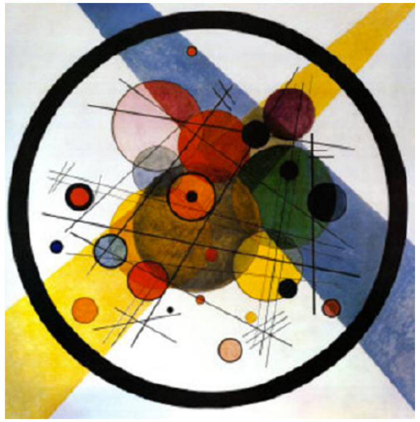
Introduction and Synergies

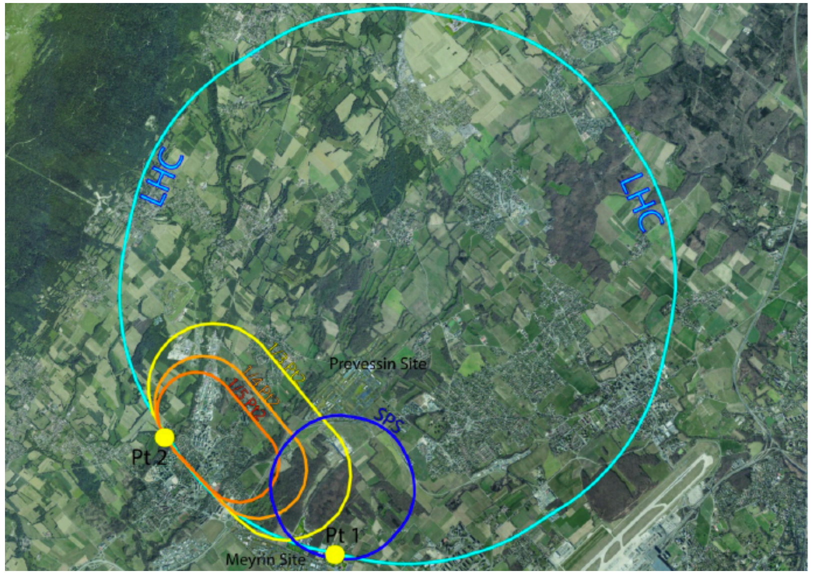
Max Klein (U Liverpool) with Oliver Bruening (CERN)
For the LHeC/PERLE/FCC-eh Collaboration (global)

Overview
Physics
Prospects
Developments
Synergies



Parallel Session on FCC-eh, on-line FCC Workshop, 12.11.2020

LHeC, PERLE and FCC-eh



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)

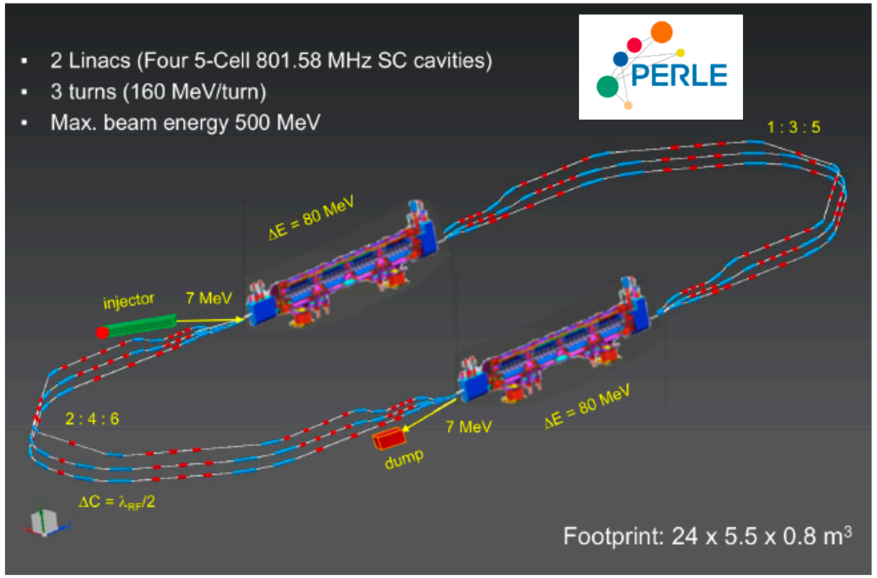
arXiv:2007.14491, subm J.Phys.G

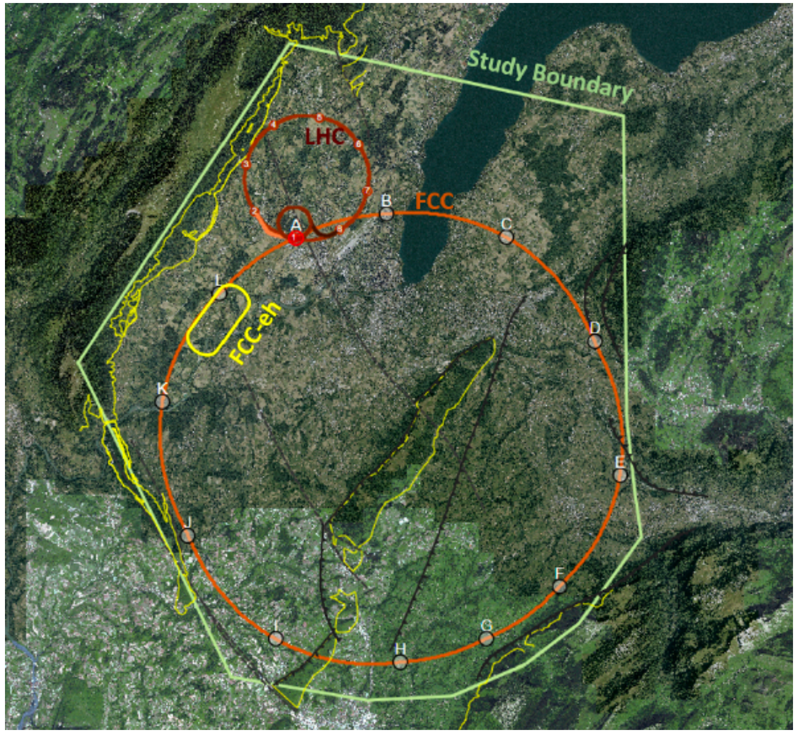
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

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), +





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+

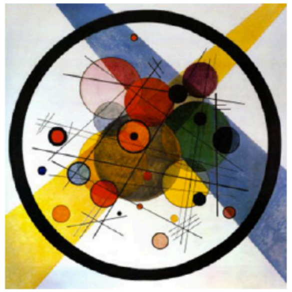
Published in 2020

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group



arXiv:2007:14491 (400 pages, 300 authors)

To be submitted to J. Phys. G

5 page summary: ECFA Newsletter Nr 5., August 20

https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

P. Agostini[1], H. Aksakal[2], H. Alan[3], S. Alekhin[4,5], P. P. Allport[6], N. Andari[7], K. D. J. Andre[8,9], D. Angal-Kalinin[10,11], S. Antusch[12], L. Aperio Bella[13], L. Apolinario[14], R. Apsimon[15,11], A. Apyan[16], G. Arduini[9], V. Ari[17], A. Armbruster[9], N. Armesto[1], B. Auchmann[9], K. Aulenbacher[18,19], G. Azuelos[20], S. Backovic[21], I. Bailey[15,11], S. Bailey[22], F. Balli[7], S. Behera[23], O. Behnke[24], I. Ben-Zvi[25], M. Benedikt[9], J. Bernauer[26,27], S. Bertolucci[9,28], S. S. Biswal[29], J. Blümlein[24], A. Bogacz[30], M. Bonvini[31], M. Boonekamp[32], F. Bordry[9], G. R. Boroun[33], L. Bottura[9], S. Bousson[7], A. O. Bouzas[34], C. Bracco[9], J. Bracinik[6], D. Britzger[37], S. J. Brodsky[36], C. Bruni[7], O. Brüning[9], H. Burkhardt[9], O. Cakir[17], R. Calaga[9], A. Caldwell[37], A. Calıskan[38], S. Camarda[9], N. C. Catalan-Lasheras[9], K. Cassou[39], J. Cepila[40], V. Cetinkaya[41], V. Chetvertkova[9], B. Cole[42], B. Coleppa[43], A. 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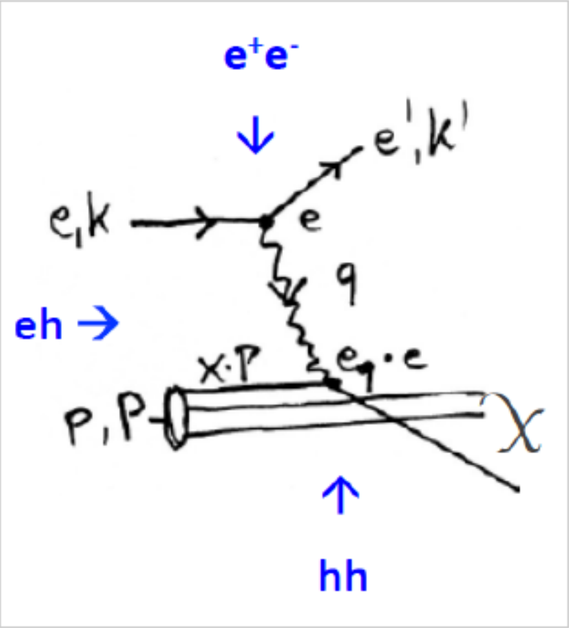
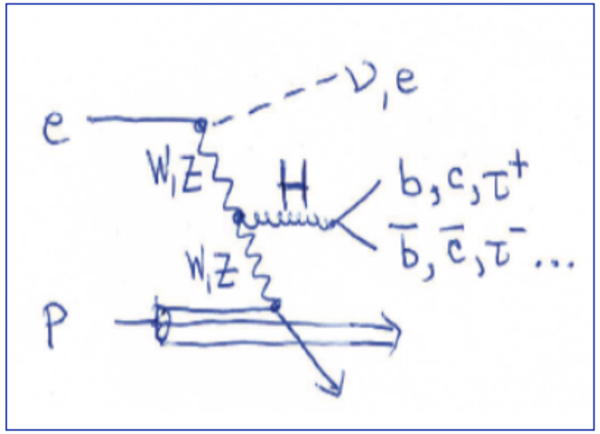
Tywoniuk[143], C. Vallerand[39], A. Valloni[9], D. Verney[39], E. Vilella[8], D. Walker[46], S. Wallon[39], B. Wang[95,96], K. Wang[95,96], K. Wang[144], X. Wang[101], Z. S. Wang[145], H. Wei[146], C. Welsch[8,11], G. Willering[9], P. H. Williams[10,11], D. Wollmann[9], C. Xiaohao[13], T. Xu[147], C. E. Yaguna[148], Y. Yamaguchi[83], Y. Yamazaki[149], H. Yang[150], A. Yilmaz[82], P. Yock[151], C. X. Yue[71], S. G. Zadeh[152], O. Zenaiev[9], C. Zhang[153], J. Zhang[154], R. Zhang[62], Z. Zhang[39], G. Zhu[95,96], S. Zhu[132], F. Zimmermann[9], F. Zomer[39], J. Zurita[155,156] and P. Zurita[35]

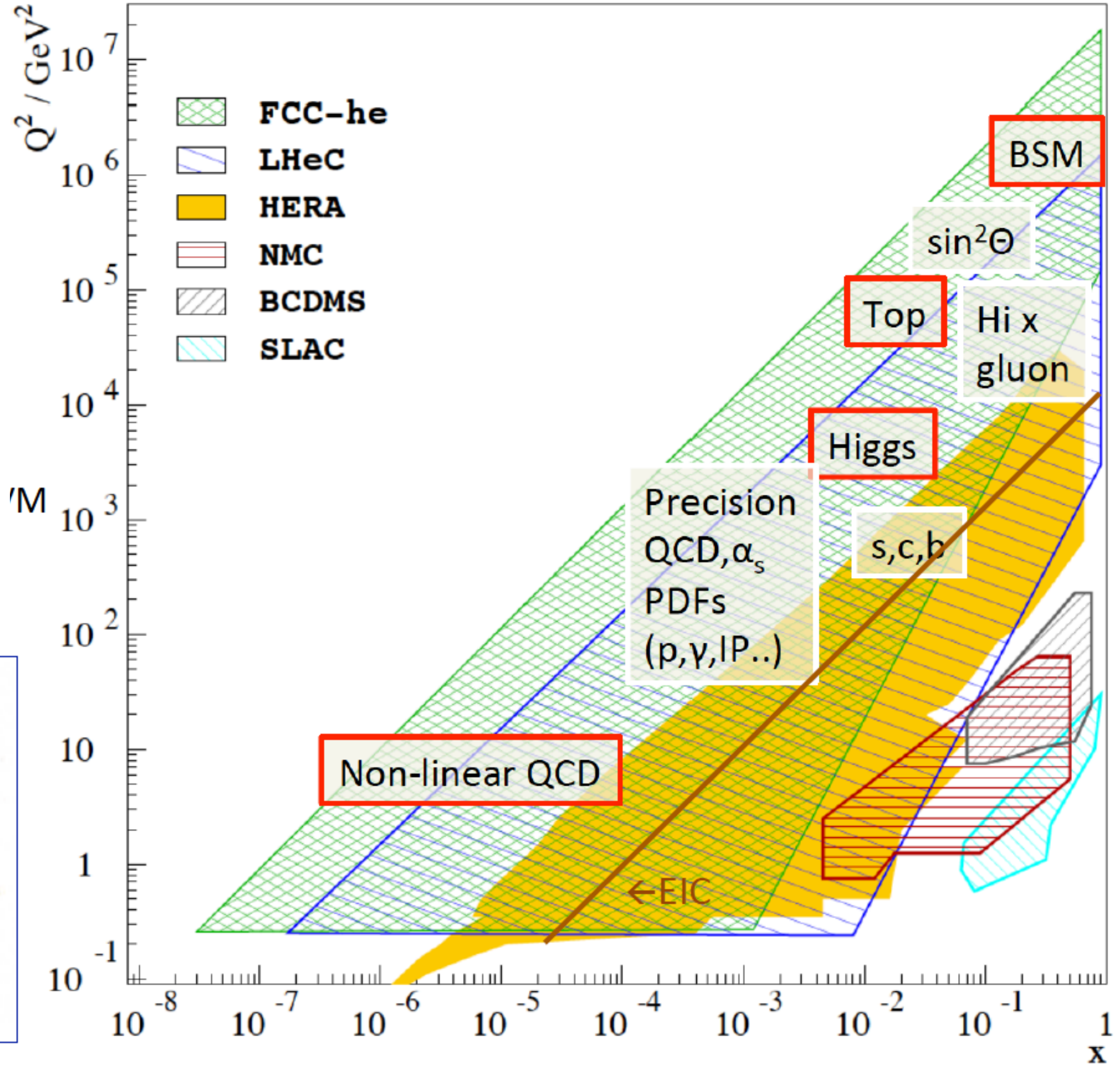
156 Institutions involved

Physics with Energy Frontier DIS

Deep Inelastic Scattering







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

Discovery (top, H, heavy ν's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

Talks at this workshop:
C Schwanenberger eh+hh+ee
M Bonvini Low x Physics
D Britzger electroweak physics

Higgs in ep and pp [LHC and FCC]

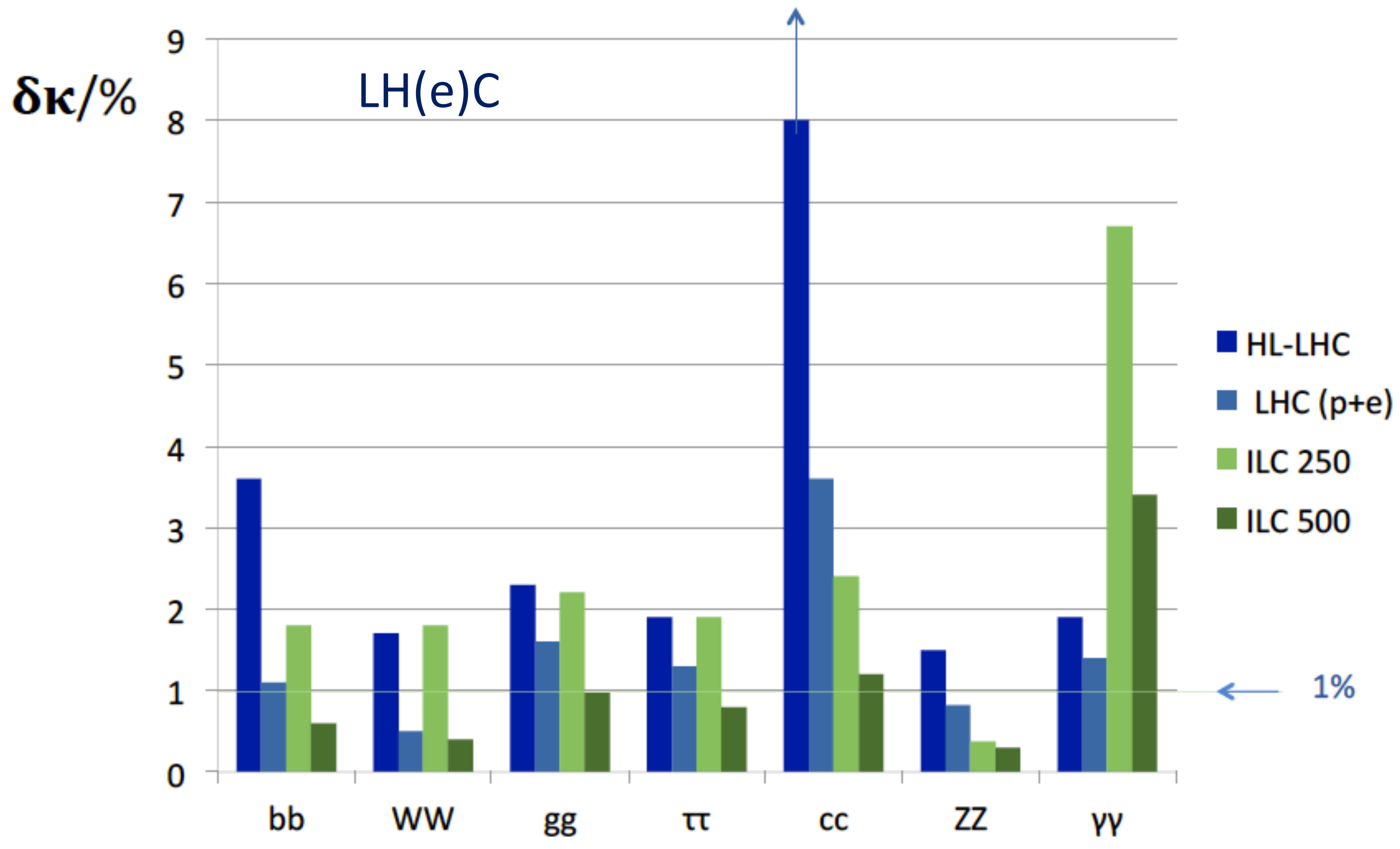


Fig.1: *Results of prospect evaluations of the determination of Higgs couplings in the SM kappa framework for HL-LHC (dark blue), LHC with LHeC combined (p+e, light blue), ILC 250 (light green) and ILC-500 (dark green).*

Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	**1.3**	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	**0.17**	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	**0.43**	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	**0.61**	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	**1.21**	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	**1.01**	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	**0.74**	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	**9.0**	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	**3.9**	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	—	1.7
BR_{EXO} (%)	< 1.0	n.a.

Prospects for high precision measurements of **Higgs couplings at FCC ee and ep**. Note ee gets the width with Z recoil. ee is mainly ZHZ, while ep is mainly WWH: complementary also to pp

Machine Parameters and Operation - ep

arXiv:2007.14401

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23	8	15

Table 2.3: Summary of luminosity parameter values for the LHeC and FCC-eh. Left: CDR from 2012; Middle: LHeC in three stages, an initial run, possibly during Run 5 of the LHC, the 50 GeV operation during Run 6, both concurrently with the LHC, and a final, dedicated, stand-alone *ep* phase; Right: FCC-eh with a 20 and a 50 TeV proton beam, in synchronous operation.

No pileup

For comparison, HERA I operated at 10^{31}cm^{-2}s^{-1}, and was upgraded by a factor of up to 4 for HERA II
The total luminosity delivered was 1 fb^{-1} over a running period of 15 years, including shutdowns.
LHeC may operate at 20 x 1000 GeV^2 and "repeat" all of HERA in a short running period.

The updated CDR considers a Ring-Ring ep collider as a back-up solution. May be revived for HE-LHC.

Machine Parameters - eA

Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β^*_A	cm	10	10	15
e-N Luminosity	$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7	14	35

Table 2.4: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent eA and AA operation mode with the LHC and the two versions of a future hadron collider at CERN. Following established convention in this field, the luminosity quoted, at the start of a fill, is the *electron-nucleon* luminosity which is a factor A larger than the usual (i.e. electron-nucleus) luminosity.

arXiv:2007.14401

The LHeC and FCC-eh are the highest energy, most powerful electron-ion colliders the world may build.

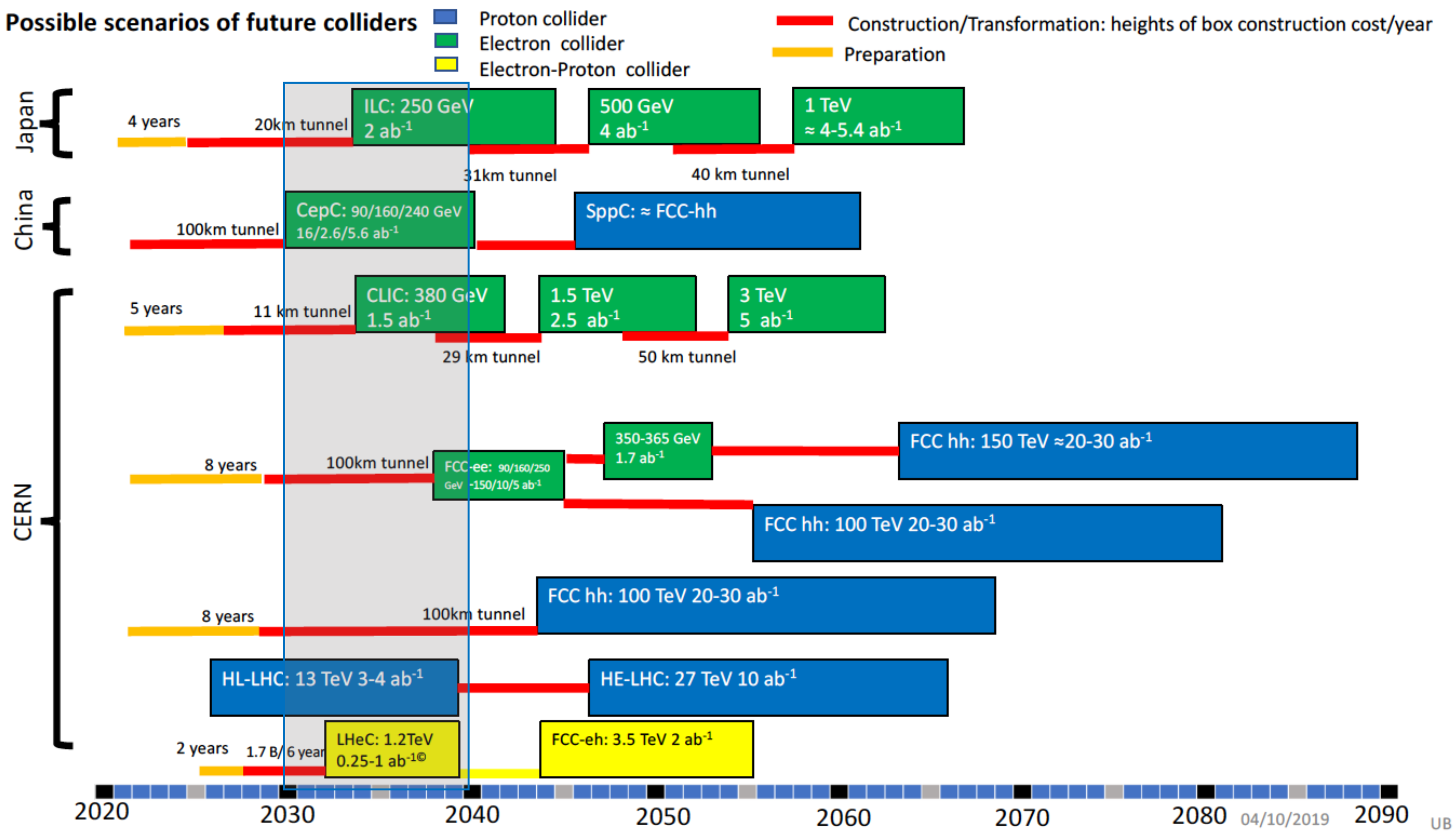


Figure 1 Timeline of Future Colliders as extracted from the submitted inputs (by U. Bassler)

Three Messages from the 2m LINAC at Stanford

-- **you do NOT need to promise to discover dark matter or know what new to expect when you increase the energy range** (we yet may have to readjust our perception about nature, its richness and as well our ability to predict and understand it. 'we like to see the field to be driven by experiment' – Burt Richter 2009)

-- **you can build a 2 mile electron linac in 3 years time, if you really want it**
we surely could build LHeC and FCC-eh in short time when decided to do so

-- **electron-proton scattering is the best means to explore the substructure of matter**
a crucial complement to the LHC/FCC and moreover, now a unique Higgs facility

50 years since the discovery of quarks by the SLAC-MIT ep scattering experiment

---

W.K.H. PANOFSKY Vienna 8/1968 SLAC-PUB-502

Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon.

Lessons/Scenarios/Prospect

A personal remark

The discussion of the past years has shown that the time is not ripe for any decision about the next big machines.
We enter a novel phase of physics (exp+thy), detector, accelerator and CE R+D "to evaluate their feasibility" (HA).

Strategy is difficult to make, just take FCC and LHC: Highest priority is for two decades the exploitation of the LHC. What may or may not happen, we do not know now, and projects are related in reality. Consider for example:

- FCC-ee asap: reduces the exploitation of the LHC (cf UB's schedule where FCC-ee operates together with LHC)
- FCC-ee later: challenged by the developments of CEPC and ILC, moves FCC-hh to beyond 2070 (Lausanne was 84, 25 years to LHC, not 50)
- FCC-hh following LHC: opens window for a bridge project (LHeC) and full exploitation of HL-LHC
- No FCC: possible revival of HE-LHC
- No FCC, No HE-LHC: muon collider by 2050ish?, CLIC?
- No big project ["soon"]? Extend HL-LHC beyond 2040 with updated programme (H-HH with 5ab^{-1}, ..)

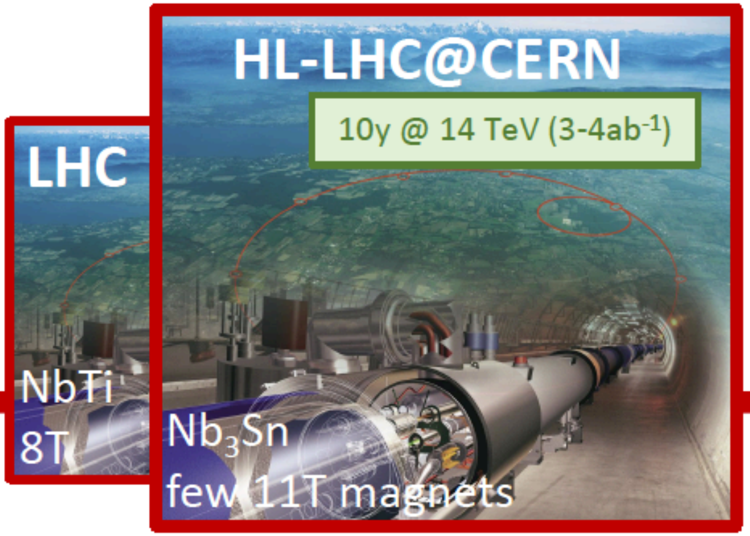
Physics is not only telling us that we shall study the Higgs boson, it tells us that we do not know now how to reach beyond the Standard Model. This calls for a desirably parallel rather than sequential, development of particle physics, triples of hh, eh and ee machines, as was crucial for the formation of the SM. HEP is a global science, with Meyrin as one key place.

The LHeC/PERLE/FCC-eh group sees many physics, cost and technology reasons to proceed. It is crucial to maintain the culture of energy frontier DIS, develop its novel technology and prepare exploiting its potential for the future of high energy physics.
In the example scenarios listed above there appear various possibilities where LHeC and/or FCC-eh may indeed be realised.

Colliders in Europe at the energy & precision frontier

Current flagship (27km)

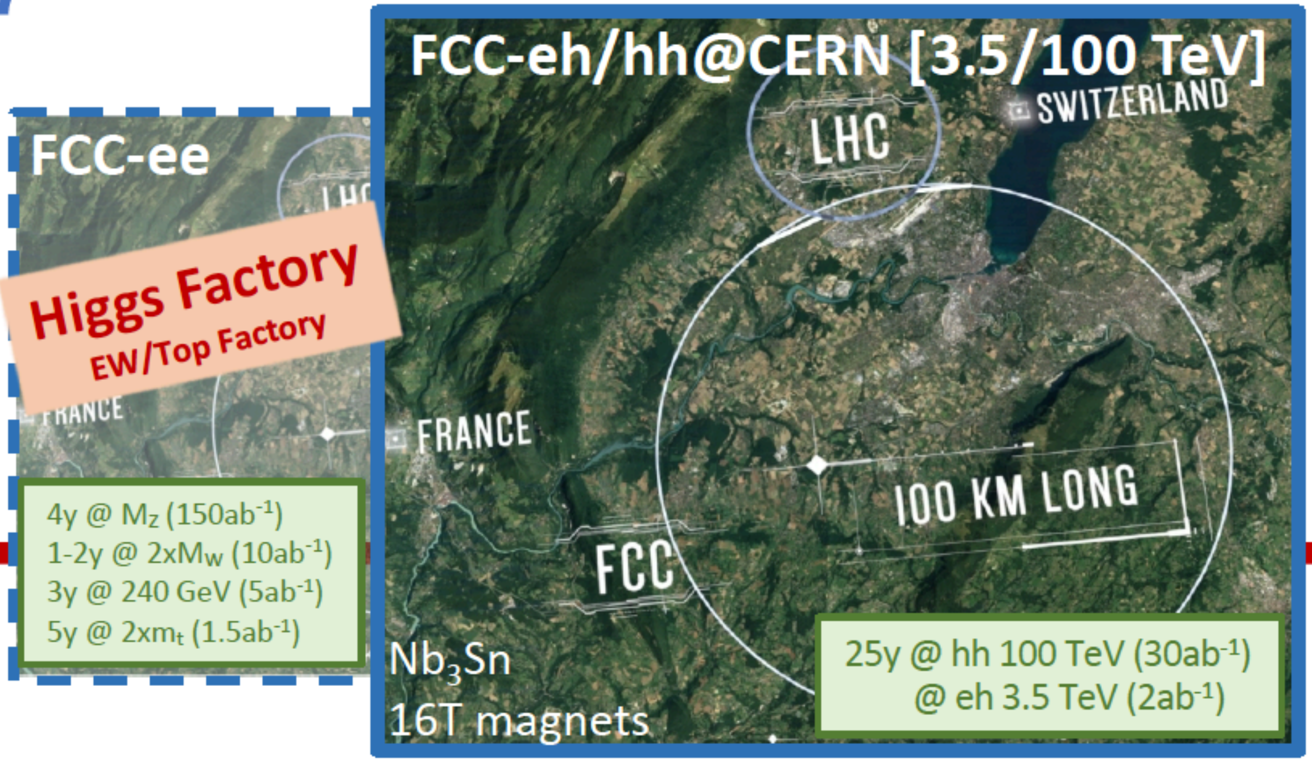
impressive programme up to 2040



ep-option with HL-LHC: LHeC

Big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier



numbers assume 2 IPs for each collider (only one for FCC-eh)

by around 2026, verify if it is feasible to plan for success (techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider

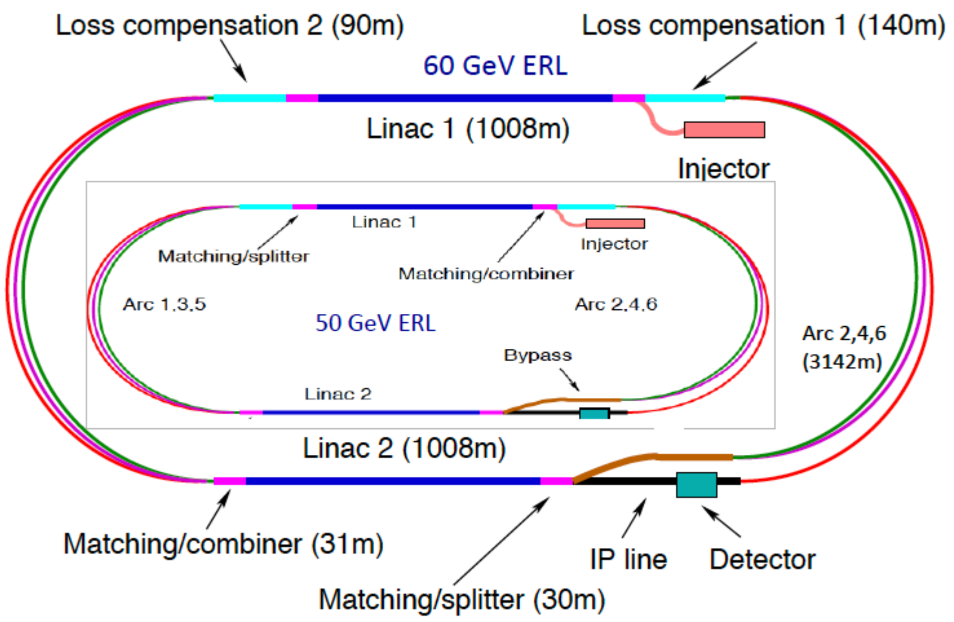
J de Hondt (5.10.20 to Snowmass)

The ERL in more Detail

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	µm	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 with spr/rec matching)	m	828.8 (980.8)
Return arc radius (length)	m	536.4 (1685.1)
Total ERL length	km	5.332

Table 10.1: Parameters of LHeC Energy Recovery Linac (ERL).

Positrons: 500pC is 3 10^9 e^-/bunch → 20mA and 1.2 10^{17} e^-/s
LHeC programme needs e^-p predominantly (Higgs) and only smaller e^+p sample, ~fb^{-1} → O(10^{15}) e^+/s, still demanding!



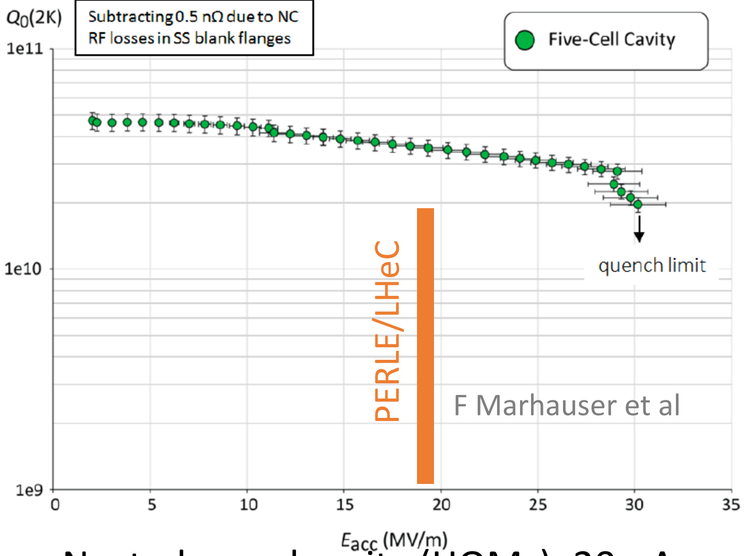
- LHeC Configuration reduced from 60 to 50 GeV.
- LINAC: 112 cryomodules with 4 cavities each
  → Total number of cavities: 896 [ILC: O(10^4)]
- Configuration may be staged with less RF
- Tunnel is small part of cost and better not reduced further, synchrotron loss, upgrades..
- ERL reduces power to << GW and dumps at < GeV
  → novel, "green" accelerator technology

Developments +Partners

Cf recent meeting: https://indico.cern.ch/event/923021/

SCRF: High Q_0, complete Cryomodule

Jointly with FCC-ee

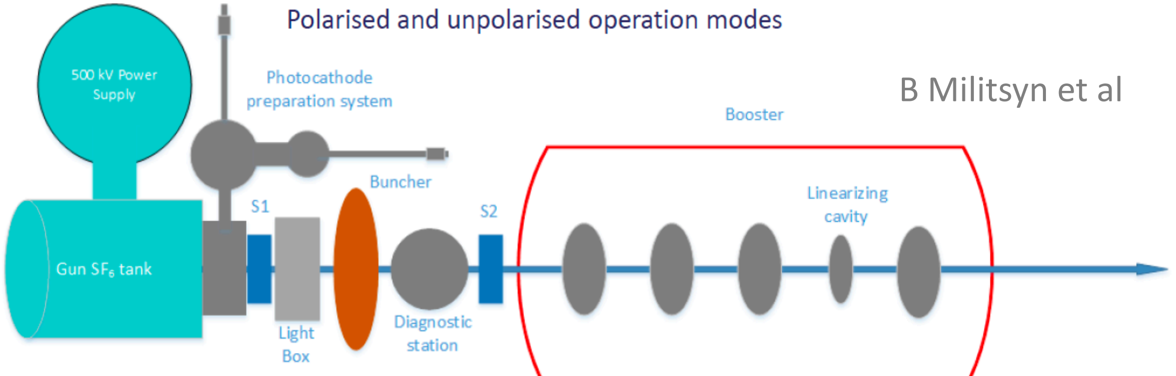


Next: dressed cavity (HOMs), 20mA
Adapt SPL Cryomodule for PERLE

CERN, Jlab, Orsay +

High Current Source (e^-, P, e^+)

ALICE gun upgraded and operates with GaAs photocathodes activated in the photocathode preparation system or with CsK_2Sb photocathodes prepared in the dedicated preparation facility.
Polarised and unpolarised operation modes

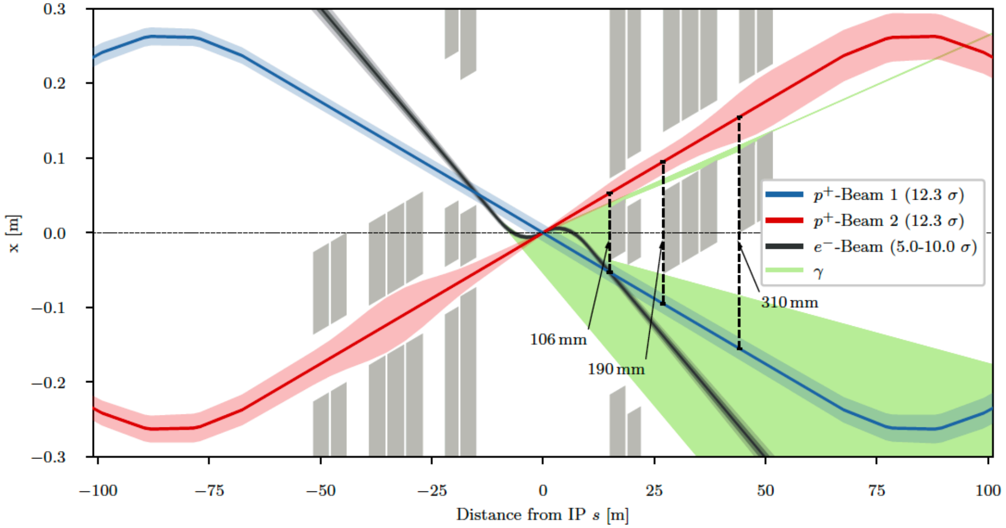


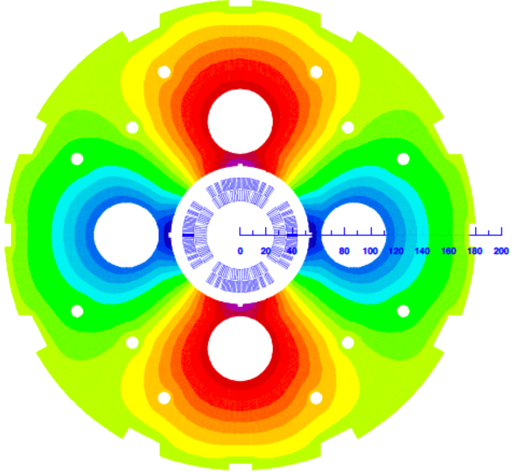
PERLE will begin with 5mA ALICE source, which has been transferred from Daresbury to Orsay while UK was in EU..

BINP, BNL/Cornell (cBETA), Daresbury, IJC, Jlab, +

Interaction Region Design and Q_1 Prototype:

B Holzer, B Parker, S Russenschuck et al





BNL, CERN, +

Energy Recovery and Synergies

LHeC/FCC-eh: high luminosity, high energy
→ High ERL power facility $P=I_e E_e$

This is a programme for high quality SRF ($Q_0 > 10^{10}$), high current sources, and multiturn to reach high E_e

Future/current ERL developments: distribution of emphasis

- CBETA: high current, single turn - for e cooler (EIC)
- MESA: polarised beam - for new PV asymmetry exp.
- CEBAF: few GeV energy - for study of syn. radiation
- PERLE: high current, multiturn - for exp's and future

Plans: Daresbury, Darmstadt, Berlin. Revival of KEK ERL
normal conducting ERL machine at BINP

Coordination: Lab Director Group (A Stocchi IJClab for ERL)
European Accelerator R+D Roadmap: CERN council 9/21
ERL Network. ERL workshop series

Technical Synergies of LHeC with other applications

- SAPPHIRE: a yy collider : Higgs, eweak and QCD machine
  F. Zimmermann et al, arXiv:1208.2827
- ERL as an injector into FCC-ee [direct into Z]
  O. Bruening, Y. Papaphilippou
- LHeC-FEL
  F. Zimmermann et al, work in progress
- Injector into FCC-hh
  R. Calaga
- Proposal of ERL Version of FCC-ee for high Lumi at high E_e
  V Litvinenko, T Roser, M Chamizo-Llatas arXiv: 1909.04437
- 802 MHz technology: PERLE, FCC-ee, eSPS
  F Marhauser, B Rimmer et al
- 704 MHz SPL Cryomodule (CERN) modified for PERLE
  F Gerigk, E Jensen et al.
- ALICE (Daresbury) Gun delivered to Orsay for PERLE
  D Angal-Kalinin, B Militsyn et al
- JLEIC Booster (Jlab) likely to be used in PERLE
  F Hannon, B Rimmer et al
- Forward Calorimetry: FCC-hh and ee colliders / CALICE..
- Inner Tracker/CMOS: ee colliders, new HI detector at IP2
- ….

Applications/ Synergy - examples

LHeC-FEL

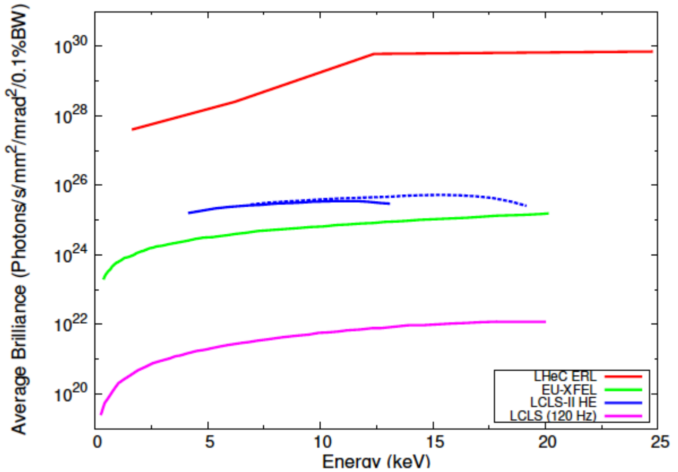


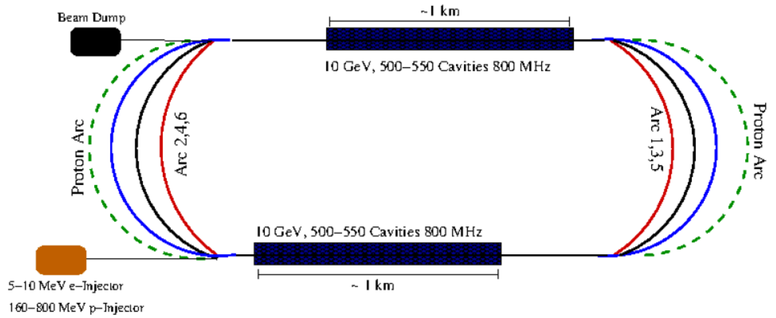
Figure 9: Comparison of FEL average brilliance for the LHeC-FEL with existing and planned world-leading hard X-ray FEL sources.

Work in progress, F Zimmermann et al. [in between LHeC and FCC-hh potentially]

e-ERL for Proton Injection

Recall: "SPL+PS2" as a new high brightness injector was already considered and abandoned for LHC

Proposal to use a single recirculating linac to directly inject to SPS (26 GeV) or SPS+ (~50 GeV), especially for 5ns bunch spacing.



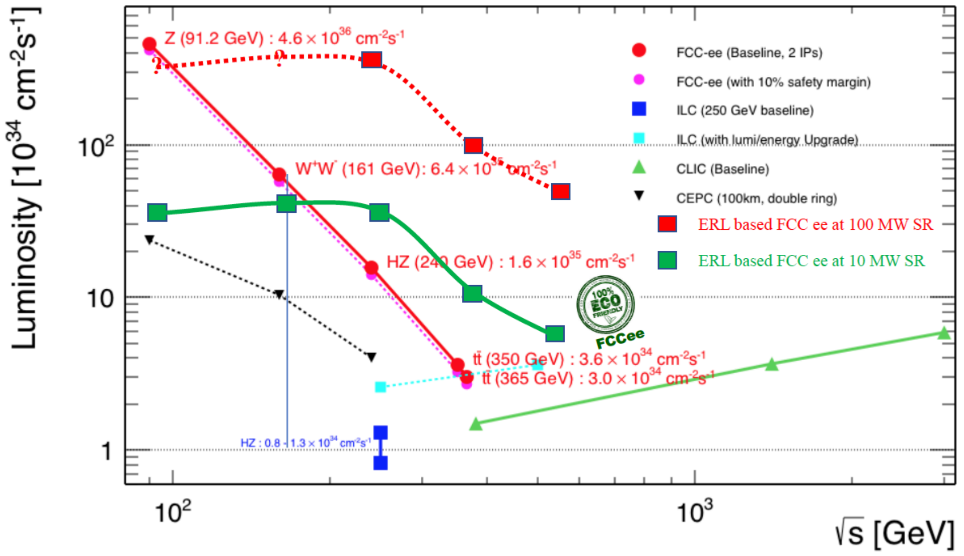
Presented by R Calaga, 2017 [worth reconsidering]

FCC-ee Injector Complex

- FCC-ee Baseline Injector Plan: e^+/e^-
  Linac with 6 GeV followed by 20GeV pre-booster ring [SPS] or 20GeV linac
  2.0 10^{10} N_b with 2 bunches per pulse and 200Hz rep-rate ➔ < 2μA average current
  Requires transfer lines from SPS or linac to FCC ➔ ca. 10km tunnel structures?
- Using LHeC type Recirculating Linac as injector: e^+/e^-
  Common hardware and infrastructure: one could use the FCC-ee pre-series SRF
  -Either using a 5km long racetrack suitable for 50GeV upgrade for FCC-eh and / or direct injection into the FCC-ee for Z production mode
  -Dedicated smaller tunnel optimized for FCC-ee injector at 6 GeV or 20 GeV
  In both cases I assume installation near point 'L' to minimize transfer line length
  In all cases the machine would be used as re-circulating linac and not in ERL mode

Presented by O Bruening, March 2019 [being rediscussed. Note PSI FEL concept]

Energy recovery configuration of FCC-ee



V Litvinenko, T Roser, M Chamizo-Llatas arXiv: 1909.04437, [ongoing study]

Under study

Could we unify the idea for a “slim” new AA detector with the one for LHeC?

For FCC: Could one integrate an AA programme into GPDs (for High scales) and eh for low pt? to resolve the issue of just four IRs?

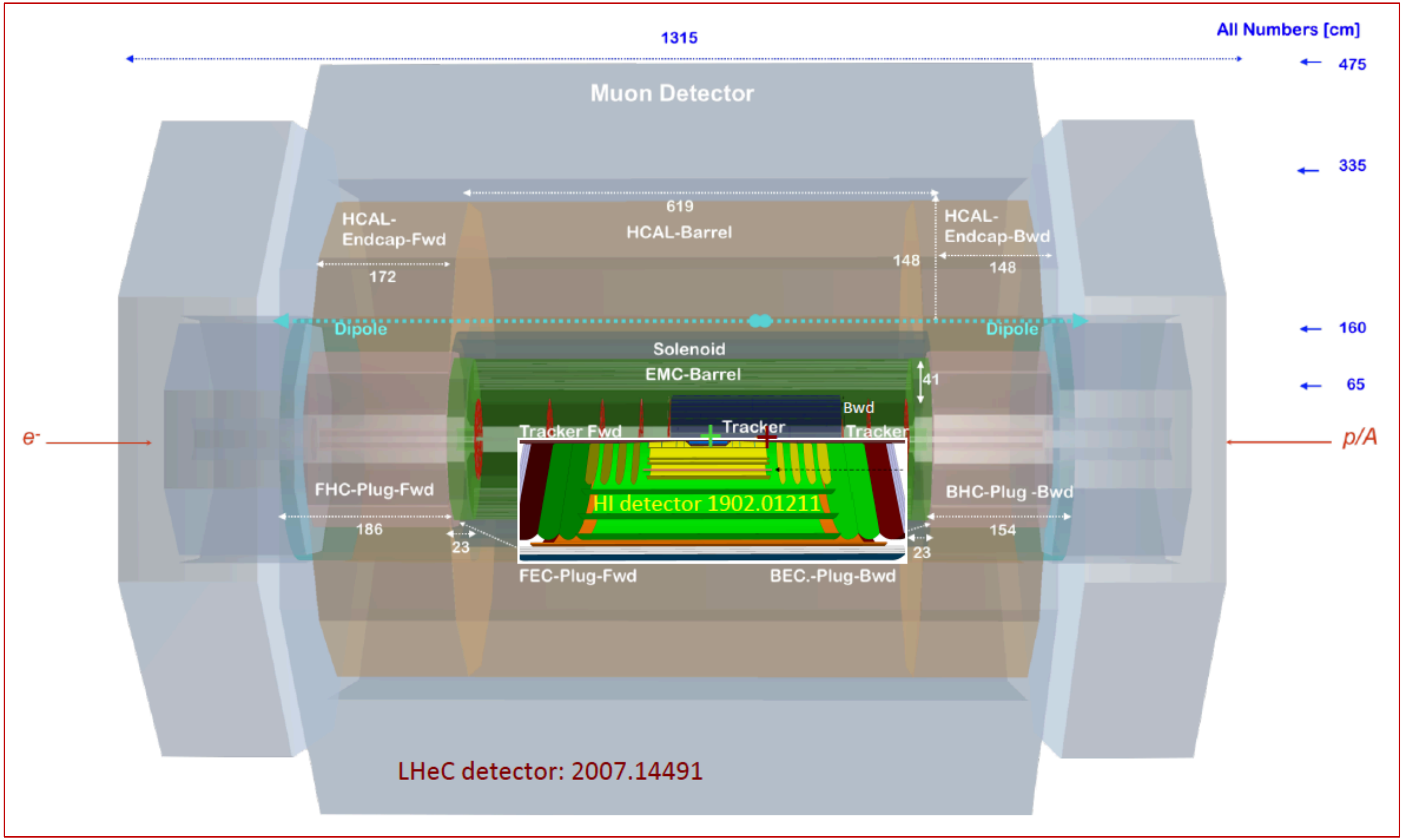
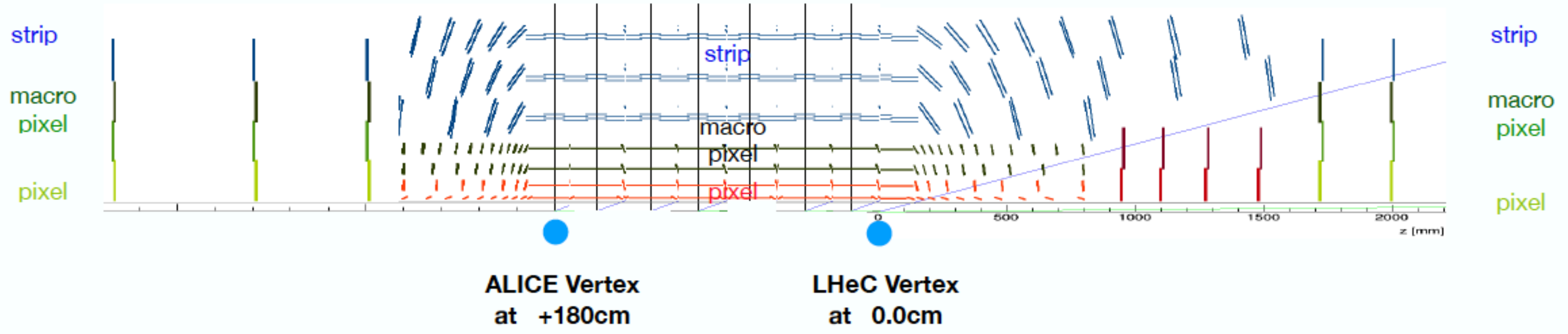


Figure 2: Sketch of the LHeC detector with a superimposed novel heavy ion detector (green) proposed for IP2 after LS4, see text.

ECFA Newsletter 5 8/2020 O Bruening M Klein

Combined ALICE - LHeC Tracker - 1. Idea



11.11.2020

P. Kostka – work in progress

Statement of the IAC to DG, published in 2007.14491

In conclusion it may be stated

- The installation and operation of the LHeC has been demonstrated to be commensurate with the currently projected HL-LHC program, while the FCC-eh has been integrated into the FCC vision;
- The feasibility of the project as far as accelerator issues and detectors are concerned has been shown. It can only be realised at CERN and would fully exploit the massive LHC and HL-LHC investments;
- The sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged;
- The addition of an ep/A experiment to the LHC substantially reinforces the physics program of the facility, especially in the areas of QCD, precision Higgs and electroweak as well as heavy ion physics;
- The operation of LHeC and FCC-eh is compatible with simultaneous pp operation; for LHeC the interaction point 2 would be the appropriate choice, which is currently used by ALICE;
- The development of the ERL technology needs to be intensified in Europe, in national laboratories but with the collaboration of CERN;
- A preparatory phase is still necessary to work out some time-sensitive key elements, especially the high power ERL technology (PERLE) and the prototyping of Intersection Region magnets.

Recommendations

i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).

ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.

iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

Herwig Schopper, Chair of the Committee, Geneva, November 4, 2019

There follows a programme for the coming years which is being established and for us to shape.

Programme until about 2025

The following focus points are evident for the coming years:
* The closer inspection of the relation of *ep* and *pp*, as well as *eA* with *AA* (*pA*), physics;
* The development of the BSM and Higgs physics of *eh* and its relation to *ee* and *hh*;
* Theory developments as outlined;
* The realisation of the first phase of PERLE (injector) towards 250 MeV beam at IJClab Orsay;
* The formation of an international proto-detector Collaboration able to present the LHeC to the LHCC at CERN and to collaborate on detector technology R&D,
* Conclusion on the machine-detector interface, including a mock-up of the first quadrupole, a plan for absorbers+masks and a prototype solution of the elliptic beam pipe.

from a UK Document 23.10.20

There is a programme for the coming years which is being established: you are cordially invited to join.

Today: B. Holzer: Interaction Region, Y. Yamazaki: Detector, W. Kaabi: PERLE – a large eh workshop to come.