



## PERLE: Status and prospects for a high power ERL

London, June 08<sup>th</sup> 2023

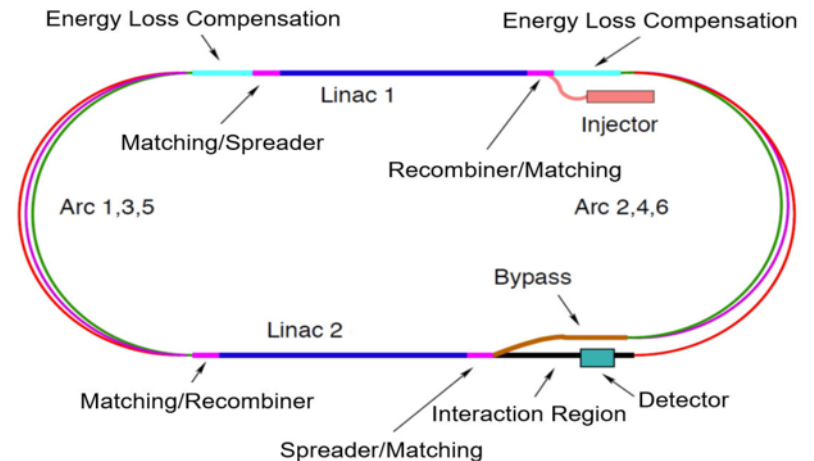
Walid KAABI on behalf of PERLE Collaboration





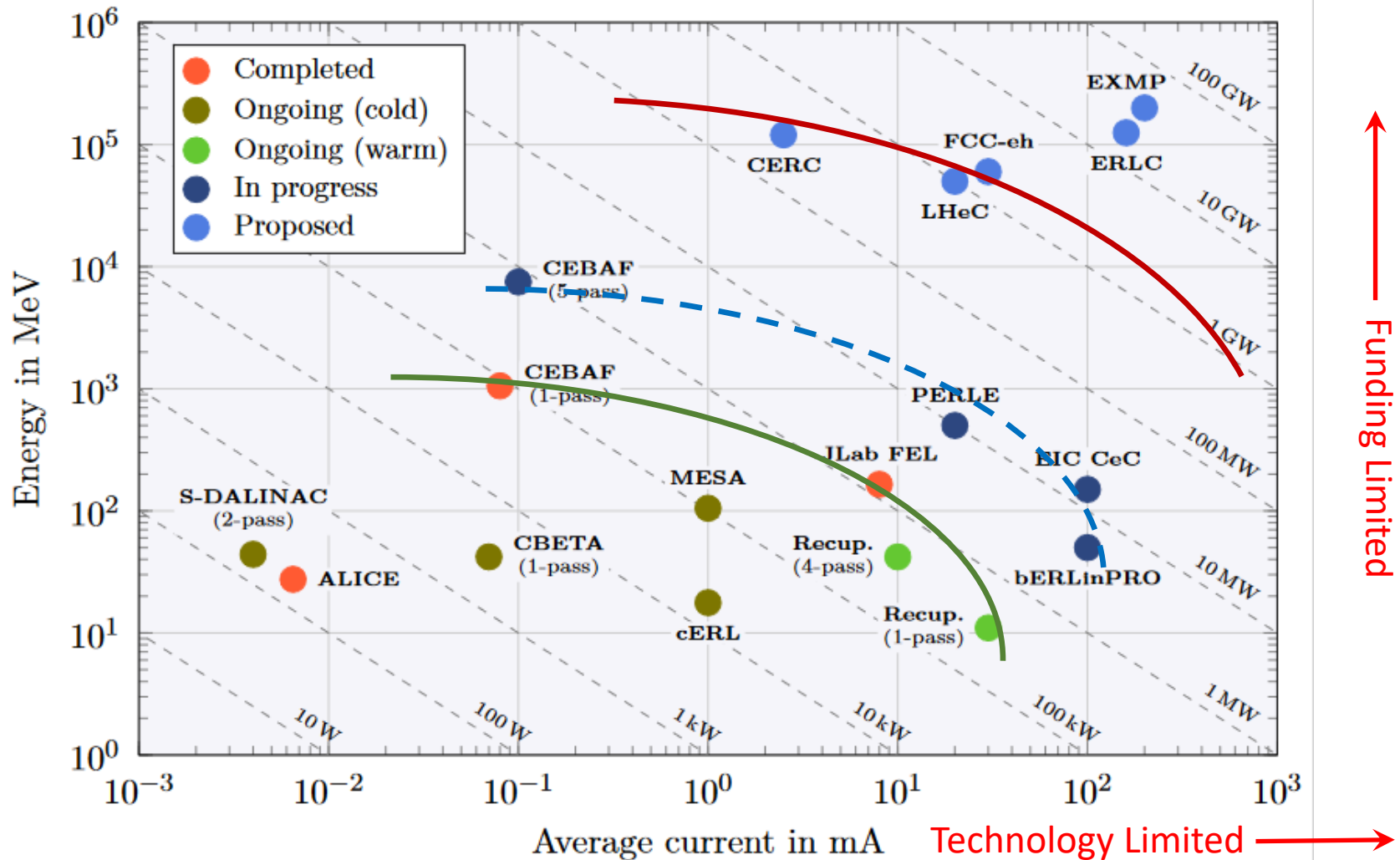
# The short story of the PERLE Genesis

- Future **particle physics imposes strong challenges on accelerators** and requires a variety of **accelerator R&D programs** not only to meet the foreseen performances, but also to **lower their energetic consumption and enhance their efficiency**.
  - **Energy Recovery Linacs offer one of the main options for energy frontier colliders**
- To probe **deep inelastic scattering at high energy** and to study the **Higgs boson**, **LHeC proposes a high luminosity collider** using the HL-LHC protons and an intense electron beam.
- For the electron beam, **the ERL scenario** has many advantages :
  - High luminosity, low interference for installation next to LHC, machine size, energy consumption
  - Concept also applied to the **FCC-eh design**
- **The ERL-ring collider concept of LHeC based on**
  - synchronous operation of HL-LHC and 50 GeV electron beams
  - circumference of e- loop about 1/5 of that of LHC (5.3 km)
  - luminosity of  $10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$
  - **Multi-turn ERL (3+3 passes), 50 GeV, RF frequency: 801 MHz, 20 mA beam current (6 x 20 = 120mA load in the cavities).**





# ERL - The global landscape



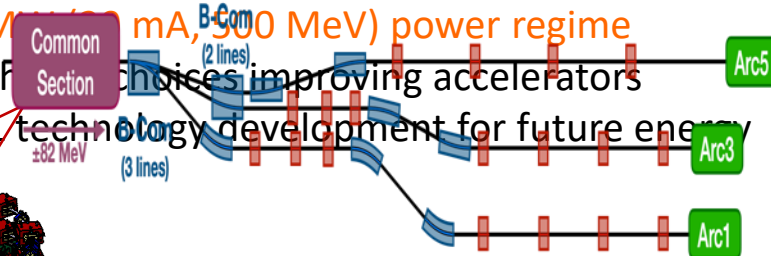
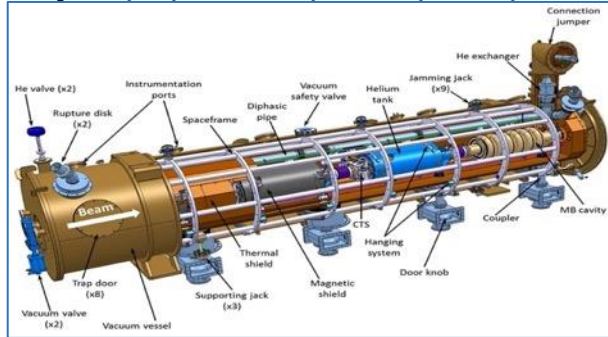


# PERLE Configuration

PERLE: first multi-turn ERL, based on SRF technology, designed to operate at 100 MeV, 20 mA, 500 MeV power regime

Study of accelerator phenomena and to validate technology choices improving accelerators  
operational power regime on the pathway of the ERL technology development for future energy

- Total gradient 82 MeV
- 3 acc & 3 decc beams at different energies travelling in the CM.



Switchyard: vertical separation/recombination of beams at different energies

3 staked isochronous recirculation arcs for

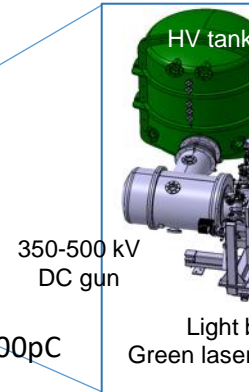
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\epsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

Beam dump

Interaction Points

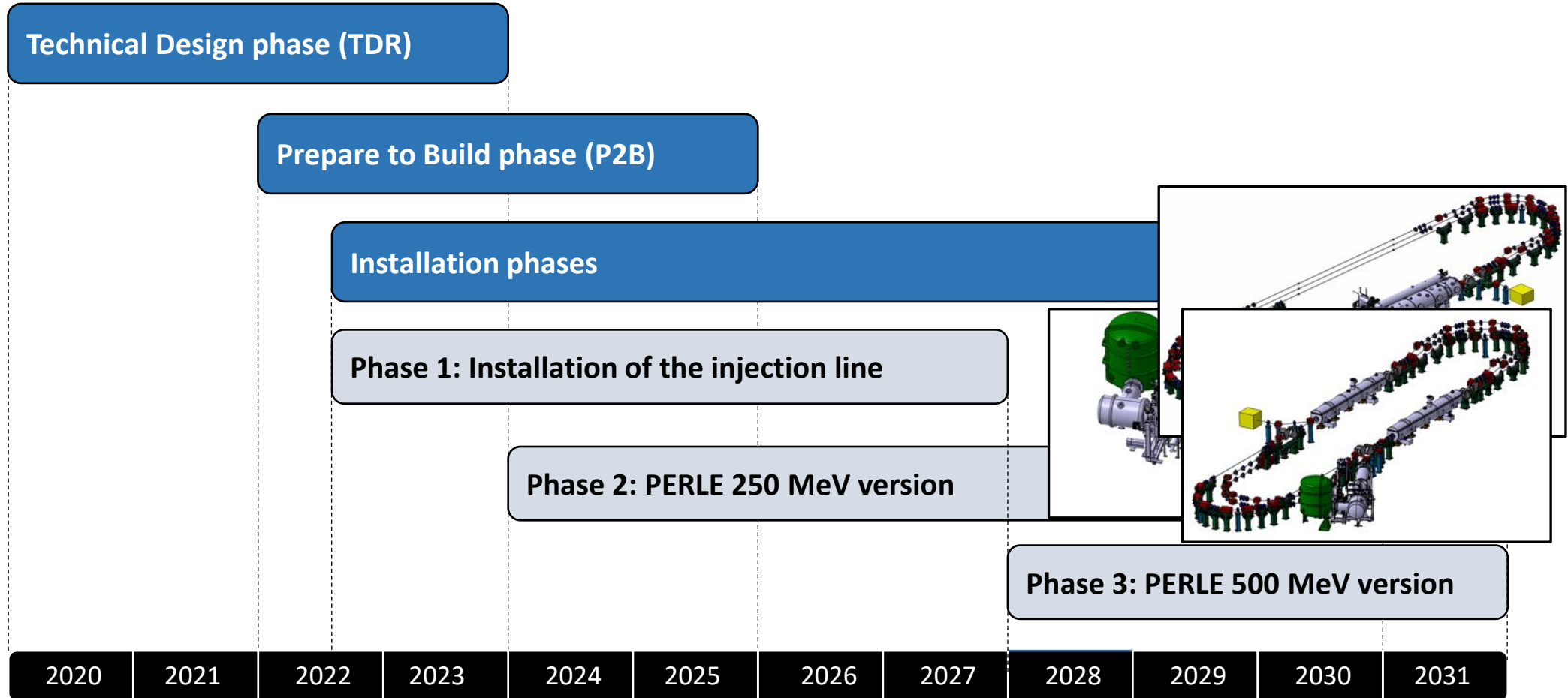
3 staked (& inversed) isochronous recirculation arcs for beams at different energies (Arcs 2, 4, 6)

Injection line delivering 500pC bunches at 7 MeV.





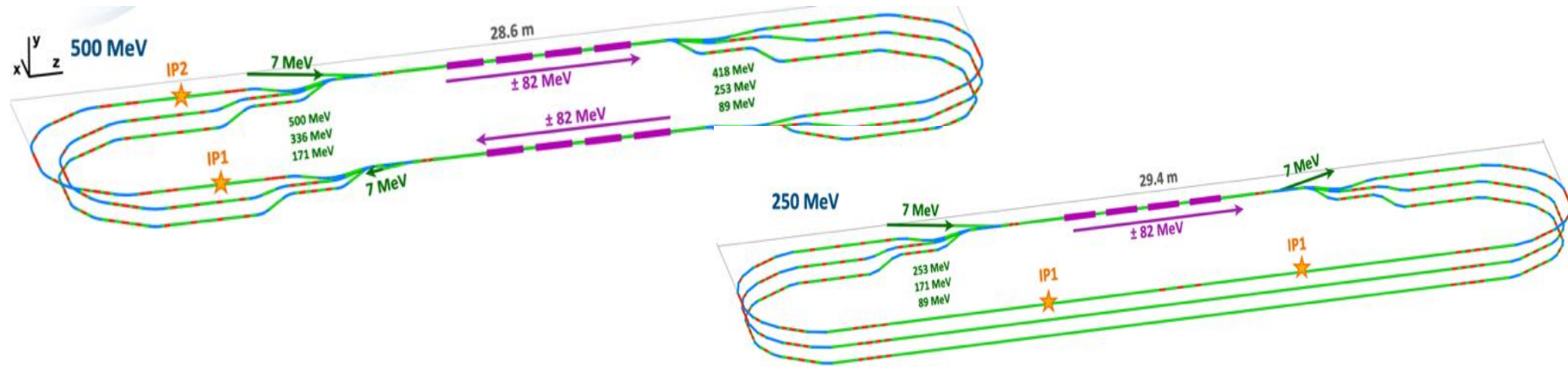
# PERLE Timeline for TDR phase and beyond





# PERLE Lattice optimization

Lattices and optics for the 500 MeV and 250MeV PERLE versions were studied and optimised:



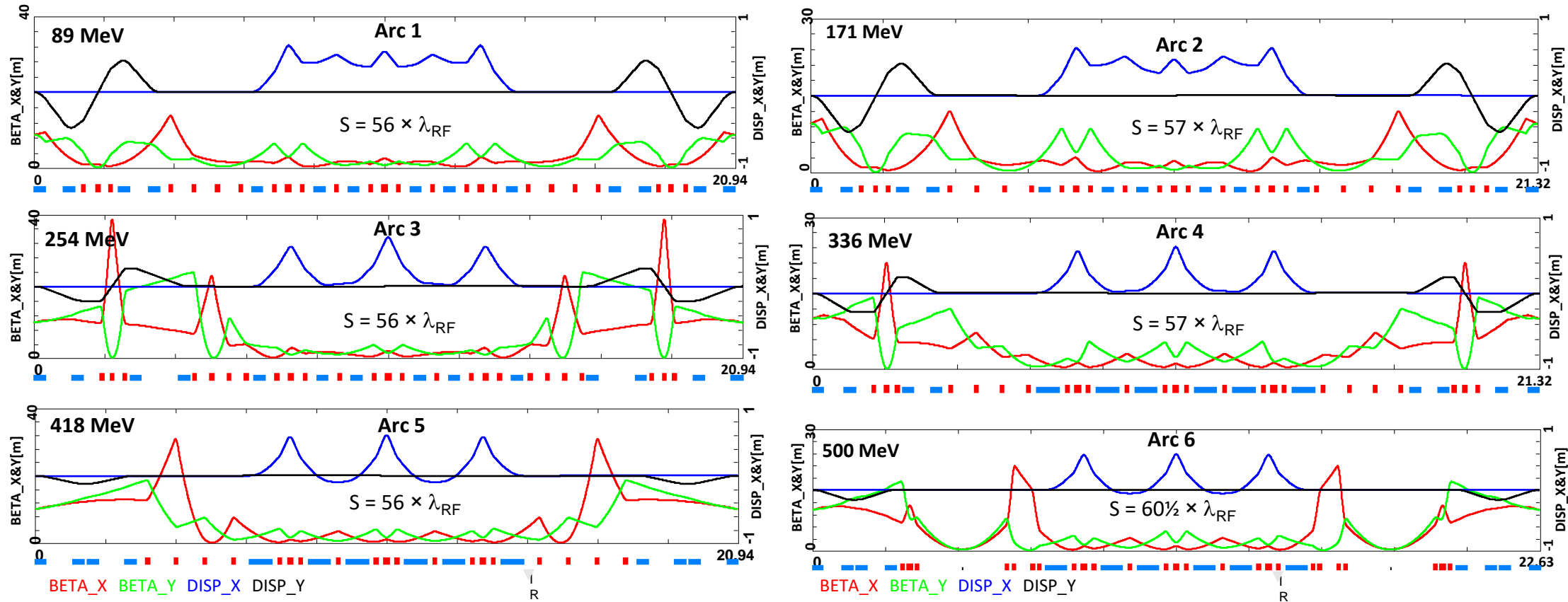
- A full 1st order calculation were finished and a complete 250 and 500 MeV lattice is now available.
- The stability of the lattice was crosscheck with different codes (OPTIM6, MADX & BMAD).
- First specifications of quadrupoles and dipoles in switchyards & arc sections are obtained.

→ Further studies are ongoing/to be done: momentum acceptance, correction of nonlinear aberrations with multipoles, longitudinal match...

→ In addition to beam dynamics studies: Start to end simulations with CSR and microbunching, Multiparticle tracking, BBU, Impedance analysis and Wakefield effect mitigation ...



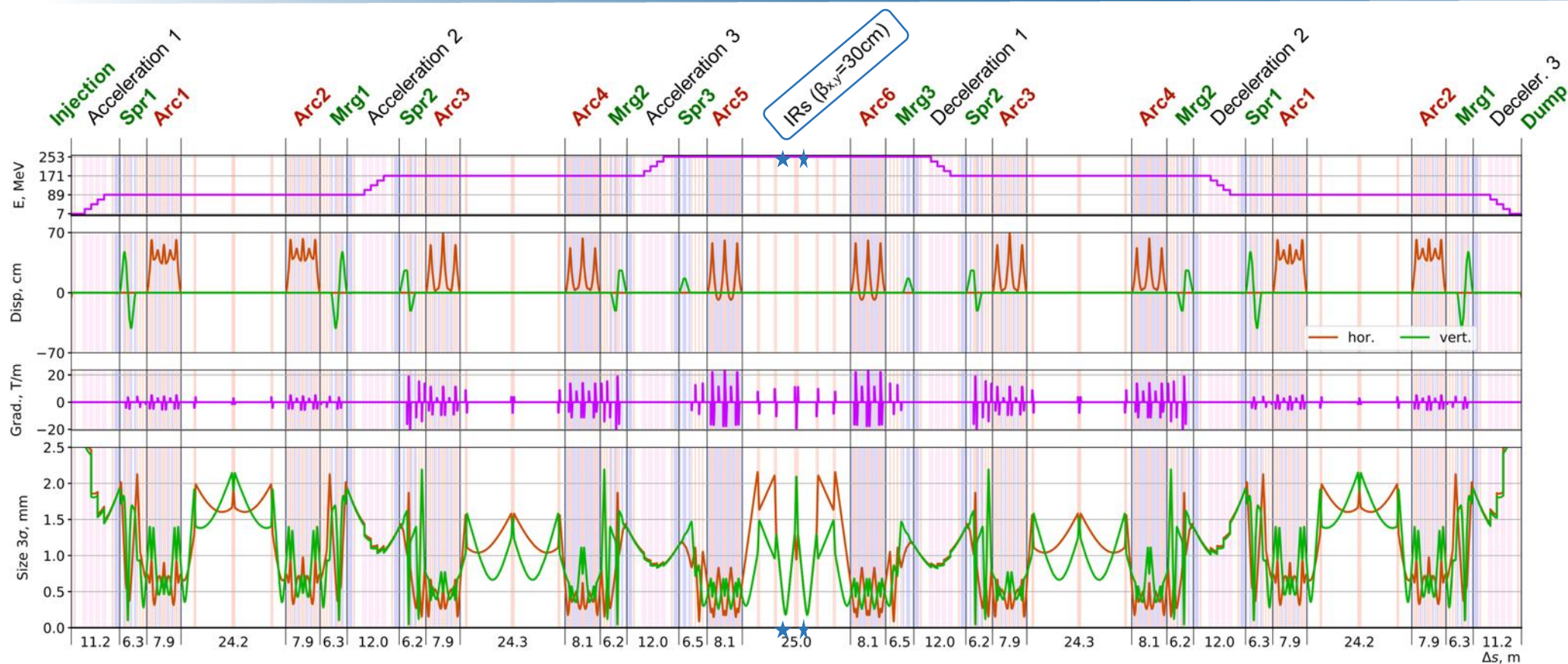
# Lattice optimization of the 500 MeV version of PERLE



S.A. Bogacz et al. International Workshop on Deep-Inelastic Scattering and Related Subjects- Stony Brook University, New York, USA (2021), doi:10.21468/SciPostPhysProc.



# Lattice optimization of the 250 MeV version of PERLE



Transverse beam size ( $3\sigma$  radius)  $< 2,2$  mm (after the 2nd RF cavity), Dispersion  $< 70$  cm and Low beta function @ the 2 IRs

Alexis Fomin et al. "Lattice design of 250 MeV version of PERLE"- IPAC'23- TUPL171



# Bunch Filling Pattern studies

## In the injection line:

- 500 pC e<sup>-</sup> bunches generated at  $f_{inj} = 40$  MHz  
 → time spacing between bunches: 25 ns  
 → average current: 20 mA
- Bunches accelerated to 7 MeV in the injector then injected into the ERL loop

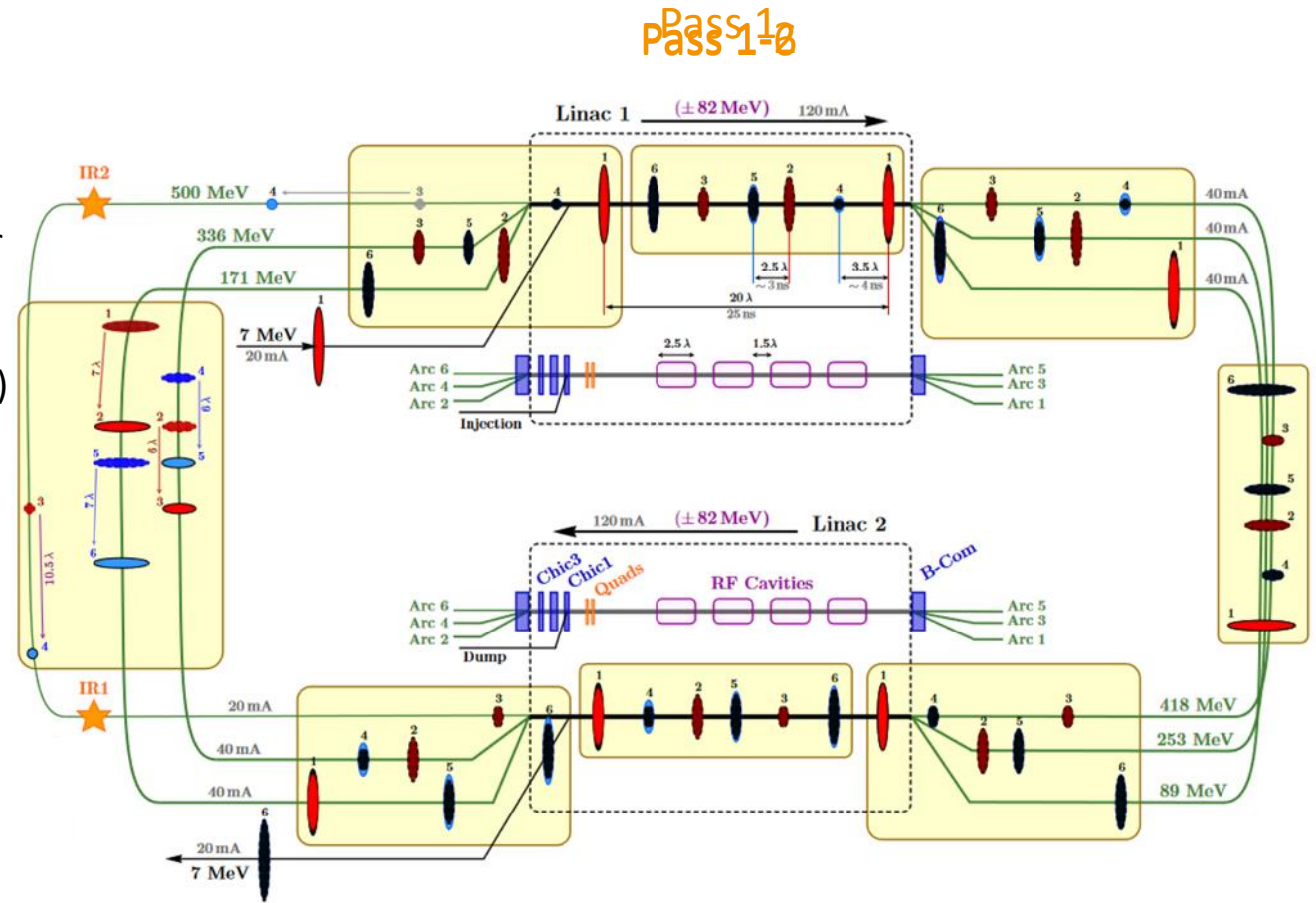
## ERL Loop:

Cavity frequency:  $f_{RF} = 801,58$  MHz ( $\lambda_{RF} = 34.7$  cm)  
 →  $f_{RF}/f_{inj} = 20$   
 → Length spacing between bunches:  $20 \lambda_{RF}$

## During the 1<sup>st</sup> Pass:

Linac 1 → Arc 1 → Linac 2 → Arc2  
 7 → 89 MeV      89 → 171 MeV

1<sup>st</sup> Pass length =  $167 \lambda_{RF}$   
 → 8 bunches injected in the 1<sup>st</sup> pass.  
 → The 9<sup>th</sup> bunch injected is followed by the 1<sup>st</sup> accelerated bunch in pass 1 that start pass 2 (spaced by  $7 \lambda_{RF}$ ).





# Bunch Filling Pattern 250 MeV Vs. 500 MeV version

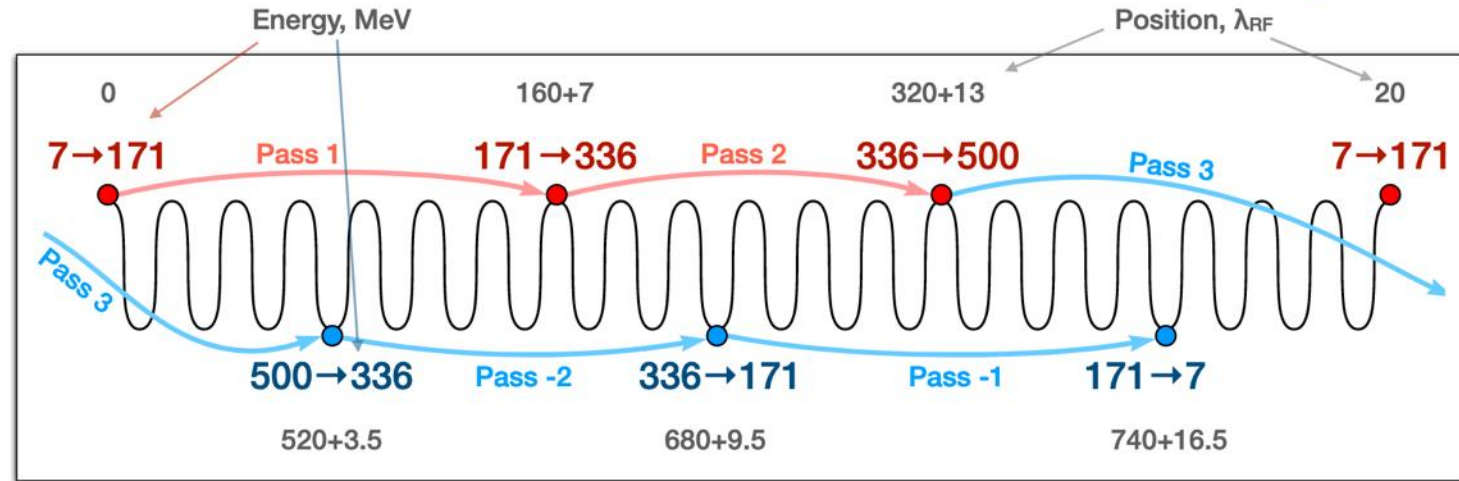
## 500 MeV

Full length of one turn:  $(160 + \Delta) \lambda_{RF}$

chosen shift:  $\Delta = 7, 6, 10.5, 6, 7$

→ 2.7 m at IPs (28.6 m total)

studies by A. Bogacz, P. Williams, R. Apsimon,  
and K. Andre



## 250 MeV

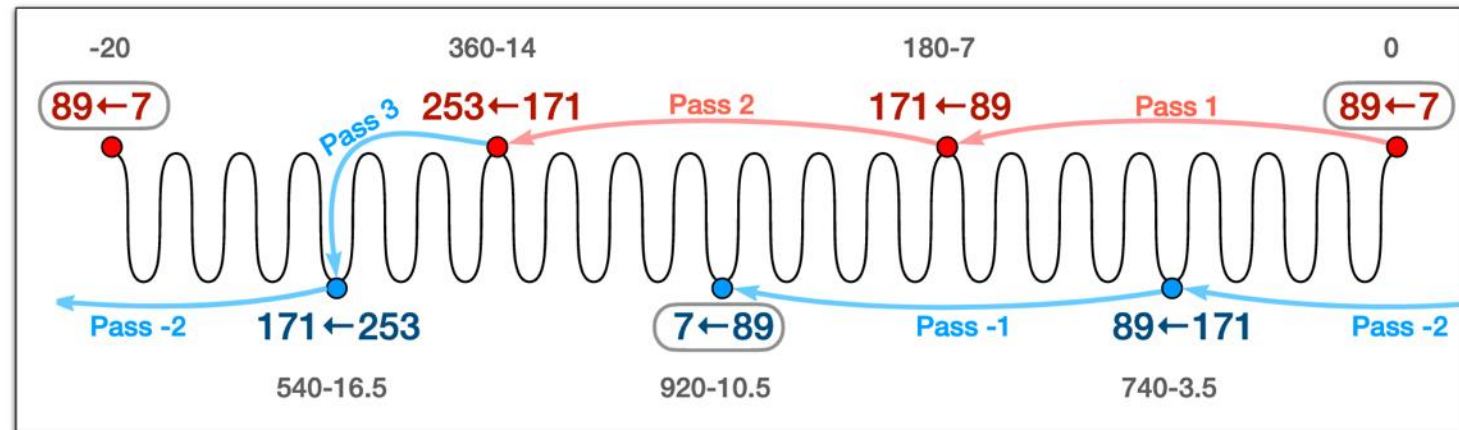
Full length of one turn:  $(180 - \Delta) \lambda_{RF}$

optimal shift:  $\Delta = 7, 7, 2.5, 7, 7$

→ bunches of lowest energies are separated  
(more important than for 500 MeV version)

→ more detailed studies will follow)

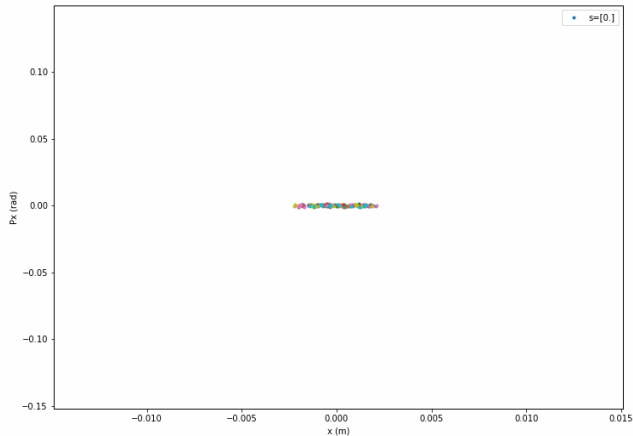
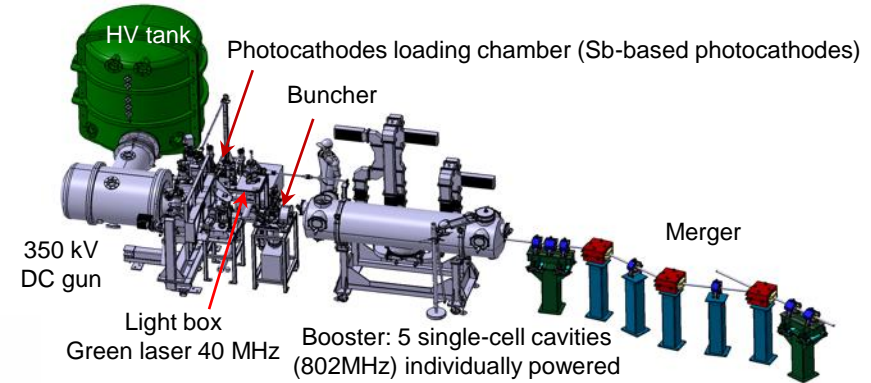
→ 29.4 m of total length



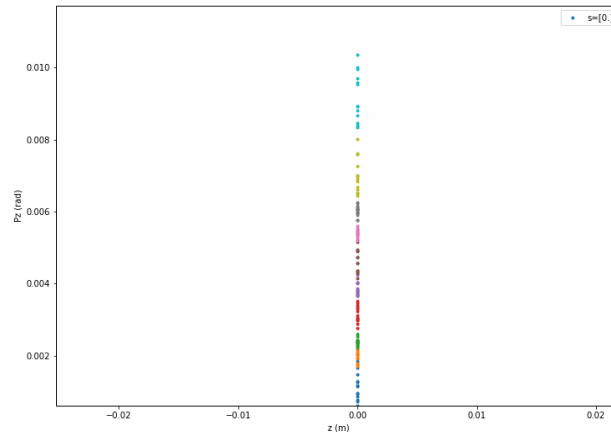


# Injection line optimisation

A conceptual design of the PERLE injector was made within a collaboration between AsTeC-Daresbury, UoL and IJCLab. This included the **DC gun cathode shape** optimisation, a **buncher cavity** and the **merger conceptual designs**, besides a complete beam dynamic studies of **space charge effects**, **phase space** and **bunch distributions**, and **emittance**. Further studies and design optimisation of the injector are currently undertaken.



Transverse phase space (x-px)



Longitudinal phase space (z-pz)

- Solenoids focus beam in transverse plans
- Buncher focus beam in longitudinal
- M shape in z-pz axis at the end of injector : Might be a problem

*B. Hounsell et al. "Conceptual design of the PERLE injector" LINAC'22- Liverpool, UK- THPOJO26*



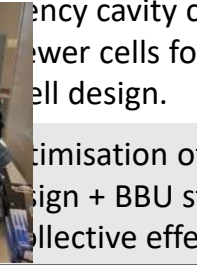
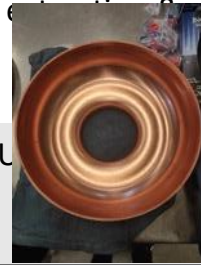
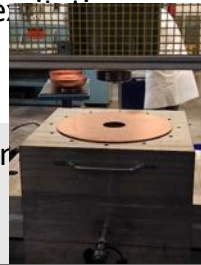
# PERLE SRF cavity

## PERLE R

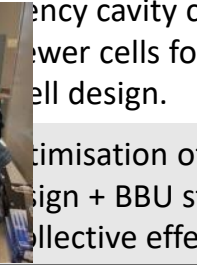
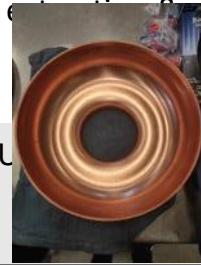
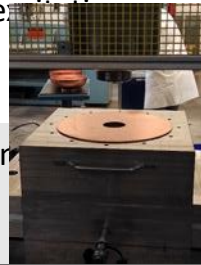
CW opera

A 5-Cell copper cavity is under fabrication @Jlab to allow end group design optimisation and to test several HOM couplers combinations to assess the best HOM damping scheme.

High current operation

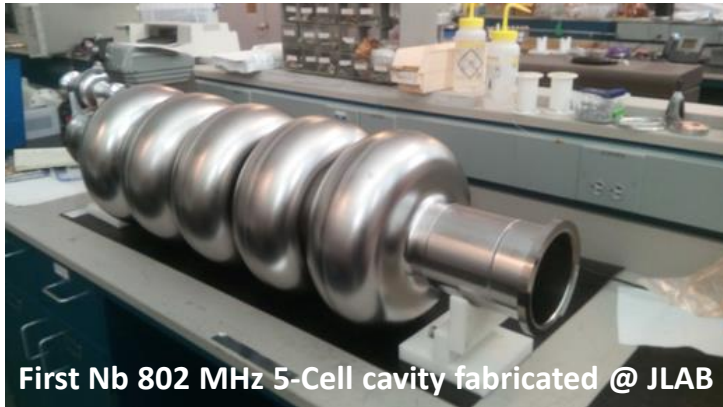


Muti-bunches operation

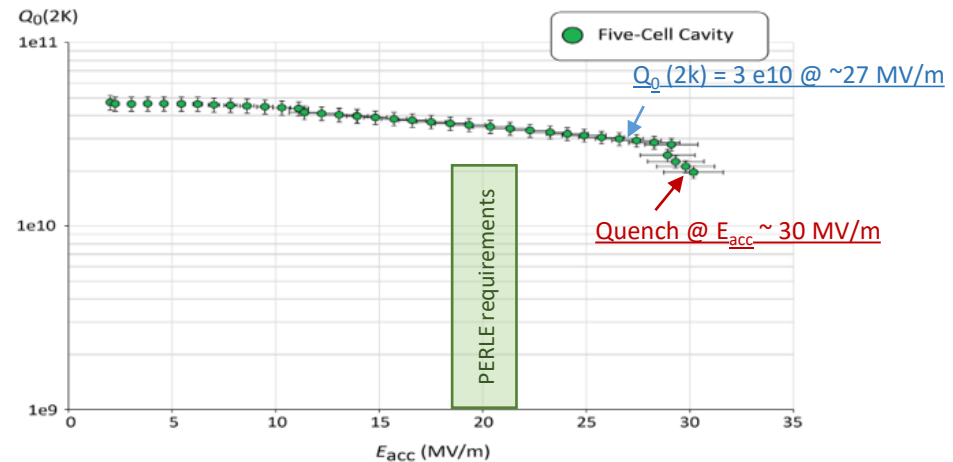


High current operation  
several HOM couplers combinations to assess the best HOM damping scheme.

Muti-bunches operation  
optimisation of the bunch design + BBU study after collective effects).



First Nb 802 MHz 5-Cell cavity fabricated @ JLAB

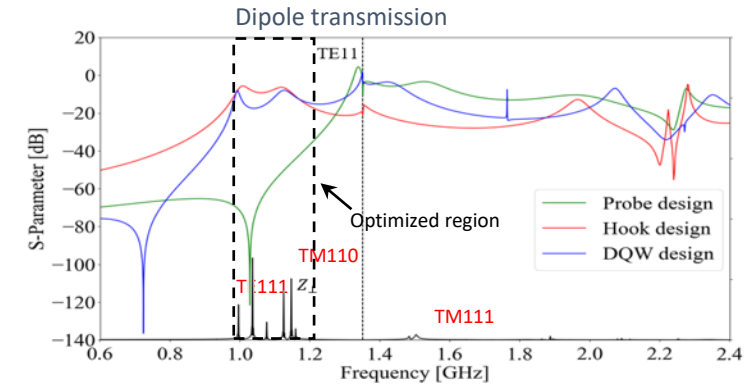
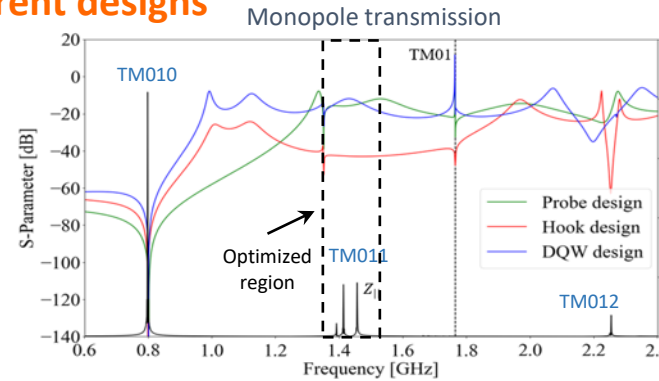
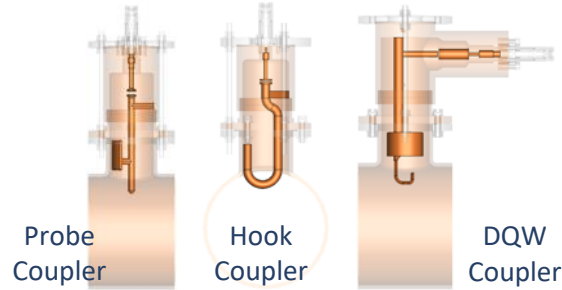


F. Marhauser et al. "802 MHz ERL cavity design and development"- IPAC2018 (Vancouver, BC, Canada)- doi:10.18429/JACoW-IPAC2018-THPAL146



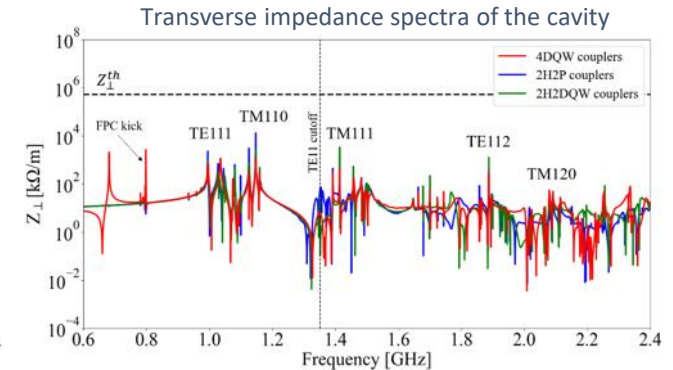
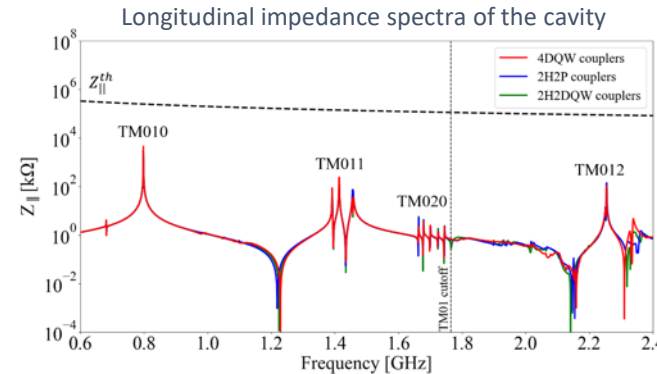
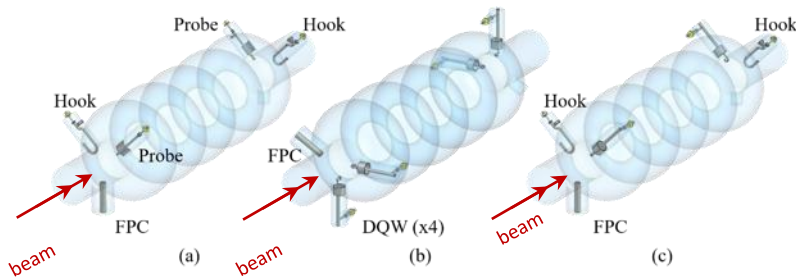
# Status of HOM design studies:

## HOM coupler optimization of 3 different designs



- Couplers were geometrically optimized according to HOM spectrum ( $Z_{||}$  and  $Z_{\perp}$ ) & S-parameters btw port 1 (beam pipe) & port 2 (coupler output) were studied.
- The hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)
- The DQW coupler exhibits a better monopole coupling for TM010 mode than the probe design.

## Study of 2 damping schemes with 4 HOM couplers (Especially for dipole HOM extraction)



→ Promising results of the 4 DQW scheme: It allows damping both monopole and dipole HOMs below the analytically-computed beam-stability limits



# Status of HOM studies :

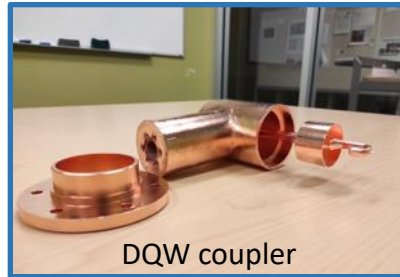
**From RF design to performance measurements:** Example of a fruitful collaborative effort between IJCLab, Jefferson Lab & CERN



Hook coupler



Probe coupler

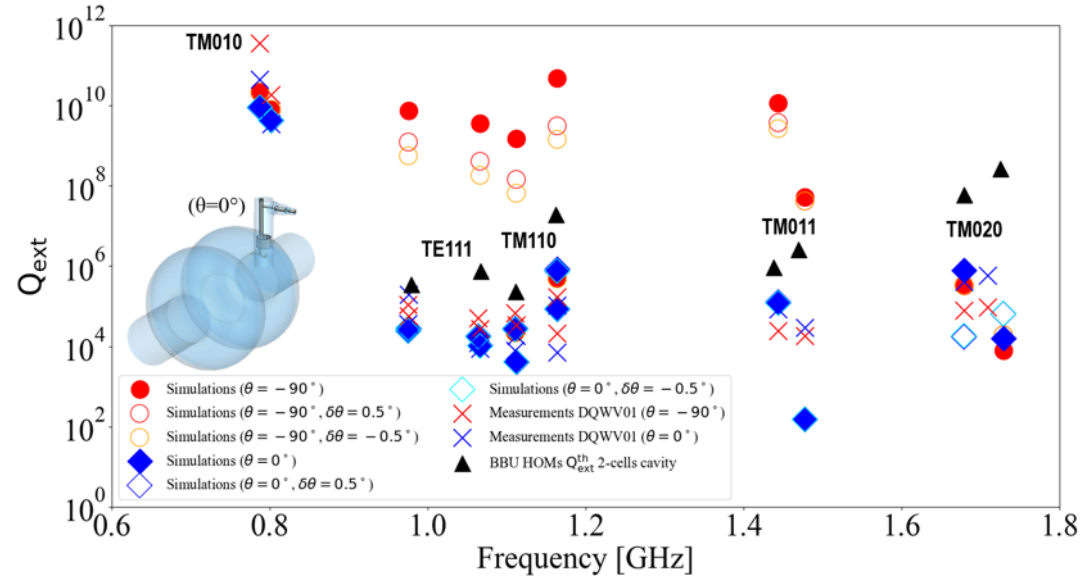


DQW coupler

3D-printed prototype (Epoxy Accura 48) copper-coated @CERN



Installation in a double-cell Cu cavity and test of performances ( $S_{12}$ ,  $\beta_1$ ,  $\beta_2$ ,  $Q_L$  and  $Q_{ext}$ ) @JLab

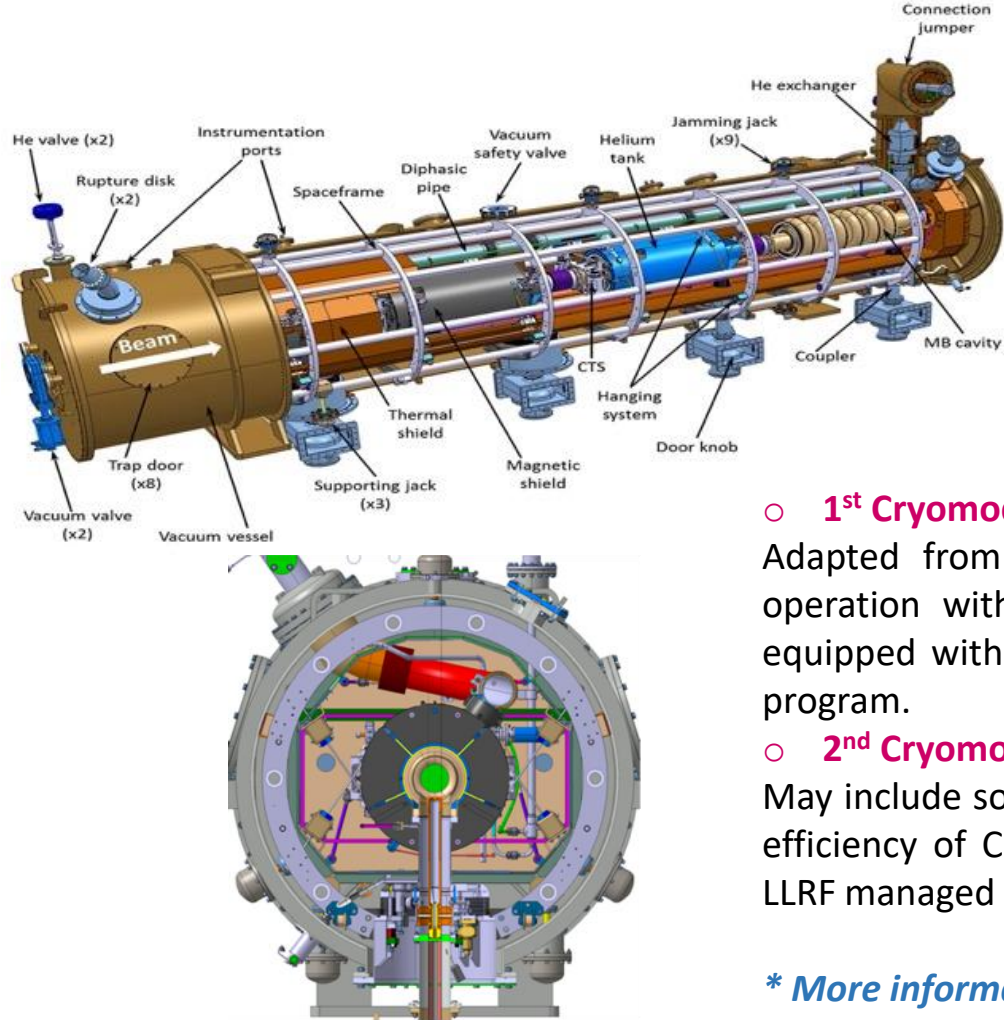


- Measurements are made as a function of rotation angle of HOM coupler hook.
- Good rejection of Fundamental Mode,  $Q_{ext} > 1E+09$ .
- Measured  $Q_{ext}$  for HOMs are below BBU limit thresholds.
- Good agreement between measured and simulated  $Q_{ext} \rightarrow$  could be improved with more appropriate boundary conditions at beam pipe apertures.

*C. Barbagallo et al. "First RF measurements of coaxial HOM coupler prototypes in a copper cavity for the PERLE project"- IPAC'23- MOPA025*



# Cryomodule design:



## ESS Cryomodule design was selected:

- Intermediate supporting structure (spaceframe)
- Cavity string hung by rods
- Insertion of the cavity string by the extremity (rollers)
- Trap doors for tuner access
- Connexion to the valve box on the top of the vacuum vessel
- Important space available inside
- Design validated: series fab. & tests ongoing (Qty 30)

### ○ 1<sup>st</sup> Cryomodule: Foreseen for 2027

Adapted from ESS design, it will be optimised for efficient high current ERL operation within the [European Infra-Tech program iSAS\\*](#). It will host cavities equipped with HOM couplers and FPC optimised and developed within the same program.

### ○ 2<sup>nd</sup> Cryomodule: Foreseen for 2030

May include some/all the technologies studied within [iSAS program](#) to improve the efficiency of Cryomodules: Fast Reactive Tuner (FRT) for microphonics mitigation, LLRF managed by AI and 4.2 K Cavities operating.

\* *More information on iSAS program:* <https://indico.ijclab.in2p3.fr/event/9521/>

## Installation of Daresbury DC gun



**Vacuum pumping of gun new chamber after ultrasonic cleaning (December 2022)**

## New opportunity under discussion

Ongoing discussions with Research Instruments GmbH (RI) to acquire load-lock e- photogun:

→ the DC gun is fabricated and commissioned up to high current operation.

*C. Quitmann et al. «Test of a DC- Photogun injector for The Lighthouse Facility” – Proceedings for IPAC’23- TUPA020*



*Installation of the former Alice DC Photogun (Daresbury) @ IJCLab-Orsay (January 2023)*



## Conclusions

- ERL machines open a **new frontier** for the physics of “**the electromagnetic probe**” (ep, eA, eN). **PERLE is a key ERL project for HEP and Nuclear Physics communities**
- **PERLE** has been recognised (together with bERLinPro) an **essential pillars of the ERL ESPP** strategy. It will be the first ERL that combines **high current** and **multi-passes** (high luminosity/higher energy), designed to operate at **10 MW power regime**.
- **PERLE is a very challenging machine** : Though to be a **hub** to explore a broad range of accelerator phenomena and to validate technical choices **improving accelerators efficiency** in an unexplored operational power regime **on the pathway of the ERL technology development** for future energy and intensity frontier machines.
- **The International collaboration is formed** and still opened to new comers.
- **Important boost in the last year in France** and we are actively entered in the **TDR** and the **P2B phases**. The **installation** of the first brick of the machine (e- DC-gun) is ongoing.



## Acknowledgments

To all the colleagues that provides me with materials and contribute to the efforts presented:  
Racha Abukechek, Hadil Abualrob, Kevin Andre, Robert Apsimon, Carmelo Barbagallo, Maud Baylac, Alex Bogacz, Oliver Bruning, Sylvain Brault, Patricia Duchesne, Alex Fomin, Alexandre Gallas, Coline Guyot, Benjamin Hounsell, Gregory Iaquaniello, Max Klein, Etienne Labussiere, Rodolphe Marie, Julien Michaud, Boris Militsyn, Guillaume Olry, Gilles Olivier, Luc Perrot, Denis Reynet, Robert Rimmer, Raphael Roux, Achille Stocchi, Peter Williams and Haipeng Wang.

# Thank you for your attention!