R&D toward next generation Energy Recovery Linacs

CNRS/IN2P3/IJCLab

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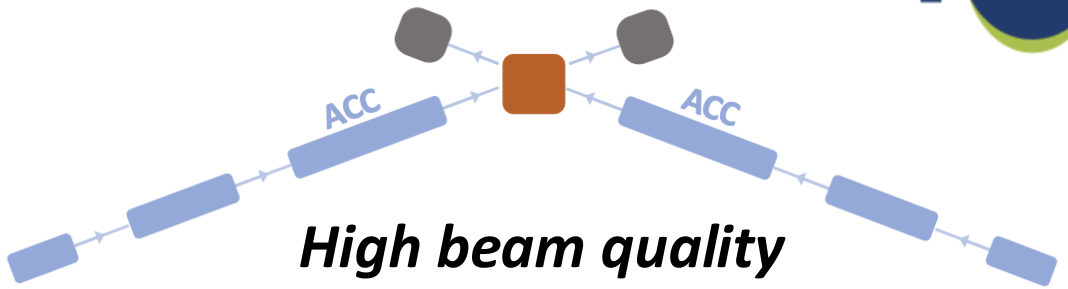
Outline

- Energy Recovery Linac and its potential and challenges
- Status and prospect of cERL (KEK/iCASA)
- Status and prospect of PERLE (IN2P3/IJCLab)
- Activities in 2024
  - FR → JP: ERL2024 workshop + participation in cavity experiment
  - JP → FR: seminar & discussions dedicated to DC gun
- Expected activities in 2025
  - FR → JP: Participation in cERL operation (November)
  - JP → FR: photocathode and/or multi-turn beam dynamics
- Conclusion

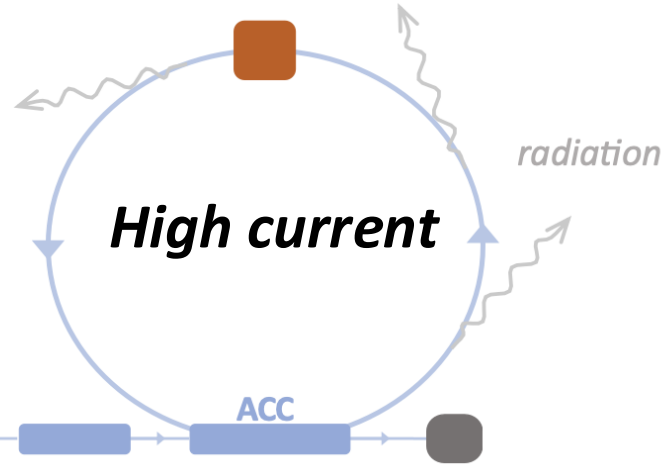
Toward more sustainable accelerators

Linear colliders



High beam quality

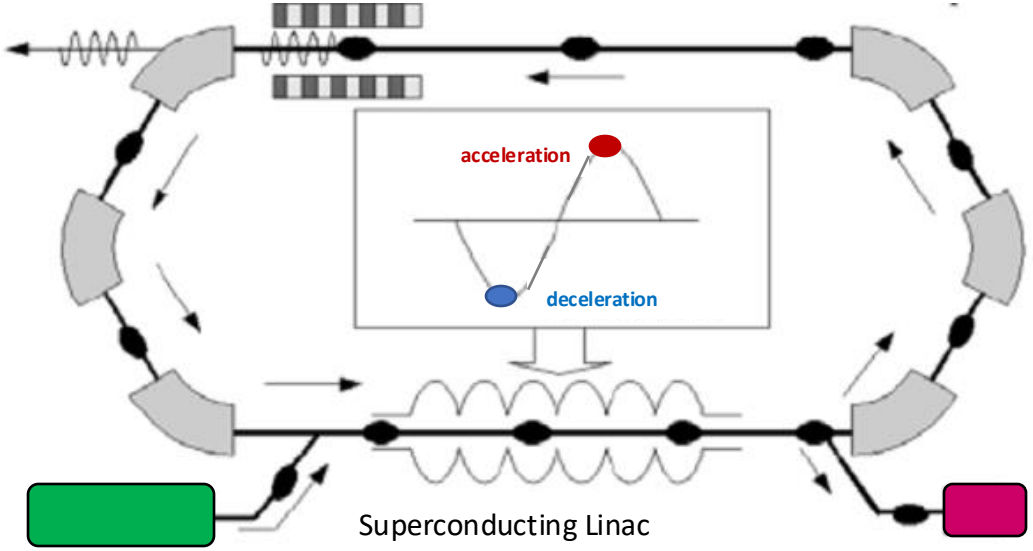
Circular colliders



Combine the advantages of linear and circular accelerators

Energy Recovery Linac

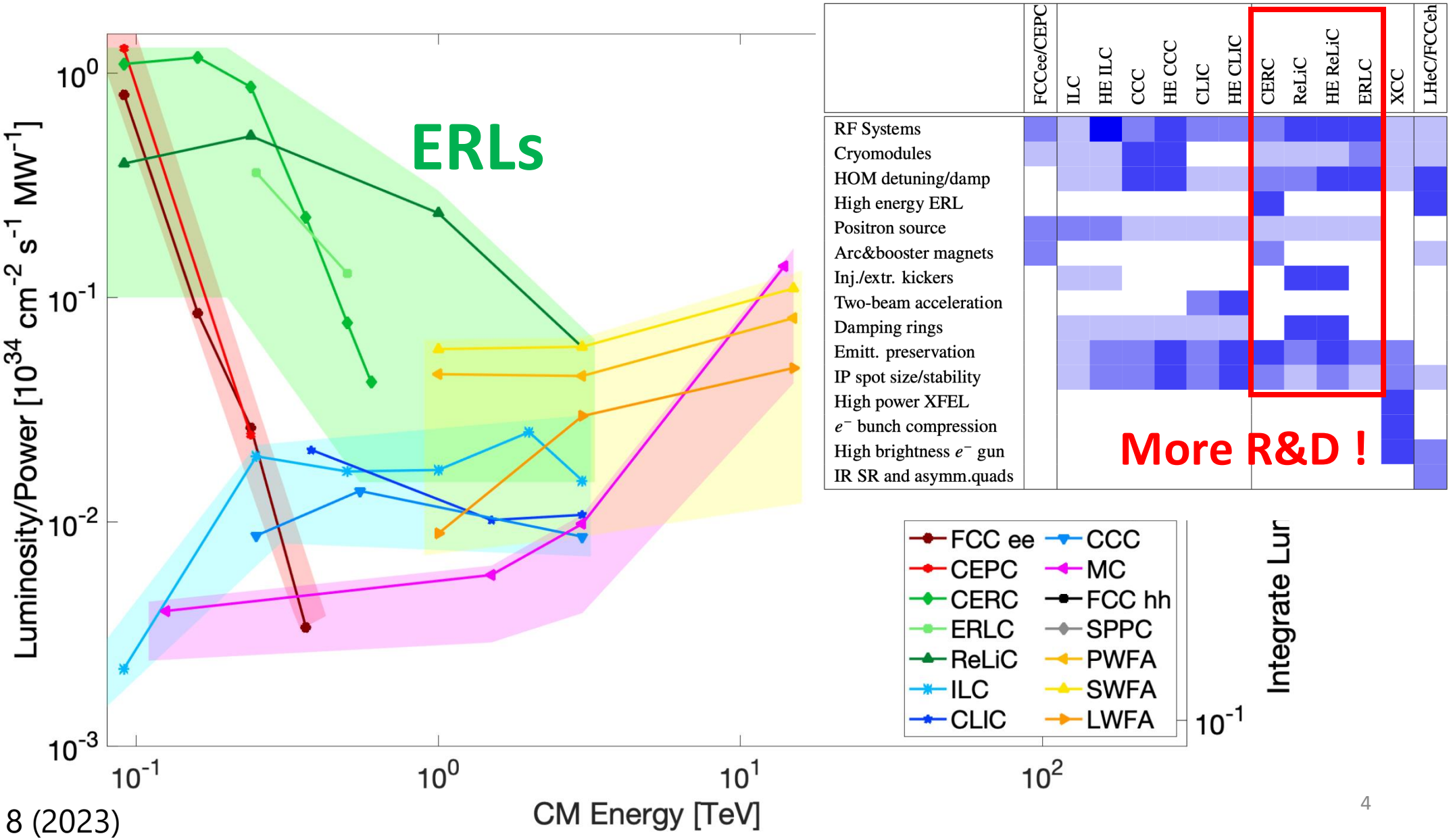
ERL Loop



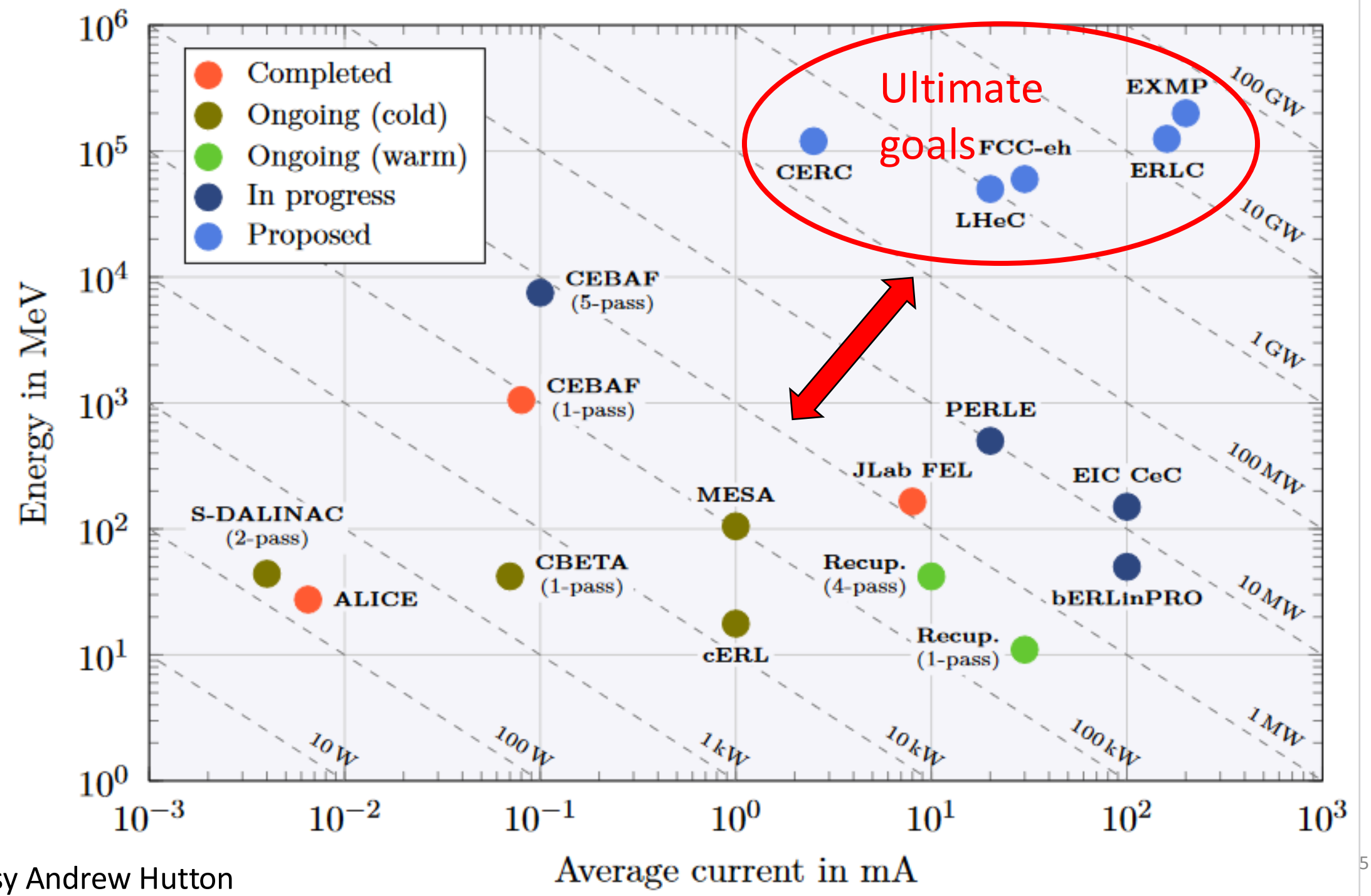
<u>Applications</u>

- Colliders
- FEL
- Nuclear physics

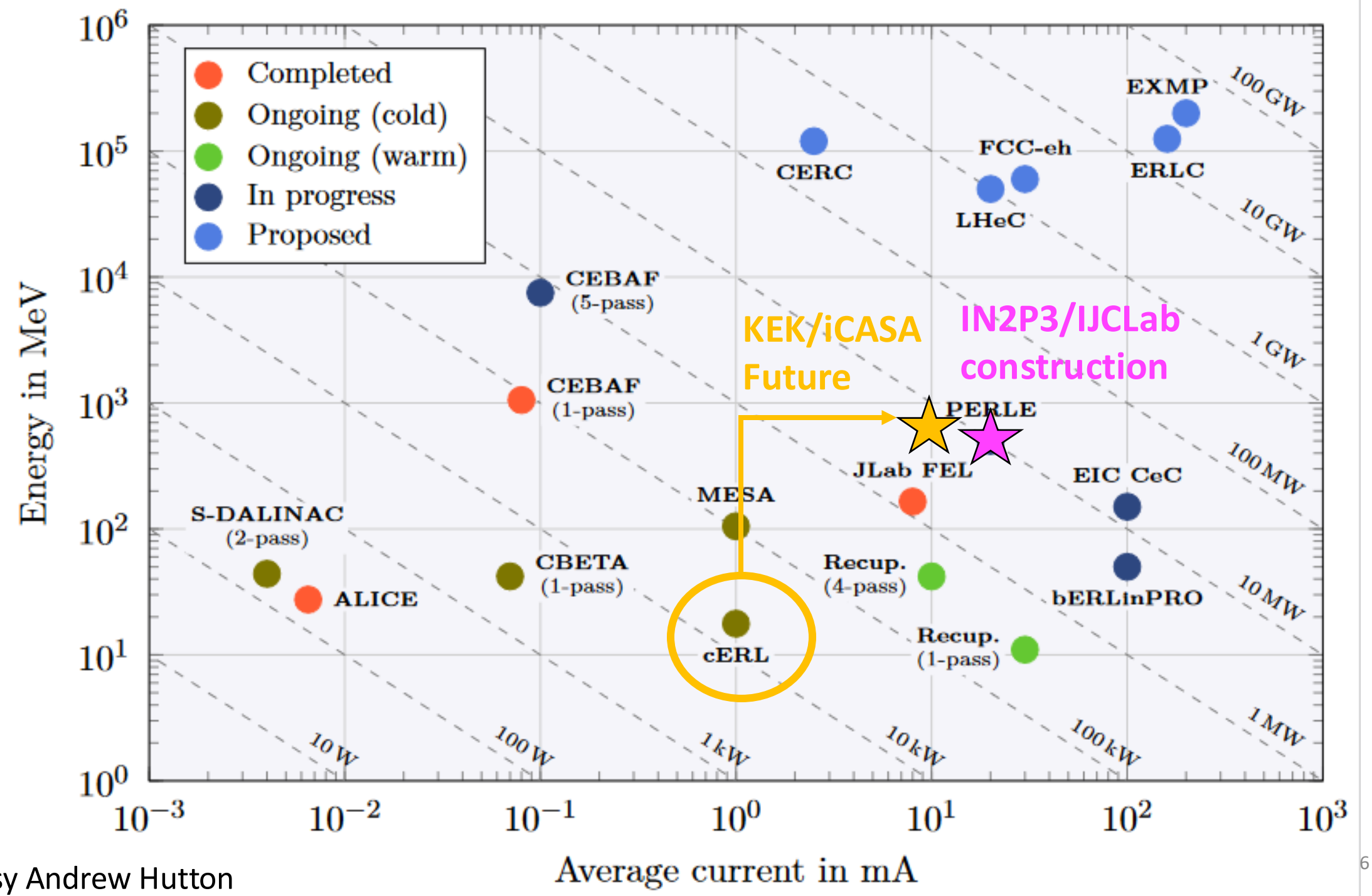
Example in colliders: case study in Snowmass



JINST 18 P05018 (2023)



Courtesy Andrew Hutton

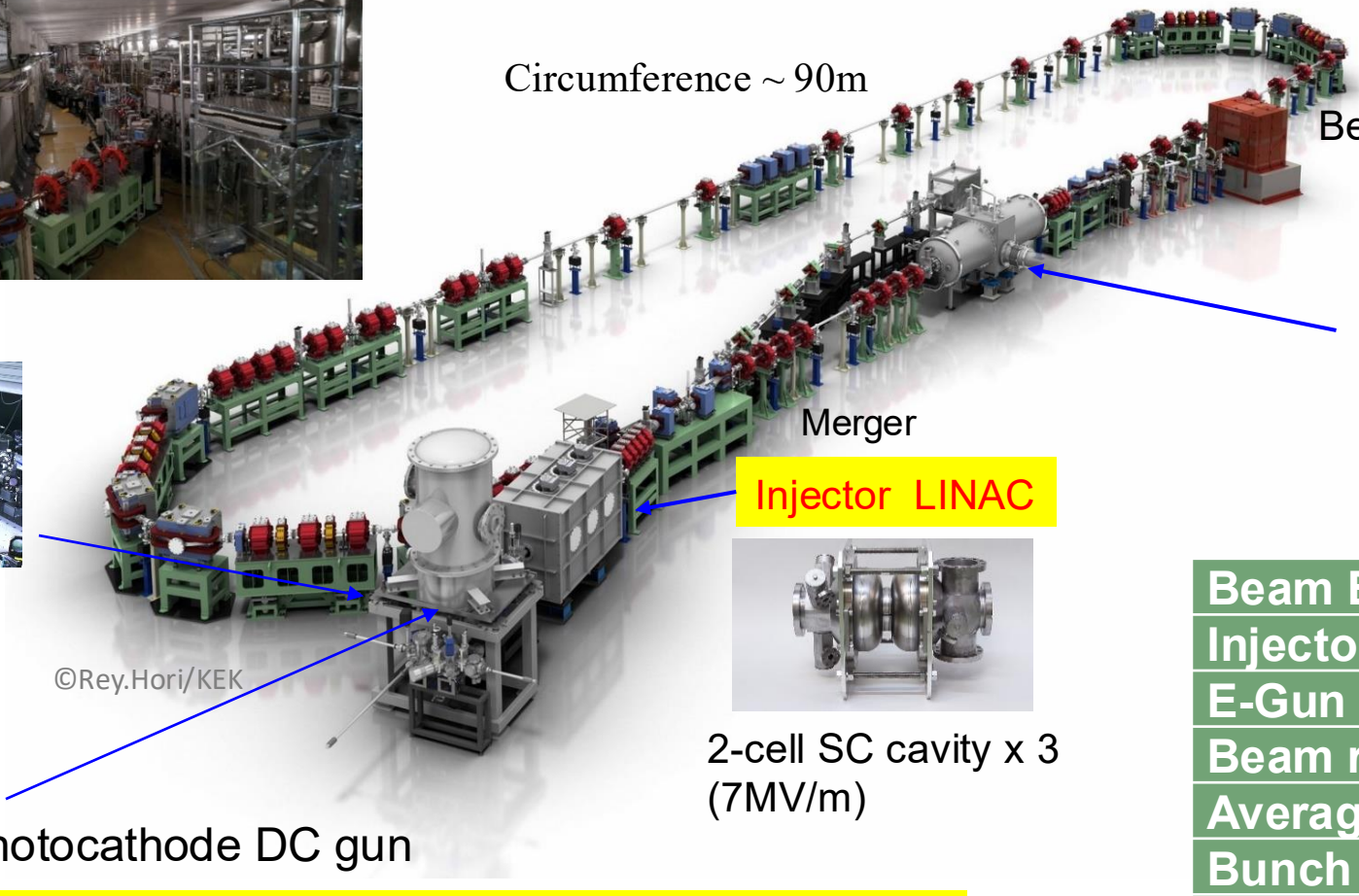


Courtesy Andrew Hutton

Status of Compact ERL (cERL) in KEK

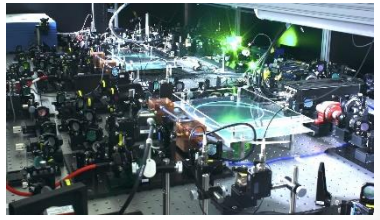
M. Akemoto *et al.*, Nucl. Instrum. Method A 877 p.197-219 (2018).

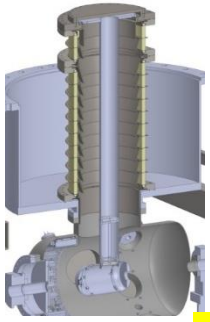
→ industrial applications



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

CW laser





Photocathode DC gun

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

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.

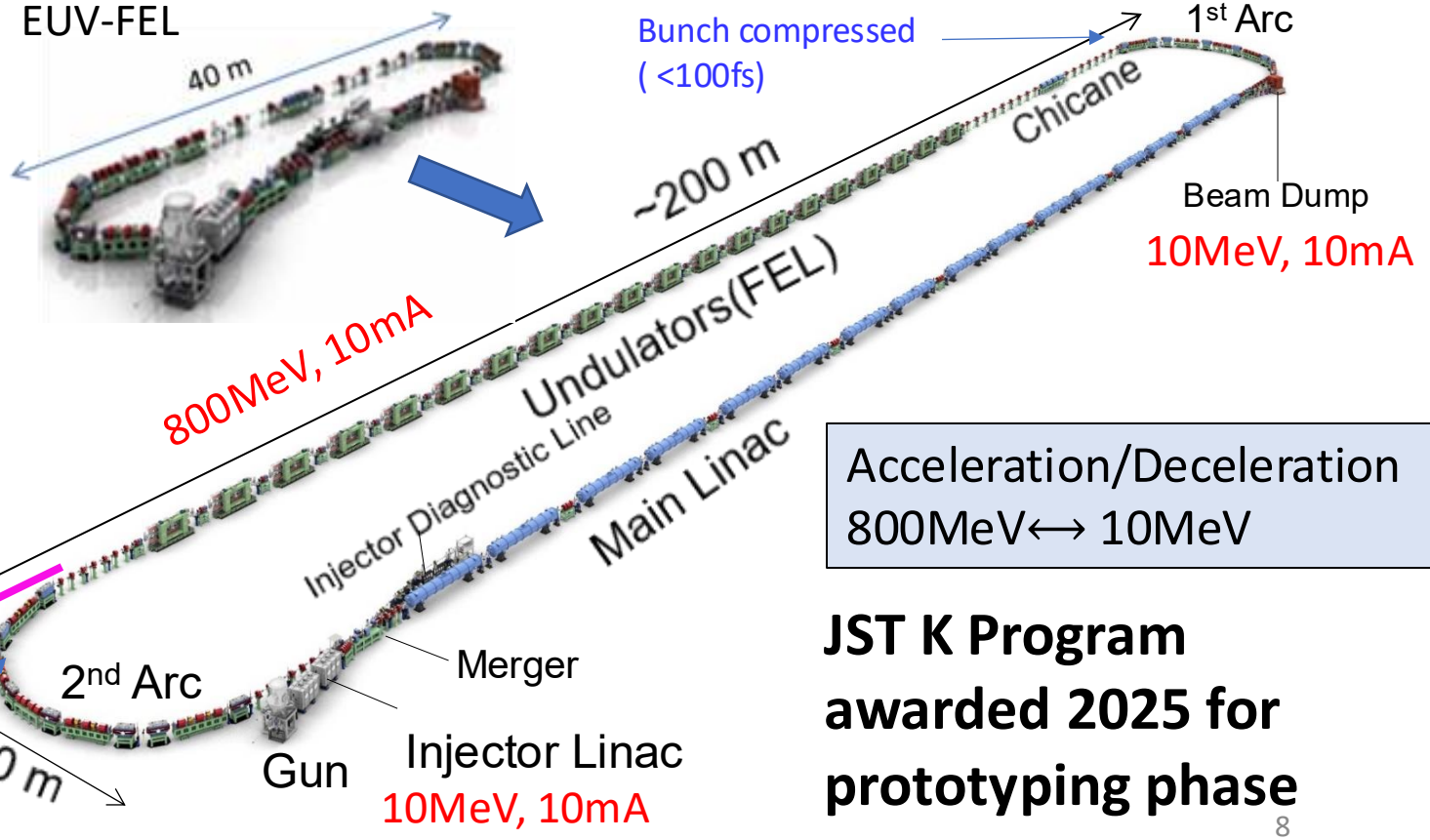
10-kW class EUV sources are required for Next Generation Lithography (>> 250 W by Laser Produced Plasma)

→ 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

Parameters	Design
Beam energy	800 MeV
Beam current	10 mA

cERL as a prototype of EUV-FEL



Acceleration/Deceleration
800MeV⟷ 10MeV

JST K Program awarded 2025 for prototyping phase

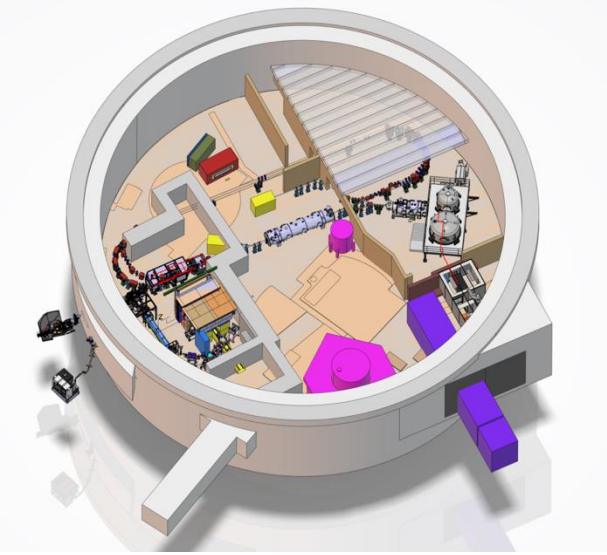
H, Kawata, et al, Journal of Micro/Nanopatterning, Materials, and Metrology 21(02) (2022)

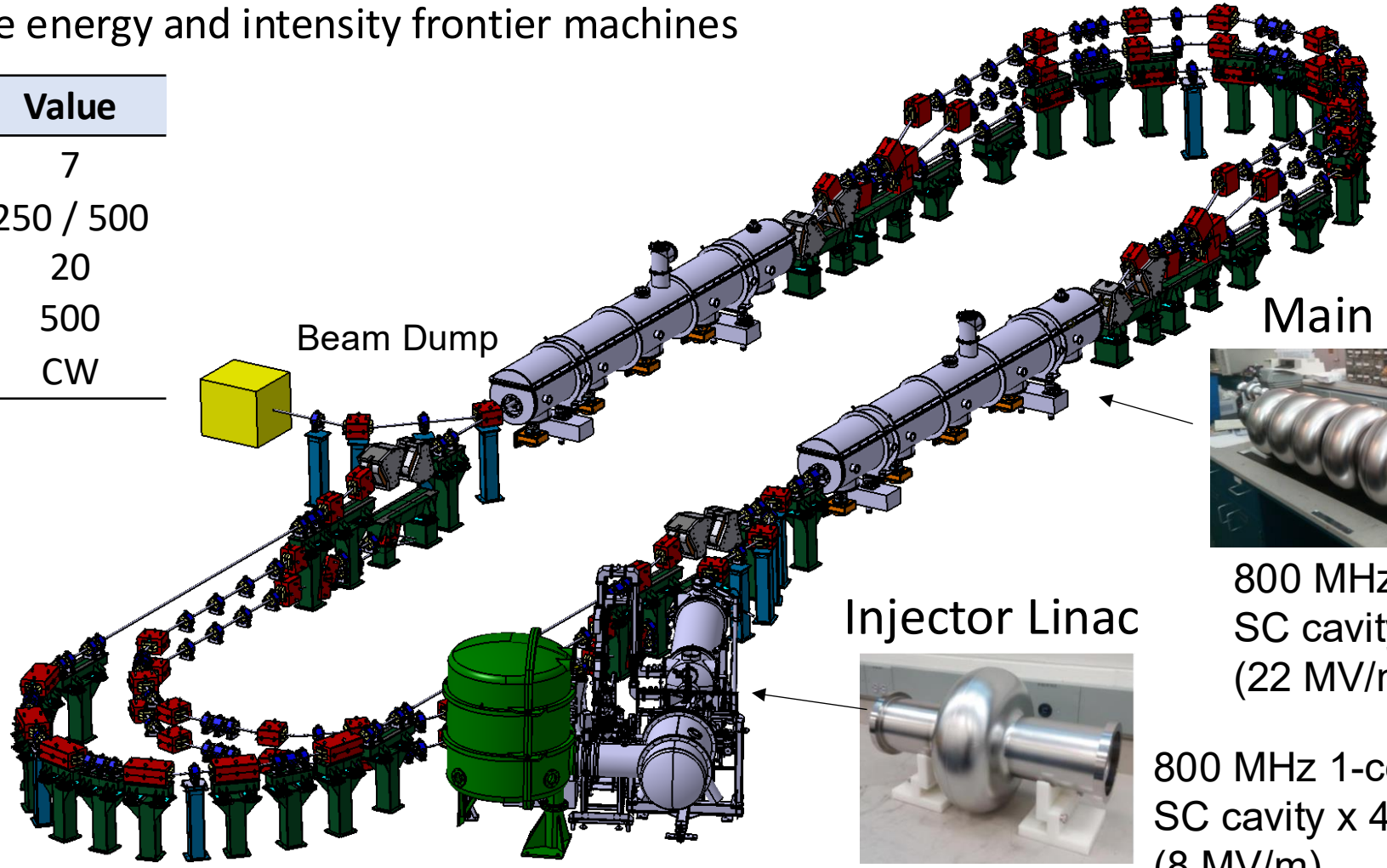
PERLE project at IN2P3/IJCLab

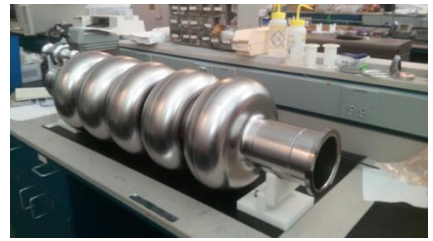
Ultimate goal of PERLE: first multi-turn ERL designed to operate at 10 MW (20 mA, 87→250→500 MeV)

→ A hub to explore a broad range of accelerator phenomena and to validate technical choices improving accelerators for future energy and intensity frontier machines

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	250 / 500
Average beam current	mA	20
Bunch charge	pC	500
Duty factor		CW







800 MHz 5-cell SC cavity x 4 (22 MV/m)

800 MHz 1-cell SC cavity x 4 (8 MV/m)

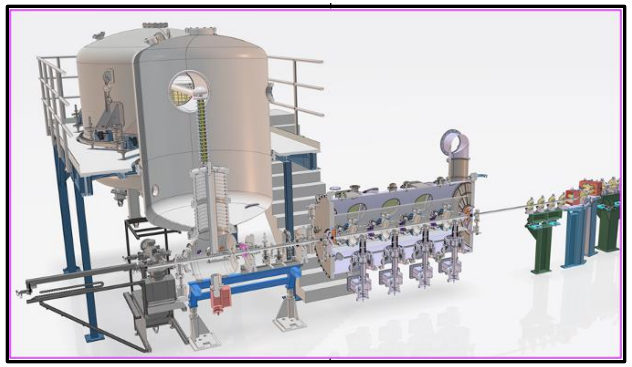
PERLE Timeline: phasing strategy

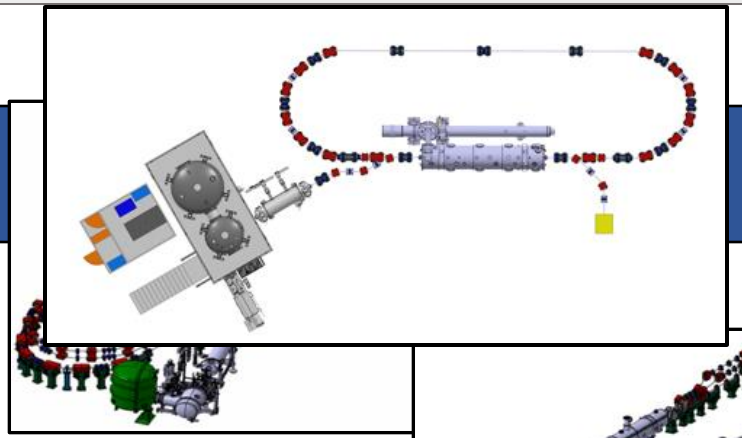
Prepare to Build phase (P2B): TDR and prototyping

Possible Single turn ERL phase under evaluation → Phase 1 to be extended to 2028

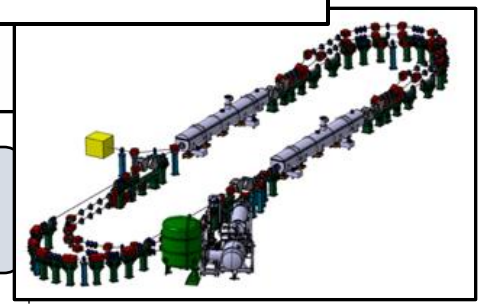
Installation phases

Phase 1: Injection line Installation





Phase 2: PERLE 250 MeV version

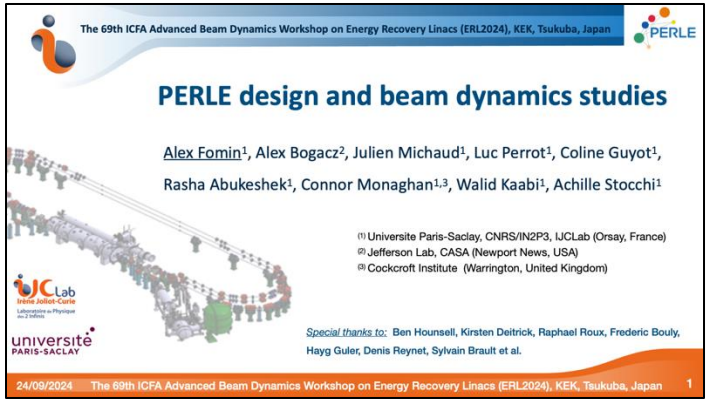


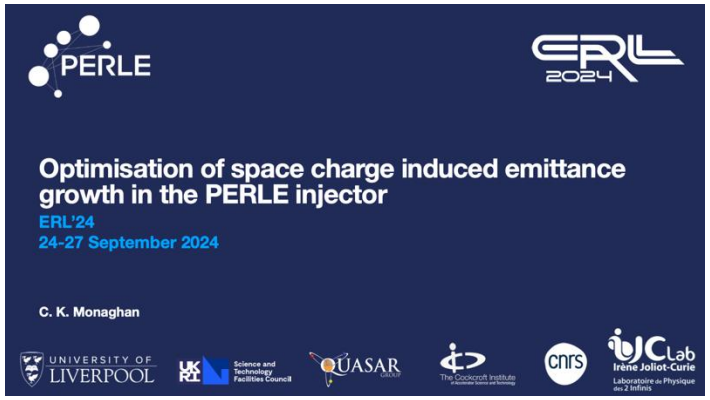
Phase 3: PERLE 500 MeV version

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

Injecter construction is on-going!

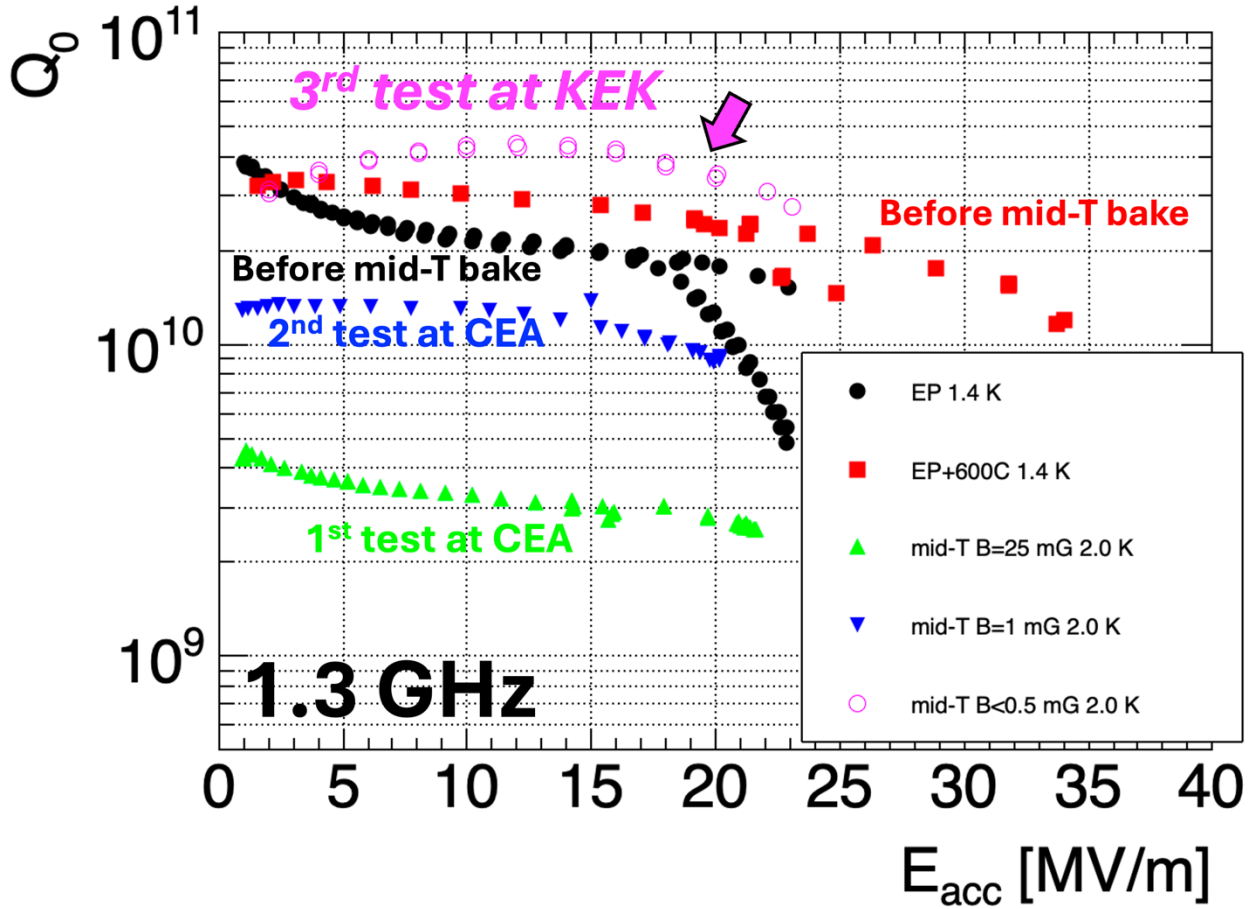
Activities in 2024 (FR→ JP): ERL2024 workshop





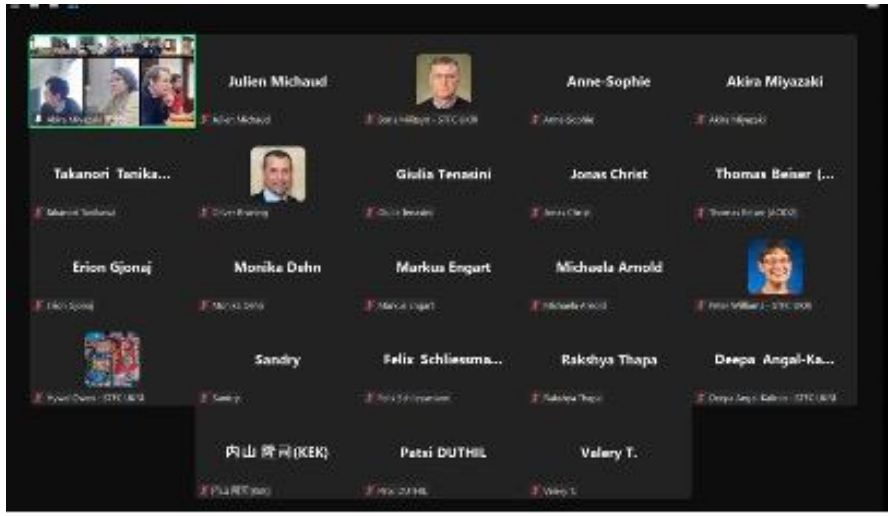
- 5 oral presentations and 3 posters
- One participant fully supported by FJPPN budget
  - Other participants covered by other funding source
- Active discussions & site visit & social dinner

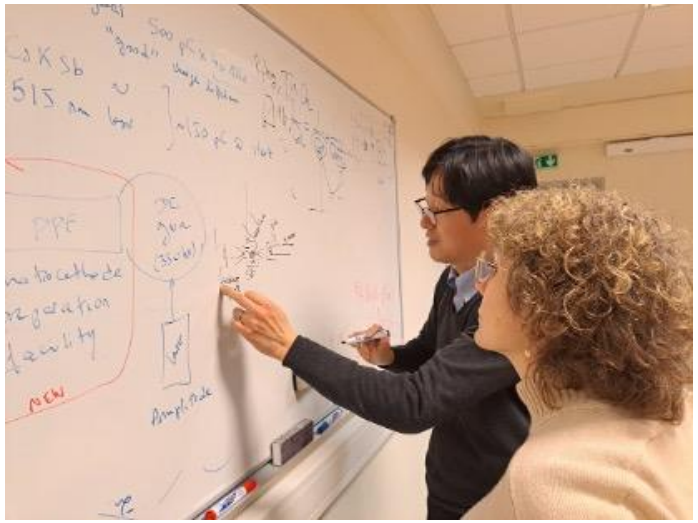
Activities in 2024 (FR → JP): cavity measurement



- A special heat-treatment (mid-T bake; cf PIP2, CEPC, etc) firstly done at IJCLab
- Measurement result at CEA was not excellent ← magnetic fields issue
- One week measurement after ERL2024 → excellent result at KEK in reduced magnetic fields

Activities in 2024 (JP→FR): DC Gun Seminar





- PERLE (IJCLab) construction is in the 1st phase: DC Gun 2024-2025
- Masahiro Yamamoto (KEK; cERL) gave a seminar dedicated to DC Gun development and precious experiences in cERL
- A lot of informal discussions about injector beam dynamics, diagnostics, photocathode, MoU, further funding opportunities, etc

<u>One interesting point was identified</u>

- PERLE design enables automatic photocathode (CsKSb) replacement
- This is potentially an interesting future upgrade of cERL

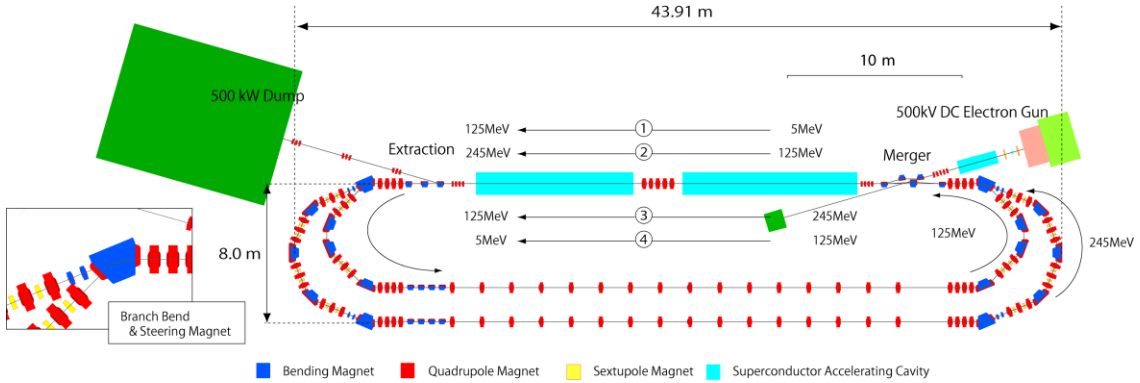
Proposal in 2025 (FR → JP)

- Olesiy Fomin (IJCLab) participates cERL operation in November to gain practical experiences to feedback into PERLE design
- Some dedicatd beam time for specific tests for PERLE (under discussion)
- Beam halo study, comparing IJCLab's calculation (mystery in cERL)
- Cofuding supports long stay in Japan

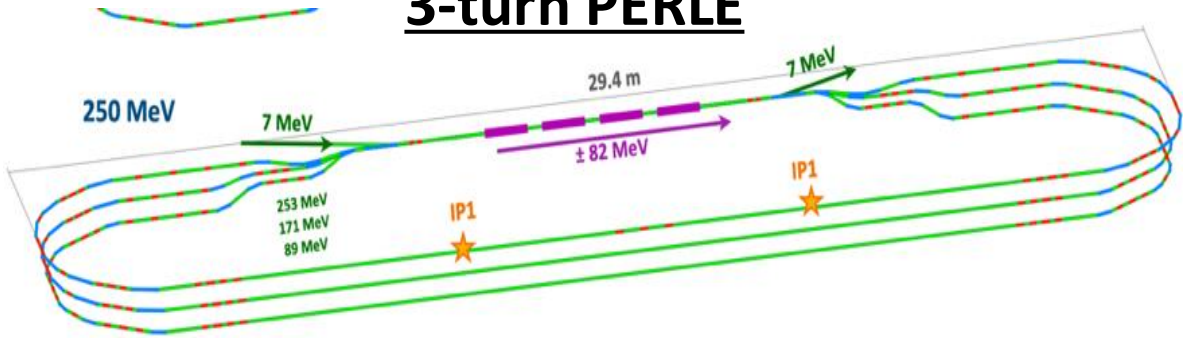
EAJADE
Europe-America-Japan Accelerator Development Exchange Programme

Proposal in 2025 (JP → FR)

Multi-turn cERL

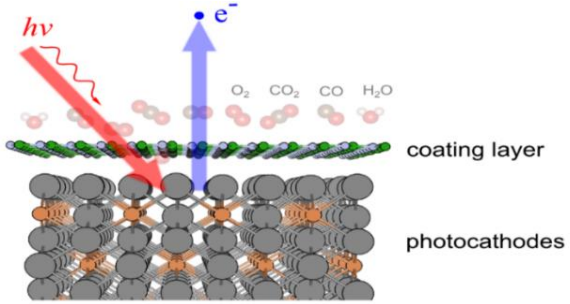


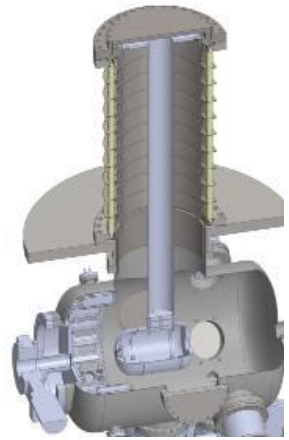
3-turn PERLE



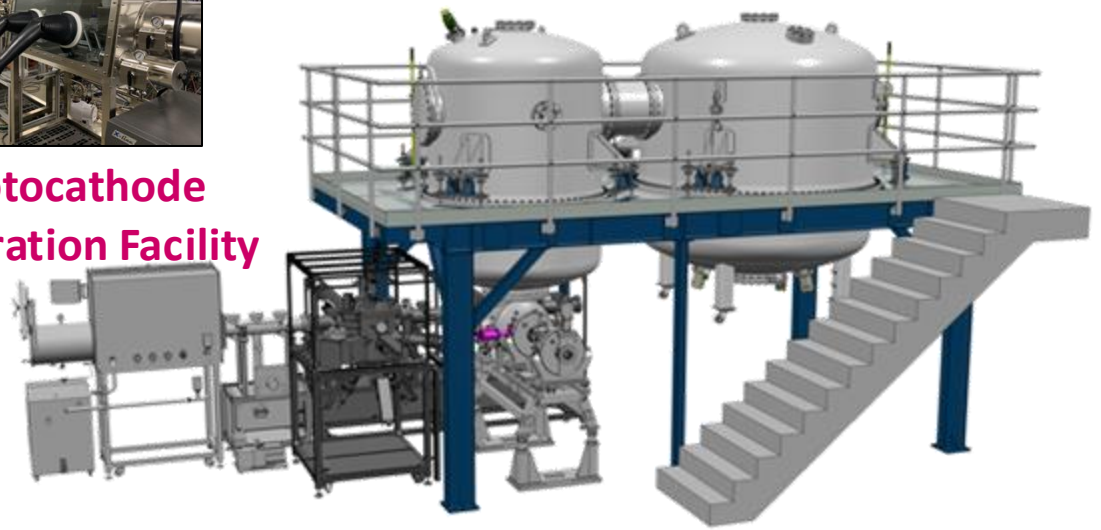
- Seminar by Miho Shimada (KEK) about multi-turn cERL and discussion about beam dynamics specific to the multi-turn operation

Photocathode JP→FR





Photocathode Preparation Facility



- Lei Guo (Hiroshima University) visit IJCLab to participate CsKSb photocathode production at PERLE

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 and IN2P3/IJCLab 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
- Activities in 2024
  - ERL2024 workshop & superconducting cavity experiment
  - Seminar dedicated to DC gun & a lot of discussions
- Proposal in 2025
  - Participation in cERL beam operation
  - Beam dynamics seminar and/or photocathode operation at PERLE