With Energy Recovery Linacs towards high-energy ep/eA physics

accelerator R&D for “Sustainable Accelerating Systems”

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iihe BRUXELLES BRUSSEL

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

beh

Epiphany Conference, Cracow, 16-19 January 2023

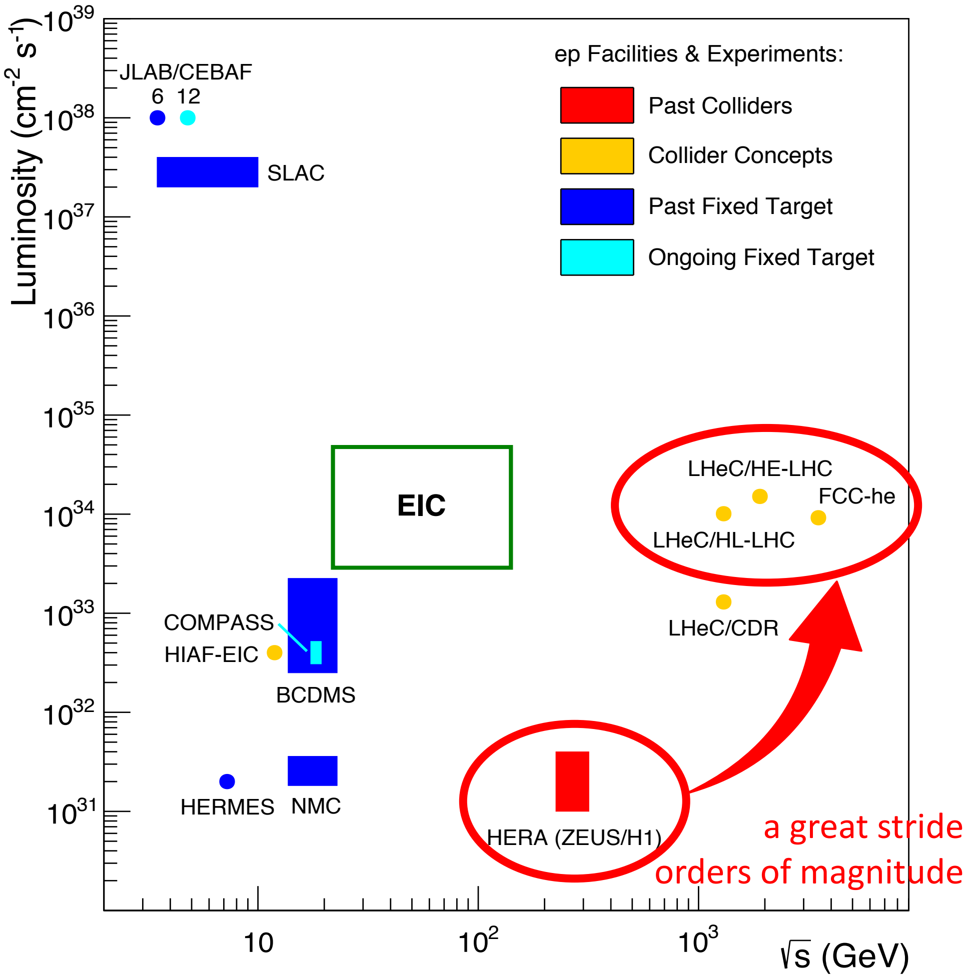
The scope

For ep/eA physics, the 2030'ies will be the decade of the EIC

The next ambition for the community will be to enable ep/eA physics both at higher luminosities and at higher energies

In my opinion, major advances in science are enabled either by reaching major steps with today's methods or by the development of major new methods

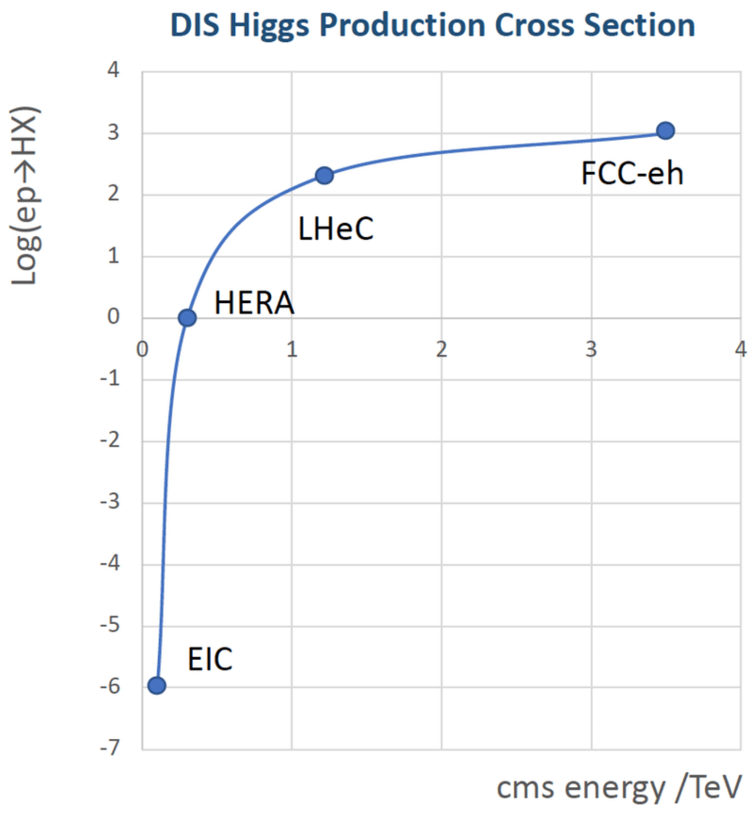
If we cannot make great strides into the unknown with current methods, we should concentrate on developing new methods



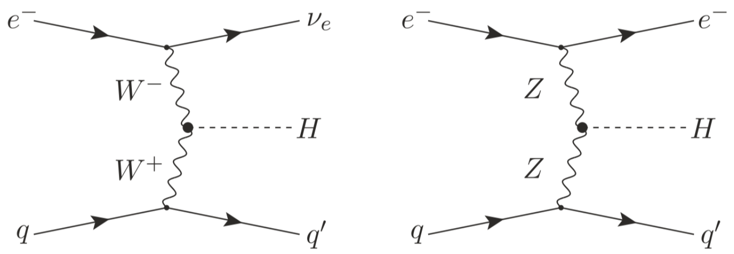
at high energies
electron-proton colliders provide
a General-Purpose experiment

Collision energy above the threshold for EW/Higgs/Top

from mostly QCD-oriented physics to General-Purpose physics



The real game change between HERA and LHC/FCC



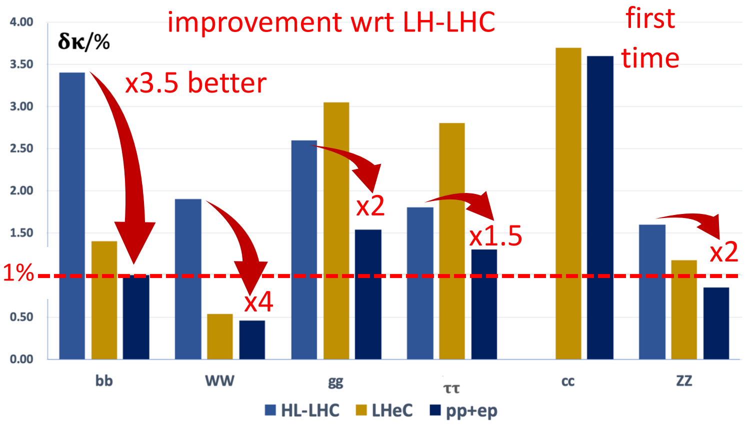
Compared to the LHC, these are reasonably clean Higgs events with much less backgrounds

at these energies, interactions with all particles in the Standard Model can be measured precisely

Some physics highlights of the LHeC (ep/eA@LHC)

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

Higgs physics



EW physics

- Δm_W down to 2 MeV (today at ~10 MeV)
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP)

Top quark physics

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

DIS scattering cross sections

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

Strong interaction physics

- α_s precision of 0.1%
- 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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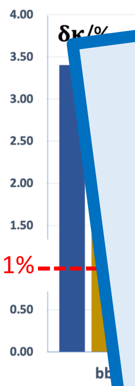
on several fronts comparable improvements between LHC → HL-LHC as for HL-LH

Higgs physics

improve



for EW/Higgs/top physics improvement factor from LHC → HL-LHC similar to HL-LHC → LHeC

eV)

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- top quark FCNC and γ, W, Z couplings

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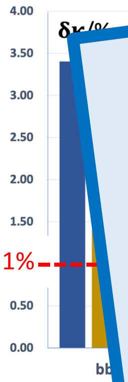

improve…

…eV)

…5%)

for EW/Higgs/top physics
improvement factor from
LHC → HL-LHC similar to HL-LHC → LHeC

A joint ep/pp interaction region with the same detector would correlate results and reach the ultimate precision

e.g. $\Delta m_W \sim 1$ MeV might be within reach

Eur.Phys.J.C 82 (2022) 1, 40

DIS sca…

- PD…
  ord…

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Higgs physics

EW physics

y at ~10 MeV)
e as LEP)

In addition, unique potential with LHeC to search for new physics phenomena

e.g. what if features appear in the interactions between leptons and quarks

% (today ~5%)
and γ, W, Z couplings

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e as LEP)

% (today ~5%)

ark FCNC and γ, W, Z couplings

A high-energy electron-proton experiment is a general-purpose experiment

i.e. H/EW/top/QCD/search factory

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on several fronts comparable improvements between LHC → HL-LHC

Higgs physics

4.00

1.5

1%

0.50

0.00

New mandate from the CERN Directorate:

Following the publication of the updated LHeC CDR, CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics. The study is to further develop the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with emphasis on FCC.

DIS

- ... extended in (Q^2,x) by orders of magnitude

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More in the upcoming talk of Nestor Armesto

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The challenge

High-intensity electron beam

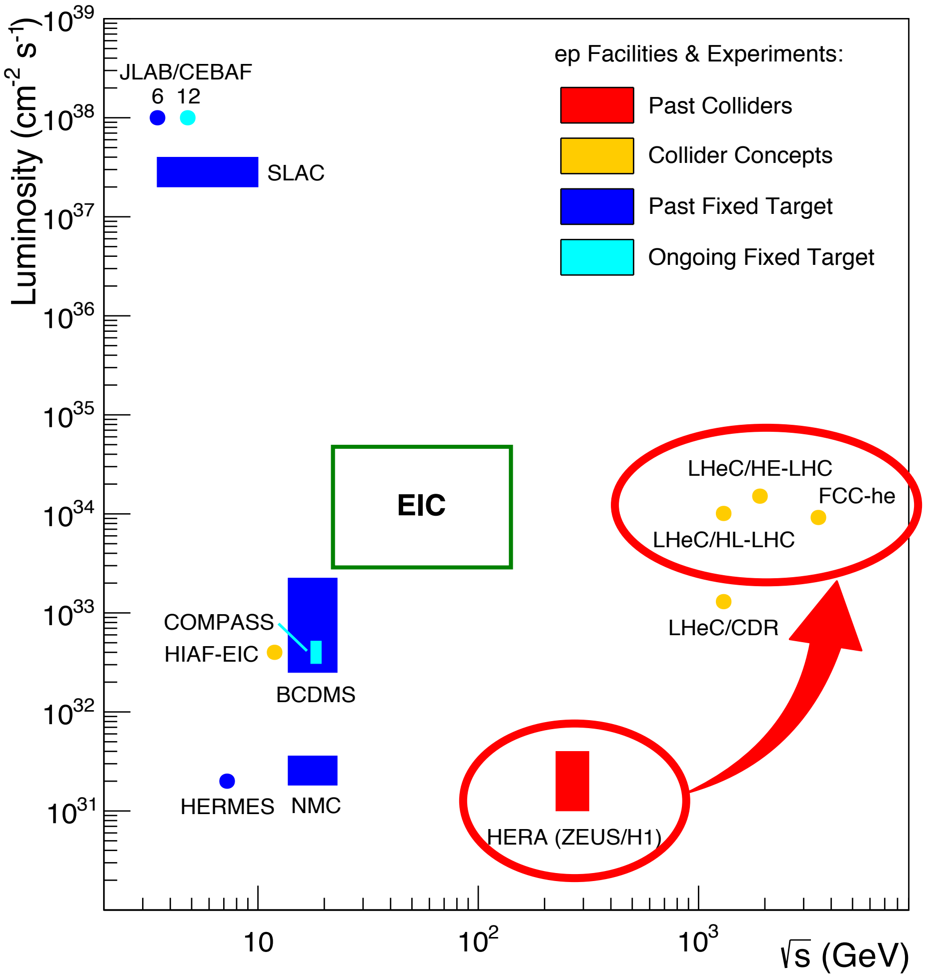
From HERA@DESY to LHeC@CERN

3 orders in magnitude in luminosity
1 order in magnitude in energy

beam current × beam energy
= beam power

LHeC ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant



The challenge

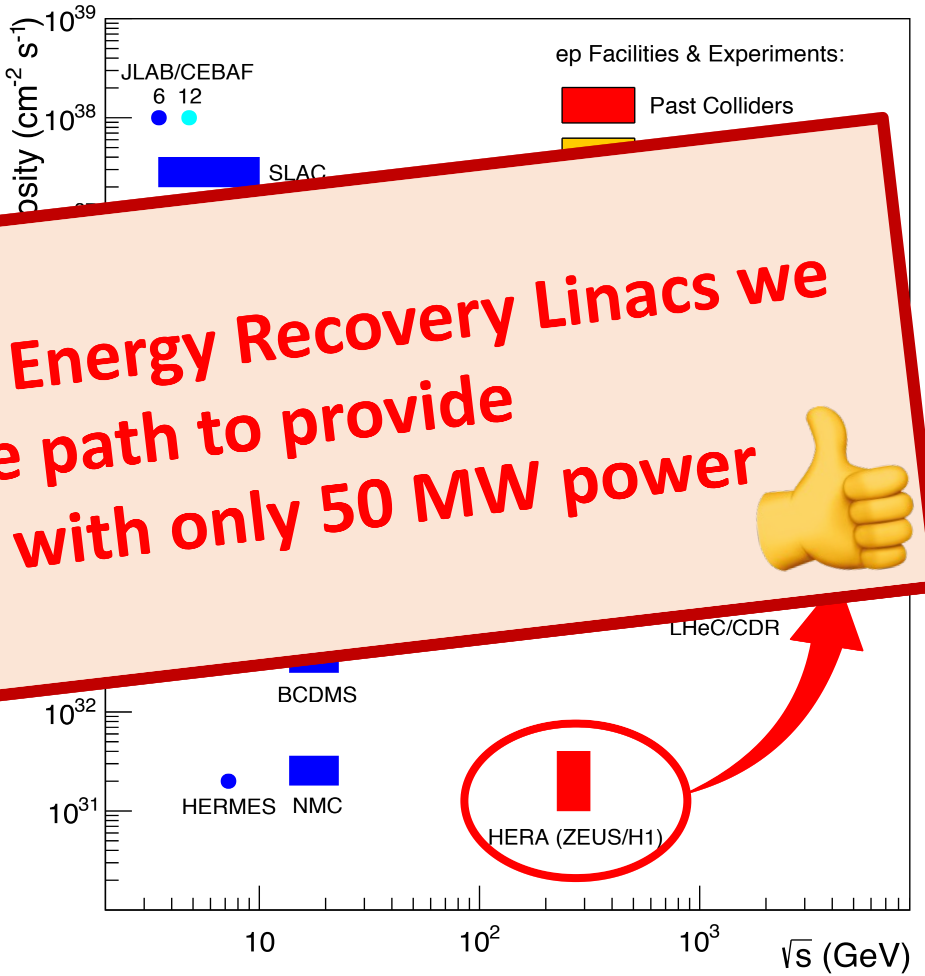
High-intensity electron beam

From HERA@DESY to LHeC@

1 GW beam power

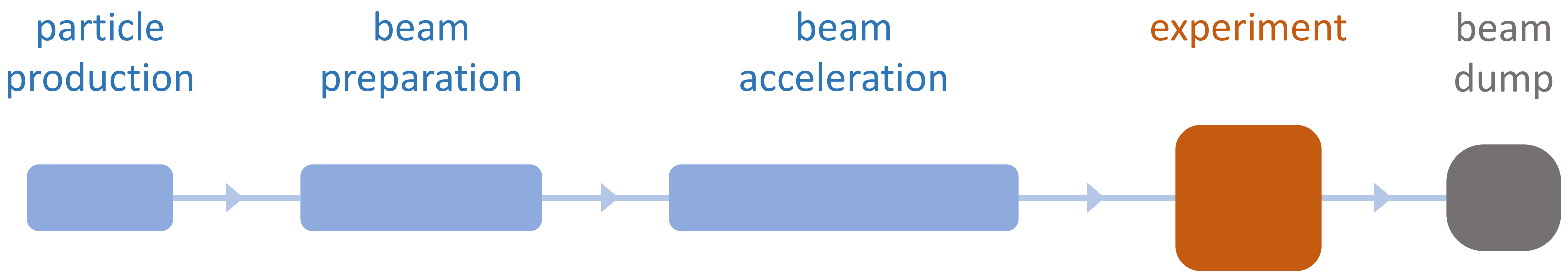
equivalent to the power delivered by a nuclear power plant

With the planned R&D on Energy Recovery Linacs we will prepare the path to provide a 1 GW electron beam with only 50 MW power



Where do we use power ?

Basic structures of a particle accelerator



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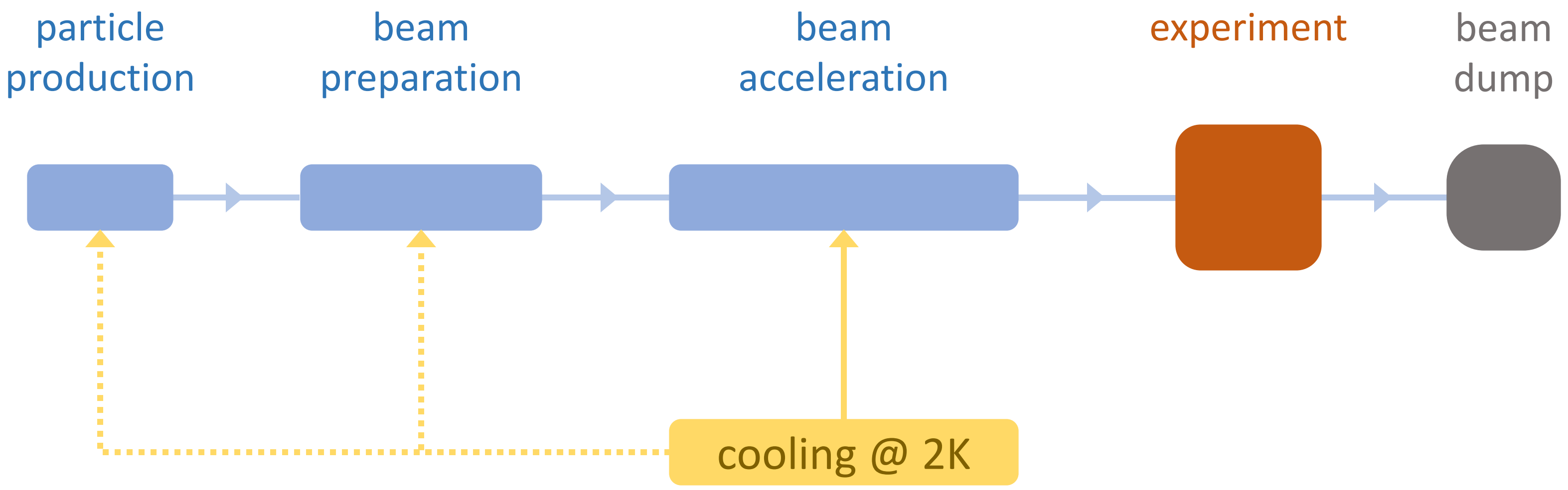

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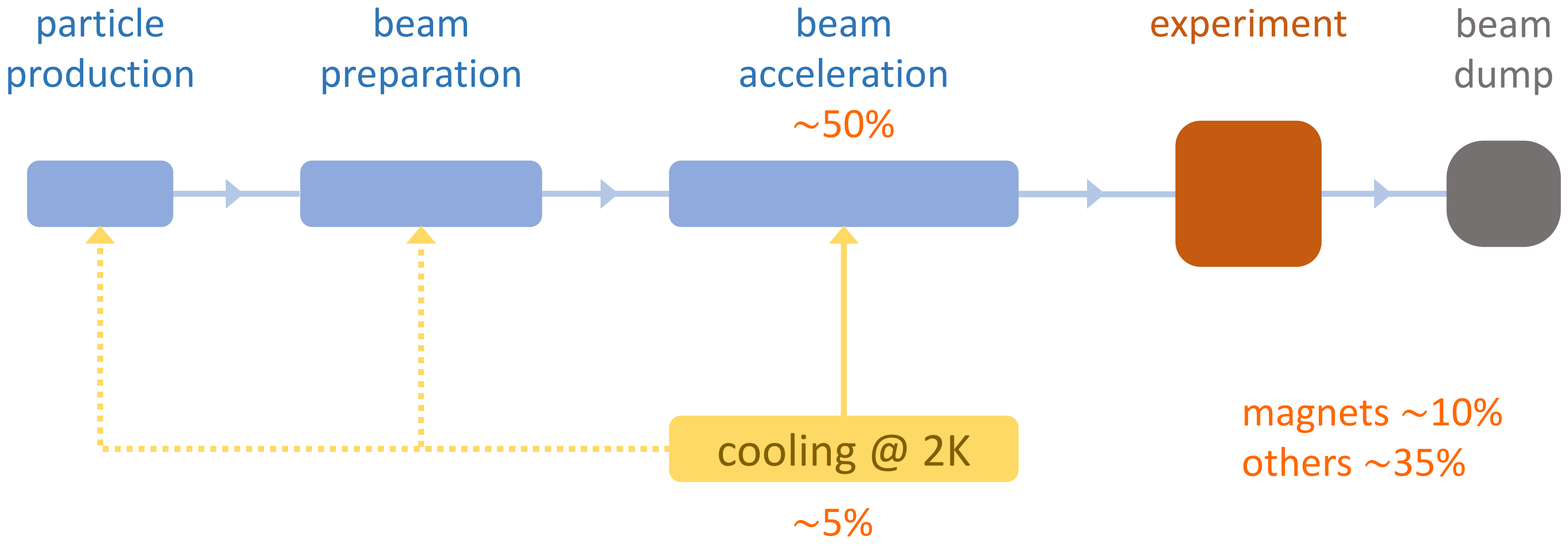
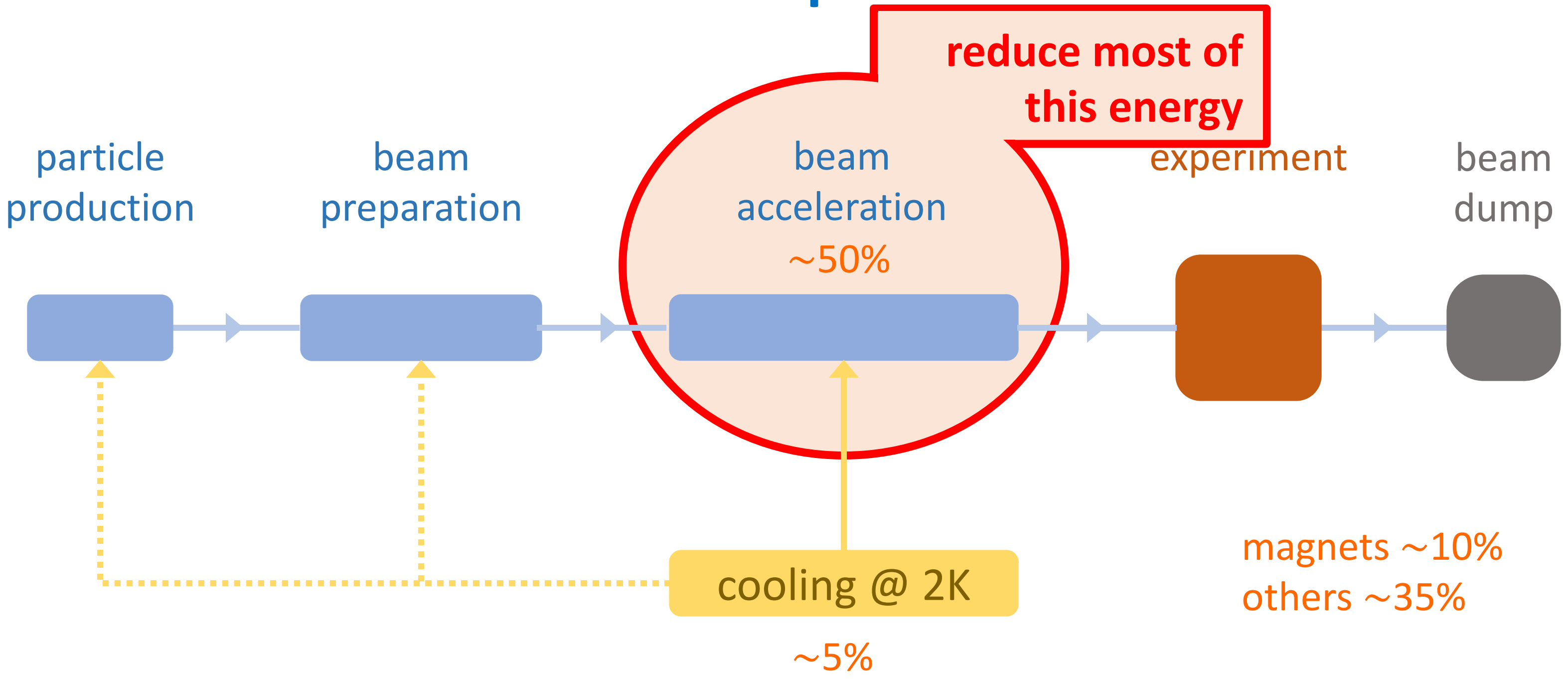


Typical power consumption for an electron-positron Higgs Factory

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

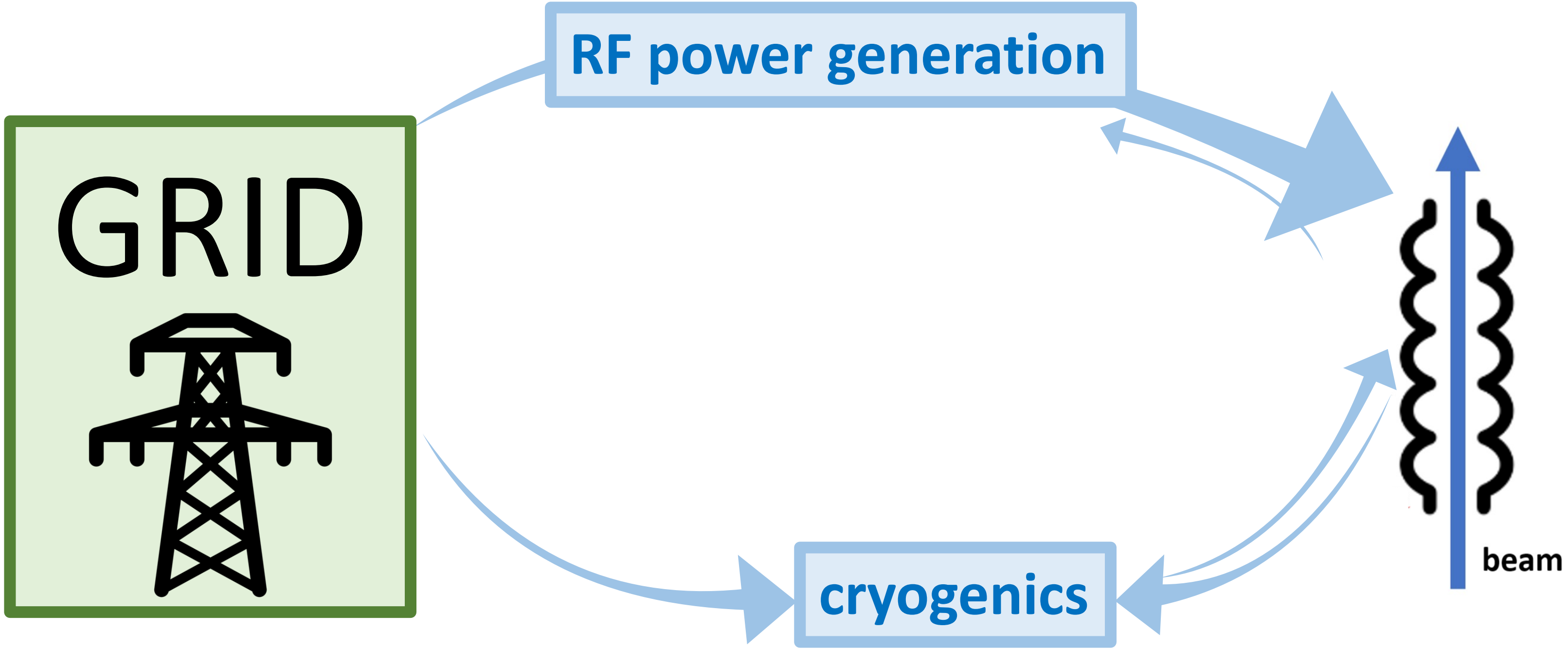
example FCC@250GeV

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

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

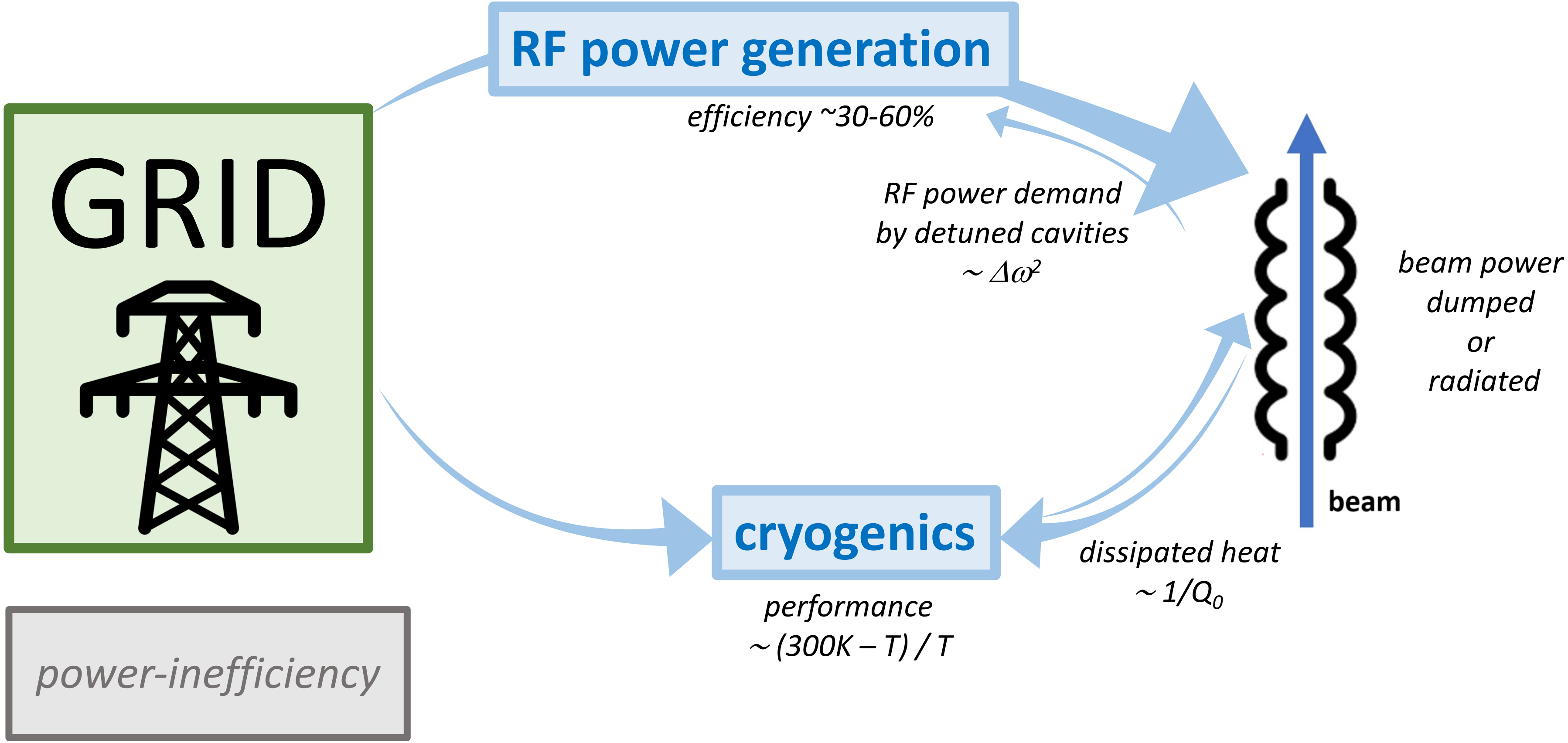
European Strategy for Particle Physics 2020

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam



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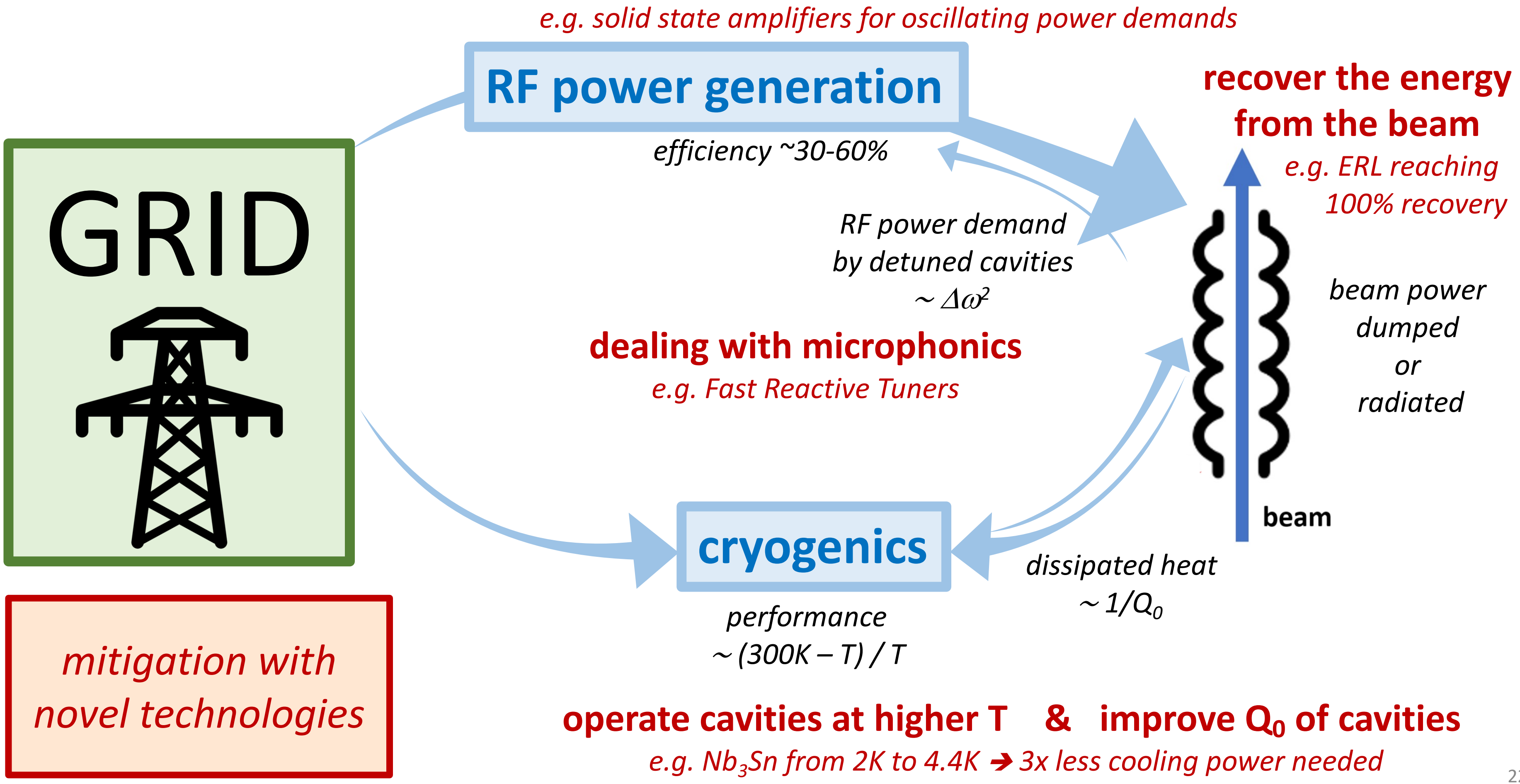

From Grid to Beam

improve amplifier efficien

e.g. solid state amplifi

Accelerating particles will always require a large amount of energy, hence achieving a minimal energy consumption is our unavoidable challenge and duty for future colliders

Thought for an overall R&D programme for "Sustainable Accelerating Systems"

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

e.g. 4.4K SRF in the ERL world is equivalent to HTS in the magnet world

performance
~ (300K – T) / T

…ipated heat
~ $1/Q_0$

operate cavities at higher T & improve Q_0 of cavities

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

From Grid to Beam

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e.g. solid state amplifi…

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

… HTS in the magnet world

e.g. 4.4K SRF in the ERL …

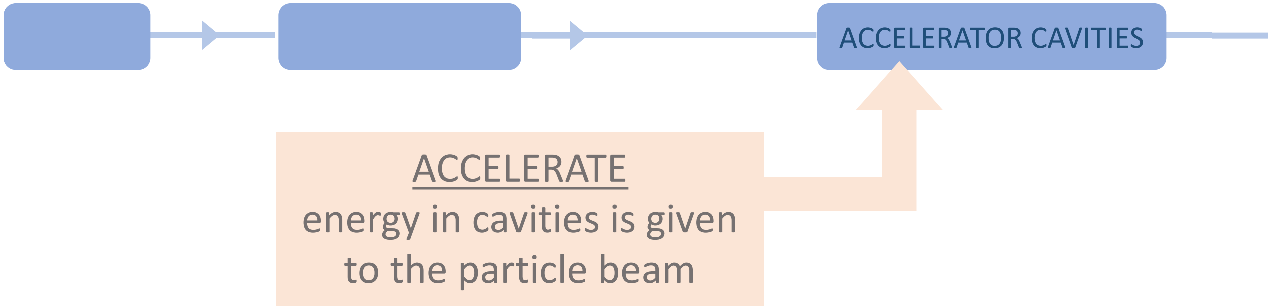
ALARA = **A**s **L**ow **A**s **R**easonable **A**chievable

principle enforced for nuclear safety,
also for energy consumption ?

operate…

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

The principle of Energy Recovery



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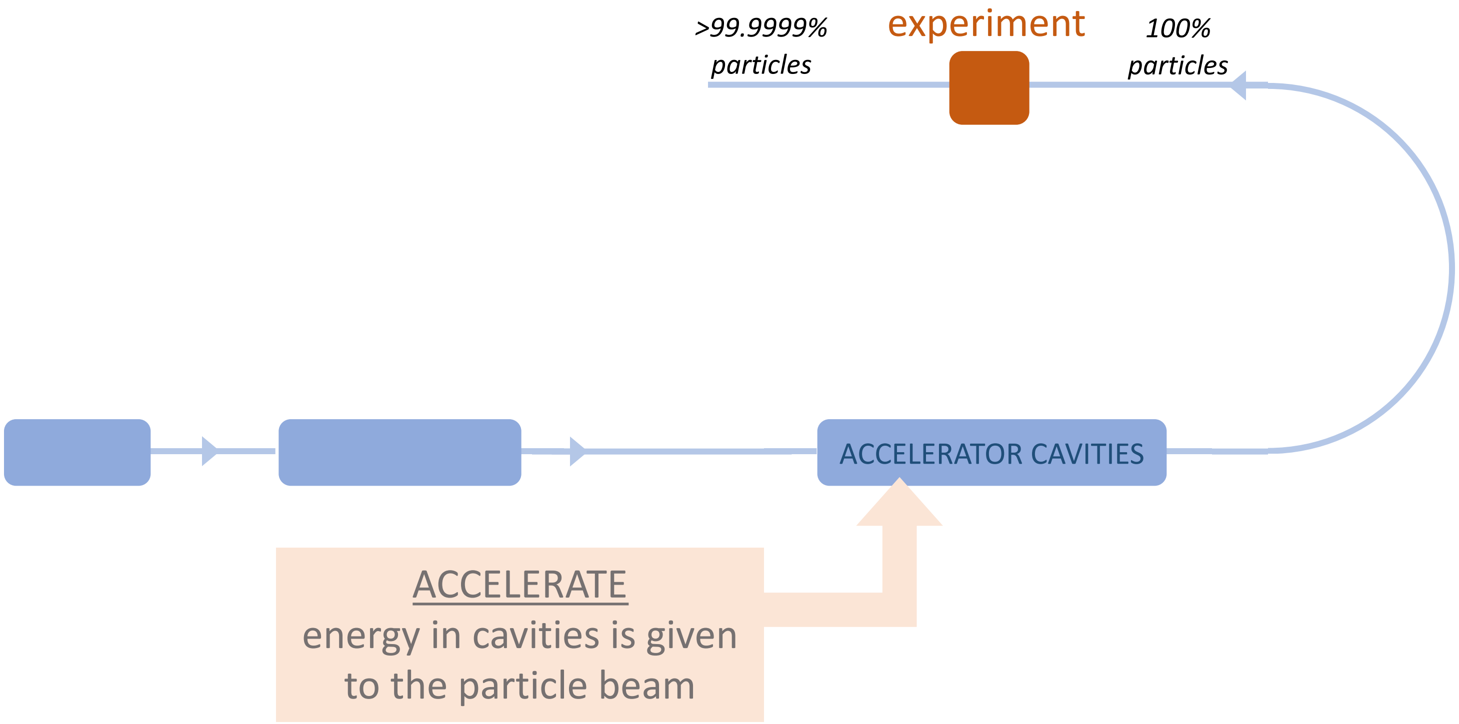

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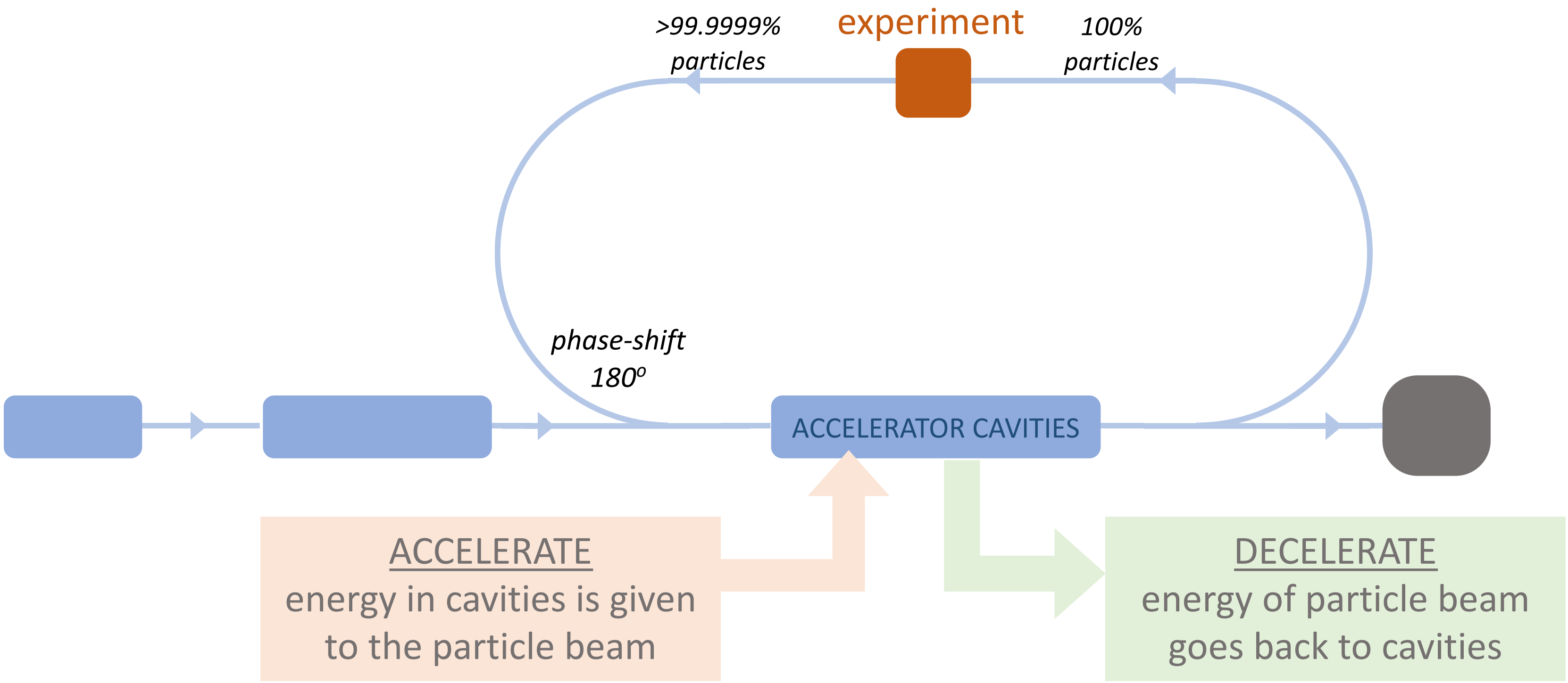

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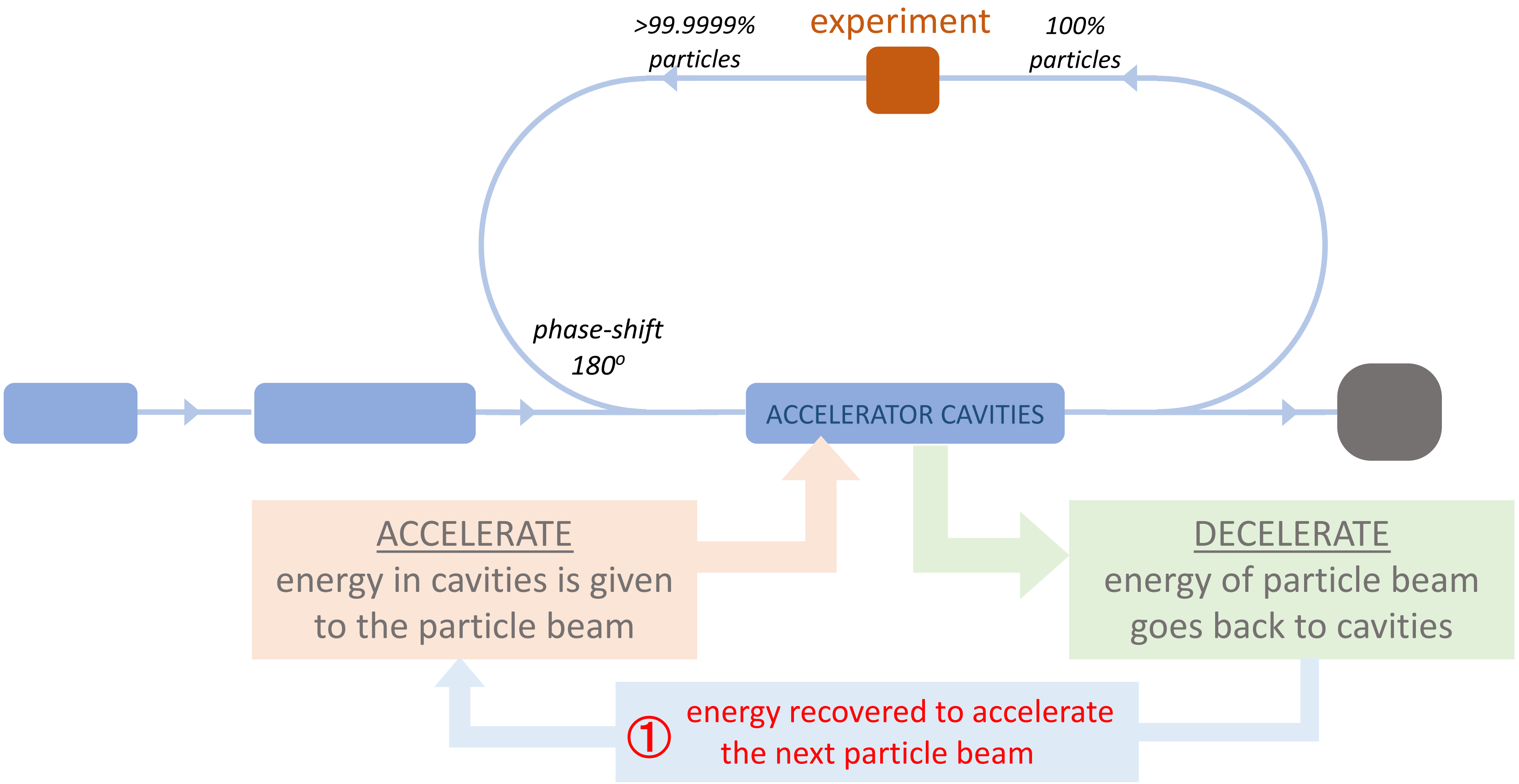

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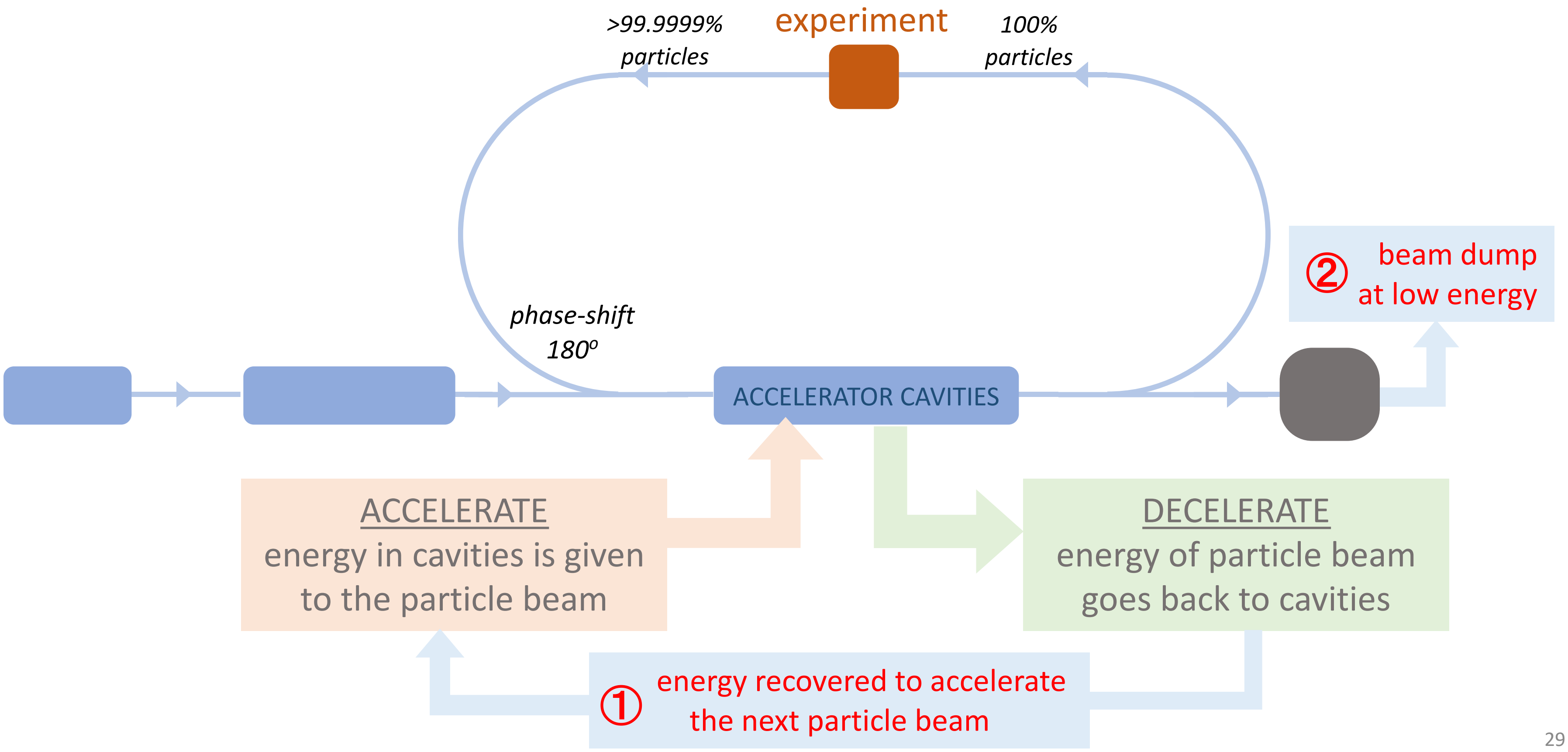

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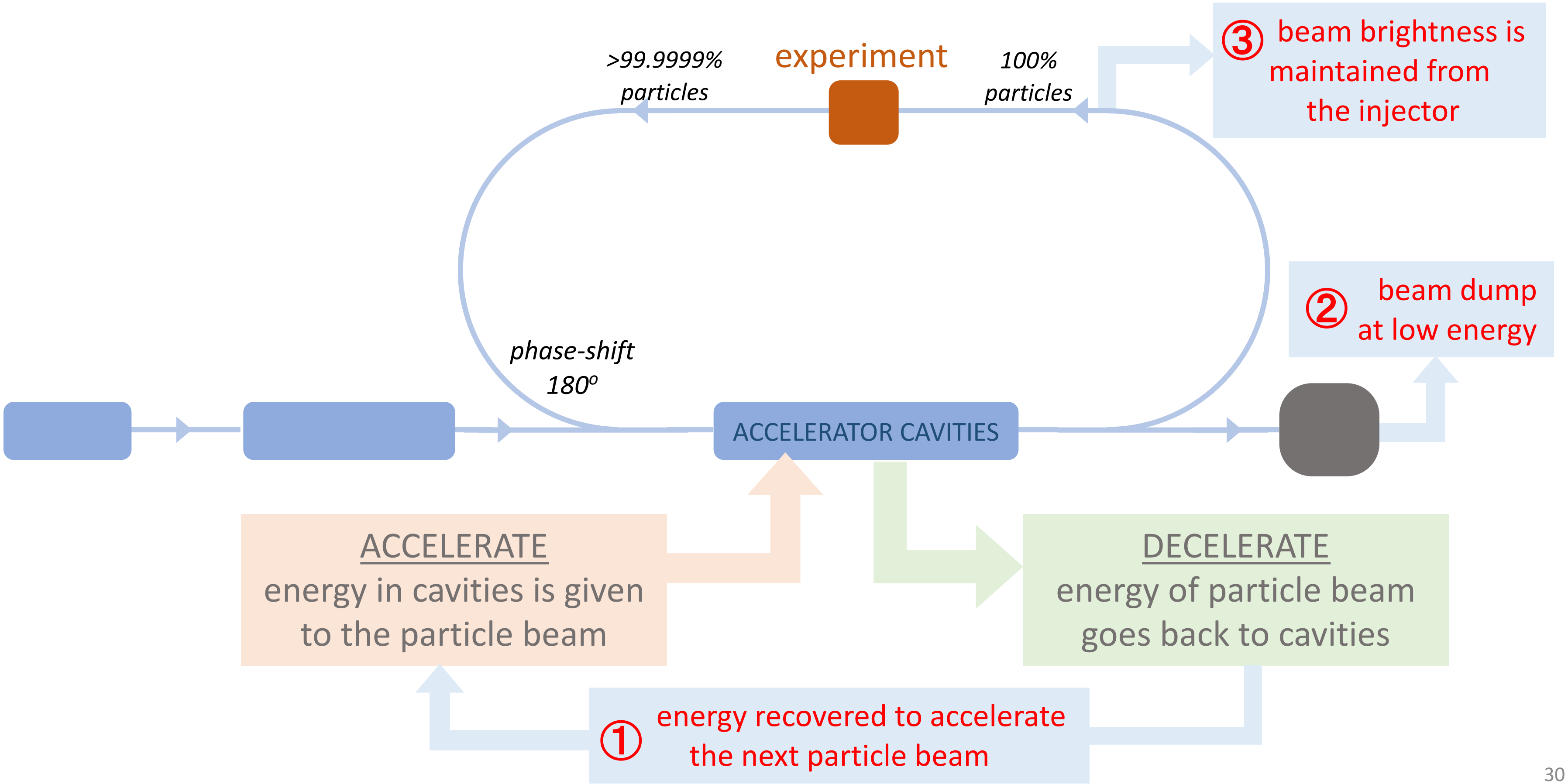

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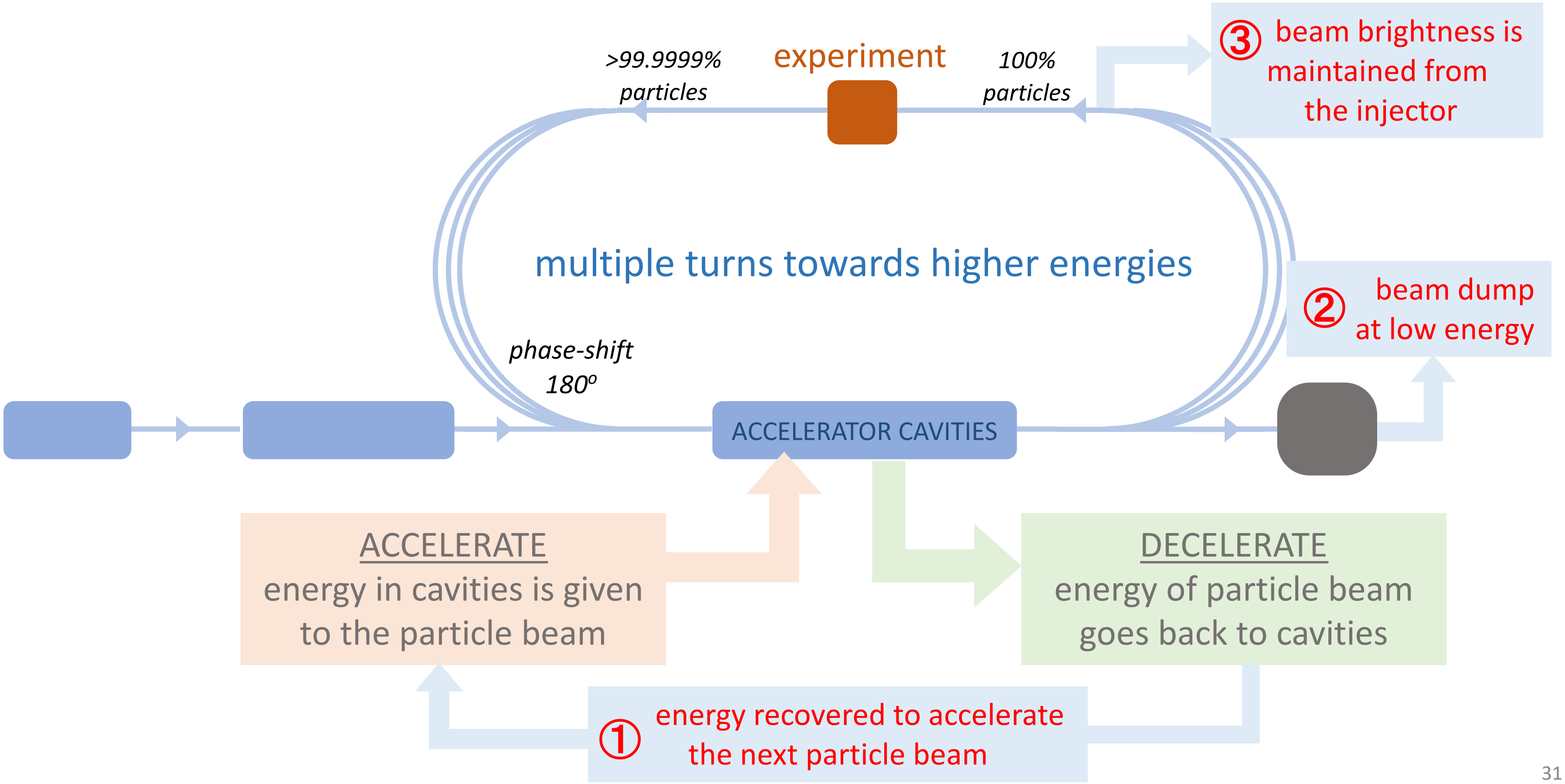

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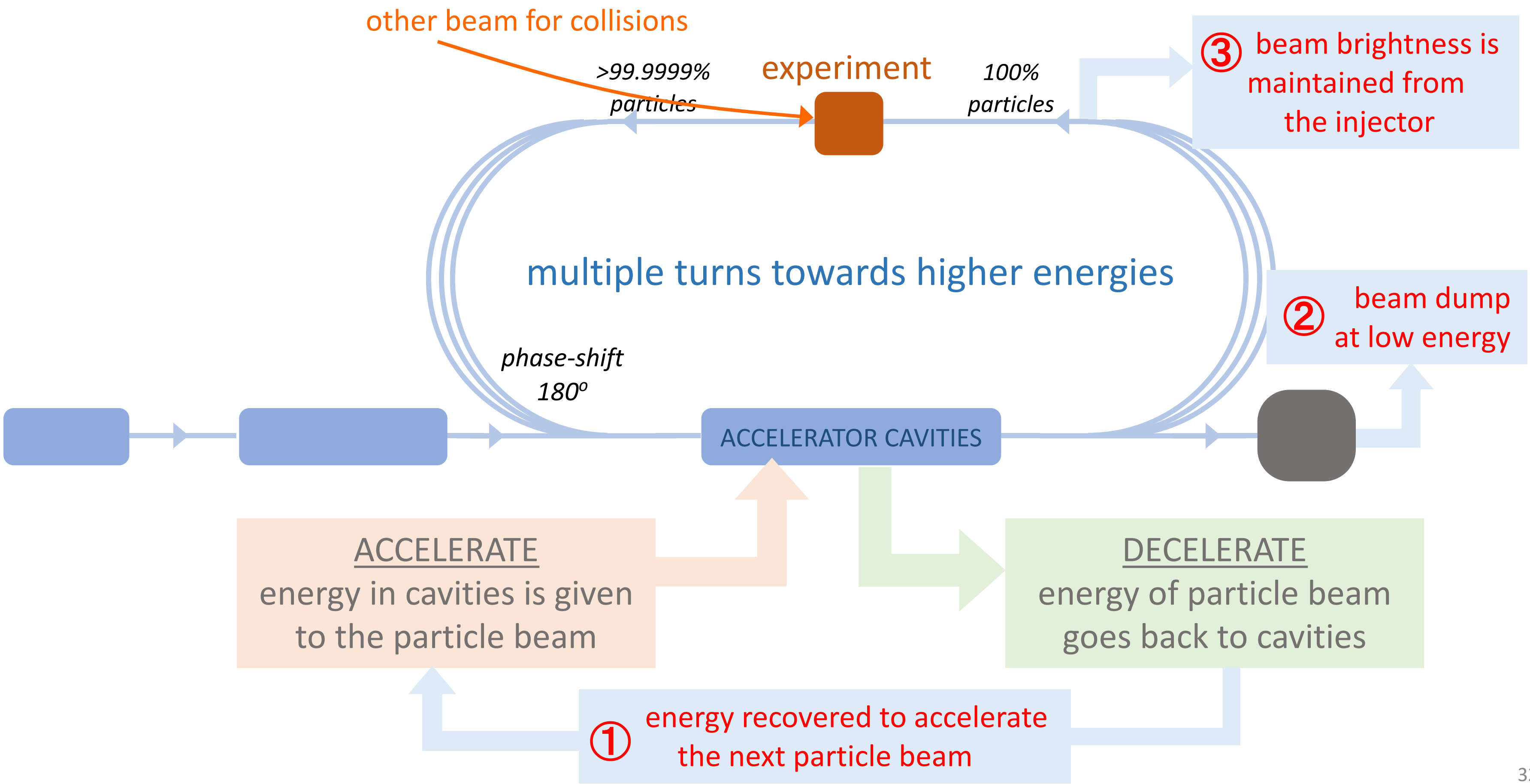

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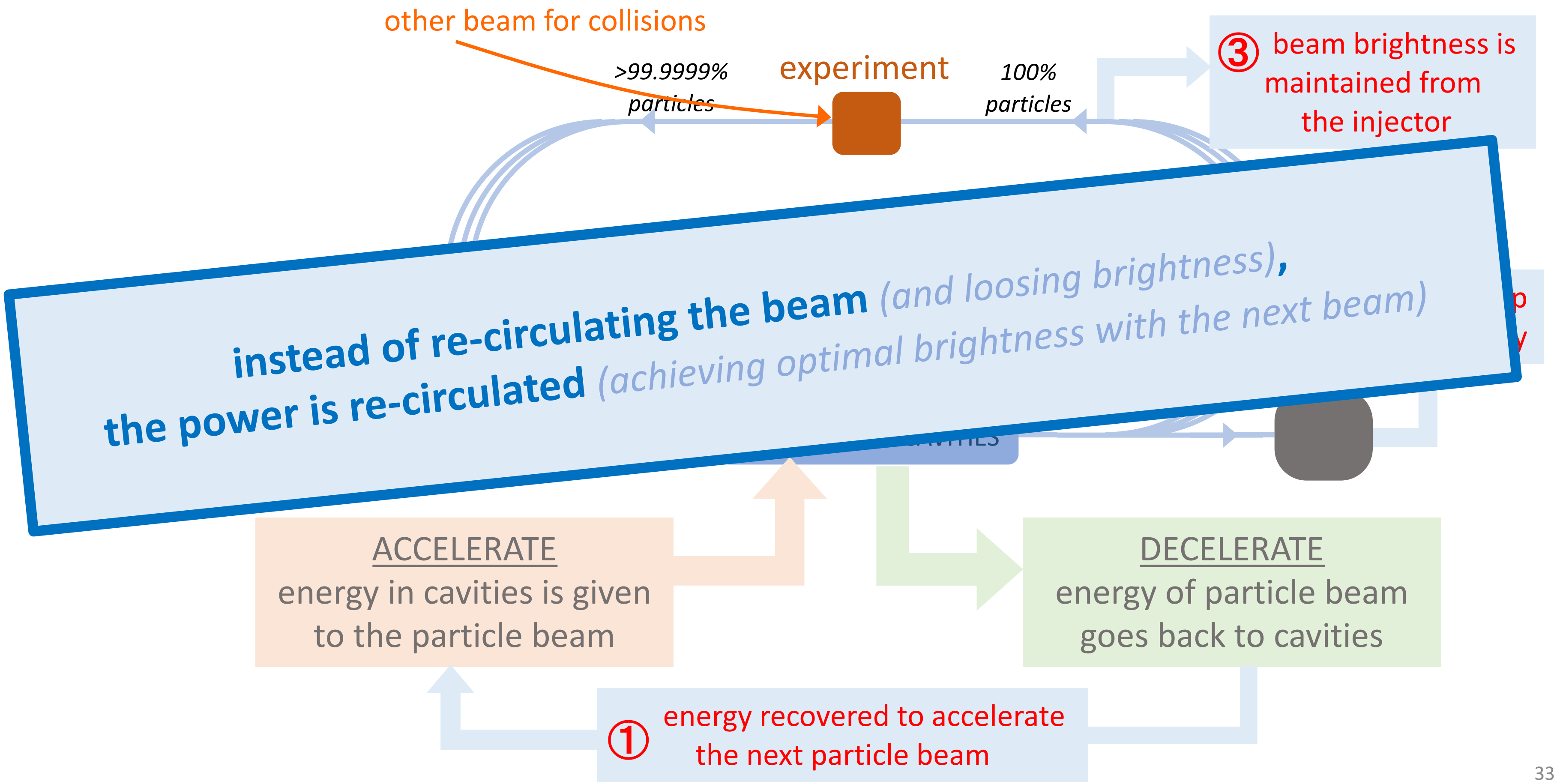
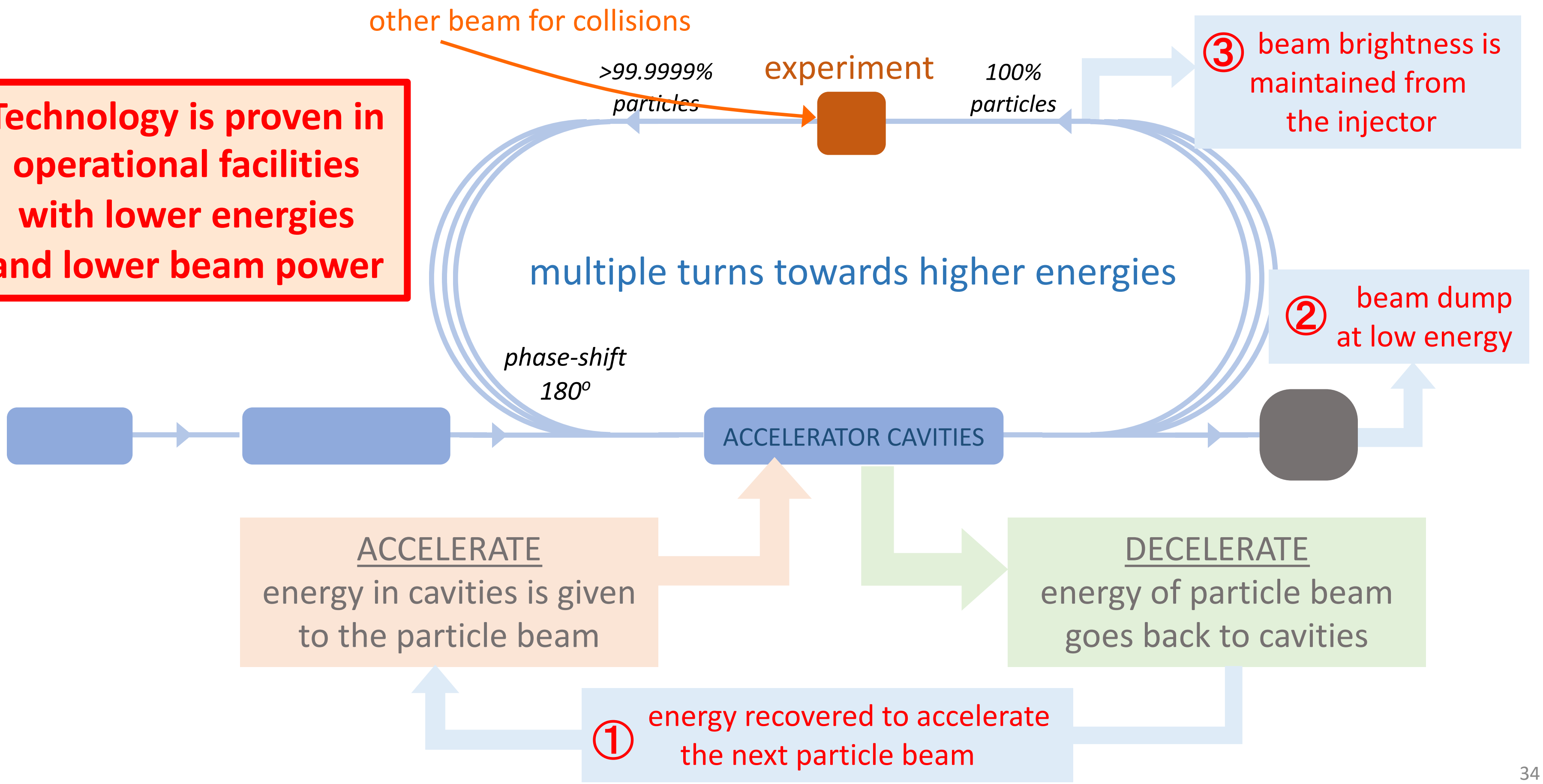


The principle of Energy Recovery

Technology is proven in operational facilities with lower energies and lower beam power



Ongoing & Upcoming facilities with ERL systems

worldwide several facilities are operational or are emerging

ongoing

s-DALINAC *TU Darmstadt, Germany*

two pass operation in progress

ongoing

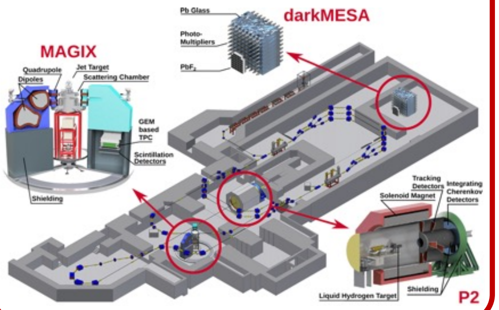
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

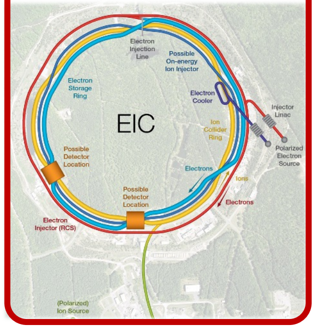
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

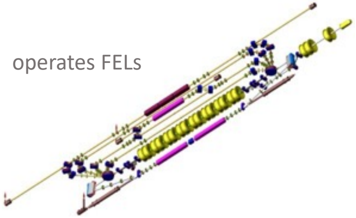
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

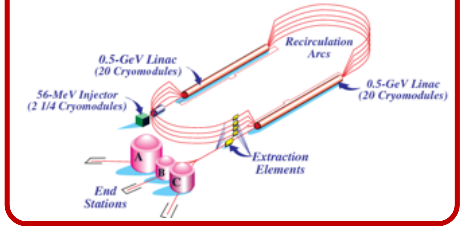
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes



in progress

bERLinPro & PERLE (next slides)

More facilities in design

- **DIANA (STFC, UK)**
- **DICE (Darmstadt, Germany)**
- **BriXSino (Milano, Italy)**

Energy Recovery Linac (ERL) technology

applications with a reduced energy footprint and cost

- **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

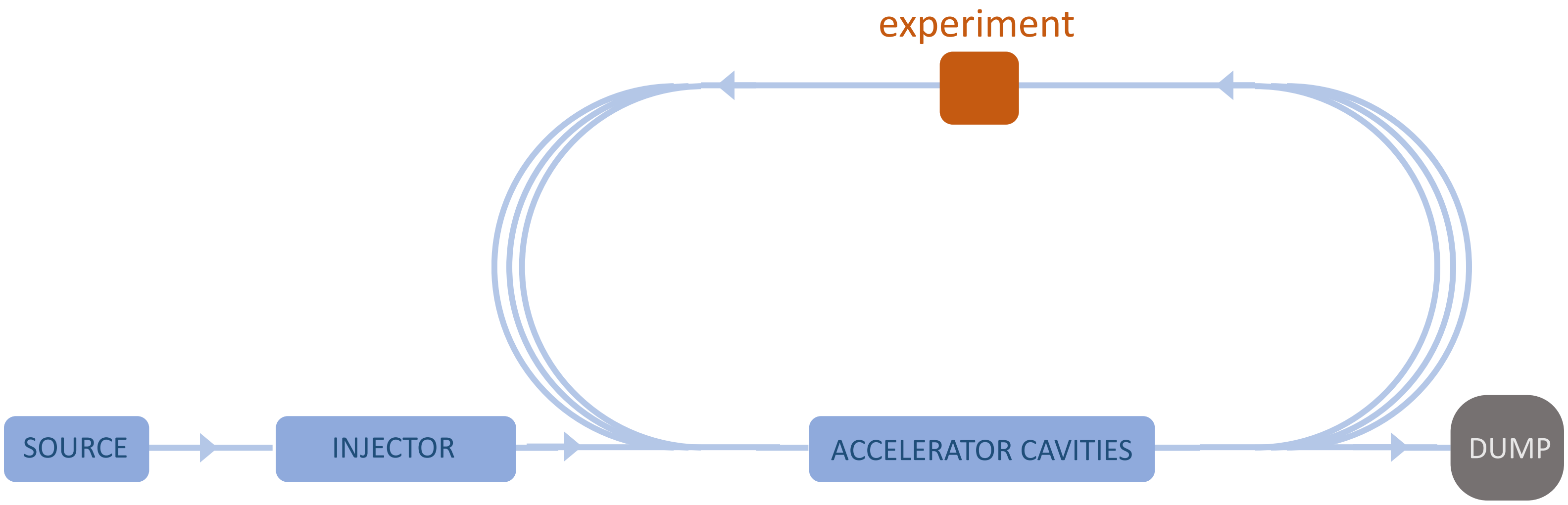
European Accelerator R&D Roadmap

for particle physics

CERN Yellow Rep. Monogr. 1 (2022) 1-270 and *arXiv:2201.07895*

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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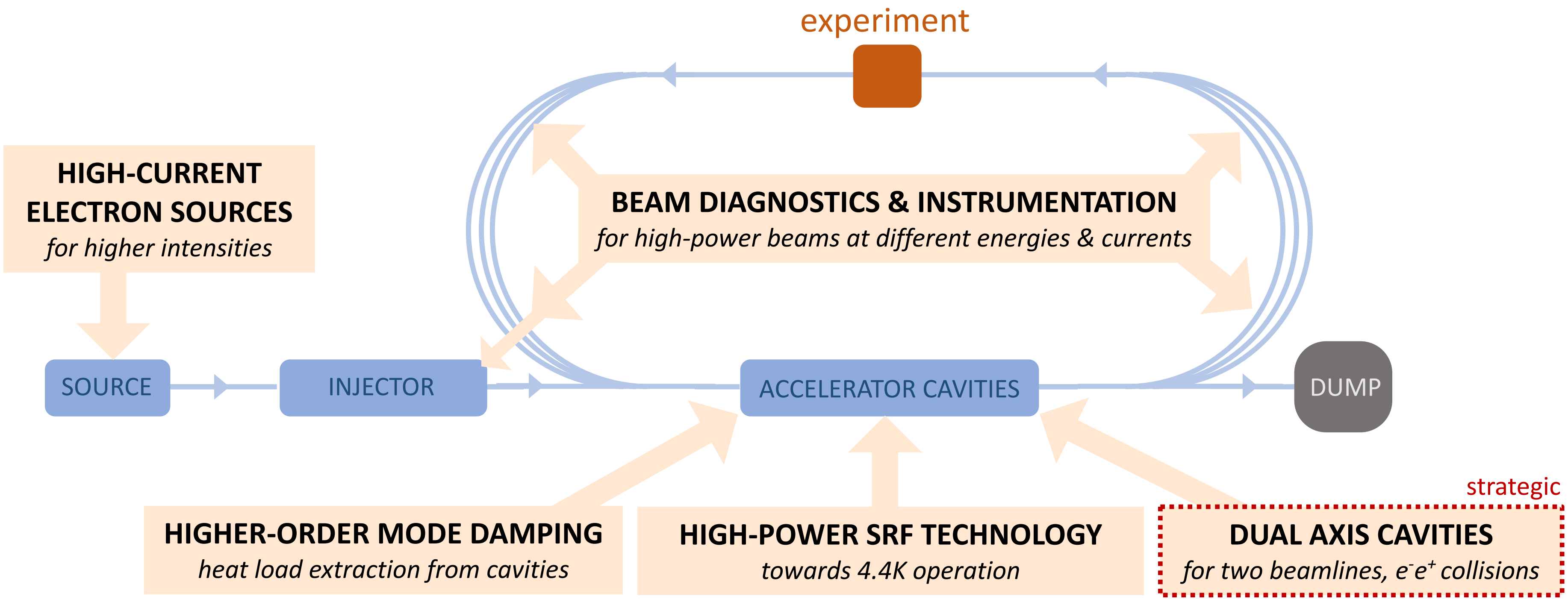


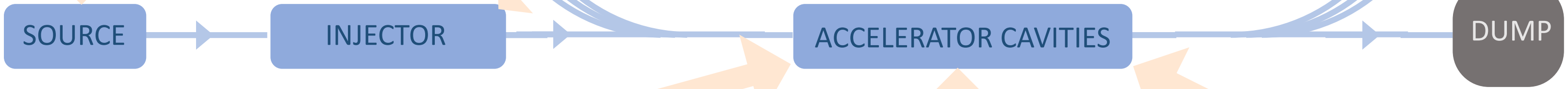
Translated into the main R&D objectives for Energy Recovery

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

HIGH-CURRENT e⁻ SOURCES
- *develop photocathode materials with high quantum efficiency*
- *design of electron gun with high cathode field & high vacuum*

BEAM DIAGNOSTICS & INSTRUMENTATION
- *develop & test beam profile wire-scanners with a high dynamic range (power, emittance, energy)*
- *develop & test optical systems for beam imaging*
- *develop & test beam position monitoring systems incl. a multi-turn beam arrival monitor system*
- *very good beam loss and beam halo monitoring*

SIMULATION & EDUCATION
beam dynamics studies to mitigate coherent synchrotron radiation, wake fields, beam breakup, …



HIGHER-ORDER MODE DAMPING
- *understand HOM powers for cryomodules*
- *design of HOM (on-cell) couplers*
- *modelling of high-frequency wakefield*

HIGH-POWER SRF TECHNOLOGY
- *SRF system design for very high beam currents*
- *develop & test Fast Reactive Tuners (FRT)*
- *deploy in beam-test facilities*
- *towards 4.4K operation reduces the capital investment for the cooling plant (*)*
- *coating SC compound materials on substrates (*)*

strategic

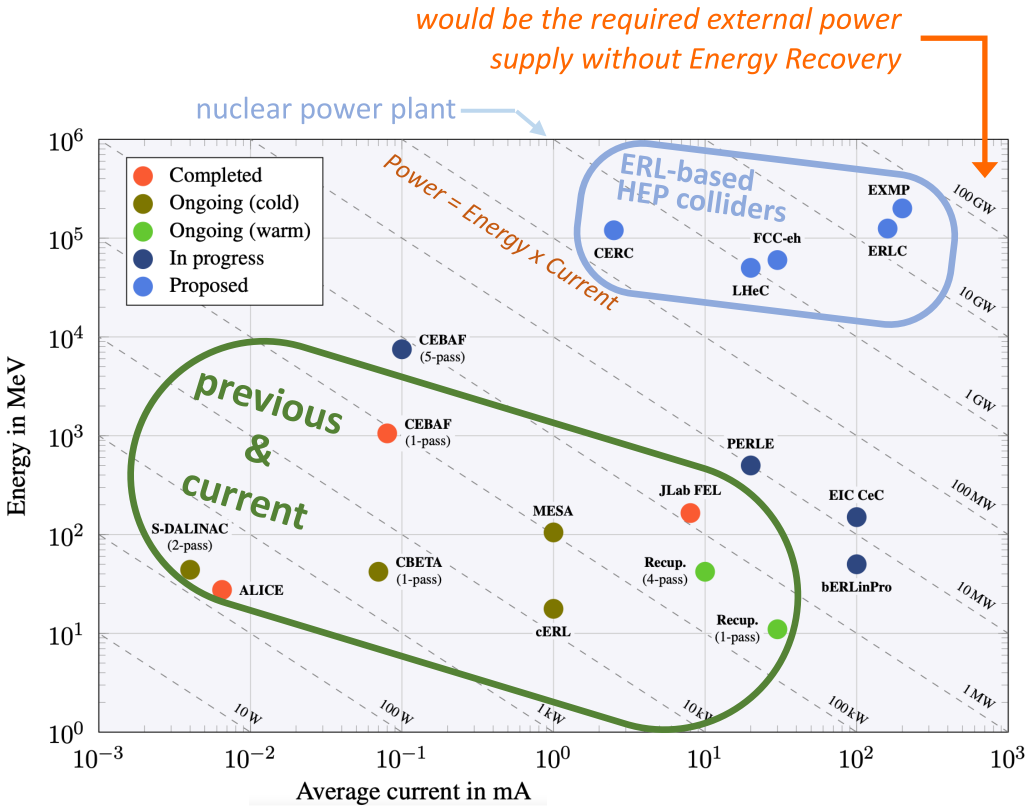
DUAL AXIS CAVITIES
- *advance both options: single cavity with two beam tubes and two cavities joined by a power bridge*
- *packing the cavity in cryomodule*
- *connecting dual axis cryomodules*
- *integrate HOM couplers in design*

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

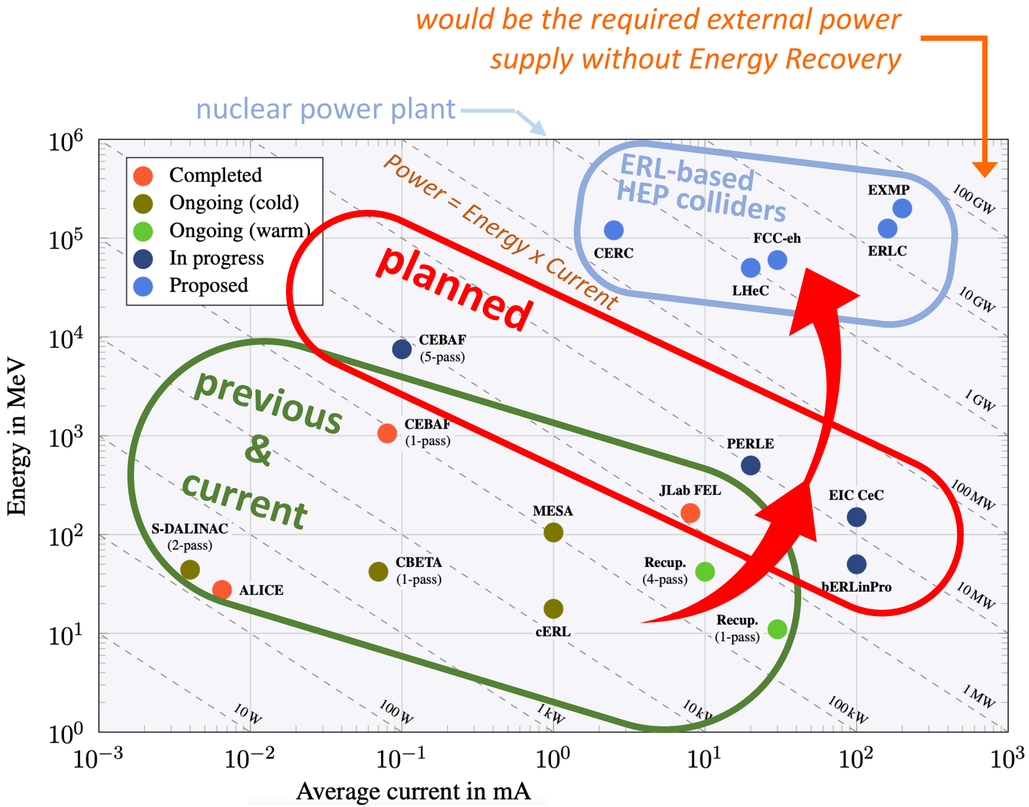


Energy Recovery

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

Energy Recovery – 50 years of innovation

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



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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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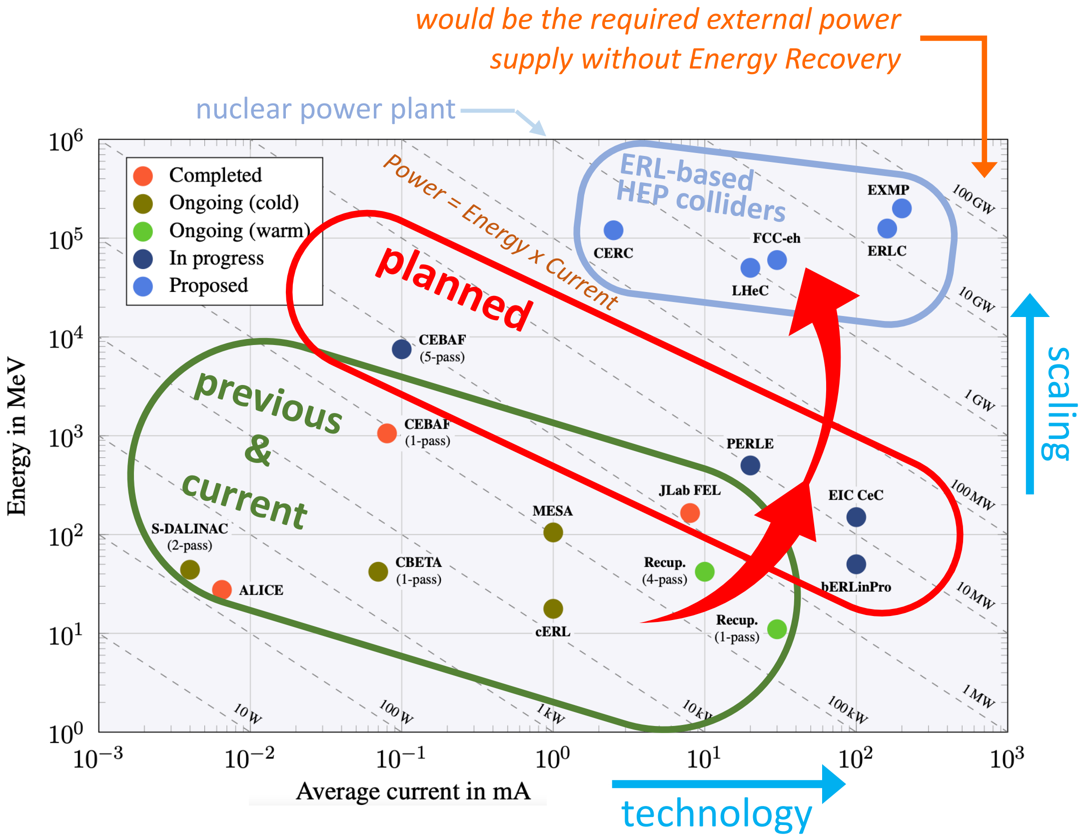

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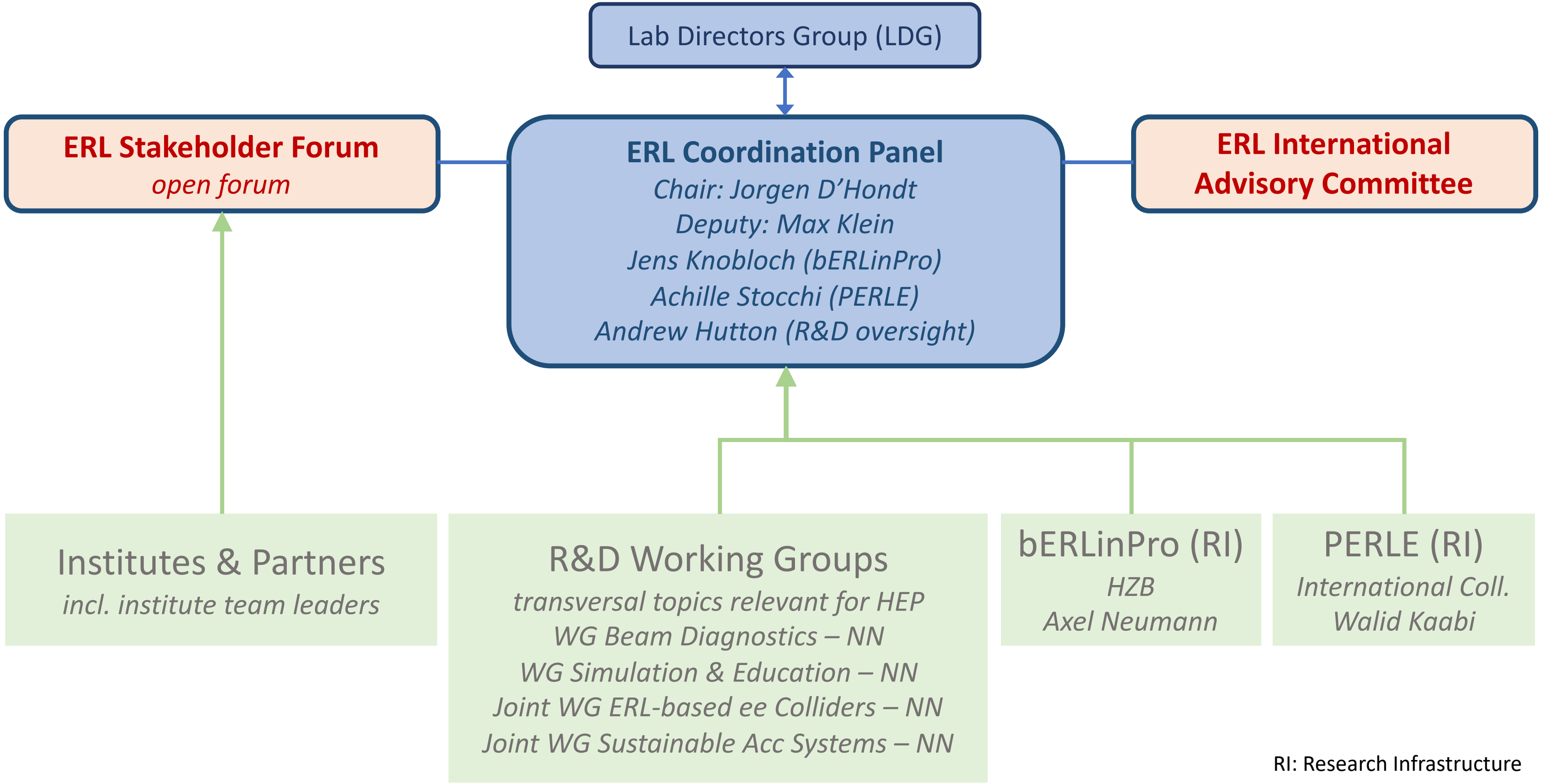
New: organising the European R&D for Energy Recovery in HEP

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



RI: Research Infrastructure

Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

bERLinPro @ Helmholtz Zentrum Berlin

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

B*ERL*inPro: 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)	$< 10^{-5}$

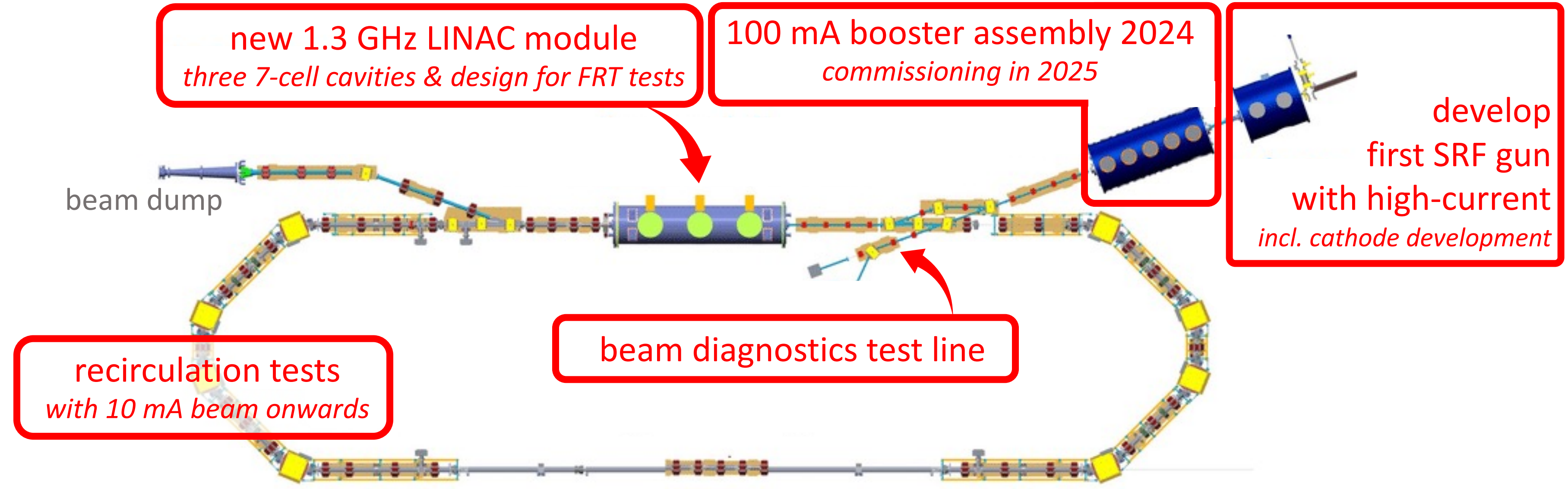
bERLinPro – Berlin Energy Recovery Linac Project

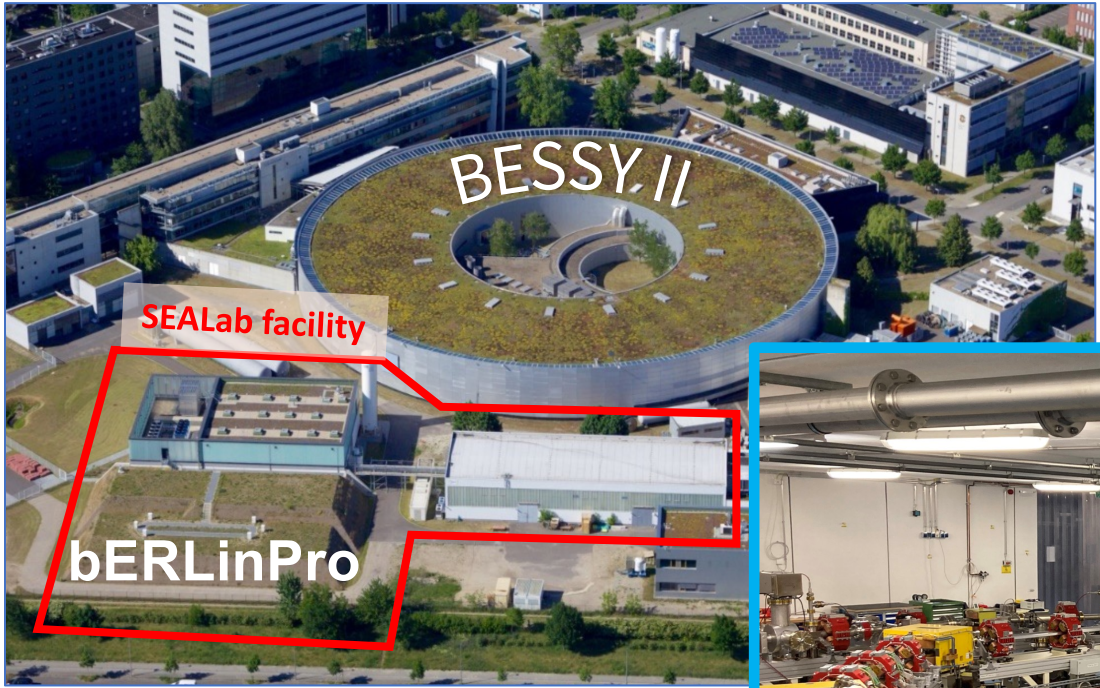
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

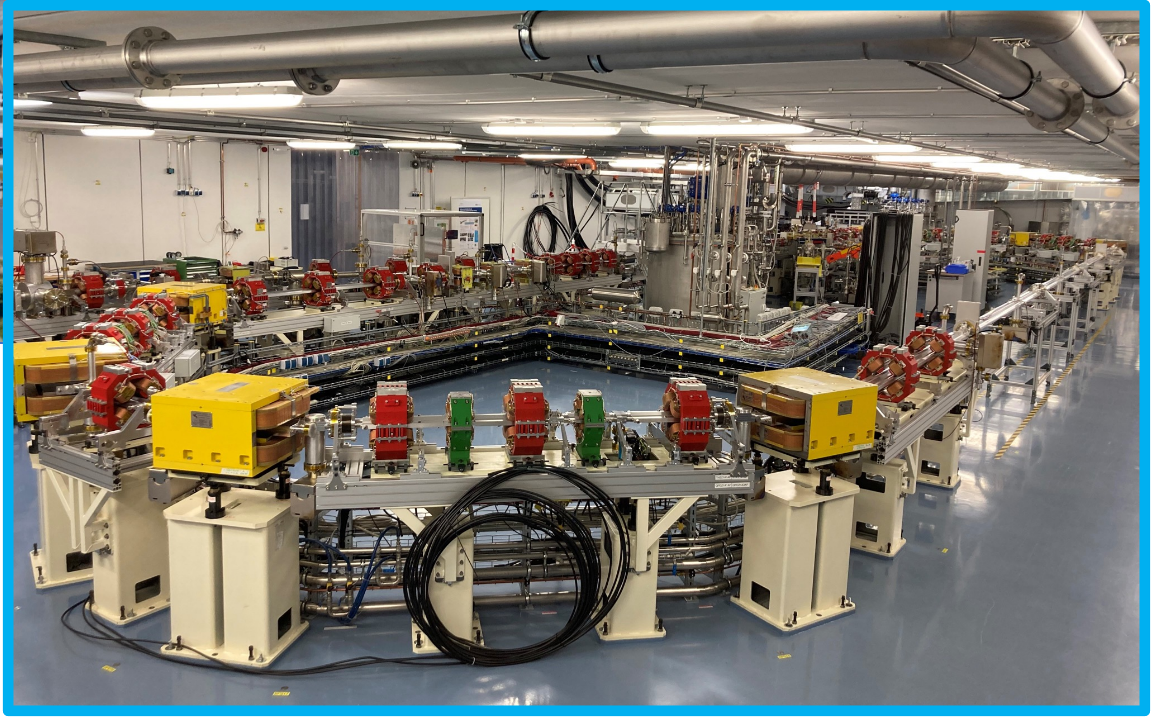
bERLinPro @ Helmholtz Zentrum Berlin
addressing HEP related challenges

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





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

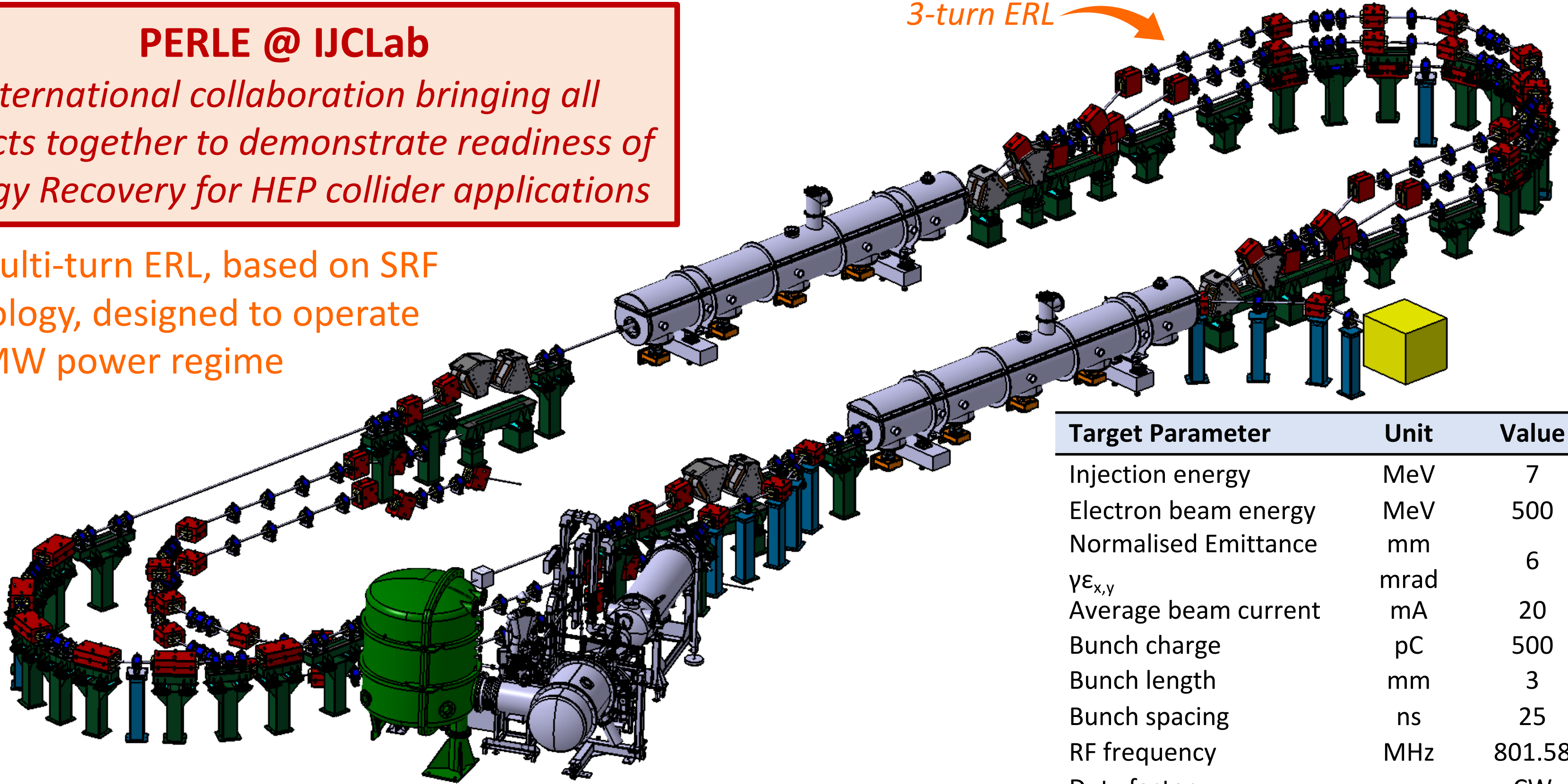
Upcoming facilities for Energy Recovery R&D

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

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

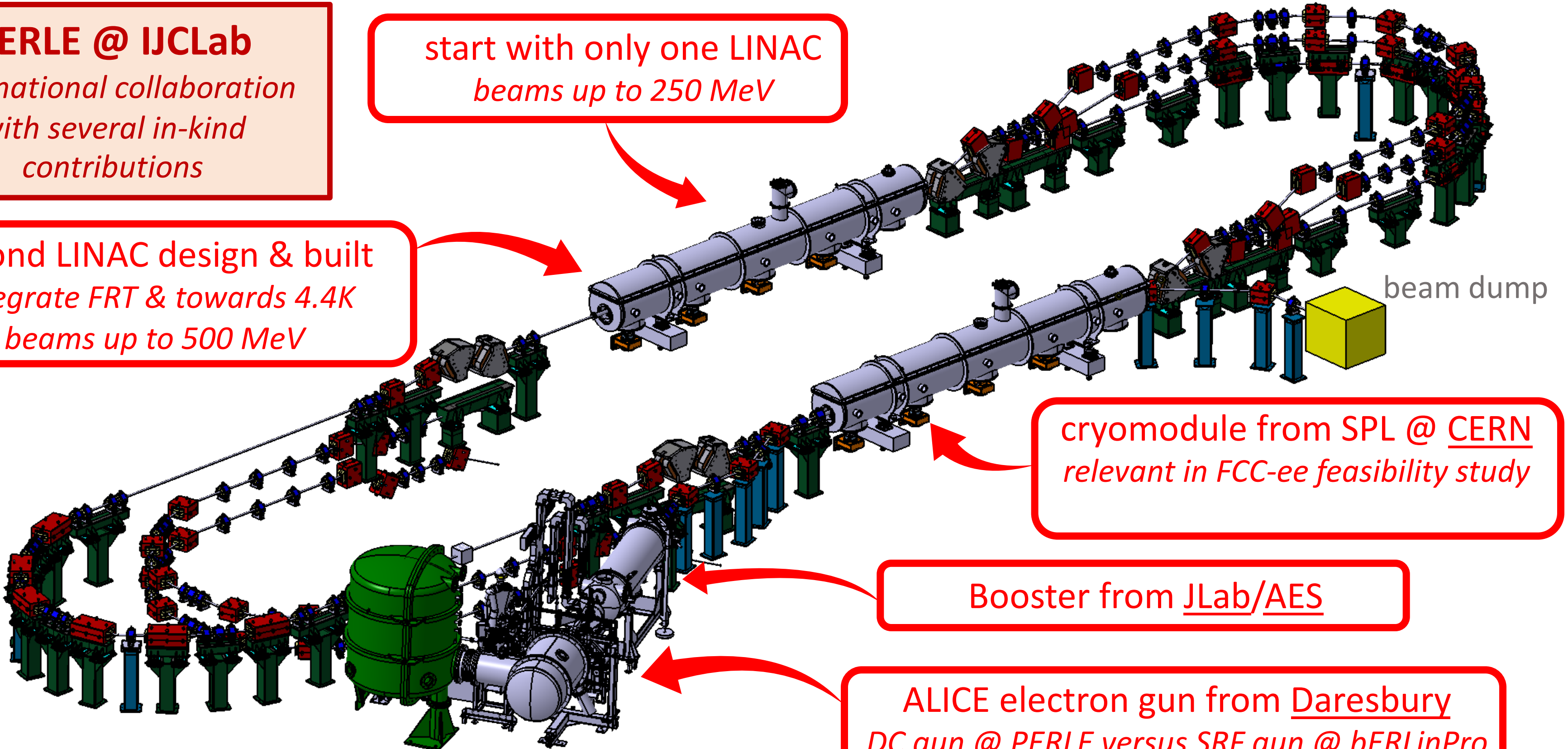
Upcoming facilities for Energy Recovery R&D

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

Booster from JLab/AES

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

Upcoming facilities for Energy Recovery R&D

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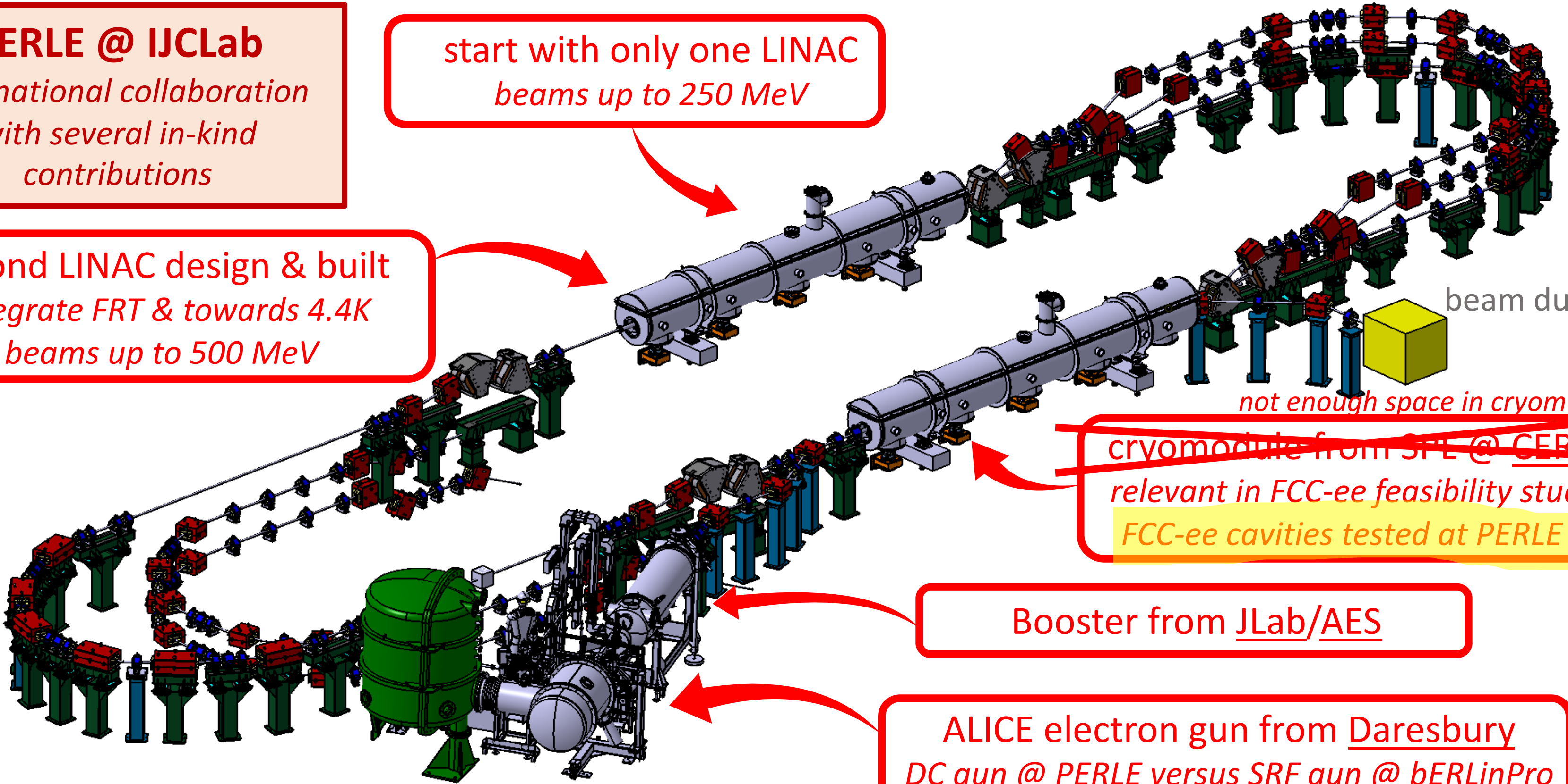

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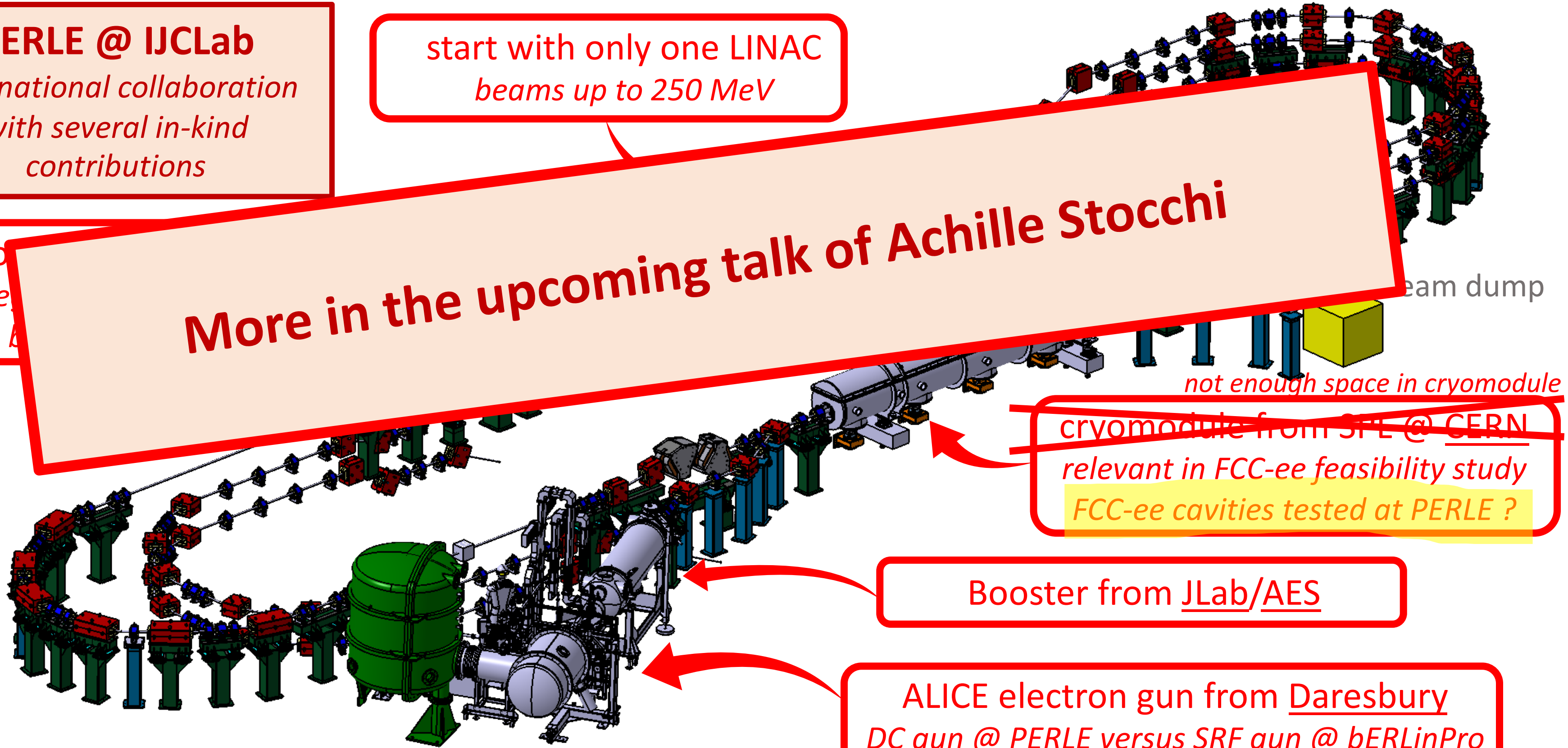
More in the upcoming talk of Achille Stocchi



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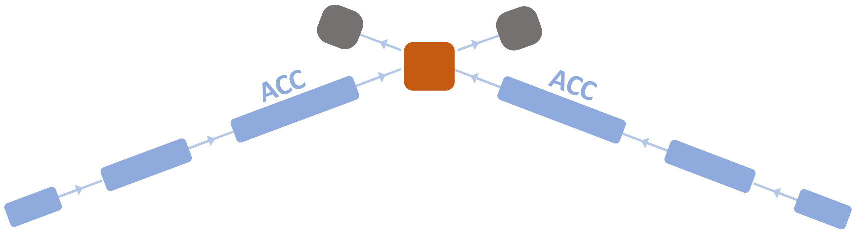
DC gun @ PERLE versus SRF gun @ bERLinPro

Sustainable Accelerating Systems with Energy Recovery at future HEP colliders

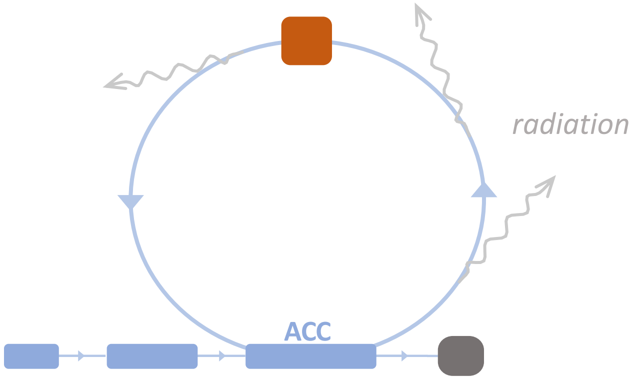
example of Higgs Factories

Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 $\simeq$ 300 MW

~2% of annual electricity consumption in Belgium

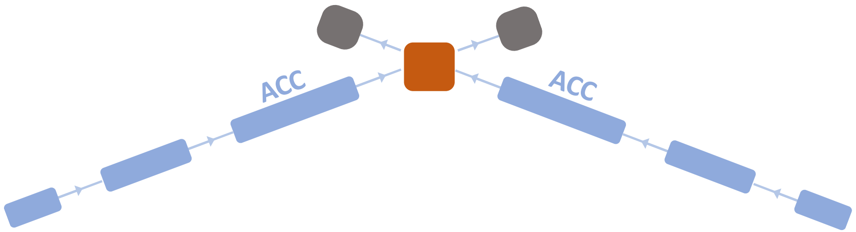
radiate away very quickly the beam power

about half of this is dumped or lost due to radiation

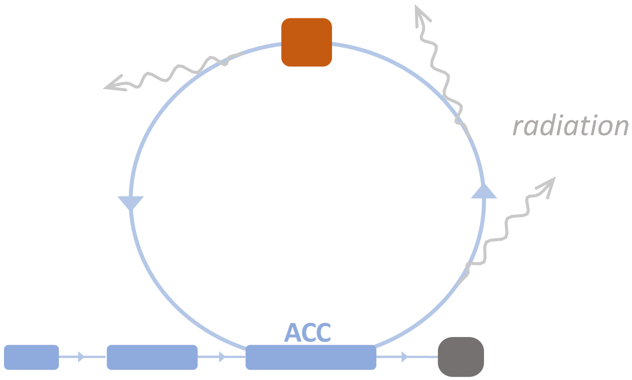
OBJECTIVE: develop accelerator technologies that recover the beam energy with an impact of saving ~1% of Belgium's electricity

Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

radiate away very quickly the beam power

Energy consumption is reducing in Europe, not excluded with ½ by 2050-2060

about half of this is dumped or lost due to radiation

OBJECTIVE: develop accelerator technologies that recover the beam energy with an **impact of saving ~2% of Belgium's electricity**

Addressing with ERL the European Strategy for Particle Physics 2020

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

ERL

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

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

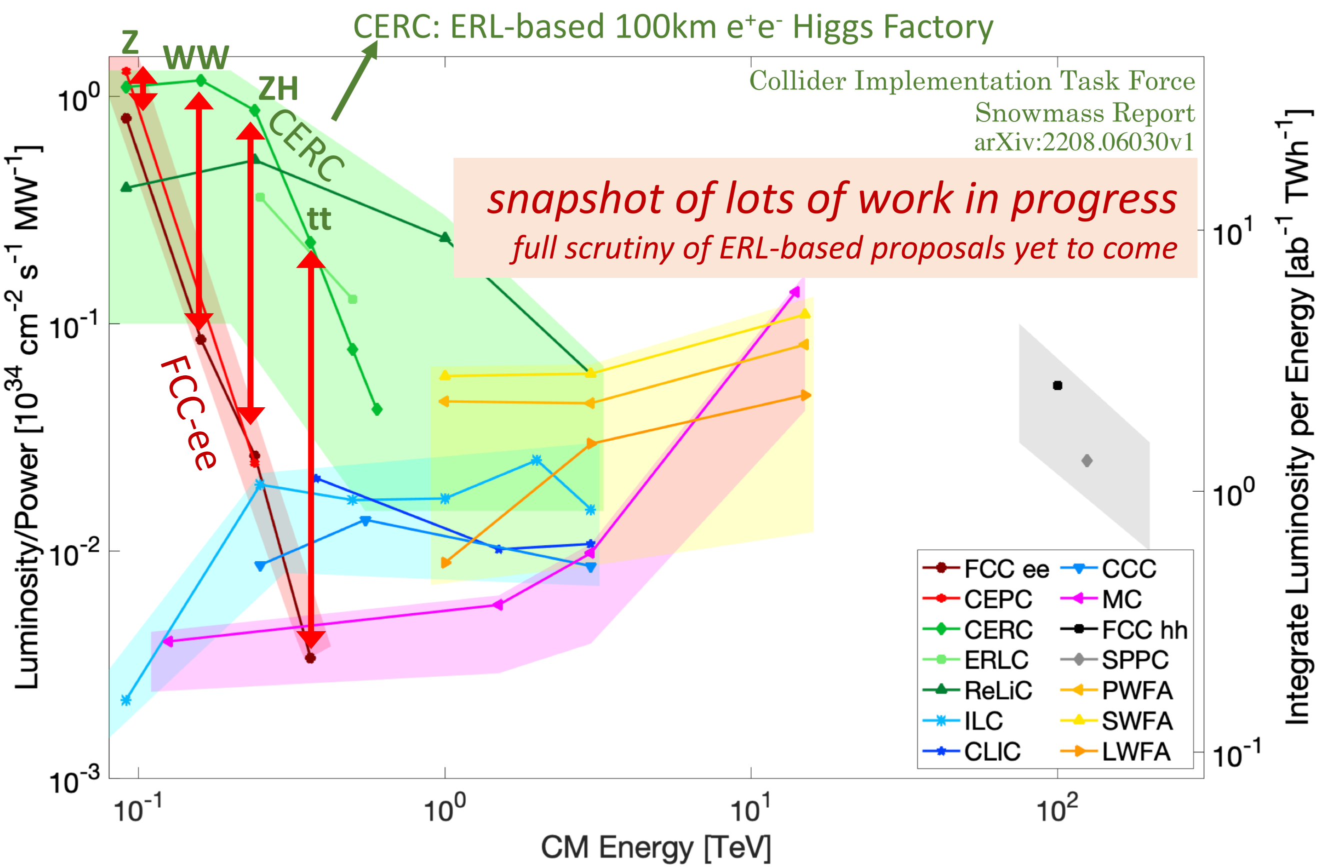
This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

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

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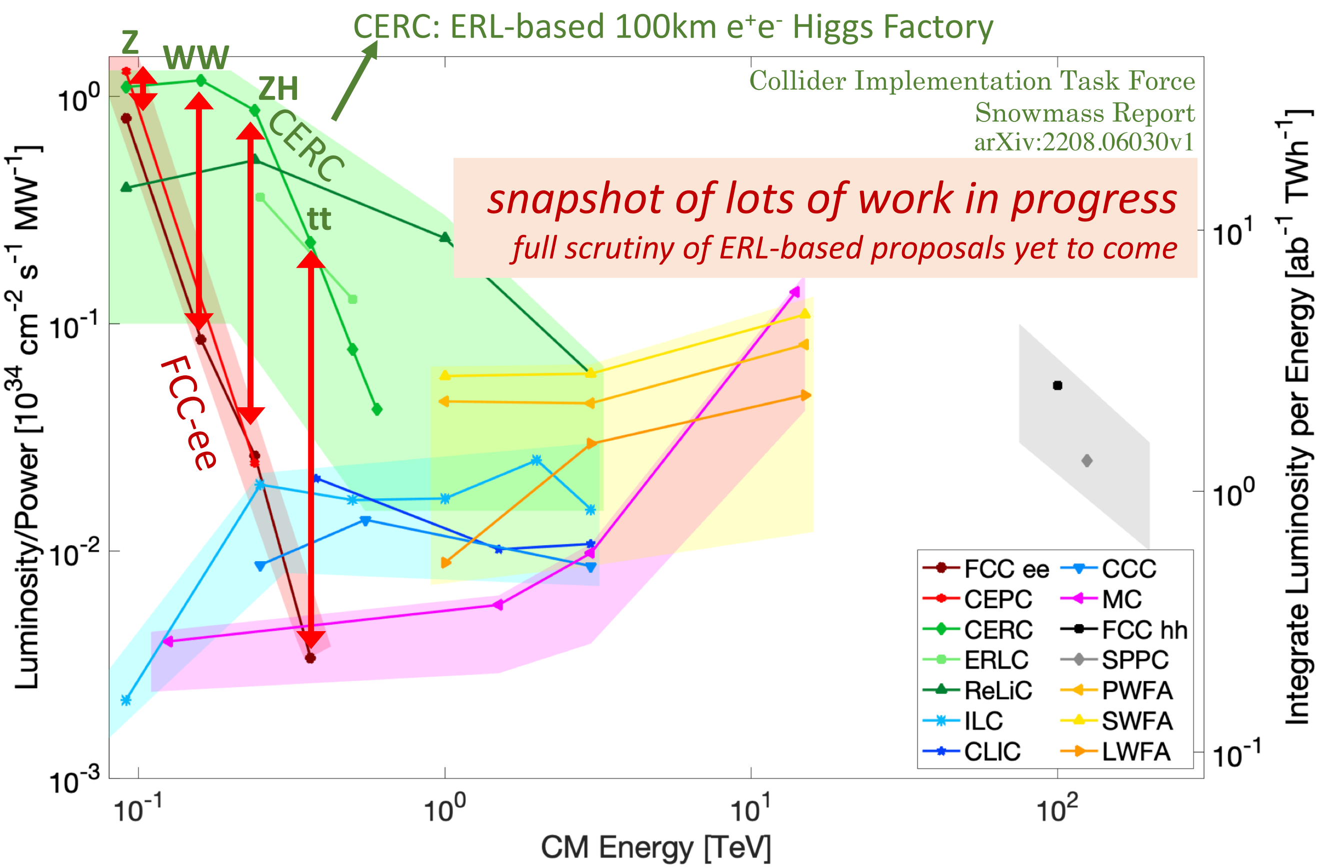
or

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

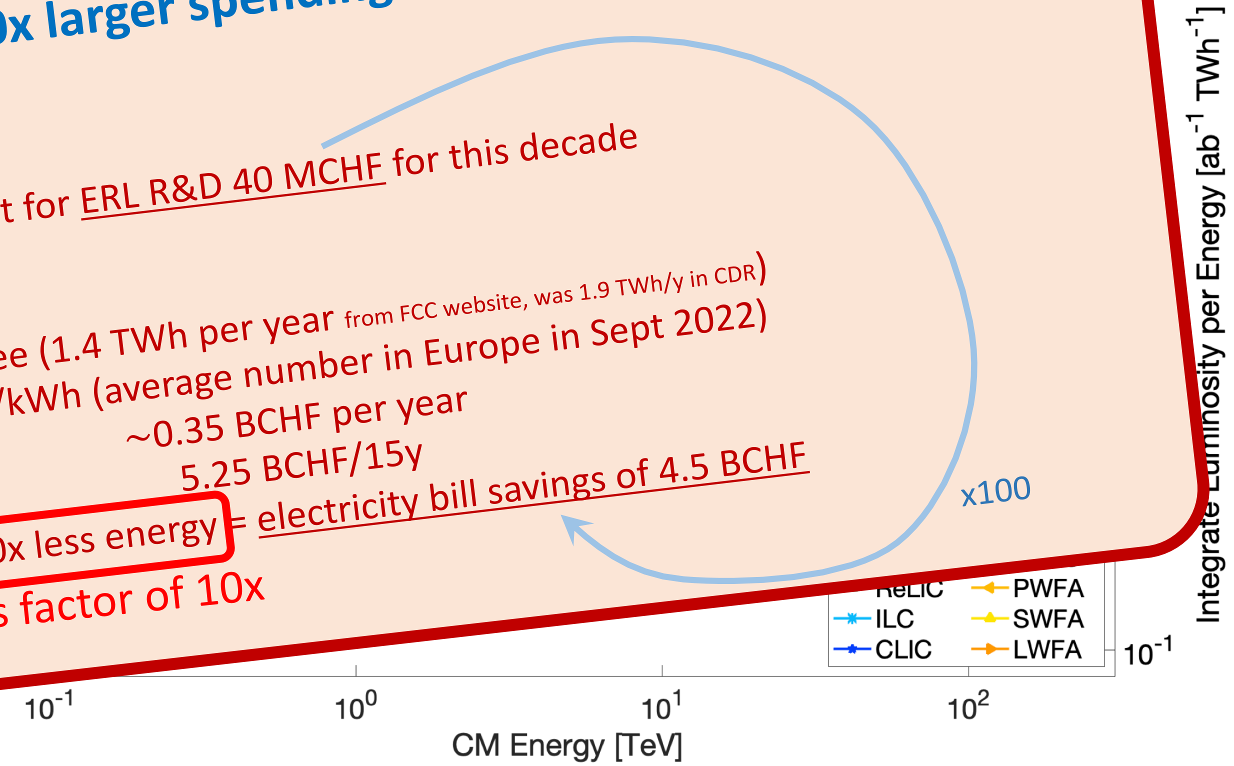
budget for ERL R&D 40 MCHF for this decade

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

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

the previous factor of 10x

x100



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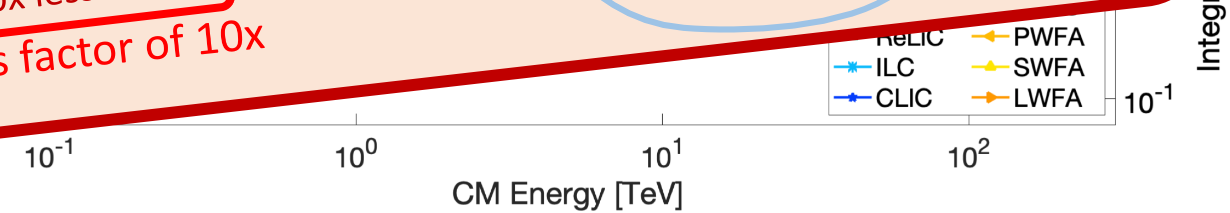
~0.35 BCHF per year
5.25 BCHF/15y

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

x100

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 HEP

This
an
Fac

x10 l

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

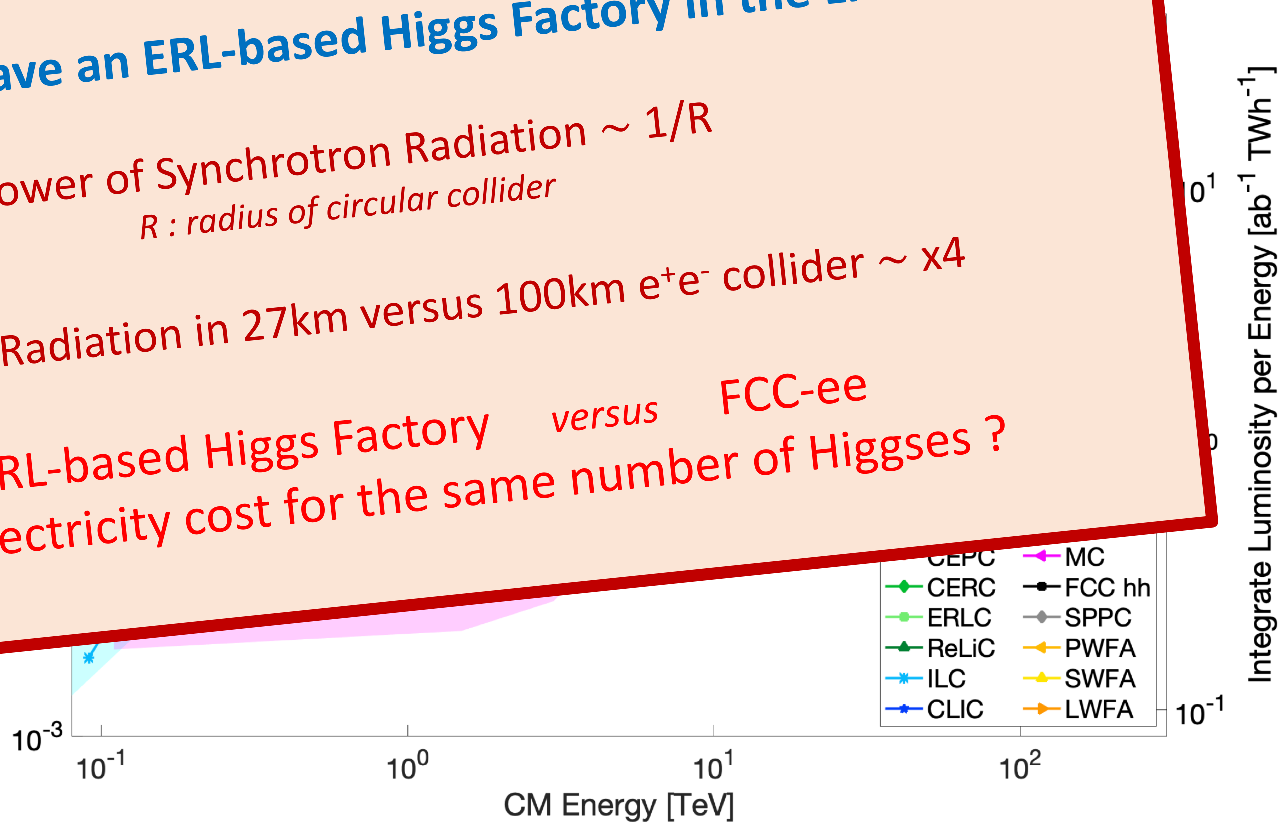
Power of Synchrotron Radiation ~ 1/R

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 ?



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Energy Recovery applications for HEP

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R : radius of circular collider

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

...ased Higgs Factory *versus* FCC-ee

...ber of Higgses ?

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

...osity per Energy [ab^{-1} TWh^{-1}]

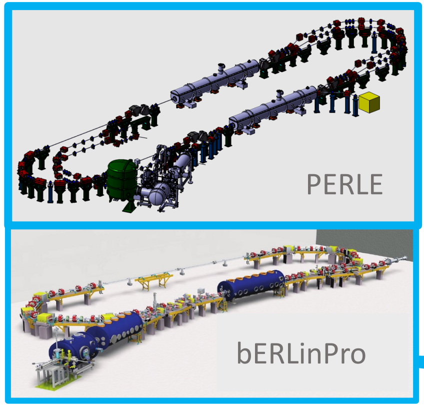
10^1

Re...

The future of ERL colliders

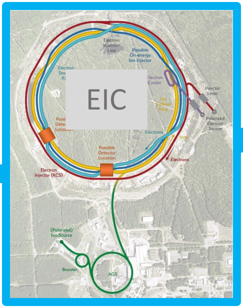
With stepping stones for innovations in technology to boost our physics reach

2020'ies



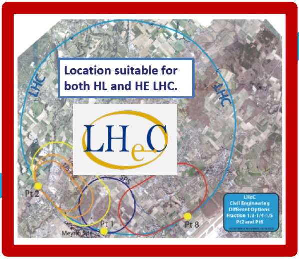
high-power ERL demonstrated

2020-2030'ies



ERL application electron cooling

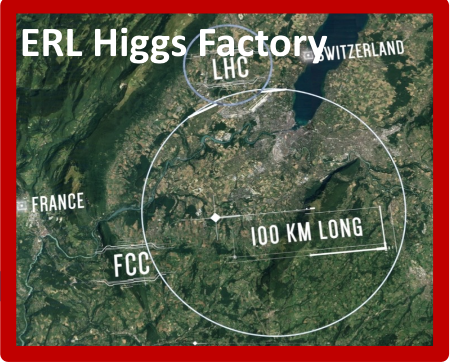
2030-2040'ies



1 ERL beam

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

2040-2050'ies



2 ERL beams

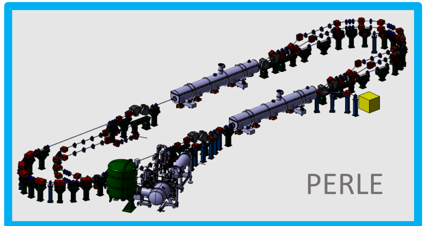
with high-power ERL
e^+e^- Higgs Factory
(Z/W/H/top program)

The future of ERL colliders

With stepping stones for innovations in technology
to boost our physics reach

the ultimate upgrade of the LHC programme

2020'ies



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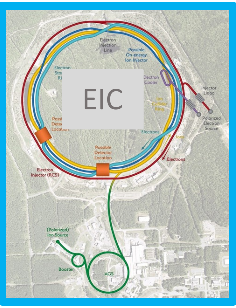
2020-2030'ies



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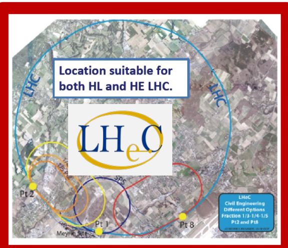

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e^- beam in collision
(ep/eA @ LHC program)

2040-2050'ies

2 ERL beams

with high-power ERL
e^+e^- Higgs Factory
(Z/W/H/top program)

the next major collider

from the European Accelerator R&D Roadmap programme together engaged into a concrete R&D project

proposal

"Innovate for Sustainable Accelerating Systems"

(iSAS)

"Innovate for Sustainable Accelerating Systems"

HORIZON-INFRA-2023-TECH-01-01

New technologies and solutions for reducing the environmental and climate footprint of RIs

REGULATIONS

- **Specific conditions**
  - *Expected EU contribution per project: around 5M EUR.*
  - *Consortia must include at least 3 different research infrastructures, each of them being an ESFRI infrastructure, and/or a European Research Infrastructures Consortium (ERIC) or another research infrastructure of European interest (i.e. a research infrastructure which is able to attract users from EU or associated countries other than the country where the infrastructure is located). Consortia should be built around a leading core of at least 3 world-class research infrastructures and can include a wider set of RIs.*
  - *Other technological partners, including industry and SMEs, should also be involved, thus promoting innovation and knowledge sharing through co-development of new technical solutions for research infrastructures.*
  - *Proposals should built on and explain any synergies and complementarities with previous or current EU grants, including those under other parts of the Framework Programmes.*
- **Expected Outcome**
  - *Reduction of environmental impacts (including climate-related)*
  - *Optimisation of resource and energy consumption integrated through the full life cycle of research infrastructures*
  - *Increased long-term sustainability of European research infrastructures*
- **Scope**
  - *The aim of this topic is to deliver innovative technologies and solutions which reduce the environmental and climate footprint of RIs through the full life cycle of research infrastructures. Proposals should identify common methodologies, among the concerned RIs, to assess environmental impact and strategies to reduce it, as well as efficiency gains in the broader ecosystem.*
  - *Proposals should address the following aspects, as relevant:*
    - *new technologies and solutions for research infrastructures enabling transformative resource efficiency (e.g. energy consumption) and reduction of environmental (including climate-related) impacts, including, when relevant, more sustainable and efficient ways of collecting, processing and providing access to data;*
    - *validation and prototyping;*
    - *training of RI staff for the operation and use of the new solutions;*
    - *action plans to deploy the new developments at wider scale and ensure their sustainability;*
    - *measures to ensure an environmentally effective integration of the solutions in the local contexts;*
    - *societal engagement to foster acceptance of the solutions in the local and regional communities.*

"Innovate for Sustainable Accelerating Systems"

HORIZON-INFRA-2023-TECH-01-01

New technologies and solutions for reducing the environmental and climate f

- **Specific conditions**
  - *Expected EU contributi*

(ERIC) or
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- S

Create strong and broad impact with a 5M EUR EU-project

***Goal*: develop, prototype and validate the essential energy-saving and energy-recovery technologies required to integrate in the design of a novel sustainable LINAC cryomodule with a broad portfolio of applications in industry and at accelerator research infrastructures**

Sustain the impactful 20th-century accelerator applications into an energy-low 21st century!

the environmental and climate footprint of RIs through the full life cycle of research
ogies, among the concerned RIs, to assess environmental impact and strategies to reduce it, as well as efficiency

address the following aspects, as relevant:

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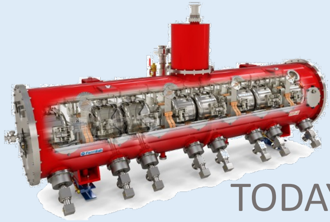
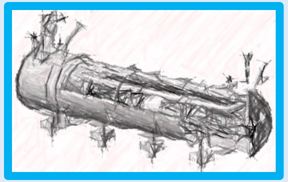


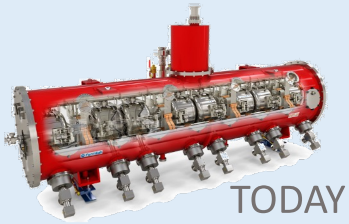
TODAY

INNOVATE TECHNOLOGIES TOWARDS A SUSTAINABLE ACCELERATING SYSTEM



NEW DESIGN

DEVELOP ENERGY-SAVING & ENERGY-RECOVERY TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE



TODAY

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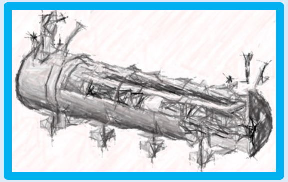

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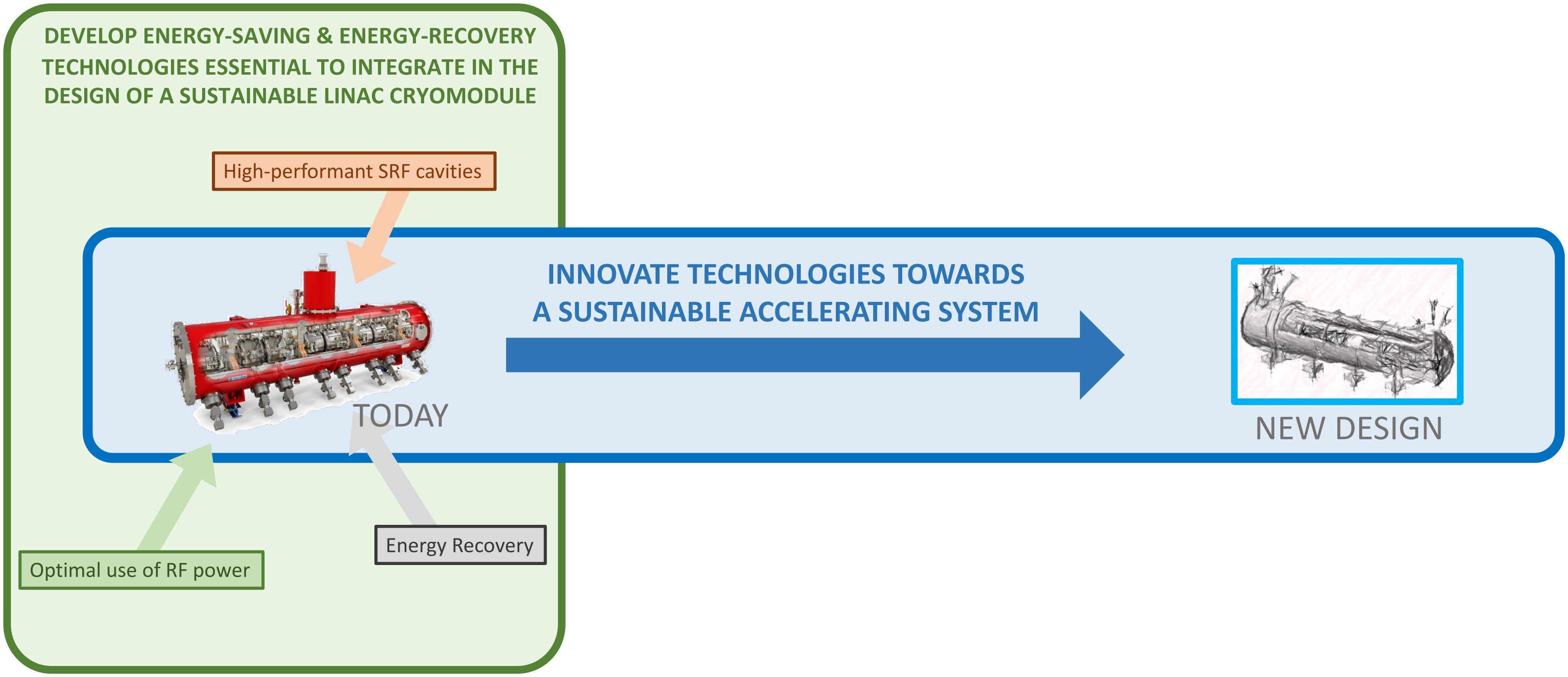
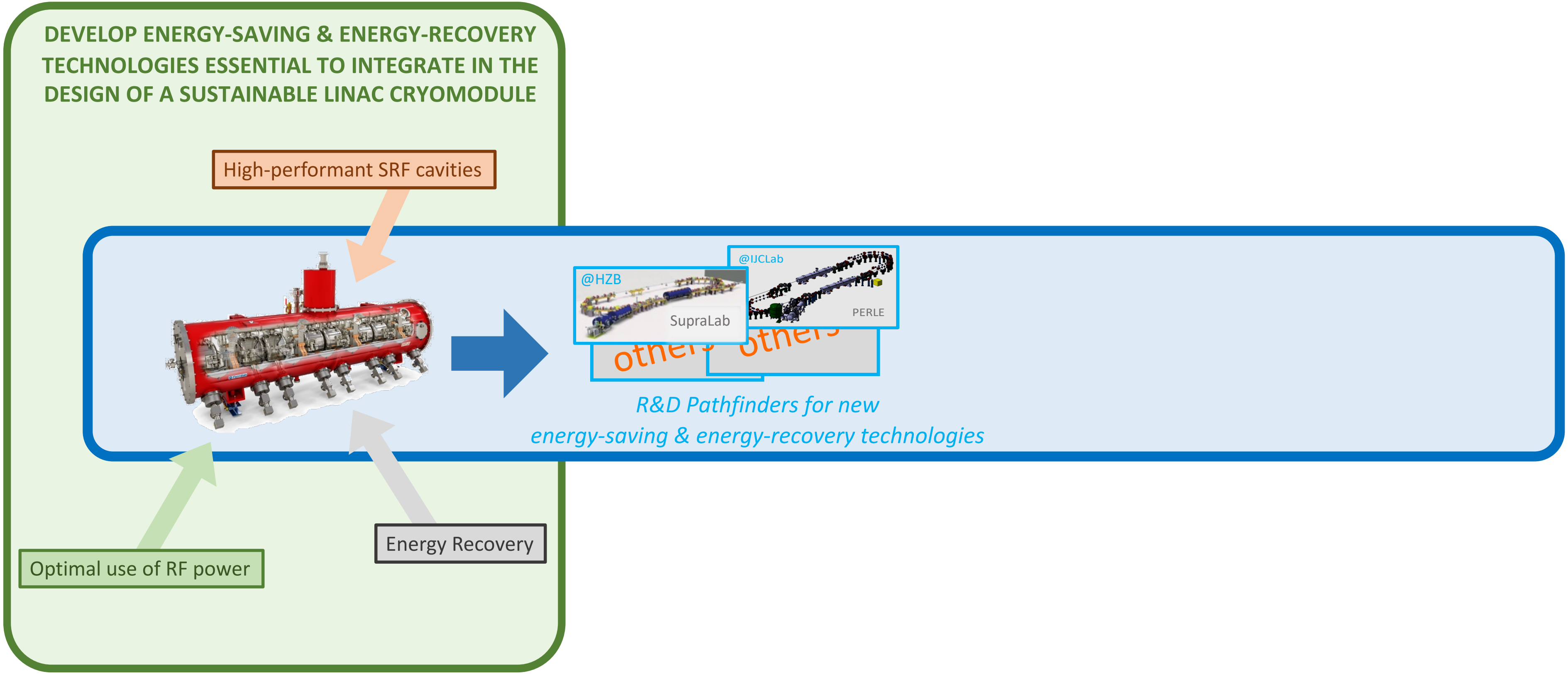


DEVELOP ENERGY-SAVING & ENERGY-RECOVERY TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
High-performant SRF cavities
INNOVATE TECHNOLOGIES TOWARDS A SUSTAINABLE ACCELERATING SYSTEM
TODAY
NEW DESIGN
Energy Recovery
Optimal use of RF power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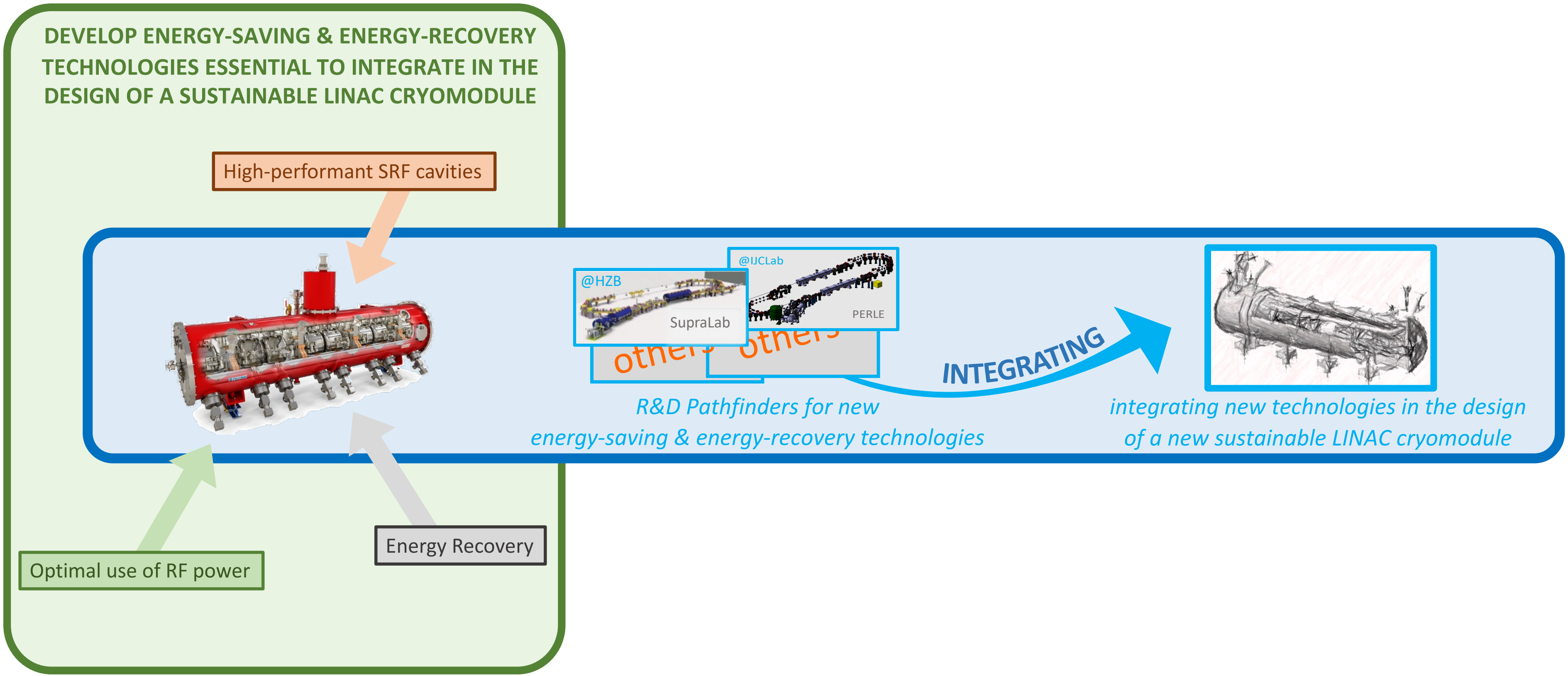
High-performant SRF cavities
@HZB
SupraLab
@IJCLab
PERLE
others
others
R&D Pathfinders for new
energy-saving & energy-recovery technologies
Optimal use of RF power
Energy Recovery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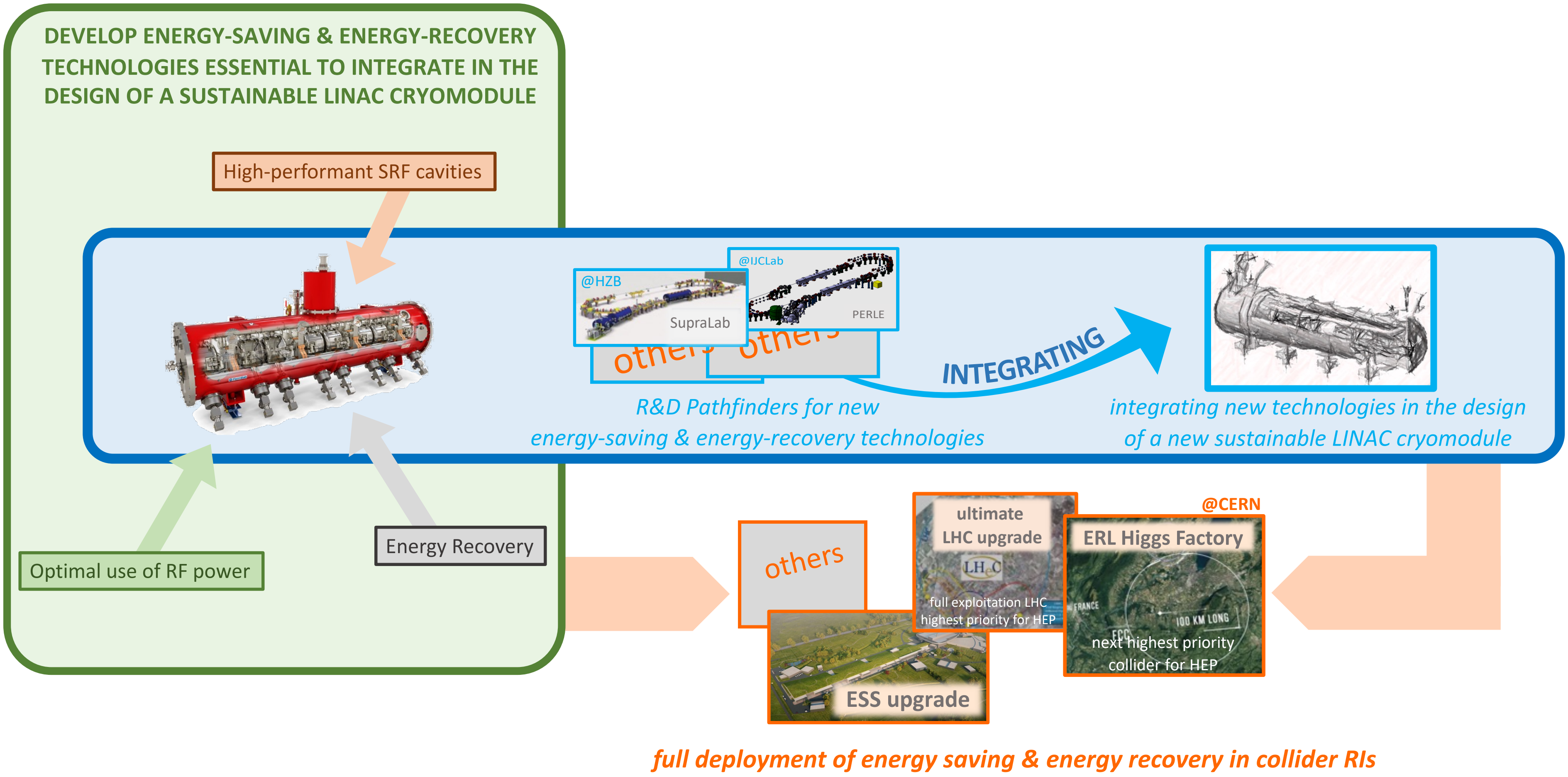
@HZB
SupraLab
@IJCLab
PERLE
INTEGRATING
R&D Pathfinders for new energy-saving & energy-recovery technologies
integrating new technologies in the design of a new sustainable LINAC cryomodule



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High-performant SRF cavities
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@HZB
SupraLab
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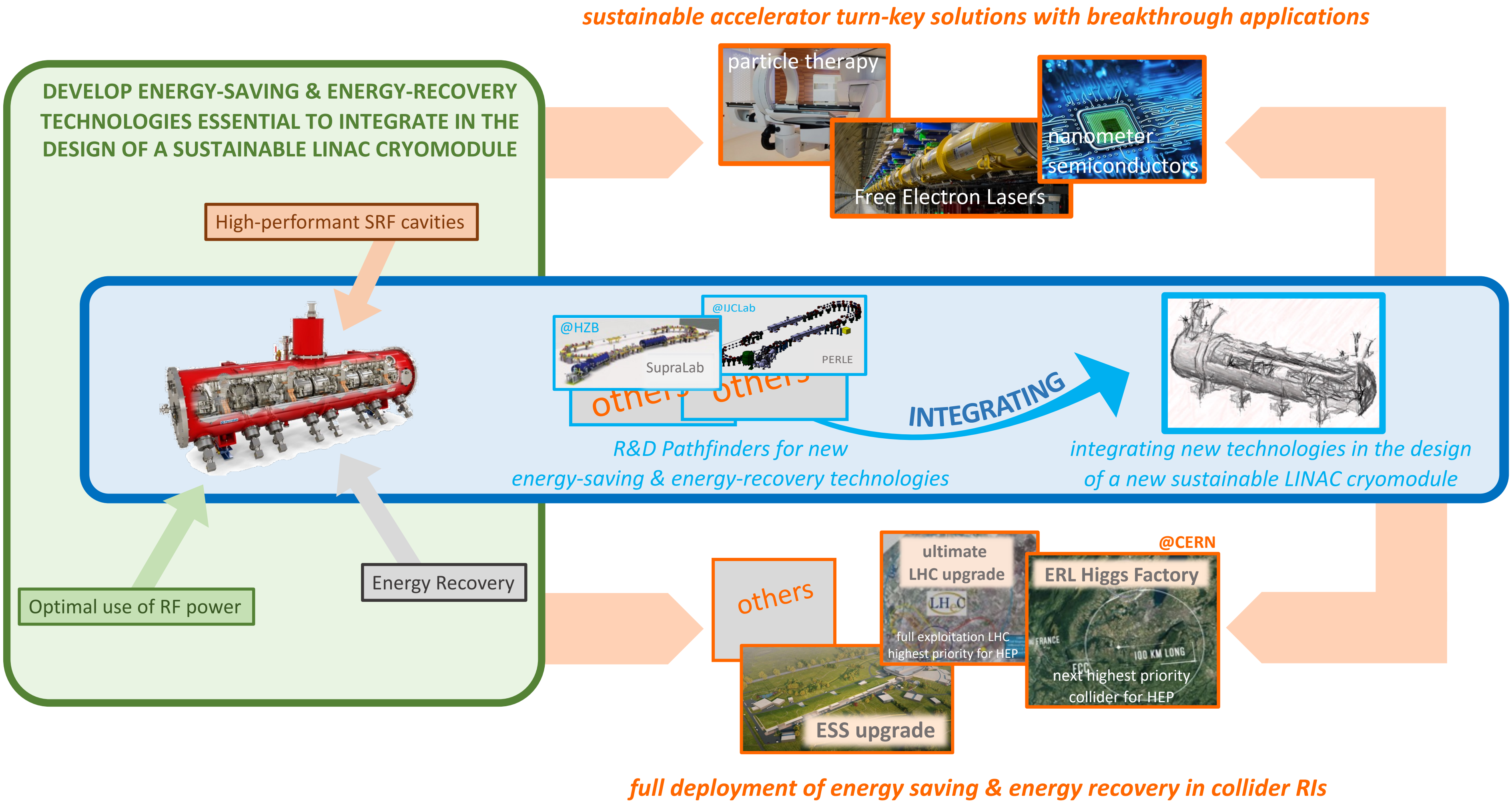
PERLE
others
others
INTEGRATING
R&D Pathfinders for new energy-saving & energy-recovery technologies
integrating new technologies in the design of a new sustainable LINAC cryomodule
others
ultimate LHC upgrade
LHeC
full exploitation LHC highest priority for HEP
@CERN
ERL Higgs Factory
FRANCE
100 KM LONG
next highest priority collider for HEP
ESS upgrade
full deployment of energy saving & energy recovery in collider RIs



sustainable accelerator turn-key solutions with breakthrough applications
DEVELOP ENERGY-SAVING & ENERGY-RECOVERY TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
particle therapy
Free Electron Lasers
nanometer semiconductors
High-performant SRF cavities
@HZB
SupraLab
@IJCLab
PERLE
others
others
INTEGRATING
R&D Pathfinders for new energy-saving & energy-recovery technologies
integrating new technologies in the design of a new sustainable LINAC cryomodule
Optimal use of RF power
Energy Recovery
others
ultimate LHC upgrade
full exploitation LHC highest priority for HEP
@CERN
ERL Higgs Factory
100 KM LONG
next highest priority collider for HEP
ESS upgrade
full deployment of energy saving & energy recovery in collider RIs

sustainable accelerator turn-key solutions with breakthrough applications

DEVELOP ENERGY-SAVING & ENERGY-RECOVERY TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE

High-performant SRF cavities

WORK IN PROGRESS

... the design
... a new sustainable LINAC cryomodule

Energy Recovery

Optimal use of RF power

@CERN

full deployment of energy saving & energy recovery in collider RIs

Deadline for applying is March 9, 2023.
Do not hesitate to contact me
for more information.

Electron-proton collisions at the core of particle physics

- The high-energy electron-hadron programme at the LHC and FCC are **truely general-purpose experiments** reaching beyond current knowledge in QCD, Higgs, EW and top quark physics and with its own BSM discovery potential
- At the same time, these programmes **empower the current research in ATLAS and CMS**, and are vital to unlock the full physics potential of a very-high-energy hadron collider
- And surely, when we look deeper into the proton we **significantly move the low-x frontier** and in this terra incognita we do not know what to discover
- 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… **Energy Recovery systems deliver on this technology front**

Innovate for Sustainable Accelerating Systems

- Developing “Sustainable Accelerating Systems” is a vital topic for the future of particle physics colliders, and a challenging responsibility we share as a community
- The R&D road ahead is very clear and well documented
- The ambition is shared with major accelerator laboratories in Europe, with a clear path to prioritise the R&D for sustainable accelerating structures in their organisation
- 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 colliders

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- 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 colliders
- The time has come to **promote and** to **commit** to 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

Innovate for Sustainable Accelerating Systems

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- **The R&D road ahead is very clear and well documented**
- The ambition is shared with major accelerator laboratories in Europe, with a clear path to prioritise the R&D for sustainable accelerating structures in their organisation
- **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 colliders**
- The time has come to **promote and** to **commit** to 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

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Thank you for your attention!

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