Power-efficient powerful beams

accelerator R&D for energy recovery for HEP

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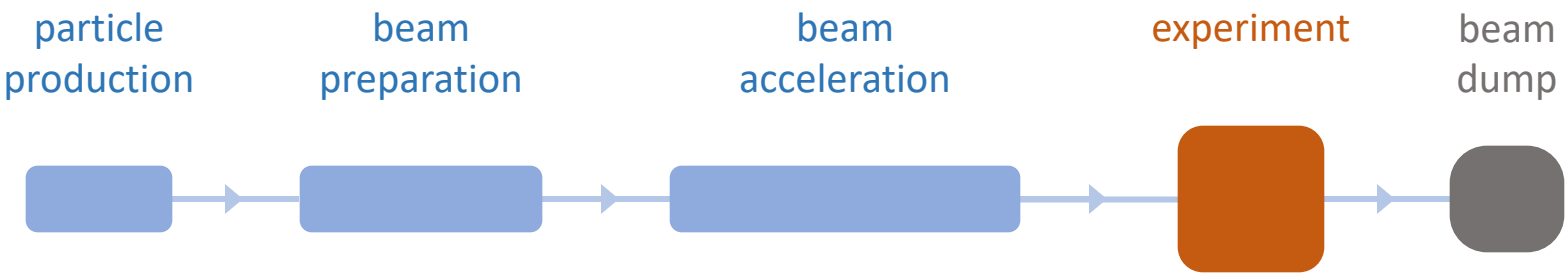
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

beln

Plenary ECFA meeting, 18 November 2022

Basic structures of a particle accelerator



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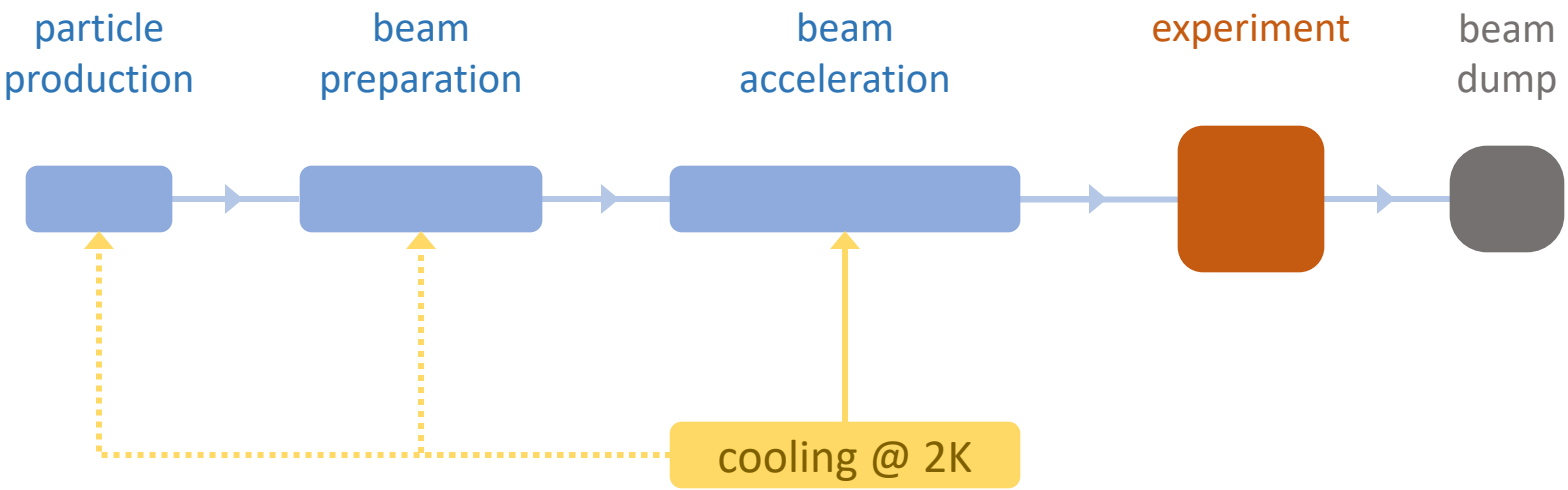

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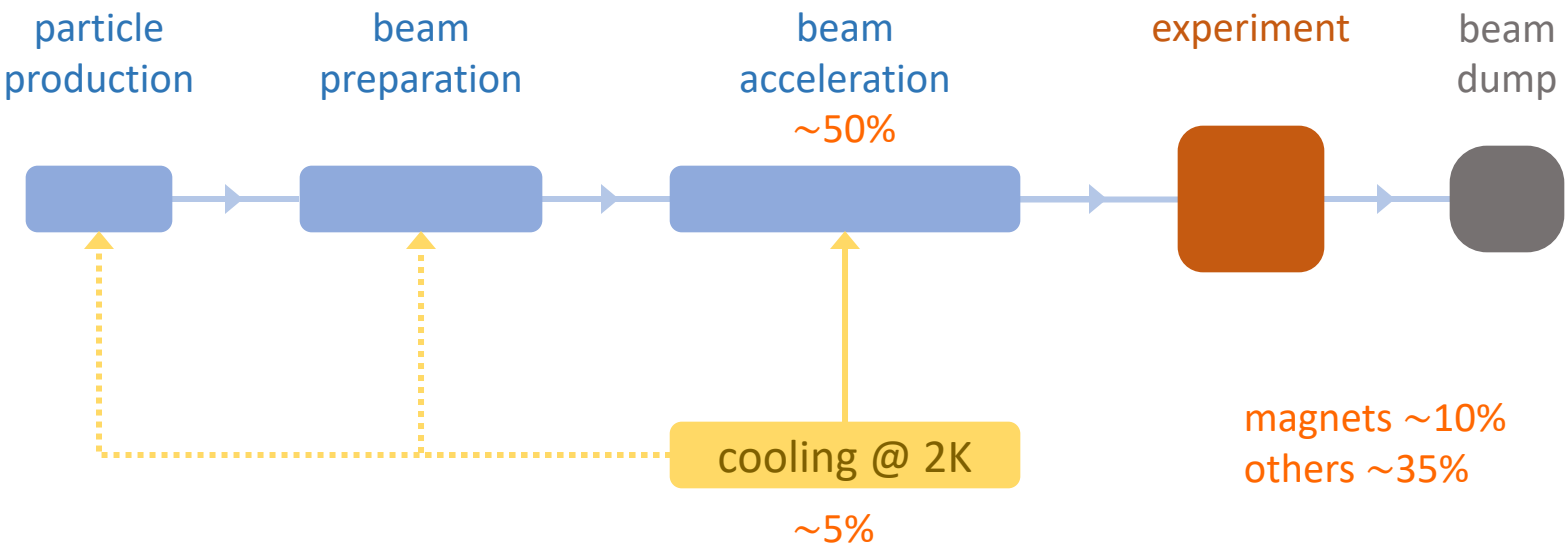
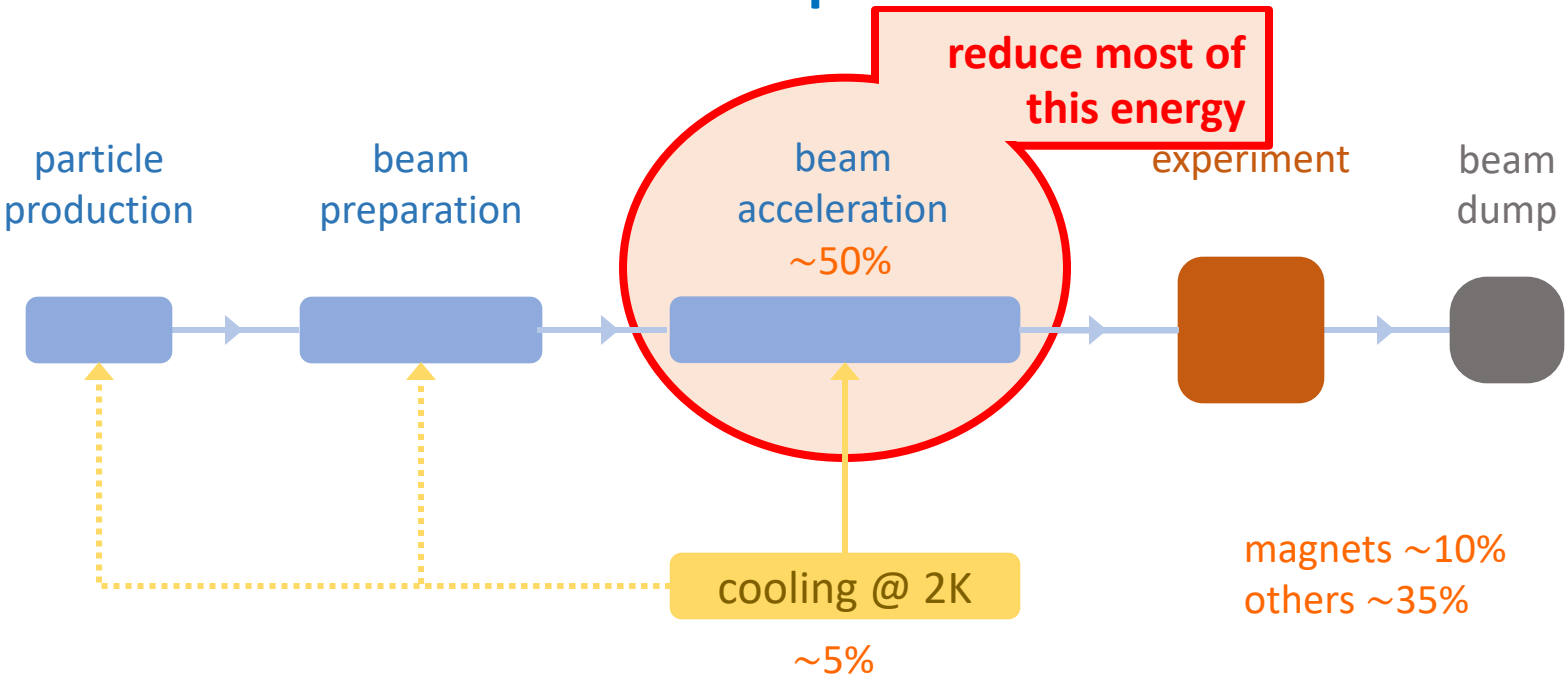


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator



Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator

The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

A detailed plan for the […] saving and re-use of energy should be part of the approval process for any major project.

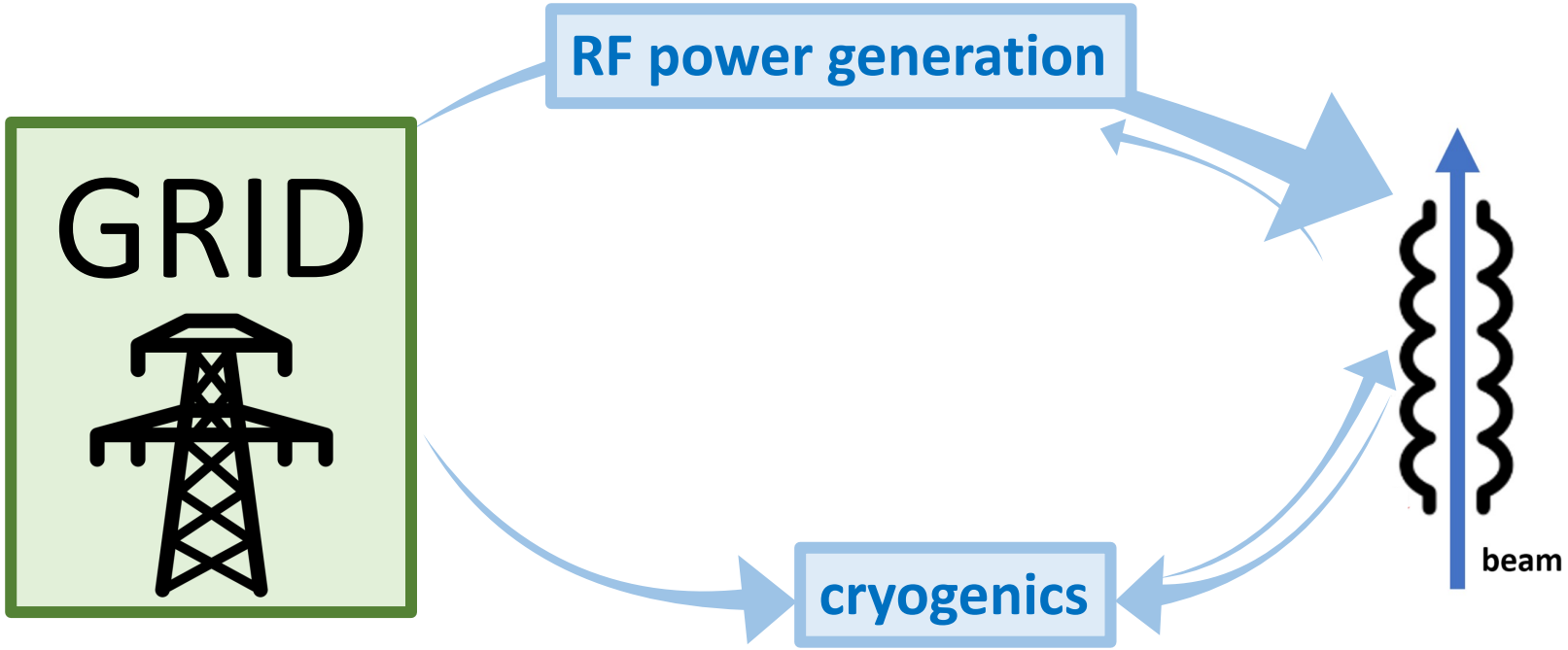
European Strategy for Particle Physics 2020

…ption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

From Grid to Beam



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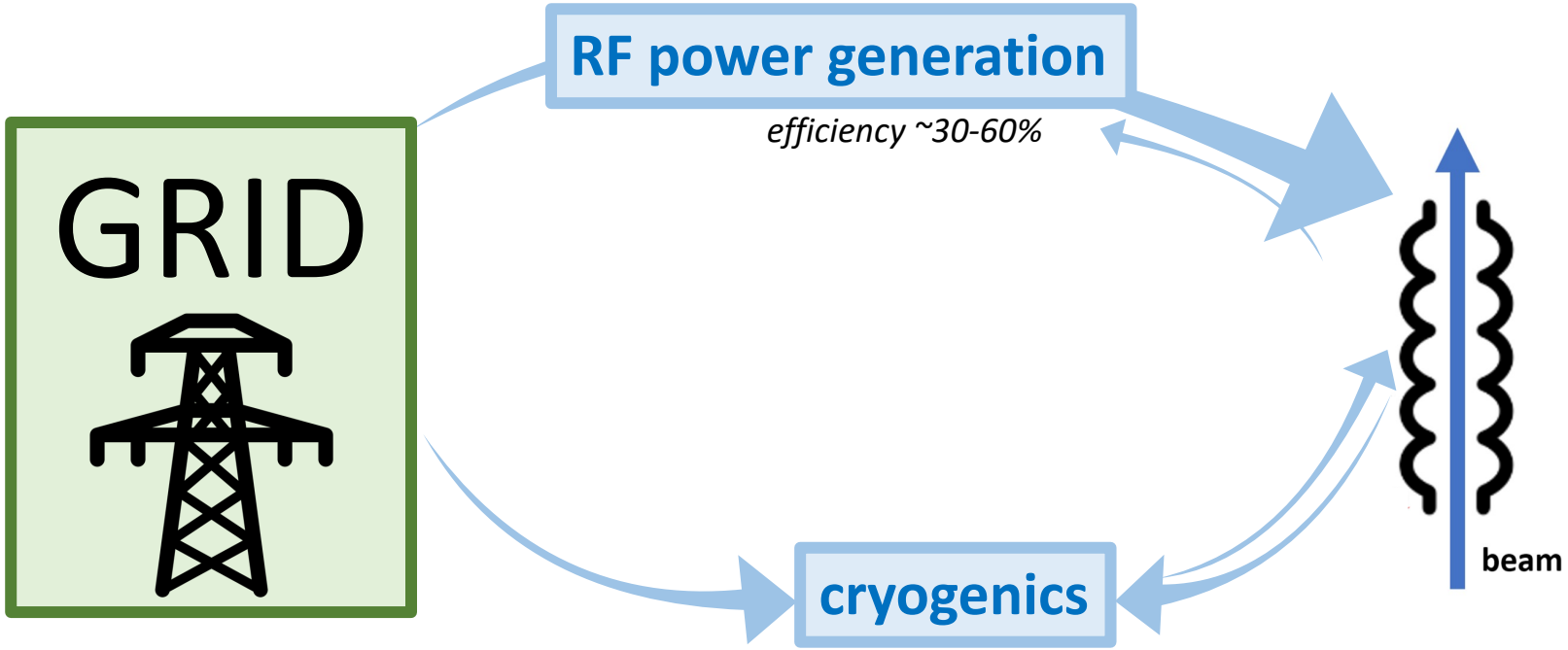

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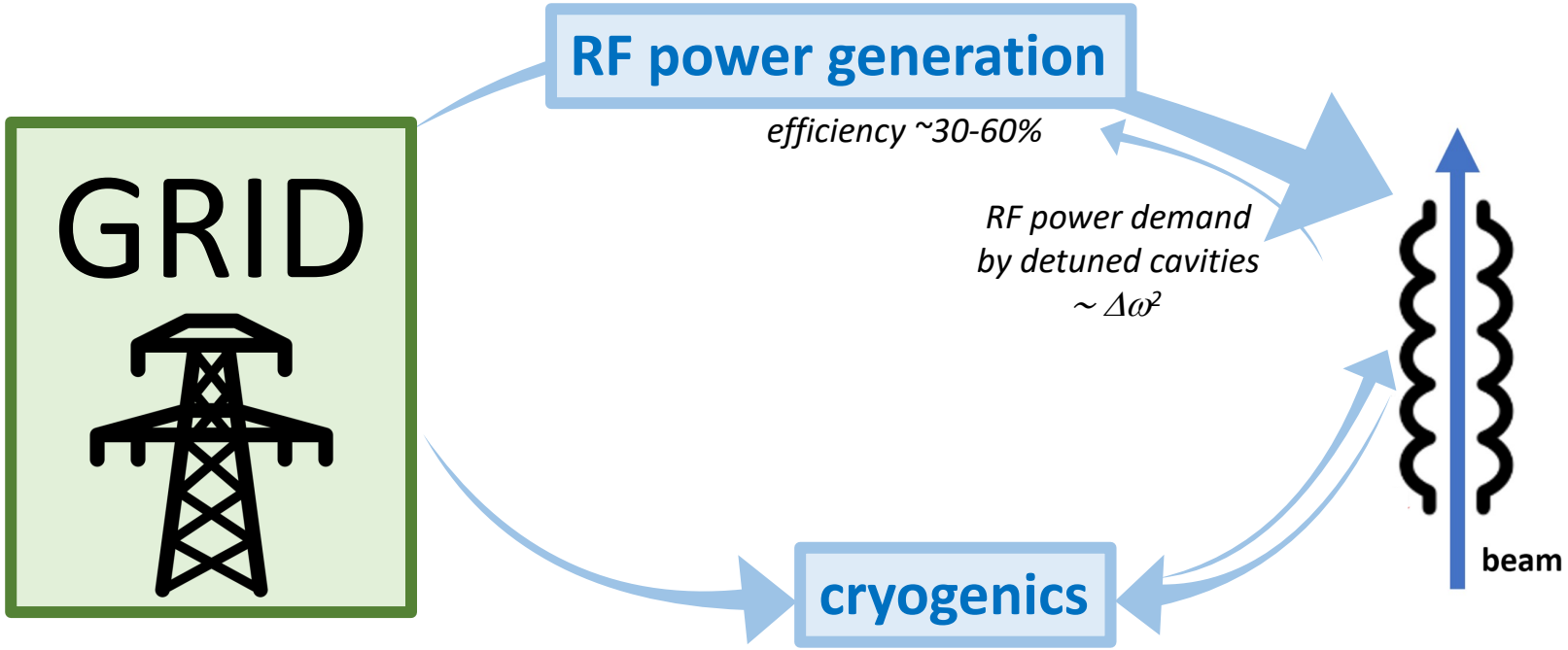

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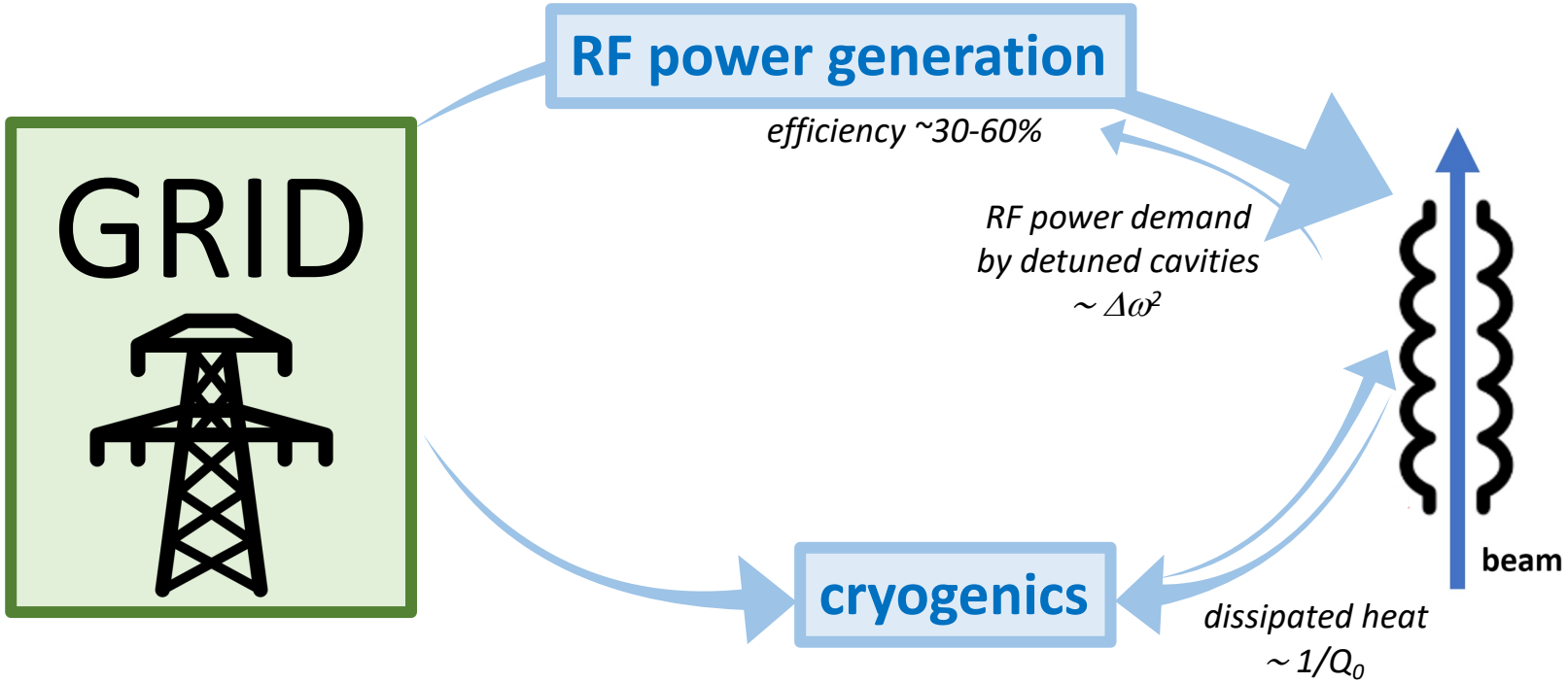

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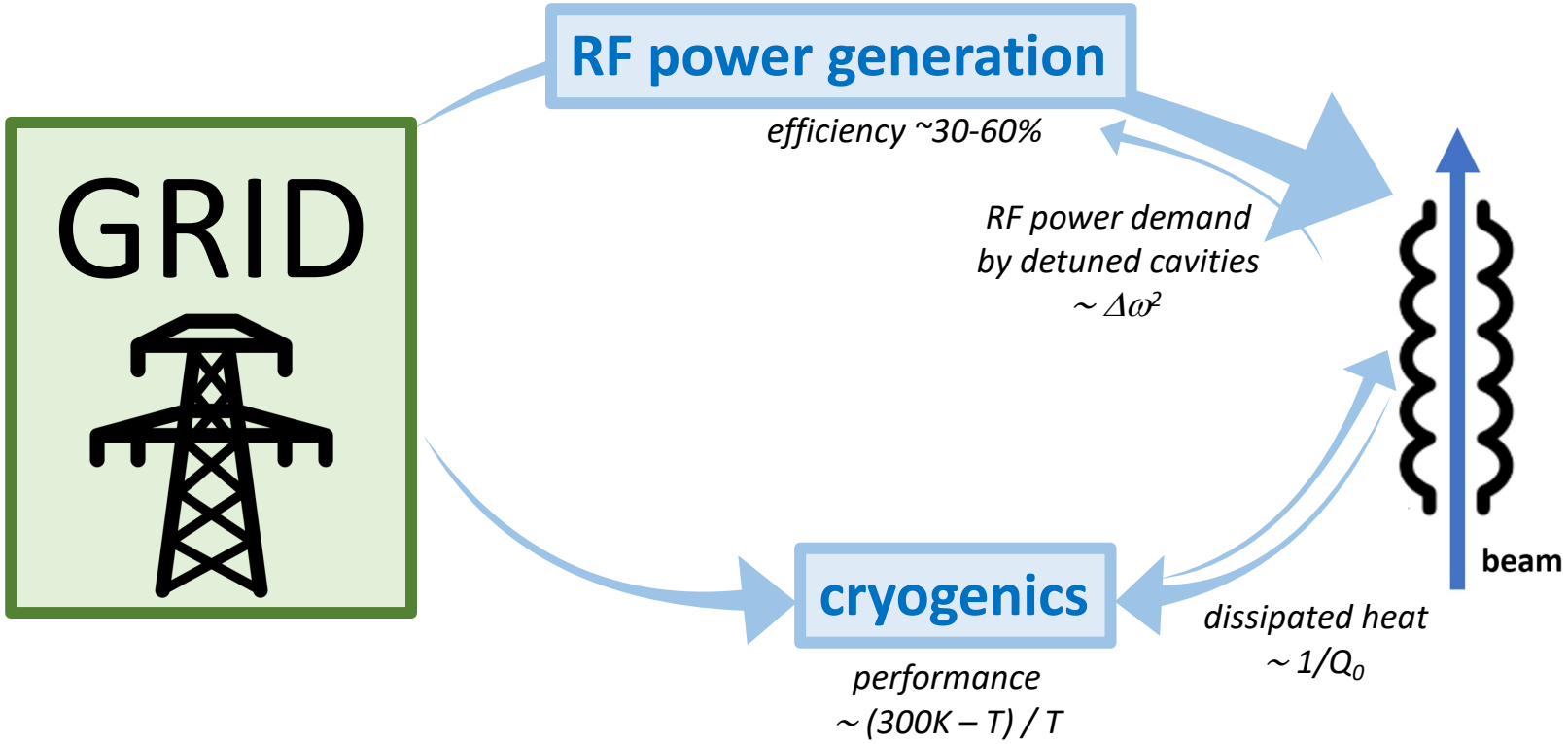

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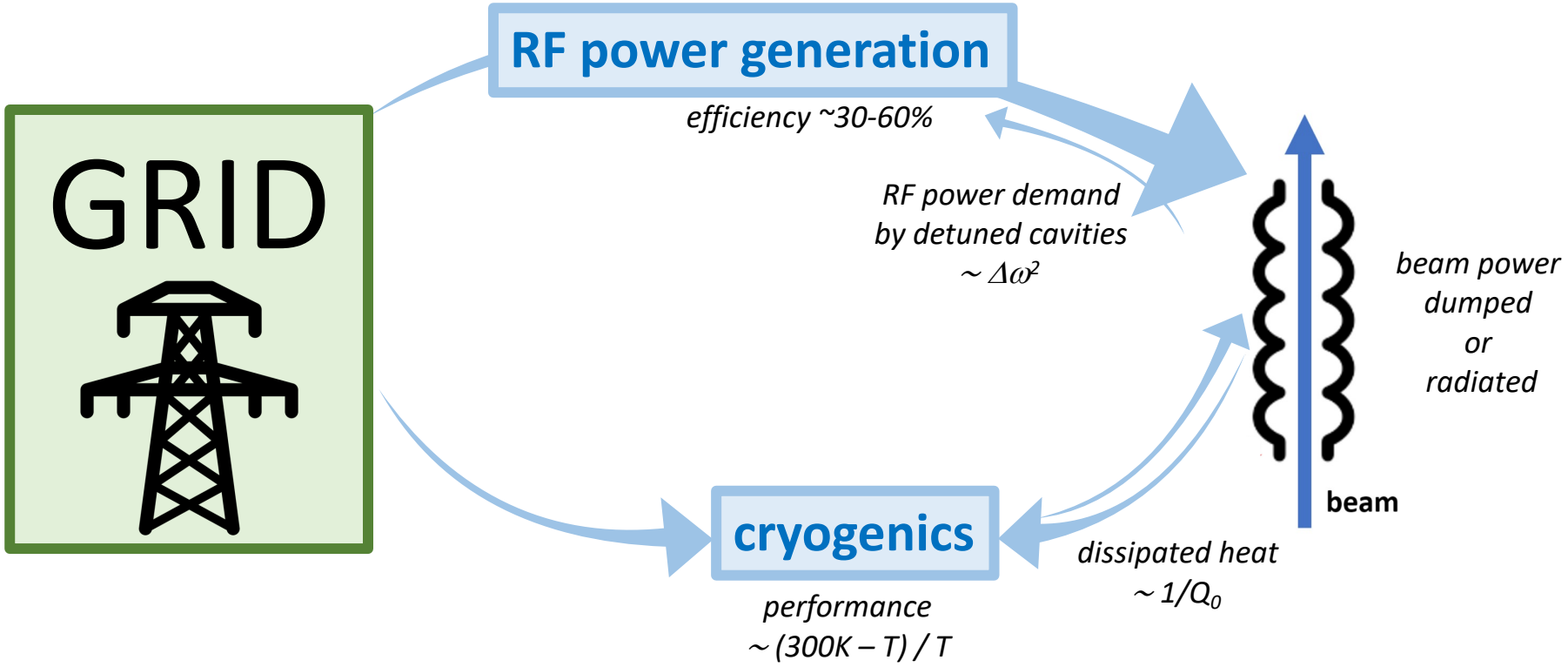

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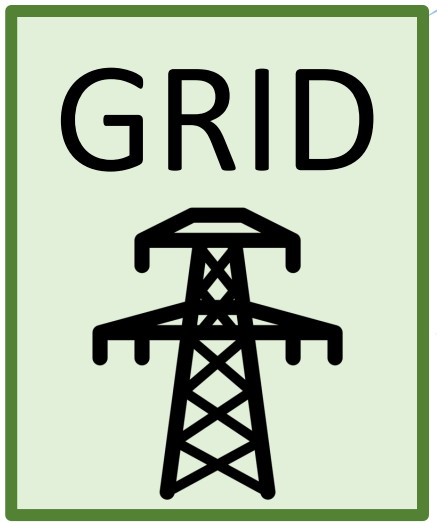

improve amplifier efficiency

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 demand by detuned cavities

$\sim \Delta\omega^2$

dealing with microphonics

e.g. Fast Reactive Tuners

beam power dumped or radiated

beam

cryogenics

dissipated heat

$\sim 1/Q_0$

performance

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

operate cavities at higher T & improve Q_0 of cavities

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

From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

RF power generation

energy

beam

reaching

recovery

power

ped

ted

Accelerating particles will always require a large amount of energy, hence an optimal use of this energy is an unavoidable challenge for particle physics

R&D for "*Sustainable Accelerating Systems*"

less energy, less cooling, less power loss, recover beam power

beam

cryogenics

dissipated heat
$\sim 1/Q_0$

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

operate cavities at higher T & improve Q_0 of cavities

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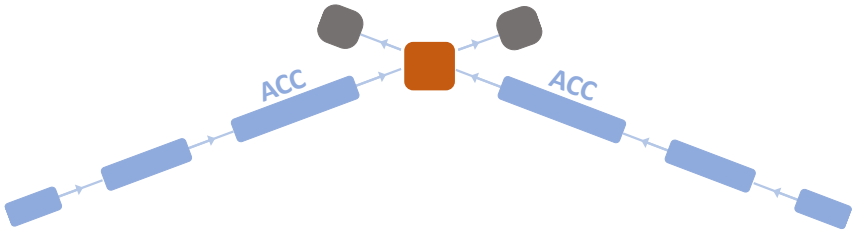
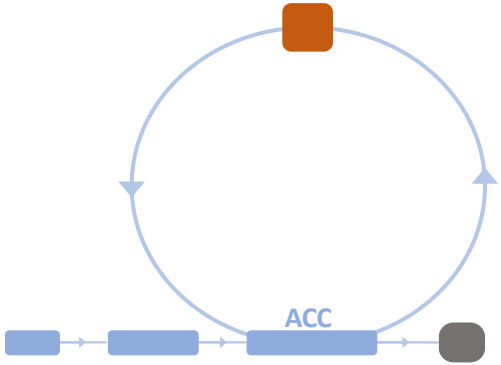
impact of power-efficiency for particle physics colliders

Designs of e^+e^- Higgs Factories

Linear colliders



Circular colliders



Designs of e^+e^- Higgs Factories

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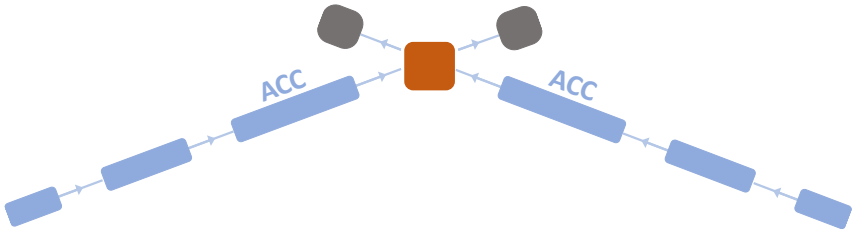
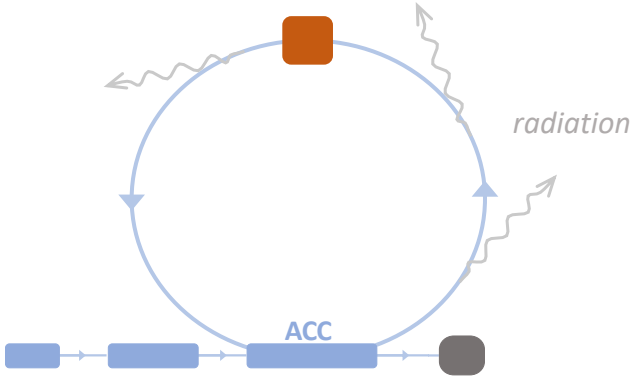


dump >99.9999% of
the beam power

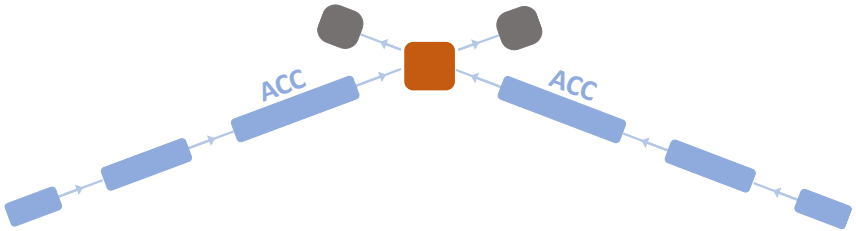
Circular colliders



radiate away very quickly
the beam power

Designs of e^+e^- Higgs Factories

Linear colliders



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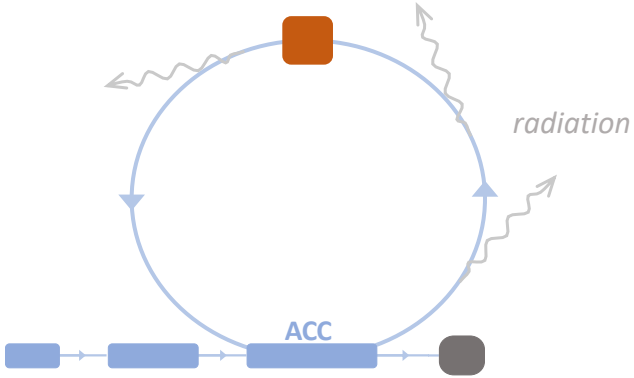


dump >99.9999% of the beam power

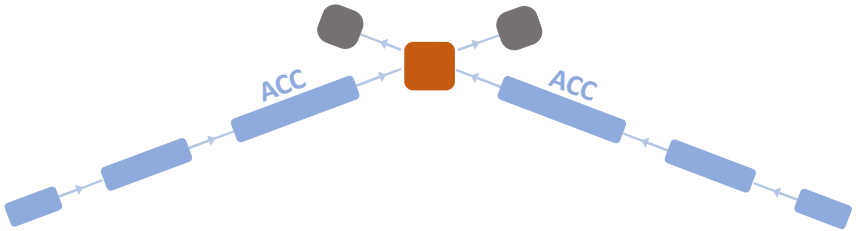
FCC-ee@250 ≃ 300 MW

radiate away very quickly the beam power

about half of this is dumped or radiated

Designs of e^+e^- Higgs Factories

Linear colliders



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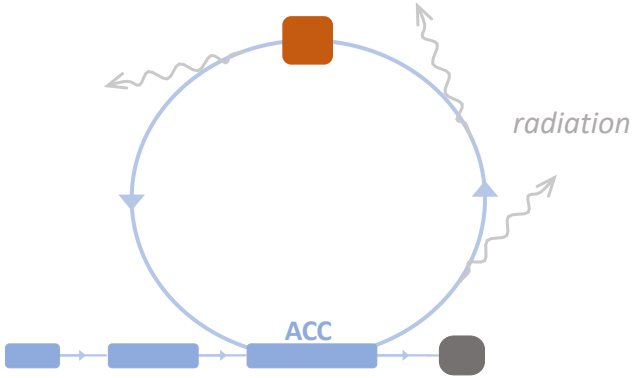

dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

radiate away very quickly the beam power

about half of this is dumped or radiated

OBJECTIVE: develop an accelerator technology that recovers energy with an impact of saving ~1% of Belgium's electricity

Designs of e^+e^- Higgs Factories

Linear colliders

Circular colliders

Energy Recovery Linacs

synergies with power-efficient SRF systems

the beam power

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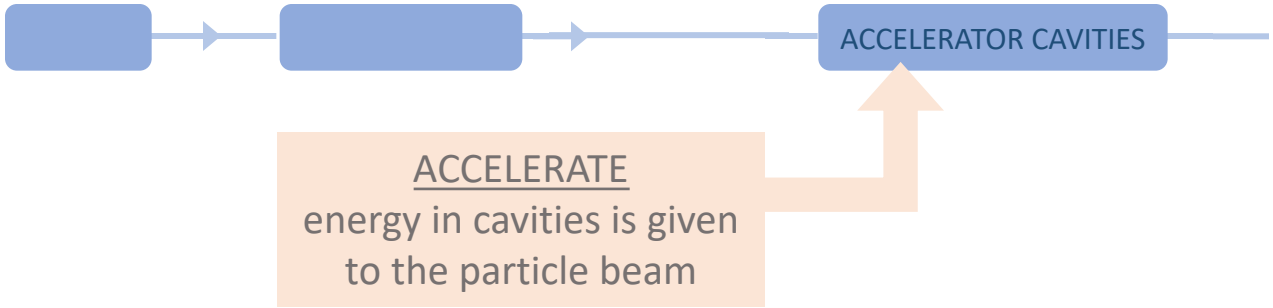
The principle of Energy Recovery



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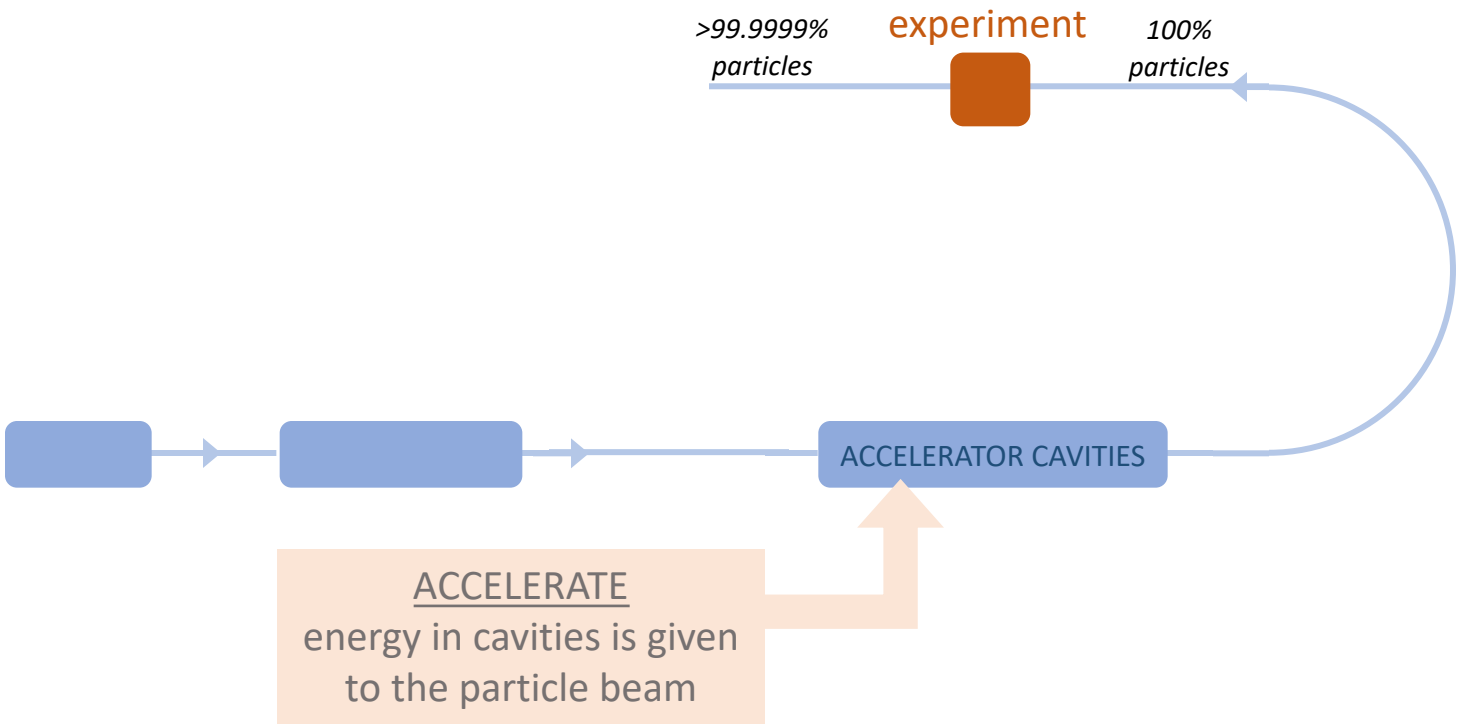

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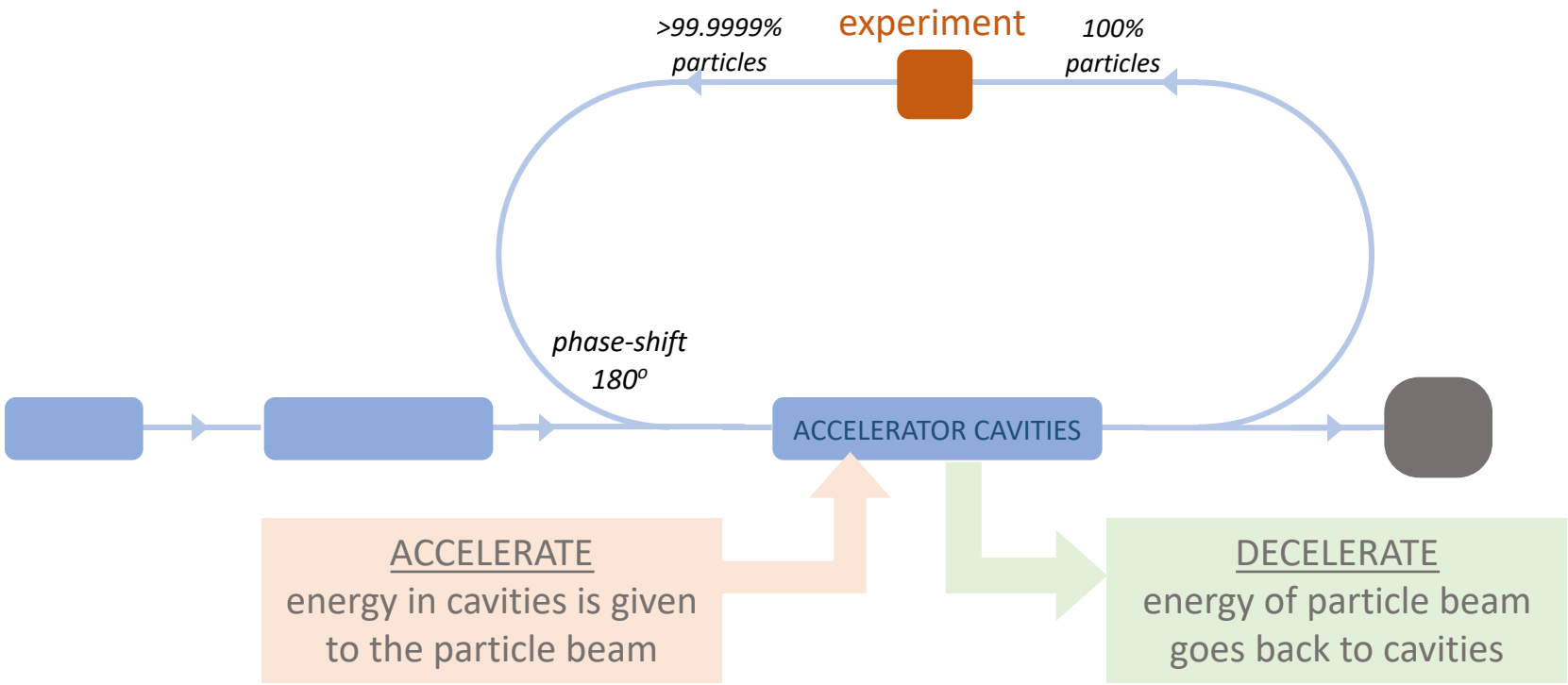

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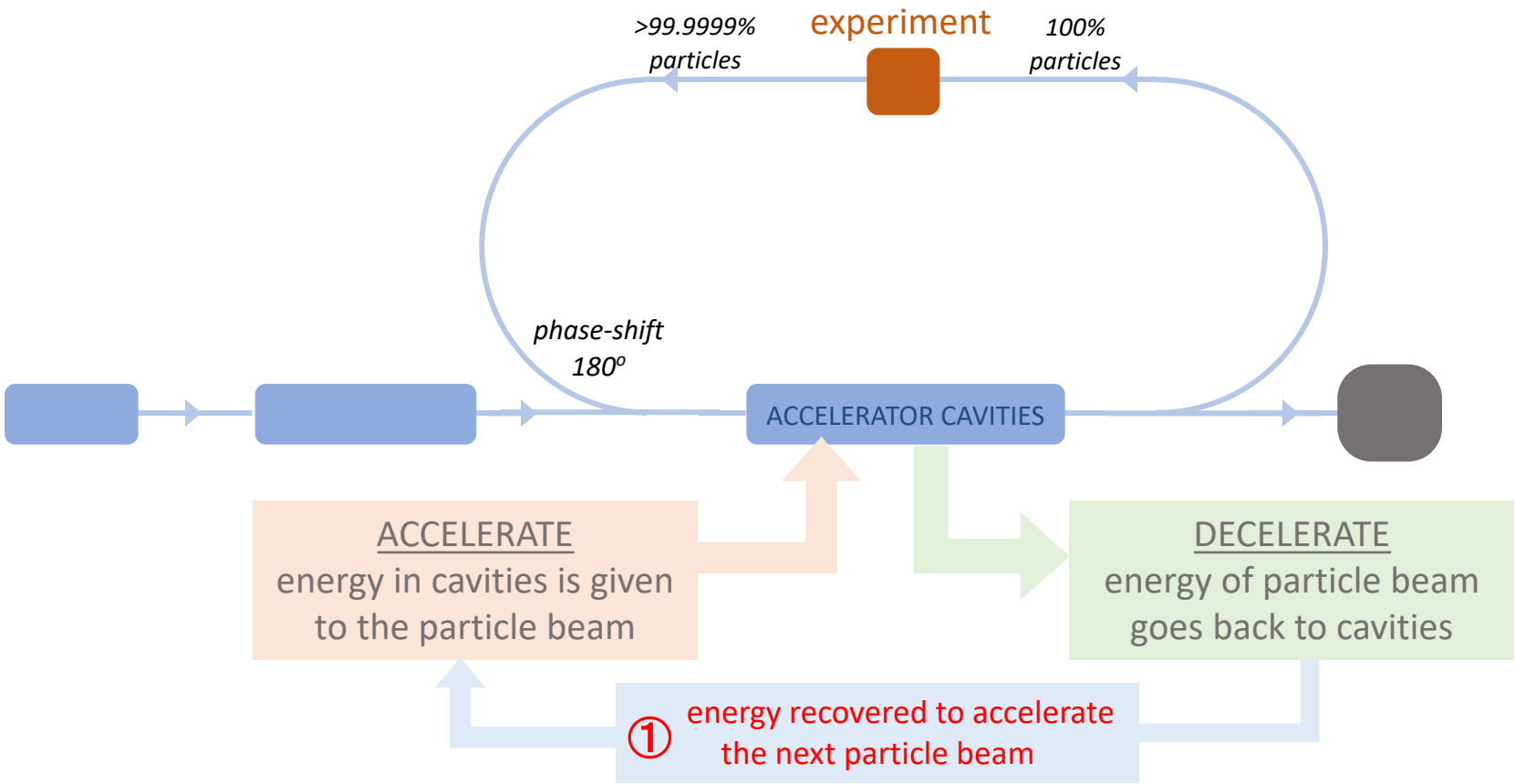

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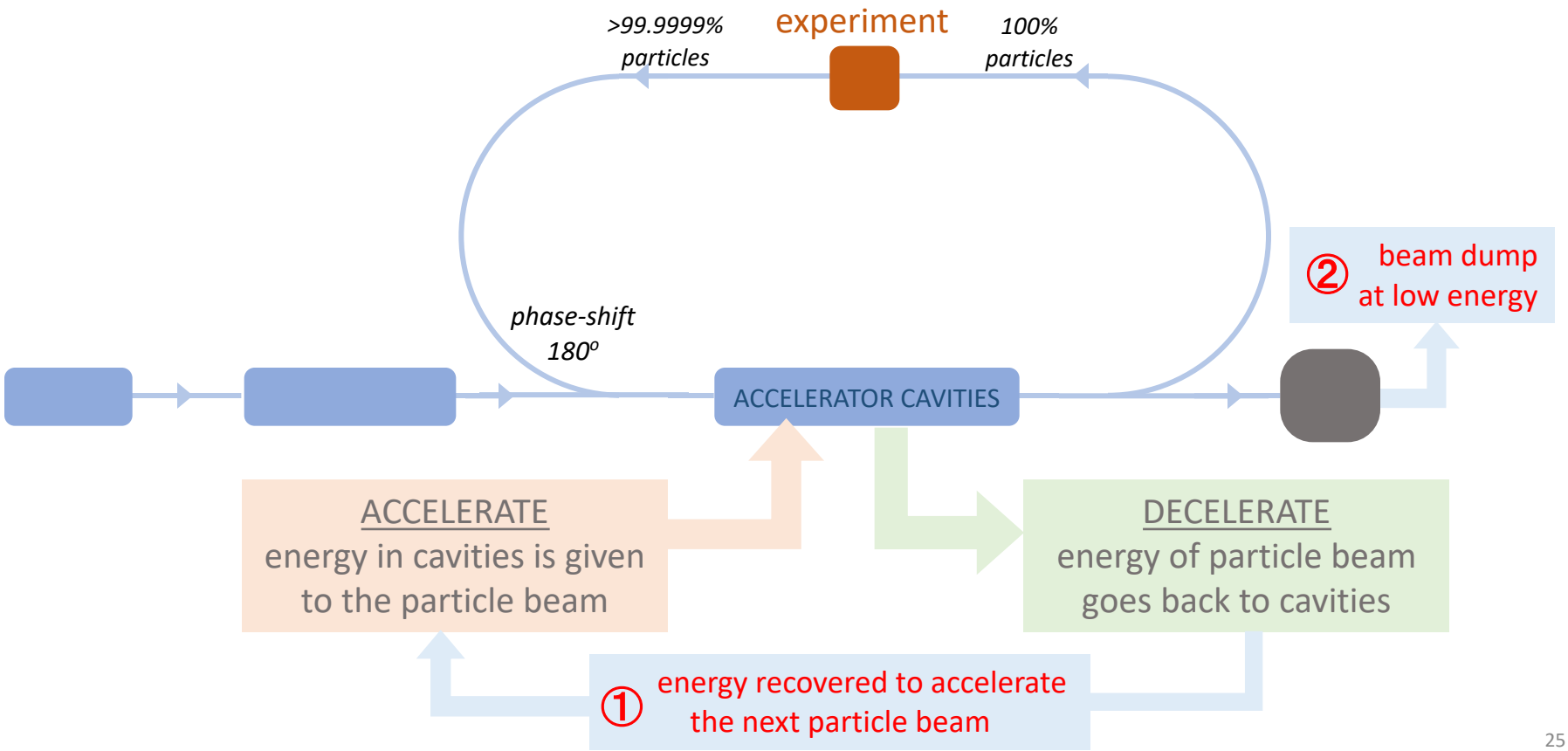

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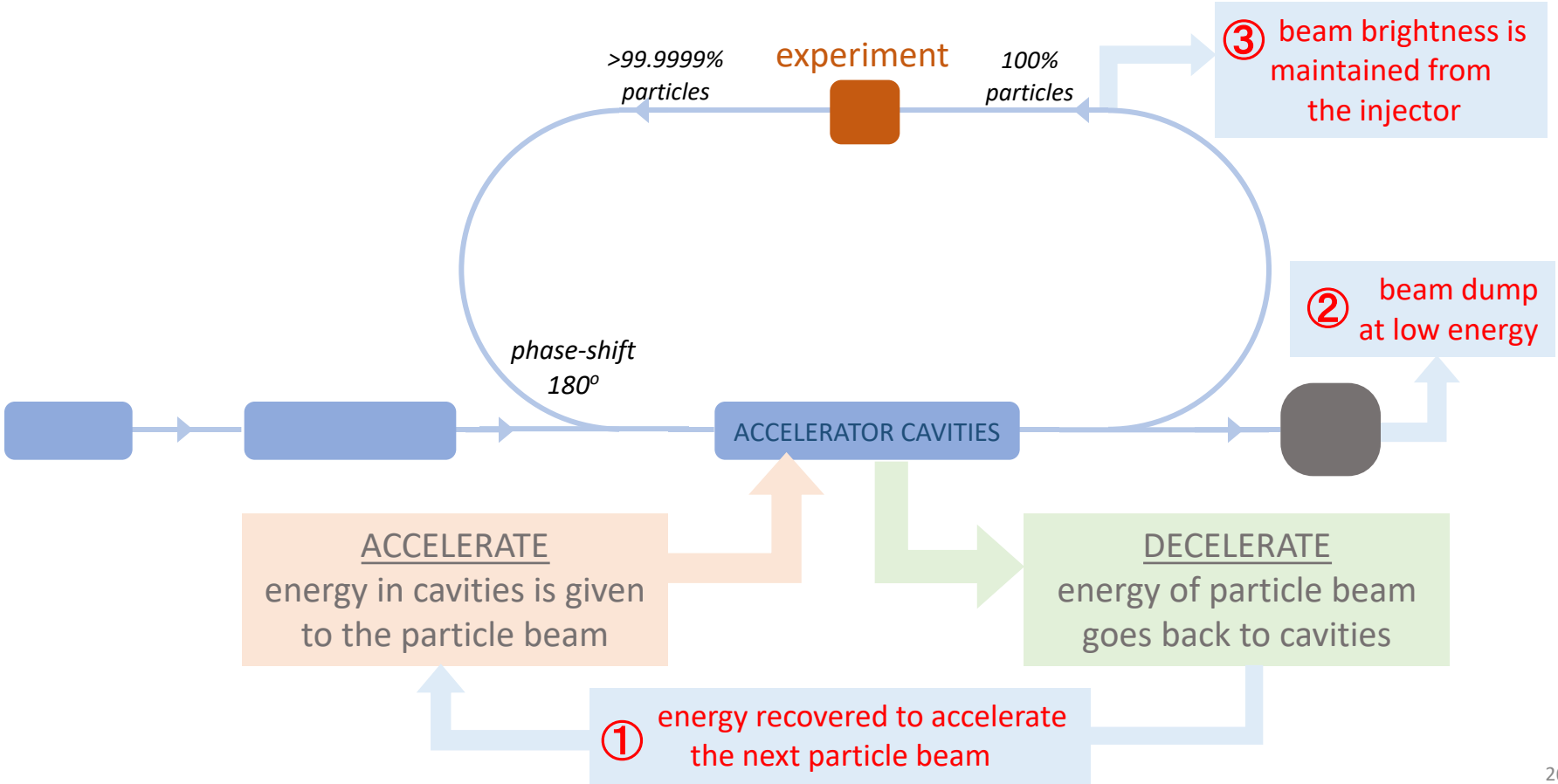

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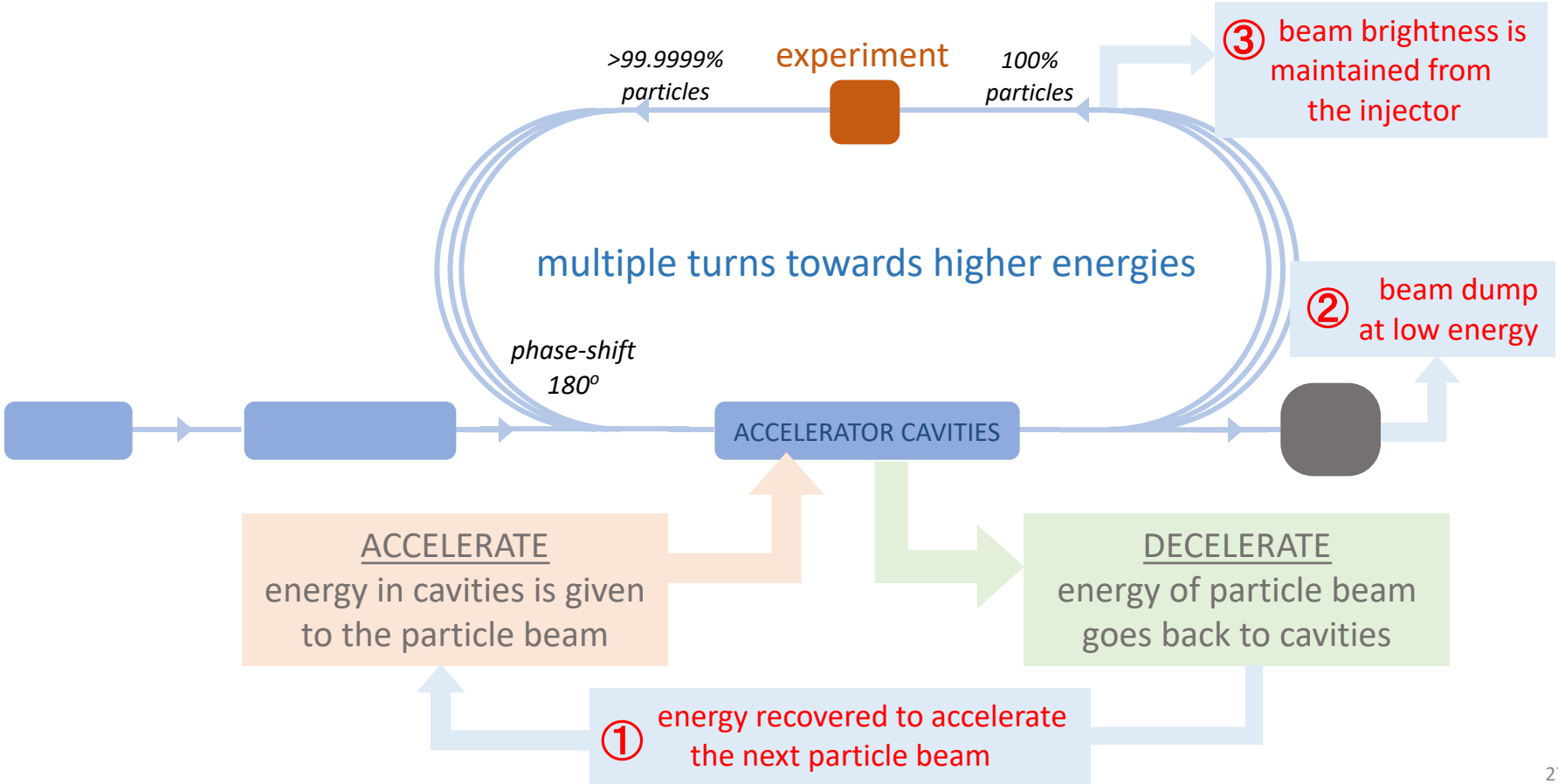

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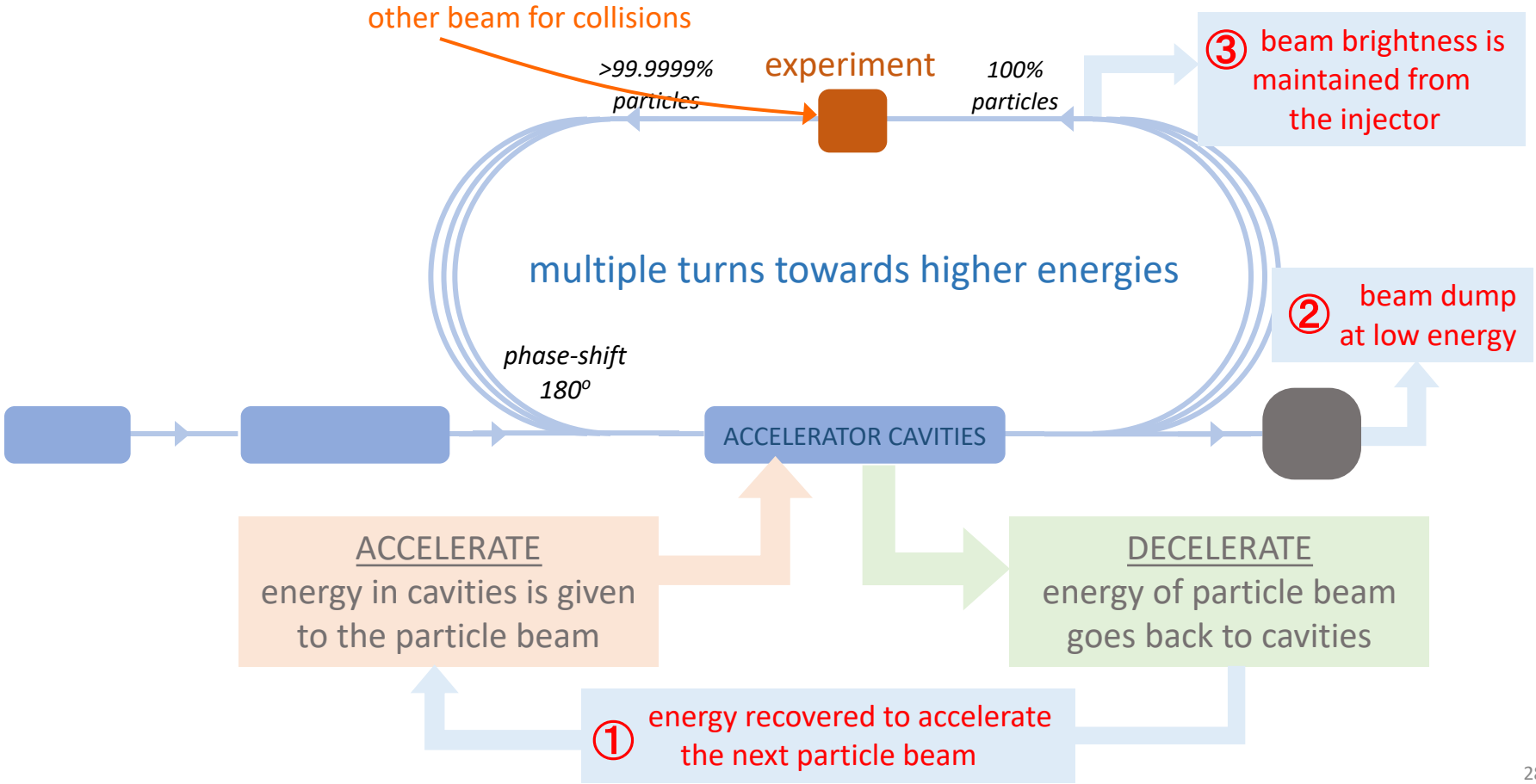

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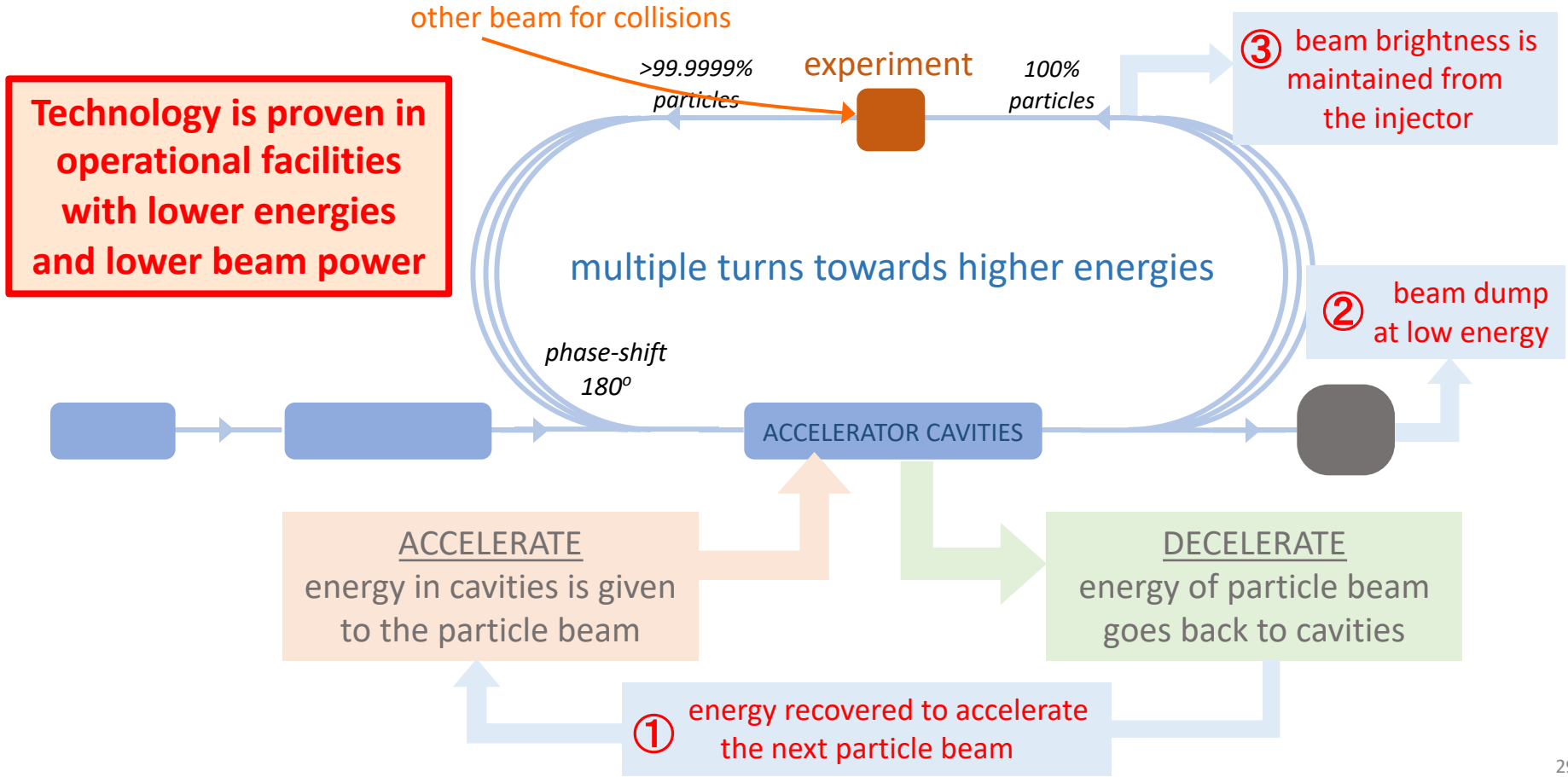


Energy Recovery technology

applications with a reduced energy footprint and cost

- **The engine of our curiosity-driven exploration is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize.**

- **Based on 50 years of successful accelerator R&D developments**
  success builts easier on previous success

- **Minimal energy consumption to accelerator particles to high energies**
  addressing scientific & societal challenges together with quasi 100% energy recovery

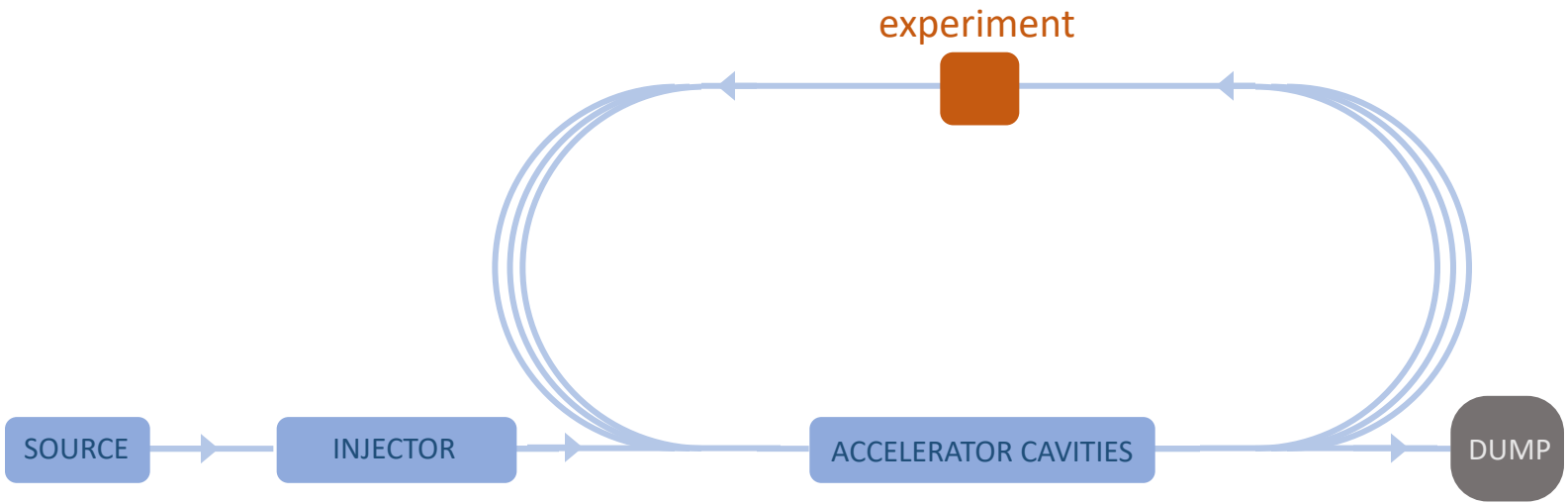
- **Maximal knowledge transfer to revolutionise applications in industry**
  e.g. nanometer-scale semiconductors, medical isotopes, gamma sources for nuclear industry, X-ray Free-Electron Lasers (XFEL), … incl. career transfer opportunities to industry

European Accelerator R&D Roadmap

for particle physics

Identified the key aspects for an Energy Recovery accelerator

towards high-energy & high-intensity beams to be used at particle colliders



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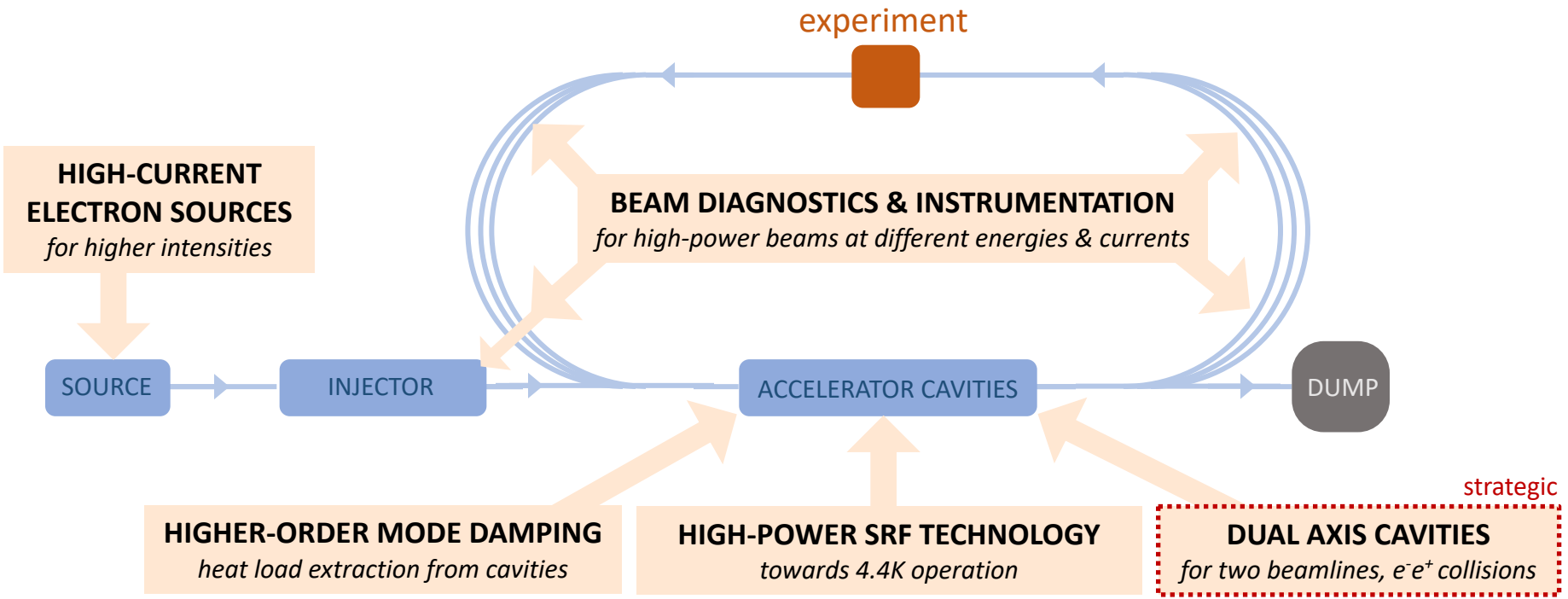
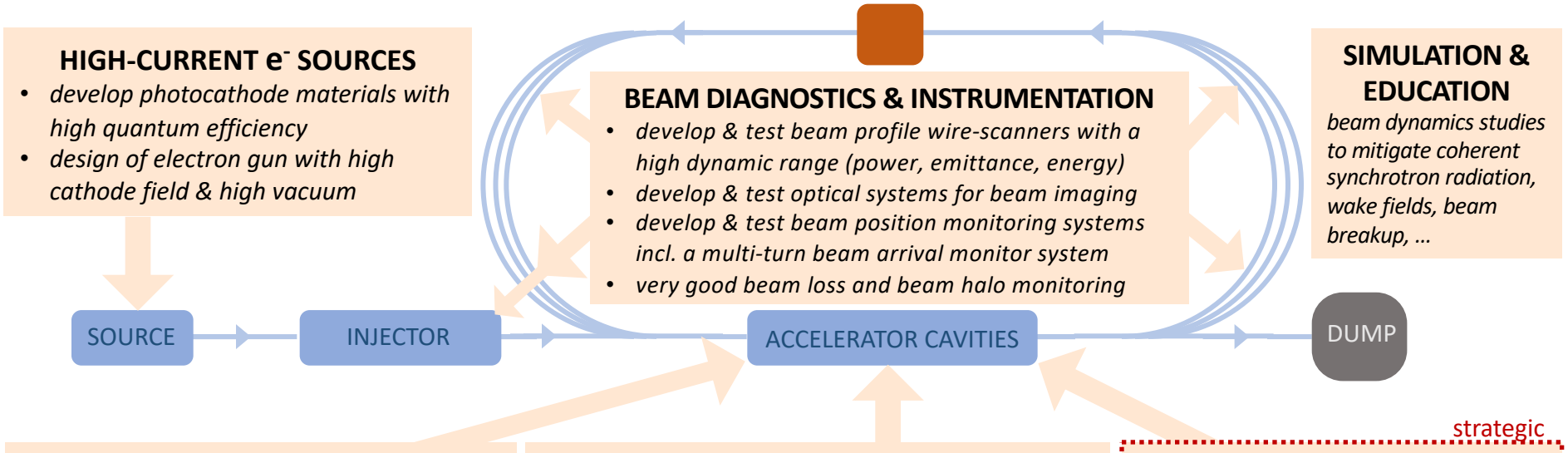


Translated into main R&D objectives for Energy Recovery

geared towards high-energy and high-intensity accelerators incl. synergies with industry



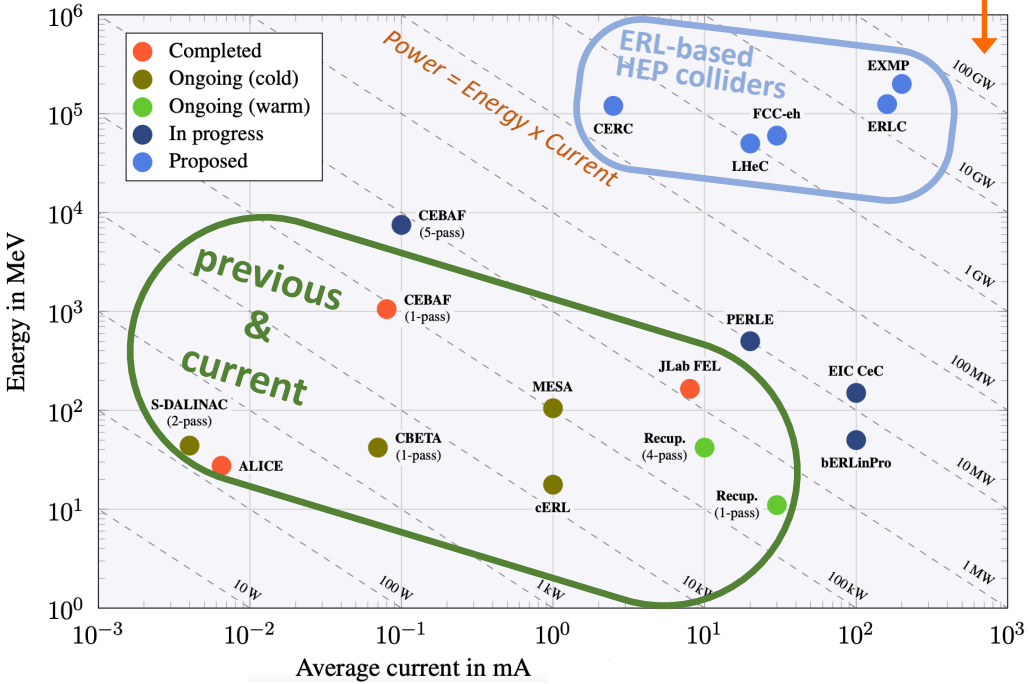
Most R&D objectives part of the bERLinPro and PERLE programs

(*) part of the RF R&D program

Energy Recovery – 50 years of innovation

from previous to current and future facilities as stepping stones for R&D

would be the required external power supply without Energy Recovery



Energy Recovery

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

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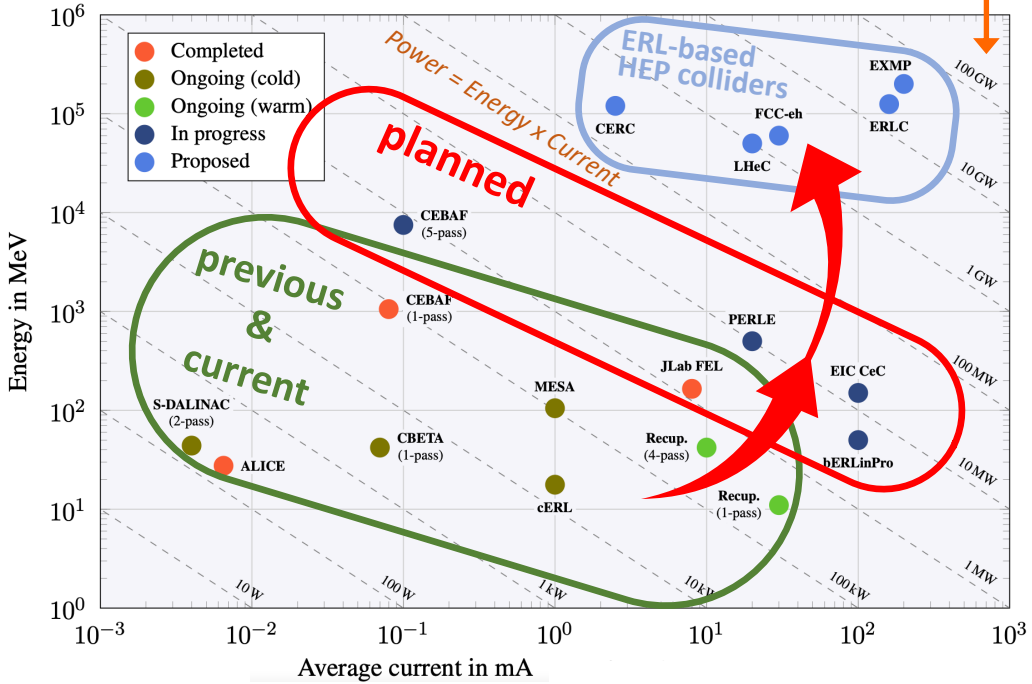

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bERLinPro & PERLE

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

towards high energy & high power

The Development of Energy-Recovery Linacs

arXiv:2207.02095, 237 pages, 5 July 2022

Energy Recovery – 50 years of innovation

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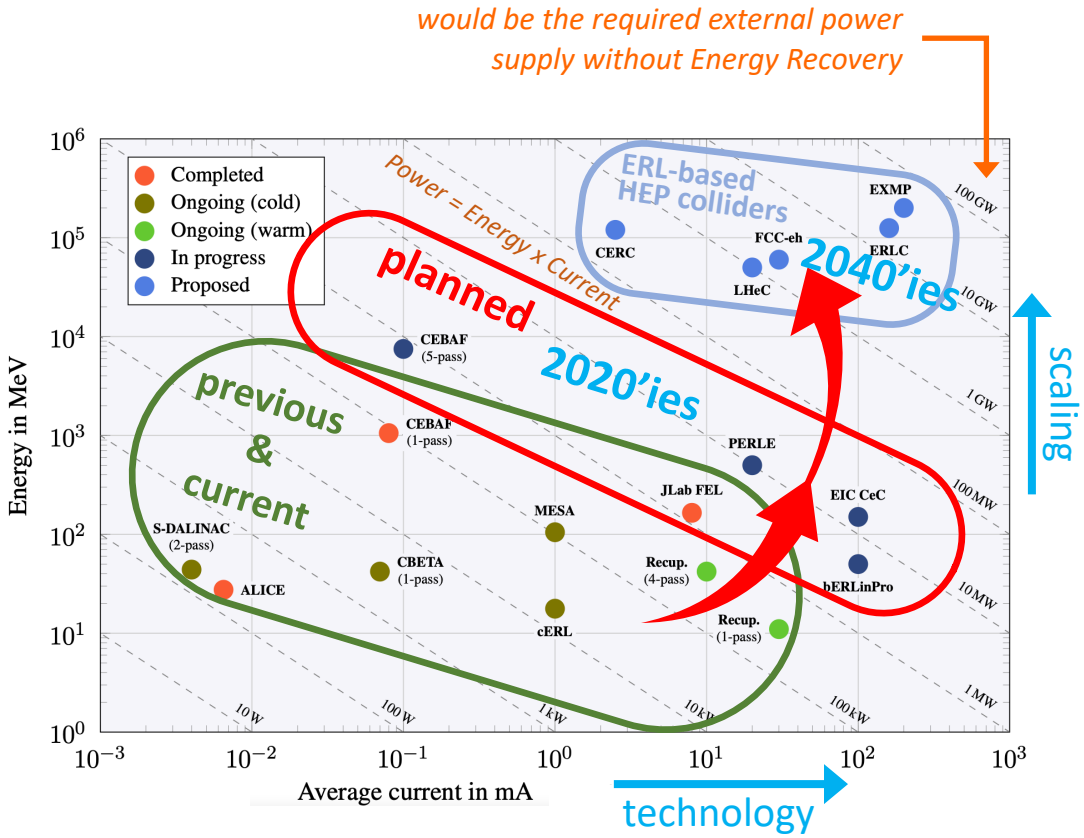

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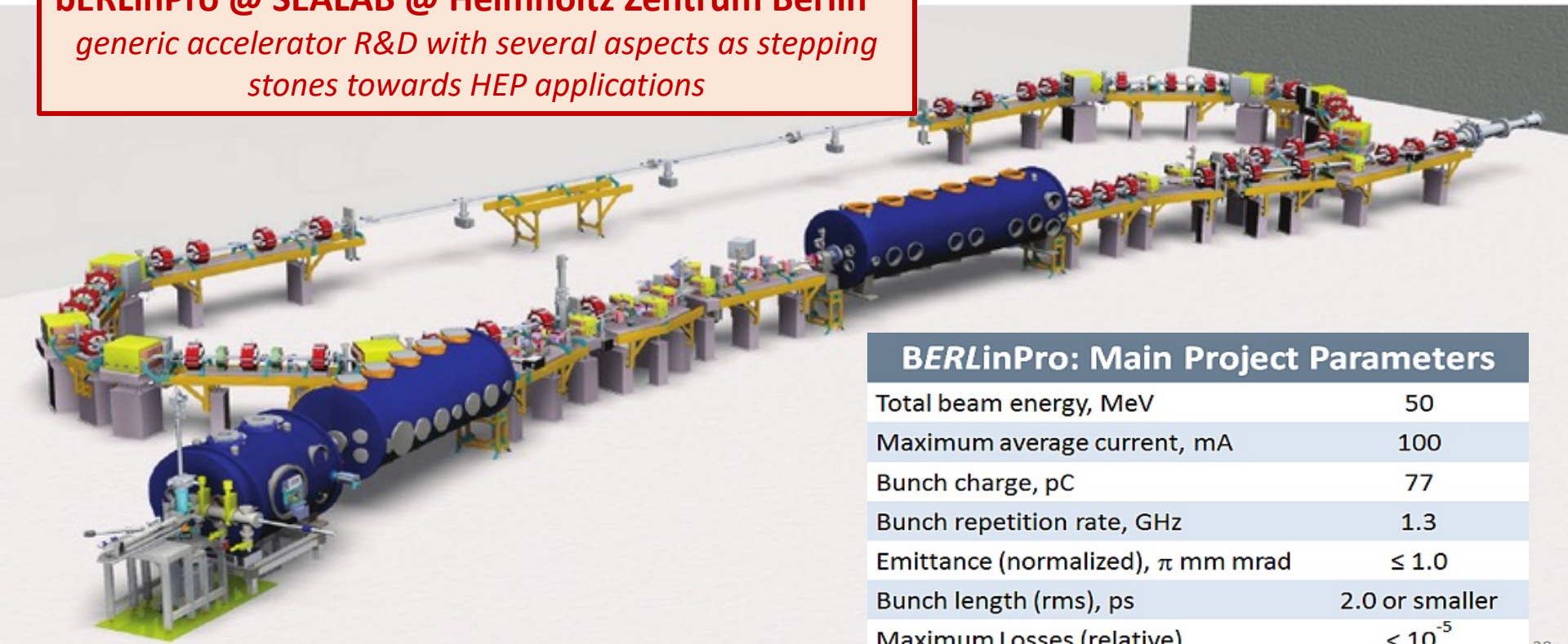
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

bERLinPro @ SEALAB @ Helmholtz Zentrum Berlin

generic accelerator R&D with several aspects as stepping stones towards HEP applications



bERLinPro: Main Project Parameters	
Total beam energy, MeV	50
Maximum average current, mA	100
Bunch charge, pC	77
Bunch repetition rate, GHz	1.3
Emittance (normalized), π mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	$< 10^{-5}$

Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

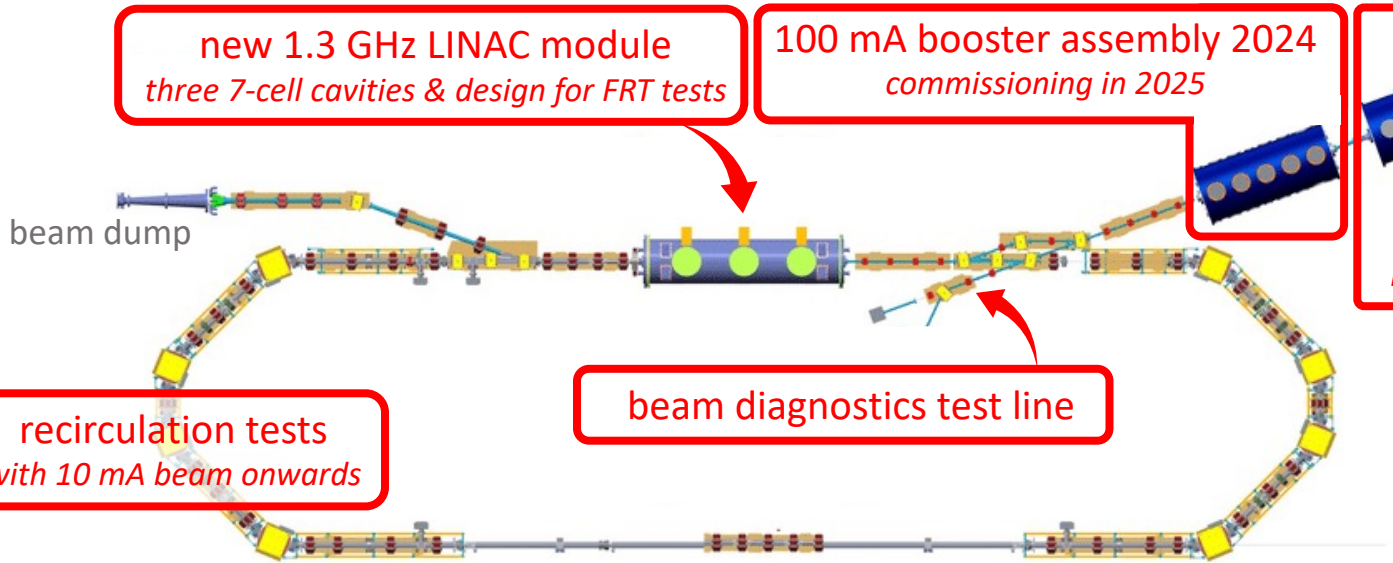
bERLinPro @ Helmholtz Zentrum Berlin
addressing HEP related challenges

bERLinPro ready for operation at 10 mA
contingent on additional budgets upgrades to 100 mA and 50 MeV can be planned to be operational by 2028

new 1.3 GHz LINAC module
three 7-cell cavities & design for FRT tests

100 mA booster assembly 2024
commissioning in 2025

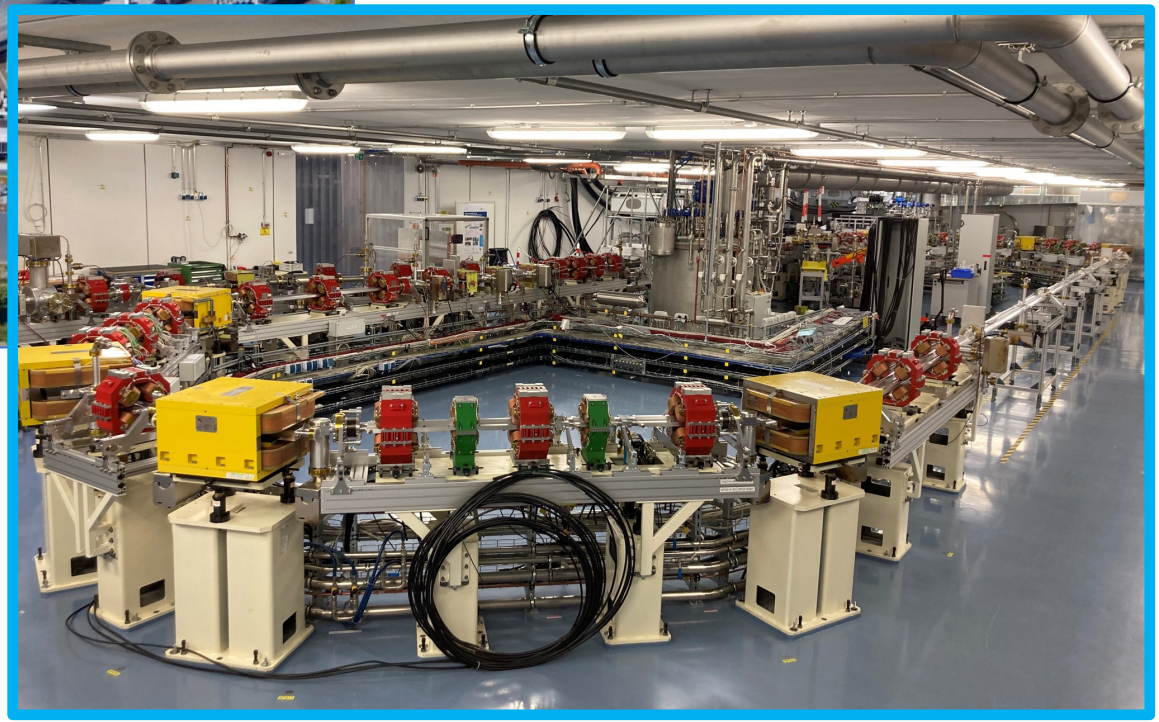
develop
first SRF gun
with high-current
incl. cathode development



recirculation tests
with 10 mA beam onwards

beam diagnostics test line

First beam of bERLinPro@SEALAB to be expected around late Spring to Summer 2023



- focus on commissioning injector with SRF gun + diagnostic line
  (map out the reachable parameter space)
- installation of the Booster module
- recirculation, when LINAC funding is secured

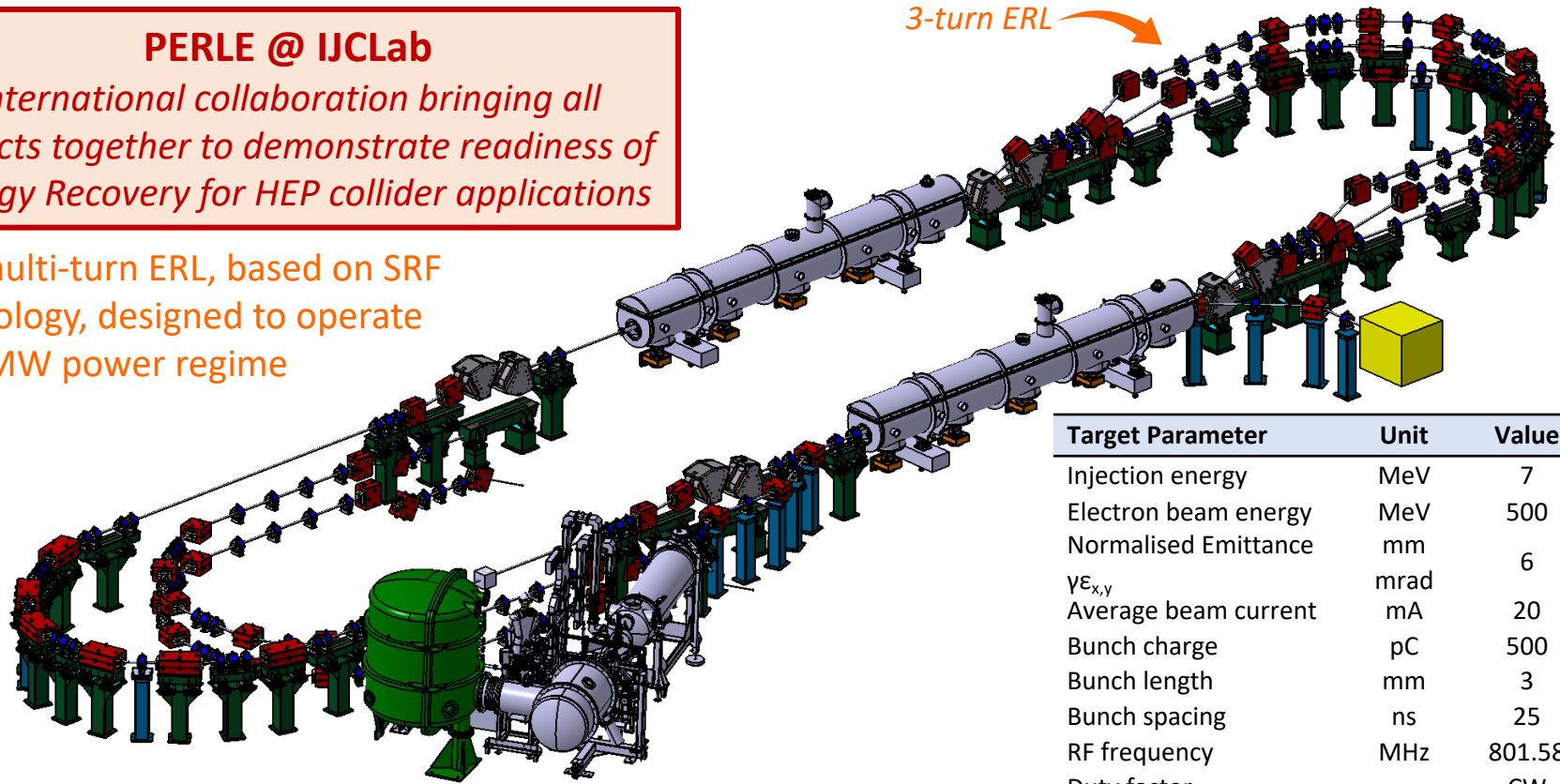
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

PERLE @ IJCLab

international collaboration bringing all aspects together to demonstrate readiness of Energy Recovery for HEP collider applications

first multi-turn ERL, based on SRF technology, designed to operate at 10MW power regime



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

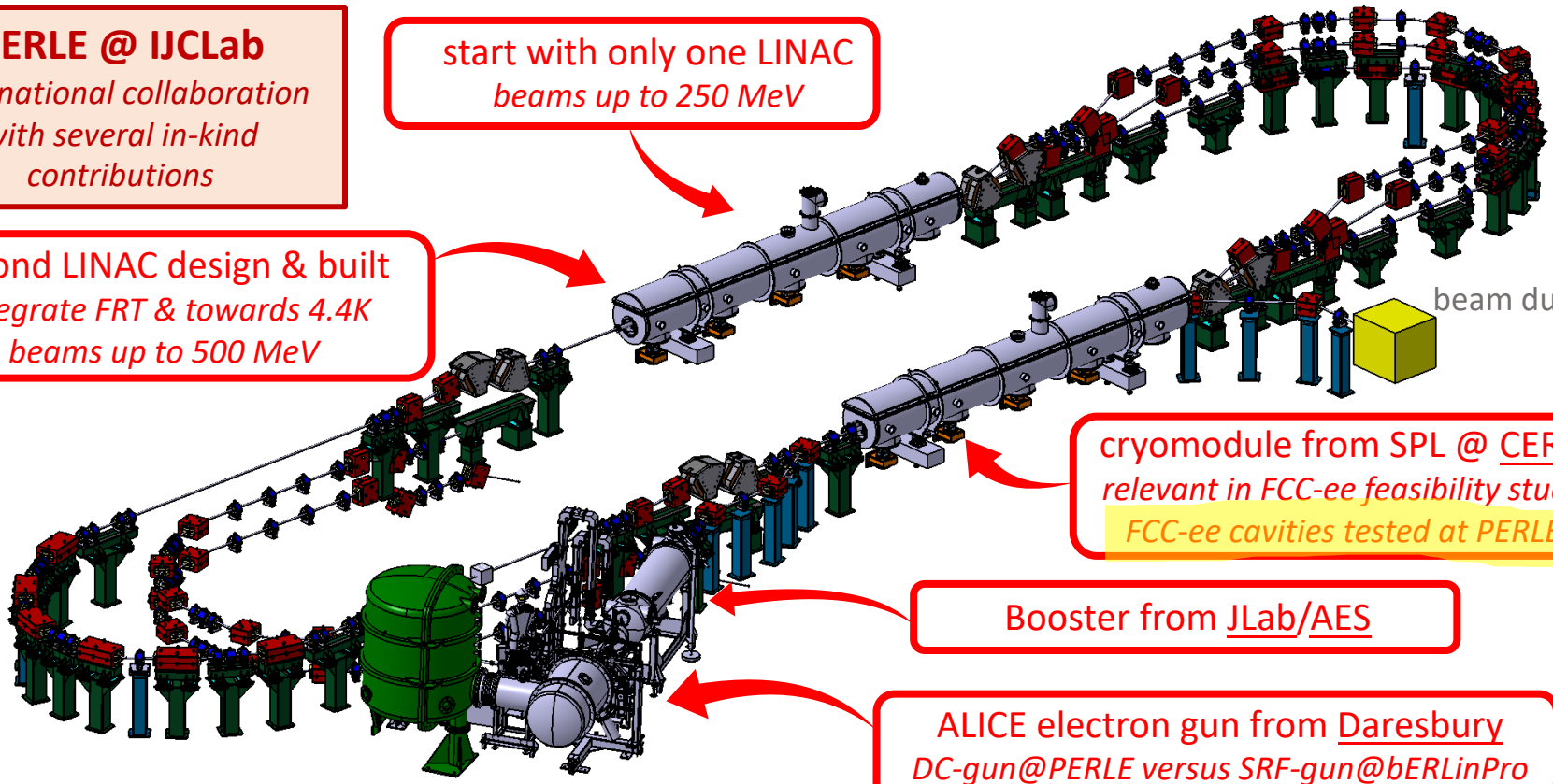
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

PERLE @ IJCLab
international collaboration with several in-kind contributions

start with only one LINAC
beams up to 250 MeV

second LINAC design & built
integrate FRT & towards 4.4K
beams up to 500 MeV



cryomodule from SPL @ CERN
relevant in FCC-ee feasibility study
FCC-ee cavities tested at PERLE

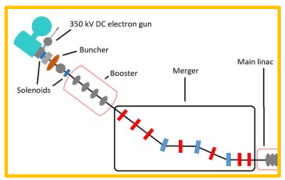
Booster from JLab/AES

ALICE electron gun from Daresbury
DC-gun@PERLE versus SRF-gun@bERLinPro

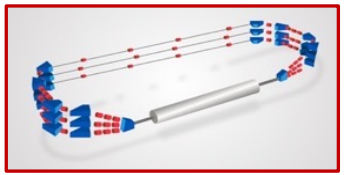
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

2025
End Phase 0: Injection line



2030
End Phase 2: PERLE @ 500MeV



2023
PERLE TDR

2028
End Phase 1: PERLE @ 250MeV

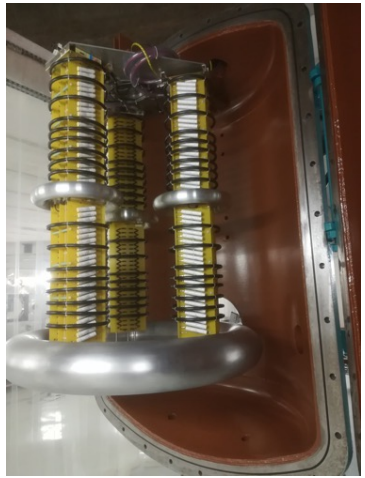
The “igloo”: equipped experimental hall to host the DC gun

progress with PERLE

Connecting cathode tank (Nov 22)

Checking HV vessel tightness (Sept 22)

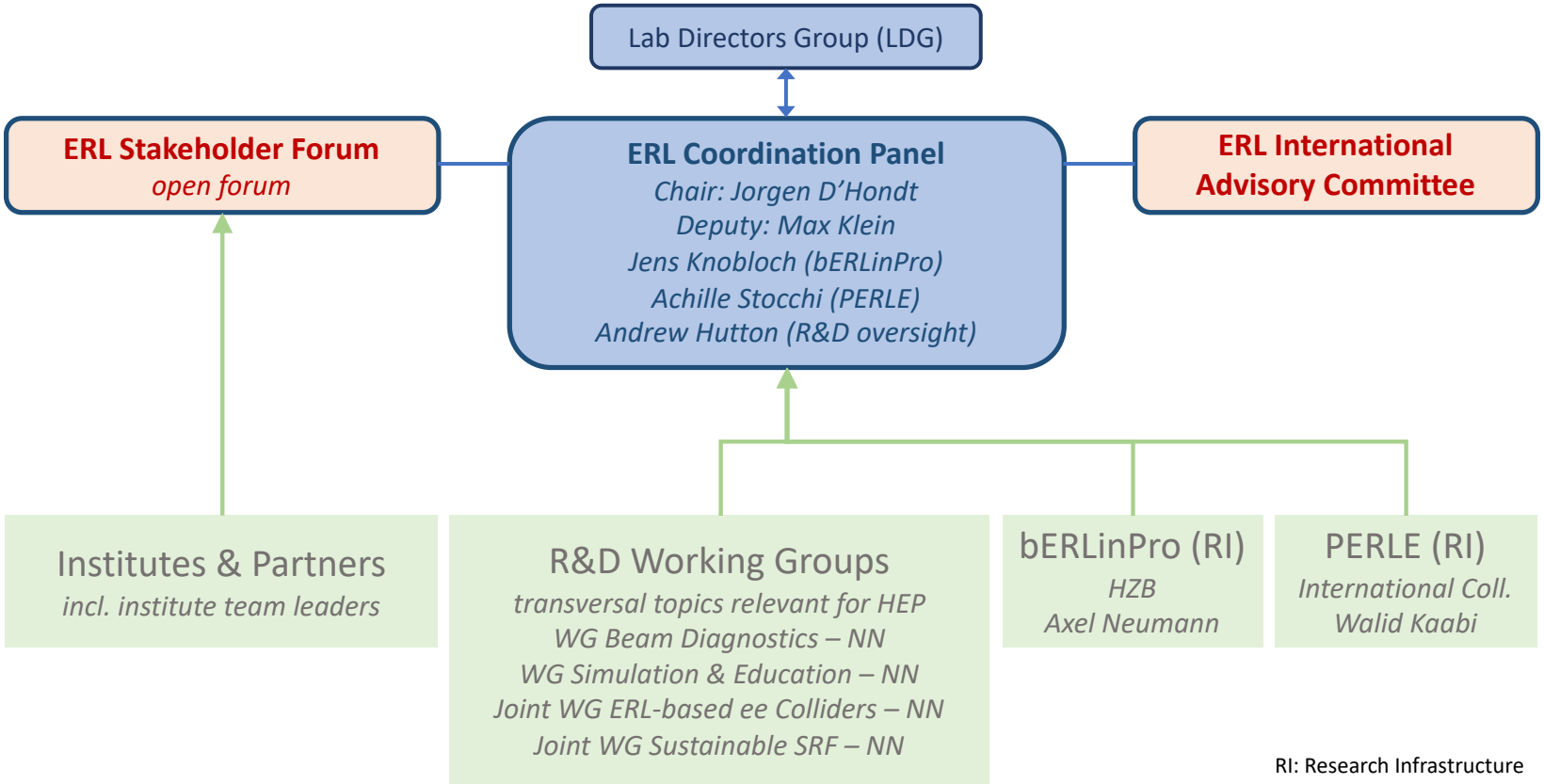
HV vessel installation (June 22)



HV power supply assembly (July 22)

Organising the European R&D for Energy Recovery in HEP

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



RI: Research Infrastructure

Organising the European R&D for Energy Recovery in HEP

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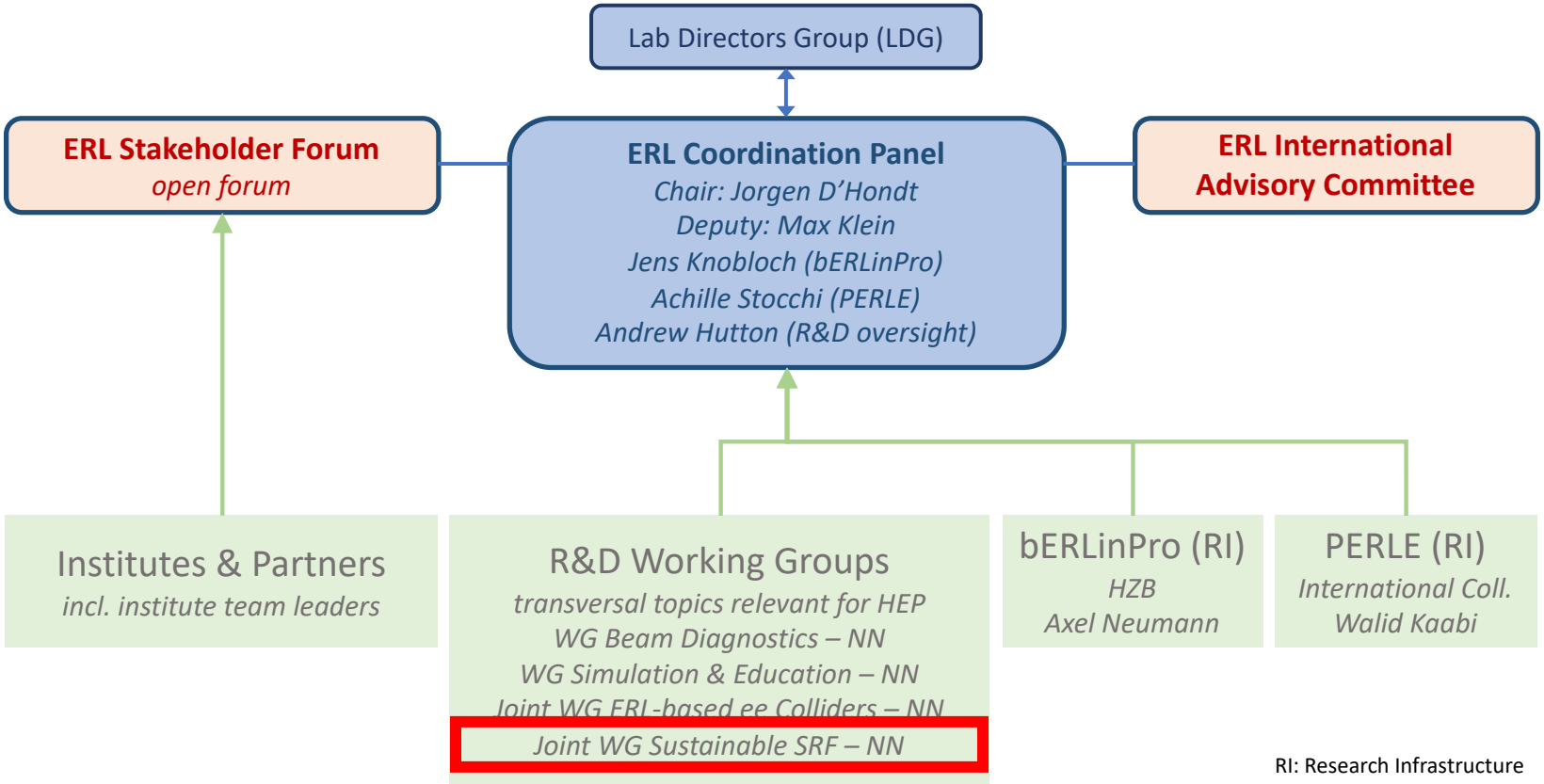

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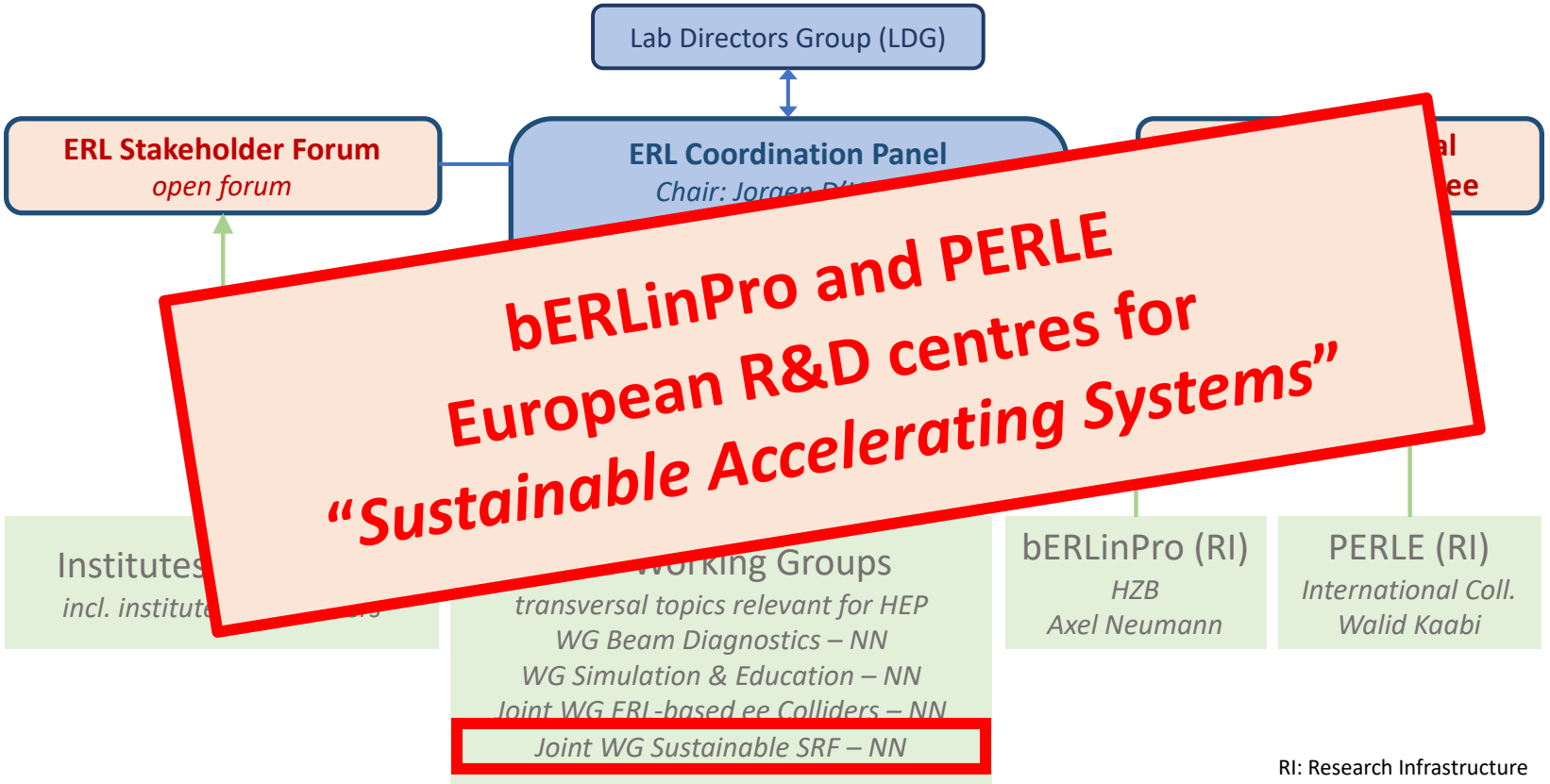

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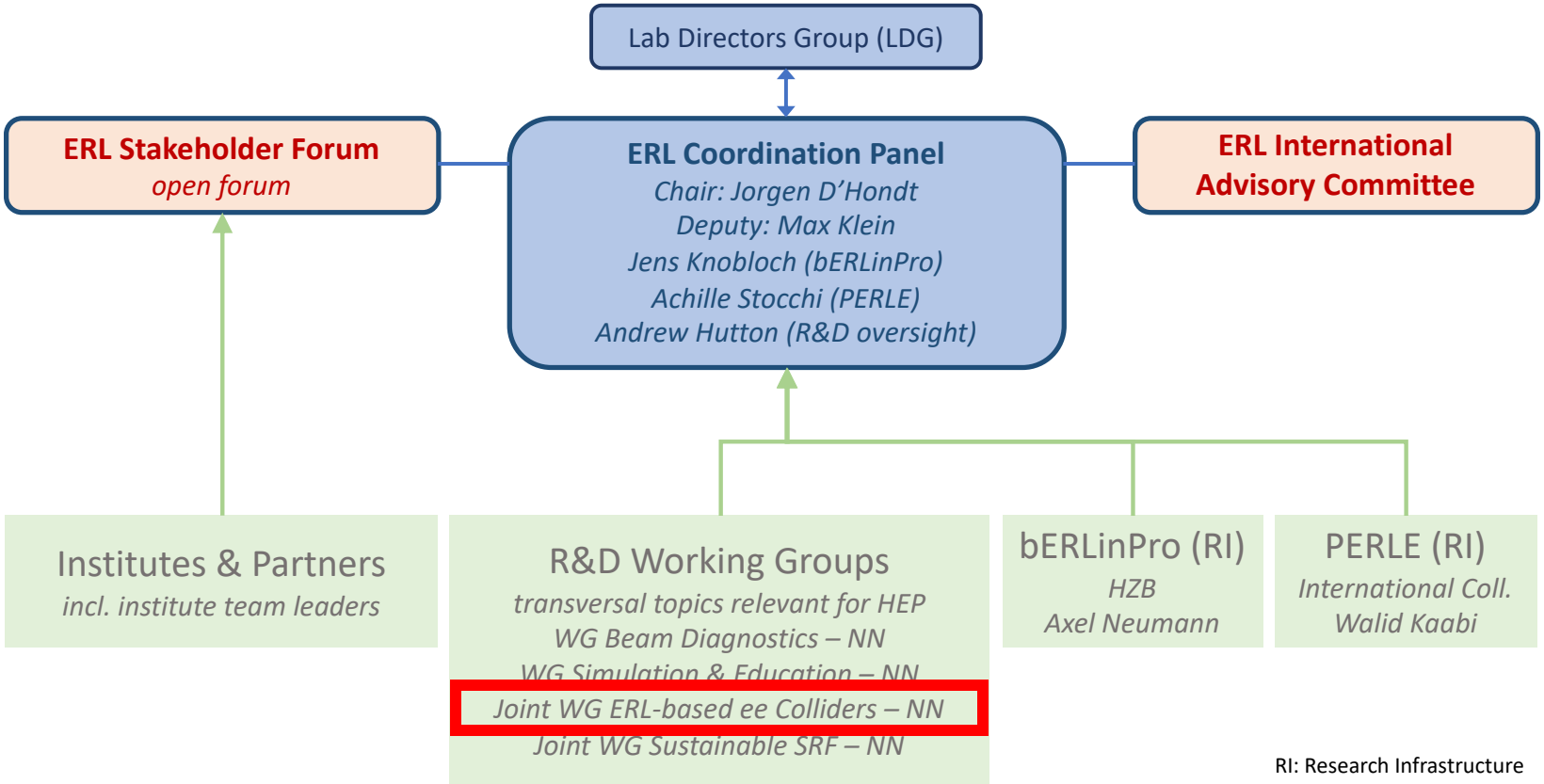


RI: Research Infrastructure

Energy Recovery applications for HEP

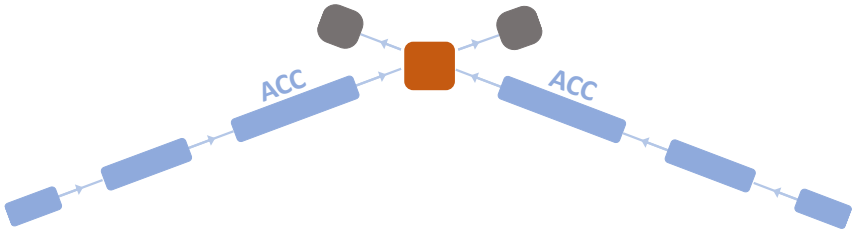
EW⊕Higgs⊕top Factories

e^+e^- colliders

the highest priority next collider in the ESPP-update@2020

Energy Recovery applications for HEP

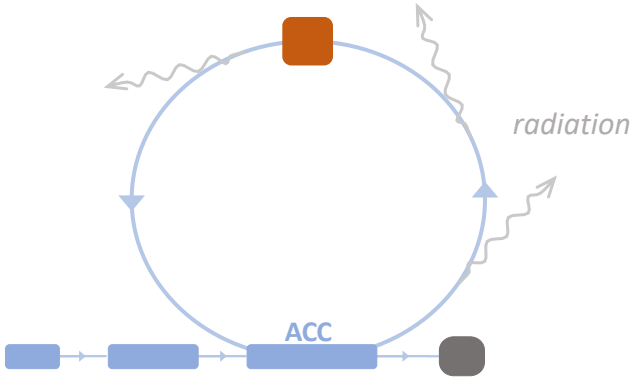
Linear colliders



CLIC and ILC

ERL-based versions: ERLC and ReLiC

Circular colliders



CEPC and FCC-ee

ERL-based version: CERC

$\mathcal{O}$(~10 BCHF)

10-15y of operation

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

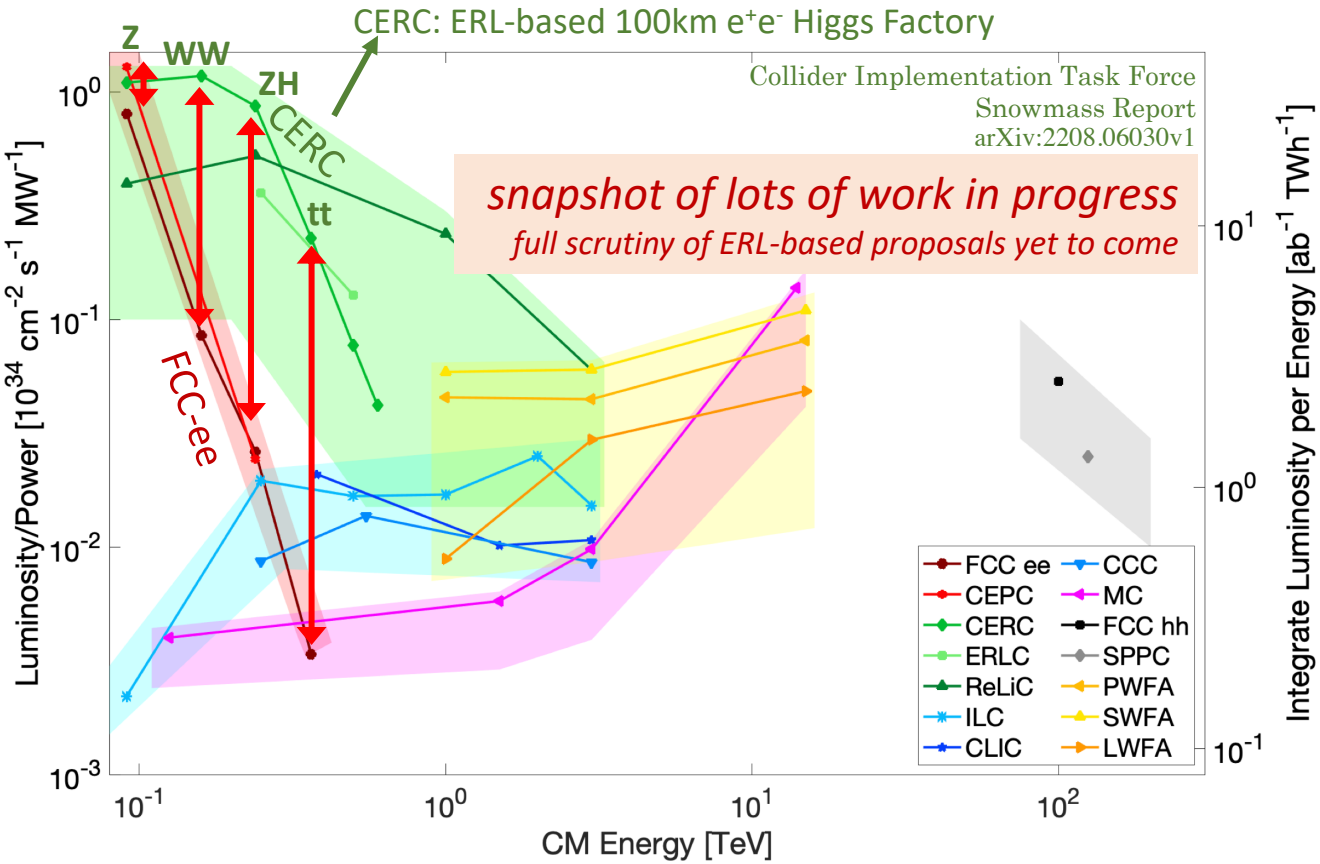
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories



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

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

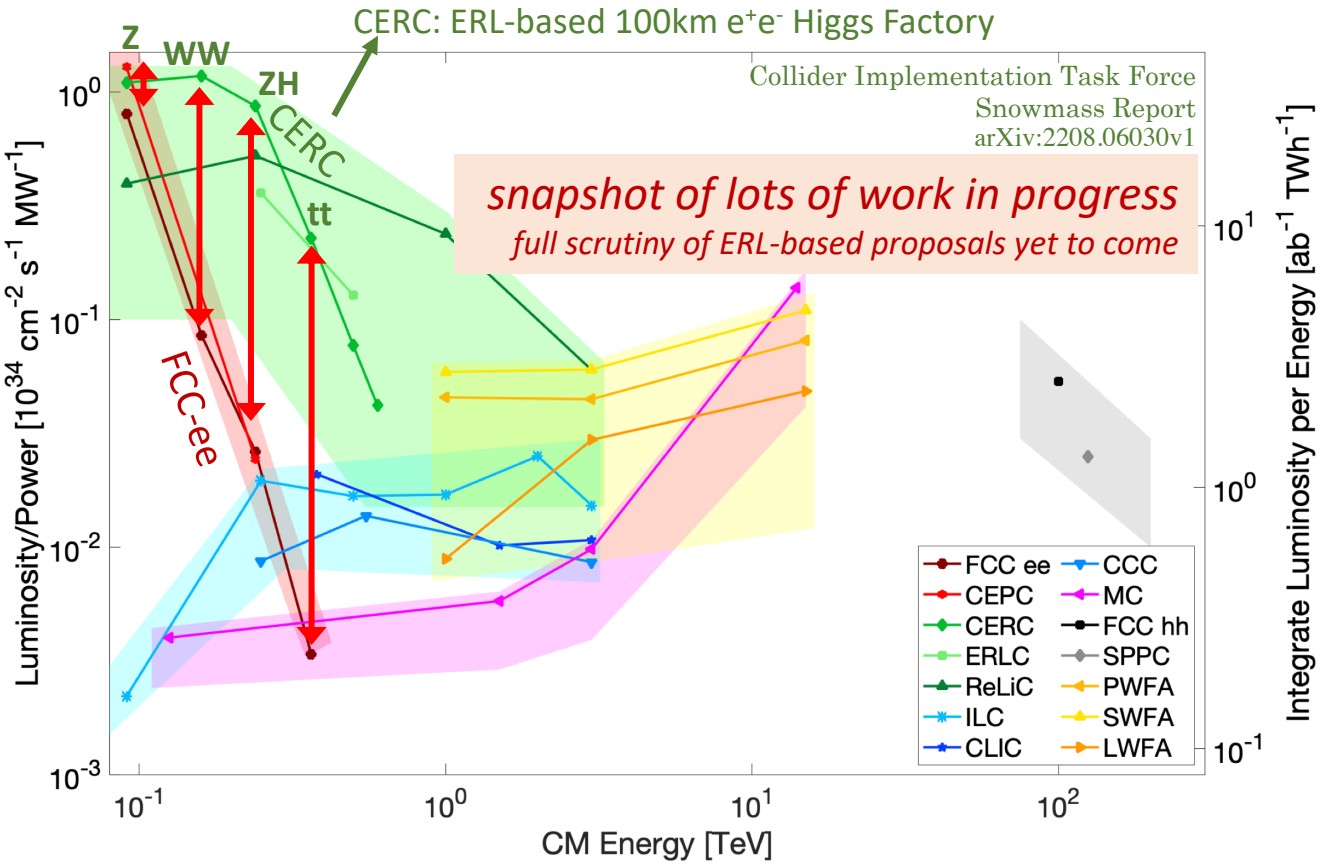
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs
next slide: what would be the concrete impact

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories



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Energy Recovery applications for HEP

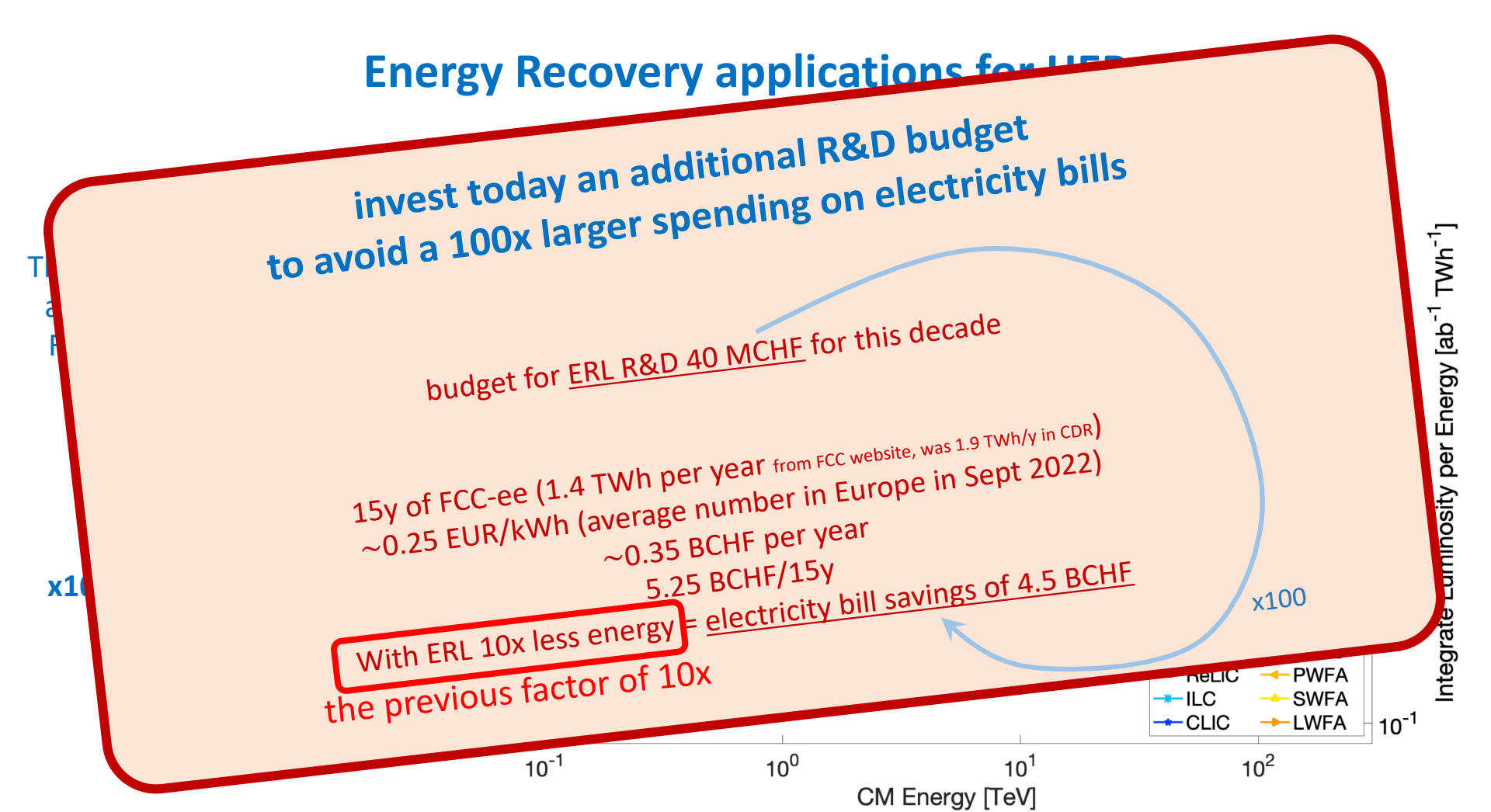
invest today an additional R&D budget
to avoid a 100x larger spending on electricity bills

budget for ERL R&D 40 MCHF for this decade

15y of FCC-ee (1.4 TWh per year from FCC website, was 1.9 TWh/y in CDR)
~0.25 EUR/kWh (average number in Europe in Sept 2022)
~0.35 BCHF per year
5.25 BCHF/15y
= electricity bill savings of 4.5 BCHF

With ERL 10x less energy
the previous factor of 10x

x100



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5.25 BCHF/15y
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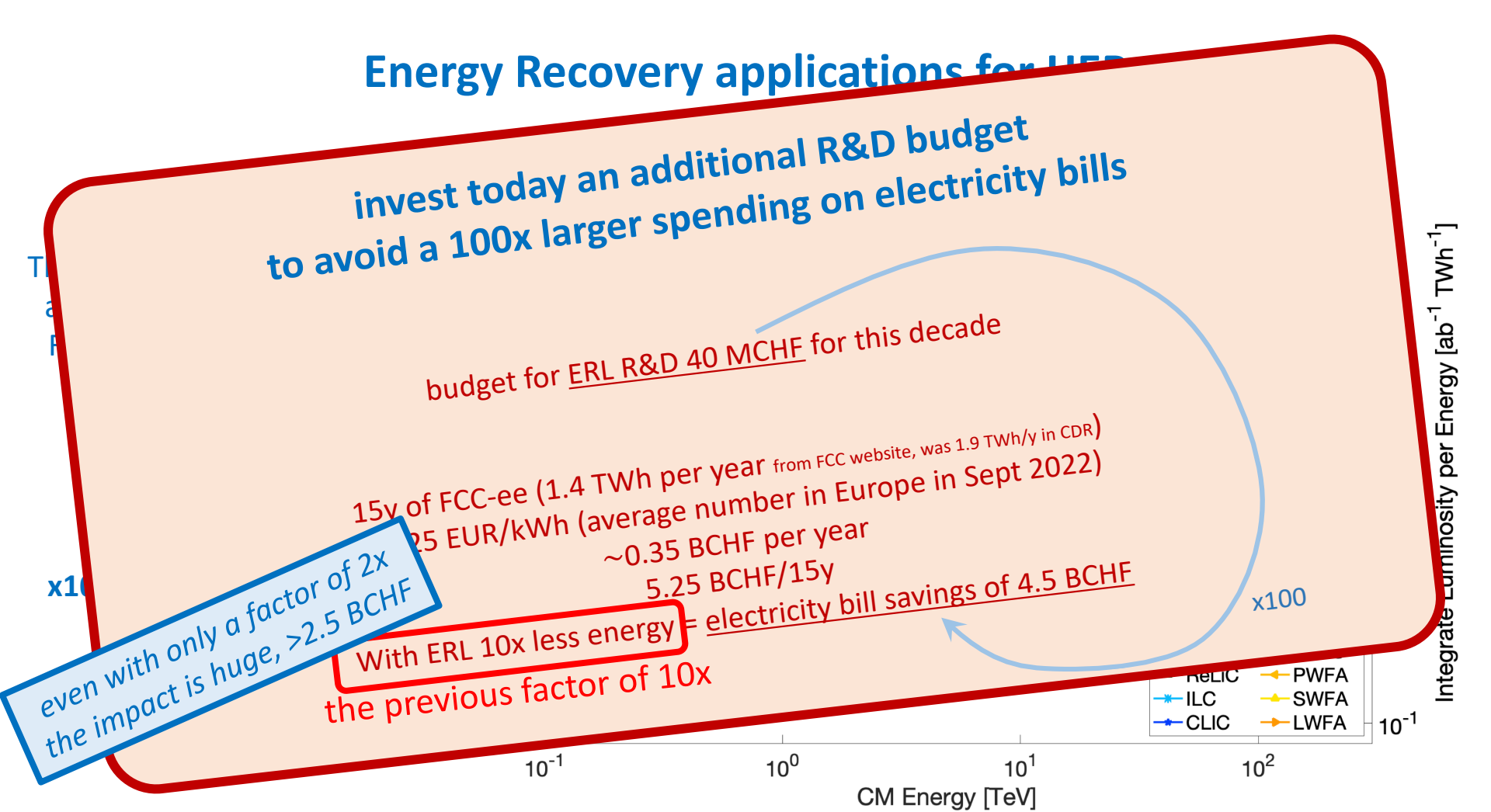
x100

With ERL 10x less energy
the previous factor of 10x

even with only a factor of 2x
the impact is huge, >2.5 BCHF



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Energy Recovery applications for

invest today an additional R&D budget
to avoid a 100x larger spending on electricity bills

Will society allow us in the 2040'ies to use that much energy for fundamental science?

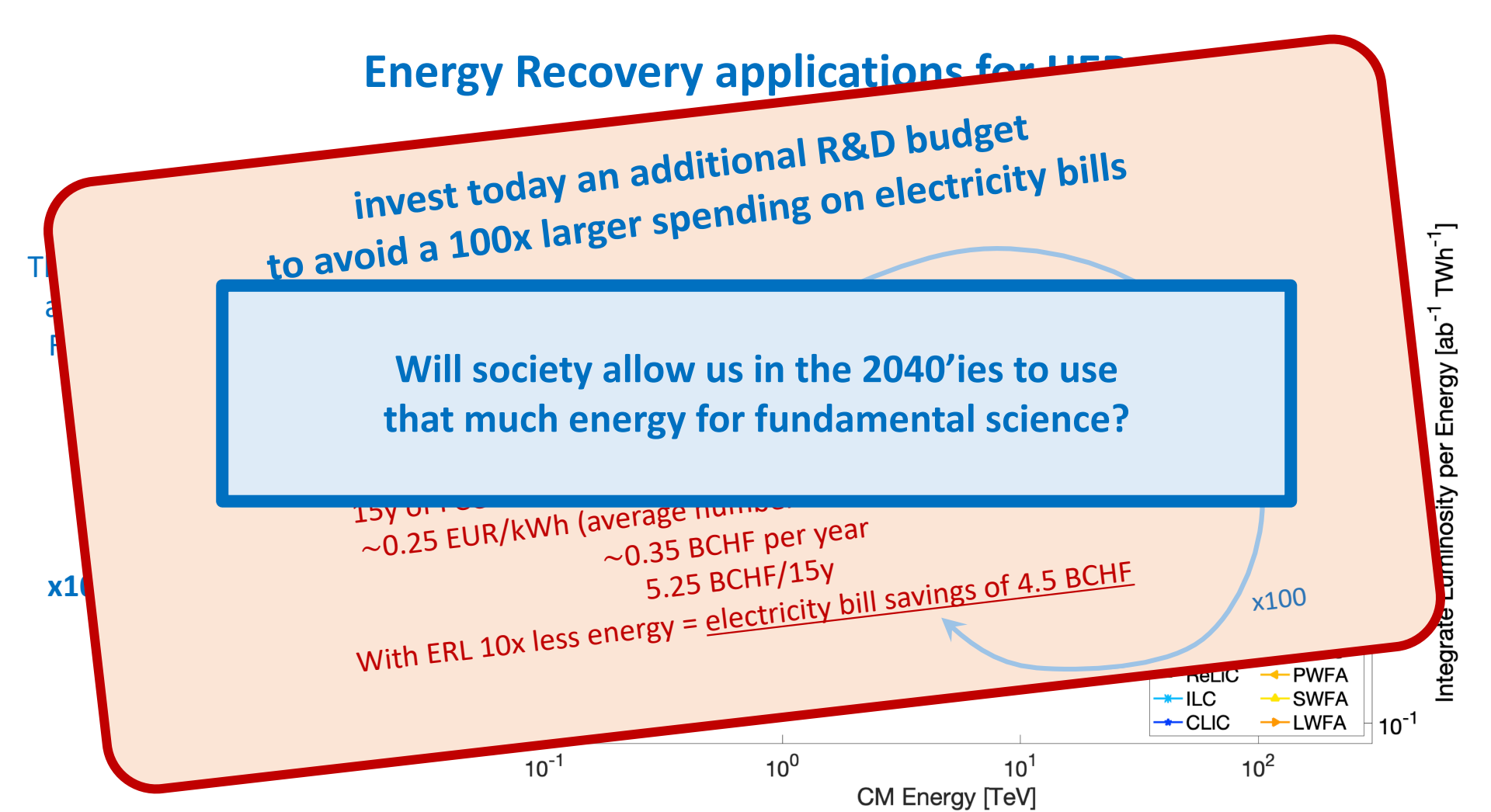
~0.25 EUR/kWh (average

~0.35 BCHF per year

5.25 BCHF/15y

With ERL 10x less energy = electricity bill savings of 4.5 BCHF

x100



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Energy Recovery applications for HEP

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

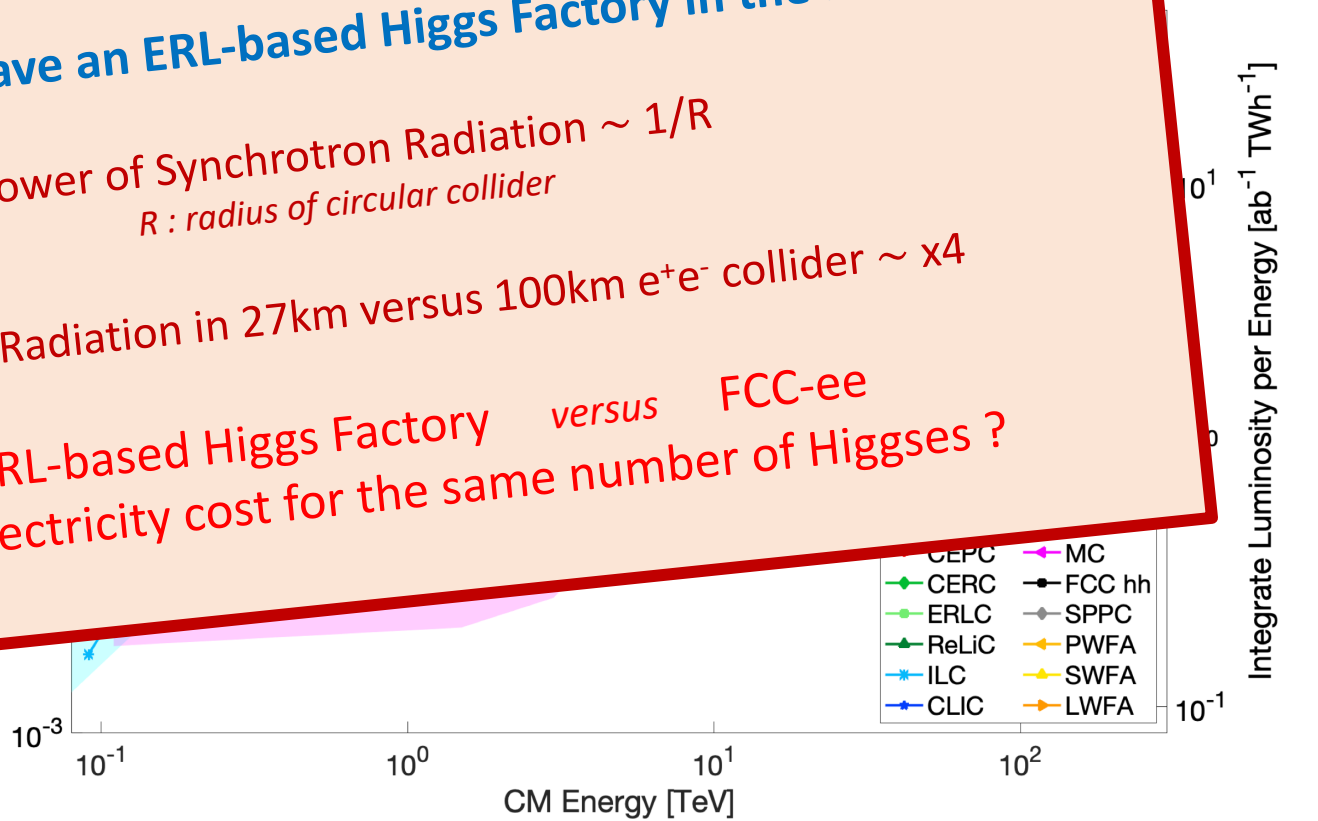
Synchrotron Radiation in 27km versus 100km e^+e^- collider ~ x4

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

the same electricity cost for the same number of Higgses ?

This
an
Fac

x10 I



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ERL-based Higgs Factory *versus* FCC-ee

Several aspects are to be verified in these initial thoughts,
but it demonstrates the potential impact of ERL,
and motivates R&D support for ERL and
sustainable accelerating systems to further explore

Addressing with ERL the European Strategy for Particle Physics 2020

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

The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

A detailed plan for the […] saving and re-use of energy should be part of the approval process for any major project.

European Strategy for Particle Physics 2020

Addressing with ERL the European Strategy for Particle Physics 2020

An electron-positron Higgs factory
is the highest-priority n

bERLinPro and PERLE essential to develop technology for a power-efficient Higgs Factory at CERN

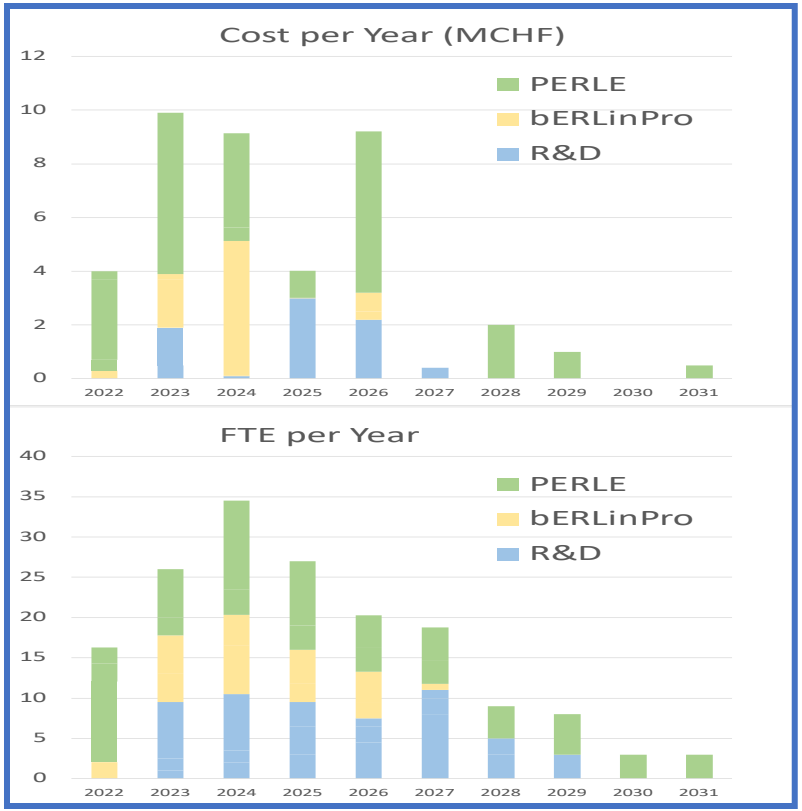
…aving and re-use of
…d be part of the approval process
for any major project.

European Strategy for Particle Physics 2020

Required resources for the R&D program for Energy Recovery

demonstrate a ready-to-go-path for high-energy colliders

	R&D Working Groups							bERLinPro		PERLE		
	Beam Diagnostics	Simulations & Education	Sustainable SRF	*(HOM Damping part)*	ERL-based ee Colliders	Electron Source	ERL-based ep-collider	Phase-1 100mA beam	Phase-2 Recirculation	Phase-1 250 MeV	Phase-2 500 MeV	
2022												
2023												
2024												
2025												
2026												
2027												
2028												
2029												
2030												
2031												
Cost (MCHF 2021)	1,4			2,7	3,5			2,4	5,9	14,6	9,6	**40,1**
FTEy	19			24,5	12,5			16	17	64	23	**176**



Towards the implemention the ERL R&D roadmap

- The R&D road ahead to demonstrate high-power ERL is very clear and well documented
- The ambition is shared with major accelerator laboratories in Europe, with a clear path to prioritise the ERL R&D programme in their organisation structure
- Both bERLinPro and PERLE strongly welcome collaborators to prepare this future together
- Experts in Europe and beyond are engaged to make it happen during this decade
- Developing “Sustainable Accelerating Systems” is a vital topic for the future of particle physics colliders at CERN and a challenging responsibility we share as a community
- It is essential to demonstrate the performance of these innovative systems during this decade in order to integrate them timely in the designs of future Higgs Factories, or other colliders

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- The time has come to promote these technological efforts as a community, a very clear statement that our community is committed to strong R&D contributions to realize a broad R&D programme for Sustainable Accelerating Systems (incl. ERL) is welcome
- Because we are reaching the critical path to realise this ambition, it is essential to resource load this ERL R&D plan today with first-stage commitments above the "we-gear-up-for-success" threshold as stepping stones and in order to have a catalyser for additional resources

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VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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Thank you for your attention!

Jorgen.DHondt@vub.be

Additional slides

Expression of Interest to join this R&D program for Energy Recovery

with a view to demonstrate its applicability in high-energy particle physics colliders

Institute	R&D Working Groups							
	Beam Diagnostics	Simulations & Education	Sustainable SRF	ERL-based ee Colliders	Electron Source	ERL-based ep-collider	bERLinPro	PERLE
Univ. NN (names individuals)	x					x	x	x

ERL R&D is at the crossroad between different disciplines.

The successful and timely realisation of the ERL R&D plan for particle physics depends on the interest and involvement of leading experts and their institutions.

In addition, and as a prerequisite, it requires the particle physics funding bodies to timely resource load the plan in order to cover the material costs and activate the concrete implementation plan.

Contact: Jorgen D'Hondt (chair, Jorgen.DHondt@vub.be) and Max Klein (deputy, mklein@hep.ph.liv.ac.uk)

European Accelerator R&D Roadmap – the process

- **In January 2021, a team of experts was assembled to develop a Roadmap for ERLs**
- **The Panel had members from every laboratory that has, or has had, an ERL bringing a wealth of experience to the Panel**

Deepa Angal-Kalinin (STFC)
Kurt Aulenbacher (Uni Mainz)
Alex Bogacz (Jefferson Lab)
Georg Hoffstaetter (Cornell)
Andrew Hutton (Jefferson Lab) – Co-Chair
Erk Jensen (CERN)
Walid Kaabi (IJCLab)
Dmitry Kayran (BNL)
Max Klein (Liverpool) – Chair
Jens Knobloch (Helmholtz-Zentrum Berlin)
Bettina Kuske (Helmholtz-Zentrum Berlin)
Frank Marhauser (Jefferson Lab)
Norbert Pietralla (Darmstadt)
Olga Tanaka (KEK)
Cristina Vaccarezza (INFN, Frascati)
Nikolay Vinokurov (BINP)
Peter Williams (STFC)
Frank Zimmermann (CERN)

- **Delivered the ERL R&D Roadmap, including timelines and costs, which was endorsed by R&D experts and HEP funding bodies in December 2021.**

https://arxiv.org/pdf/2201.07895.pdf

- **The long report for ERL was completed in July 2022**
  - *49 authors*
  - *22 institutions*
  - *270 pages*
- **Accepted for publication in JINST**
- https://arxiv.org/abs/2201.07895

The Development of Energy-Recovery Linacs

Chris Adolphsen,[t] Kevin Andre,[d,i] Deepa Angal-Kalinin,[f] Michaela Arnold,[g] Kurt Aulenbacher,[j] Steve Benson,[o] Jan Bernauer,[m] Alex Bogacz,[o] Maarten Boonekamp,[l] Reinhard Brinkmann,[u] Max Bruker,[o] Oliver Brüning,[d] Camilla Curatolo,[p] Patxi Duthill,[k] Oliver Fischer,[i] Georg Hoffstaetter,[e,c] Bernhard Holzer,[d] Ben Hounsell,[k,i] Andrew Hutton,[o,1] Erk Jensen,[d] Walid Kaabi,[k] Dmitry Kayran,[c] Max Klein,[i] Jens Knobloch,[a,s] Geoff Krafft,[o] Julius Kühn,[a] Bettina Kuske,[a] Vladimir Litvinenko,[m] Frank Marhauser,[o] Boris Militsyn,[f] Sergei Nagaitsev,[v] George Neil,[o] Axel Neumann,[a] Norbert Pietralla,[g] Bob Rimmer,[o] Luca Serafini,[p] Oleg A. Shevchenko,[b] Nick Shipman,[d,q] Hubert Spiesberger,[j] Olga Tanaka,[n] Valery Telnov,[b,r] Chris Tennant,[o] Cristina Vaccarezza,[h] David Verney,[k] Nikolay Vinokurov,[b] Peter Williams,[f] Akira Yamamoto,[n] Kaoru Yokoya,[n] Frank Zimmermann[d]

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[b] *Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[c] *Brookhaven National Lab*
[d] *CERN*
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[f] *Daresbury (STFC)*
[g] *Technische Universität Darmstadt, Dept. of Physics, Institute for Nuclear Physics*
[h] *INFN Frascati*
[i] *University Liverpool*
[j] *University Mainz*
[k] *IJCLab Orsay*
[l] *CEA Saclay*
[m] *Center for Frontiers in Nuclear Science, Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY, USA*
[n] *KEK Tokyo*
[o] *Thomas Jefferson National Accelerator Facility*
[p] *INFN Milano and LASA*
[q] *Lancaster University*
[r] *Novosibirsk State University, 630090, Novosibirsk, Russia*
[s] *University of Siegen*
[t] *SLAC*
[u] *DESY*
[v] *Fermilab*

Organising the European R&D for Energy Recovery in HEP

① connecting the ERL R&D community with the HEP steering and funding bodies
② synergies with ongoing ERL R&D towards implementations in HEP applications
③ strengthen collaboration across the field to reach the HEP-related R&D objectives

Coordination: *Jorgen D'Hondt (chair), Max Klein (deputy)*
bERLinPro: *Jens Knobloch (HZB)*
PERLE: *Achille Stocchi (IJCLab)*

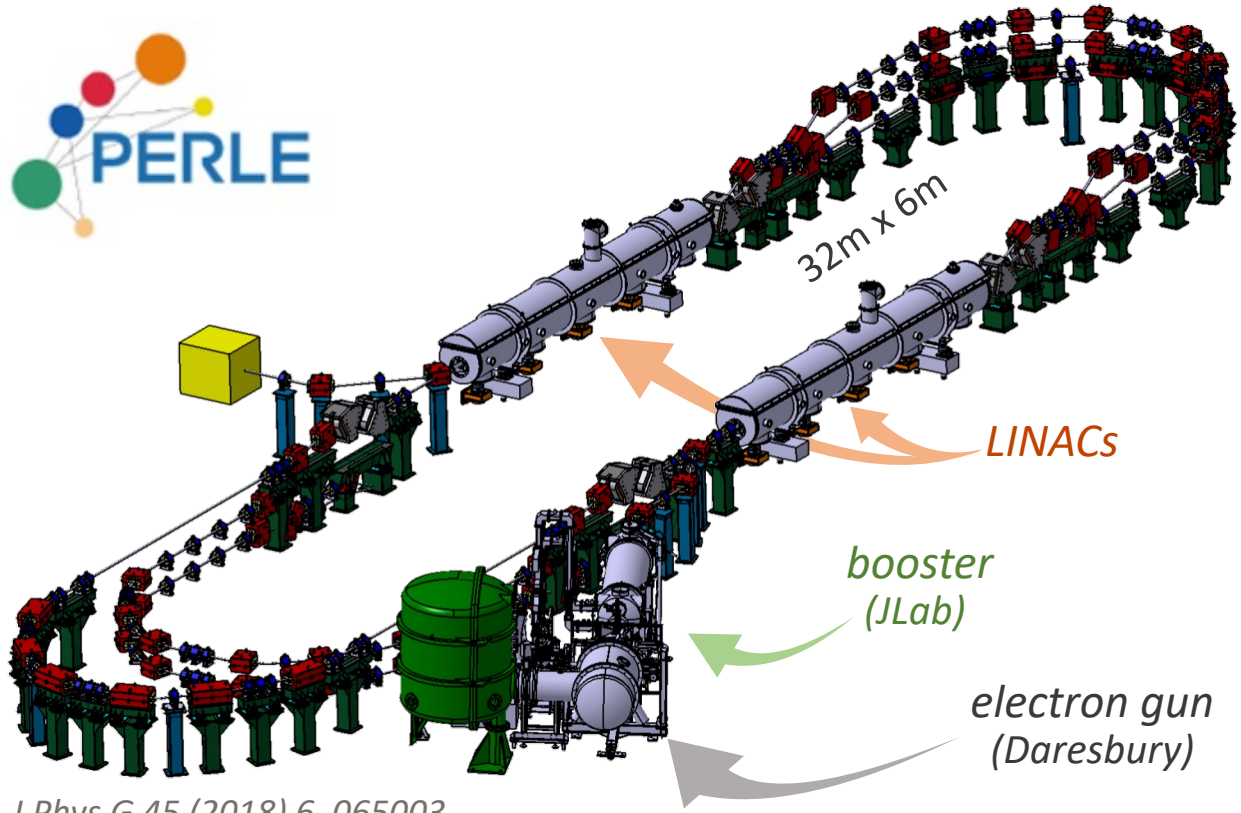
R&D oversight: *Andrew Hutton (JLab)*
Working Groups

1. Beam Diagnostics & Instrumentation
2. Simulations (incl. education)
3. Designs of e^+e^- colliders with Energy Recovery (incl. Dual Axis R&D) – joint with RF Coordination Panel
4. Sustainable SRF (incl. HOM damping, FRT, >4K operation) – joint with RF Coordination Panel

Joint WG as a stepping stone for generic R&D towards potential integration in the PERLE and bERLinPro programmes

Additional

- Electron Source — *work integrated in the bERLinPro & PERLE programmes*
- Design of ep collider — *ongoing in the realm of the LHeC and FCC-eh programmes*



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