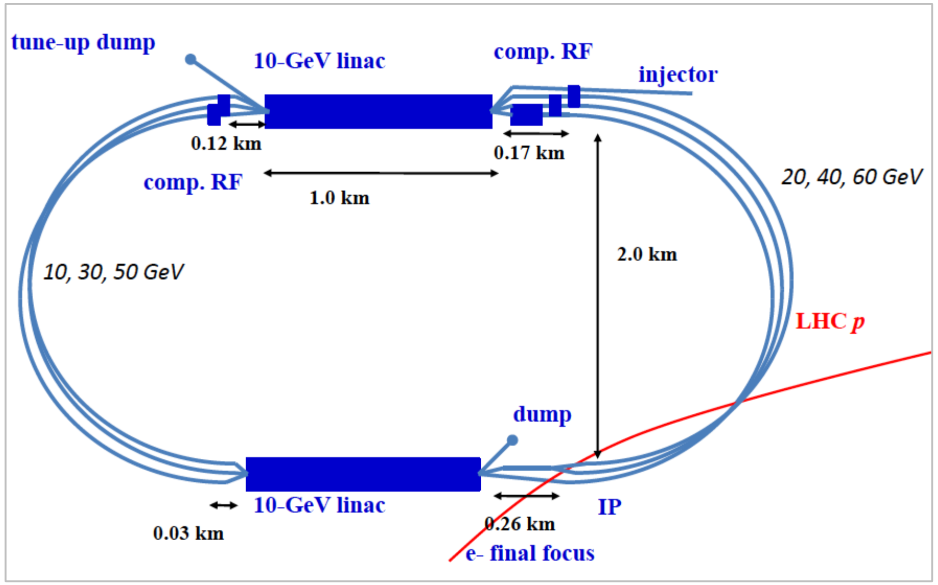
# 60GeV ERL Baseline Configuration:

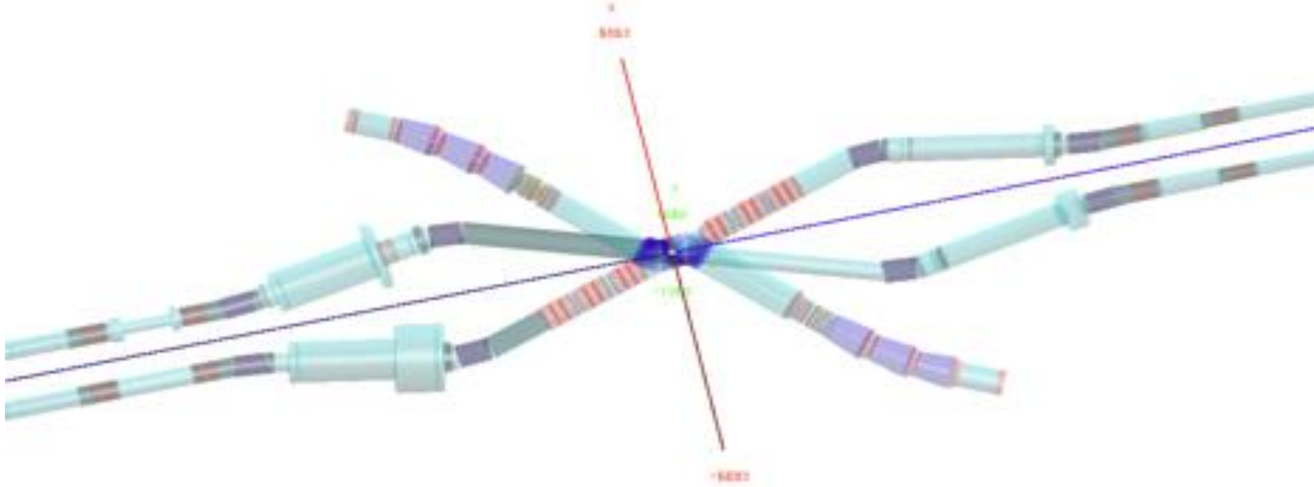
* LHeC CDR, arXiv:1206.2913

## Super Conducting Recirculating Linac with Energy Recovery

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

- TeV scale collision energy
  - ➔ 50-150 GeV electron beam energy
- power consumption < 100 MW
  - ➔ 60 GeV beam energy
- int. luminosity > 100 * HERA
- peak luminosity L > $10^{34}$ $cm^{-2}s^{-1}$

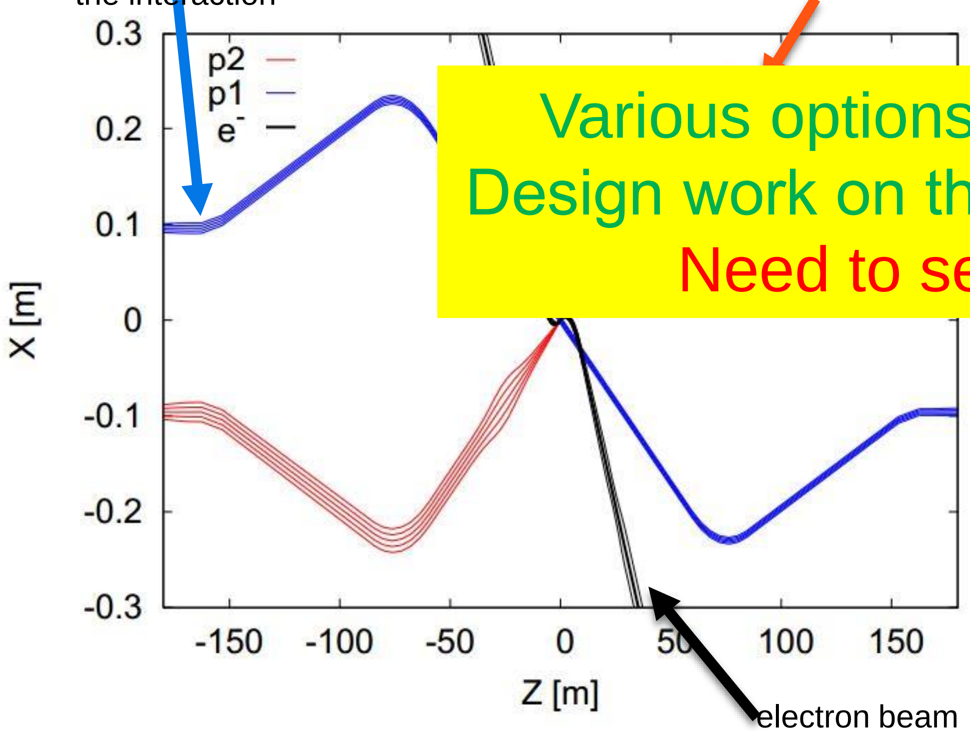


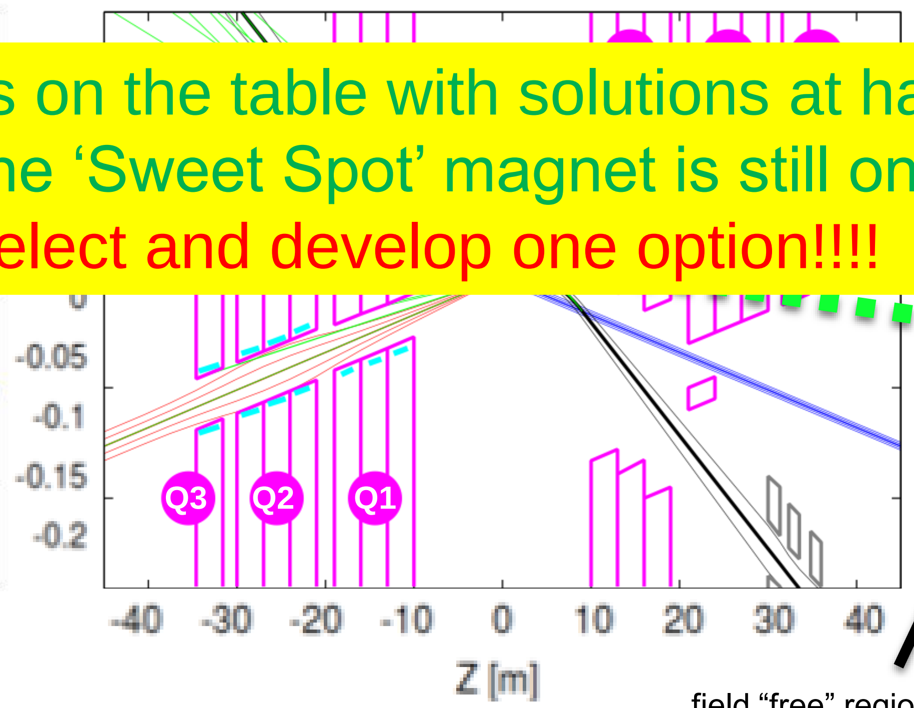



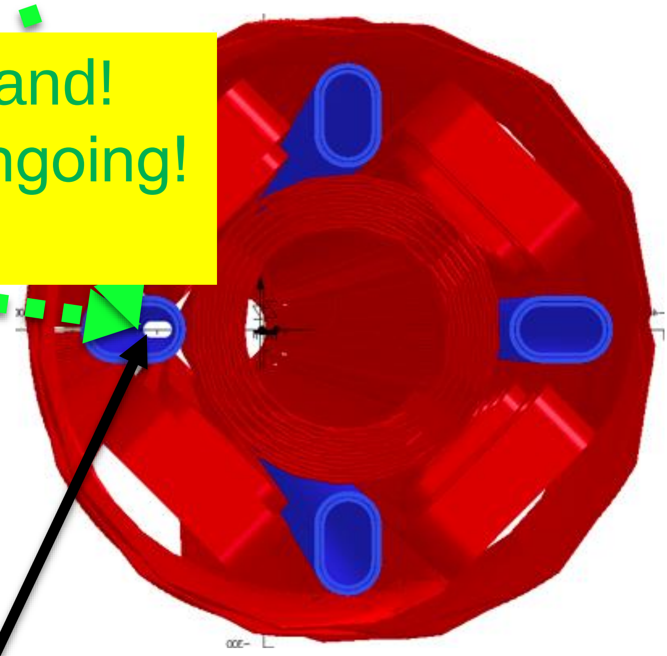
➔ 1072 cavities; 134 cryo modules per linac
➔ ca. 9 km underground tunnel installation
➔ more than 4500 magnets

courtesy H.Burkhardt, BE-ABP CERN ( layout scaled ! )

# LHeC/FCC-eh interaction region




Various options on the table with solutions at hand!
Design work on the 'Sweet Spot' magnet is still ongoing!
Need to select and develop one option!!!!

E. Cruz, R. Tomas, F. Zimmermann et al.

Tentative: $\varepsilon_p$=2µm, $\beta^*$=20cm → $\sigma_p$=3µm ≈$\sigma_e$ matched! $\varepsilon_e$=5µm ..

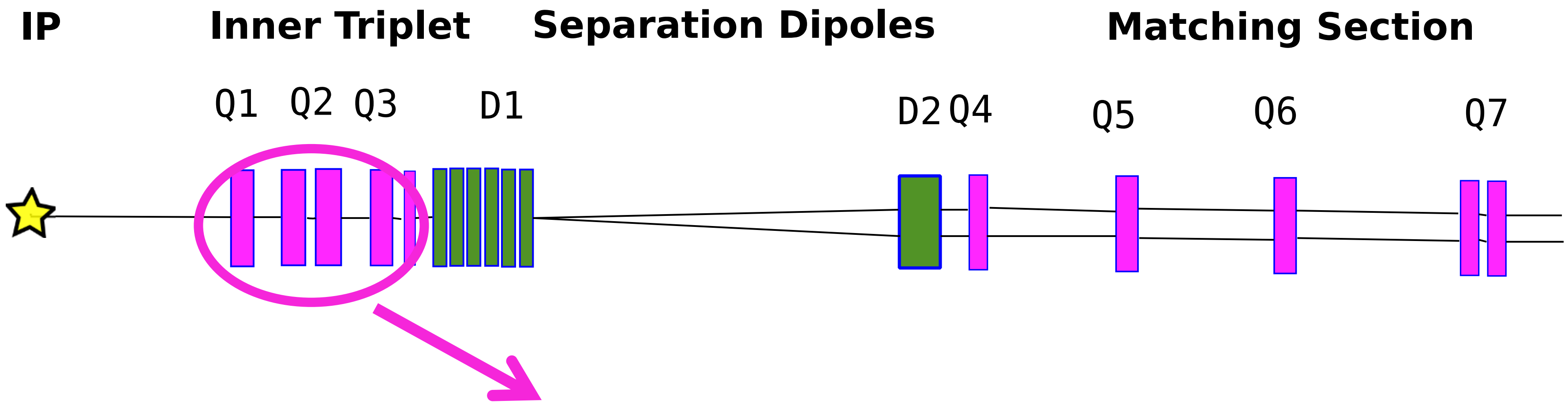
electron proton beams well matched!

B. Parker, S. Russenschuck et al.

# LHeC / FCC-eh Configuration and Performance

## Hadron IR design:

E. Cruz @ FCC week in Rome




Implementation of new triplet Q1-Q3 with aperture for 2 proton beams and one electron beam ➔ current studies based on layout WITHOUT Crab Cavities!

➔ strong synchrotron radiation and dipole inside detector!

We need:

- $\beta^* \approx 50$ cm ($10^{33}$ $cm^2s^{-1}$)
- $\beta^* \approx 5$ cm ($10^{34}$ $cm^2s^{-1}$)

**SEVERE LIMITATIONS**

1. Quadrupole apertures
2. Quadrupole gradients
3. Limits of the chromatic correction scheme

# LHeC: RL with ERL Operation as Baseline

## Performance:

* LHeC CDR, arXiv:1206.2913

*Post LHeC CDR, using HL-LHC parameters

| $10^{33}$ cm$^{-2}$ s$^{-1}$ Luminosity reach | PROTONS | ELECTRONS |
|---|---|---|
| Beam Energy [GeV] | 7000 | 60 |
| Luminosity [$10^{33}$cm$^{-2}$s$^{-1}$] | 1 | 1 |
| Normalized emittance $\gamma\varepsilon_{x,y}$ [$\mu$m] | 3.75 | 50 |
| Beta Funtion $\beta^*_{x,y}$ [m] | 0.1 | 0.12 |
| rms Beam size $\sigma^*_{x,y}$ [$\mu$m] | 7 | 7 |
| rms Beam divergence $\sigma^*_{x,y}$ [$\mu$rad] | 70 | 58 |
| Beam Current @ IP [mA] | 860 | 6.6 |
| Bunch Spacing [ns] | 25 | 25 |
| Bunch Population | $1.7*10^{11}$ | $1*10^{9}$ |
| Bunch charge [nC] | 27 | 0.16 |

| $10^{34}$ cm$^{-2}$ s$^{-1}$ Luminosity reach | PROTONS | ELECTRONS |
|---|---|---|
| Beam Energy [GeV] | 7000 | 60 |
| Luminosity [$10^{33}$cm$^{-2}$s$^{-1}$] | 16 | 16 |
| Normalized emittance $\gamma\varepsilon_{x,y}$ [$\mu$m] | 2.5 | 20 |
| Beta Funtion $\beta^*_{x,y}$ [m] | 0.05 | 0.10 |
| rms Beam size $\sigma^*_{x,y}$ [$\mu$m] | 4 | 4 |
| rms Beam divergence $\sigma^*_{x,y}$ [$\mu$rad] | 80 | 40 |
| Beam Current @ IP[mA] | 1112 | 25 ← 15 |
| Bunch Spacing [ns] | 25 | 25 |
| Bunch Population | $2.2*10^{11}$ | $2.3*10^{9}$ |
| Bunch charge [nC] | 35 | 0.64 |

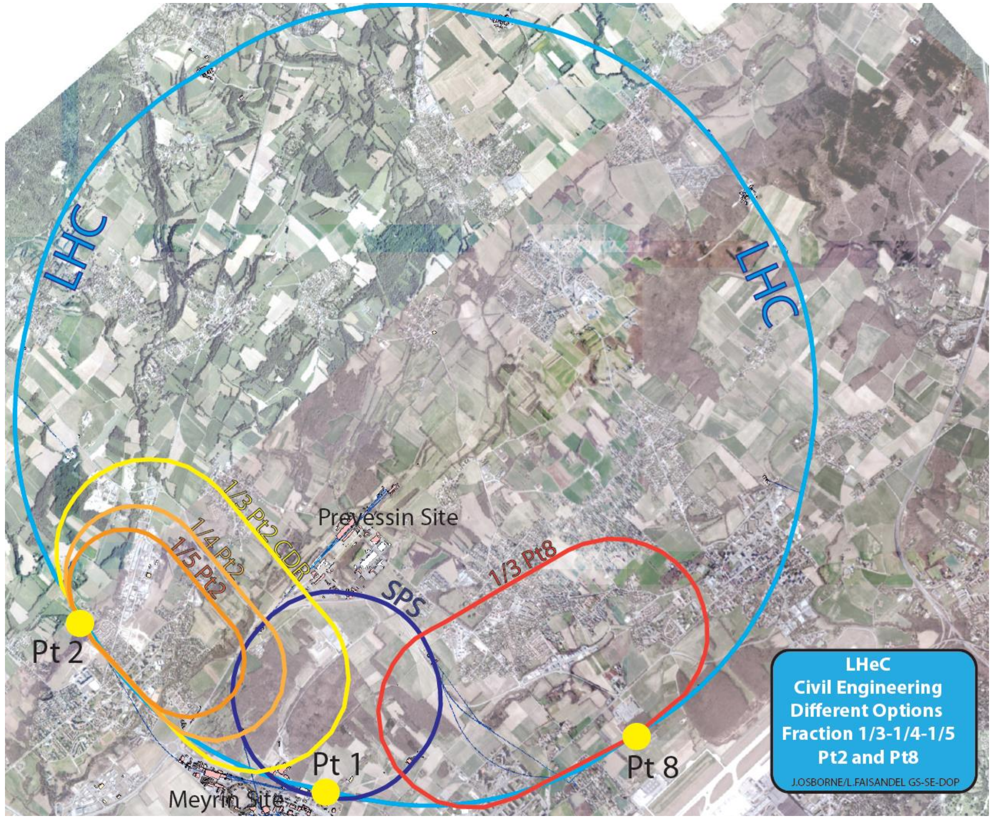
# LHeC / FCC-eh Configuration: Layout Options

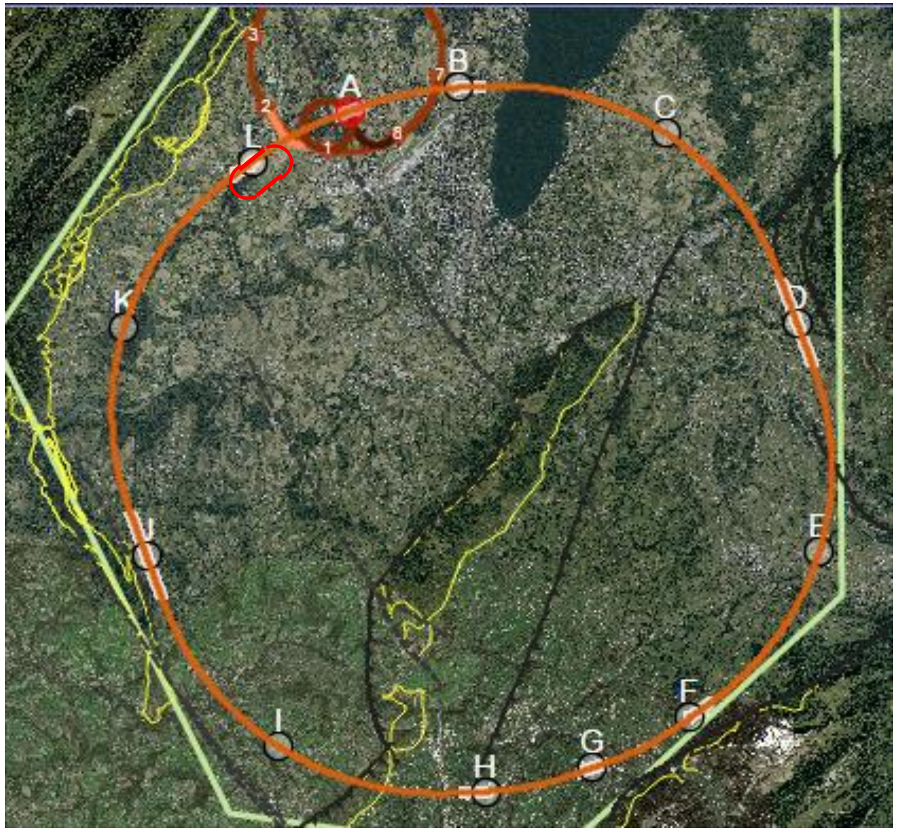
C. Cook @ FCC week in Rome

## Configuration:

LHeC

FCC-he considers Point ‘L’ since FCC Week in Berlin

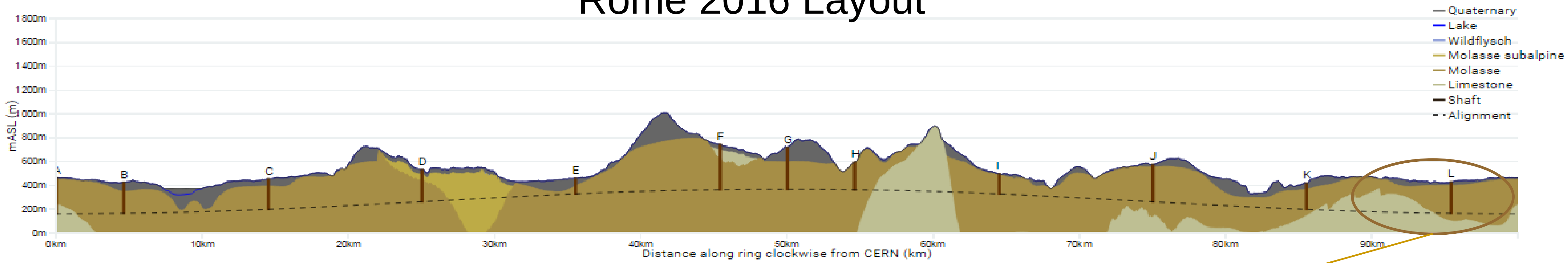


# FCC Layout Changes (profile)

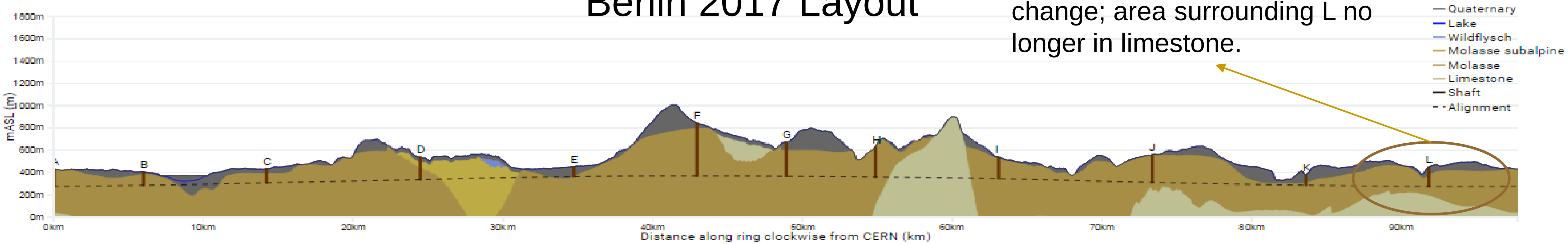
Jo Stanyard

Rome 2016 Layout




Berlin 2017 Layout

Reduced Depth & alignment change; area surrounding L no longer in limestone.



# LHeC & FCC-eh Machine Configuration

## Configuration:

Modular design elements:

- -60 GeV ERL configuration with 3 re-circulations for the 'e' beam
  - documented in the LHeC CDR — * LHeC CDR, arXiv:1206.2913
  - applicable to LHC, HE-LHC and FCC ➔ varied sizes possible;
- -IR configuration with head-on collisions
  - ➔ without Crab Cavities (vs EI in US)! ➔ Performance boost with CC?
  - ➔ SR acceptance in detector and beam separation
  - ➔ Dipole integrated into detector ➔ Impact of Crab Cavities?
  - ➔ 'Sweetspot' IR magnet design ➔ β* reach versus e-beam current!
- -802MHz SRF: synergy between LHeC, FCC-eh, FCC-ee and FCC-hh

# Difference in LHeC and FCC-eh costing:

- Civil Engineering:

  Geological conditions are different for the LHeC and the FCC-eh

  → Different consultancy companies with different estimates

  Different tunnel depth

  → Different cost for the shafts even for equal tunneling cost

  → In the following we concentrate on the LHeC costing

  → FCC-eh civil engineering costing will be part of the FCC costing

# Cost Items not simply Scaling with Energy:

- IR Magnets:

  Assume these require a comparable development as the HL-LHC triplet magnets

  ➔ 15 years of R&D cost + production cost ➔ ca. 80MCHF

- Auxiliary Systems:

  Not yet fully evaluated ➔ assume a placeholder of 69MCHF for this exercise; including 19MCHF for surface buildings based on Amberg estimate

- ERL Injector: One off proto-type like object

  ➔ cost estimate based on CERN SRF R&D and cost for SPL and PERLE facility

  ➔ ca. 40MCHF

# Cost Items not simply Scaling with Energy:

- ERL Tunnel without RF and arc:

  Assume 400m for transfer lines and 400m space in each straight for beam dump and ERL spreader and combiner sections ➔ ca. 30MCHF

- Access shafts and Access Shaft Caverns: Amberg; ILF and HL-LHC

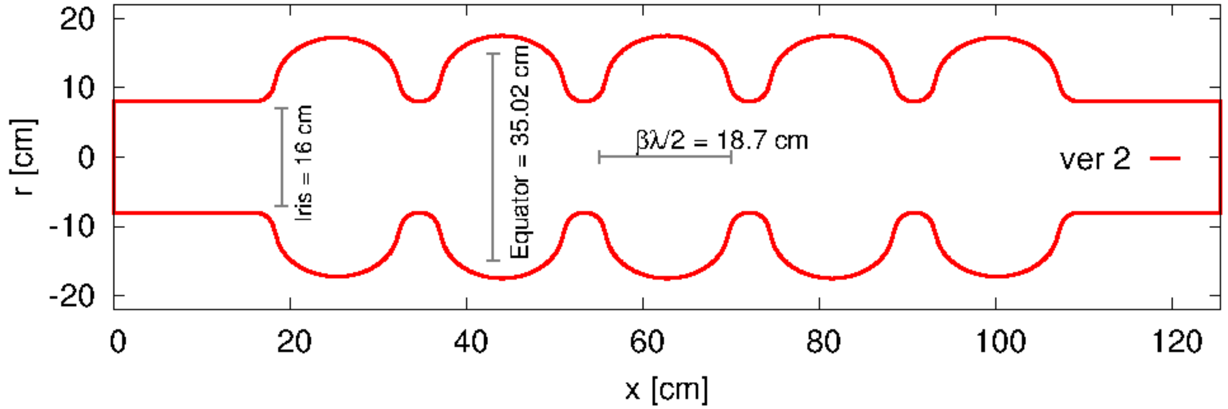
  Assume 2 shafts with LHC depth ➔ ca. 34MCHF for 2 shafts

  [for comparison: the HL-LHC shafts cost 10.4MCHF per shaft]

- Beam Dump: ➔ ca. 5MCHF placeholder

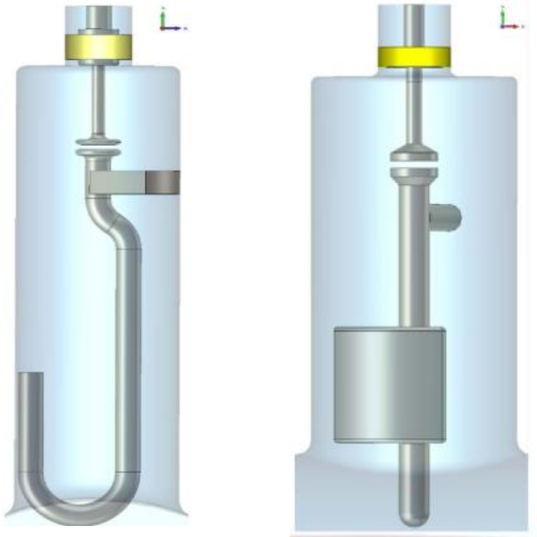
# ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

Rama Calaga




| Parameter | Ver 1 (Scaled) | Ver 2 |
|---|---|---|
| Frequency [MHz] | 801.58 | 801.58 |
| Number of cells | 5 | 5 |
| Active cavity length [mm] | 935 | 935 |
| Voltage [MV] | 18.7 | 18.7 |
| $E_p$ [MV/m] | 45.1 | 48.0 |
| $B_p$ [mT] | 95.4 | 98.3 |
| R/Q [Ω] | 430 | 393 |
| Cell-cell coupling (mid-cell) | 4.47% | 5.75% |
| Stored Energy [J] | 154 | 141 |
| Geometry Factor [Ω] | 276 | 283 |
| Field Flatness | 97% | 96% |

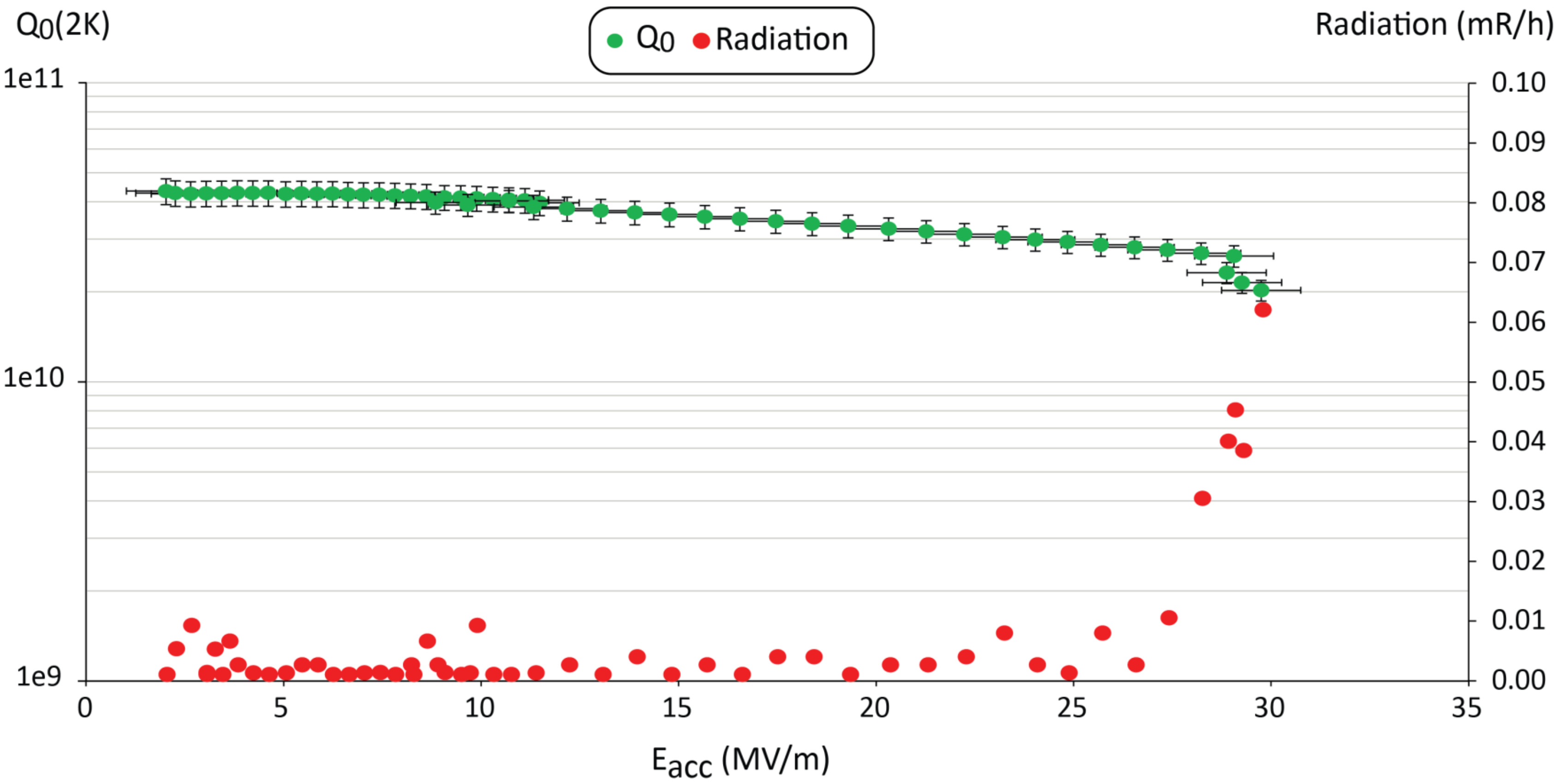
HOM Coupler: LHC-like dual concept

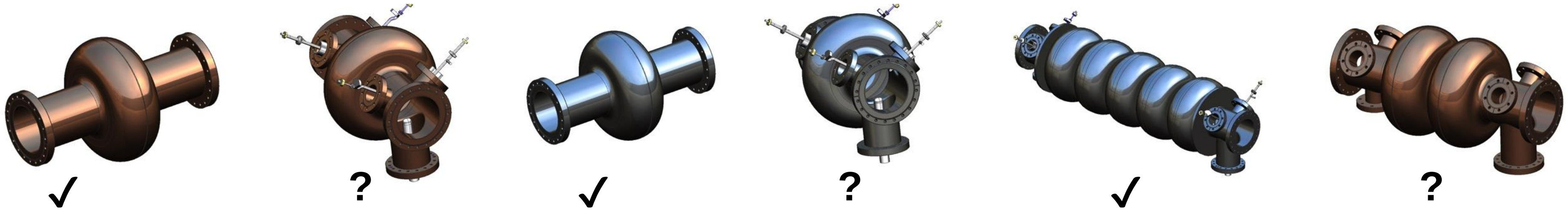


# ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

JLAB / CERN collaboration

F. Marhauser Feb 2018




✓ = in plan, **?** = option

# ERL Cost Items scaling with Energy: SRF Cryo Module

- Primary source of estimate: European XFEL

  Proje

  ➔Ca. 3MCHF per 7.5m long ERL Cryo Module

  ize]

- Secondary cost comparison: LCLSII

  Project has a comparable size of SRF system [and CW] but is not yet finished

  -Assume the SRF cost per Cryomodule scales roughly with CM length

- Terti

  C-BE

  ➔Ca. 6.1MCHF per 7.5m long R&D Cryo Module

  -Use the estimates for the SRF Prototypes for the injector costing

# ERL Cost Items scaling with Energy: Cryogenic System:

Primary source of estimate: LHC experience [Laurent Tavian and Serge Claudet]

➔ Cryo-plant cost as a function of achievable $Q_0$ in the SRF system

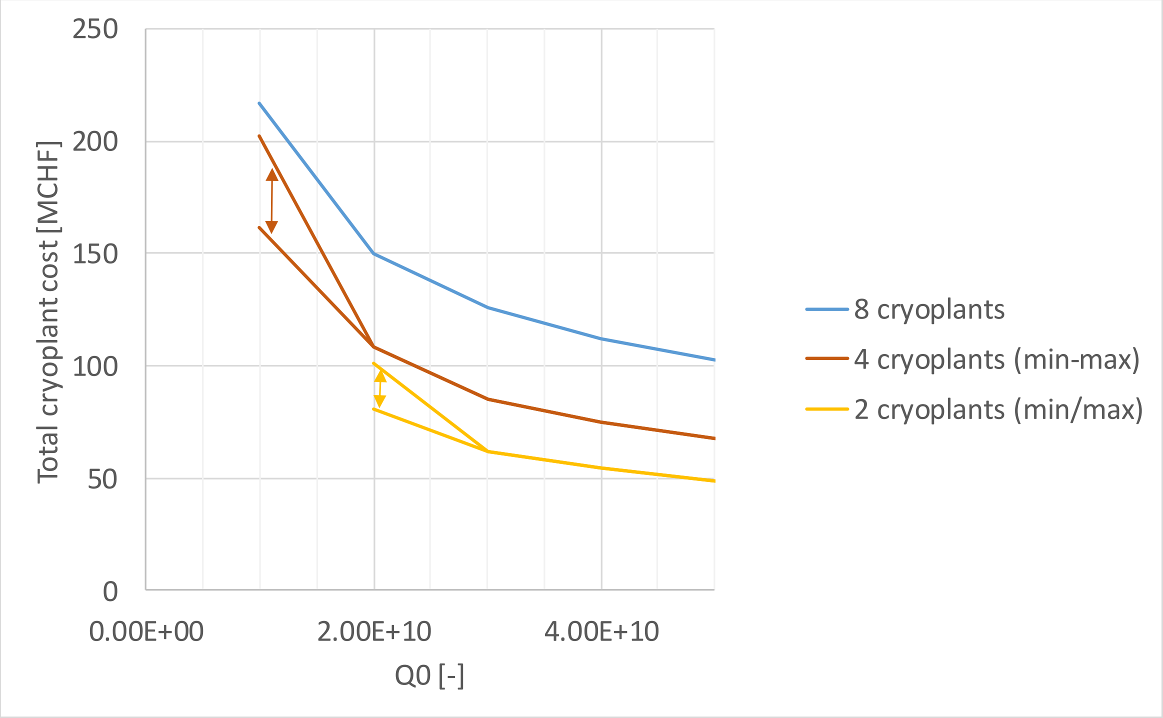
Analysis of optimum number of Cryo-plants

$Q_0 = 10^{10}$ implies Cryo-Plants comparable in size to that of the LHC

➔ The baseline configuration assumes $Q_0 = 2.5\ 10^{10}$

➔ Attractive options of 2 or 4 cryo-plants

➔ For the scaling we assume 4CPs [100MCHF] and scale the cryo cost with the SRF linac length ➔ reducing the system to 2 plants might bring further savings of up to 25MCHF



# LHeC Baseline Configuration Costing

## 60 GeV ERL Beam Energy:

| Budget Item | Cost |
|---|---|

**→But SRF is clearly the main cost driver!**

**→Motivation to look at energy and size cost scaling!!!**

**For this we keep the budget for SR power and total Wall-Plug Power consumption constant**

→ Main cost drivers are SRF [scales with linac length] and return arcs [scales with $E^4$]

# Assumptions and Boundary Conditions for Scaling

- **Baseline Assumptions:**

  Limit the Wall-plug Power consumption of the ERL to 100MW

  -Assume 50% of that are required for SR [rest for cryo and magents]

  documented in the LHeC CDR

- **Synchrotron Radiation Power per arc:**

$$P_{arc} = \frac{N_b}{n_b} \frac{e^2 \gamma^4}{6 \epsilon_0 \rho}$$

Scales with $E^4$ and $\rho^{-1}$ ➔ ca. 40% of SR power comes from high energy return arc

-Assume 50MW limit for energy consumption for SR losses

➔ scale return arc radius of curvature for a given beam energy to stay within this limit

# Assumptions and Boundary Conditions for Scaling

- Civil Engineering:

  LEP cost as a reference → inflation adapted cost

  Plus two estimates from external consultant companies:

  Amberg for LHeC and ILF for FCC related CE → ca. 25kCHF / m for scaling

- SRF Tunnel:

  Scales with E. For CE costing we assume a 50% tariff for the CE cost per meter to account for the required space for RF power sources

- Magnet and vacuum system: scales with $E^4$

  The full magnets and vacuum system had been costed for the LHeC CDR:

  140MCHF for the complete LHeC system → ca. 11.15kCHF per arc meter

# FCC-eh Configuration: Layout & Civil Engineering

## Configuration:

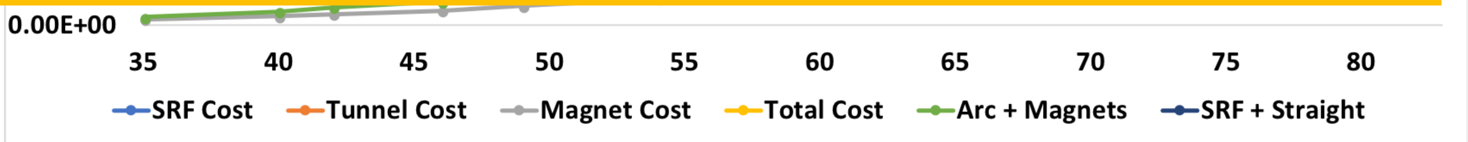
Different Size Variations:
e.g LHeC

Preliminary cost estimates based 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 $E^4$ dependence on the arc length only becomes dominant for beam energies above 75GeV!**

**[Unless the SRF cost becomes significantly lower!]**

# 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

# 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***

# End

## 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***

***➔250GeV Version with 11km SRF:***

- ***Tunnel ca. 0.75BCHF***
- ***SRF ca 4.4BCHF***
- ***Cryo ca. 0.5BCHF ➔ total ca 5.5BCHF***

***➔ fits to ILC estimates [we assumed +30% for SRF scaling!]***

# FCC-eh ERL Configuration:

## Consistent Performance Projections for ep:

| 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 |
| $\gamma\epsilon_p$ [$\mu$m] | 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 $\beta_p^*$ [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 |

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
"A Baseline for the FCC-he"

Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann

# FCC-eh ERL Configuration:

[Daniel Schulte]

## Performance Simulations for FCC-ep:

| Parameter | Unit | Protons | Electrons |
|---|---|---|---|
| Beam energy | GeV | 50000 | 60 |
| Normalised emittance | $\mu$m | $2.2 \rightarrow 1.1$ | 10 |
| IP betafunction | mm | 150 | $42 \rightarrow 52$ |
| Nominal RMS beam size | $\mu$m | $2.5 \rightarrow 1.8$ | $1.9 \rightarrow 2.1$ |
| 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 | $[\mathrm{ab}^{-1}]$ | 1.2 | |

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
"A Baseline for the FCC-he"

Daniel Schulte

# FCC-eh ERL Configuration:

| parameter [unit] | LHeC (HL-LHC) | eA at HE-LHC | FCC-he |
|---|---|---|---|
| $E_{\text{Pb}}$ [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 |
| $\gamma\epsilon_A$ [$\mu$m] | 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 $\beta_A^*$ [cm] | 7 | 10 | 15 |
| hourglass factor $\text{H}_{geom}$ | 0.9 | 0.9 | 0.9 |
| pinch factor $\text{H}_{b-b}$ | 1.3 | 1.3 | 1.3 |
| bunch filling $\text{H}_{coll}$ | 0.8 | 0.8 | 0.8 |
| luminosity [$10^{32}\text{cm}^{-2}\text{s}^{-1}$] | 7 | 18 | 54 |

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
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