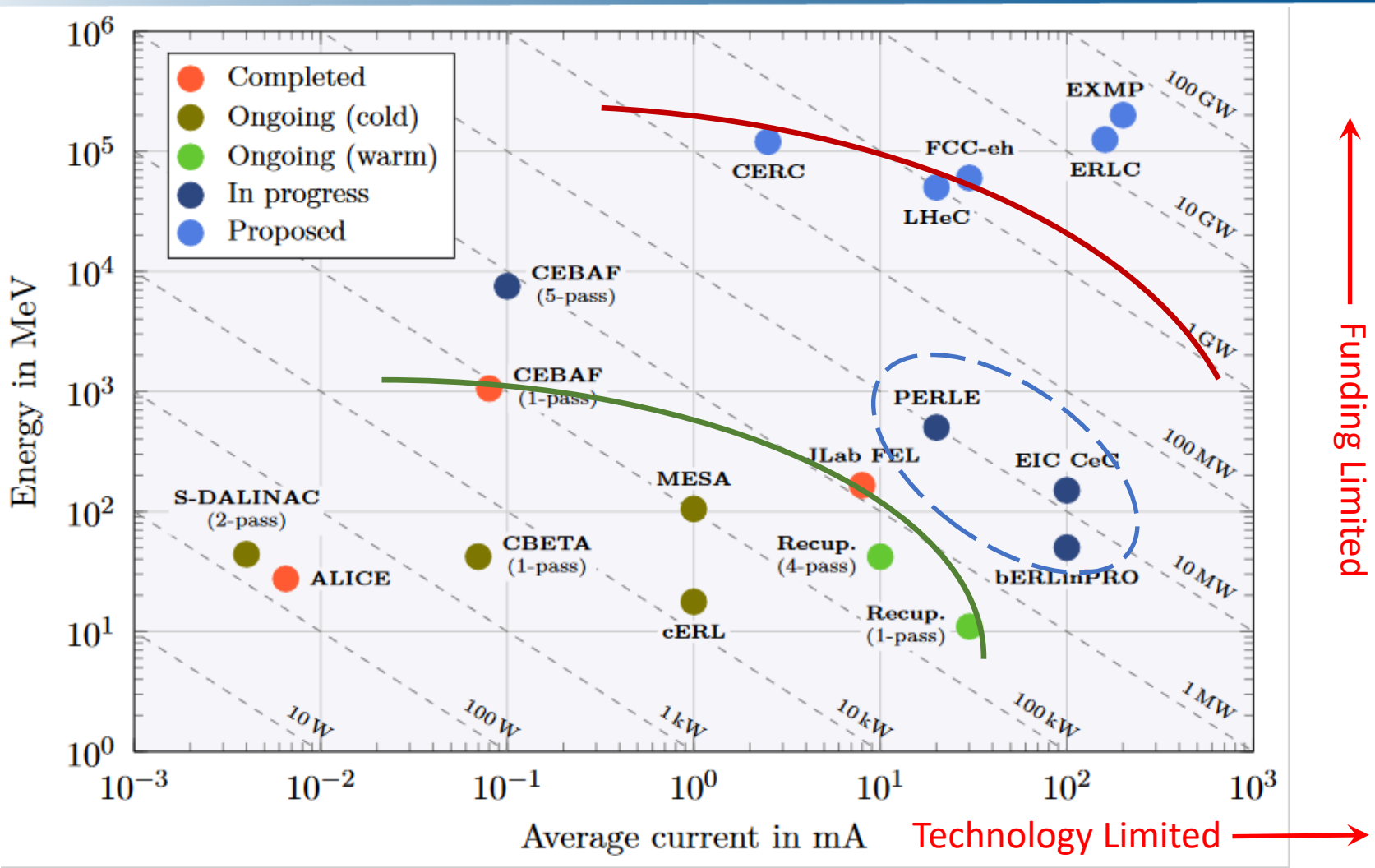
42nd International Conference on High Energy Physics

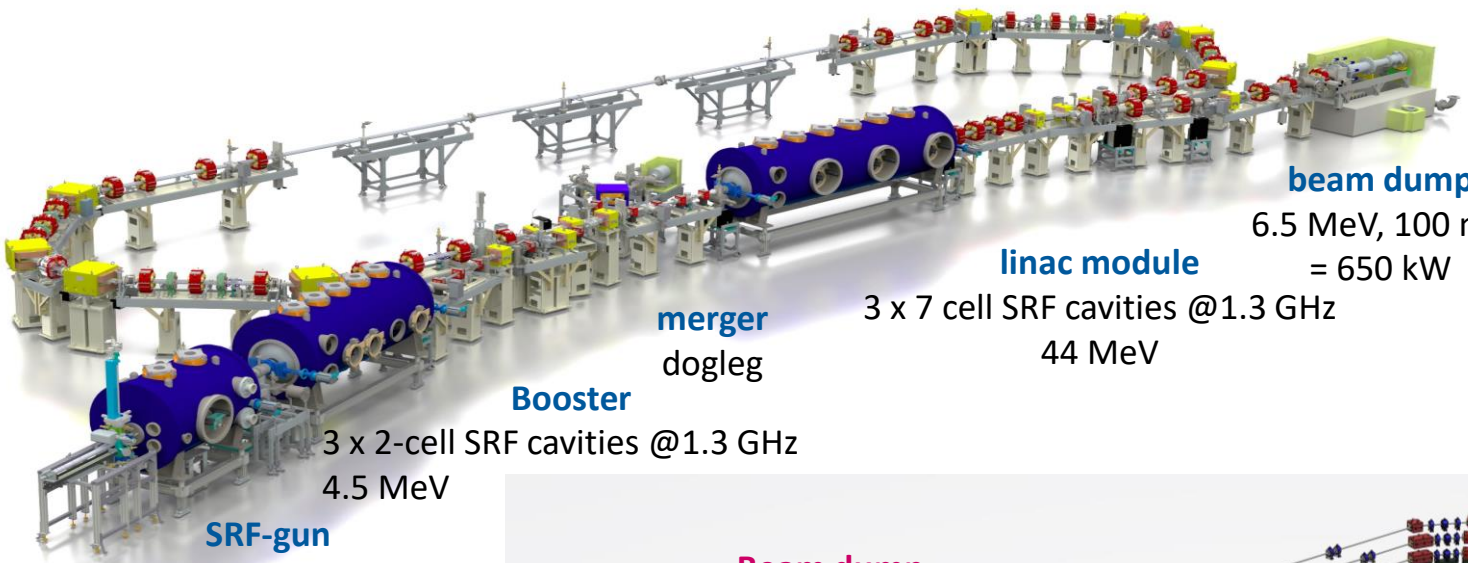
PERLE & bERLinPro: Two key accelerator projects as pathfinders for future ERL based HEP colliders

Walid Kaabi (IJCLab-CNRS)
On behalf of PERLE Collaboration
Axel Neumann (HZB)
For the bERLinPro team @ SEALAB

ERL - The global landscape



bERLinPro and PERLE layout



beam dump
6.5 MeV, 100 mA
= 650 kW

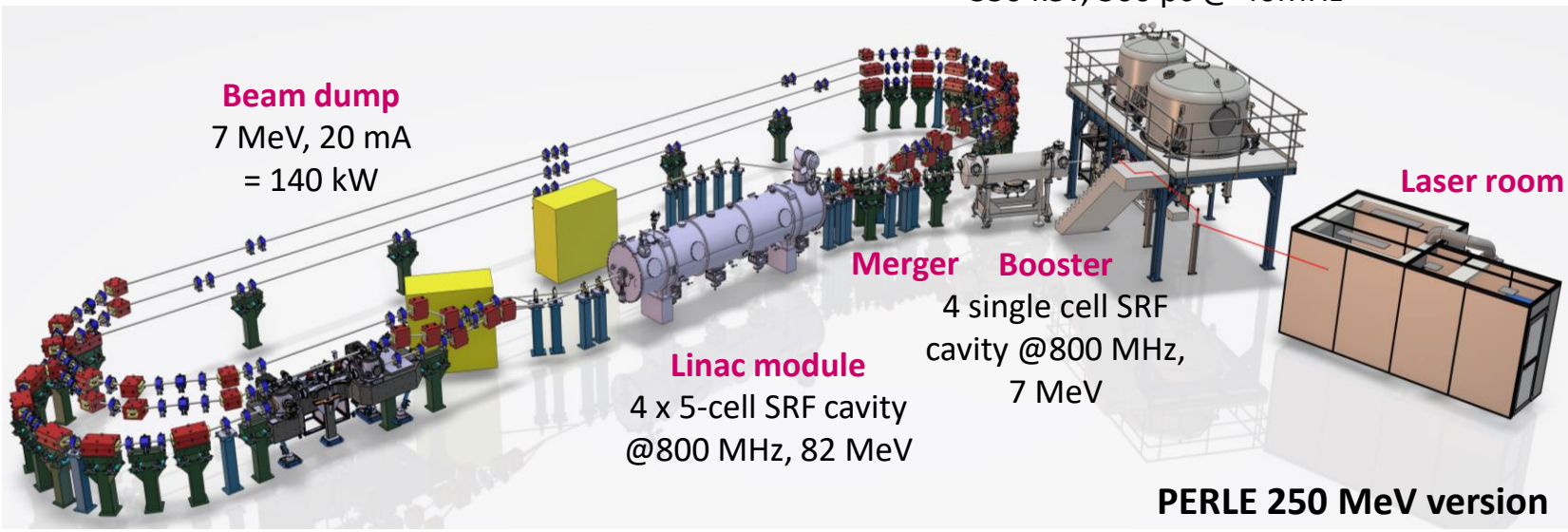
linac module
3 x 7 cell SRF cavities @1.3 GHz
44 MeV

merger
dogleg

Booster
3 x 2-cell SRF cavities @1.3 GHz
4.5 MeV

SRF-gun
1.4 cell SRF cavities
1.5-2.3 MeV, single SC
solenoid,

DC-gun
350 keV, 500 pc @ 40MHz



Beam dump
7 MeV, 20 mA
= 140 kW

Merger **Booster**
4 single cell SRF
cavity @800 MHz,
7 MeV

Laser room

Linac module
4 x 5-cell SRF cavity
@800 MHz, 82 MeV

3 stacked isochronous circulation arcs
for 3 different energy beams

PERLE 250 MeV version

Stages at bERLinPro

Presently installed facility

- Installed: 10-mA SRF gun + merger + recirculation + dump
- Installed: Proof-of-principle UED experiment

} CW photoinjector studies < 10 mA
Long-pulse injector studies < 100 mA

- Funded: Booster module. Produced but assembly required

— High-power beam studies (“long pulse”)

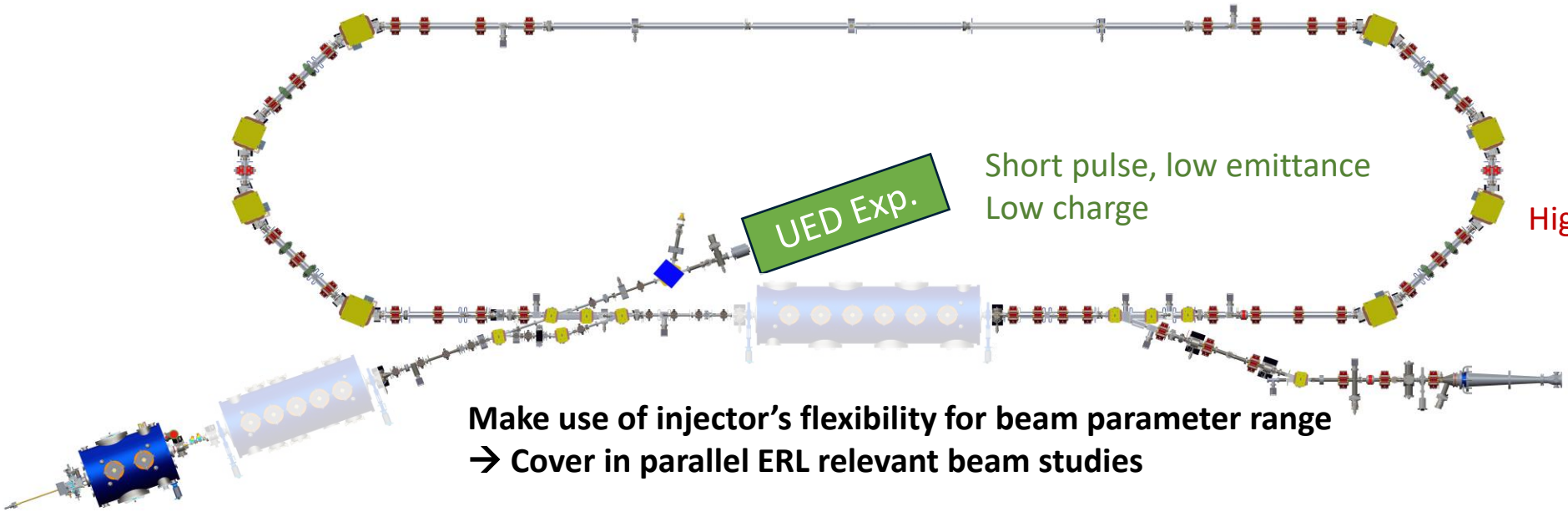
- Not funded: LINAC module
- Not funded: 100-mA class photoinjector

} High-power energy recovery
Energy-efficient RF operation

Stages at bERLinPro

Presently installed facility

Applications



Make use of injector's flexibility for beam parameter range
→ Cover in parallel ERL relevant beam studies

- Installed: 10-mA SRF gun + merger + recirculation + dump
- Installed: Proof-of-principle UED experiment
- Planned: Waste water treatment demonstrator
- Funded: Booster module. Produced but assembly required
- Not funded: LINAC module
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CW photoinjector studies < 10 mA
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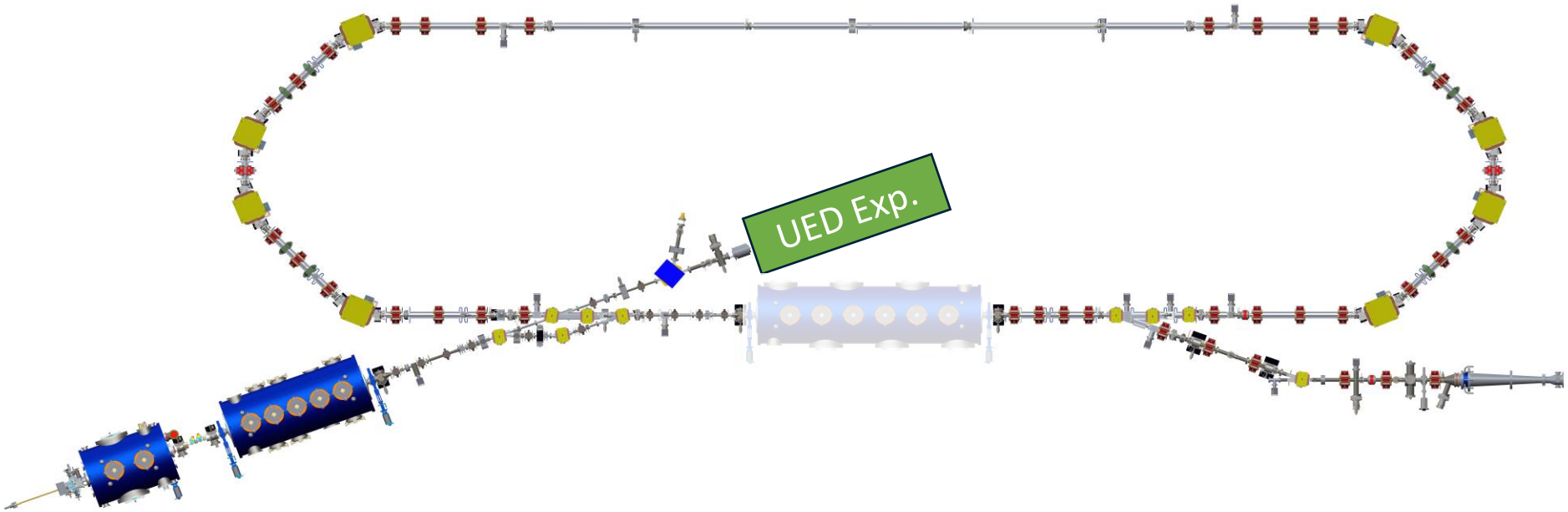

Waste Water

- Installed: 10-mA SRF gun + merger + recirculation + dump
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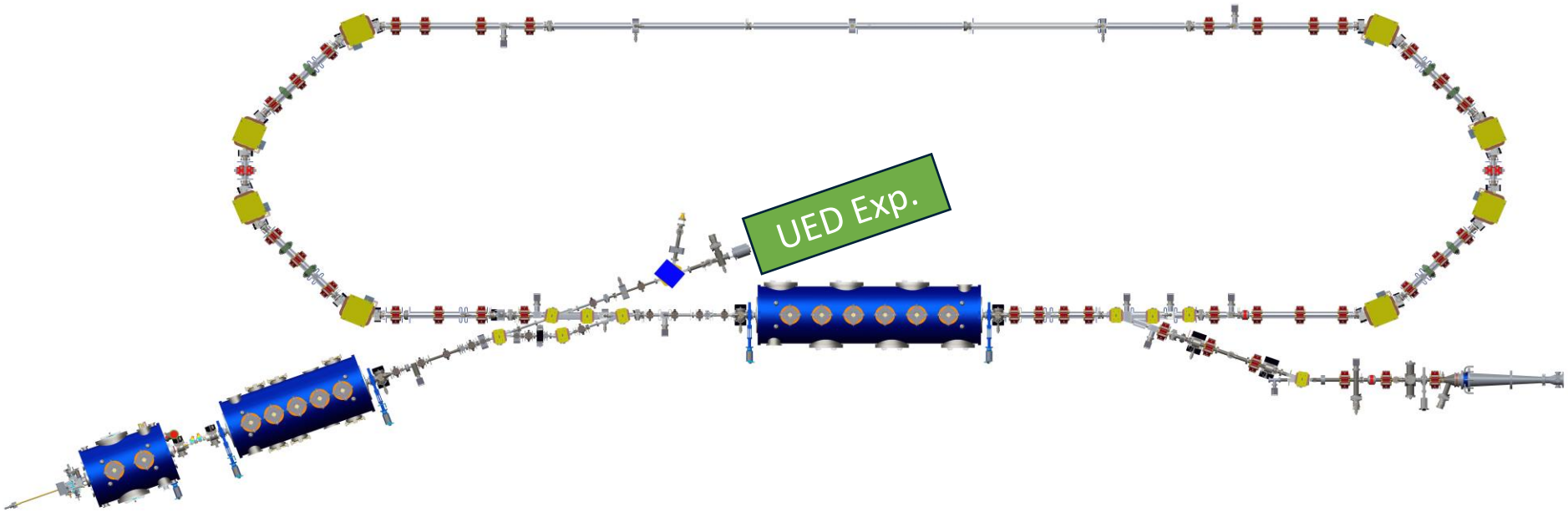

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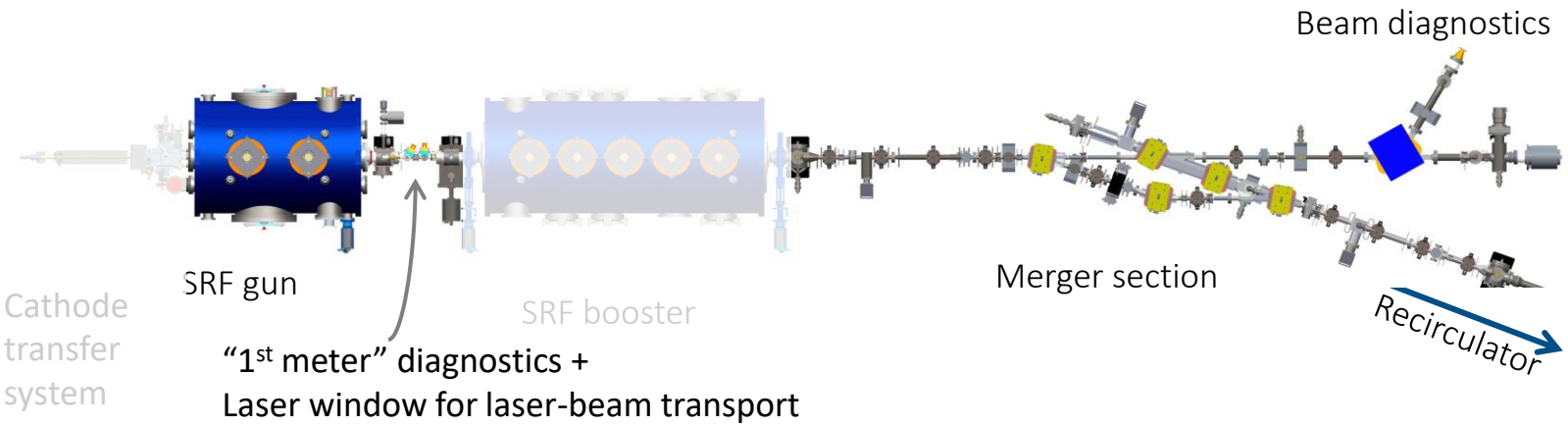
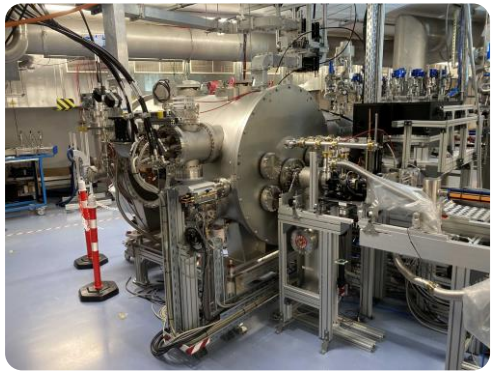
High-power energy recovery
Energy-efficient RF operation

Status of bERLinPro

Injector installation at present





- SRF photo-injector and diagnostics ready for commissioning
- Final preparation of cathode-laser beam transport
- 1.3 GHz laser demonstrated 23 W CW sufficient for 100 mA @ 2.5% QE
- **Cool-down in Jan. 2023** prerequisite for rad. permit application for RF operation
- **RF test of photoinjector Q2 2024** prerequisite for rad. permit application for beam operation
- Cathode-transfer unit ready for installation following RF test
- **Beam operating permit expected Q3 2024 ⍰ First beam from SRF Gun around 10-11/2024**
- Start of Booster assembly H1/2024 (all parts in house)

Status of bERLinPro

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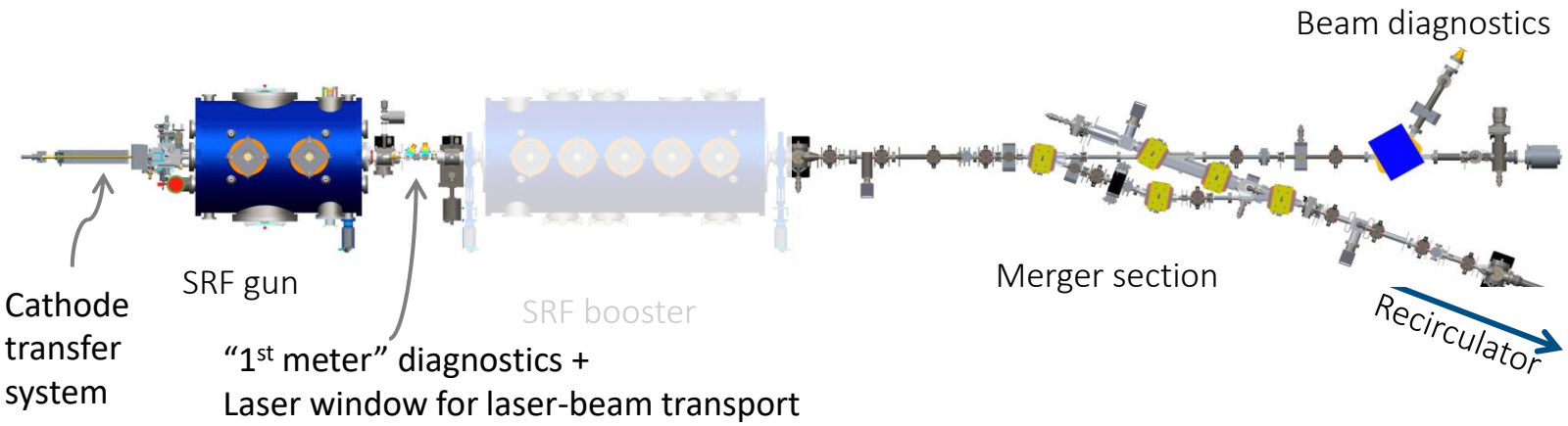

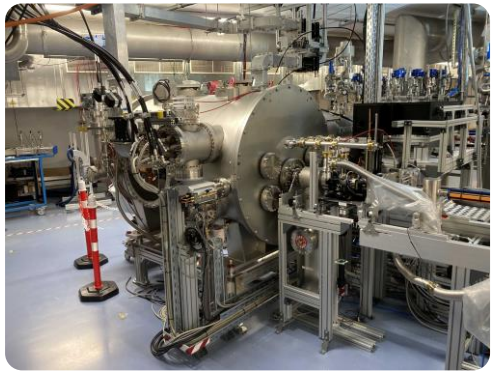

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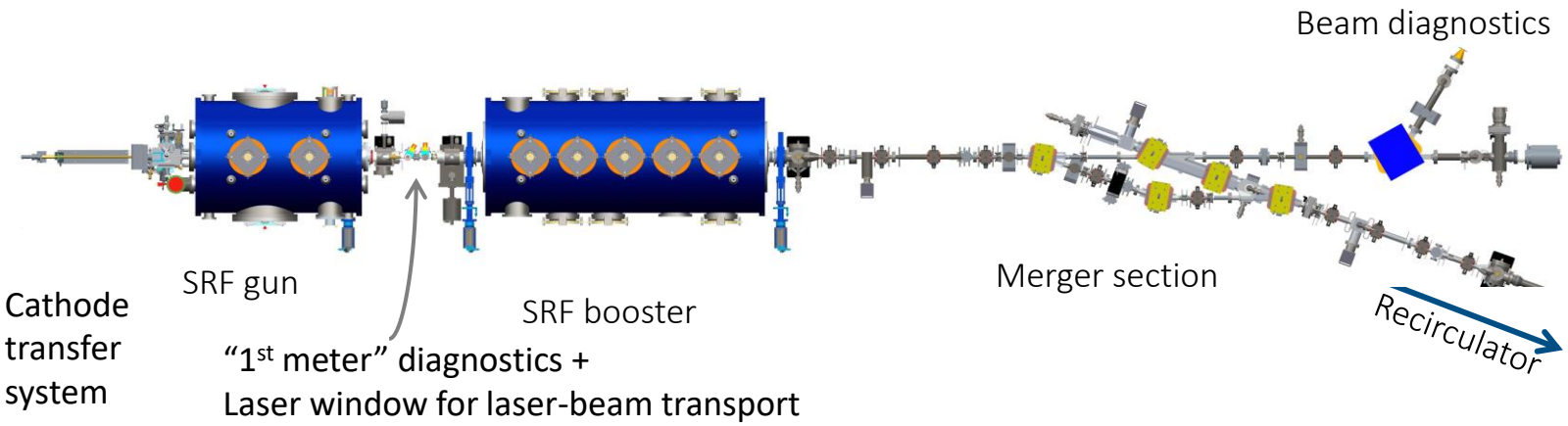

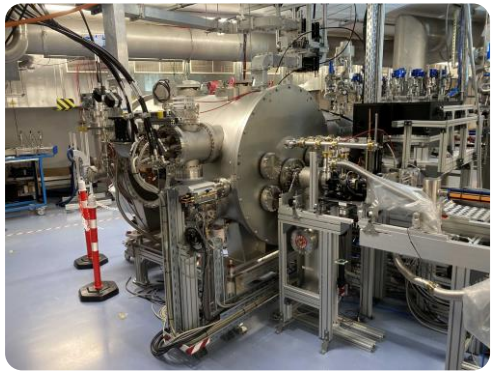

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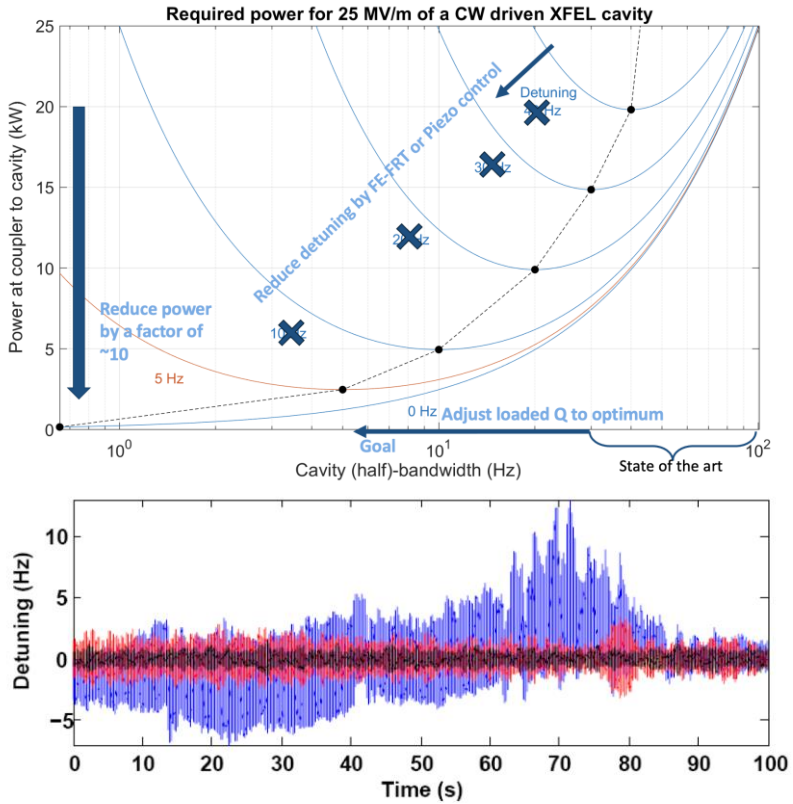
Further R&D to improve accelerator efficiency

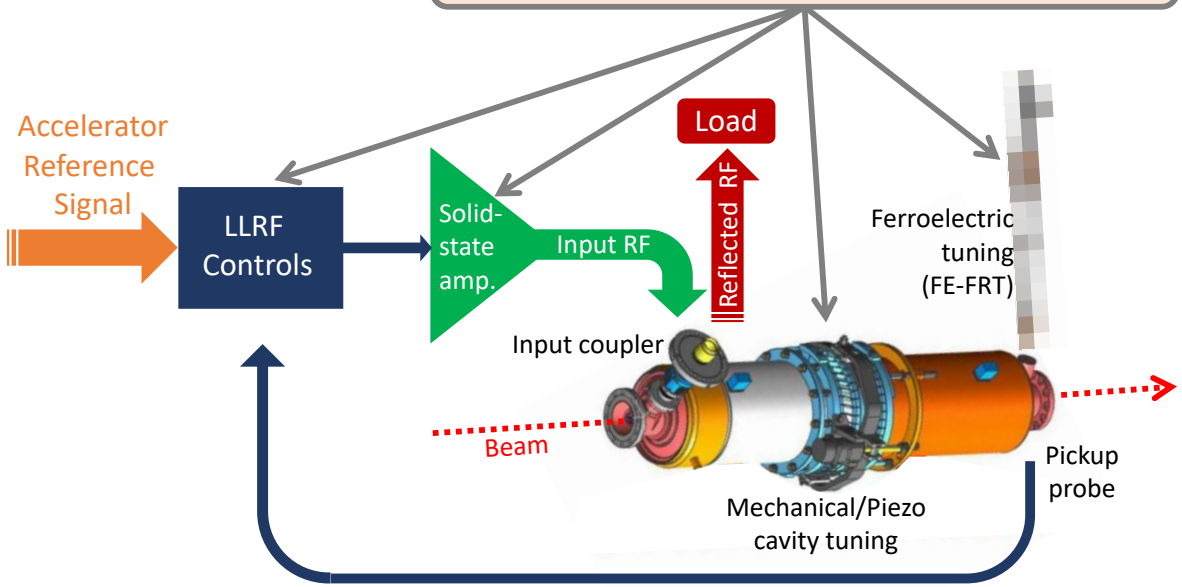


From A. Neumann et al.,
Phys. Rev. ST Accel. Beams **13**, 082001 (2010)

Compensation of disturbances in the acoustic frequency regime

Integrated iSAS approach to save grid power for RF

- Digital AI/ML-assisted field and detuning control
- Reduced detuning by piezo and new FE-FRT tuners
- Smart amplifier control

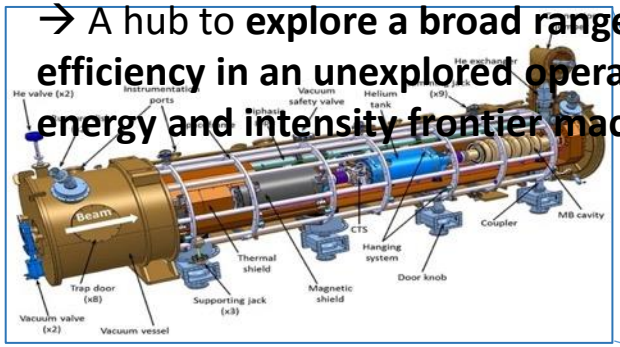


This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101131435

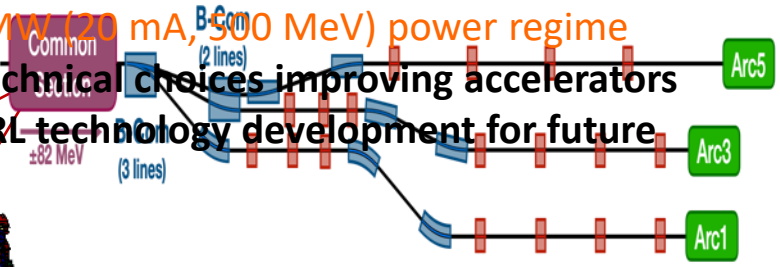
PERLE @ IJCLab-Orsay

PERLE: first multi-turn ERL, based on SRF technology, designed to operate at 10MW (20 mA, 500 MeV) power regime

→ 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**.



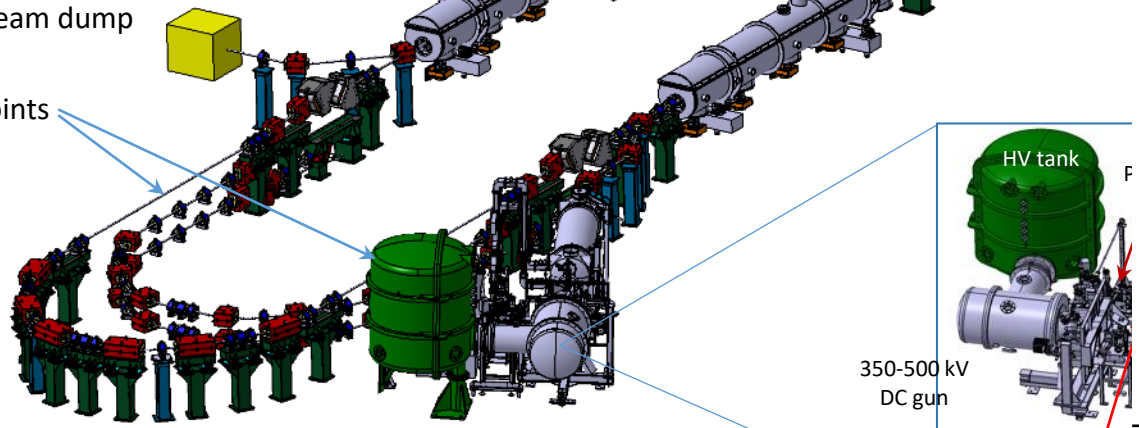
- Cryomodule with **5** five-cell cavities
- Total gradient 82 MeV
- 3 acc & 3 decc beams at different energies travelling in the CM.



Switchyard: vertical separation/recombination of beams at different energies

Beam dump

Interaction Points



Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	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

3 st[illegible]) isochronous recirculation arc[illegible]fere[illegible]es (Arcs 2, 4, 6)

Booster: 5 single-cell cavities [illegible] 802MHz individually powered

bunches at 7 MeV.

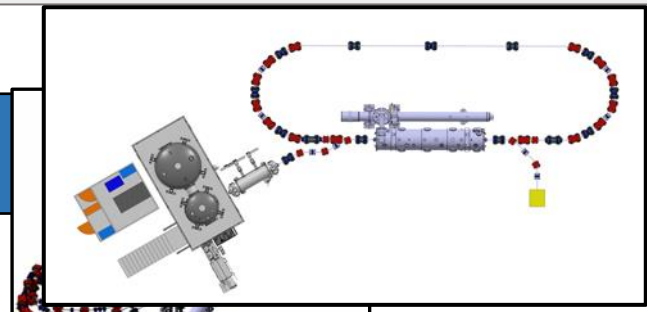
PERLE Timeline (macroscopic view)

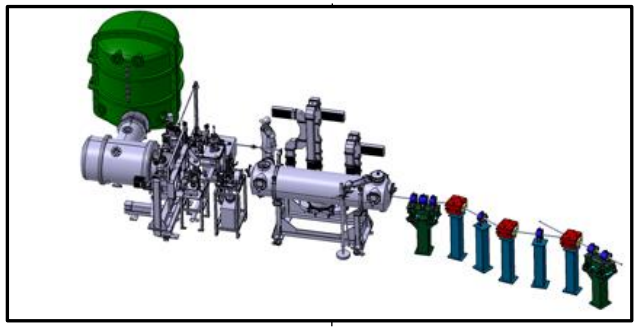
Prepare to Build phase (P2B): TDR and prototyping

Single turn ERL phase
→ Phase 1 to be extended to 2028

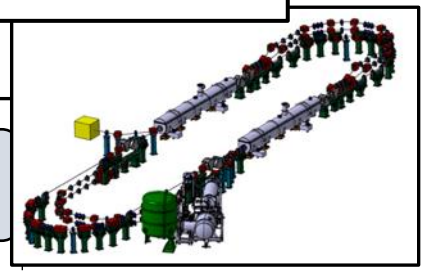
Installation phases

Phase 1: Injection line Installation





Phase 2: PERLE 250 MeV version



Phase 3: PERLE 500 MeV version

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031

Recent paper of PERLE collaboration (centered on beam dynamics)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 031603 (2024)

Editors' Suggestion

Beam dynamics driven design of powerful energy recovery linac for experiments

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STFC Daresbury Laboratory, Sci-Tech Daresbury, Warrington, United Kingdom

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Lancaster University, Bailrigg, Lancaster, United Kingdom

R. Abukeshek, C. Barbagallo,‖ M. Ben Abdillah, C. Bruni, P. Duchesne, P. Duthil, A. Fomin, C. Guyot, W. Kaabi, J. Michaud, G. Olry, L. Perrot, D. Reynet, R. Roux, A. Stocchi, and S. Wurth
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M. Baylac and F. Bouly
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B. Jacquot
Grand Accélérateur Nat. d'Ions Lourds (GANIL), Grenoble, Caen, France

(Received 4 December 2023; accepted 5 March 2024; published 26 March 2024)

Powerful ERL for experiments (PERLE) is a novel energy recovery linac (ERL) test facility [1], designed to validate choices for a 50 GeV ERL foreseen in the design of the Large Hadron Electron Collider and the Future Circular Collider and to host dedicated nuclear and particle physics experiments. Its main goal is to demonstrate the high current, continuous wave, multipass operation with superconducting cavities at 802 MHz. With very high beam power (10 MW), PERLE offers an opportunity for controllable study of every beam dynamic effect of interest in the next generation of ERLs and becomes a "stepping stone" between the present state-of-the-art 1 MW ERLs and the future 100 MW scale applications.

DOI: 10.1103/PhysRevAccelBeams.27.031603

The first paper on Beam Dynamics and PERLE Design has been published in Physical Review Accelerators and Beams (PRAB) and was also selected as a « PRAB Editors Suggestion » on the journal homepage alongside other highlighted articles: https://journals.aps.org/prab

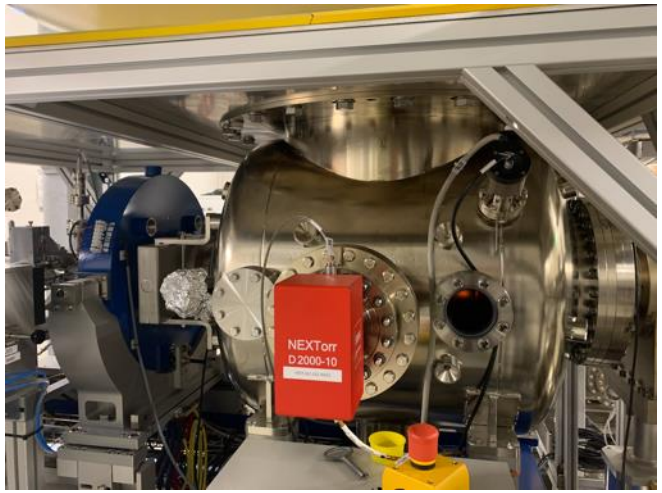
The following studies was reported in this paper for the 500 MeV version of PERLE:

- Lattice architecture and optics
- Staging construction
- Injector and merger, space charge study
- Longitudinal matching
- Filling pattern and bunch timing options
- Start to end simulations with CSR and Wakefield
- BBU study

PERLE e- Source

Collaboration IJCLab-LPSC & RI GmbH

Within a Collaboration Agreement for photoinjector R&D between IJCLab (IN2P3) and Research Instruments GmbH (RI), Hardware of lighthouse project (terminated) transferred to IJCLab for PERLE. The gun was commissioned and tested at high rep rate, at a limited bunch charge. It includes:



A DC Gun, Cornell design (400 pC, 50 MHz demonstrated), fully equipped (all pumps) in load-lock version

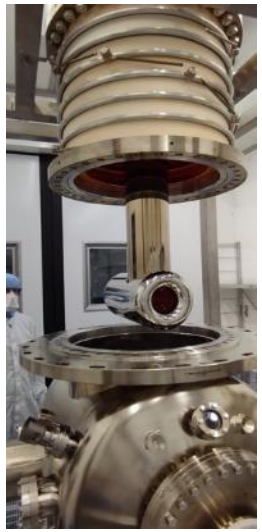
HV power supply suited for high bunch charge (designed for 40 mA, 450 kV)

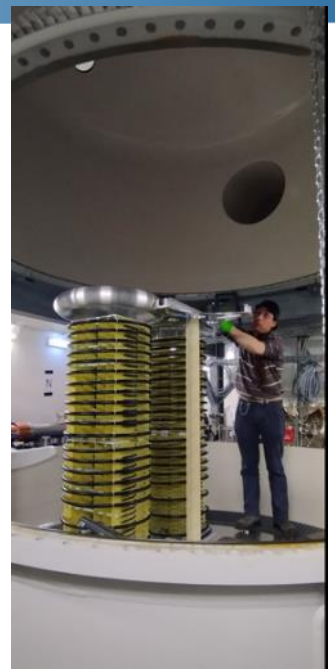
A Photocathode Preparation Facility (PPF)

PERLE e- Source

Dismantling of the PPF (September 2023)

Gun status : dismantling of the gun in clean room (January 2024)

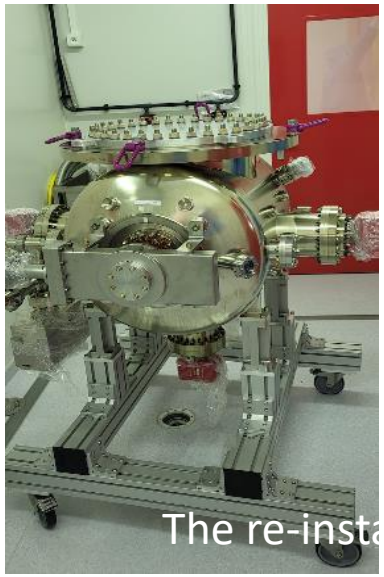




Dismantling of the HV Columns tanks
Dismantling of the platform done by Baumann (November 2023)

PERLE e- Source

The equipment were received at Orsay end of January



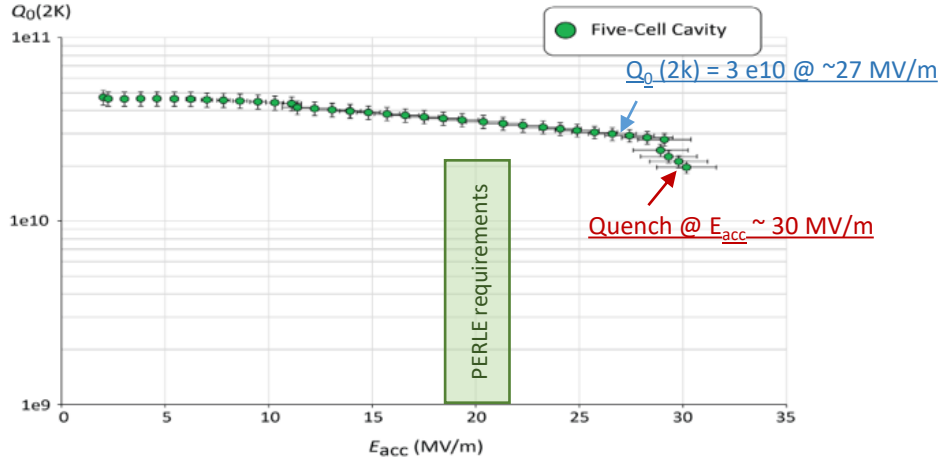
The re-installation at IJCLab is well advanced

PERLE SRF cavity : reminder

Collaboration IJCLab-CERN and JLab

PERLE Requirements	Impacts	Challenges	Possible Solutions
CW operation (RF)	High dynamic losses	The highest cavity Q_0	Cavity post-treatment (Doping, infusion…)
High current operation	High HOMs excitation	Efficient HOMs extraction & damping	Act on cavity design: low frequency cavity choice (< 1GHz), larger cavity aperture, fewer cells for the a given gradient, optimisation of end-cell design.
Muti-bunches operation	Increase beam instabilities	The highest BBU threshold	Regular spacing of bunches: optimisation of the bunch filling pattern during Lattice design + BBU study after HOM optimisation (including collective effects).

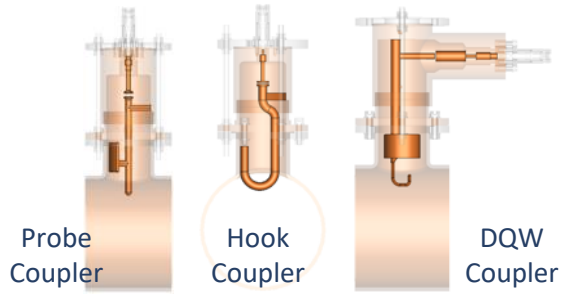

First Nb 802 MHz 5-Cell cavity fabricated @ JLAB

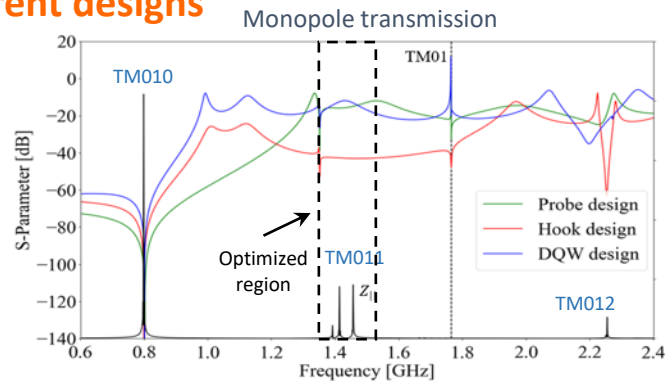


F. Marhauser et al. "802 MHz ERL cavity design and development"- IPAC2018 (Vancouver, BC, Canada)- doi:10.18429/JACoW-IPAC2018-THPAL146

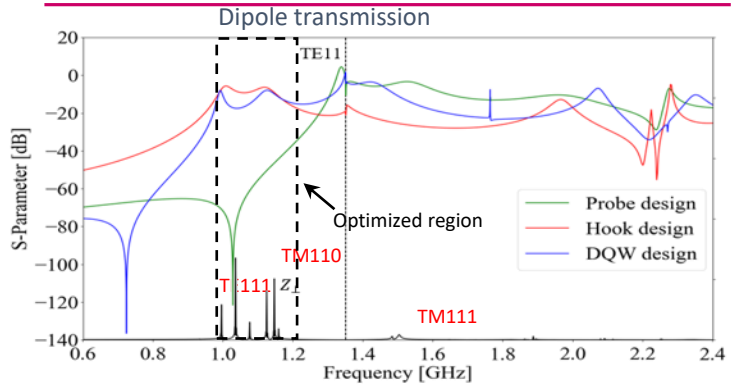
Status of HOM studies : news

HOM coupler optimization of 3 different designs



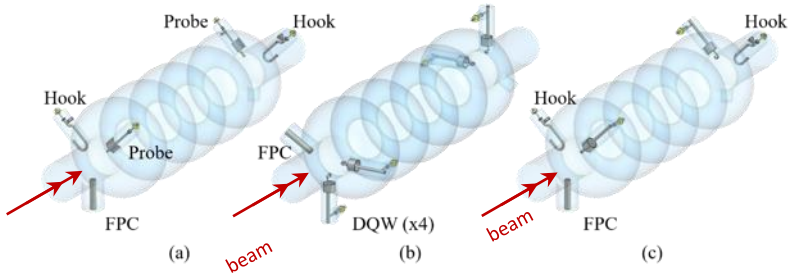


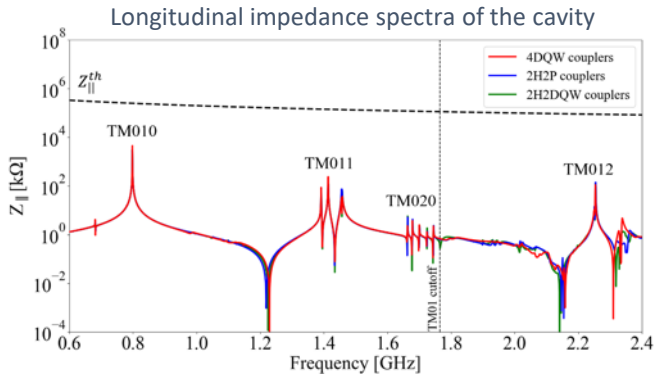
Collaboration IJCLab-Jlab and CERN

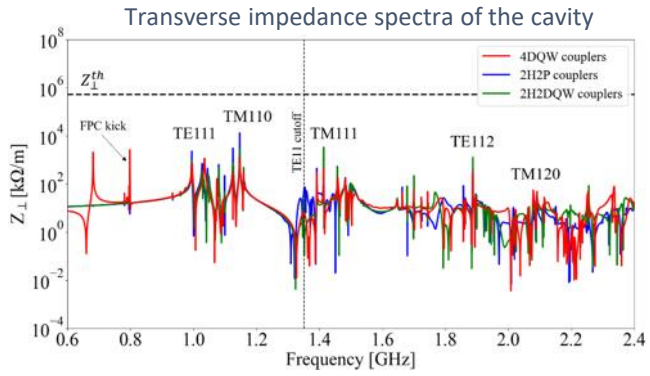


- Couplers were geometrically optimized according to HOM spectrum ($Z_{||}$ and $Z_{\perp}$) & S-parameters btw port 1 (beam pipe) & port 2 (coupler output) were studied.
- The hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)
- The DQW coupler exhibits a better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

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



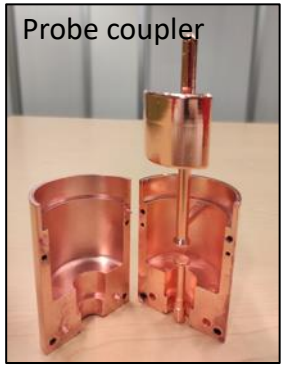


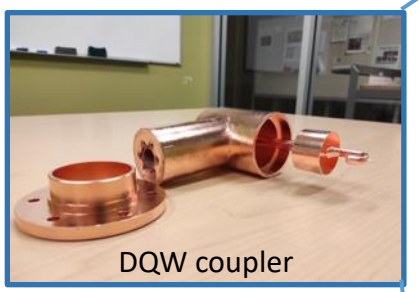


→ Promising results of the 4 DQW scheme: It allows damping both monopole and dipole HOMs below the analytically-computed beam-stability limits

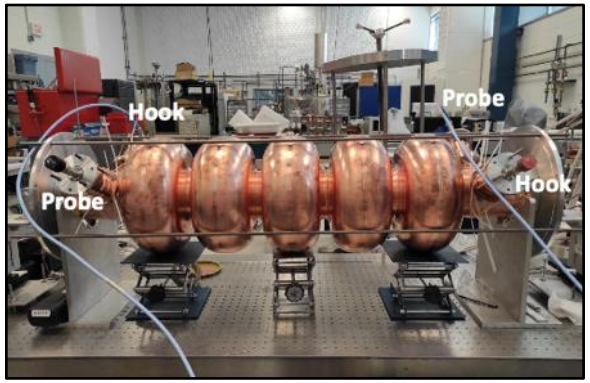
Status of HOM studies : news more details

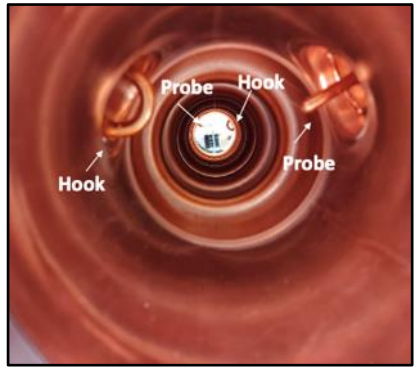
From RF design to performance measurements: **Successful collaborative effort between IJCLab, Jefferson Lab & CERN**

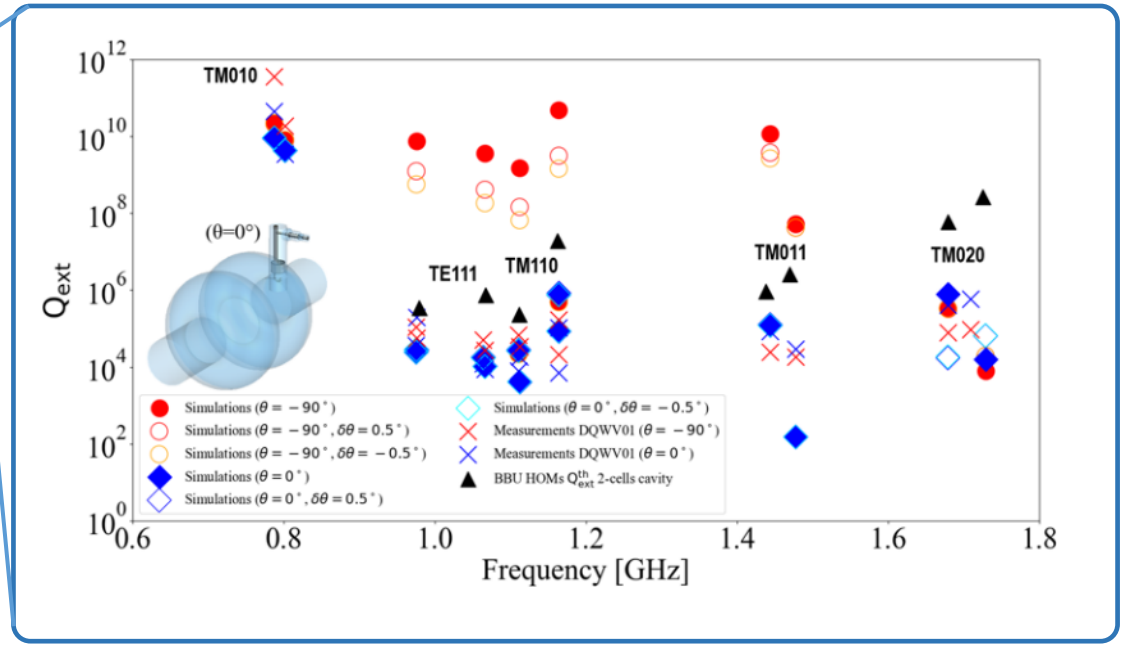




3D-printed prototype (Epoxy Accura 48) copper-coated @CERN







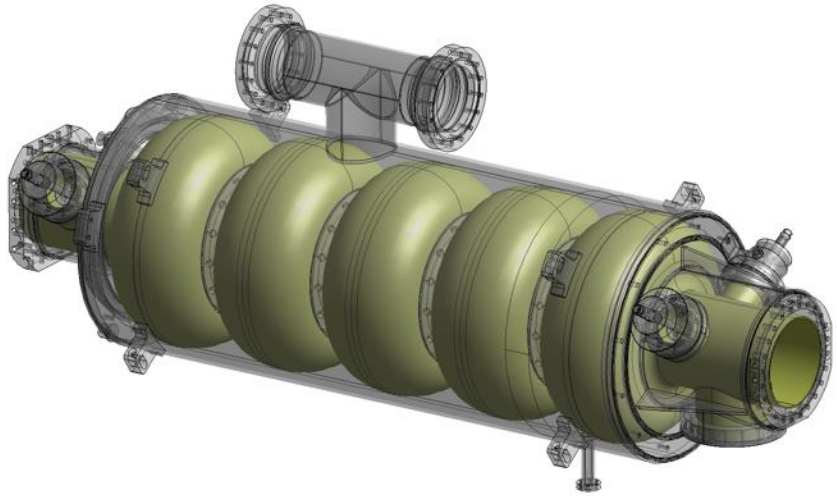
Ultimately, we aim to produce Nb HOM couplers with optimised design and to install them on a new Nb 5-cell PERLE cavity with optimised end groups. **The Production of 4 cavity scheduled within the ISAS program (Starting from 2024).**

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

SRF cavity : latest news

Current work:

- Specifications of the 5-Cell 800 MHz cavity is under finalisation.
- A review meeting on the cavity post-production processes recipes (EP, BCP, Mid-T baking…) was organised end of March with international experts.



Within iSAS program:

- The Nb procurement procedure will be lunched end of July (for single and multi-cell cavities).
- It is foreseen to lunch the procurement procedure of four 5-cell cavities in fall 2024.

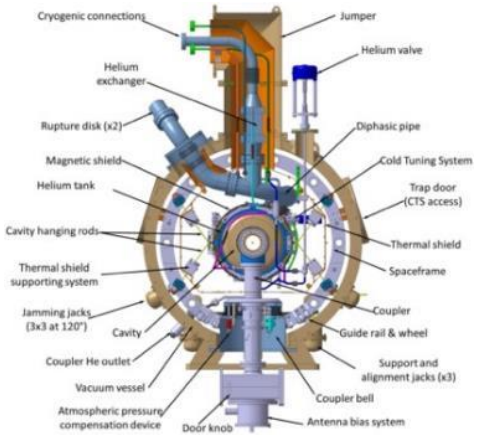
IJCLab, JLab, CERN and including now LASA-Milano

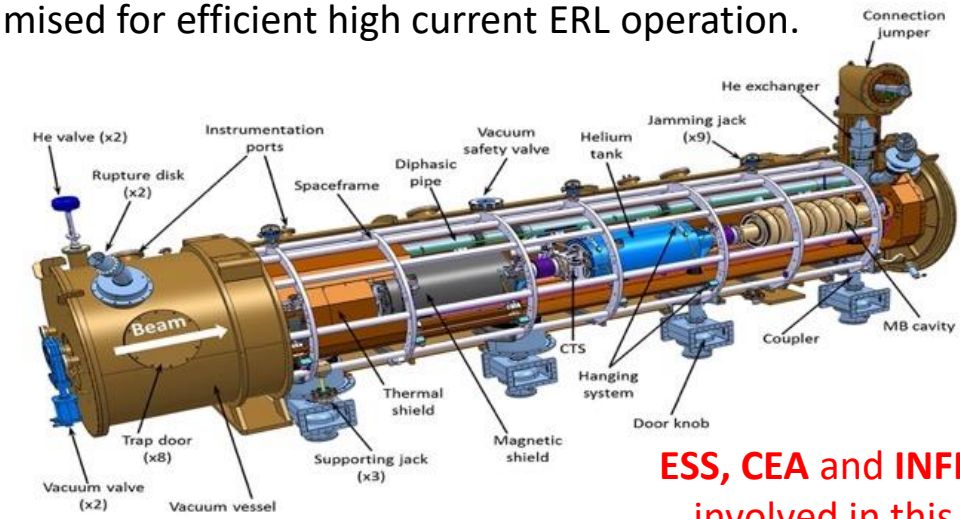
Cryomodule design

April 15-16, 2024: Kick-off of the European project ISAS (Innovate for Sustainable Accelerating Systems)
https://indico.ijclab.in2p3.fr/event/9521/

WP6: Integration of RF systems (SRF Cavities, HOM couplers & absorbers, Fundamental Power Couplers) optimized and developed within ISAS project into the 1st Cryomodule for PERLE- Foreseen for 2027

The cryomodule adapted from ESS design, will be optimised for efficient high current ERL operation.





ESS, CEA and **INFN-LASA** involved in this work

- **The 2nd Cryomodule of PERLE: Foreseen after 2030**

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

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101131435

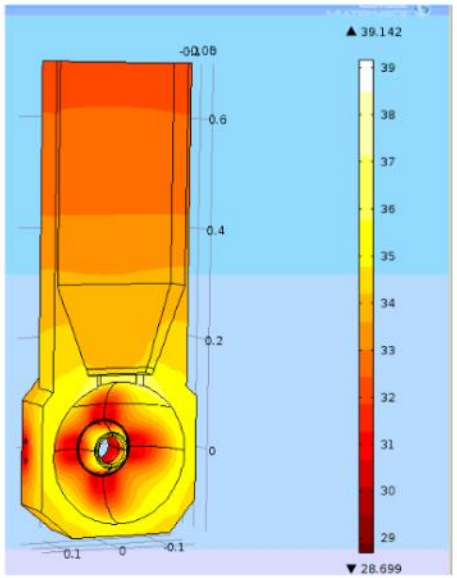
Thank you for your attention!

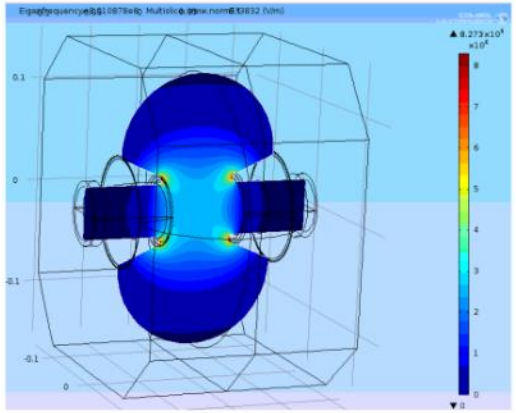
Buncher cavity design

- PERLE buncher cERL-type design
  - cERL-type buncher heating and cooling

Collaboration IJCLab-ESS Bilbao

(some summary highlights...)





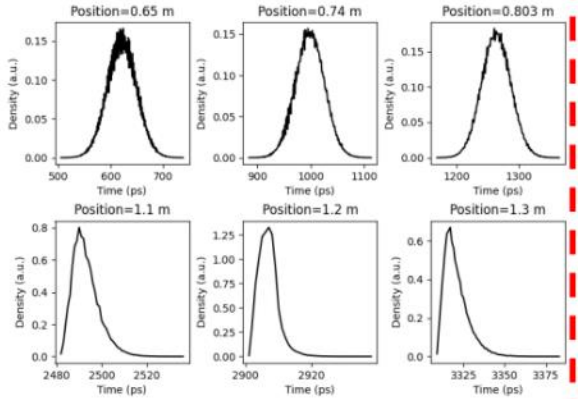
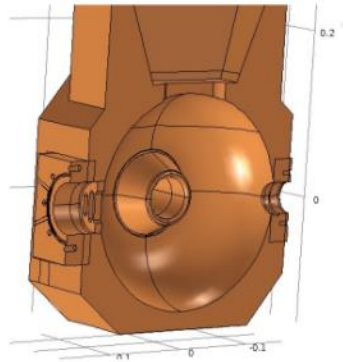


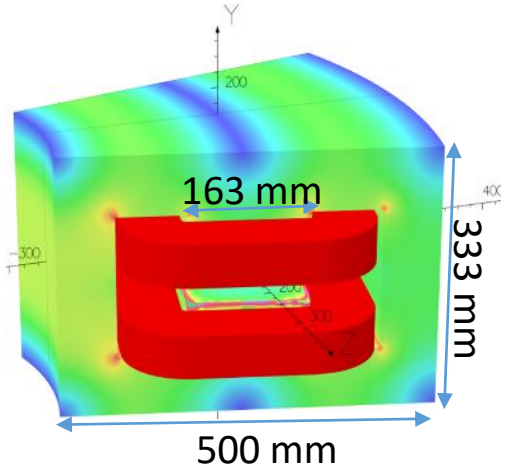
Figure of merit	PERLE buncher cERL-like optimized	Figure of merit	PERLE buncher cERL-like optimized
Input power	5 kW	Iris a	0.070 m
V0	0.21 MV	Iris b	0.020 m
TTF	0.84	Wave guide	WR-975 (274.65 mm, 123.80 mm). Taper=0.5
Gradient (V_0T/L_{cav})	1.392 MV/m	S11dB	-35.81 dB
Power loss	4972 W	ZTT	49.7 MΩ/m
RsTT = (V0T)² / Ploss	6.26 MΩ	Esurf_max	8.21 MV/m



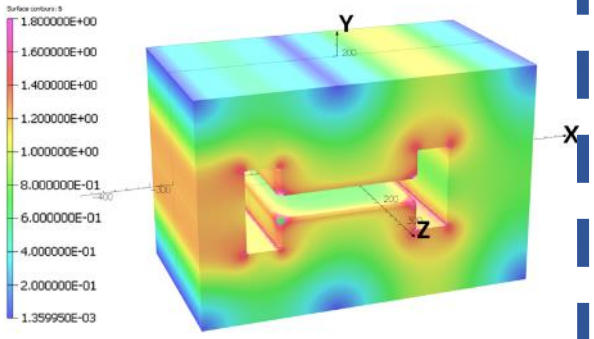
Important progress in the RF design, thermal and beam dynamics simulations of a buncher cavity for PERLE by colleagues from ESS-Bilbao.

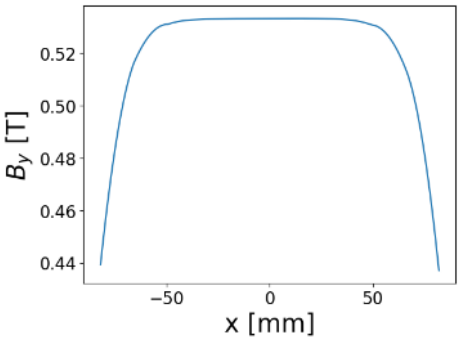
Magnet Design

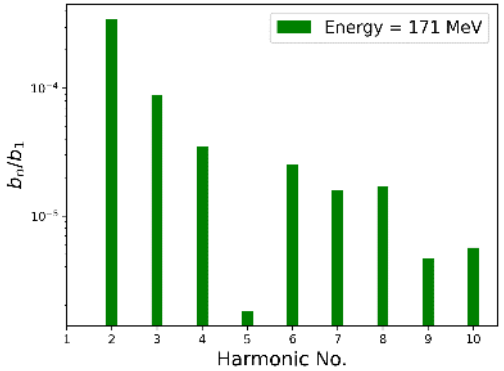
S-bend in Arcs



B-com in Spreader

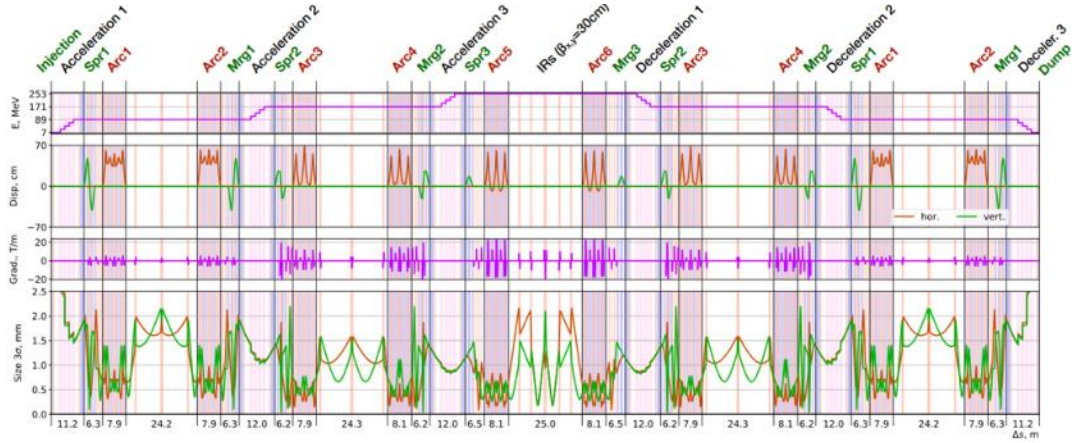




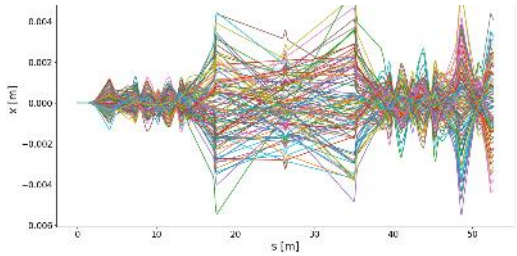


IJCLab, LPSC, Jlab, An-Najah

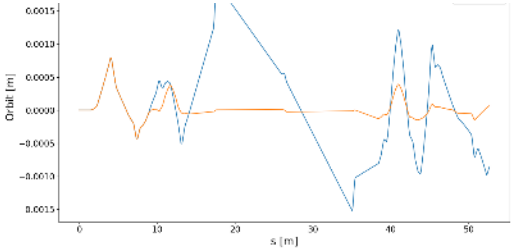
Misalignments and Corrections



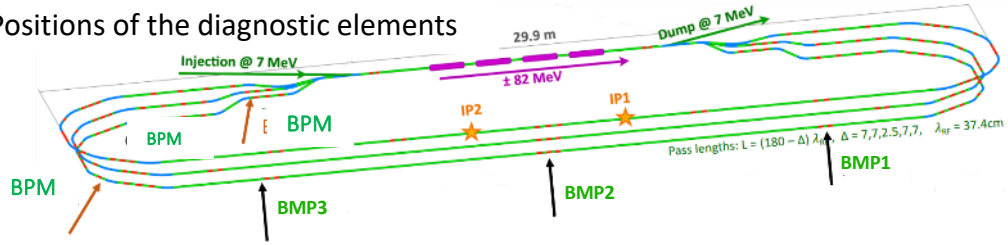
Effect of quads misalignments on x-orbit



Before/after correction (with kickers)



Positions of the diagnostic elements



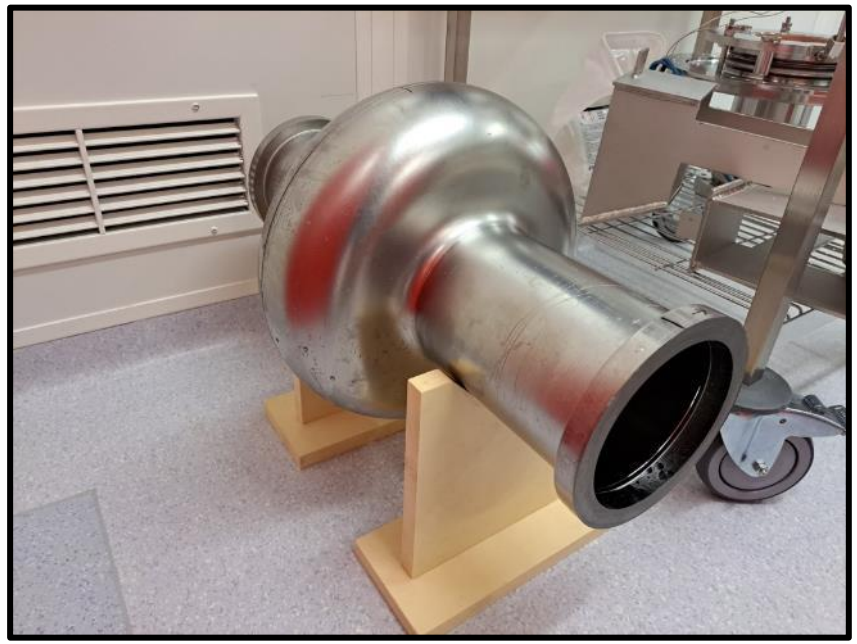
SRF cavity : latest news

Discussions/work with **Jlab & CERN** to pursue the R&D on 802 MHz cavities (Synergy with FCCee):

→ Optimisation surface treatment recipe (Mid-T baking, EP/PCB) and cold tests.

→ **A CERN single-cell cavity fabricated by Jlab was received at IJLab end of May.**

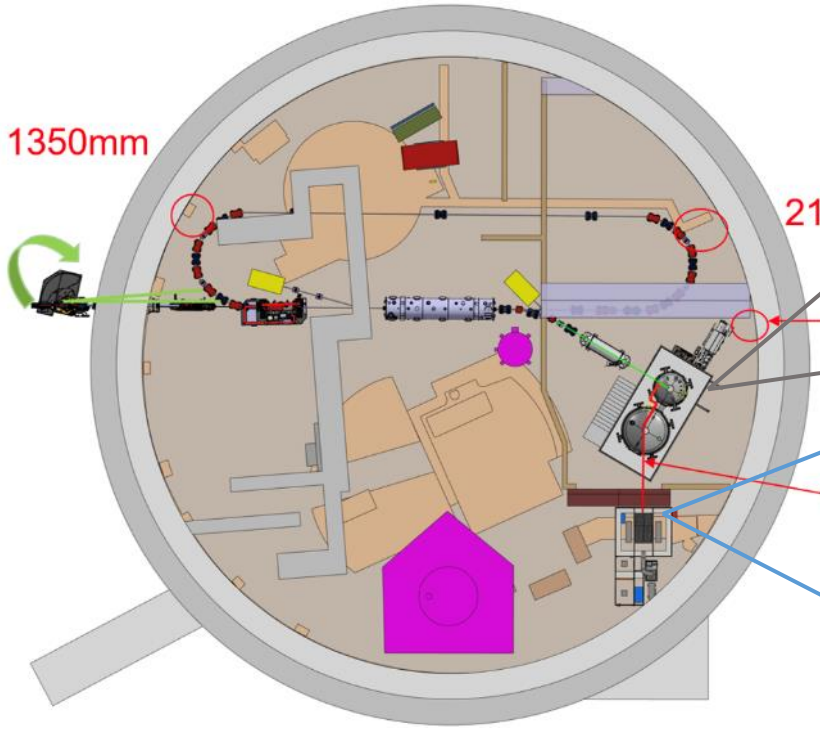
→ A common single-cell shape will be adopted for FCCee R&D and PERLE booster.

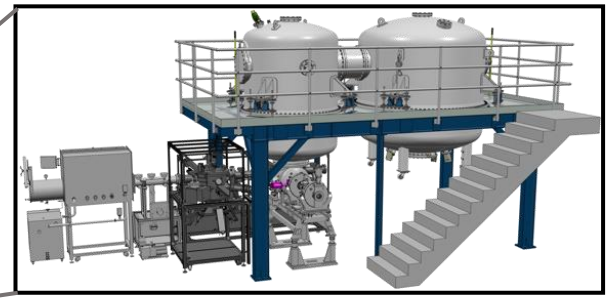


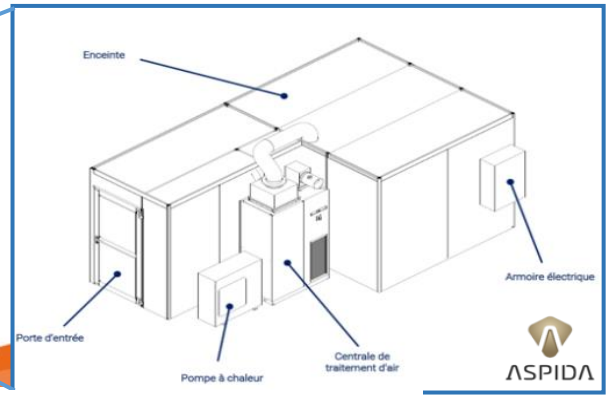
Site implementation

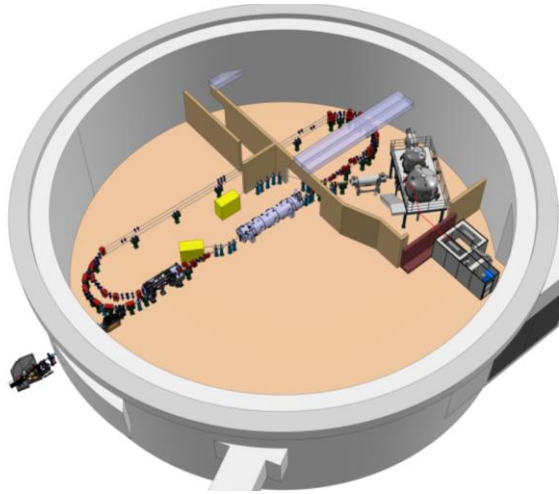
After site studies of the the two possible locations to host PERLE (Super ACO hall and Igloo):

The IGLOO was the preferred solution. Progress on Infrastructure and safety issues





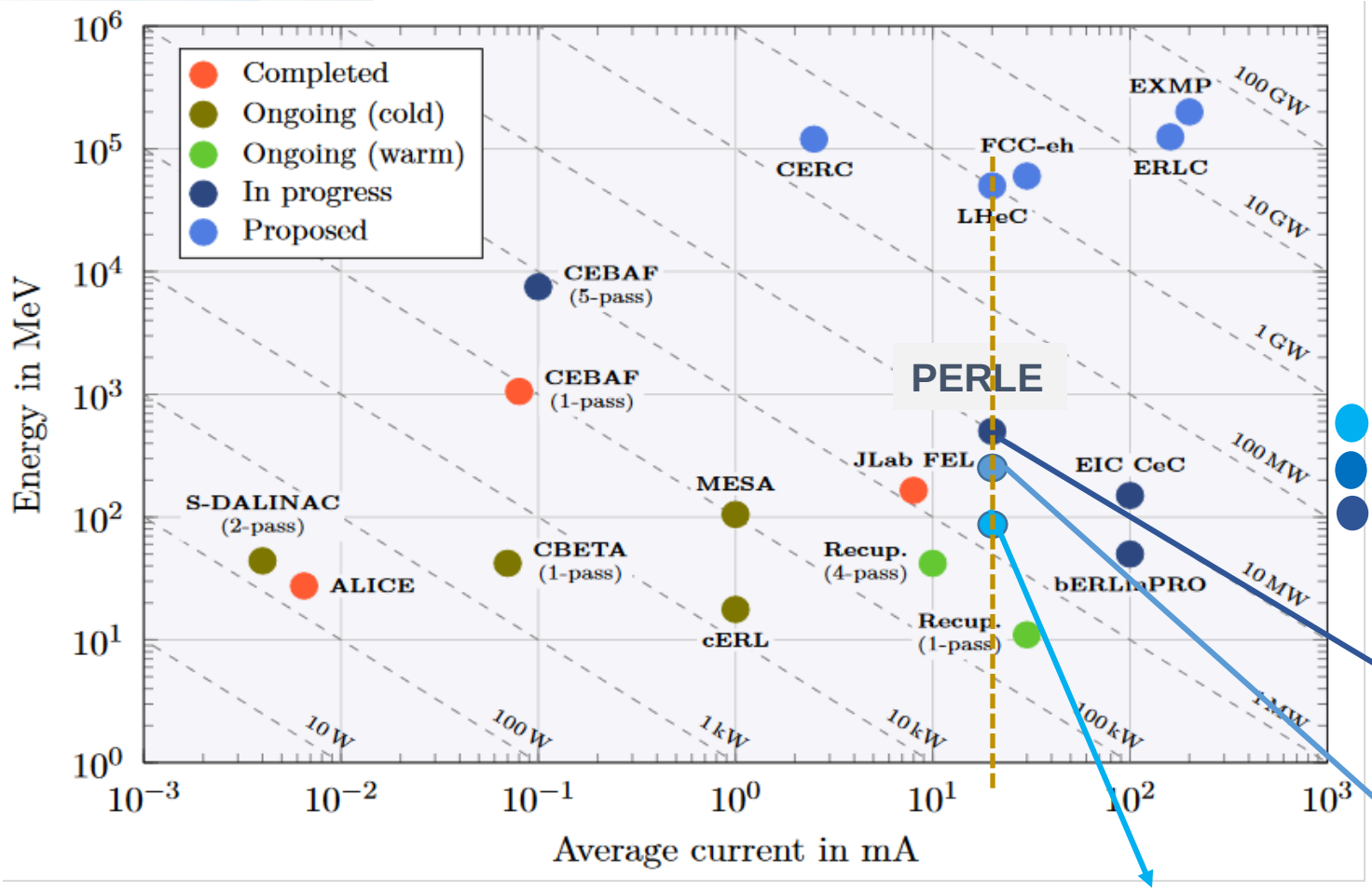




Laser clean room: delivered in July 2024

Implantation in igloo being finalized

PERLE Timeline (macroscopic view)



PERLE signle tour
PERLE 3 tours 250 MeV
PERLE 3 tours 500MeV

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031

Conclusions and remarks

- **PERLE@Orsay : International collaboration formed**
  Recently extended within iSAS for cryomodule work

+ Contributions through iSAS of

Still opened to new comers

- **PERLE@Orsay proceed by phases :**
  - Phase 1: Injection line Installation + Single turn (2028)
  - Phase 2: PERLE 250 MeV version (2030)
  - Phase 3: PERLE 500 MeV version (> 2030)

- **PERLE@Orsay : Recent achievements**
  - The site is chosen : IGLOO. Progresses on Infrastructure and Safety issues
  - Installation of the DC gun started – will be finalised by end 2024, commissioning in 2025.
  - Significant progresses in buncher design.
  - A common single-cell shape cavity will be adopted for FCCee R&D and PERLE booster.
  - Progresses on magnet design and orbit corrections / diagnostic
  - Specifications of the 5-Cell 800 MHz cavity is under finalisation. Procurement of 4 cavities before summer 2024
  - The cryomodule adapted from ESS design. Significant progress → in phase with the 2027 delivery (iSAS)

- **PERLE@Orsay**
  - Human resources significantly increased (permanent researchers, technical staff, Post-Doc & PhD)
  - Financial support for Phase 1 (single tour) strongly depends on the succes of ERL4ALL

Important discussions / actions on going

- We have proposed a project (**ERL4ALL) to CNRS** which should allow to finance **the full injection line and a part of a first tour equipment**. Money required 3M€. Led by Maud Baylac , Walid Kaabi, Eliane Bouquelrel We received a first green light and the project will be presented the **27 June for final decision/approval.**

- Discussions well advanced with **HZB** to recuperate part of the equipment of **BESSY VSR - Cryogenic plant, valve box and transfer lines.** Recuperation of all materiel by Summer 2026.

- Discussion on going for receiving in-kind some material from **CBETA (quadrupoles essentially to equip the first tour of PERLE)**

- Increasing collaborations with
  - **CERN** (**R&D on 800MHz SRF Cavities (FCC)** : production and post-production processes. Discussion well advanced
  - **LASA-Milano** (cavities LINAC Cryomodule, booster, DC-gun/photocathode). Discussion started
  - **Jlab** (Hom/Absorbers/cavities). Discussion on going

Challenges toward PERLE realisation

Development of high current electron sources:

- **DC gun**: high charge production at high repetition rate, high cathode field & high vacuum
- **New photocathode materials** with high quantum efficiency and long life time (CsKSb, GaAS…)

Beam dynamics & instrumentation:

- Specific simulation tools for ERL adapted to high-power beams at different energies and currents
- Development of **high dynamic range instrumentation** allowing high beam control at different functioning phases (commissioning, ramping-up and operation), and also to decern beams from “undesired” one (halo):
  - **Non-invasive** diagnostics: optical system for beam imaging
  - BPMs and BAMs **adapted to multi-turn**
  - Sensitive BLMs for the **monitoring of beam loss and beam halo**

SRF Cavity and High Order Mode (HOM) damping:

- For operation in CW mode with the **minimum dynamic loss**, cavity should have the **highest Q_0**: **Thermal treatment** (Doping, infusion, medium temperature annealing) or R&D on SRF material for 4,2K operation (Nb3Sn or others…)
- Development of **Fast Reactive Tuners (FRTs)** adapted to cavity and cryomodule to mitigate cavity detuning by microphonics.
- Efficient HOM extraction w/o increasing cryoload, to preserve beam quality & avoid its disruption by wakefields
  - **Cavity design choices** should integrate the HOM extraction issue: frequency optimisation, large aperture, few cells, optimised end group)
  - Design of **specific HOM couplers** & optimisation of the damping scheme
  - Study the need of **additional absorber** in the beam line