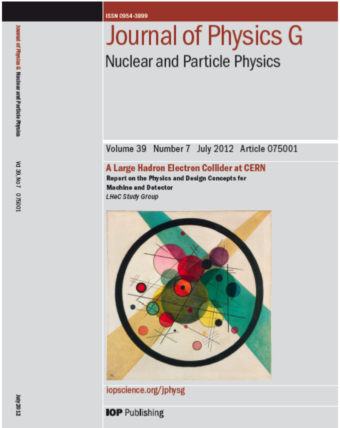
LHeC (HL or HE), FCC-eh and its test facility, PERLE

R. Tomás, D. Pellegrini and M. Klein
for the LHeC Machine Study Group

July 17, 2017

The Large Hadron Electron Collider



http://lhec.web.cern.ch

- ERL facility to provide electrons for collision with HL-LHC, HE-HLC or FCC-eh.

Total grid power consumption < 100 MW

Trade off between energy and luminosity:

- 60 GeV as baseline energy
- Luminosities $\geq 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Next decades

Rolf Heuer at
Aix Les Bains
1. 10. 2013

Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (**ILC** or CLIC) ?)

CERN scientific strategy: 3 main pillars

F. Gianotti, 2017

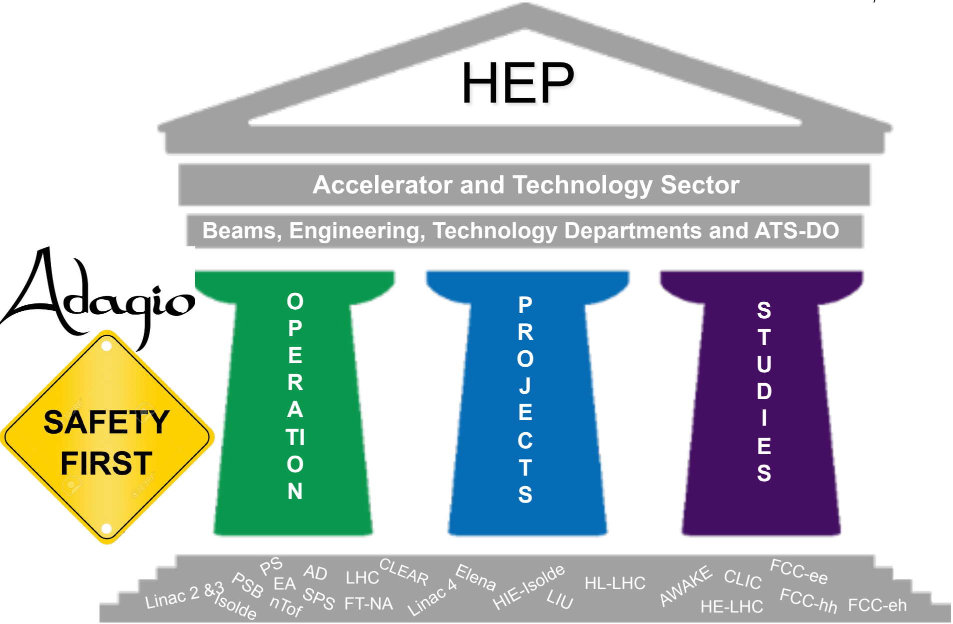
Full exploitation of the LHC:
- ❑ successful operation of the nominal LHC (Run 2, LS2, Run 3)
- ❑ construction and installation of LHC upgrades: LIU (LHC Injectors Upgrade) and HL-LHC

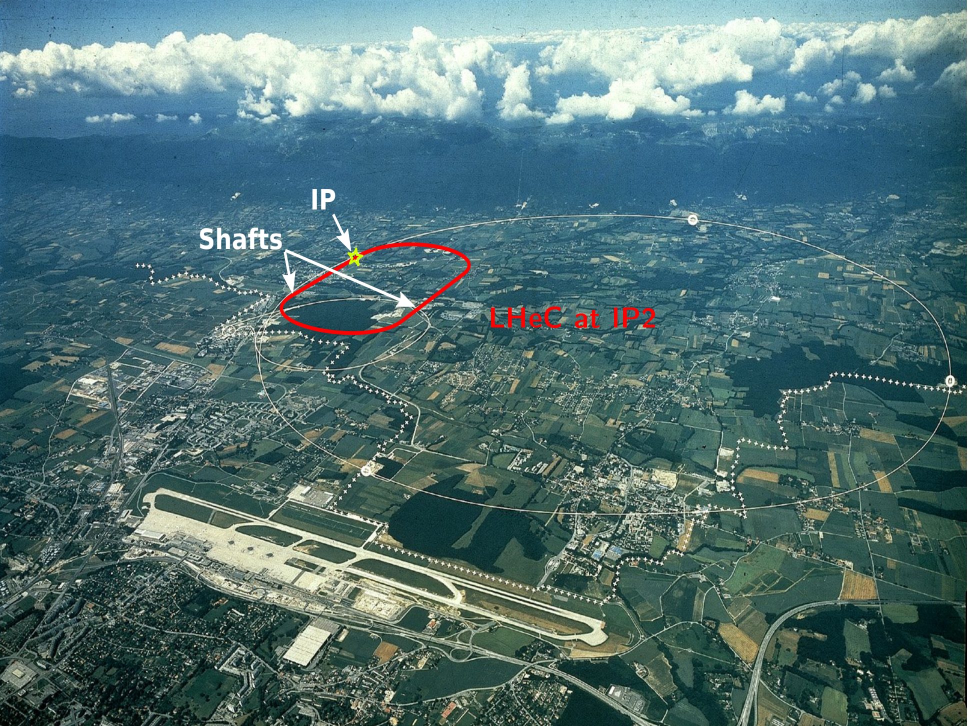
Scientific diversity programme serving a broad community:
- ❑ current experiments and facilities at Booster, PS, SPS and their upgrades (Antiproton Decelerator/ELENA, ISOLDE/HIE-ISOLDE, etc.)
- ❑ participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through CERN Neutrino Platform

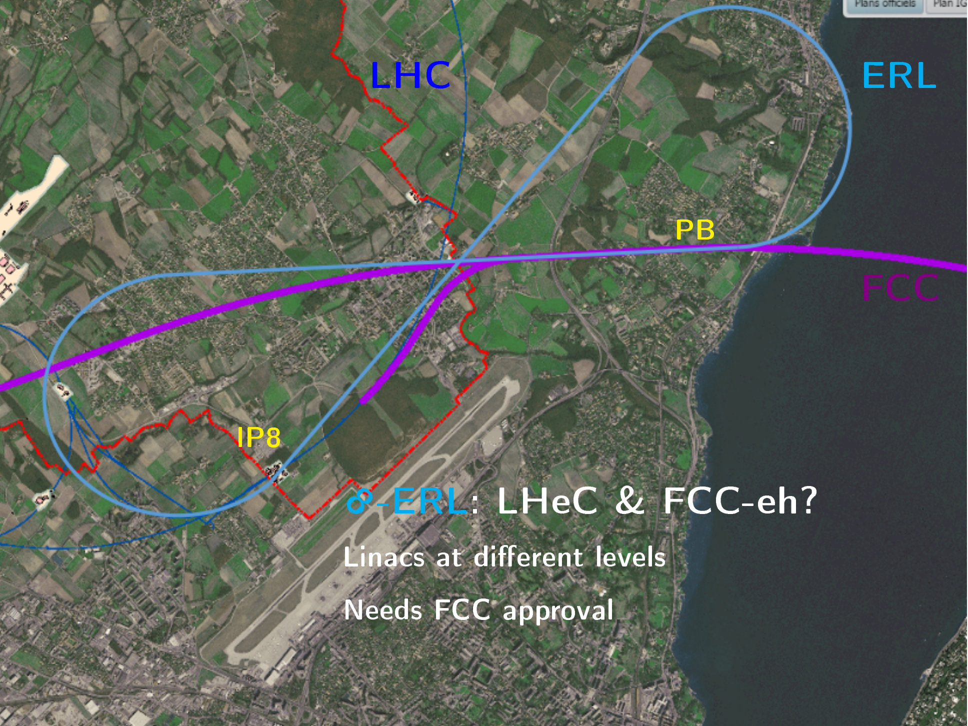
Preparation of CERN's future:
- ❑ vibrant accelerator R&D programme exploiting CERN's strengths and uniqueness (including superconducting high-field magnets, AWAKE, etc.)
- ❑ design studies for future accelerators: CLIC, FCC (includes HE-LHC)
- ❑ future opportunities of scientific diversity programme ("Physics Beyond Colliders" Study Group)

Important milestone: update of the European Strategy for Particle Physics (ESPP), to be concluded in May 2020

F. Gianotti, 2017




IP
Shafts
LHeC at IP2



∞-ERL: LHeC & FCC-eh?

Linacs at different levels

Needs FCC approval

Machine Parameters - ep

CERN-ACC-2017-0019

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

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- 10^{34} allows to collect $\sim$1 ab^{-1} necessary to study the Higgs in many channels with kinematic cuts ($\sigma_{e+p\rightarrow H+X} \approx 200$ fb).

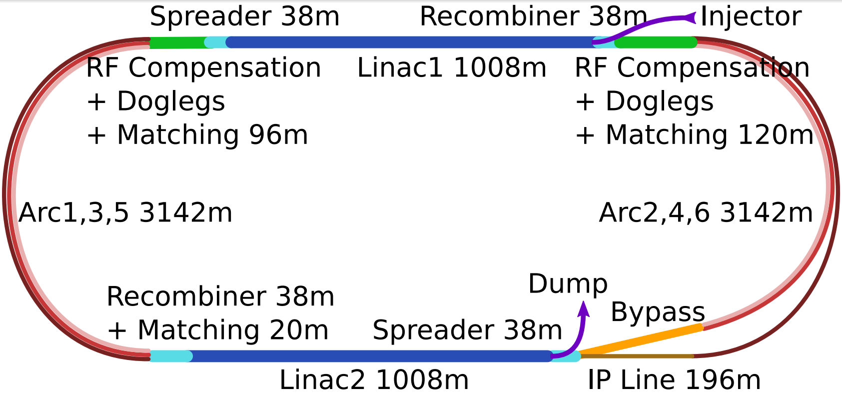
Performance in FCC-eh

Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \rightarrow 1.1$	10
IP betafunction	mm	150	$42 \rightarrow 52$
Nominal RMS beam size	μm	$2.5 \rightarrow 1.8$	$1.9 \rightarrow 2.1$
Waist shift	mm	0	$65 \rightarrow 70$
Bunch population	10^{10}	$10 \rightarrow 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$18.3 \rightarrow 14.3$	
Int. luminosity per 10 years	[ab^{-1}]	1.2	

electron-ion collider configurations

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{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
$\gamma\epsilon_A$ [μm]	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 β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54

ERL baseline design

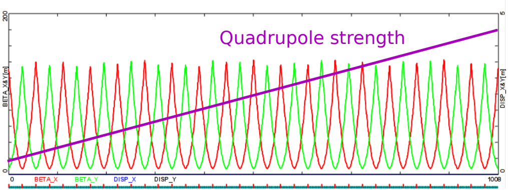


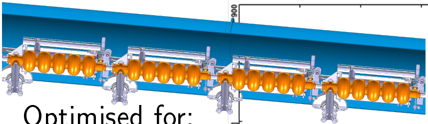
- CW operation: bunches are continuously injected and extracted from the racetrack.
- Bunches at different number of turns (accelerating and decelerating) are interleaved.
- Integer fraction of the LHC length (1/3) so that a gap for ion clearing does not shift with respect to the proton beam.

Two Superconducting Linacs

Each 1 km long, providing 10 GeV acceleration

802 MHz RF, 5-cell cavity:	
λ	37.38 cm
L_c $(5\lambda/2)$	93.45 cm
Gradient	18 MeV/m

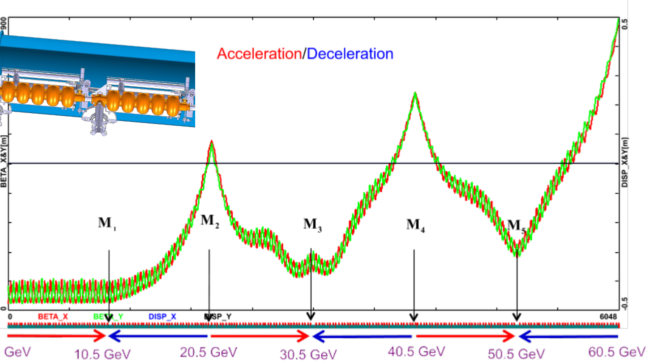




Optimised for:

$$\int \frac{\beta}{E} ds$$

to reduce impact of wakefields.

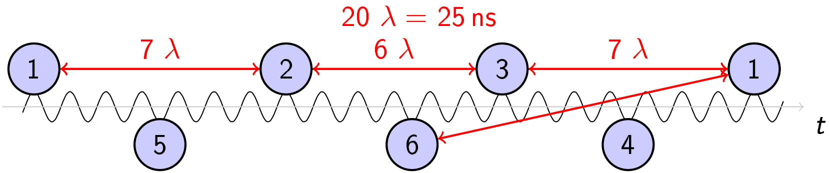


RF frequency and Bunch Pattern

LHC bunch spacing requires bunch spacing with multiples of 25 ns (40.079 MHz).
Available designs:

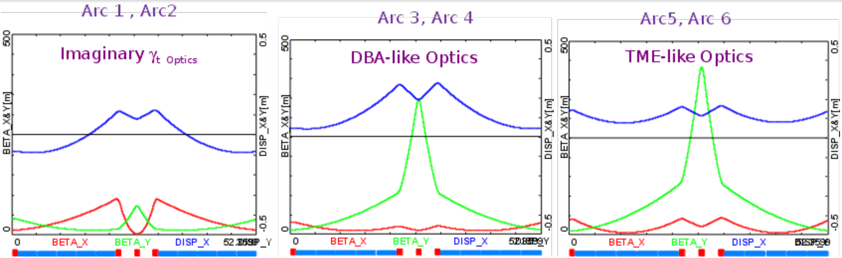
- SPL & ESS: 704.42 MHz
- ILC & XFEL: 1.3 GHz

Chose 801 MHz ($h = 20$) for bucket matching in the LHC and for synergies with FCC.
Not a 6-fold multiple of 25 ns. Spacing in linac is a bit irregular.



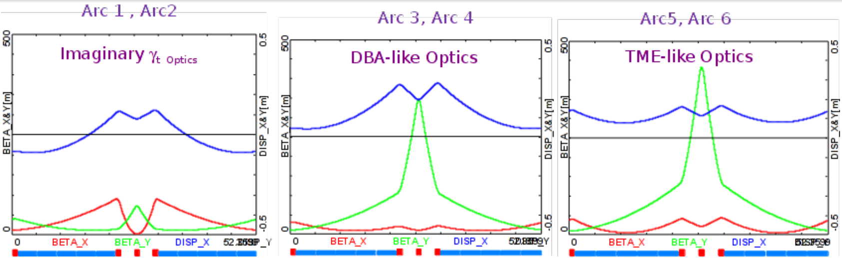
Max separation between the bunches at 1st and 6th turn to mitigate wakefields.

Arcs – Flexible Momentum Compaction



- 1 km radius for all of them, stacked vertically.
- Tunable cells:
  - Highest energy arcs are tuned to minimize the energy spread induced by synchrotron radiation,
  - Lowest energy arcs are tuned to contain the beam size and compensate for the bunch lengthening.

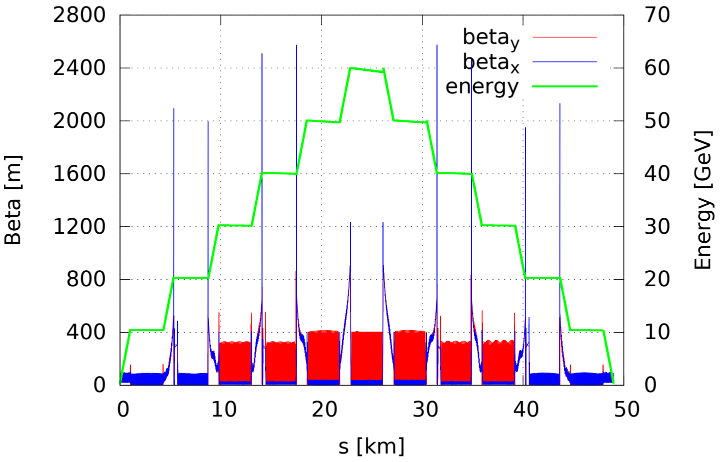
Arcs – Flexible Momentum Compaction



- 1 km radius for all of them, stacked vertically.
- Tunable cells:
  - Highest energy arcs are tuned to minimize the energy spread induced by synchrotron radiation,
  - Lowest energy arcs are tuned to contain the beam size and compensate for the bunch lengthening.
- Possibility for FFAG arcs?
  - Tracking simulations with strong-focussing combined-function magnets performed for Arc 6 (on energy: uniform bending) looked ok.
  - Need for a full design and experimental validation.

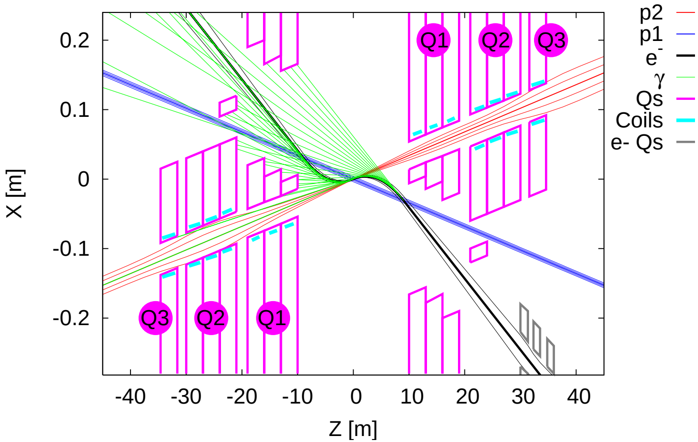
End-to-end Optics

Computed with PLACET2, extracting the optics parameters from the particles distribution followed from the injector to the dump.



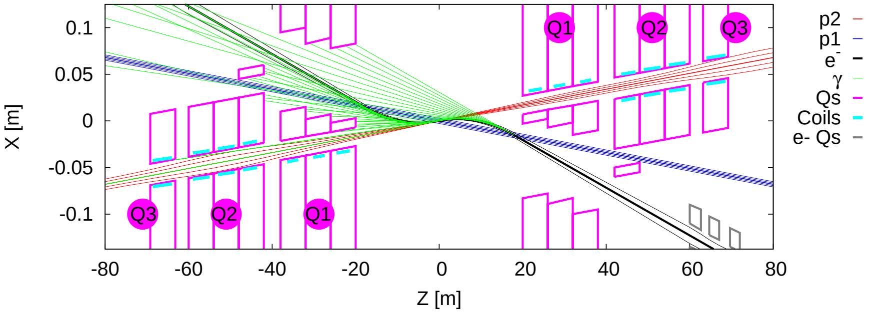
Notable: the energy loss due to synchrotron radiation in Arc 6, the different average β in the arcs, the recovery of the mismatch generated in the linacs.

Interaction Region - LHeC

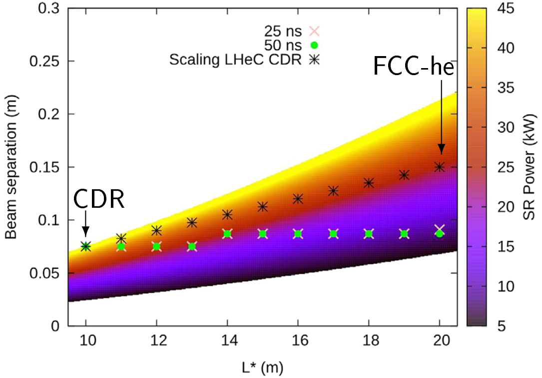


Interaction Region - FCC-eh

Factor 2 length and β scale:



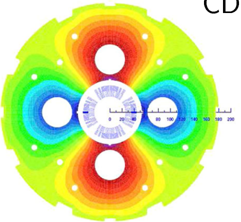
Synchrotron radiation power in the IR dipoles



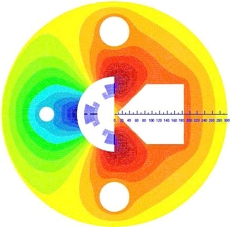
E. Cruz et al, Phys. Rev. ST Accel. Beams **18**, 111001 (2015)

IR magnet design

CDR



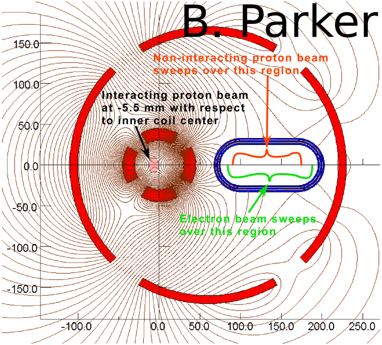
Q2



Q1

New proposal for Q1:

Requires larger xsing angle or L*

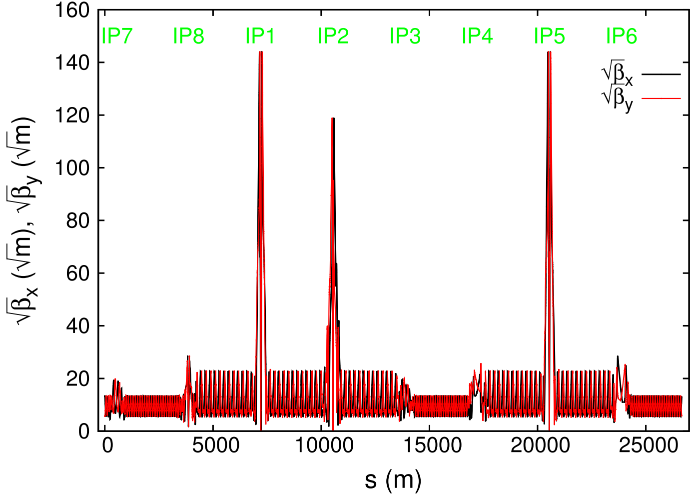


Why not using Crab Cavities?

- LHeC full crossing angle is about $\approx$60 mrad
- Example: HL-LHC crossing angle is $\approx$500 μrad (6.8 MV of CCs per IP side, per beam). Impedance and emittance growth are a serious concerns
- LHeC would need 120 times more CCs than HL-LHC $\rightarrow$ 800 MV

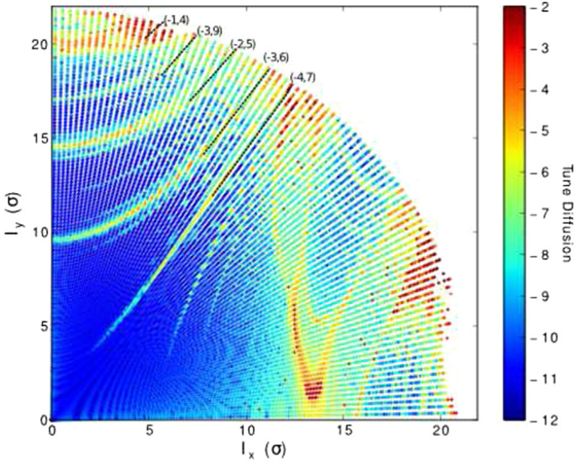
Proton optics - Extended ATS

ATS beta-beating wave over 3 arcs to squeeze IP1 and IP2:



E. Cruz et al, Phys. Rev. ST Accel. Beams **18**, 111001 (2015)

Proton Dynamic Aperture, LHeC



L*=10m

β^*=10cm

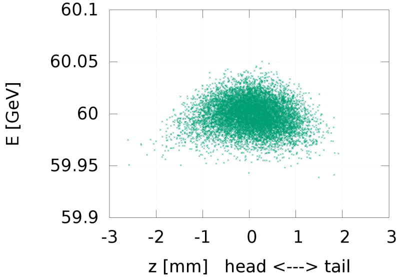
DA is about 14σ. There might be margin for slightly longer L* (same β^*) or smaller β^* (same L*). Current design goal is β^*=7cm.

e^- beam at the IP

Higgs Factory Parameters - $L = 10^{34}$ cm^{-2}s^{-1}

Injection/Dump Energy	500 MeV
Bunch Spacing	25 ns
Particles per bunch	$4 \times 10^9 = 640$ pC
Normalised RMS Emittance	50 μm
IP β function	0.032 m

Longitudinal phase space at IP

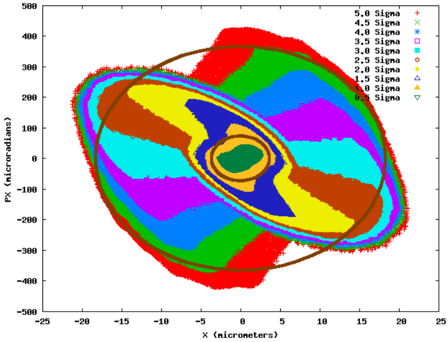


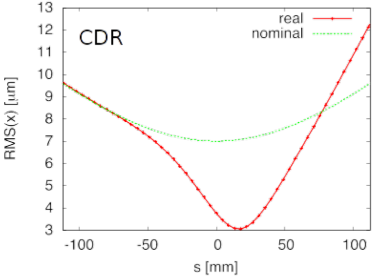
	initial/CDR	IP
ε_x [μm]	50	57.4
ε_y [μm]	50	50.8
δ	0.0020	0.0026
RMS x [μm]	7.20	7.66
RMS y [μm]	7.20	7.21
RMS z [mm]	0.600	0.601
RMS e [MeV]	-	15.4

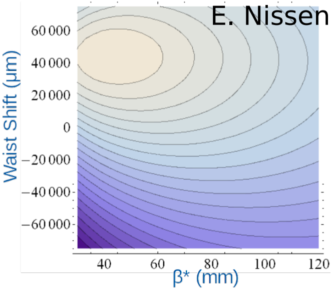
- The beam at the IP maintains a very good quality, still need to verify imperfections and stability;

Beam-Beam effect

Effect of the proton beam on the electron beam with the high lumi parameters:







Tails are folded back, but the core is disrupted.

Beta [mm]	Waist [mm]	Luminosity [$10^{33}cm^{-2}s^{-1}$]
120	0	8.1
120	45	9.6
39	45	9.8

PERLE

Powerful Energy Recovery Linac for Experiments

Conceptual Design Report

to be published in J.Phys.G

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and
ASTeC Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab
Newport News, BINP Novosibirsk, IPN and LAL Orsay

May 13^{th}, 2017

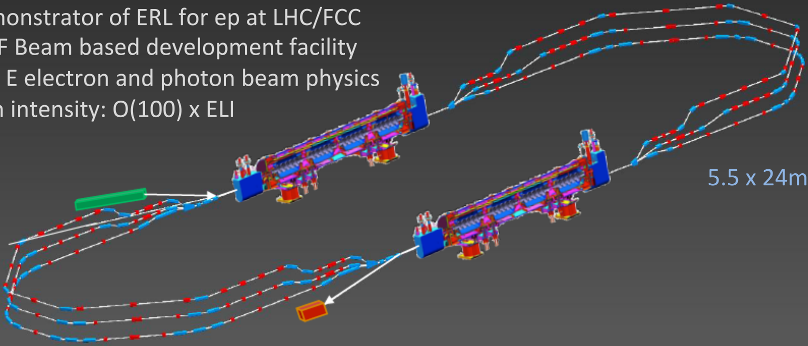
Powerful ERL for Experiments (ep,γp): PERLE at Orsay

title

PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +

3 turns, 2 Linacs, 400 MeV, 15mA, 802 MHz, Energy Recovery Linac facility

- -Demonstrator of ERL for ep at LHC/FCC
- -SCRF Beam based development facility
- -Low E electron and photon beam physics
- -High intensity: O(100) x ELI



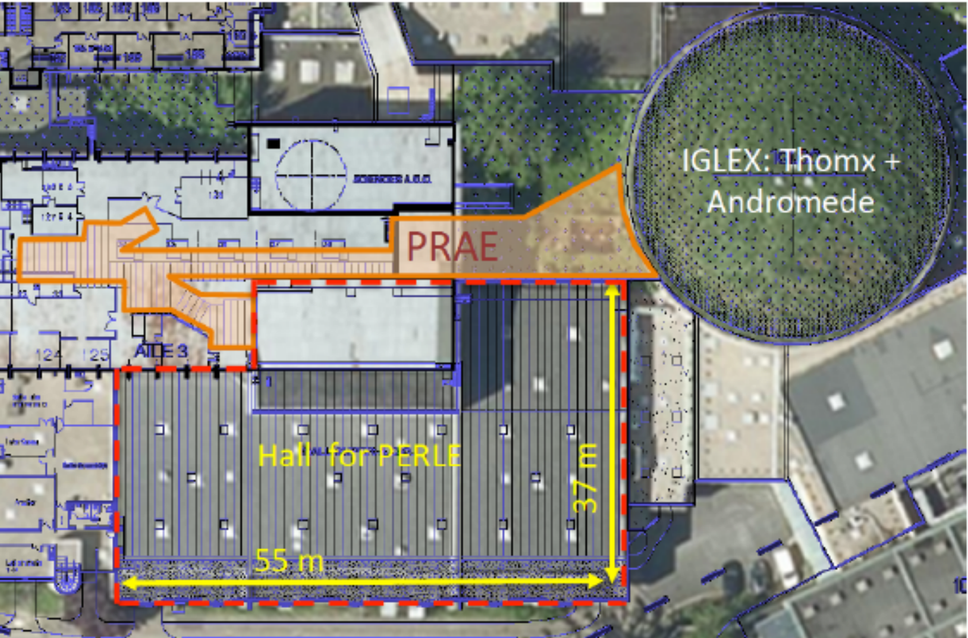
5.5 x 24m^2

CDR to appear in J Phys G [arXiv:1705. 08783]

See also https://indico.lal.in2p3.fr/event/3428/

A.Bogacz

The PERLE site



Outlook

- Large spectrum of ep and eA physics at the TeV energy scale (LHC, HL-LHC, HE-LHC, FCC-eh) with high luminosity: $1 \times 10^{34}\,\mathrm{Hz\,cm}^{-2}$ for ep and $\sim 1 \times 10^{33}\,\mathrm{Hz\,cm}^{-2}$ for eA,
- A new facility with a potential user community beyond HEP
- Main challenges:
  - High energy, high power ERL
  - IR design with synchrotron radiation β^{*}=7cm; magnet design
  - Transparent operation to proton/ion physics

Need for a demonstrator: PERLE@Orsay

PERLE CDR: `https://arxiv.org/abs/1705.08783`