Energy Recovery & Future Colliders

Develop ep/eA colliders with a reduced energy footprint

Jorgen D'Hondt
Vrije Universiteit Brussel

PERLE/LHeC/FCC-eh Workshop, IJCLab (Paris, Orsay), 26-28 October 2022

Our curiosity drives us to the extremes

observable universe
8.8 10^{26}m

quarks
< 10^{-19}m

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

biological cell

atoms

proton neutron

observable universe
8.8 10^{26}m

visible with our own eyes

quarks
< 10^{-19}m

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

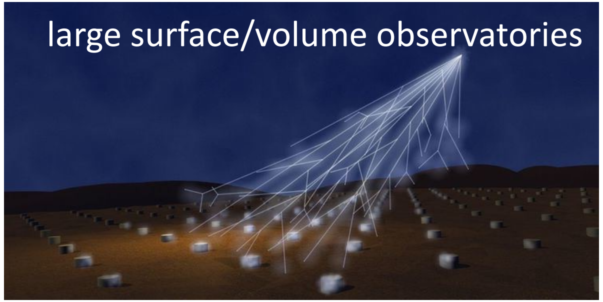
biological cell

atoms

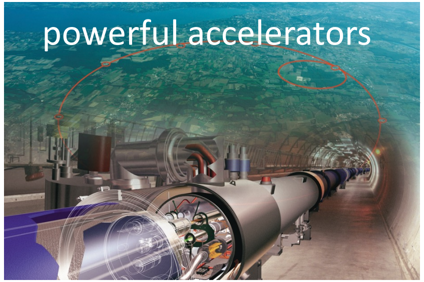
proton neutron

observable universe

$8.8\ 10^{26}m$



visible with our own eyes



quarks

$< 10^{-19}m$

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

biological cell

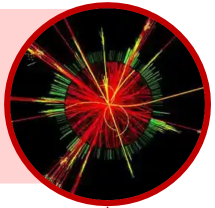
atoms

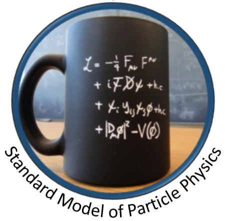
proton neutron

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

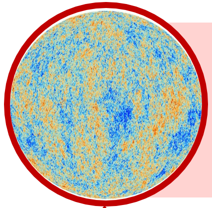
observations how small objects behave in our laboratories





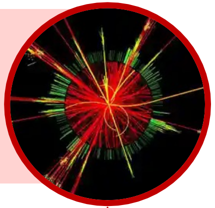
~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

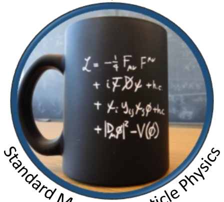


observations how large objects behave in our universe

Standard Model of Cosmology

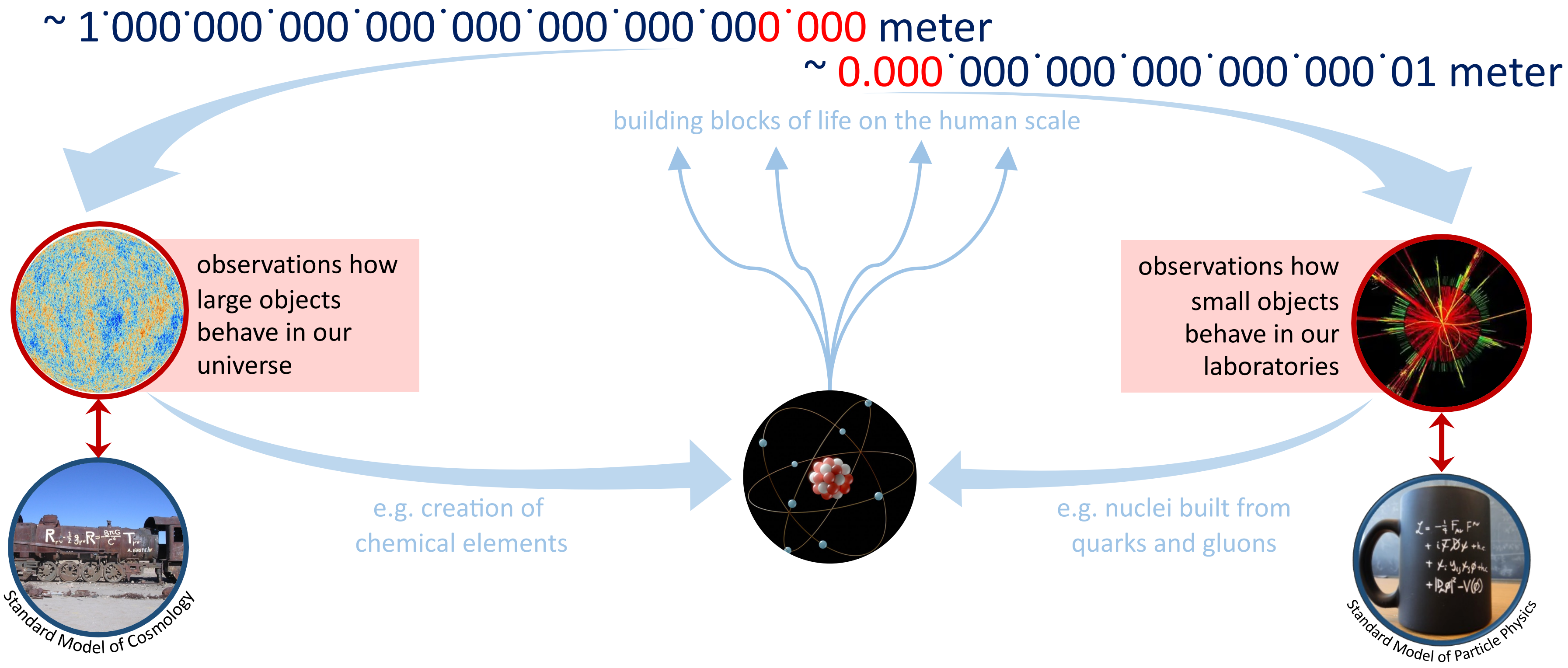


observations how small objects behave in our laboratories



Standard Model of Particle Physics

Einstein's field equations of gravity from which the Friedmann equations are derived to model the evolution of the universe

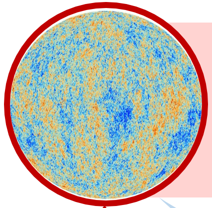

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter
~ 0.000˙000˙000˙000˙000˙000˙01 meter
building blocks of life on the human scale
observations how large objects behave in our universe
observations how small objects behave in our laboratories
e.g. creation of chemical elements
e.g. nuclei built from quarks and gluons
Standard Model of Cosmology
Standard Model of Particle Physics

A century of scientific revolutions

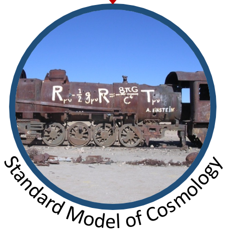
~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

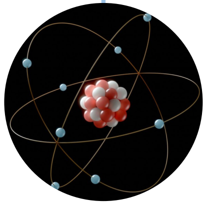
~ 0.000˙000˙000˙000˙000˙000˙01 meter

building blocks of life on the human scale

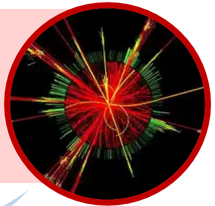


observations how large objects behave in our universe

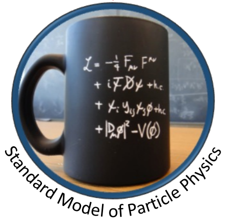




e.g. creation of chemical elements

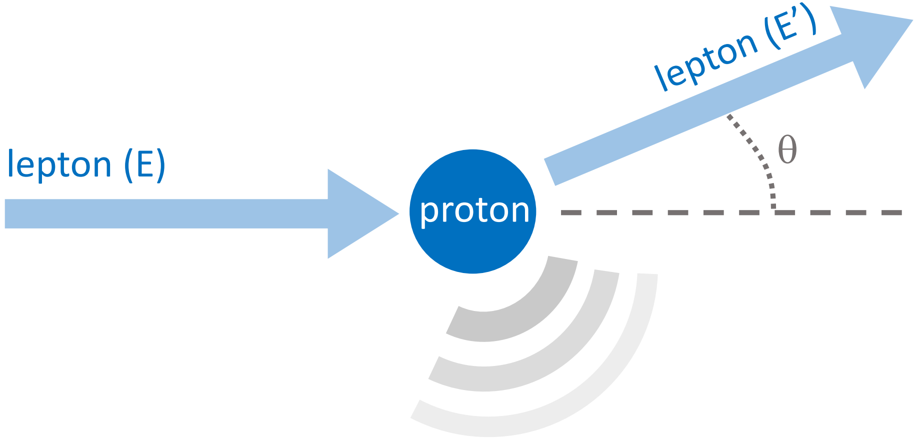


observations how small objects behave in our laboratories

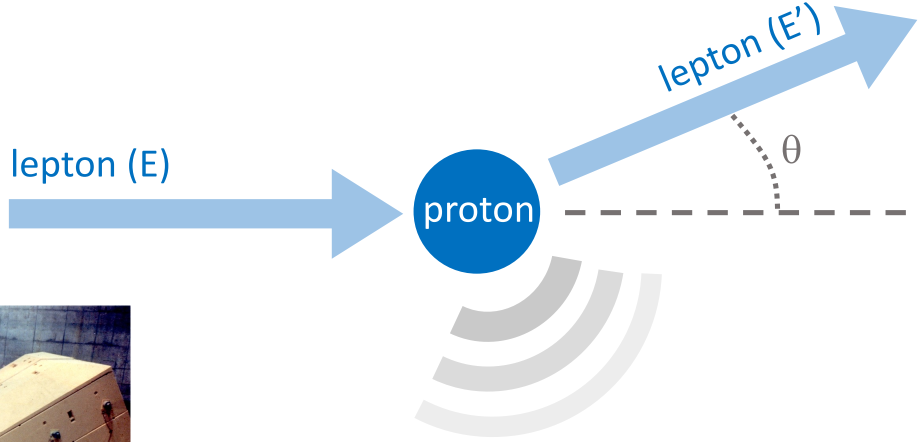


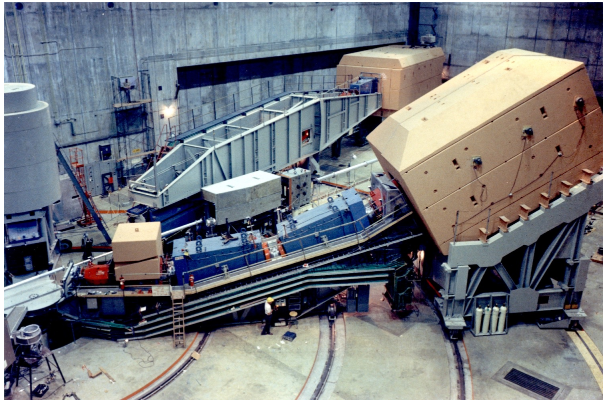
e.g. nuclei built from quarks and gluons

The 50+ years success story of DIS



The 50+ years success story of DIS

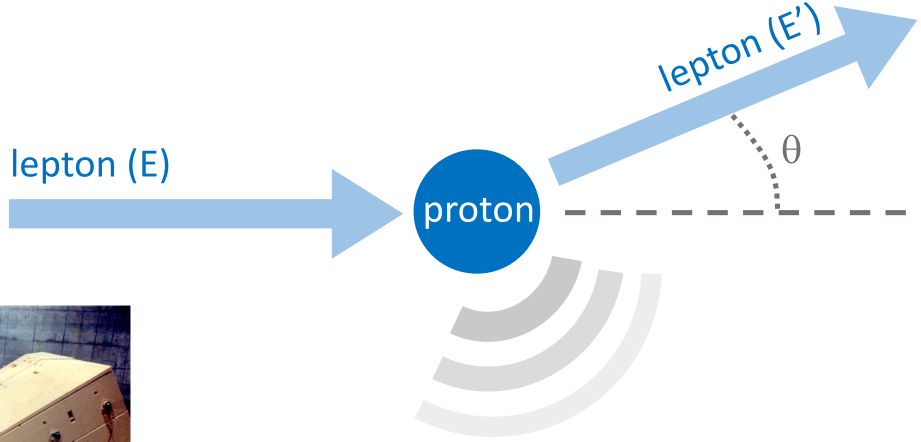


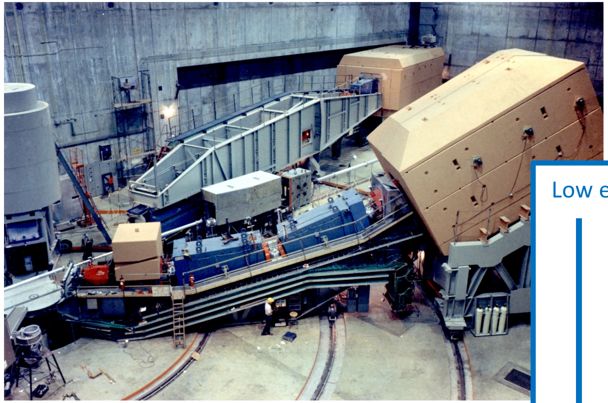


Discovery of quarks

(1968, ep@MIT-SLAC experiment)

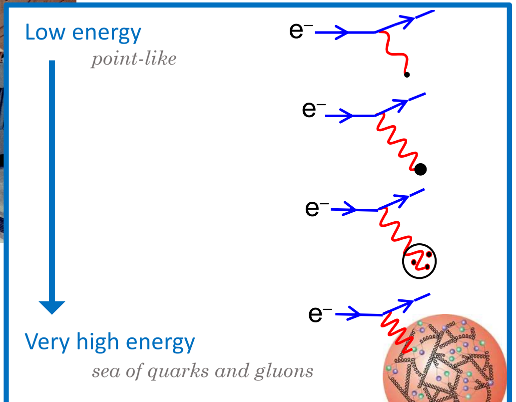
The 50+ years success story of DIS





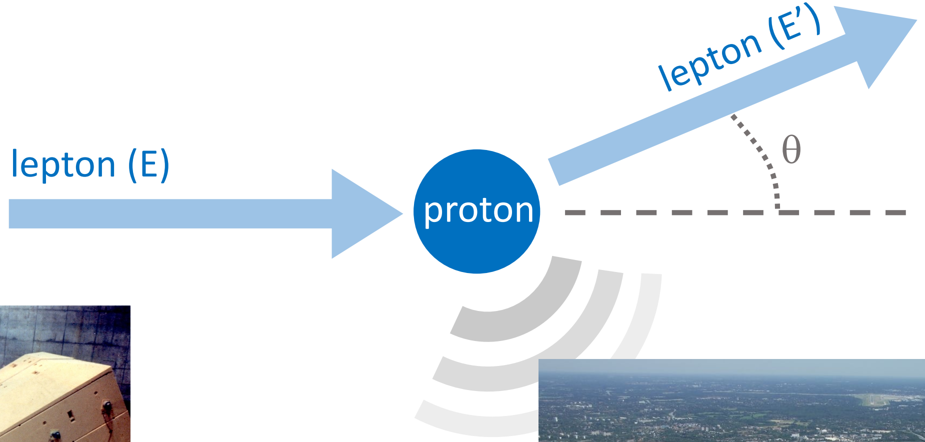
Discovery of quarks

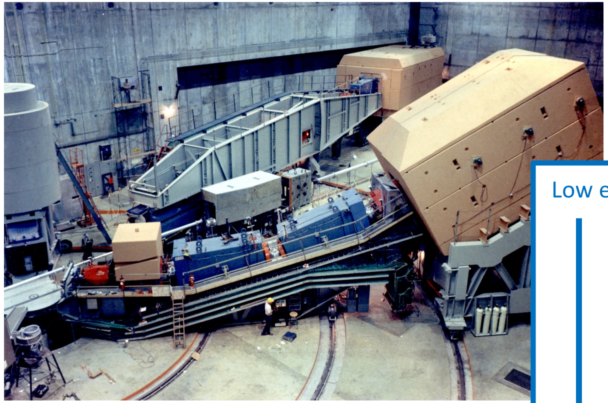
(1968, ep@MIT-SLAC experiment)



Parton model

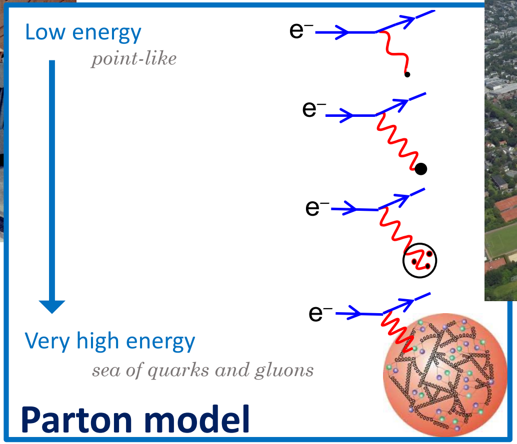
The 50+ years success story of DIS



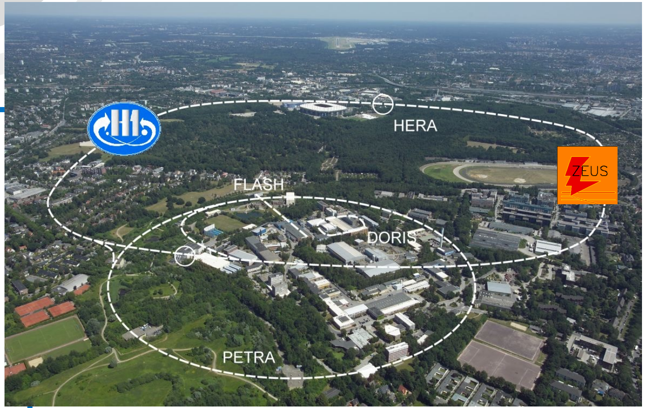


Discovery of quarks

(1968, ep@MIT-SLAC experiment)



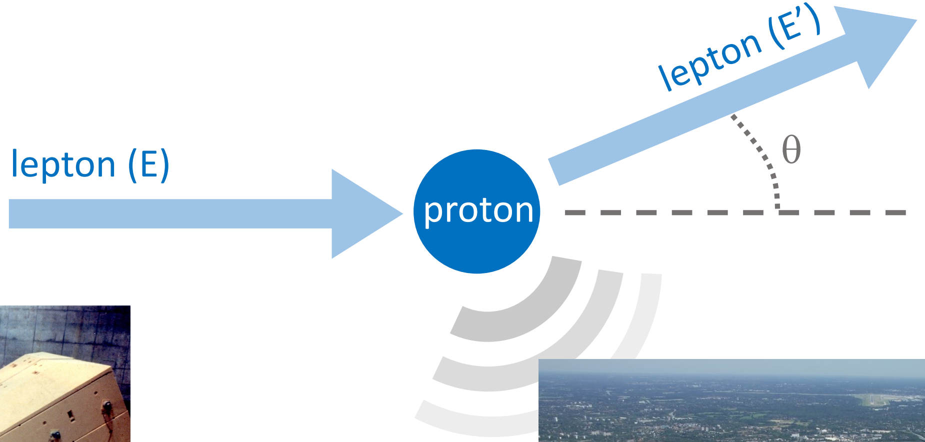
Parton model

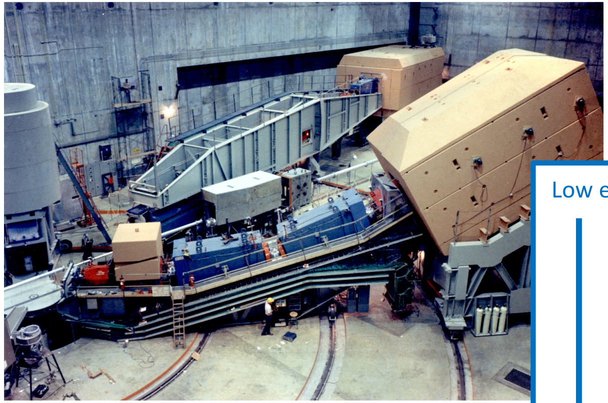


The DIS precision era

(1992-2007, $e^{\pm}p$@HERA)

The 50+ years success story of DIS



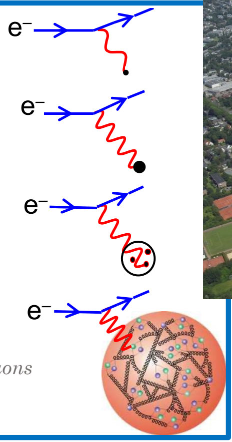


Discovery of quarks

(1968, ep@MIT-SLAC experiment)

Low energy

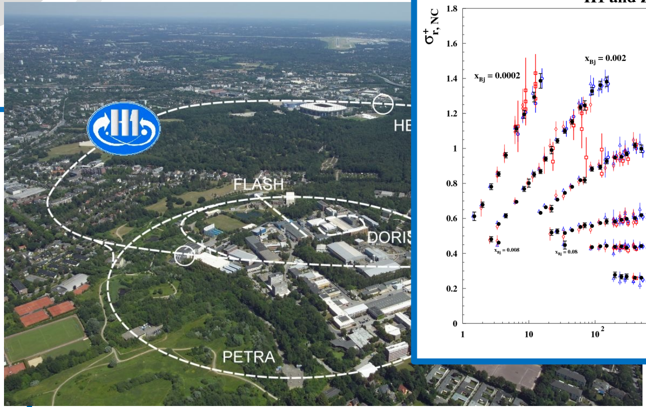
point-like

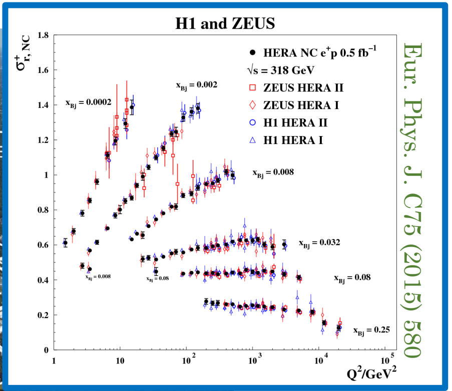


Very high energy

sea of quarks and gluons

Parton model

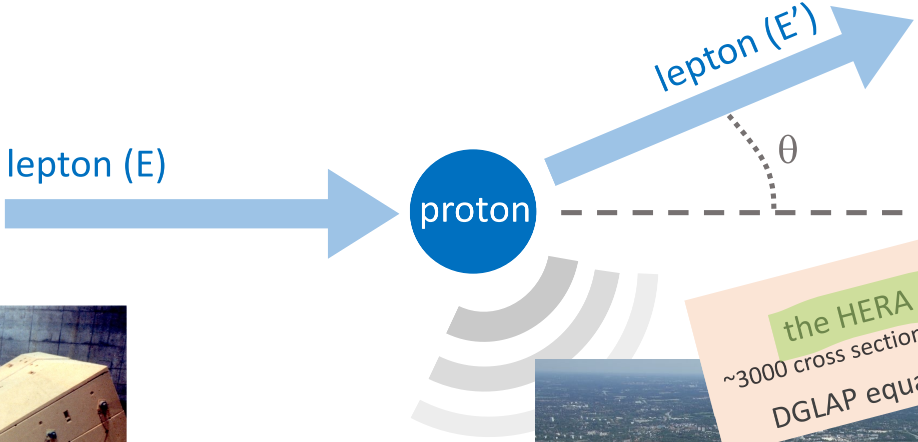




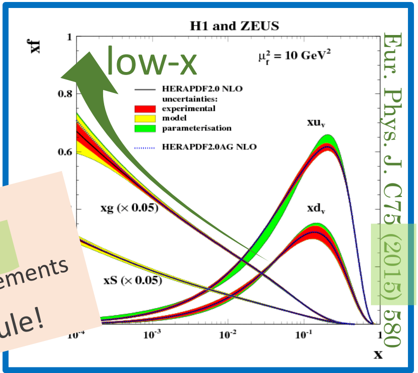
The DIS precision era

(1992-2007, e±p@HERA)

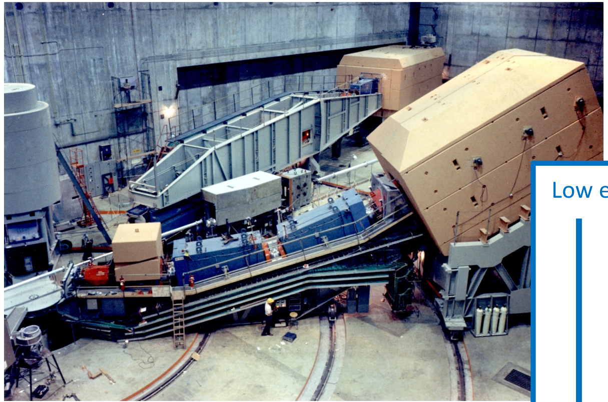
The 50+ years success story of DIS



Parton Distribution Functions

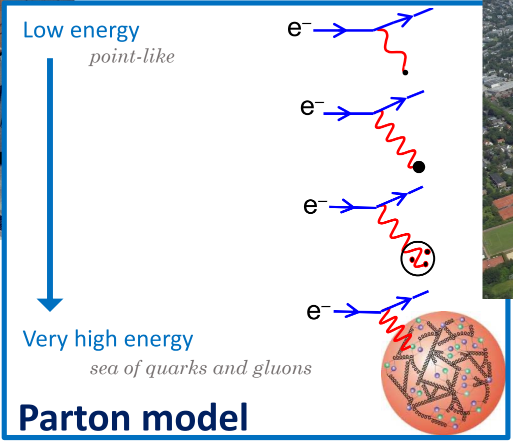


the HERA legacy
~3000 cross section measurements
DGLAP equations rule!

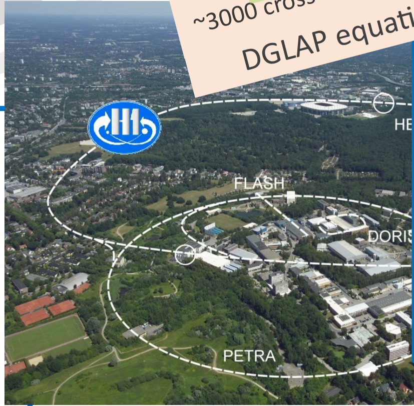


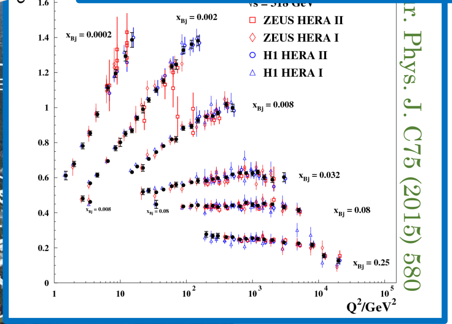
Discovery of quarks

(1968, ep@MIT-SLAC experiment)



Parton model





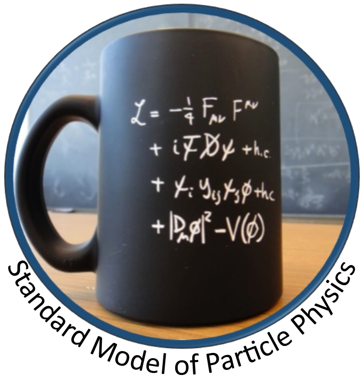
The DIS precision era

(1992-2007, $e^{\pm}p$@HERA)

DIS is alive!

381 registrations for DIS2022

The quest for understanding physics

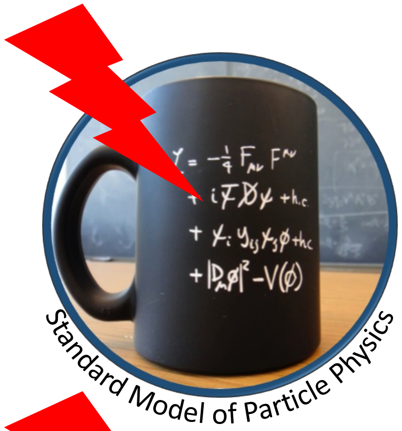


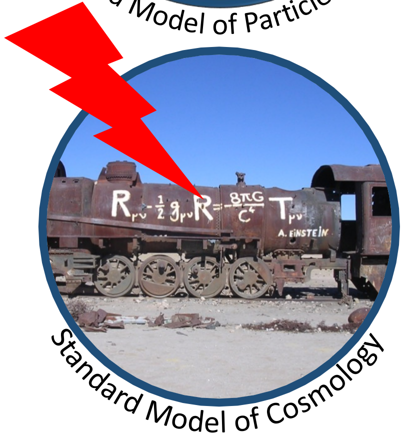
“Problems and Mysteries”

e.g. Abundance of dark matter?

Abundance of matter over antimatter?
What is the origin and engine for high-energy cosmic particles?
Dark energy for an accelerated expansion of the universe?
What caused (and stopped) inflation in the early universe?
Scale of things (why do the numbers miraculously match)?
Pattern of particle masses and mixings?
Dynamics of Electro-Weak symmetry breaking?
How do quarks and gluons give rise to properties of nuclei?
Resolution of the structure and dynamics inside hadrons? …

The quest for understanding physics





"Problems and Mysteries"

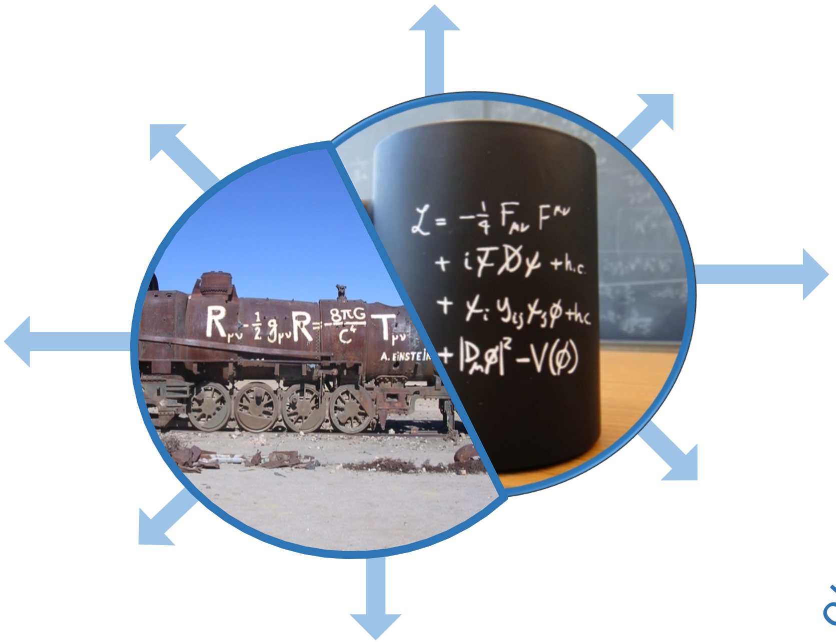
e.g. Abundance of dark matter?
Abundance of matter over antimatter?
What is the origin and engine for high-energy cosmic particles?
Dark energy for an accelerated expansion of the universe?
What caused (and stopped) inflation in the early universe?
Scale of things (why do the numbers miraculously match)?
Pattern of particle masses and mixings?
Dynamics of Electro-Weak symmetry breaking?
How do quarks and gluons give rise to properties of nuclei?
Resolution of the structure and dynamics inside hadrons? …

Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

higher energy interactions
in the lab

earlier universe

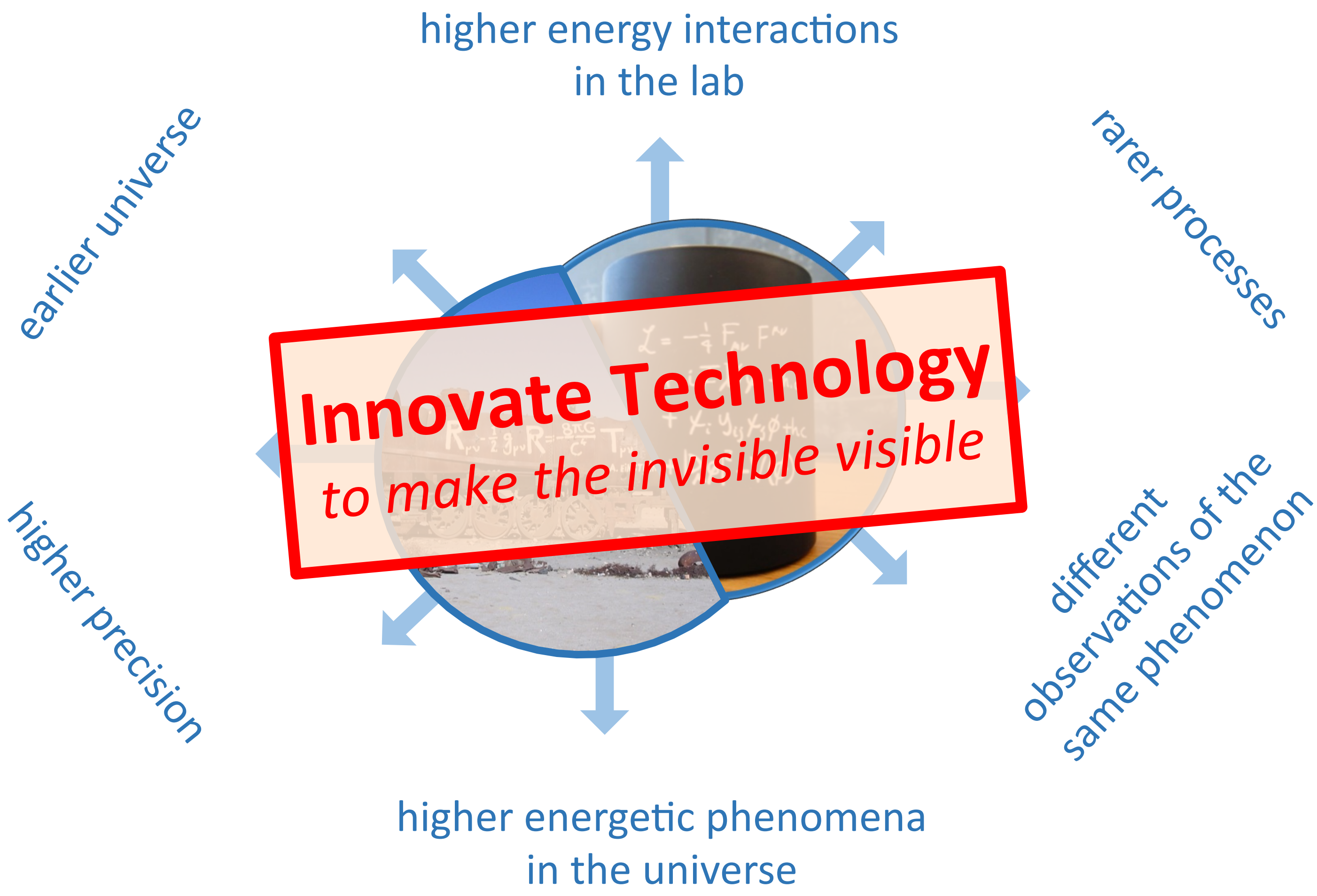
rarer processes



higher precision

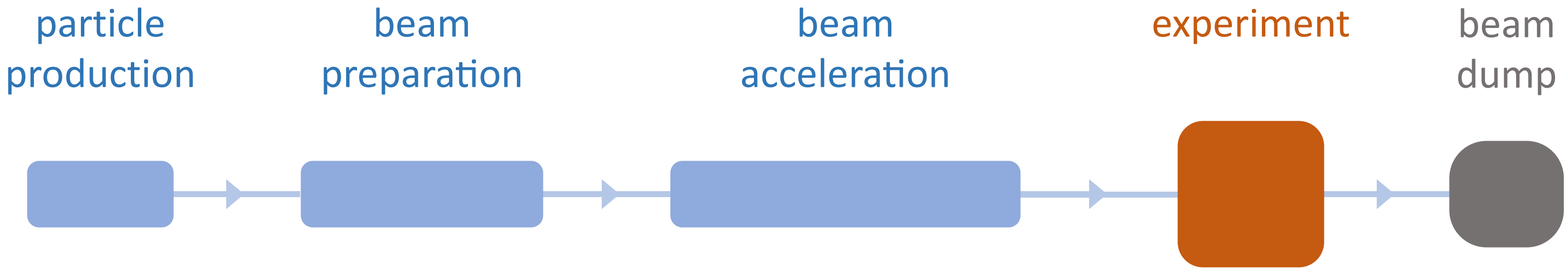
different
observations of the
same phenomenon

higher energetic phenomena
in the universe

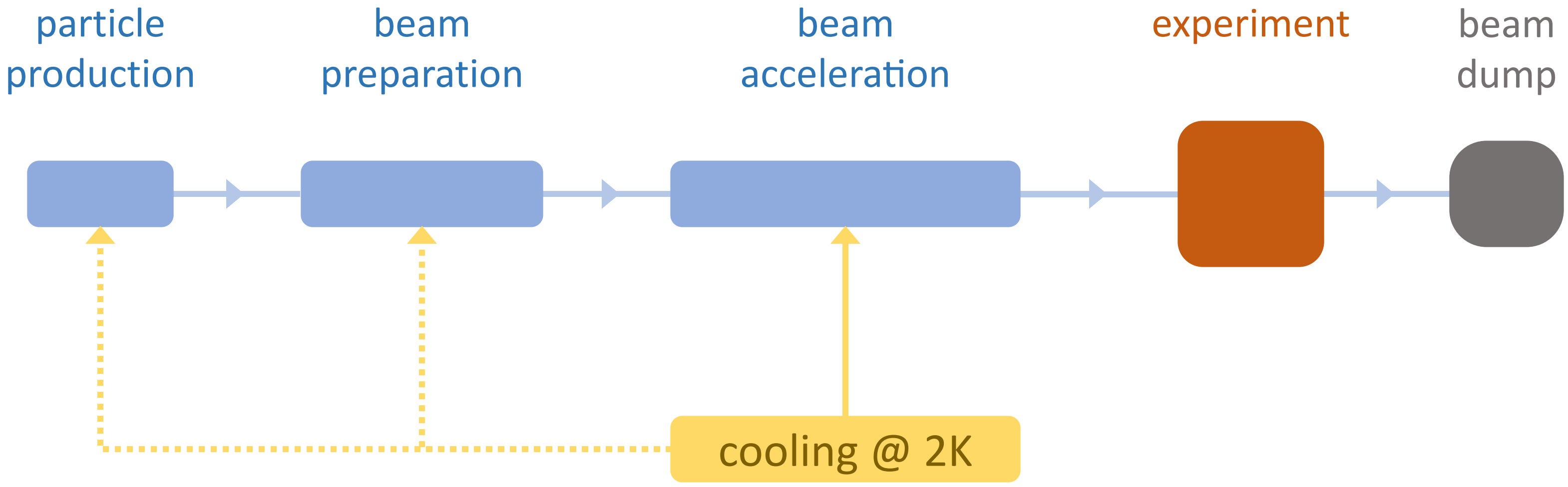

higher energy interactions
in the lab
earlier universe
rarer processes
Innovate Technology
to make the invisible visible
higher precision
different
observations of the
same phenomenon
higher energetic phenomena
in the universe

High Energy Physics
requires
powerful accelerators

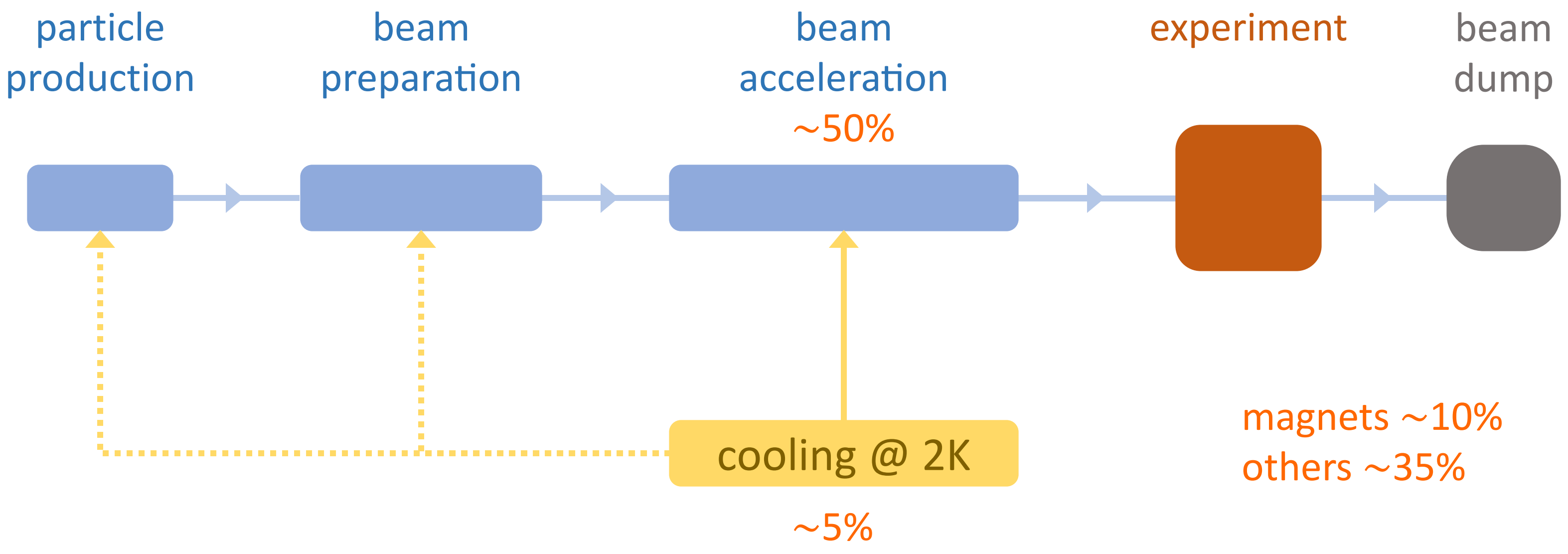
Basic structures of a particle accelerator



Basic structures of a particle accelerator



Basic structures of a particle accelerator

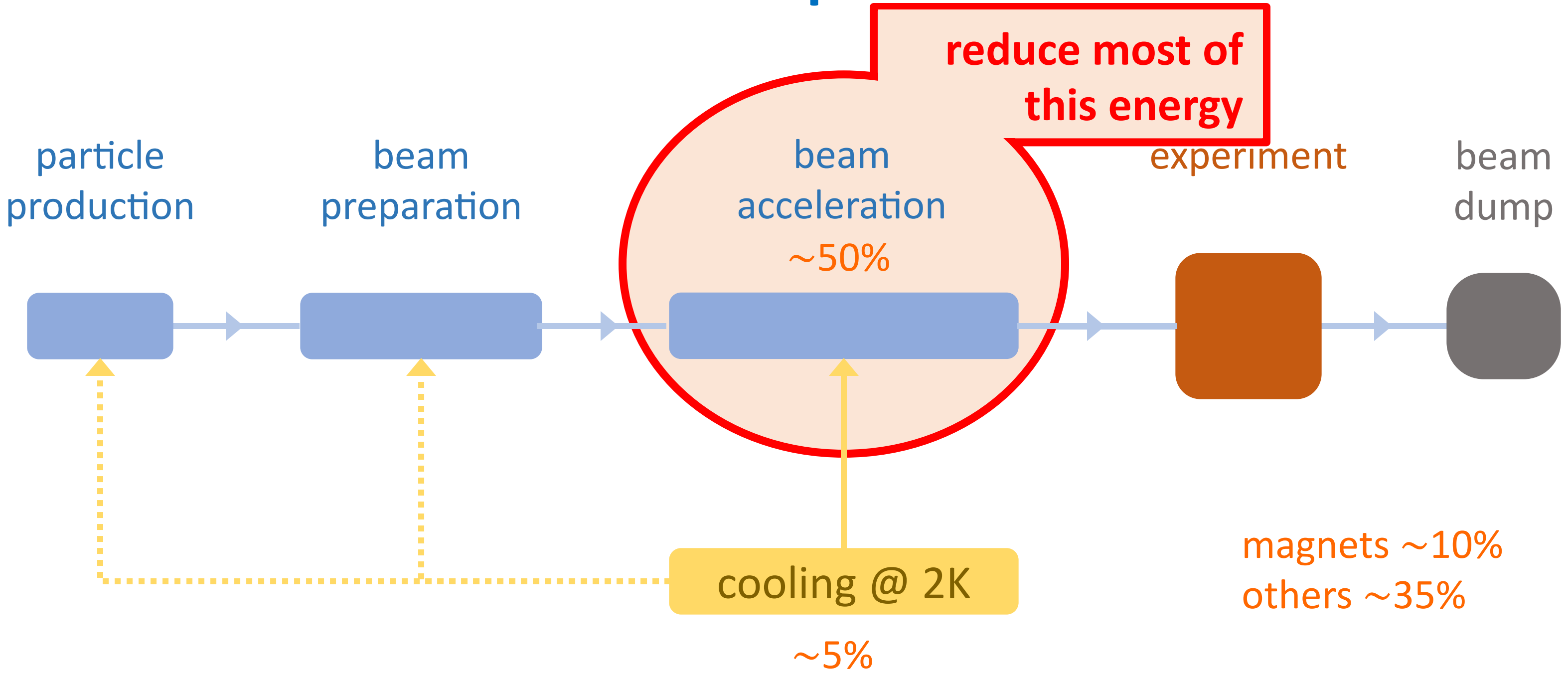


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator

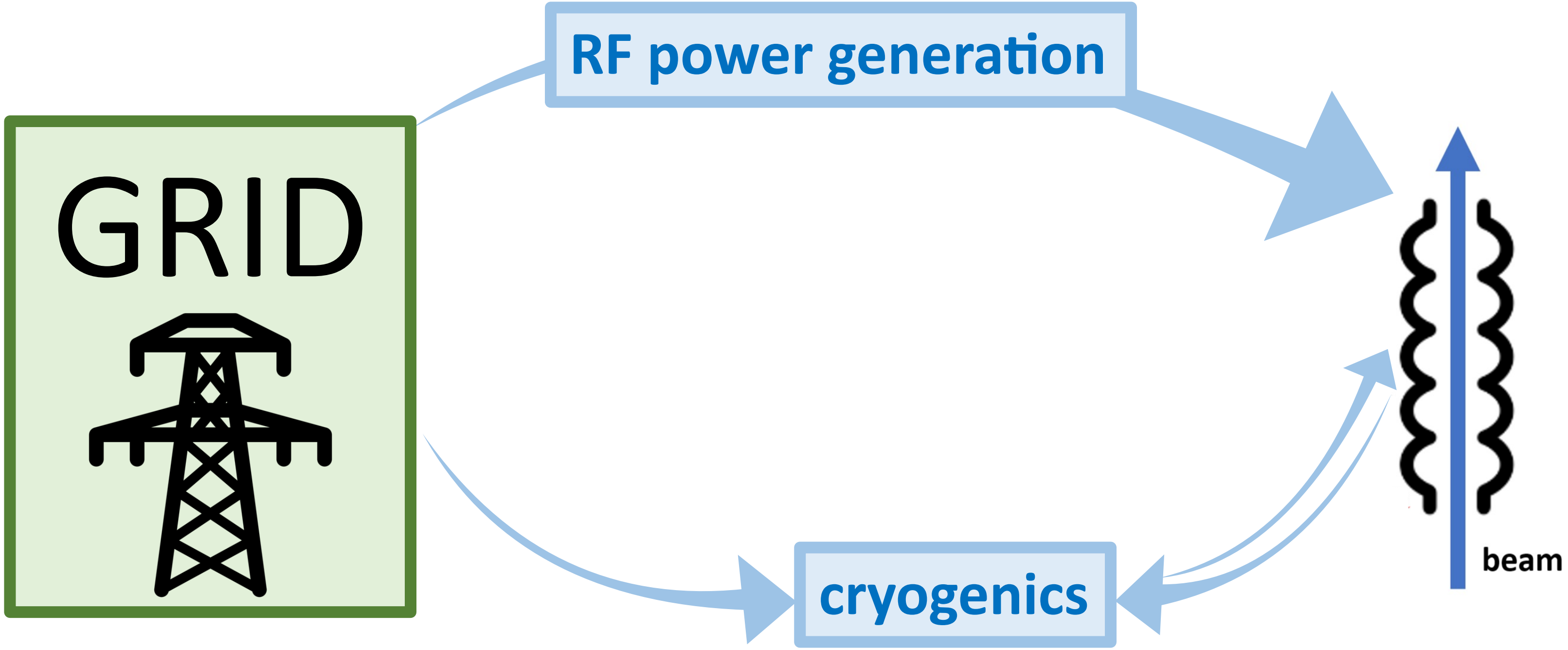


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

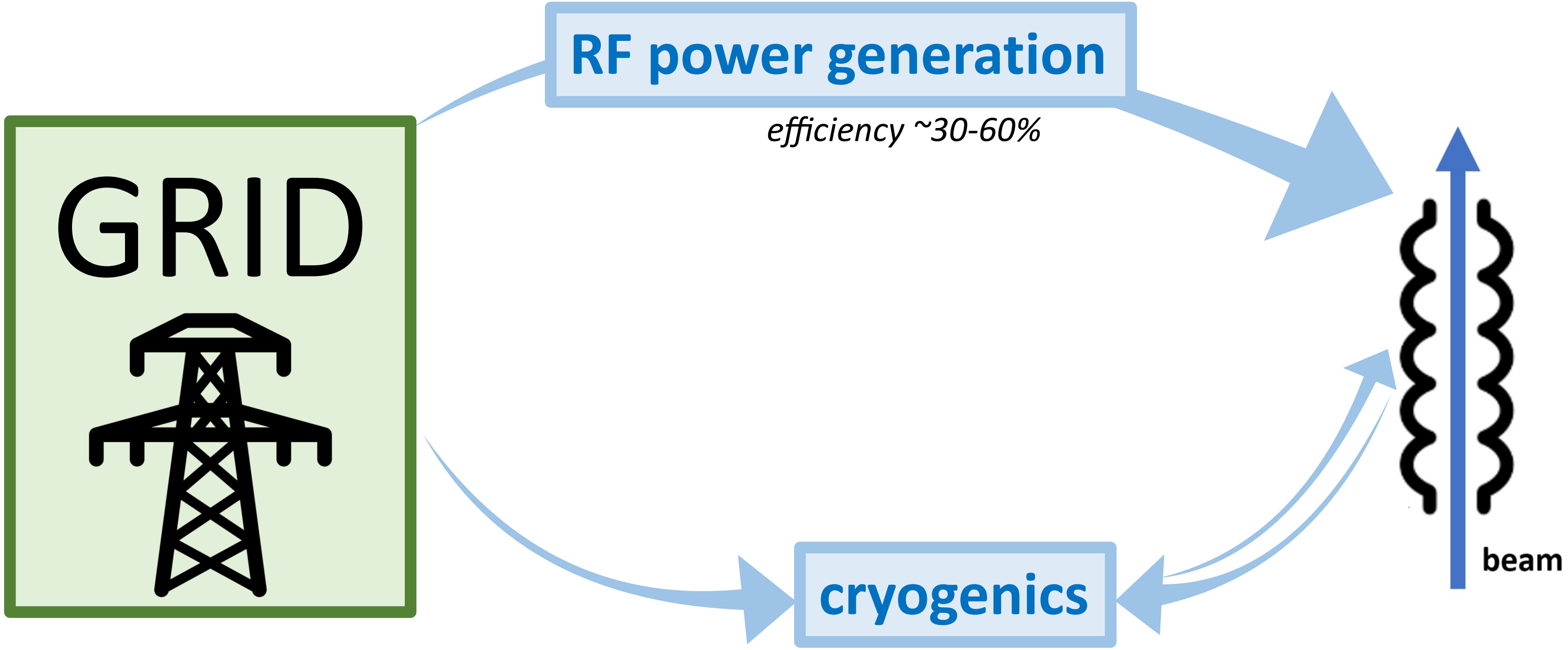
example FCC@250GeV

From Grid to Beam

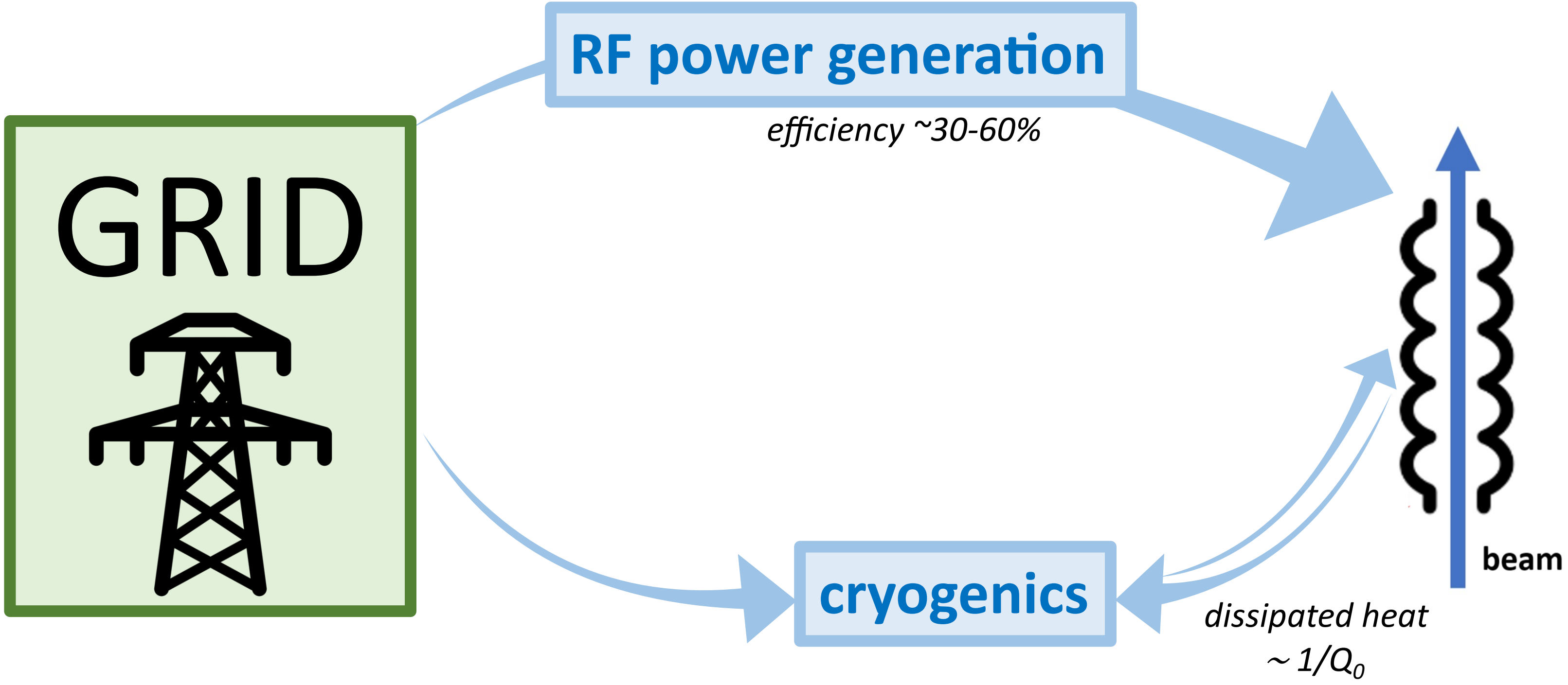


Picture adopted from M. Seidel (IPAC 2022)

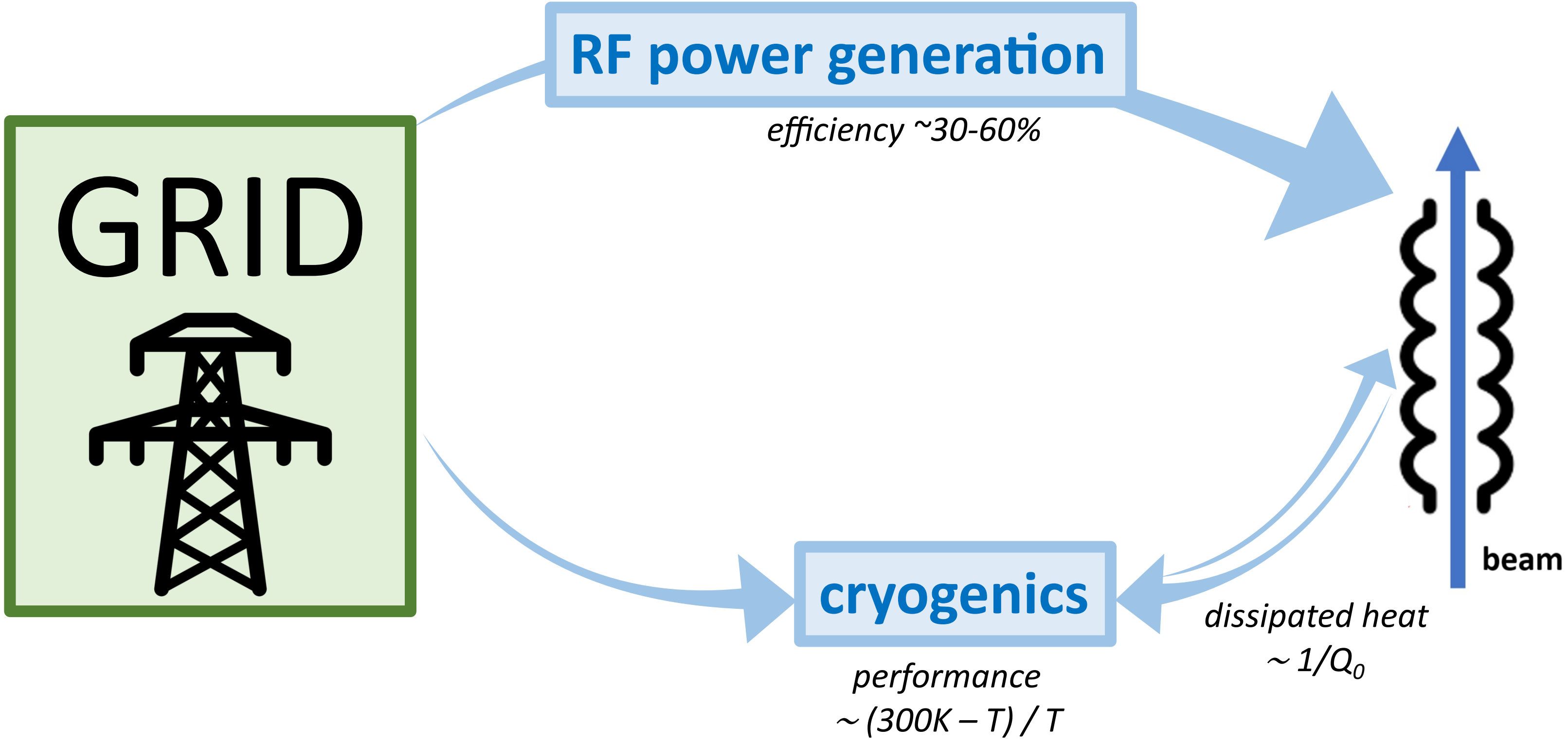
From Grid to Beam



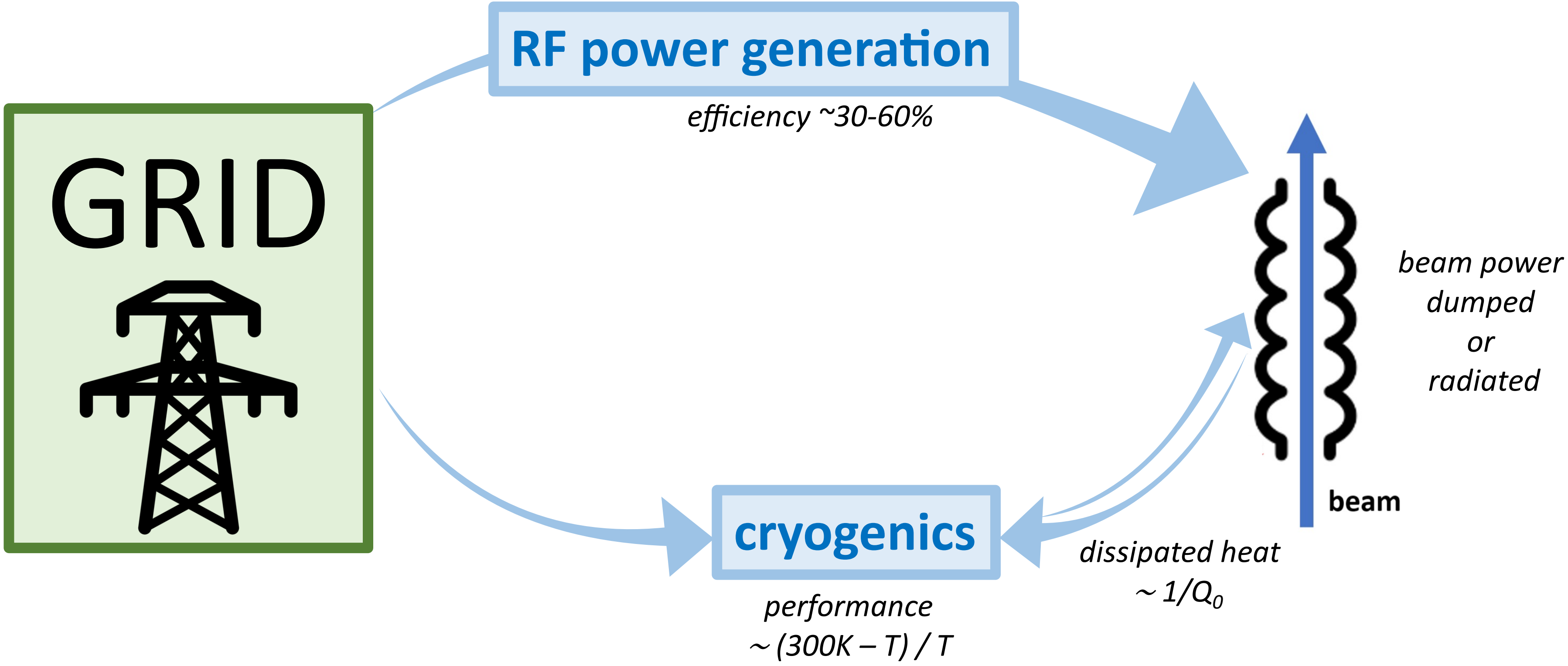
From Grid to Beam



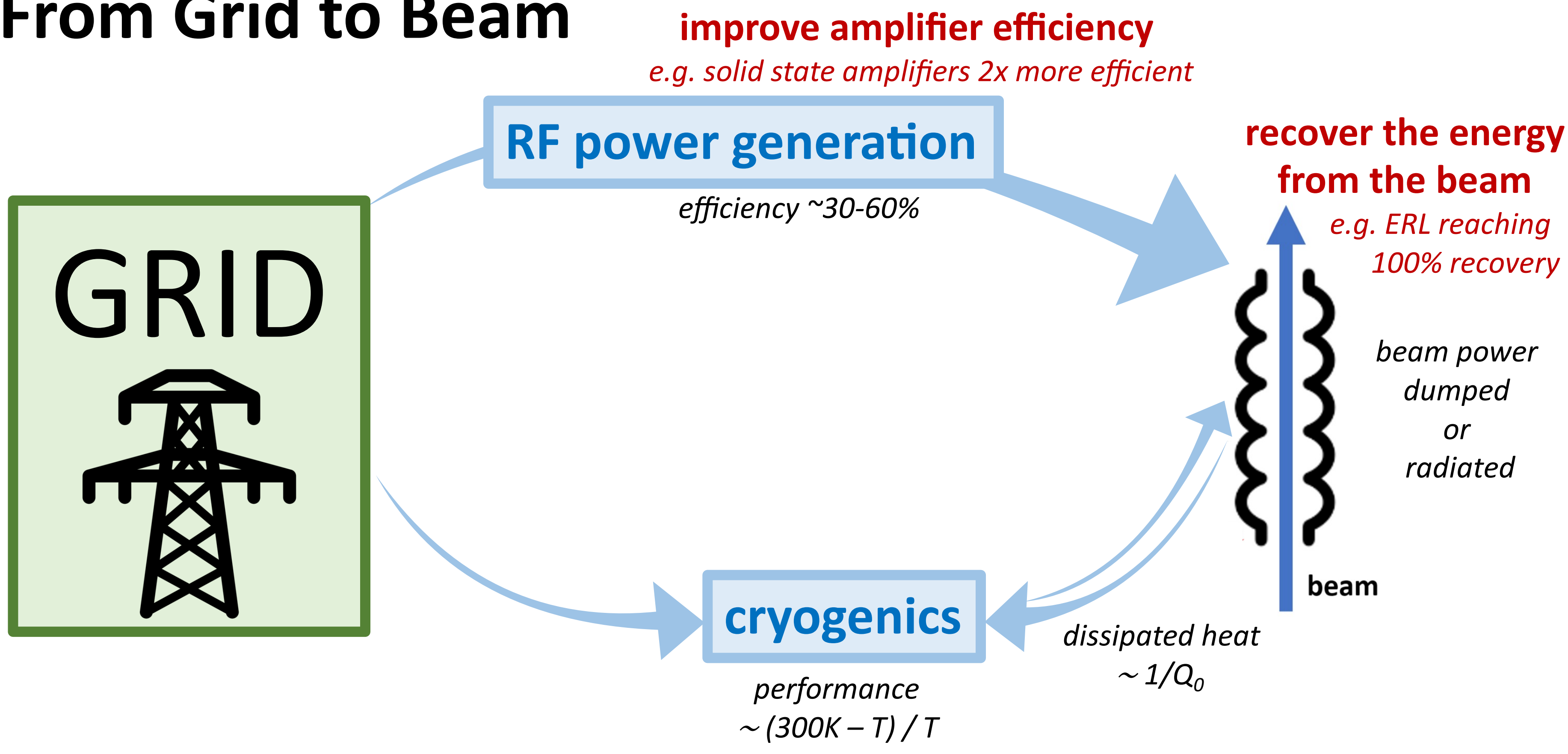
From Grid to Beam



From Grid to Beam



From Grid to Beam



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 2x more efficient

RF power generation

… the energy
… the beam
… ERL reaching
…00% recovery

…eam power
dumped
or
…adiated

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

R&D for Sustainable Accelerating Structures
less energy, less cooling, less power loss, recover beam power

beam

cryogenics

dissipated heat
~ $1/Q_0$

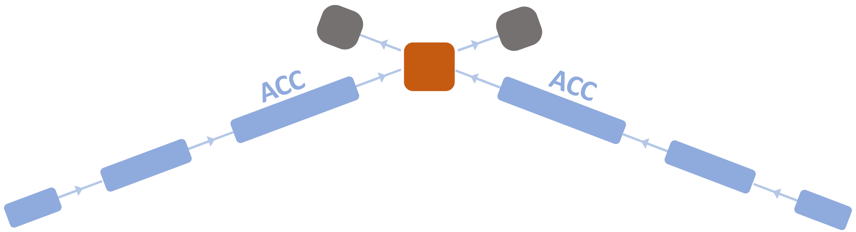
performance
~ (300K – T) / T

operate cavities at higher T & improve Q_0 of cavities
e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

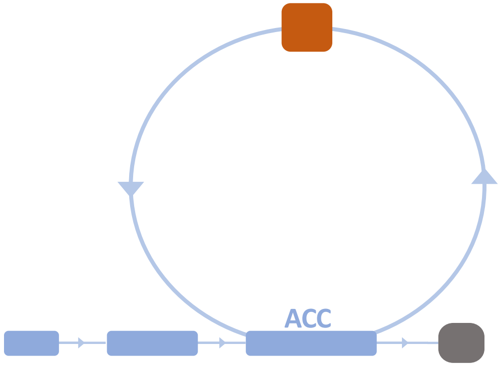
focus here on the energy recovery part

Designs of high-energy particle colliders

Linear colliders

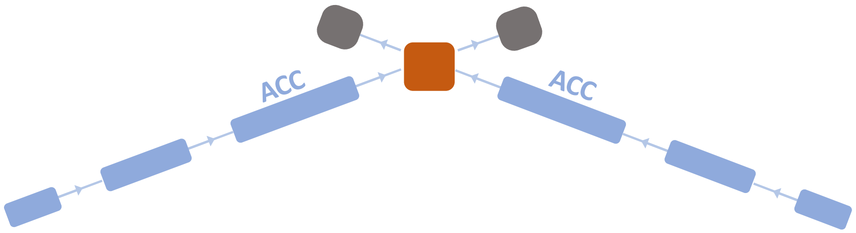


Circular colliders



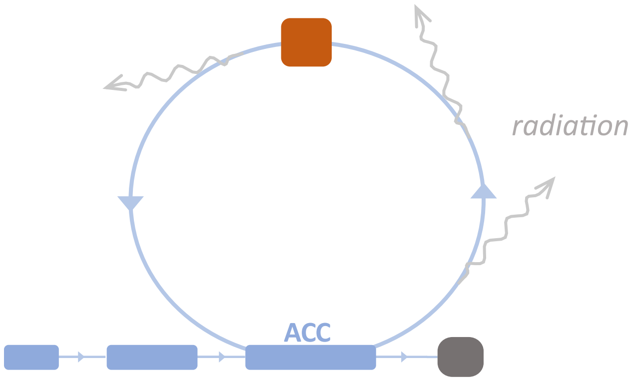
Designs of high-energy particle colliders

Linear colliders



dump >99.9999% of
the beam power

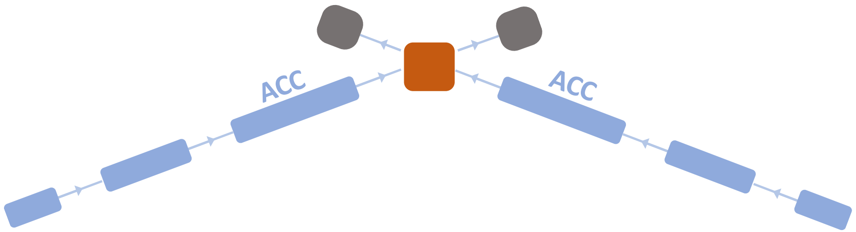
Circular colliders



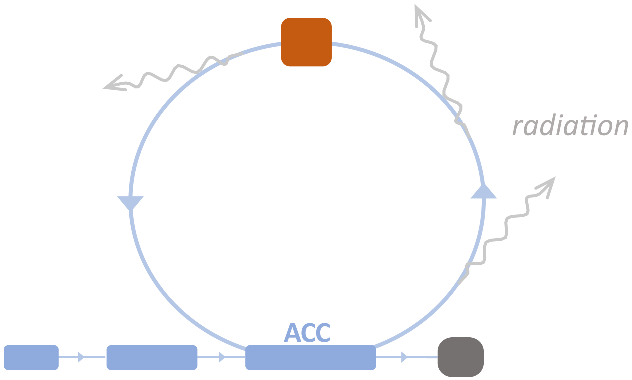
radiate away very quickly
the beam power

Designs of high-energy particle colliders

Linear colliders



Circular colliders



dump >99.9999% of the beam power

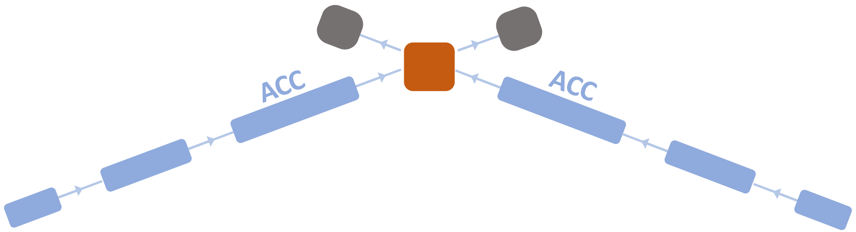
FCC-ee@250 $\simeq$ 300 MW

radiate away very quickly the beam power

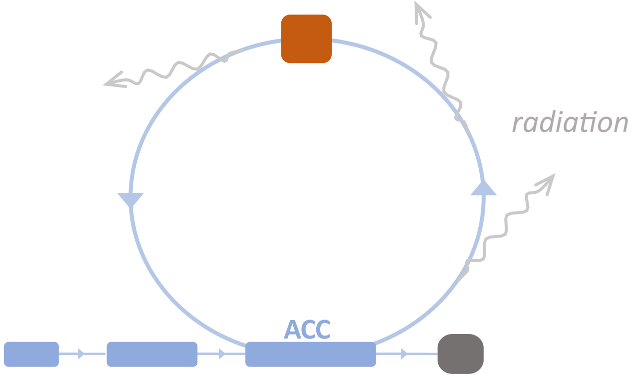
about half of this is dumped or radiated

Designs of high-energy particle colliders

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

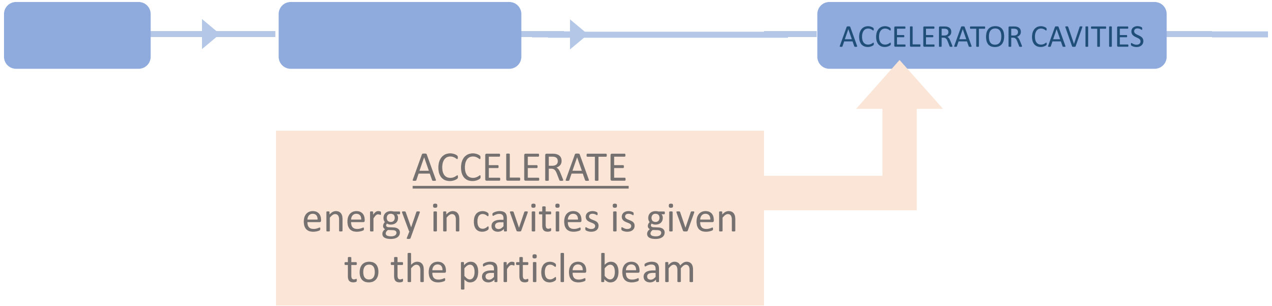
~2% of annual electricity consumption in Belgium

radiate away very quickly the beam power

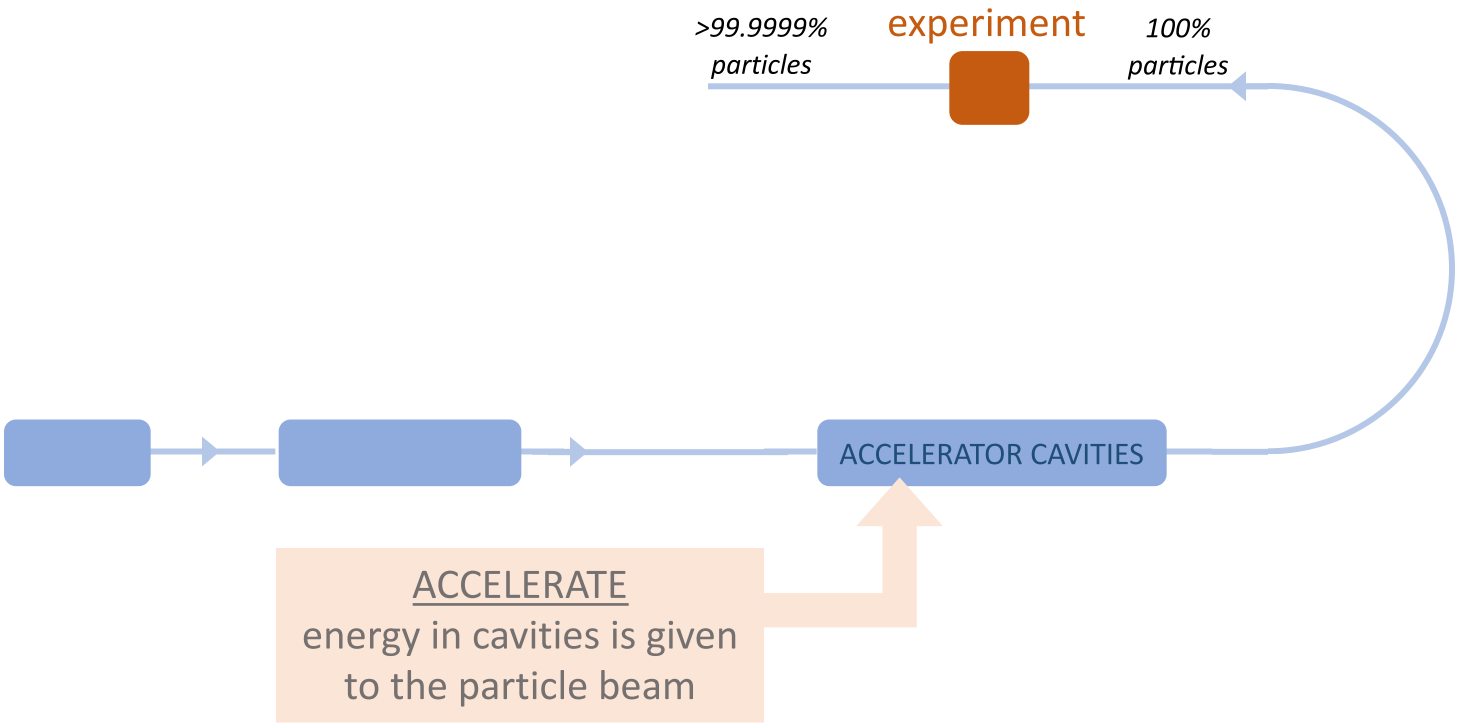
about half of this is dumped or radiated

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

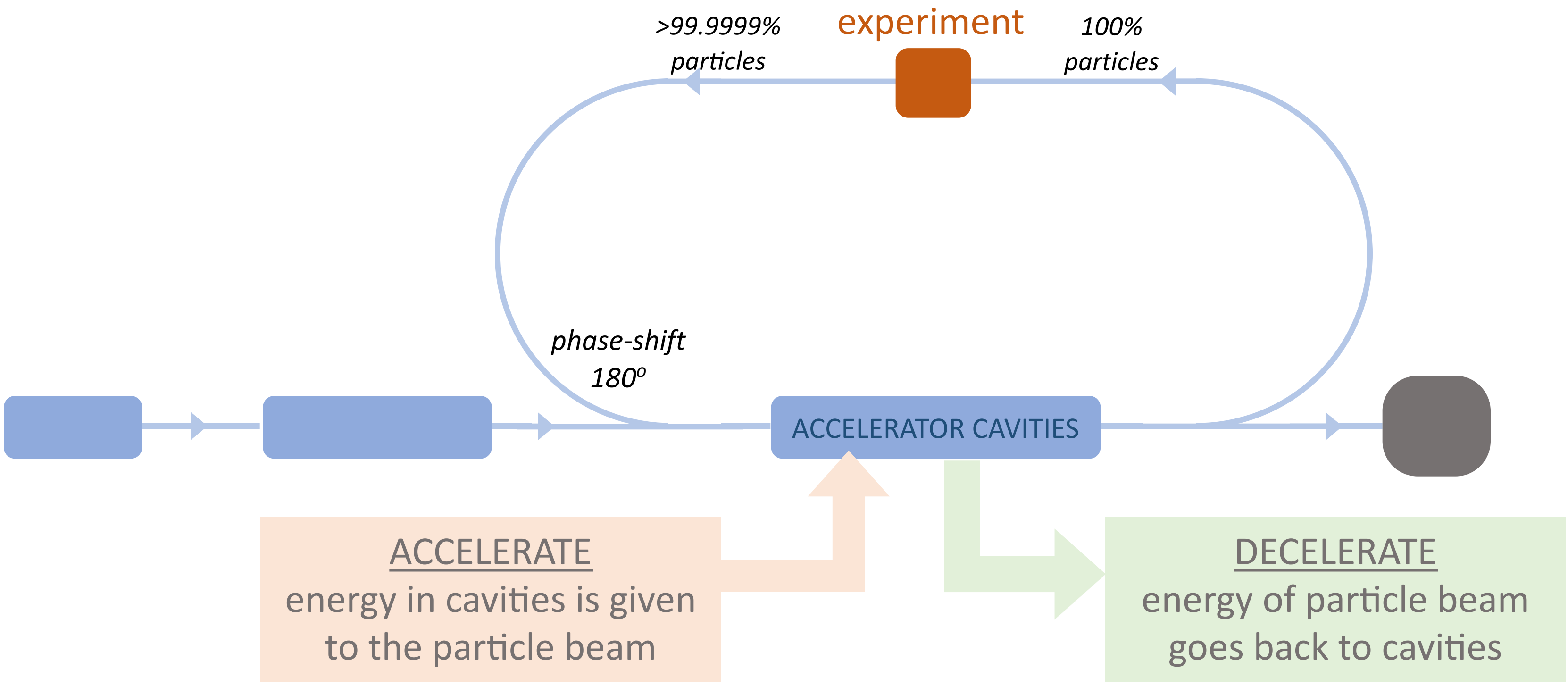
The principle of Energy Recovery



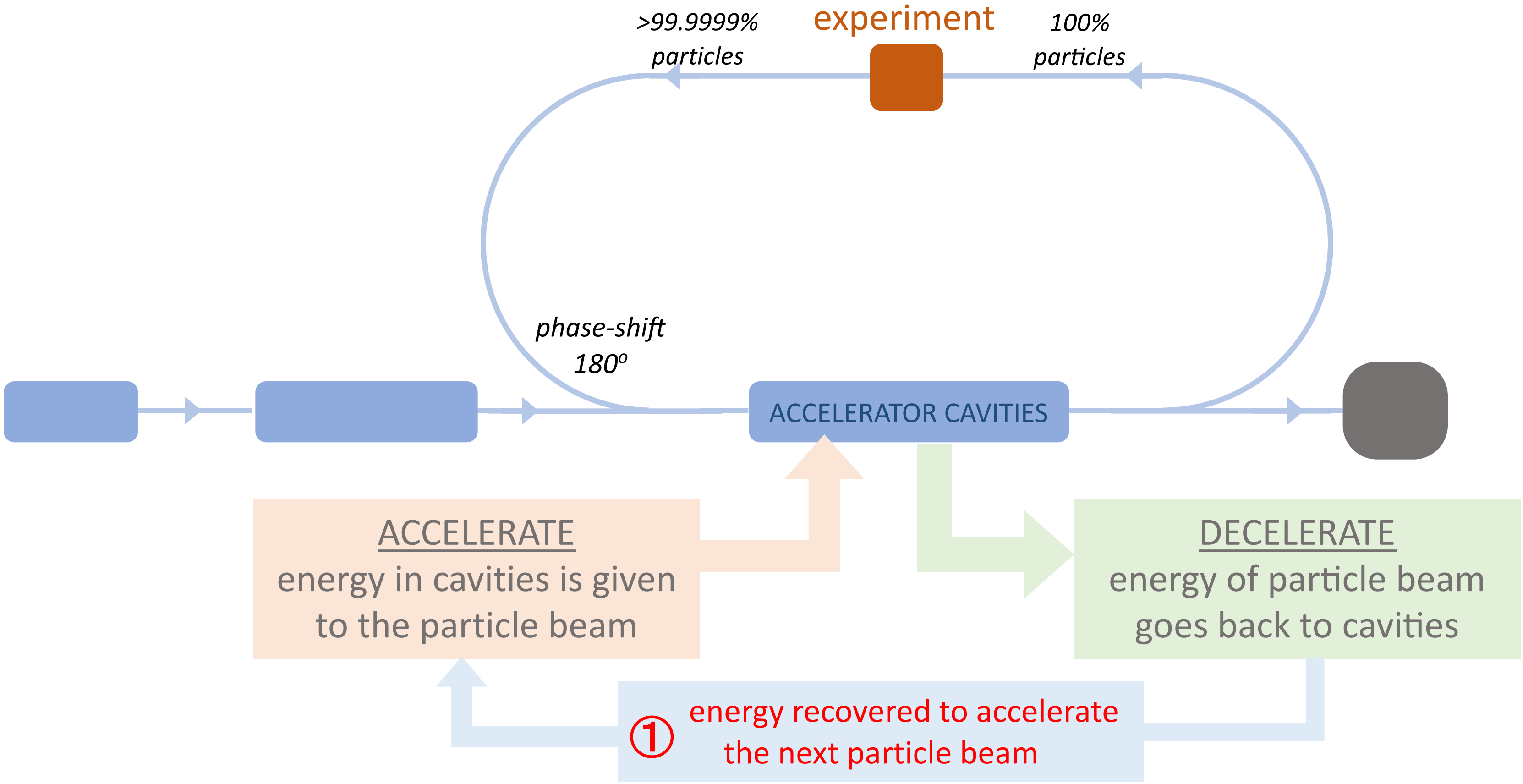
The principle of Energy Recovery



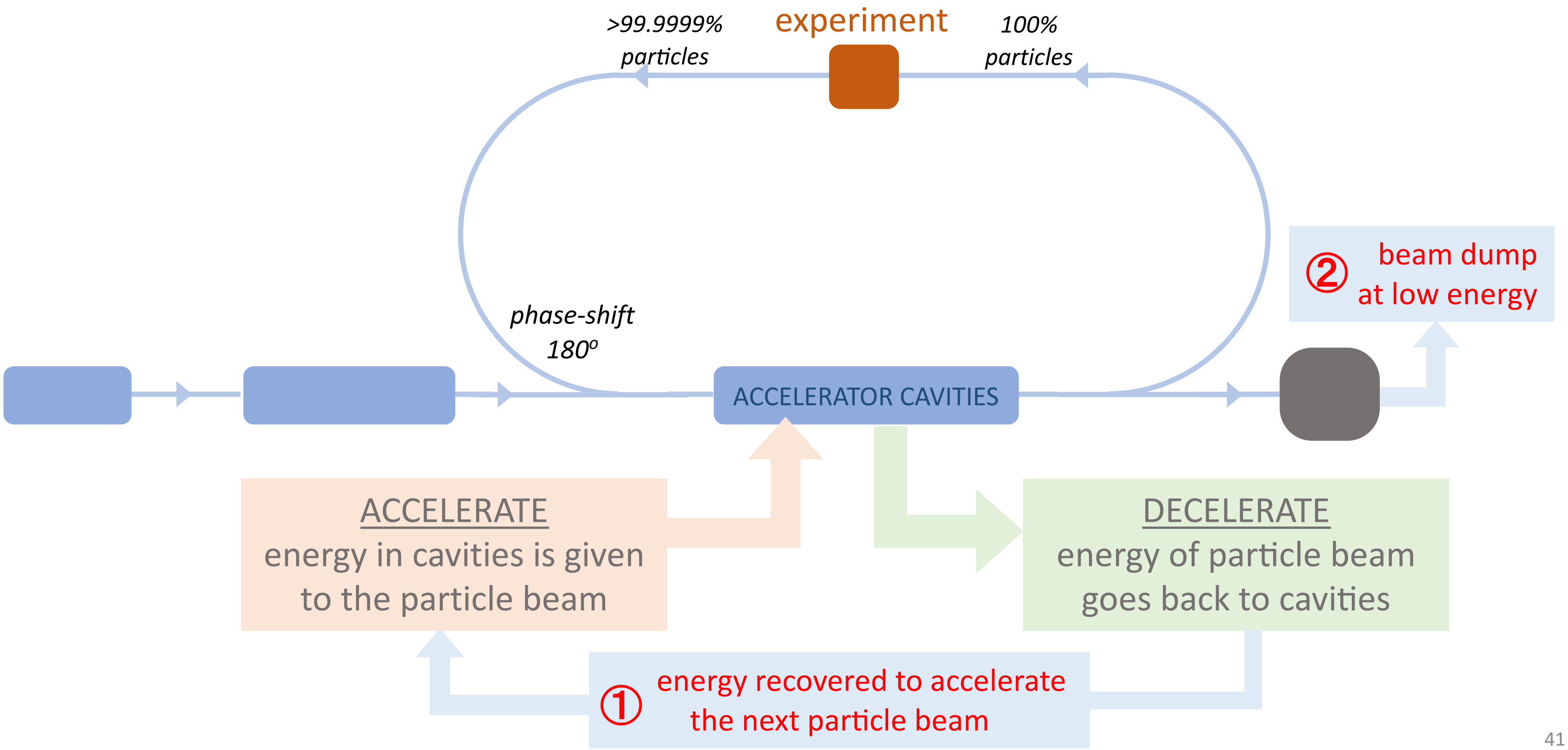
The principle of Energy Recovery



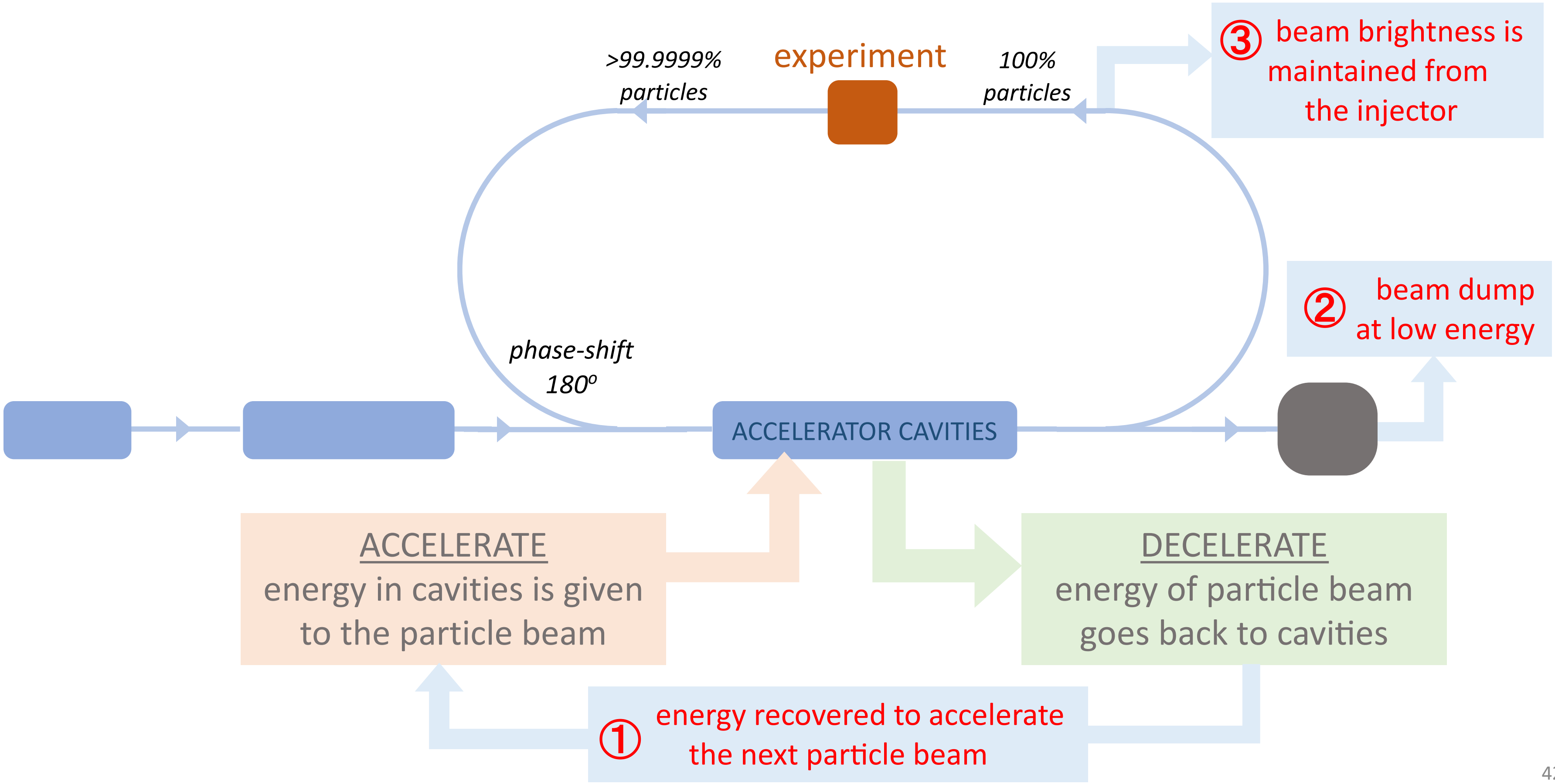
The principle of Energy Recovery



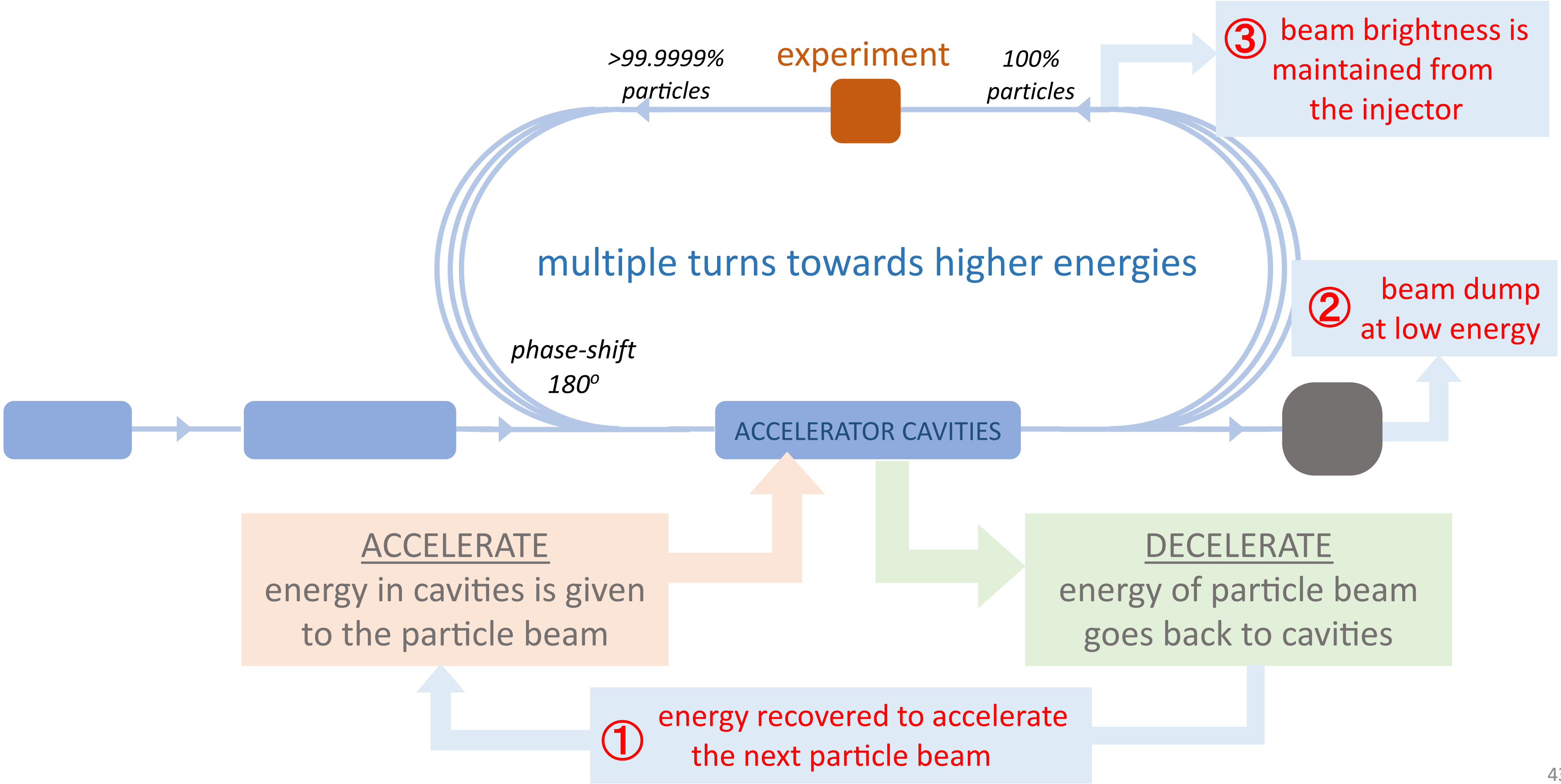
The principle of Energy Recovery



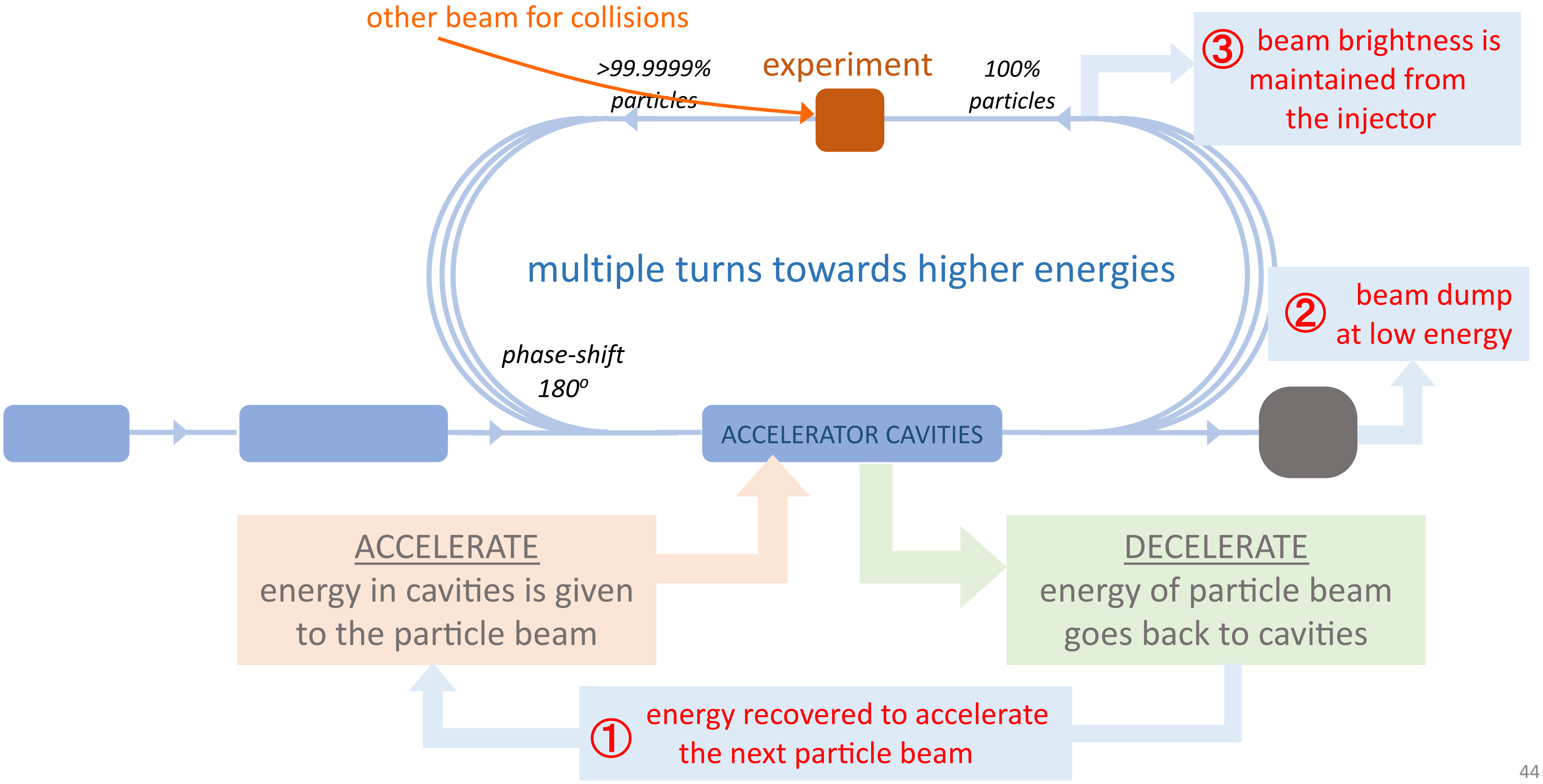
The principle of Energy Recovery



The principle of Energy Recovery

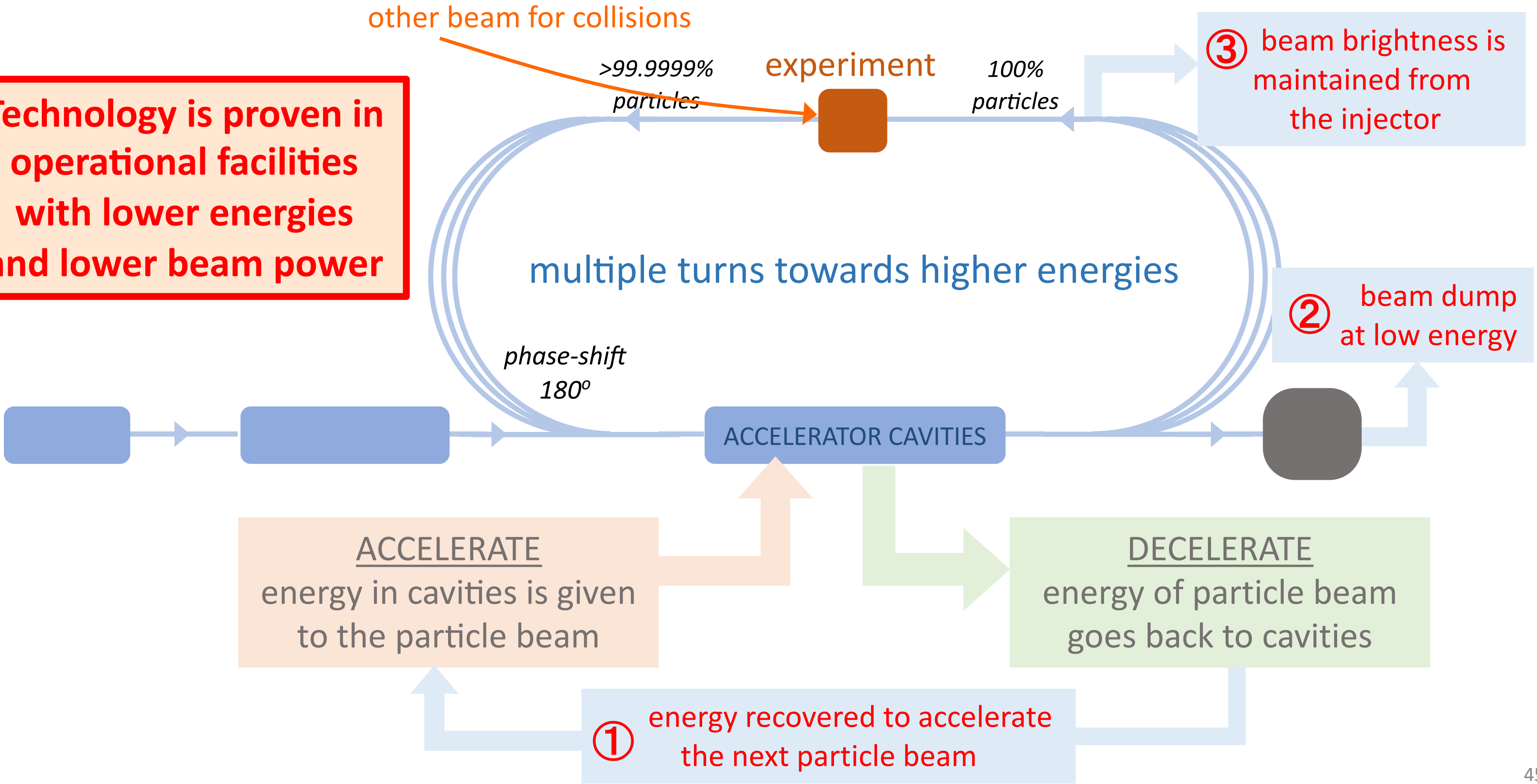


The principle of Energy Recovery



The principle of Energy Recovery

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



Energy Recovery technology

towards high-energy collisions with a reduced energy footprint and cost

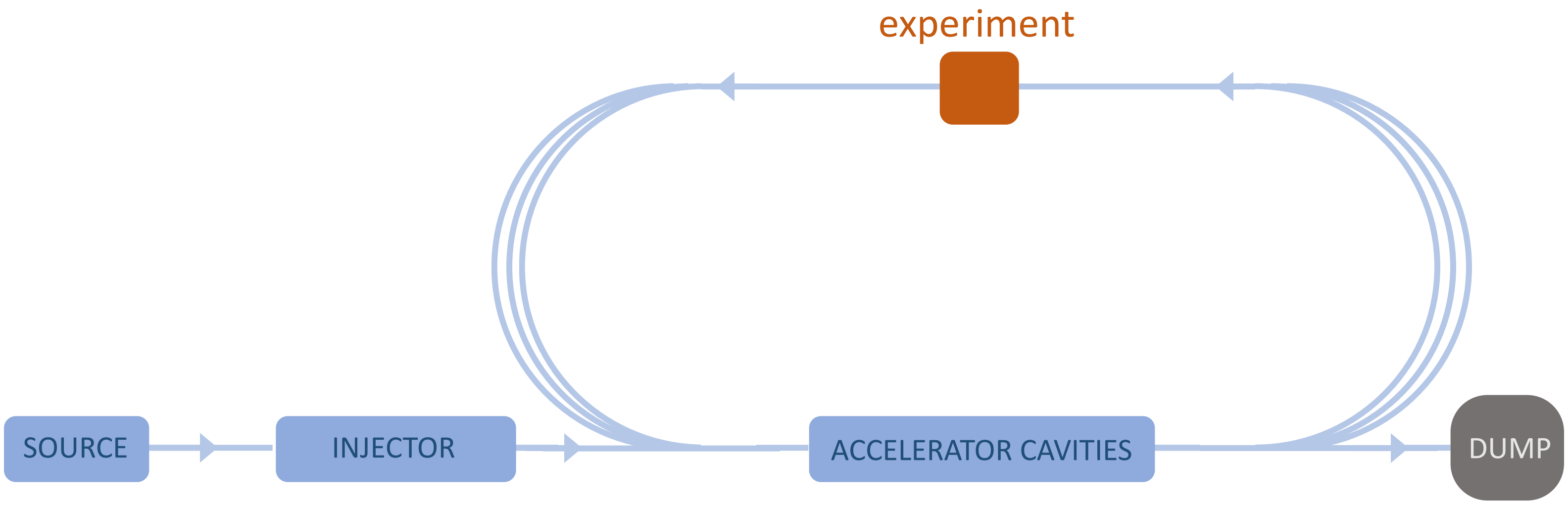
- **Based on 50 years of successful accelerator R&D developments**
  success builts easier on previous success

- **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

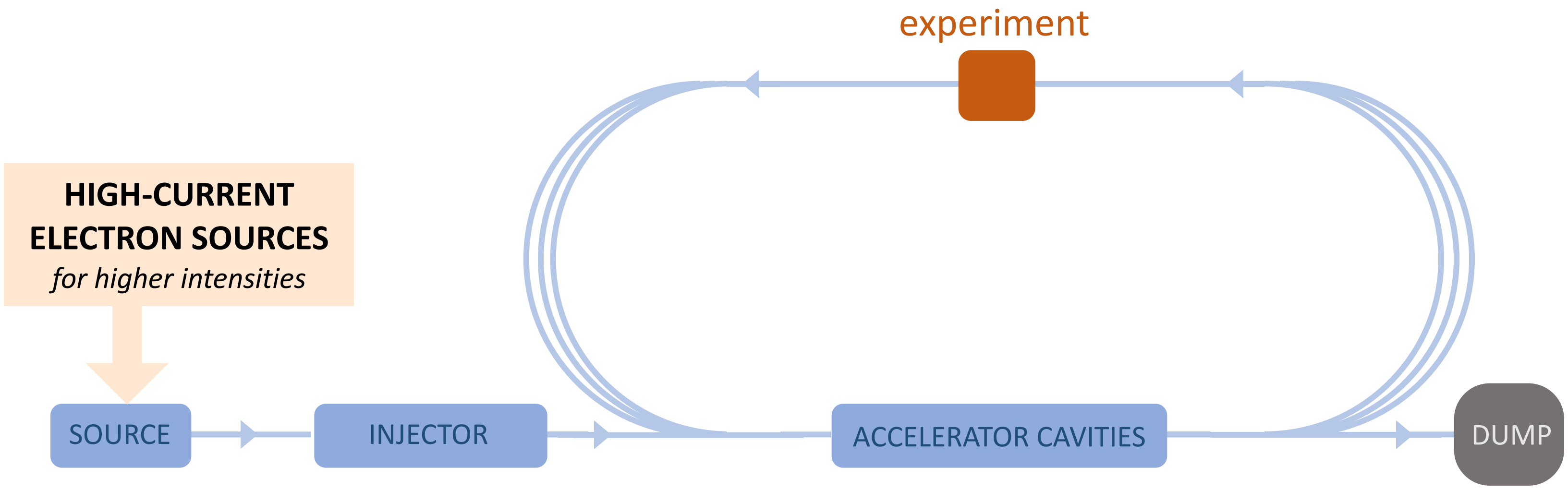
Key aspects for an Energy Recovery accelerator

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



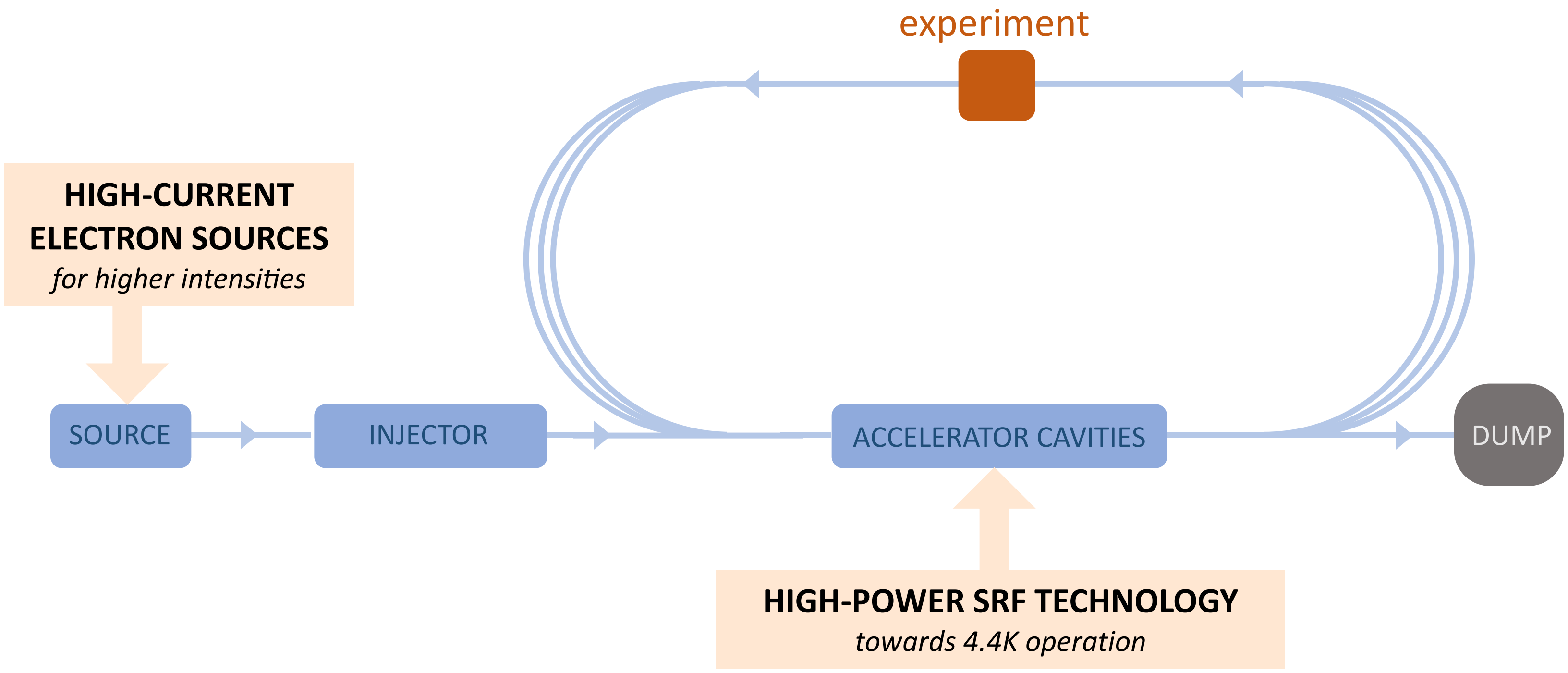
Key aspects for an Energy Recovery accelerator

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



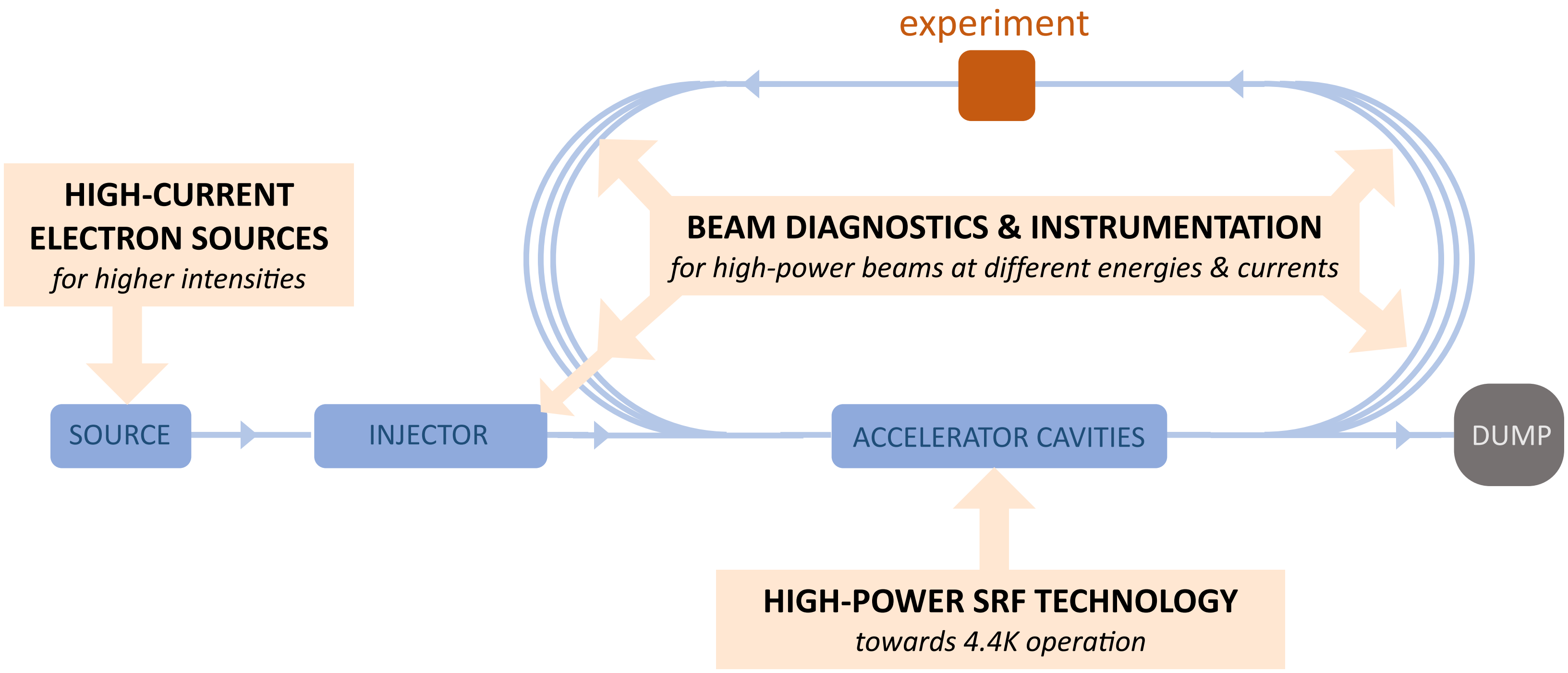
Key aspects for an Energy Recovery accelerator

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



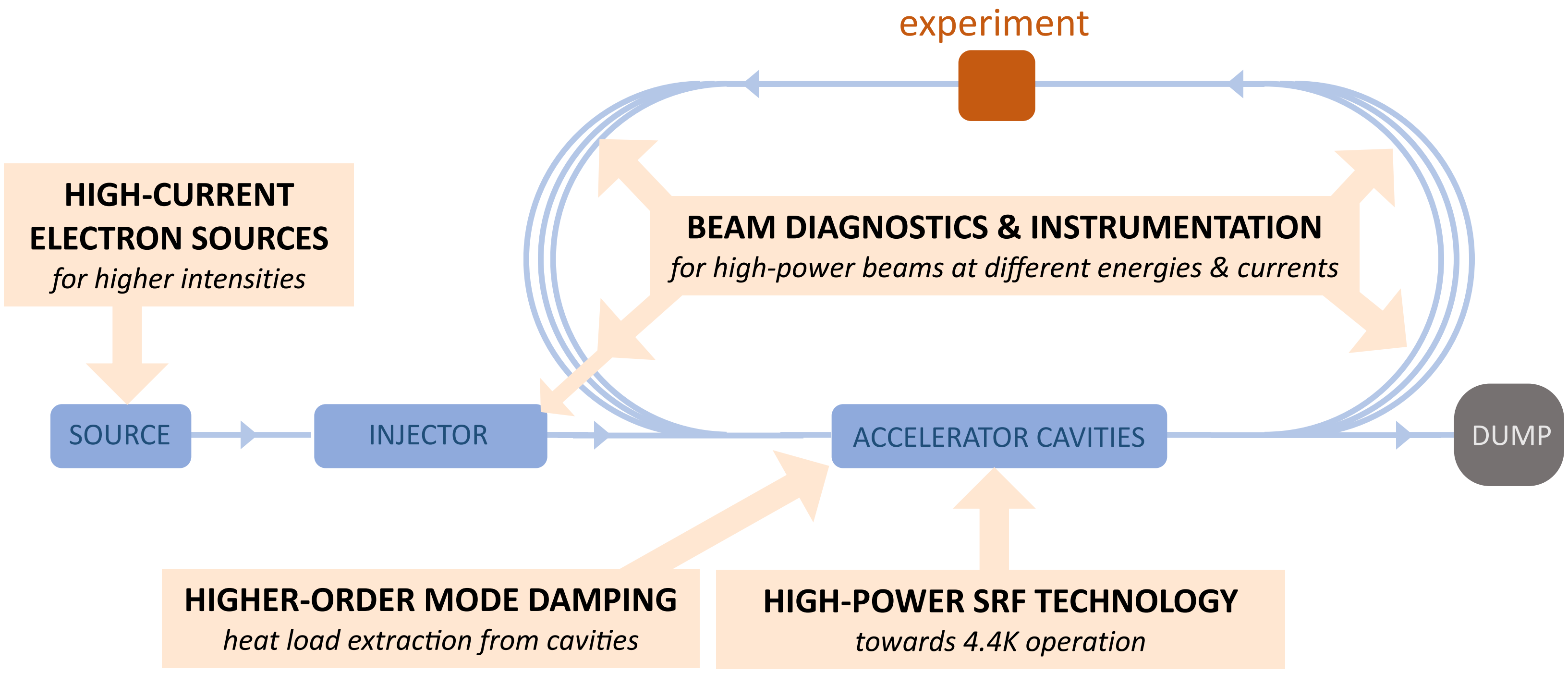
Key aspects for an Energy Recovery accelerator

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



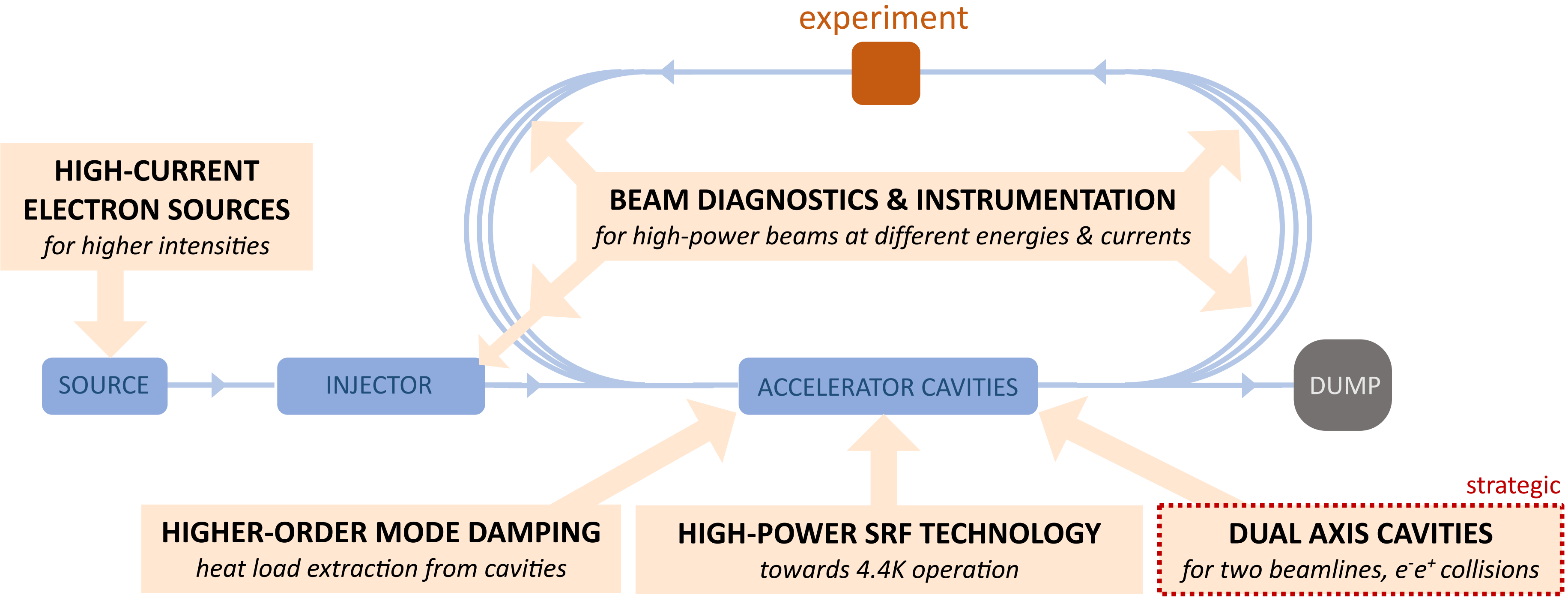
Key aspects for an Energy Recovery accelerator

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



Key aspects for an Energy Recovery accelerator

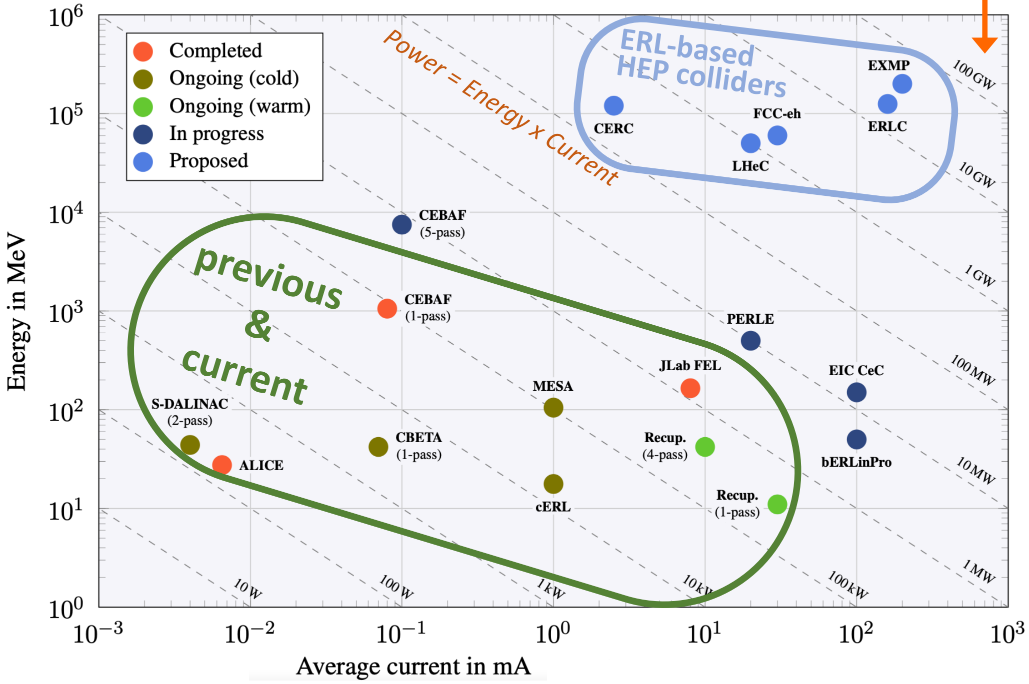
towards high-energy & high-intensity beams to be used at particle colliders



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

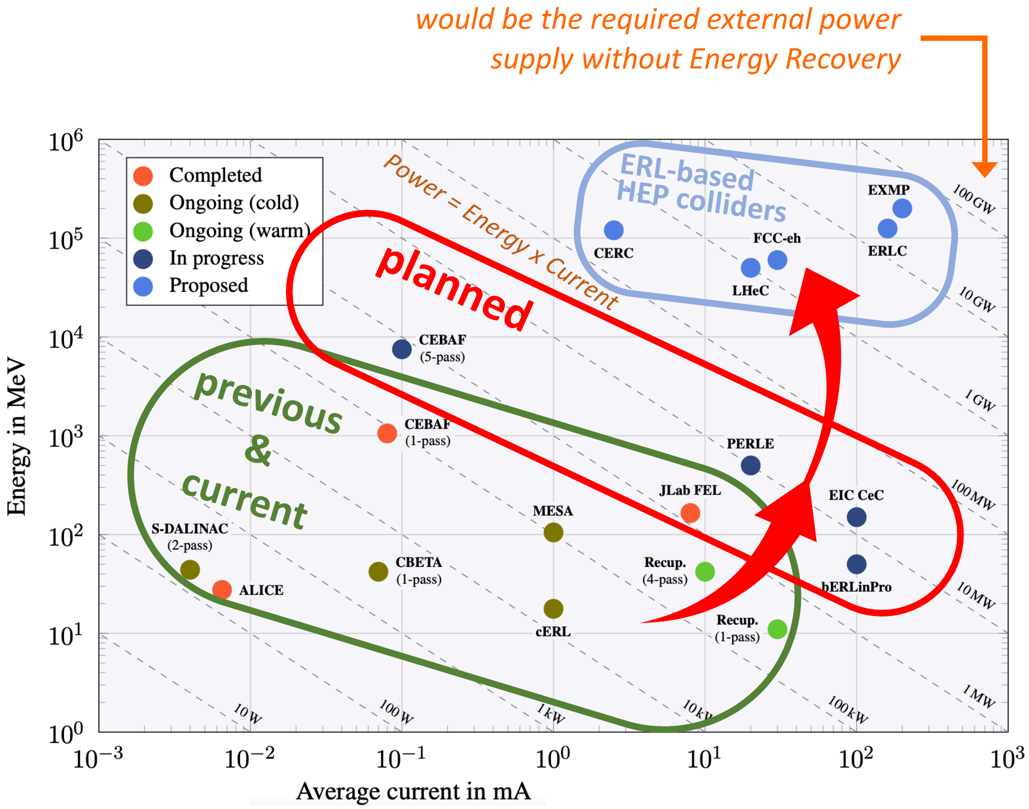


Energy Recovery

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

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

bERLinPro & PERLE

essential technology stepping stones for future HEP implementations of Energy Recovery accelerators

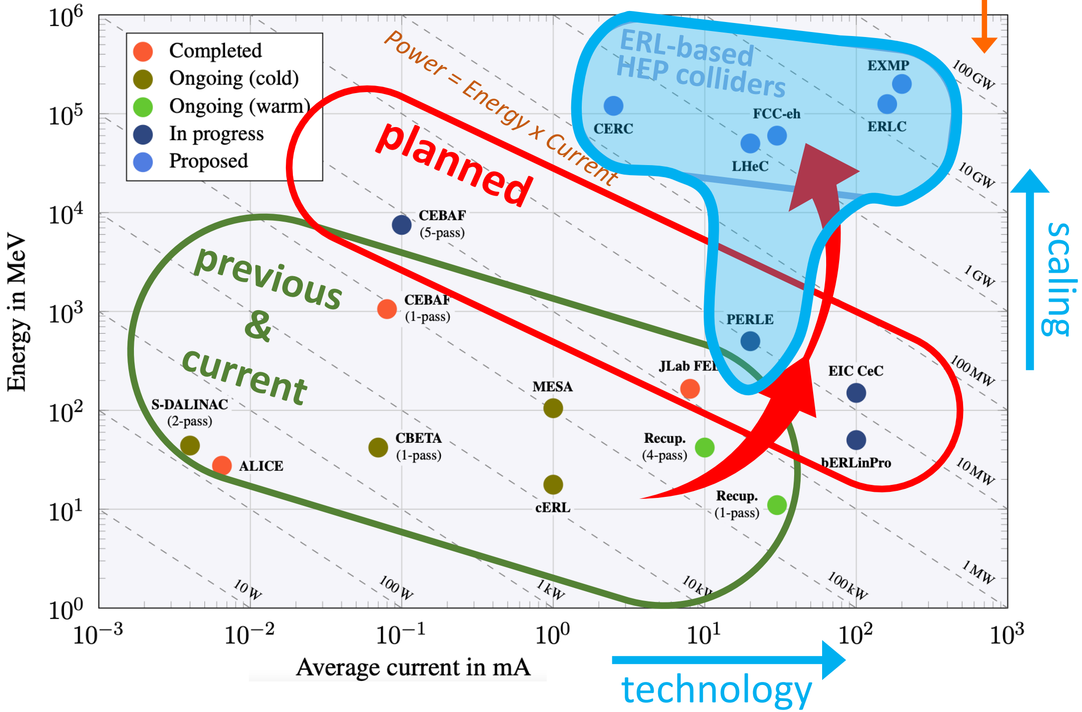
towards high energy & high power

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

Energy Recovery – 50 years of innovation

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

bERLinPro & PERLE

essential technology stepping stones for future HEP implementations of Energy Recovery accelerators

towards high energy & high power

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

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

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)	$< 10^{-5}$

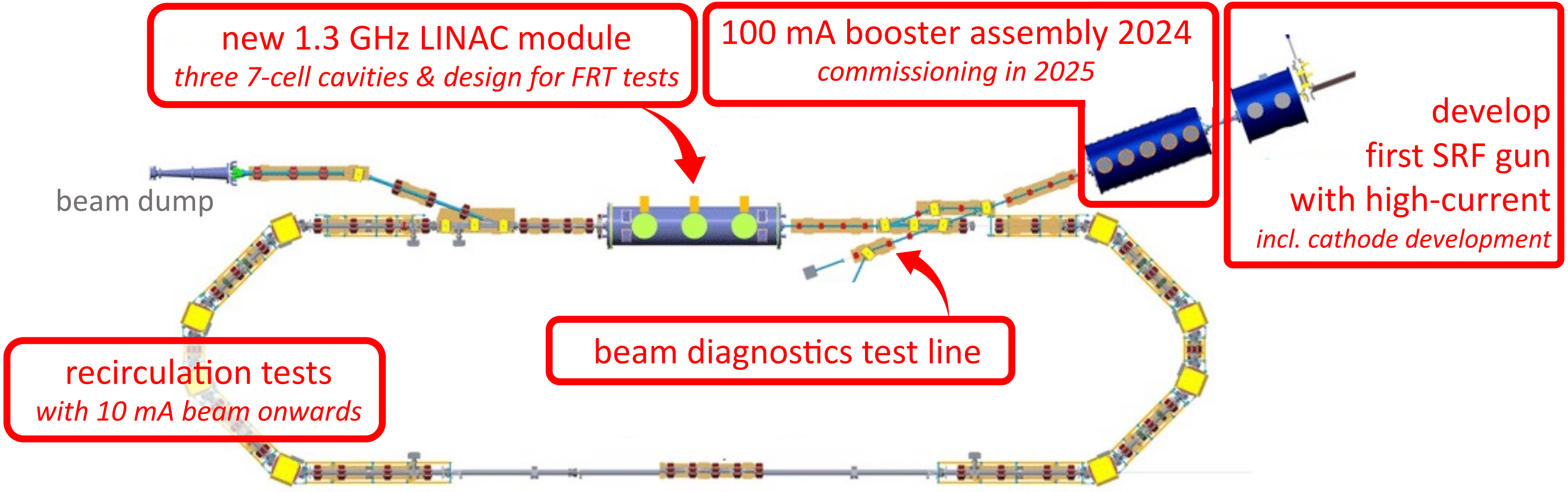
bERLinPro – Berlin Energy Recovery Linac Project

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 50 MeV can be planned to be operational by 2028



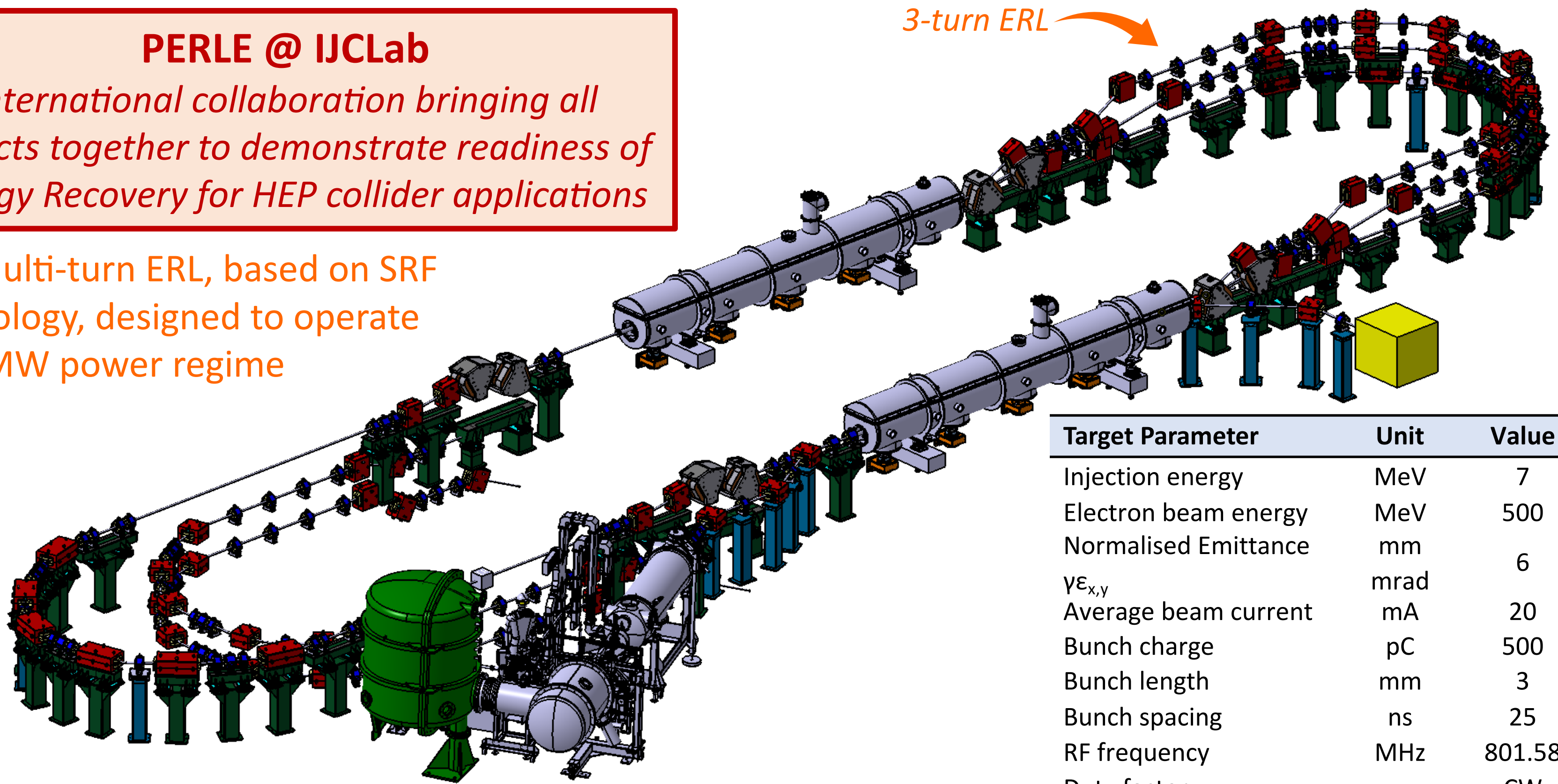
Upcoming facilities for Energy Recovery R&D

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

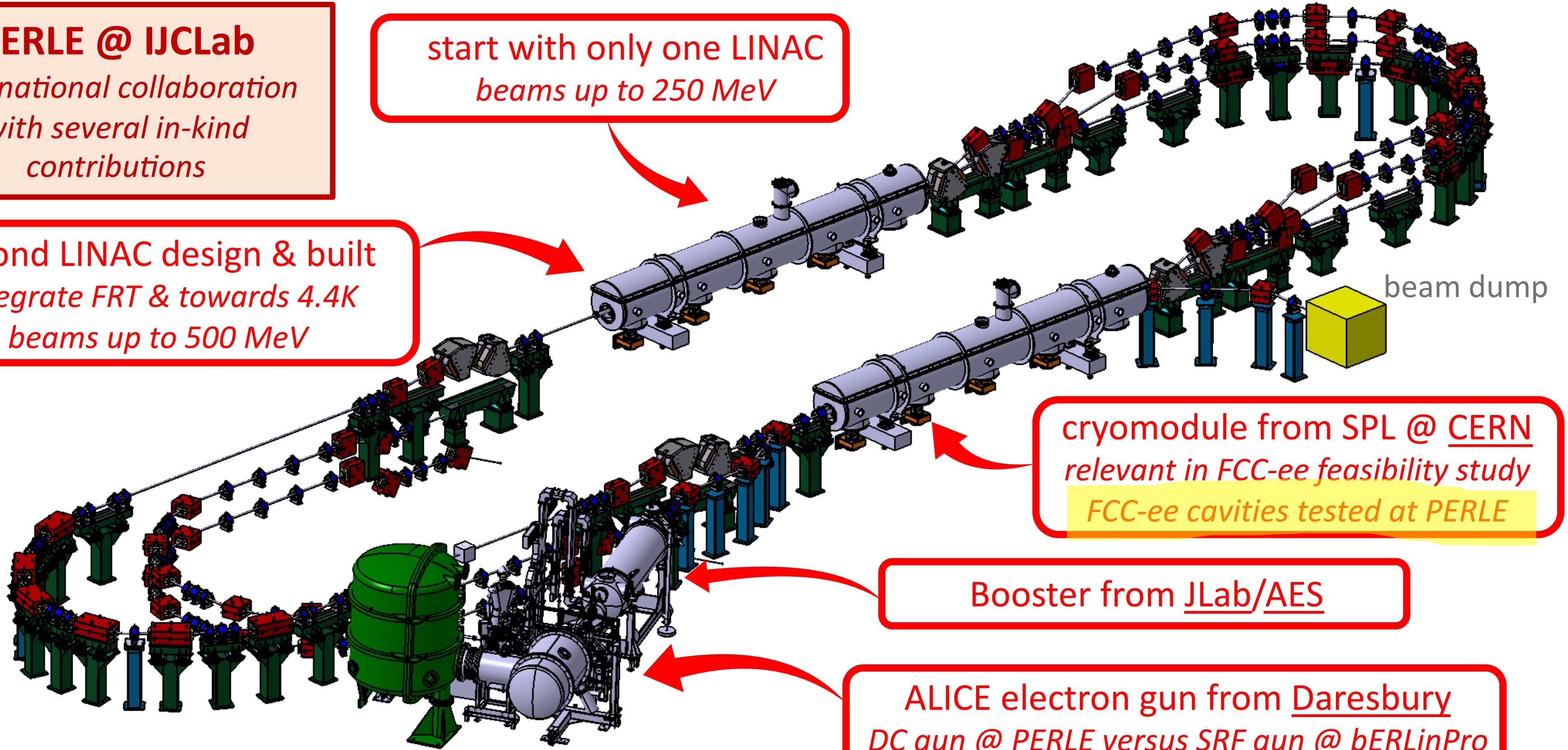
start with only one LINAC

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

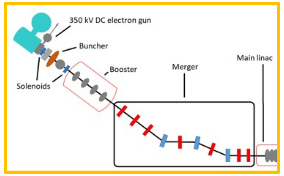
DC gun @ PERLE versus SRF gun @ bERLinPro

Upcoming facilities for Energy Recovery R&D

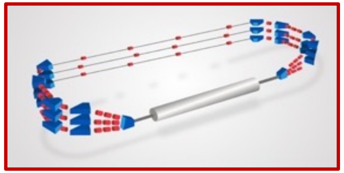
complementary in addressing the R&D objectives for Energy Recovery

2023
PERLE TDR

2025
End Phase 0: Injection line

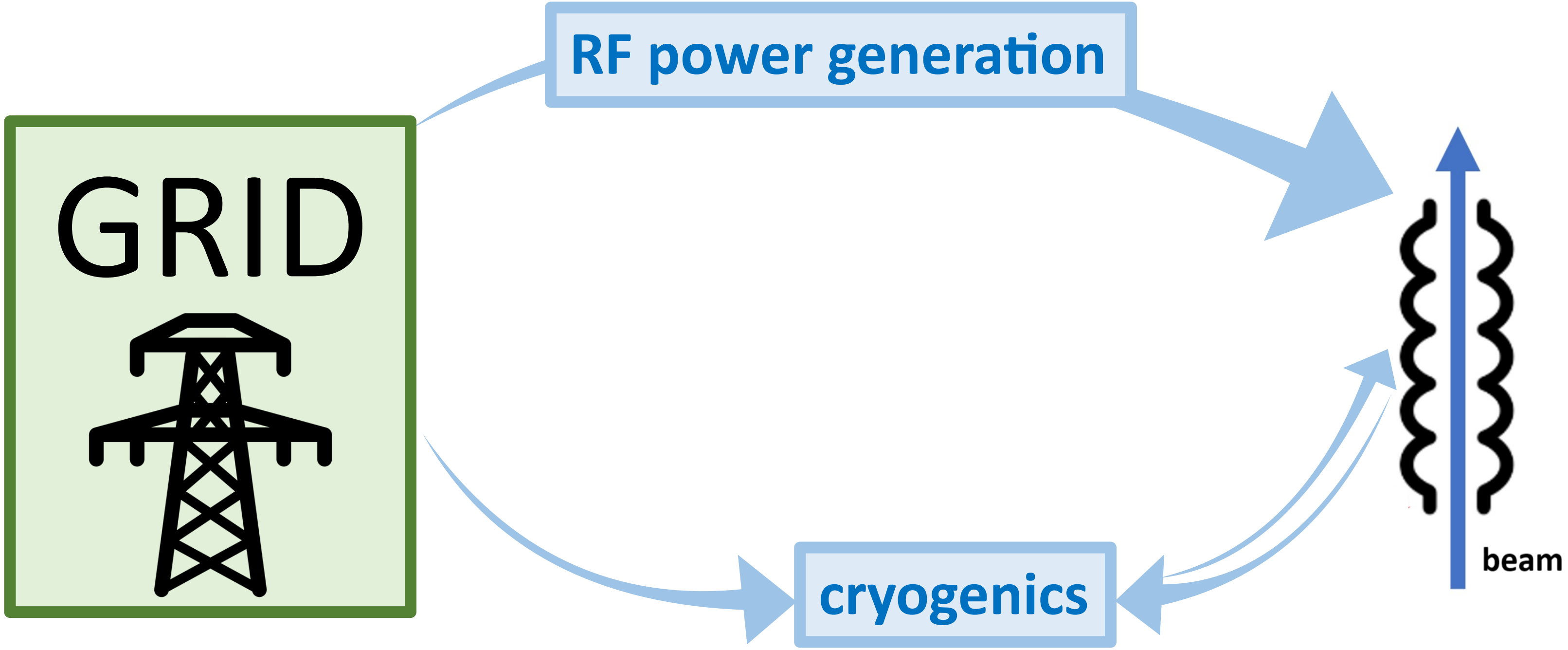


2028
End Phase 1: PERLE @ 250MeV

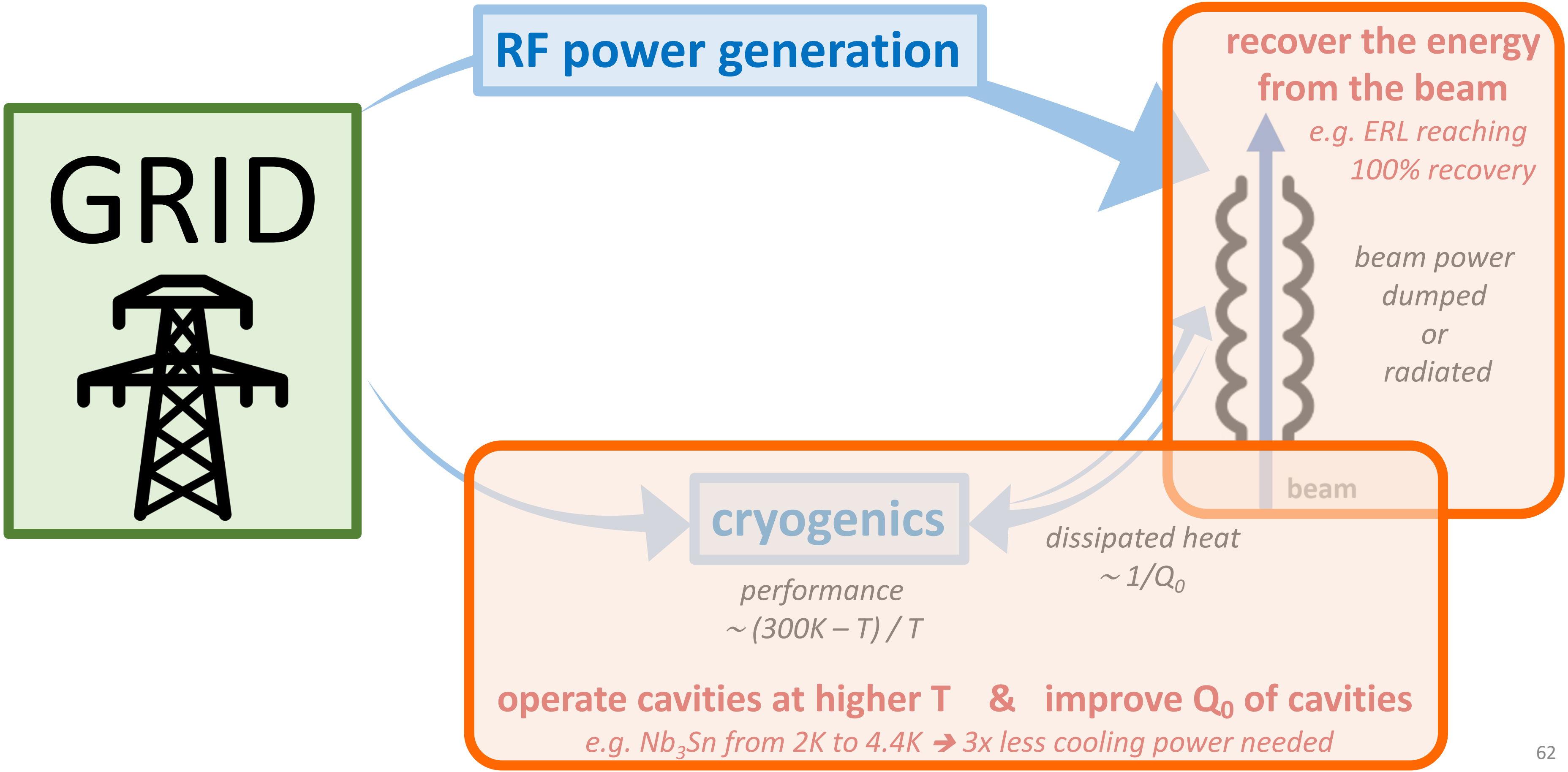


2030
End Phase 2: PERLE @ 500MeV

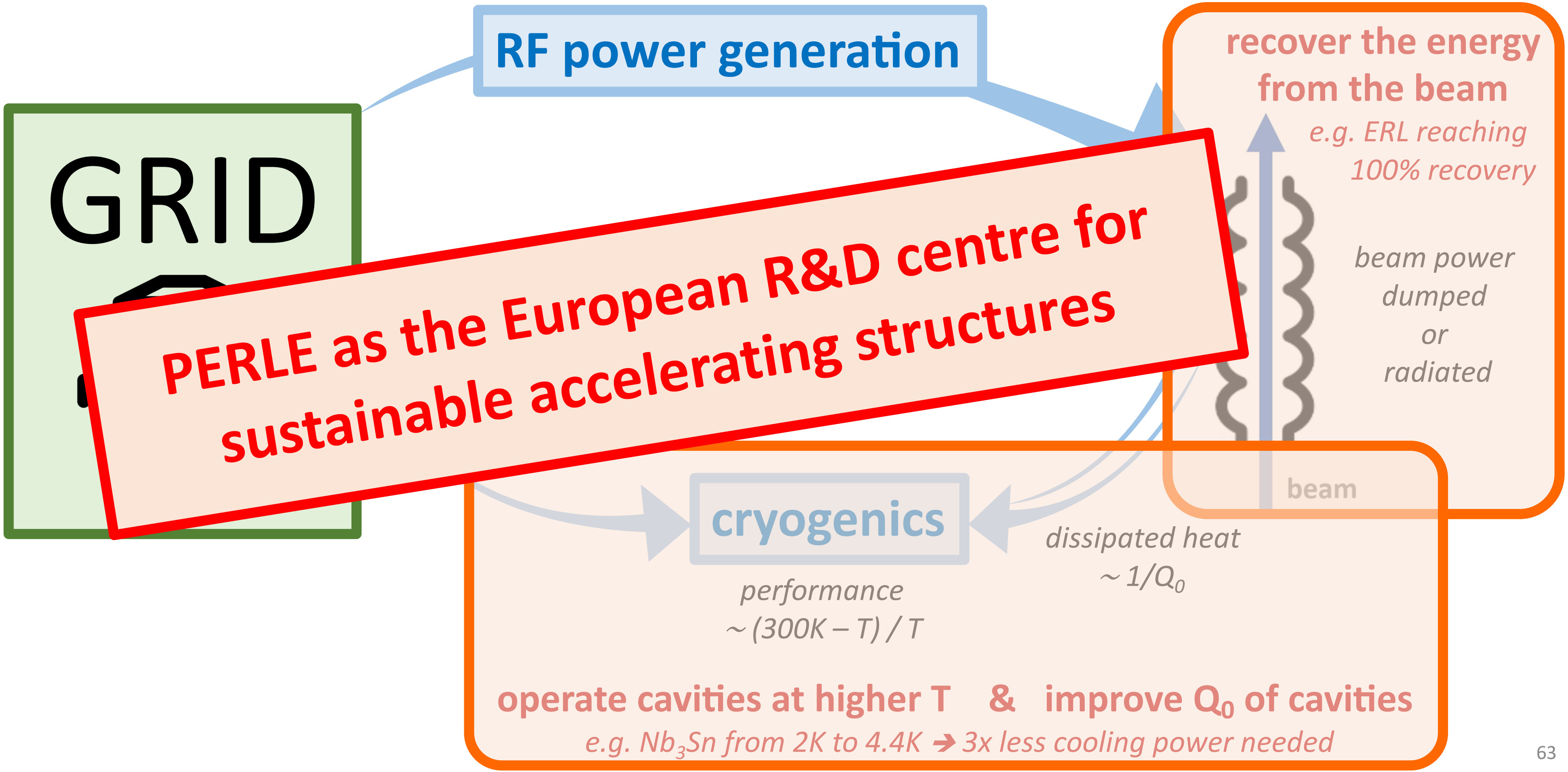
From Grid to Beam



From Grid to Beam



From Grid to Beam



Ongoing & Upcoming facilities with ERL systems

worldwide several other facilities are operational or are emerging

ongoing

s-DALINAC *TU Darmstadt, Germany*

two pass operation in progress

ongoing

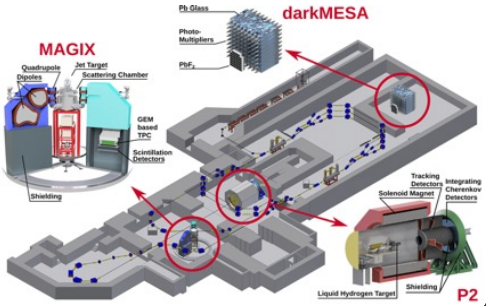
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

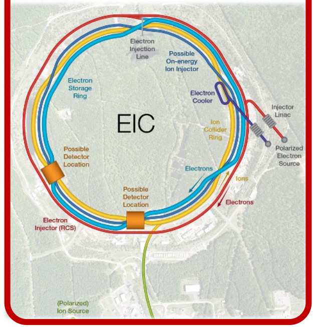
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

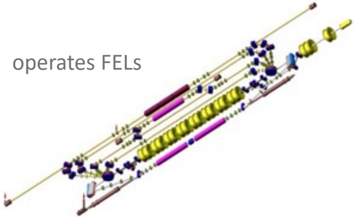
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

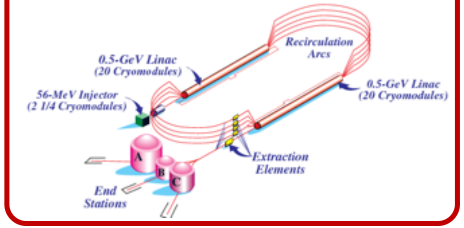
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes



in progress

More facilities in design

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

Energy Recovery applications for HEP

for fundamental science at the energy and intensity frontier

Energy Recovery applications for HEP

for fundamental science at the energy and intensity frontier

EW⊕Higgs⊕top Factories

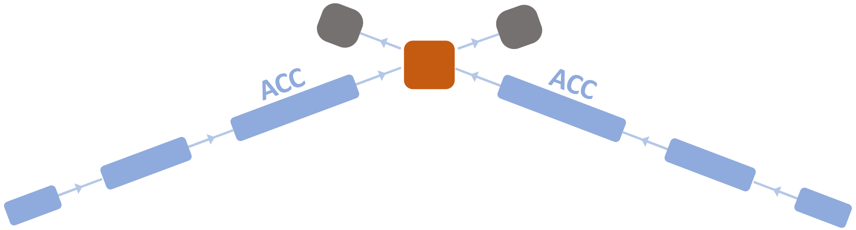
(e^+e^- colliders)

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

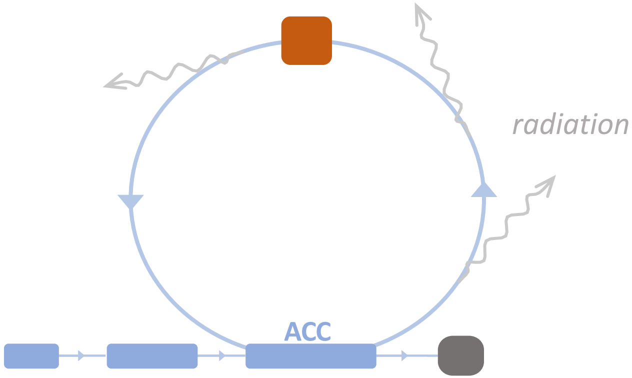
Energy Recovery applications for HEP

for fundamental science at the energy and intensity frontier

Linear colliders



Circular colliders



CLIC and ILC

ERL-based versions: ERLC and ReLiC

CEPC and FCC-ee

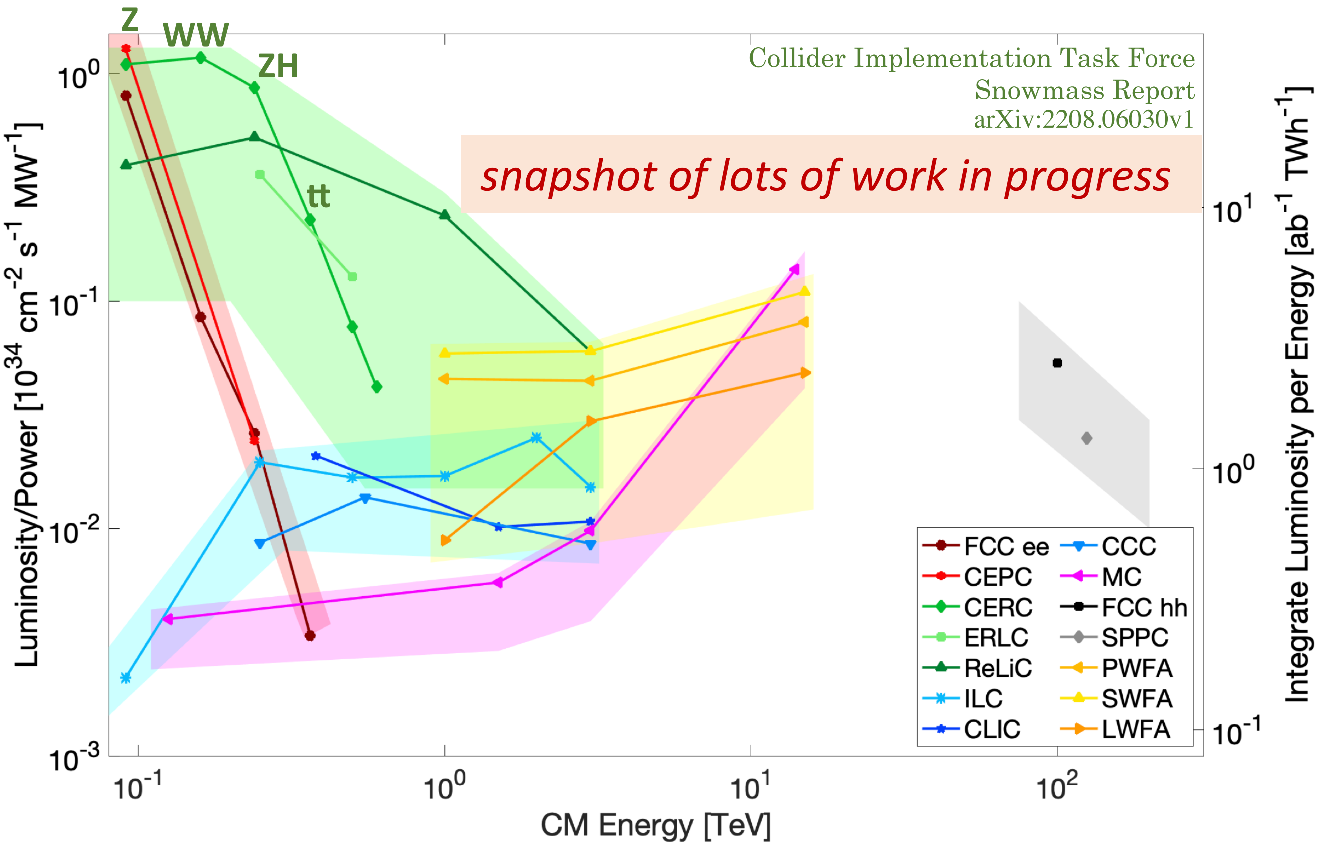
ERL-based version: CERC

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

(10-15y of operation)

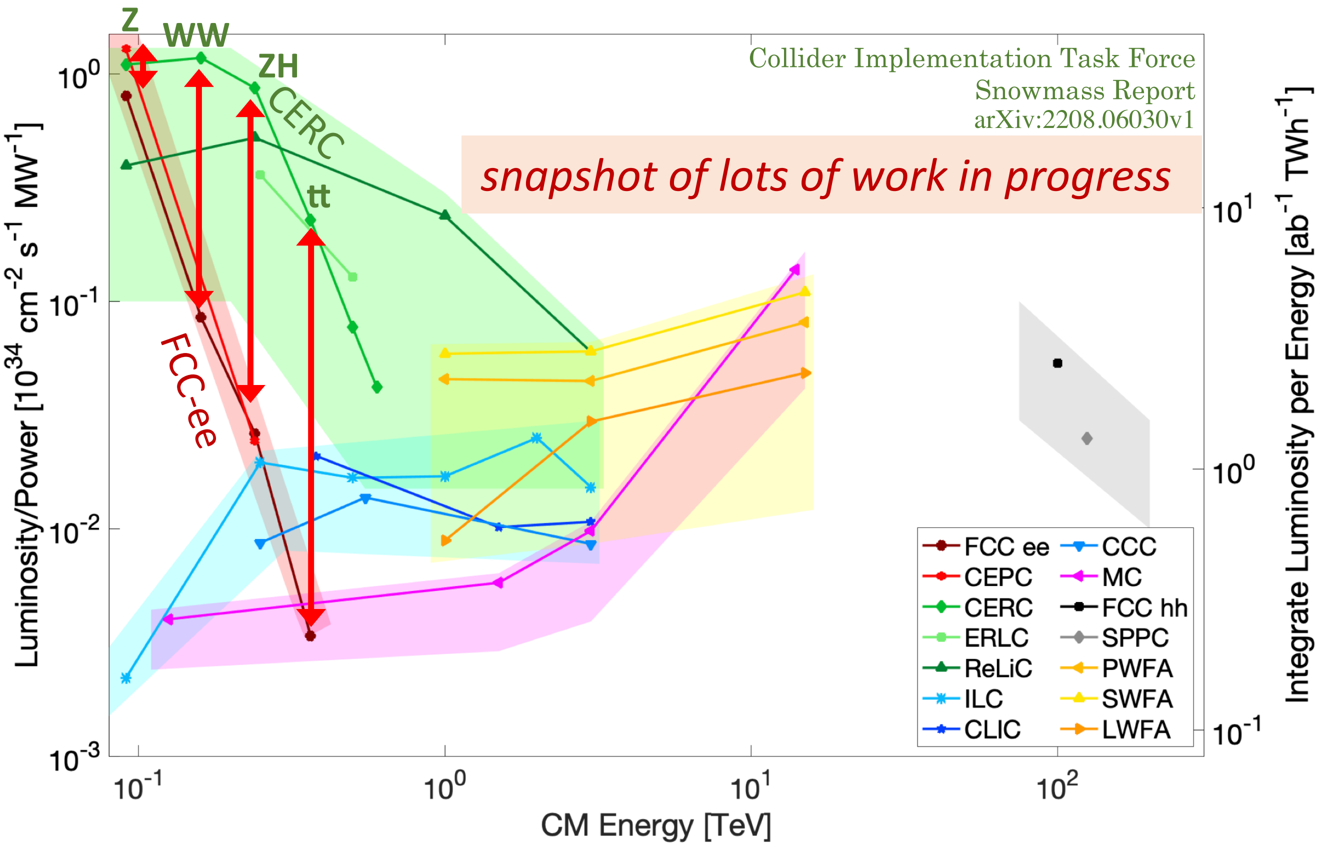
Energy Recovery applications for HEP

for fundamental science at the energy and intensity frontier



Energy Recovery applications for HEP

for fundamental science at the energy and intensity frontier



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

Energy Recovery applications for HEP

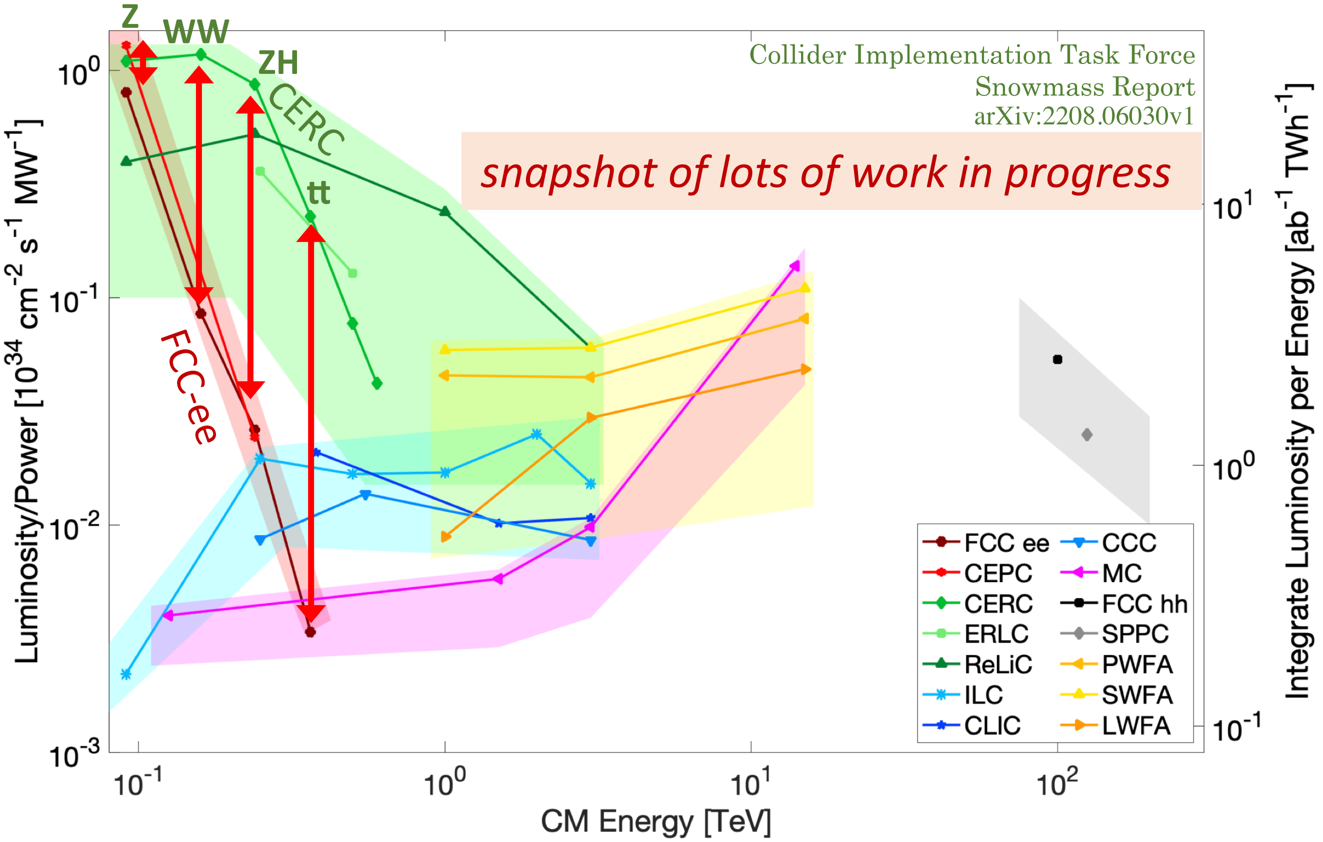
for fundamental science at the energy and intensity frontier

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

x10 more H's

or

x10 less electricity costs



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

Energy Recovery applications for HE

for fundamental sci

Th
a
F

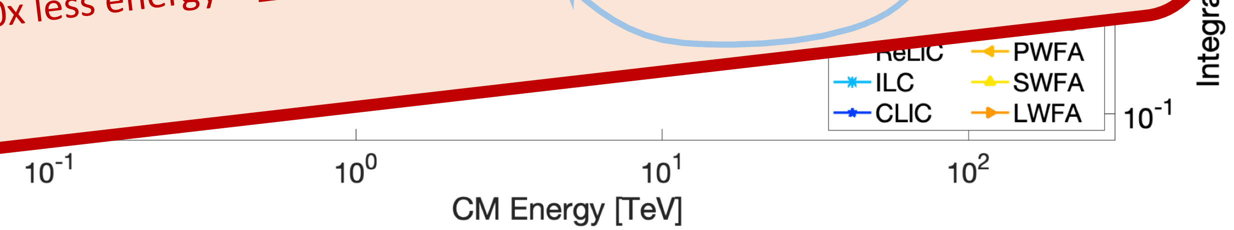
x10

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

x100



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

Energy Recovery applications for HEP

for fundamental scien

This
an
Fac

x10 l

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

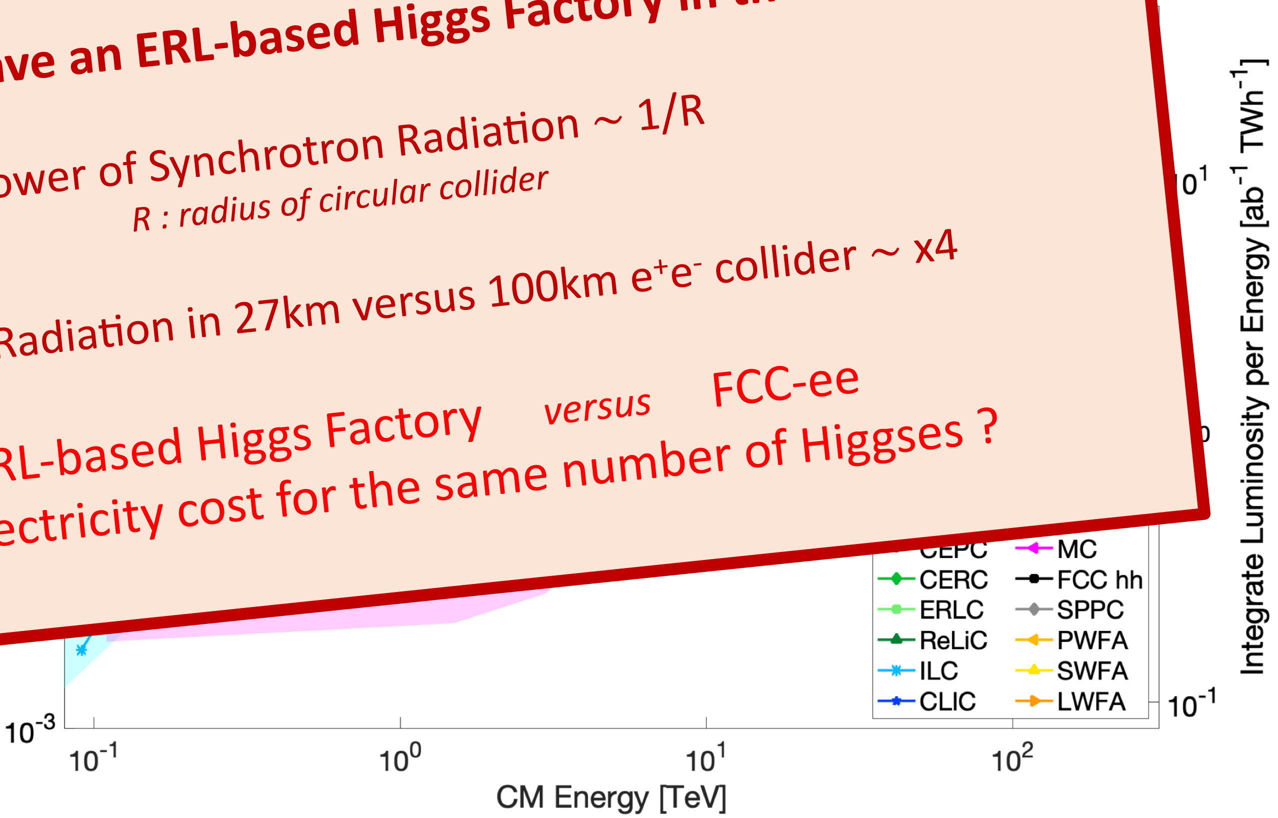
Power of Synchrotron Radiation ~ 1/R

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 ?



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

Energy Recovery applications for HEP

for fundamental scienc

This
an
Fac

x10 l

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

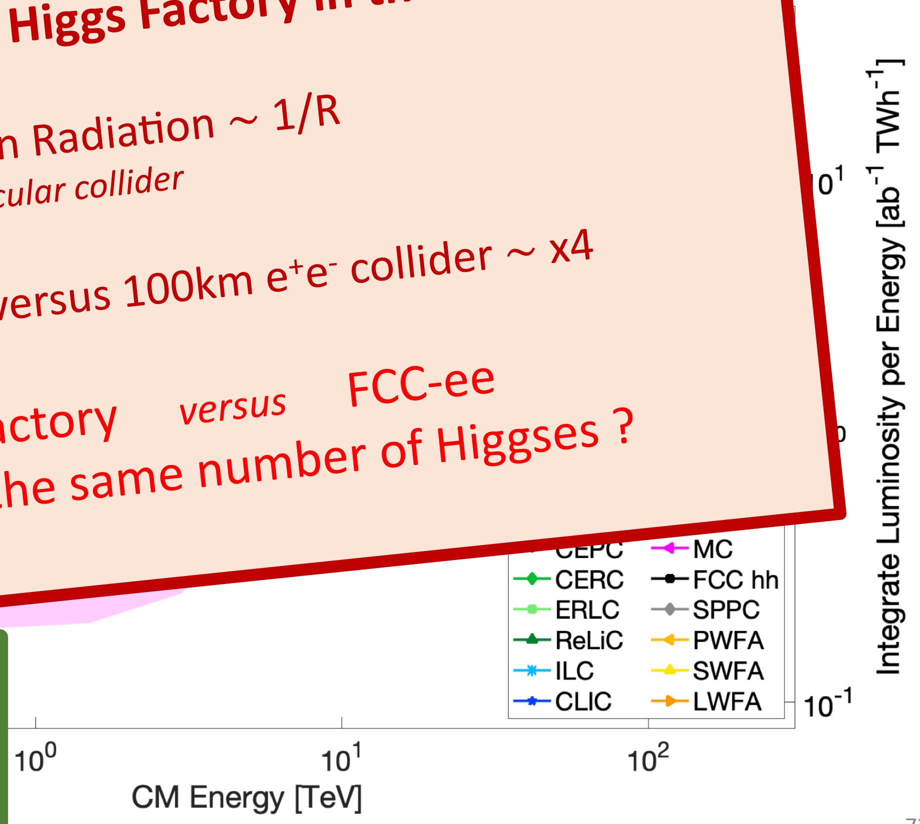
Power of Synchrotron Radiation ~ 1/R

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 ?



R&D support for ERL is required to further explore

Energy Recovery applications for HEP

for fundamental science at the energy and intensity frontier

Scattering experiments

(ep/eA/μA colliders)

With ERL from lower to higher energy scattering experiments

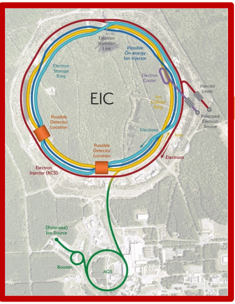
A global ep/eA/μA program bridging nuclear & particle physics for a profound understanding of the structure of matter

2020'ies

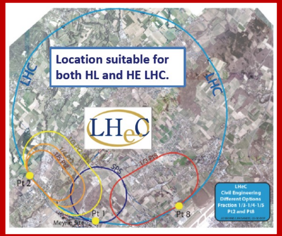
Lower-energy scattering

MESA, COMPASS++/AMBER, NA61, …

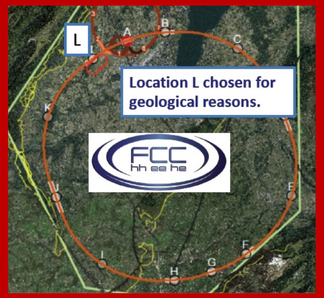
2020-2030'ies



2030-2040'ies



> 2050



Driven by unique science

nuclear structure

ElectroWeak & Higgs

new physics searches

theory & experiment

Driven by remarkable technology

energy recovery & RF structures

precision detectors

leverage on other colliders

electron beam
from an ERL

With ERL from lower to higher energy scattering experiments

A global ep/eA/μA program bridging nuclear & particle physics for a profound understanding of the structure of matter

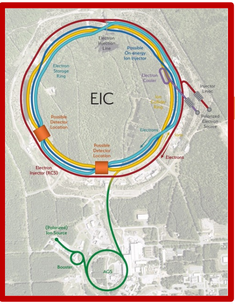
Driven by unique science

nuclear structure
ElectroWeak & Higgs
new physics searches
theory & experiment

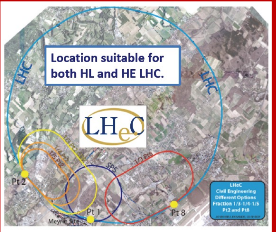
2020'ies

Lower-energy scattering
MESA, COMPASS++/AMBER, NA61, …

2020-2030'ies

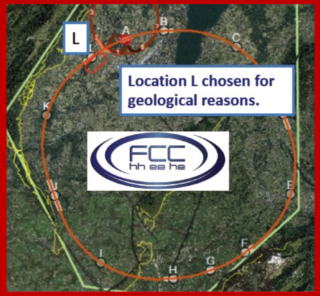


2030-2040'ies



$\mathcal{O}$(~1.4 BCHF)
(10-15y of operation)

> 2050



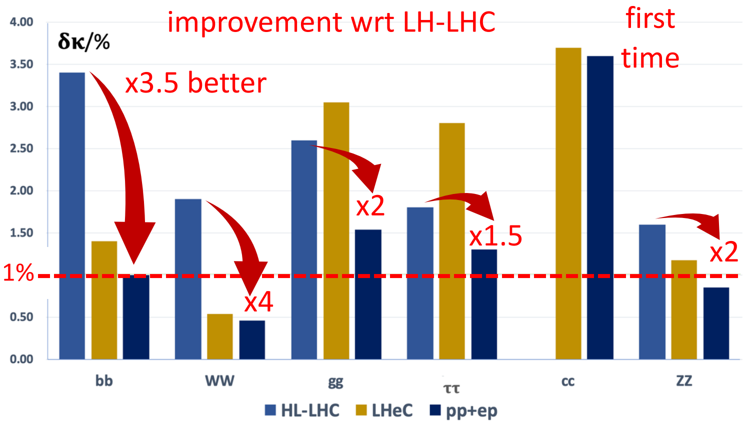
Driven by remarkable technology

energy recovery & RF structures
precision detectors
leverage on other colliders

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)

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

…y at ~10 MeV)
…e as LEP)

…% (today ~5%)
…and γ, W, Z couplings

In addition, unique potential to search for new physics phenomena

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

DIS scattering cross sections

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

Strong interaction physics

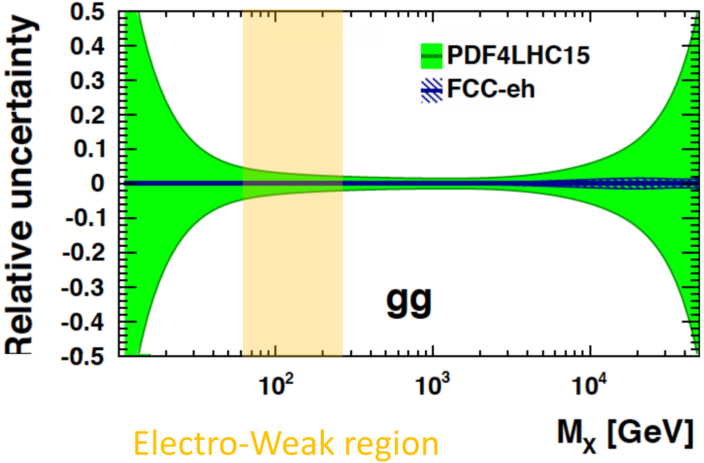
- α_s precision of 0.1%
- low-x: a new discovery frontier

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

Empowering the Higgs sector quest with FCC-eh

Measurements of proton Parton Distribution Functions are vital to improve the precision

pp @ 100 TeV

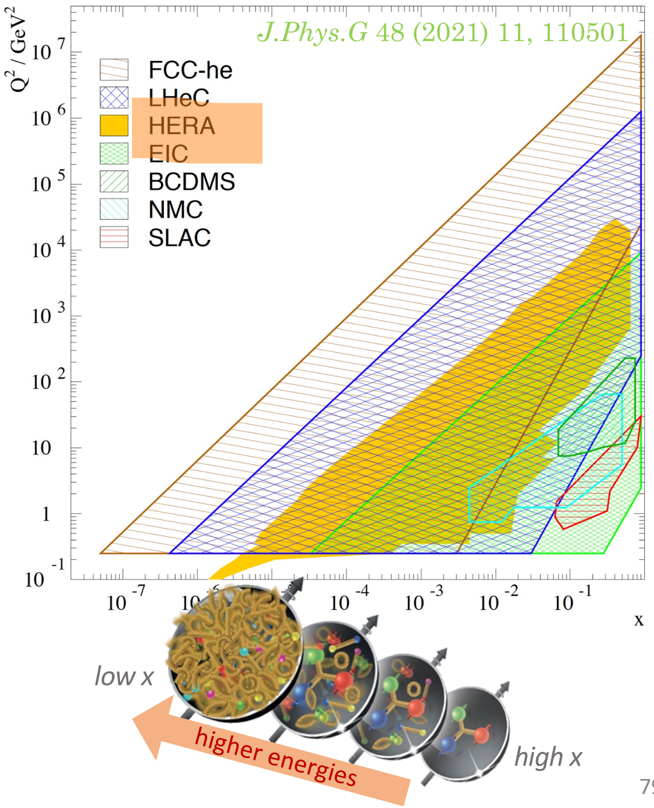


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

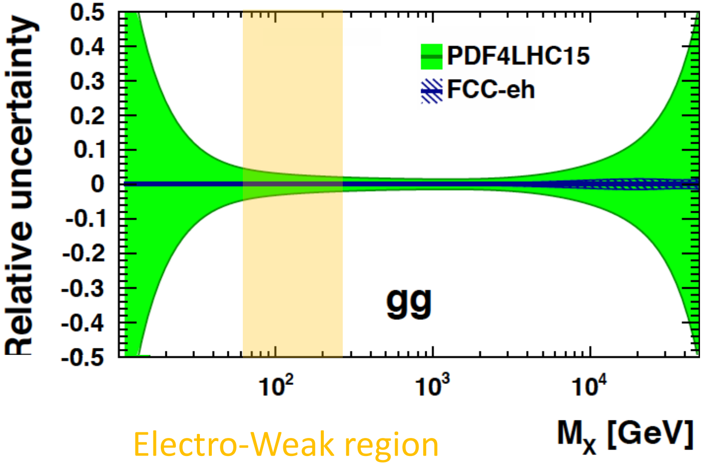
Kinematic range Parton Distribution Functions



Empowering the Higgs sector quest with FCC-eh

Measurements of proton Parton Distribution Functions are vital to improve the precision

pp @ 100 TeV



Electro-Weak region

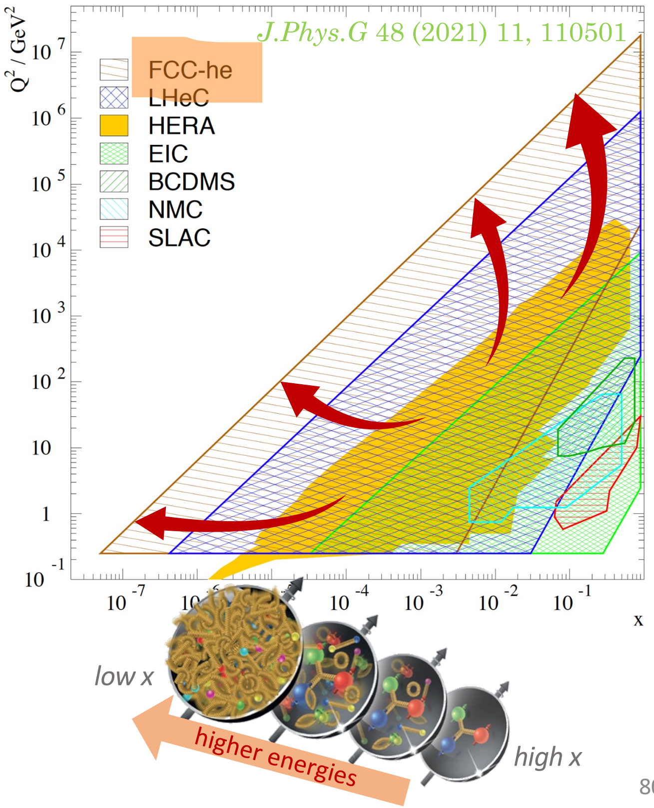
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

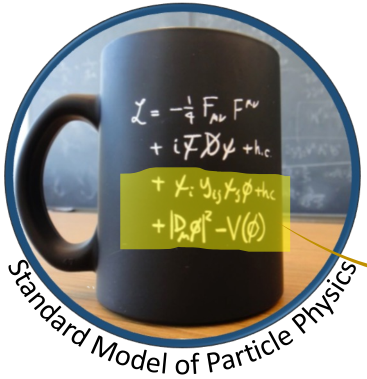
~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



Empowering the Higgs sector quest with FCC-eh

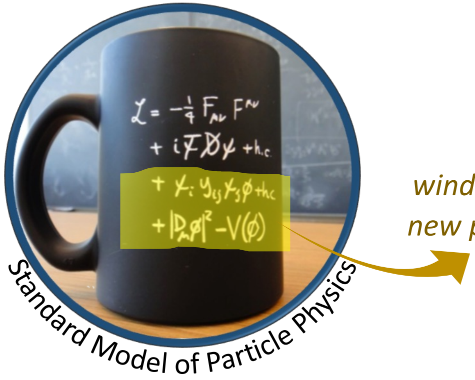
Essentially all problems of the Standard Model are related to the Higgs sector.



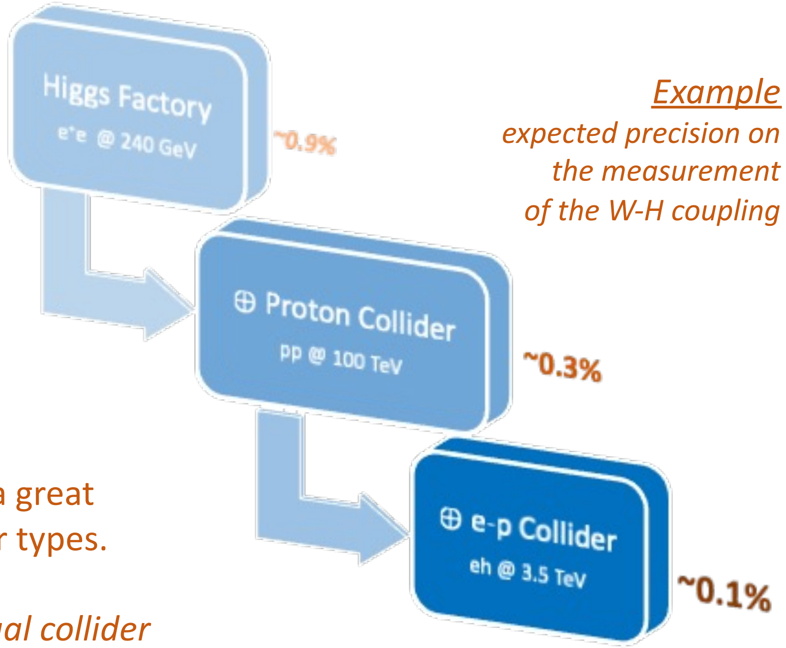
window to new physics

Empowering the Higgs sector quest with FCC-eh

Essentially all problems of the Standard Model are related to the Higgs sector.



window to new physics



__Example__

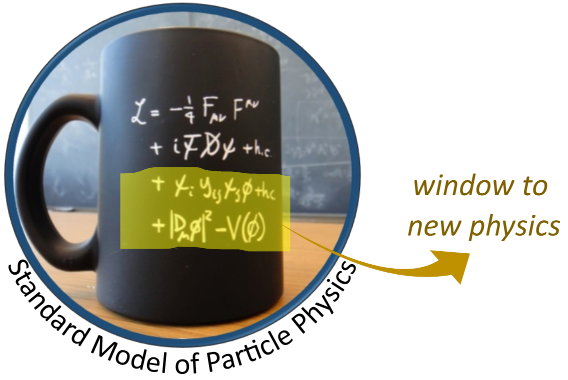
expected precision on the measurement of the W-H coupling

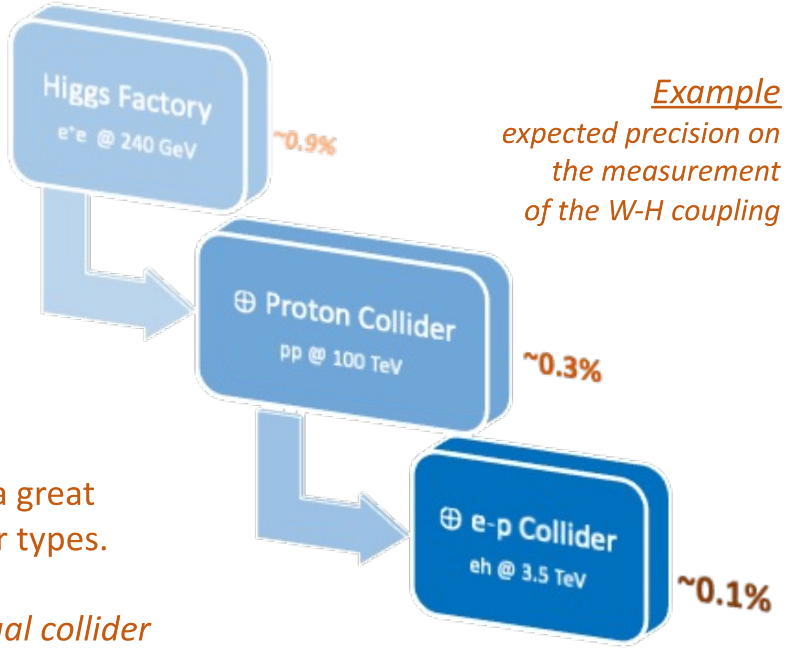
In the search for answers to open questions, we discovered a great complimentarity among the science reach of different collider types.

the combined precision is much better than that of each individual collider

Empowering the Higgs sector quest with FCC-eh

Essentially all problems of the Standard Model are related to the Higgs sector.





<u>Example</u>
expected precision on the measurement of the W-H coupling

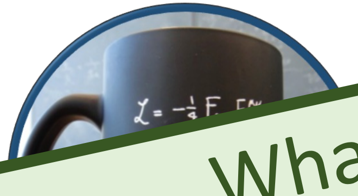
In the search for answers to open questions, we discovered a great complimentarity among the science reach of different collider types.

the combined precision is much better than that of each individual collider

We need a coherent program allowing for a variety of future colliders

Empowering the Higgs sector quest with FCC-eh

Essentially all problems of the Standard Model are related to the Higgs sector.



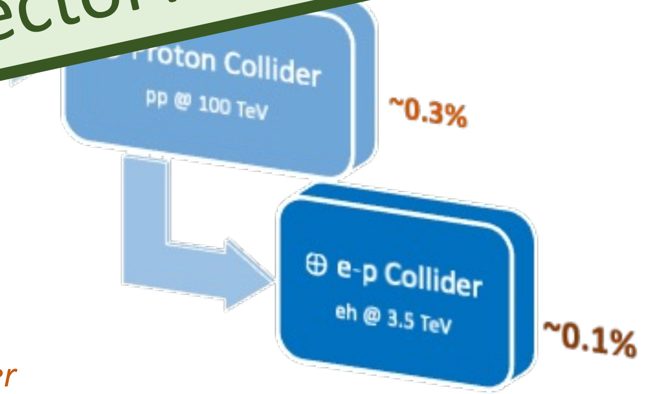
What science could we unlock when studying pp and ep collisions with the same detector?

Example

recision on

asurement

H coupling



In the nswers to open questions, we discovered a great complimentarity among the science reach of different collider types.

the combined precision is much better than that of each individual collider

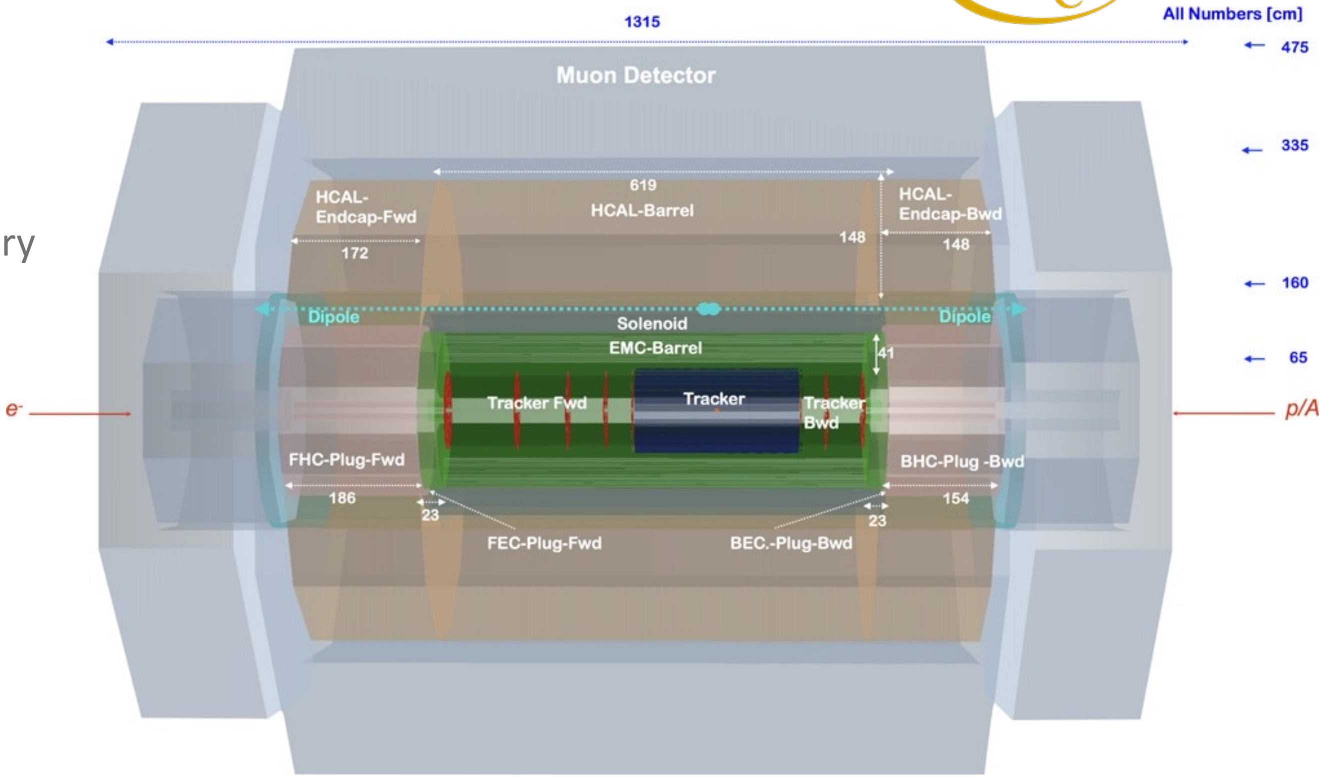
We need a coherent program allowing for a variety of future colliders

Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

Major challenges:

- Tracking & Vertexing
- 1^{o} close to the beamline
- High-resolution calorimetry



Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

European Detector R&D Roadmap (2021)

Major challenges:

- Tracking & Vertexing
- 1° close to the beamline
- High-resolution calorimetry

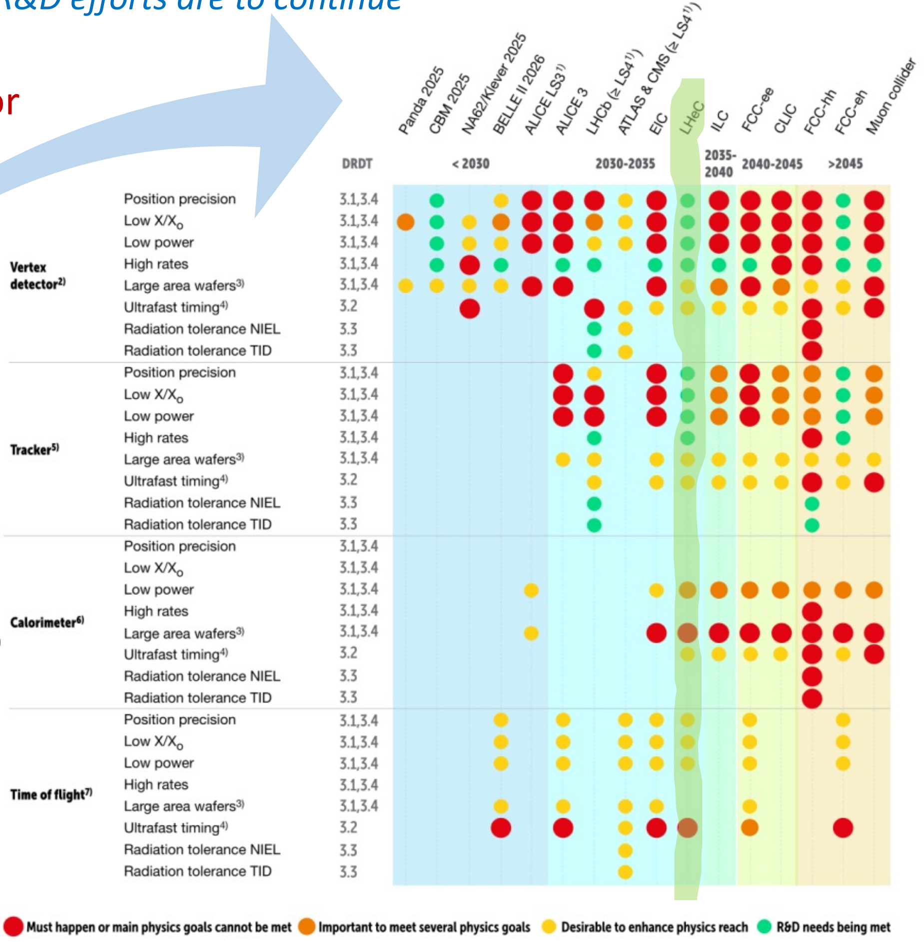
Synergies with many other major projects, potentially as stepping stones

Potentially one detector for a joint DIS, pp and Heavy-Ion program @ HL-LHC/FCC

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

Detector Requirements

e.g. Solid State Devices



https://cds.cern.ch/record/2784893?ln=en

Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

European Detector R&D Roadmap (2021)

Major challenges:
- Tracking & Vertexing
- 1° close to the beamline
- High-resolution calorimetry

Syner… major… steppi…

New Detector R&D Collaborations will be created the ep/eA detector community must participate

Potentially one detector for a joint DIS, pp and Heavy-Ion program @ HL-LHC/FCC

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

https://cds.cern.ch/record/2784893?ln=en

The future of HEP colliders

The future of HEP colliders

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.

The future of HEP colliders

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.

Looking ahead, our key ambition beyond the HL-LHC programme is to develop a Higgs Factory.

The future of ERL colliders

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.

Looking ahead, our key ambition beyond the HL-LHC programme is to develop a Higgs Factory.

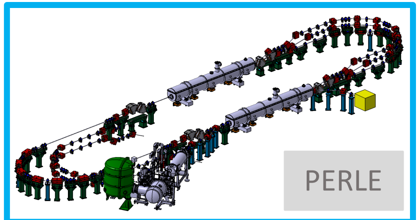
The future of ERL colliders

How it might look

The future of ERL colliders

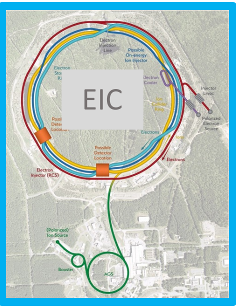
With stepping stones for innovations in technology to boost our physics reach

2020’ies



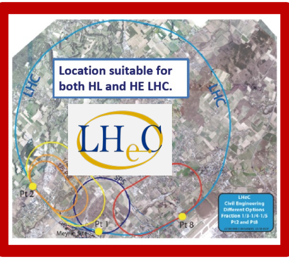
high-power ERL demonstrated

2020-2030’ies



ERL application electron cooling

2030-2040’ies



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

2040-2050’ies

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

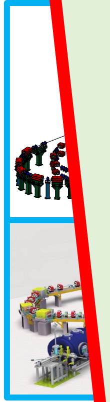
The future of ERL colliders

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

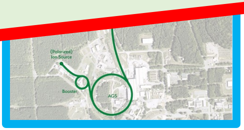
However, let's not dwell too much on strategy at this stage…

the European Stategy for Particle Physics is out and will be discussed in due time

meanwhile let us focus on further developments for an attractive high-energy ep/eA programme at CERN and perform R&D to achieve the required technological innovations



demonstrated



ERL application
electron cooling

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

(Z/W/H/top program)

Energy Recovery technology & Future Colliders

develop high-energy colliders with a reduced energy footprint

- ERL is a mature technology at relatively lower energy and lower intensity
- R&D program revolves around essential stepping stone facilities to reach the high energy and high intensity frontier required in HEP
- A timely realisation of the PERLE and bERLinPro programs is essential for the technology to make sufficient progress towards HEP applications
- Strengthen collaboration across the field to enhance synergies in R&D and to harmonize technical components to reach the HEP related R&D objectives together

- ERL technology may revolutionize our thinking about future high-energy colliders
- On a path towards high-energy ep/eA collisions and potentially an ERL Higgs Factory

Energy Recovery technology & Future Colliders

develop high-energy colliders with a reduced energy footprint

- ERL is a mature technology at relatively lower energy and lower intensity
- R&D program revolves around essential stepping stone facilities to reach the high energy and high intensity frontier required in HEP
- A timely realisation of the PERLE and bERLinPro programs is essential for the technology to make sufficient progress towards HEP applications
- Strengthen collaboration across the field to enhance synergies in R&D and to harmonize technical components to reach the HEP related R&D objectives together

- ERL technology may revolutionize our thinking about future high-energy colliders
- On a path towards high-energy ep/eA collisions and potentially an ERL Higgs Factory

A sustainable path towards beautiful science and technology

Energy Recovery technology & Future Colliders

develop high-energy colliders with a reduced energy footprint

- ERL is a mature technology at relatively lower energy and lower intensity
- R&D program revolves around essential stepping stone facilities to reach the high energy and high intensity frontier required in HEP
- A timely realisation of the PERLE and bERLinPro programs is essential for the technology to make sufficient progress towards HEP applications
- Strengthen collaboration across the field to enhance synergies in R&D and to harmonize technical components to reach the HEP related R&D objectives together

- ERL technology may revolutionize our thinking about future high-energy colliders
- On a path towards high-energy ep/eA collisions and potentially an ERL Higgs Factory

A sustainable path towards beautiful science and technology

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

iihe BRUXELLES BRUSSEL

Thank you for your attention!

Jorgen.DHondt@vub.be

One more thing…

In 2018, I had a very interesting conversation with a very wise scientist…


In 2018, I had a very interesting conversation with a very wise scientist…
Today, I am grateful for his leadership as scientist and friend


In 2018, I had a very interesting conversation with a very wise scientist…
Big thanks to Max Klein for past, present and future
Today, I am grateful for his leadership as scientist and friend

A road ahead

ep/eA program

The way forward: a mindset

The way forward: a mindset

- 1st law of Newton

  No external forces… keep calm, keep moving

The way forward: a mindset

- 1st law of Newton

  No external forces… keep calm, keep moving

- 2nd law of Newton

  If there are external forces… built up inertia, keep moving

The way forward: a mindset

- 1st law of Newton

  No external forces… keep calm, keep moving

- 2nd law of Newton

  If there are external forces… built up inertia, keep moving

- 3rd law of Newton

  If there is action… prepare to react, keep moving

The way forward: objectives

The way forward: objectives

beyond the impressive CDR

The way forward: objectives

beyond the impressive CDR

- Innovate

  Methodologies are evolving… prepare to jump
  Physics hot topics come (and go)… prepare to surf the good waves

The way forward: objectives

beyond the impressive CDR

- **Innovate**

  Methodologies are evolving… prepare to jump

  Physics hot topics come (and go)… prepare to surf the good waves

- **Demonstrate**

  We are not alone… prepare to show uniqueness

  People have no time… prepare adequate guidance towards results

The way forward: objectives

beyond the impressive CDR

- Innovate

  Methodologies are evolving… prepare to jump
  Physics hot topics come (and go)… prepare to surf the good waves

- Demonstrate

  We are not alone… prepare to show uniqueness
  People have no time… prepare adequate guidance towards results

- Promote

  Large, larger, largest… prepare to create awareness
  Trust your intuition… prepare to engage enthousiastic researchers
  Talented researchers make the difference … promote science and scientists

The way forward: objectives

beyond the impressive CDR

- Innovate – Coordination Panel to steer

  Methodologies are evolving… prepare to jump
  Physics hot topics come (and go)… prepare to surf the good waves

- Demonstrate – Conveners to steer

  We are not alone… prepare to show uniqueness
  People have no time… prepare adequate guidance towards results

- Promote – all together, and Coordinator to help

  Large, larger, largest… prepare to create awareness
  Trust your intuition… prepare to engage enthousiastic researchers
  Talented researchers make the difference … promote science and scientists

The way forward: objectives

beyond the impressive CDR

- **Innovate** – Coordination Panel to steer

  Blue sky & steered innovations

  Methodologies are evolving… prepare to jump

  Physics hot topics come (and go)… prepare to surf the good waves

- **Demonstrate** – Conveners to steer

  We are not alone… prepare to show uniqueness

  People have no time… prepare adequate guidance towards results

- **Promote** – all together, and Coordinator to help

  Large, larger, largest… prepare to create awareness

  Trust your intuition… prepare to engage enthousiastic researchers

  Talented researchers make the difference … promote science and scientists

The way forward: objectives

beyond the impressive CDR

- **Innovate** – Coordination Panel to steer

  Blue sky & steered innovations

  Methodologies are evolving… prepare to jump
  Physics hot topics come (and go)… prepare to surf the good waves

- **Demonstrate** – Conveners to steer

  DIS program empowers particle and nuclear physics

  We are not alone… prepare to show uniqueness
  People have no time… prepare adequate guidance towards results

- **Promote** – all together, and Coordinator to help

  Large, larger, largest… prepare to create awareness
  Trust your intuition… prepare to engage enthousiastic researchers
  Talented researchers make the difference … promote science and scientists

The way forward: objectives

beyond the impressive CDR

- Innovate – Coordination Panel to steer

  Blue sky & steered innovations

  Methodologies are evolving… prepare to jump
  Physics hot topics come (and go)… prepare to surf the good waves

- Demonstrate – Conveners to steer

  DIS program empowers particle and nuclear physics

  We are not alone… prepare to show uniqueness
  People have no time… prepare adequate guidance towards results

- Promote – all together, and Coordinator to help

  Promotion objectives & strategy

  Large, larger, largest… prepare to create awareness
  Trust your intuition… prepare to engage enthousiastic researchers
  Talented researchers make the difference … promote science and scientists

Time to discuss

all together