»The LHeC
Study of an ERL based Electron Proton Collider at LHC«

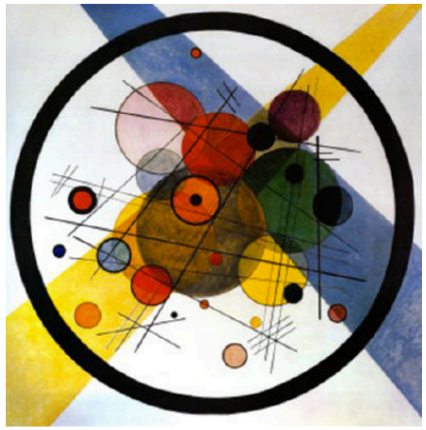
B.J. Holzer for the LHeC and FCC-he Study Group

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

Published in J.Phys. G

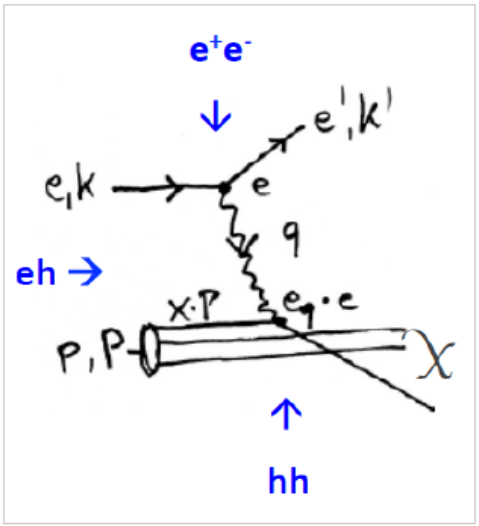
The Large Hadron-Electron Collider at the HL-LHC

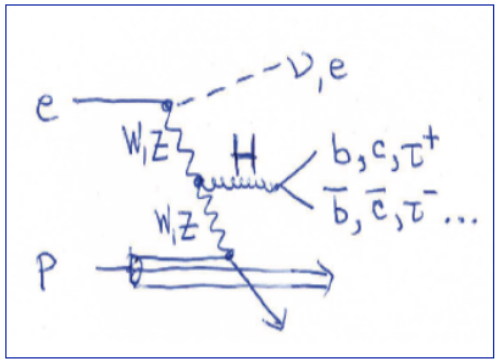
LHeC Study Group

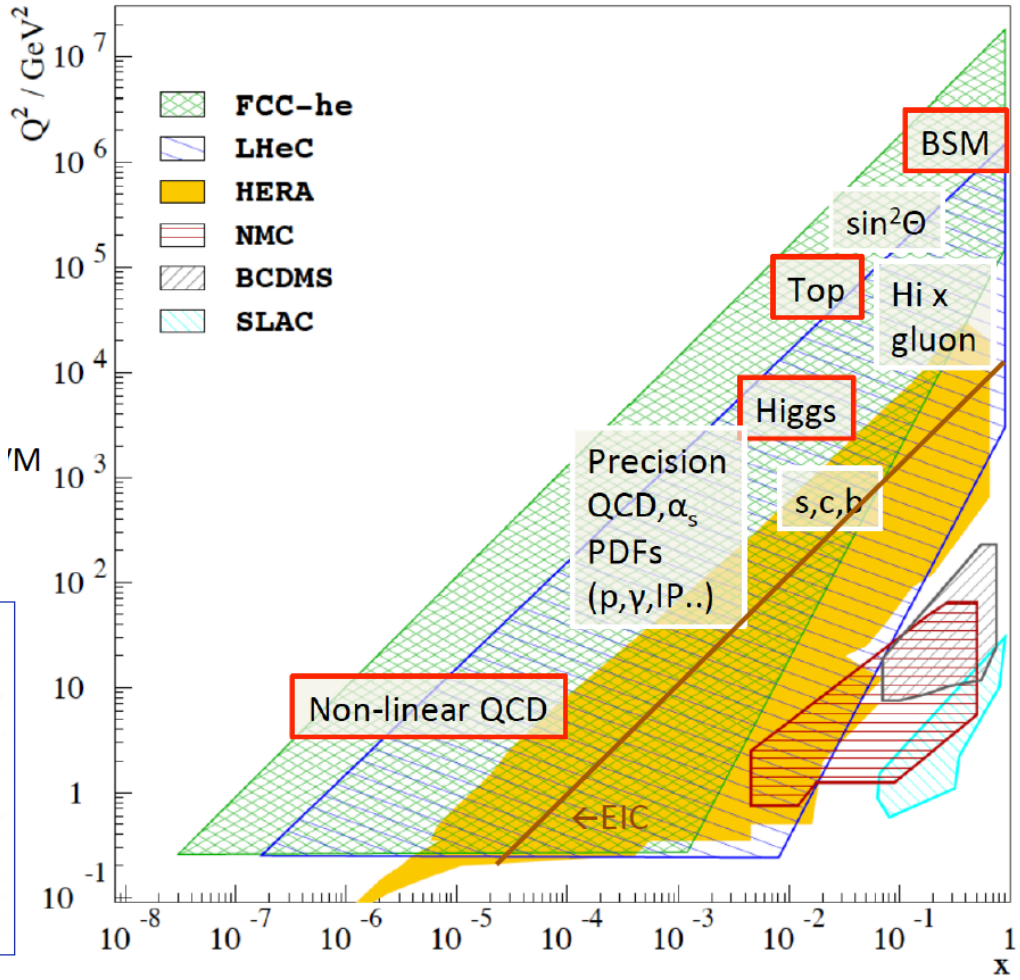


Physics with Energy Frontier DIS

Deep Inelastic Scattering







court. Max Klein

Raison(s) d'etre of ep/ eA at the energy frontier

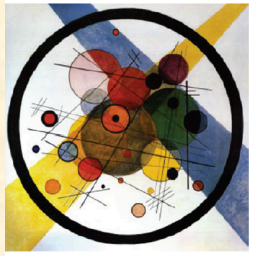
Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC/ FCC Search Programme

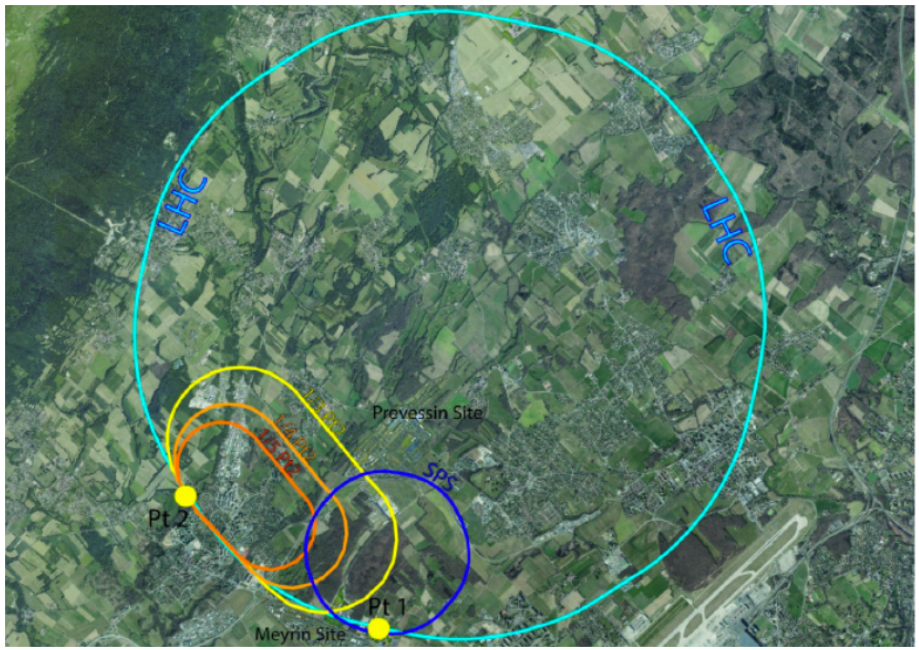
Transformation of LHC/ FCChh into high precision Higgs facility

LHeC / FCC-eh / PERLE

Energy Recovery Linacs towards high resolution DIS



LHeC



50 GeV × 7 TeV

—> 1.2 TeV collider

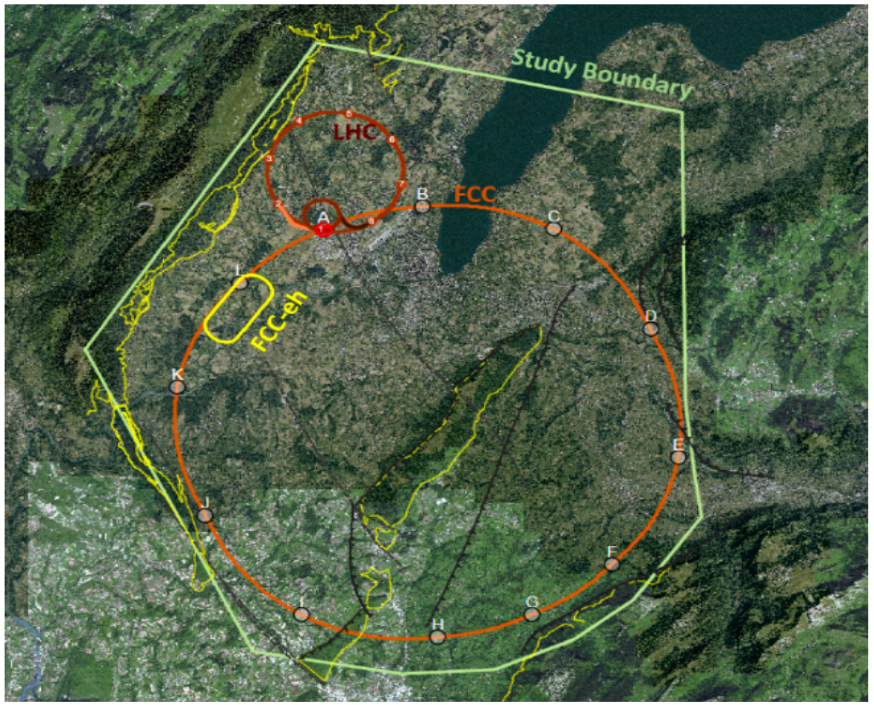
Operation: 2035 +

Cost: 1.3 10^9 CHF (50 GeV ERL)

CDR: 1206.2913 J. Phys.G

CERN Acc. Note-2020-0002

FCC-eh



60 GeV × 50 TeV

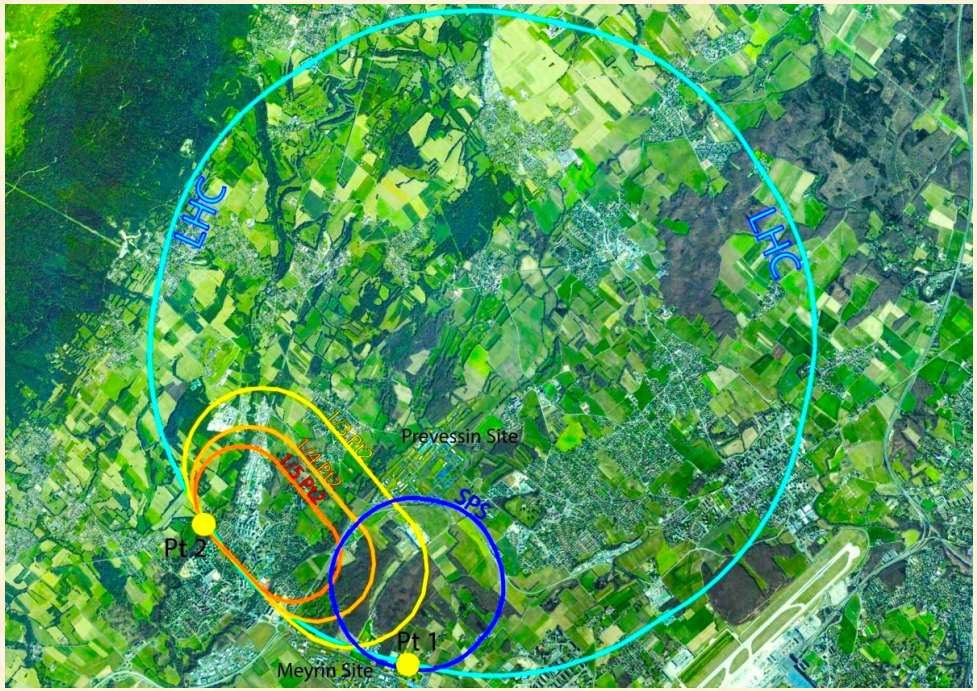
—> 3.5 TeV collider

Operation: 2050 +

Cost: 1-2 10^9 CHF (60 GeV ERL)

FCC-CDR: Eur.Phys.J.ST 228 (2019, 4.755) FCC-hh/eh

General Outline & Main Parameters:

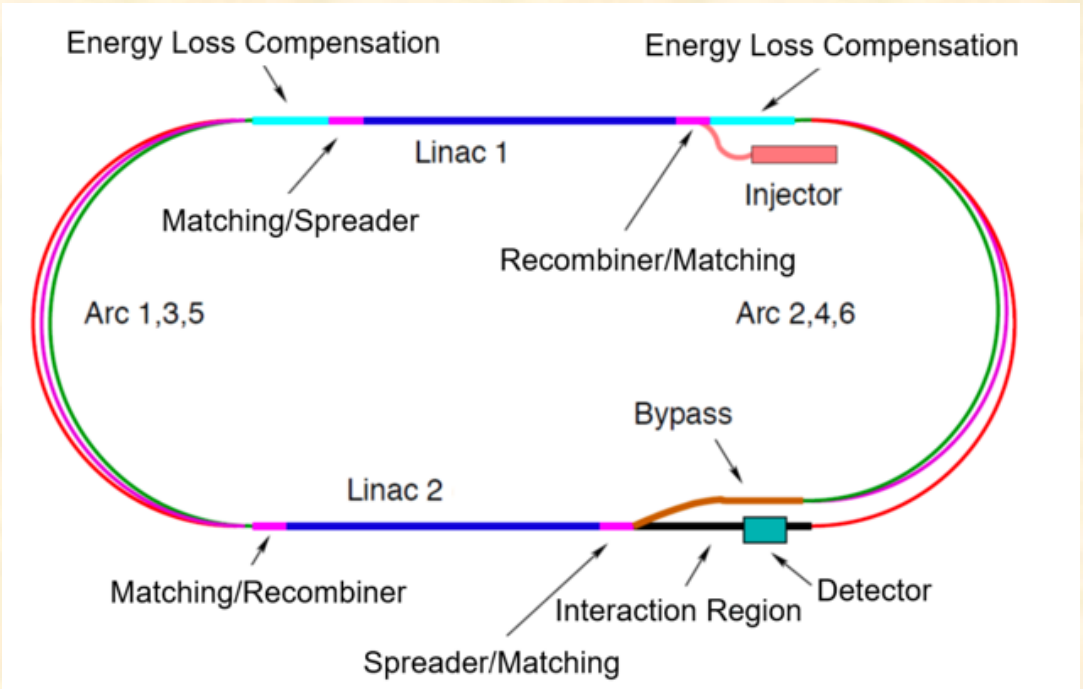


	Electrons
Energy (GeV)	50
N_p /bunch (10^{11})	2.2
N_e /bunch (10^9)	3.1
bunch distance (ns)	25
I_e (mA)	20
Emittance (nm)	0.31
Beam size @ IP (μm)	6 / 6
Luminosity (cm^{-2} s^{-1})	$9*10^{33}$

wall plug power: 100 MW

Combine the LHC proton beam with 50 GeV electrons from a Energy Recovery Linac (ERL)

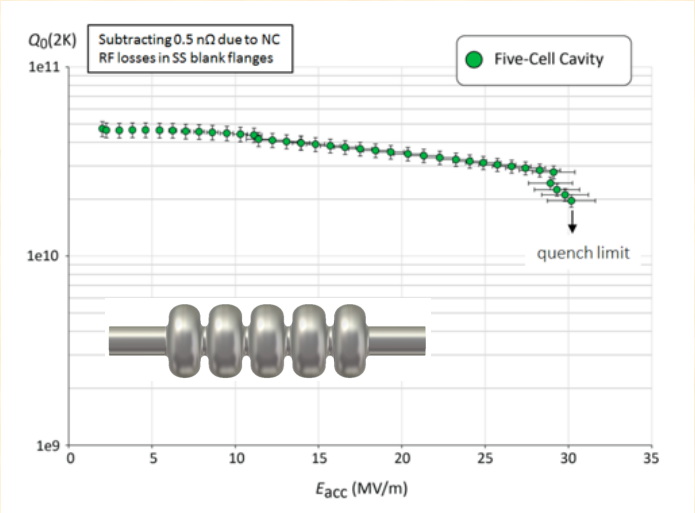
ERL:
three turn racetrack Linac
800 MHz sc. Cavities
Circumference 9 km
Electron Energy 50 GeV



Main Systems:

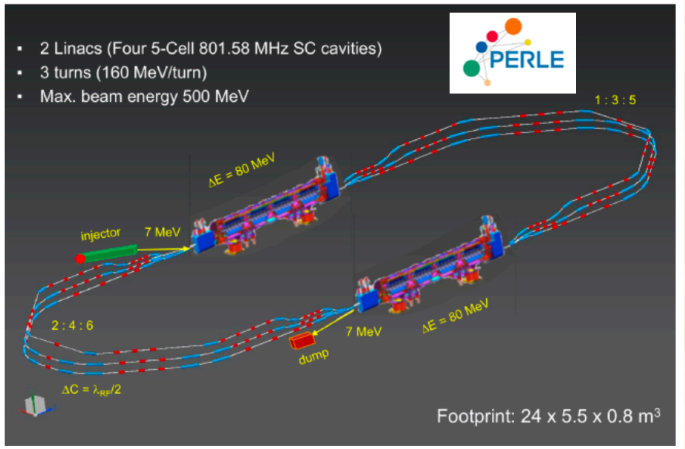
s.c. RF System: 20 MV/m

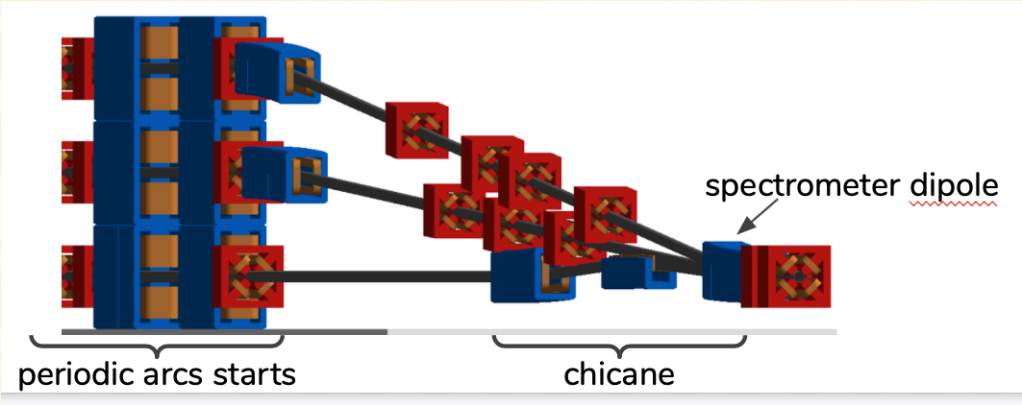
J-lab: Prototype design of a 5 cell cavity



ERL: 20mA, 3 turn

prototype: PERLE



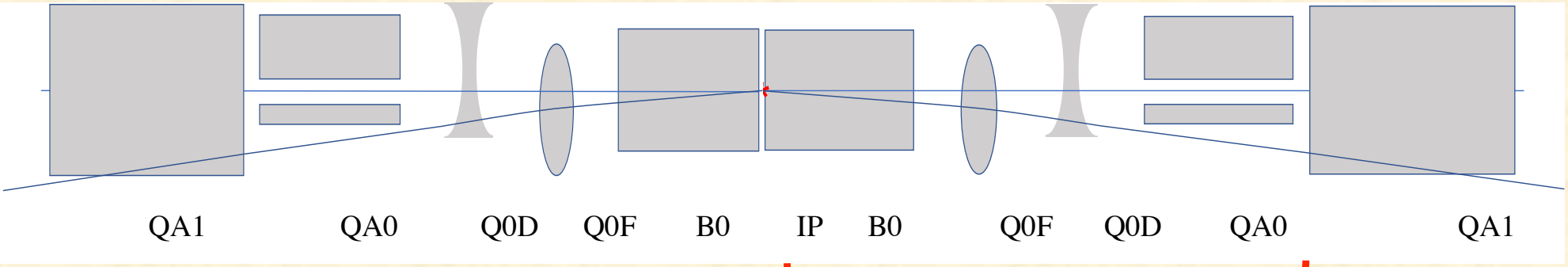


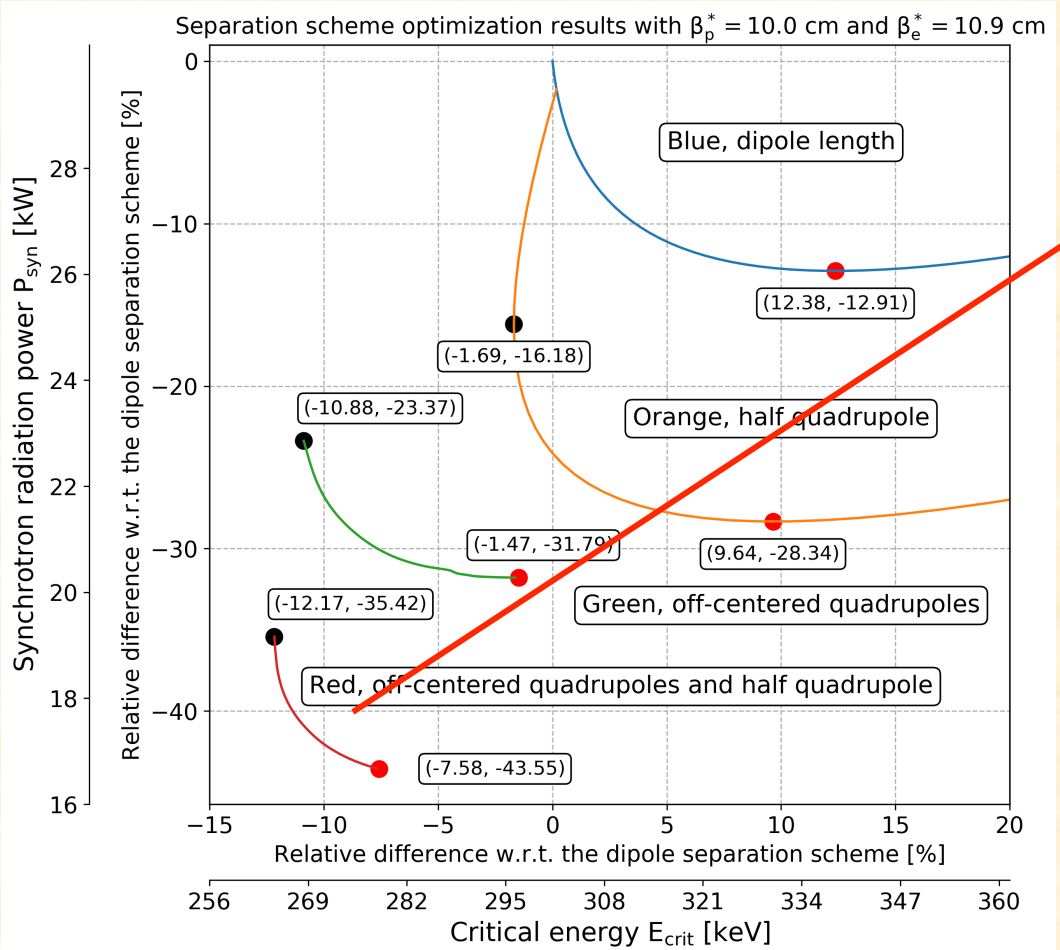
Electron beam spreader / recombiner

—> emittance preservation

$$\Delta\varepsilon_0 = \frac{2\pi}{3} C_q r_0 < \mathcal{H} > \frac{\gamma^5}{\rho^2} \quad , \quad \mathcal{H}_x = \gamma_x(\eta_x)^2 + 2\alpha_x\eta_x\eta_x' + \beta_x(\eta_x')^2 \qquad \text{... per arc}$$

Main Systems: *The Interaction Region, optimise for smallest synchr. radiation*

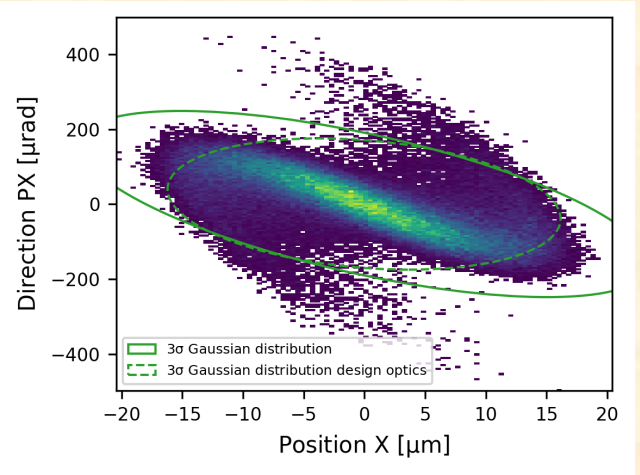




combine a detector integrated dipole field with an early focusing scheme, off-centre quadrupoles ($1/\rho = const$) and very compact proton quadrupole design

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

Beam Physics Challenges:



interaction region:

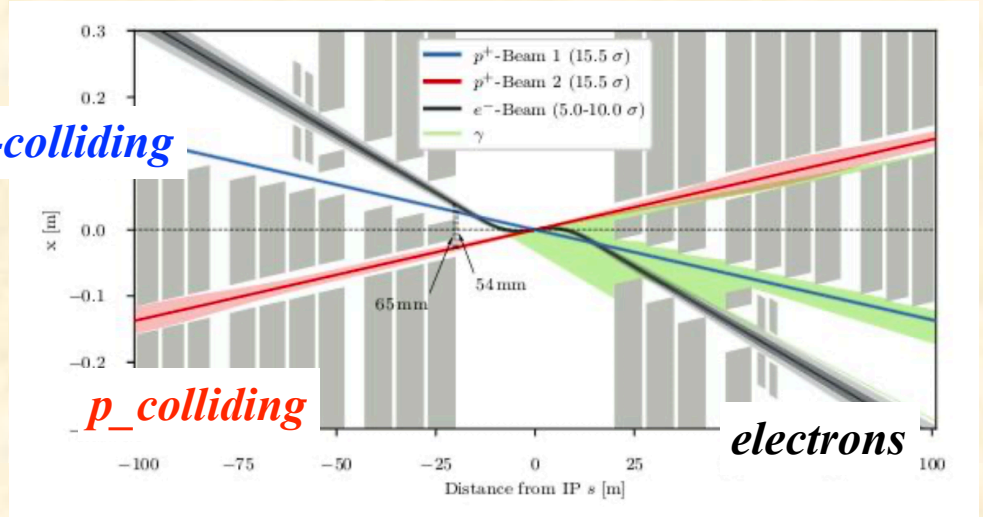
synchrotron radiation,
beam-beam effect
beam optics & separation

energy recovery performance:

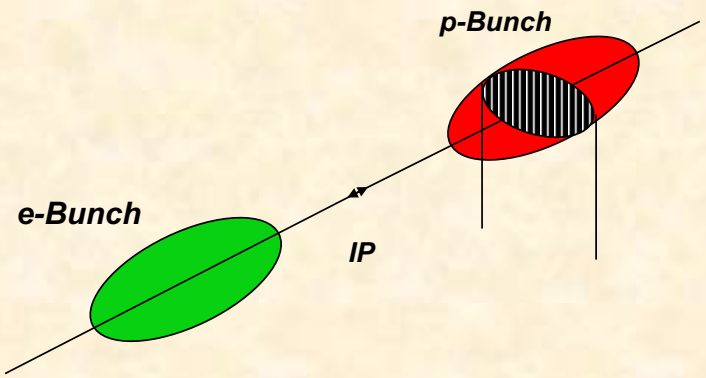
front to end tracking

1/3	unit	Injection	Until IP	Post IP	Dump	Energy recovery
$\varepsilon_{n(x,y)}$	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	

it's a three beam problem



Luminosity



$N_p = 2.2 * 10^{11}$
$N_e = 3.1 * 10^{9}$
$\varepsilon_{en} = 30\ \mu m$
$\varepsilon_{e0} = 3.1 * 10^{-10} m$
$\beta_x^* = 10\ cm$

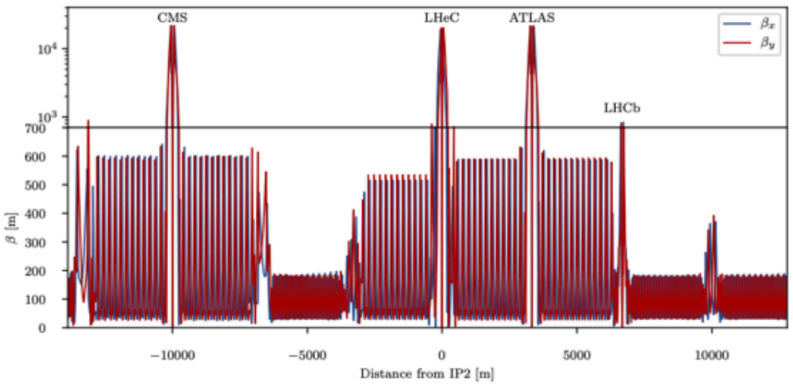
$\Big\}\ \sigma_e^* = 5.8\ \mu m$

"matched beam sizes" required at the IP: $\sigma_x^*(e) = \sigma_x^*(p)\ ,\ \ \sigma_y^*(e) = \sigma_y^*(p)$

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

hourglass factor, $H_1 \simeq 0.9$
pinch or beam-beam factor, $H_2 \simeq 1.3$
filling factor $H_3 = H_{coll} \simeq 0.8$

$\Big\}\ \Sigma_i H_i \approx 1$



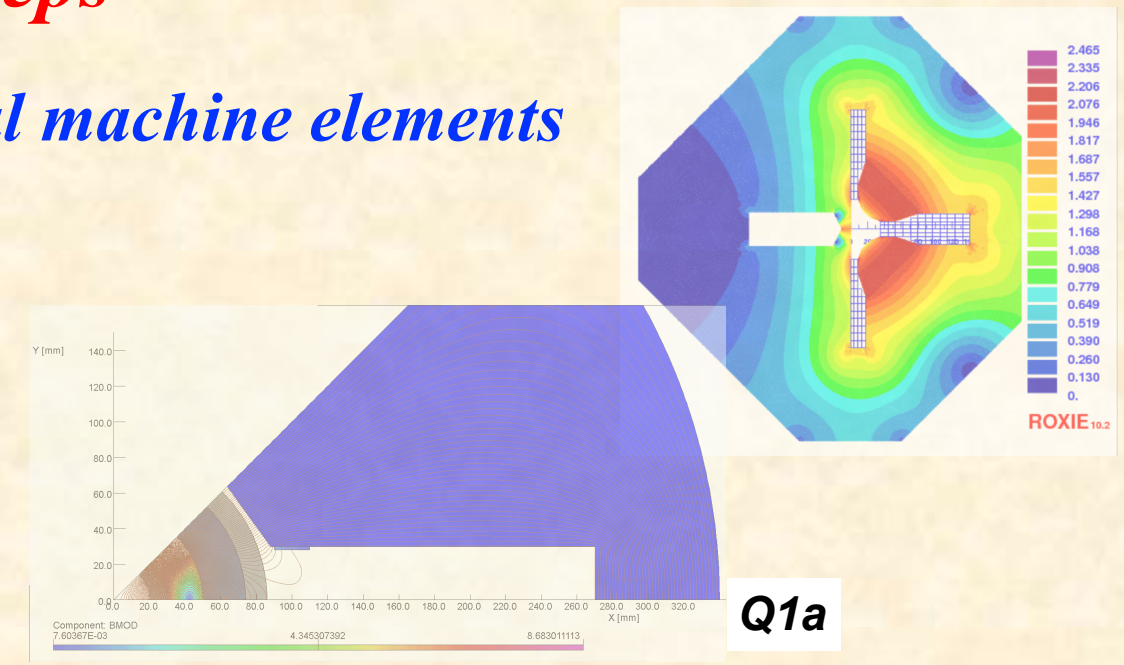
Proton Optics: HL-LHC
"ATS" design

Peak Luminosity: $L \approx 10^{34} cm^{-2} s^{-1}$

The Challenges & Next steps

Design for prototypes of special machine elements

- *half-quadrupole in IR*
- *sc. "field free" quadrupole*

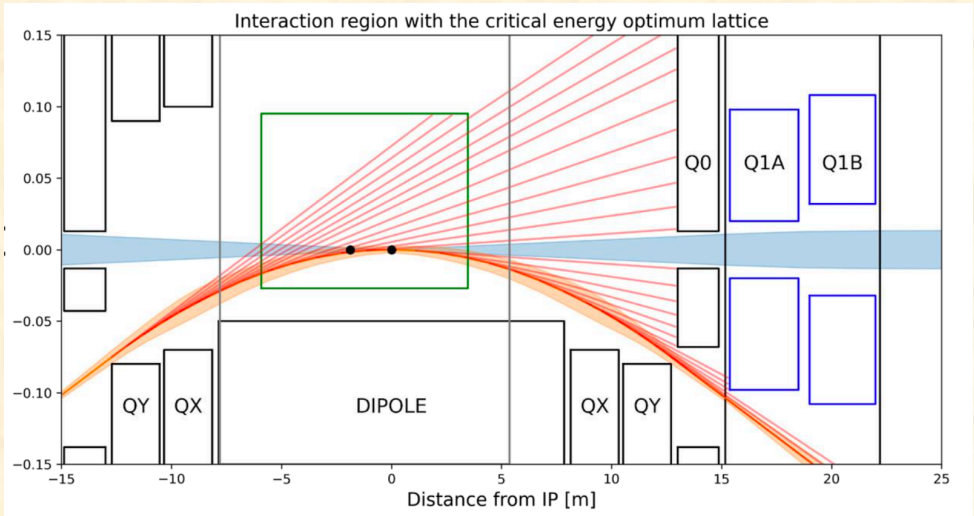


Q1a

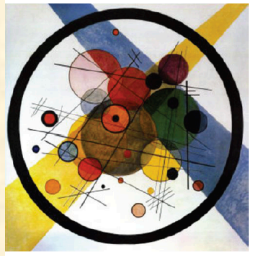
- *R&D is now a time critical factor*

Machine Detector Interface

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



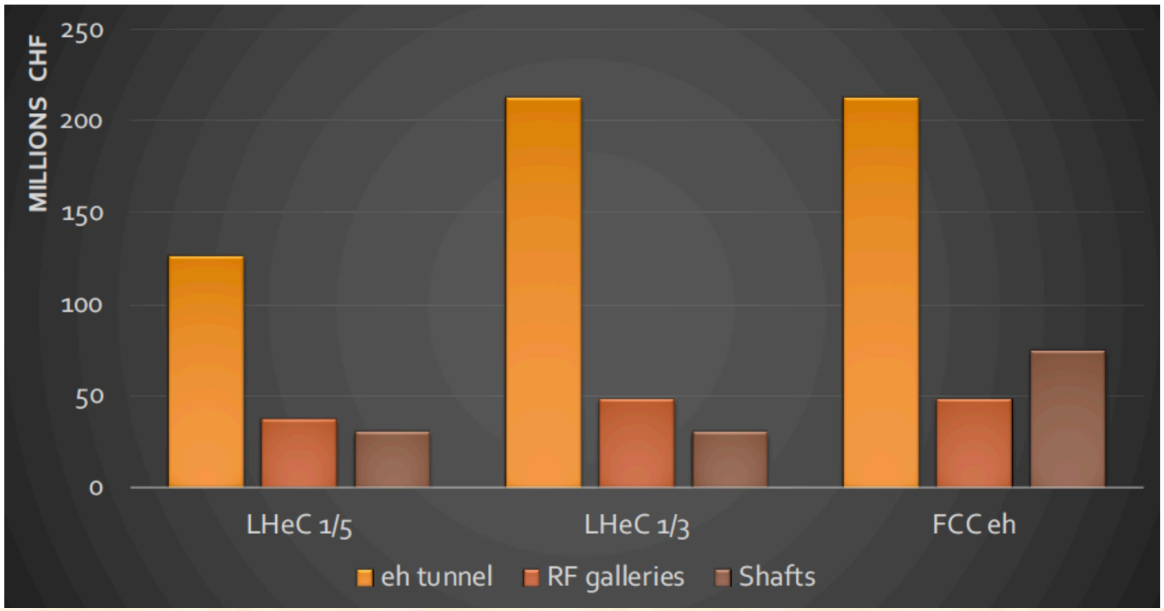
ERL Circumference … & Tunnel cost

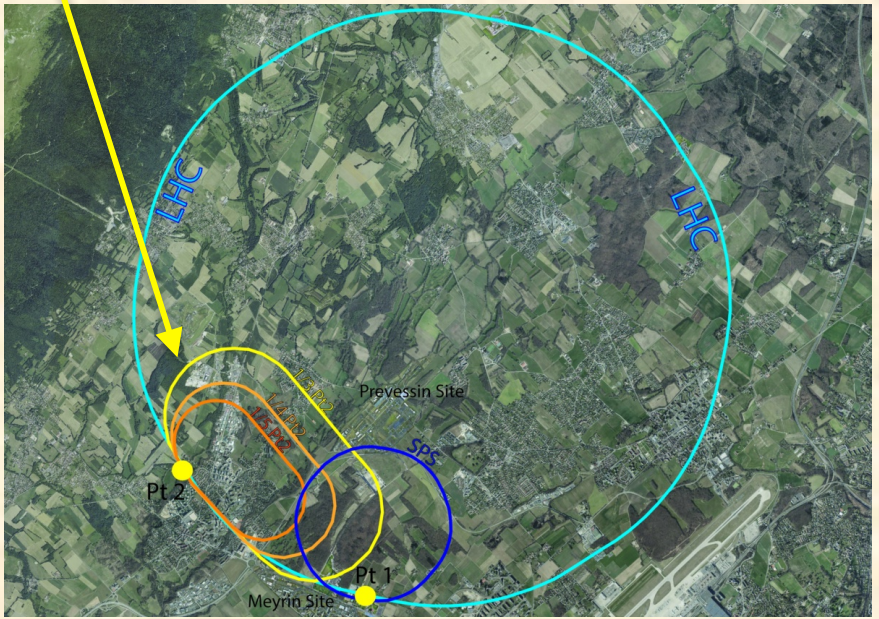


Challenge: find balance between …

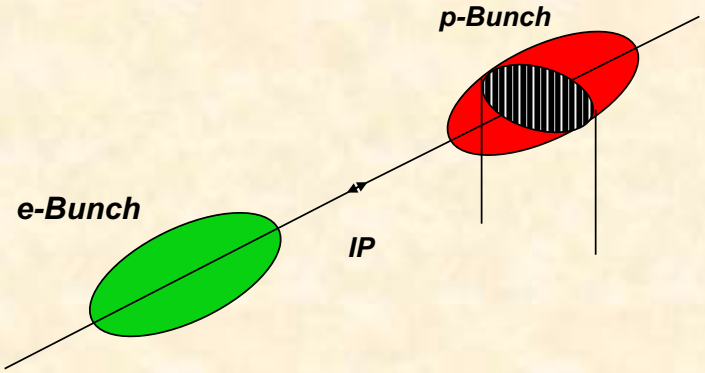
- *construction cost*
- *synchrotron light —> operational cost*
- *energy reach … up to 60 GeV electron energy*

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





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.***

Overall Technical Maturity

2 - Some R&D in a few key areas required

sc quadrupole with field free region

2 - ERL concept

high power ERL

—> PERLE as proof of concept

TDR by 2022,

Phase 0 by 2025, Phase 1 by 2028, Phase 2 by 2030.

Technically limited timeline

≈ 4 ys magnet R&D, & PERLE

Main Advantages:

energy recovery
limit synchrotron losses
to the very last energy step
staging via rf equippment in the linacs,
e.g. start at 30 GeV

The Agora Questionnaire

CoM Energy and upgrades	$E_e = 50GeV,\ \ E_p = 7TeV \ \rightarrow \ E_{cm} \approx 1.3TeV$
Peak Luminosity (10^{34} cm^{-2} s^{-1})	$\approx 10^{34} cm^{-2} s^{-1}$
IP **Challenges**	*MDI, Synchr. rad. background*
Length of facility, km	*9km (ERL) +27 km (LHC)*
Length of new accelerators, km	*9km ... for the 1/3 LHC version*
Beam parameters challenges	*20 mA in 3 pass ERL —> PERLE as prototype*
Special technologies	*ERL technology —> PERLE as prototype*
R&D/validation (yrs. needed); constr. start year	*special sc. magnet with field-free aperture for the e- beam ≈ 4 years R&D, NbTi / Nb_3 Sn*
Construction time, yrs.	*10 + 2 years (estimate)*
Cost (wrt ILC) (+/-, %), level of maturity	$1.3 \cdot 10^9$ *CHF* $\longrightarrow$ 1/10 *ILC*
Environment issues: AC power consumption of facility, resources (Nb, LHe...) needed	*AC power < 100 MW, delib. limited*