Energy Recovery Linacs (ERL) – European R&D Roadmap

the R&D program towards ERL-based particle colliders

Jorgen D'Hondt
Vrije Universiteit Brussel
(stepping in for Andrew Hutton, JLab)

on behalf of the ERL Coordination Panel
European Accelerator R&D Roadmap

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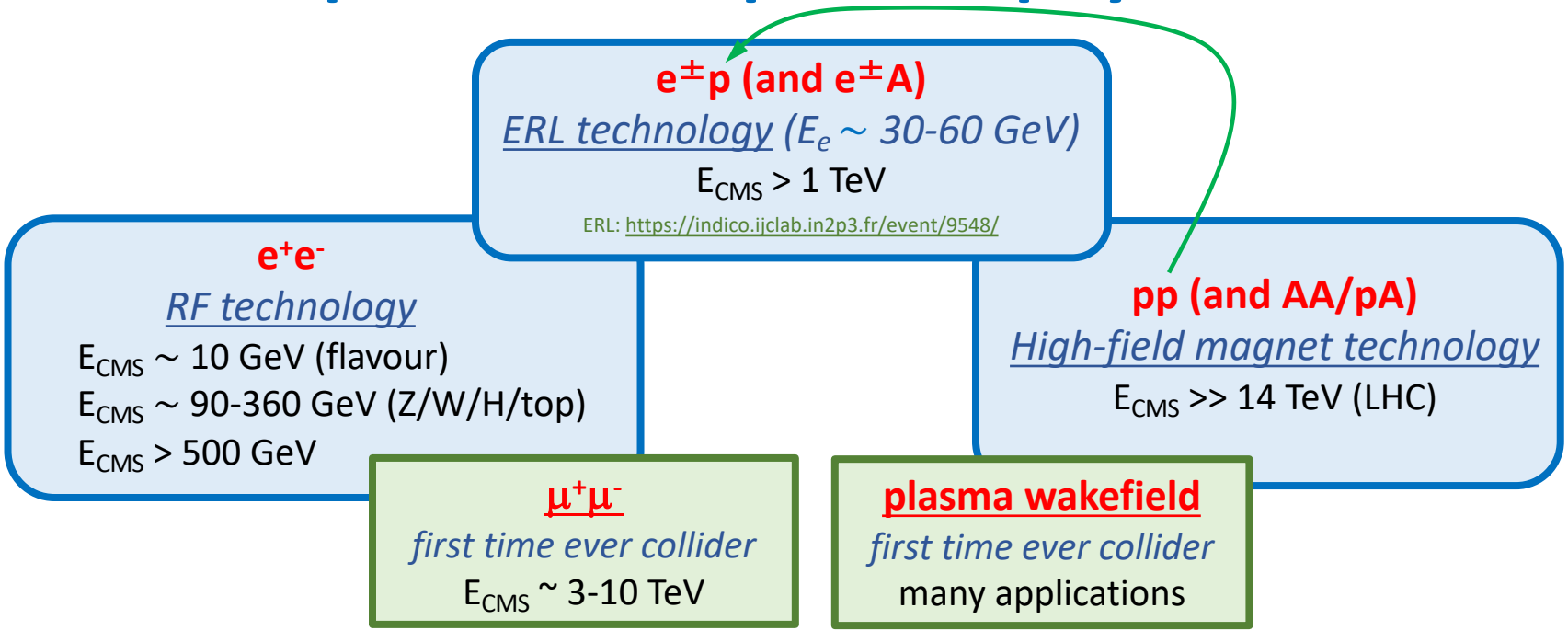
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

ICHEP 2024, Prague, July 2024

The landscape of future particle physics colliders

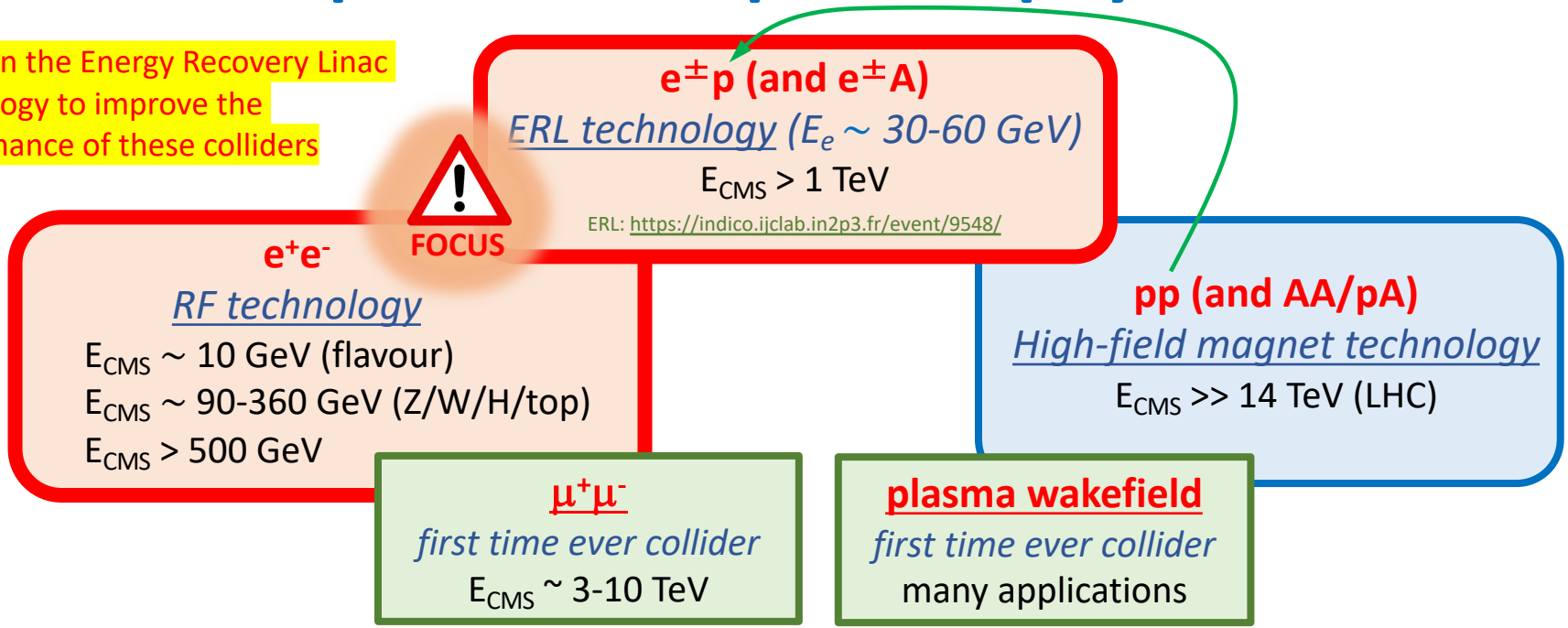


Accelerator R&D Roadmap prioritizes progress on these technologies to enable future particle accelerators in a timely, affordable and sustainable way

CERN Yellow Rep. Monogr. 1 (2022) 1-270, https://cds.cern.ch/record/2800190?ln=en

The landscape of future particle physics colliders

Focus on the Energy Recovery Linac technology to improve the performance of these colliders



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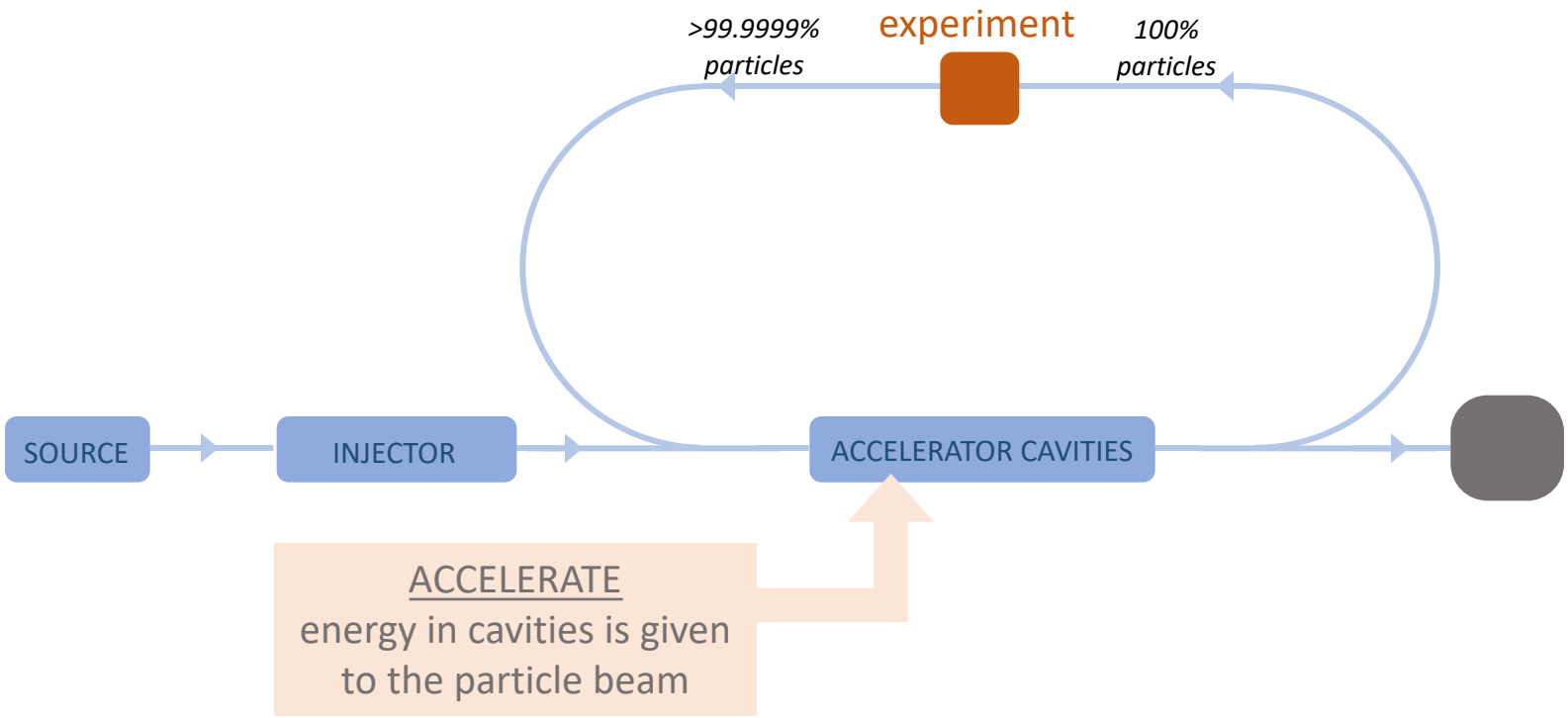
The principle of Energy Recovery Linacs



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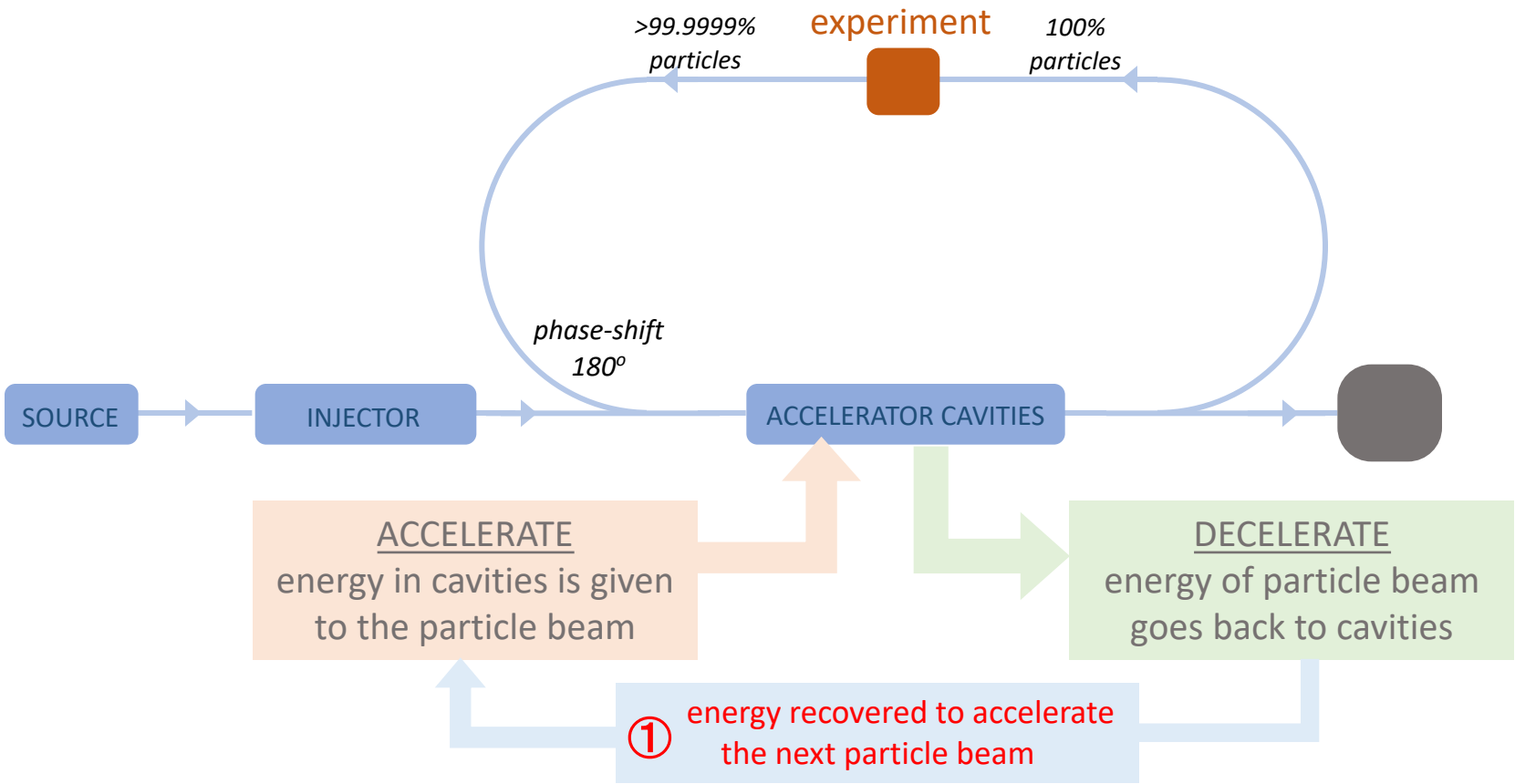

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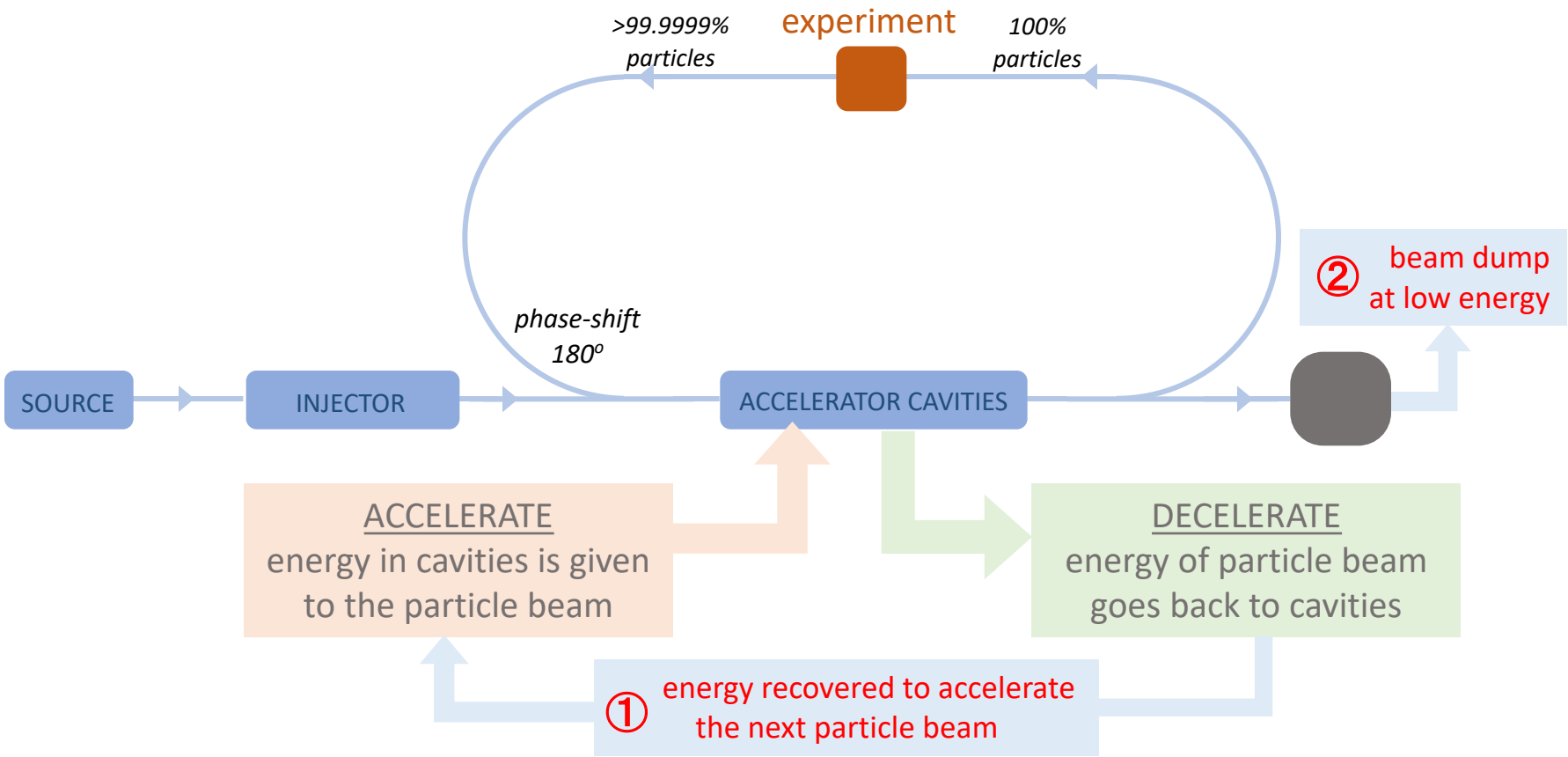

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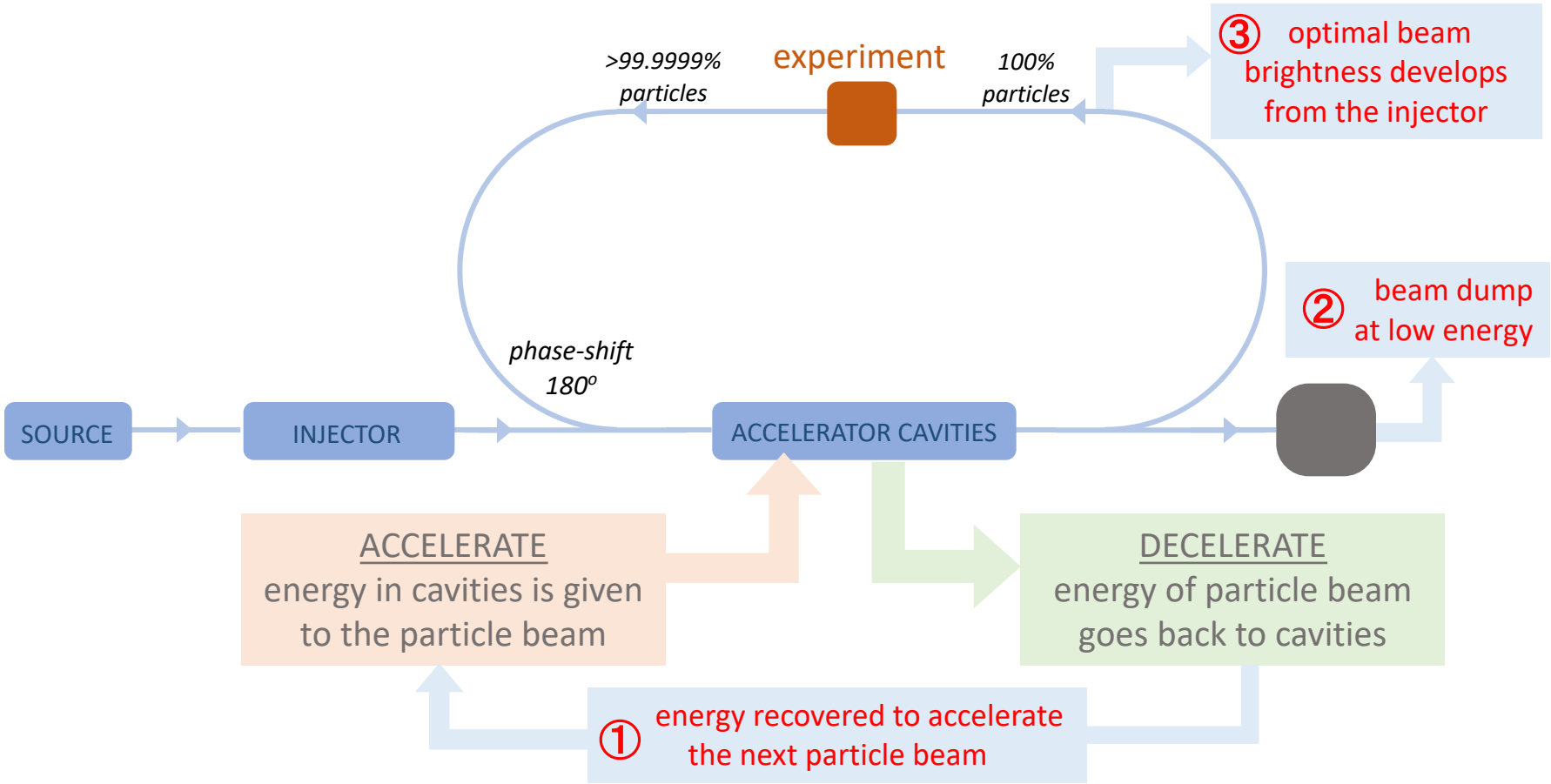

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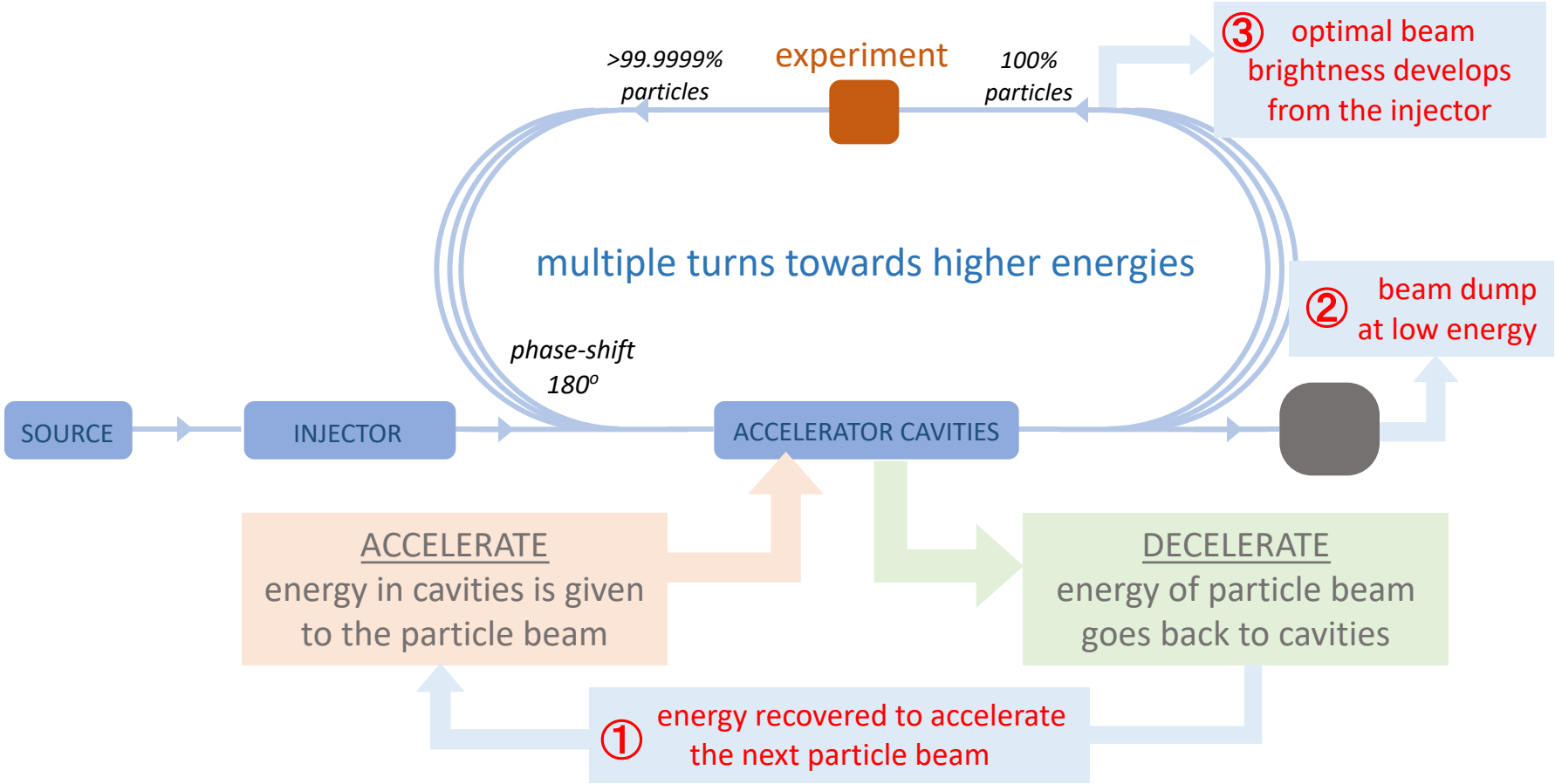

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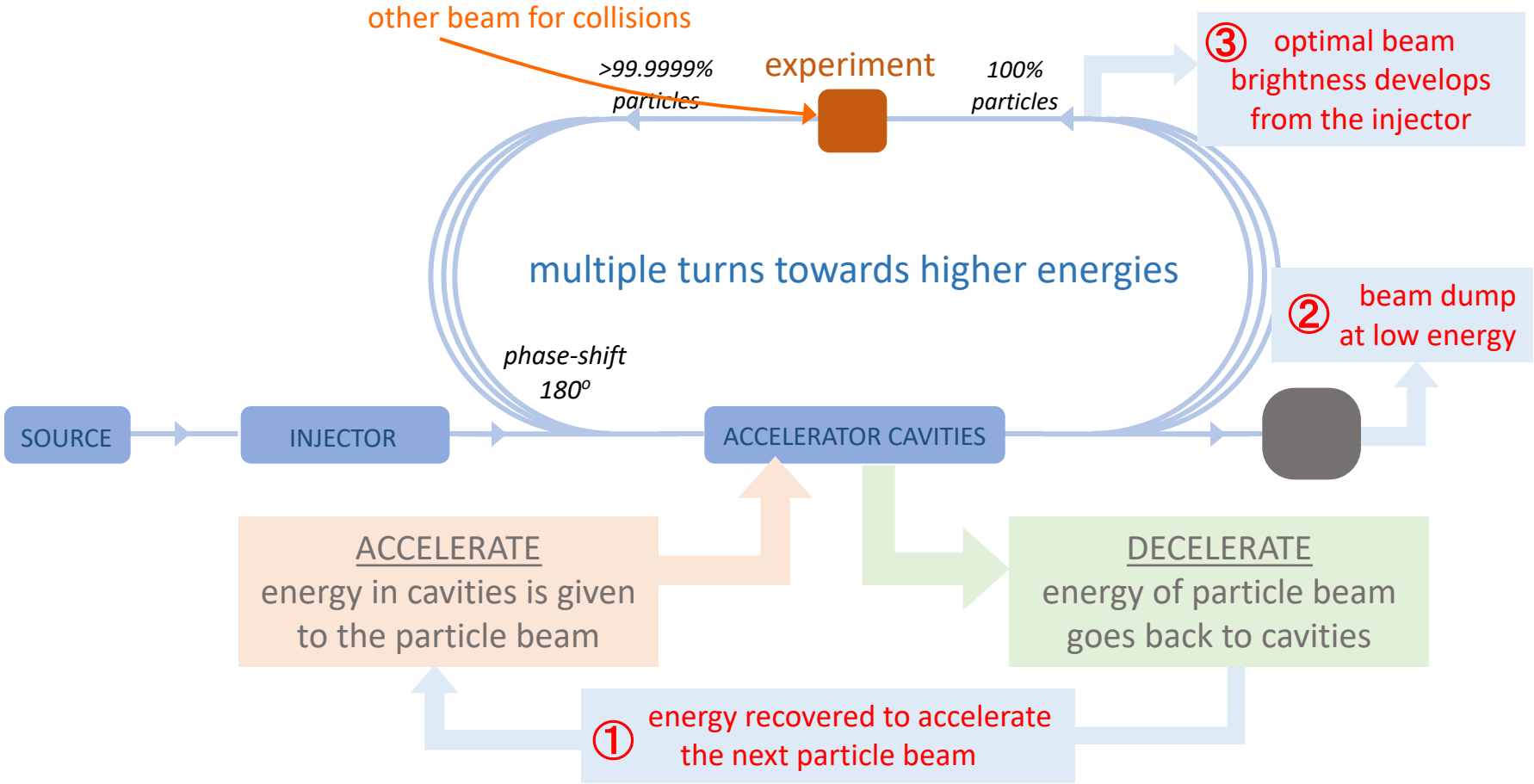

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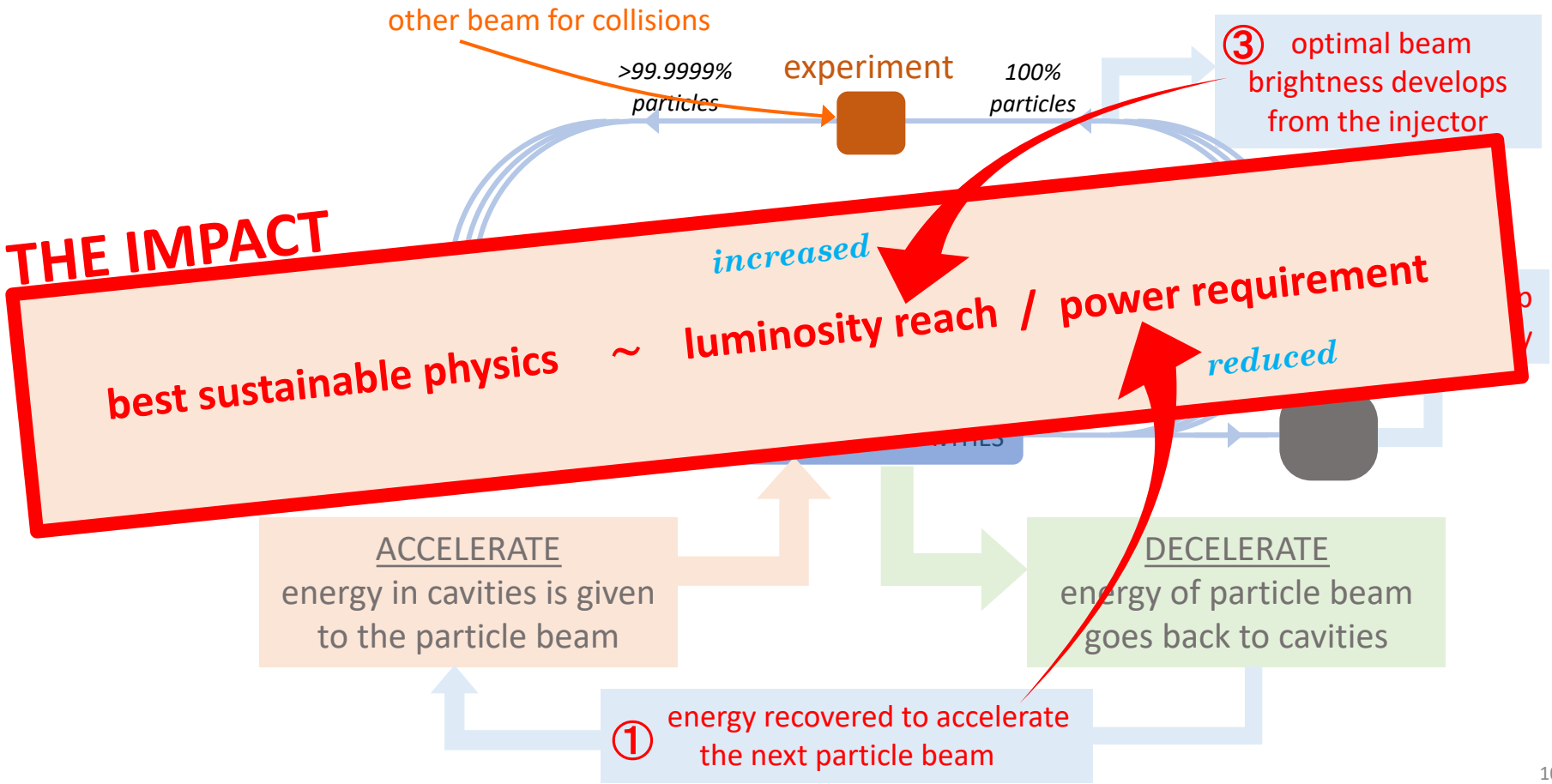
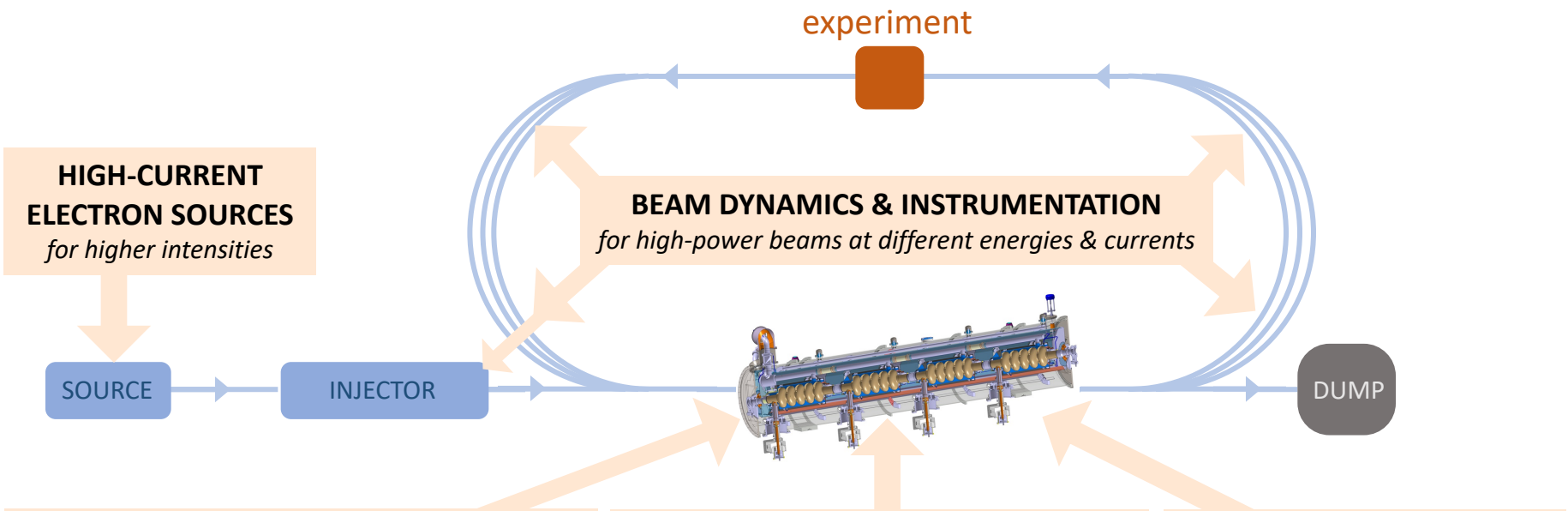


Accelerator R&D objectives



The Development of Energy-Recovery Linacs
arXiv:2207.02095, 237 pages, 5 July 2022

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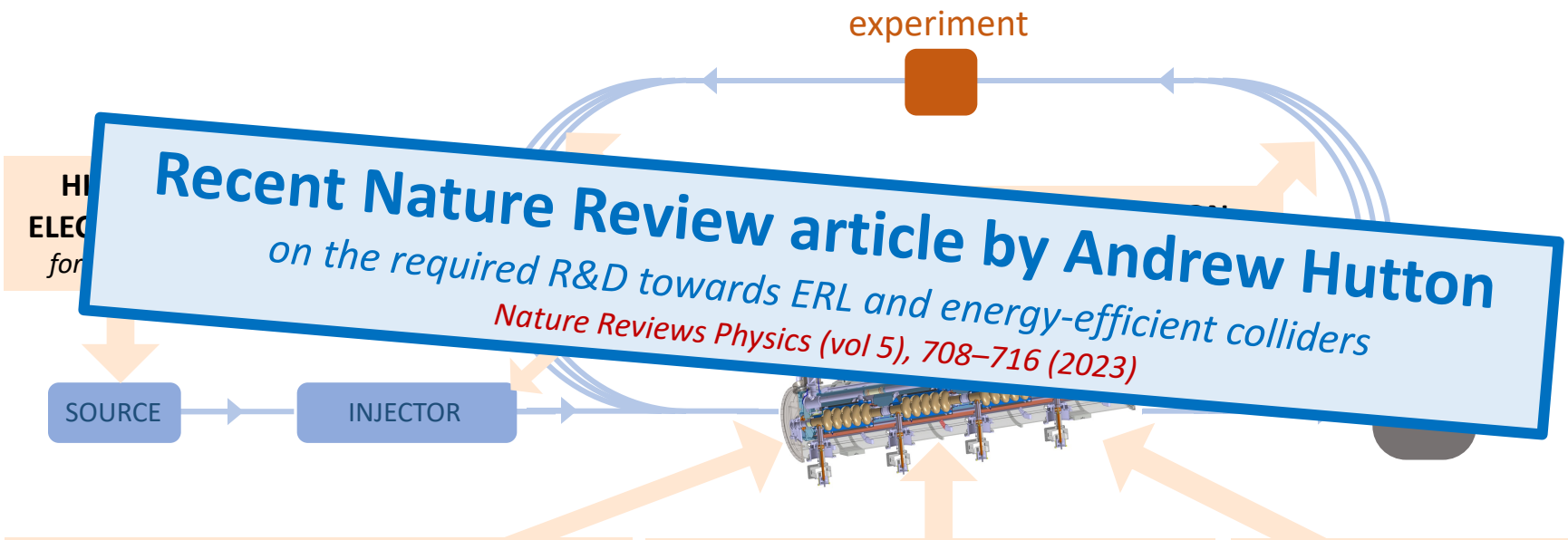

Recent Nature Review article by Andrew Hutton

on the required R&D towards ERL and energy-efficient colliders

Nature Reviews Physics (vol 5), 708–716 (2023)

HIGHER-ORDER MODE DAMPING
efficient HOM extraction w/o increasing cryoload

HIGH-TEMPERATURE SC TECHNOLOGY
towards 4.2 K operation

FRT & RF power source
efficient RF operation

HIGH-Q_0 & GRADIENT

RF POWER GENERATION

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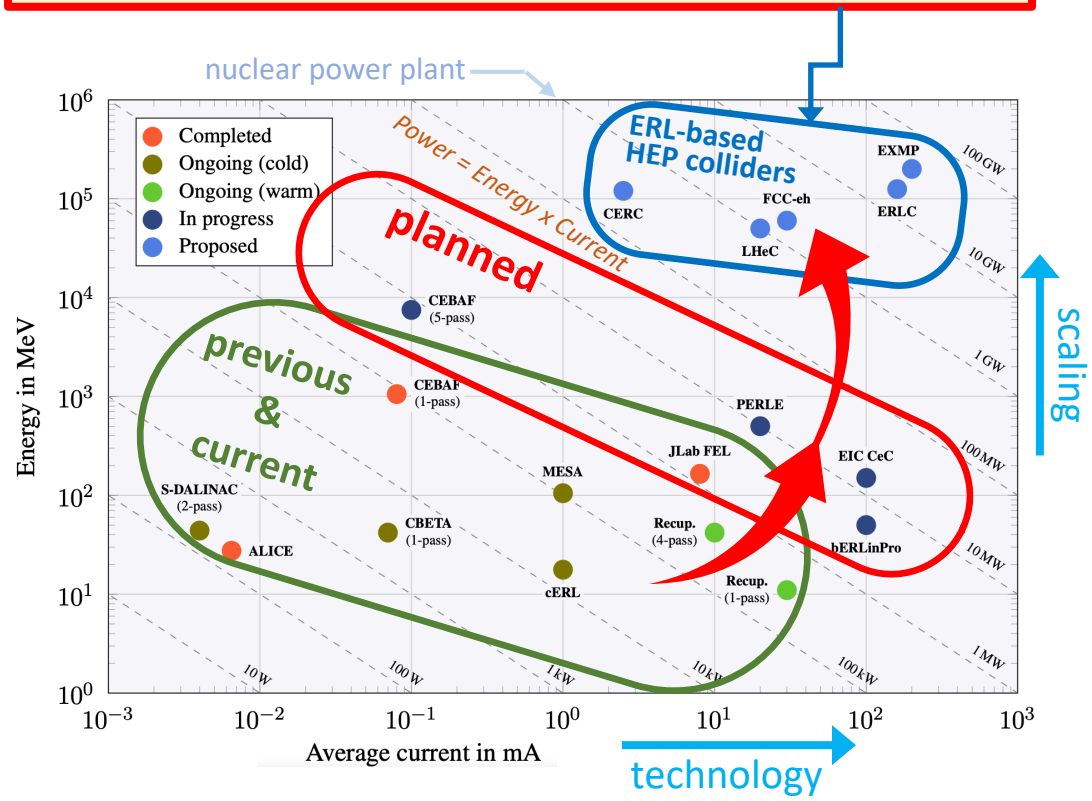
ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Future ERL-based Colliders

H, HH, ep/eA, muons, …

bERLinPro & PERLE

essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high energy & high power

Energy Recovery demonstrated

great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

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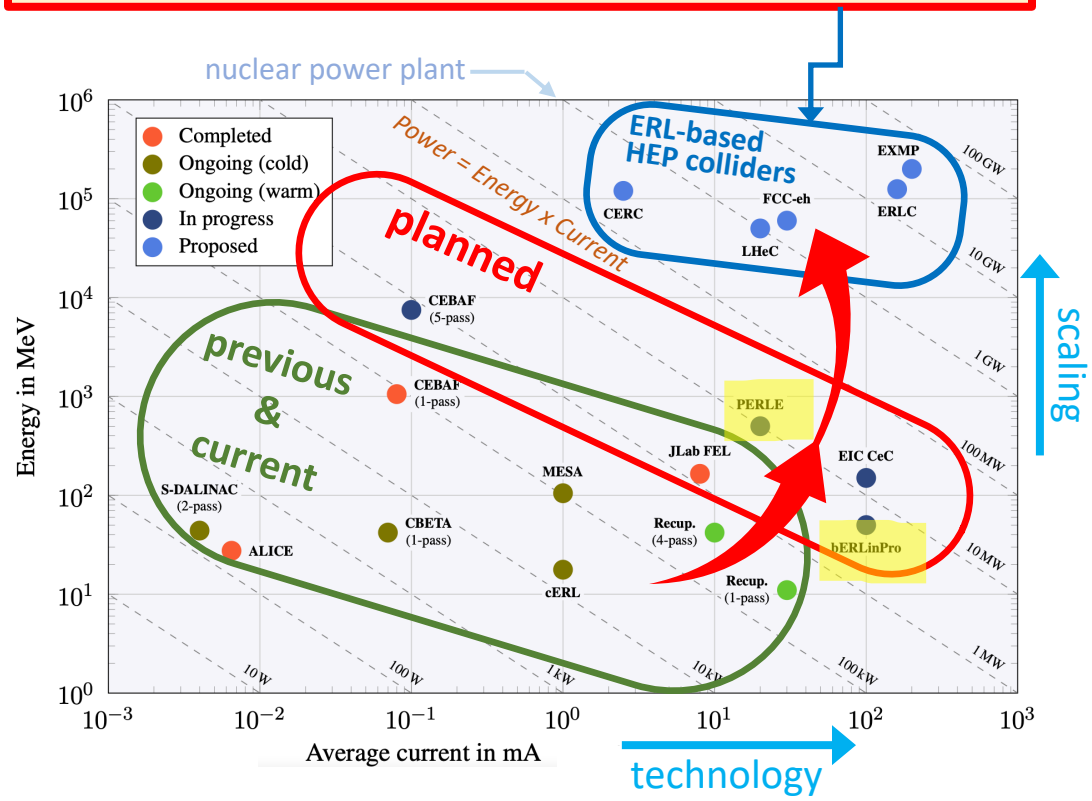

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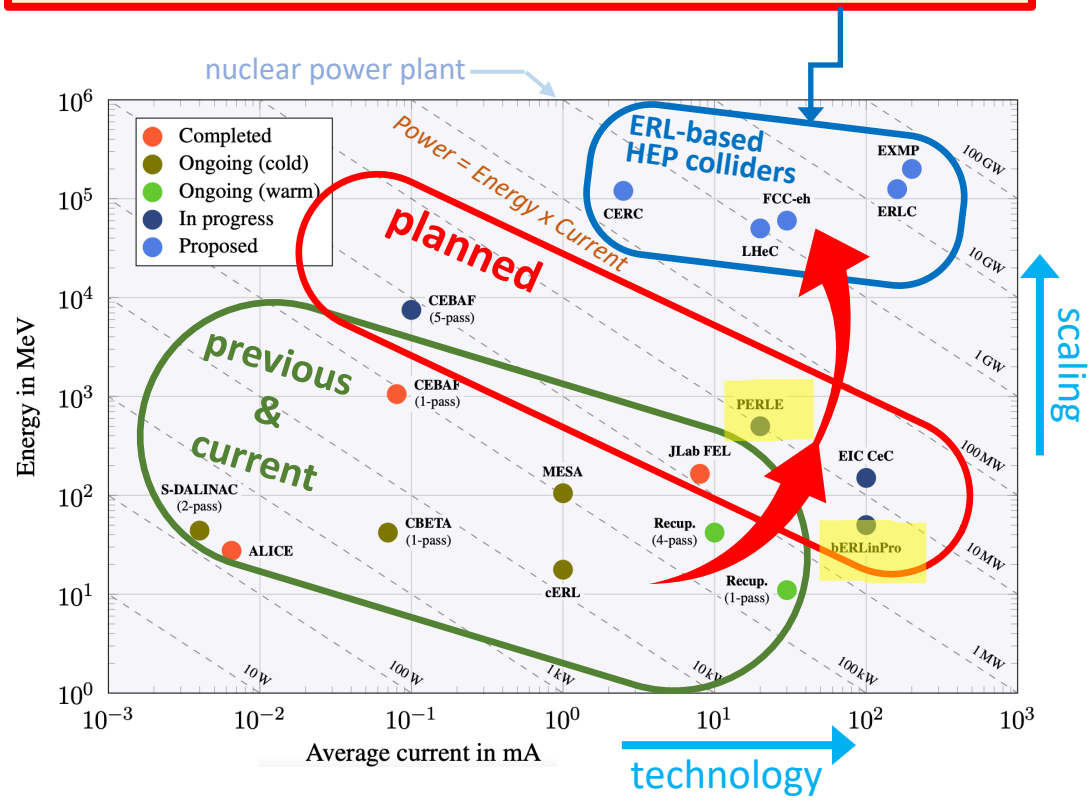

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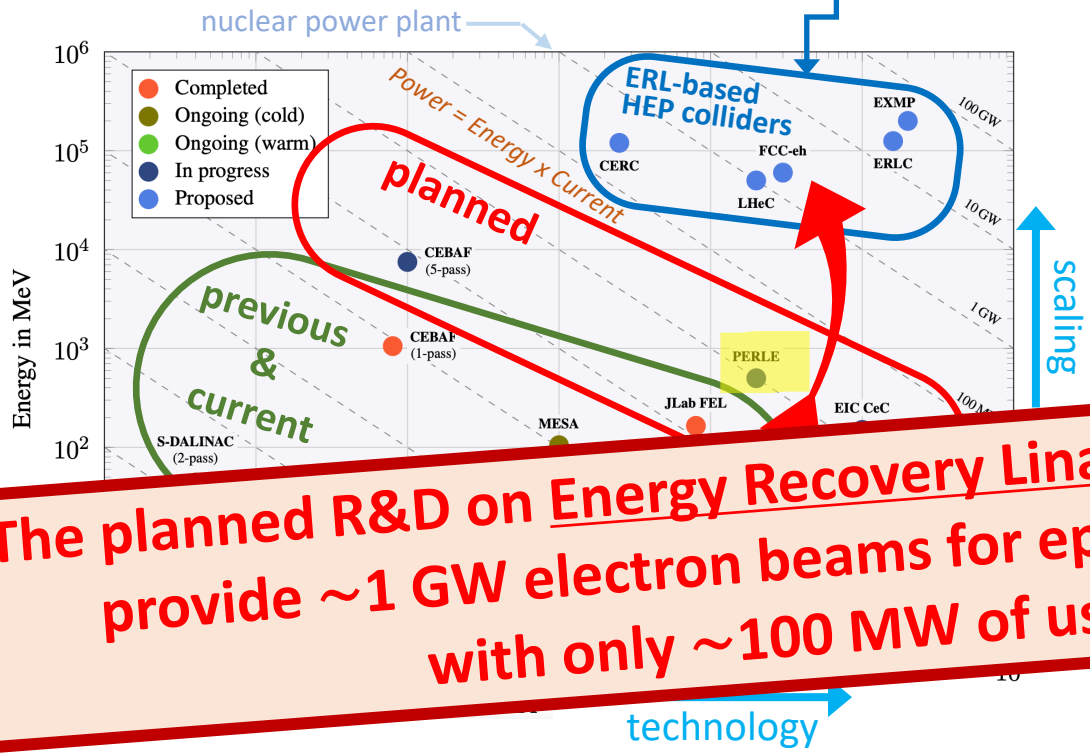

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R&D Roadmap

bERLinPro & PERLE

essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high energy & high power

based on Energy Recovery systems have been operated successfully

The planned R&D on Energy Recovery Linacs will enable the path to provide ~1 GW electron beams for ep and/or e^+e^- collisions with only ~100 MW of used power

PERLE – Powerful Energy Recovery Linac for Experiments

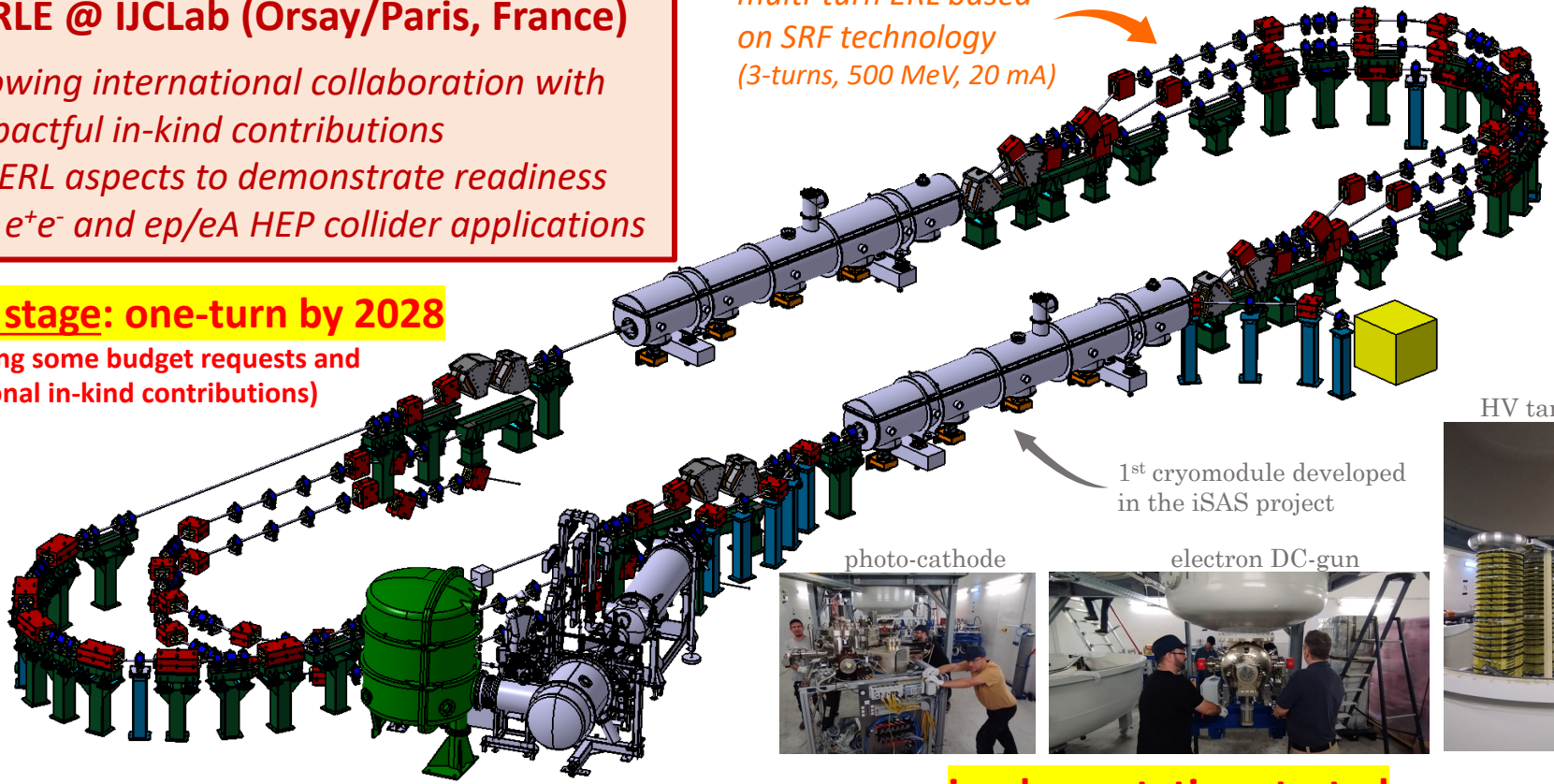
PERLE @ IJCLab (Orsay/Paris, France)

- *growing international collaboration with impactful in-kind contributions*
- *all ERL aspects to demonstrate readiness*
- *for e^+e^- and ep/eA HEP collider applications*

multi-turn ERL based on SRF technology (3-turns, 500 MeV, 20 mA)

First stage: one-turn by 2028

(pending some budget requests and additional in-kind contributions)



1st cryomodule developed in the iSAS project

photo-cathode

electron DC-gun

HV tanks

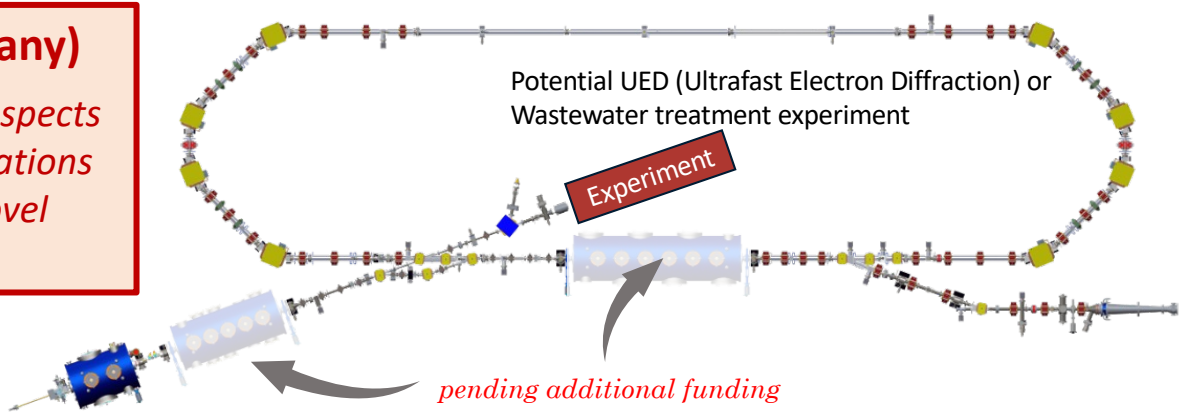
implementation started

CDR: *J.Phys.G* 45 (2018) 6, 065003

bERLinPro – Berlin Energy Recovery Linac Project

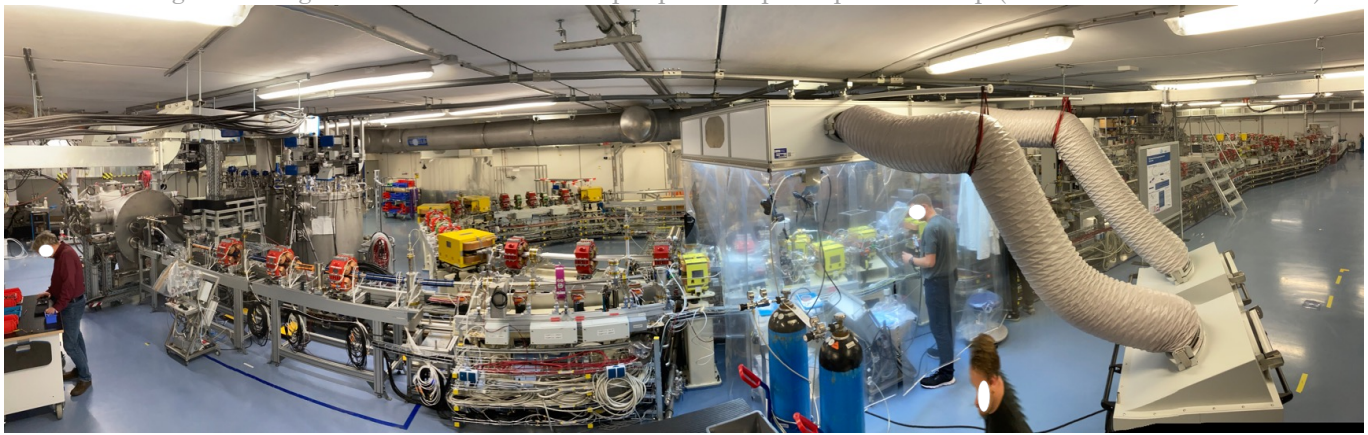
bERLinPro @ HZB (Berlin, Germany)

- *generic accelerator R&D with several aspects as stepping stones towards HEP applications*
- *potential for developing and testing novel energy-saving technologies*



commissioning for beam in 2024

10-mA SRF gun + merger + recirculation + dump + proof-of-principle UED exp (booster module is funded)



The current installation will allow high-power beam studies of the injector (up to 100 mA in long-pulse mode).

first beam from injector end of 2024

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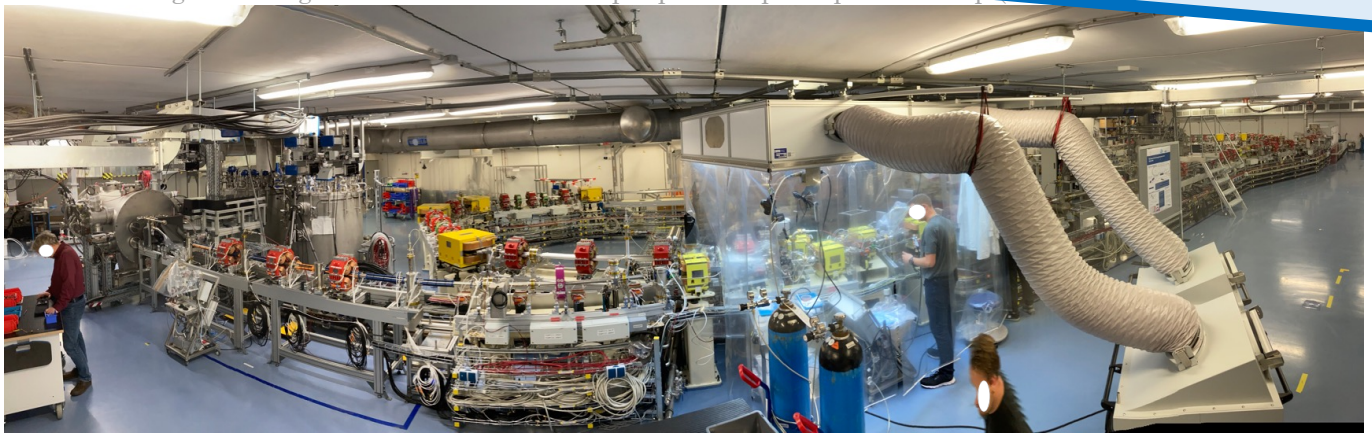
- *potential fo… …ing and testing novel energy-sav…*

commissio…

More on PERLE and bERLinPro in the presentation of Walid Kaabi

10-mA SRF gun + merger + recirculation + dump + proof-of-principle …



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first beam from injector end of 2024

Potential impact of ERL technology

for particle physics colliders

demonstrate (multi-turn) high-power ERL

2020'ies

high-power ERL demonstrated

See dedicated presentations at ICHEP 2024 on the iSAS project (Jorgen D'Hondt) and on PERLE and bERLinPro (Walid Kaabi)

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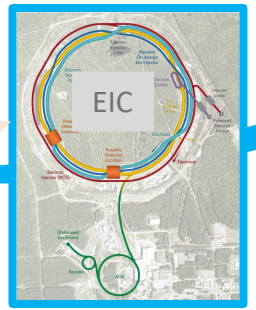

ERL application electron cooling

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demonstrate (multi-turn) high-power ERL

enables the ultimate upgrades of the LHC/FCC programmes ***(ep collisions)***

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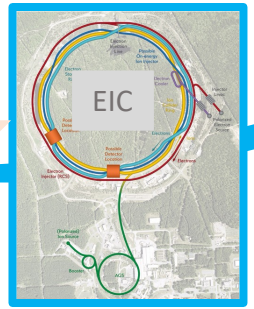
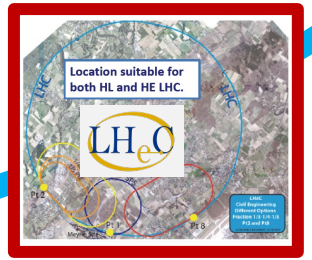


ERL application electron cooling

2030-2040'ies



high-power ERL
e^- beam in collision
(ep/eA @ LHC programme)

1 ERL beam

2070'ies

reuse ERL

See dedicated presentation at ICHEP 2024 on the LHeC/FCC-eh programmes (Jorgen D'Hondt)

enables the ultimate upgrades of the LHC/FCC programmes
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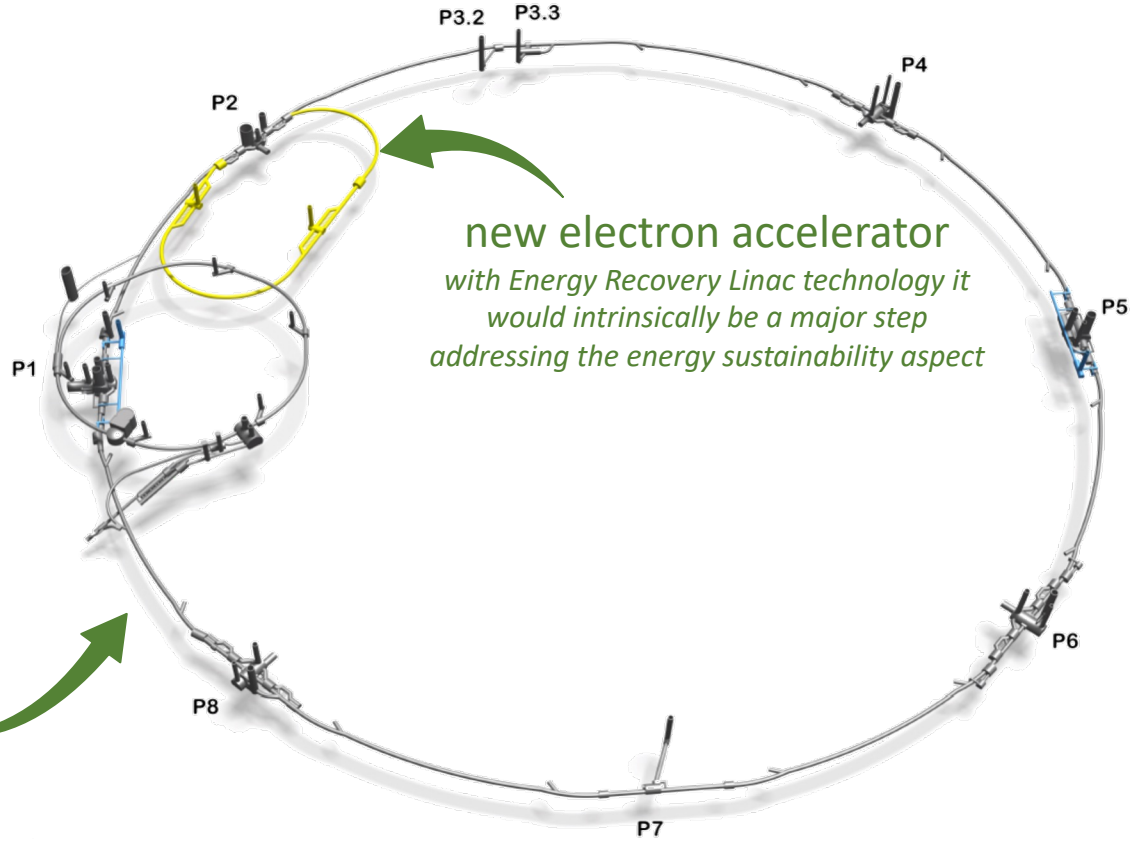

new electron accelerator
with Energy Recovery Linac technology it would intrinsically be a major step addressing the energy sustainability aspect

existing/future proton accelerator

Potential impact of ERL technology

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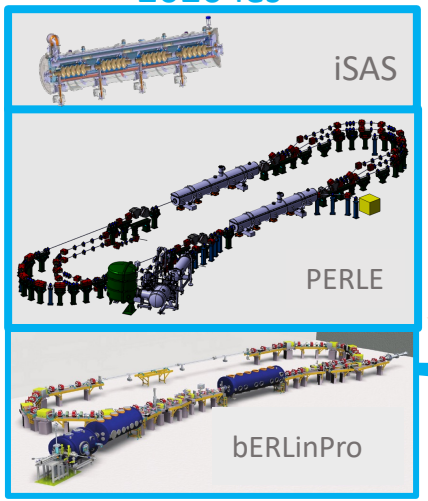
demonstrate (multi-turn) high-power ERL

enables the ultimate upgrades of the LHC/FCC programmes ***(ep collisions)***

2020'ies



high-power ERL demonstrated

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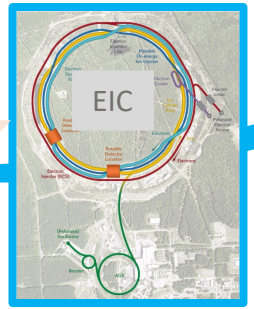

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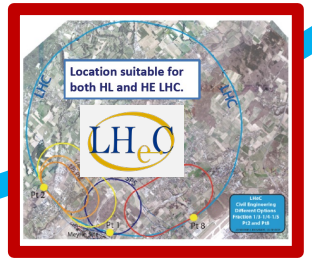
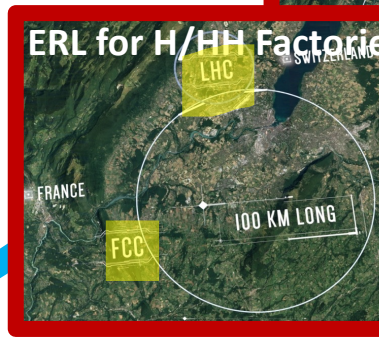


high-power ERL e⁻ beam in collision (ep/eA @ LHC programme)

1 ERL beam

2070'ies



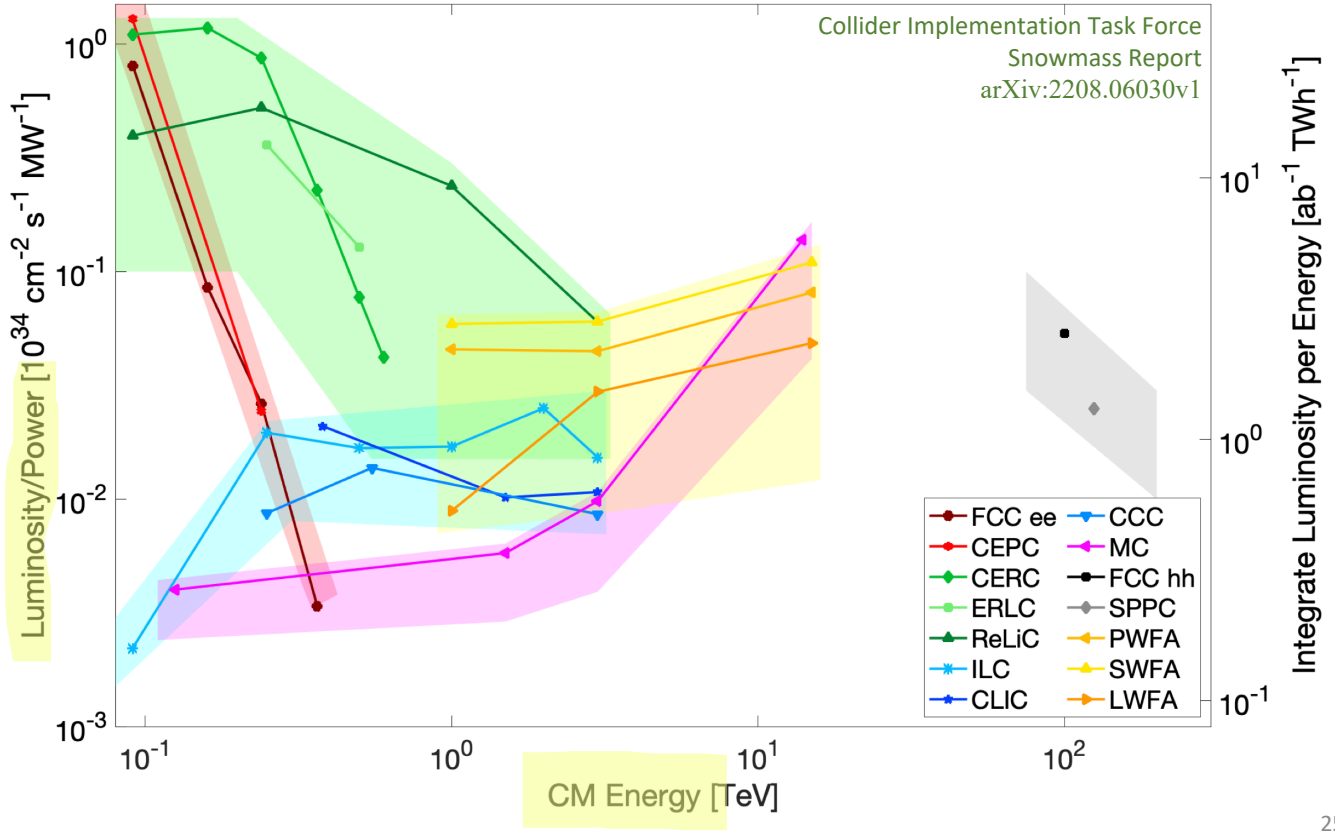
high-power ERL for e^+e^- Higher Factories (Z/W/H/top/HH programme)

2 ERL beams

reuse ERL

increases the performance of the next major e^+e^- colliders

Energy Recovery applications for HEP e^+e^- colliders



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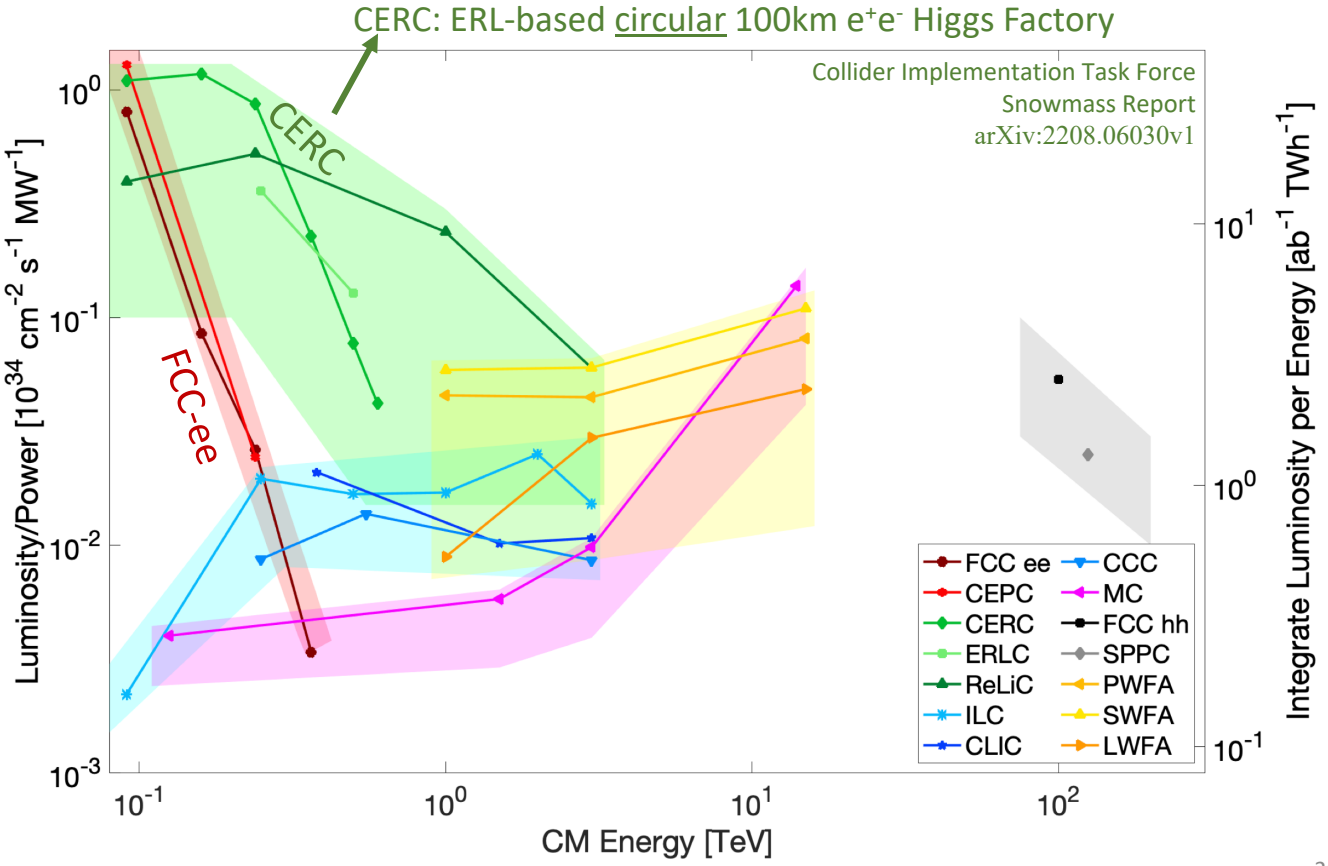


Energy Recovery applications for HEP e^+e^- colliders

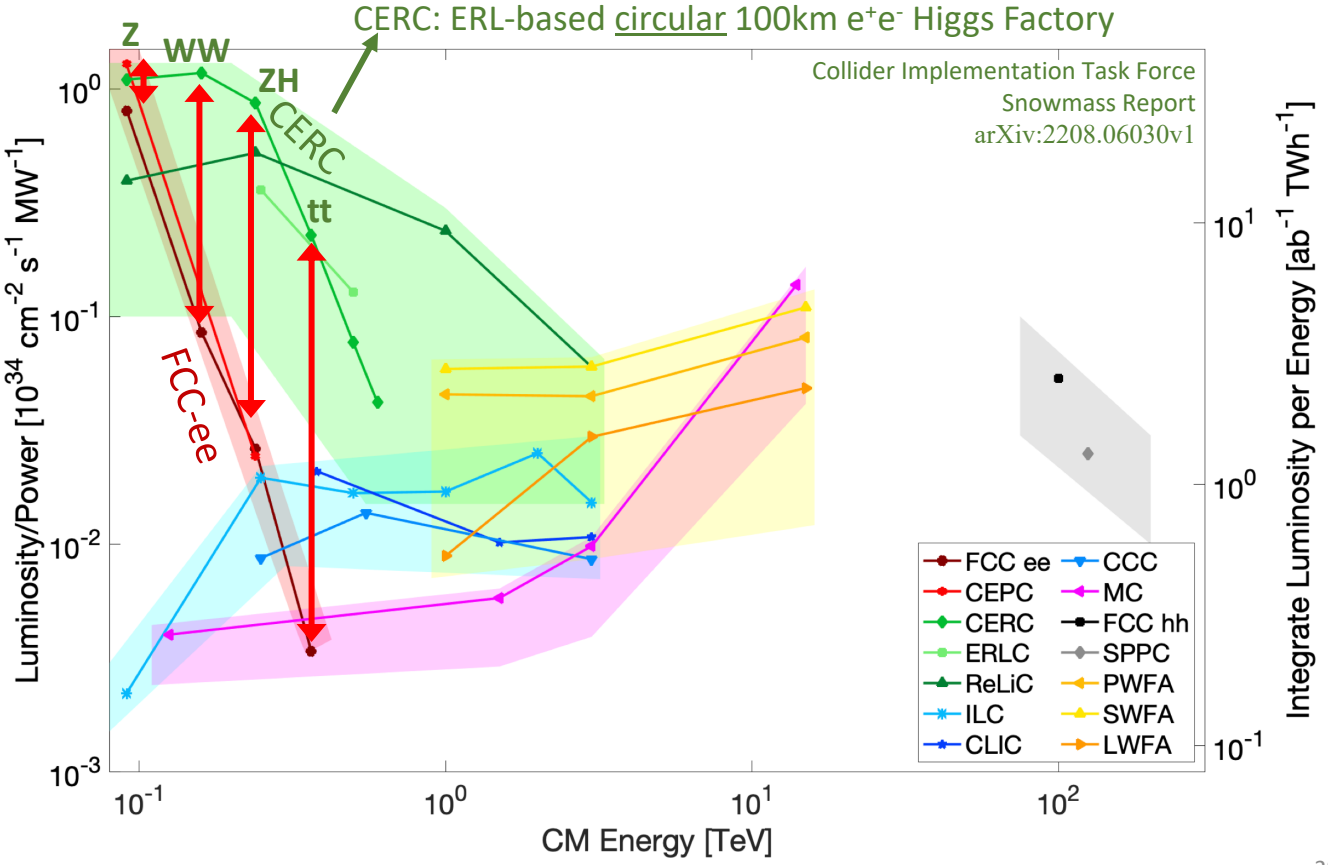
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

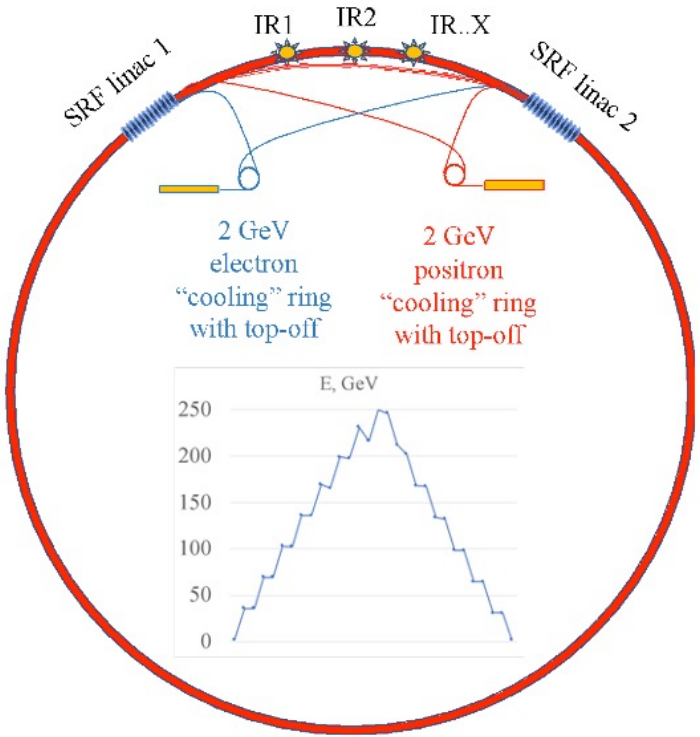
or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories
(hence the large uncertainty band in the plot)



Energy Recovery applications for HEP e^+e^- colliders: CERC



- Two 11 to 90 GeV SRF linacs in 4 pass configuration
- 1/3rd of power consumption as compared to circular collider
- CM Energy reach of 600 GeV in 100 km circumference tunnel
- Damping rings for emittance reduction and recycling of beams

- Maximum Power of 300 MW per beam @ 120 GeV and 2.47 mA

Refs for CERC: V. Litvinenko, T. Roser, M.C. Llatas, PLB 804 (2020) 135394 and arXiv:2203.07358

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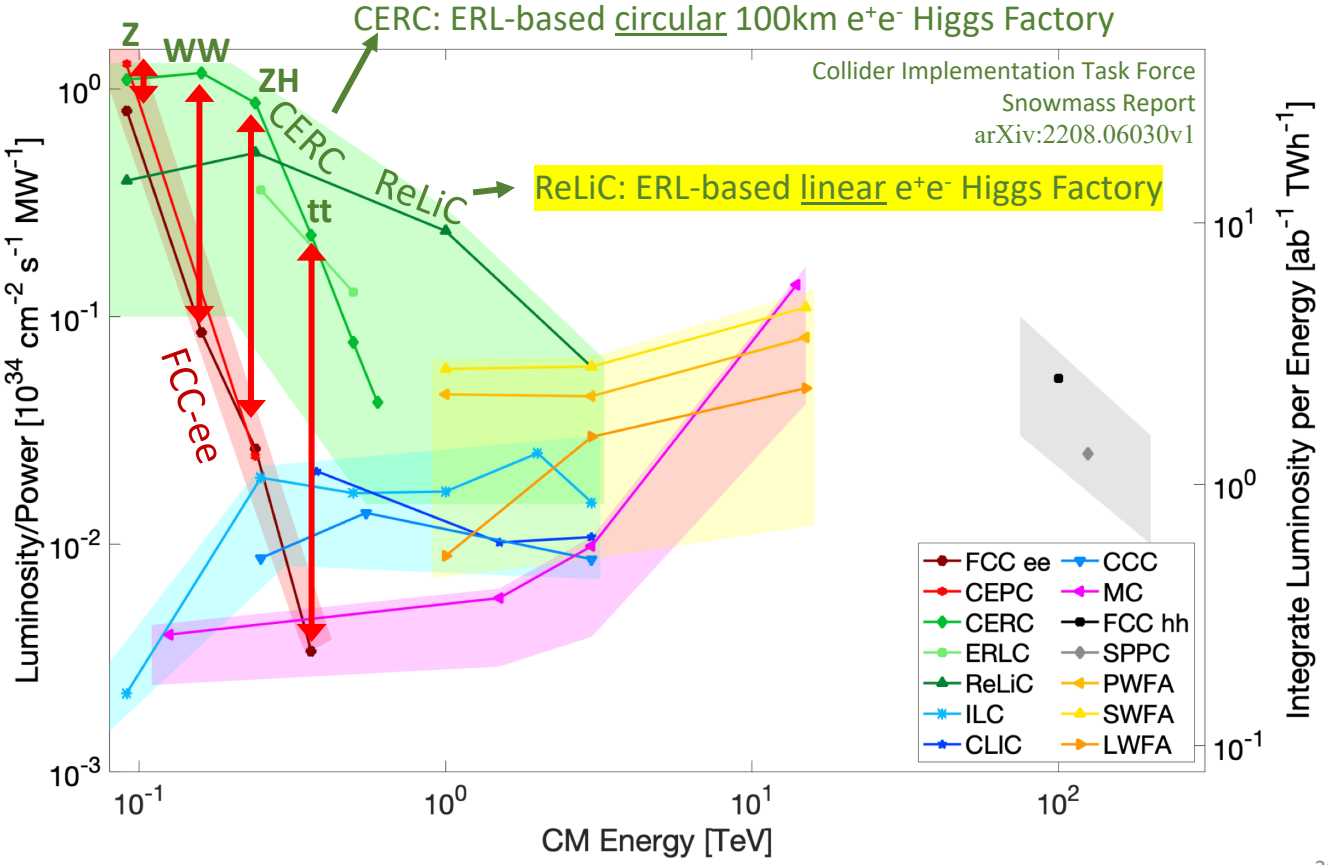

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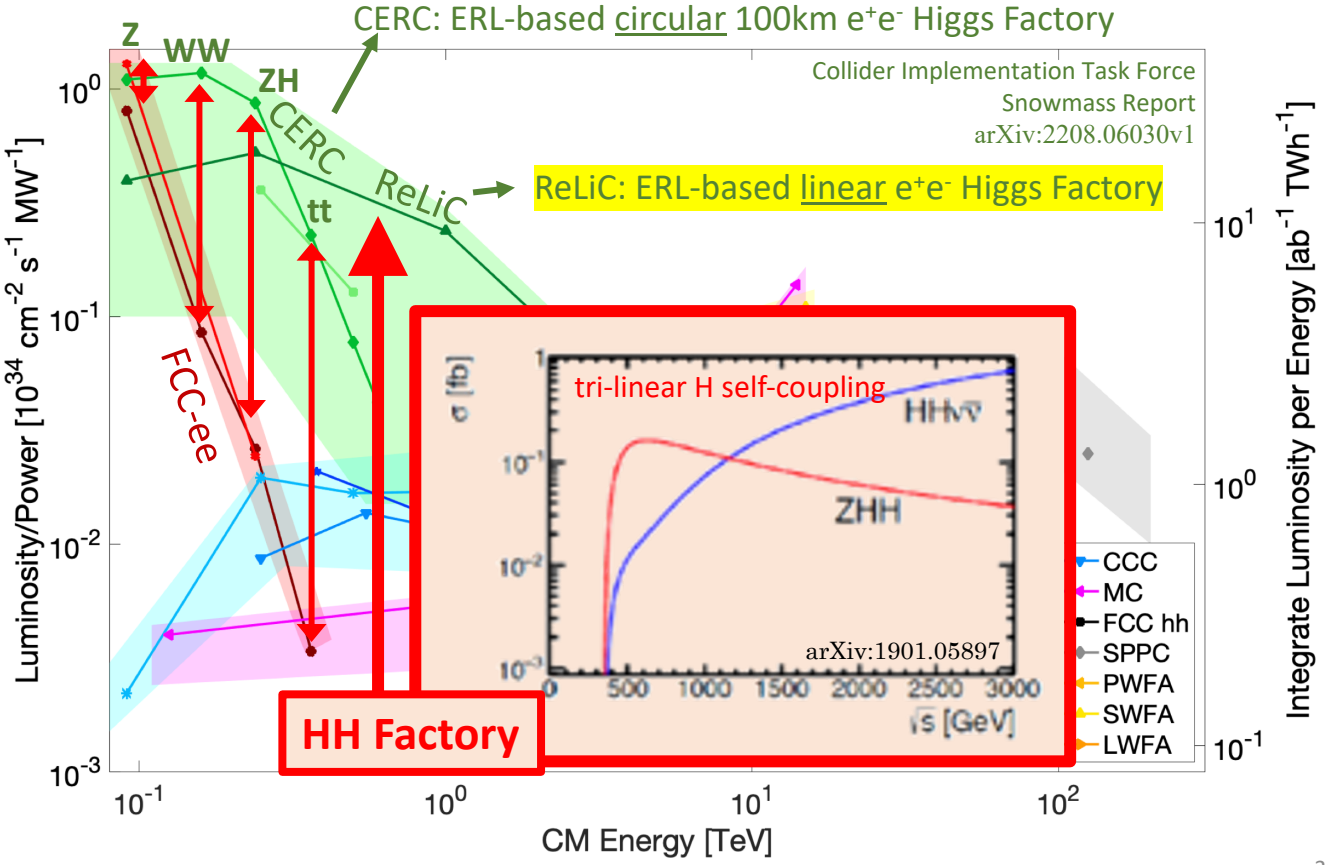
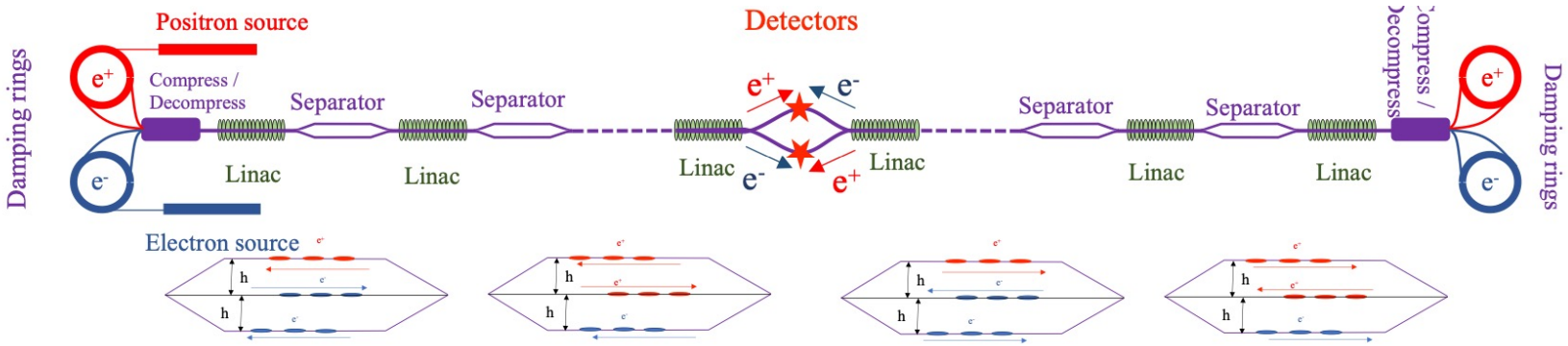


Energy Recovery applications for HEP e^+e^- colliders: ReLiC



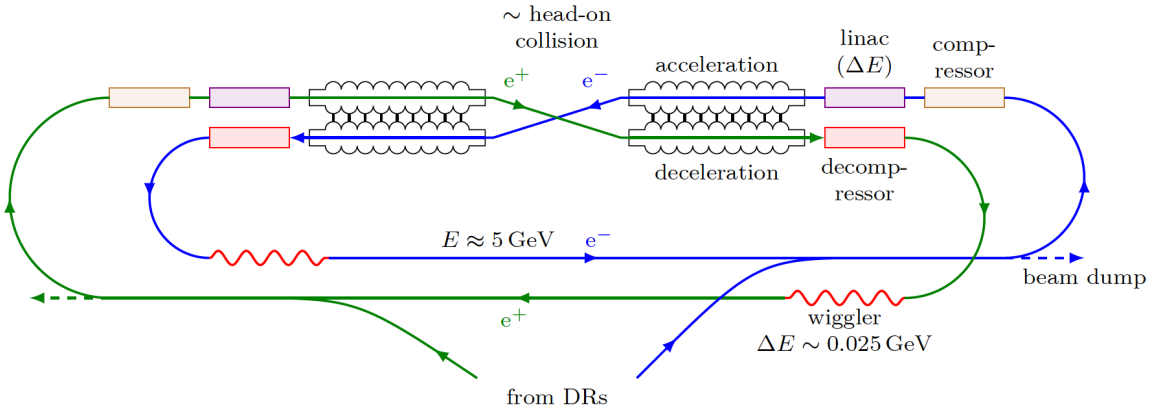
- Flat beams are cooled in damping rings
- Beams are accelerated on-axis in SRF linacs and collide in one of the detectors
- After collision, beams are decelerated in the opposite linacs and periodically separated off-axis

- Natural polarization of both beams builds up in the damping rings
- Depolarization during the trip between damping rings is minuscular, hence providing a high degree of polarization at collision

- With top-off to replace burned particles (1 nA level), the beam lifetime is about 10 hours

Ref for ReLiC: V. Litvinenko et al., arXiv:2203.06476

Energy Recovery applications for HEP e^+e^- colliders: ERLC



- ERLC consists of two parallel superconducting linacs connected to each other with RF-couplers, so that the fields are equal at any time
  - One line is for acceleration, the other for deceleration.
- Damping is provided by wigglers (no damping rings) at the “return” energy about E~5 GeV
- The energy loss per turn δE/E~1/100
- Damping is needed to reduce the energy spread arising from collision of beams

Ref for ERLC: V.I. Telnov, JINST 16 (2021) P12025

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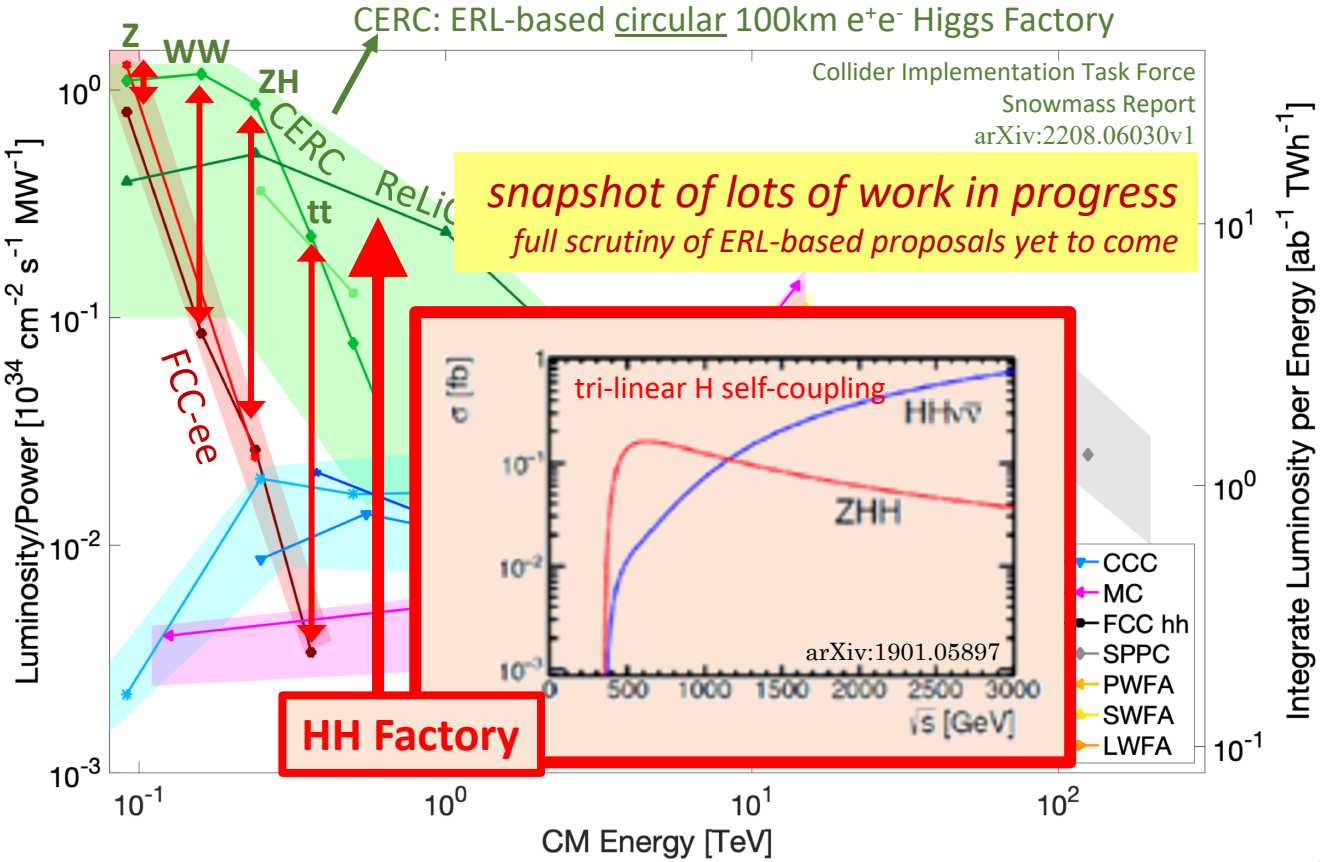

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Ref for ReLiC: arXiv:2203.06476

Energy Recovery applications for HEP e+e- colliders

Can we dream to have an ERL-based Higgs Factory in the LHC tunnel?

Power of Synchrotron Radiation ~ 1/R

R : radius of circular collider

Synchrotron Radiation in 27km versus 100km e^+e^- collider ~ x4

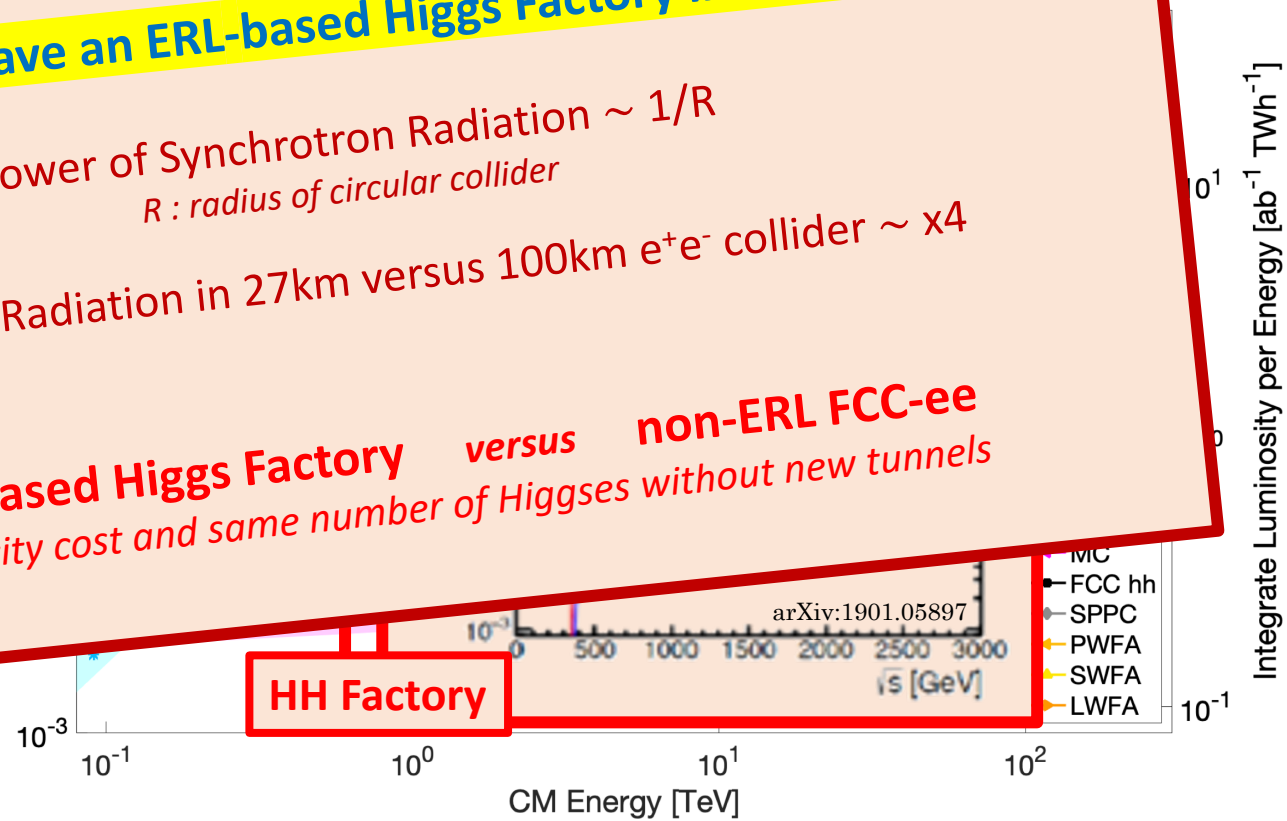
LHC ERL-based Higgs Factory ***versus*** **non-ERL FCC-ee**

same electricity cost and same number of Higgses without new tunnels

Th
a
F

x10

NO
challe
these E
(hence the large uncertainty band in the plot)



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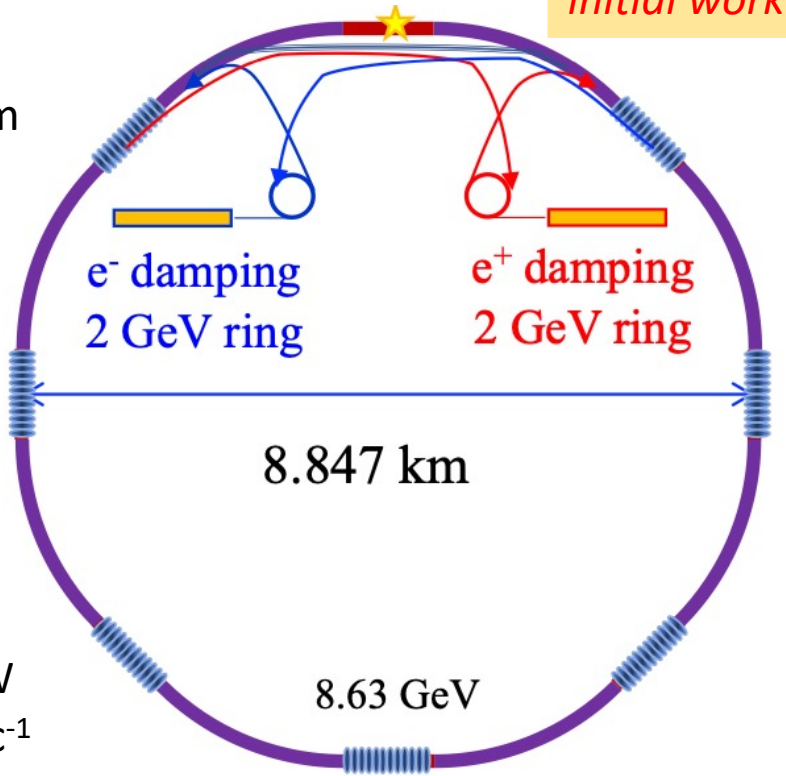
CERC version in the LEP/LHC tunnel for CoM energy of 240 GeV

initial work

- Extrapolated from the CERC (100 km) version
- Splitting the SRF linac in seven parts filling 545 m of straight sections with seven 8.63 GeV SRF linacs
- Section eight is available for <u>one detector</u>, where the beam passes only at top energy
  - *beams with intermediate energy by-pass the IR*
- Two-pass ERL
- Luminosity is proportional to SR power – 30 MW SR power loss corresponds to 4.5 x 10^{34} cm^{-2} sec^{-1}

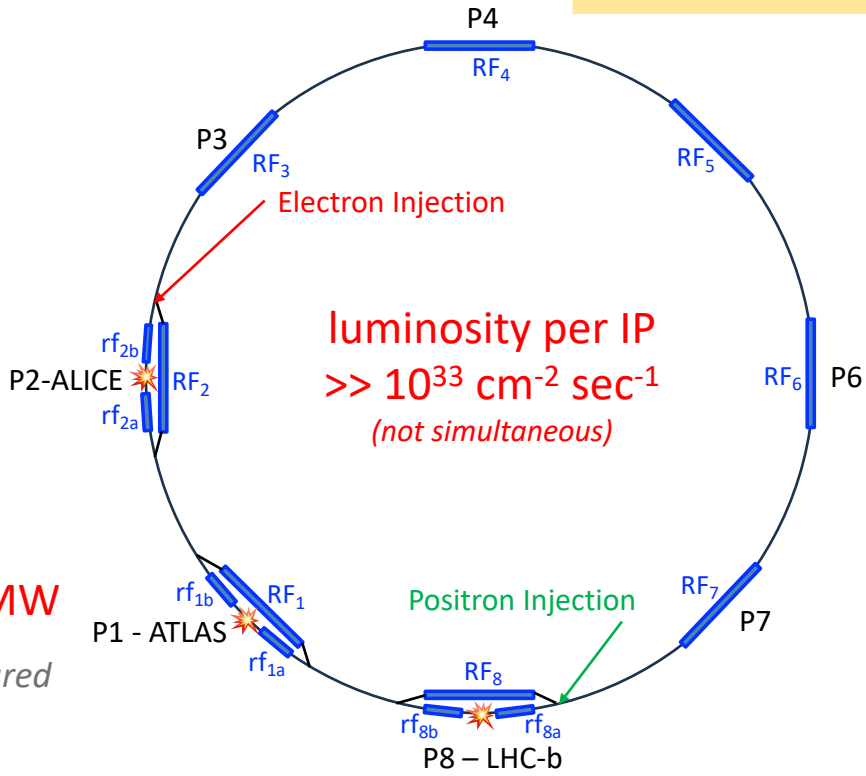


V. Litvinenko, "Future High Energy High Luminosity Polarized e^+e^- Colliders using Recycling Energy Recovery Linacs" at EPS-HEPP 2023, https://indico.desy.de/event/34916/contributions/147045/attachments/84336/111710/EPS-HEP_Litvinenko.pdf

ERC@CERN in the LEP/LHC tunnel for CoM energy of 250 GeV

initial work

- Two-pass ERL version for <u>three detectors</u>
- Including two MAX IV like 3 GeV damping rings
- Power calculations based on *(requires aggressive R&D)*
  - *4.5 K cavities with 31.33 MV/m gradient (70% filling factor)*
  - *same cavities for e^- and e^+ ($Q_0 = 10^{10}$ and 10 mA)*
  - *duty factor 1/10 (5 Hz operation & 20 ms pulse length)*
  - *ε_x (norm) = 0.42 mm-mrad & ε_y (norm) 4.2 μm-mrad*
  - *8 MHz bunch frequency during RF pulse (2×10^{10} part/bunch)*
- RF $\oplus$ Cryo power = 13.6 MW + 43.7 MW = 57 MW
  - *total synchrotron energy lost in 2 turns is 6.83 GeV, compared to 7 GeV per turn for a non-ERL version*



New work done by A. Hutton; interesting baseline for more detailed simulations to verify for example the beam disruption factor

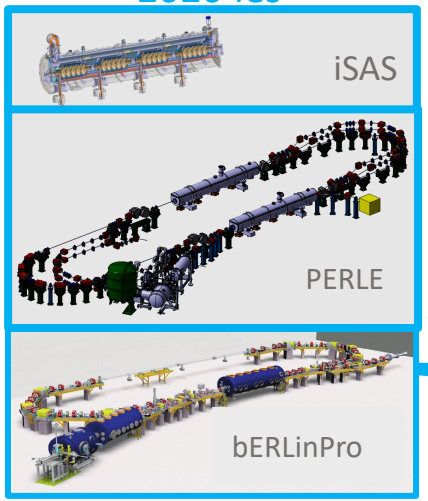
Potential impact of ERL technology

for particle physics colliders

demonstrate (multi-turn) high-power ERL

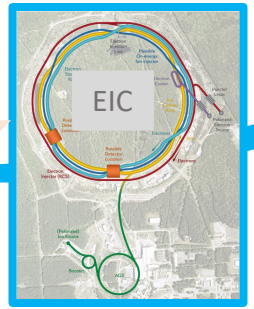
enables the ultimate upgrades of the LHC/FCC programmes ***(ep collisions)***

2020'ies



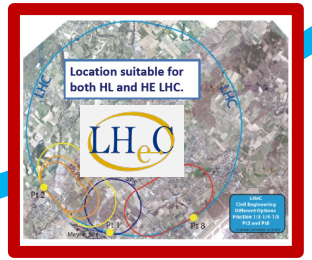
high-power ERL demonstrated

2030'ies



ERL application electron cooling

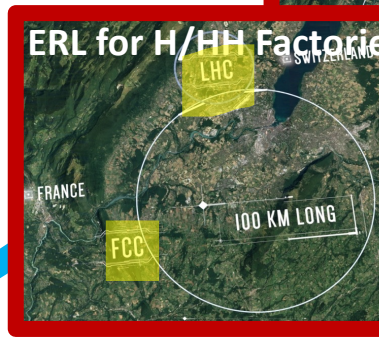
2030-2040'ies



high-power ERL e⁻ beam in collision (ep/eA @ LHC programme)

1 ERL beam

2070'ies



high-power ERL for e^+e^- Higher Factories (Z/W/H/top/HH programme)

2 ERL beams

reuse ERL

increases the performance of the next major e^+e^- colliders

Potential impact of ERL technology

for particle physics colliders

demonstrate

enables t
upgra

An electron-positron Higgs factory is the highest-priority next collider.

European Strategy for Particle Physics 2020

An ERL-route towards an e^+e^- Higgs Factory

potentially enabling additional (ep/eA) and more (e^+e^-) physics
with less impact on the environment and less power requirements
with a timely and affordable realisation (ep/eA)

demonstrated

electron cooling

the next major e^+e^- colliders

Potential impact of ERL technology

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demonstrate

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European Strategy for Particle Physics 2020

An ERL-route towards an e^+e^- Higgs Factory

potentially enabling additional (ep/eA) and more (e^+e^-) physics
with less impact on the environment and less power requirements
with a timely and affordable realisation (ep/eA)
requires additional support to complete the R&D program (e.g. PERLE, bERLinPro, iSAS)
requires enhanced interest and resources for design efforts of ERL-based colliders

Not without challenges!

demonstrated

electron cooling

the next major e^+e^- colliders

Future particle physics colliders with Energy Recovery Linacs

- The engine of our curiosity-driven exploration with particle physics is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize: power requirements are on the minds now
- To achieve the best physics for the least power, energy savings and energy recovery is an ambition expressed in the European Strategy for Particle Physics
- ERL is an enabling technology for our most prominent future ep/eA and e^+e^- colliders, delivering breakthrough performances on an interesting timeline

Future particle physics colliders with Energy Recovery Linacs

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The potential impact of ERL on the performance of particle colliders is so appealing that we must foster this R&D path

ERL Panel website: *https://indico.ijclab.in2p3.fr/event/9548/ (incl. registration to mailing list)*

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE
iihe BRUXELLES BRUSSEL
fwo

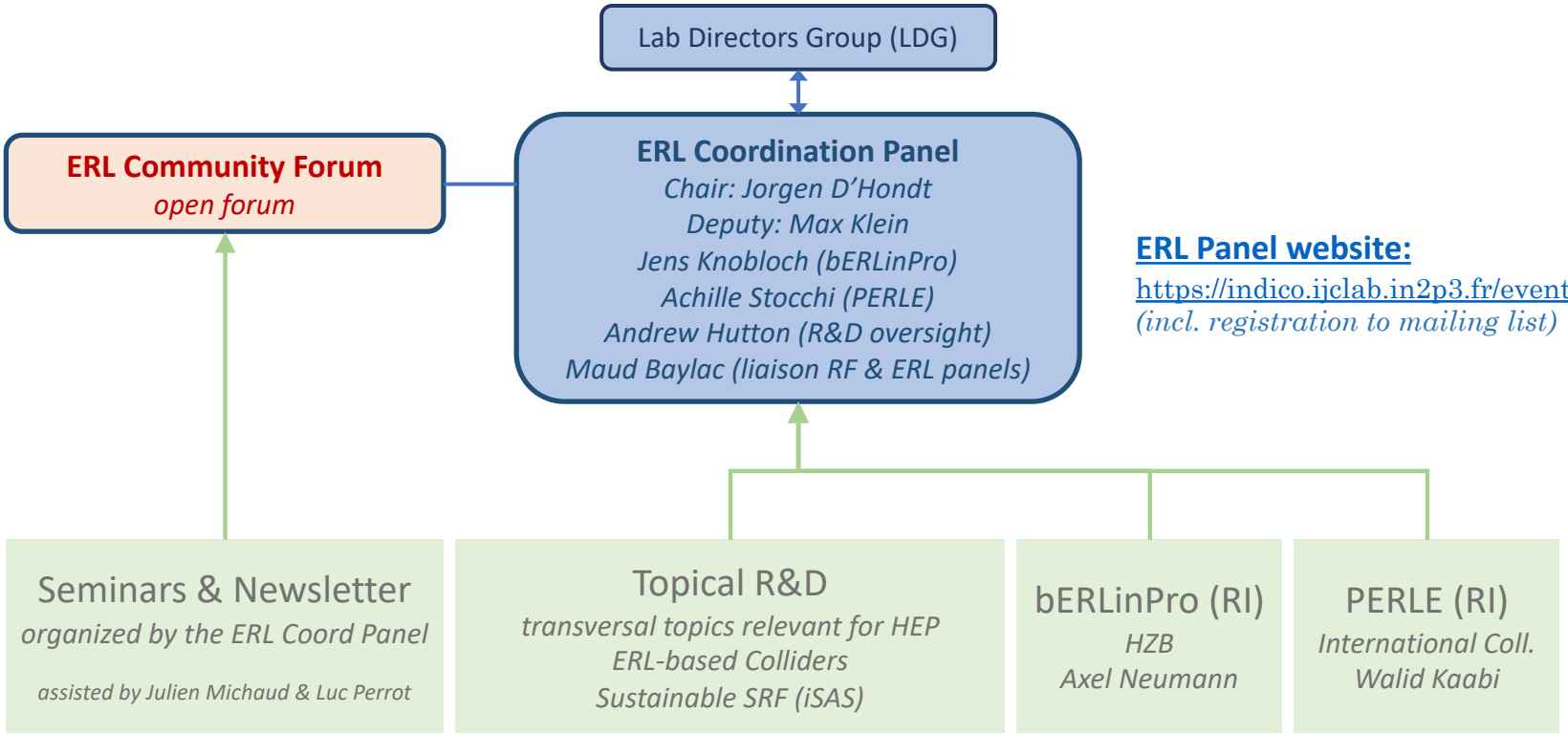
Thank you for your attention!

Jorgen.DHondt@vub.be

EXTRA

Organising the European R&D for ERL in HEP

strengthen collaboration across the field to reach the HEP-related R&D objectives together



RI: Research Infrastructure

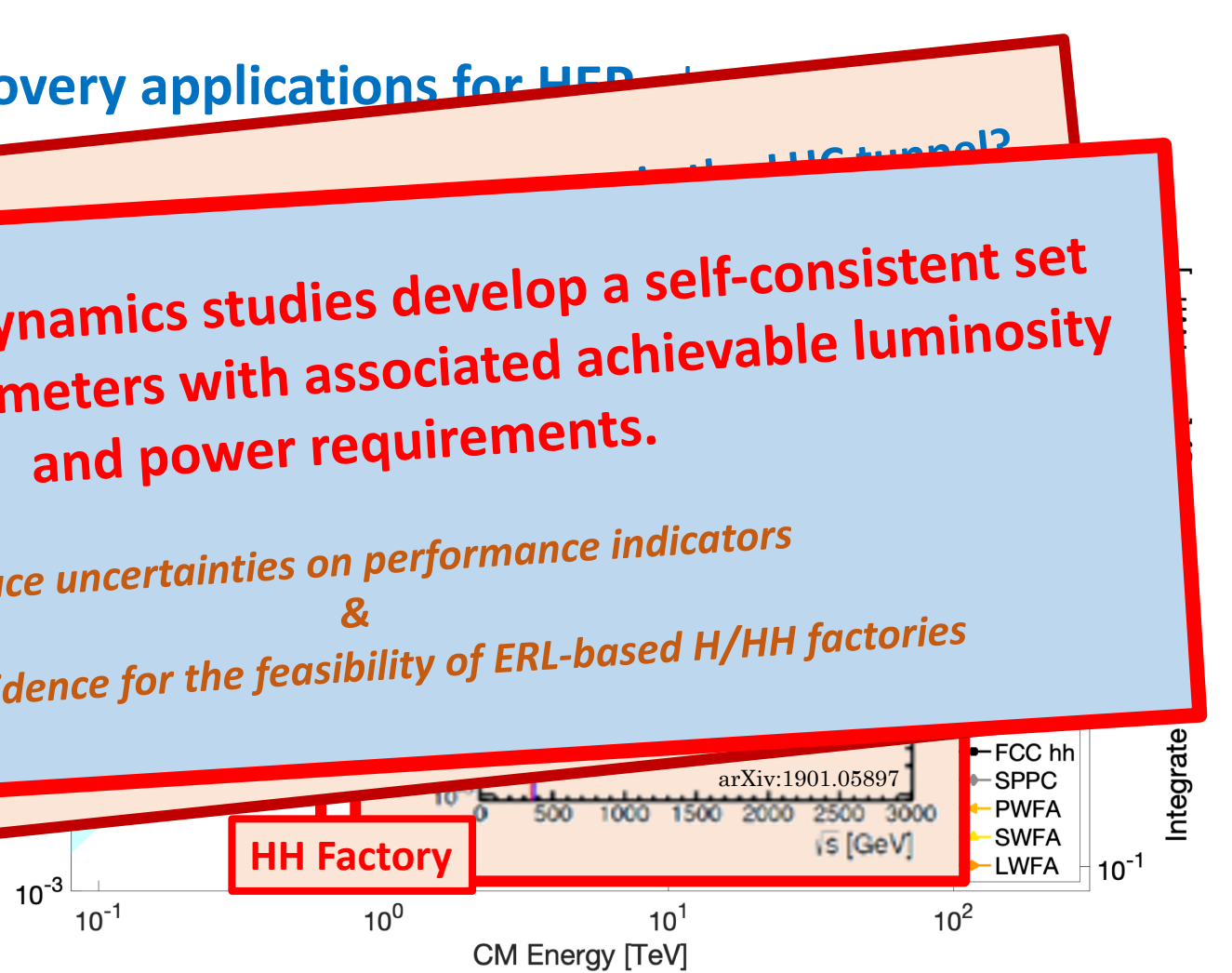
Energy Recovery applications for HEP

Th

Through beam dynamics studies develop a self-consistent set of operating parameters with associated achievable luminosity and power requirements.

Reduce uncertainties on performance indicators
&
Develop confidence for the feasibility of ERL-based H/HH factories

cl
these E
(hence the *certainty band in the plot)*



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Ref for ReLiC: arXiv:2203.06476