R&D toward next generation Energy Recovery Linacs

CNRS/IN2P3/IJCLab (Orsay, France)

Alex Fomin*, Rasha Abukeshek, Walid Kaabi, Julien Michaud, Akira Miyazaki, Raphaël Roux

CNRS/IN2P3/LPSC (Grenoble, France)

Maud Baylac

KEK/iCASA (Tsukuba, Japan)

Hiroshi Sakai, Miho Shimada, Kensei Umemori, Masahiro Yamamoto

Hiroshima University (Hiroshima, Japan)

Lei Guo

**On behalf of the PERLE Collaboration*

Outline

Introduction

- cERL and PERLE in the ERL landscape

Status and prospect of cERL (KEK/iCASA)

Status and prospect of PERLE (IN2P3/IJCLab, LPSC)

Activities in 2025

- FR → JP: Participation in cERL operation (November—December)
- JP → FR: seminar & discussions on photocathode production and characterization

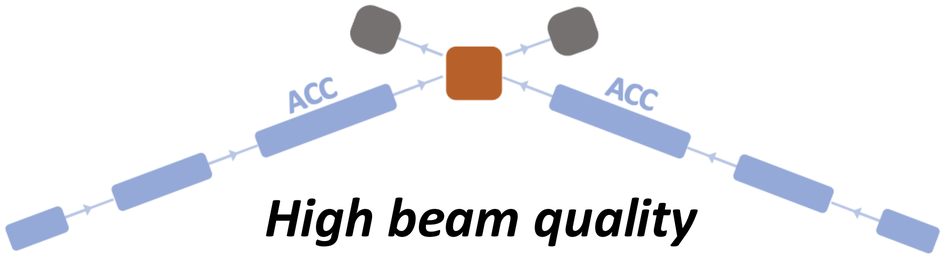
Expected activities in 2026

- FR → JP: Participation in **cERL operation** (November)
- JP → FR: Participation in **ERL'26** and **PhASE26**; validation of **photocathode preparation recipe** transfer; **surface analysis at XPS** (IJCLab)

Conclusion

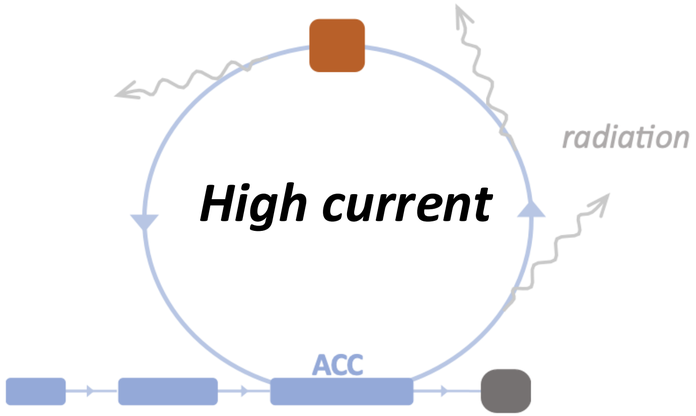
ERL concept and why it matters

Linear colliders



High beam quality

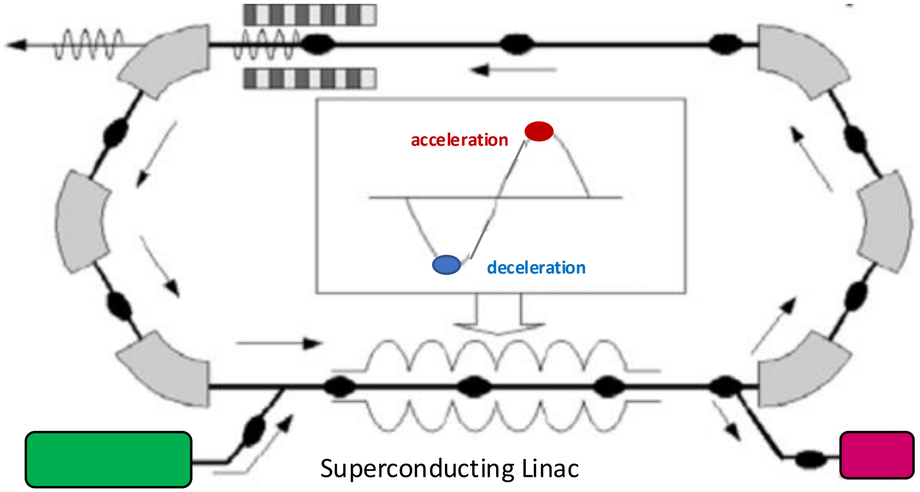
Circular colliders



Combine the advantages of linear and circular accelerators

Energy Recovery Linac

ERL Loop

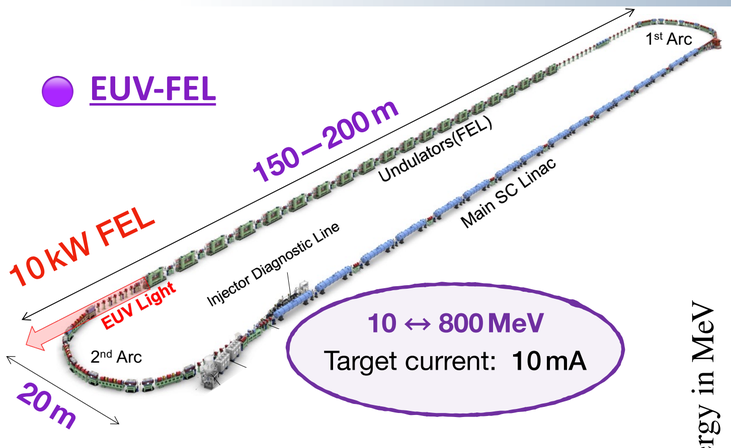


<u>Applications</u>

- Colliders
- FEL
- Nuclear physics

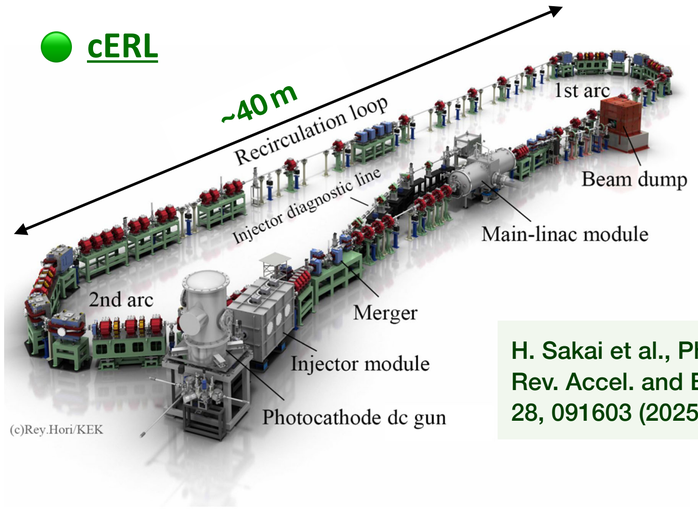
cERL and PERLE in the ERL landscape

EUV-FEL

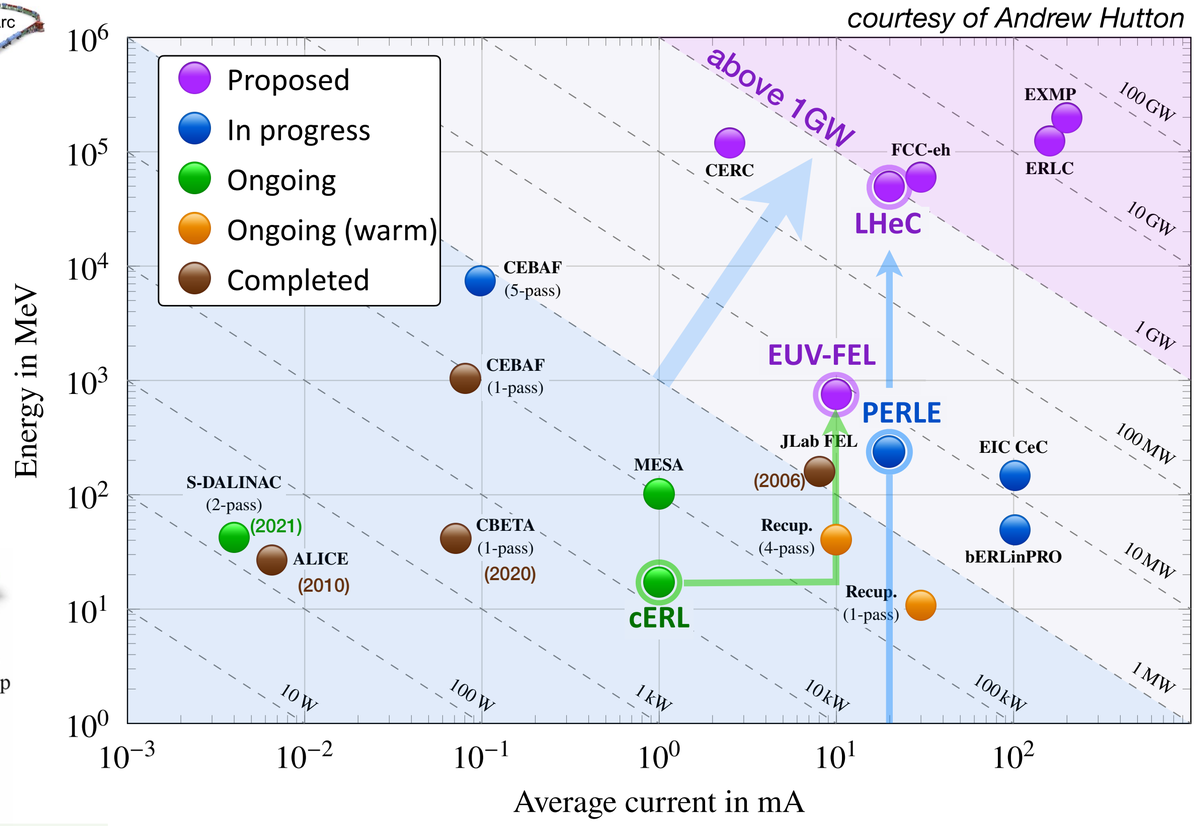


10 ↔ 800 MeV
Target current: 10 mA

cERL

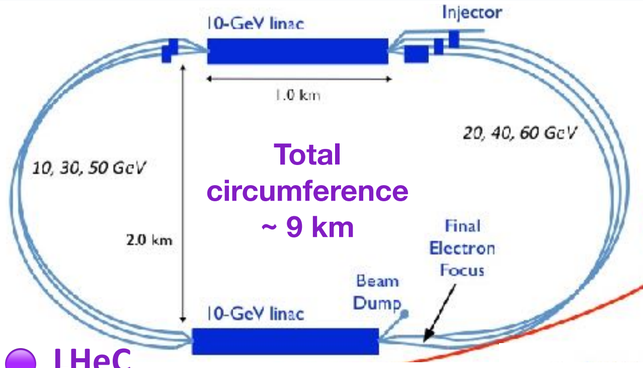


courtesy of Andrew Hutton



H. Sakai et al., Phys. Rev. Accel. and Beams 28, 091603 (2025)

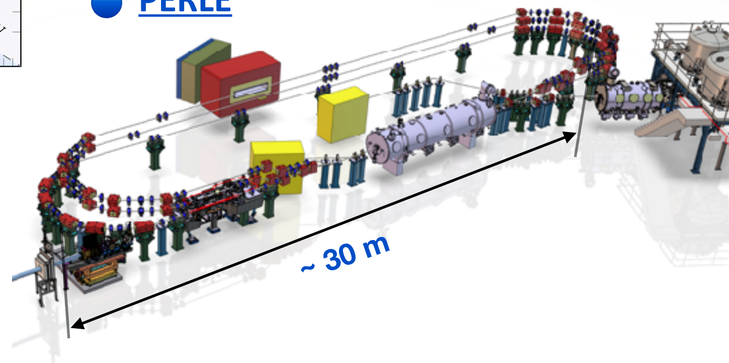
LHeC



The same bunch parameters

- Injection rate: 40 MHz
- Bunch charge: 500 pC
- Target current: 20 mA
- RF cavities: 802 MHz

PERLE



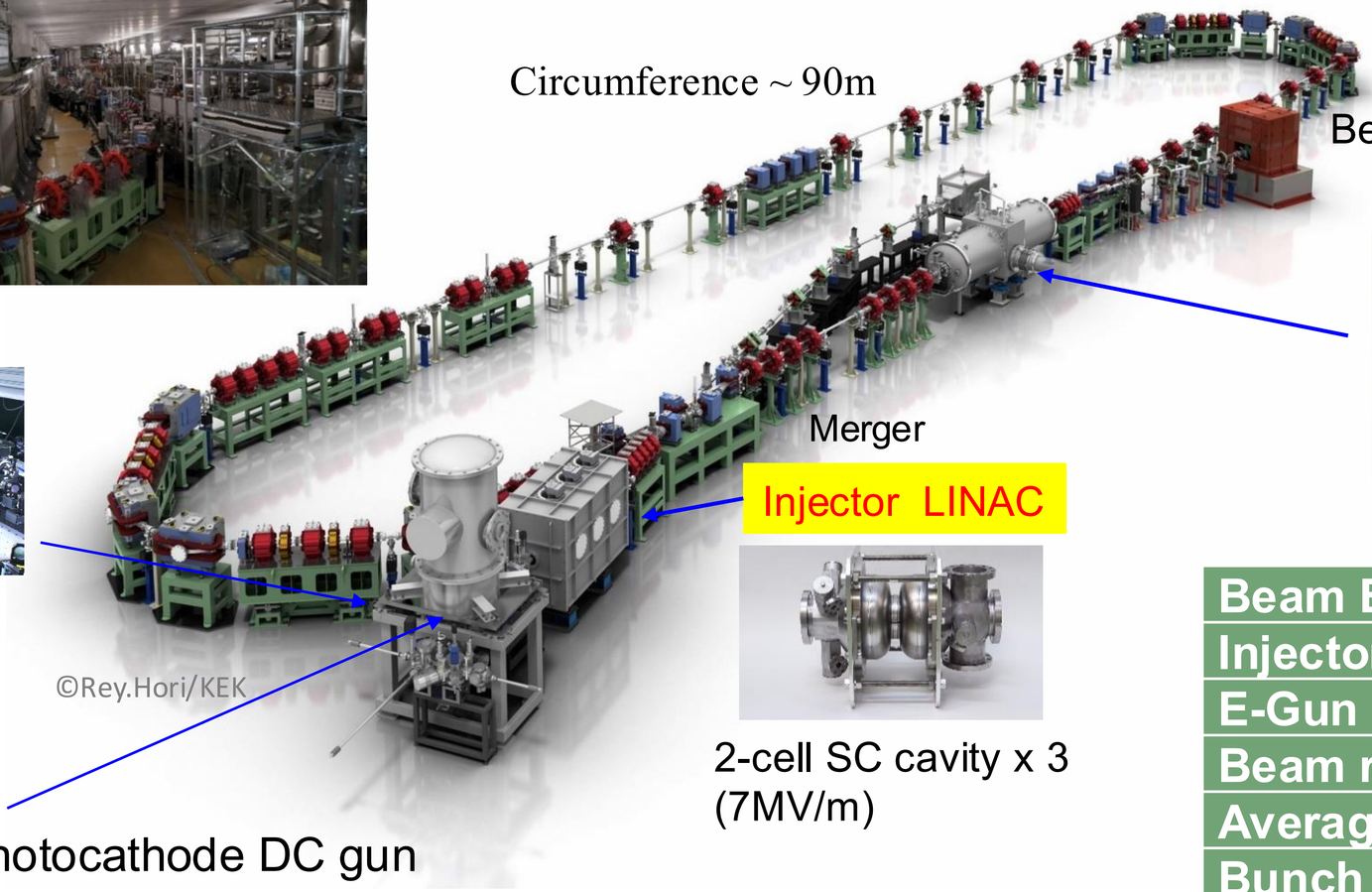
- **Demonstrate high-current, low-emittance CW ERL operation**
- **Validate energy recovery and beam commissioning methods**
- **Serve as a testbed for future high-power applications** e.g. the KEK EUV-FEL direction

- **Demonstrate multi-turn and high current operation**
- **Validation of technical choices:** DC electron gun, 802 MHz SRF, non-invasive diagnostics
- **Host experiments:** Fabry–Perot inverse Compton source, DESTIN (inelastic eA scattering)

Status of Compact ERL (cERL) in KEK

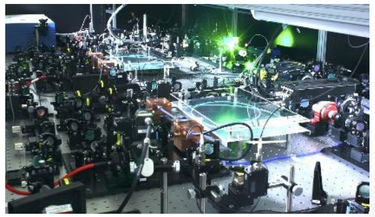
H. Sakai et al., Phys. Rev. Accel. and Beams 28, 091603 (2025)

→ industrial applications

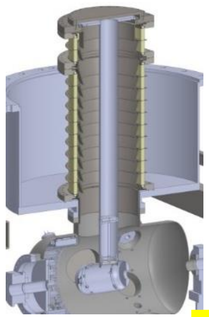


1.3 GHz 9-cell SC cavity x 2 (8 MV/m)

CW laser



2-cell SC cavity x 3 (7MV/m)



Photocathode DC gun

500kV DC Gun (highest DC voltage in the world)

Operating parameters

Beam Energy	17.6 MeV
Injector Energy	3.0 – 5.0 MeV
E-Gun Energy	500 keV
Beam repetition	1.3 GHz
Average current	1 mA CW (max)
Bunch charge	60 pC/bunch (max)
Operation mode	CW or Burst

Future prospect of ERL activities in KEK/iCASA $1\ \mathrm{mA} \rightarrow 10\ \mathrm{mA}$

Towards Extreme-Ultraviolet (EUV)-FEL light source based on ERL

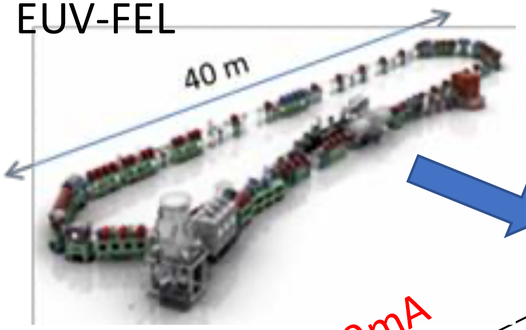
More than 10 mA Energy recovery and high brightness gun will be established in cERL beam operation with ERL-SASE-FEL.

10-kW class EUV sources are required for Next Generation Lithography (>> 250 W by Laser Produced Plasma)

→ ERL-FEL is the most promising option

- High EUV power (> 10 kW) with CW short pulses (SASE-EUV-FEL)
- Low electric power consumption (99% recycle) thanks to energy recovery

cERL as a prototype of EUV-FEL



Parameters	Design
Beam energy	800 MeV
Beam current	10 mA

Acceleration/Deceleration
800MeV⟷ 10MeV

JST K Program awarded 2025 for prototyping phase

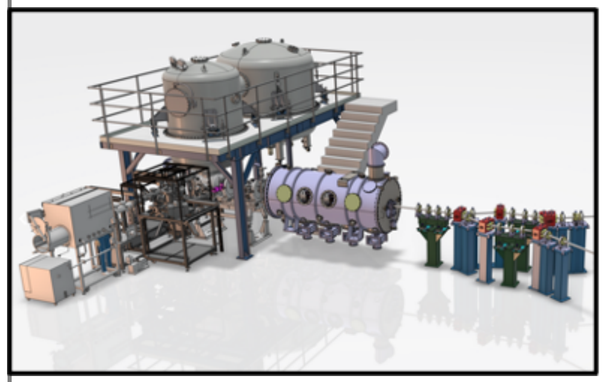
H, Kawata, et al, Journal of Micro/Nanopatterning, Materials, and Metrology 21(02) (2022)

PERLE in a nutshell: target machine and staged build

Main target parameters:

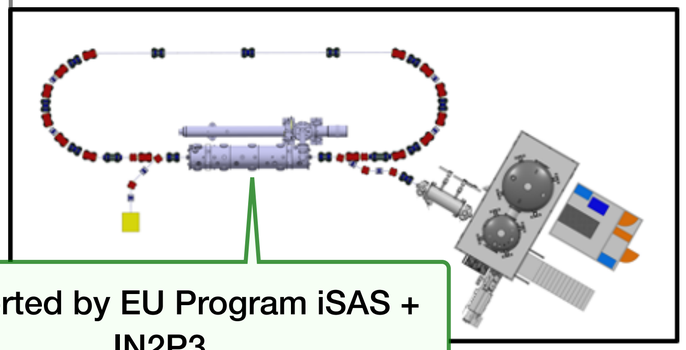
Injection energy	7 MeV
Electron beam energy	250 MeV
Normalised Emittance	6 mm mrad
Average beam current	20 mA
Bunch charge	500 pC
Bunch length	3 mm
Bunch spacing	25 ns
RF frequency	801.58 MHz
Duty factor	CW

Phase 1: Injector Line



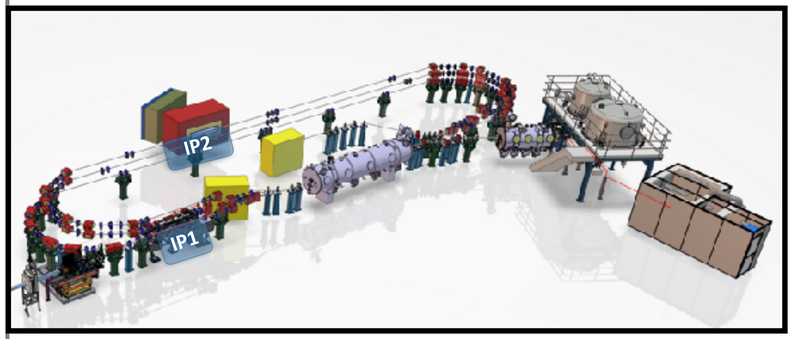
Supported by National Program France 2030 / ANR

Phase 2: PERLE Single Turn



Supported by EU Program iSAS + IN2P3

Phase 3: PERLE 250 MeV



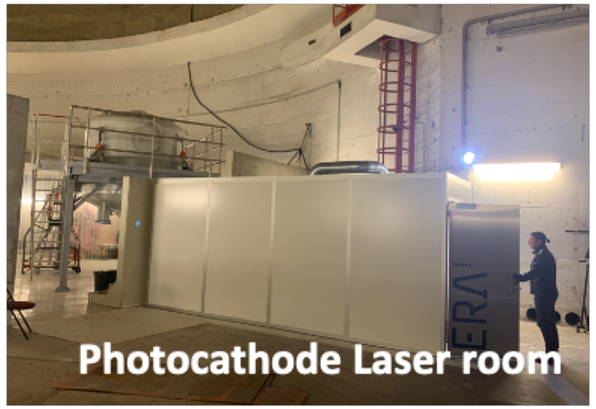
TDR and Prototyping Phase

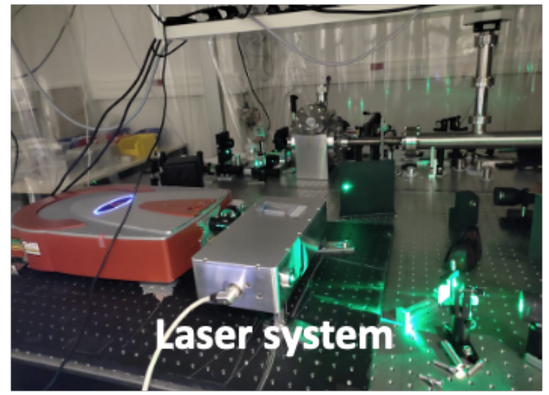
2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031

PERLE status:

03.2024 — Start of building phase

04.2026 — HV conditioning up to 350 kV (ongoing)





This work received government funding managed by the Agence Nationale de la Recheche (ANR) in the France 2030 framework - reference ANR-24-RRII-0001

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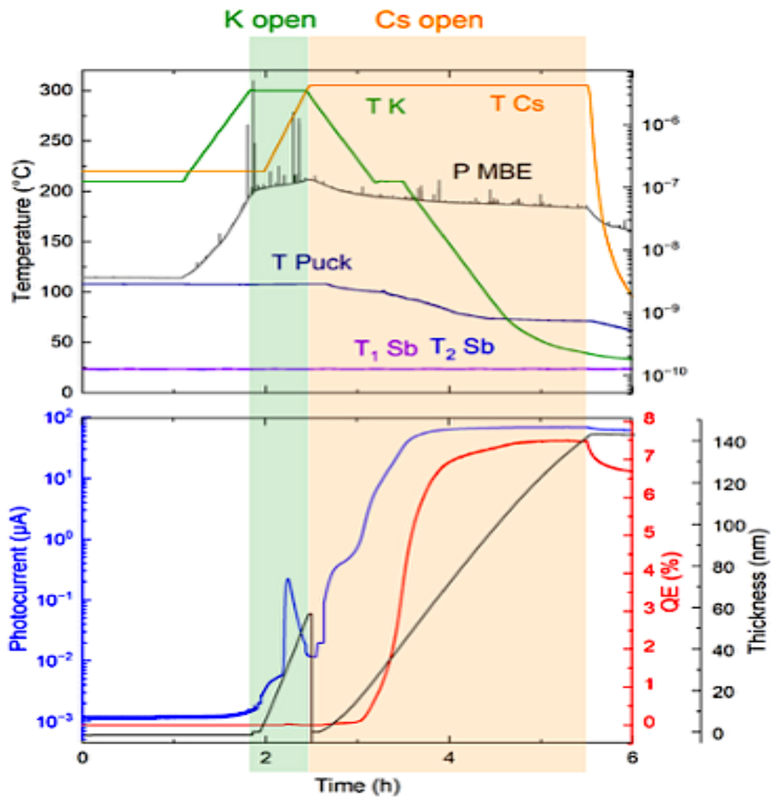
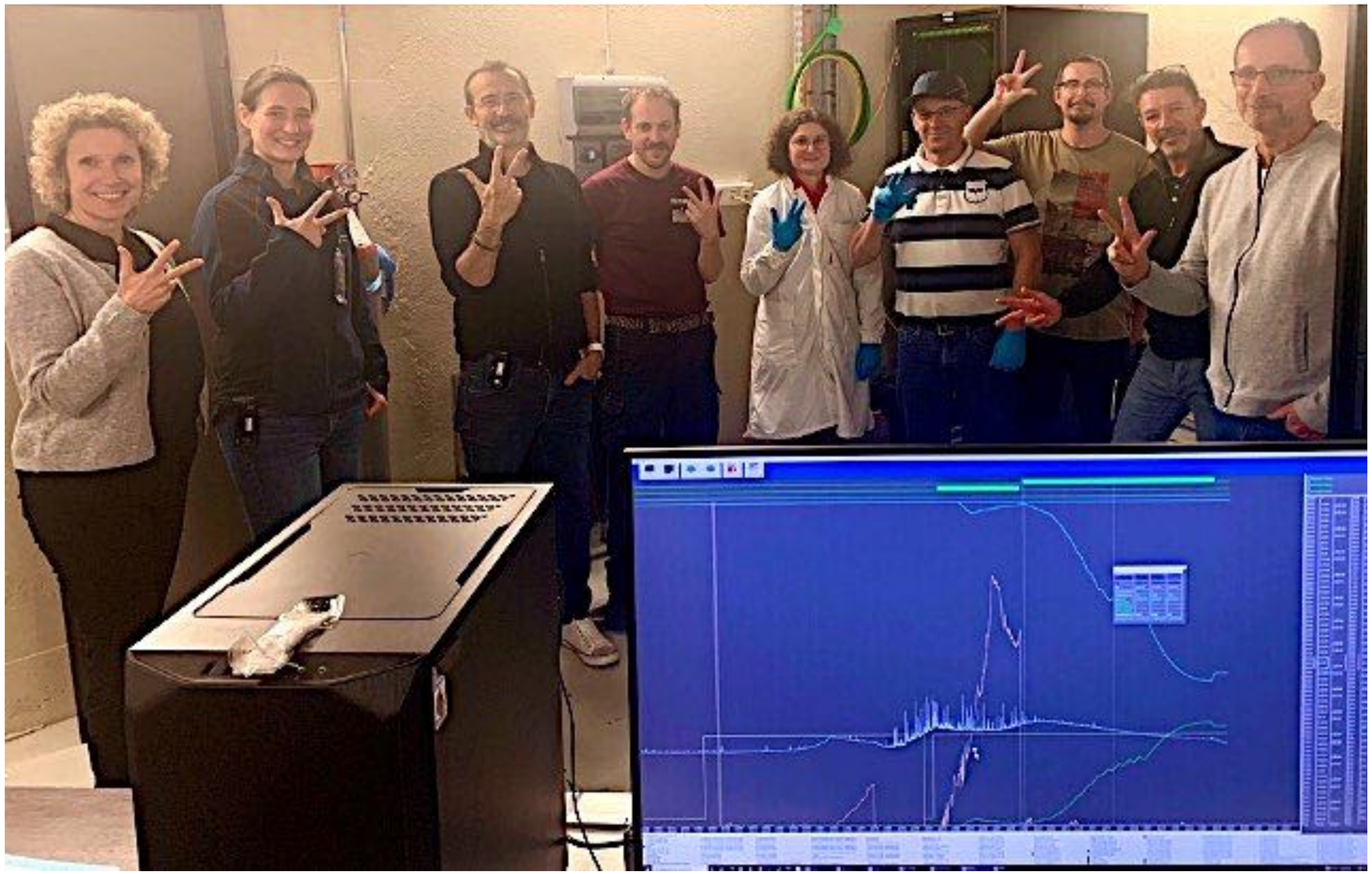
04.2026 — CsK_2Sb synthesized, QE = 6.5%





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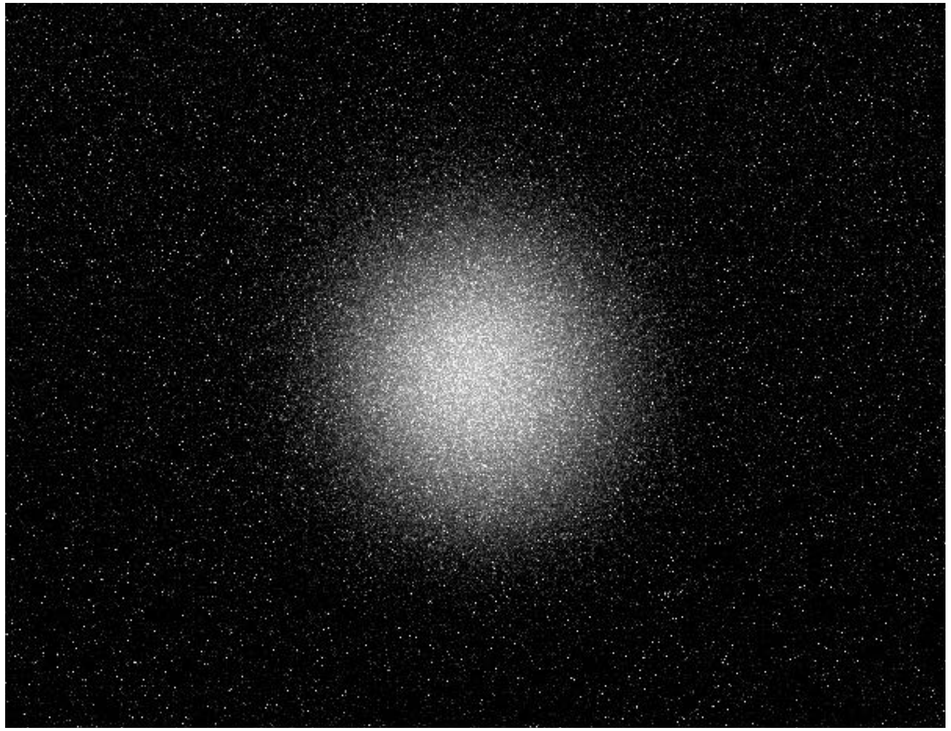
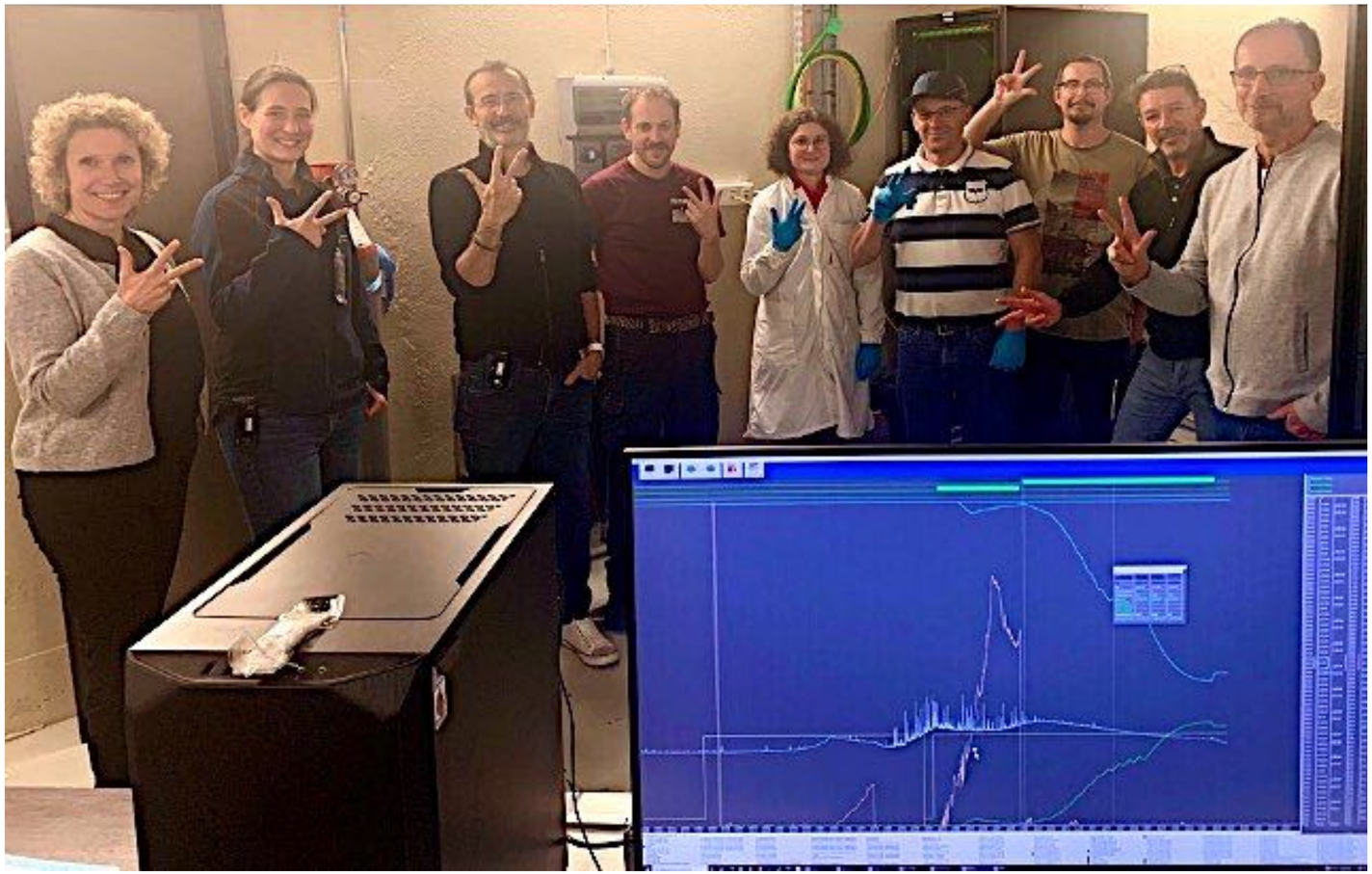
11.05.2026 — **First electrons !!!**





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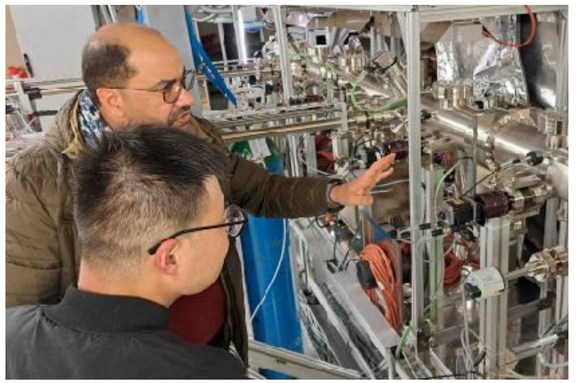
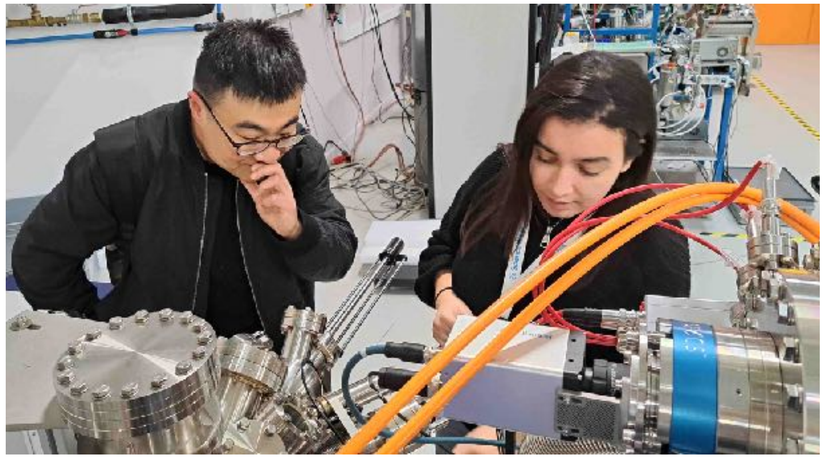
Activities in 2025 (JP → FR)

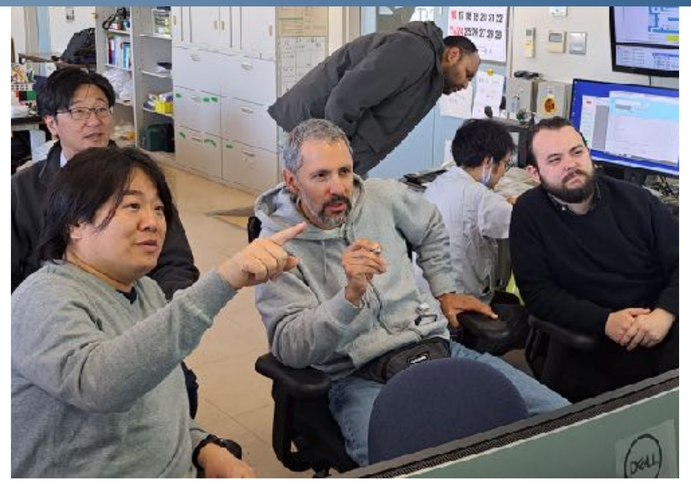
- Visit of **Lei Guo** to IJCLab for **discussions** with the **accelerator group** and **laboratory management**.
- Tour of the **PERLE bunker** (Igloo) and the **Vidé et Surface platform**, including presentation of **XPS**, **SEM**, and **XRD surface analysis** techniques.
- Technical exchanges on photocathode development and preparation of future collaboration on photocathode production and characterization.
- Seminar: “An **Introduction to CsK_2Sb Photocathodes**: Growth Physics and Performance Optimization”, covering growth mechanisms, performance optimization, and graphene-based substrate reuse concepts.
- Exploration of photocathode preparation know-how transfer, including validation of **Japanese preparation recipes** at IJCLab and potential **XPS characterization** of photocathodes produced in Hiroshima.

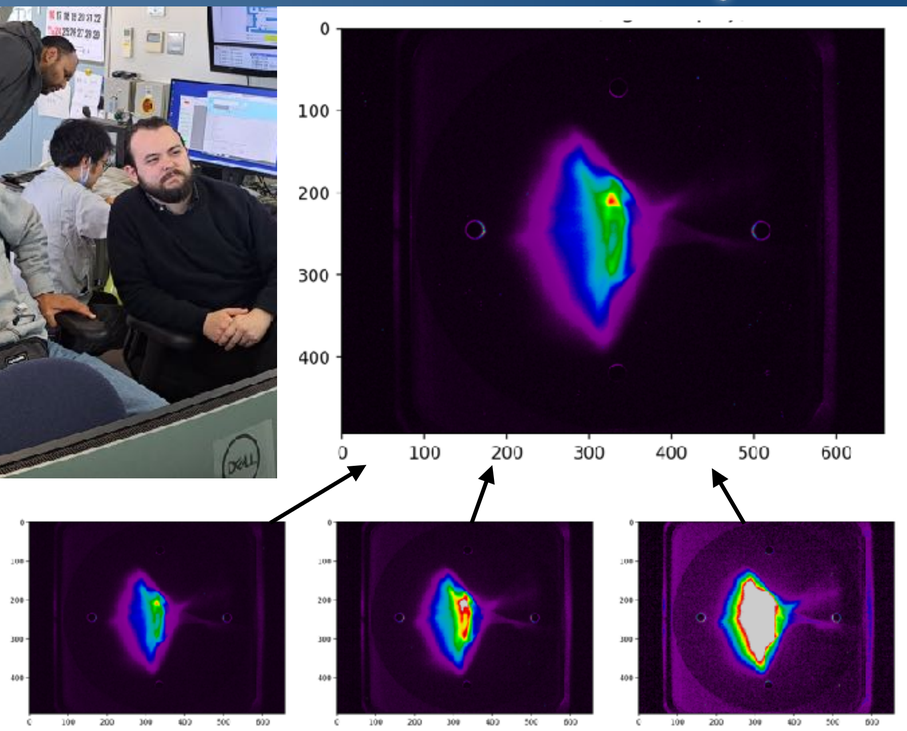


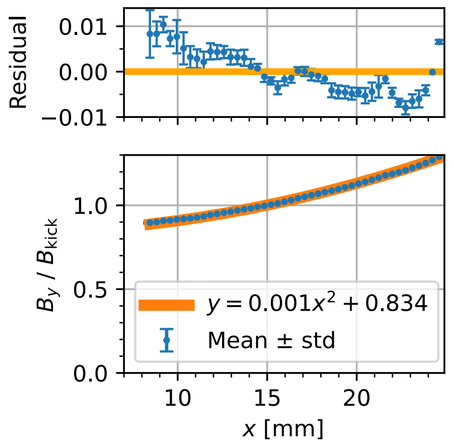


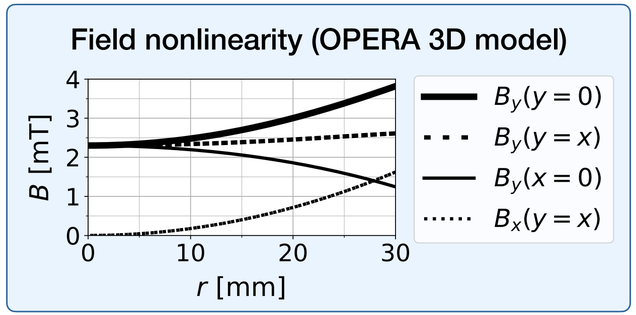
Activities in 2025 (FR → JP)

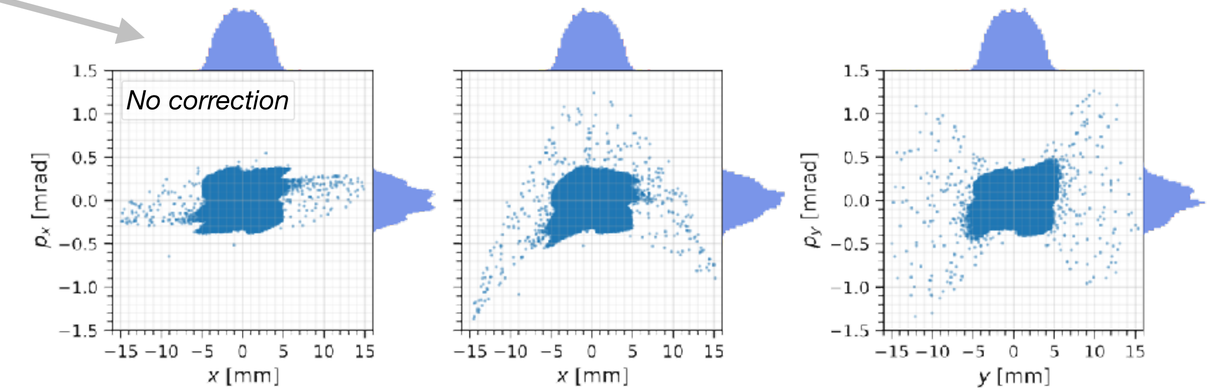
- **One-month** visit of **Alex Fomin** and PhD student **Connor Monaghan** to KEK for **participation in cERL beam commissioning**.
- **Experimental study of injector beam halo formation** under space-charge dominated conditions relevant for PERLE.
- Transverse beam profile measurements performed at several locations in the injector and merger sections.
- Application of **high dynamic range imaging** techniques to characterize beam halo formation and its **sensitivity to machine tuning parameters**.
- **Beam-based** magnetic field **mapping** of a quadrupole magnet with embedded correctors at cERL.
- **Comparison** of measured magnetic field with **simulations** for the corresponding **PERLE magnet**.
- Follow-up studies at IJCLab, first **simulations for the PERLE lattice** using the **new magnet design**.











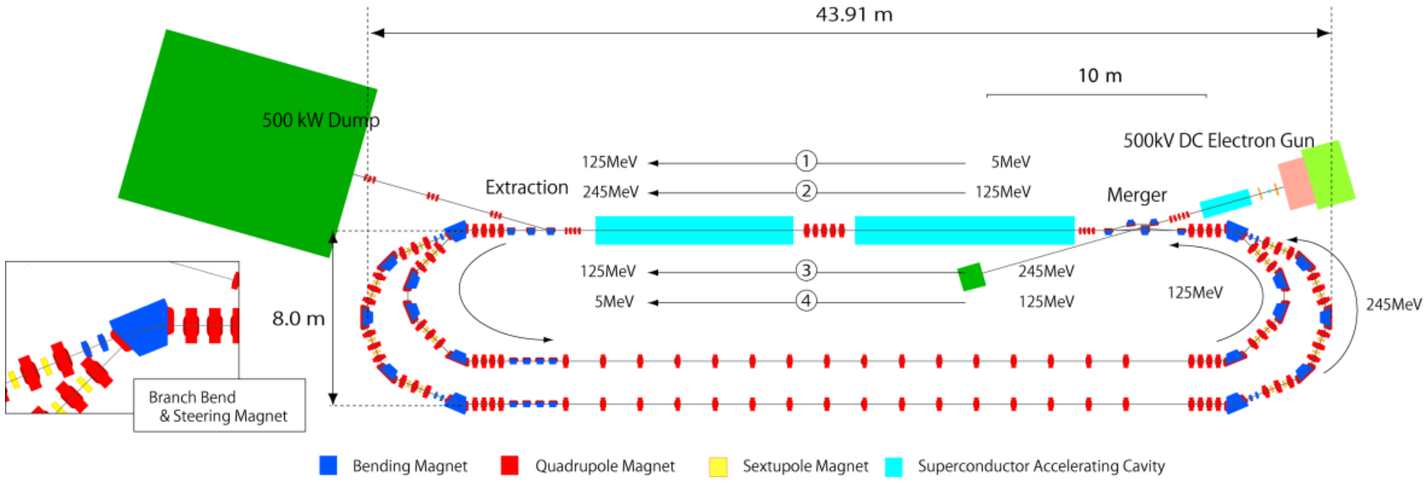
Proposal for 2026 (FR → JP)

- **Participation** of two PhD students and two researchers from IJCLab in **cERL beam commissioning** and operation.
- Gain practical experience in **beam tuning, diagnostics, beam alignment**, and optics commissioning for PERLE.
- Possible dedicated cERL beam time for PERLE-related studies (under discussion):
  - **longitudinal beam dynamics**,
  - **beam halo formation** and mitigation using **collimation** systems.
- **Co-funding support** for extended stays in Japan.

EAJADE
Europe-America-Japan Accelerator Development Exchange Programme

Proposal for 2026 (FR → JP)

- **Visit of Lei Guo to IJCLab** to collaborate on CsKSb photocathode production for PERLE.
- Exploration and validation of **photocathode preparation recipe** transfer from Japan to IJCLab.
- Use of IJCLab advanced surface analysis facilities (**XPS**) to **characterise photocathodes produced in Japan**.
- Seminar by **Miho Shimada** on multi-turn cERL operation and **discussions on beam dynamics for multi-turn ERLs**.
- Continued **collaboration on ERL** beam dynamics, lattice design, and diagnostics studies.
- Japanese contributions to **international ERL activities in September of 2026**: ERL'26 workshop, photocathode workshop PhASE26, PERLE beam dynamics review.



Conclusions

Energy Recovery Linac is one of the possible options for future accelerator

- Efficiency → improved sustainability
- Still a lot of R&D subjects are lying in front of us

KEK/iCASA, IN2P3/IJCLab and LPSC are planning to develop next generation ERL

Very strong technical synergy

- KEK has developed and operated cERL as well as future projects (higher energy)
- IJCLab is building PERLE

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  validation of **photocathode preparation recipe** transfer;
  surface analysis at XPS (IJCLab)