ERL as Injector for FCC

O. Bruning, R. Corsini

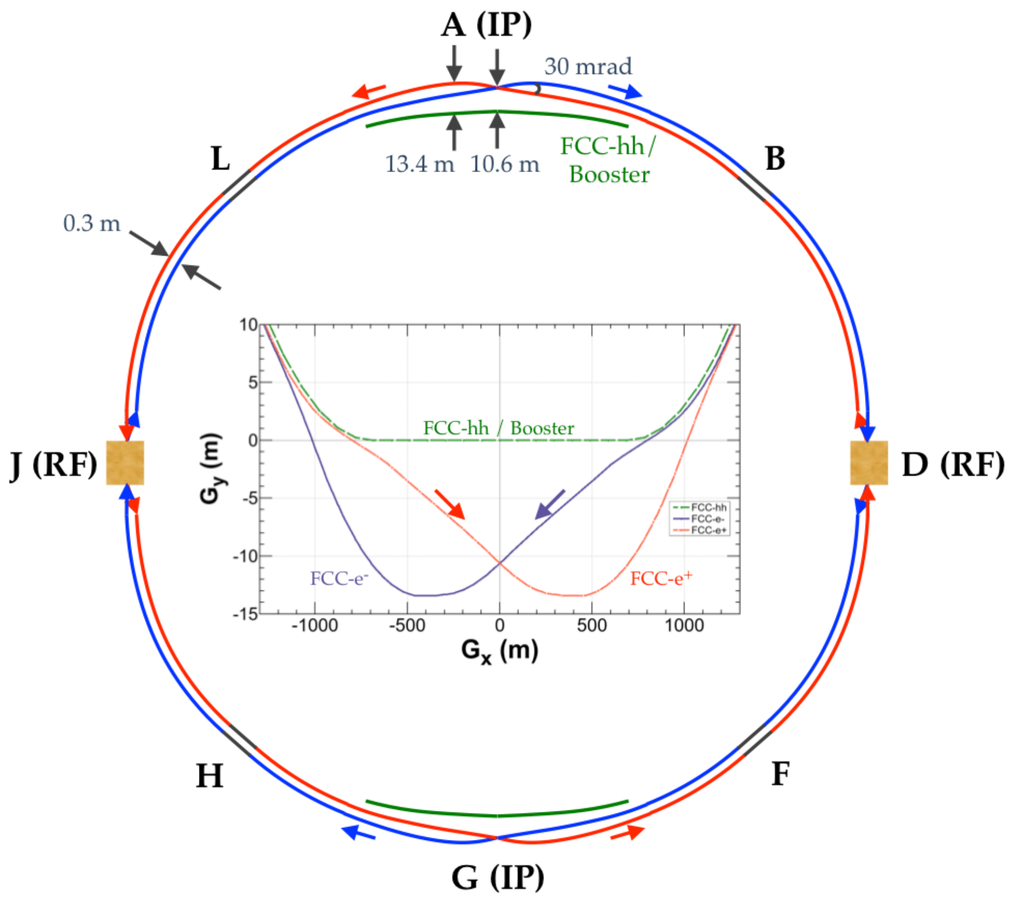
- Most slides from Oliver -

Material also from H. Braun, K. Oide, D. Schulte, F. Zimmermann, …

(thanks)

FCC-ee basic design choices

- **Double ring** e^+e^- collider ~100 km
- **Follows footprint of FCC-hh**, except around IPs
- **Asymmetric IR layout & optics** to limit synchrotron radiation towards the detector
- **Presently 2 IPs**, large horizontal crossing angle 30 mrad, crab-waist optics
- **Synchrotron radiation power 50 MW/beam** at all beam energies; tapering of arc magnet strengths to match local energy
- **Top-up injection** scheme; requires **booster synchrotron in collider tunnel**



The Baseline scheme for the FCC-ee injector

Baseline layout, as documented in the CDR

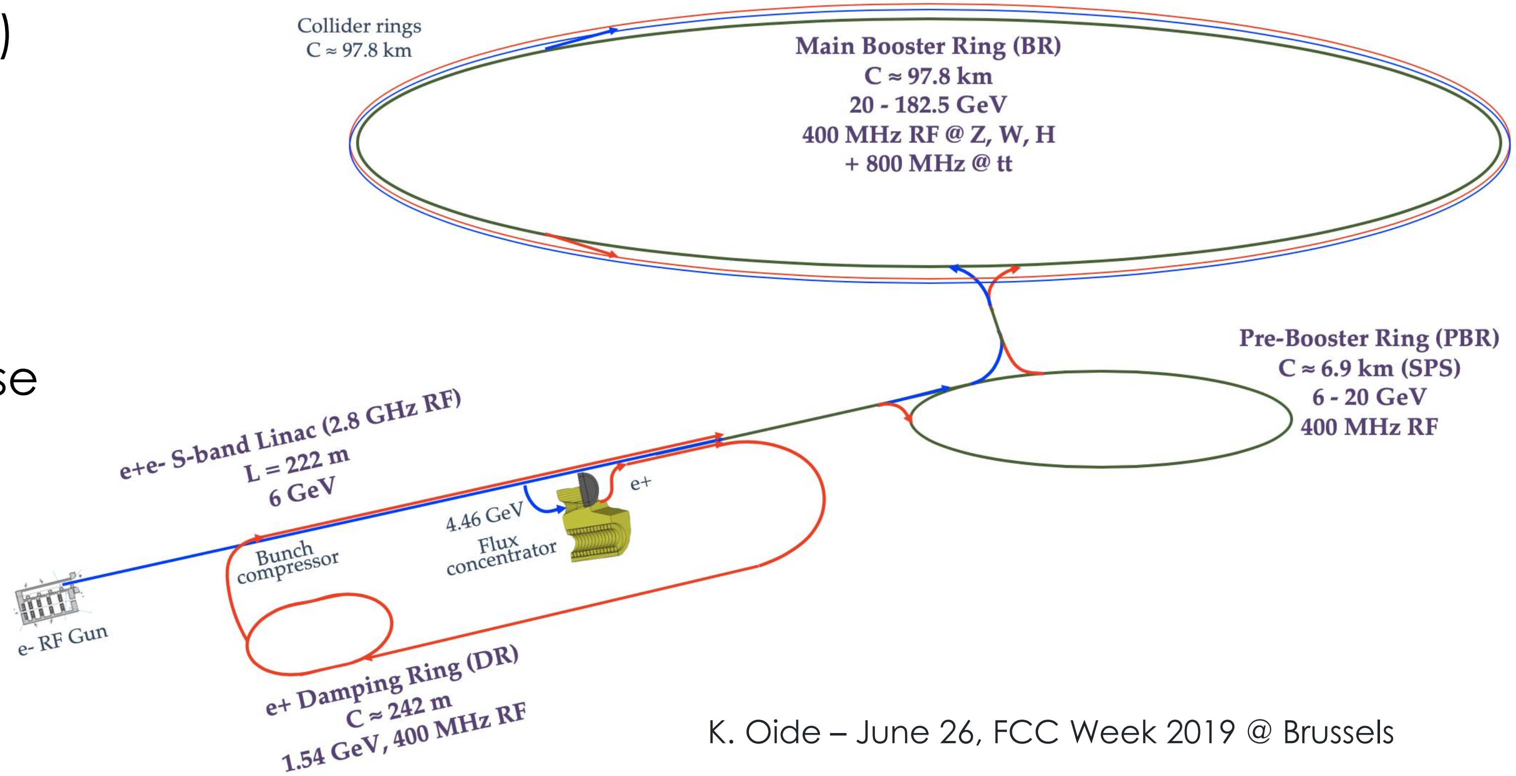
- **Linac** with 6 GeV followed by 20 GeV **Pre-Booster Ring** [**SPS**]

  (Alternative: 20 GeV **Linac** C band)

- **Main Booster Ring** from 20 GeV to full energy (45 GeV - 180 GeV)

- About 2.0 10^{10} N_b with 2 bunches per pulse and 200 Hz rep-rate → < 1.5 μA average current

- Requires also transfer lines from SPS to FCC → ~ 10 km tunnel



K. Oide – June 26, FCC Week 2019 @ Brussels

FCC-ee Injector Requirements

- Four different energies from Booster ring (45.6 GeV to 182.5 GeV)
- Injection in Booster ring at 20 GeV
- Initial fill + top-up
- Maximum current for Z-pole operation
- Rather long filling time especially for Z operation (issue with SPS occupation)

Parameter (unit)	Z		W		H		$t\bar{t}$	
Beam energy (GeV)	45.6		80		120		182.5	
Type of filling	Initial	Top-up	Initial	Top-up	Initial	Top-up	Initial	Top-up
Linac bunches/pulse	2				1			
Linac repetition rate (Hz)	200		100					
Linac RF frequency (GHz)	2.8							
Bunch population (10^{10})	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
No. of linac injections	1040		1000		328		48	
PBR minimum bunch spacing (ns)	10		10		70		477.5	
No. of PBR cycles	8		1					
No. of PBR bunches	2080		2000		328		48	
PBR cycle time (s)	6.3		11.1		3.7		0.9	
PBR duty factor	0.84		0.56		0.30		0.08	
No. of BR/collider bunches	16640		2000		328		48	
No. of BR cycles	10	1	10	1	10	1	20	1
Filling time (both species) (s)	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

Future Circular Collider Study. Volume 2: The Lepton Collider (FCC-ee) Conceptual Design Report, preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0057, Geneva, December 2018. Published in Eur. Phys. J. ST.

http://fcc-cdr.web.cern.ch/#FCCEE

Using LHeC type Recirculating Linac as FCC-ee injector

Parameter (unit)	Z		W		H		$t\bar{t}$	
Beam energy (GeV)	45.6		80		120		182.5	
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Filling time (both species) (s)	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

→ Average beam current of < 1.5 μA

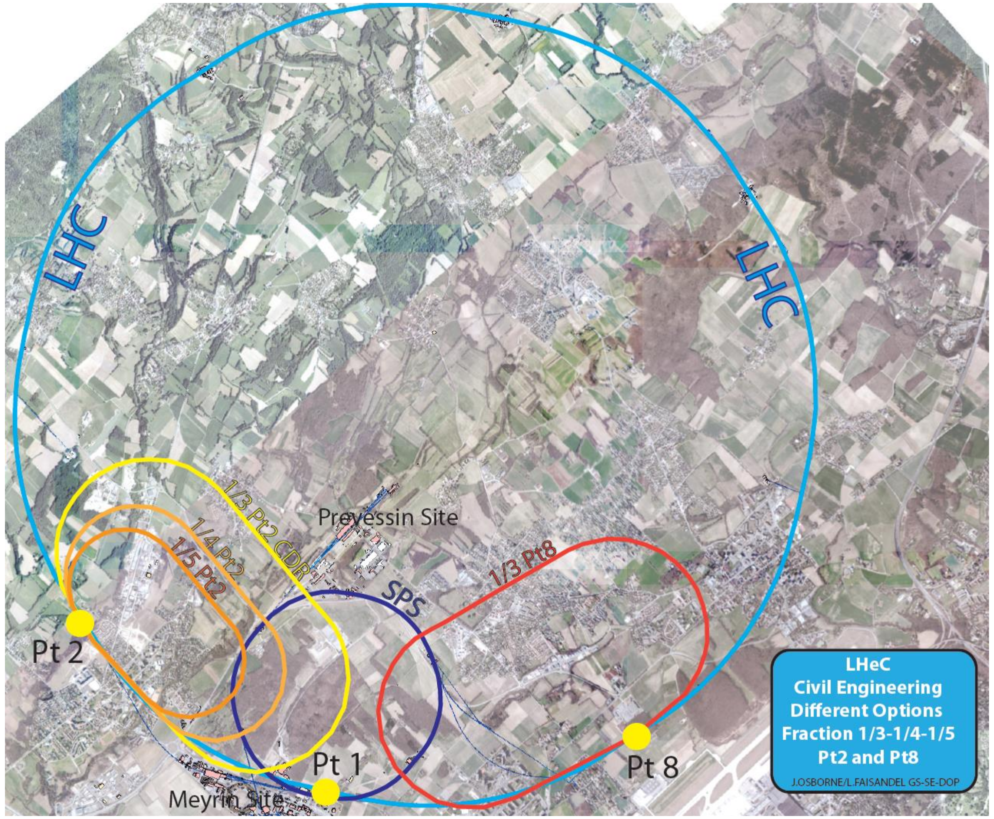
→ More than 4 orders of magnitude smaller than the currents in the LHeC ERL !!!

ERL Alternatives:

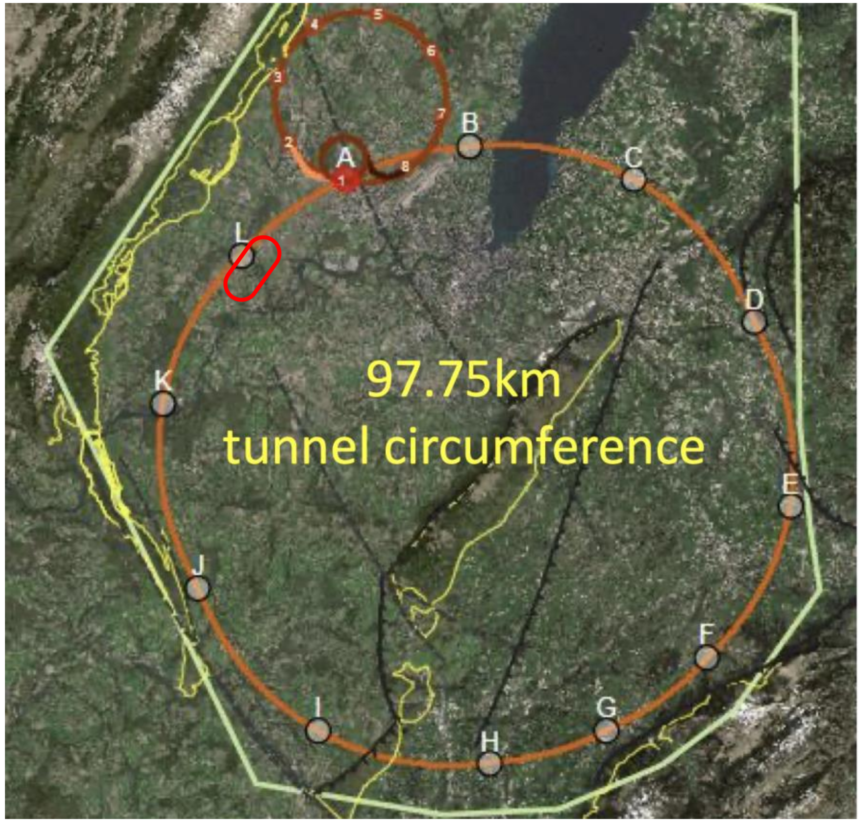
- Use a 5 km long racetrack suitable for 50 GeV upgrade for FCC-eh
  - Initial stage at 20 GeV to inject in Booster Ring
  - 50 GeV machine, direct injection in FCC-ee for Z mode – still need Booster for W, H and tt
- Smaller machine (PERLE…) optimized as FCC injector
  - at 6 GeV to substitute linac
  - or 20 GeV to inject in Booster Ring
- Common hardware and infrastructure: one could use the FCC-ee pre-series SRF
- 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

ERL Configuration for LHC and FCC: 30 GeV to 60 GeV

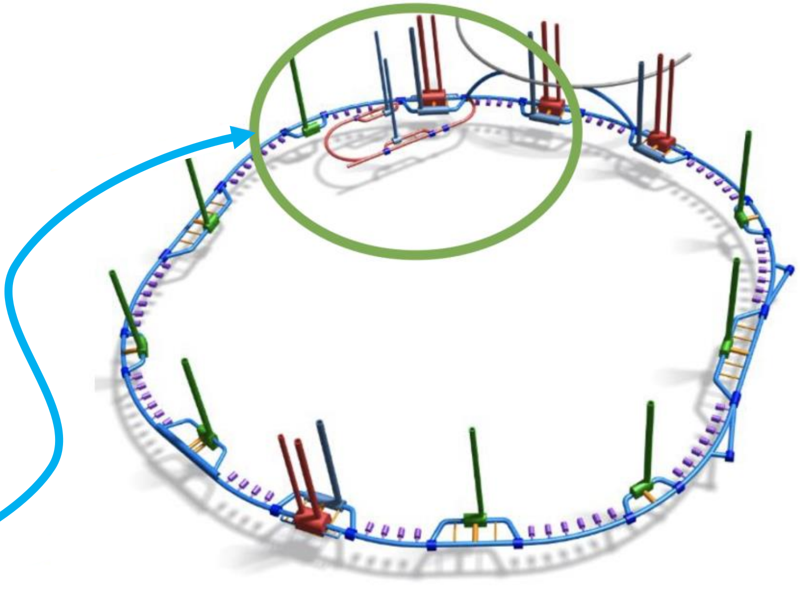
Different Size Variations:
e.g LHeC and HE-LHC-eh

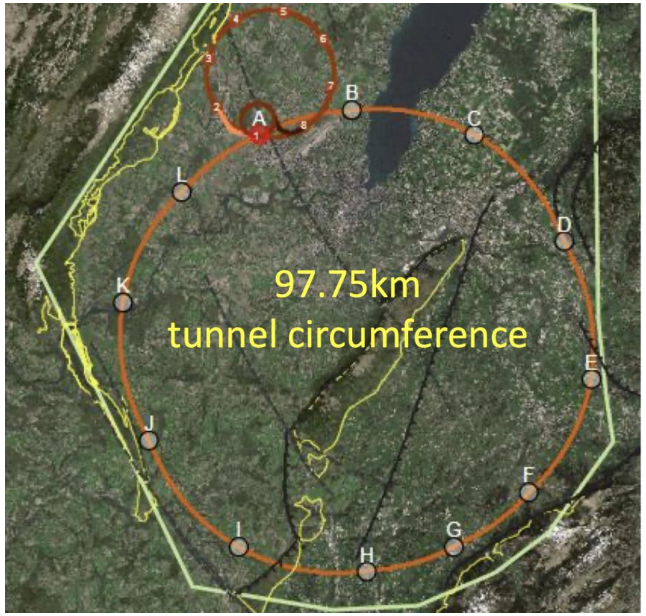


Interaction region 'L' as
baseline choice for FCC-eh

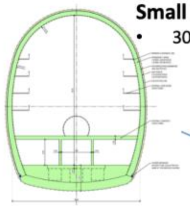


Conceptual Baseline Footprint

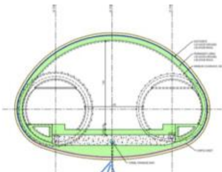


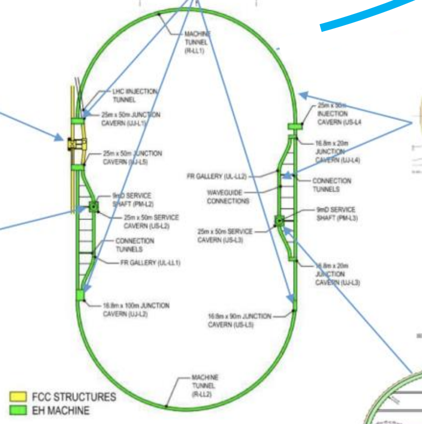


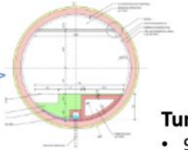
Small Experimental Caverns
- 30 m x 35 m x 66m



Junction Caverns
- 16.8 m x 15 m x 100 m
- 25 m x 15 m x 50 m
- 16.8 m x 15 m x 90 m

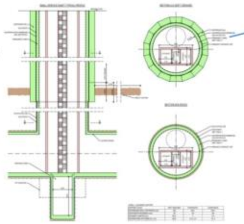




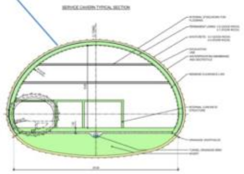


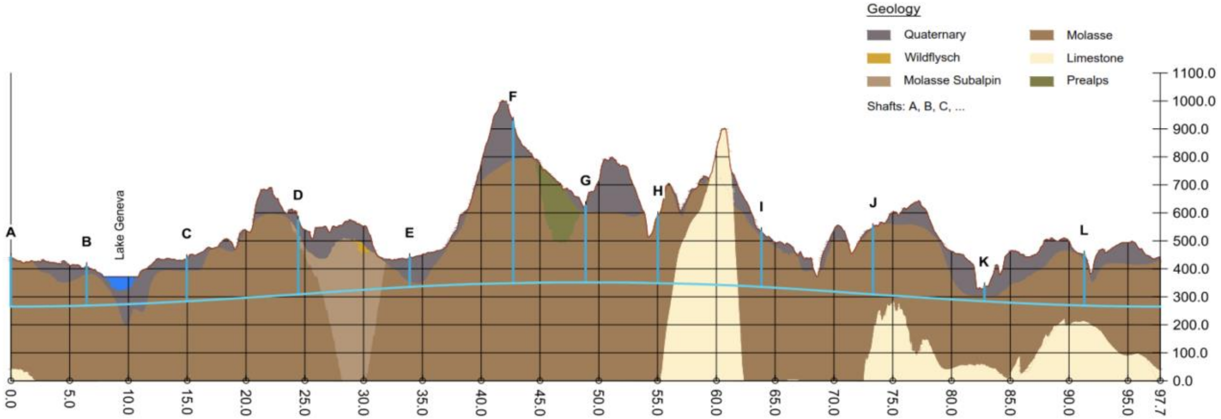
Tunnels:
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

Shafts:
2 x Service shafts:
9 m dia. x 175 m depth



Service Caverns
- 25 m x 15 m x 50 m



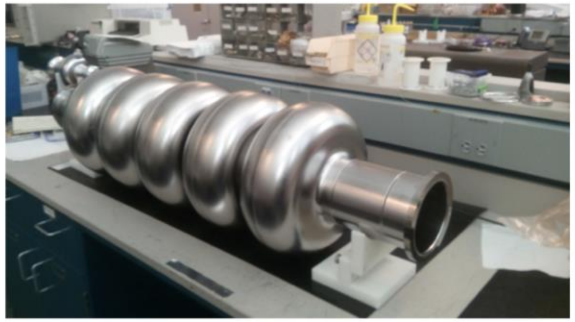


Cavity fabrication and test:

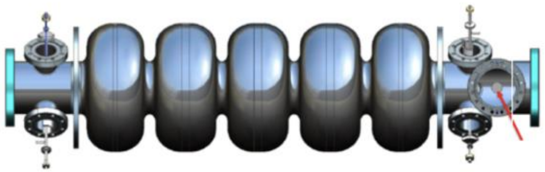
LAL/IPNo – CERN - JLAB Collaboration

Courtesy to Frank Marhauser

Parameter	Unit	Value
Frequency	MHz	801.58
Number of cells		5
Iris/tube ID	mm	130
L_{act}	mm	917.9
$R/Q = V_{eff}^2/(\omega \cdot W)$	Ohm	524
G	Ohm	274.7
R/Q·G/cell		143940
$\kappa_{\|\|}$ (2mm rms bunch length)	V/pC	2.74
E_{pk}/E_{acc}		2.26
B_{pk}/E_{acc}	mT/(MV/m)	4.20
k_{cc}	%	3.21



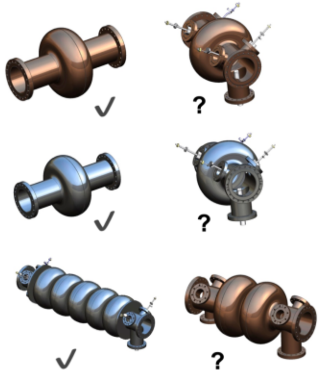
The first Nb 802 MHz 5-Cell cavity fabricated October 2017 at JLAB



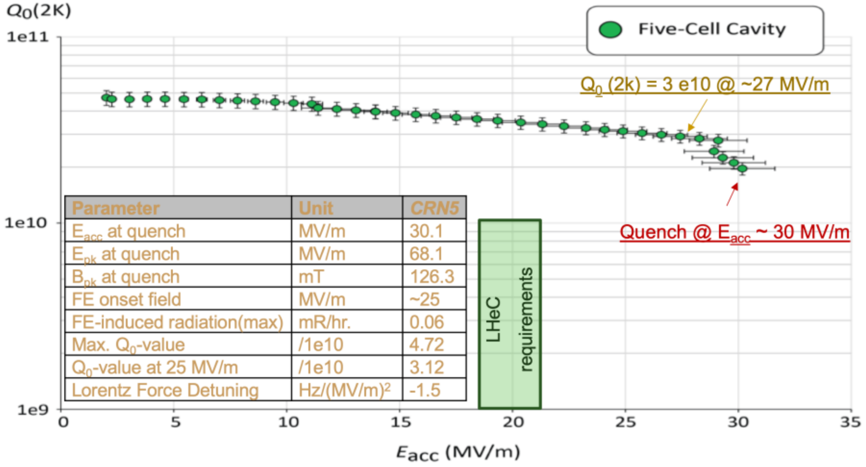
ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

JLAB / CERN collaboration

F. Marhauser Feb 2018

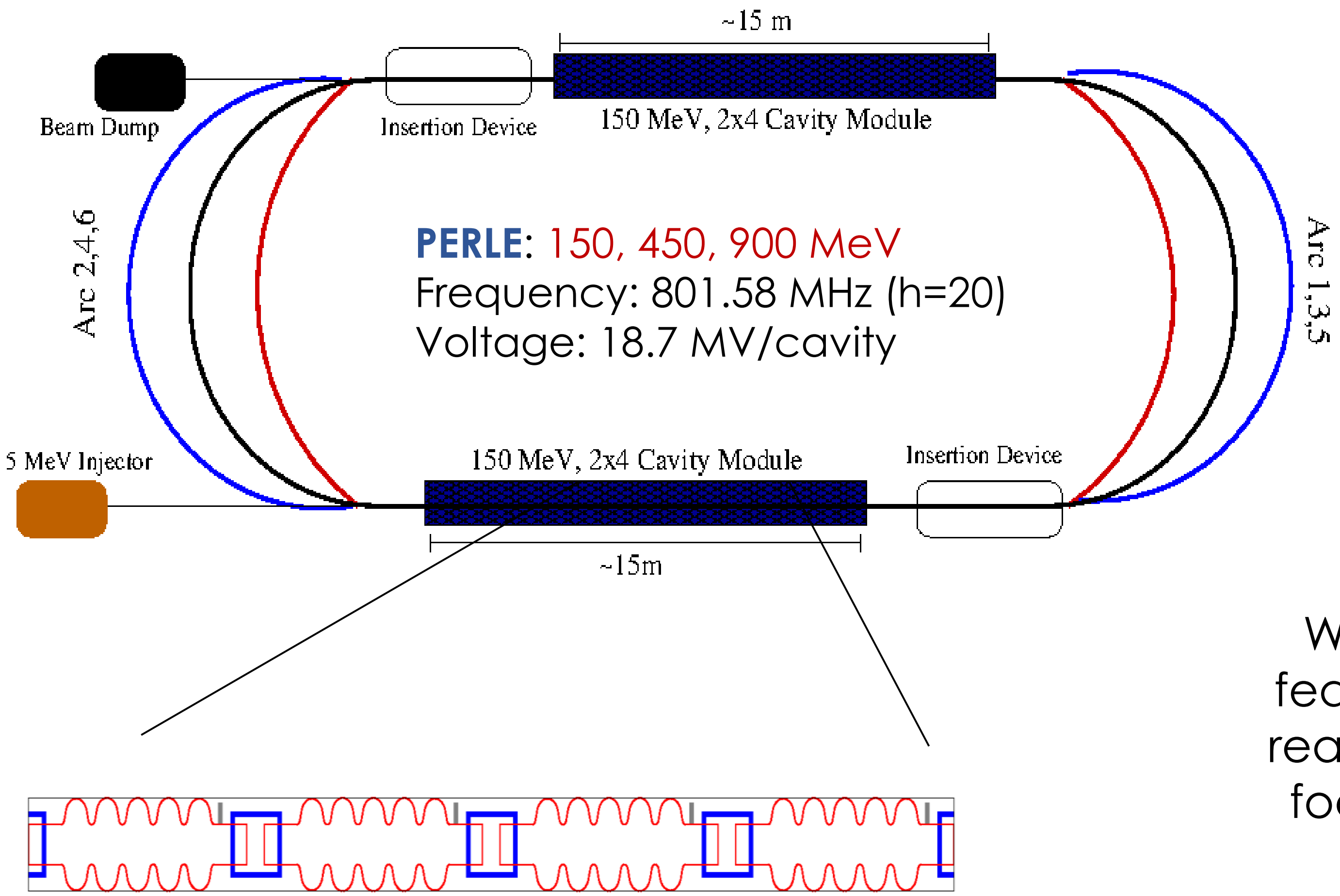


✓ = done, ? = option



Parameter	Unit	CRN5
E_{acc} at quench	MV/m	30.1
E_{pk} at quench	MV/m	68.1
B_{pk} at quench	mT	126.3
FE onset field	MV/m	~25
FE-induced radiation(max)	mR/hr.	0.06
Max. Q_0-value	/1e10	4.72
Q_0-value at 25 MV/m	/1e10	3.12
Lorentz Force Detuning	Hz/(MV/m)²	-1.5

PERLE @ Orsay as high power ERL demonstrator



Basic unit: 5-cell cavity into 4-cavity module

Designed for 6*25mA Inside the SRF system

➔ MP, SR and Cryogenics!

➔ Can be significantly downsized for μA beam currents!!!!

Without ERL configuration PERLE could feature easily 6 re-circulations and could reach ~ 6 GeV beam energy with a small footprint facility, using 2*2 4-cavity Cryo Modules

➔ Estimated cost ~ 50-100M€

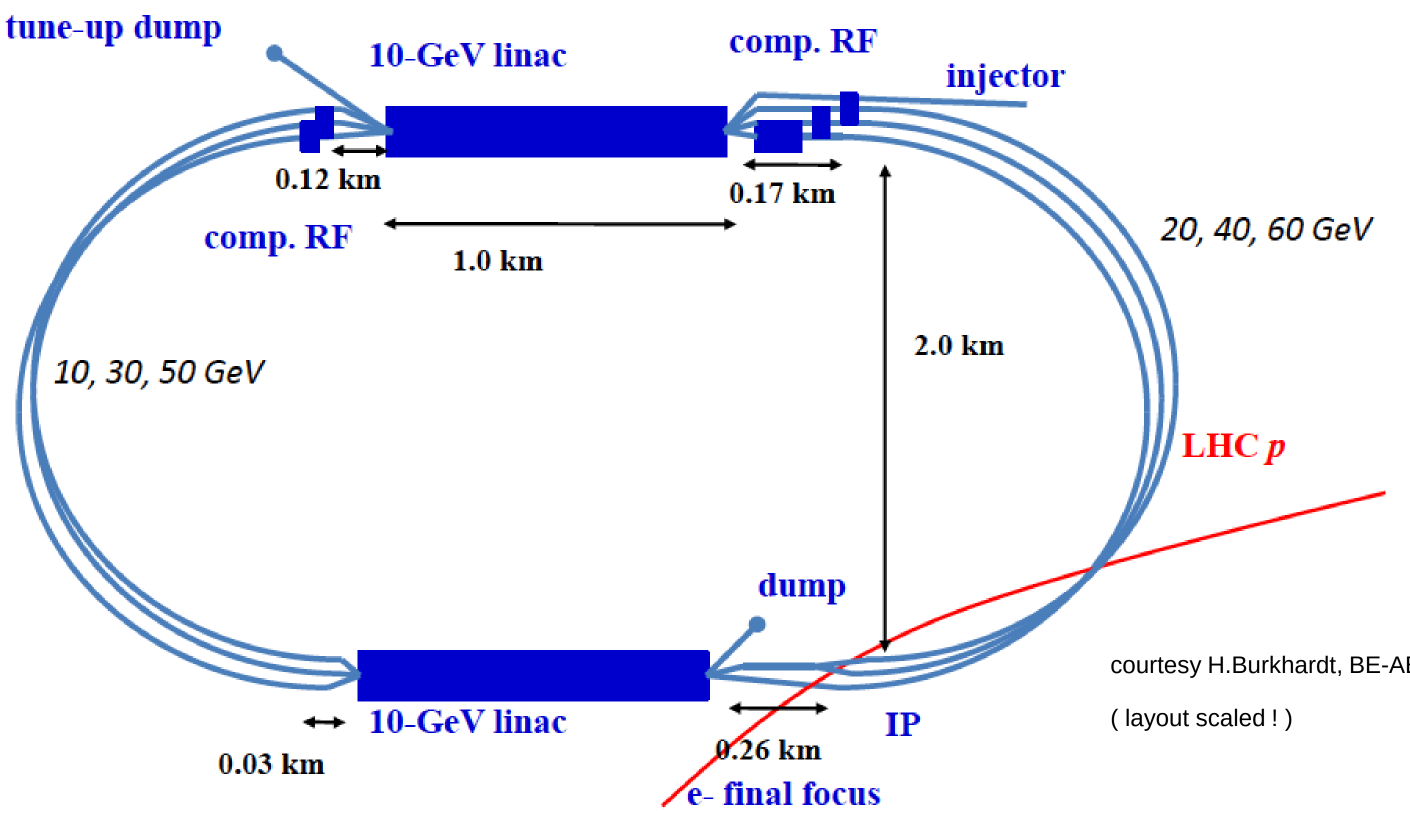
60 GeV ERL Baseline Configuration

Super Conducting
Recirculating Linac
with Energy Recovery

Designed for 6*25mA
Inside the SRF system

➔ MP, SR and Cryogenics!

➔ Can be significantly downsized for µA beam currents!!!!



courtesy H.Burkhardt, BE-ABP CERN

(layout scaled !)

➔ 1072 cavities; 134 cryo modules per linac

➔ ~ 9 km underground tunnel installation with more than 4500 magnets or 3 return arcs

LHeC ERL Configurations & costing

SRF is the main cost driver for the 60 GeV configuration:

➔ Reducing the electron beam energy can almost half the ERL cost
➔ Design and build the arcs for higher beam energy to allow for later upgrades
➔ Provide free space in the linac sections for later upgrades

30 GeV to 50 GeV variation:

➔ Reducing the initial SRF cost by 50%
➔ Provide upgrade potential for up to 50 GeV ➔ total cost reduction ca. 40%
➔ Overall size reduction from 1/3rd to 1/5th of the LHC circumference

The LHeC ERL SRF could be re-used for the first installation phase of FCC-ee and/or [part of it] as an FCC-ee injector and as ERL for the FCC-eh option

Assumptions and Boundary Conditions for Scaling

Baseline Assumptions:

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

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

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 r^{-1} ➔ ~ 40% of SR power comes from high energy return arc

- Assume 50 MW 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 ➔ ~ 25kCHF / m for scaling

SRF Tunnel:

Scales with E. For CE costing we assume a 50% tariff for the CE to account for the RF power generation

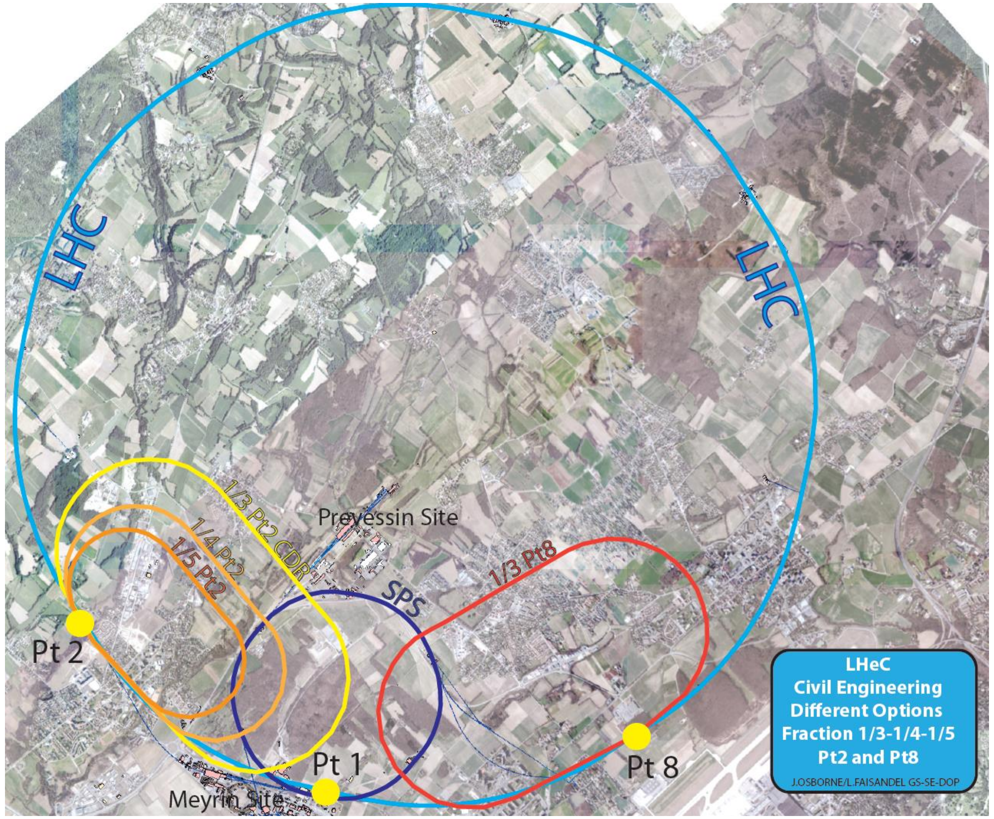
Magnet and vacuum system:

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

140 MCHF for the complete LHeC system ➔ ~ 11.15kCHF per arc meter

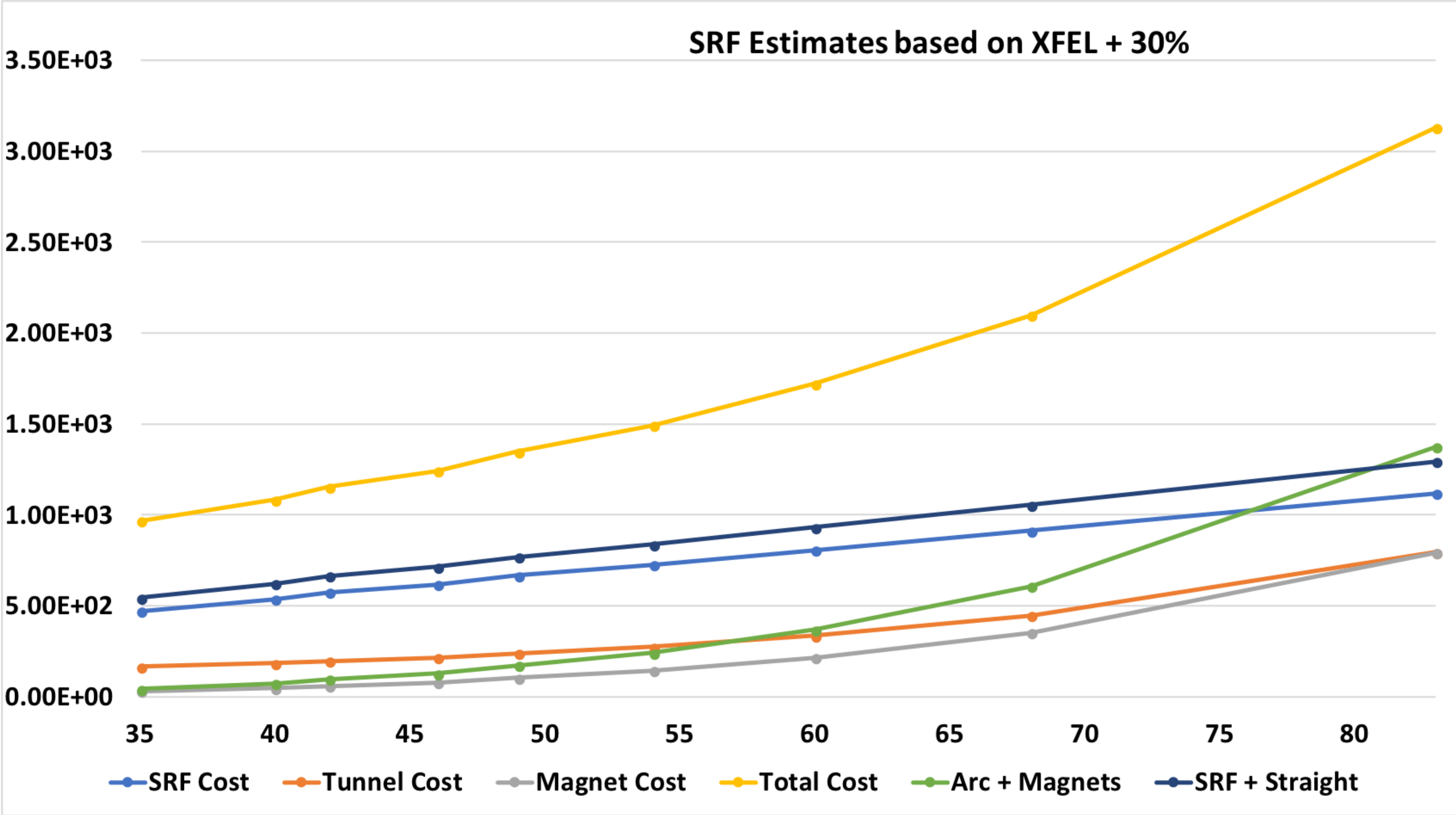
FCC-eh Configuration: Layout & Civil Engineering

Different Size Variations:
e.g LHeC



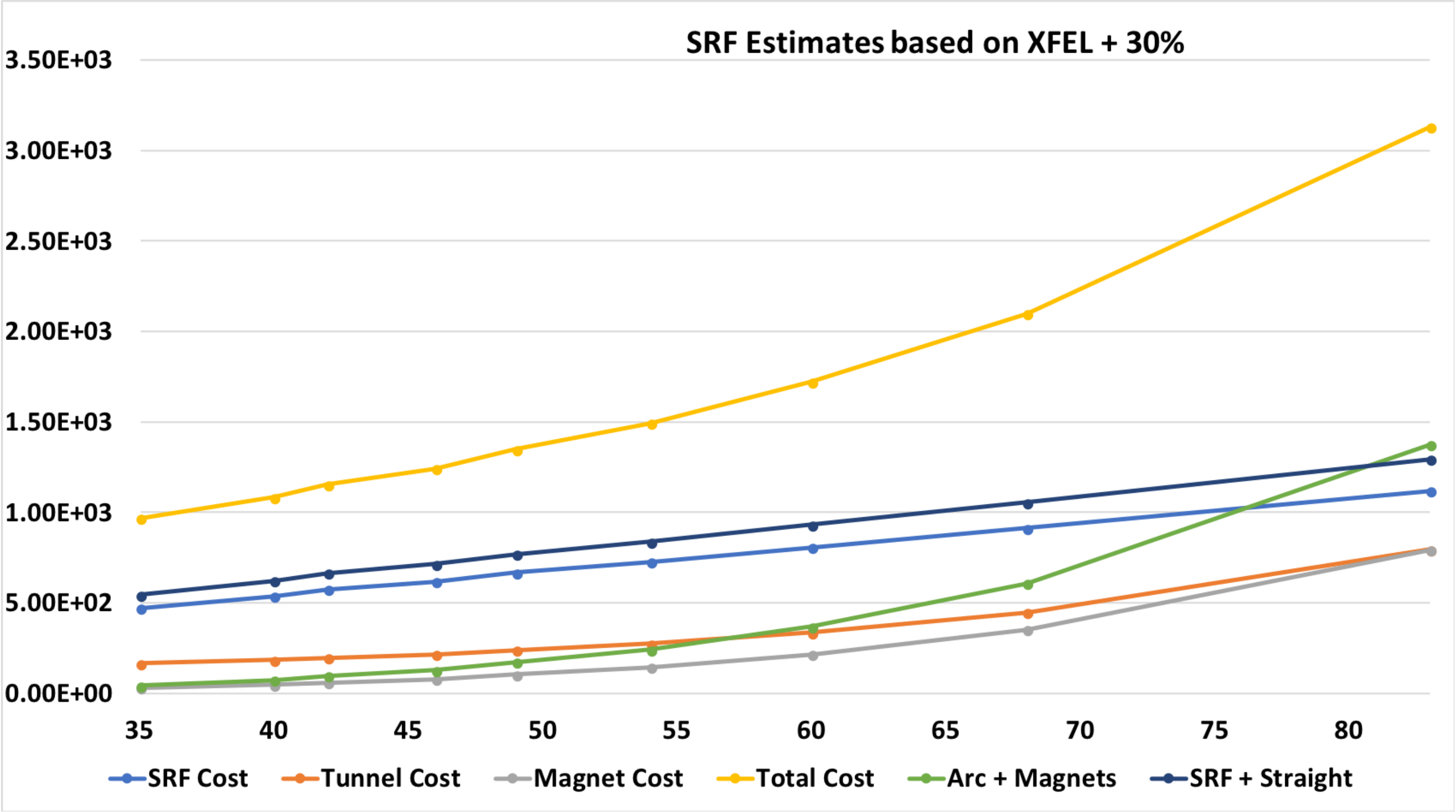
Preliminary cost estimates based on XFEL, LCLS-II budgets

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 75 GeV



FCC-eh Configuration: Layout & Civil Engineering

Nominal 60 GeV Configuration

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	353MCHF
Total	1723MCHF

30 GeV to 50 GeV Variation

Budget Item	Cost 30GeV	→ 50GeV
SRF System	402MCHF	+268MCHF
SRF R&D and Proto Typing	31MCHF	
Injector	40MCHF	
Magnet and Vacuum System	103MCHF	
SC IR magnets	105MCHF	
Dump System and Source	5MCHF	
Cryogenic Infrastructure	41.5MCHF	+28MCHF
General Infrastructure and installation	58MCHF	
Civil Engineering	256MCHF	
Total	1042MCHF	→ 1338MCHF

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

➔ Without ERL configuration and with the much reduced beam current compared to FCC-eh one can significantly save on the cryogenics.

Furthermore, one does not need to consider the cost for the IR magnets and the SRF prototyping.

➔ ~200 MCHF lower cost

Additional Optimization Options

Recirculating Linac Operation:

Already demonstrated by CEBAF and could be extended to more re-circulations

SRF current limitations:

We assume for the SRF system a maximum beam current of 150 mA that limits the number of re-circulations for the ERL operation ➔ 3 for FCC-eh

➔ For the injector application one could go to higher number of re-circulations and reduce the SRF installation accordingly

For example:

6 re-circulations would allow to half the SRF installation but would require a doubling of the magnet and vacuum cost ➔ ca. 240MCHF further cost reduction

Summary

Dedicated PERLE like injector at 6GeV:

- ➔ between 50 MCHF and 100 MCHF based on PERLE model
- ➔ Could be cheaper if the linac could use pre-series SRF modules from FCC-ee
- ➔ Not re-usable as electron machine for future eh option
- ➔ Re-usable as a future electron beam facility [e.g. QCD]

50 GeV to 60 GeV recirculating linac:

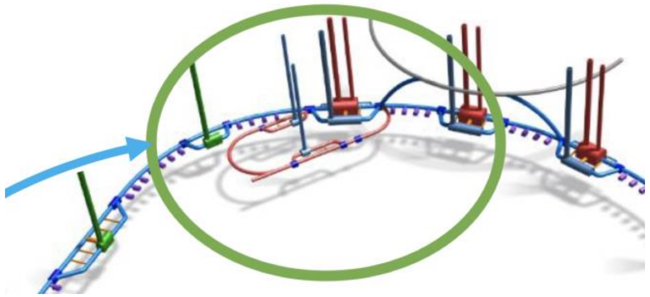
- ➔ between 800 MCHF and 900 MCHF based on LHeC and FCC-eh cost model
- ➔ Could allow direct injection into FCC-ee for Z physics operation
- ➔ Could be cheaper if one could use SRF from FCC-ee [pre-series and or top/H]
- ➔ Re-usable as electron machine for future eh option
- ➔ Re-usable as a future electron beam facility [e.g. QCD]

Outlook

FCC-ee Injector Collaboration

- Proposed starting point is **consolidation and analysis of present baseline scheme** that matches exactly the bunch number and fill pattern requirements that came out of the collider luminosity optimization.
- Should be good starting point for investigations of alternative designs and future optimization.

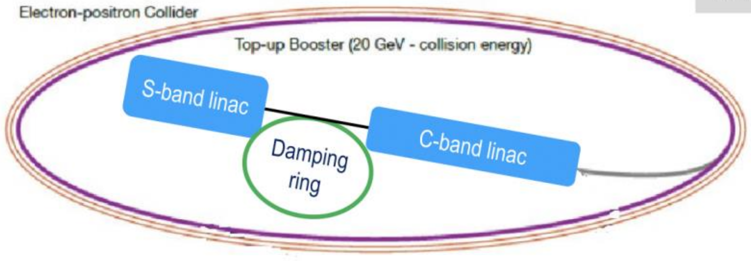
D. Schulte – June 26, FCC Week 2019 @ Brussels



First Proposals Already Appeared

FCC-ee injector, second look at Linac

H. Braun
Yesterday



	S-band Linac	C-band Linac Opt. 2	C-band Linac Opt. 3
Energy gain	2 GeV	18 GeV	44 GeV
Final energy	n.a.	20 GeV	46 GeV
Length	0.12 km	0.7 km	1.7 km
Gradient	20 MV/m	30 MV/m	30 MV/m
Number RF stations	17	75	184
Cost incl. building	50 MCHF	230 MCHF	550 MCHF

O. Brüning

Recirculating linac from LHeC/FCC-eh