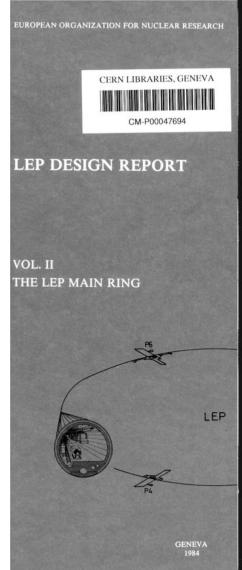
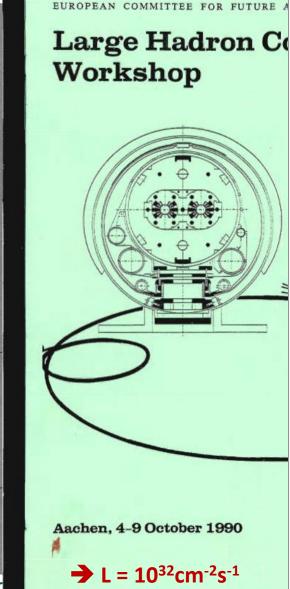
LEP Design Report 1984





2006

Nov

00

arXiv:hep-ex/0603016v2

Deep Inelastic Electron-Nucleon Scattering at the LHC

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 Daresbury International Science Park, UK
 DESY, Hamburg and Zeuthen, Germany
 School of Physics and Astronomy, University of Birmingham, UK
 CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

Abstract

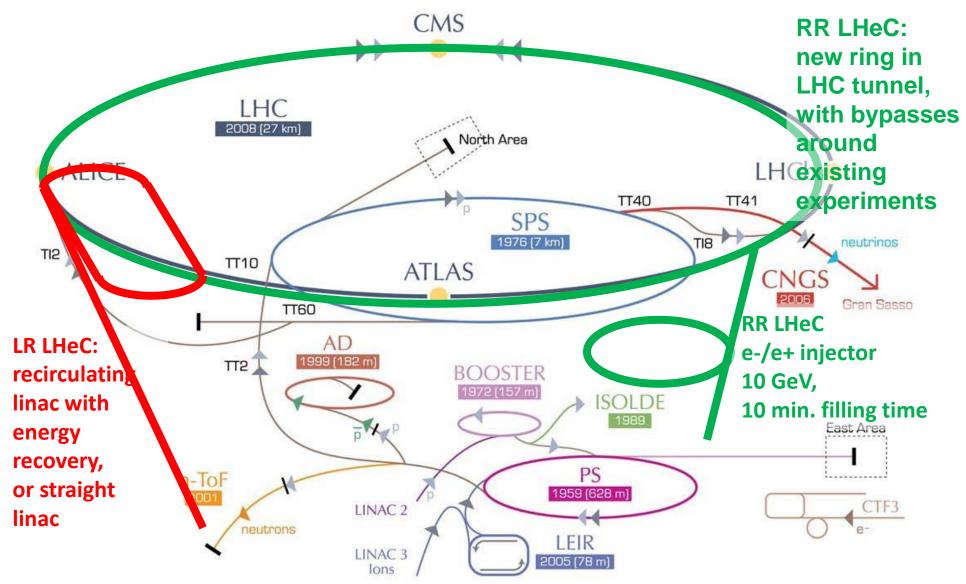
The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33} {\rm cm}^{-2} {\rm s}^{-1}$, and high energy, $\sqrt{s}=1.4\,{\rm TeV}$, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,{\rm GeV}^2$ and for Bjorken x down to the 10^{-6} . New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

 \rightarrow L = 10³³cm⁻²s⁻¹

111th Plenary ECFA Meeting, CERN Geneva

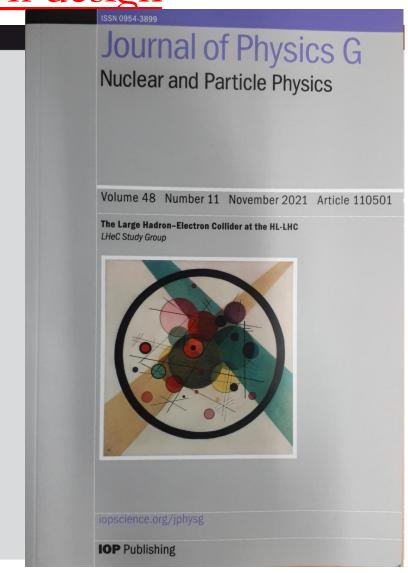
LHeC options: RR and LR





Technical Challenges of the e-h design

CDR Study assumptions: -Assume parallel operation to HL-LHC / FCC-hh -ERL configuration adopted for both LHeC and FCC-eh -TeV Scale collision energy for LHeC → 50-150 GeV Beam Energy -Limit power consumption to 100 MW → (beam & SR power < 70 MW) → > 50GeV → 60 GeV beam energy -Int. Luminosity > 1000 * HERA -Peak Luminosity $> 10^{33}$ cm⁻²s⁻¹ Higgs @ 125 GeV $\rightarrow > 10^{34} \text{ cm}^{-2} \text{s}^{-1} \& \text{Cost Study}$



arXiv Number 2007.14491



LHeC Proposal endorsed by ECFA (30.11.2007)

As an add-on to the LHC, the LHeC delivers in excess of 1 TeV to the electron-quark cms system. It accesses high parton densities 'beyond' what is expected to be the unitarity limit. Its physics is thus fundamental and deserves to be further worked out, also with respect to the findings at the LHC and the final results of the Tevatron and of HERA.

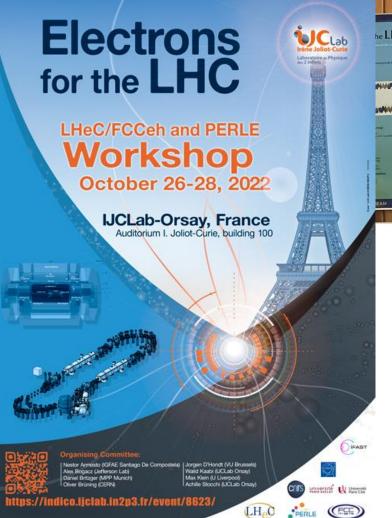
First considerations of a ring-ring and a linac-ring accelerator layout lead to an unprecedented combination of energy and luminosity in lepton-hadron physics, exploiting the latest developments in accelerator and detector technology.

It is thus proposed to hold two workshops (2008 and 2009), under the auspices of ECFA and CERN, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.

Unanimously supported by rECFA and ECFA plenary in November 2007

Out of 2 initially requested workshops grew over 10!







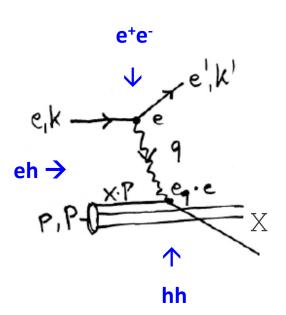
Plus many participations to FCC and EIC Workshops!

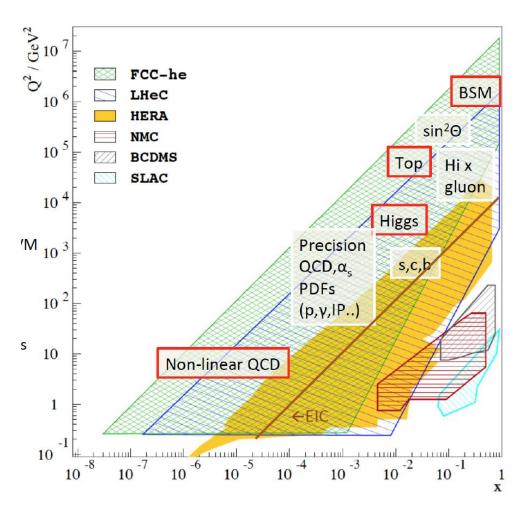
Physics Motivation: LHeC/FCC-eh as the most powerful microscope:





Complementarity of ee,eh, hh:





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

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

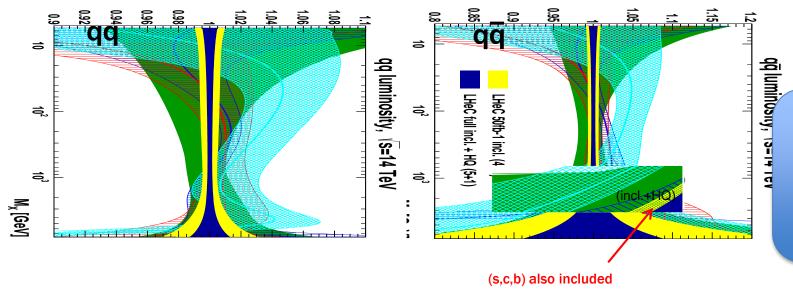
Discovery (top, H, heavy v's..) Beyond the Standard Model

A Unique Nuclear Physics Facility Parton-Parton "luminosities" @ 14 TeV

PDFs for small X as input for HL-LHC and FCC main experiments!

Very high precision x section predictions for LHC

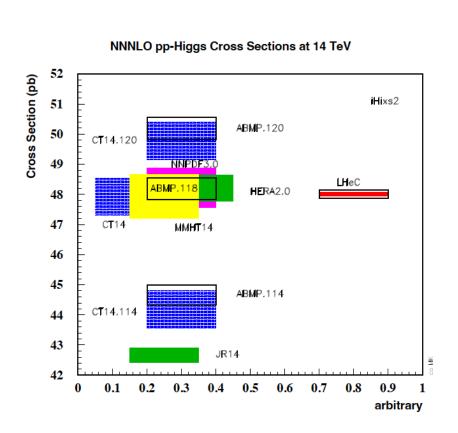
Side remark: HERA data taking ended in 2007, we now elect(ed) new spokes.. 15 years later.



Plus LHeC / FCC-eh as highly performant energy frontier Electron Ion Colliders!

Higgs with LHC/LHeC and ILC - high precision PDFs/xsection and Higgs

Couplings



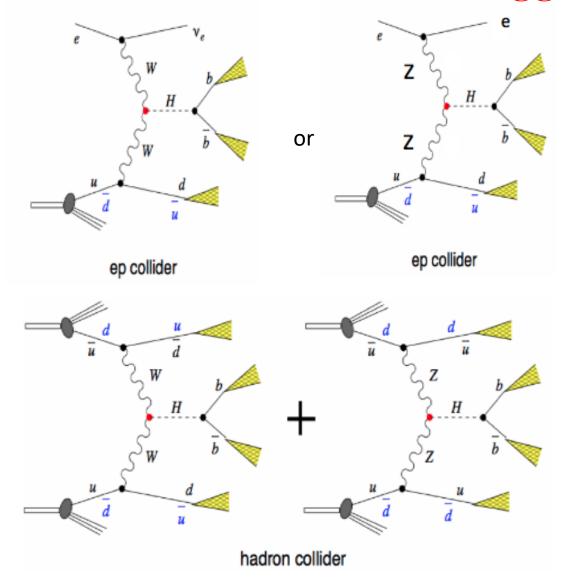
δκ/% 6 ■ HL-LHC LHC (p+e) ■ ILC 250 ■ ILC 500 bb ww gg π CC ZZ γγ

(sub) per cent level determination of Higgs couplings in pp/ep and ILC500

High precision control of pp→ H

Physics Motivation: LHeC as a Higgs Factory



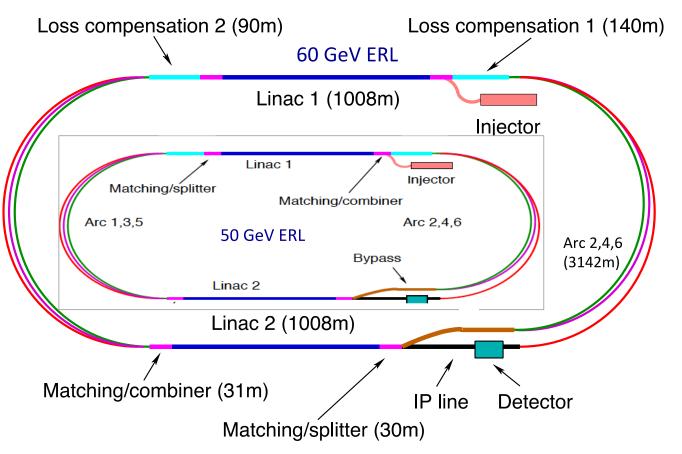


- -Cross section of 200fb @ LHeC
- -Clean bb final state (S/B \approx 1)
- -e-h cross calibration → precision
- -Pile-up in ep @ 10³⁴cm⁻²s⁻¹ is 0.1
- -pile-up in pp @ 5 10³⁴cm⁻²s⁻¹ is 140

Variations in the ERL Configuration:







O. Brüning, M. Klein and LHeC and PERLE Collaboration Topical Review Exploring the energy frontier with deep inelastic scattering at the LHC Journal of Physics G: Nuclear and Particle Physics, Volume 46 #2; November 2019

Operation in parallel with LHC/HE-LHC/FCC-hh

- TeV scale collision energy
 - → 50-60 GeV electron beam energy
- power consumption < 100 MW
 - → CDR 2012 option with 9.3km [1/3rd of LHC]; 60 GeV
 - → CDR 2018 with smaller version: 5km [1/5th of LHC]; 50 GeV

LHeC / FCC-eh ERL Configuration: Layout Options & Scaling



Cost scaling study based on comparisons with completed projects: on XFEL, LCLS-II budgets These estimates also fit well with estimates from CBETA and ESS studies

→ SRF is the main cost driver up to energies of 70GeV!!!

The E⁴ dependence on the arc length only becomes dominant for beam energies above 75GeV!

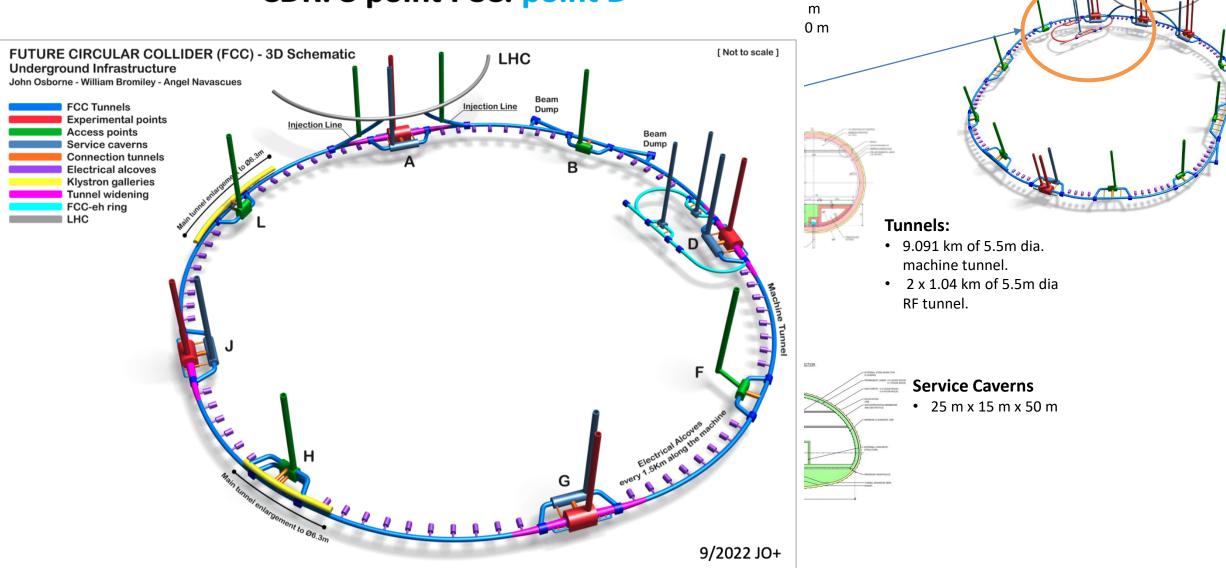
[Unless the SRF cost becomes significantly lower!]



FCC-eh Studies

CDR: 8 point FCC: point D

FCC-he initially considered Point 'L' since FCC Week in Berlin



ERL eh Collider Configuration





Configuration:

Challenges:

- -SRF Cryomodule design with couplers <
- -Front-End simulations for beam stability 🗸
- -IR design and β^* reach \checkmark
- -High Current multi-turn ERL → PERLE & CBETA
- -IR SC magnet design and R&D!!!

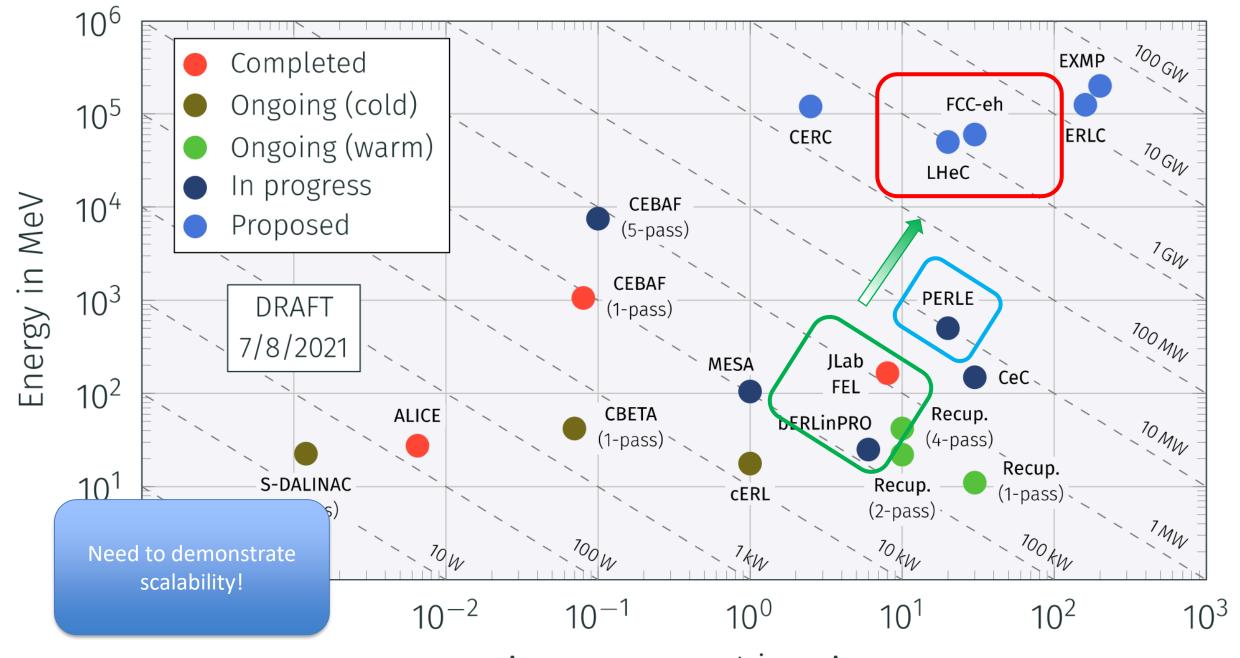
ons for the 'e' beam

sizes possible;

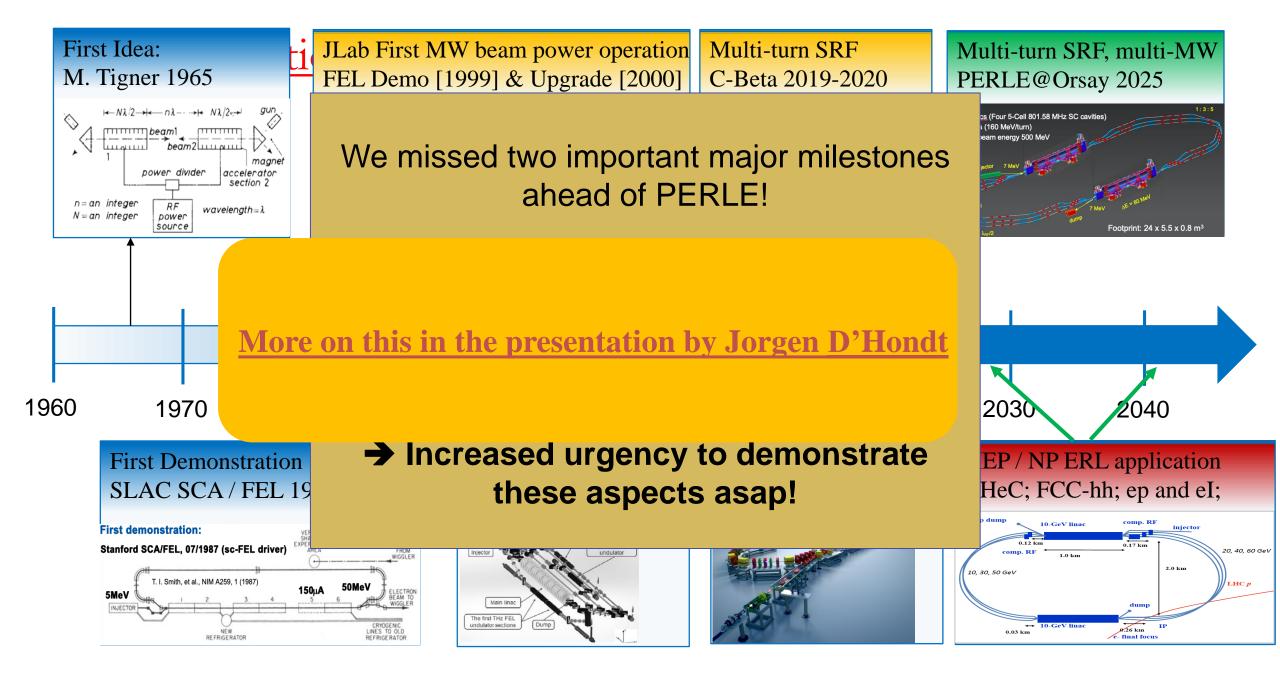
Could also be used as injector with Top-Up
Capabilities up to W production for FCC-ee
[when being operated in
Recirculating-Linac mode]



Infrastructure Investment for Future FCC



Average current in mA



New LHeC / FCC-eh Study Mandate given by CERN in November 2022

Following the publication of the updated CDR, CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics.

The study is to further develop the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with emphasis on FCC.

LHeC & FCC-eh Summary

- Full infrastructure exploitation of the existing LEP tunnel and the LHC / HL-LHC components / investment
- Unique DIS and Higgs physics program, complementary to HL-LHC, FCC-ee and FCC-hh
- High precision enabler for HL-LHC and FCC-hh e.g. small and very high X PDFs
- Compelling electron Ion collider program extension of kinematic range by 3-4 orders of magnitude [2-3 wrt EIC in the US]
- Technology driver for future projects: e.g. SRF, ERL, e+e- collider, ERL, sources, IR magnets
- Ideal bridge project at fraction of the cost of the next flagship project: Total accelerator cost of ca. 1BCHF
- Lepton accelerator can be used as injector for FCC-ee with W energy top-up capability

Mission

PERLE at Orsay

1. Demonstration of high current (20mA) multi (3) turn ERL operation and low energy nuclear/particle physis

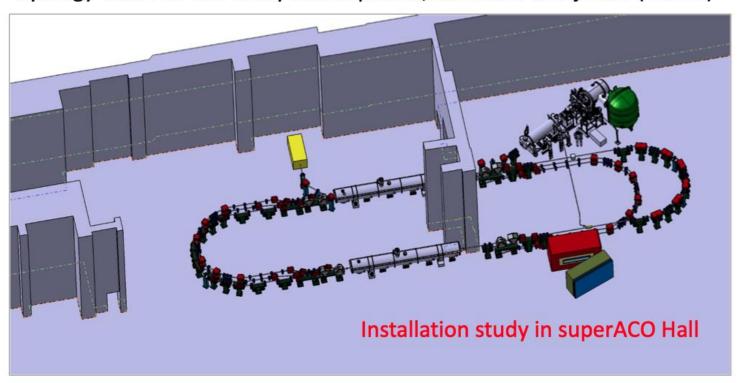
CDR in 2017 (J.Phys.G 45 (2018) 6, 065003 and arXiv:1705.08783)

current Composition of PERLE Collaboration:

IJCLab (host), AsTEC, BINP (on hold), CERN, Cockcroft, U Cornell, Grenoble, Jlab, U Liverpool, U Nablus, open to further partners

2. Technology (802 MHz, high Q₀, 20MV/m, ESS cryomodule, 4K...)

Synergy with FCC-ee: cavity development, racetrack as injector (Yannis)





HV vessel tightness test 9/22

Cost and Configuration Option

Motivation: look for a configuration where the ERL cost comes down to 1BCHF

Approach 1:

With the SRF as the primary cost driver: reduce SRF system by 50% → 30GeV

Approach 2:

Keep remaining infrastructure compatible with a later energy upgrade

→ Design the arcs, linac tunnel, cryo etc for a beam energy of 50GeV

Costing:

Provide cost estimate for initial 30GeV version plus the required additional funds for an upgrade to 50GeV beam energy

FCC-eh Configuration: Layout & Civil Engineering

Budget Item	Cost	Budget Item	en choice 13 8	*
SRF System	805MCHF	ctimate WI		IF
SRF R&D and Proto Typing	31N**	us a higher esting		
Injector	ch00si	ng the river acuracy	-4	
Magnet and Va	estimate Cire	with $\pm 30\%$ acc	103MCHF	
anservative	u perhi	aps With	105MCHF	
Rather com	Overall For	Budget Item Budget Item The higher estimate What he higher estimate which has been estimated by the higher estimate which has been estimated by the higher estimate which has been estimated by the higher estimat	5MCHF	
•	~111	Cryogenic Infrastructure	41.5MCHF	+28MCHF
G ins	69MCHF	General Infrastructure and installation	58MCHF	
Civ	353MCHF	Civil Engineering	256MCHF	
Total	1723MCHF	Total	1042MCHF	→ 1338MCHF

[→] The scaled ERL circumference corresponds to 1/5th of the LHC circumference: 5.4km

Consistent HL-LHC Performance Projections for ep:



Three Operation scenarios for LHeC:

1) Parasitic

2) Pushed

3) Dedicated

Parameter	Unit	Initial: Run 5	Design: Run 6	Dedicated
Brightness $N_p/(\gamma \epsilon_p)$	$10^{17} \; \mathrm{m}^{-1}$	2.2/2.5	2.2/2.5	2.2/2.5
electron beam current I_e	mA	15	25	50 ?
proton β^*	m	0.1	0.07	0.07
peak luminosity	$10^{34} \text{ cm}^{-2} \text{s}^{-1}$	0.5	1.2	2.4
p beam lifetime	h	16.7	16.7	100
fill duration	h	11.7	11.7	21
turnaround time	h	4	4	3
overall efficiency	%	54	54	60
Physics time / year	$_{ m days}$	160	180	185
Annual integrated lumin.	fb^{-1}	20	50	180

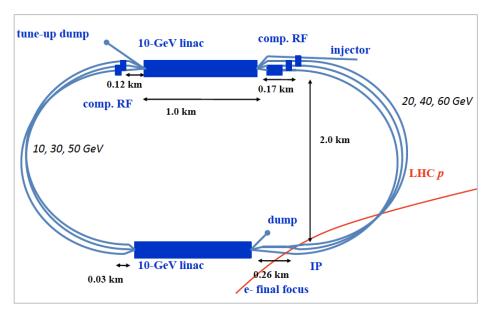
A Dascille IOI the I CC-HE

Electron ERL & Proton Synchrotron Configuration:



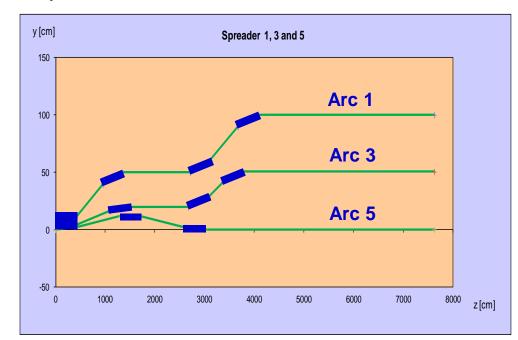
TeC CDR, arXiv:1206.2913

Example LHeC: 3-turn Recirculating SRF Linac and ERL operation



Operation in parallel with LHC/HE-LHC/FCC-hh

- TeV scale collisions → 50-60 GeV e-beam energy
- power consumption < 100 MW



- → 2 1km long SRF linacs
- → 3 separate return arcs at each end of the linac, matched for the beam energies
- → Each beam passes 6 times through the SRF:
 - 3 passes with acceleration and 3 with passes deceleration \rightarrow 6 times I_e in SRF!

Performance Optimization for ERL Configurations

- Synchrotron Radiation Power:
 - → Can not be avoided for the racetrack configuration → requires scaling of the return arcs with beam energy! But can reduce SRP by about 50% wrt ring
- Beam-Beam interaction:
 - \rightarrow Not a limit similar to linear colliders \rightarrow can increase I_{bunch}
 - → Beam size defined by source [like in a LC] and thus can be optimized
 - → But beam size can not be pushed as extreme as in LC as the beam still needs to pass through the SRF without losses during the deceleration phase
- Lattice and Optics design of return arcs:
 - → Novel lattice design requirements for return-arcs!!!

Summary of Key Challanges

Source Concept:

Need to demonstrate high current operation with good lifetime \rightarrow underway in Orsay

- SRF challenges:
 - -HOM couplers integration and FE FRT systems -> need cryomodule finalization
 - -N doping and higher $Q_0 \rightarrow$ would need R&D now
- Magnet challenges:

Interaction Region design and Synchrotron Radiation

Asymmetric magnet designs with high peak field in coils \rightarrow need magnet R&D now!

Integration of LHeC optics into ALICE III layout

further optics and layout studies

Energy Recovery Linac Concept:

Need to demonstrate feasibility / scalability to multi-turn multi-MW beam power

Performance limitation of circular colliders

Beam-Beam Interaction:

Imposes a limit to the maximum acceptable bunch intensity

→ Limits the luminosity reach of a circular collider

Synchrotron Radiation in arcs:

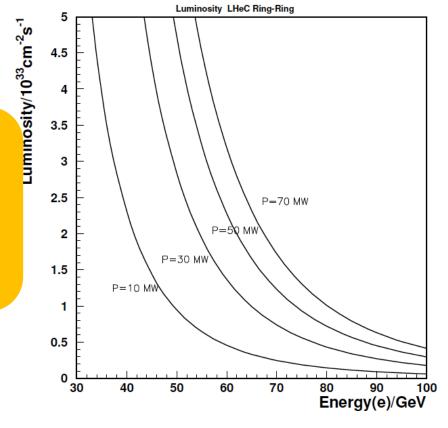
Circular lepton collide performance is limited by:

Beam-beam

Equilibrium beam size formation

Synchrotron Radiation power

→ Reduced performance reach for higher
 beam energies → limits number of bunches!



Linac Luminosity

D.

A linear Collider overcomes the beam-beam limit of a circular collider

[as the beam does not need to remain to be stable over many passages] and even utilizes it for performance enhancement [pinch factor] and minimizes the power losses through Synchrotron Radiation [no bends]

But it does so at the price of power requirements for luminosity production and that the particles have only once the chance to collide!!!

→ Luminosity proportional to beam power [Beam Current x Energy]

And e⁺ production might be challenging!

Markus Roth TU Darmstadt; Accelerators for Medical Applications 2015; Vösendorf, Austria

Sanity Check - apply costing model to ILC.

Geoffrey Norman Taylor @ FCC Week in Amsterdam

500GeV Version with 1824, 12m long XFEL CM modules 30km accelerator with 22km SRF linacs

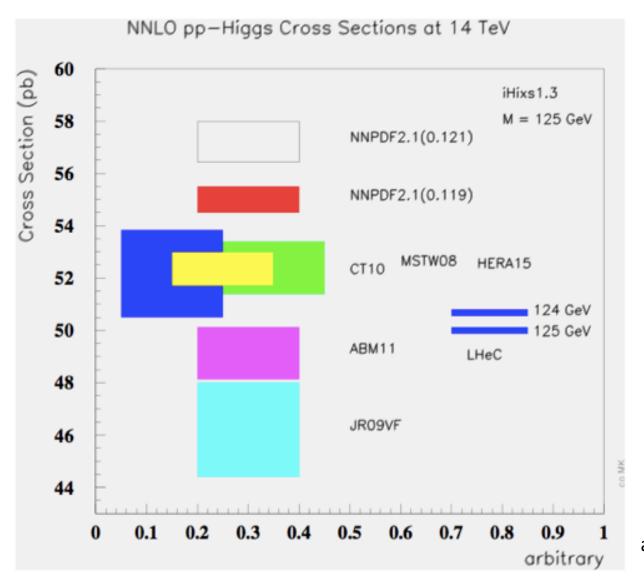
- Tunnel ca. 1.5BCHF [but ILC tunnel should be cheaper]
- SRF ca 8.8BCHF
- Cryo ca. 1BCHF

 total ca 11BCHF
- → fits to ILC estimates [we assumed +30% for SRF scaling!]

 → total of ca. 8BCHF quoted by Barry Barish

Physics Motivation: Precision for Higgs @ LHC





Experimental uncertainty
H cross section becomes
0.25% (stat + uncertainty)
with LHeC

Leads to mass sensitivity

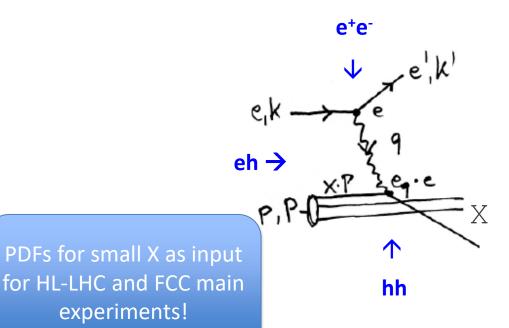
Needs N³LO calculations

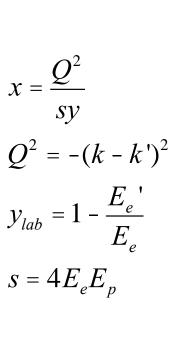
arXiv:1305.2090, MPLA 2013

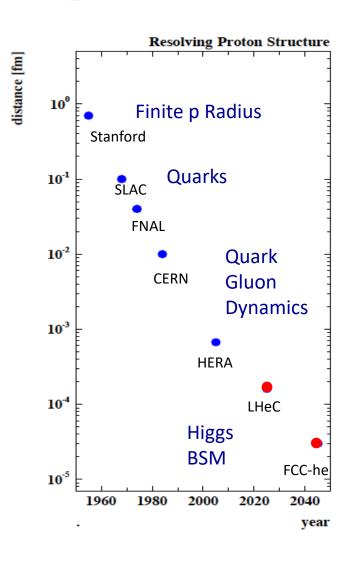


Physics Motivation: LHeC/FCC-eh as the most powerful microscope:

- Finest microscope with resolution varying like $\sqrt{1/Q^2}$
- Parton momentum fixed by electron kinematics:







experiments!