Staged approach to LHeC

& ESPPU

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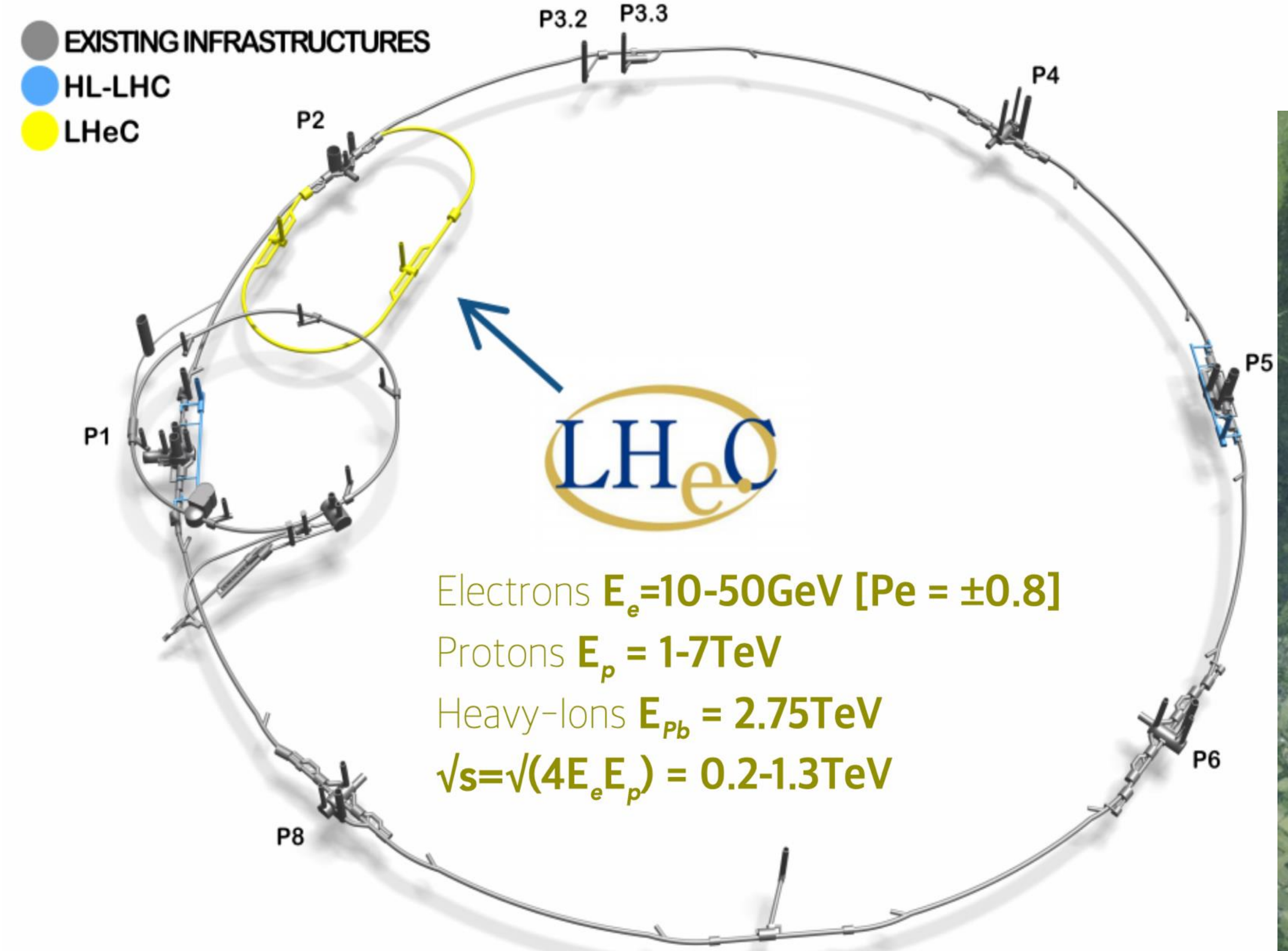

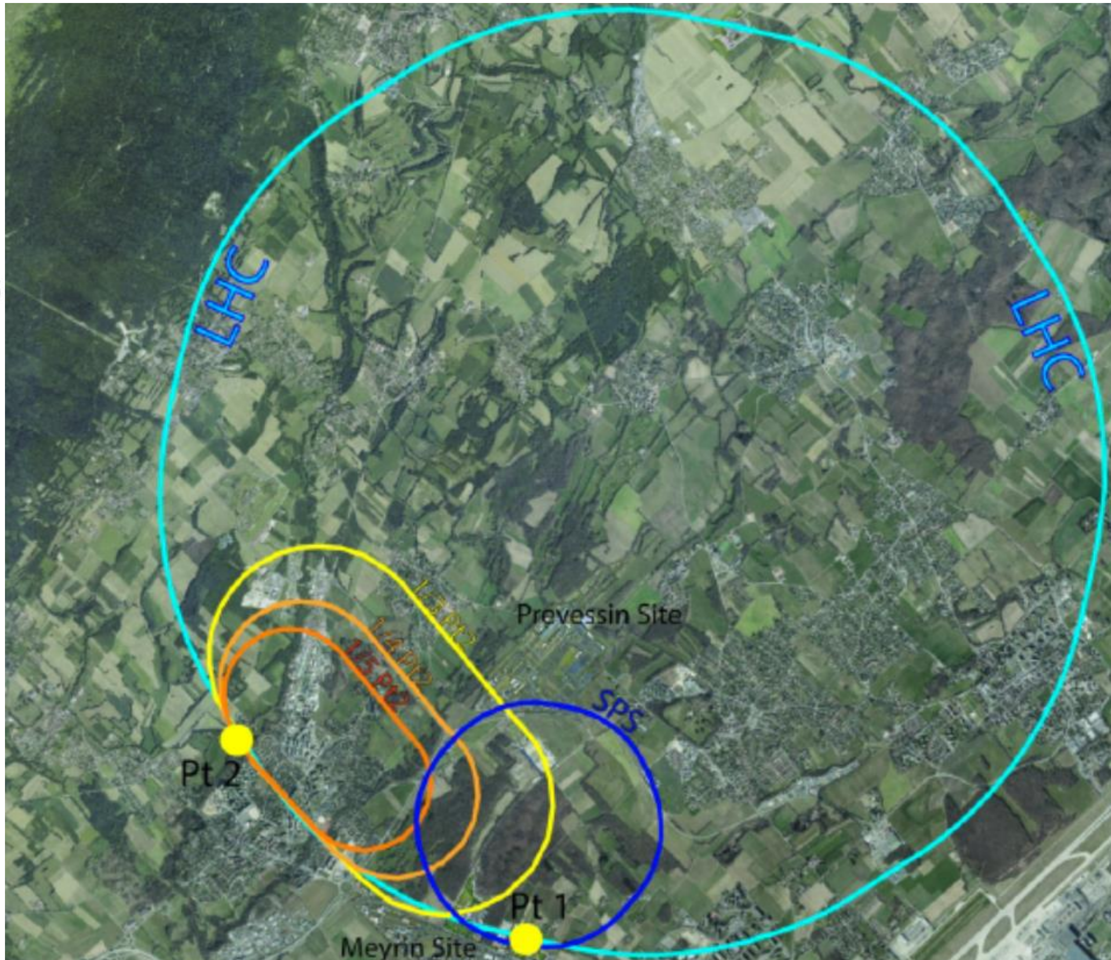

Experiment for *eh* (and *hh*) scattering @ P2

Back in 2019 two proposals were released in parallel ⇒ *CDR* for LH*e*C and *EoI* for “ALICE 3” – both at P2…

In 2022 novel P2 design was proposed to accommodate **both** *electron-hadron* and *hadron-hadron* collisions

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https://doi.org/10.1140/epjc/s10052-021-09967-z

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

An experiment for electron-hadron scattering at the LHC

K. D. J. André[1,2], L. Aperio Bella[3], N. Armesto[4,a], S. A. Bogacz[5], D. Britzger[6], O. S. Brüning[1], M. D’Onofrio[2], E. G. Ferreiro[4], O. Fischer[2], C. Gwenlan[7], B. J. Holzer[1], M. Klein[2], U. Klein[2], F. Kocak[8], P. Kostka[2], M. Kumar[9], B. Mellado[9,10], J. G. Milhano[11,12], P. R. Newman[13], K. Piotrzkowski[14], A. Polini[15], X. Ruan[9], S. Russenschuk[1], C. Schwanenberger[3], E. Vilella-Figueras[2], Y. Yamazaki[16]

https://link.springer.com/article/10.1140/epjc/s10052-021-09967-z

Electron-Hadron Scattering – Reminder

Huge advantage for *eh* experiments ⇒ **total inelastic cross-section:**

$$\sigma_{eh} \ll \sigma_{hh}$$

Event pileup is very small/negligible at LH*e*C

↓

Data streaming *aka* "no triggering" is possible (as at EIC and **ALICE**!)

↓

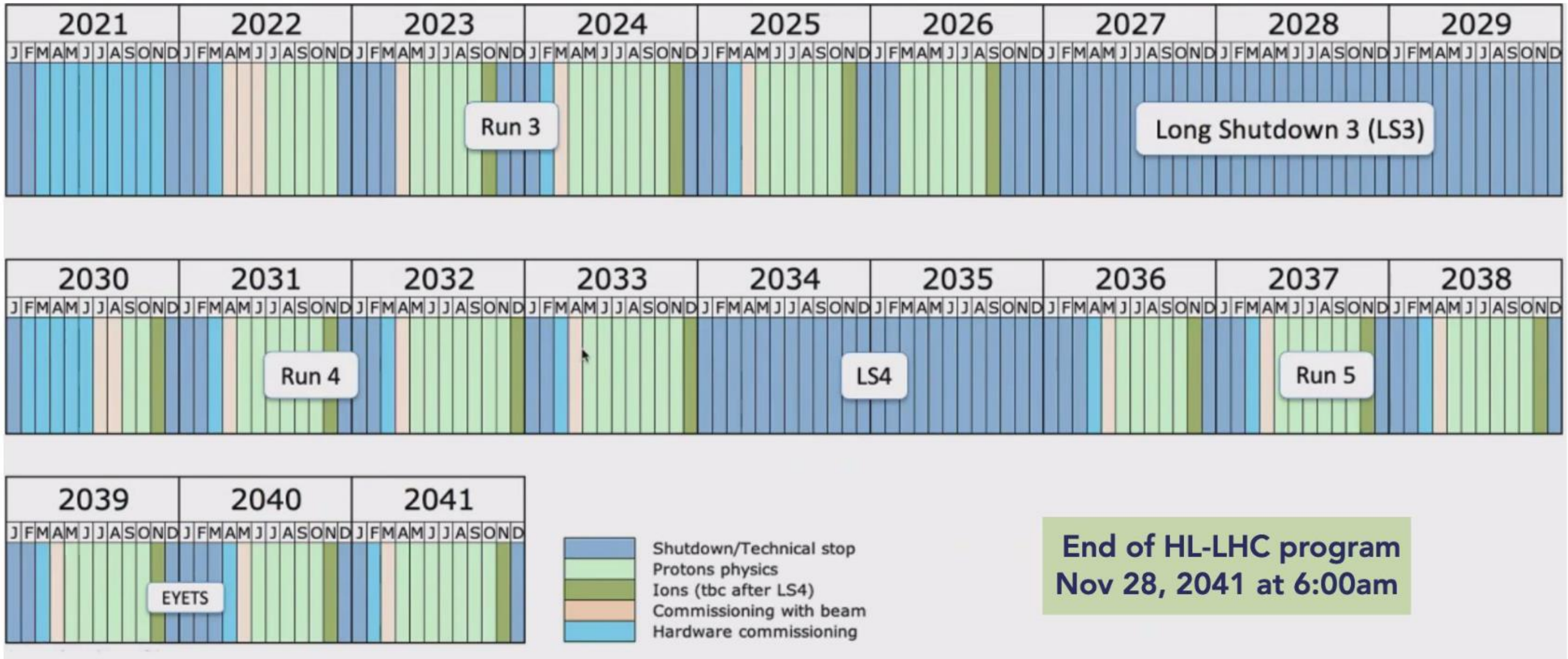
Much broader types of final states/decay channels are feasible

↓

Unique capabilities

LHeC in Run 5

LH*e*C was conceived to provide *eh* collisions **concurrently** to *hh* collisions at HL-LHC (at other IPs) ⇒ its schedule defines time constraints



Question:

It is possible to commission *eh* collisions at P2 in 2036?

Proposed answer: yes!

1. By staging LH*e*C project
2. By accommodating *eh* experiment in "ALICE 3e"

LHeC: Staging Proposal

If one targets LH*e*C commissioning **in 2036 then staging is necessary**

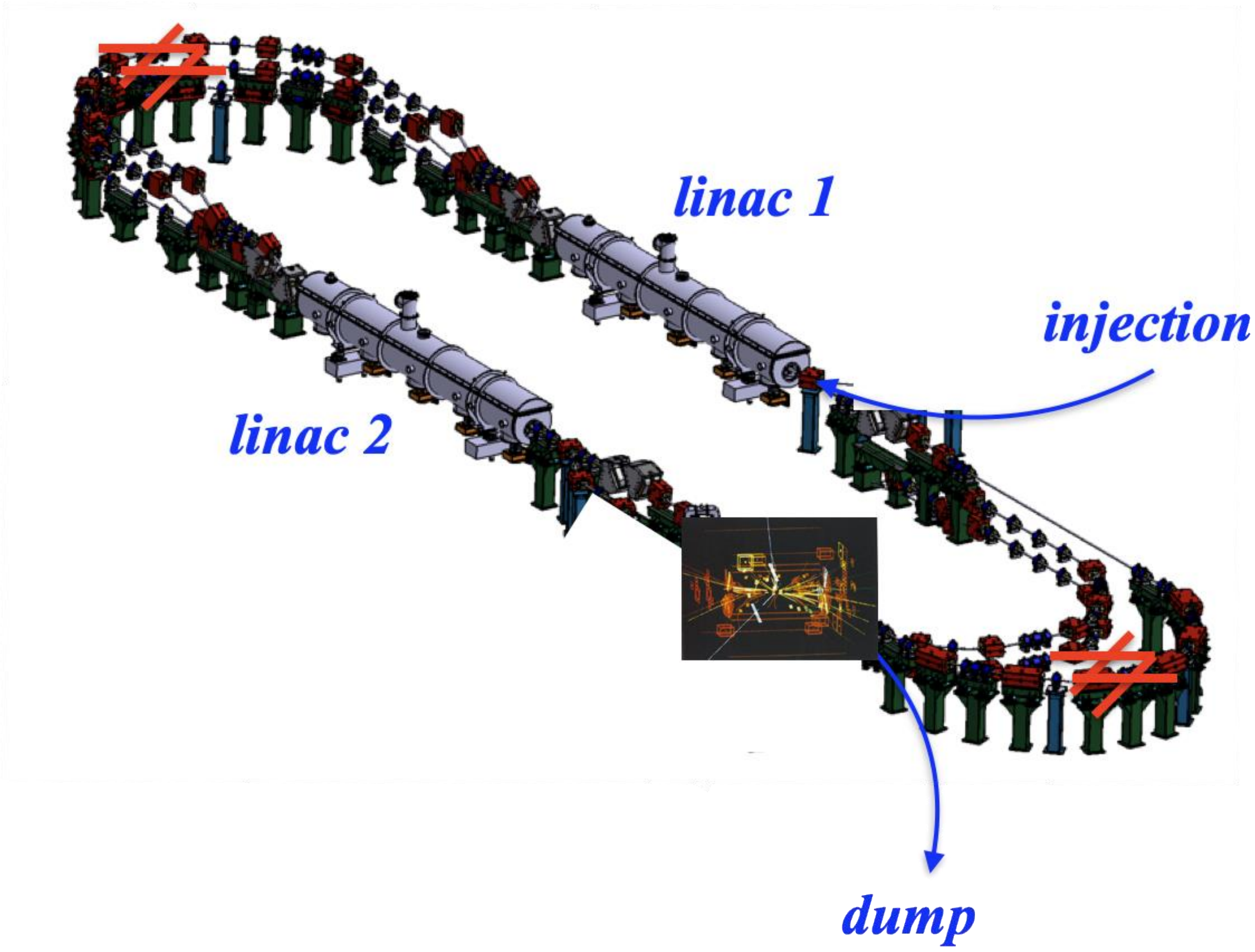
⇒ **20 GeV electron beam offers significant simplifications in design & running:**

- Center-of-mass energy of **0.75 TeV** ensures excellent science
- Only **one-pass ERL** is required with significantly lower power use
- **Synchrotron Radiation is much softer** and simplifies MDI design
- Electron beam **separation is easier**
- Very high luminosity might be **easier** to achieve

ALICE 3 requires rather minor adaptations to accommodate *eh* physics:

- ALICE is already using data streaming
- Beneficial dipole field at IP2 was considered in ALICE 3 proposal

Electrons at 20 GeV: Layout and geometry



~~arc 3,4,5,6~~
~~spreader / re-combiner~~
~~bypass~~

keep two linacs,
keep sc RF design
keep geometry
keep beam separation scheme?

=> in order to allow for staging to two / three turn ERL

Synchrotron Light at 20 GEV

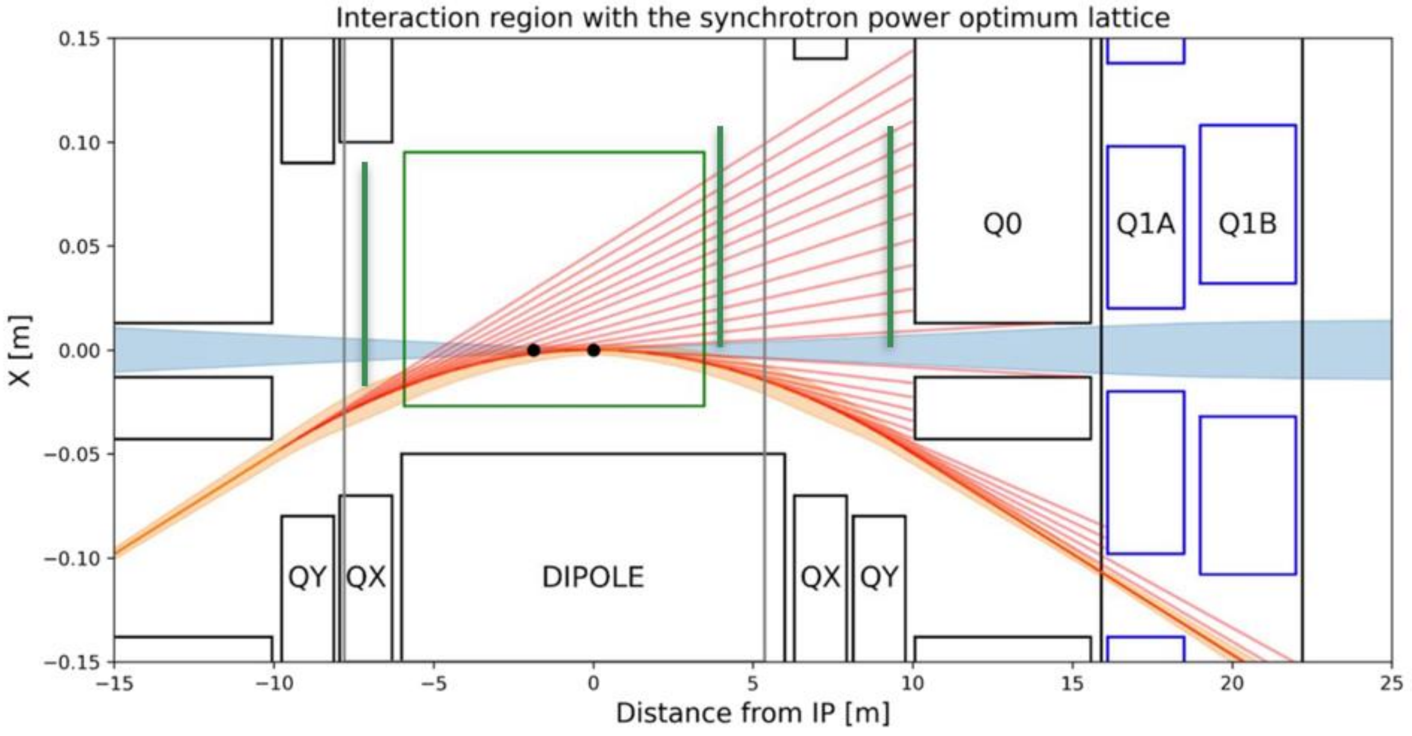
$$E_{crit} = \frac{3hc}{2}\frac{\gamma^3}{\rho}$$ critical energy

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

The IR radiation: goes down to about 250 W and 10 keV critical energy, very small.

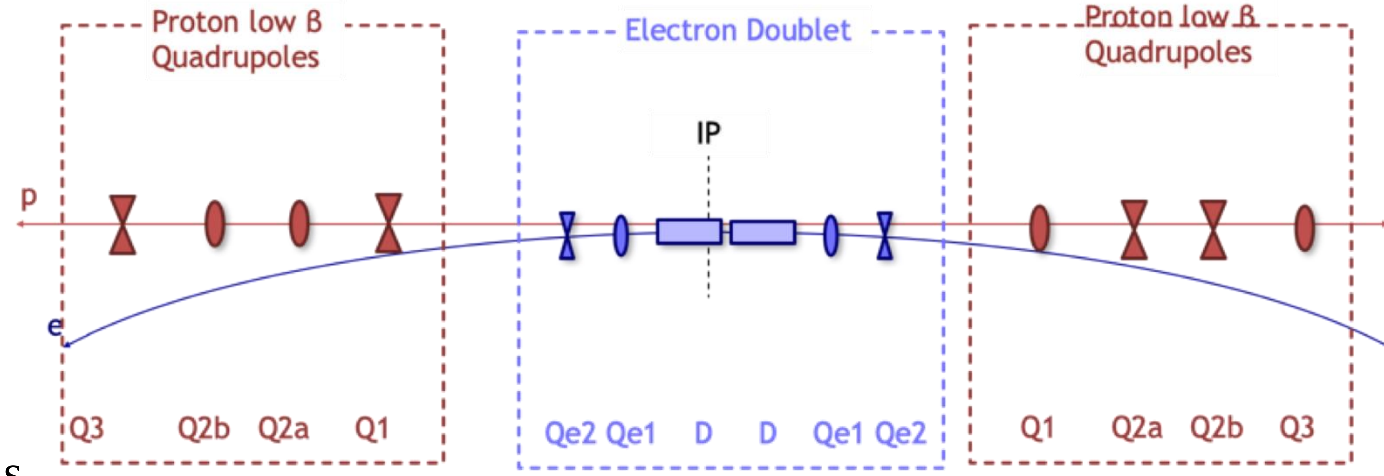
We could even think of bending electron beam completely outside before first proton quadru-pole.

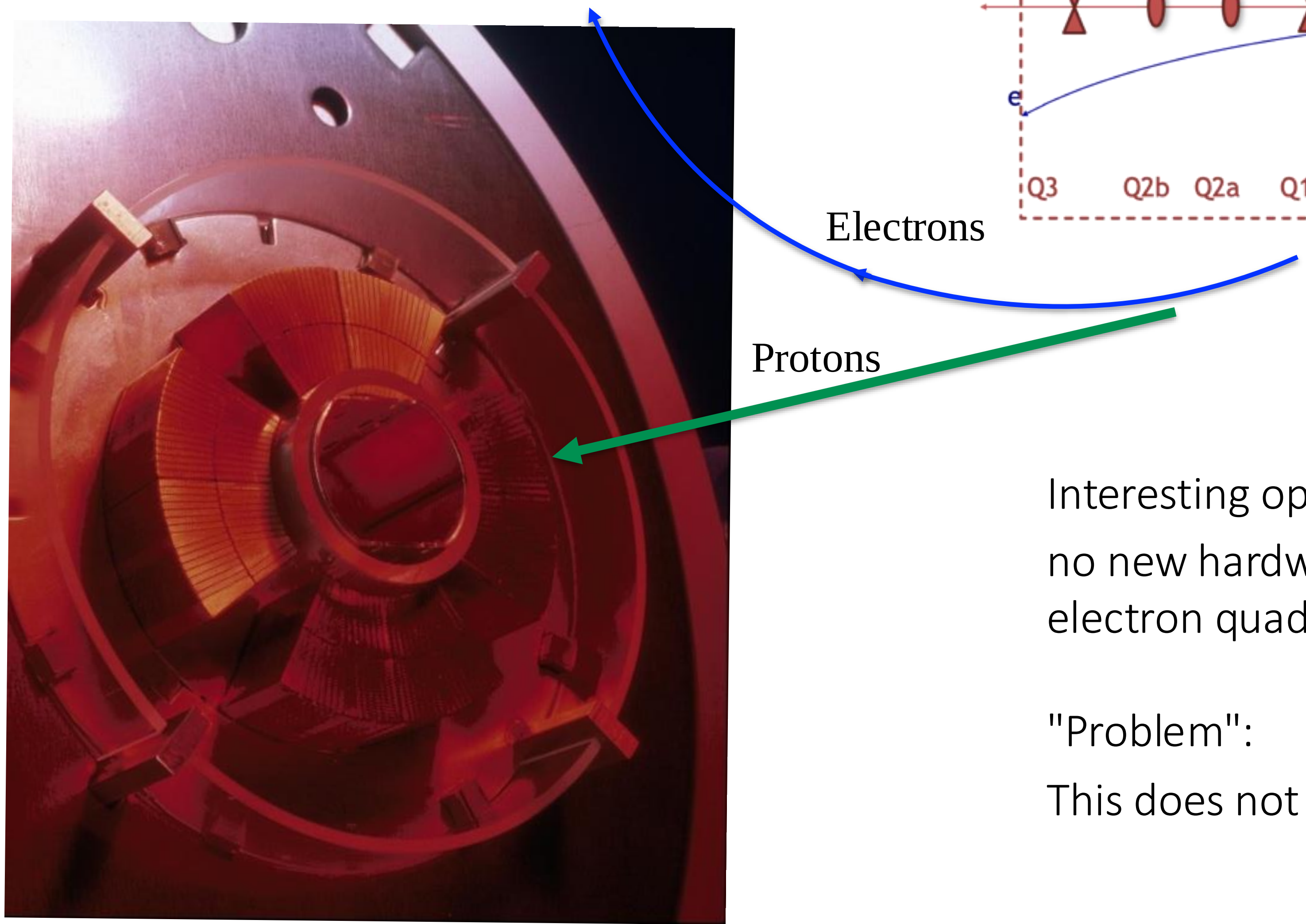
For instance beam separation of 1 m at 23 m from IP would give about 15 kW and 68 keV critical energy .



Need to determine new collimator positions & geometry

Separating electron beam at 20 GeV





Interesting option:

no new hardware needed on proton side, but using off-axis electron quads for that (as at HERA)

"Problem":

This does not work at 50 GeV

Arc Radiation Low Losses

Summing up gammas

$$\gamma^4_{Linac_1} = \frac{10GeV}{511keV} = 1.95 \cdot 10^4$$

$$\gamma^4_{Linac_2} = \frac{20GeV}{511keV} = 3.91 \cdot 10^4$$

$$\Sigma\gamma_s^4 = 2 \cdot \gamma^4_{Linac_1} + \gamma^4_{Linac_2}$$

$$\Sigma\gamma_s^4 = (1.95 \cdot 10^4)^4 + (3.91 \cdot 10^4)^4 = 262.6 \cdot 10^{16}$$

$$P_{\gamma_{1turn}} = CONST \cdot \Sigma\gamma_s^4$$

$$P_{\gamma_{1turn}} = 7.9 \cdot 10^{-14} \cdot 262.6 \cdot 10^{16} = 207.4kW$$

For parameters …

$C_0 = 6.7$ km $\quad I_e = 20$ mA

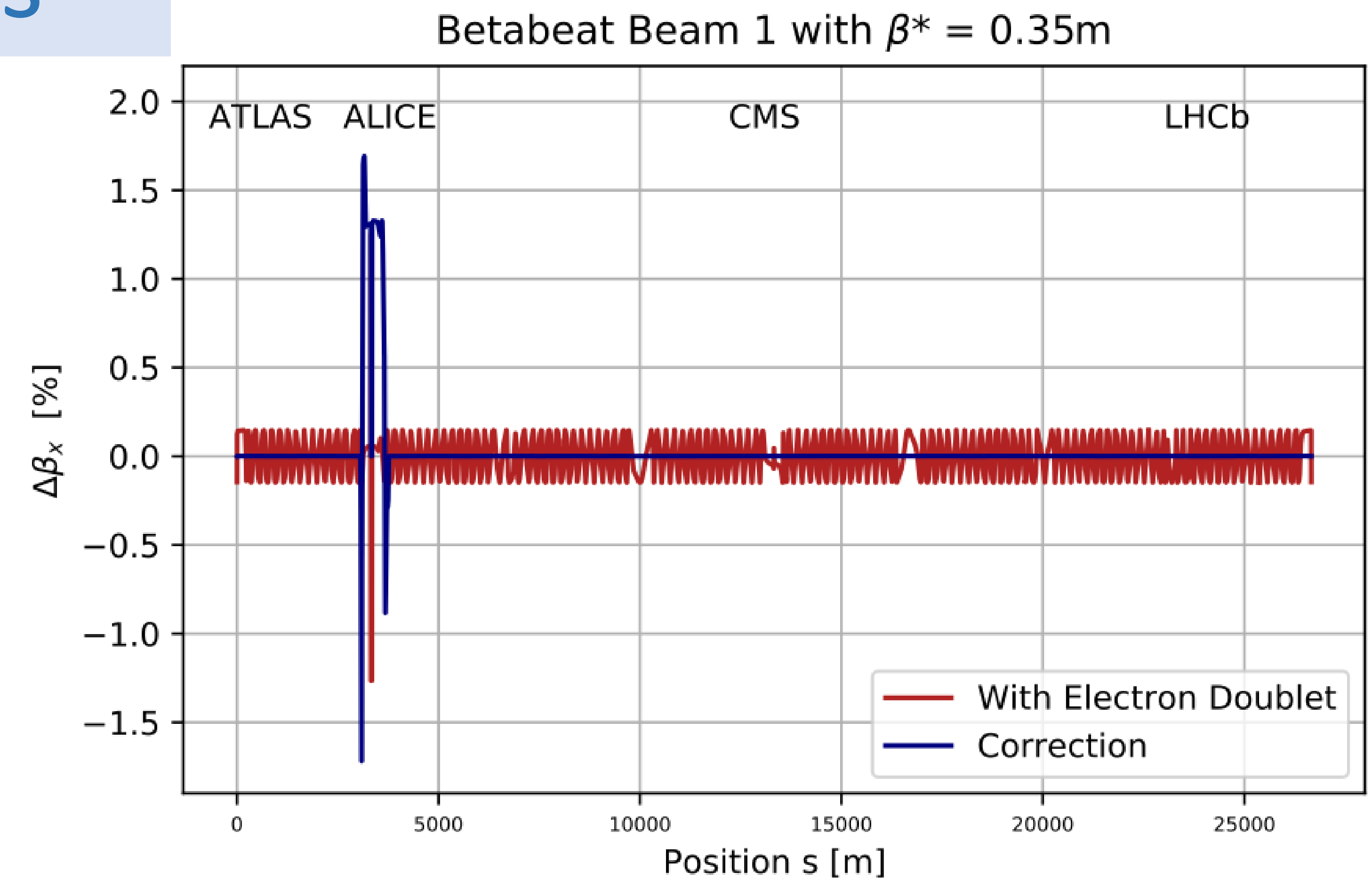
$\rho_{arc} = 740$ m $\quad E_e = 20$ GeV

Should be ok on a 10% -20 % level,

more exact numbers —-> BDSIM.

Proton Beam Dynamics

$E_e = 50 \text{ GeV}, E_p = 7 \text{ TeV}$



local orbit bump

local optics distortion

—> on colliding proton beam

—> non-colliding proton beam

corrected locally via LHC matching quadrupoles

Effect on optics scales down to sub - % level

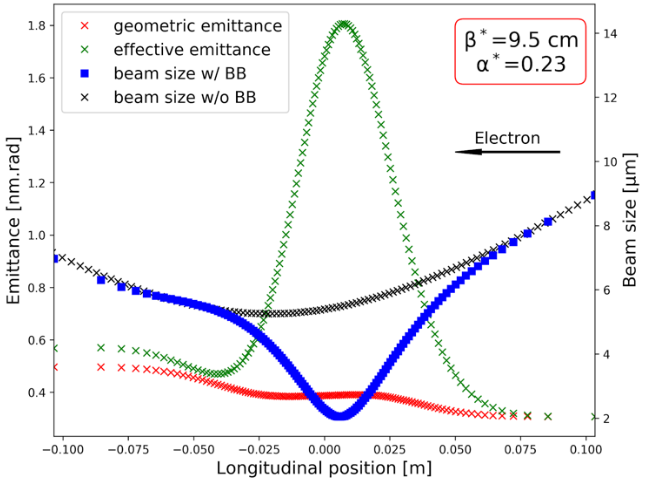
$\Delta\beta/\beta \approx 0.6\%$ ... for 20 GeV / 7 TeV

Reminder: Tolerance limit for LHC : $\Delta\beta/\beta \approx 10\%$

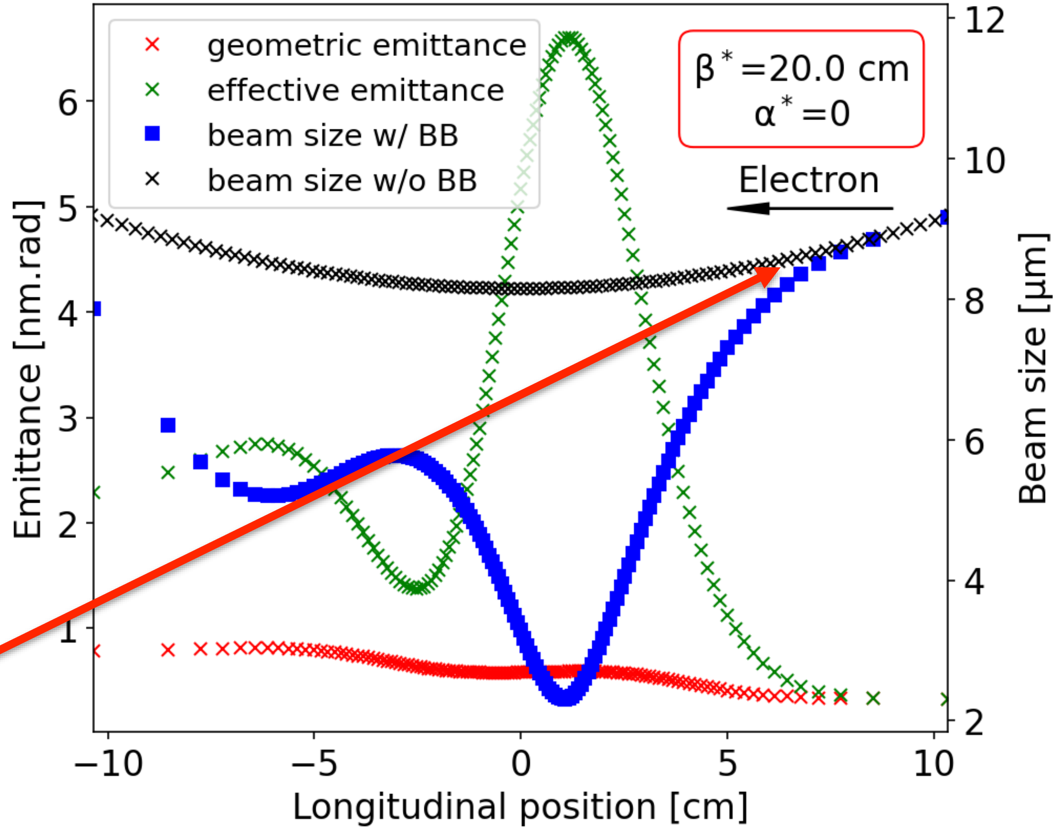
Electron Beam-Beam Effect

$E_e = 20\text{ GeV}, E_p = 7\text{ TeV}$

Beam-beam disruption parameter for electron goes from ~7 to ~18 between 50 GeV and 20 GeV that is similar disruption parameter as in 50 GeV and proton/electron β* = 10 cm configuration so no violent beam-beam disruption expected even if electron energy is much smaller.



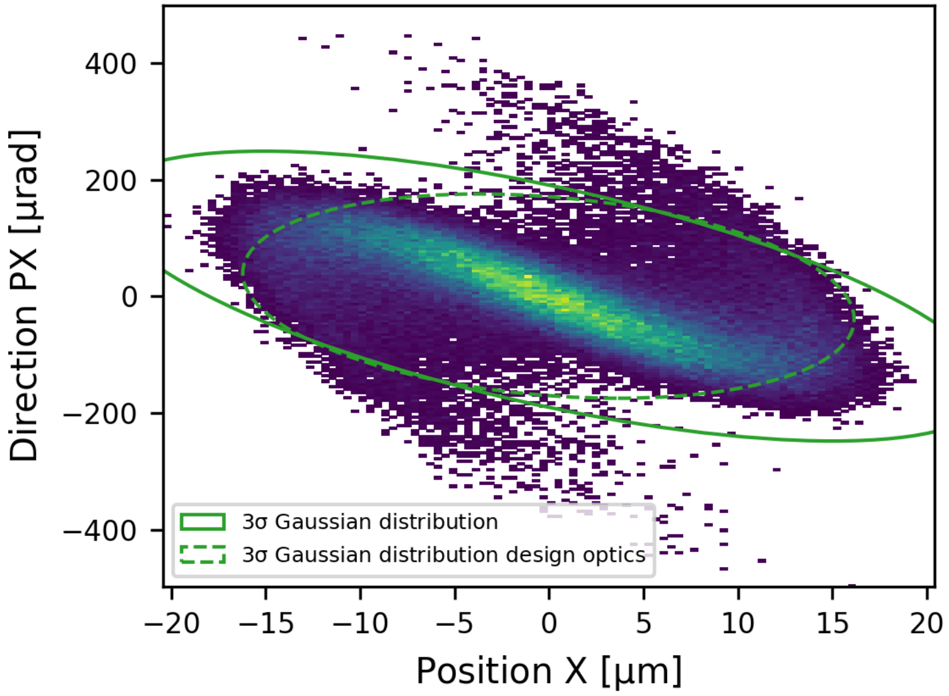
Old: 50 GeV



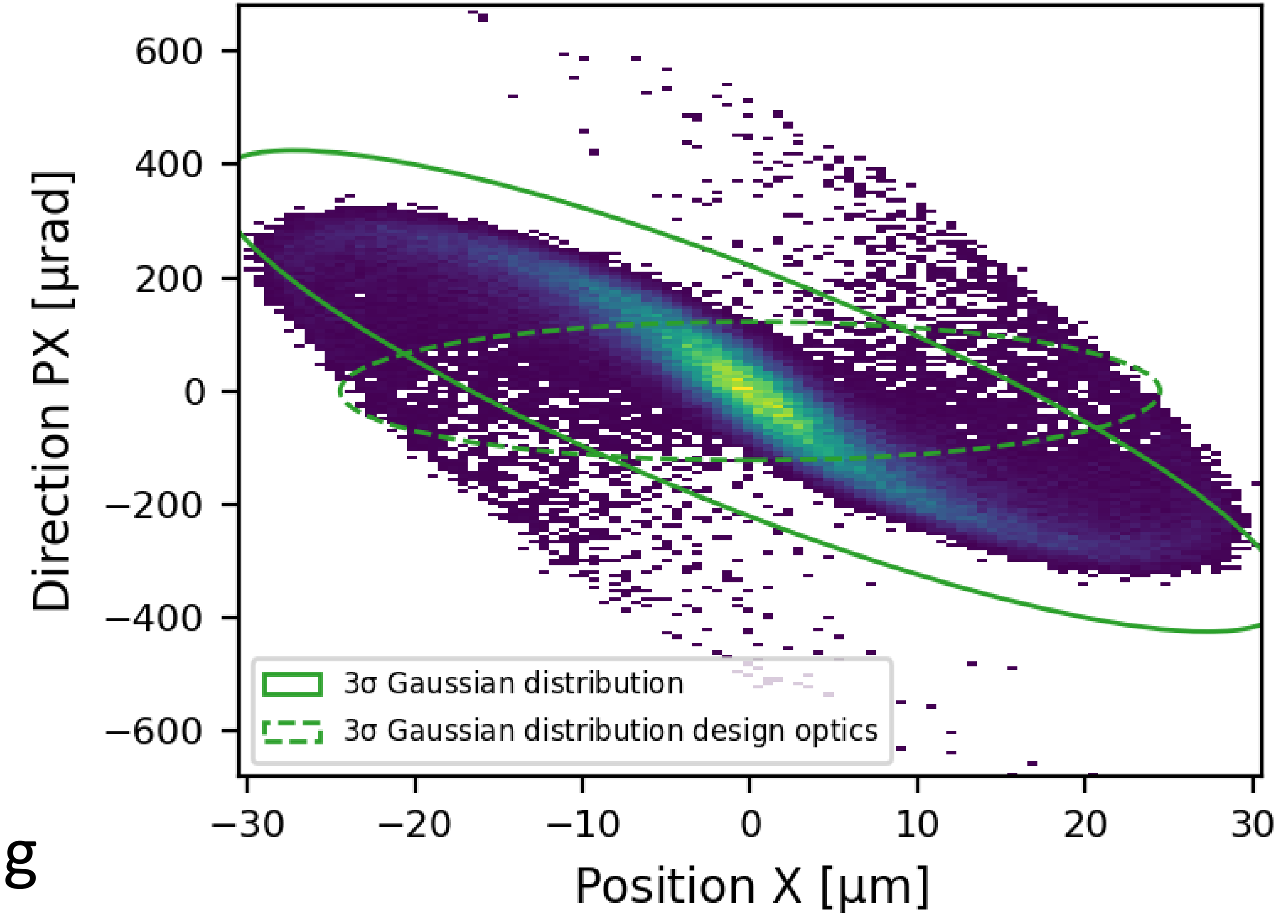
New: 20 GeV

Electron Optics re-matched to fit exactly to return arc structure

Beam-Beam Effect: Phase Space after Collision



Old: 50 GeV



Looks very promising

New: 20 GeV

Electron Emittance

ε scales up with lower energy $\epsilon_0 = \epsilon_n \cdot \frac{1}{\gamma}$

LHeC Design $\epsilon_0 = 3.3 \cdot 10^{-10}$ $\sigma = \sqrt{\epsilon \cdot \beta} = 8.1\mu m$

$\beta^* = 20cm$ $L \approx 3.3 \cdot 10^{33} cm^{-2} s^{-1}$

no chance to scale down β∗ to compensate for larger emittance.

However …

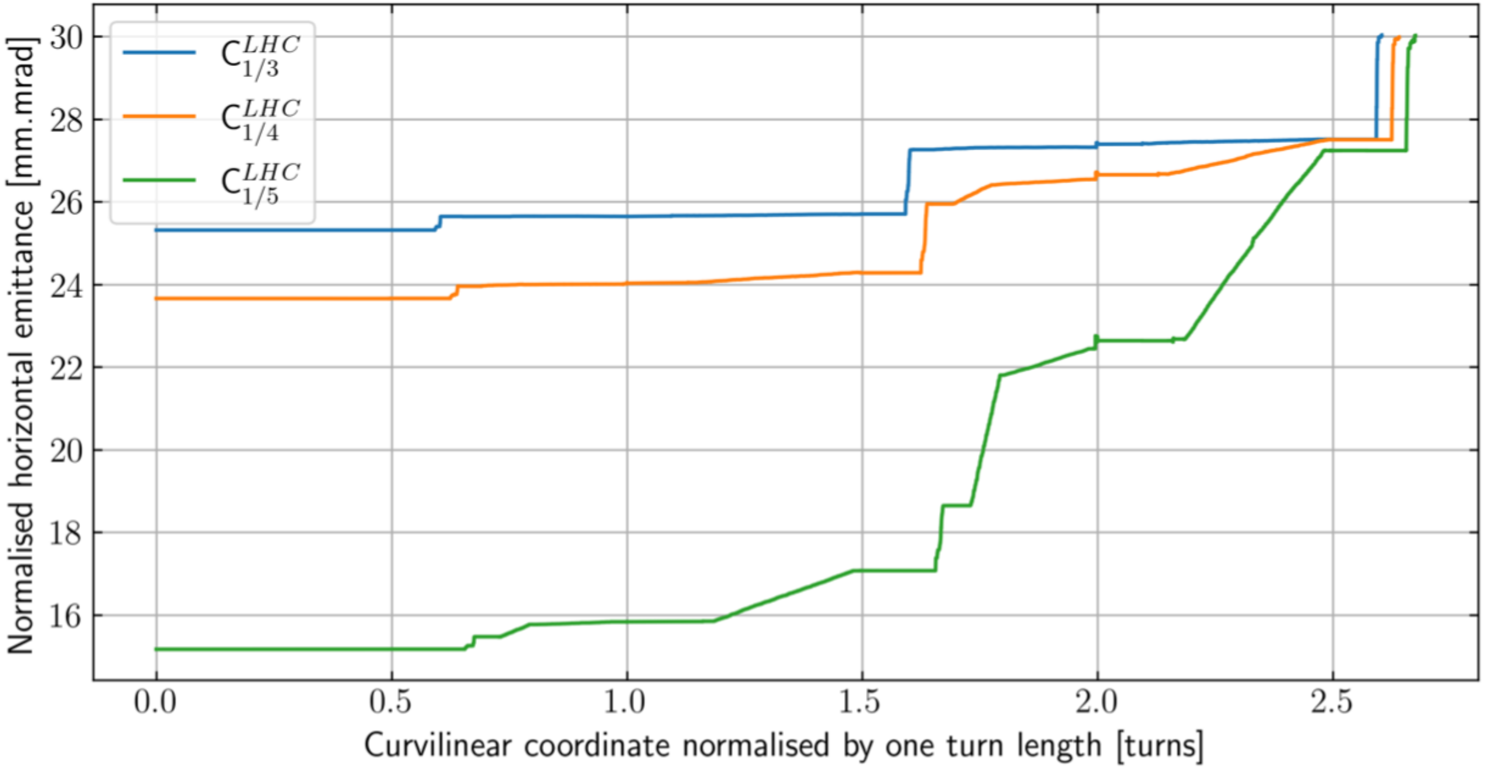
excellent emittance of electron source

$\epsilon_{n_{source}} < 6$

Parameter	Unit	Value
Booster energy	MeV	7*
Bunch repetition rate	MHz	40.1
Average beam current	mA	20
Bunch charge	pC	500
RMS bunch length	mm	3
Normalised transverse emittance	π·mm·mrad	<6
Uncorrelated energy spread	keV	10
Beam polarisation		Unpolarised/Polarised

Table 10.15: General specification of the LHeC ERL electron source.

Electron Emittance



emittance increase marginal for one turn.

In order to get back $\epsilon_{0_{20GeV}} = 3.3 \cdot 10^{-10} mrad$ we have to assume $\epsilon_{n_{source}} \approx 13$ mm mrad

remember CDR source specifications: $\epsilon_{n_{source}} = 6$ mm mrad

Luminosity (and Polarization) Expectations

Electron emittance at 20 GeV is larger by 5/2

with careful emittance tuning and smaller start emittances we should be able to stay within emittance regime that allows for compensation of beam optics and unchanged luminosity values.

Electron beam current for 1-pass ERL should reach 50 mA – *for total current in cavities of* 100 mA *instead of* 120 mA – and luminosity of 10^{34} $cm^{-2}s^{-1}$ may be achieved [→ 500 fb^{-1} of data in Run 5?] ⇒ needs verification asap

High electron longitudinal polarization seems possible as couple of on-going low energy experiments are demonstrating ⇒ needs further investigations

Cost Savings for Stage 1

cost reduction for 1 turn ERL hardware: ~~arc 3-6 spreader~~ / ~~recombiner~~ / ~~bypass~~

≈ 100M CHF saving

If HERA electron separation is used: ~~Superconducting Interaction Region (Proton) Magnets~~ ⇒

≈ 100M CHF extra saving

+ much smaller costs for detector at P2
  and significantly lower ERL running costs thanks to negligible SR losses

Detector for Electron-Hadron Scattering @ P2

Measurements of *eh* scattering require very good detectors for scattered electrons AND for jets (⇒ HCAL)

Bending power for electron separation of about 1 Tm is needed, but can be also done with off-axis/combined function electron quadrupoles

Precise electron-hadron luminosity measurements will directly follow EIC design

"Triggerless" data streaming is essential

Staged LHeC: Summary

LH*e*C will complete HL-LHC science in profound & relevant ways – in **QCD**, HF, top, **Higgs*** & **Electroweak** sectors. In addition, PDFs determined at LH*e*C will **significantly decrease systematic uncertainties** of *pp* experiments

LH*e*C offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions (and other exclusive processes) and will open new era in *eA* studies

win-win-win for science programme at HL-LHC

making unique LH*e*C science + improving precision of *pp* experiments + enhancing HI research with ALICE 3*e*

[have begun properly writing up concept of LHeC 1st phase]

Thank you for attention!

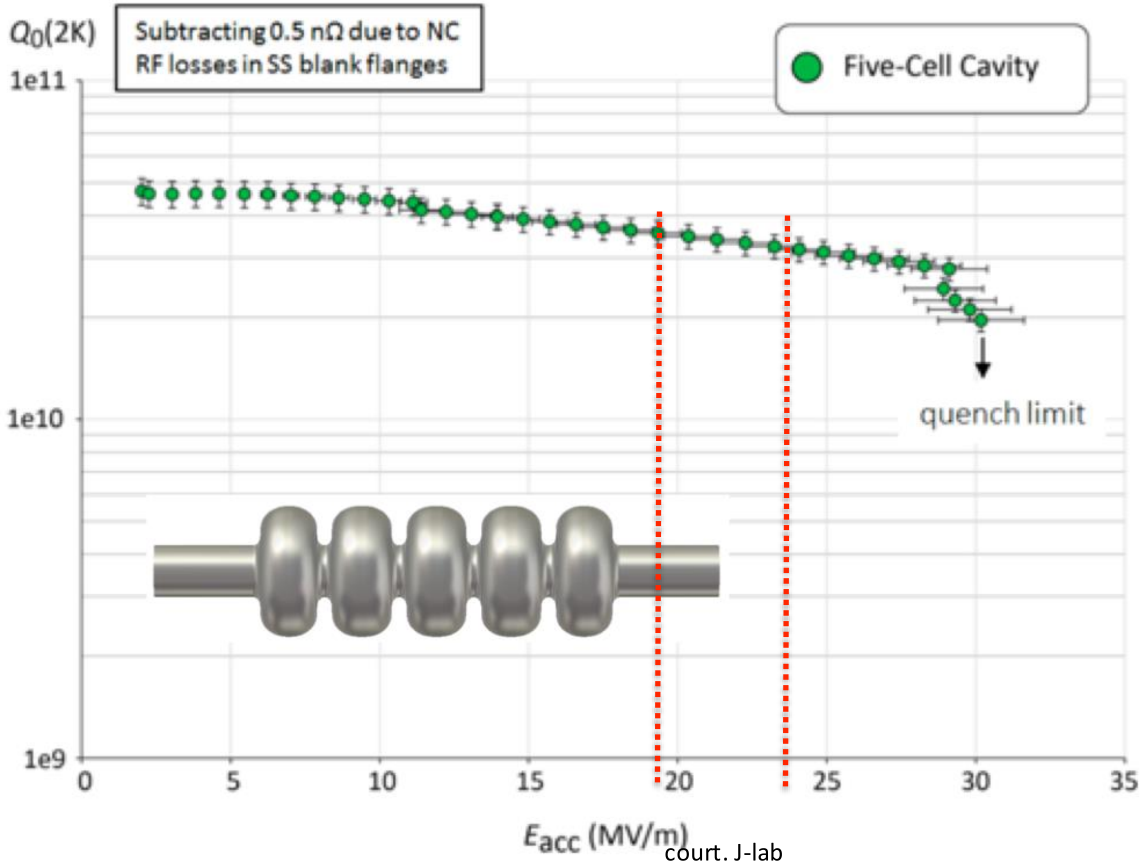
ERL@LH*e*C as *Relay* Speed Skating

Backup slides

RF System

E_e=50~GeV —> three turns
8.33 GeV energy gain / turn
—> Cavity Gradient 19.7 MV/m

E_e=20~GeV —> 10 GeV energy gain / turn
—> Cavity Gradient 24.2 MV/m



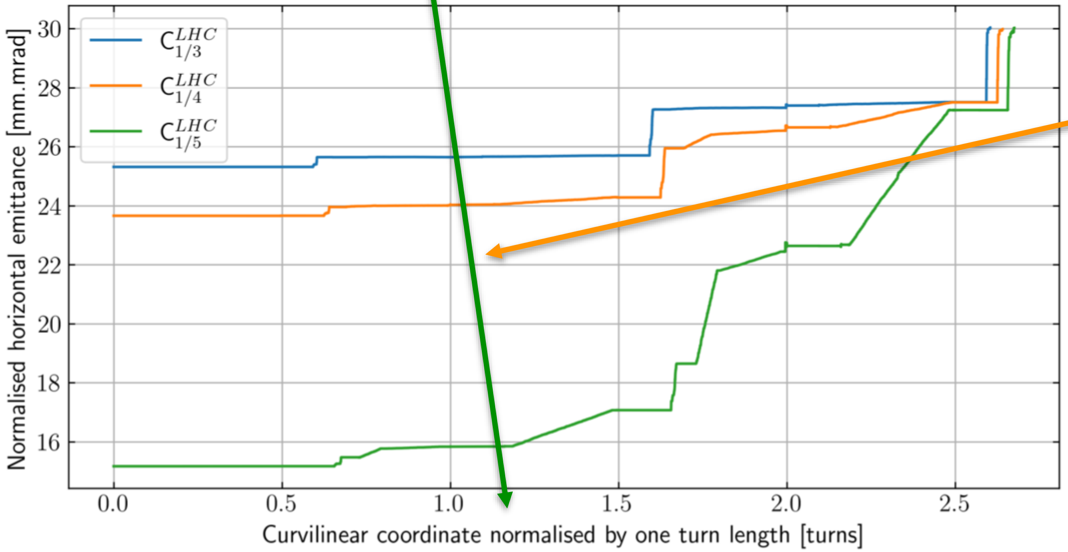
court. J-lab

challenging
but should be ok.

Electron Emittance

Reminder: Excellent emittance of the electron source was needed for the quantum effect on ε at high energies in the 1/5 LHC version!!

$\epsilon_{n_{source}} < 6mmmrad$



emittance increase marginal for one turn.

Synchrotron Light —> 20 GEV Arc Radiation Losses

Synchrotron Radiation for a single electron in a storage ring $P_\gamma = \frac{e^2 c \cdot \gamma^4}{6\pi\epsilon_0\rho^2}$

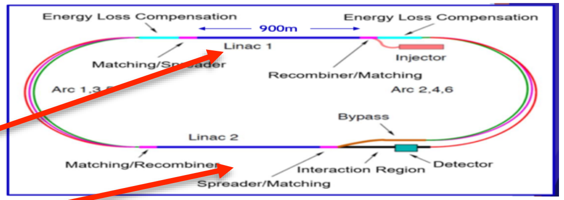
Scaling to one return arc, for N_e electrons per bunch and a bunch distance of $\Delta t = 25ns$ we can rewrite

$$P_{\gamma(arc)} = \frac{N_e e^2 c}{6 \cdot \Delta t \cdot \epsilon_0 \cdot \rho} \cdot \gamma^4 = CONST \cdot \gamma^4$$

$$CONST == \frac{N_e e^2 c \cdot}{6 \cdot \Delta t \cdot \epsilon_0 \cdot \rho} = \frac{3.1 \cdot 10^9 1.6^2 \cdot 10^{-19^2} (As)^2}{25 \cdot 10^{-9} s \cdot 6 \cdot 8.910^{-12} As/Vm \cdot 740m}$$

$$CONST = \frac{N_e e^2 c \cdot}{6 \cdot \Delta t \cdot \epsilon_0 \cdot \rho} = \frac{3.1 \cdot 10^9 1.6^2 \cdot 10^{-19^2} (As)^2}{25 \cdot 10^{-9} s \cdot 6 \cdot 8.910^{-12} As/Vm \cdot 740m}$$

$$CONST = 7.910^{-14} W$$



Summing up the gammas

$$\Sigma\gamma_s^4 = 2 \cdot \gamma^4_{Linac_1} + \gamma^4_{Linac_2}$$

$$\gamma^4_{Linac_1} = \frac{10GeV}{511keV} = 1.95 \cdot 10^4$$

$$\gamma^4_{Linac_2} = \frac{20GeV}{511keV} = 3.91 \cdot 10^4$$

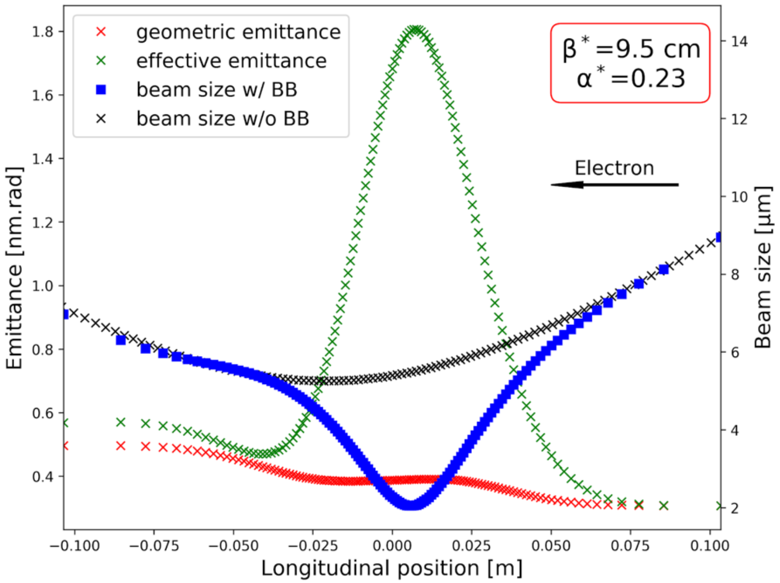
Beam Beam Effect: Electrons

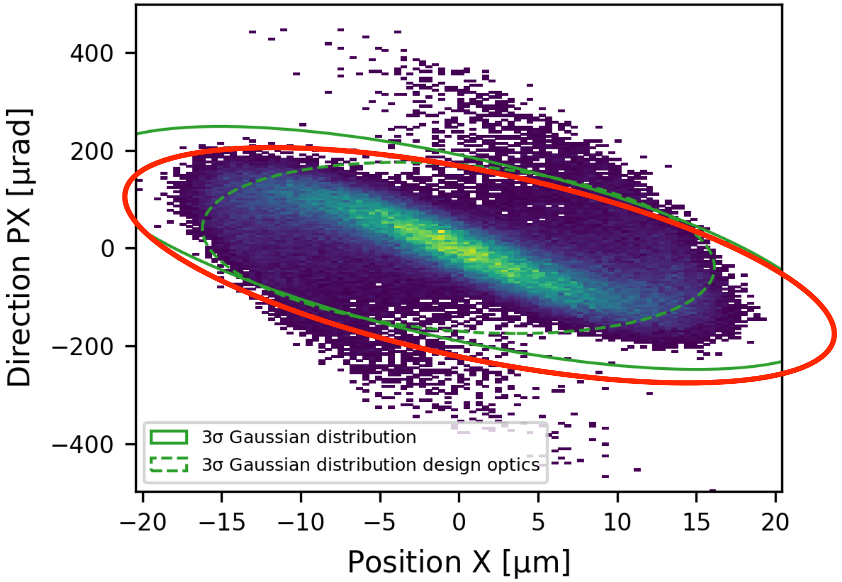
remember: b-b effect ∝ $1/\gamma$
and quasi independent of $\beta*$

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

IR Optics for minimum
Optics mismatch

$E_e = 50GeV, E_p = 7Tev$





Performance Limit: Beam disruption

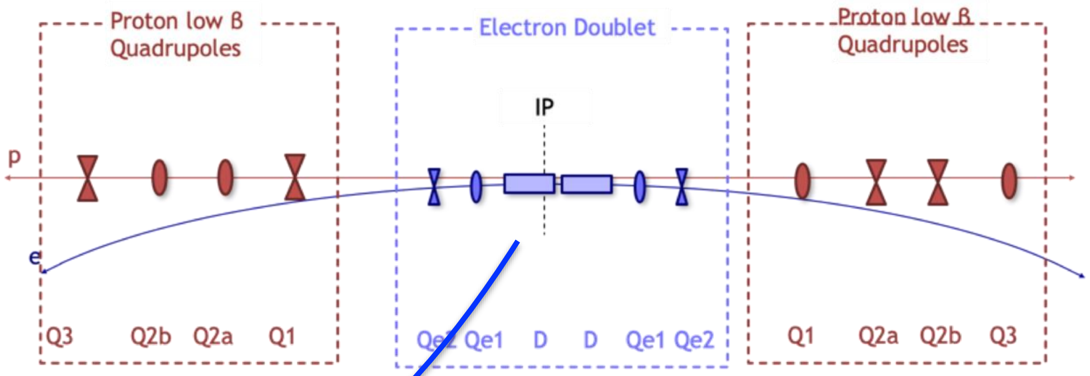
development of tails due to
non-linear beam beam force

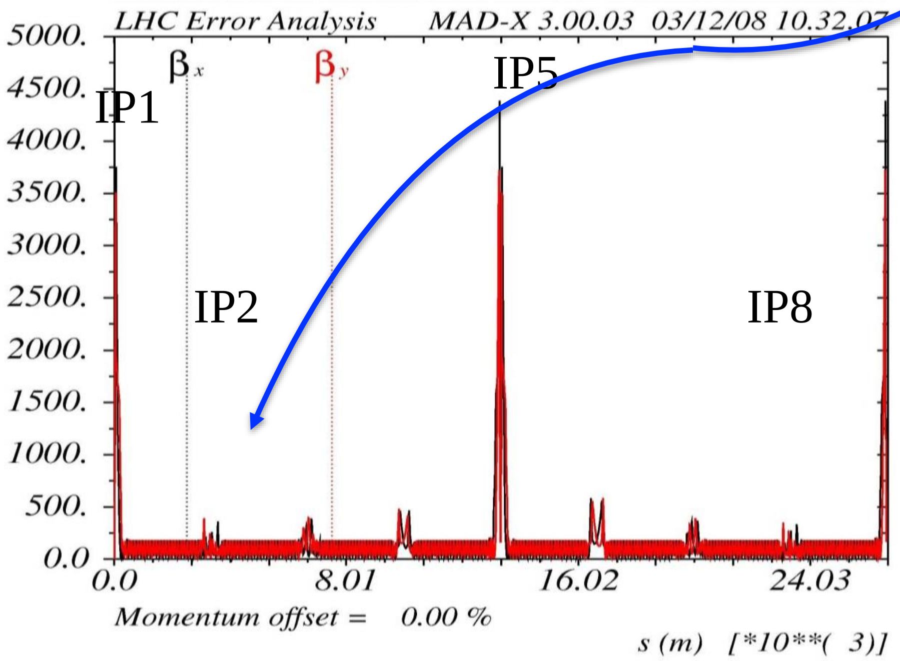
details —> Kevin André

Beam Dynamics “p”

Lattice Design for a e-p Interaction Region

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