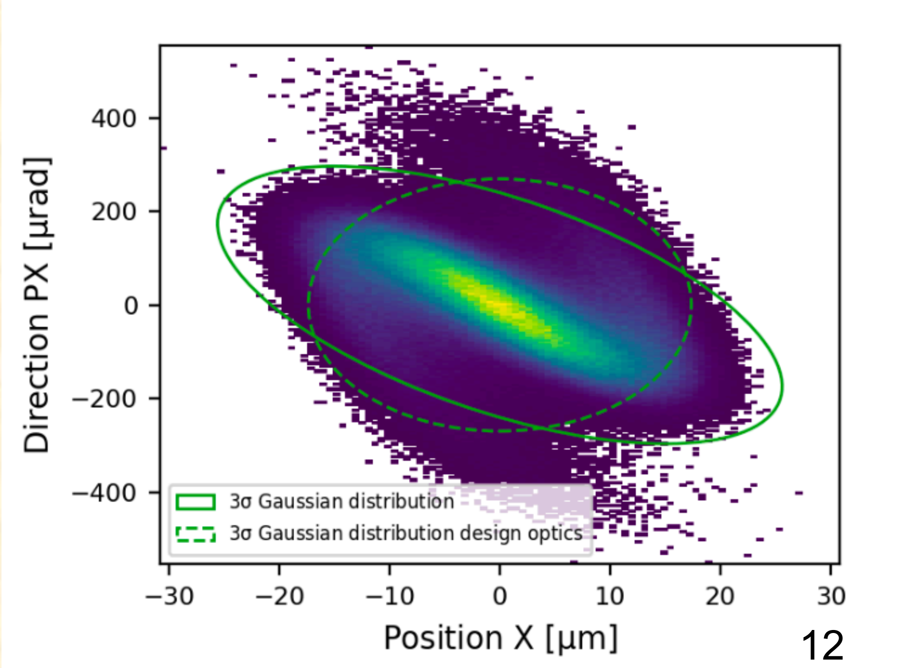


beam size at IP

no bb-effect / with bb-effect
beam beam force used to
enhance luminosity

phase space diagram at IP incl. beam-beam-effect

defines starting conditions for
front-to-end simulation



The Interaction Region: FCC-eh Proton Optics

Tech Report CERN-ACC-2017-0019

Parameter	LHeC CDR	FCC-he
E_P [TeV]	7	50
γ_P	7460	53300
E_e [GeV]	60	60
$\sqrt{(s)}$ [TeV]	1.3	3.5
bunch spacing [ns]	25	25
protons per bunch [10^{11}]	1.7	1
$\gamma_p \epsilon_p$ [µm]	3.7	2.2
electrons per bunch [10^9]	1	3.0
electron current [µA]	6.4	20
IP beta function β^* [m]	0.1	$\boxed{0.15}$
hourglass factor H_{geom}	0.9	0.9
pinch factor $H_{b\text{-}b}$	1.3	1.3
proton filling H_{coll}	0.8	0.8
luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	1	15

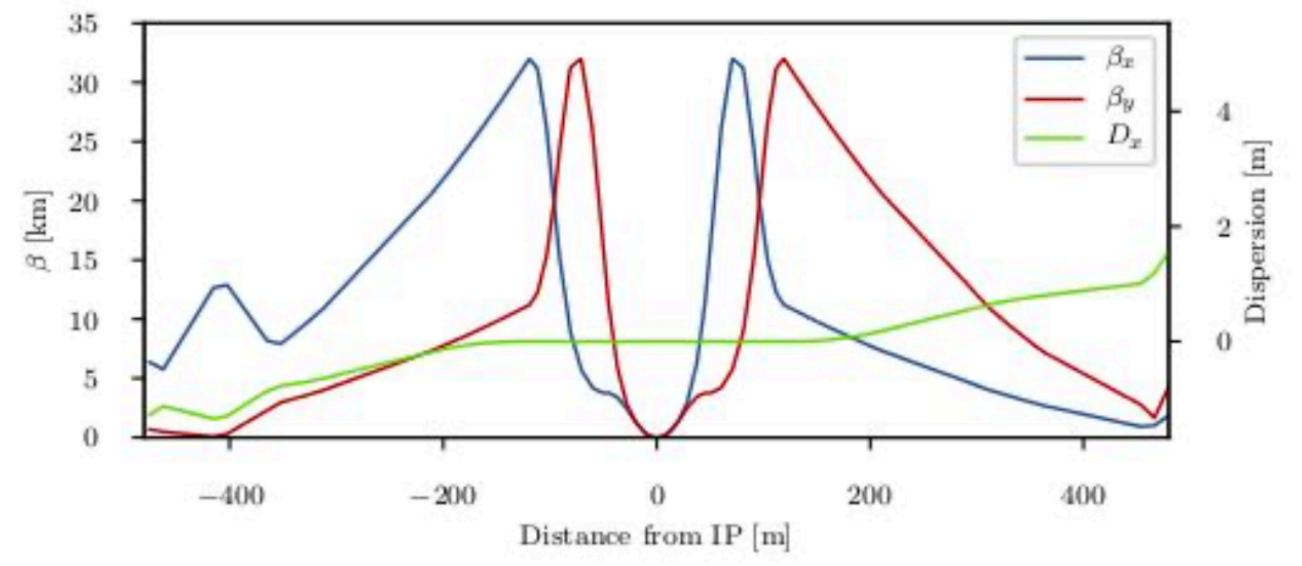
Goal: $\gamma\epsilon_e = 10\,\mu\text{m}$

Roman Martin:
p-optics reach down to β = 30 cm*

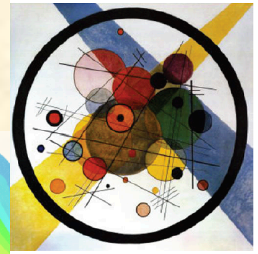
Try β*=0.3 m first

Strict boundary condition:
matched beam size request determines the p-beam size

$$\sigma_x^*(e) = \sigma_x^*(p),\ \sigma_y{}^*(e) = \sigma_y^*(p)$$

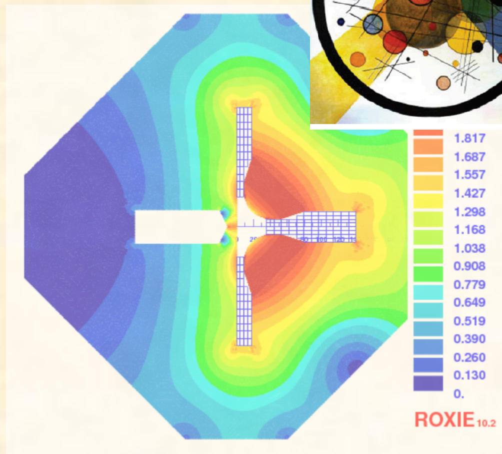


The Challenges:



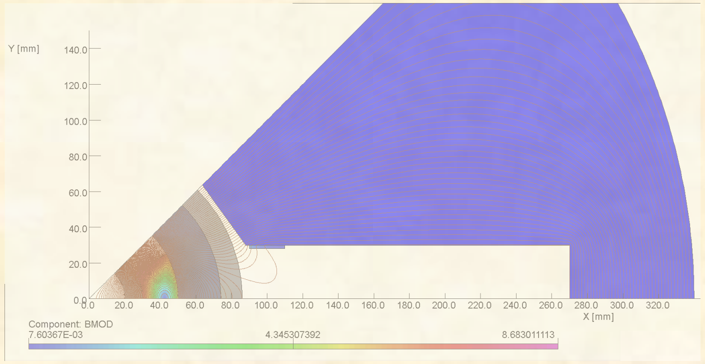
Design for prototypes of special machine elements

- *half-quadrupole in IR*
- *spectrometer dipole in spreader*



Synchrotron light power in arcs

- *absorber design*
- *cooling*



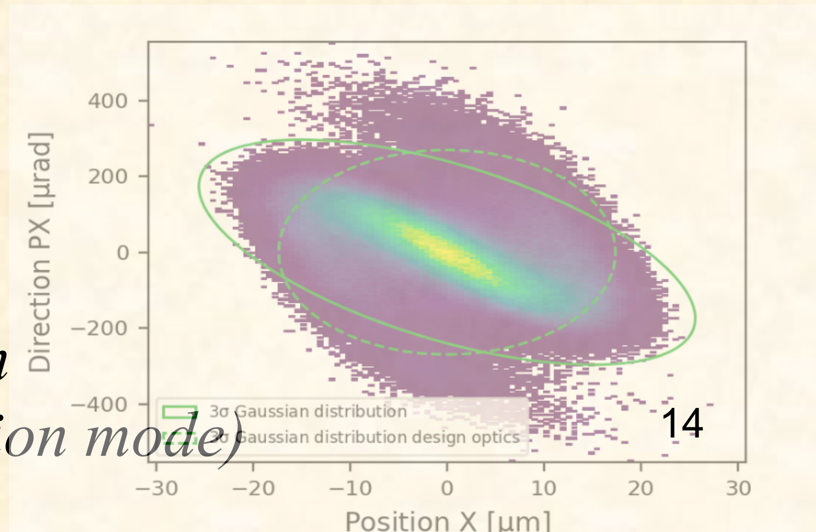
Q1a

Machine Detector Interface

- *geometry of synchrotron light fan*
- *absorber design*
- *protection of acc. magnets*

Front-to-End tracking ✓

- *ERL performance / emittance preservation (including beam-beam effect & decelaration mode)*



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 (—> ρ)

β^* is determined by L^*

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

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

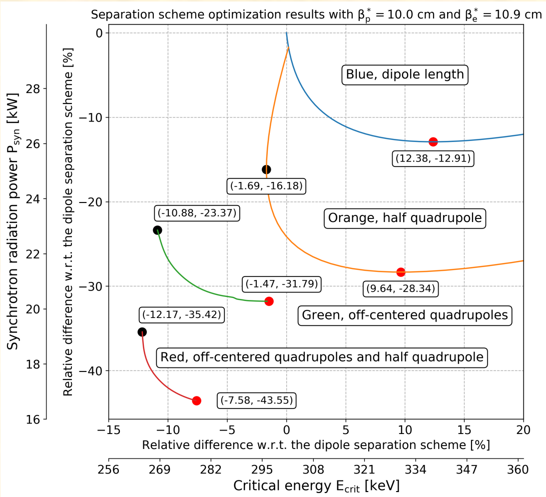
—> determines circumference and beam energy

keep the beams matched at IP

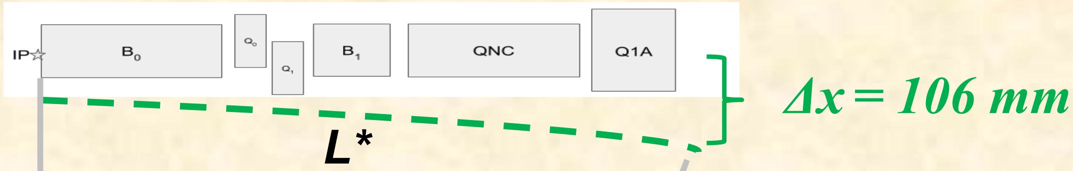
$$\sigma_x^*(e) = \sigma_x^*(p) \qquad \sigma_y^*(e) = \sigma_y^*(p)$$

and finally … optimise luminosity

Conclusion:
a scaled FCC-eh Parameter List



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



ρ

ρ

LHeC —> FCC-eh:

Increasing L — > increasing ρ*

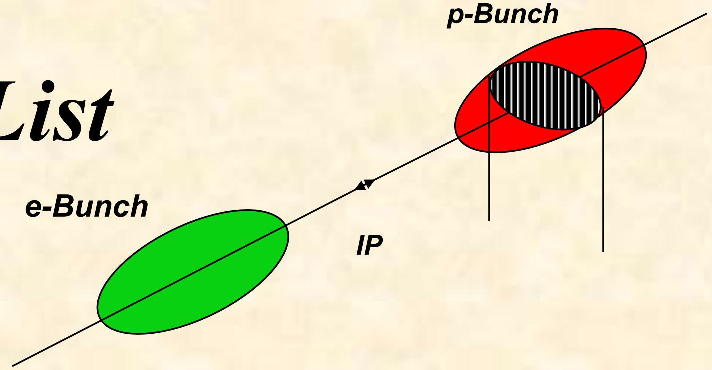
L^* = 15 m — > 23 m

E_{crit} = 260 keV —> 170 keV, P_γ = 17 kW —> 7 kW

E_{beam} = 50 GeV —>60 GeV

E_{crit} = 170 keV —> 293 keV, P_γ = 7 kW —> 14.4 kW

Conclusion:
a scaled FCC-eh Parameter List



Status, scaled from LHeC to FCC-eh parameters:

$N_e = 3.1 * 10^9$
$\varepsilon_{en} = 30\ \mu m$
$\varepsilon_{e0} = 2.5 * 10^{-10} m$
$\beta_x^* = 7.5\ cm$

$\sigma_e^* = 4.3\ \mu m$

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

matched conditions:

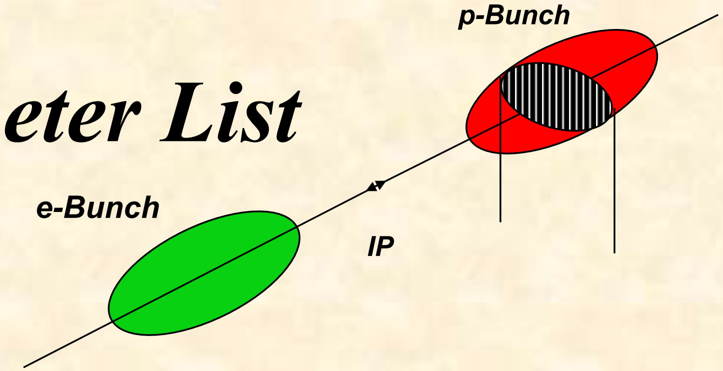
$N_p = 1.0 * 10^{11}$
$\varepsilon_{pn} = 2.2\ \mu m$
$\varepsilon_{p0} = 4.1 * 10^{-11} m$
$\beta_x^* = 46\ cm$

$\sigma_p^* = 4.3\ \mu m$

$$L = 5.2 * 10^{33} cm^{-2} s^{-1}$$

Push for maximum luminosity:
—> ***Minimise emittance of electron beam***
—> ***Circumference of ERL part***

Conclusion:
an *optimistic* FCC-eh Parameter List



Status, scaled from LHeC to FCC-eh parameters:

$N_e = 3.1 * 10^9$

$\varepsilon_{en} = 10\ \mu m$

$\varepsilon_{e0} = 0.8 * 10^{-10} m$

$\beta_x^* = 7.5\ cm$

$\sigma_e^* = 2.5\ \mu m$

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

matched conditions:

$N_p = 1.0 * 10^{11}$

$\varepsilon_{pn} = 2.2\ \mu m$

$\varepsilon_{p0} = 4.1 * 10^{-11} m$

$\beta_x^* = 15\ cm$

$\sigma_p^* = 2.5\ \mu m$

$$L = 1.5 * 10^{34} cm^{-2} s^{-1}$$

Push for maximum luminosity:

—> ***Minimise emittance of electron beam***

—> ***Circumference of ERL part***

$L \approx 1 * 10^{34} cm^{-2} s^{-1}$ ***in reach.***

Merci

Conclusion:
a scaled FCC-eh Parameter List

ERL tracking injection → dump - with BB

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	

1/4	unit	Injection	Until IP	Post IP	Dump	Energy recovery
εx, εy	um.rad	22.7, 28.6	30.0, 30.0	46.4, 44.7	478.3, 372..2	
dpp	%	0.02	0.0290	0.0290	4.743	96.7 %
Transmission	%	-	100	100	98.89	

1/5	unit	Injection	Until IP	Post IP	Dump	Energy recovery
εx, εy	um.rad	15.1, 28.5	30.0, 30.0	47.7, 47.5	412.2, 1173.8	
dpp	%	0.01	0.0407	0.0407	6.609	95.4 %
Transmission	%	-	100	100	98.4	

Front to end tracking:
emittance evolution in the ERL

Kevin André

Front to end tracking:
norm emittance during acceleration,
beam-beam and de-celeration