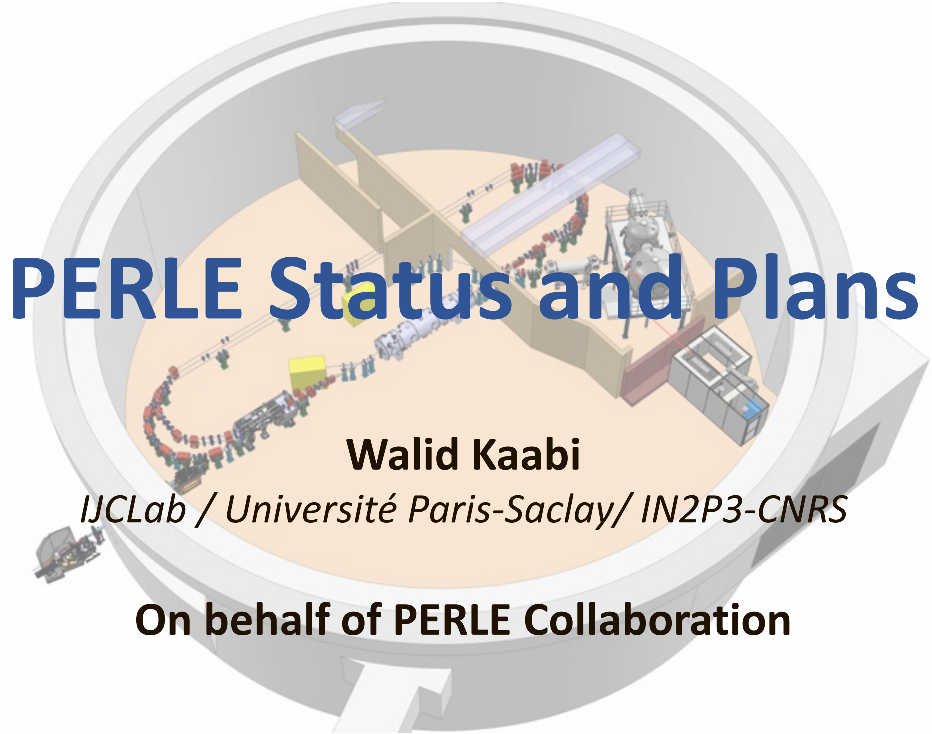


PERLE Status and Plans

Walid Kaabi

IJCLab / Université Paris-Saclay/ IN2P3-CNRS

On behalf of PERLE Collaboration

ERL 2024

September 24-27, 2024

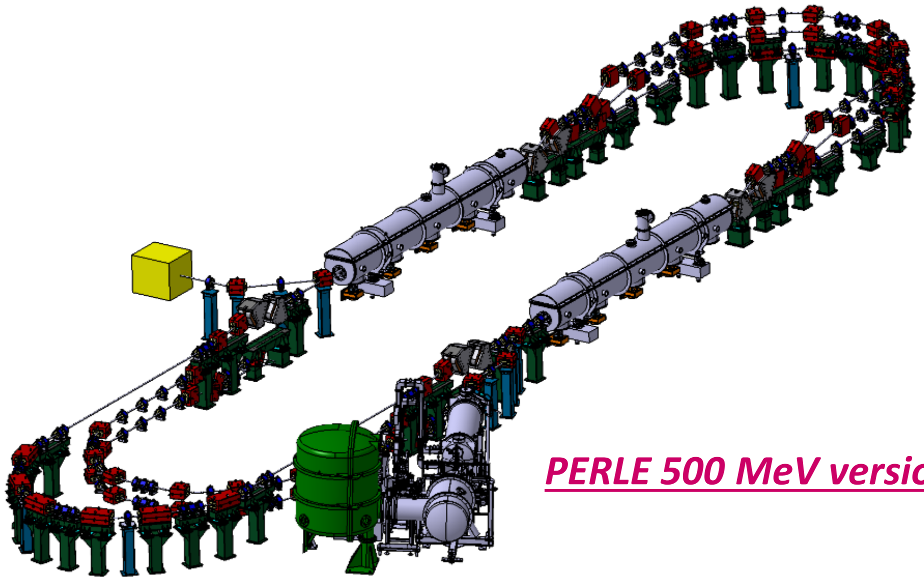
KEK, Tsukuba, Japan

PERLE's Impact on ERL panorama

PERLE main objectives:

- Demonstrate multi-turn and high current operation → access to unexplored power regimes
- Validation of important technical choices:
  - High-charge electron gun: 500 pC at 40 MHz
  - Optimized 800 MHz SRF system: Maximise the efficiency
  - Common circulation arcs for accelerated and decelerated beams
  - Non-invasive diagnostics
- Host experiments of interest for our lab and institute.

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

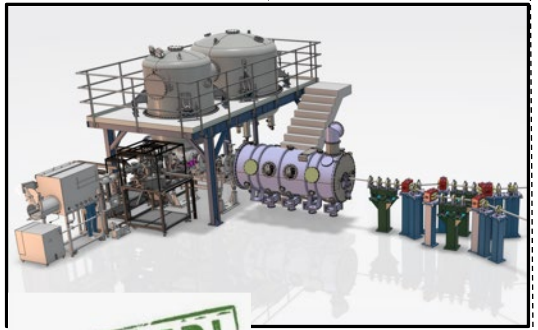


PERLE 500 MeV version

PERLE Timeline (macroscopic view)

TDR and prototyping

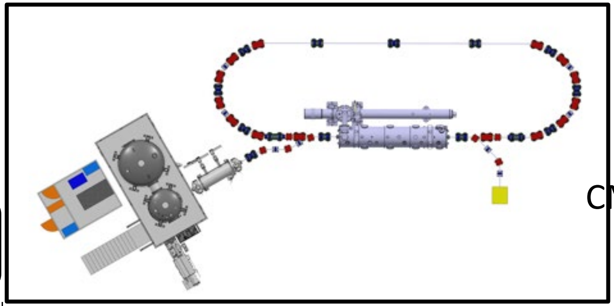
Phase 1: Injection line



FUNDED!

By CNRS National Program RI2

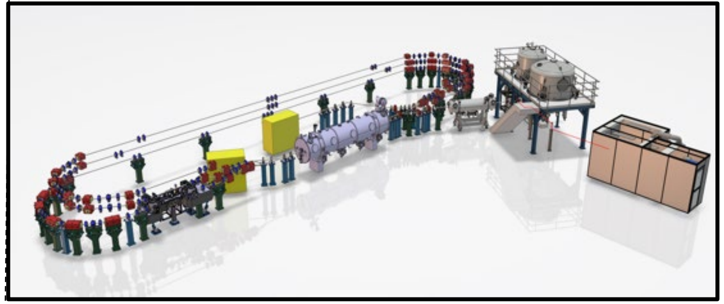
Phase 2: PERLE 1 tour



"Partially" FUNDED!

CM funded by EU Program iSAS
+ Matching funds (IN2P3)

Phase 3: PERLE 250 MeV

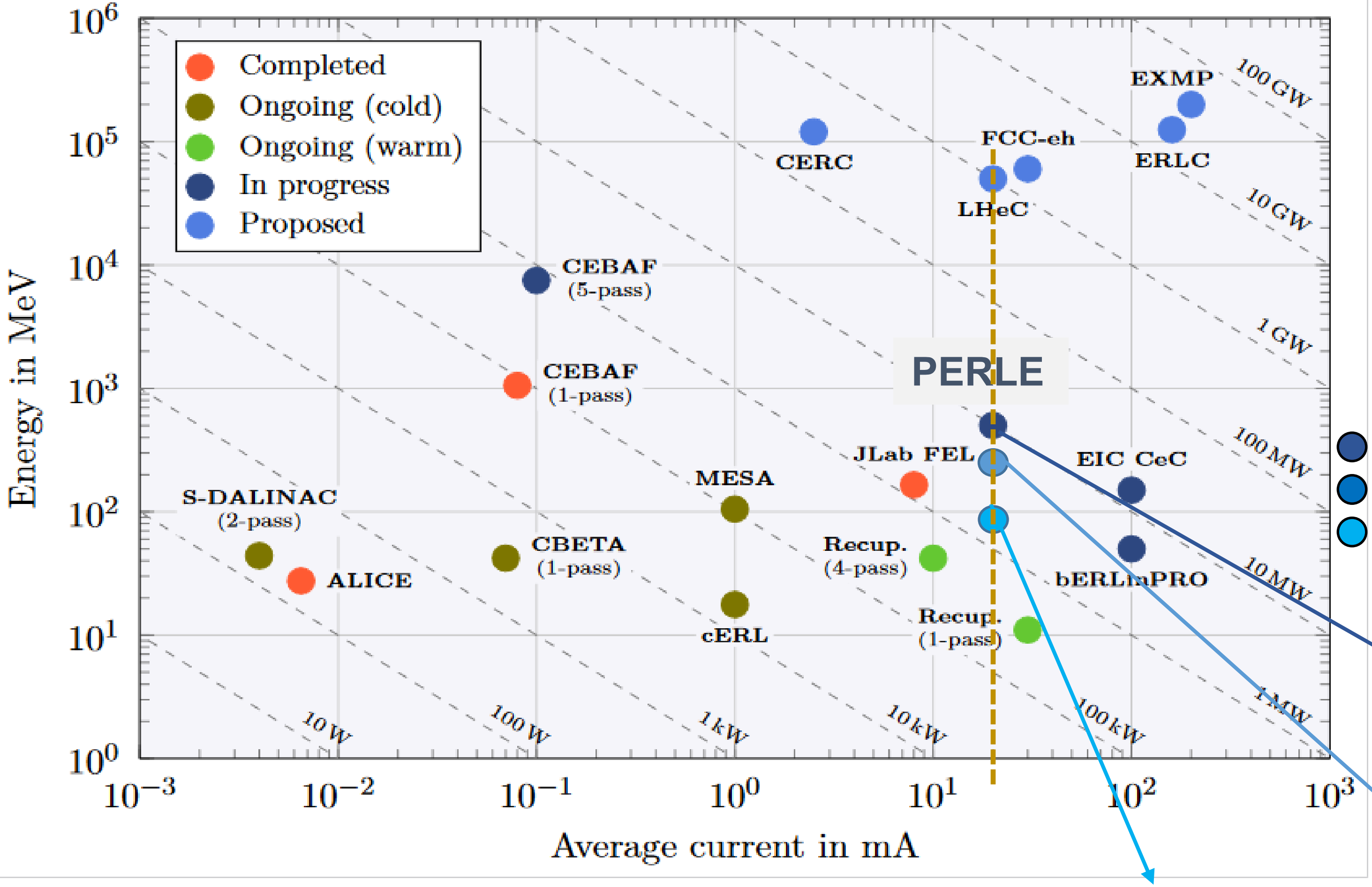


Extra funding needed for 6 arcs configuration

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031

Phase 4: PERLE 500 MeV

PERLE Timeline (macroscopic view)



- PERLE 3 tours @ 500MeV
- PERLE 3 tours @ 250 MeV
- PERLE single tour

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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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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(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

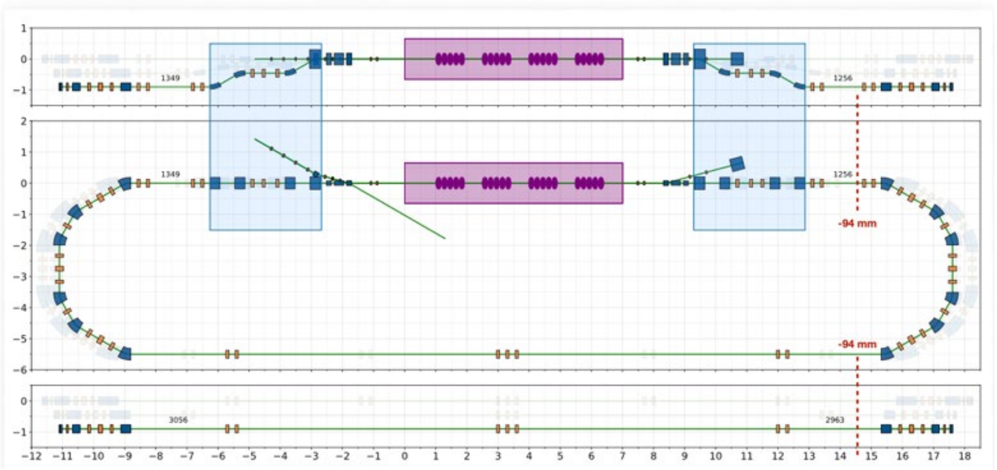
The following studies was reported in this paper for the **500 MeV version** of PERLE:

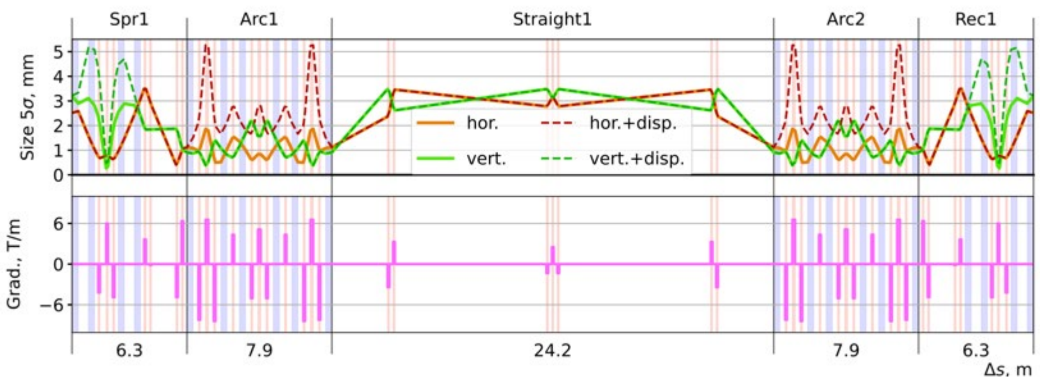
- Lattice architecture and optics
- Staging construction
- Injector and merger, space charge study
- Longitudinal matching
- Filling pattern and bunch timing options
- Start to end simulations with CSR and Wakefield
- BBU study

Further design and beam dynamics studies ongoing

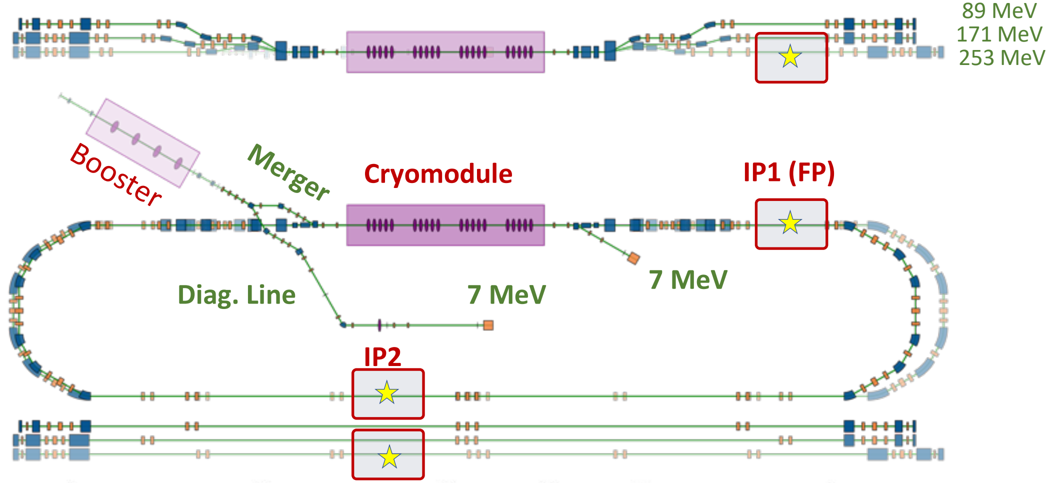
More details in Alex Fomin talk

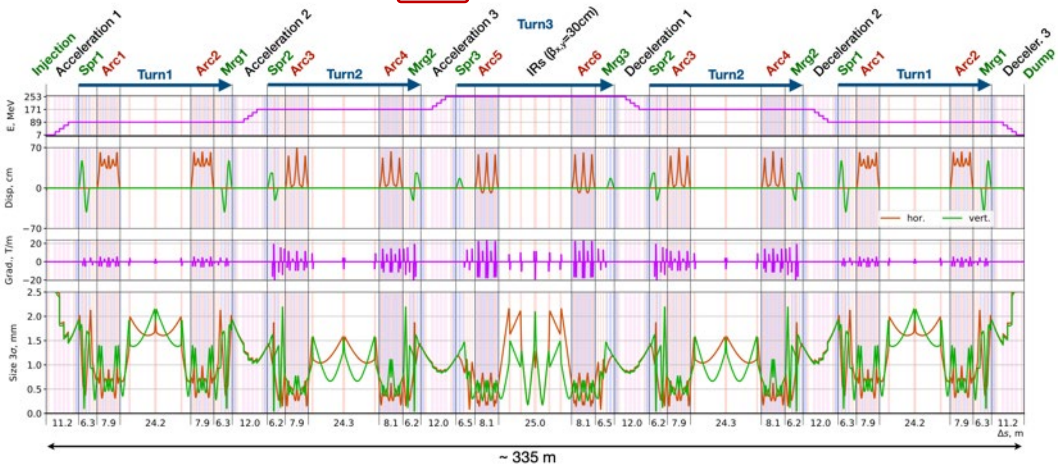
Single-Turn "with B-Coms"





PERLE 250 MeV version



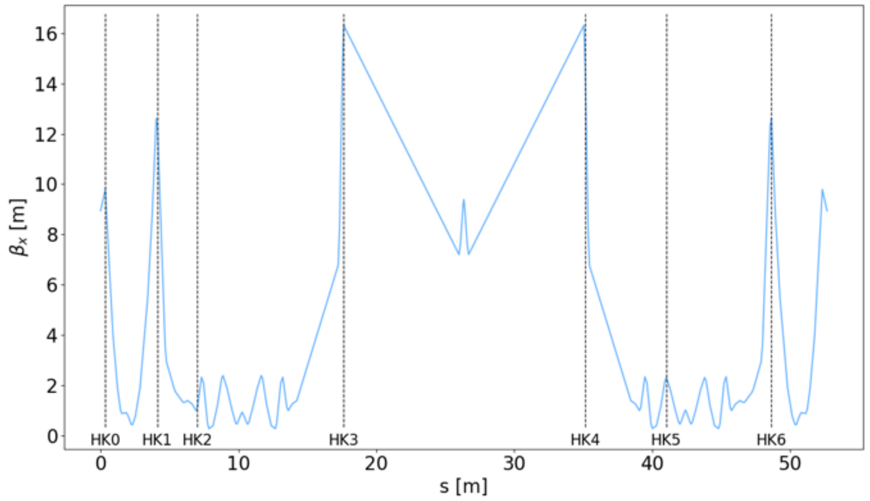


Lattice misalignment and corrections (250MeV machine)

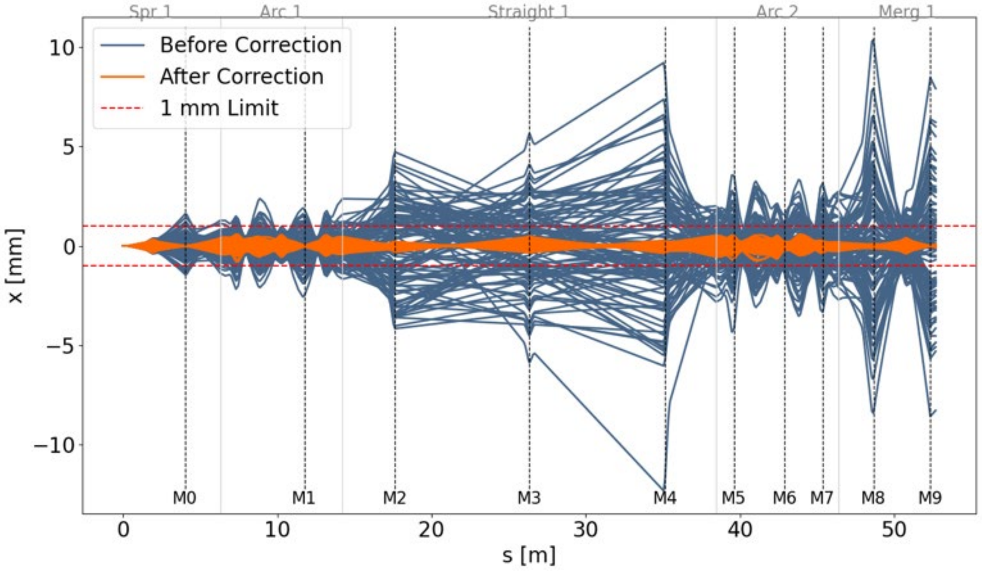
More details in Rasha Abukeshek Poster

First results of misalignment corrections studies:

- Recalculating the optics of Turn 1 with all (45) quadrupoles misaligned: Misalignment affects the dispersion in both planes. No effect on Beta function.
- Gradually adding kicker-Monitor pair and observe the next places to mount the BPMs. In each step, the value of the previous HK_n are fixed from the previous optimization and introduced directly to the lattice



- positions of all kickers & monitors for the 1st turn are found: 7 kickers and 10 BPMs are needed.



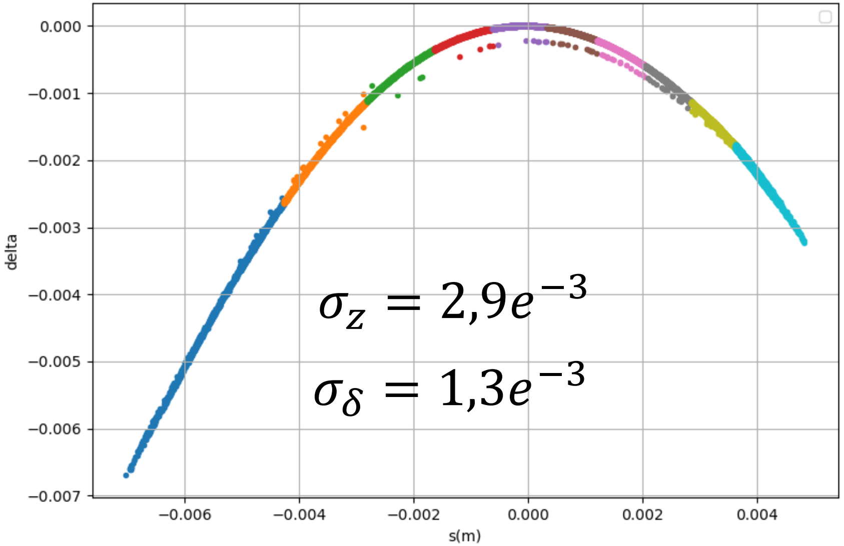
Simulation of 100 beam orbits along the 1st pass of PERLE (**blue**) and corrections (**orange**)

PERLE beam dynamics (250MeV machine)

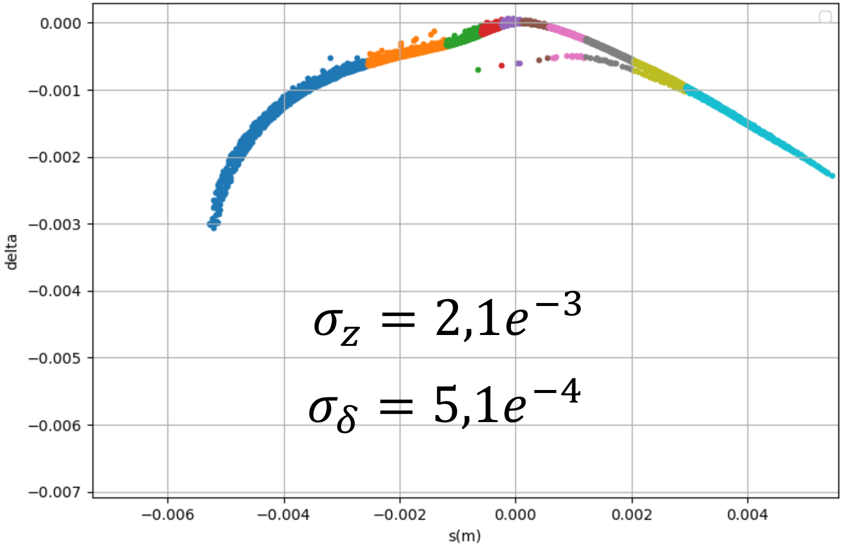
Longitudinal matching for energy spread compression at EP:

More details in Julien Michaud poster

No longitudinal match



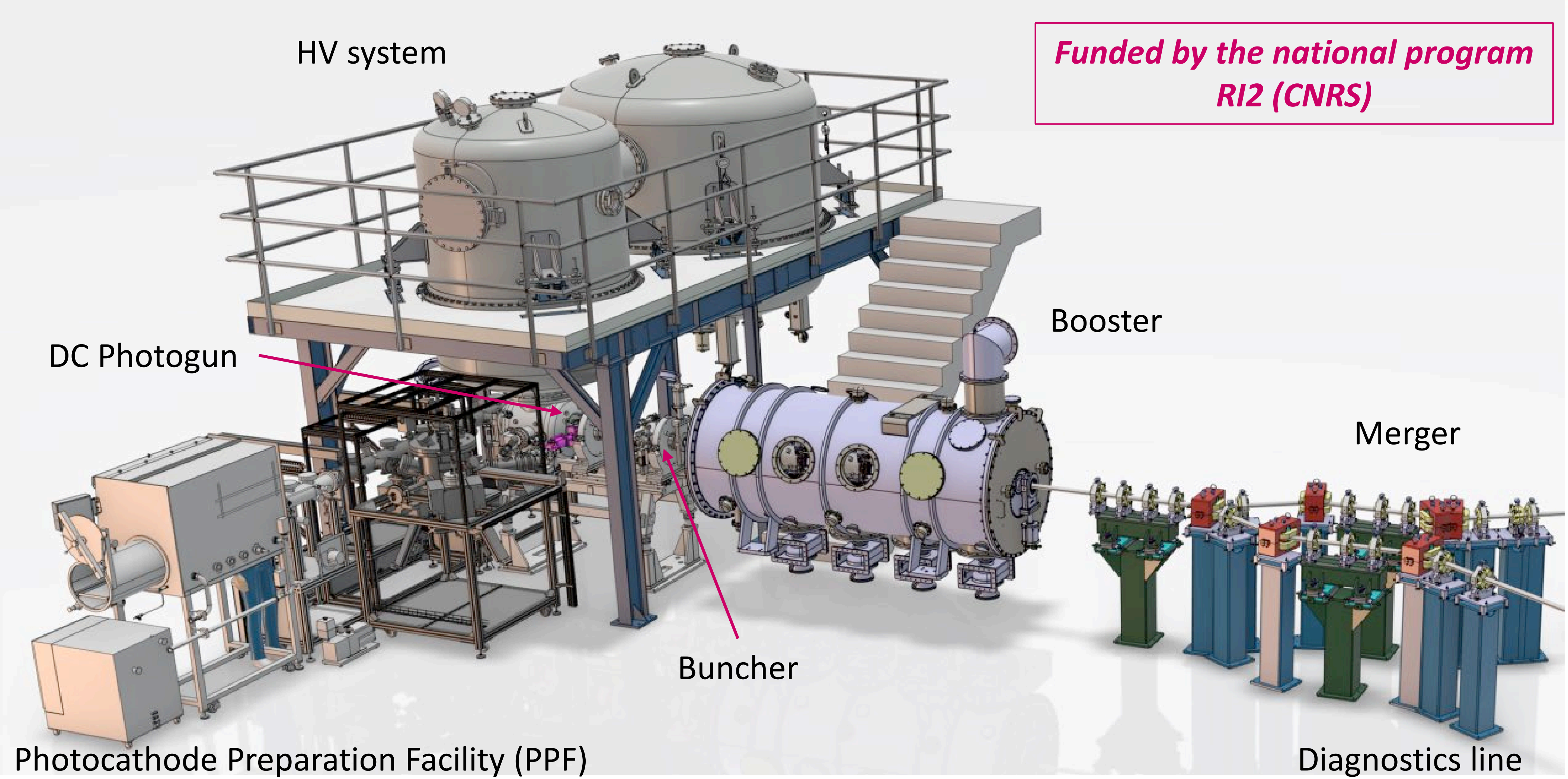
With energy spread compression



	R56	R566	Phase	
Pass 1	-0,05	-8	7	→ 0,6 MeV
Pass 2	-0,8	-8	-11	→ 1,5 MeV
Pass 3			-2	→ 0,05 MeV

$1^\circ \approx$ 1mm path correction
Max : 18mm

The injection line

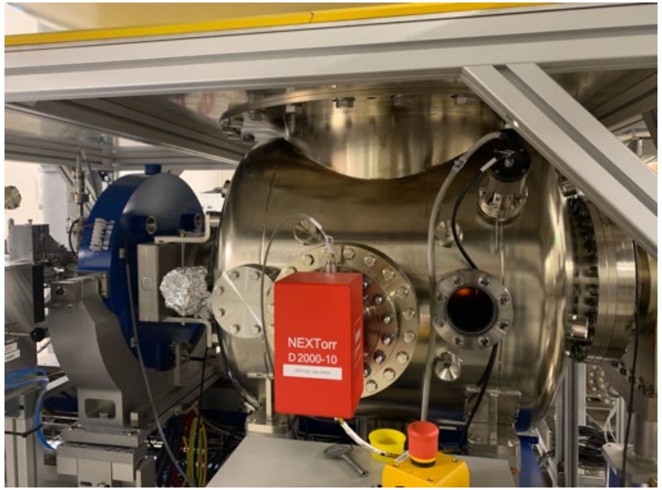


Funded by the national program RI2 (CNRS)

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)

Specifications:

- **Electron beam requirements for PERLE**
    - Q_{bunch} = 500 pC
    - Repetition rate : 40 MHz

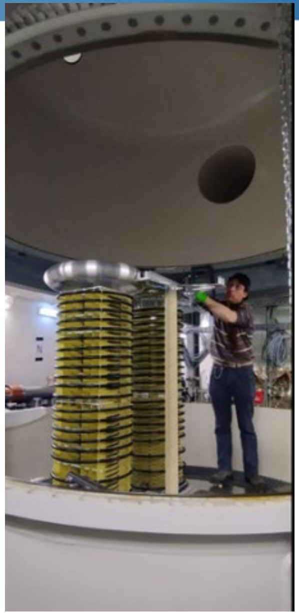
    } I= 20 mA

- **High DC voltage to extract high bunch charge**
    - 350 kV
- **Multi-alkali antimonide photocathode (CsK_2Sb)**
    - Well suited for high current : typical QE ~ 1% (green light) considering degradation
- **Load-lock configuration**
    - Loading of photocathodes without full gun bake for fast exchange
- **Laser power**
    - 5 W (on the photocathode) of green light laser (500-550 nm)
- **Excellent vacuum level for good operational lifetime**
    - ~ 10^{-11} mbar or better
- **Anode bias to limit QE degradation**

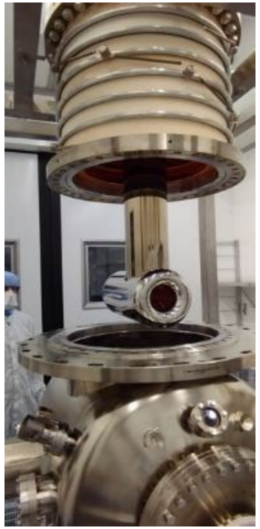
PERLE e- Source

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)



The equipment were received at Orsay end of January

PERLE e- Source

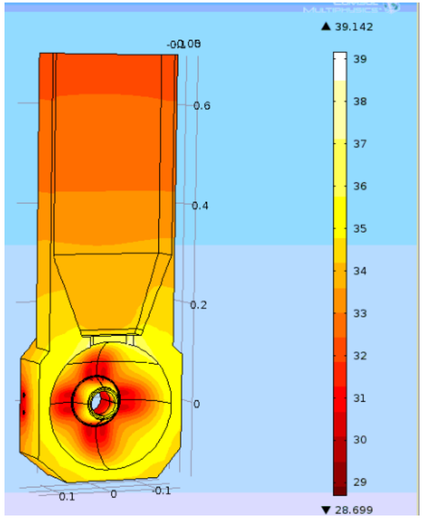
Photocathode laser room installation
(Yesterday photo)

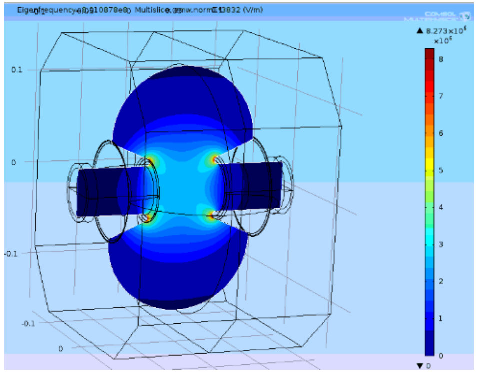
Buncher cavity design

Collaboration IJCLab-ESS Bilbao

- PERLE buncher cERL-type design

(some summary highlights...)





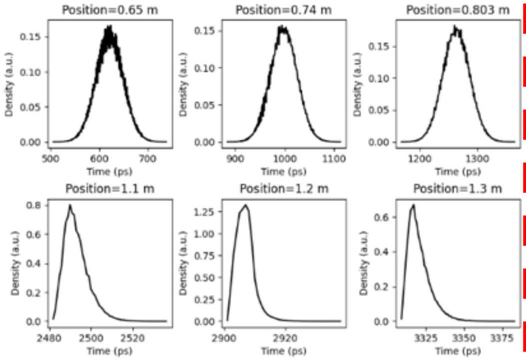
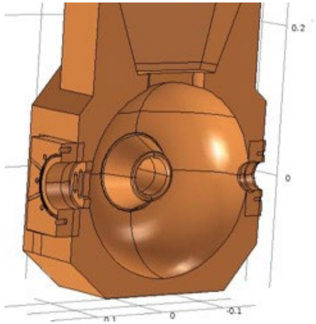


Figure of merit	PERLE buncher cERL-like optimized	Figure of merit	PERLE buncher cERL-like optimized
Input power	5 kW	Iris a	0.070 m
V0	0.21 MV	Iris b	0.020 m
TTF	0.84	Wave guide	WR-975 (274.65 mm, 123.80 mm). Taper=0.5
Gradient (V_0T/L_{cav})	1.392 MV/m	S11dB	-35.81 dB
Power loss	4972 W	ZTT	49.7 MΩ/m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

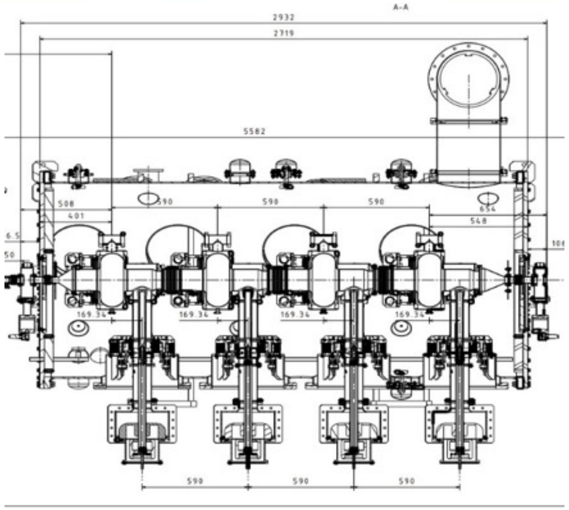


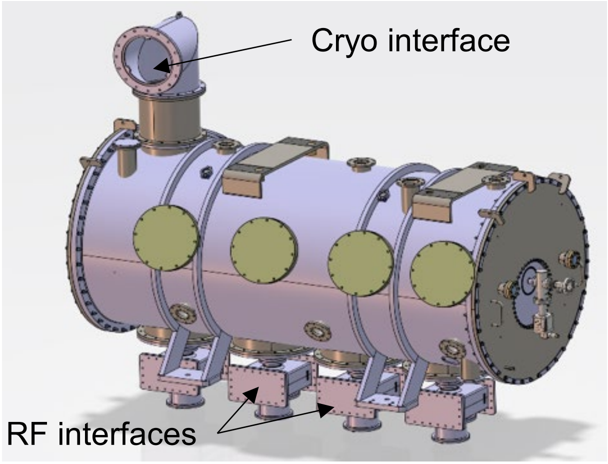
Important progress in the RF design, thermal and beam dynamics simulations of a buncher cavity for PERLE by colleagues from ESS-Bilbao.

Booster specifications and possible design investigation

The booster study just started this summer, the specifications are:

- **Bring the beam energy up 7 MeV:**
  - x4 single cell SRF cavities, Qo > 3E+10 @ 10 MV/m
  - T= 2K (dynamic losses < 5W /cavity)
  - F = 801.58 MHz
  - RF Power/cavity~40kW
  - No HOM couplers but absorbers needed
- **Adapt as much as possible the Linac cryomodule design to the booster requirements:**
  - Same vacuum vessel type (same diameter, alignment supports, openings for accessibility, end-caps...)
  - Same cryogenic interface (jumper connection)
  - Same interface to the RF network
  - Same tuning systems





Booster single cell cavity

More in Raphael Roux Poster

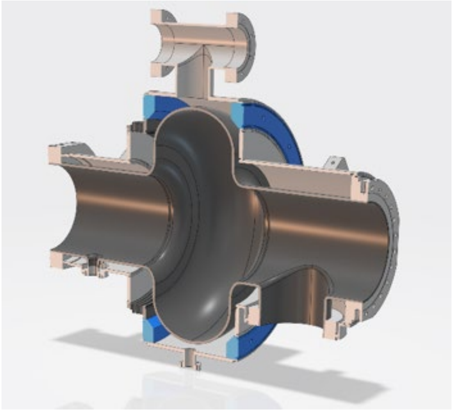
We tried to standardize its design as much as possible w.r to the 5 cell cavity design:

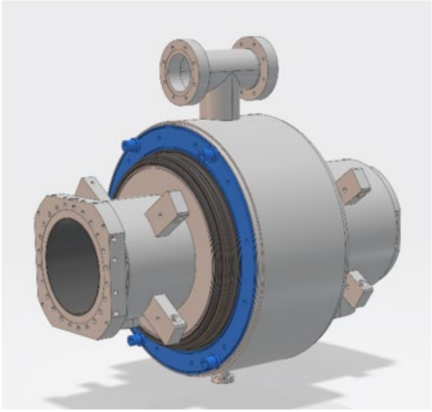
- RF design from the 5-cell cavity
- Helium vessel made also of Titanium
- Same flanges
- Same coupler port aperture
- Same bellows
- Same tuning system
- ... no HOM coupler ports!

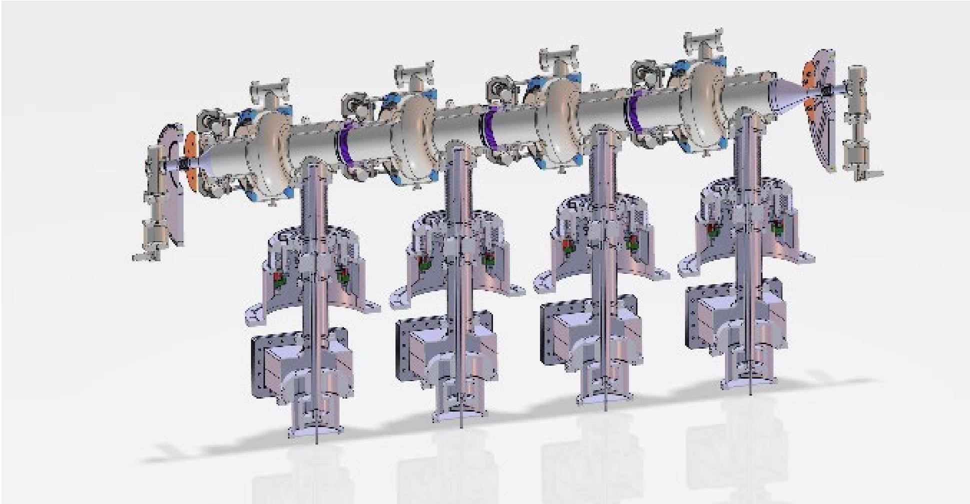
→ To be compatible with our vertical cryostat configuration for testing at 2K

Simulations & Injector design optimization studies were performed with different codes (OPAL and Astra)

More in Connor Monaghan talk and Raphael Roux Poster

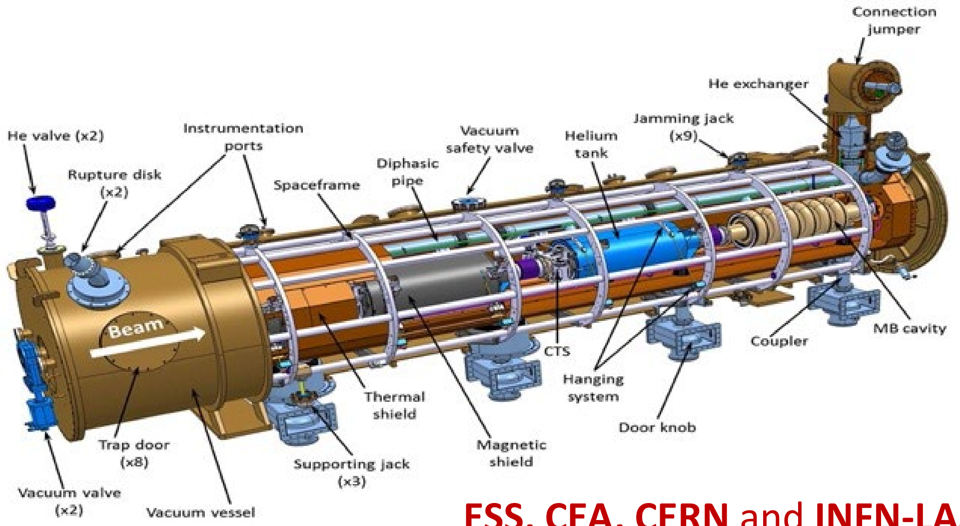






Linac cryomodule design

PERLE 1st cryomodule is adapted from ESS design and will be optimised for efficient high current ERL operation. It will integrate the RF systems (SRF Cavities, HOM couplers & absorbers, Fundamental Power Couplers) optimized and developed within the **European project ISAS**.



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

As In-kind contribution of ESS to iSAS, the 1st cryomodule of the linac will reuse ESS medium beta prototype components:

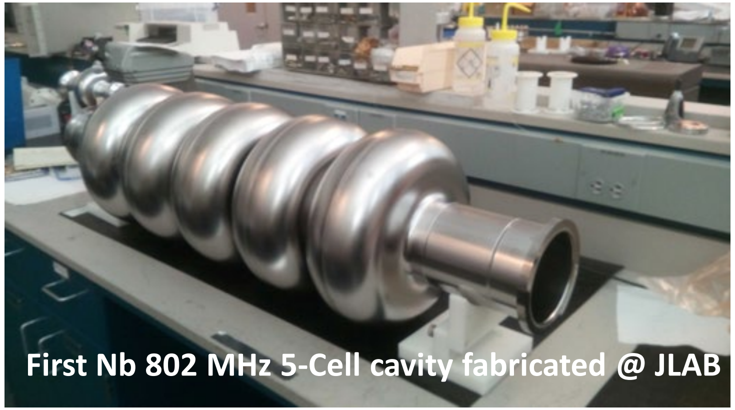
And will host new optimized components developed within the iSAS project

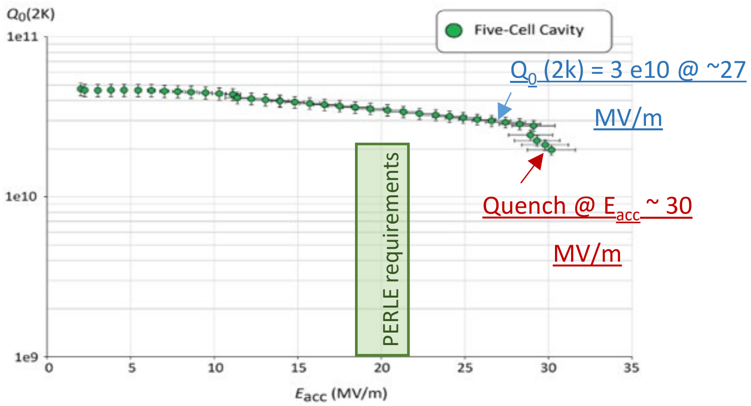
- Cavity string (SRF cavities, RF couplers, Tuning systems, Beam Line Absorbers, HOM couplers...)
- Magnetic shield
- Cryogenics circuit...

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).



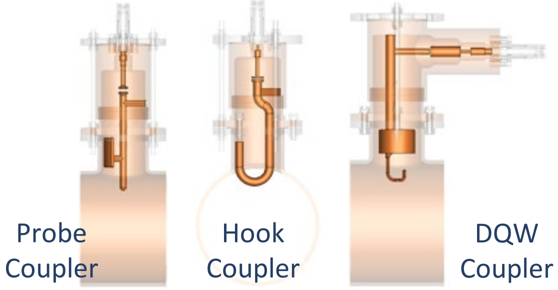


F. Marhauser et al. "802 MHz ERL cavity design and development"- IPAC2018 (Vancouver, BC, Canada)- doi:10.18429/JACoW-IPAC2018-THPAL146

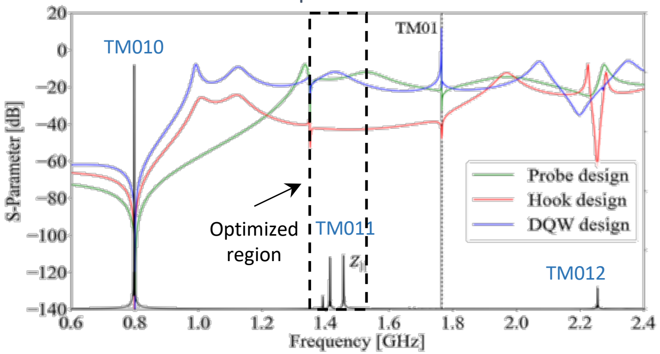
Status of HOM studies :

HOM coupler optimization of 3 different designs

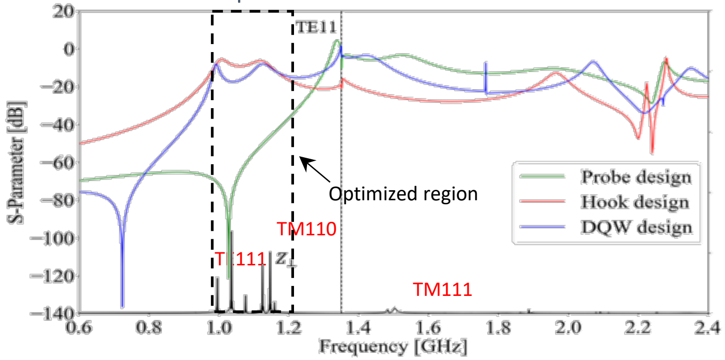
Collaboration IJCLab-Jlab and CERN



Monopole transmission

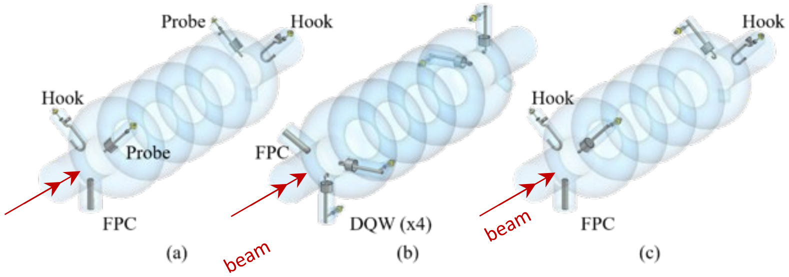


Dipole transmission

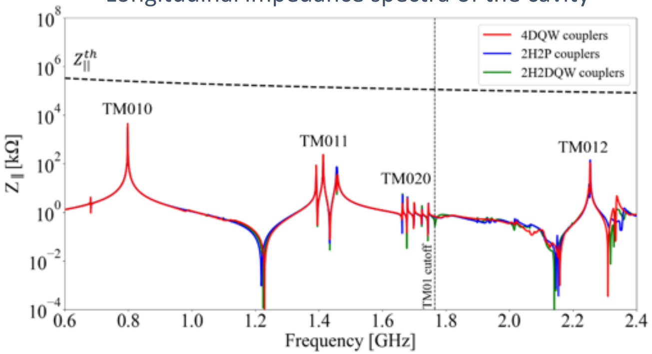


- Couplers were geometrically optimized according to HOM spectrum ($Z_{||}$ and $Z_{\perp}$) & S-parameters btw port 1 (beam pipe) & port 2 (coupler output) were studied.
- The hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)
- The DQW coupler exhibits a better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

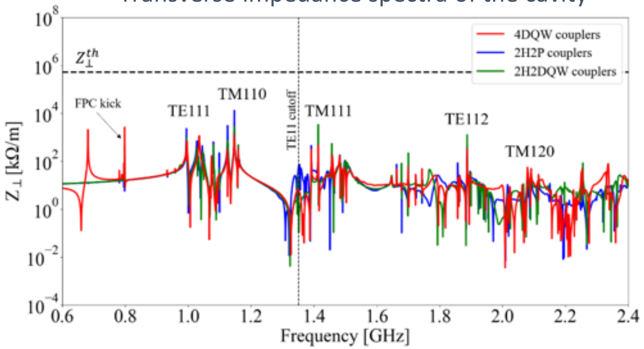
Study of 2 damping schemes with 4 HOM couplers (Especially for dipole HOM extraction)



Longitudinal impedance spectra of the cavity



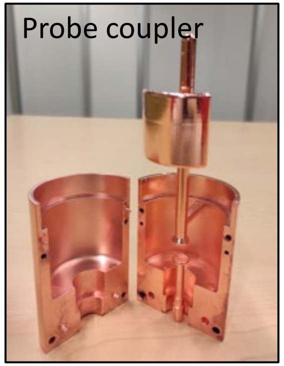
Transverse impedance spectra of the cavity

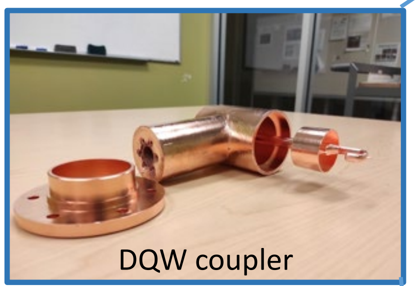


→ Promising results of the 4 DQW scheme: It allows damping both monopole and dipole HOMs below the analytically-computed beam-stability limits

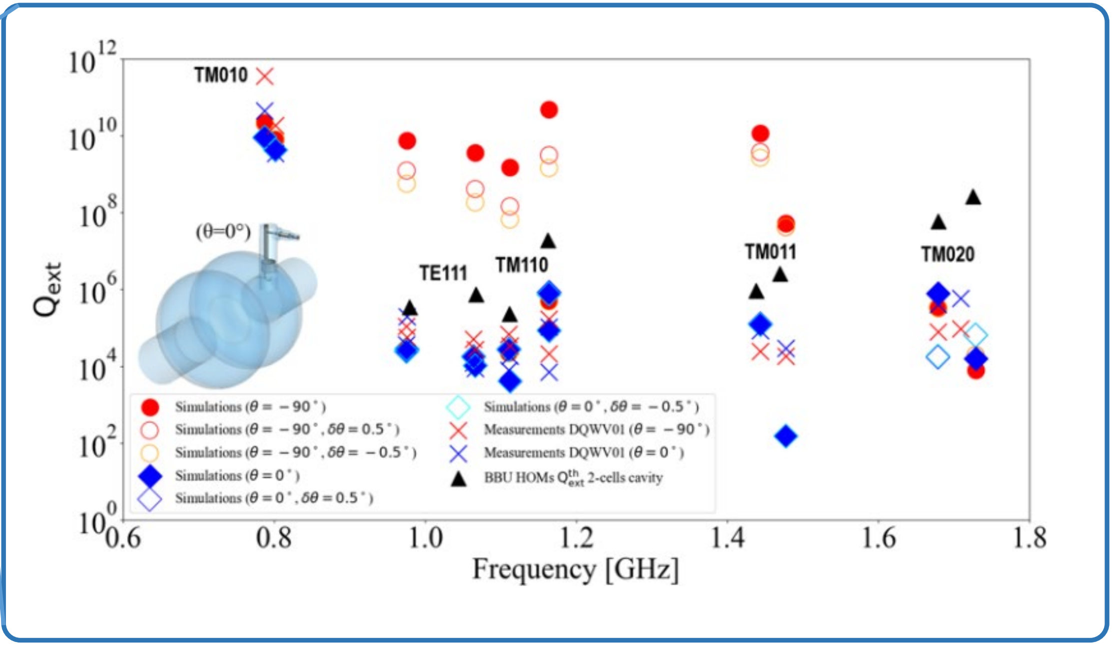
Status of HOM studies :

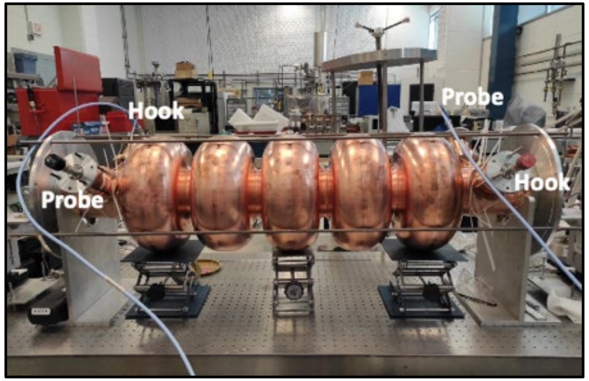
From RF design to performance measurements: **Successful collaborative effort between IJCLab, Jefferson Lab & CERN**

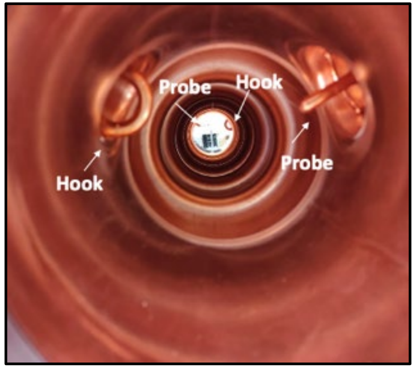




3D-printed prototype (Epoxy Accura 48) copper-coated @CERN







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**

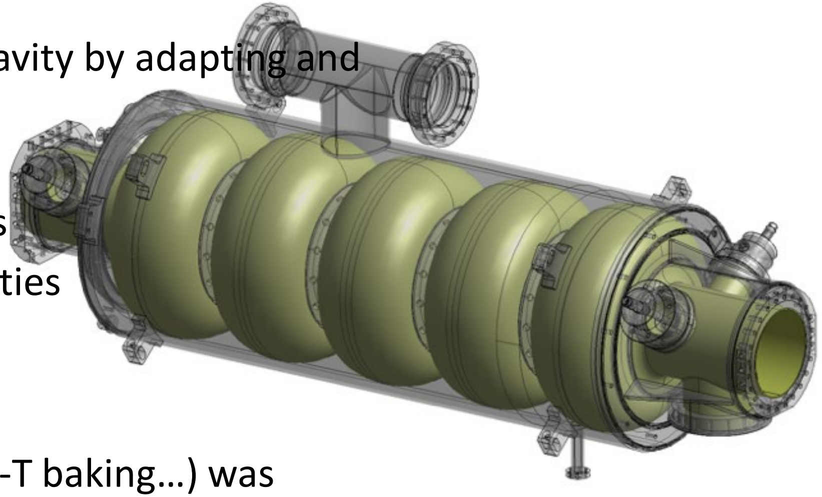
C. Barbagallo et al. "First RF measurements of coaxial HOM coupler prototypes in a copper cavity for the PERLE project"- IPAC'23- MOPA025

SRF cavity : latest news

More in Akira Miyazaki talk

With the results of the previous studies, we complete the design of the 5-Cell cavity by adapting and integrating:

- A helium jacket made of Titanium (including the beam pipes)
- 4 HOM couplers and the fundamental power coupler to the end-groups
- A “classical” tuning system as the one developed for the ESS Spoke cavities
- A BLA (very preliminary design) between cavities
- A “cold” magnetic shield



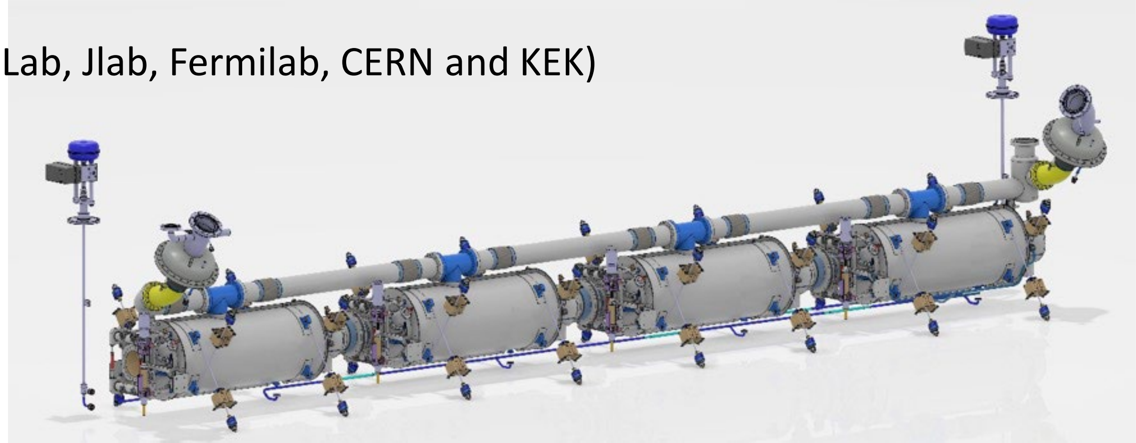
A review meeting on the cavity post-production processes recipes (EP, BCP, Mid-T baking…) was organised end of March with international experts.

→ An R&D program ongoing for recipe optimization (Coll. IJCLab, Jlab, Fermilab, CERN and KEK)

Within iSAS program:

→ The Nb procurement procedure is lunched (for single and multi-cell cavities).

→ It is foreseen to lunch the procurement procedure of 4 cavities also before end of the year.



Conclusions and further comments:

- We are making good progress on design phase, **PERLE TDR is foreseen to be released fall 2025**.
- We adopt a **staging approach to build PERLE** in respect to available funds and in-kind contributions. **More funds are needed for the complete program.**
- **DC-gun + photocathode+ preparation chamber** acquired **by RI within a Collaboration Agreement**. All material has been shipped to IJCLab end of January 2024. Installation is ongoing on the chosen site (The “Igloo” at IJCLab). The **Laser** has been also purchased and delivered.
- **iSAS:** European INFRA-TECH project 11 research partners (**CNRS, CERN, ESS, DESY, VUB, CEA, HZB, INFN, UKRI, UL, EPFL**). Financial support for the construction of the **full LINAC cryomodule** (with IN2P3 matching funds + CM vessel from ESS).
- **Funds obtained within RI2 national program (CNRS)** which should allow to finance **the full injection line and a part of a first tour equipment.**
- Agreement with HZB to recuperate part of the Cryogenic equipment**: Cryogenic plant, valve box and transfer lines.** Materiel transfer to IJCLab is foreseen for October 2026.

In Memory of Max Klein

We lost a friend and a brilliant scientist.

Our particle physics and accelerator community owes him so much.
In particular PERLE would not exist without Max's hard work and tenacity.