

# *Energy Frontier DIS at CERN LHeC and FCC-eh*

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

*Update of the 2012 CDR  
on arXiv today !*



The Large Hadron-Electron Collider at the HL-LHC

LHeC Study Group



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

To be submitted to J.Phys. G

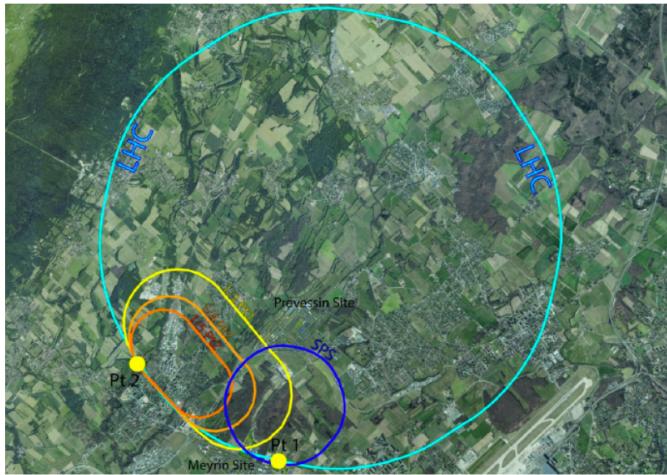
# LHeC / FCC-eh / PERLE

## Energy Recovery Linacs towards high resolution DIS



### LHeC

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



50 x 7000 GeV<sup>2</sup>: 1.2 TeV ep collider

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

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

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

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

CERN-ACC-Note-2020-0002 → arXiv (July)

### PERLE

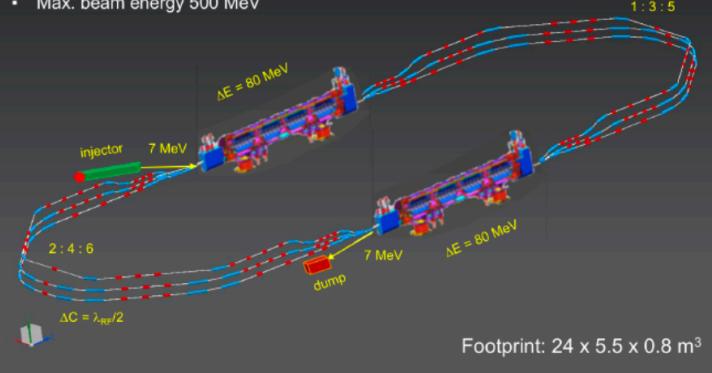
Powerful ERL for Experiments @ Orsay  
CDR: 1705.08783 J.Phys.G  
CERN-ACC-Note-2018-0086 (ESSP)

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

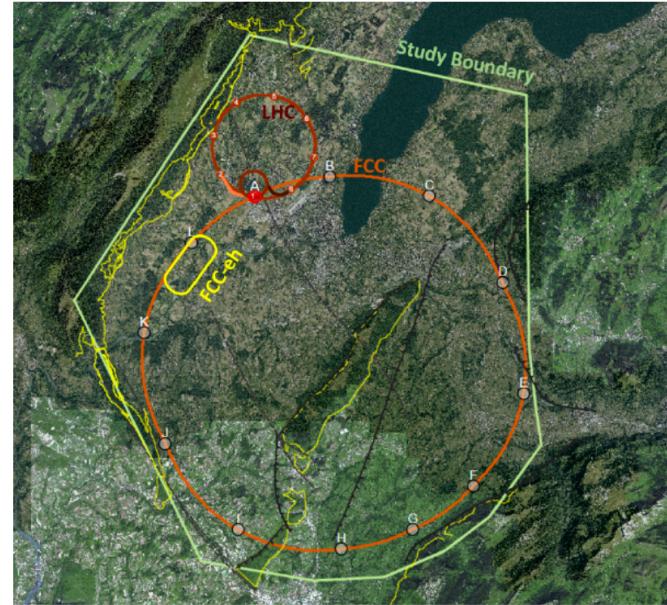
LHeC ERL Parameters and Configuration  
 $I_e=20\text{mA}$ , 802 MHz SRF, 3 turns →  
 $E_e=500\text{ MeV}$  → first 10 MW ERL facility

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

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV



### FCC-eh



60 x 50000 GeV<sup>2</sup>: 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  
2

Future CERN Colliders: 1810.13022 Bordry+

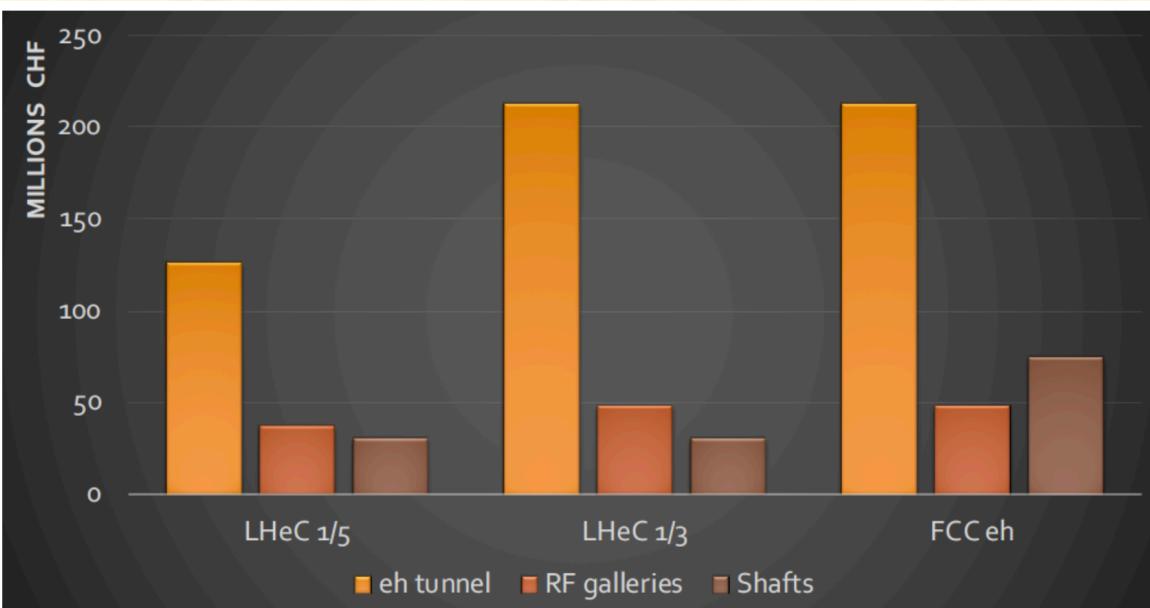
# The LHeC: Circumference



**Challenge: find balance between ...**

- construction cost
- synchrotron light → operational cost
- energy reach

| 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 recombinder length | $m \cdot 4$    | 76          | 76      | 76      | 76      |
| Electron energy                 | GeV            | 61.1        | 54.2    | 49.1    | 45.2    |



# LHeC Layout

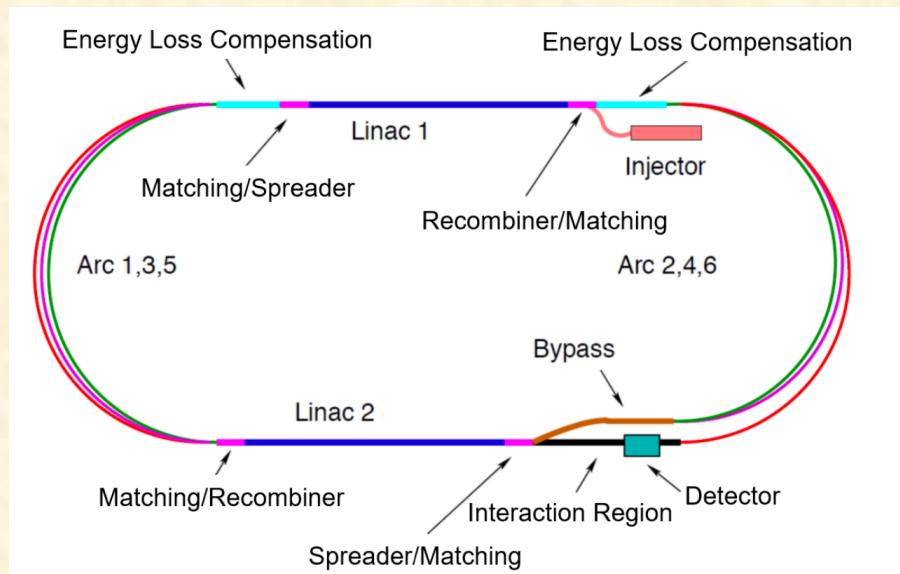
*recirculating energy recovery electron linac  
colliding with HL-LHC protons*



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

*Parameters pre-defined by HL-LHC*

$$L = \frac{N_e N_p n_p f_{rev} \gamma_p}{4\pi \epsilon_p \beta^*} \cdot \prod_{i=1}^3 H_i,$$



$N_e$       *number of electrons per bunch*

$N_p$       *number of protons per bunch*

$n_p * f_{ref}$  *collision frequency —> bunch distance*

$\epsilon_p * \beta^*$  *beam size at IP*

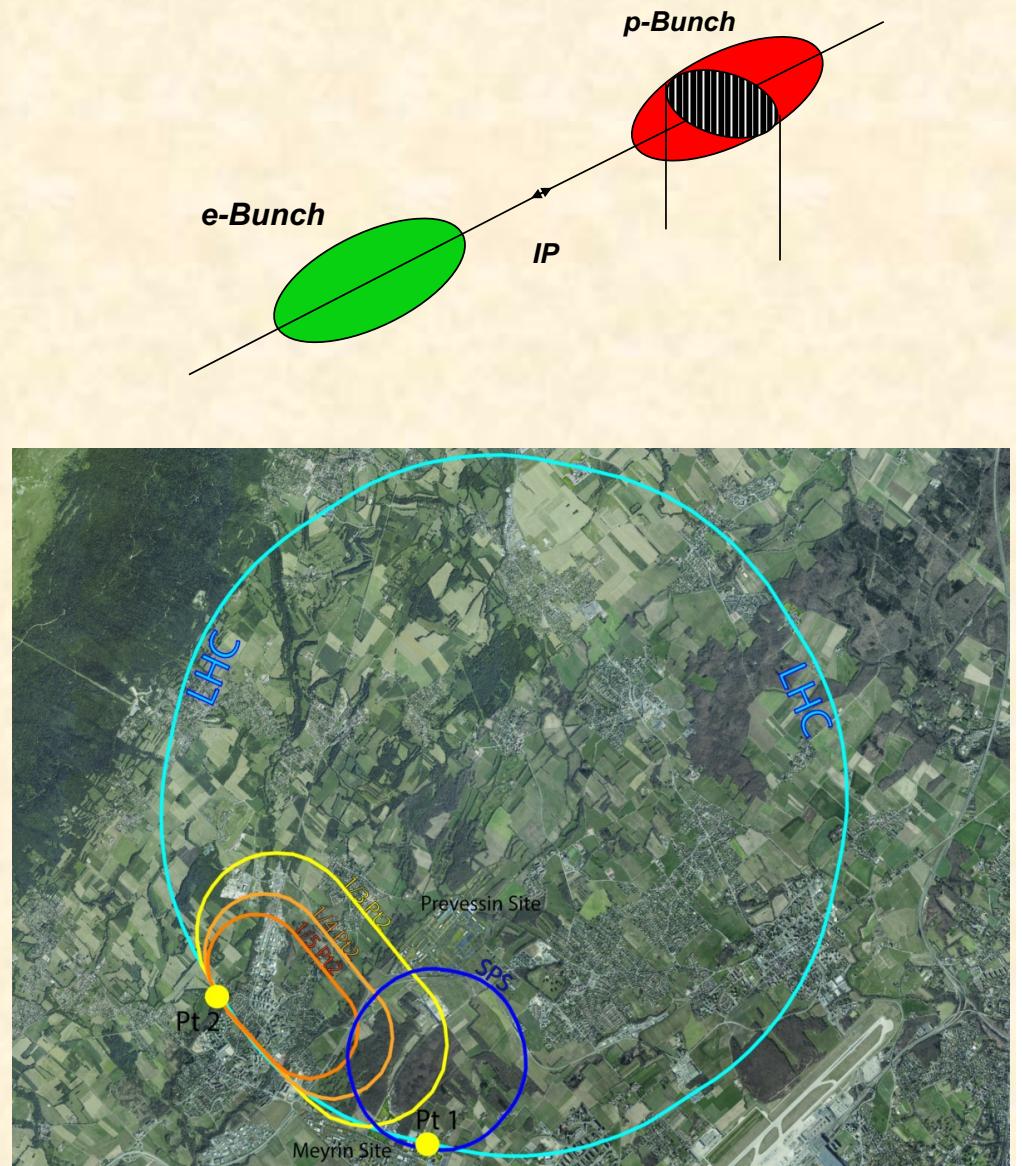
$$\prod_{i=1}^3 H_i \approx 1, \quad H_i = \text{hourglass factor} \\ \text{pinch effect} \\ \text{fill factor}$$

# LHeC Main Parameter List

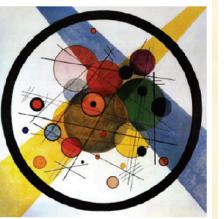


|                        |                                     |                  |
|------------------------|-------------------------------------|------------------|
| $E_e$                  | GeV                                 | 50               |
| $E_p$                  | TeV                                 | 7                |
| $N_e$                  | $10^9$                              | 3.1              |
| $I_e$                  | mA                                  | 20               |
| $N_p$                  | $10^{11}$                           | 2.2              |
| $\beta_p$              | cm                                  | 7                |
| $\epsilon_p$           | $\mu\text{m}$                       | 2.5              |
| $n_p * f_{\text{ref}}$ | ns                                  | 25               |
| $L$                    | $\text{cm}^{-2}$<br>$\text{s}^{-2}$ | 9 *<br>$10^{33}$ |

*Circumference ... 1/5 ... 1/4 ... 1/3 ... LHC*



# LHeC Main Parameters



**$E = 50 \text{ GeV}$**

**$I = 20 \text{ mA}$**

**$C_0 = 5332 \text{ m}$**

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

| Parameter  | Unit          | Value          |
|--|---------------|----------------|
| Injector energy                                    | GeV           | 0.5            |
| Total number of linacs                             |               | 2              |
| Number of acceleration passes                      |               | 3              |
| Maximum electron energy                            | GeV           | 49.19          |
| Bunch charge                                       | pC            | 499            |
| Bunch spacing                                      | ns            | 24.95          |
| Electron current                                   | mA            | 20             |
| Transverse normalized emittance                    | $\mu\text{m}$ | 30             |
| Total energy gain per linac                        | GeV           | 8.114          |
| Frequency  | MHz           | 801.58         |
| Acceleration gradient                              | MV/m          | 19.73          |
| Cavity iris diameter                               | mm            | 130            |
| Number of cells per cavity                         |               | 5              |
| Cavity length (active/real estate)                 | m             | 0.918/1.5      |
| Cavities per cryomodule                            |               | 4              |
| Cryomodule length                                  | m             | 7              |
| Length of 4-CM unit                                | m             | 29.6           |
| Acceleration per cryomodule (4-CM unit)            | MeV           | 289.8          |
| Total number of cryomodules (4-CM units) per linac |               | 112 (28)       |
| Total linac length (with spr/rec matching)         | m             | 828.8 (980.8)  |
| Return arc radius (length)                         | m             | 536.4 (1685.1) |
| Total ERL length                                   | km            | 5.332          |

( remember: SPS = 6911 m )

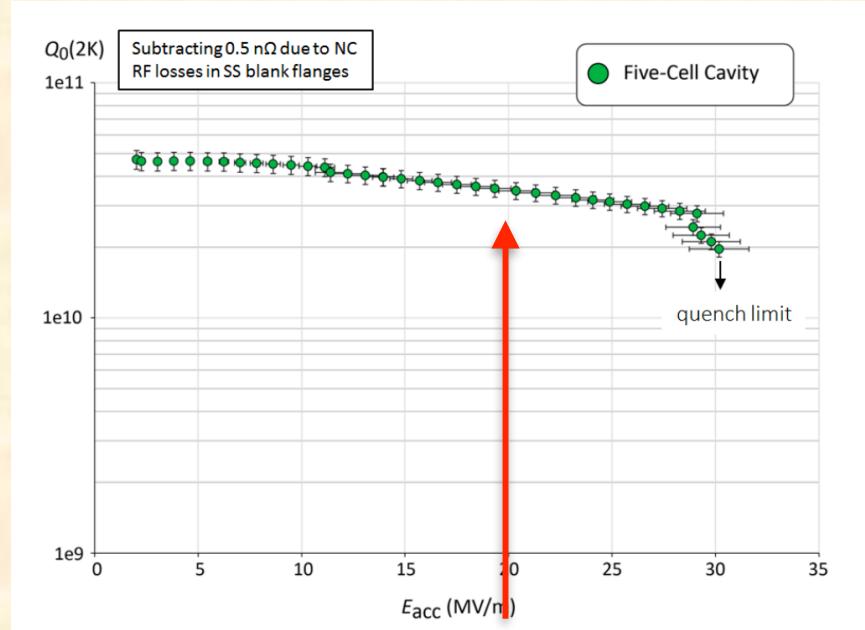
# The LHeC Modules: Linacs- RF



800 MHz 5 cell cavity nominal acceleration gradient: 19.73 MV/m

| Parameter                       | Unit | Value  |
|---------------------------------|------|--------|
| Frequency                       | MHz  | 801.58 |
| Bunch charge                    | pC   | 499    |
| Bunch spacing                   | ns   | 24.95  |
| Electron current                | mA   | 20     |
| Injector energy                 | MeV  | 500    |
| Gradient                        | MV/m | 19.73  |
| Cavity length, active           | m    | 0.918  |
| Cavity length, flange-to-flange | m    | 1.5    |
| Cavities per cryomodule         |      | 4      |
| Length of cryomodule            | m    | 7      |
| Acceleration per cryomodule     | MeV  | 72.45  |
| Total number of cryomodules     |      | 112    |
| Acceleration energy per pass    | GeV  | 8.1    |

896 cavities (802 MHz),  
< 10% of ILC needs



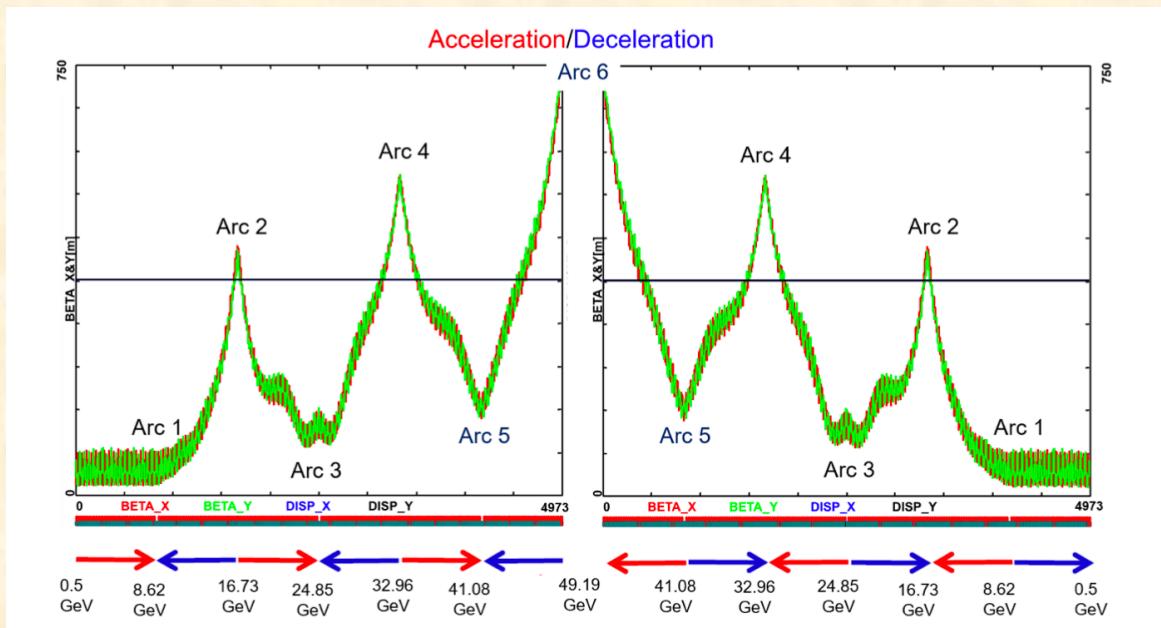
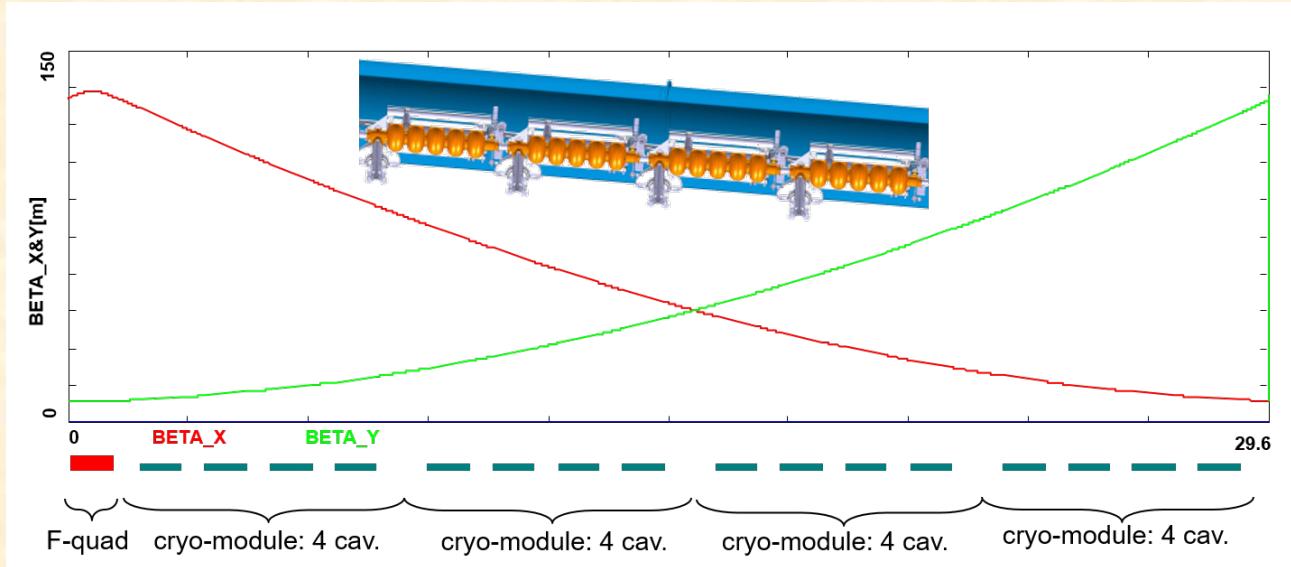
CERN-JLAB collaboration,  
Q0 vs gradient test measurement

Linac length: 828.8m,  
Per linac: 28 units of 4 cryomodules ,  
Each cryo module contains four 5-cell cavities,  
Energy gain per Linac: 8.114 GV.  
Challenge: **large beam current (up to 120 mA).**

# The LHeC Modules: Linacs,



Linac length: 828.8m,  
130° FODO structure  
2 x 16 cavities per cell



matched beam optics for  
the three energy steps  
in acc & decal. mode

# The LHeC Modules: Arcs



**Challenge: Emittance preservation highest priority**

Transverse emittance dilution = defined by the emittance dispersion function,  $\mathcal{H}$ , of the arcs

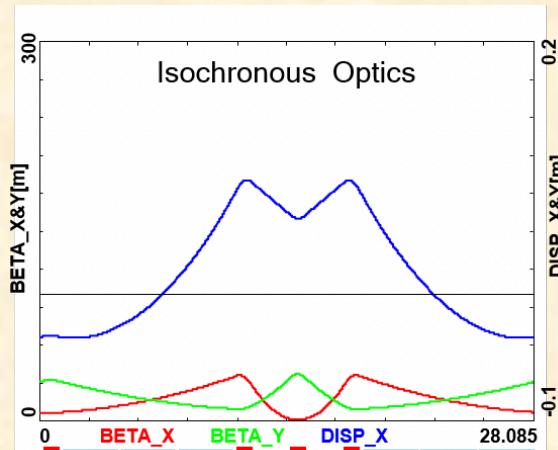
$$\Delta\epsilon = \frac{2\pi}{3} C_q r_0 \langle H \rangle \frac{\gamma^5}{\rho^2}$$

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

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

low energy: Arc 1 ... 3 :

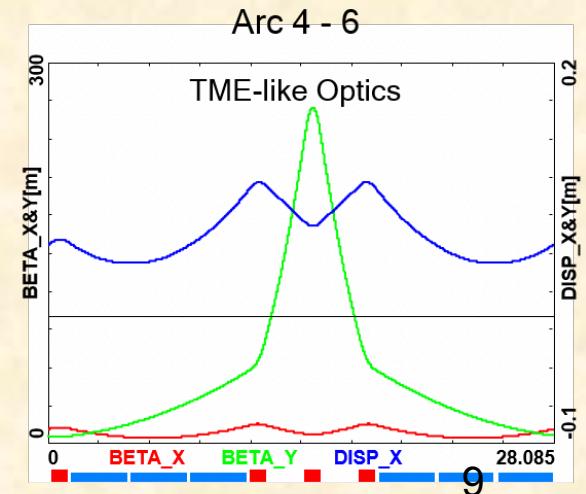
compensate for the bunch elongation  
 → *isochronous optics*.



$$\langle H \rangle = 3.62 \times 10^{-3} \text{ m}$$

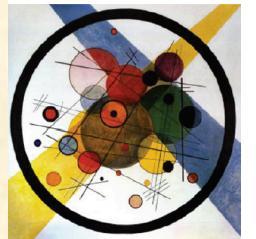
high energy: Arc 4 ... 6:

reduce quantum effects of synchr. light  
 → *TME (theor. minimum, emittance) lattice*



$$\langle H \rangle = 0.59 \times 10^{-3} \text{ m}$$

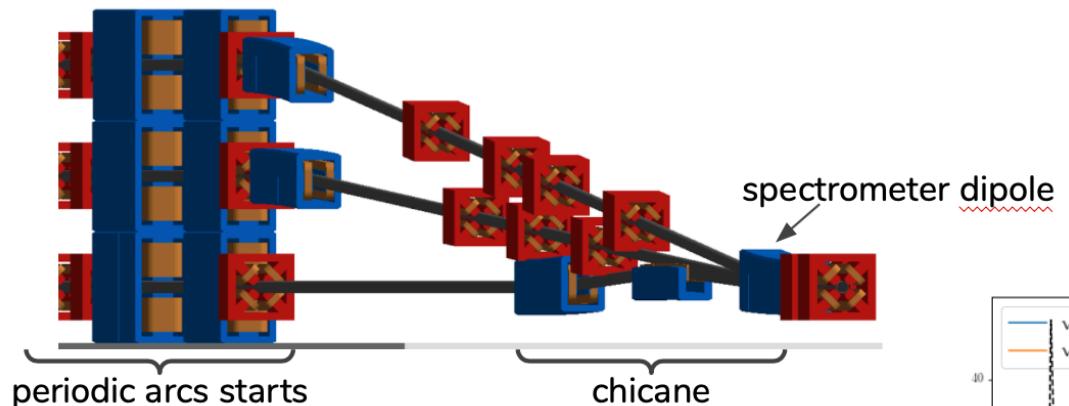
# The LHeC Modules: Spreader / Re-Combiner



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

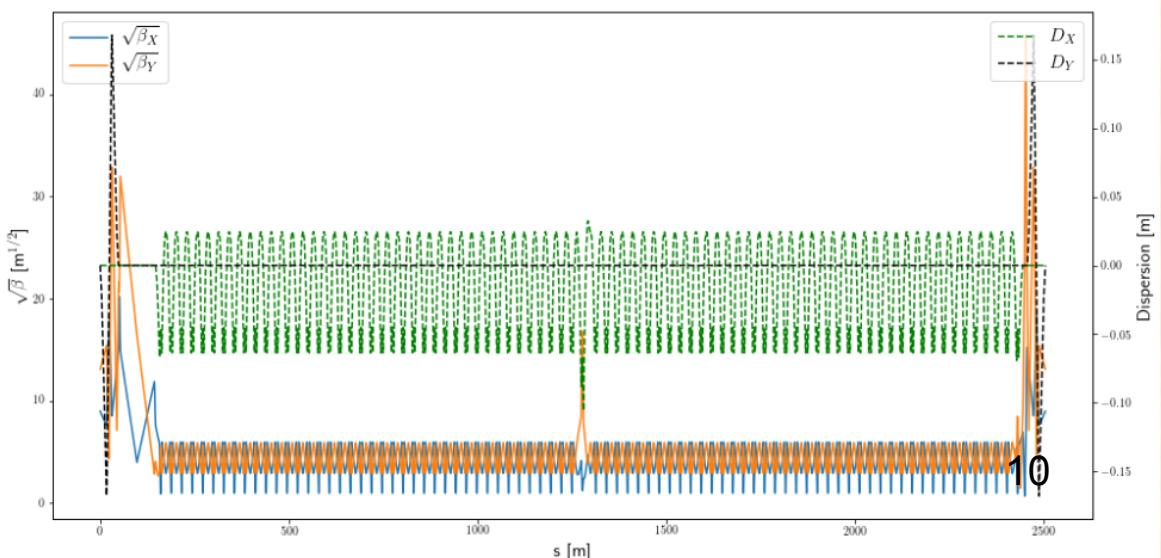
**Challenge:** minimise emittance dilution ... in the vertical plane  $\rightarrow \mathcal{H}_y$

- Non-dispersive (i.e. “achromatic”) vertical deflection system
- Gently matched beam optics between Linacs and Arcs
- Optimised for smallest impact on  $\varepsilon_y$



one-step spreader design

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



# The LHeC Modules:

## Synchrotron Light & Emittances,

(D. Clayton, D. Hanstock, Liverpool Student Internship at CERN)



Damping parameter

$$\mathcal{D} = I_4$$

$$I_2 = \int \frac{ds}{\rho^2}$$

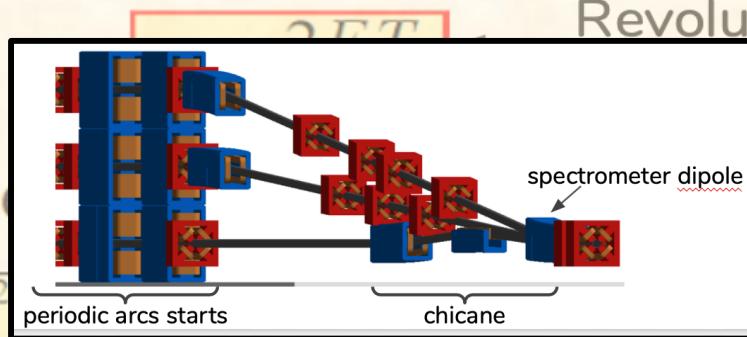
**synchrotron light calculations for the complete machine**

Damping times, partition numbers

$$J_{\varepsilon} = 2 + \mathcal{D}, \quad J_x = 1 - \mathcal{D}, \quad J_y = 1$$

Arc

**Spreader**



Equilibrium energy

$$\left(\frac{\sigma_{\varepsilon}}{E}\right)^2 = \frac{C_q E^2}{J_{\varepsilon}} \cdot \frac{I_2}{I_4}$$

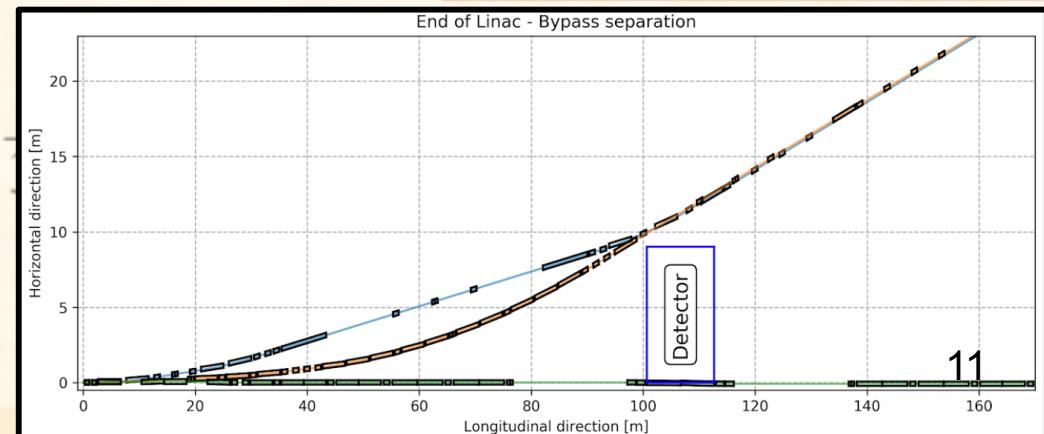
Equilibrium emittance

$$\varepsilon_{x0} = \frac{\sigma_{x0}^2}{\beta} = \frac{C_q E^2}{J_x} \cdot \frac{I_5}{I_4}$$

**Bypass**

Arc

Revolution



# The LHeC Modules: Synchrotron Light & Emittances,



critical energy

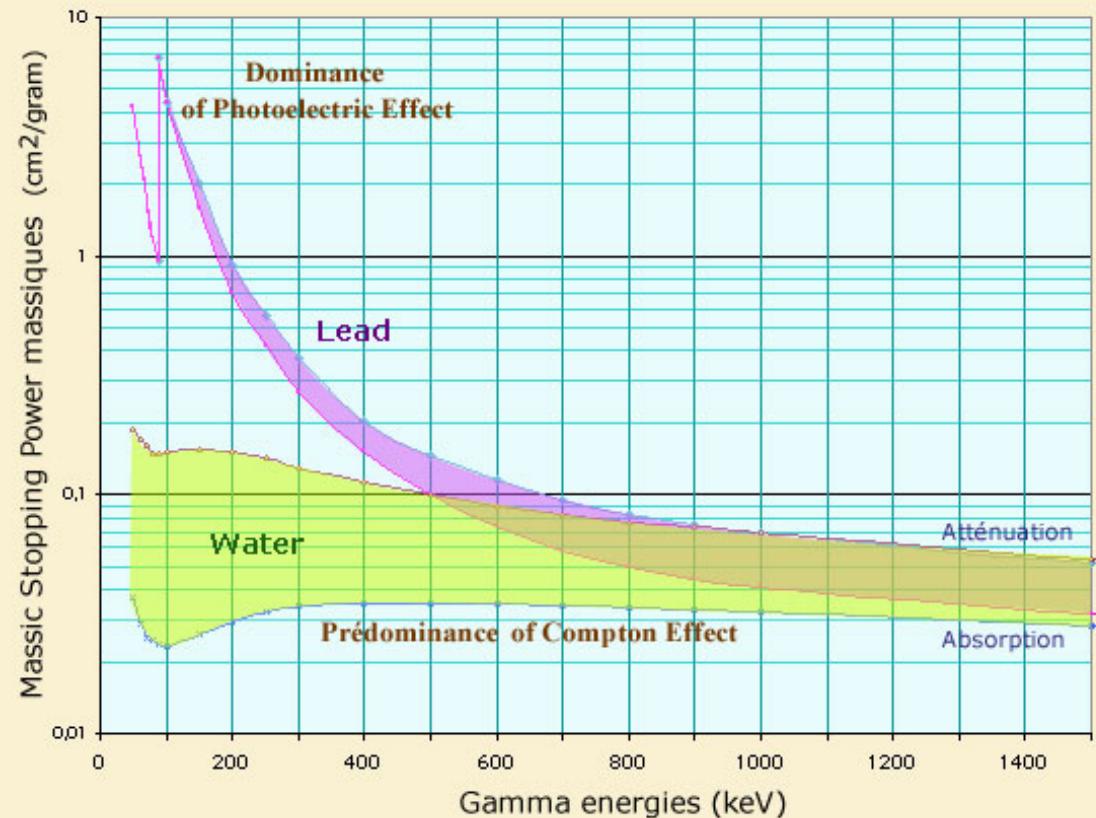
$$E_{crit} = \frac{3hc}{2} \frac{\gamma^3}{\rho}$$

radiated power

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

beam emittance  
increase

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



# The LHeC Modules: Synchrotron Light & Emittances,



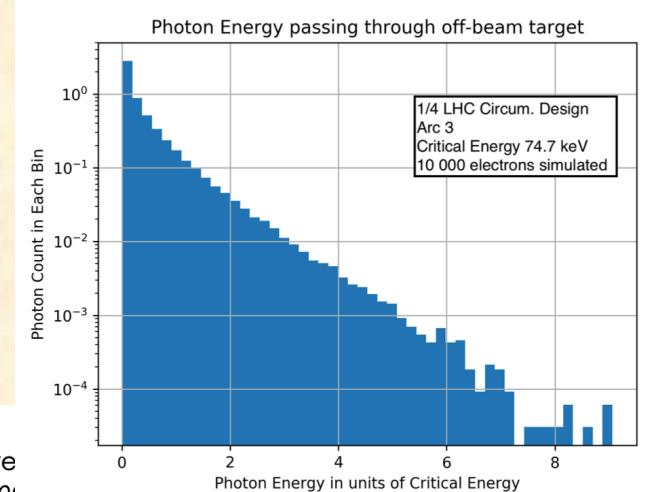
*synchrotron light catalogue  
of complete machine  
for 1/3 ... 1/4 ... 1/5 LHC circumference*

For 1/4 LHC Design Size, Beam current 20 mA

Line Power Density: power radiated by beam per m

| Arc | Energy (GeV) | Critical Energy (keV) | Energy lost per e <sup>-</sup> in Arc (GeV) | Total Power Radiated (MW) | Line Power Density (kW/m) |
|-----|--------------|-----------------------|---|---------------------------|---------------------------|
| 1   | 8.61         | 3.11                  | 0.001                                       | 0.01                      | 0.005                     |
| 2*  | 16.7         | 22.7                  | 0.008                                       | 0.15                      | 0.067                     |
| 3   | 24.8         | 74.6                  | 0.037                                       | 0.73                      | 0.329                     |
| 4*  | 33.0         | 174                   | 0.114                                       | 2.29                      | 1.02                      |
| 5   | 41.08        | 337                   | 0.276                                       | 5.51                      | 2.46                      |
| 6   | 49.2         | 579                   | 0.568                                       | 11.4                      | 5.05                      |

Replenishment: Can supply ~ 30MeV per cavity

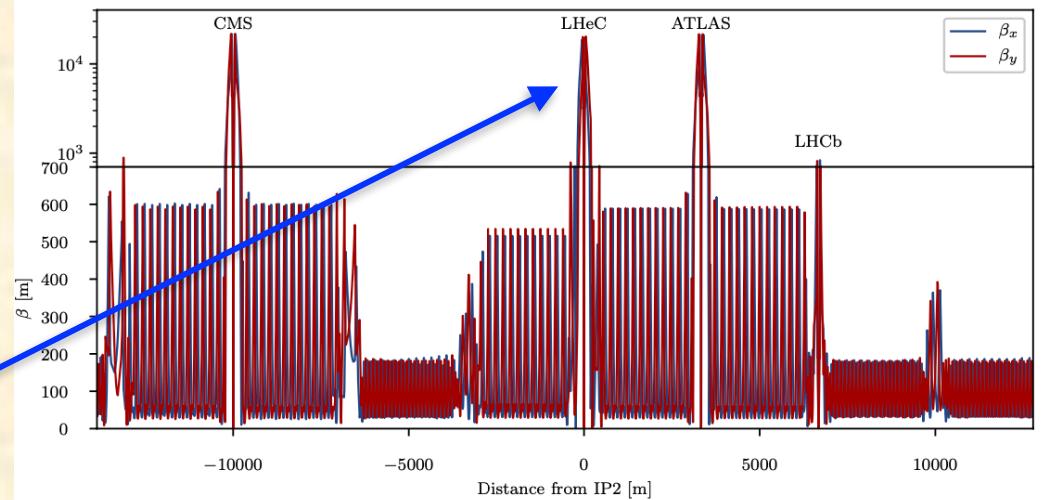
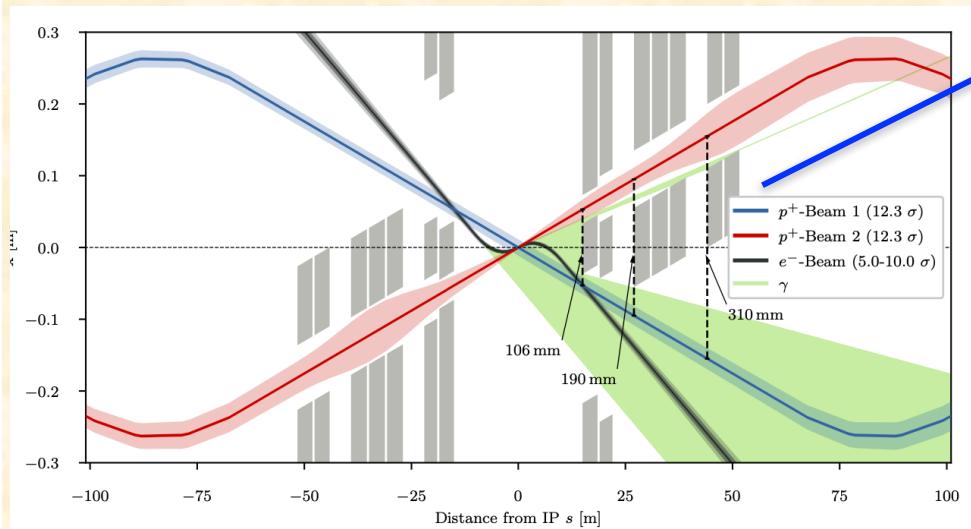


# The LHeC Modules: The Interaction region



- 1.) luminosity optics for proton beam  $\rightarrow \beta_p^* = 7.0 \text{ cm}$
  - 2.) luminosity optics for electron beam  $\rightarrow \beta_e^* = 7.4 \text{ cm}$
  - 3.) relaxed optics for 2nd protons
  - 4.) beam separation:  
electrons must not enter the focusing structure of the proton mini-beta
  - 5.) keep synchrotron radiation as low as possible
- } *matched beam sizes in x & y*

*qualitative layout of the IR*



*HL-LHC proton optics with LHeC-IR*

# The LHeC Modules: The Interaction region



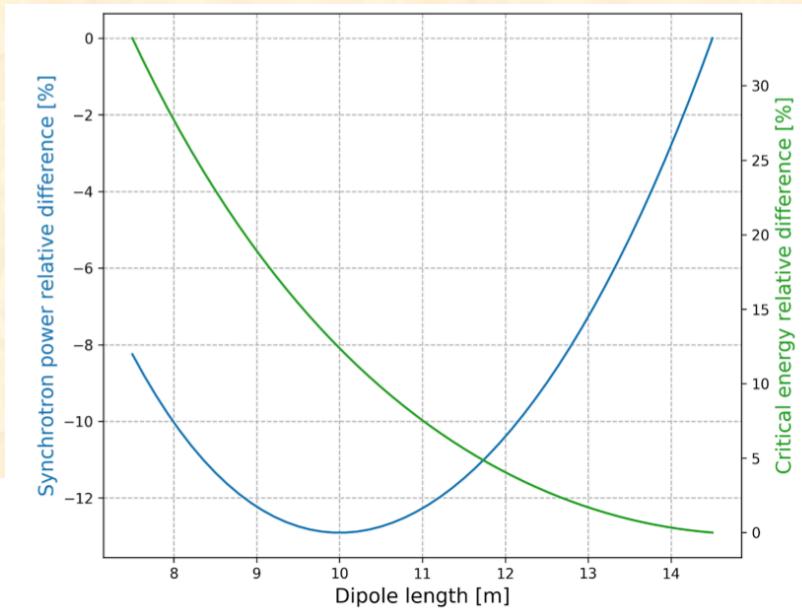
**Challenge: re-optimised beam separation design for smallest synchrotron radiation load**

protect / shield the particle detector

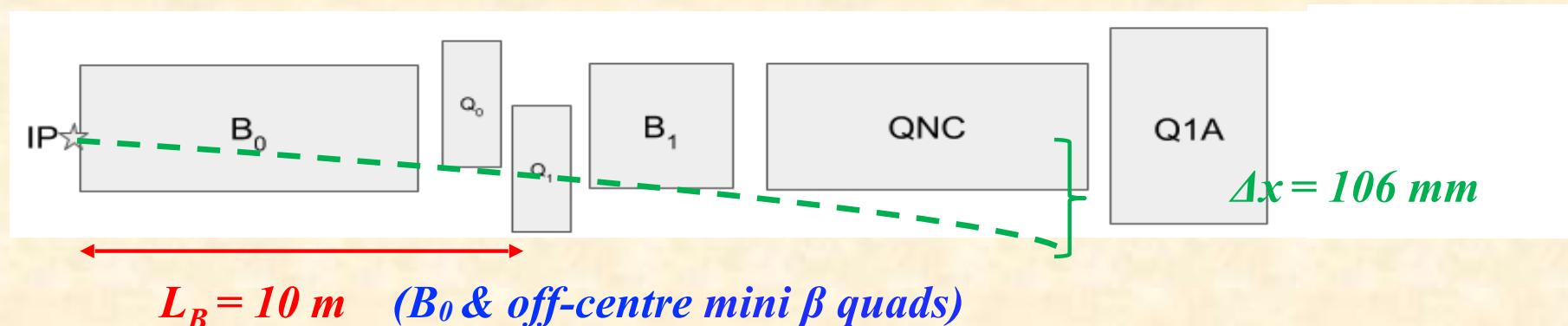
protect / shield the s.c. proton magnets

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

*optimisation of different IR elements  
for best beam separation*



**New Design:**



# Beam-Beam Interaction:

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

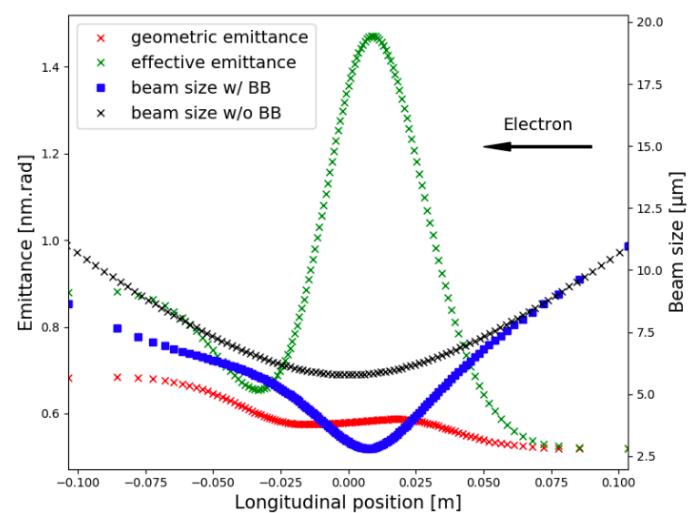


| Beam parameter            | Unit                   | LHeC at HL-LHC        |               |
|---------------------------|------------------------|-----------------------|---------------|
|                           |                        | Proton beam           | Electron beam |
| Energy                    | GeV                    | 7000                  | 49.19         |
| Normalized emittance      | mm·mrad                | 2.5                   | 50            |
| Beam sizes $\sigma_{x,y}$ | μm                     | 5.8                   | 5.8           |
| Intensity                 | $10^9$ particles/bunch | 220.00                | 3.12          |
| Bunch length $\sigma_s$   | mm                     | 75.5                  | 0.6           |
| $\beta_{x,y}^*$           | cm                     | 10.00                 | 6.45          |
| Disruption factor         |                        | $1.2 \times 10^{-5}$  | 14.5          |
| Beam-beam parameter $\xi$ |                        | $1.52 \times 10^{-4}$ | 0.99          |

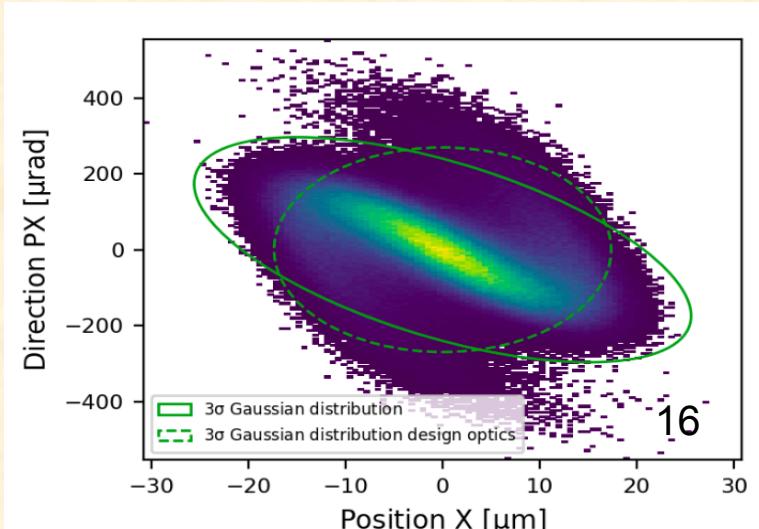
(remember: b-b parameter LHC Standard: 0.0037    LEP: 0.0700 )

beam size at IP

no bb-effect / with bb-effect



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



# LHeC: The Next Challenges:



## Design for prototypes of special machine elements

- half-quadrupole in IR
- spectrometer dipole in spreader
- 800MHz cavities for high current operation

## Synchrotron light power in arcs

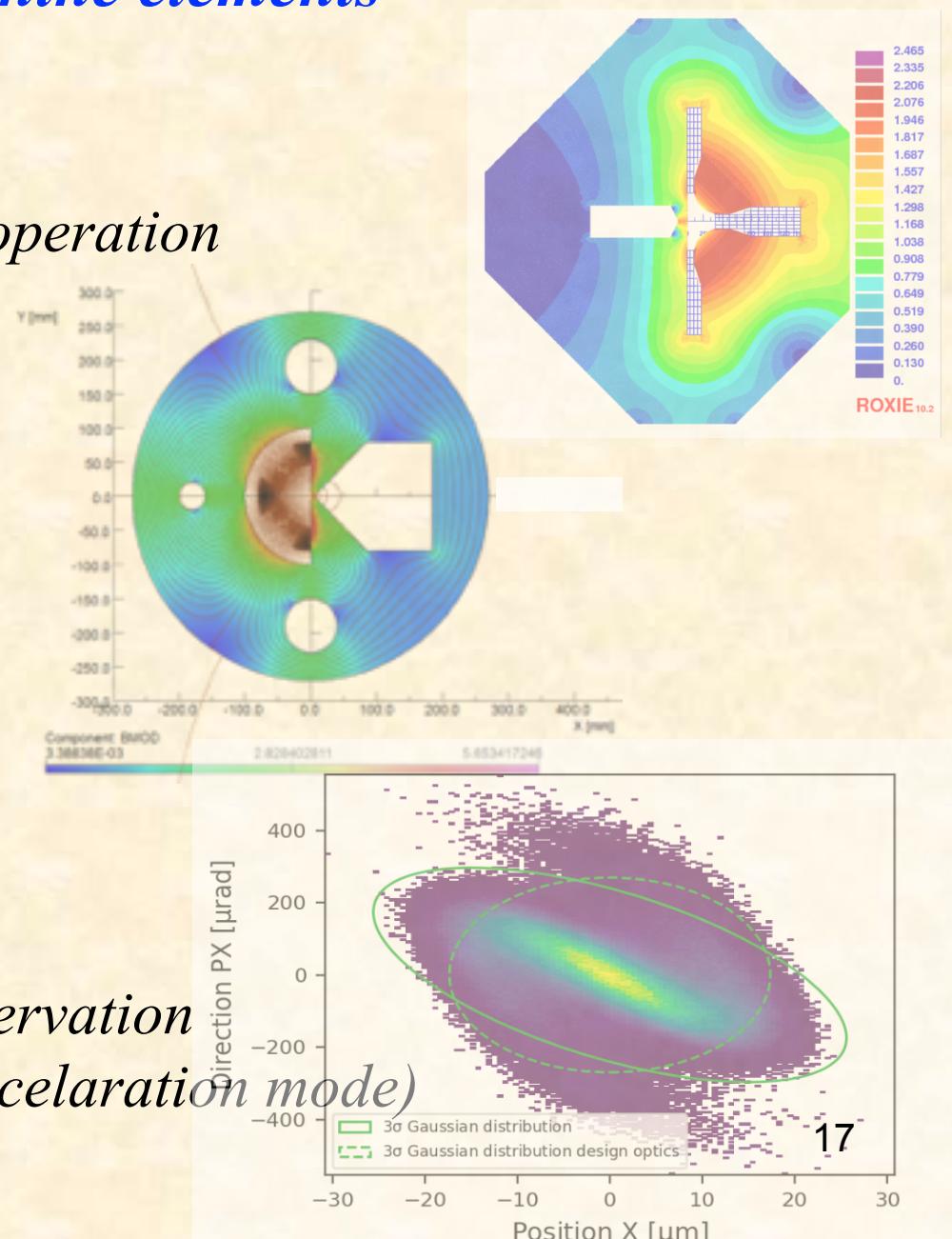
- absorber design
- cooling

## 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 & deceleration mode)



# *Summary & Conclusion*



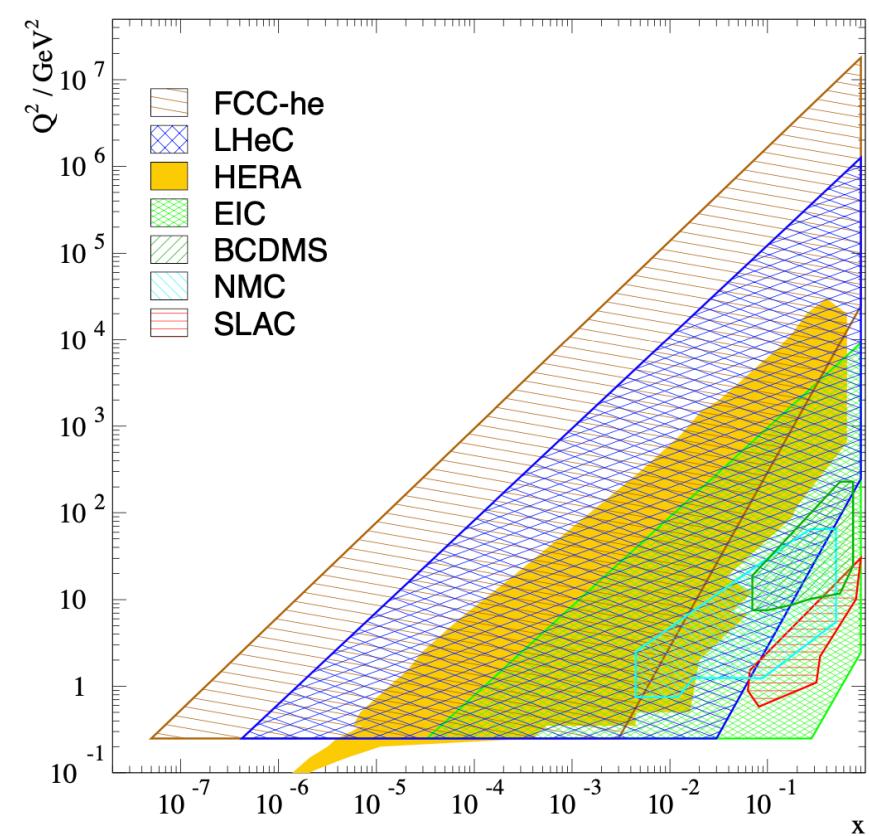
2012 CDR updated and published today (!)

337 authors

Physics, LHeC Accelerator, PERLE, ep Detector

focussed on:

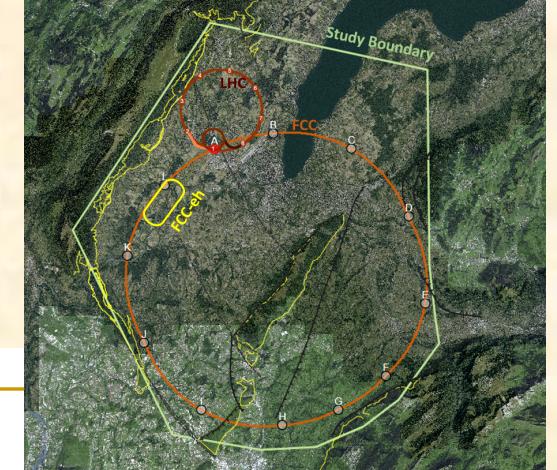
- optimised arc-structure
- synchrotron light catalogue available
- beam spreader & bypass re-optimised
- emittance budget reviewed
- Interaction region optimised



Coverage of the kinematic plane in DIS

The updated CDR and PERLE pave the way to a TDR.  
ERL is recognised as a key future accelerator technique.

The LHeC (and later FCC-he) are the highest resolution microscopes one may build, with a striking potential also on Higgs, BSM, top and nuclear physics.



## FCC-eI Operation:

| parameter [unit]                                     | LHeC (HL-LHC) | eA at HE-LHC | FCC-he |
|--|---------------|--------------|--------|
| $E_{\text{Pb}}$ [PeV]                                | 0.574         | 1.03         | 4.1    |
| $E_e$ [GeV]  | 60            | 60           | 60     |
| $\sqrt{s_{eN}}$ electron-nucleon [TeV]               | 0.8           | 1.1          | 2.2    |
| bunch spacing [ns]                                   | 50            | 50           | 100    |
| no. of bunches                                       | 1200          | 1200         | 2072   |
| ions per bunch [ $10^8$ ]                            | 1.8           | 1.8          | 1.8    |
| $\gamma \epsilon_A$ [ $\mu\text{m}$ ]                | 1.5           | 1.0          | 0.9    |
| electrons per bunch [ $10^9$ ]                       | 4.67          | 6.2          | 12.5   |
| electron current [mA]                                | 15            | 20           | 20     |
| IP beta function $\beta_A^*$ [cm]                    | 7             | 10           | 15     |
| hourglass factor $H_{\text{geom}}$                   | 0.9           | 0.9          | 0.9    |
| pinch factor $H_{b-b}$                               | 1.3           | 1.3          | 1.3    |
| bunch filling $H_{\text{coll}}$                      | 0.8           | 0.8          | 0.8    |
| luminosity [ $10^{32} \text{cm}^{-2}\text{s}^{-1}$ ] | 7             | 18           | 54     |

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,  
"A Baseline for the FCC-he"

John Jowett, Frank Zimmermann