PERLE Status Report

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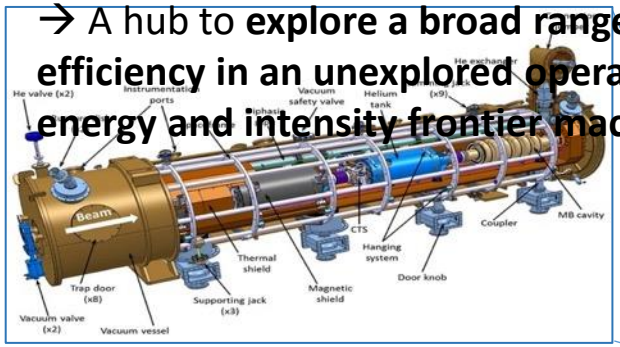
on behalf of PERLE Collaboration

European Laboratory Directors Group Meeting and Accelerator R&D Workshop
6-7 June 2024 - ***LBL*** Brookhaven National Laboratory

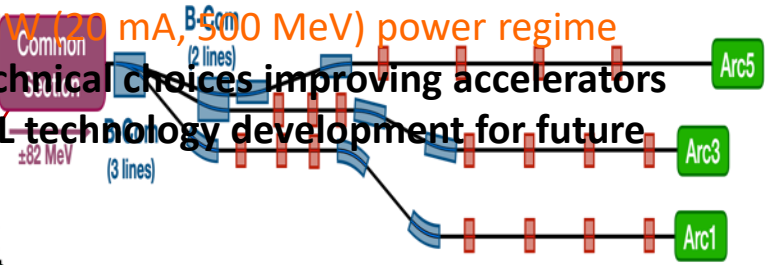
PERLE @ IJCLab-Orsay

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

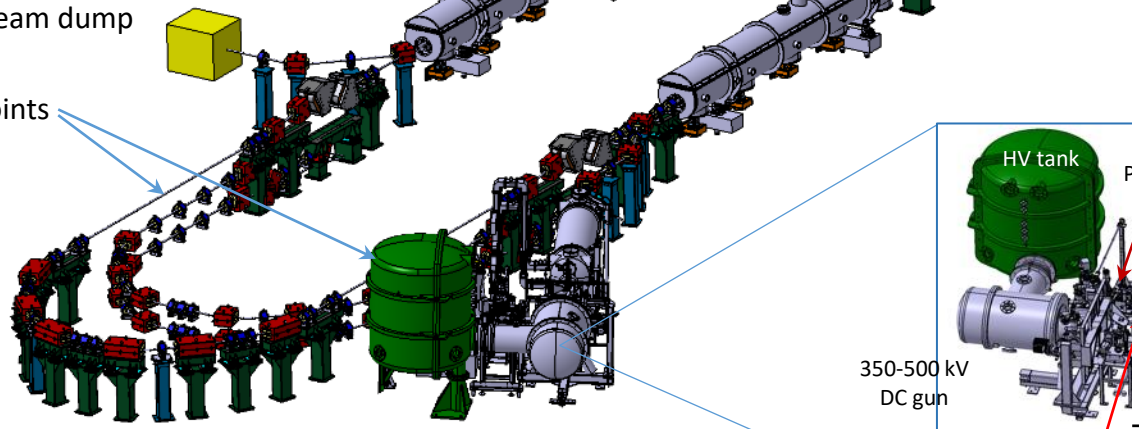
→ A hub to **explore a broad range of accelerator phenomena** and to **validate technical choices improving accelerators efficiency in an unexplored operational power regime** on the pathway of the **ERL technology development for future energy and intensity frontier machines**.



- 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



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)

bunches at 7 MeV.

Booster: 5 single-cell cavities [illegible]

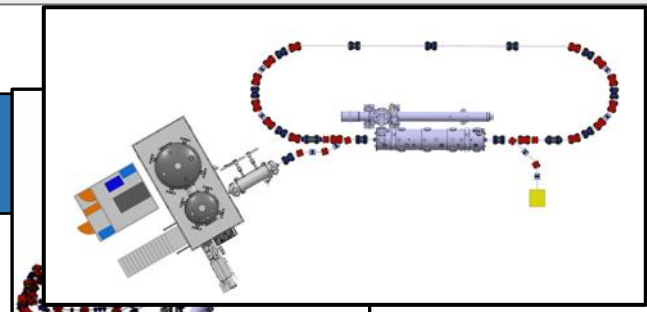
PERLE Timeline (macroscopic view)

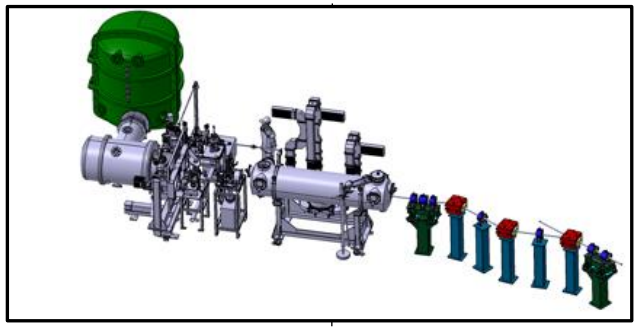
Prepare to Build phase (P2B): TDR and prototyping

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

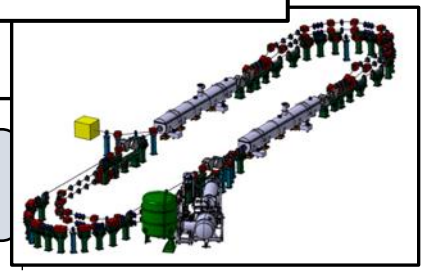
Installation phases

Phase 1: Injection line Installation





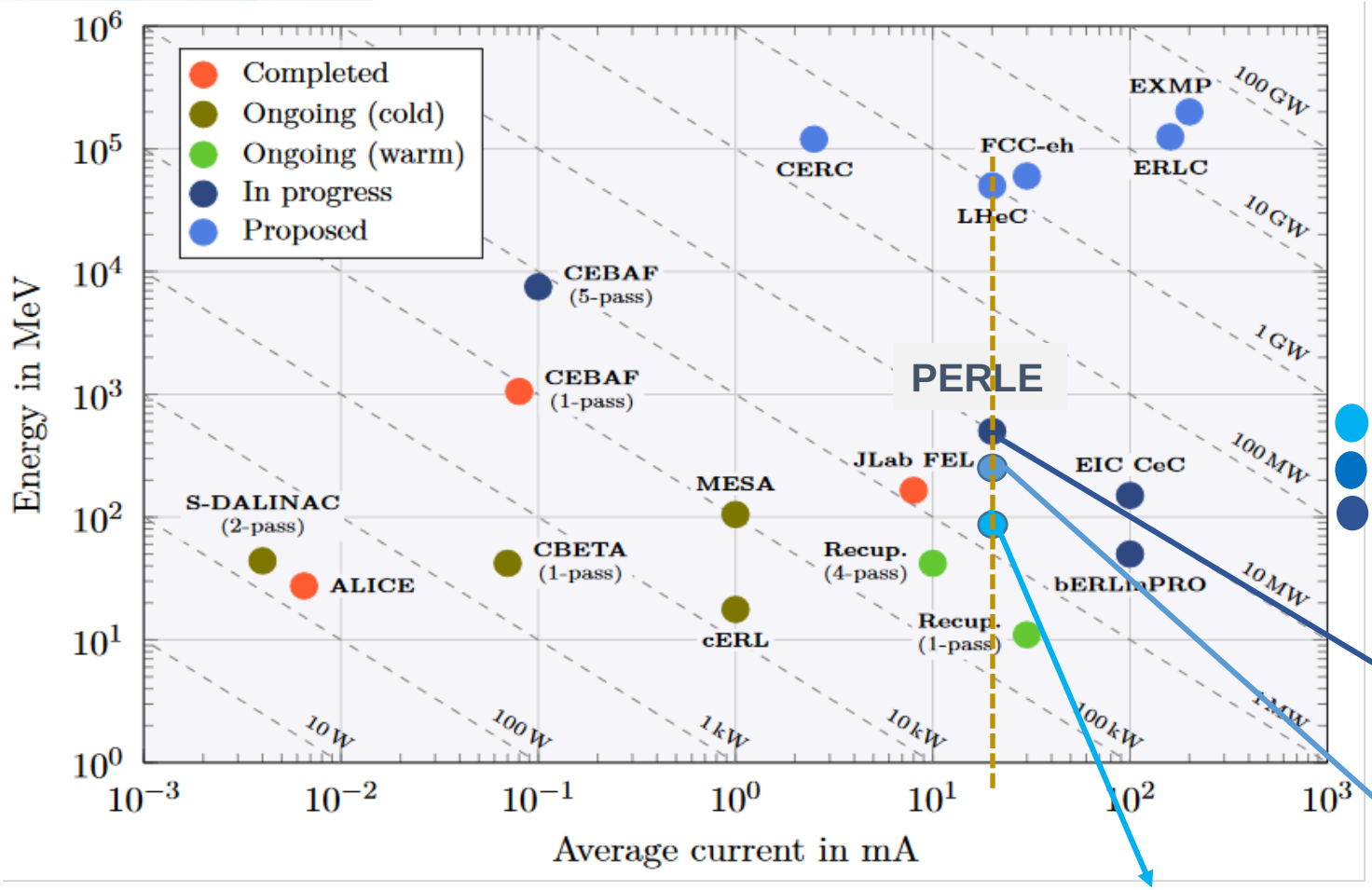
Phase 2: PERLE 250 MeV version



Phase 3: PERLE 500 MeV version

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

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

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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(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.

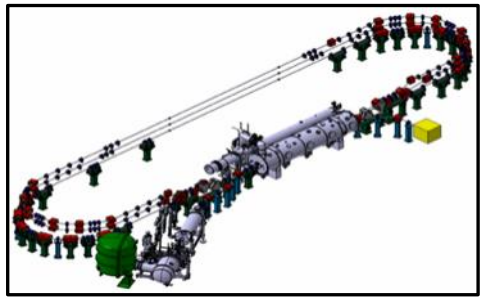
DOI: 10.1103/PhysRevAccelBeams.27.031603

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:

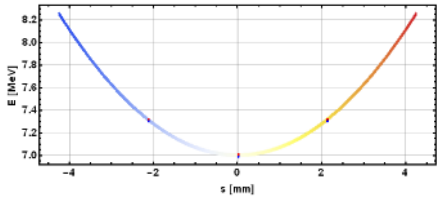
- Lattice architecture and optics
- Staging construction
- Injector and merger, space charge study
- Longitudinal matching
- Filling pattern and bunch timing options
- Start to end simulations with CSR and Wakefield
- BBU study

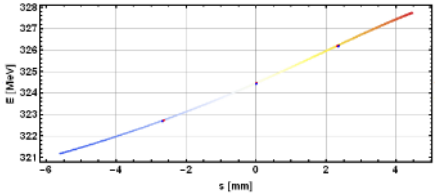
Further design and beam dynamics studies ongoing



The effort is currently focused on the 250 MeV version of PERLE with a phase with a single tour.
The following beam dynamics studies are ongoing or done:

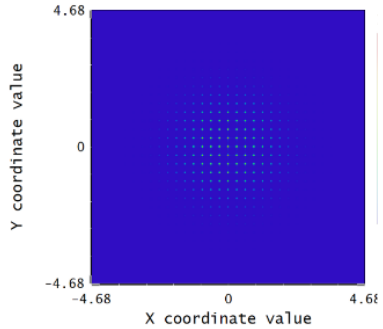
- Matching with collective effects

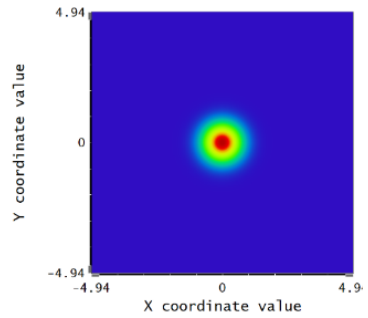




- Longitudinal phase space tuning and linearization
  - Linacs phases
  - Arc length correction
  - Focal conditions at IRs

- Diagnostics
  - Non destructive emittance measurement (DMD, MLA)
  - Beam losses and halo formation
  - 6D beam qualification

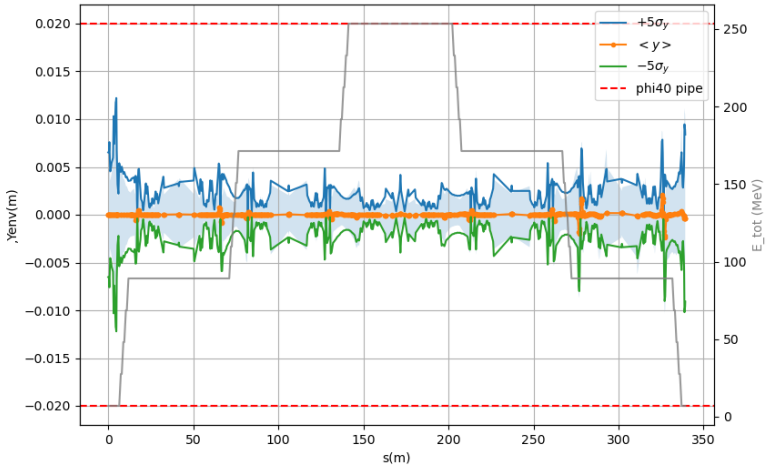




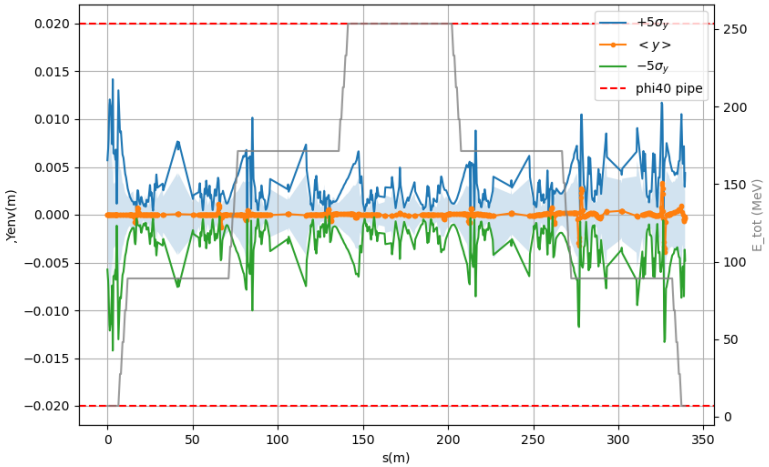
IJCLab, LPSC, CERN, Jlab, Liverpool, STFC, Lancaster, An-Najah

Further design and beam dynamics studies ongoing : 1 example

Beam Losses study: Vertical 5σ beam envelop through PERLE (with space charge and CSR)



Matched injector's distribution



Unmatched injector's distribution

Beam pipe of $\phi 40$ mm should be sufficient

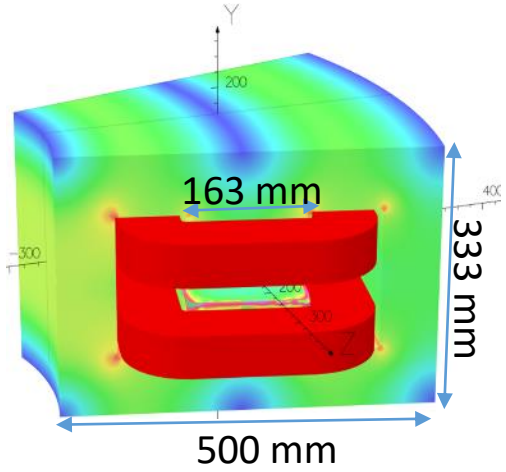
	X (mm)	px (mrad)	Y (mm)	py (mrad)	delta (%)
Max value tolerable	2.5	2	7	5	1
Min value tolerable	-2	-2	-9	-5	-1

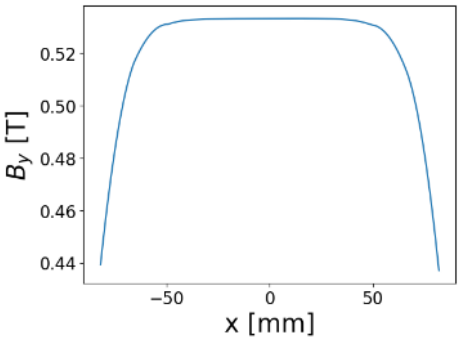
Table 2: Tolerances of PERLE for shifts in the phase space of the initial distribution (Connor).

Magnet Design

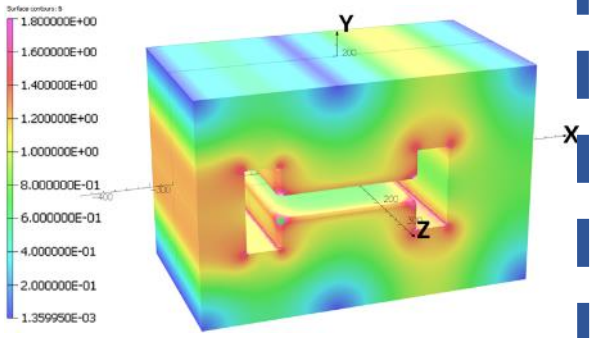
Misalignments and Corrections

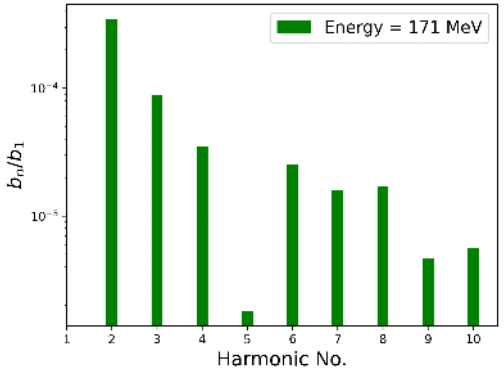
S-bend in Arcs



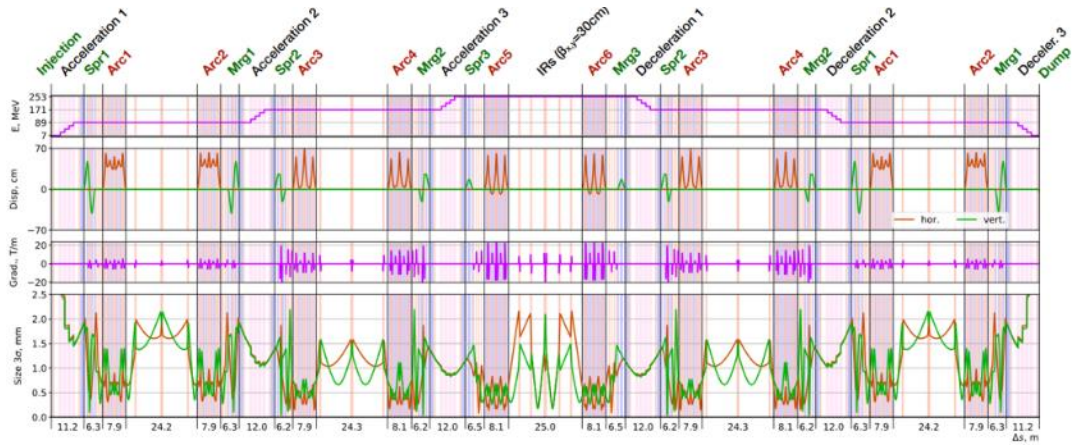


B-com in Spreader

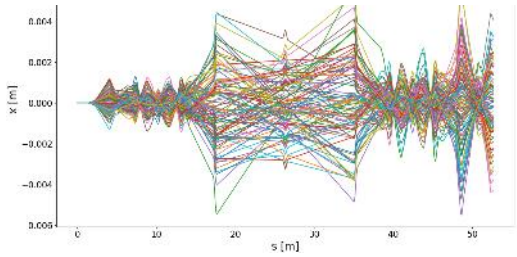




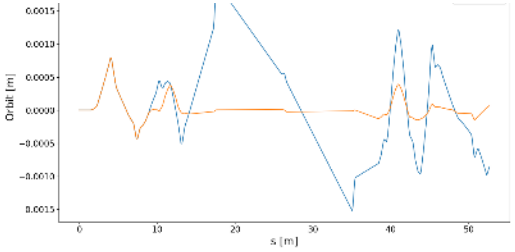
IJCLab, LPSC, Jlab, An-Najah



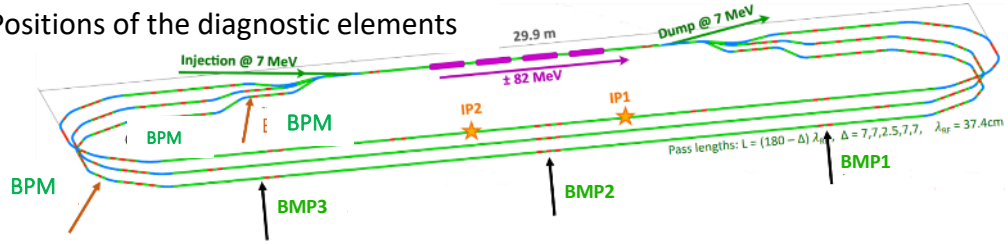
Effect of quads misalignments on x-orbit



Before/after correction (with kickers)



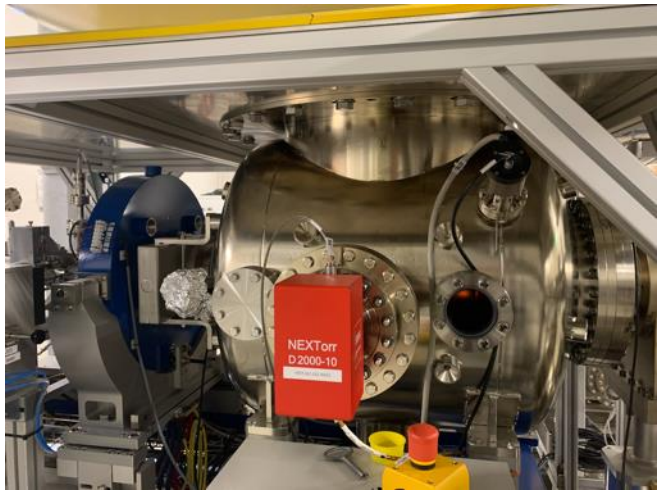
Positions of the diagnostic elements



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

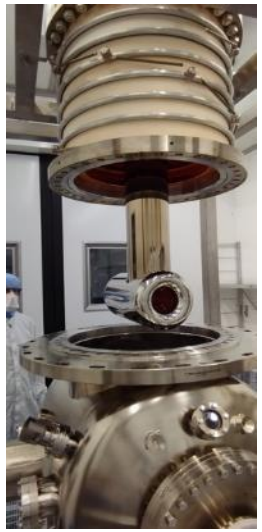
HV power supply suited for high bunch charge (designed for 40 mA, 450 kV)

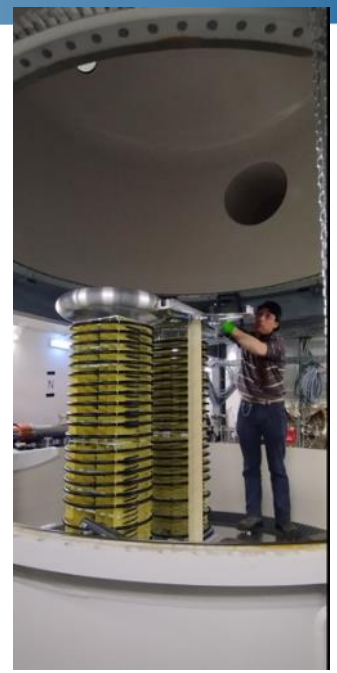
A Photocathode Preparation Facility (PPF)

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

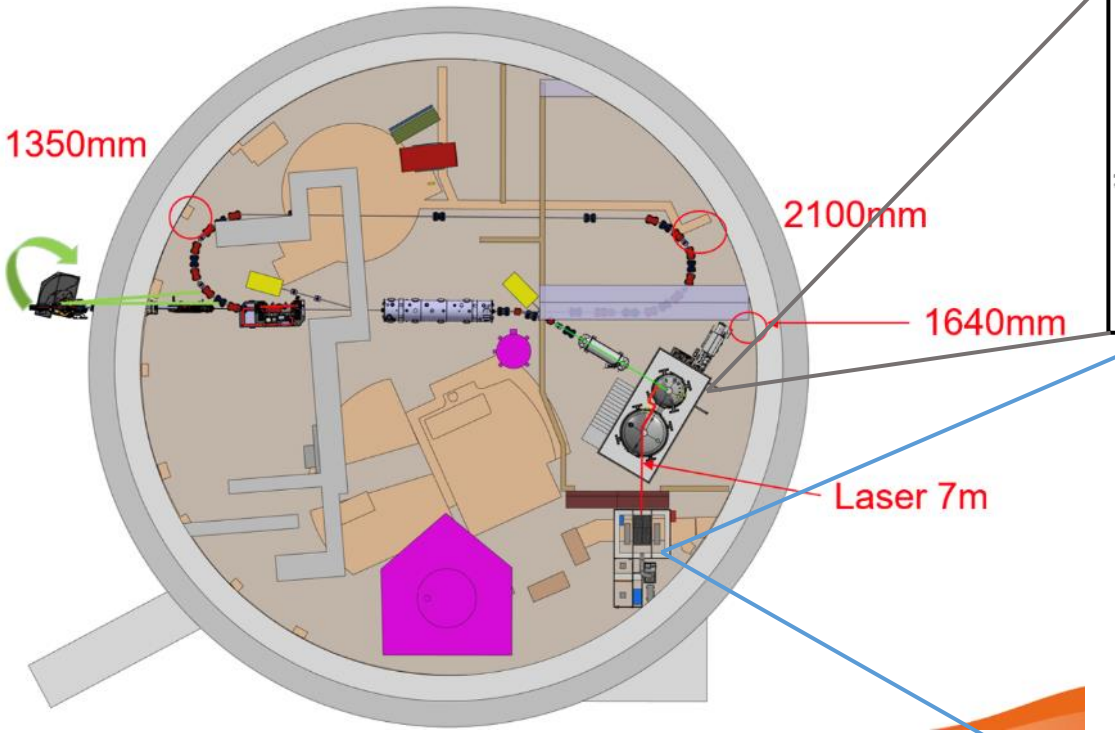
The equipment were received at Orsay end of January

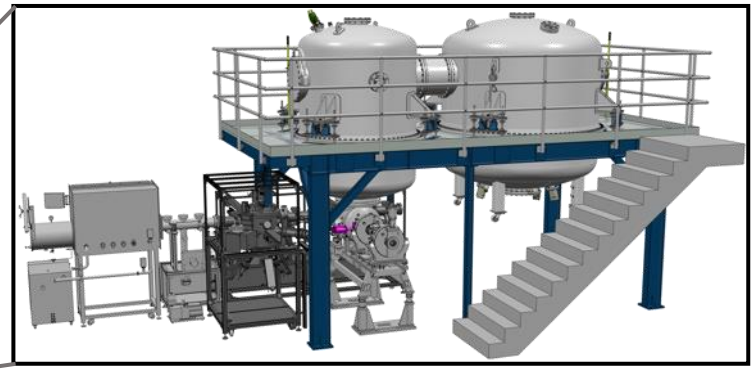
The installation at IJCLab well advanced in the IGLOO

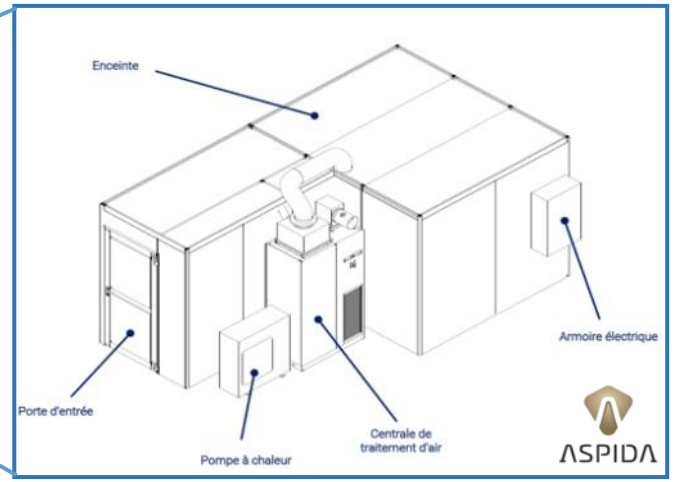
Site choice done and first equipment implementation

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







Implantation in igloo being finalized

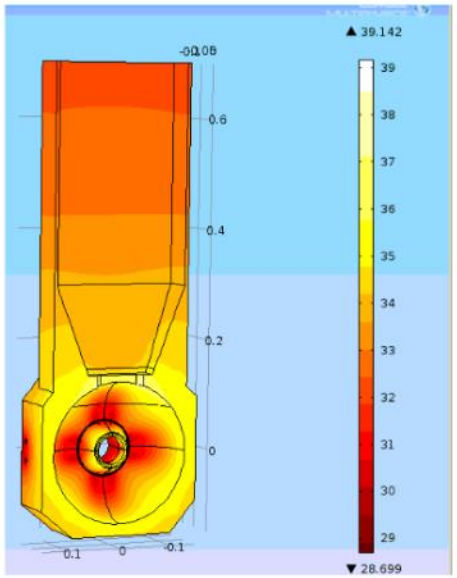
Laser clean room: delivered in June 2024

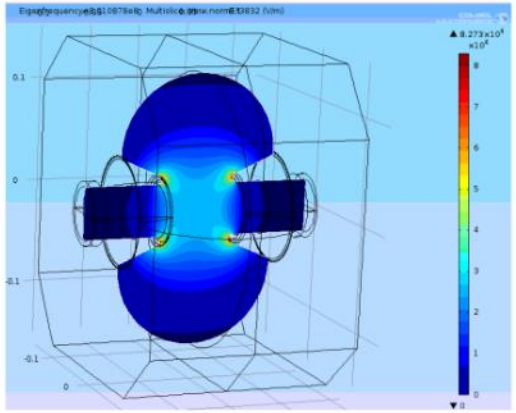
Buncher cavity design

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

Collaboration IJCLab-ESS Bilbao

(some summary highlights...)





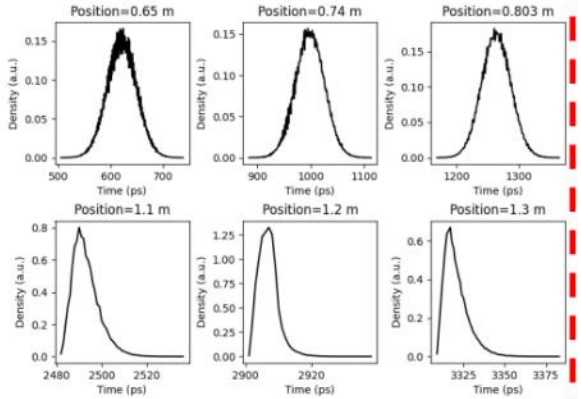
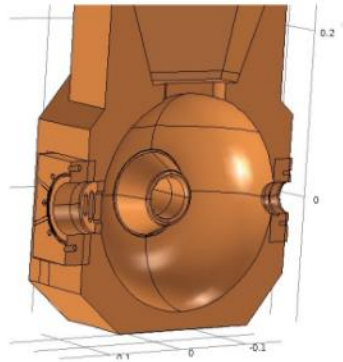


Figure of merit	PERLE buncher cERL-like optimized	Figure of merit	PERLE buncher cERL-like optimized
Input power	5 kW	Iris a	0.070 m
V0	0.21 MV	Iris b	0.020 m
TTF	0.84	Wave guide	WR-975 (274.65 mm, 123.80 mm). Taper=0.5
Gradient (V_0T/L_{cav})	1.392 MV/m	S11dB	-35.81 dB
Power loss	4972 W	ZTT	49.7 MΩ/m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



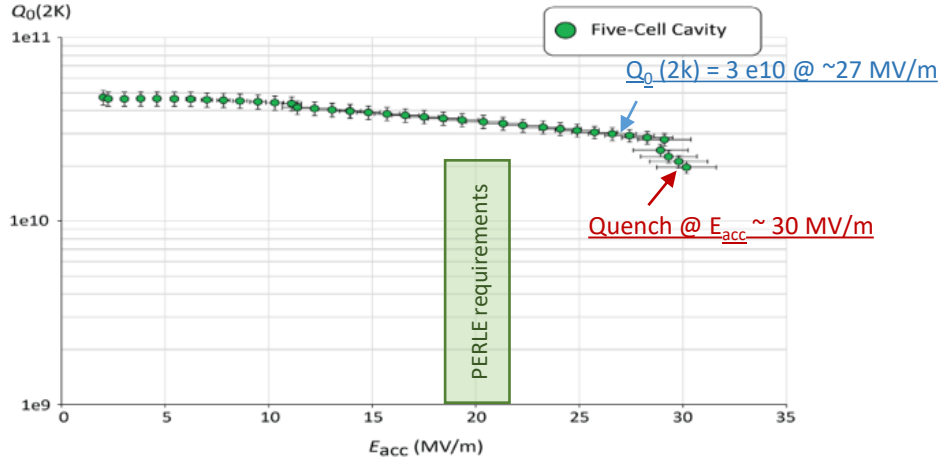
Important progress in the RF design, thermal and beam dynamics simulations of a buncher cavity for PERLE by colleagues from ESS-Bilbao.

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).

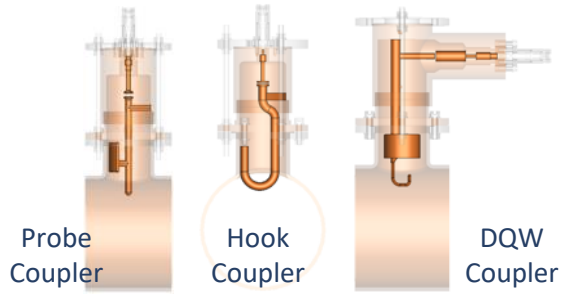

First Nb 802 MHz 5-Cell cavity fabricated @ JLAB

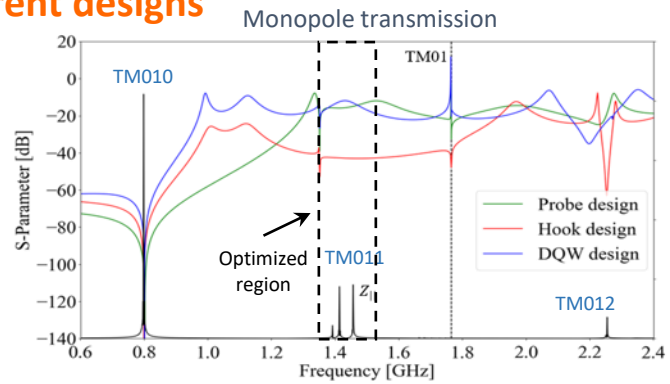


F. Marhauser et al. "802 MHz ERL cavity design and development"- IPAC2018 (Vancouver, BC, Canada)- doi:10.18429/JACoW-IPAC2018-THPAL146

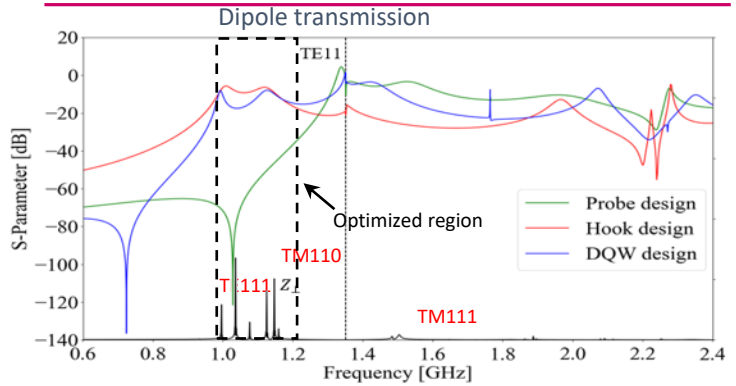
Status of HOM studies : news

HOM coupler optimization of 3 different designs



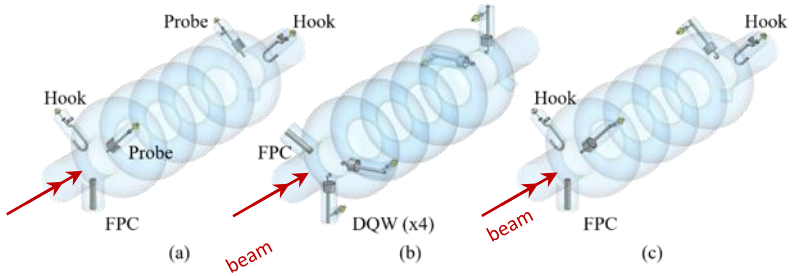


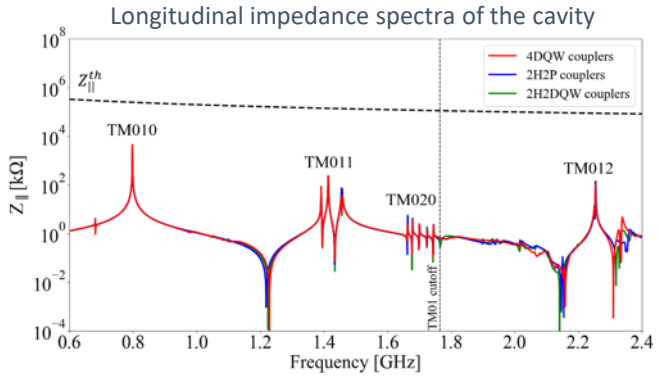
Collaboration IJCLab-Jlab and CERN

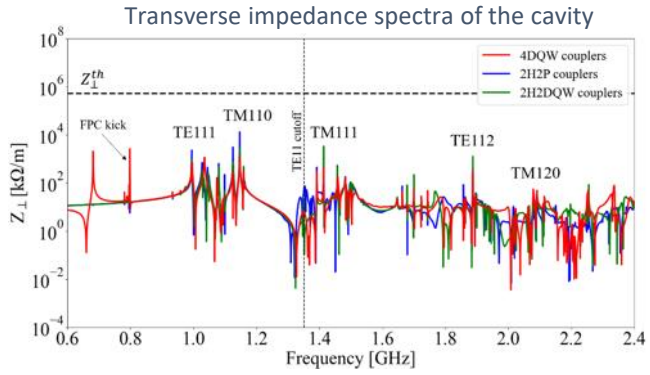


- Couplers were geometrically optimized according to HOM spectrum ($Z_{||}$ and $Z_{\perp}$) & S-parameters btw port 1 (beam pipe) & port 2 (coupler output) were studied.
- The hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)
- The DQW coupler exhibits a better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

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



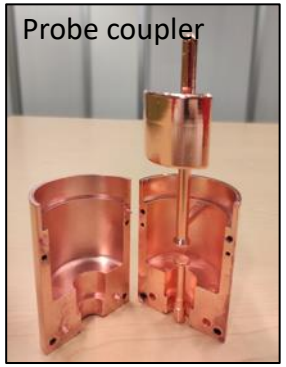


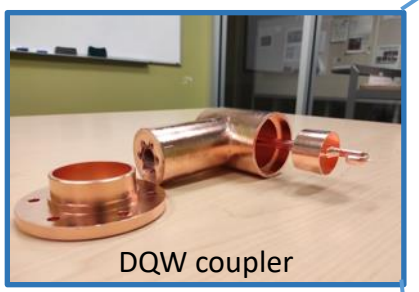


→ Promising results of the 4 DQW scheme: It allows damping both monopole and dipole HOMs below the analytically-computed beam-stability limits

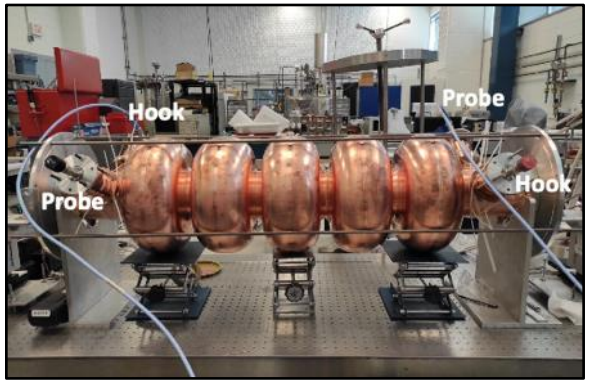
Status of HOM studies : news more details

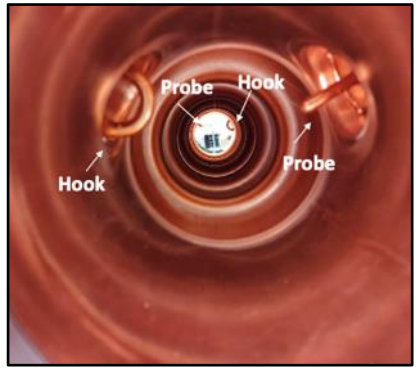
From RF design to performance measurements: **Successful collaborative effort between IJCLab, Jefferson Lab & CERN**

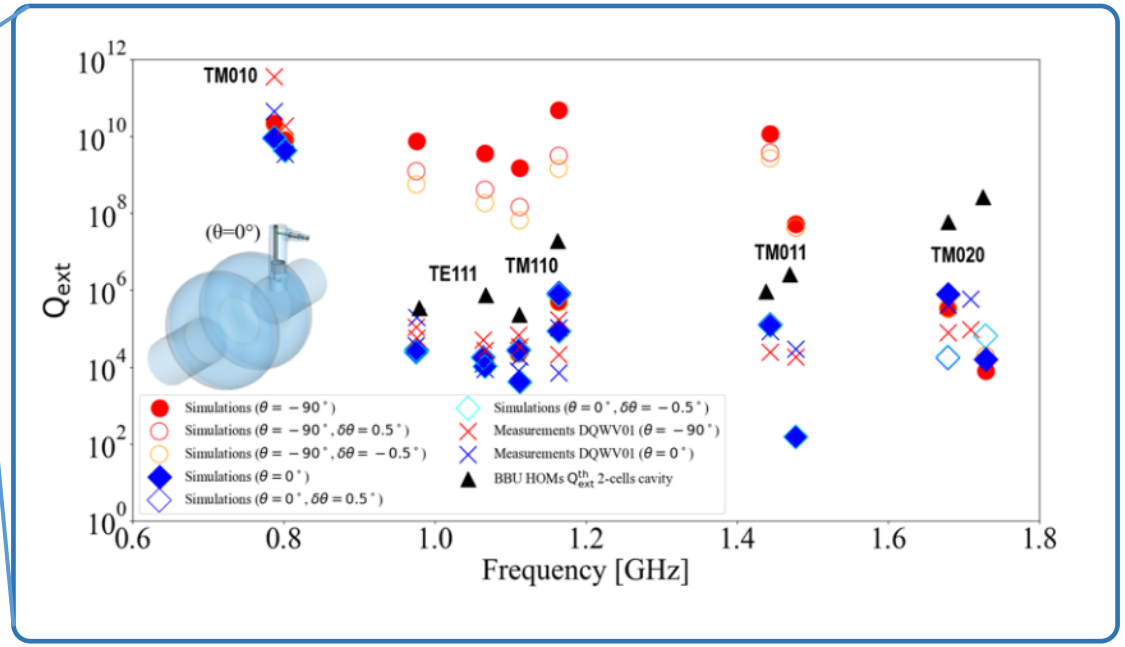




3D-printed prototype (Epoxy Accura 48) copper-coated @CERN







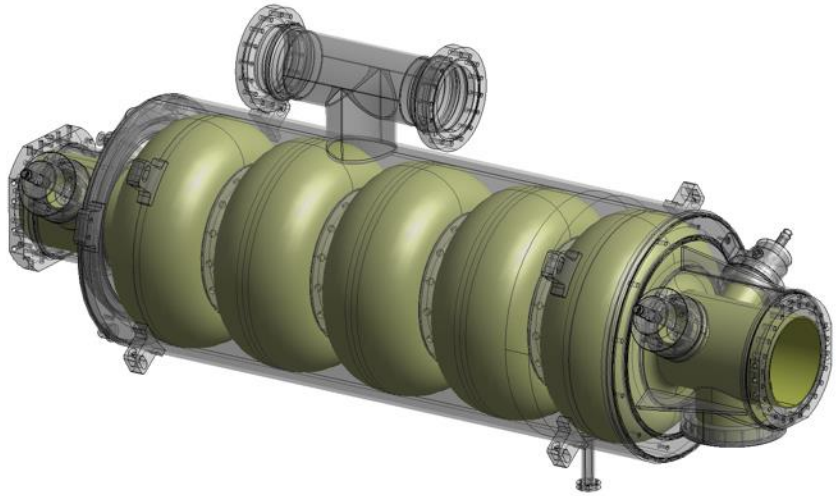
Ultimately, we aim to produce Nb HOM couplers with optimised design and to install them on a new Nb 5-cell PERLE cavity with optimised end groups. **The Production of 4 cavity scheduled within the ISAS program (Starting from 2024).**

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 before summer (for single and multi-cell cavities).
- It is foreseen to lunch the procurement procedure of 4 cavities also before summer.

IJCLab, JLab, CERN and including now LASA-Milano

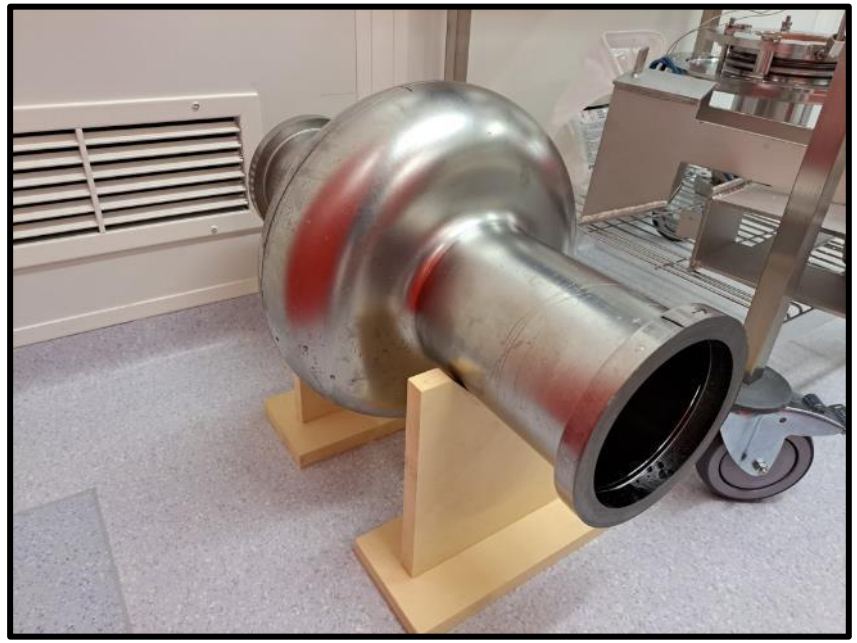
SRF cavity : latest news

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.

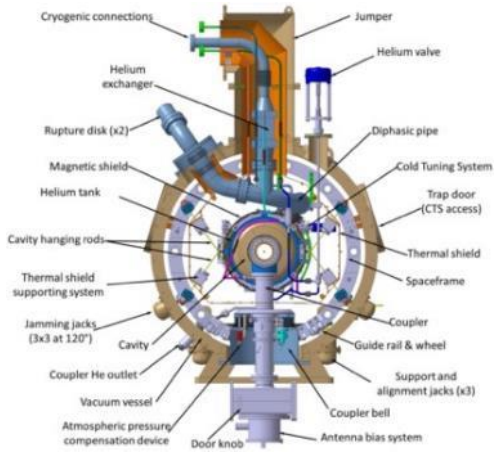


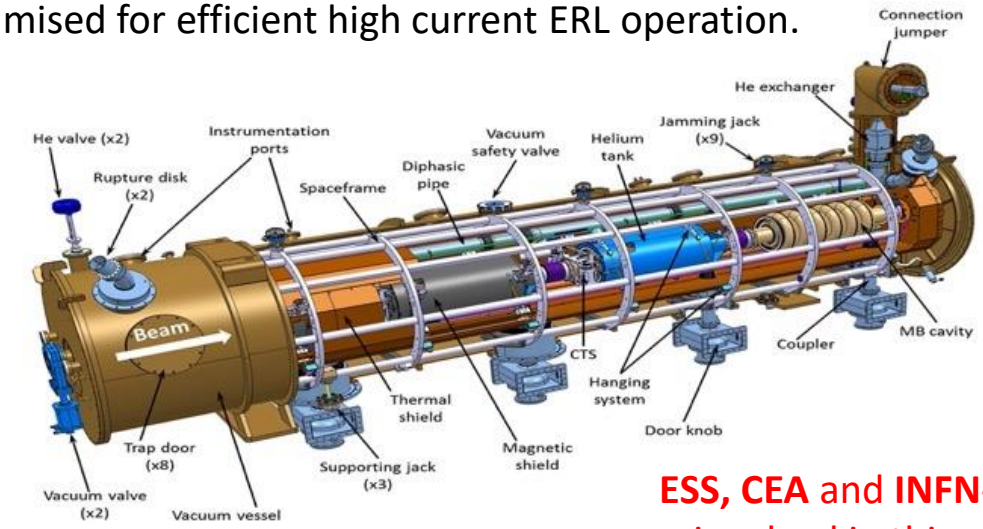
Cryomodule design

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.

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) well on the way to completion.

Backup

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:

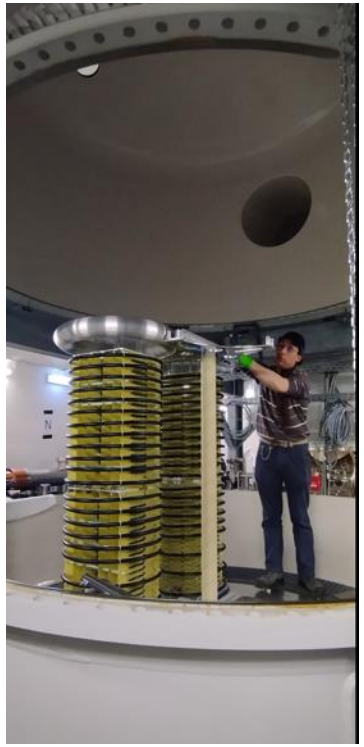
- Specific simulation tools for ERL adapted to high-power beams at different energies and currents
- Development of **high dynamic range instrumentation** allowing high beam control at different functioning phases (commissioning, ramping-up and operation), and also to decern beams from "undesired" one (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:

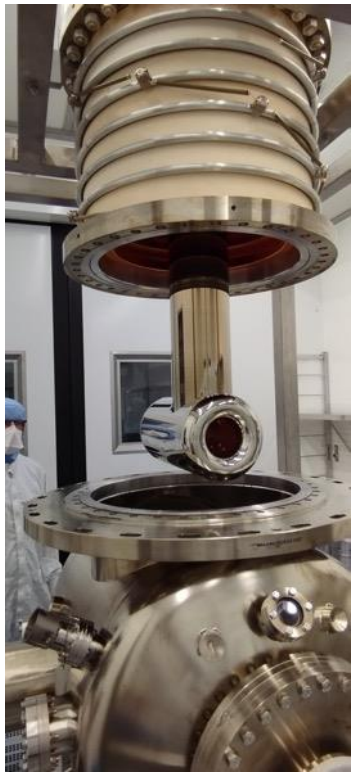
- For operation in CW mode with the **minimum dynamic loss**, cavity should have the **highest Q_0**: **Thermal treatment** (Doping, infusion, medium temperature annealing) or R&D on SRF material for 4,2K operation (Nb3Sn or others…)
- Development of **Fast Reactive Tuners (FRTs)** adapted to cavity 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

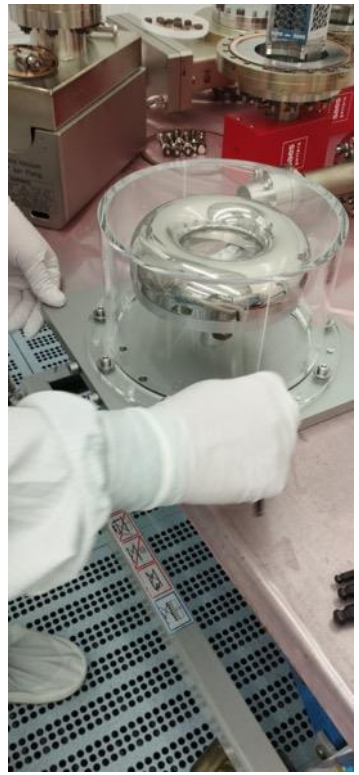
Dismantling of the PPF (September 2023)

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



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



PERLE e- Source

The equipment were received at Orsay in 2 lots, end of December and end of January. The installation at IJCLab already started

PERLE e- Source

The equipment were received at Orsay end of January

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