Energy Recovery Linacs & *HEP applications*

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Vrije Universiteit Brussel & Nikhef
on behalf of the ERL Coordination Panel

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VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

Nikhef

Plenary ECFA Meeting at CERN
November 14-15, 2024

The principle of Energy Recovery Linacs

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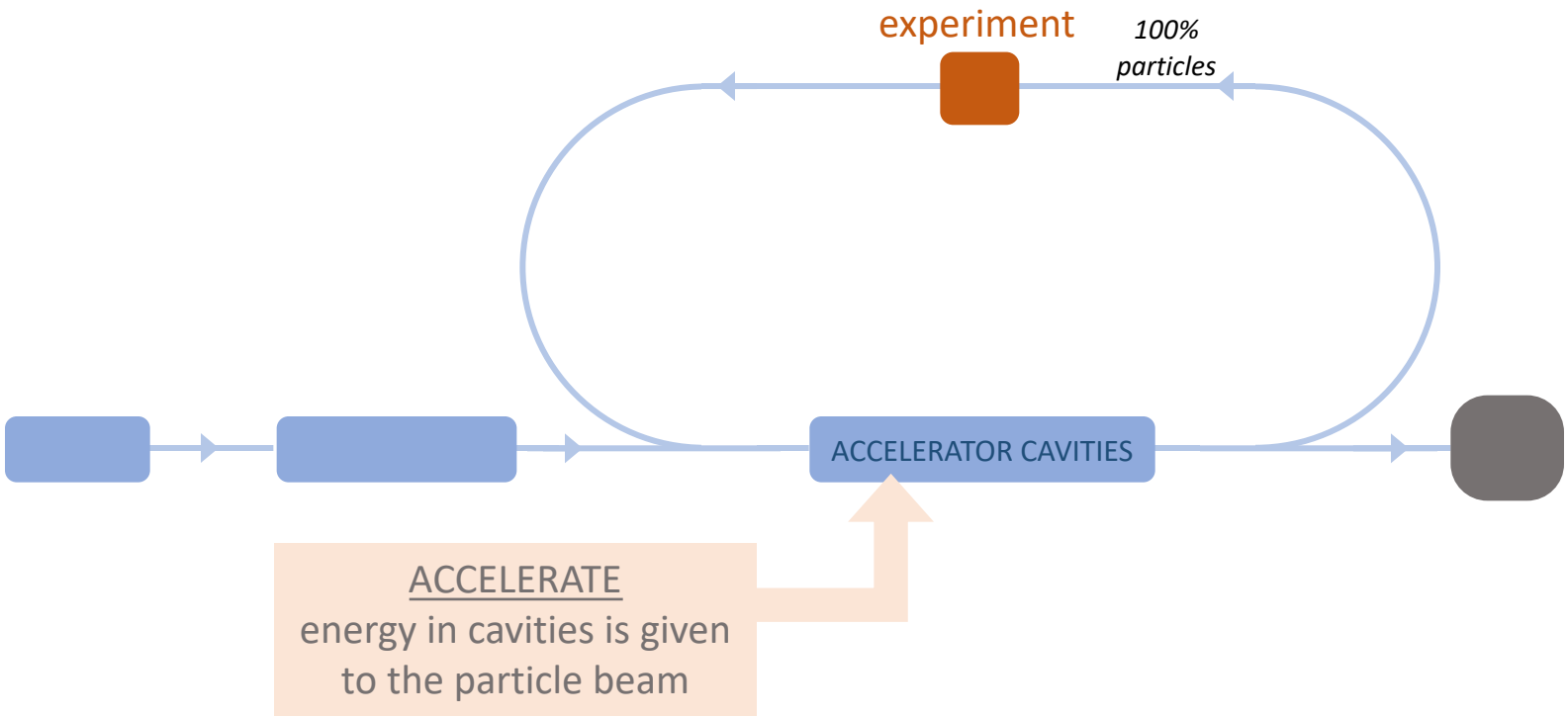

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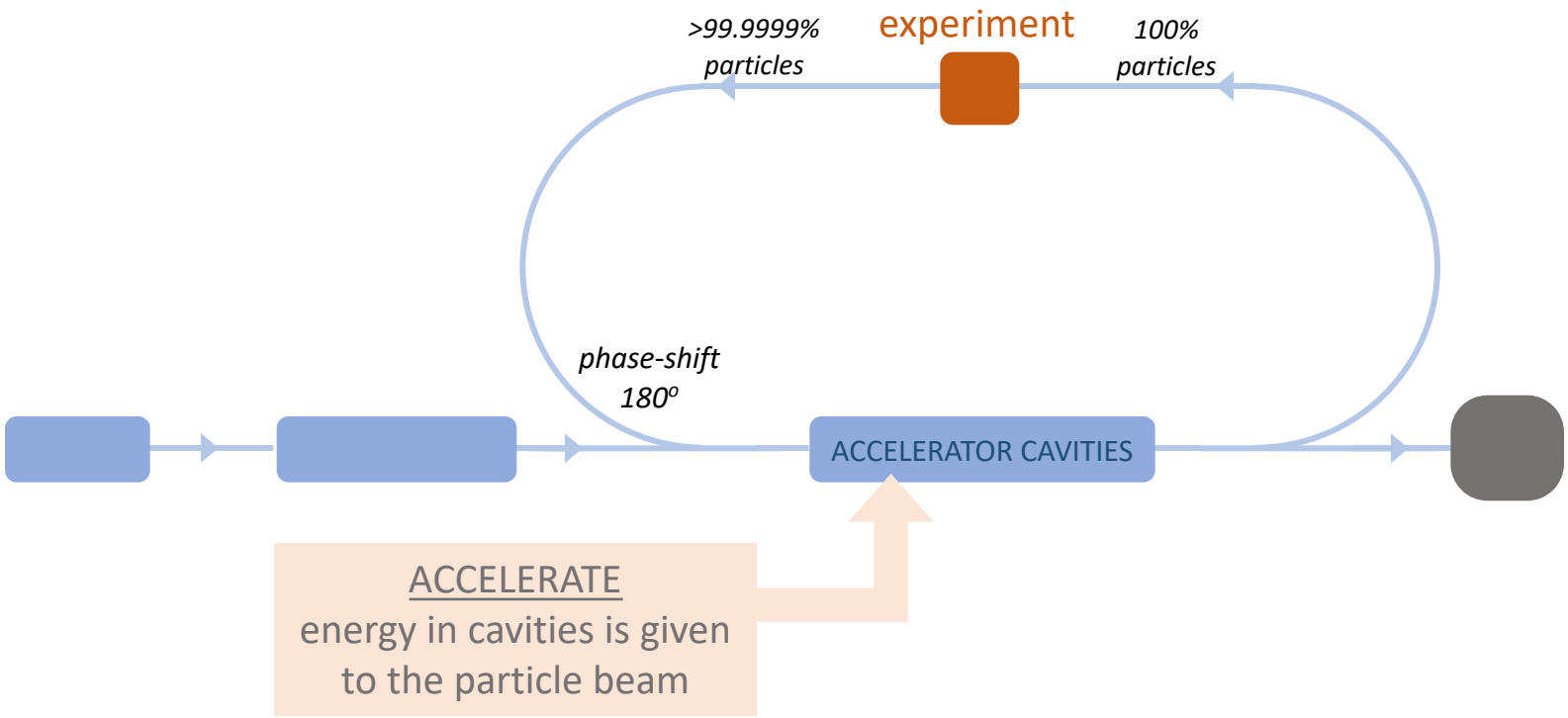

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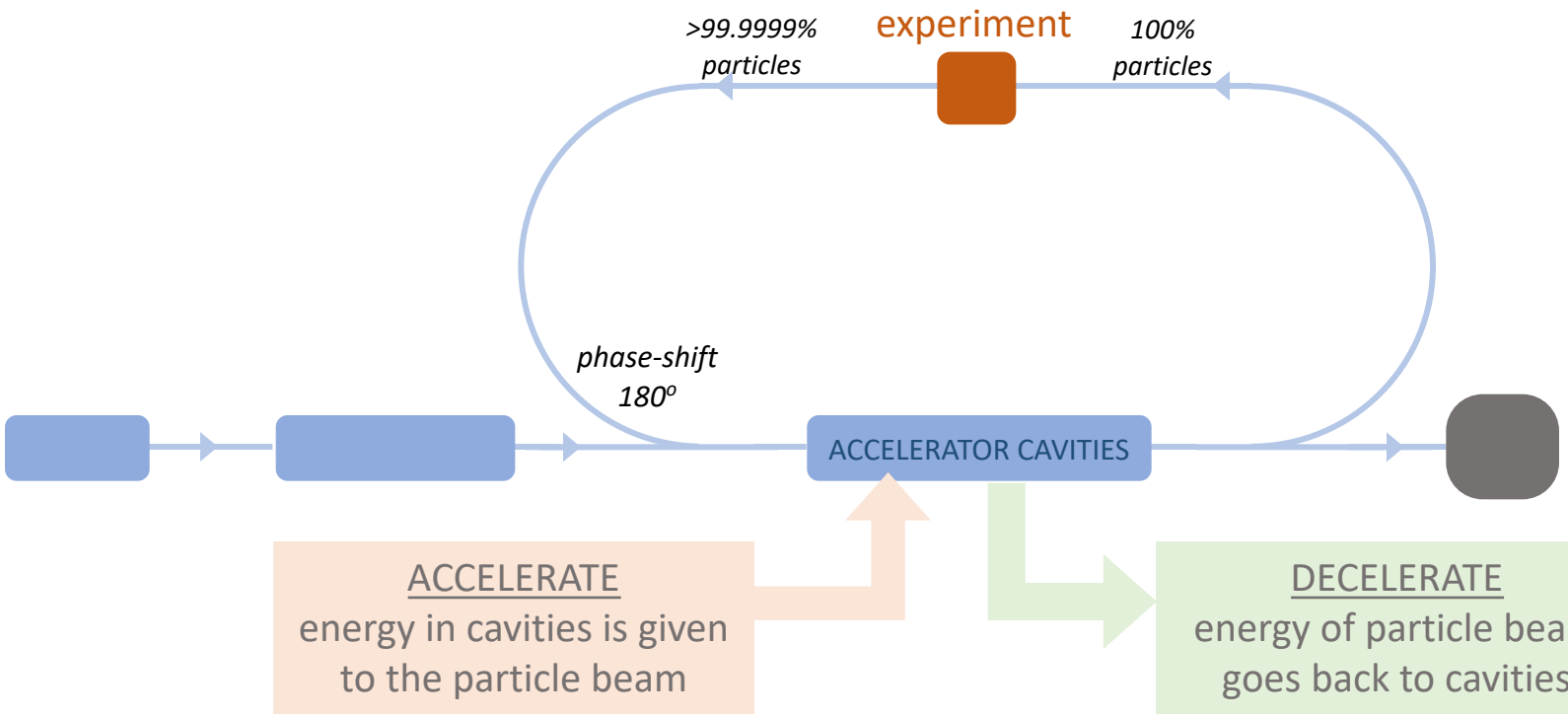

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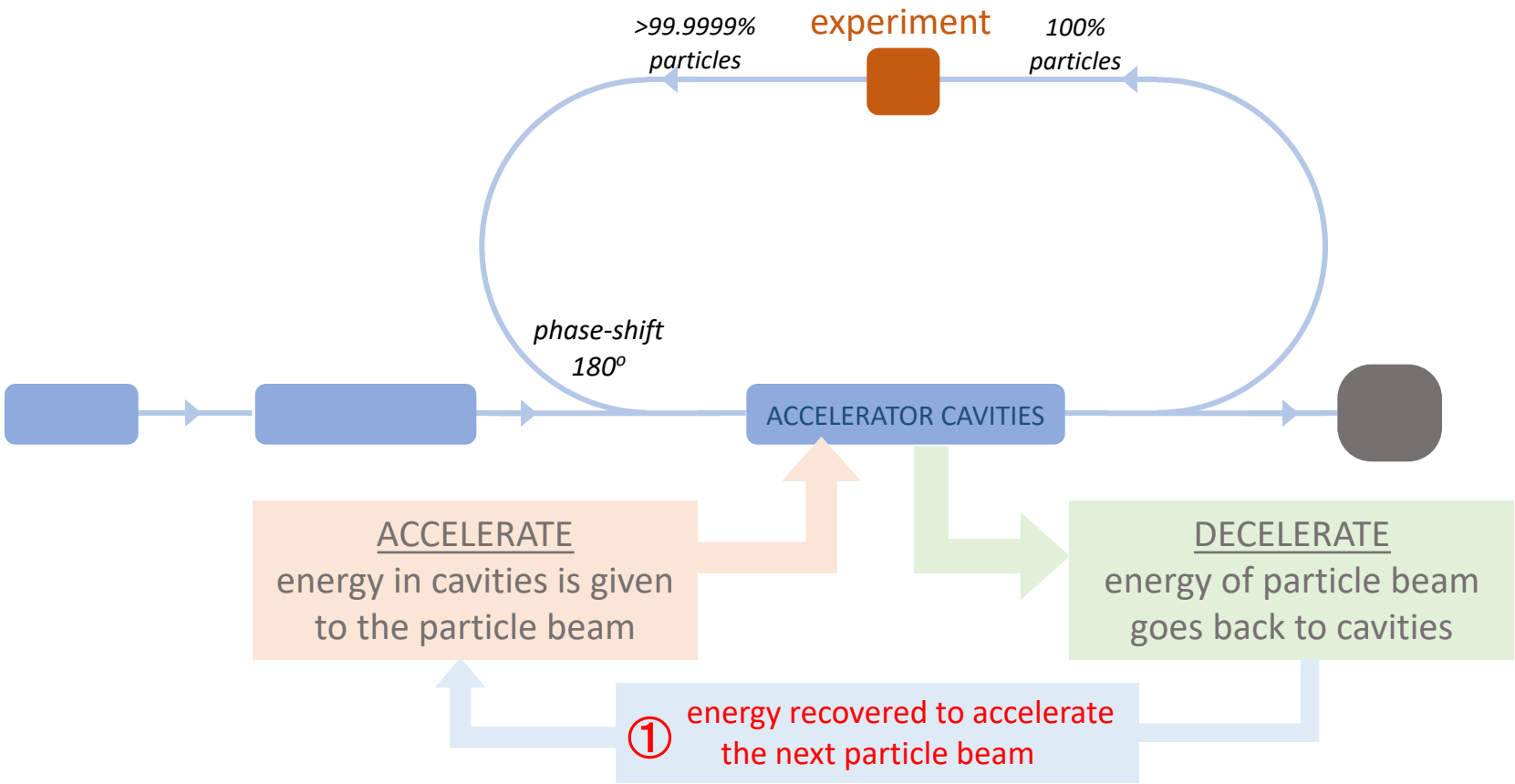

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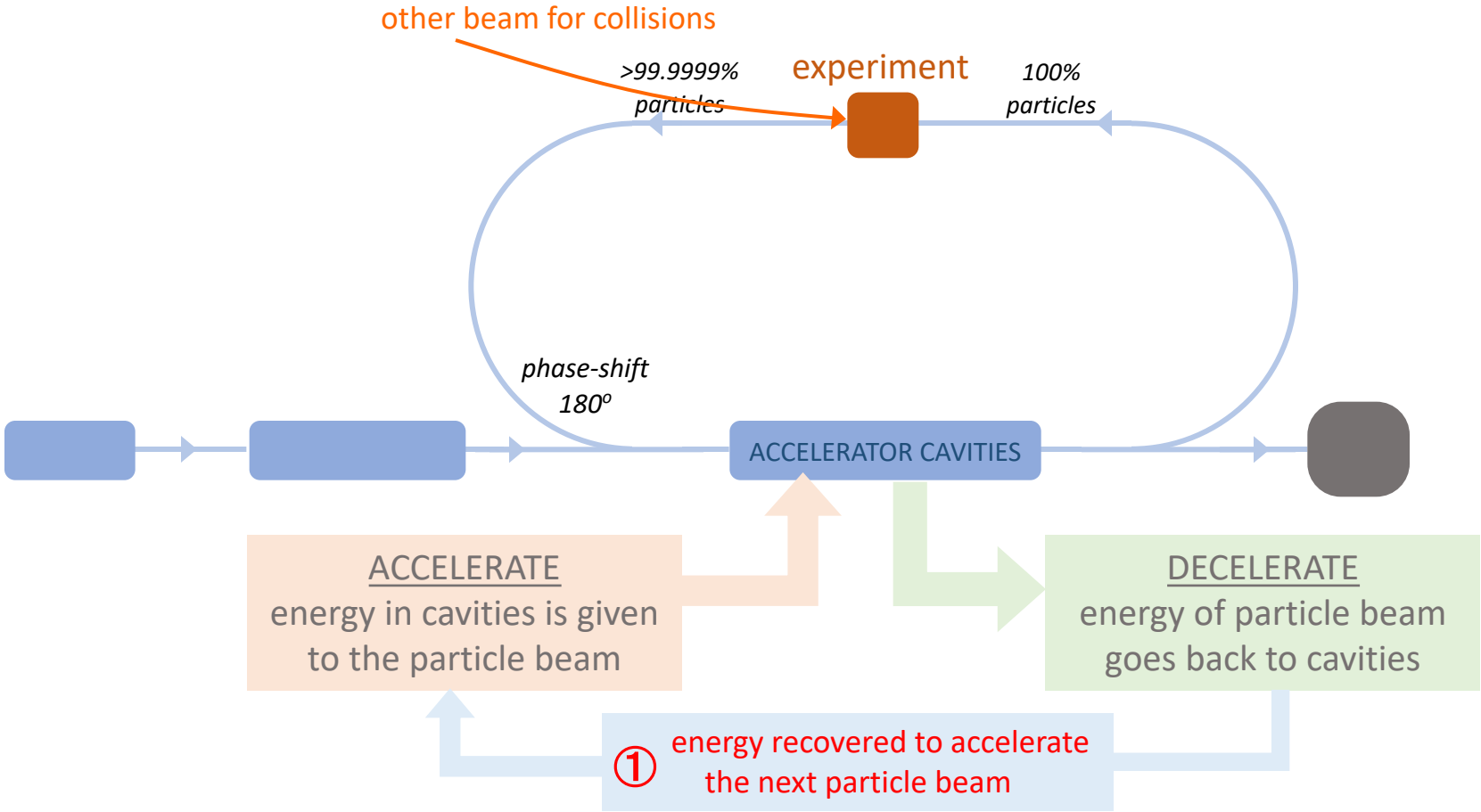

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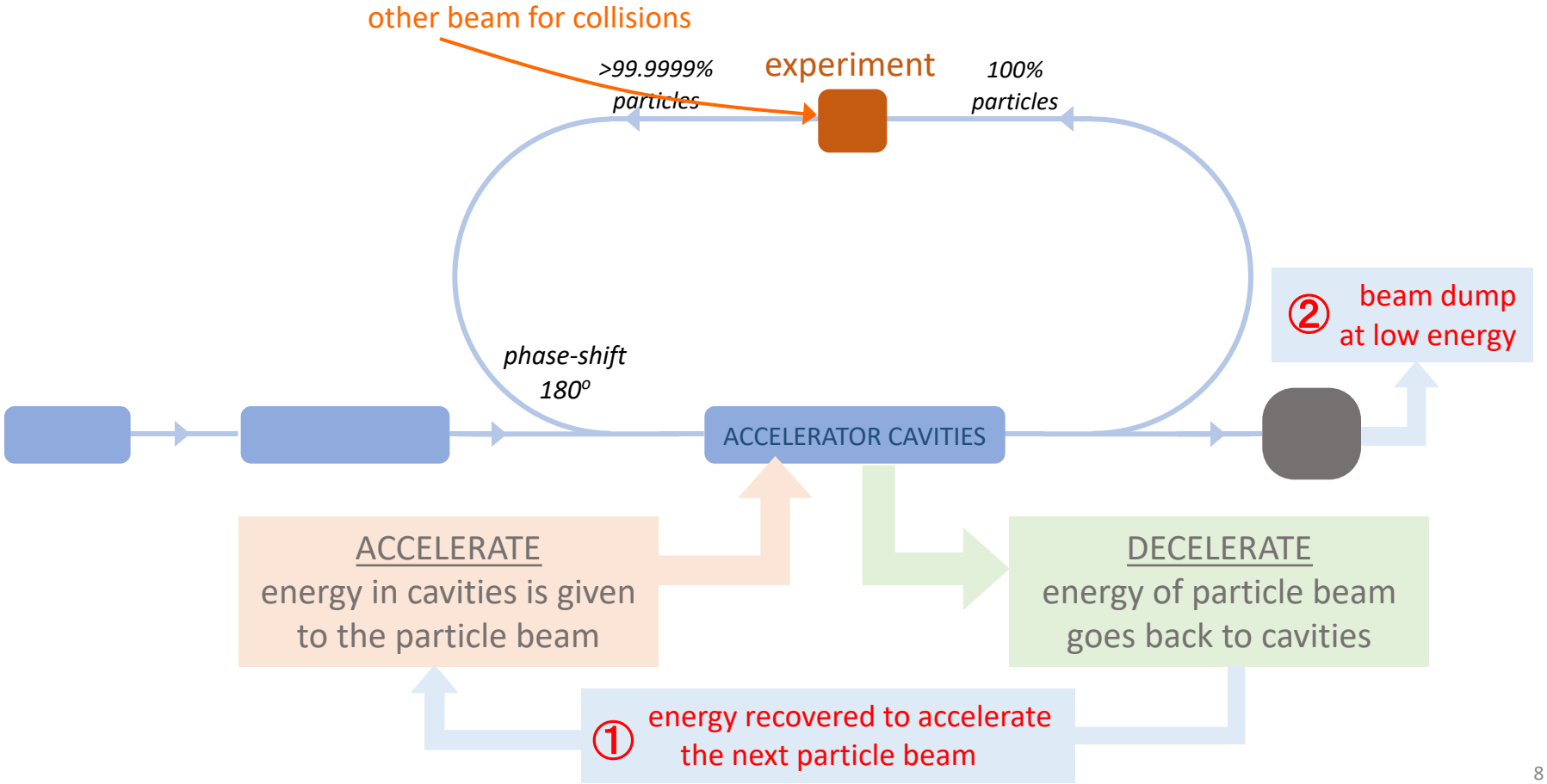

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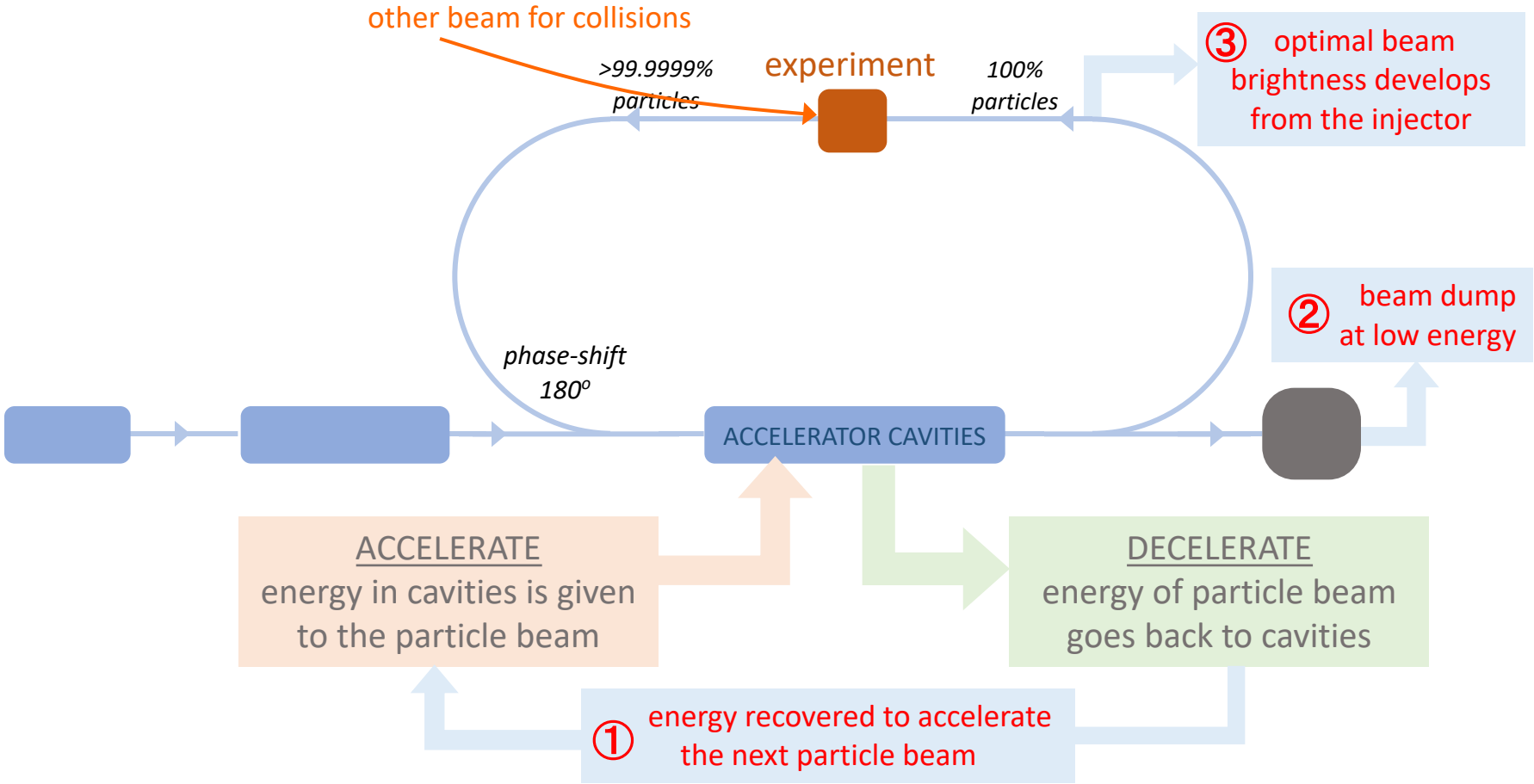

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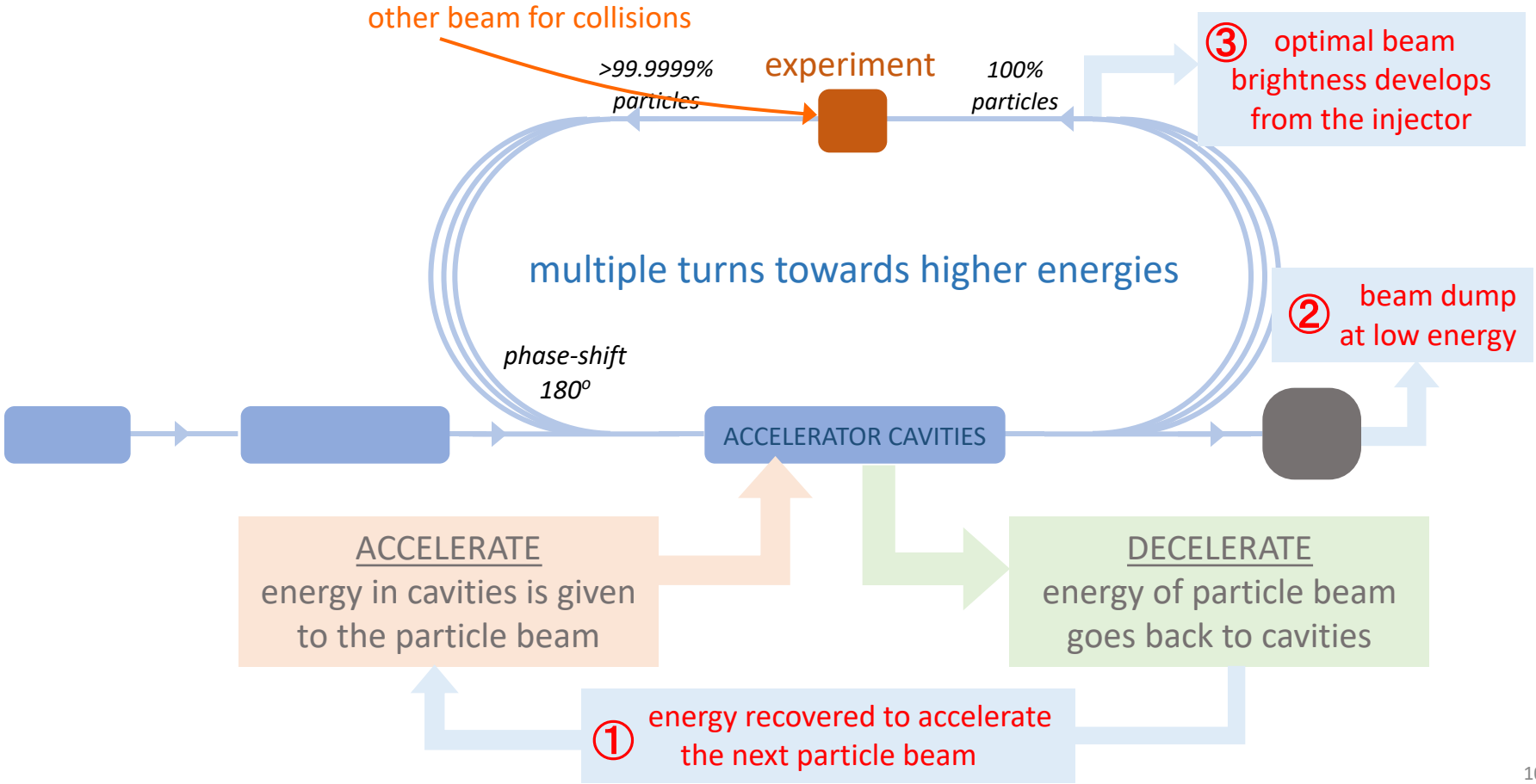

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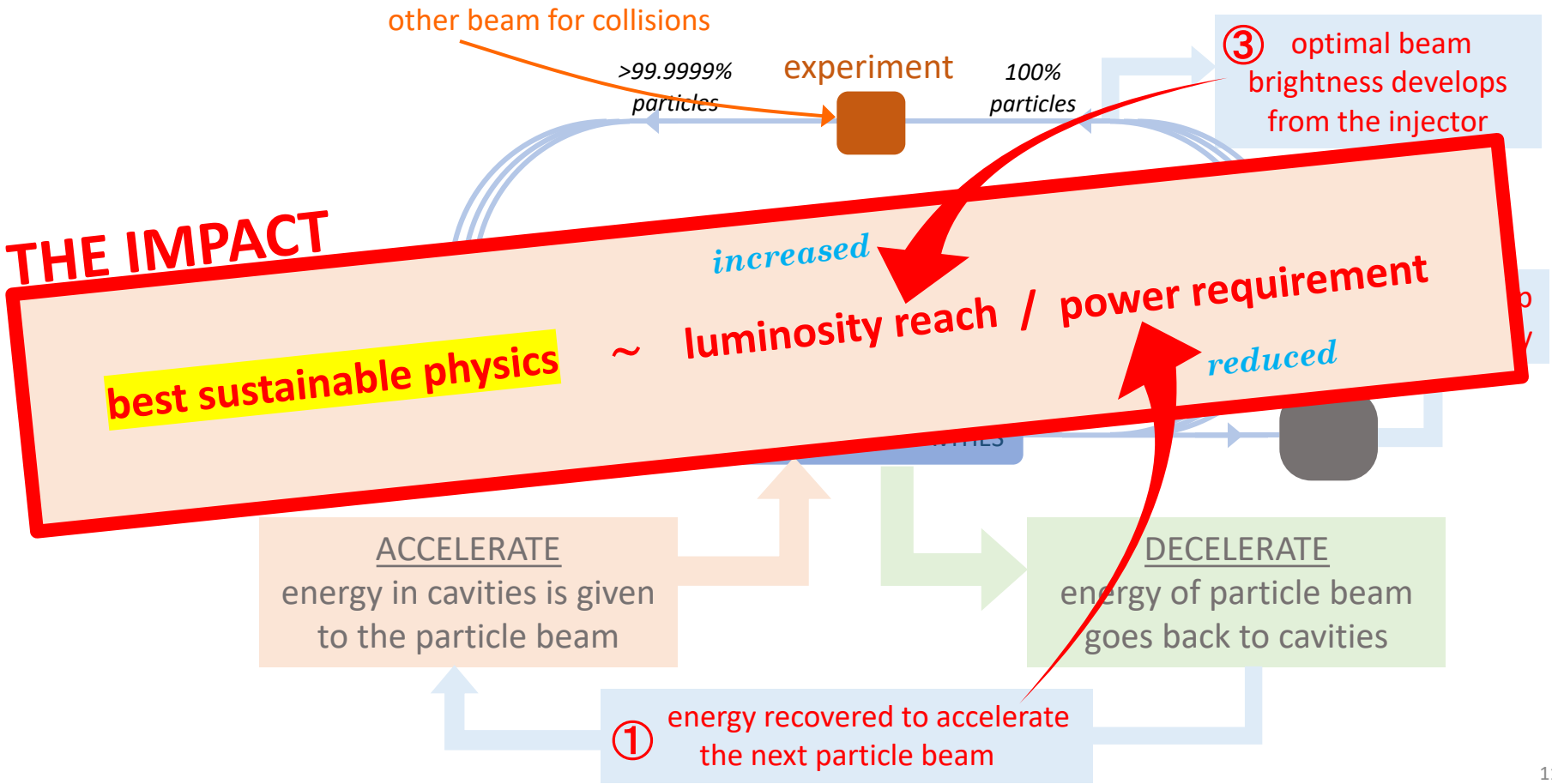
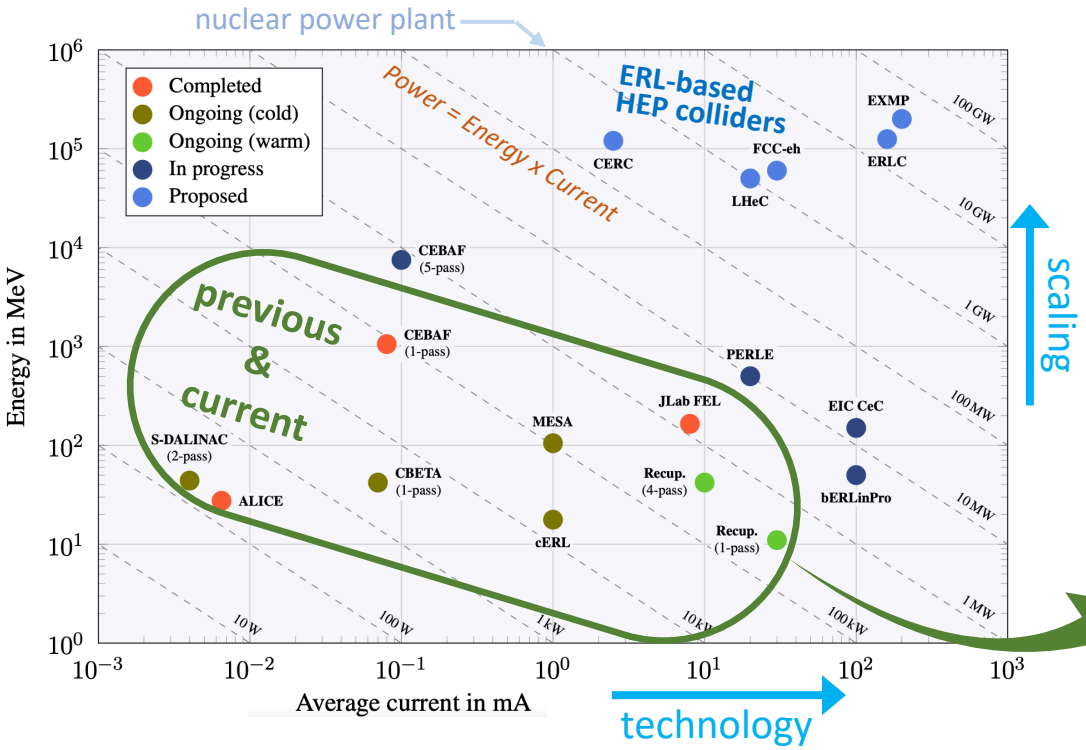


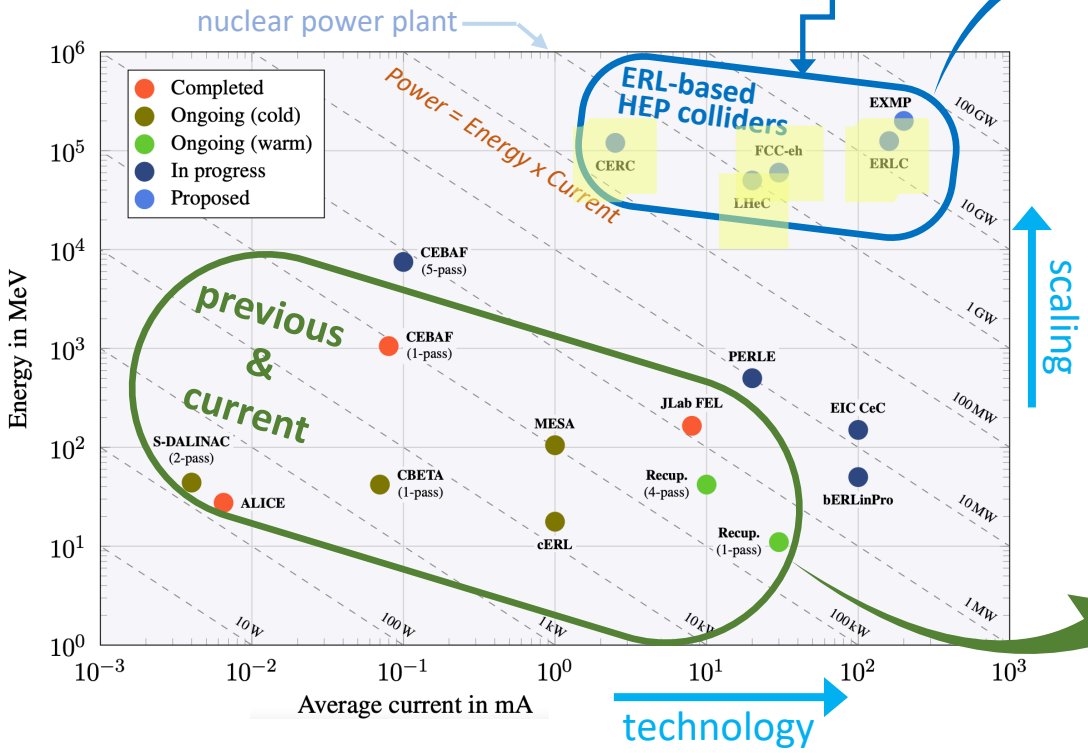
The ERL technique is not new



Energy Recovery demonstrated

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

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, …

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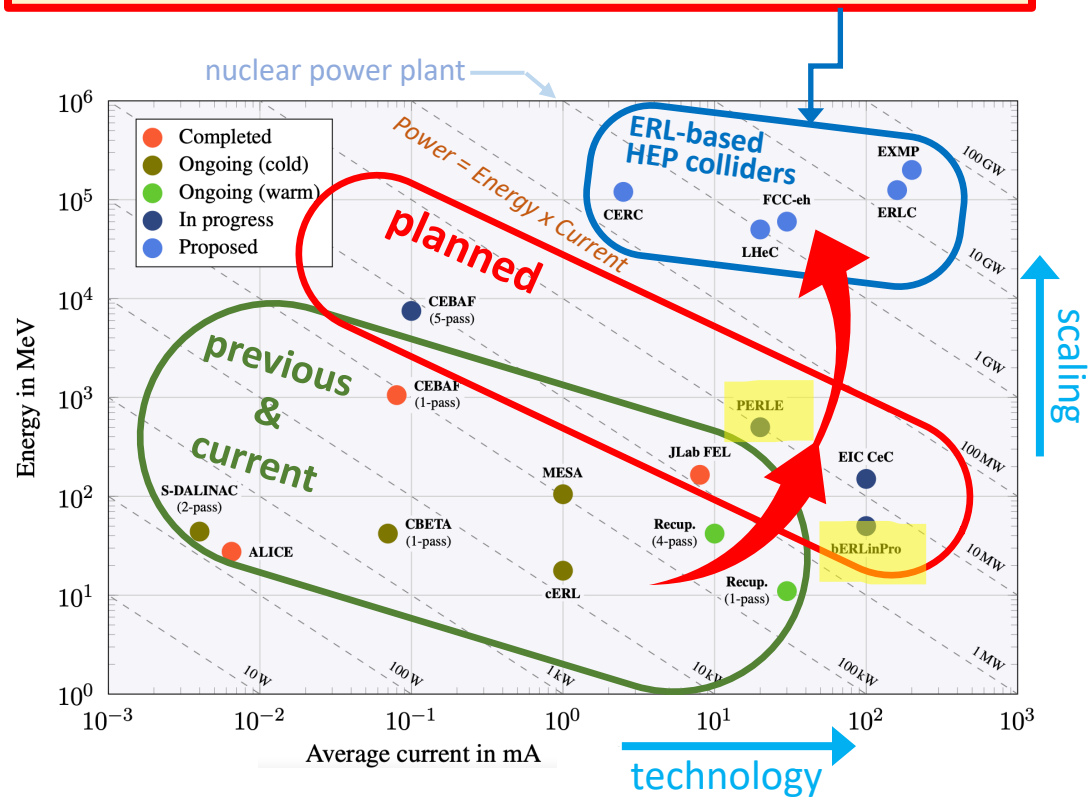

Future ERL-based Colliders

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

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DOI: https://doi.org/10.23731/CYRM-2022-001

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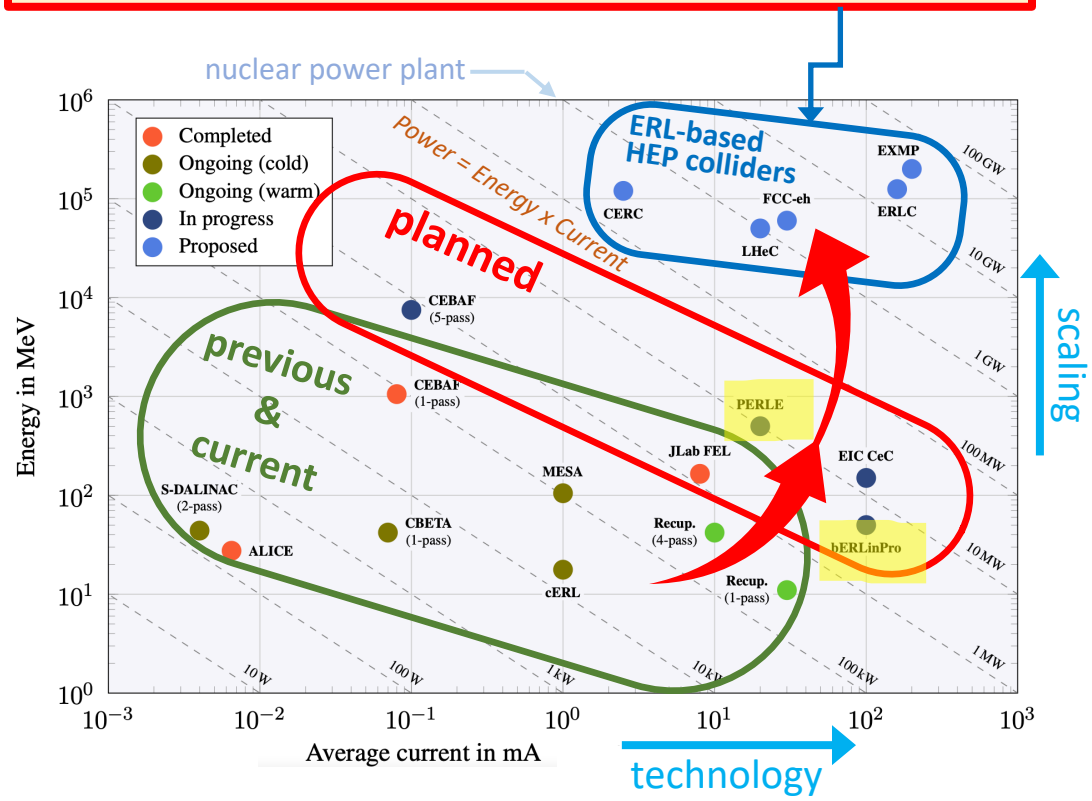


Future ERL-based Colliders

H, HH, ep/eA, muons, …

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

Energy Recovery demonstrated

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

Upcoming facilities for Energy Recovery Linac R&D

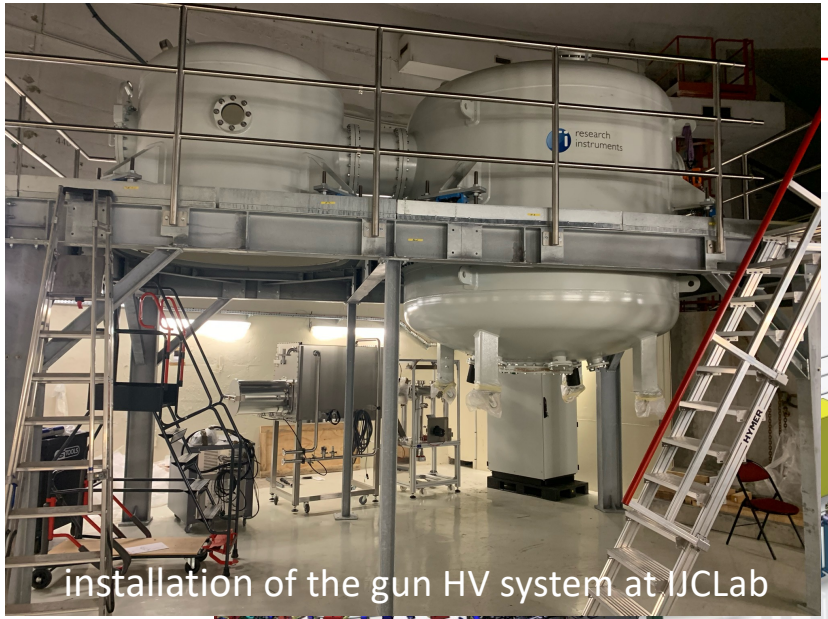
PERLE @ IJCLab (Orsay)

- *growing international collaboration*
- *all ERL aspects to demonstrate readiness*
- *design, build and operation this decade*
- *for e^+e^- and ep/eA HEP collider applications*

PERLE will demonstrate high-power ERL this decade

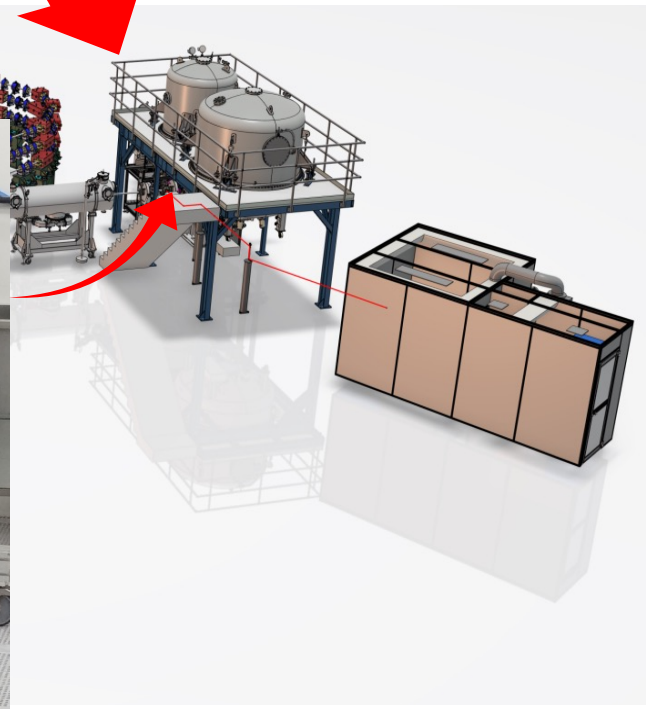
PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

From drawings to reality with PERLE



installation of the gun HV system at IJCLab

cleaning of the gun chamber in the clean room at IJCLab

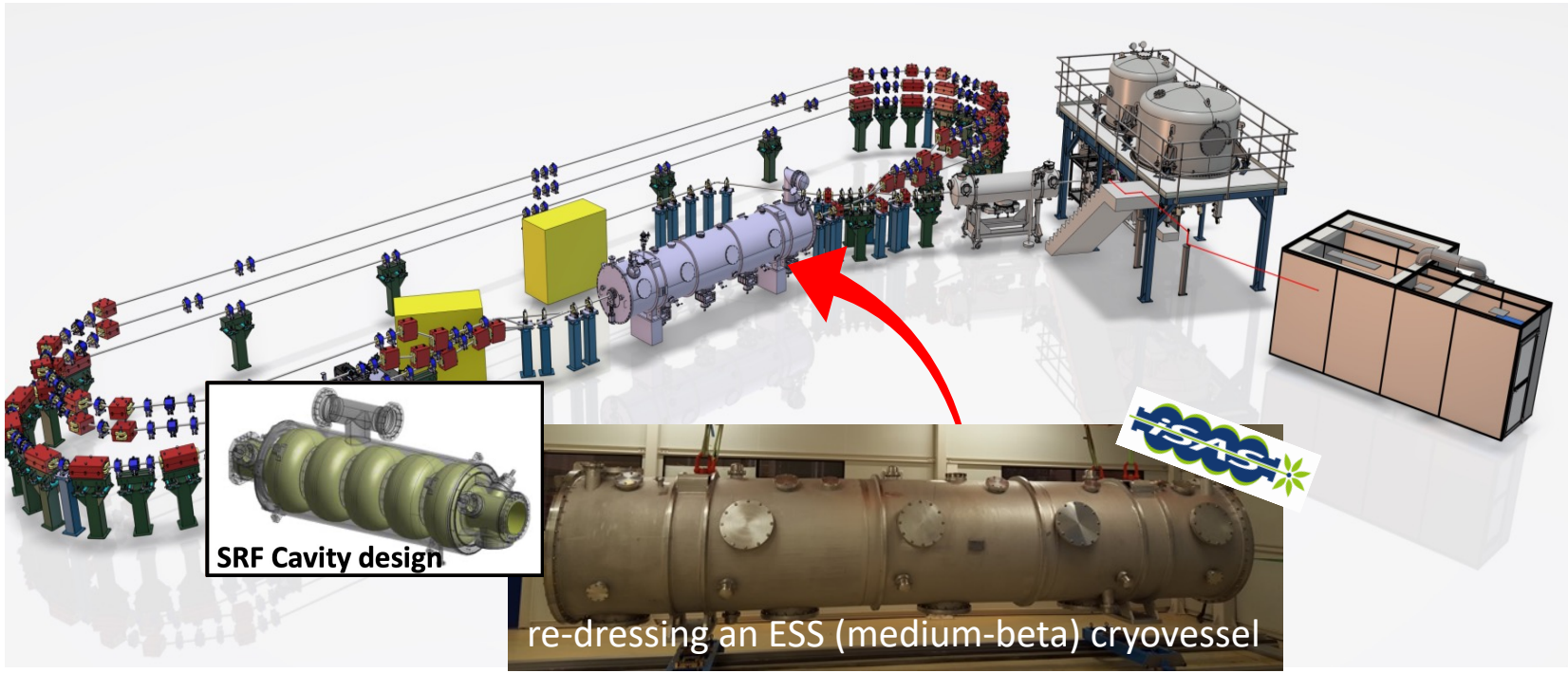


From drawings to reality with PERLE

Photocathode Production Facility (PPF) assembly

Laser room installation

From drawings to reality with PERLE

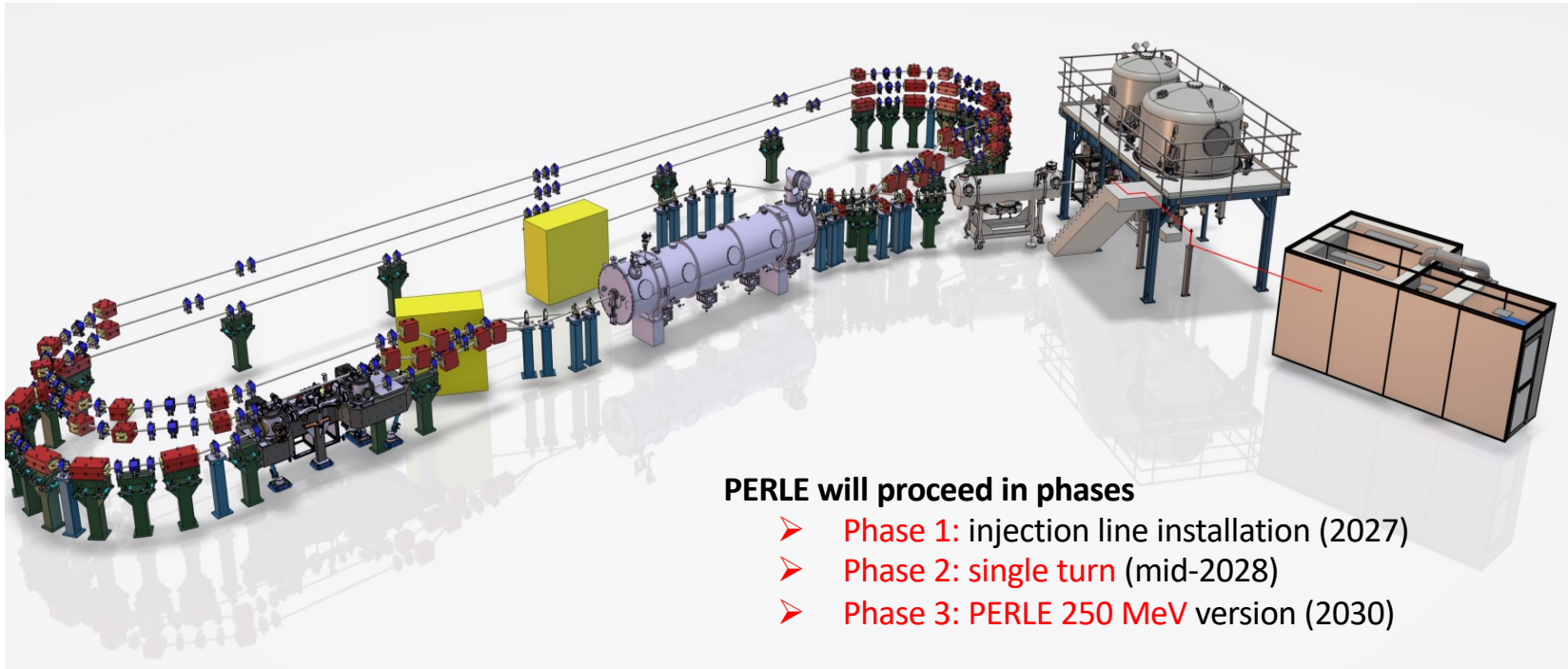


From drawings to reality with PERLE

Various (in-kind) contributions

e.g. cryoplant from HZB

+ Contributions through iSAS of



PERLE will proceed in phases

- Phase 1: injection line installation (2027)
- Phase 2: single turn (mid-2028)
- Phase 3: PERLE 250 MeV version (2030)

From drawings to reality with PERLE

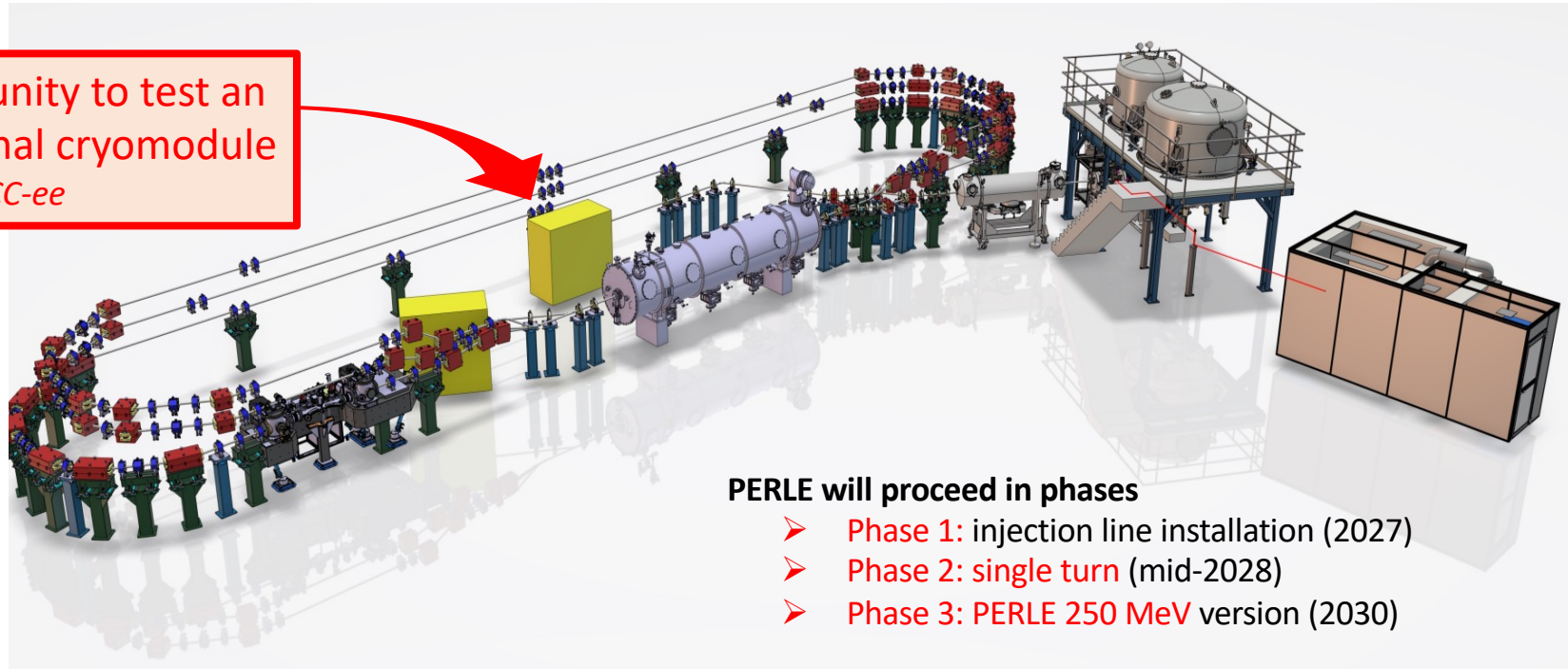
Various (in-kind) contributions

e.g. cryoplant from HZB

+ Contributions through iSAS of

opportunity to test an additional cryomodule

e.g. for FCC-ee



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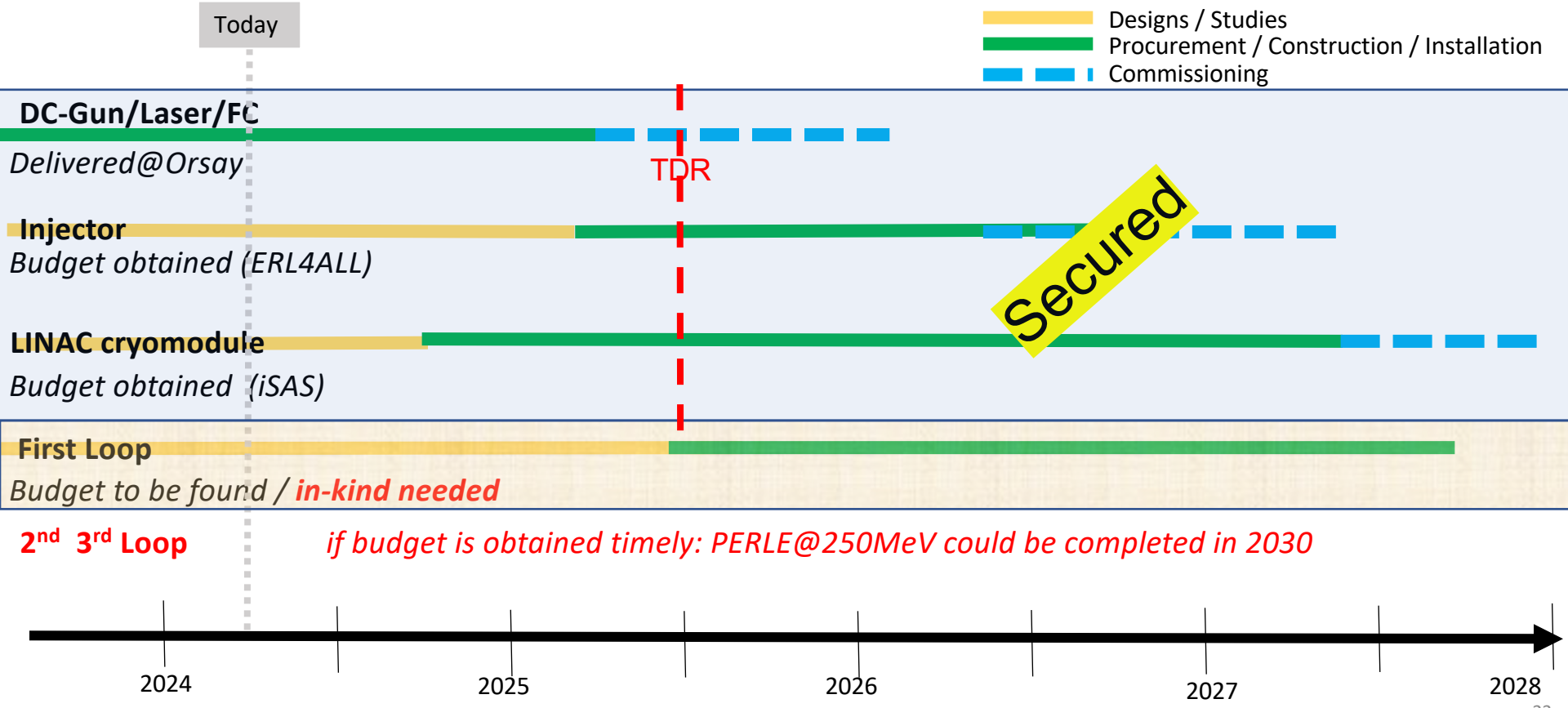
Timeline towards PERLE 1-turn by mid-2028



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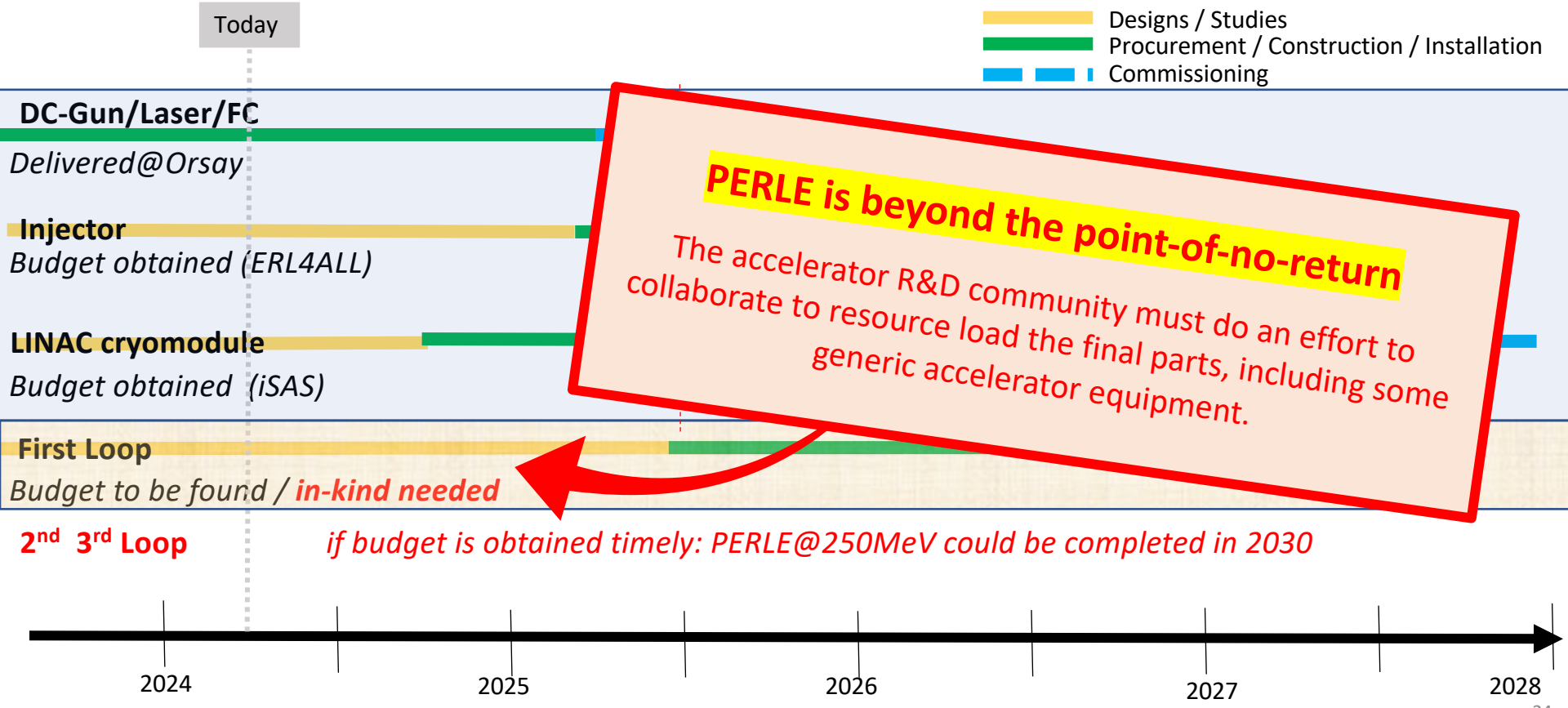
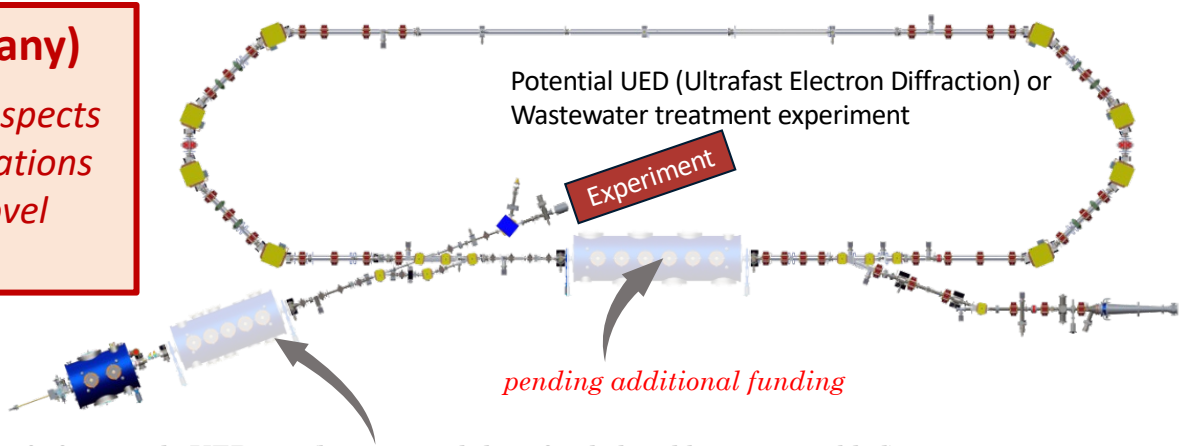


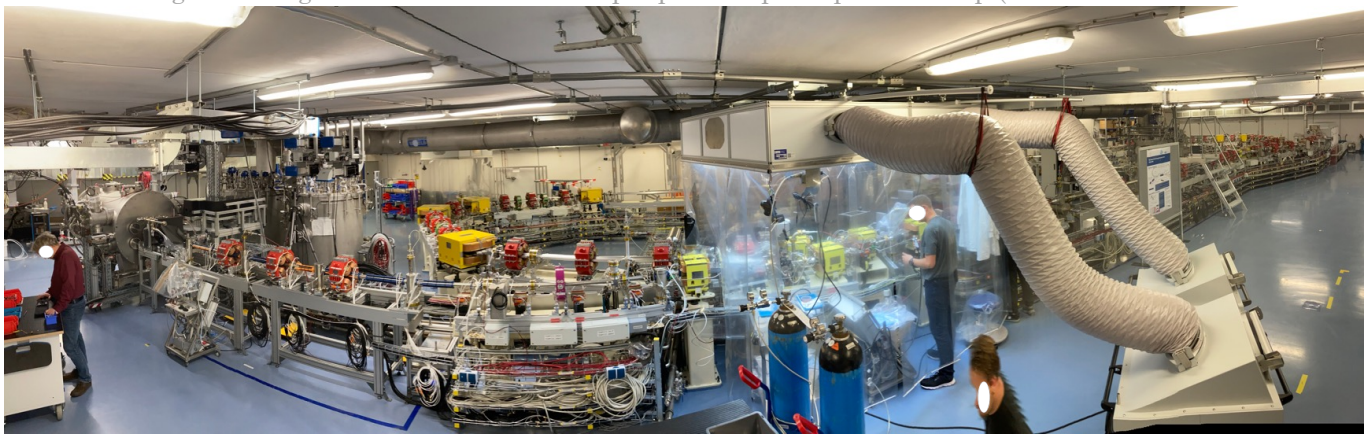
bERLinPro @ HZB (Berlin)

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*



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



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

Potential impact of ERL technology

for particle physics colliders

demonstrate (multi-turn) high-power ERL

2020'ies

high-power ERL demonstrated

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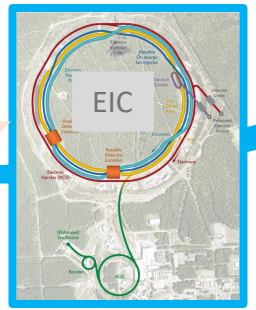


ERL application electron cooling

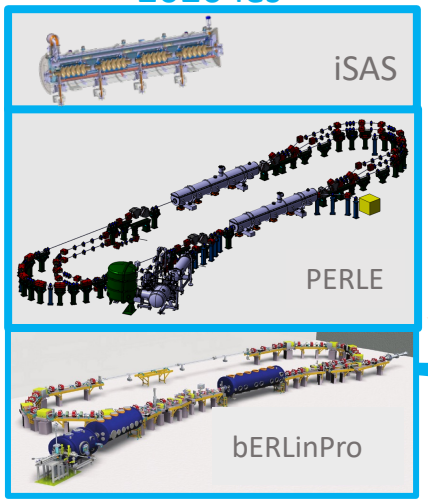
Potential impact of ERL technology

for particle physics colliders

demonstrate (multi-turn) high-power ERL

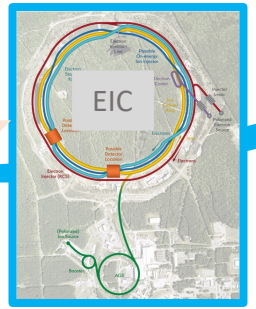
enables the ultimate upgrades of the LHC/FCC programmes ***(ep collisions)***

2020'ies



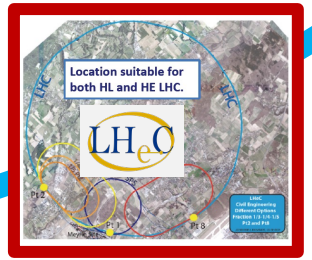
high-power ERL demonstrated

2030'ies



ERL application electron cooling

2030-2040'ies



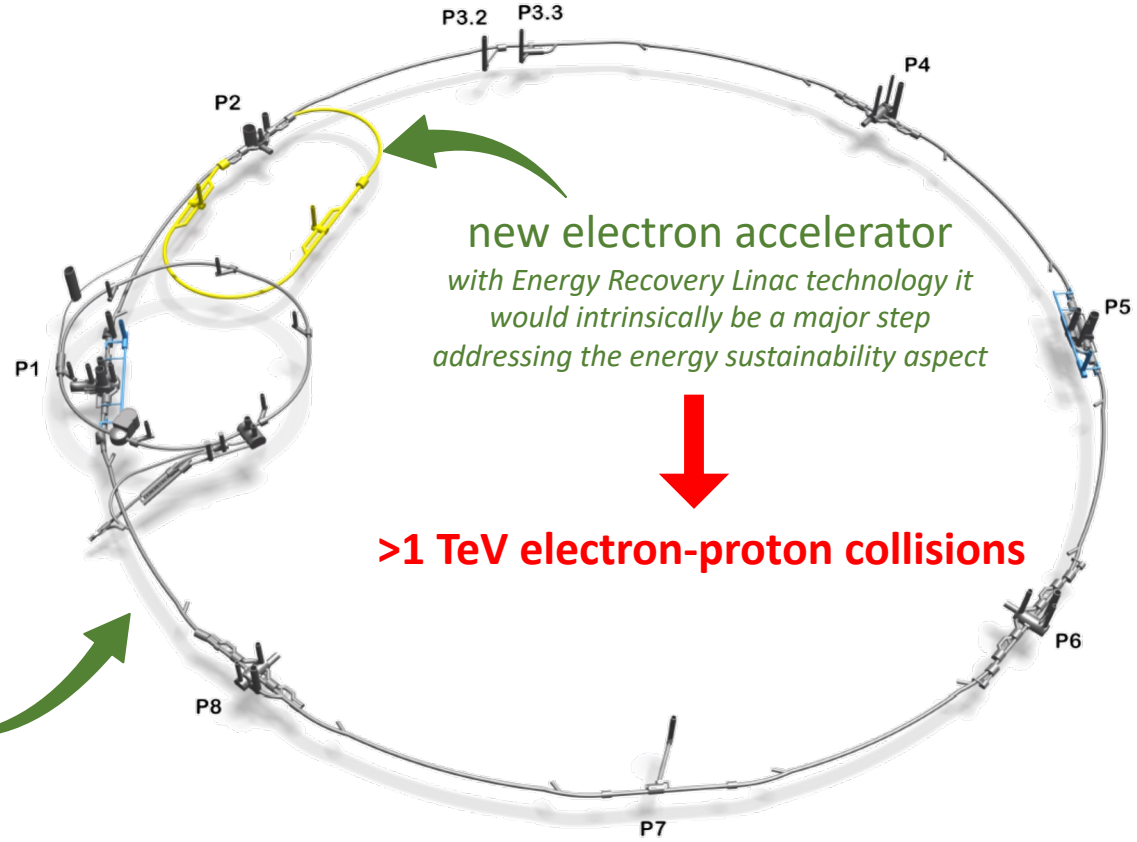
high-power ERL
e^- beam in collision
(ep/eA @ LHC programme)

1 ERL beam

2070'ies

reuse ERL

high-energy & high-luminosity electron-proton collisions



new electron accelerator

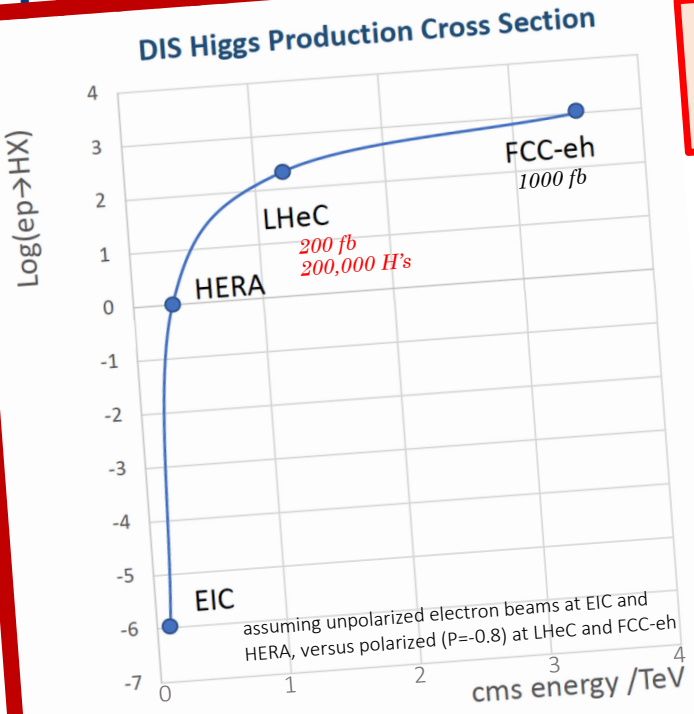
with Energy Recovery Linac technology it would intrinsically be a major step addressing the energy sustainability aspect

>1 TeV electron-proton collisions

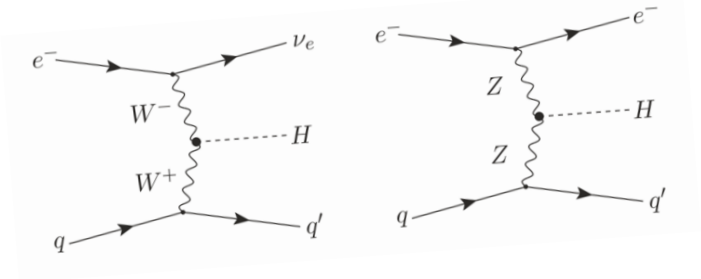
existing/future proton accelerator

https://indico.cern.ch/event/1423870/

high-energy & high-luminosity electron-proton collisions



These electron-proton collisions enable a general-purpose experiment



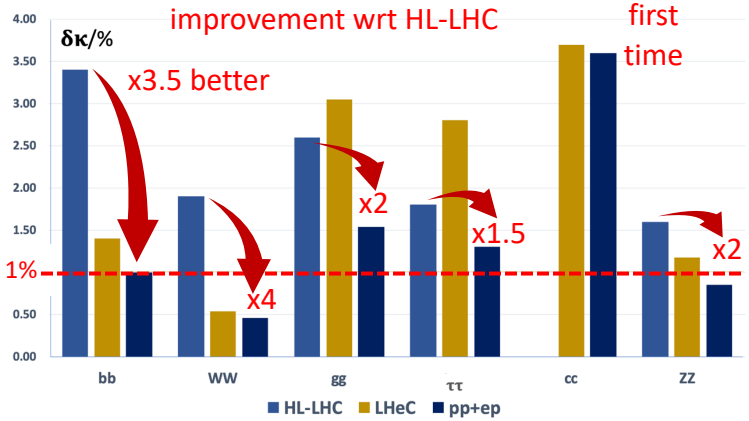
compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

https://indico.cern.ch/event/1423870/

Some physics highlights of the LHeC

on several fronts comparable improvements between LHC → HL-LHC as for HL-LHC → LHeC

Higgs physics - pp+ep comb



EW physics – pp & ep

- Δm_W to 2 MeV (today at ~10 MeV) **pp with ep input**
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP + scale dep) **ep only**

Top quark physics – ep only

- $|V_{tb}|$ precision better than 1% (today ~5%)
- top quark FCNC and γ, W, Z couplings

DIS scattering cross sections - ep 1y

- complete unfolding of PDFs extended in (Q^2,x) by orders of magnitude

Strong interaction physics - ep 1y

- α_s precision of 0.2%
- low-x: a new discovery frontier

The Large Hadron-Electron Collider at the HL-LHC, J. Phys. G 48 (2021) 110501, 364p (updated CDR)

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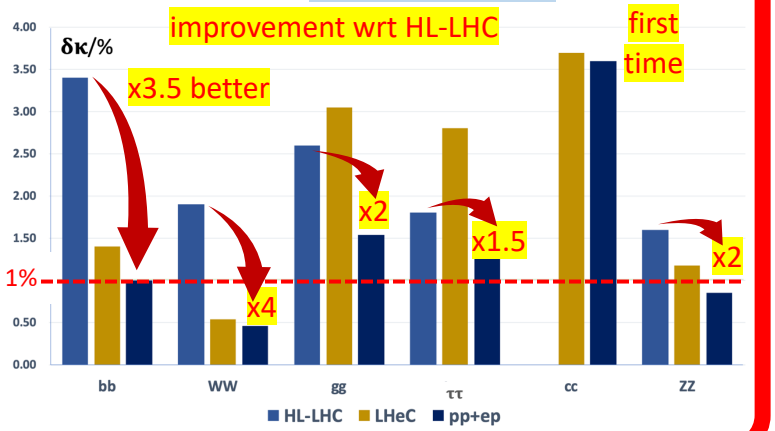

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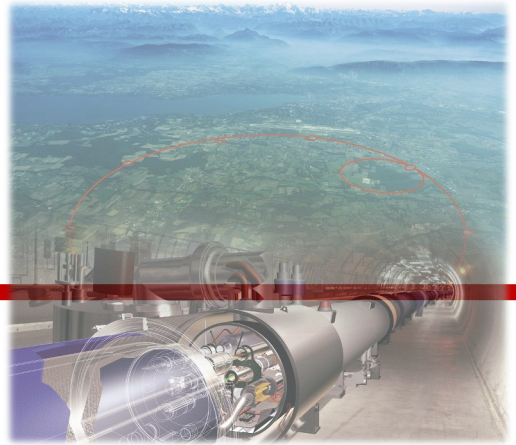
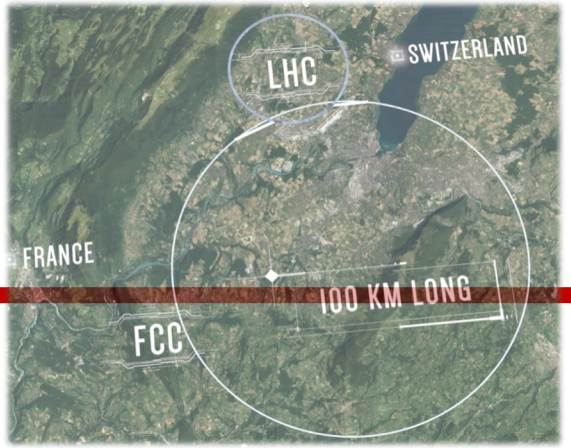
How does the LHeC fits into the collider landscape?



LHC

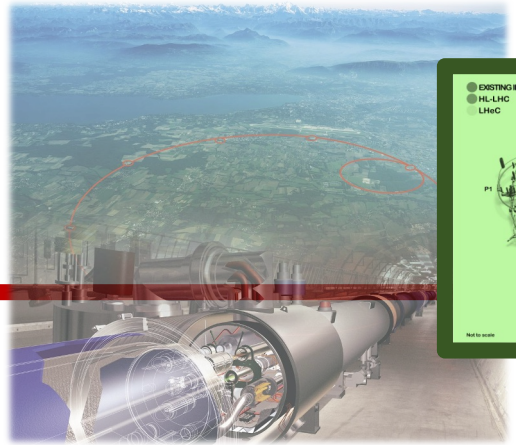


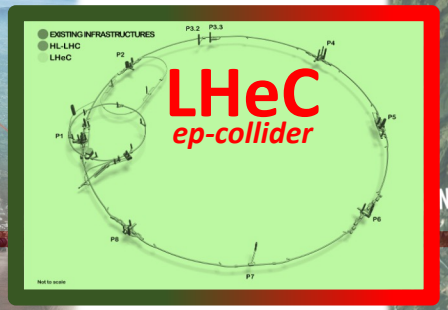
e.g. FCC (ee or hh)

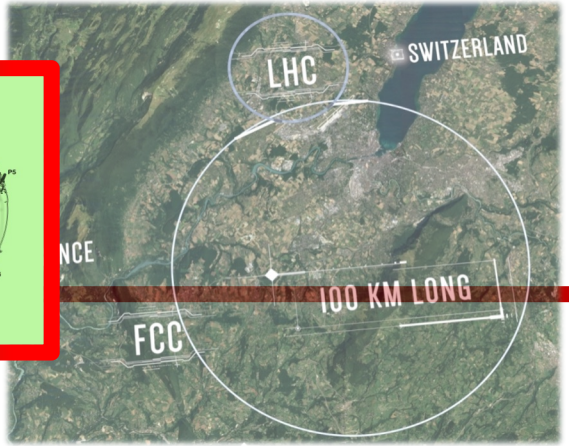
An impactful "*bridge*" between major colliders @ CERN

ep-option with HL-LHC: LHeC

e.g. 6 years ep-only@LHC > 1 ab^{-1}







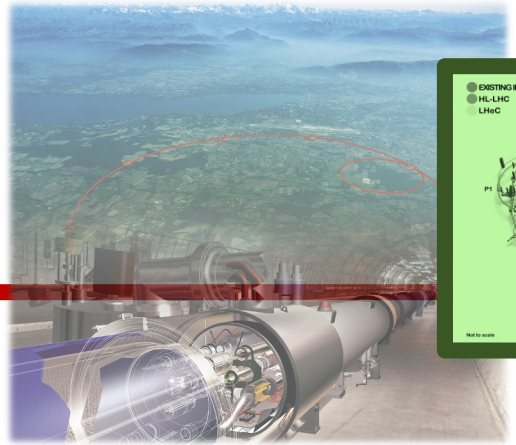
LHC

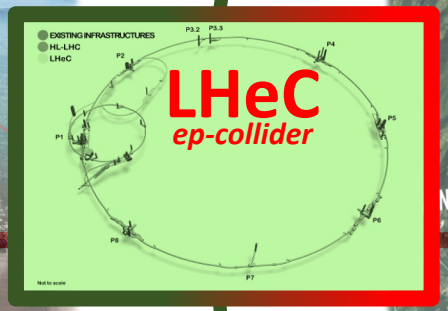
e.g. FCC (ee or hh)

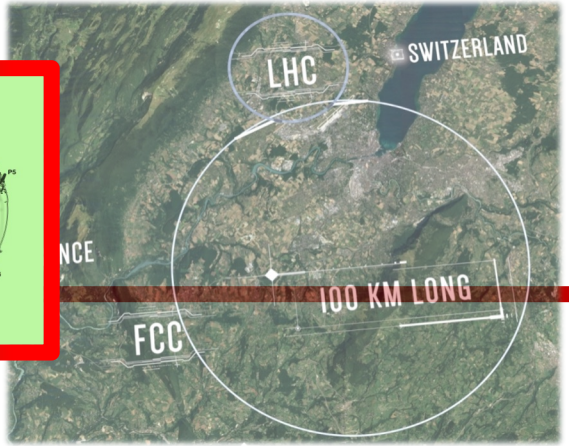
An impactful "*bridge*" between major colliders @ CERN

ultimate upgrade of the LHC physics reach

see previous slide







fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

An impactful "*bridge*" between major colliders @ CERN

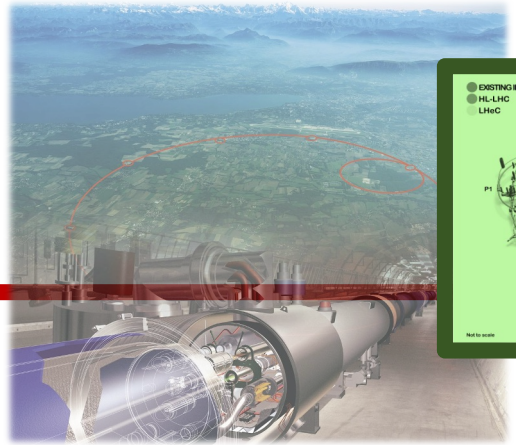
cost-effective investment

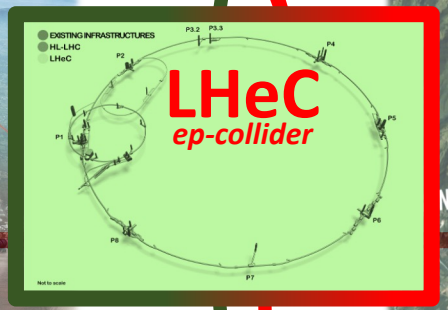
re-use
FCC-hh/eh

injector
FCC-ee

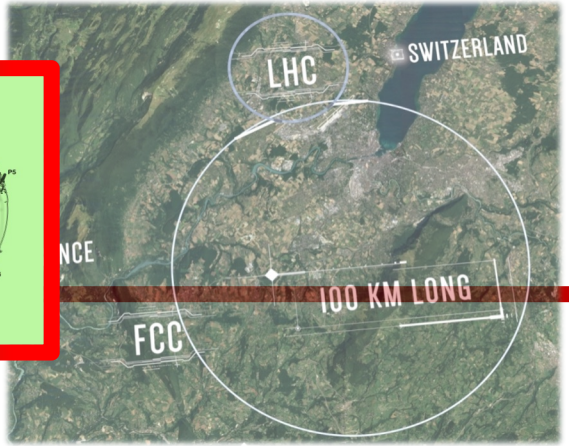
essential enabler for the physics at any new high-energy hadron collider

ultimate upgrade of the LHC physics reach
see previous slide





LHeC
ep-collider



i.e. SRF@LHeC as prototype series and training for SRF@FCC-ee

fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee

An impactful "*bridge*" between major colliders @ CERN

cost-effective investment

re-use

injector

ultimate upgrade of the LHC physics reach

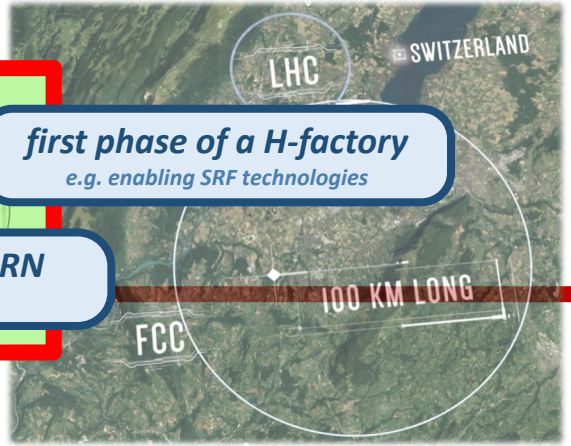
essential enabler for the physics at any new high-energy hadron collider

LHeC
ep-collider

last phase of the LHC
e.g. enabling more physics

first phase of a H-factory
e.g. enabling SRF technologies

always collisions at CERN
e.g. enabling careers



fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee

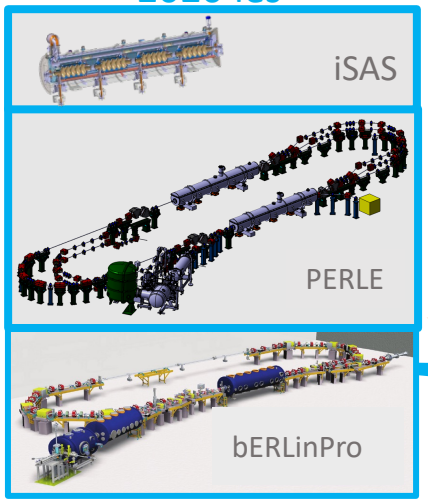
Potential impact of ERL technology

for particle physics colliders

demonstrate (multi-turn) high-power ERL

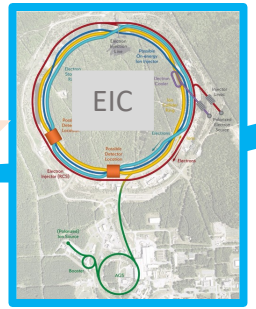
enables the ultimate upgrades of the LHC/FCC programmes ***(ep collisions)***

2020'ies



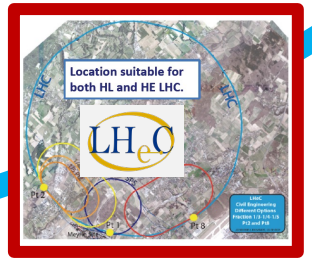
high-power ERL demonstrated

2030'ies



ERL application electron cooling

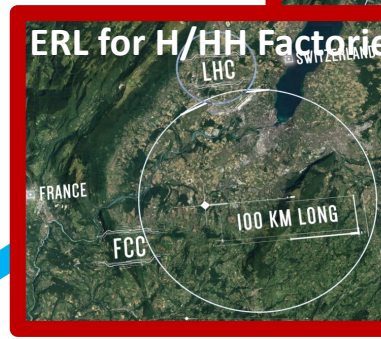
2030-2040'ies



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

1 ERL beam

2070'ies



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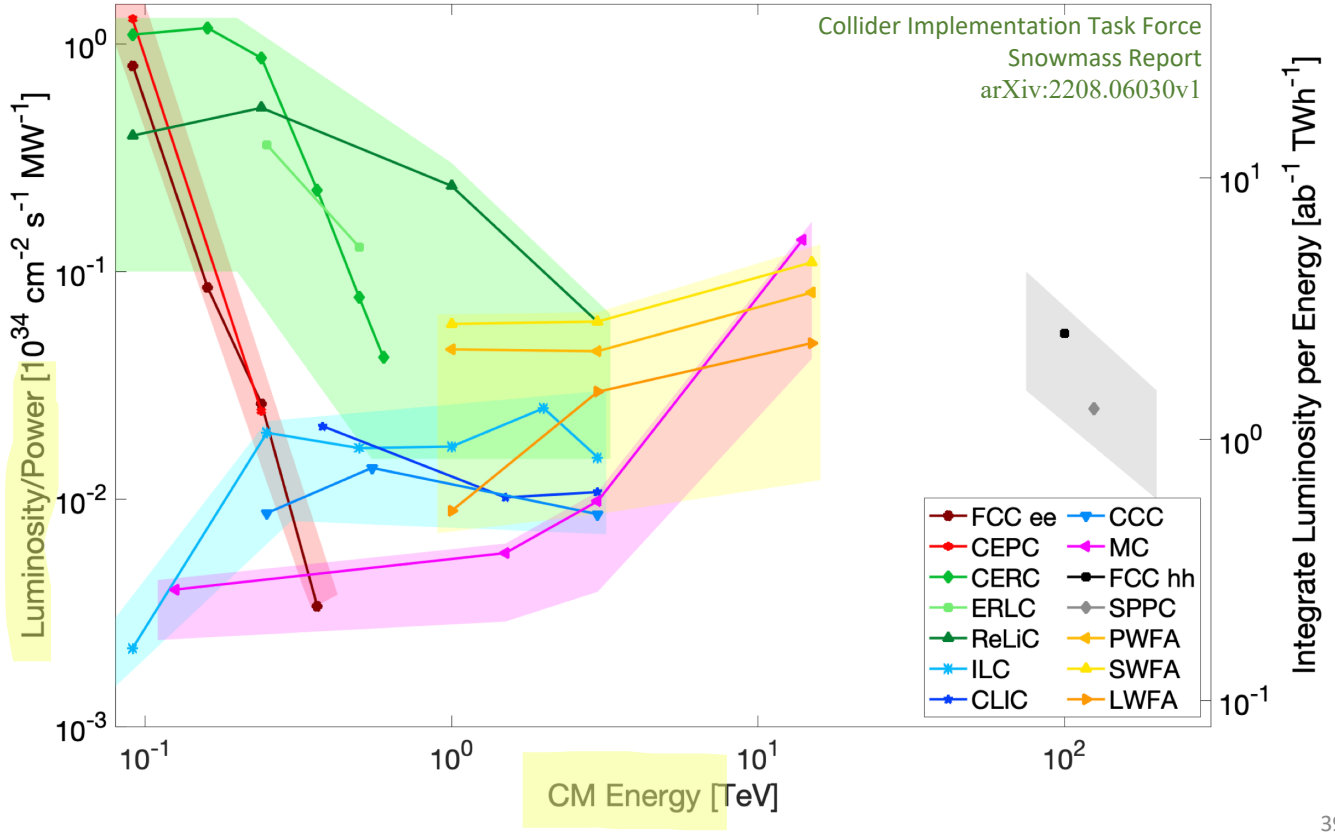
2 ERL beams

reuse ERL

increases the performance of the next major e⁺e⁻ colliders

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



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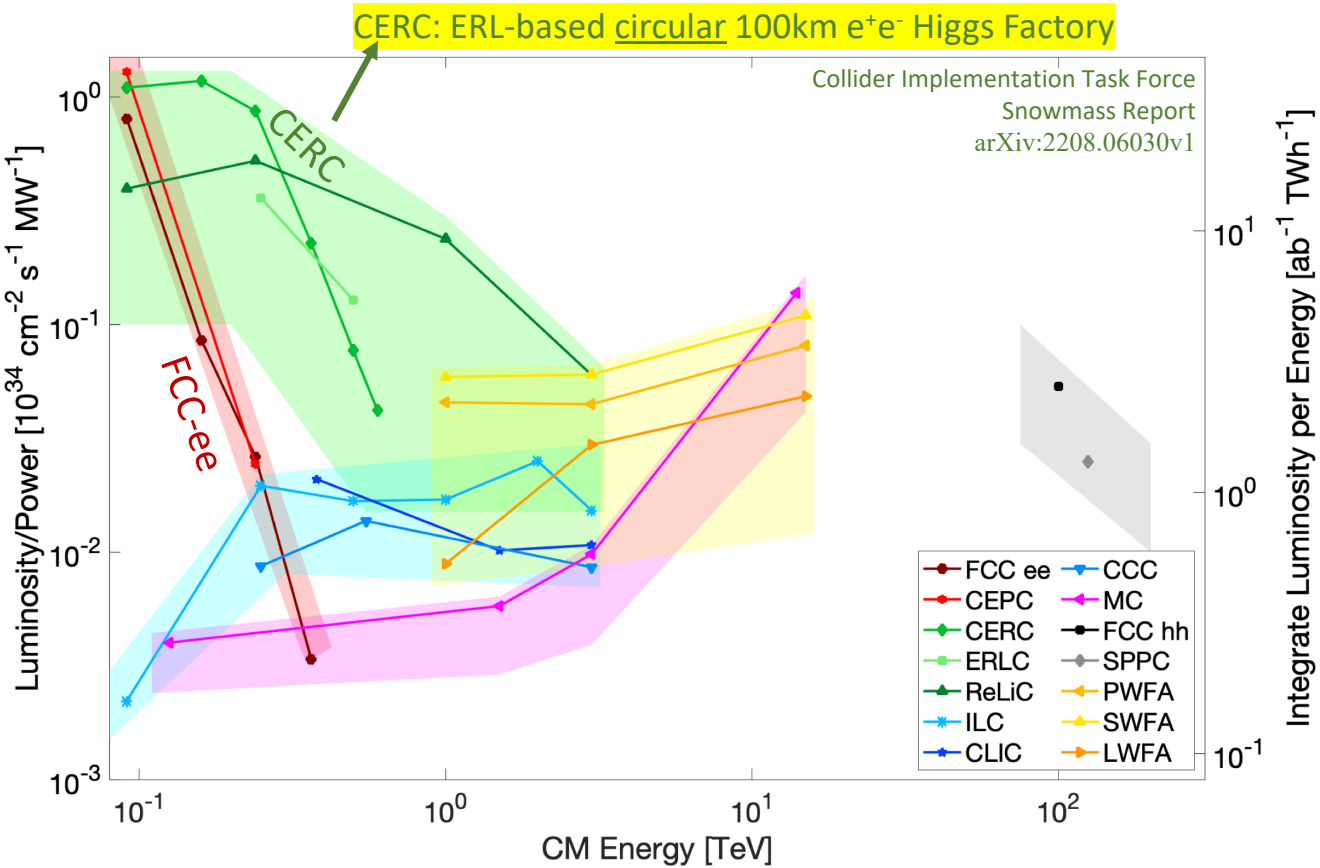


Refs for CERC: V. Litvinenko, T. Roser, M.C. Llatas, PLB 804 (2020) 135394 and arXiv:2203.07358

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

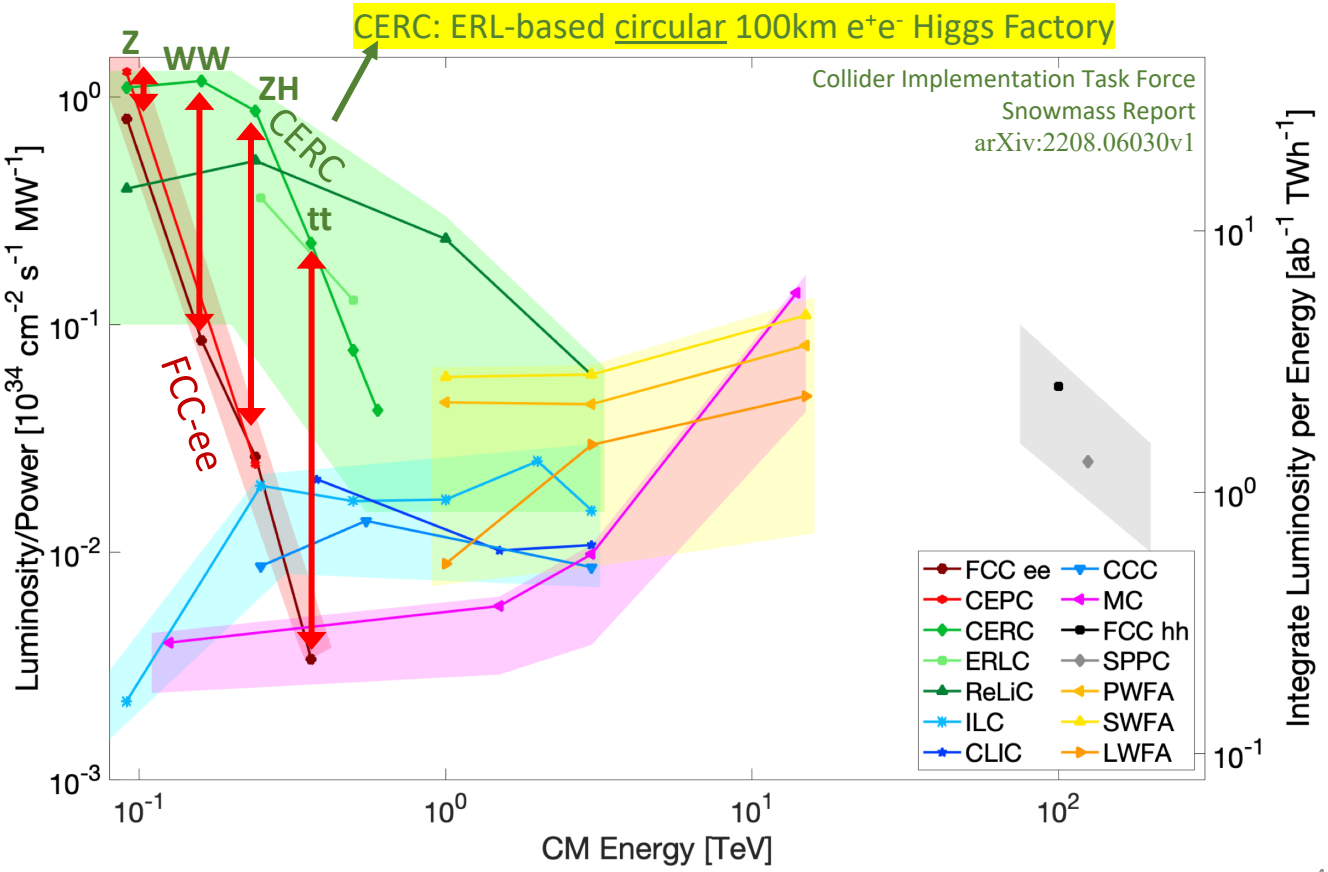
This plot suggests that with an ERL version of a Higgs Factory one might reach

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)



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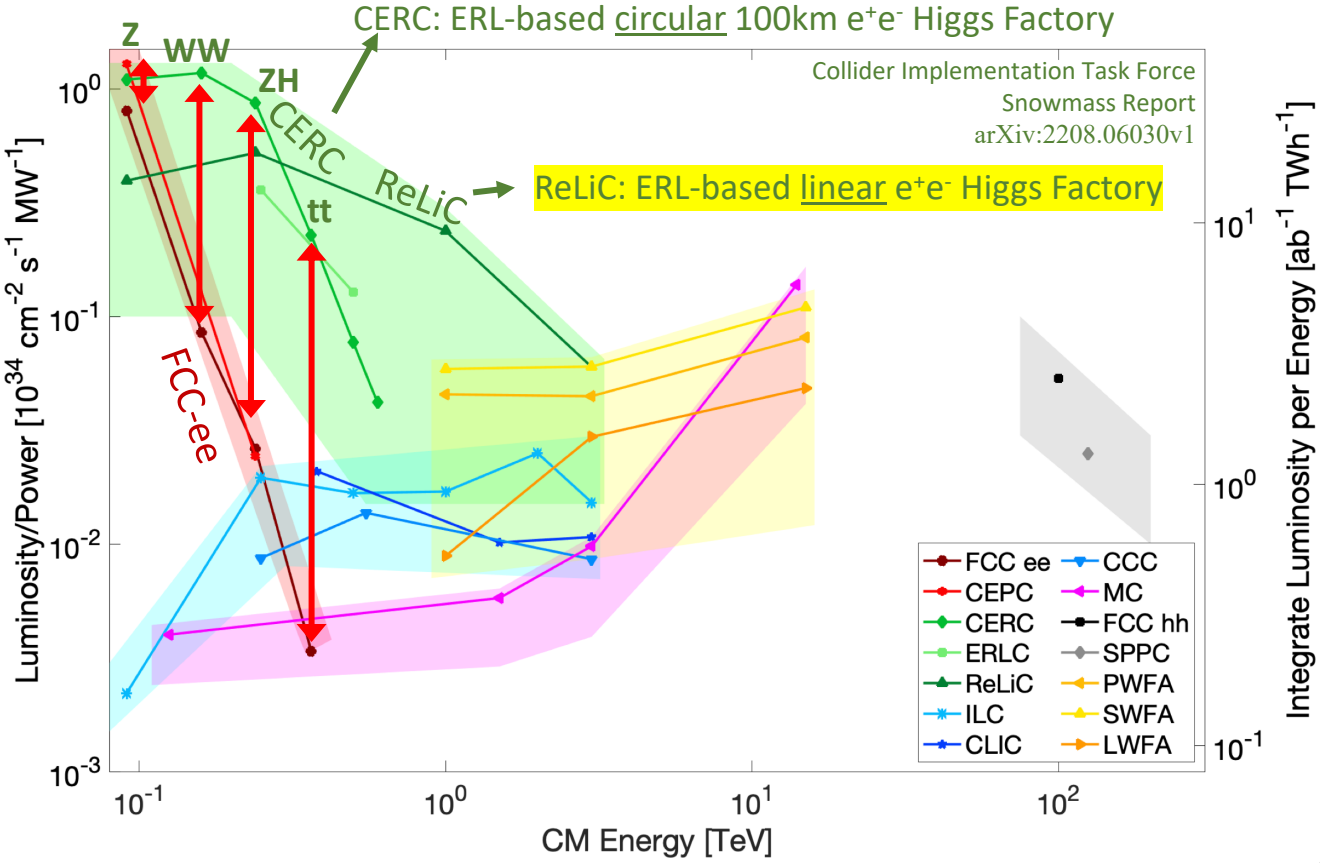

Ref for ReLiC: V. Litvinenko et al., arXiv:2203.06476

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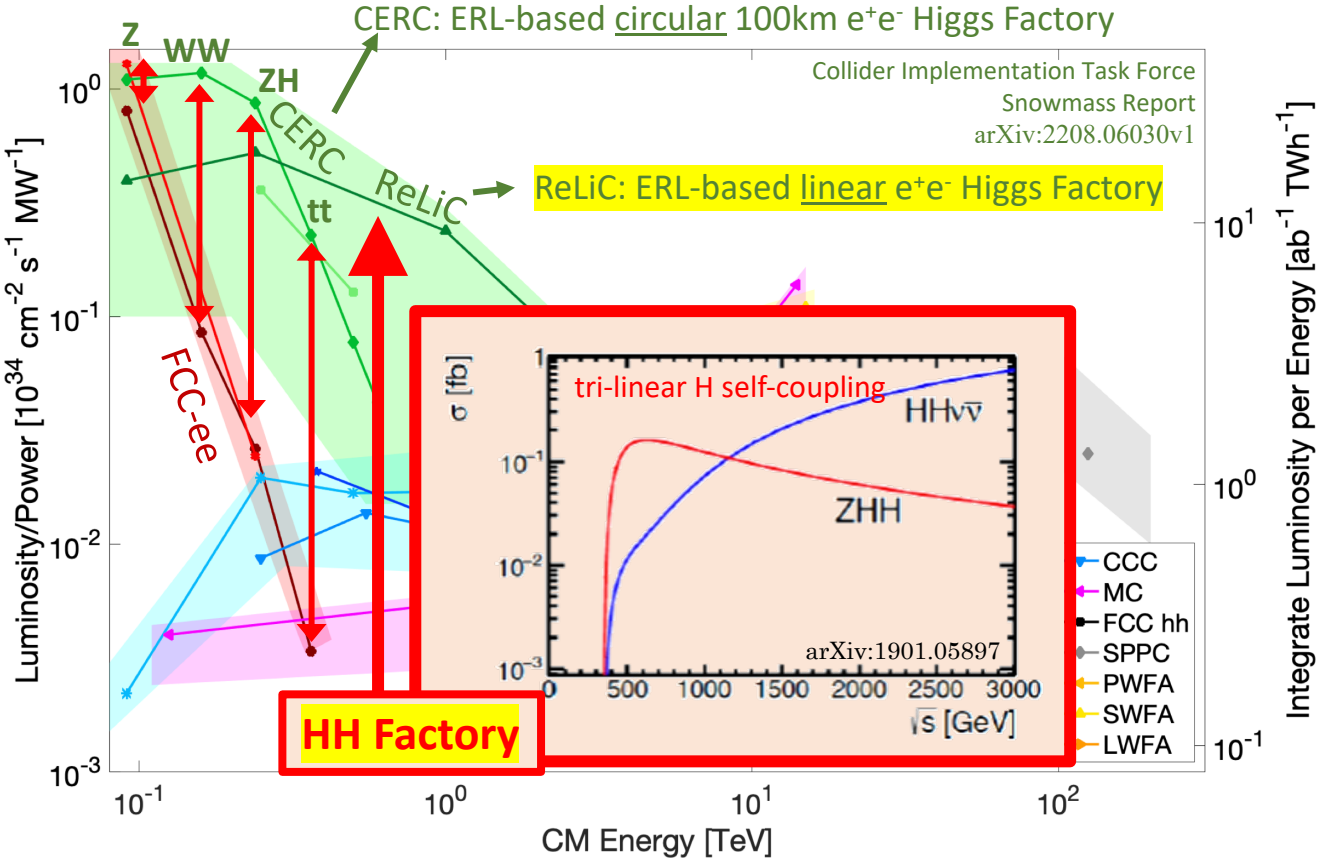


Energy Recovery applications f…

Can we dream to have an ERL-based Higgs Factory in the LEP/LHC tunnel?
"spend the factor of 10 in the size of the tunnel"

Power of Synchrotron Radiation ~ 1/R
R : radius of circular collider

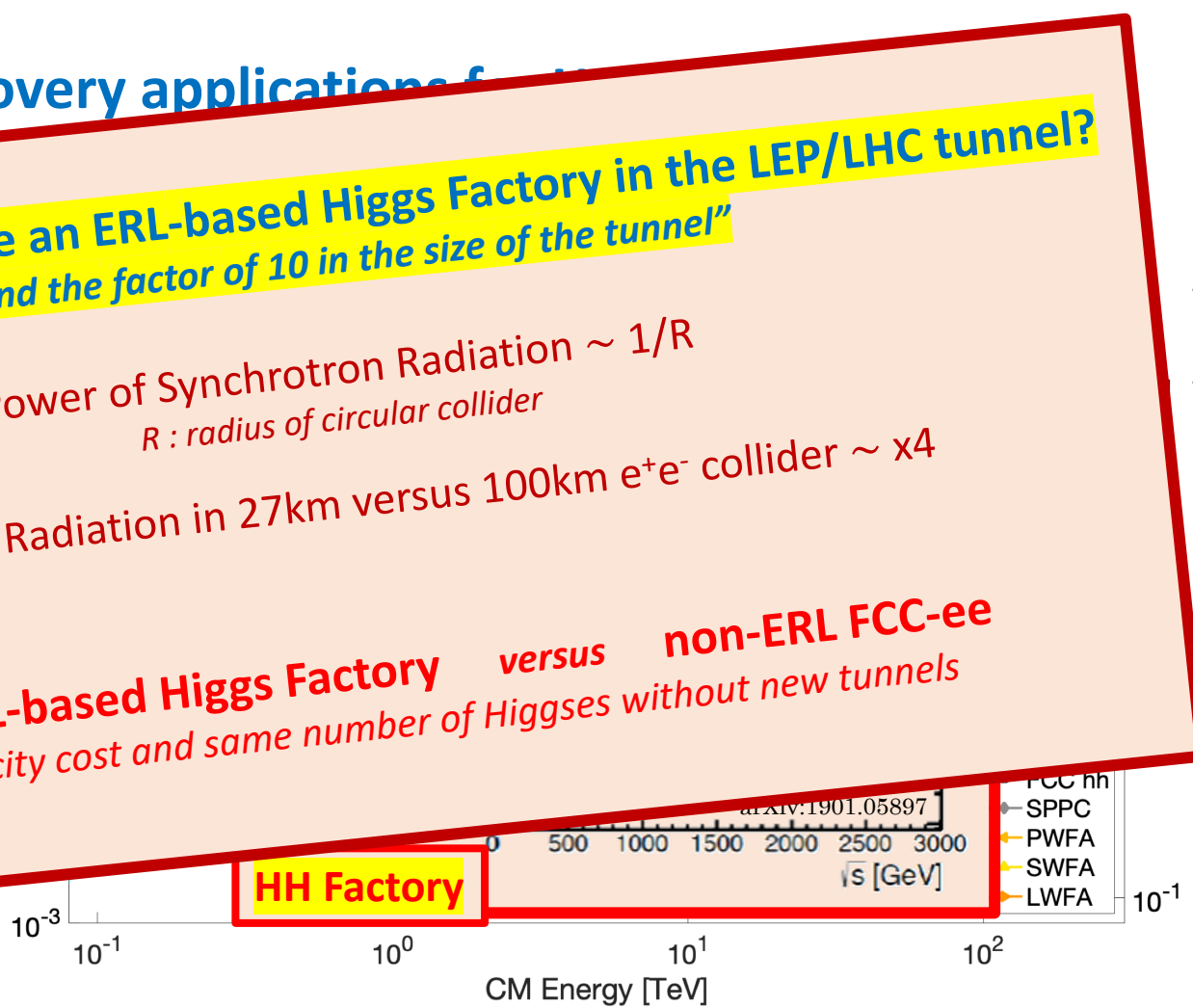
Synchrotron Radiation in 27km versus 100km e^+e^- collider ~ x4

LEP/LHC ERL-based Higgs Factory ***versus*** **non-ERL FCC-ee**
same electricity cost and same number of Higgses without new tunnels

T…

x1…

N… challe… these … (hence th…

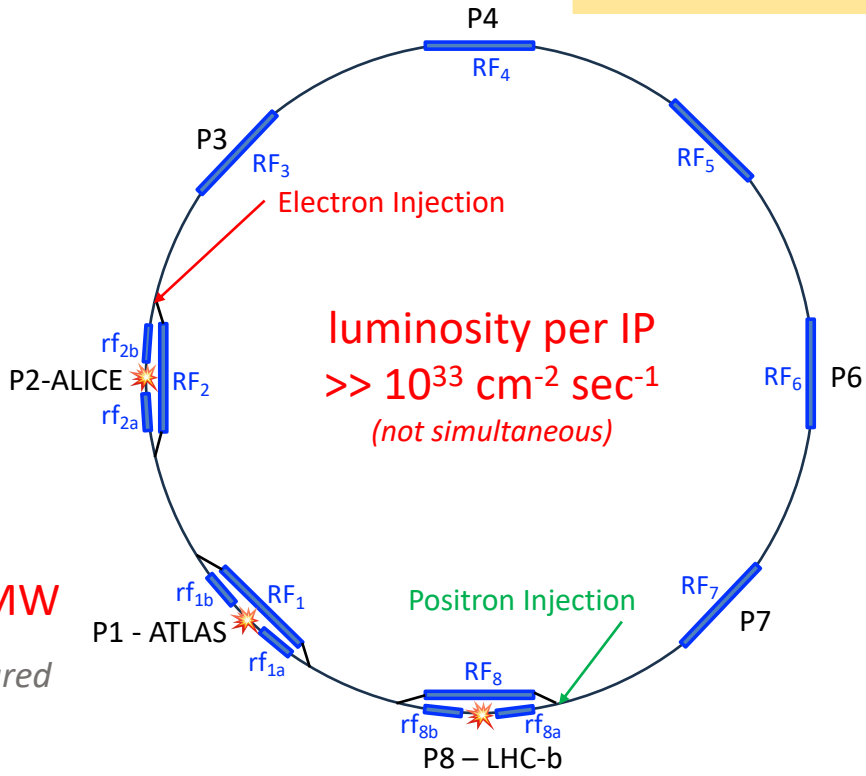


Ref for ReLiC: arXiv:2203.06476

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 x 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

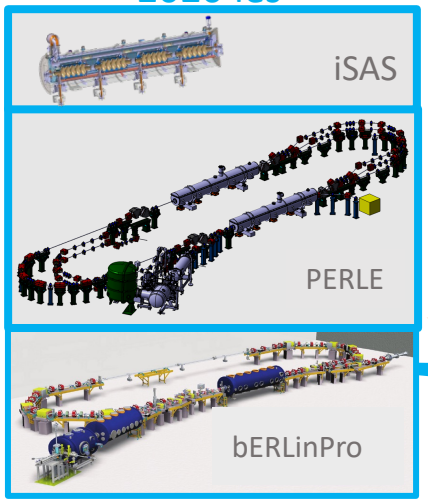
Potential impact of ERL technology

for particle physics colliders

demonstrate (multi-turn) high-power ERL

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

2020'ies



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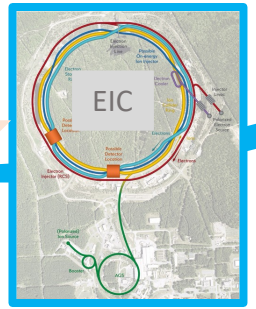

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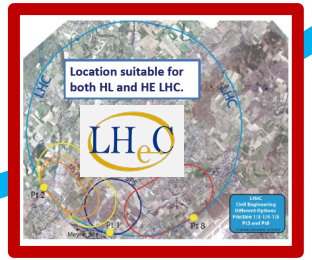

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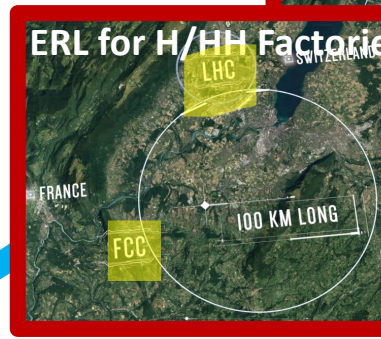

high-power ERL for
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2 ERL beams

reuse ERL

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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

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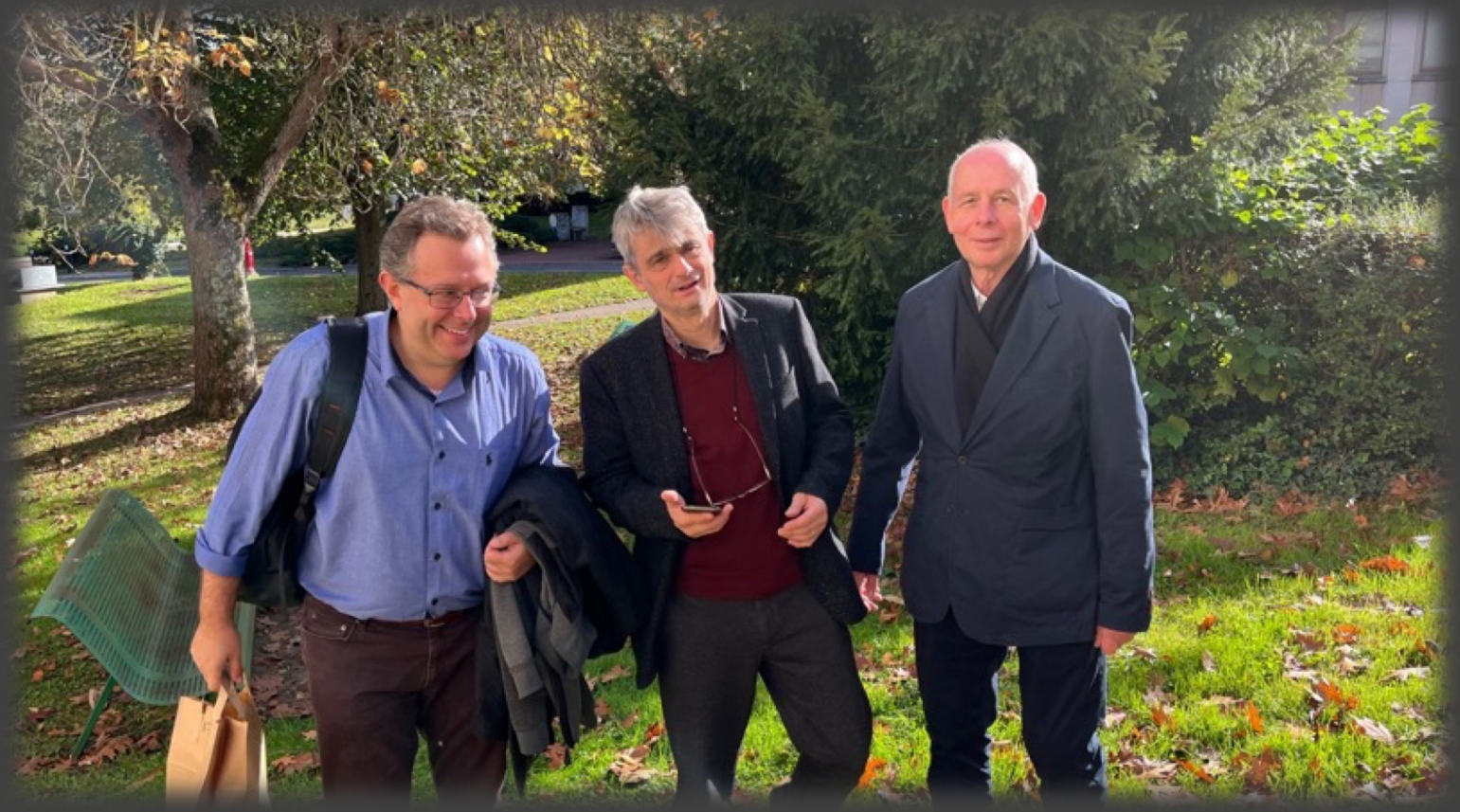
The potential impact of ERL on the performance of particle colliders is so appealing that we must foster this R&D path

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

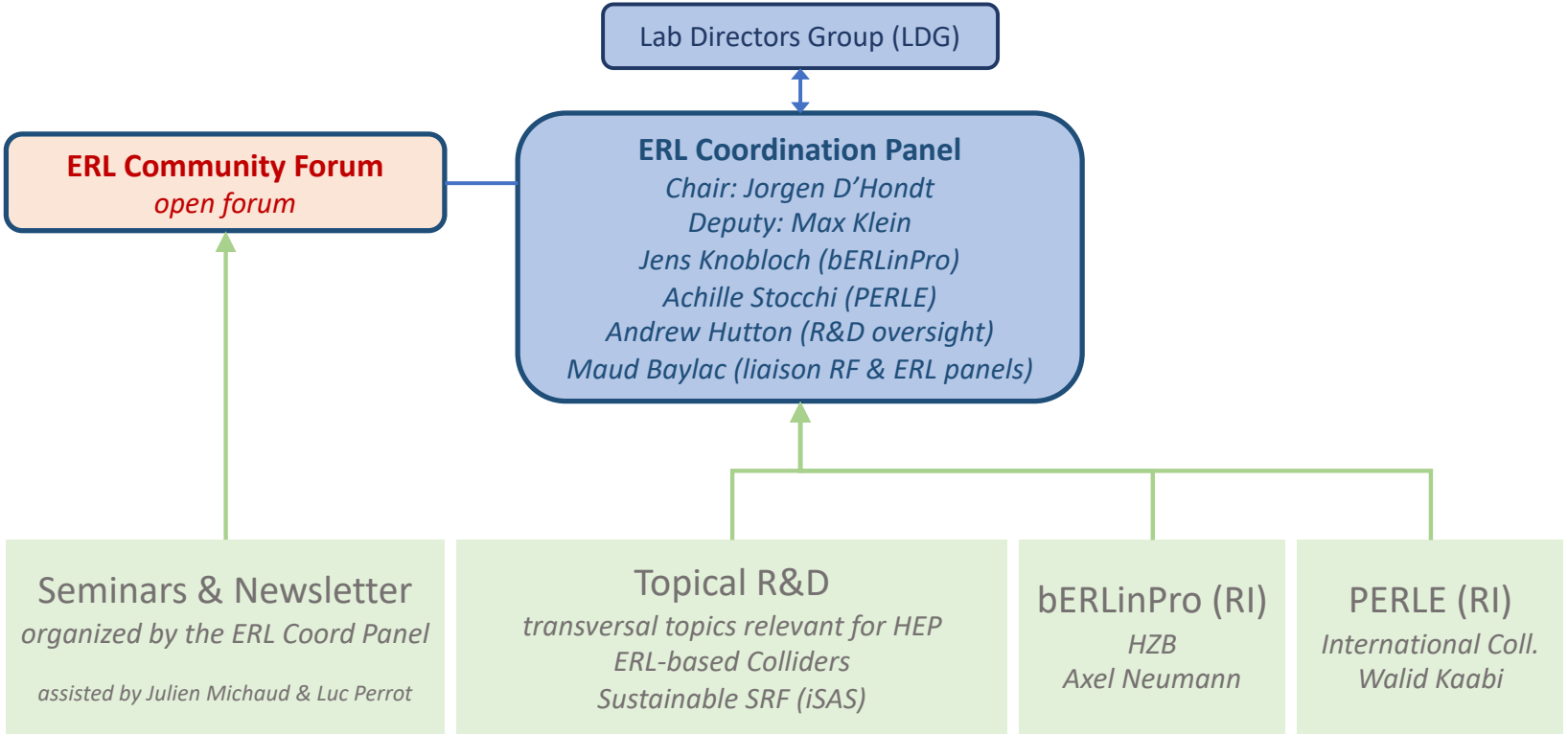
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE Nikhef iihe BRUXELLES BRUSSEL fwo

Thank you for your attention!
Jorgen.DHondt@nikhef.nl



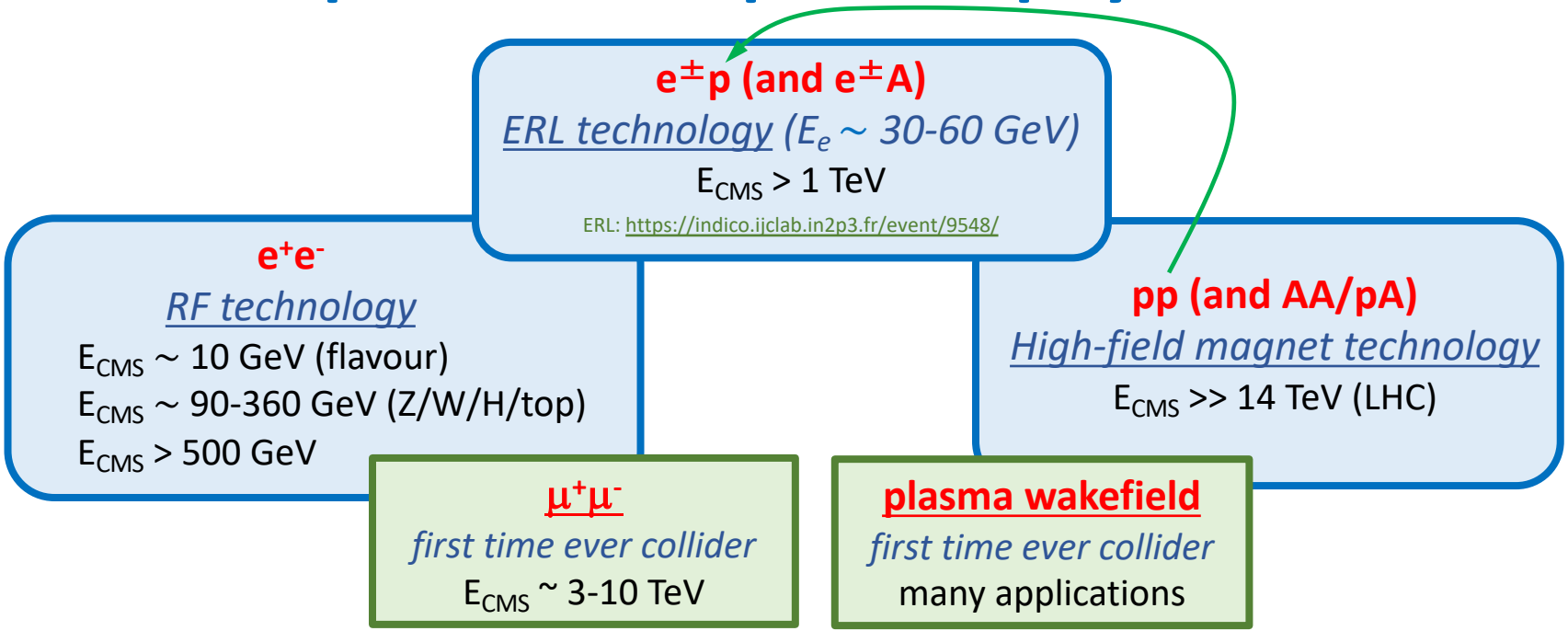
Max Klein (1951–2024)

EXTRA



RI: Research Infrastructure

The landscape of future particle physics colliders

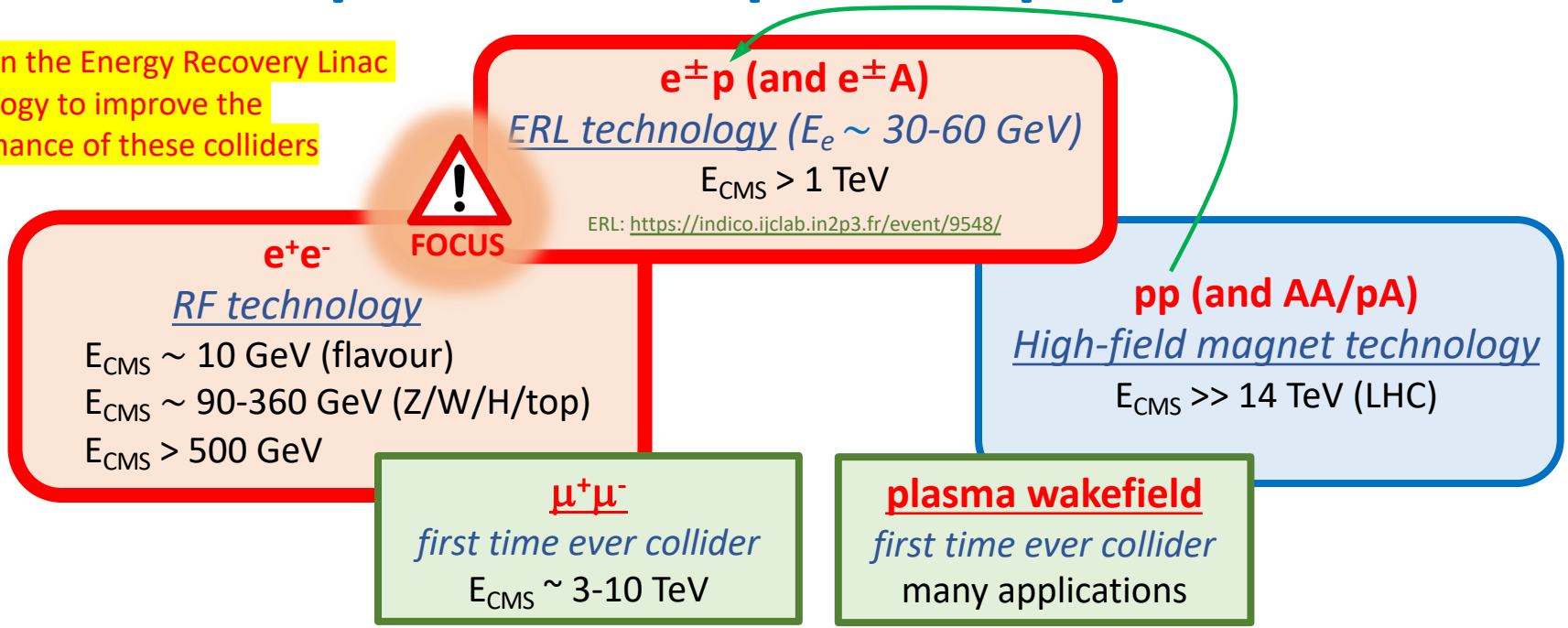


Accelerator R&D Roadmap prioritizes progress on these technologies to enable future particle accelerators in a timely, affordable and sustainable way

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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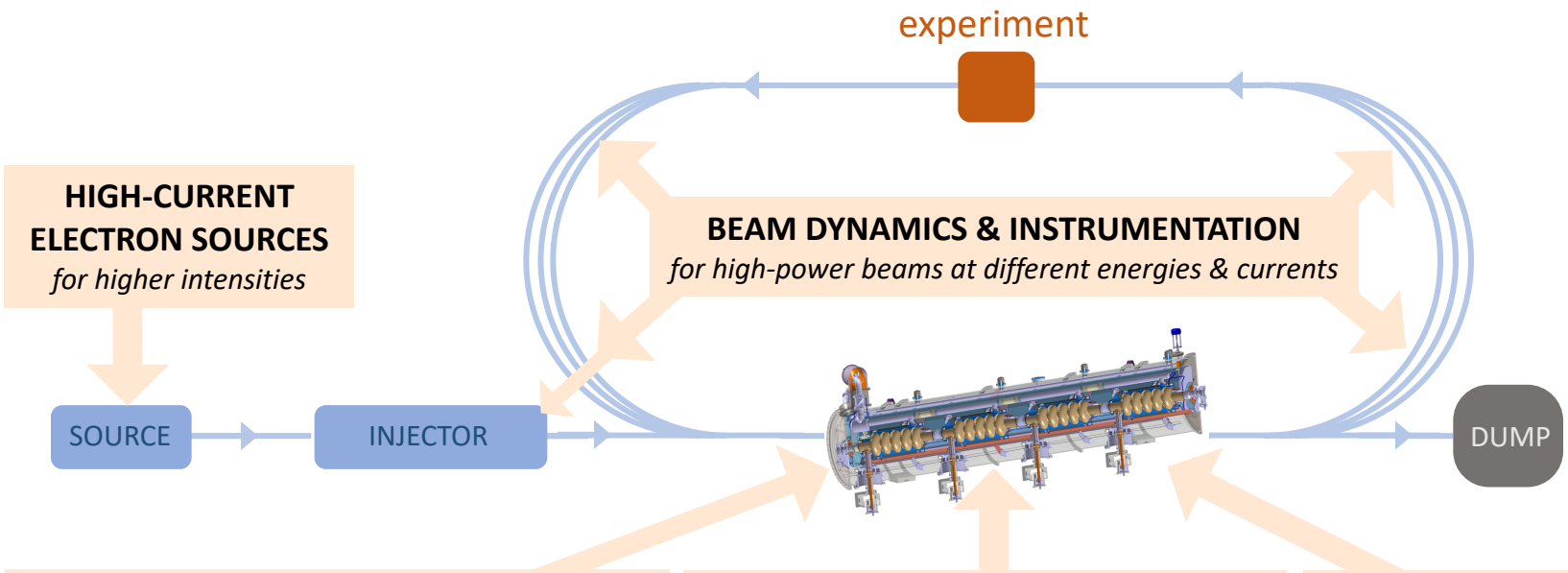
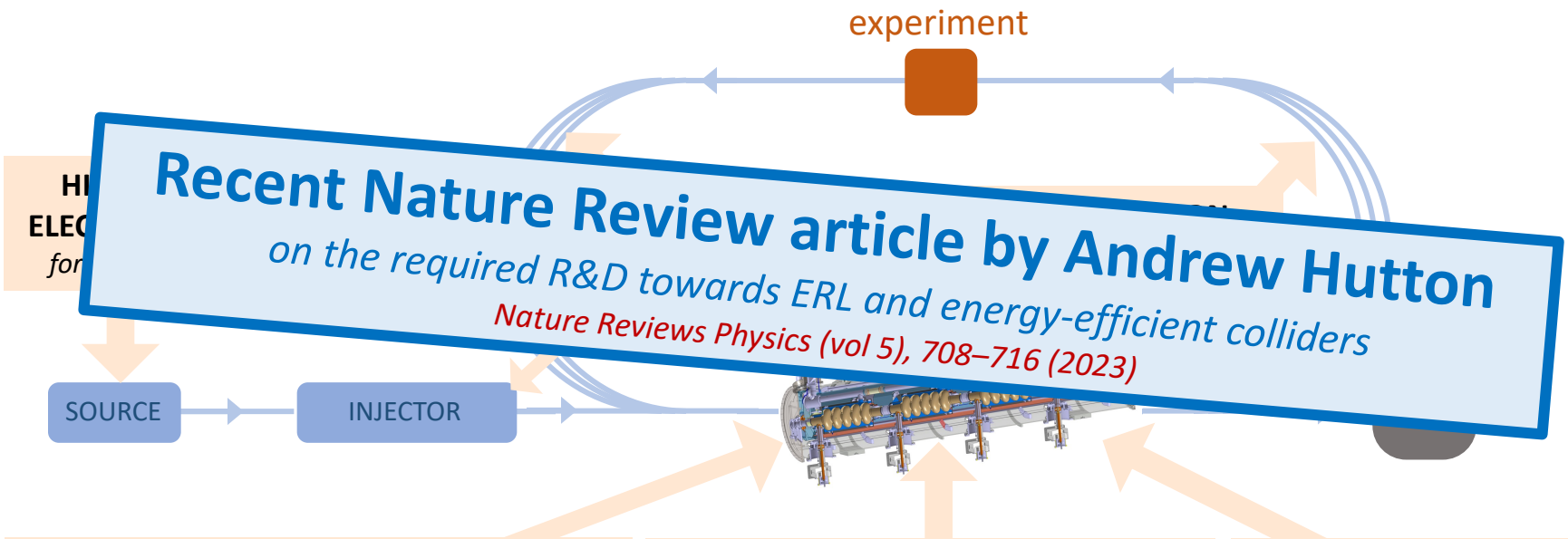
Accelerator R&D objectives

Accelerator R&D objectives



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

Accelerator R&D objectives



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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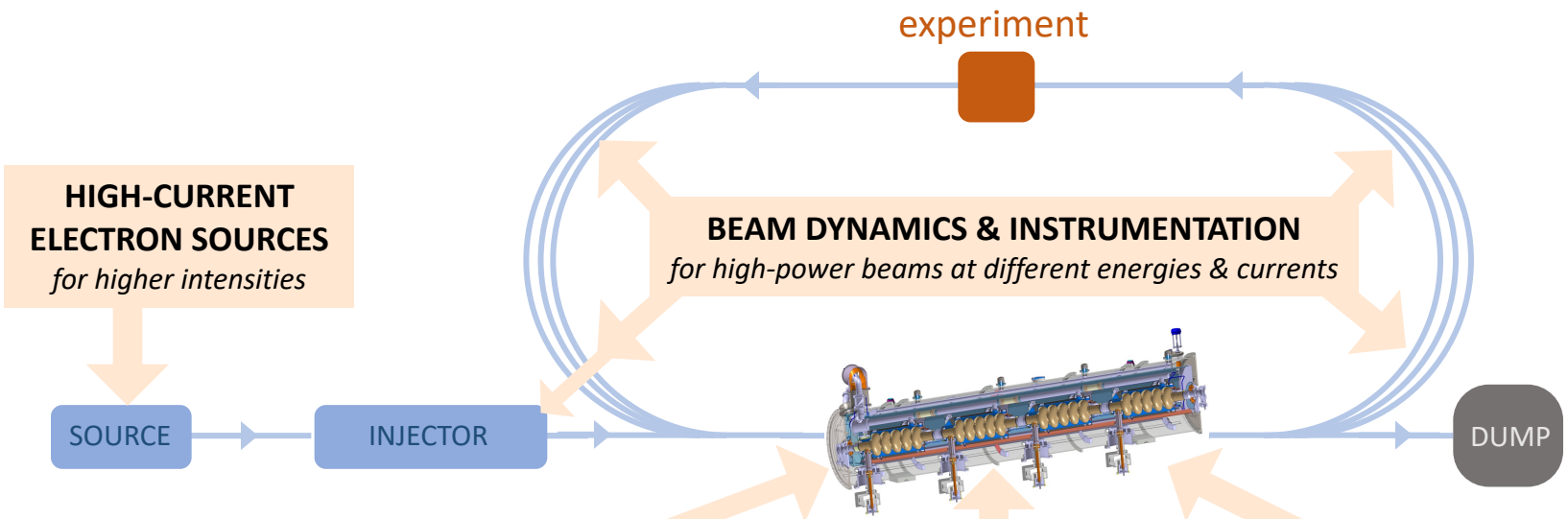

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efficient RF operation

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RF POWER GENERATION

Innovate for Sustainable Accelerating Systems (iSAS)

develop a new design of an SRF cryomodule

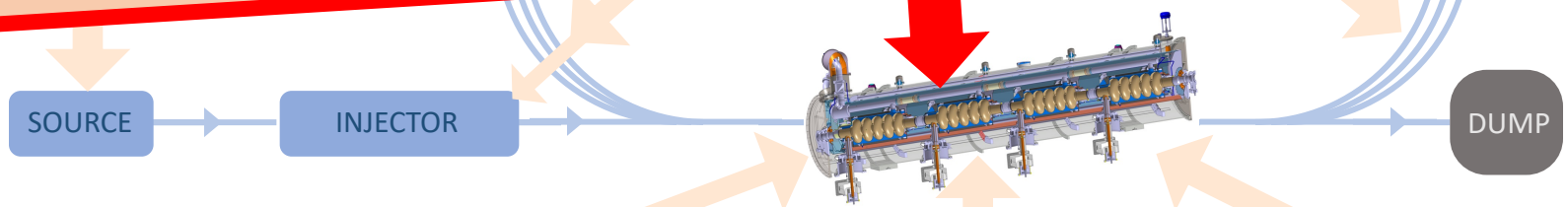
integrating the most impactful energy-saving technologies (incl. RF & ERL aspects)

period: 2024-2028; ~13M EUR total budget; ~1000 person months; 17 partners

develop, prototype and test energy-efficient technologies

https://isas.ijclab.in2p3.fr (website = work in progress)

Horizon Europe



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FRT & RF power source
efficient RF operation

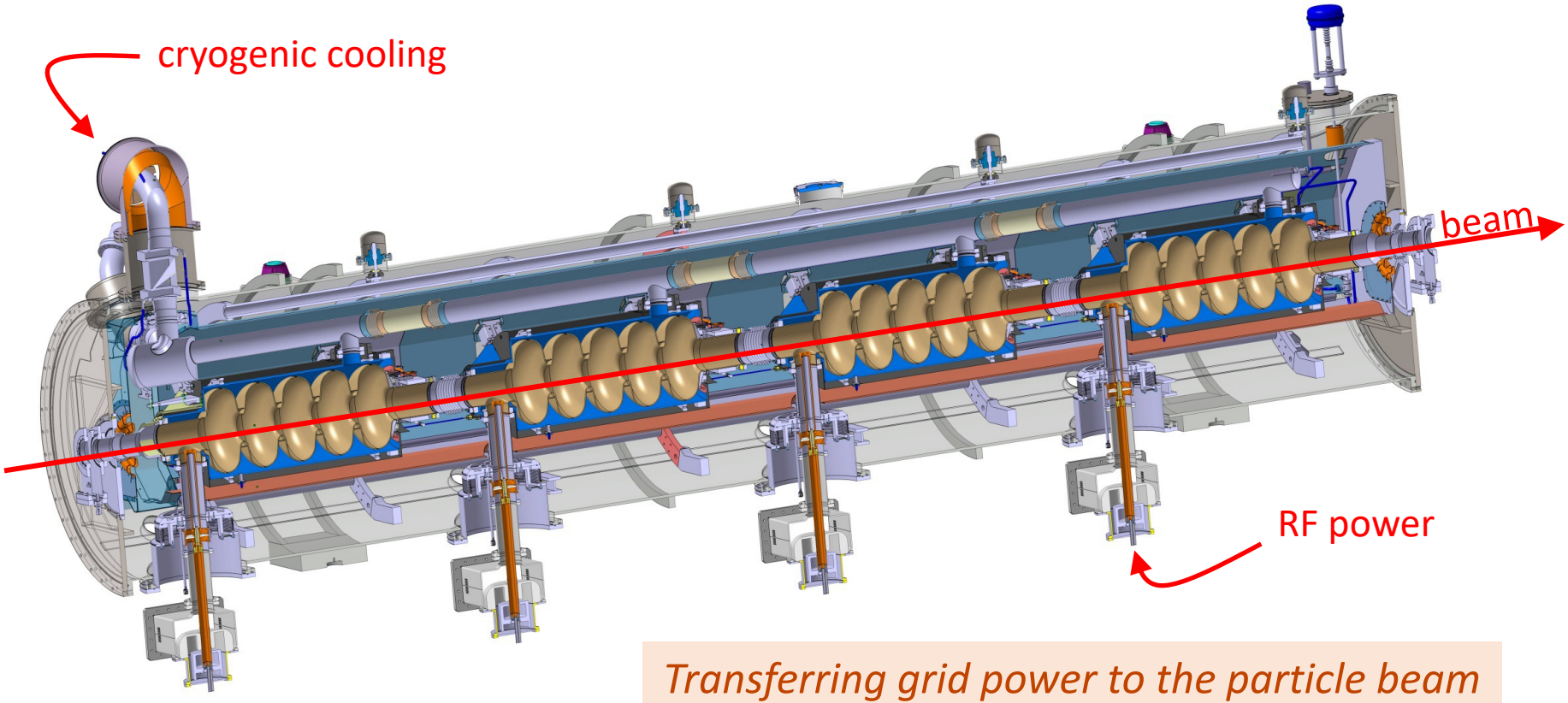
HIGH-Q_0 & GRADIENT

RF POWER GENERATION

The SRF cryomodule is a key building block for most modern accelerators

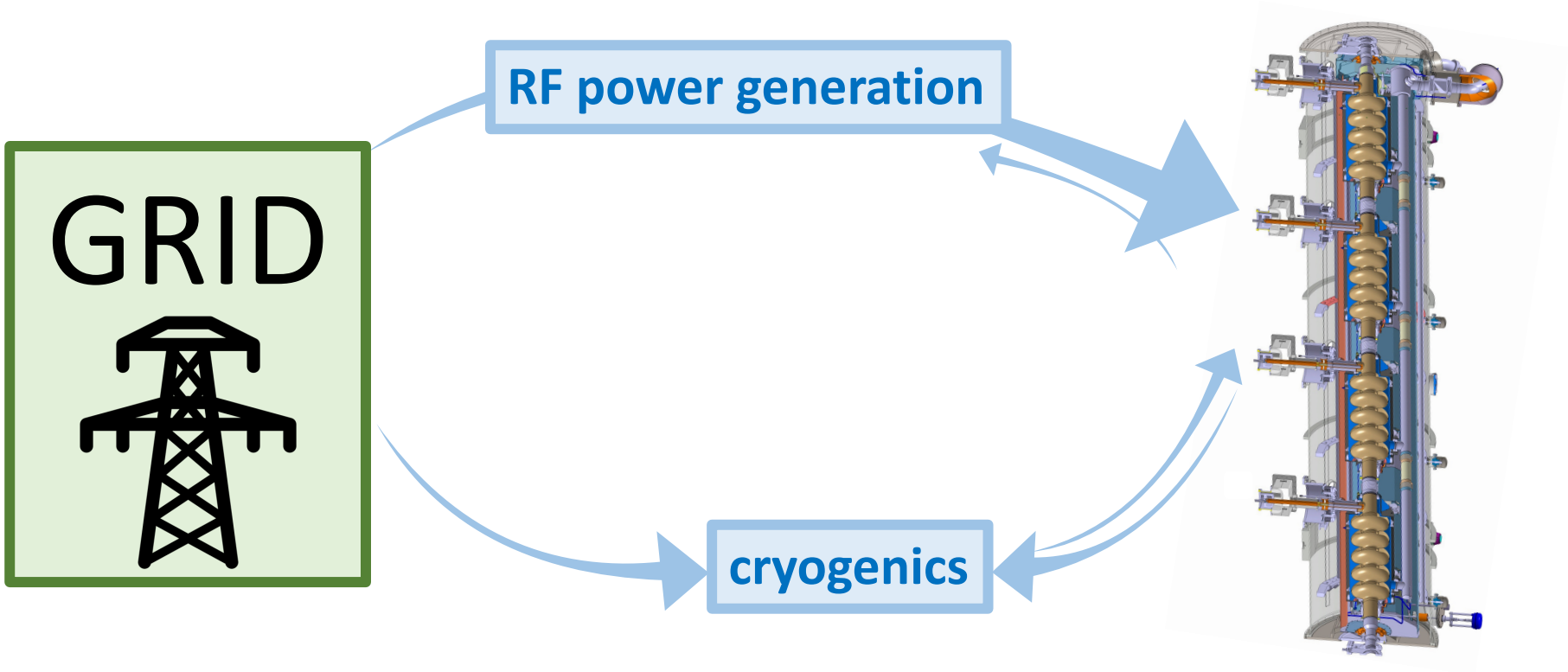
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

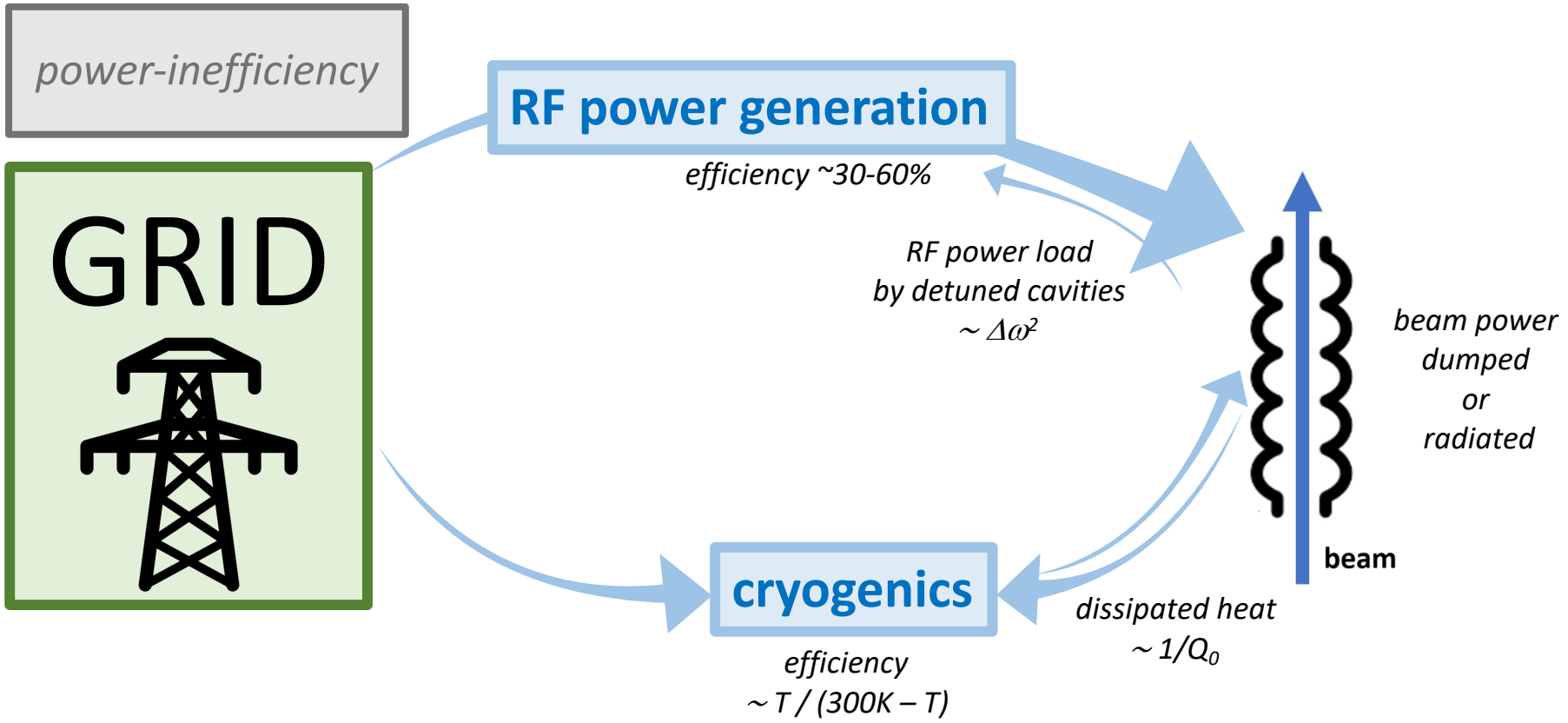


Transferring grid power to the particle beam

Sustainable Accelerating Systems – from Grid to Beam

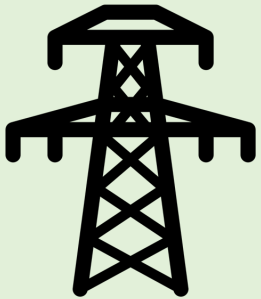


Picture adopted from M. Seidel (IPAC 2022)


power-inefficiency
GRID
RF power generation
efficiency ~30-60%
RF power load
by detuned cavities
~ Δω²
beam power
dumped
or
radiated
beam
cryogenics
dissipated heat
~ 1/Q0
efficiency
~ T / (300K – T)

power-inefficiency

GRID



mitigation with novel technologies

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

RF power generation

efficiency ~30-60%

recover the energy from the beam

e.g. ERL reaching 100% recovery

RF power load by detuned cavities

$\sim \Delta\omega^2$

dealing with microphonics

e.g. Fast Reactive Tuners

beam power dumped or radiated

cryogenics

efficiency

$\sim T / (300K - T)$

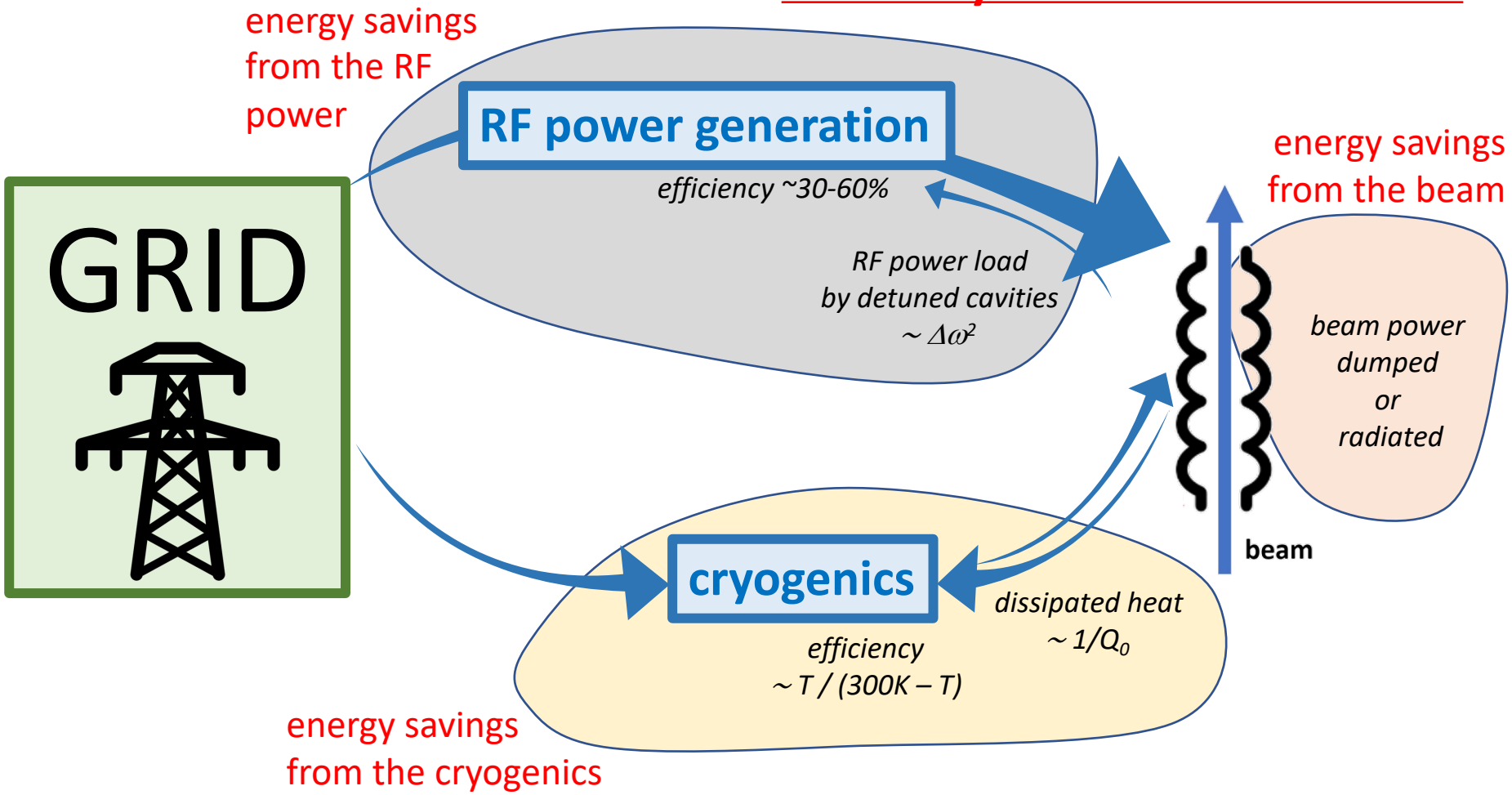
dissipated heat

$\sim 1/Q_0$

operate cavities at higher T & improve Q_0 of cavities

e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

Three key innovation directions



Three key innovation directions

energy savings
from the RF

iSAS is a coherent R&D programme on "Sustainable Accelerating Systems" to reduce the power requirements of SRF accelerators

https://isas.ijclab.in2p3.fr (website = work in progress)

vings
eam
er

beam

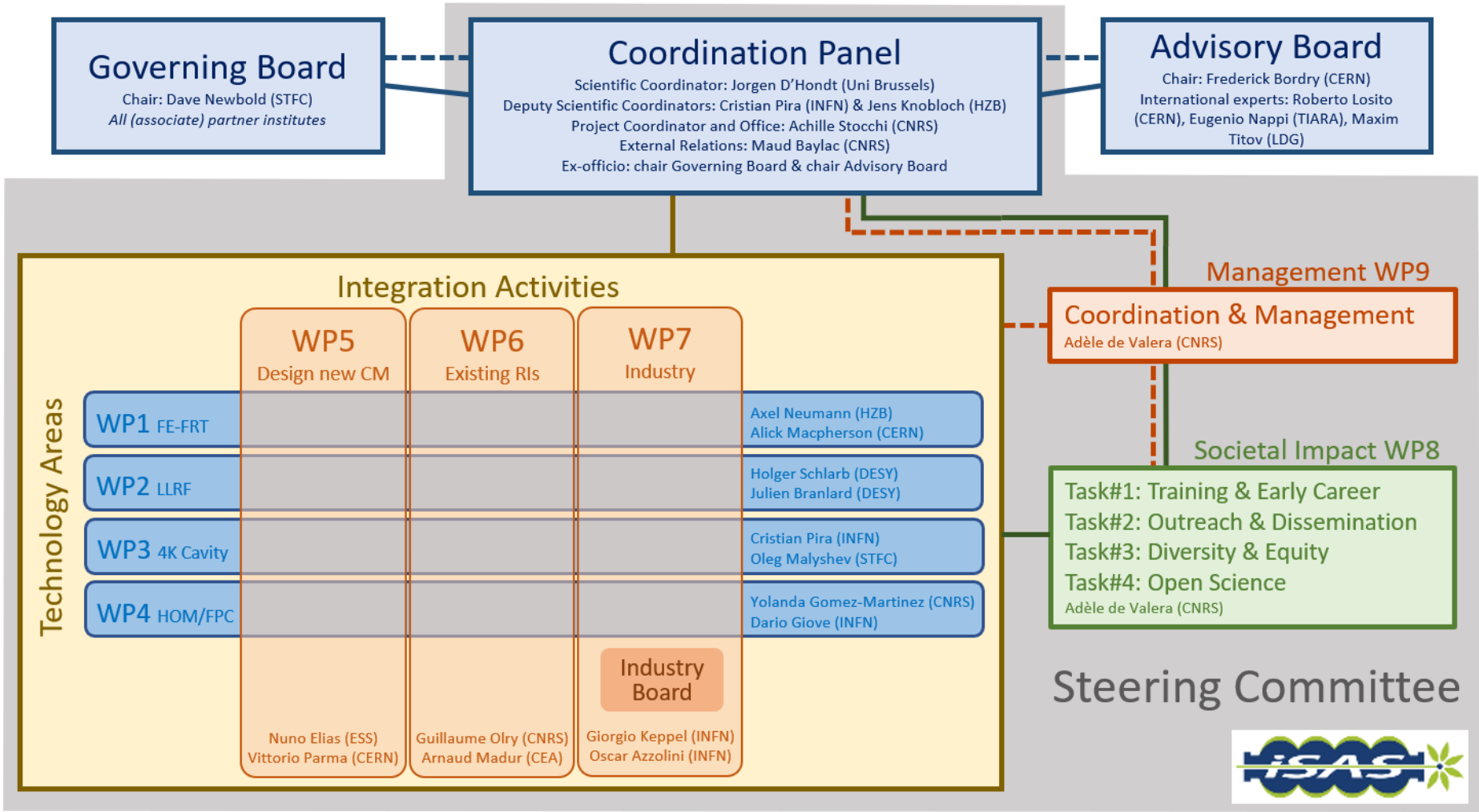
cryogenics

efficiency
~ T / (300K – T)

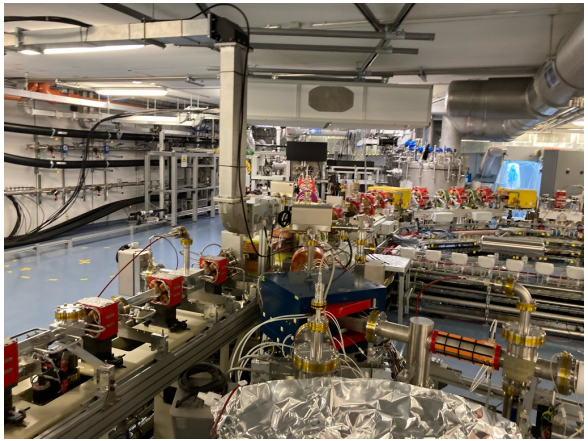
dissipated heat
~ 1/Q_0

energy savings
from the cryogenics

October 2024

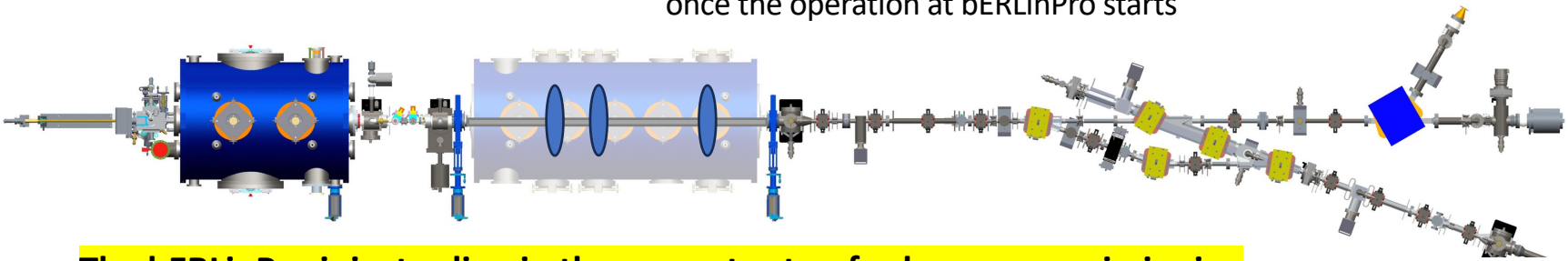


bERLinPro @ HZB (Berlin)



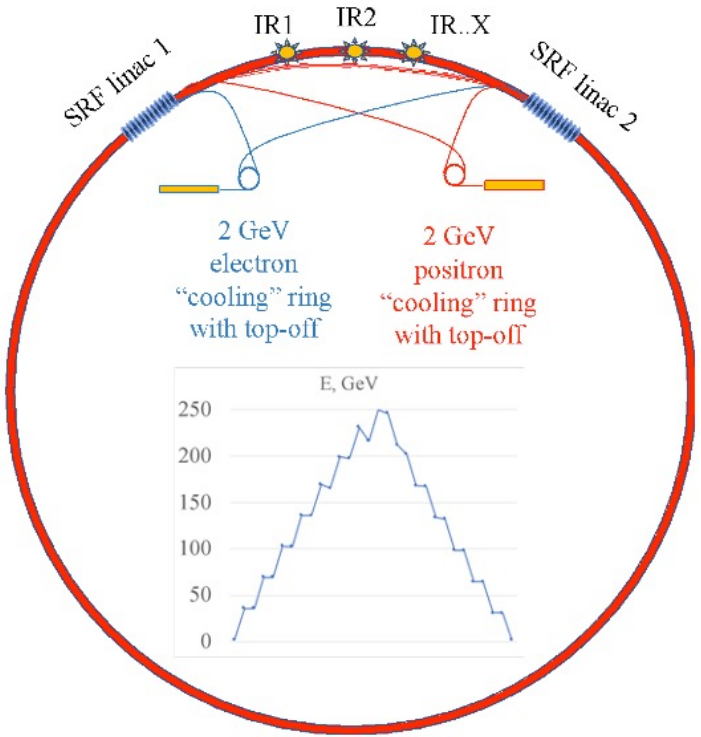
View from the injector line beam-dump towards the SRF photo-injector: Ready for beam commissioning

- Successful twice cooldown and follow-up RF test of the SRF photo-injector with field levels for beam energies ≥ 2 MeV and I_{avg}≤ 10 mA given by the RF coupler power limit (Jan-May 2024)
- Finalization of all required components for the injector characterization and first beam operation, e.g. diagnostics, cathode laser, photo-cathode transfer system
- Awaiting permit for beam operation starting from about mid of October
- Work on assembly of Booster has started and will come to full force, once the operation at bERLinPro starts



The bERLinPro injector line in the current setup for beam commissioning

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

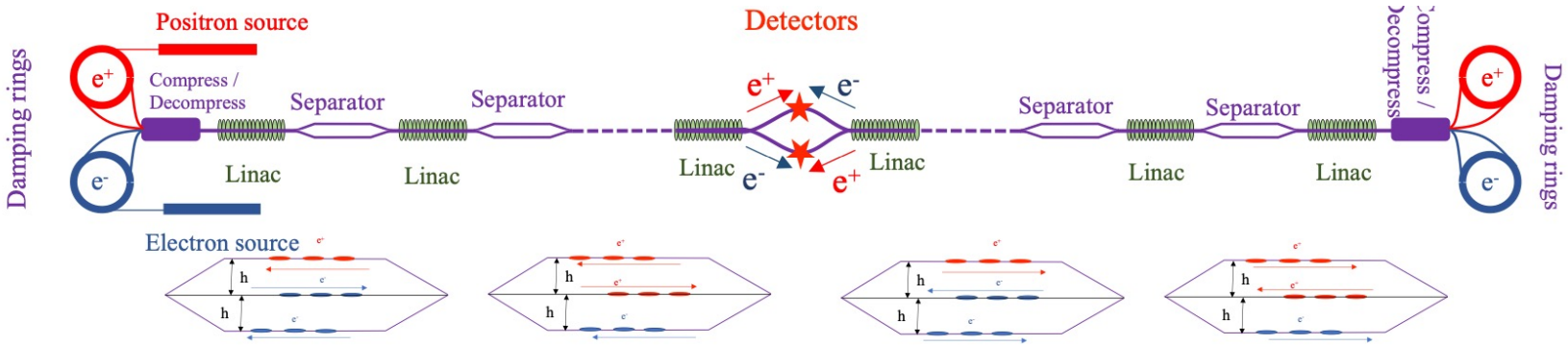


- Two 11 to 90 GeV SRF linacs in 4 pass configuration
- 1/3rd of power consumption as compared to circular collider
- CM Energy reach of 600 GeV in 100 km circumference tunnel
- Damping rings for emittance reduction and recycling of beams

- 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

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



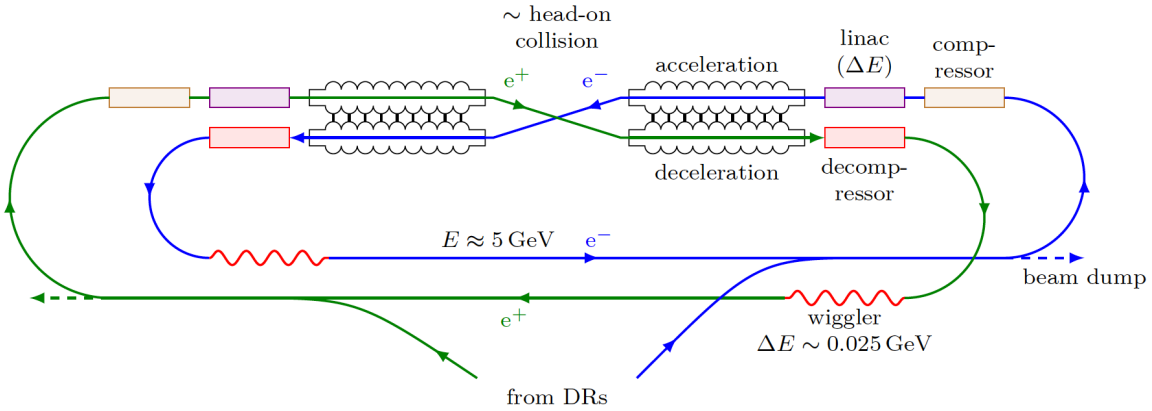
- Flat beams are cooled in damping rings
- Beams are accelerated on-axis in SRF linacs and collide in one of the detectors
- After collision, beams are decelerated in the opposite linacs and periodically separated off-axis

- 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



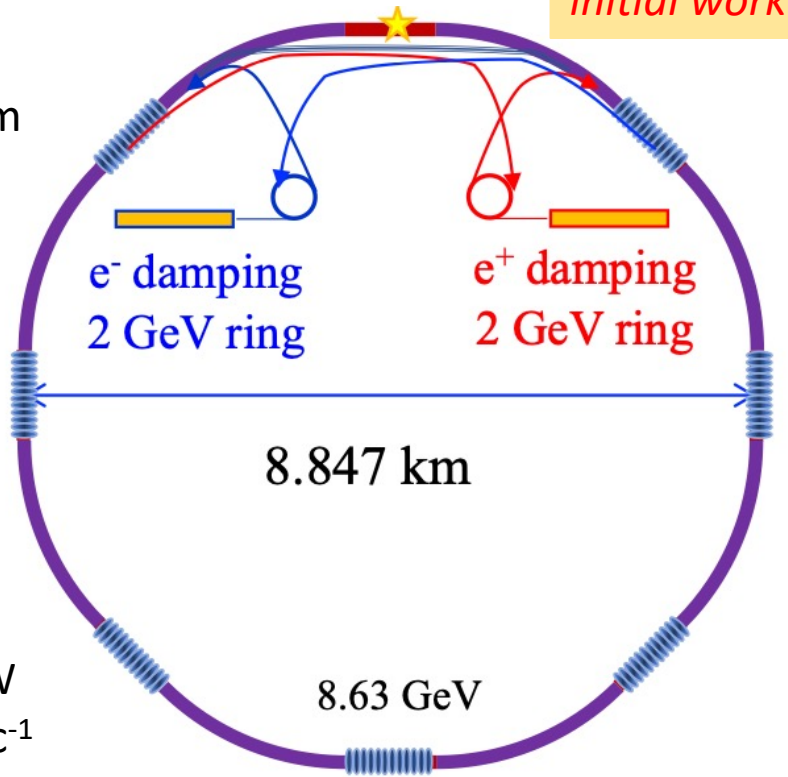
- ERLC consists of two parallel superconducting linacs connected to each other with RF-couplers, so that the fields are equal at any time
  - One line is for acceleration, the other for deceleration.
- Damping is provided by wigglers (no damping rings) at the “return” energy about E~5 GeV
- The energy 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

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