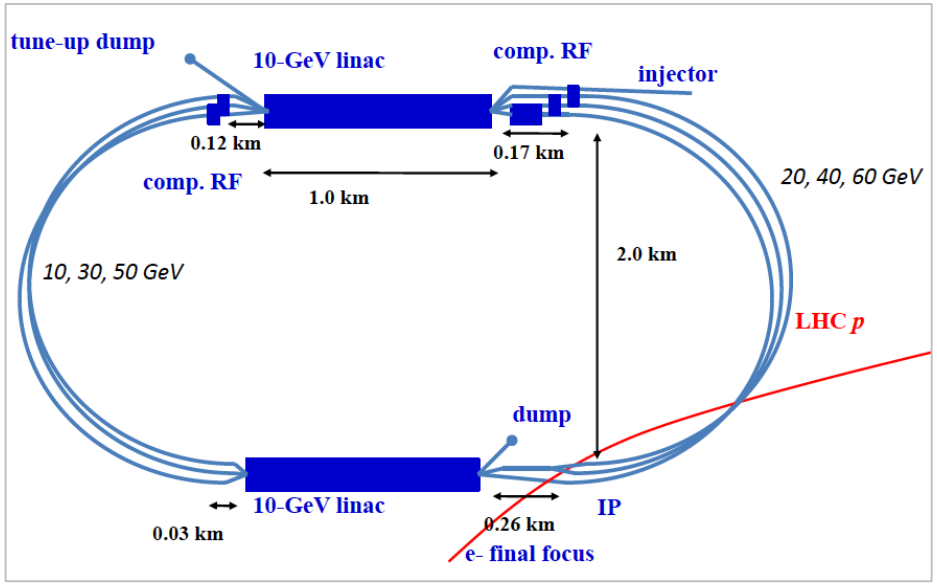
60GeV ERL Baseline Configuration:

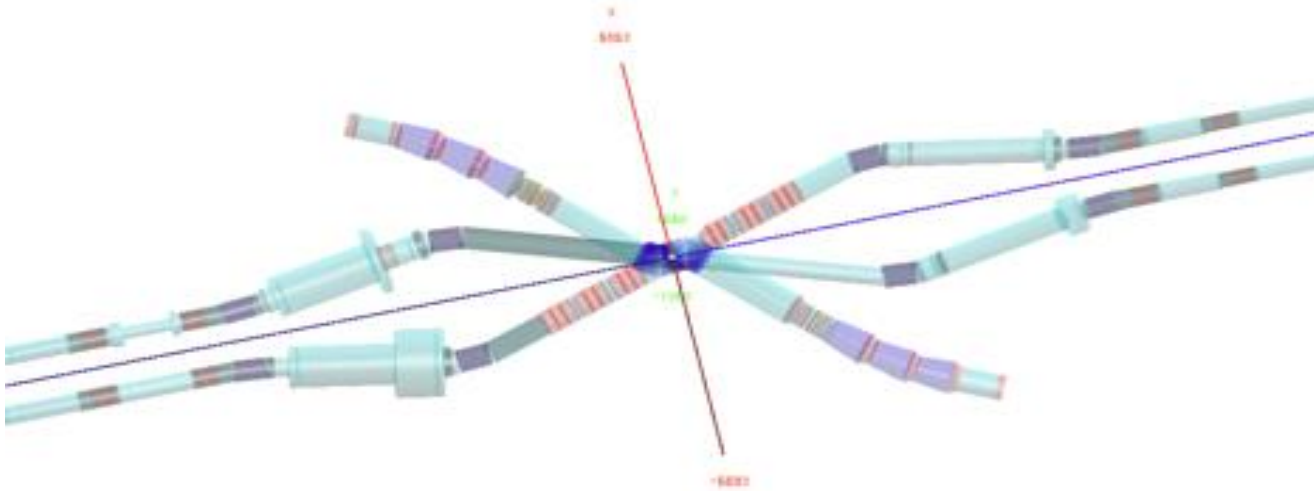
* LHeC CDR, arXiv:1206.2913

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

non focused beam bypasses the interaction

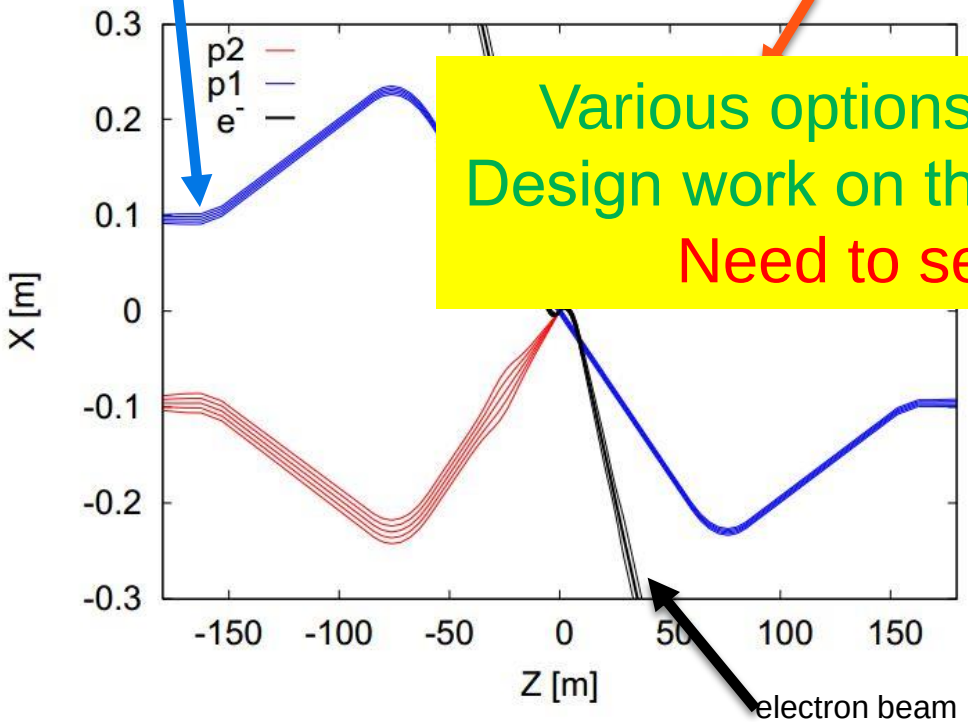
focused interacting proton beam

Synchrotron Radiation and various beams

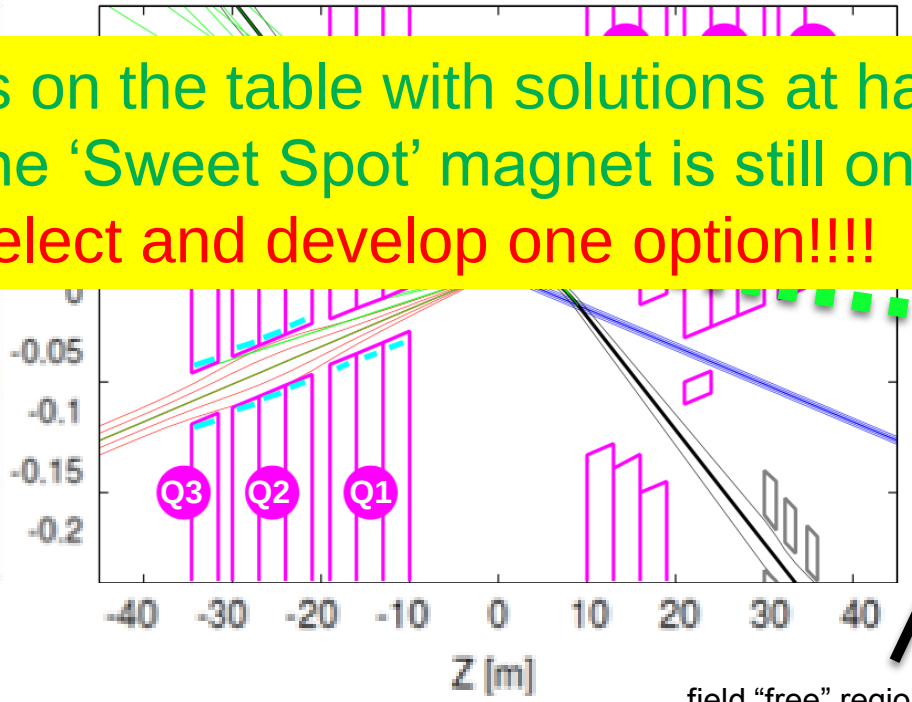
SR fan

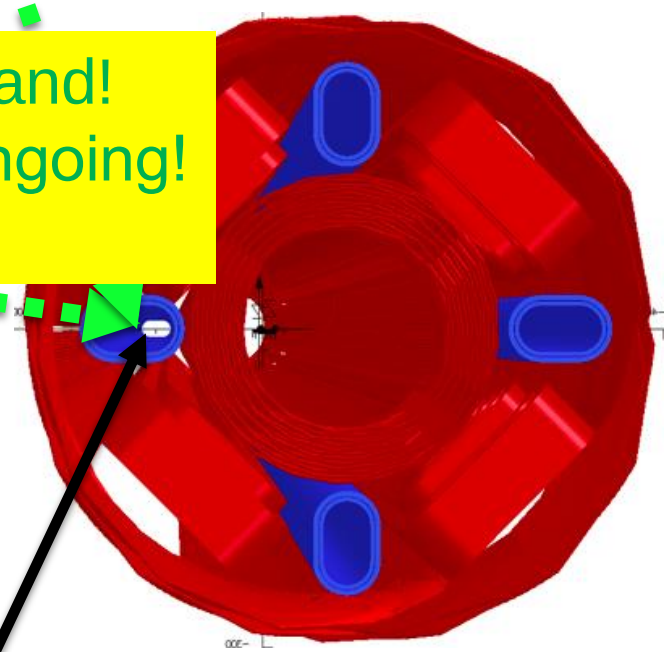
exit hole - electrons and non-colliding protons

Final quadrupole magnet Q1 example design "sweet spot"



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!!!!





electron beam from ERL

field "free" region

Tentative: ε_p=2μm, β*=20cm → σ_p=3μm ≈σ_e matched! ε_e=5μm ..

electron proton beams well matched!

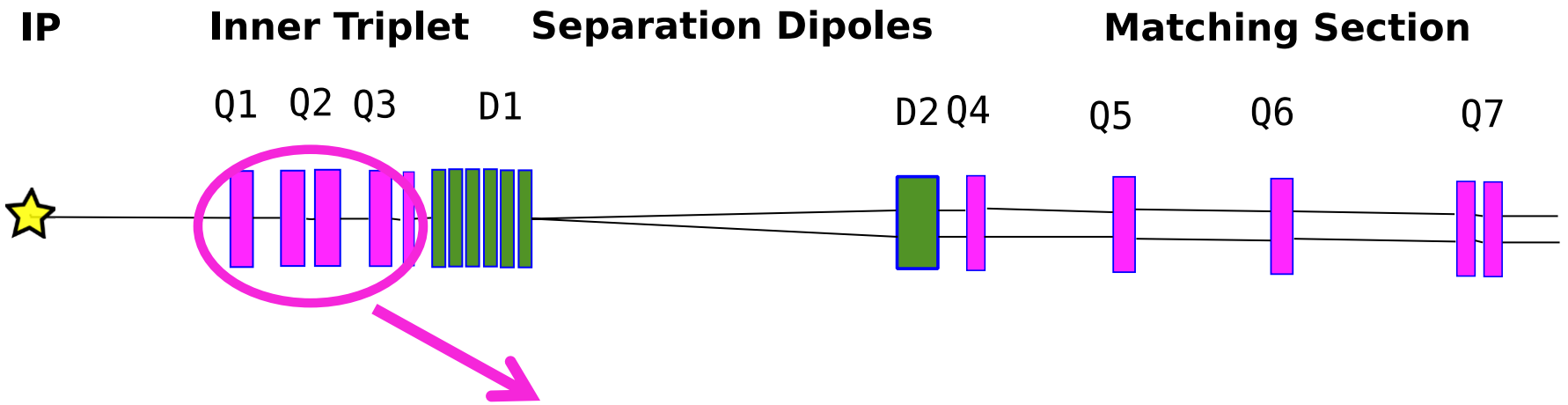
E. Cruz, R. Tomas, F. Zimmermann et al.

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

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 $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Beam divergence $\sigma\square^*_{x,y}$ [μrad]	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

*Post LHeC CDR, using HL-LHC parameters

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 $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma\square^*_{x,y}$ [μrad]	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

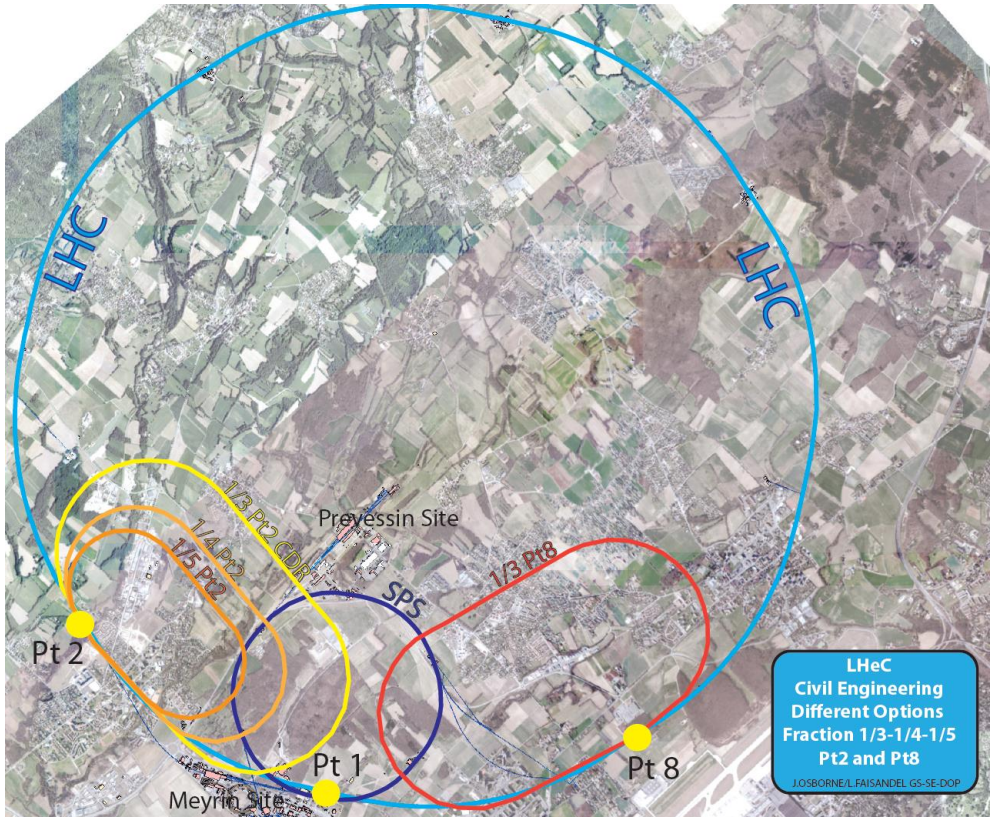
LHeC / FCC-eh Configuration: Layout Options

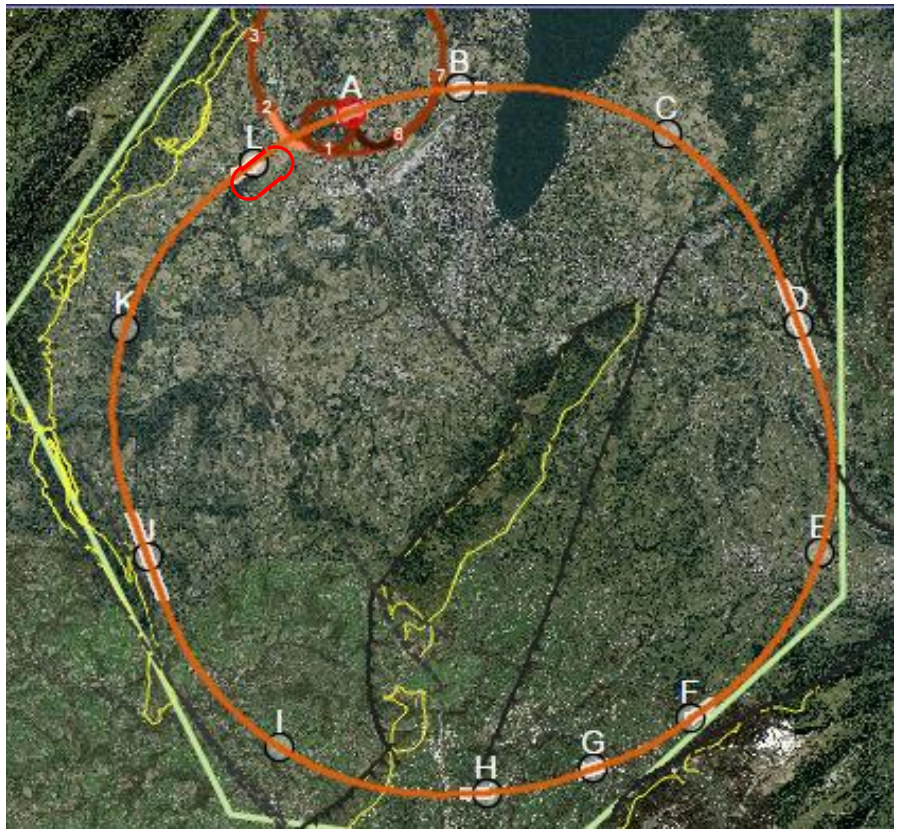
C. Cook @ FCC week in Rome

Configuration:

LHeC

FCC-he considers Point 'L' since FCC Week in Berlin

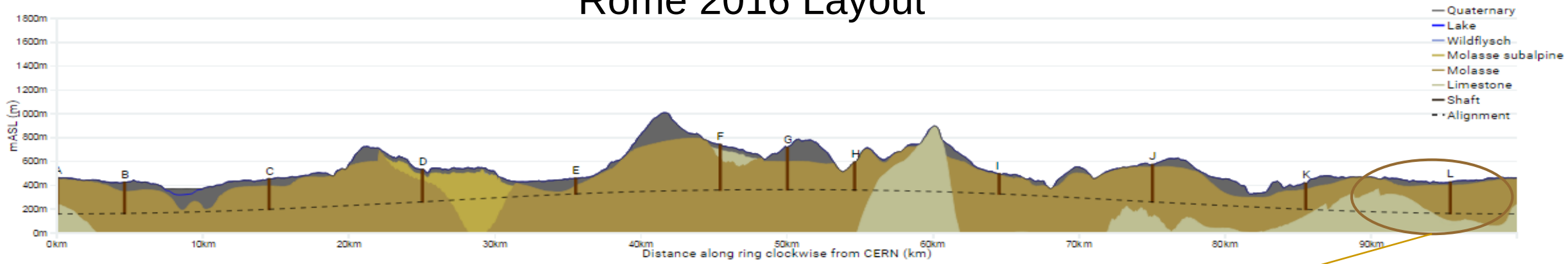




FCC Layout Changes (profile)

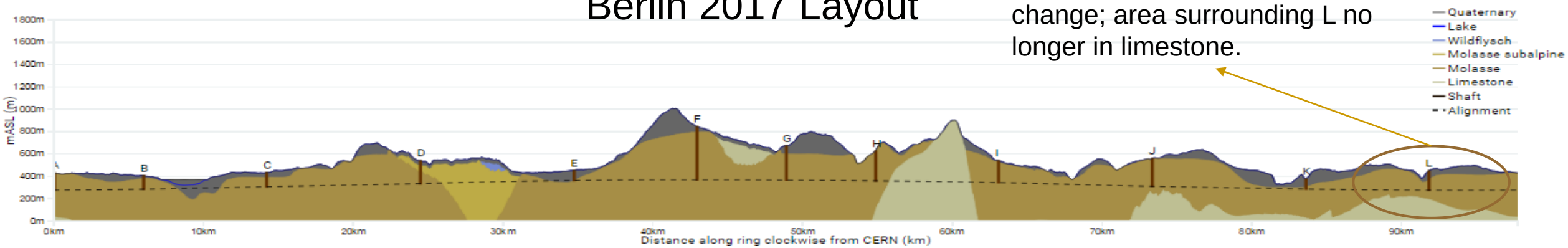
Jo Stanyard

Rome 2016 Layout



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

Berlin 2017 Layout



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

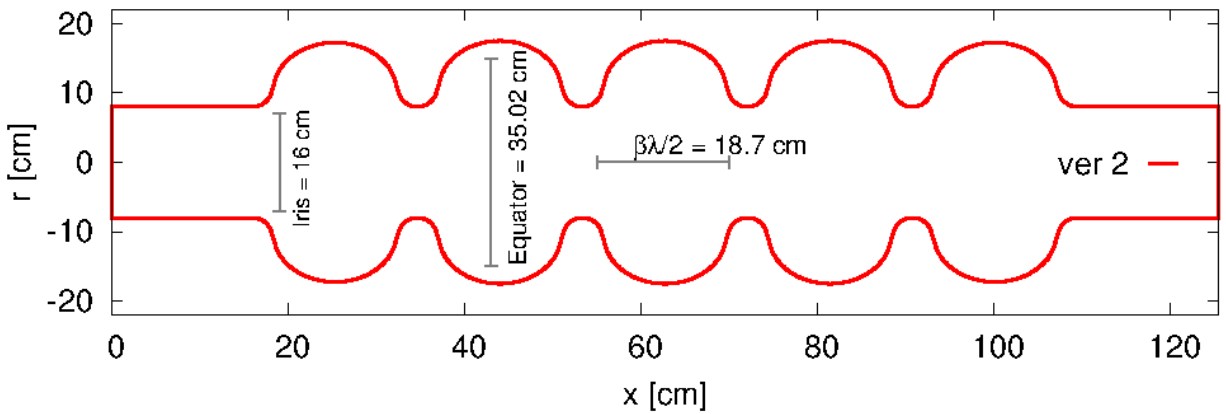
  Assume 2 shafts with LHC depth ➔ ca. 34MCHF for 2 shafts

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

- Beam Dump: ➔ ca. 5MCHF placeholder

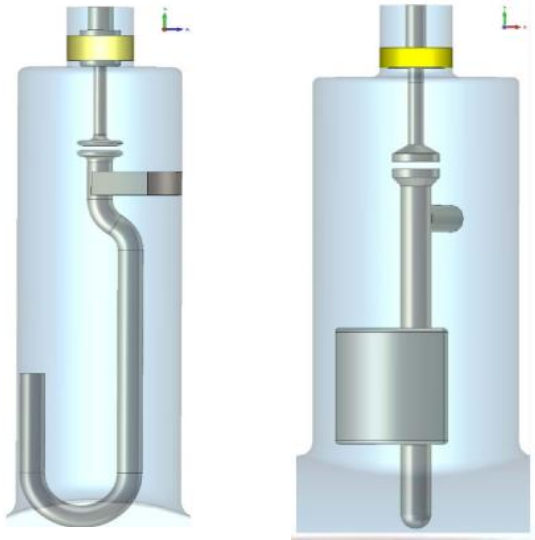
ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

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%

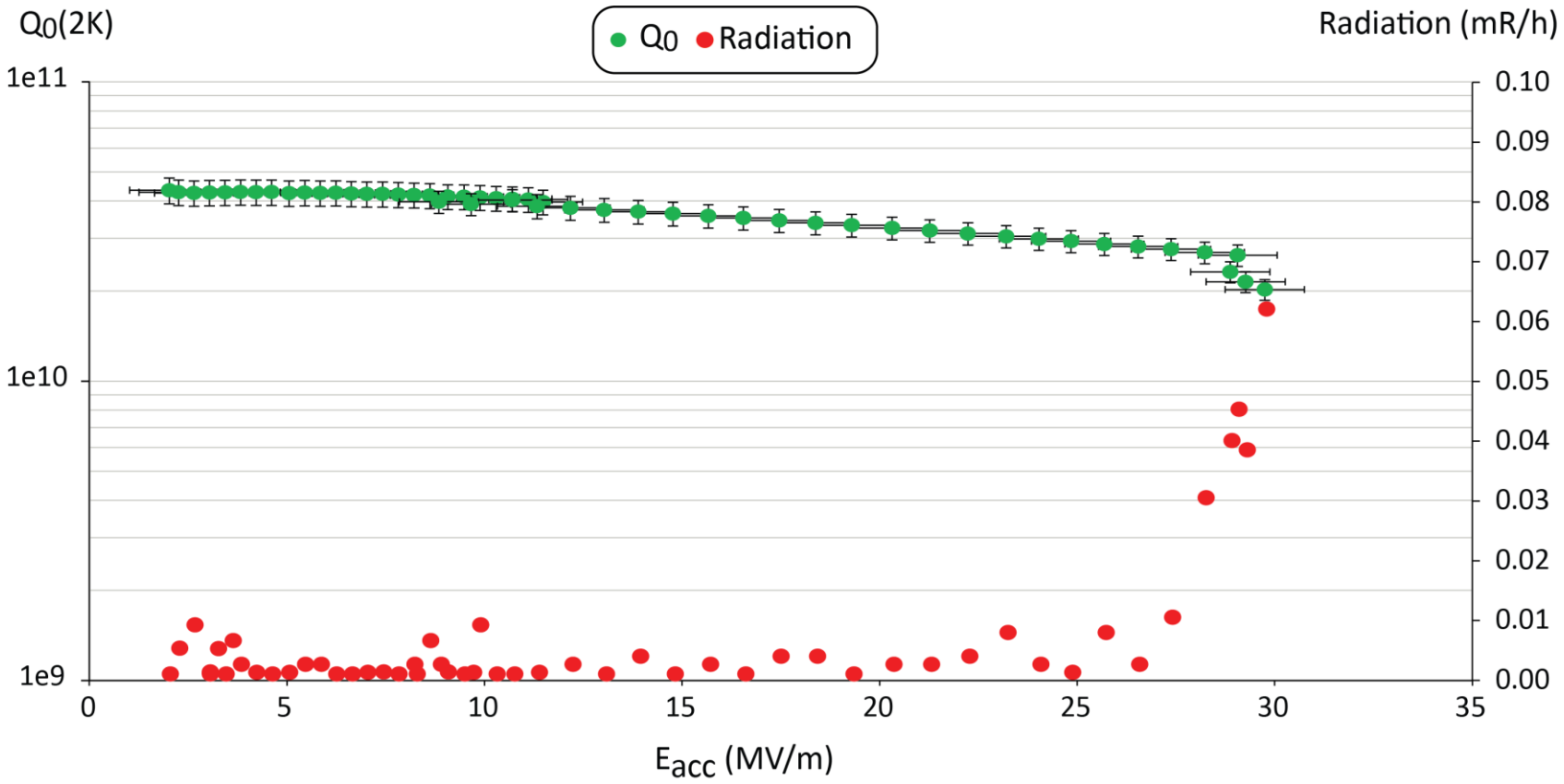
HOM Coupler: LHC-like dual concept

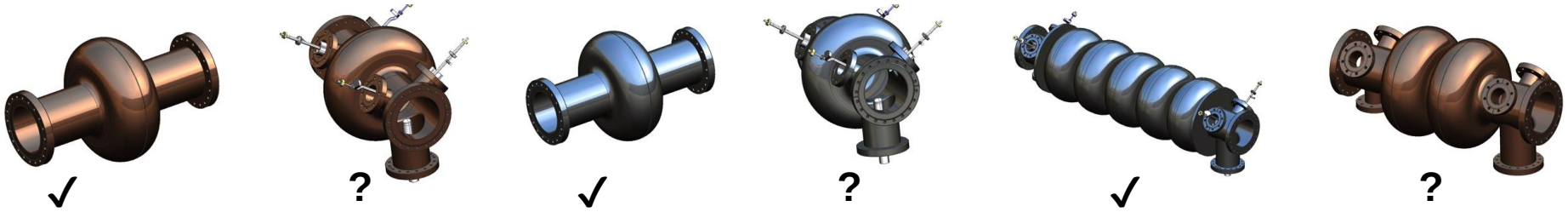


ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

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

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

  C-BE

  -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

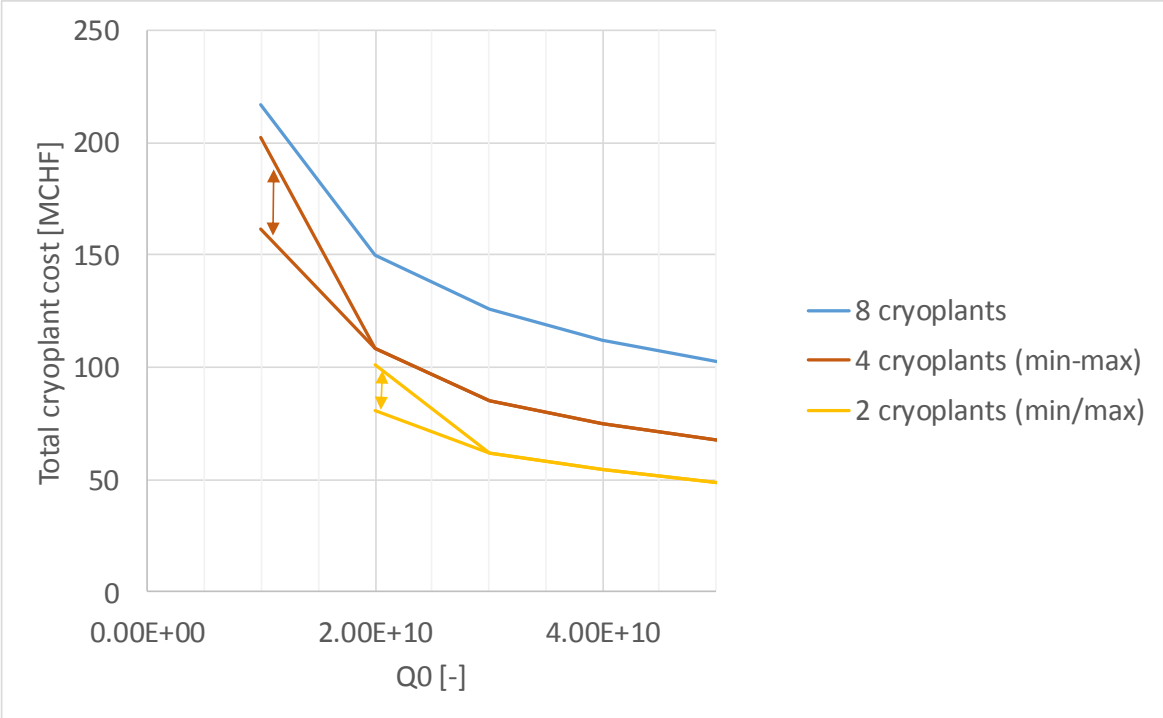
Analysis of optimum number of Cryo-plants

$Q_0 = 10^{10}$ 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

➔ Based on XFEL and LCLS2 costing scaled by CM length

➔ 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 ρ^{-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:

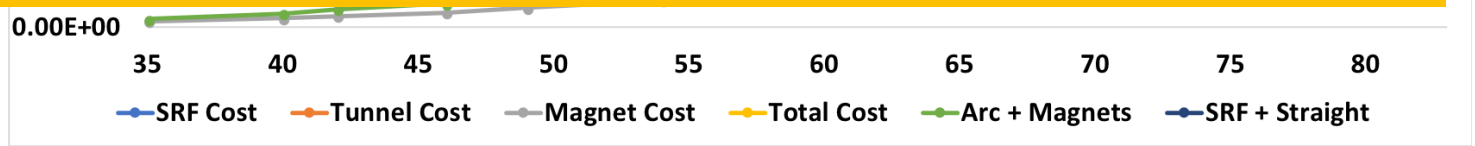
Different Size Variations:
e.g LHeC

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
$\gamma\epsilon_p$ [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

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	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	$[\mathrm{ab}^{-1}]$	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_{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

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

John Jowett, Frank Zimmermann