An Energy Recovery Linac for Energy-Frontier eh Scattering at CERN: the LHeC and the FCC-eh

Oliver Brüning (CERN), Max Klein (U Liverpool), Daniel Schulte (CERN), Frank Zimmermann

for the LHeC/PERLE/FCCeh Collaboration

Talk at ICHEP Seoul, 6 July, 2018
60 GeV Electron ERL added to LHC

Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
$10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity and factor of 15/120 (LHC/FCCeh) extension of $Q^2$, $1/x$ reach
1000 times HERA luminosity. It therefore extends up to $x \sim 1$.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.
Published 600 pages conceptual design report (CDR) written by 200 authors from 60 Institutes and refereed by 24 world experts on physics, accelerator and detector, which CERN had invited.
CDR: VERY detailed design of the LHeC Linac (and Ring) – Ring Collider, + components, CE..
“you never walk alone”
New LHeC Document
Reasons: CERN Mandate and

- Higgs: higher luminosity goal
- LHC: no BSM + precision
- New ep/eA Physics prospects
- eh appeared with FCC design
- Updates on IR, CE, ...
- Insight from FCC study
- Vision for eh with HE LHC
- Options for ERL based Physics beyond eh scattering.
- Low energy test facility PERLE
- Implementation of ERL at CERN

Preparation for early 2019

Submissions of eh Papers to European Strategy:

- FCC eh as part of FCC hh
- LHeC with HL
- PERLE technology development
Location, Footprint, Use of the Electron Racetrack

ebeam external to LHC. Location suitable for both HL and HE LHC.

- $U(ERL) = 1/n U(LHC)$: 60 GeV: $1/3$
- BSM, top, Higgs, Low x all want maximum $E_e$
- Cost goes almost linearly down with $E_e$

For FCC can realise ep/A collisions
With IR at point L, not far from CERN
$U(ERL) = 1/11 U(FCC)$

Energy – Cost – Physics – Footprint are being reinvestigated for EU strategy
Civil Engineering for ERL

For LHC: re-use IP2. For FCC: deeper shafts, new IP cavern
Refinement of CE study, see J Osborne Amsterdam FCC week
and see Matt Stuart at LHeC Workshop, 28.6.18 at Orsay
# Luminosity for LHeC, HE-LHeC and FCC-ep

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

Oliver Brüning¹, John Jowett¹, Max Klein², Dario Pellegrini¹, Daniel Schulte¹, Frank Zimmermann¹

EDMS 17979910 | FCC-ACC-RPT-0012

Contains update on eA: 6 $10^{32}$ in e-Pb for LHeC.
Collider Luminosities vs Year (pp and ep)
### FCC-eh ERL Configuration:

Performance Simulations for FCC-ep:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Protons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>50000</td>
<td>60</td>
</tr>
<tr>
<td>Normalised emittance</td>
<td>$\mu$m</td>
<td>2.2 → 1.1</td>
<td>10</td>
</tr>
<tr>
<td>IP betafunction</td>
<td>mm</td>
<td>150</td>
<td>42 → 52</td>
</tr>
<tr>
<td>Nominal RMS beam size</td>
<td>$\mu$m</td>
<td>2.5 → 1.8</td>
<td>1.9 → 2.1</td>
</tr>
<tr>
<td>Waist shift</td>
<td>mm</td>
<td>0</td>
<td>65 → 70</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$10^{10}$</td>
<td>10 → 5</td>
<td>0.31</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{33}\text{cm}^{-2}\text{s}^{-1}$</td>
<td>18.3 → 14.3</td>
<td></td>
</tr>
<tr>
<td>Int. luminosity per 10 years</td>
<td>[ab$^{-1}$]</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>
DA and Status of Lattices

LHeC

- Based on HL-LHC lattice (round optics $\beta^*=15$ cm in IR1 and IR5)
- New low-$\beta^*$ IR (IR2)
- ATS-scheme implemented in 3 low-$\beta^*$ IRs
- Previous DA studies were implemented for different IR options
- Update: Studies with errors in IR1/IR5 magnets and new magnet design for IR2

FCC-eh

- Based on FCC-hh lattice ($\beta^*=30$ cm in IRA and IRG)
- New low-$\beta^*$ IR (IRL)
- No ATS-scheme
- Extensive DA studies have been performed for FCC-hh lattice
- Update: Implement same techniques for FCC-eh

Update of Lattice and IR Design Study: see E Cruz, R Martin and B Parker at Orsay Workshop
LHeC-FEL – world’s best X-ray source

**SASE FEL simulation results**

- Evolution of the pulse power along the undulator
- Spatial (temporal) profile of the radiation pulse
- Wavelength spectrum of the radiation

For $\lambda = 0.45 \text{ Å (K = 4.24)}$

Z. Nergiz, F. Zimmermann, H. Aksakal
PERLE. Powerful energy recovery linac for experiments. Conceptual design report

D Angal-Kalinin¹, G Arduini², B Auchmann², J Bernauer³, A Bogacz⁴, F Bordry², S Bousson⁵, C Bracco², O Brüning², R Calaga², K Cassou⁶, V Chetvertkova², E Cormier⁷, E Daly⁴, D Douglas⁴, K Dupraz⁶, B Goddard², J Henry⁴, A Hutton⁴, E Jensen², W Kaabi⁶, M Klein⁸, P Kostka⁸, N Lasheras², E Levichev⁹, F Marhauser⁴, A Martens⁶, A Milanese², B Millsyn¹, Y Peinaud⁶, D Pellegrini², N Pietralla¹⁰, Y Pupkov⁹, R Rimmer⁴, K Schirm², D Schulte², S Smith¹, A Stocchi⁶, A Valloni², C Welsch⁸, G Willering², D Wollmann², F Zimmermann² and F Zomer⁶
Powerful ERL for Experiments at Orsay

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

cf Walid Kaabi at Amsterdam FCC

New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics
Why PERLE [as seen from LHeC]?

FUNDAMENTAL MOTIVATION:

- Validation of key LHeC Design Choices

- Build up expertise in the design and operation for a facility with a fundamentally new operation mode:
  - ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)

- Proof validity of fundamental design choices:
  - Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  - Implications of high current operation ($2 \times 3 \times [6\text{mA} - 25\text{mA}] \Rightarrow 30-150\text{mA}$!!)

- Verify and test machine and operation tolerances before designing a large scale facility
  - Tolerances in terms of field quality of the arc magnets and cavity alignment
  - Required RF phase stability (RF power) and LLRF requirements
  - Halo and beam loss tolerances
Frequency Choice

Cost, dynamic heat losses, resistance, $Q_0$... point to $f < 1 \text{ GHz}$ (F Marhauser, Orsay 2/17)

Beam beam interactions unstable for $f > 1 \text{ GHz}$ (D Schulte, D Pellegrini March 2013)

Compatibility with LHC: **Decision for 802 MHz** (E Jensen CI Workshop 1/2015, FM input)
Towards PERLE: 802 MHz cavity, Source, Cryomodule, Magnets

First 802 MHz cavity successfully built (Jlab)

BINF, CERN, Daresbury/Liverpool, Jlab, Orsay, +
CDR 1705.08783 [J.Phys G] → TDR in 2019
Summary and Plans

- Following the CDR and the Higgs Boson Discovery in 2012, Physics from LHC, as well as Technology Developments, the ERL Concept for the LHeC has been updated to design for $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ep scattering with the HL LHC, HE LHC and the FCCeh.

- New physics (Higgs, BSM, top) studies have substantially widened the scope.

- The LHeC is designed for concurrent ep operation, with pp, in order to accumulate $O(1) \text{ ab}^{-1}$ of integrated luminosity, at a power limit of 100 MW.

- New studies on lattice and the IR optics and configuration support this as a realistic goal.

- The heart of ep with HL LHC, HE LHC and FCC-eh is an energy recovery electron linac.

- A first SC cavity of 802 MHz frequency has been designed and successfully tested showing stability of up to 29 MV/m and a weak $Q_0$-gradient dependence around $3 \times 10^{10}$, exceeding the design goal. Single cells will be infused with N, + the CM designed

- A PERLE CDR has been published in 2017 and a TDR is scheduled for 2019. PERLE will be the first 10 MW, multi-turn 802 MHz facility and is suited to accompany the development of the LHeC as a technology development facility, with low E physics.

- PERLE and LHeC (HL/HE) inputs are under preparation for the HEP strategy update + beyond
Most up-to-date Information: [https://indico.cern.ch/event/698368/](https://indico.cern.ch/event/698368/)

Workshop: LHeC/FCCeh and PERLE
End of June at Orsay near Paris

**Electrons for the LHC**

LHeC/FCCeh and PERLE Workshop

**June 27-29, 2018**
LAL-Orsay, France

 fucking

New and Updates on

**Physics** (PDFs, QCD, H, t, BSM, eA + Relation eh-hh..)

**Accelerator**: IR, Optics, Lattice, Cost-Energy, CE..

**Detector**: the GPD and its fwd and bwd detectors

**PERLE**: Source, Injector, Cavity, Cryomodule,.. Physics

**Project** Development towards the ES2020:
LHeC + FCCeh+ PERLE input 12/18. PERLE TDR in 2019.

[http://lhec.web.cern.ch](http://lhec.web.cern.ch)
backup
Determination of SM Higgs Couplings, **HL-LHC and LHeC → LHC**

The addition of ep to pp (LHeC to LHC (HL,HE) and FCC-e+e- to FCC-pp) transforms these machines into precision Higgs facilities. **Vital complementarity with e^+e^-** (JdB Amsterdam)

Note that the HL LHC prospects are being updated (HL/HE LHC Physics workshop).

**ttH at LHeC to 15%**
Large Hadron Electron Collider on one page

\[ E_e = 10-60 \text{ GeV}, \quad E_p = 1-7 \text{ TeV}: \sqrt{s} = 200 - 1300 \text{ GeV}. \textbf{Kinematics:} \quad 0 < Q^2 < s, \quad 1 > x \geq 10^{-6} \text{ (DIS)} \]

Electron Polarisation \( P = \pm 80\% \). Positrons: significantly lower intensity, unpolarised

**Luminosity:** \( O(10^{34}) \text{ cm}^{-2} \text{ s}^{-1} \). integrated \( O(1) \text{ ab}^{-1} \) for HL LHC and 2 \( \text{ ab}^{-1} \) for HE LHC/FCCeh

e-ions \( 6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \), \( O(10) \text{ fb}^{-1} \) in ePb . \( O(1) \text{ fb}^{-1} \) for ep F_L measurements

**Physics:** QCD: develop + break? The world’s best microscope. BSM (H, top, ν, SUSY..) Transformations: Searches at LHC, LHC as Higgs Precision Facility, QCD of Nuclear Dynamics

The LHeC has a deep, unique QCD, H and BSM precision and discovery physics programme.

**Time:** Determined by the Large Hadron Collider (HL LHC needs till \( \sim 2040 \text{ for } 3 \text{ ab}^{-1} \))

- LHeC: Detector Installation in 2 years, earliest in LS4 (2030/31).
- HE LHC: re-use ERL. In between HL-HE, 10 years time of ERL Physics (laser, γγ..)

Very long term: FCC-eh

http://lhec.web.cern.ch

**Challenges:** Demonstration of ERL Technology (high electron current, multi-turn)
Design 3-beam IR for concurrent ep+pp operation, New Detector with Taggers - in 10 years.

**The LHeC is a great opportunity to sustain deep inelastic physics within future HEP.**
The cost of an ep Higgs event is \( O(1/10) \) of that at any of the 4 e⁺e⁻ machines under consideration
It can be done: the Linac is shorter than 2 miles and the time we have longer than HERA had.

**CERN and world HEP:** Vital to make the High Luminosity LHC programme a success.
LHeC Prospects

- The ep interaction does not disturb pp, i.e. the LHC may become a twin collider, ep and pp operate concurrently and no luminosity loss is planned for pp. This requires a premounted eh detector which may then be inserted in 2 years.

- At LS4 (~2030) the heavy ion LHC operation ends and one may propose a different use of IP2 which currently houses ALICE.

- The electron beam energy (> 50 GeV) and luminosity \(O(10^{34}) \text{ cm}^{-2} \text{ s}^{-1}\) goals are derived from Higgs, top and BSM physics, also DIS itself \(F_L, \text{ low } x\sim 1/s\).

- The cost of the O(1) TeV ep collider is a small fraction of any other big project currently under discussion. The LHC determines the time frame. This may extend considerably if CERN moves to HE LHC in the fourties.

- The ERL technology is being developed worldwide (Darmstadt, Cornell, Berlin, Novosibirsk, Jefferson Lab). PERLE would be a multi-turn 802 MHZ ERL technology development and test facility which would timely accompany the LHeC progress.

- We celebrate this year the 50th anniversary of the discovery of quarks. This was not planned and achieved by a step in energy with a linac SHORTER than LHeC’s.

- There is a very long term future for eh as part of hh in the FCC vision.
Further use of ERL in between HL and HE LHC

Reconfiguring LHeC → SAPPHiRE

LHeC-ERL → SAPPHiRE

γγ Higgs factory

F. Zimmermann at LHeC WS 9/17

LHeC: perfect FCC-ee injector!

LHeC-FEL

undulator

10 GeV cw linac

up to 60 GeV,
~25 mA,
1 MeV photons?

3-15x higher beam energy
(10-200x higher γ energies),
300-600x higher current

XFEL: 20 GeV e, 0.03 mA, 24 keV photons. LCLSII: 4 GeV e, 0.06 mA, 5 keV photons
4 An Electron Energy Recovery Linac at CERN

4.1 The ERL Configuration of the LHeC
  4.1.1 Basic Structure and Design Choices
  4.1.2 Component Summary
  4.1.3 Performance Estimates and Operation Scenarios
  4.1.4 Electron-Ion Scattering

4.2 ERL Beam Dynamics and Performance Limitations
  4.2.1 Front-end Simulation
  4.2.2 BBI, Filling Patterns and Bunch Structure

4.3 LINAC and SRF
  4.3.1 Choice of Frequency and Cavity Prototype
  4.3.2 Sources
  4.3.3 Injector
  4.3.4 LINAC and Cavity-CryoModule
  4.3.5 Infrastructure: Power and Cryogenics

4.4 Magnets and Dumps
  4.4.1 Arc Magnets
  4.4.2 Dumps

4.5 Interaction Region
  4.5.1 Layout
  4.5.2 Triplet Magnet Design
  4.5.3 Optics
  4.5.4 IR and L* Optimisation

4.6 Civil Engineering

4.7 Stand-Alone Operation and Physics with the ERL, post HL LHC
  4.7.1 Photo-Nuclear Physics with the ERL
  4.7.2 A High Energy and Intensity Laser Facility
  4.7.3 A Photon-Photon Higgs Collider at CERN

5 Executive Summary and Further Project Development

6 Appendix
  6.1 The Technology Development Facility PERLE
  6.2 Cost-Energy-Physics Optimisation of the LHeC
1 Modern Particle Physics and the Large Hadron Collider

2 Higgs, Discovery and Precision Physics
   2.1 Electron-Hadron Scattering at the HL and HE LHC
   2.1.1 Kinematics and Reconstruction of Final States
   2.1.2 Opportunities through Energy Frontier ep and eA Interactions
   2.1.3 Luminosity and Operation of an eh Collider at the LHC
   2.2 Higgs Physics
      2.2.1 High Precision Higgs Coupling Measurements
      2.2.2 Htt Coupling Measurement
      2.2.3 Combined ep and pp Analysis - the Potential for Precision Higgs Physics at the LHC
      2.2.4 Discovery of the H-HH Selfcoupling
      2.2.5 Exotic Higgs Decays and Dark Matter
      2.2.6 Extension of the SM Higgs Sector
   2.3 Challenging the Standard Model through High Precision and Energy
      2.3.1 Resolving the Parton Substructure of the Proton
      2.3.2 Electroweak, W Boson and Top Quark Physics
      2.3.3 Non-Conventional Proton Structure Resolution
   2.4 Searches for Physics Beyond the Standard Model
      2.4.1 Heavy Neutrinos
      2.4.2 Flavour Changing Neutral Currents
      2.4.3 Substructure
      2.4.4 Leptoquarks
   2.5 Discovery through Precision QCD
      2.5.1 High Mass and Bjorken x Searches at the LHC
      2.5.2 Strong Coupling and Grand Unification
      2.5.3 New QCD Dynamics at small x
      2.5.4 A New Era of Nuclear Particle Physics with eA

3 Experimentation at the LHeC
   3.1 Detector Design Considerations for HL and HE LHC
   3.2 Detector Overview
      3.2.1 Magnets
      3.2.2 Interaction Region, Beam Pipe and Radiation
      3.2.3 Inner Tracking
      3.2.4 Calorimetry
      3.2.5 Muon Detector
      3.2.6 Central Detector Performance
   3.3 Forward and Backward Detectors
      3.3.1 Proton and Neutron Forward Taggers
      3.3.2 Electron and Photon Backward Detectors
   3.4 Detector Installation and Infrastructure
Observations post CDR/EUSPP - 2012+ affecting ep at CERN:

**LHC lifetime** now extended to ~2040 to collect 3 [4] ab\(^{-1}\). LS3 2024-2026+..

**Discovery of the Higgs**: \( L(\text{ep}) : 10^{33} \rightarrow 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) [HERA in days]
LHC brightness \( N_p/\varepsilon \) about 3 times higher than “ultimately” expected

**No further discovery at the LHC**, so far

**Detector technology** developments (LHC Det. Upgrades)

Strong **accelerator technology** developments, notably SCRF ERL. LHeC: 720 → 802 MHz. enhanced \( Q_0 > 10^{10} \)

**EU strategy 13**: exploit LHC, study Higgs, develop SCRF+,
   CERN: new accelerators “with emphasis on pp and ee”
   Fine with the LHeC cost being a small fraction of ILC, CLIC, FCC

→ CERN in 14 set up a new LHeC organisation with a new mandate and IAC (H.Schopper et al) to prepare for the next EU strategy 2019+
**Two main tasks (IAC): Update of CDR for HL-LHeC/FCCeh + Testfacility**
Framework of the Development

Following the CDR in 2012: Mandate issued by CERN:2014 (RH), confirmed in 2016 (FG)

Mandate to the International Advisory Committee

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

- Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

- Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

Chair: Herwig Schopper, em. DG of CERN. IAC+CERN have invited four of its members to follow the study with special attention (Stefano Forte, Andrew Hutton, Leandro Nisati and Lenny Rifkin). Collaboration also with the FCC Review Committee chaired by Guenther Dissertori.

LHeC has been a development for and initiated by CERN, ECFA and NuPECC, so far, it’s formal status is that of a community study, not a proposal, which holds for the FCC also, of which ‘eh’ is a part.
### Organisation

**International Advisory Committee**

Mandate by CERN to define “...Direction for ep/A both at LHC+FCC”

Sergio Bertolucci (CERN/Bologna)  
Nichola Bianchi (Frascati)  
Frederick Bordry (CERN)  
Stan Brodsky (SLAC)  
Hesheng Chen (IHEP Beijing)  
Eckhard Elsen (CERN)  
Stefano Forte (Milano)  
Andrew Hutton (Jefferson Lab)  
Young-Kee Kim (Chicago)  
Victor A Matveev (JINR Dubna)  
Shin-Ichi Kurokawa (Tsukuba)  
Leandro Nisati (Rome)  
Leonid Rivkin (Lausanne)  
**Herwig Schopper (CERN) – Chair**  
Jurgen Schukraft (CERN)  
Achille Stocchi (LAL Orsay)  
John Womersley (ESS)

We miss Guido Altarelli.

### Coordination Group

**Accelerator+Detector+Physics**

Gianluigi Arduini  
Nestor Armesto  
Oliver Brüning – Co-Chair  
Andrea Gaddi  
Erk Jensen  
Walid Kaabi  
Max Klein – Co-Chair  
Peter Kostka  
Bruce Mellado  
Paul Newman  
Daniel Schulte  
Frank Zimmermann

5(12) are members of the FCC coordination team

OB+MK: co-coordinate FCCeh

### Working Groups

**PDFs, QCD**

Fred Olness,  
Claire Gwenlan  
**Higgs**

Uta Klein,  
Masahiro Kuze  
**BSM**

Georges Azuelos,  
Monica D’Onofrio  
Oliver Fischer  
**Top**

Olaf Behnke,  
Christian Schwanenberger  
**eA Physics**

Nestor Armesto  
**Small x**

Paul Newman,  
Anna Stasto  
**Detector**

Alessandro Polini  
Peter Kostka

*) April 2018
60 GeV Energy Recovery Linac

CDR: Default configuration, 60 GeV, 3 passes, 720 MHz, synchronous ep+pp, $L_{ep}=10^{33}$
Parameter Choice for FCC-he

For matched electron and proton beam sizes:

\[ \mathcal{L} \propto \frac{N_p}{\epsilon_p} \frac{1}{\beta_p} I_e H_{geom} H_{b-b} H_{coll} \]

- Proton beam brilliance
- Proton ring design
- Hourglass effect
- Beam-beam effect
- Fill pattern matching

\( O(1ab^{-1}) \) in a decade of operation, see D Schulte, FCC week at Rome, 2016
Recent Progress on IR Magnets

- The yoke and a small fine tuning coil add 5% to the bare coil gradient and create zero field sweet spot region just outside coil structure.
- If this were made an actively shielded coil the gradient would have instead dropped by 7% and the “septum region” made 10% thicker.
- A weak fine tuning coil allows to adjust field in the slot and compensate for saturation effects.

- Self-supporting coil structure presents smallest possible “septum” region between the beams.
- Quadrupole symmetric yoke with deep slot cut out regions bypasses magnetic flux around the near zero field space used for beam separation.
- Yoke slots are sized to cleanly pass the synrad fan cleanly to far from IP and thereby avoid adding backscatter background.