LHeC & FCC-eh Machine Configuration and Performance

- Configuration:

  Modular design elements:

  -60 GeV ERL configuration 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)!

  → SR acceptance in detector and beam separation

  → Dipole integrated into detector

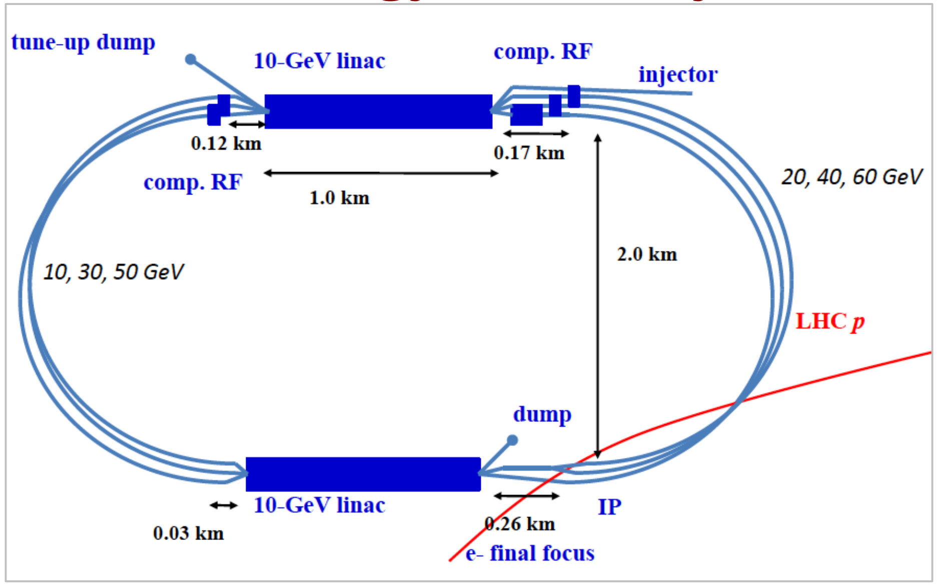
  → 'Sweetspot' IR magnet design

  -802MHz SRF: synergy with FCC-ee and FCC-hh

60GeV ERL Baseline Configuration:

* LHeC CDR, arXiv:1206.2913

Super Conducting Recirculating Linac with Energy Recovery



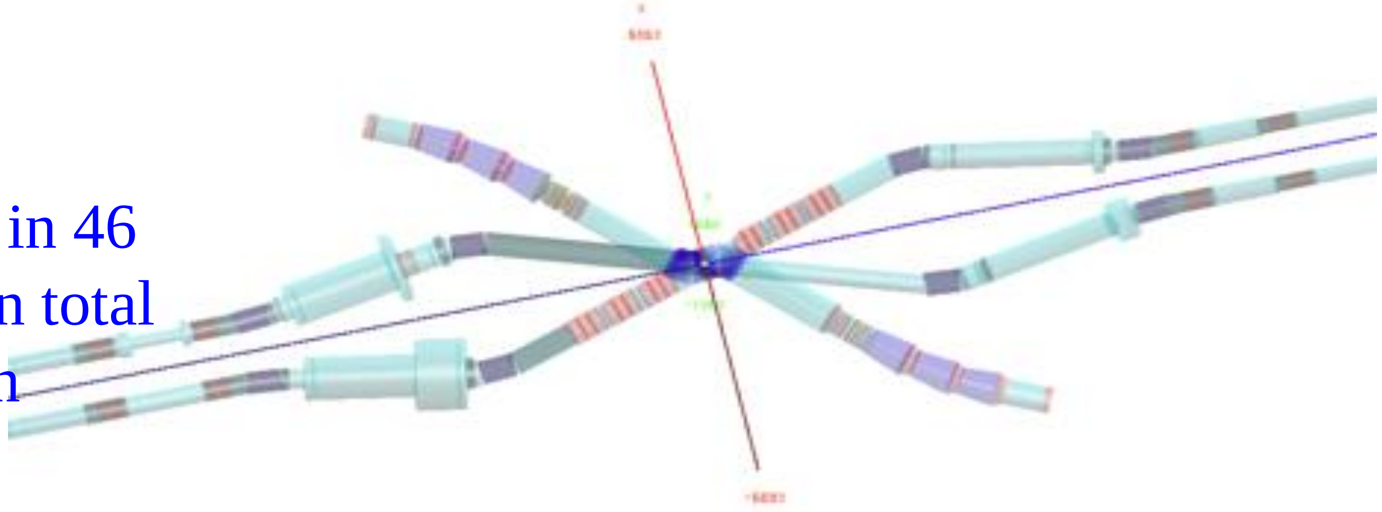
Operation in parallel with LHC/HE-LHC/FCC-hh

- 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} $cm^{-2}s^{-1}$

➔ 184 5-cell cavities @ 18.2MeV / cavity in 46 cryo modules per linac ➔ 368 cavities in total

➔ ca. 9 km underground tunnel installation

➔ more than 4500 magnets



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

LHeC: RL with ERL Operation as Baseline

Performance:

* LHeC CDR, arXiv:1206.2913

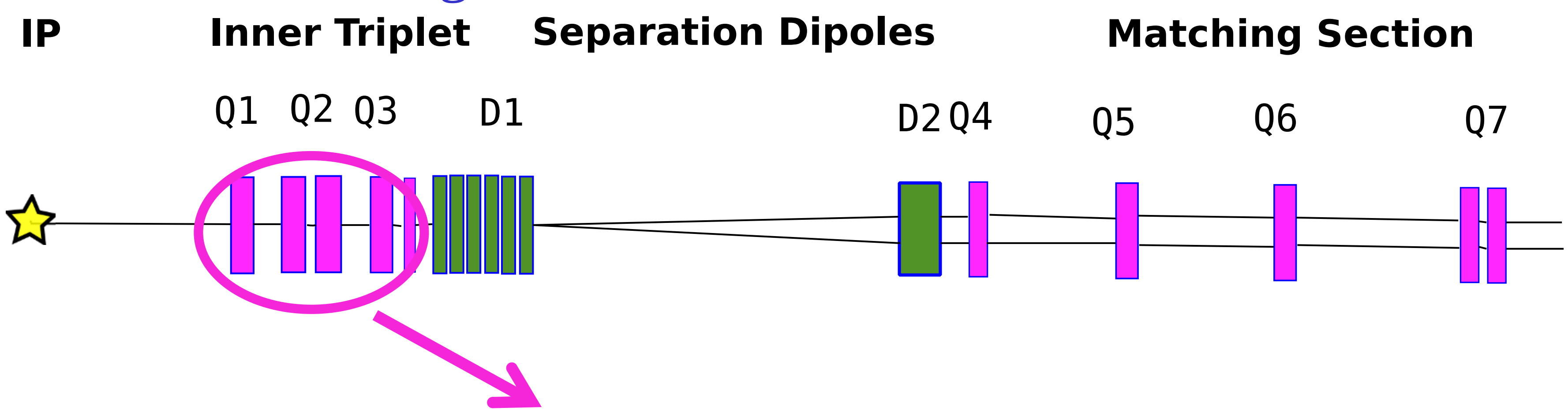
*Post LHeC CDR, using HL-LHC parameters

10^{33} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	1	1	Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50	Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.1	0.12	Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7	rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma^*_{x,y}$ [μrad]	70	58	rms Beam divergence $\sigma^*_{x,y}$ [μrad]	80	40
Beam Current @ IP [mA]	860	6.6	Beam Current @ IP[mA]	1112	25
Bunch Spacing [ns]	25	25	Bunch Spacing [ns]	25	25
Bunch Population	$1.7*10^{11}$	$1*10^{9}$	Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	27	0.16	Bunch charge [nC]	35	0.64

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:

- β*=10 cm (10^{33} cm^{2}s^{-1})
- β*=5 cm (10^{34} cm^{2}s^{-1})

SEVERE LIMITATIONS

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

LHeC/FCC-eh interaction region

non focused beam bypasses the interaction

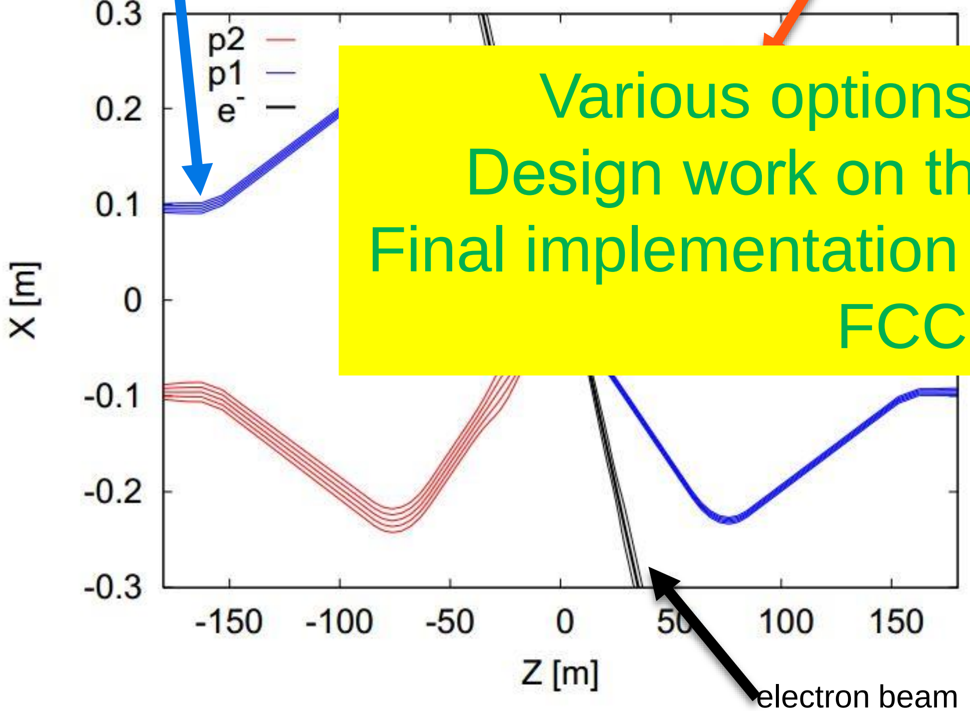
focused interacting proton beam

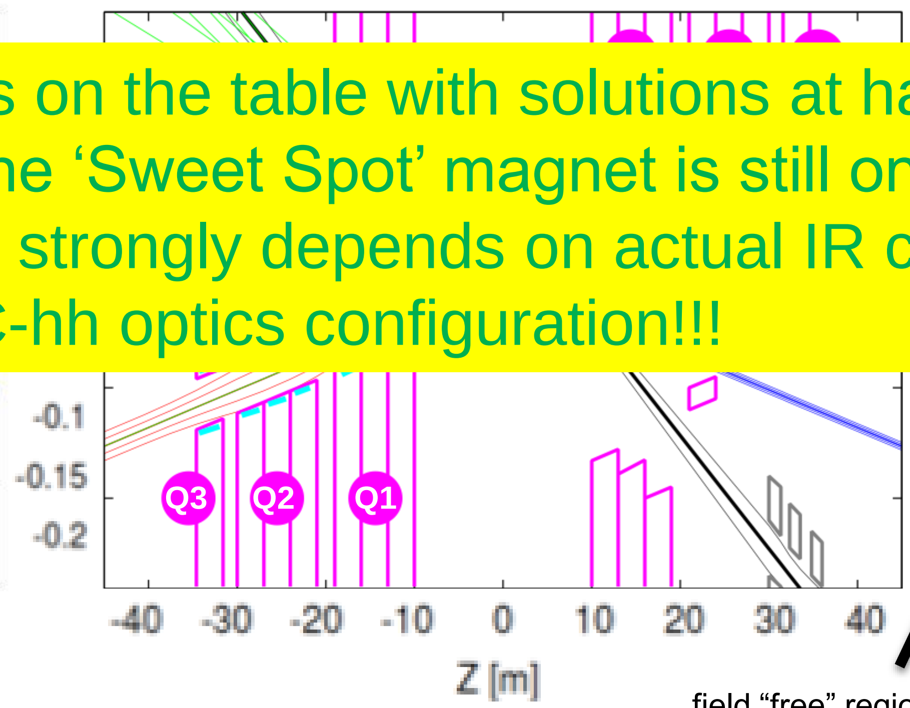
Synchrotron Radiation and various beams

Final quadrupole magnet Q1 example design "sweet spot"

SR fan

exit hole - electrons and non-colliding protons





Various options on the table with solutions at hand!
Design work on the 'Sweet Spot' magnet is still ongoing!
Final implementation strongly depends on actual IR choice and FCC-hh optics configuration!!!

electron beam from ERL

field "free" region

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

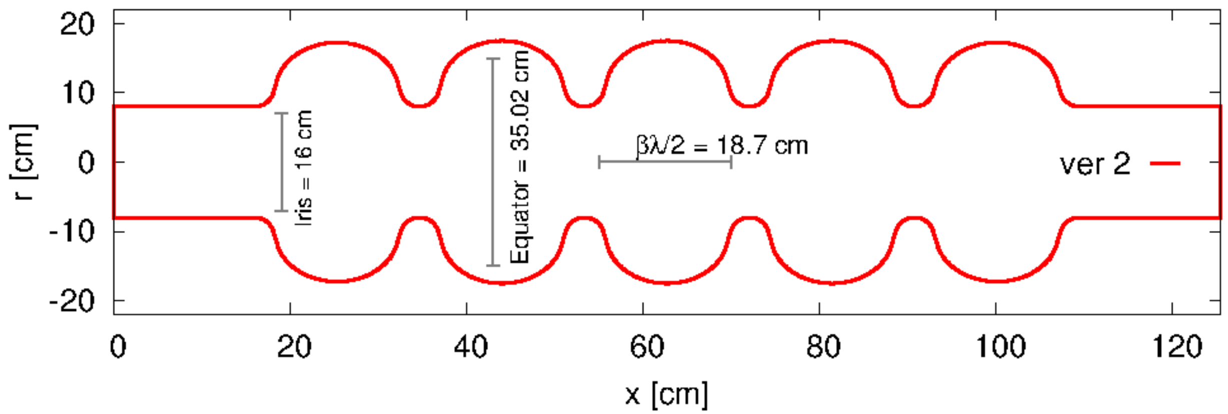
electron proton beams well matched!

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

B. Parker, S. Russenschuck et al.

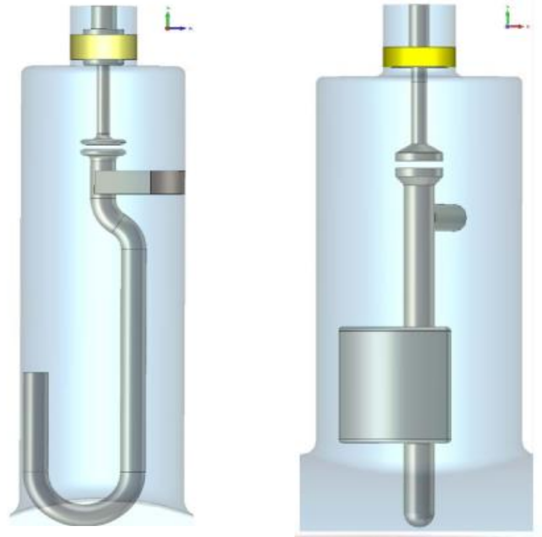
SRF: 802 MHz 5-Cell design minimizing HOM

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

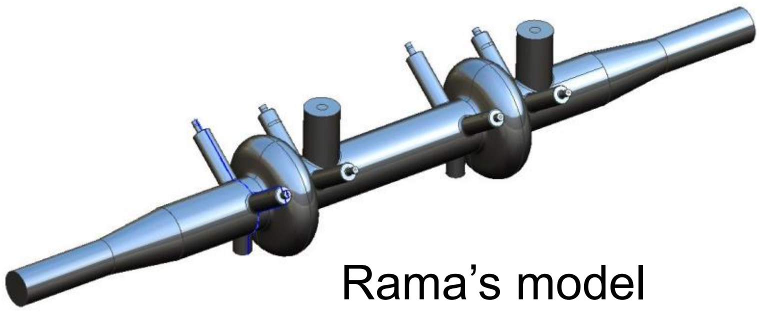


SRF: Prototyping in collaboration with JLab

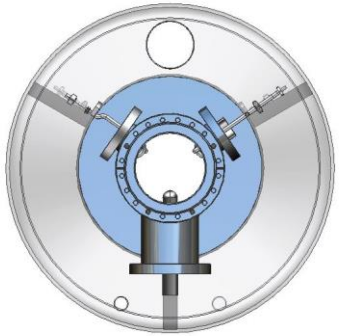
Robert Rimmer JLab

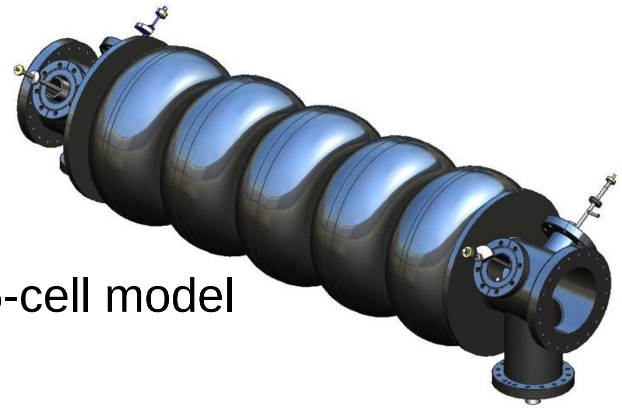
Evaluate scaled LHC type coupler and HOM dampers
[CERN model by Rama Calaga]

- LHC power coupler is well proven but may be overkill
- JLab FEL waveguide dampers may be overkill*
- LHC HOM dampers are somewhat narrow band (tuned)
- High power capability (~1 kW), active cooling
- Demountable
- Evaluate scaled TESLA couplers in the same location



Rama’s model





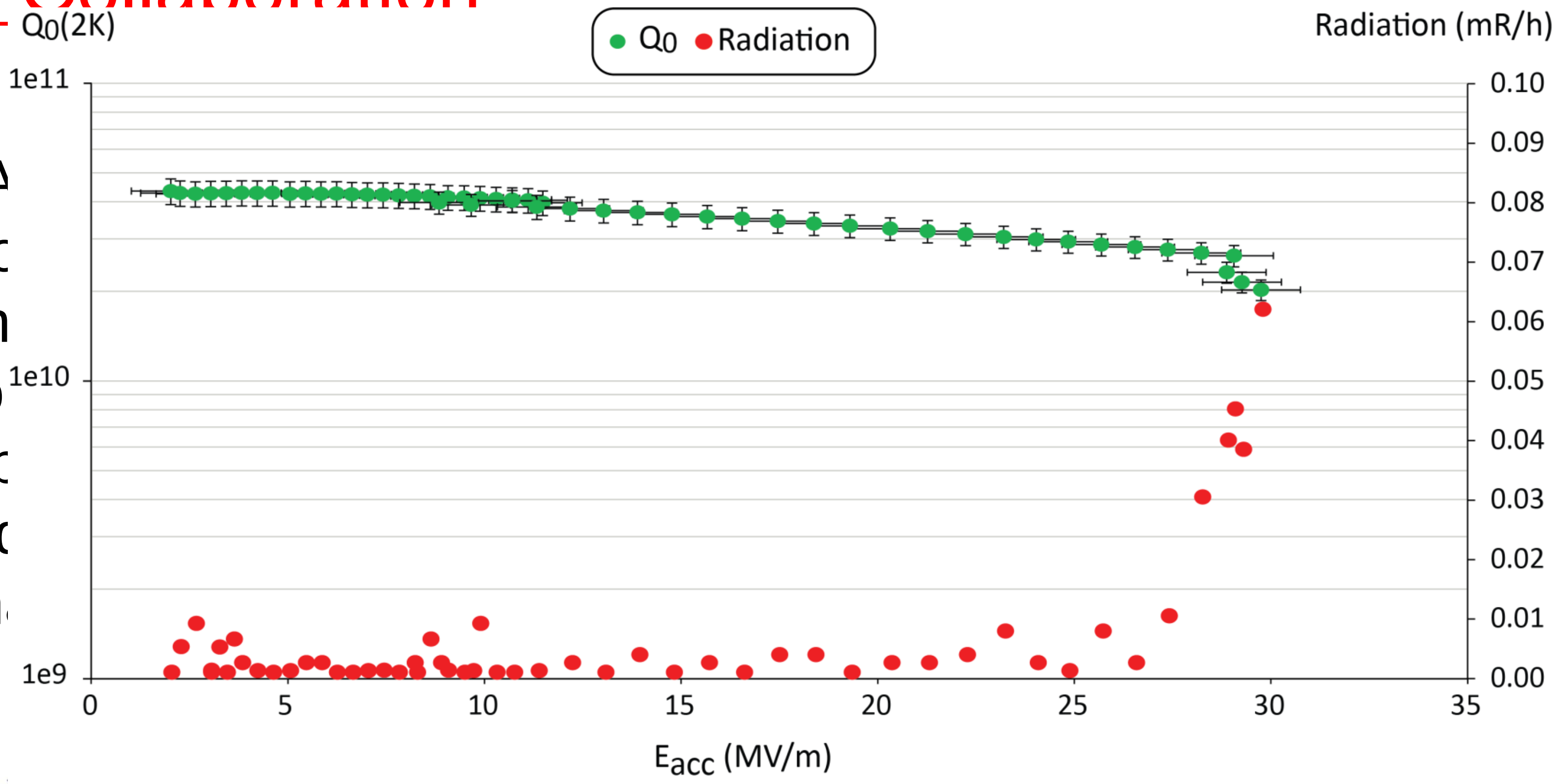
5-cell model

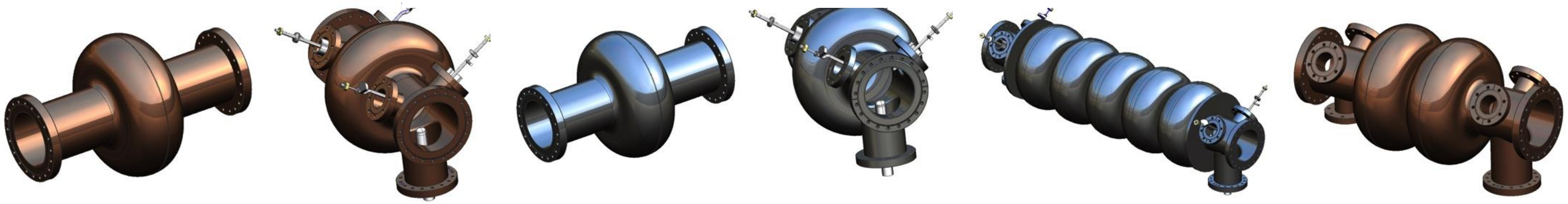
* Or not, depending on filling pattern

SRF: JLab Collaboration

F. Marhauser Feb 2018

Fabricate dies.
Test dies with A
Fabricate one c
    Check tunin
    Can add po
Fabricate one b
    Validate fre
    Option to m
Fabricate bare





✓ ? ✓ ? ✓ ?

✓ = in plan, **?** = option

SRF Design: Power

Rama Calaga

800 MHz IOTs (~60 kW) for the SPS 3rd harmonic system

Chain of 8 IOTs installed powering two cavities in the SPS

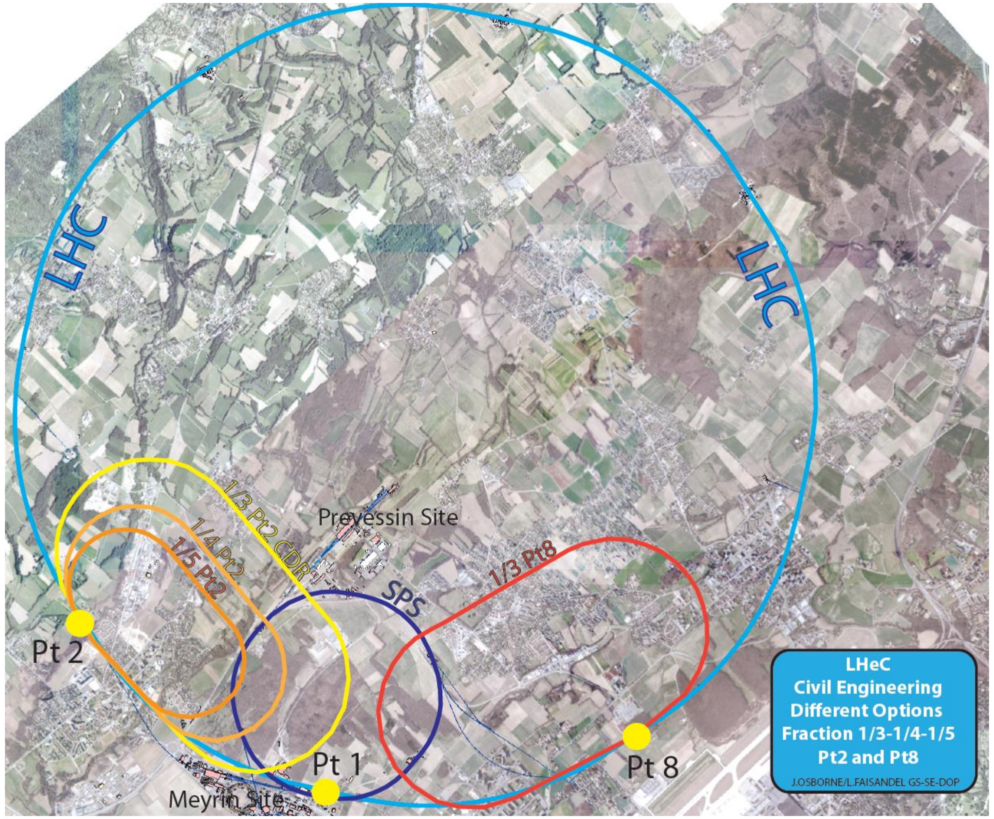
FCC-eh Configuration: Layout & Civil Engineering

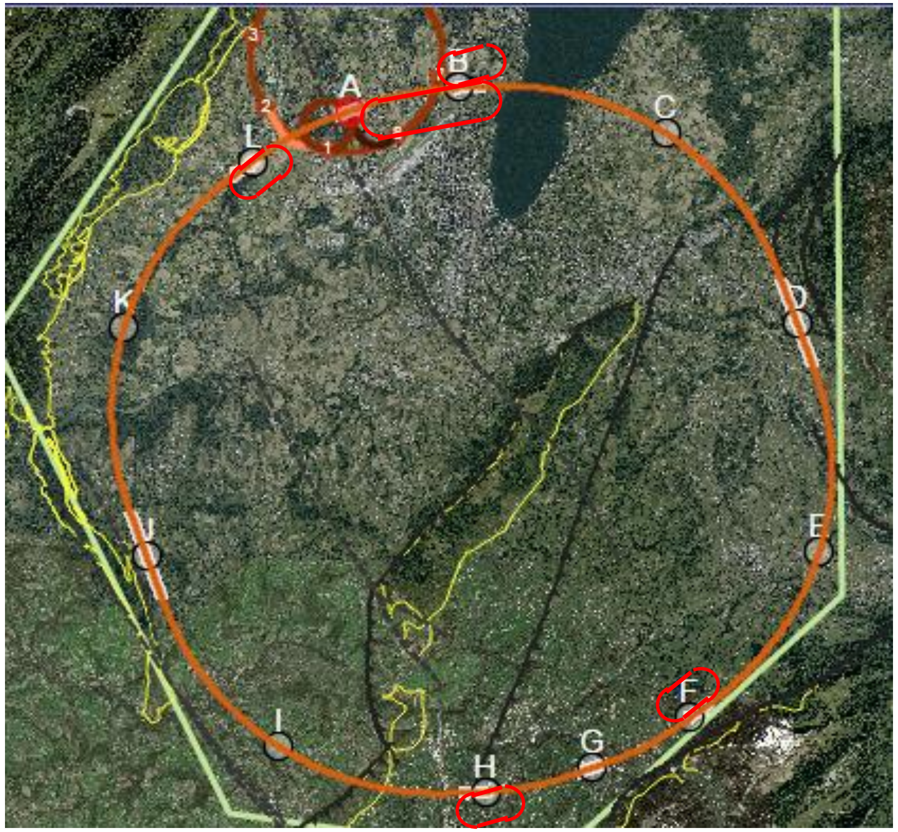
C. Cook @ FCC week in Rome

Configuration:

Different Size Variations:
e.g LHeC

Independent FCC-he
Several IP considered
before FCC Week in Berlin

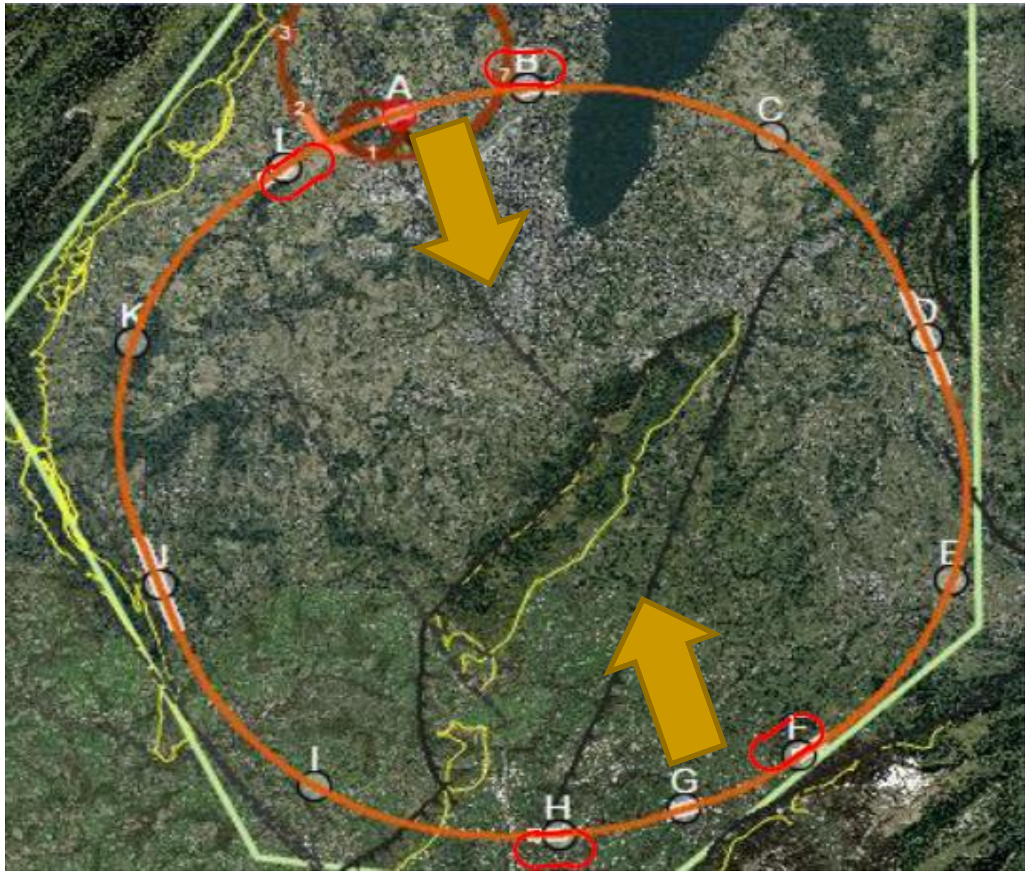




FCC Layout Changes

Rome 2016 Layout

Jo Stanyard



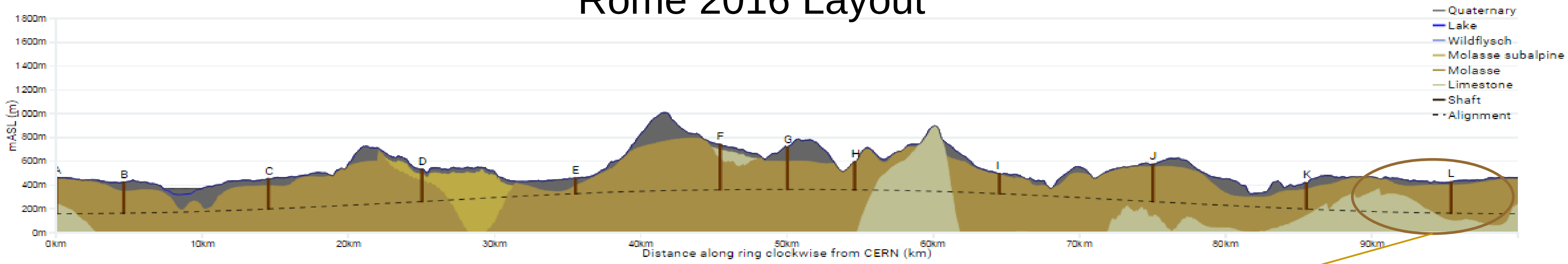
Updates since Rome 2016 layout:

- Reduced depth below surface level.
- Reduced length of straight sections at J and D.
- Increased tunnel length from A-L, A-B and G-F, G-H.
- Avoids Jura Limestone and Pre-Alps region.
- Reduced Total Tunnel Length.
- Choice of IP 'L' for low luminosity experiments implies sharing of the IR with injection equipment (reduced available space for the experiment).

FCC Layout Changes (profile)

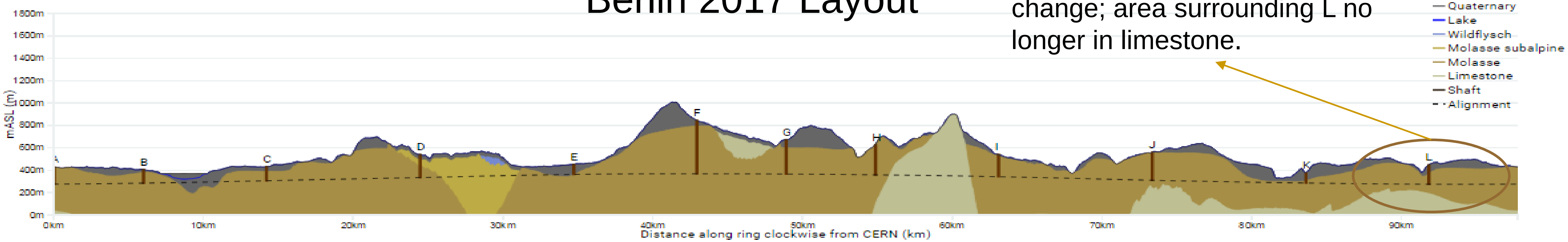
Jo Stanyard

Rome 2016 Layout



Berlin 2017 Layout

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

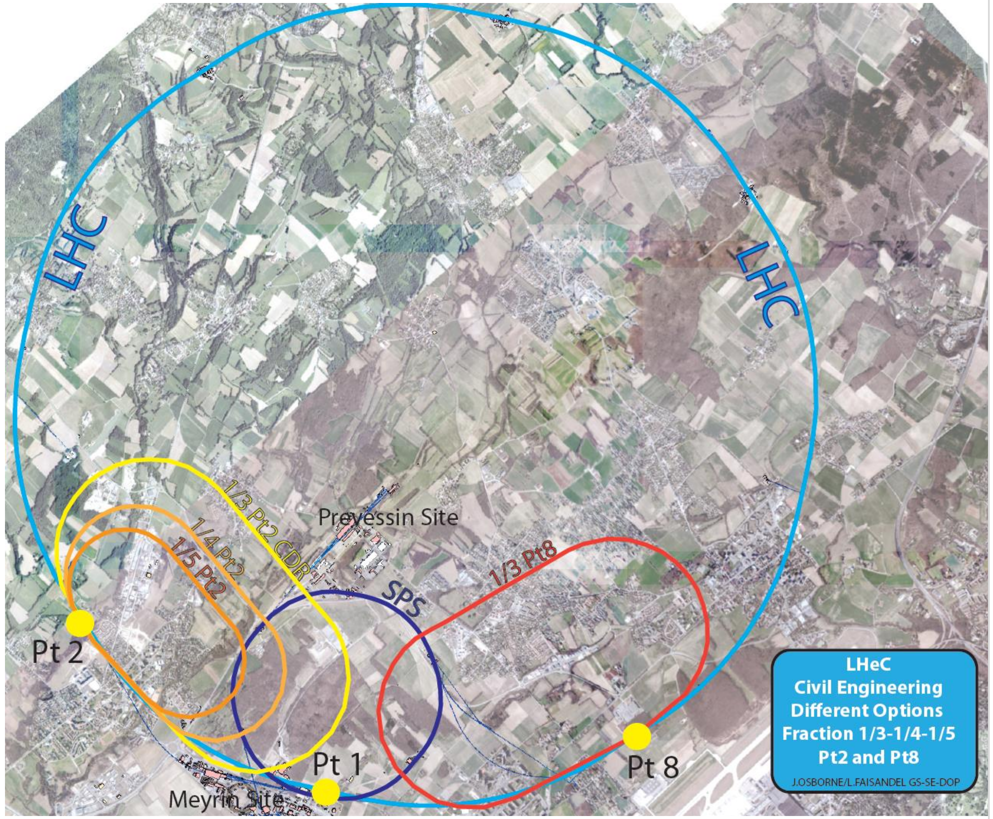


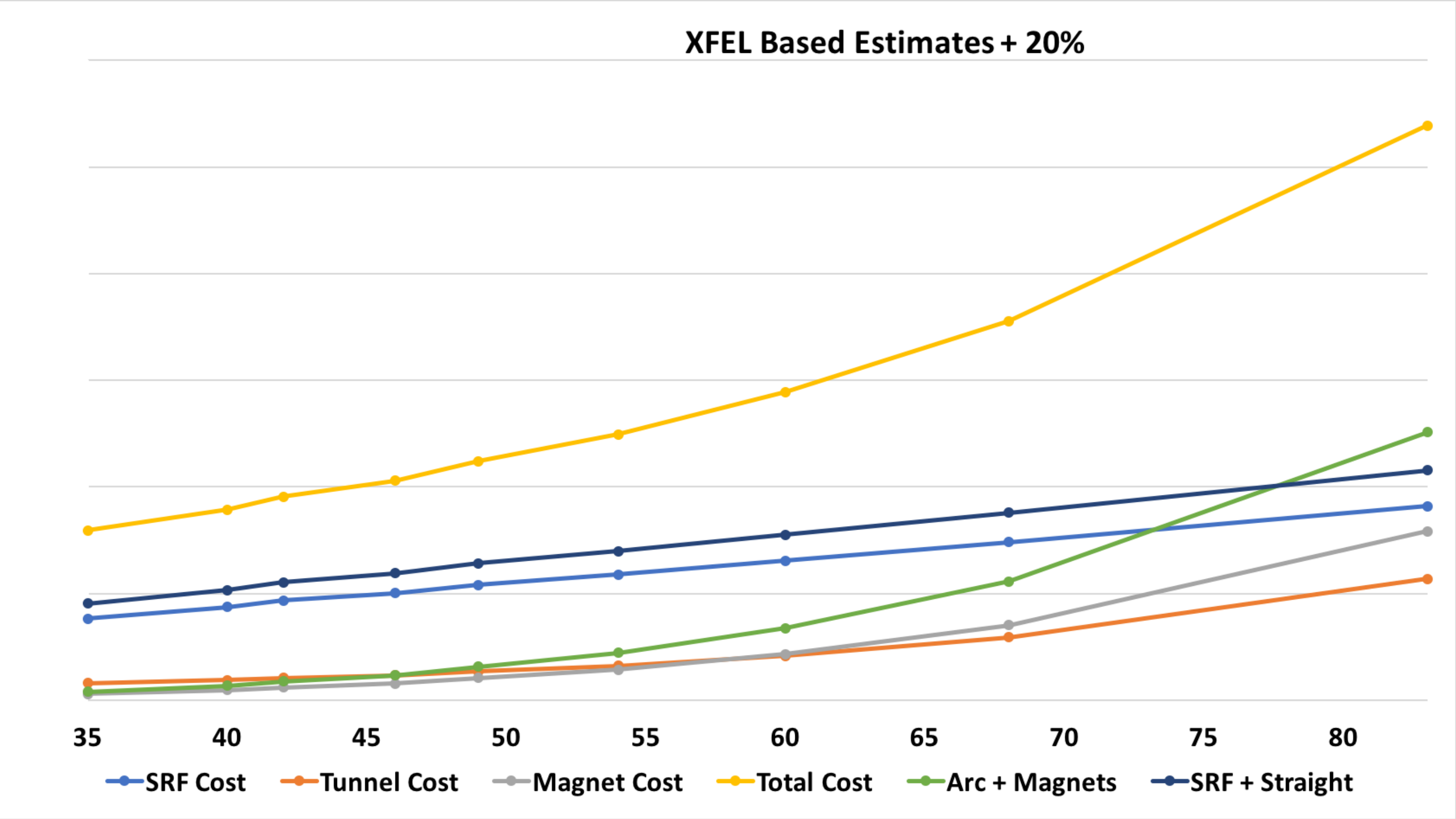
LHeC Configuration: Layout & Civil Engineering

Configuration:

Different Size Variations:
e.g LHeC

Preliminary cost estimates based on XFEL, LCLS-II, CBETA and ESS studies:





LHeC Configuration: Size variations

- SRF as 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
- 30GeV to 50GeV Variation:
  - ➔ Reducing the initial SRF cost by 50%
  - ➔ Provide upgrade potential for up to 50GeV
  - ➔ Overall size from 1/3rd to 1/5th of the LHC circumference
- The LHeC could be re-used for the first installation phase for the FCC-eh

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	[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"

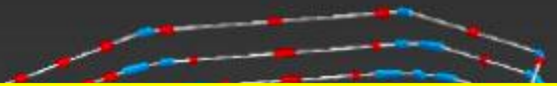
John Jowett, Frank Zimmermann

PERLE: Powerfull ERL for Experiments @ Orsay

PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +

3 turns, 2 Linacs, 400 MeV, 15mA, 802 MHz, Energy Recovery Linac facility

-Demonstrator of ERL for ep at LHC/FCC



Machine Study Goals:

- -High current, multi-turn (3) ERL concept with 802MHz SRF
- -Beam Breakup intensity limit and filling patterns,
- -ERL efficiency,
- -beam size evolution etc.
- -SRF LLRF feedback and control
- -Failure scenarios
- -Beam Halo formation and dump line acceptance
- -Beam Instrumentation
- -Build up operational experience
- -Source and injector

Main eh Tasks for Completion of CDR

4 areas of activity

Accelerator: Update of the eh IR design for LHC/HE-LHC/FCC at 10^{34}

PERLE: Technical design and fabrication+test of an 802 MHz cavity

Detector: Update detector technology choice (collaboration with hh)

Physics: Update wrt LHC results and integration with hh+ee

Contributions to 4 FCC CDR Books (see M Benedikt today)

B1: Physics with the FCC (hh-he-ee)

B2: Summary of FCC-hh with integrated FCC-eh

B3: Details to B2

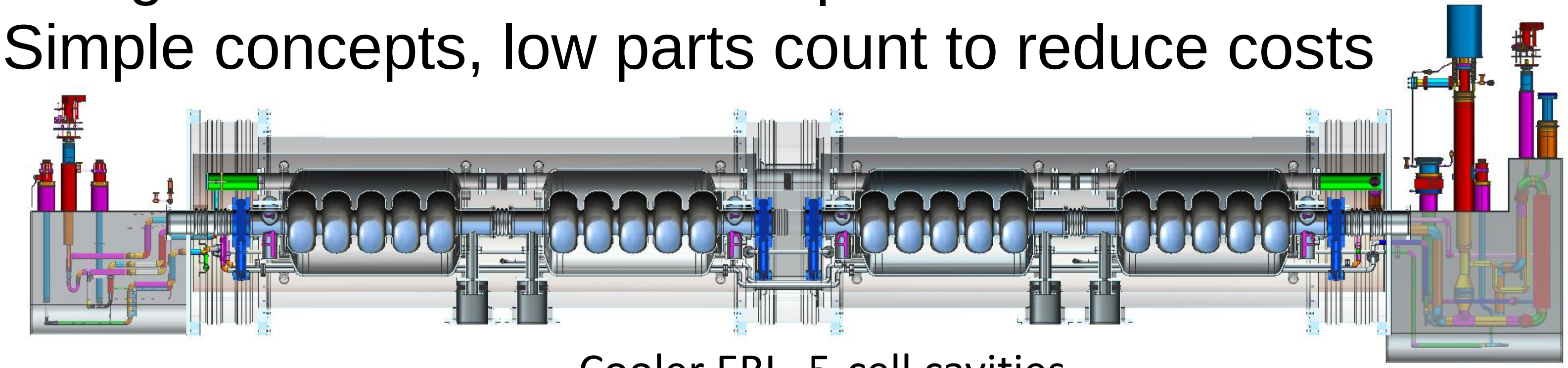
B6: HE LHC with eh (based on LHeC CDR Update B0)

a total of ~300 FCC pages

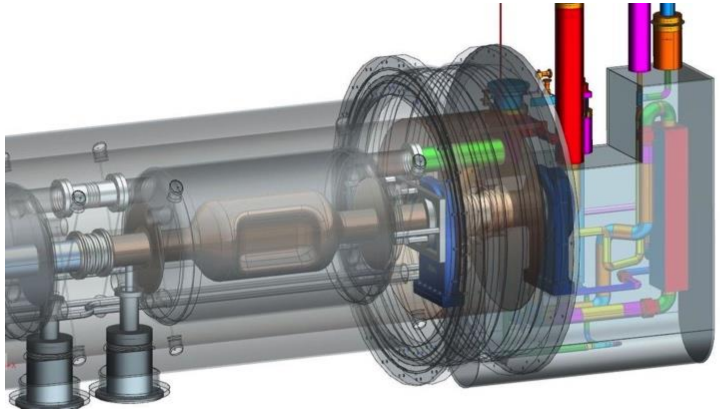
End

Jlab Modular Cryostat

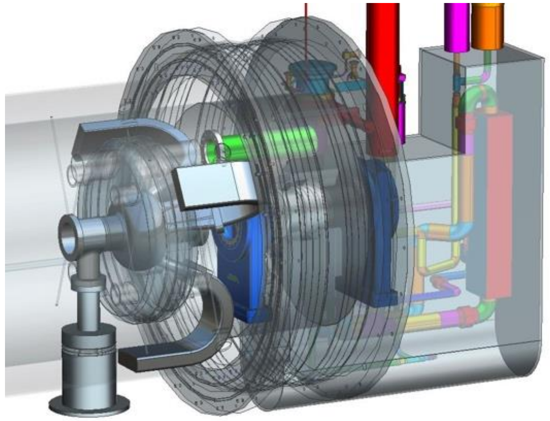
- Take the best features of previous JLab designs
- Modular approach to hold various different cavities
- Design suitable for industrial production
- Simple concepts, low parts count to reduce costs



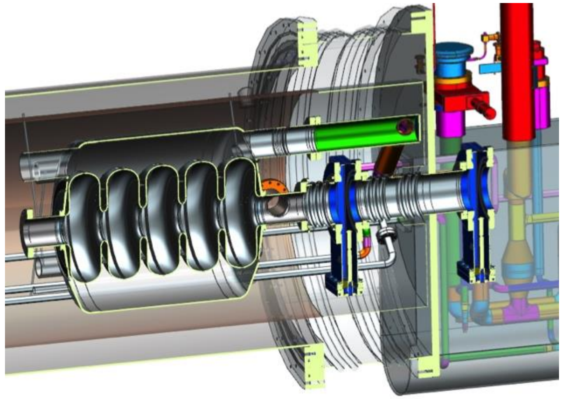
Cooler ERL, 5-cell cavities



476.3 MHz Crab cavity

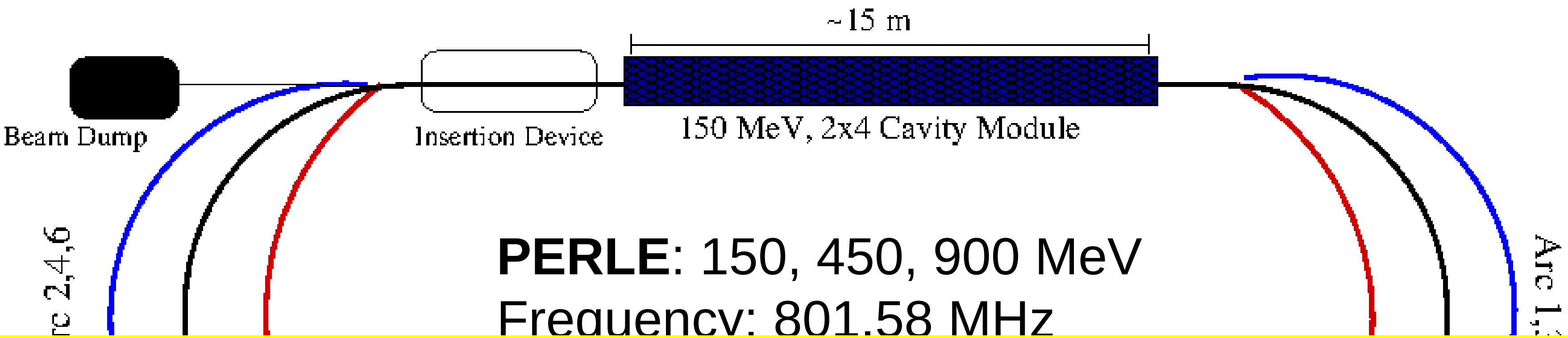


On-cell damper concept



β=0.6 650 MHz cavity

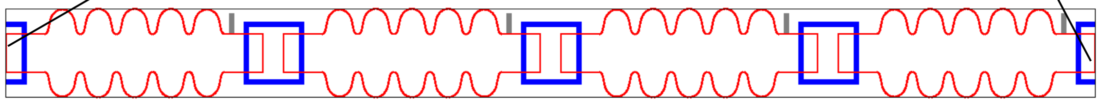
ERL SRF: PERLE @ Orsay



PERLE: 150, 450, 900 MeV
Frequency: 801.58 MHz

High current, multi-turn (3) ERL concept with 802MHz SRF
to be tested at PERLE facility in LAL in Orsay!!!

Key questions to be addressed: BB limit, ERL efficiency, beam size evolution etc.



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

FCC-eh: 60 GeV, ERL
1km SRF linac; 944 cavities; 59 cryo modules / linac
Number of passes: 6
Beam current: 6.6-25.6 mA