



Energy frontier DIS at CERN: the LHeC and the FCC-eh, PERLE

G. Arduini (CERN) for the LHeC and FCC-eh Study Groups and the PERLE Collaboration

Acknowledgments: N. Armesto Perez, A. Bogacz, O. Brüning, R. Calaga, D. Douglas, E. Jensen, J. Jowett, W. Kaabi, M. Klein, F. Markhauser, R. Martin, B. Parker, R. Rimmer, D. Schulte, J. Stanyard, M. Stewart, A. Stocchi, C. Tennant, R. Tomas, A. Valloni, F. Zimmermann



Outline

- LHeC at CERN
 - CDR parameters and evolution
- HE-LHeC and FCC-eh
- Design concepts/choices and challenges
- Electron accelerator demonstrator → PERLE



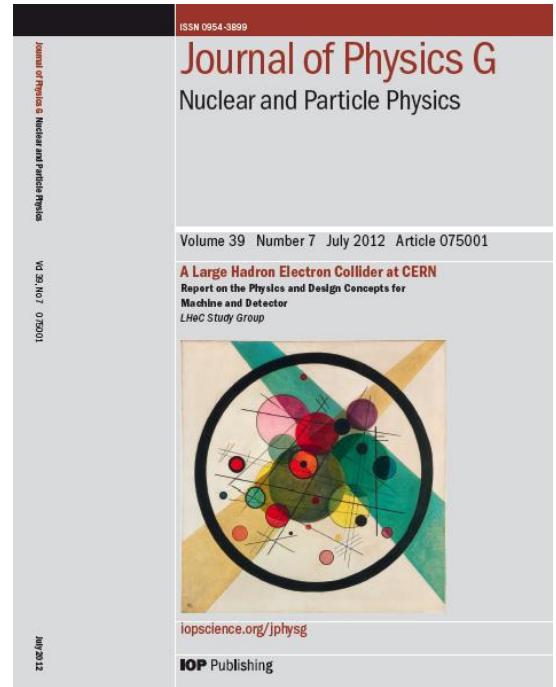
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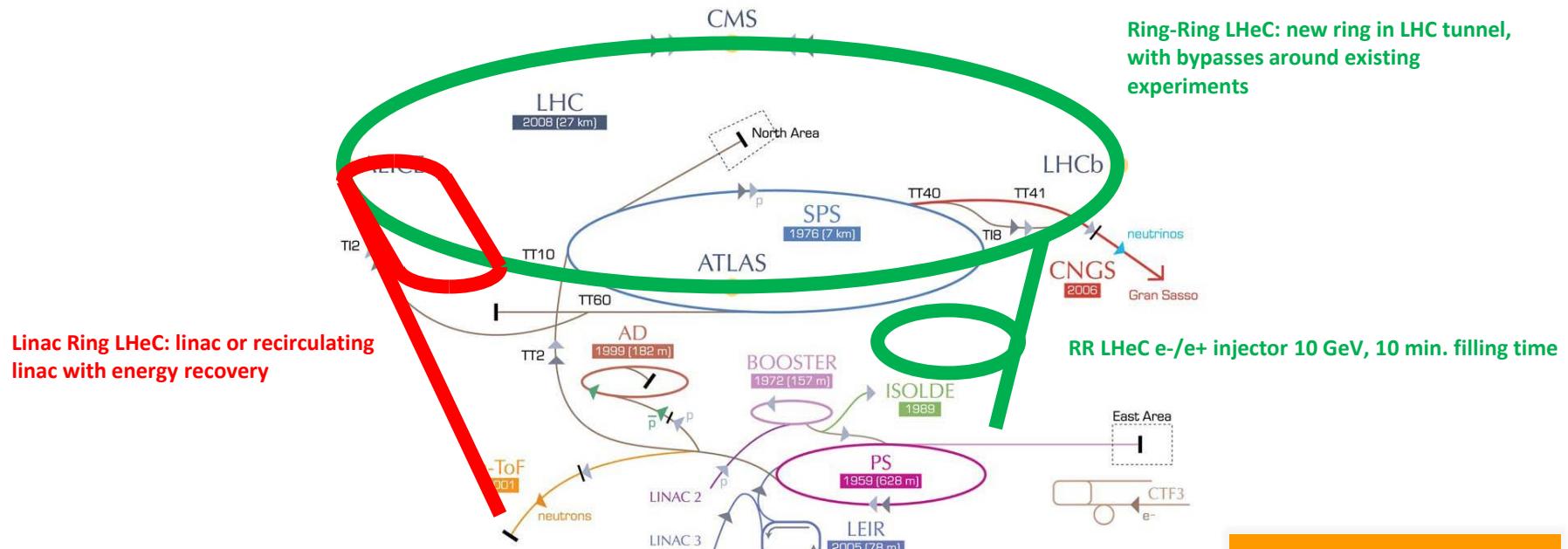


LHeC CDR

- CDR Study assumptions:
 - Parallel operation with LHC/HL-LHC
 - TeV Scale c.o.m energy
⇒ 40-150 GeV Beam Energy
 - Limit power consumption to 100 MW
(beam & SR power < 70 MW)
⇒ 60 GeV beam energy
 - Int. Luminosity > 100 × HERA
 - LHeC as Higgs factory ⇒ $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$



LHeC CDR

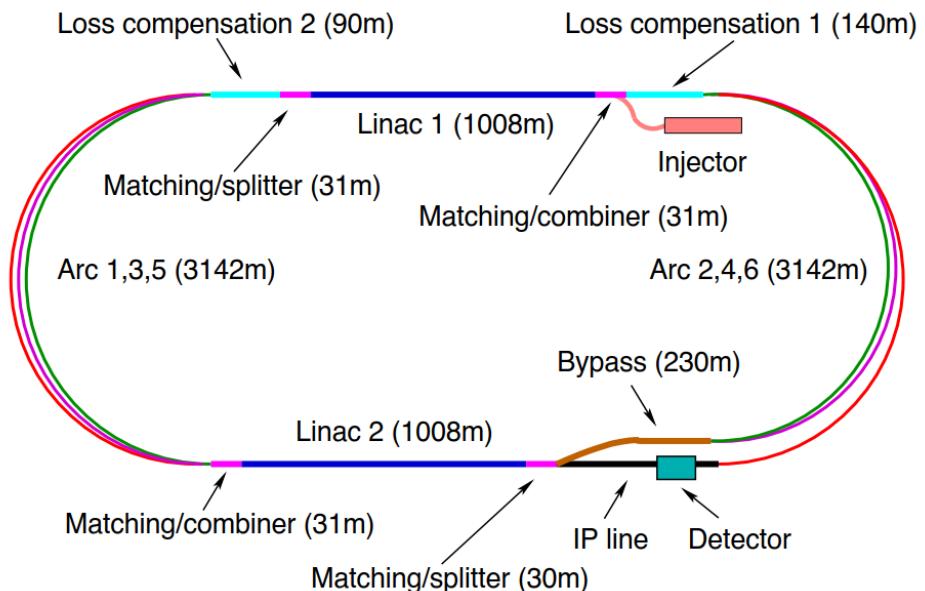


F. Zimmermann



60 GeV ERL Configuration (LHeC baseline)

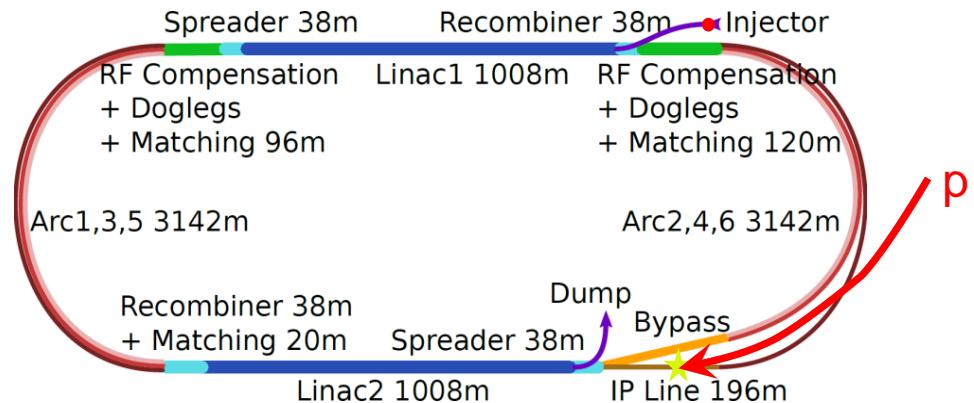
- Super Conducting Recirculating Linac with Energy Recovery ($\frac{1}{3}$ of LHC circumference) to minimize power consumption
- Two 1 km long, 10 GeV SC LINACs with 3 accelerating and 3 decelerating passes in CW operation
- Circulating bunches = $6 \times$ colliding bunches
- $Q_0 > 10^{10}$ to minimize requirements on cryogenic cooling power



Schematic
Total circumference ~ 8.9 km

Recirculating Linac with Energy Recovery

- 60 GeV acceleration with Recirculating Linacs
- Three accelerating passes through each of the two 10 GeV linacs (**efficient use of LINAC installation!**)
- RF systems (at twice the LINAC frequency) to compensate for the synchrotron radiation loss in the arcs



Animation from A. Bogacz (JLab)

Recirculating Linac with Energy Recovery

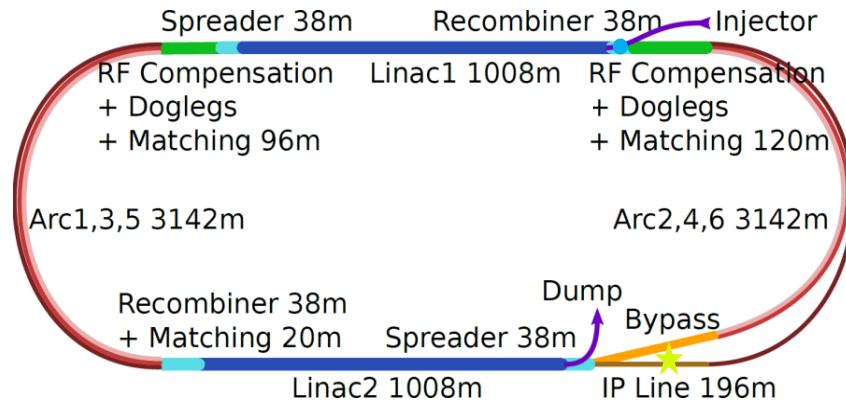
- 1/2 RF wave length shift on return arc following the collision



Animation from A. Bogacz (JLab)

Recirculating Linac with Energy Recovery

- 60 GeV deceleration with Recirculating Linacs
- Three decelerating passes through each of the two 10 GeV linacs (**energy recovery**).
- Beam dump at injection energy (e.g. 500 MeV)



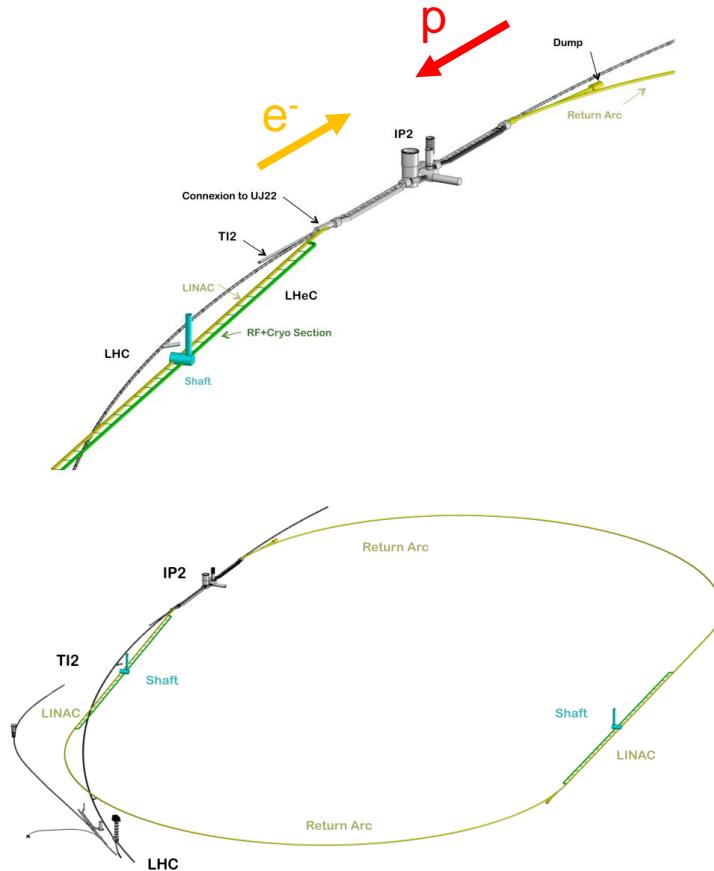
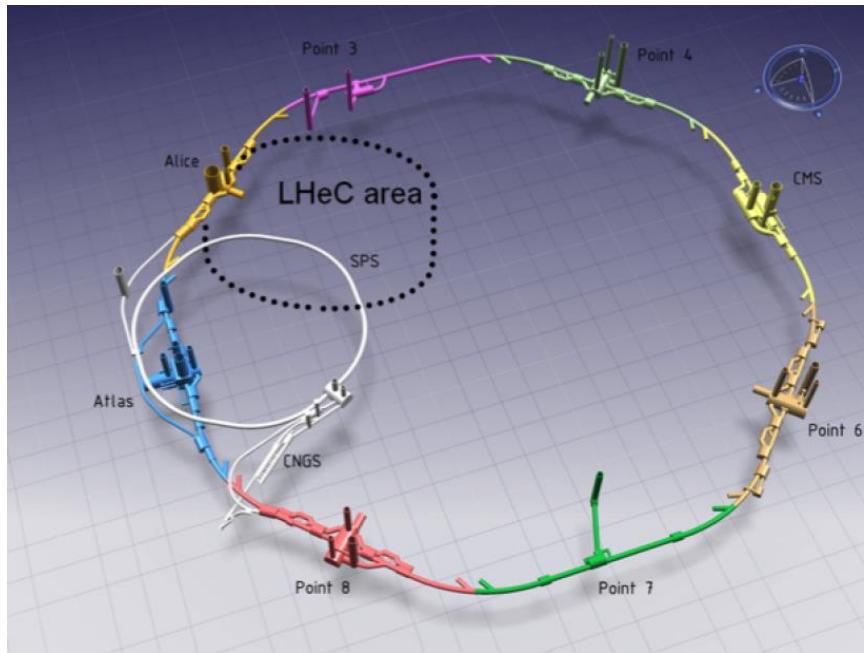
Animation from A. Bogacz (JLab)

Why ERLs?

- (nearly) linac quality/brightness beam at (nearly) storage ring beam powers:
 - beam quality source limited: $\varepsilon_{\text{beam}} < \varepsilon_{\text{ring equilibrium}}$
 - Virtual $P_{\text{beam}} >> P_{\text{RF}}$ power differential made up by recovered beam
- high power beam with reduced RF drive \Rightarrow cost savings!
- radiation control: beam is dumped at low energy



LHeC layout (IP2)



LHeC with ERL Operation as Baseline

$\sqrt{s} = 1.3 \text{ TeV}$	CDR - LHeC		HL-LHeC	
	p	e ⁻	p	e ⁻
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33} \text{ cm}^{-2} \text{s}^{-1}$]		1		8
Normalized emittance $\gamma \epsilon_{x,y} [\mu\text{m}]$	3.75	50	2.5	20
Beta Function $\beta^*_{x,y} [\text{m}]$	0.1	0.12	0.05	0.1
rms Beam size $\sigma^*_{x,y} [\mu\text{m}]$	7	7	4	4
Beam Current @ IP [mA]	860	6.4	1100	15
Bunch Spacing @ IP [ns]	25	25	25	25
Bunch Population [10^{11}]	1.7	0.01	2.2	0.023
Bunch charge [nC]	27	0.16	35	0.37

$\sim 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ allows to collect $\sim 1 \text{ ab}^{-1}$ to study the Higgs in many channels

0.9 GW beam power → ERL
90 mA circulating!

HL-LHC beam parameters

Very low beta functions at the IP!

>20 mA e⁻ current achievable/exceeded with DC guns

O. Brüning, J. Jowett, M. Klein, D. Pellegrini, D. Schulte, F. Zimmermann



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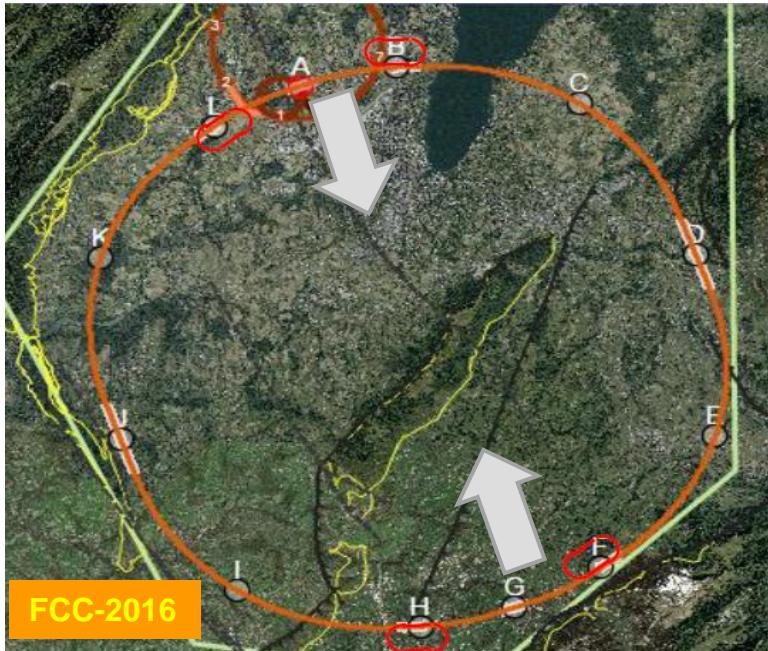
HE-LHeC/FCC-eh

- Based on:
 - the same electron machine concept (ERL @ 60 GeV)
 - HE-LHC (~13 TeV/beam hadron collider with 16 T superconducting magnets) in existing LHC tunnel
 - FCC-hh (~50 TeV/beam hadron collider with 16 T superconducting magnets) in 97.7 km new tunnel



FCC-eh layout

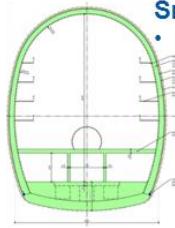
J. Stanyard



- Several IP considered
- Since Rome FCC meeting (2016):
 - 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.

FCC-eh Structures

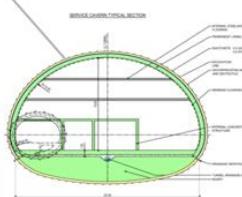
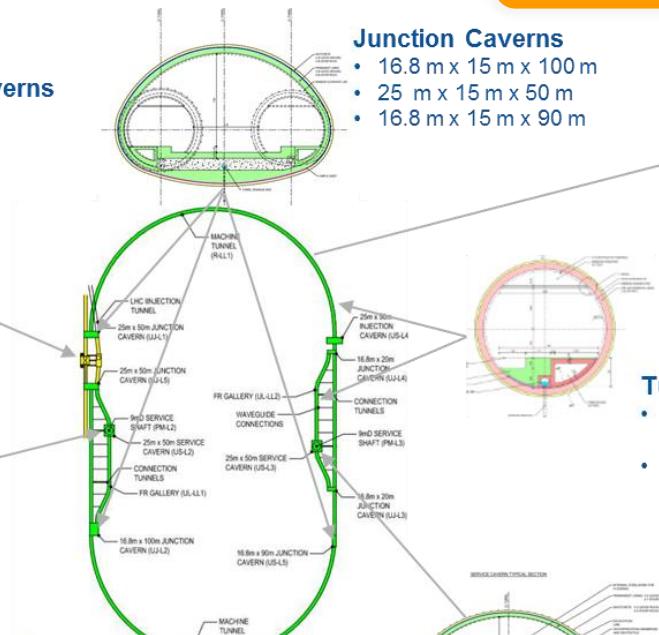
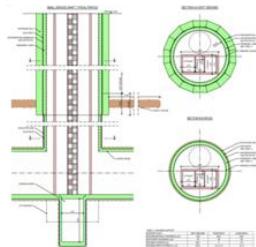
Point L selected for e-h IR – sharing with injection area – asymmetric optics



Small Experimental Caverns

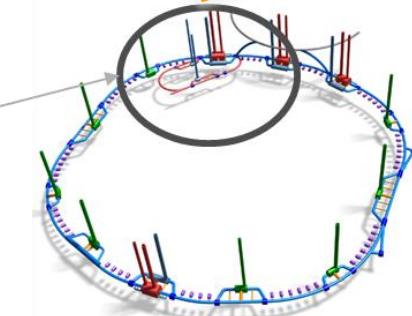
- 30 m x 35 m x 66m

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



Service Caverns

- 25 m x 15 m x 50 m



Tunnels:

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

J. Osborne



HE-LHC/FCC parameters

$\sqrt{s} = 1.7 \text{ TeV}$		HE-LHeC	
	p	e ⁻	
Beam Energy [GeV]	12500	60	
Luminosity [$10^{33} \text{cm}^{-2}\text{s}^{-1}$]		12	
Normalized emittance $\gamma\varepsilon_{x,y} [\mu\text{m}]$	2.5	10	
Beta Function $\beta_{x,y}^* [\text{m}]$	0.1	0.2	
rms Beam size $\sigma_{x,y}^* [\mu\text{m}]$	4	4	
Beam Current @ IP [mA]	1250	20	
Bunch Spacing @ IP [ns]	25	25	
Bunch Population [10^{11}]	2.5	0.03	
Bunch charge [nC]	40	0.5	

Smaller electron beam emittance but 1 μm expected at the source!

Beam Energy [GeV]	50000	60
Luminosity [$10^{33} \text{cm}^{-2}\text{s}^{-1}$]		15
Normalized emittance $\gamma\varepsilon_{x,y} [\mu\text{m}]$	2.2	10
Beta Function $\beta_{x,y}^* [\text{m}]$	0.15	0.05
rms Beam size $\sigma_{x,y}^* [\mu\text{m}]$	2.5	2
Beam Current @ IP [mA]	500	20
Bunch Spacing @ IP [ns]	25	25
Bunch Population [10^{11}]	1	0.03
Bunch charge [nC]	16	0.5

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Parameters for e-Pb operation

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 [$10^{32}\text{cm}^{-2}\text{s}^{-1}$]	7	18	54

J. Jowett, F. Zimmermann



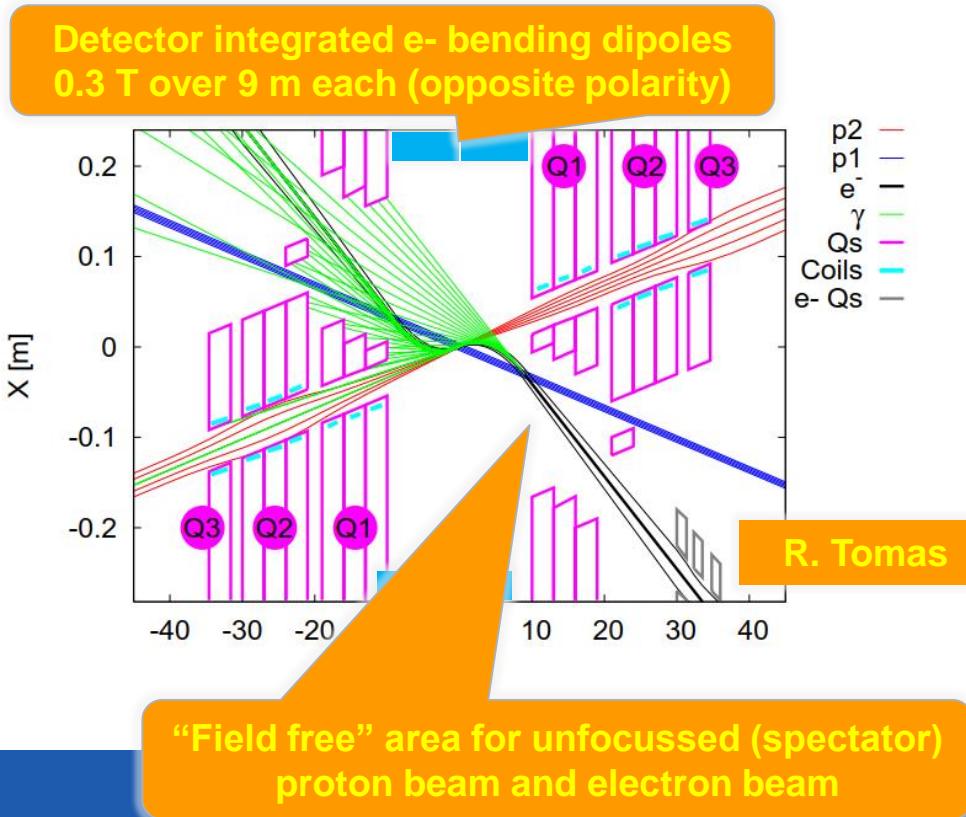
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Interaction Region layout

- Complex geometry:
 - Collision of electron beam with counter clock-wise LHC proton beam (a.k.a. Beam 2 – red beam)
 - “Spectator” clock-wise rotating beam (a.k.a. Beam 1 – blue beam)

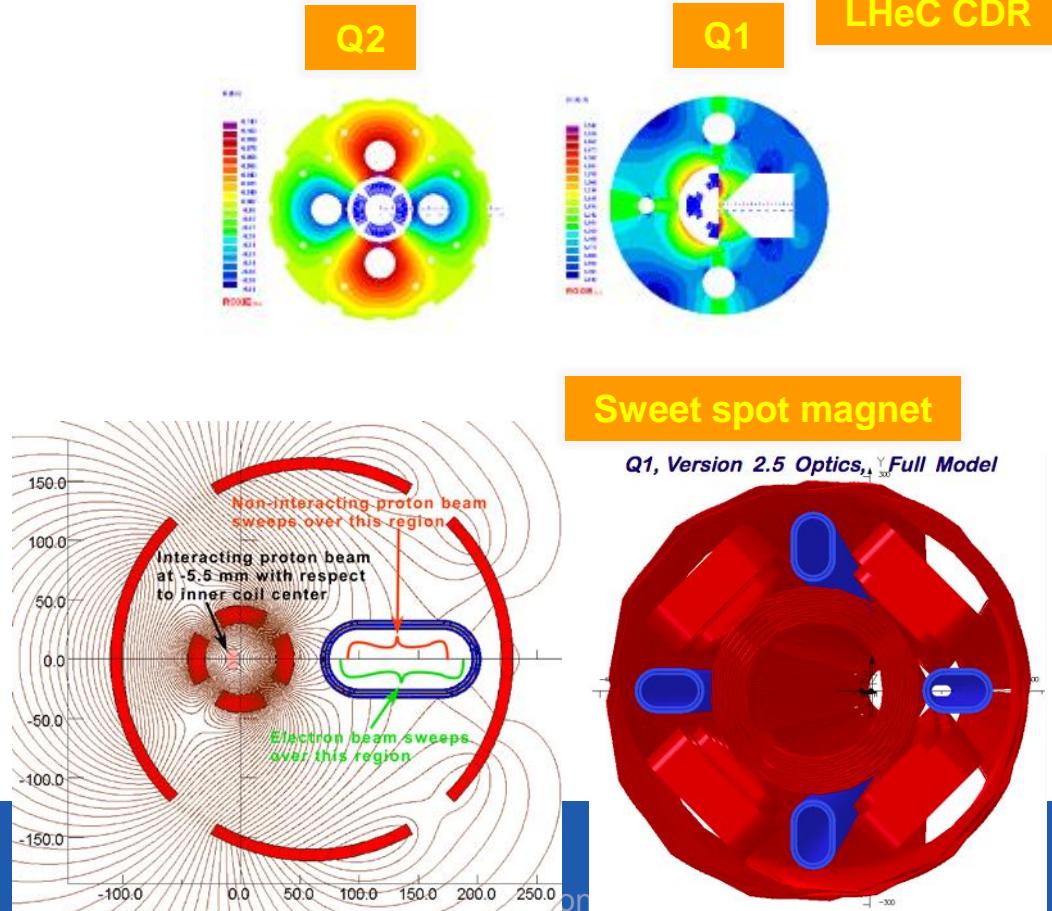


IR Magnet Design

- Stray fields in the 'field-free' region → difficult to match the e^- beam + additional synchrotron radiation
- Use of outer coils to create a reduced field region inside the quadrupole (Sweet Spot)
- Higher gradient for a given aperture → more space to put masks through the whole length of Q1

B. Parker

18/04/2018

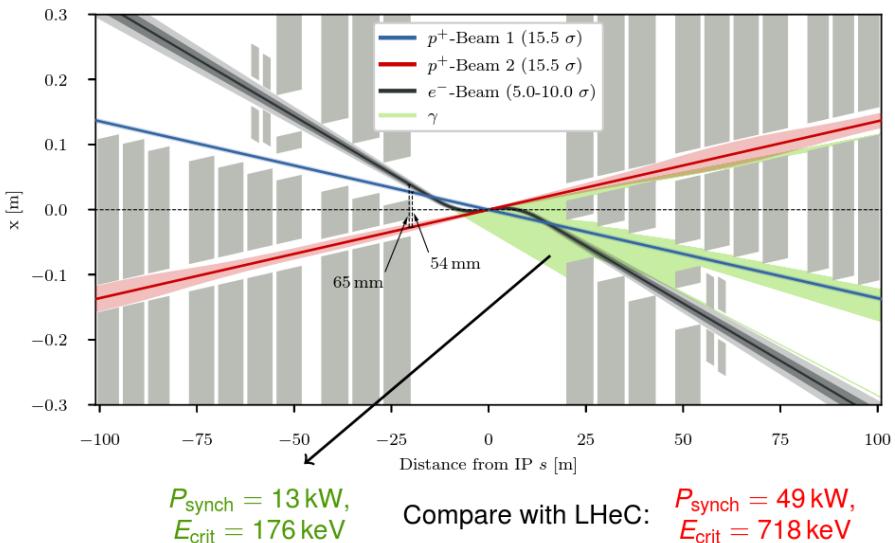


LHeC CDR

Interaction Region

FCC-eh

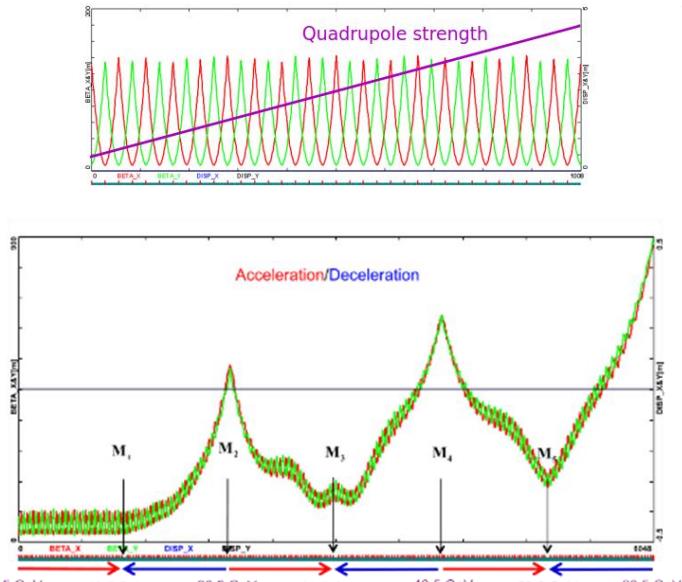
- LHeC has largest challenge in the SR
- FCC-eh looks easier in terms of SR but optics design is now challenged by short and asymmetric IR
- Designed optics for $\beta^*=30$ cm, work ongoing towards $\beta^*=15$ cm



R. Martin



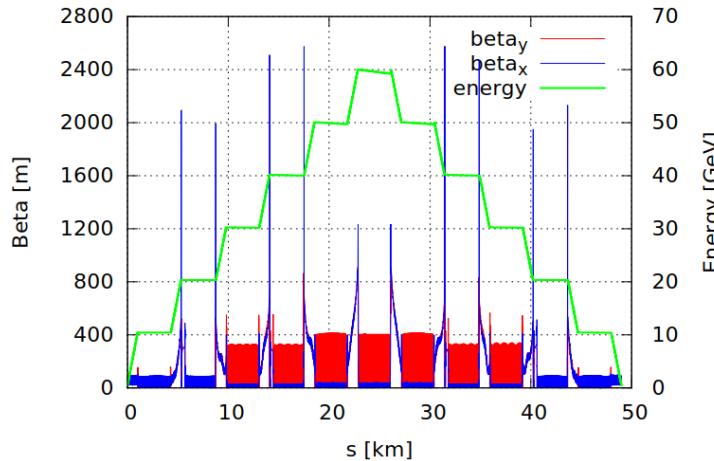
ERL optics



A. Bogacz

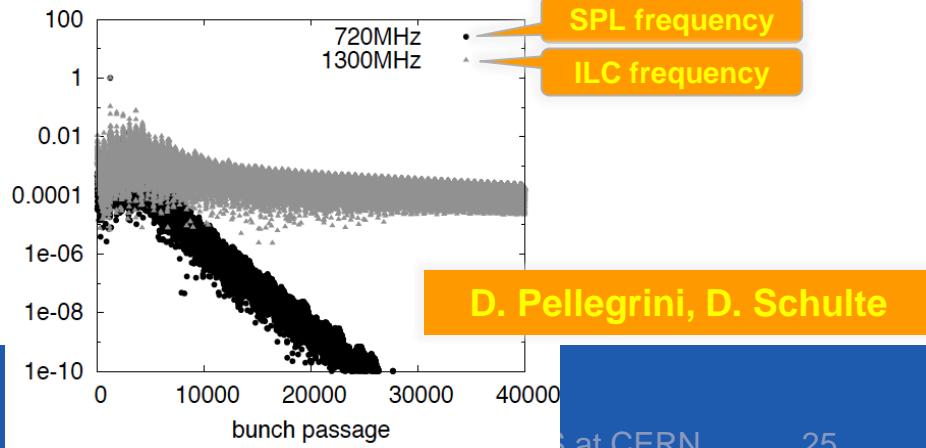
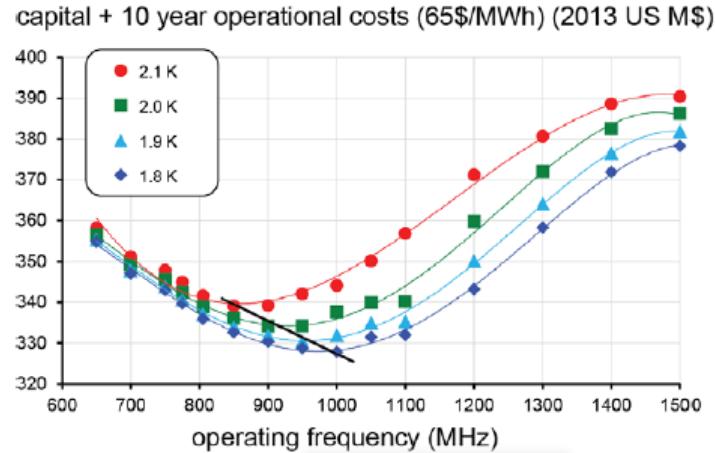
18/04/2018

- Energy change at the various passages through the linac leads to a mismatched optics to be recovered in the arcs



Choice of ERL RF frequency

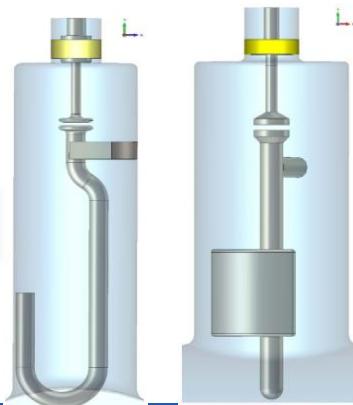
- Cost, dynamic heat losses, resistance, high- Q_0 ... point to $f < 1$ GHz
- Stability in the presence of Higher Order RF Modes and beam-beam interactions: unstable for $f > 1$ GHz
- Compatibility with LHC/HL-LHC/FCC potential developments. **Decision for 802 MHz**



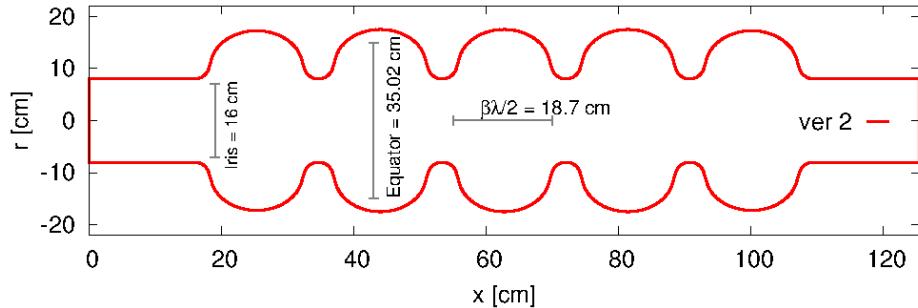
Main RF System at 802 MHz

R. Calaga

- High Q_0 , Superconducting (SC) RF cavities, 5-Cell design minimizing High Order Modes to minimize beam instabilities and losses (together with an optimized filling scheme)



LHC HOM coupler design

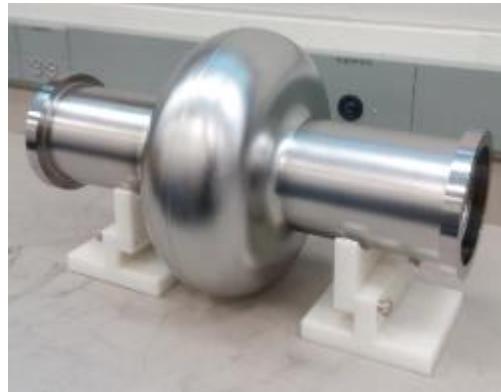


Parameter	Ver 1 (Scaled)	Ver 2
Frequency [MHz]	801.58	801.58
Number of cells	5	5
Active cavity length [mm]	935	935
Voltage [MV]	18.7	18.7
E_p [MV/m]	45.1	48.0
B_p [mT]	95.4	98.3
R/Q [Ω]	430	393
Cell-cell coupling (mid-cell)	4.47%	5.75%
Stored Energy [J]	154	141
Geometry Factor [Ω]	276	283
Field Flatness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



SC RF cavity prototype: JLab Collaboration

- J-Lab/CERN collaboration
 - to build:
 - Single-cell fine-grain niobium 802 MHz cavity (**completed**)
 - One 5-cell fine-grain niobium 802 MHz cavity (**completed**)
 - Two single-cell OFHC 802 MHz cavities for R&D (**advanced**)
 - to design
 - Higher Order Mode (HOM) coupler
 - Cryomodule



F. Marhauser
R. Rimmer

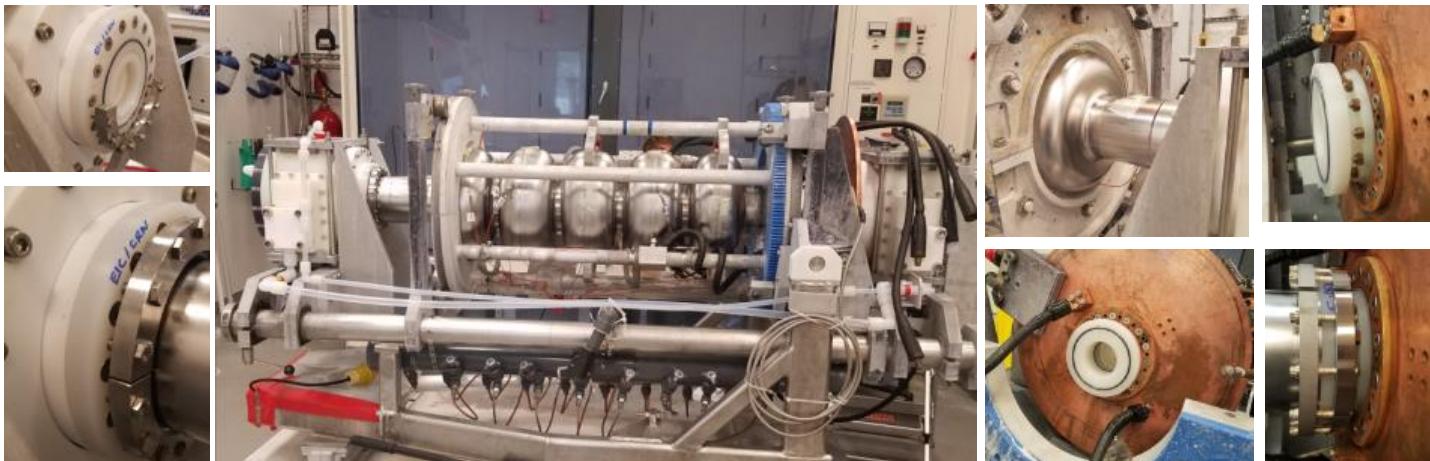


SC RF cavity prototype: JLab Collaboration

Tooling

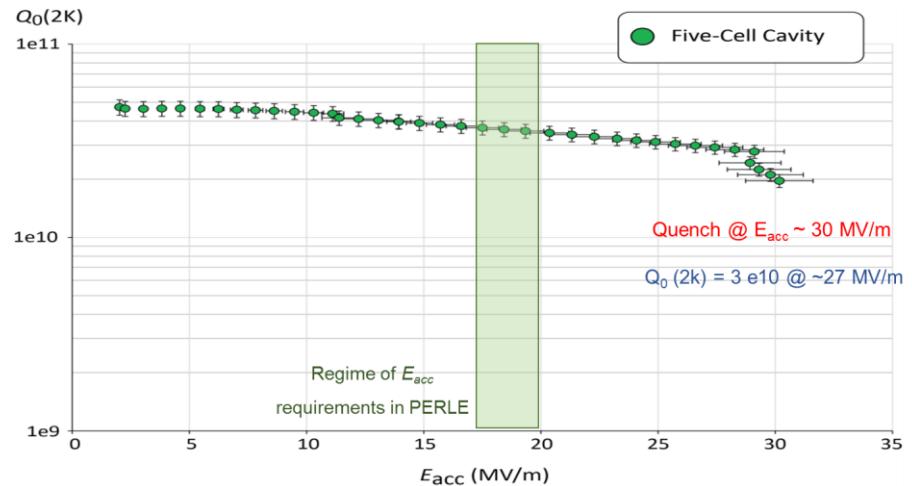


Electro-polishing



SC RF cavity prototype: JLab Collaboration

- Requirements:
 - 18 MV/m
 - $Q_0 > 2 \times 10^{10}$
- Design parameters exceeded!
- Next: HOM adapter and cryomodule design – cavity production to proceed.

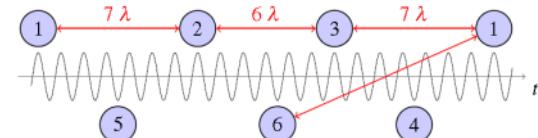
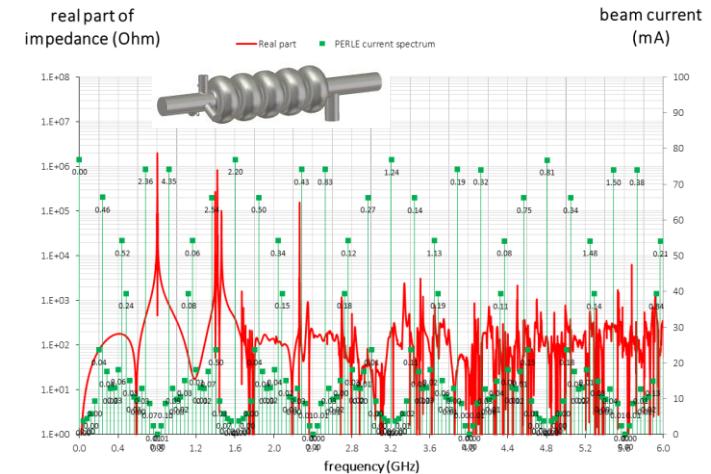


F. Marhauser
R. Rimmer

SC RF cavity prototype: JLab Collaboration

- HOM wake-field analysis:
 - no crucial HOMs close to beam spectral lines
 - At 25 mA injected current low HOM power of ~30 Watts (here shared by 3 coaxial HOM couplers and beam tubes)
 - Optimized filling scheme

D. Pellegrini



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ERL challenges

- Multi-pass recirculation and energy recovery at high current and energy (~1 GW beam power)
- Need **demonstrator** of this key LHeC element → **PERLE (Powerful Energy Recovery Linac for Experiments)**



Why PERLE [as seen from LHeC]?

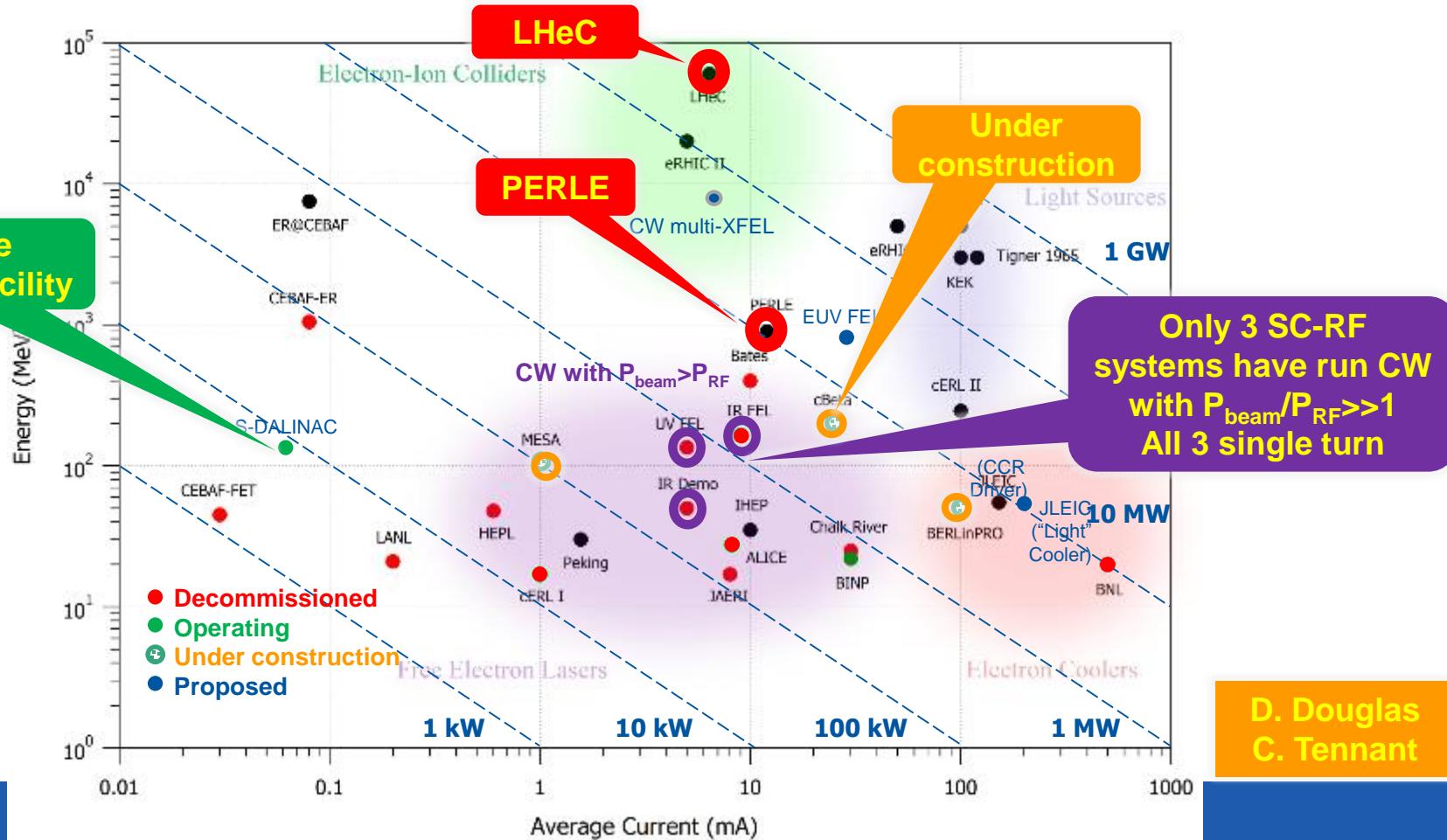
FUNDAMENTAL MOTIVATION:

- 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 ($2 * 3 * [6\text{mA} - 25\text{mA}] \rightarrow 30\text{-}150\text{mA}!!$)
- 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

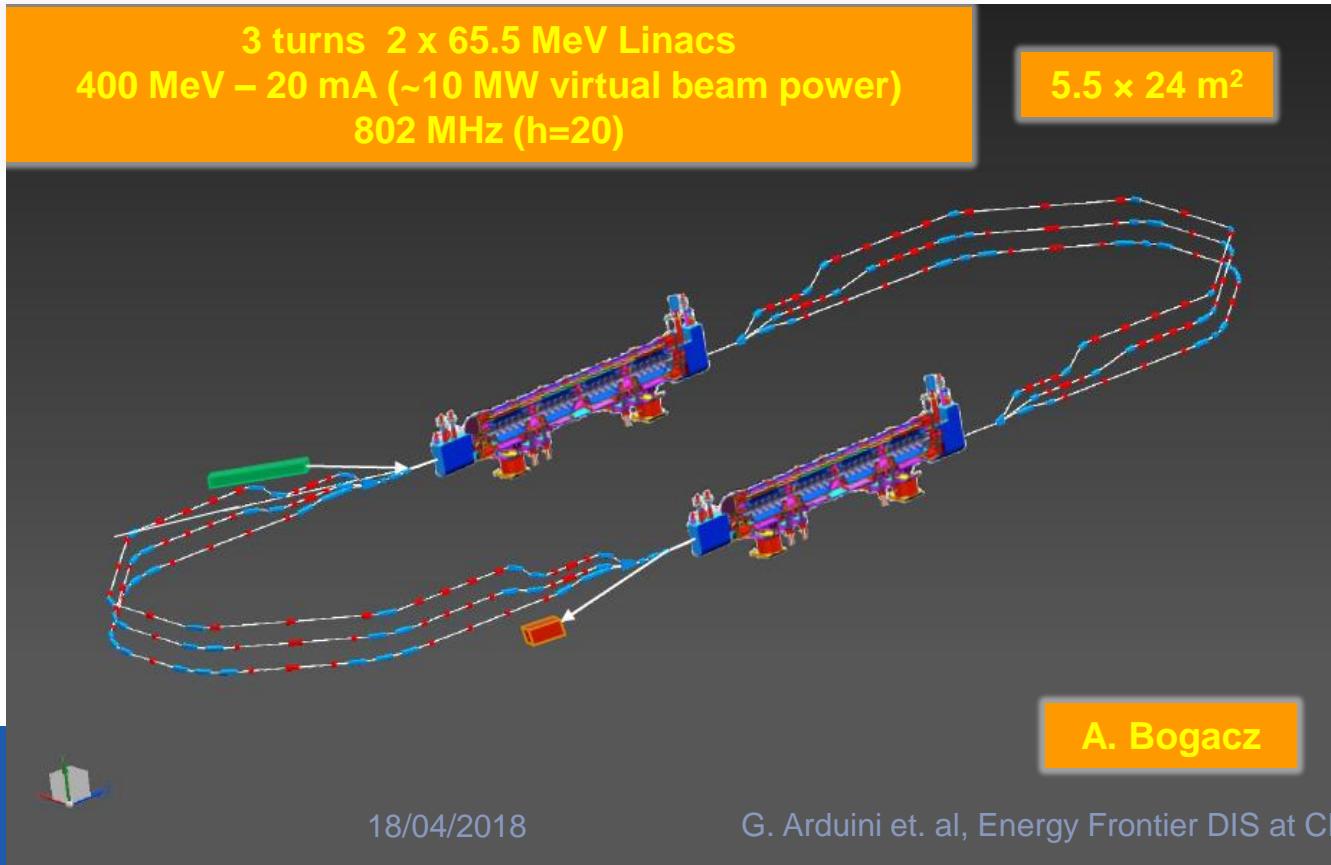
Powerful ERL for Experiments (PERLE)

- Collaboration of BINP, CERN, Daresbury/Liverpool, JLab, Orsay INP+LAL (**CDR in press**)
- **ERL Demonstrator** for ep at LHC/FCC
 - Key questions to be addressed: Beam Break-up limit, ERL efficiency, beam size evolution (CSR and μ bunching) , etc
- SC-RF beam based development facility
- Low energy electron and high energy photon beams (O(10) MeV) physics
 - low energy nuclear, particle and astro physics

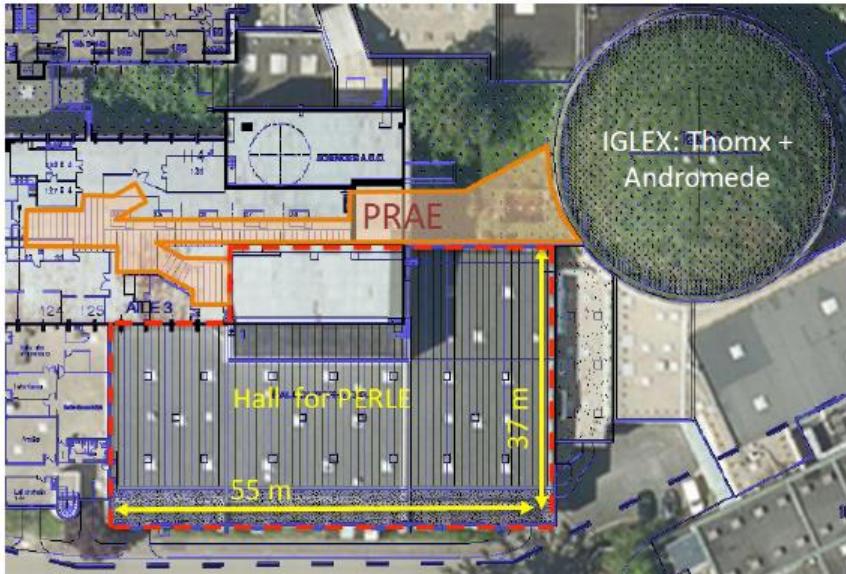




PERLE @ Orsay (LAL/INP)



PERLE @ Orsay



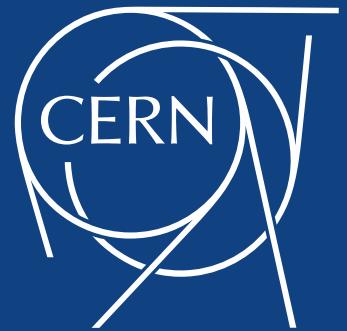
Summary and Conclusions

- The conceptual design of LHeC and its “higher energy” brothers (HE-LHeC and FCC-eh) is progressing in preparation of the next **Review of the European Strategy for Particle Physics**: effort in the design of the complex Interaction Region towards $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- The design relies on a **high energy/high current/multipass Energy Recovery Linac** ($\sim 1 \text{ GW}$ virtual beam power)
- A collaboration towards the realization of a **ERL demonstrator (PERLE)** in the 10 MW region has been launched

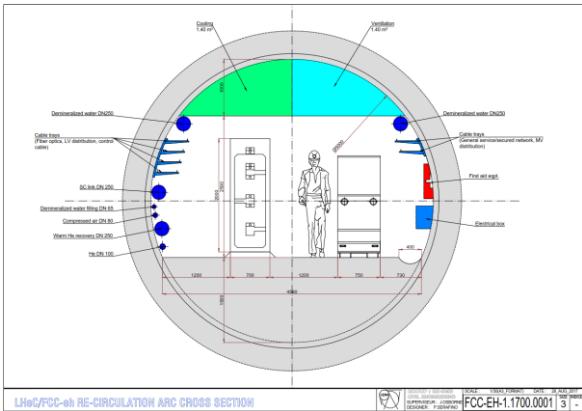




Join us!

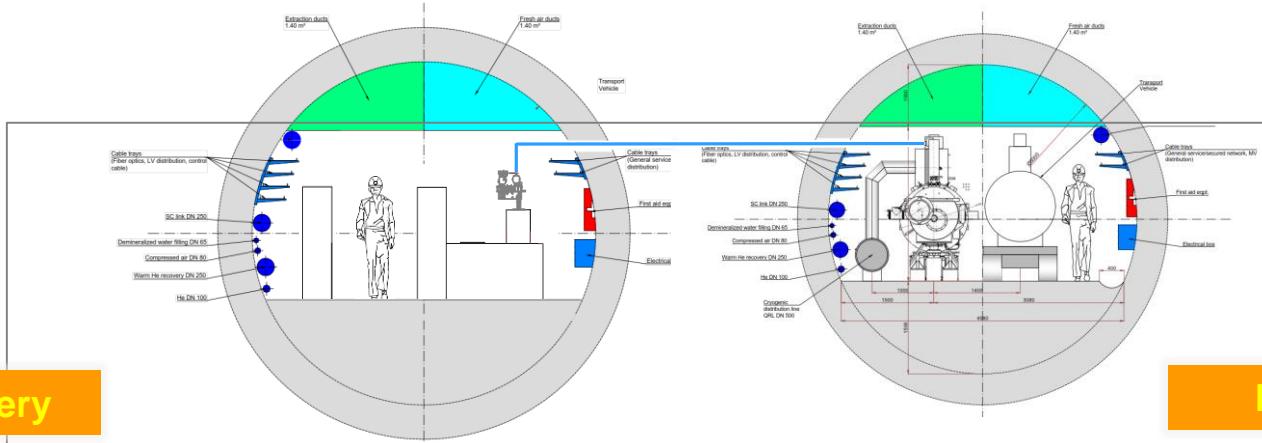


Tunnels



Arc

M. Stewart

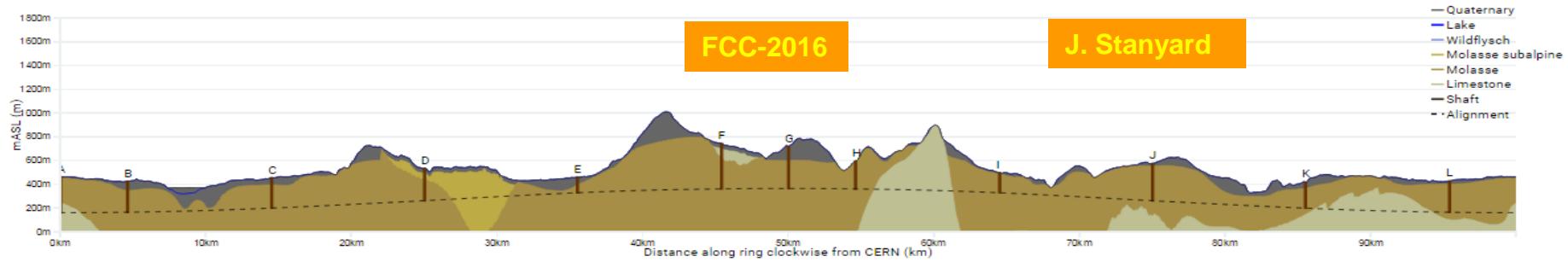


RF Gallery

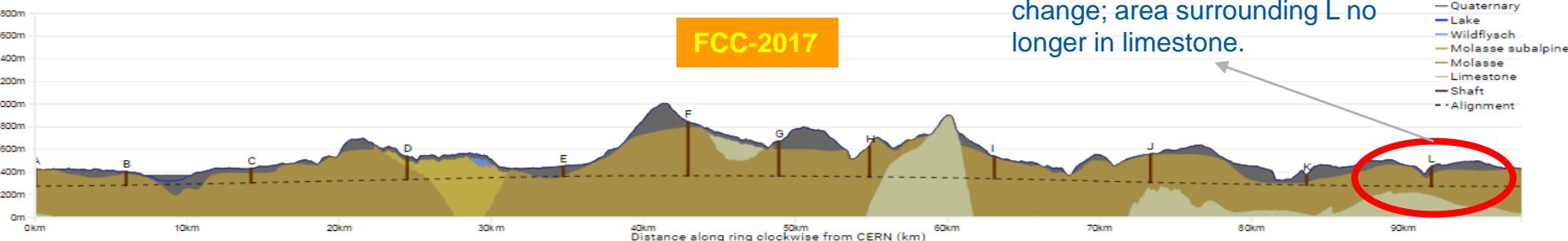
LINAC



FCC-eh layout

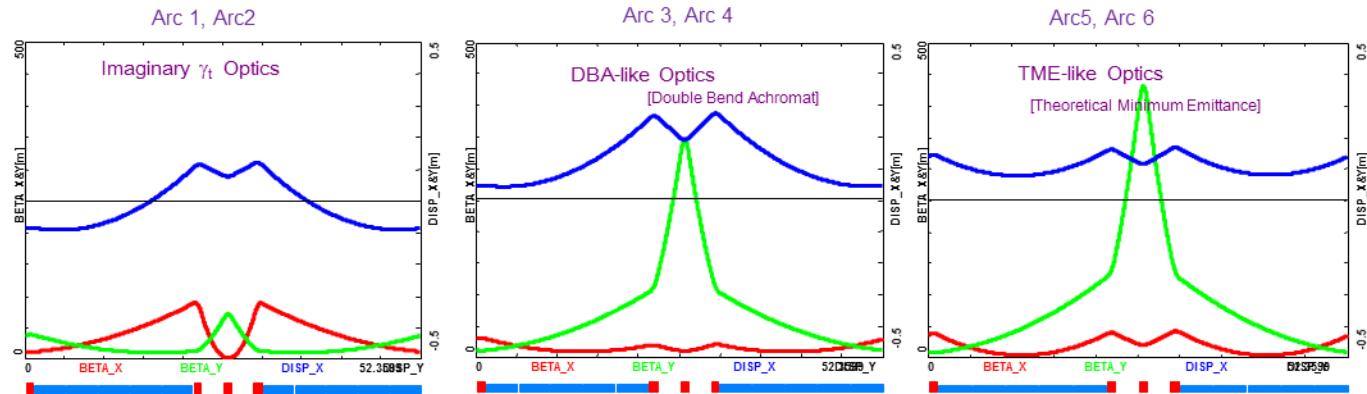


Reduced Depth & alignment
change; area surrounding L no
longer in limestone.



ERL optics

A. Bogacz



- Minimize emittance growth due to quantum excitation ($\sim \gamma^6$)
- Tunable cells:
 - Highest energy arcs tuned to minimize energy spread induced by synchrotron radiation,
 - Lowest energy arcs tuned to contain beam size and compensate for bunch lengthening.