Energy Recovery Linacs (ERL): R&D plans and impact

an impactful accelerator technology for future colliders in particle physics

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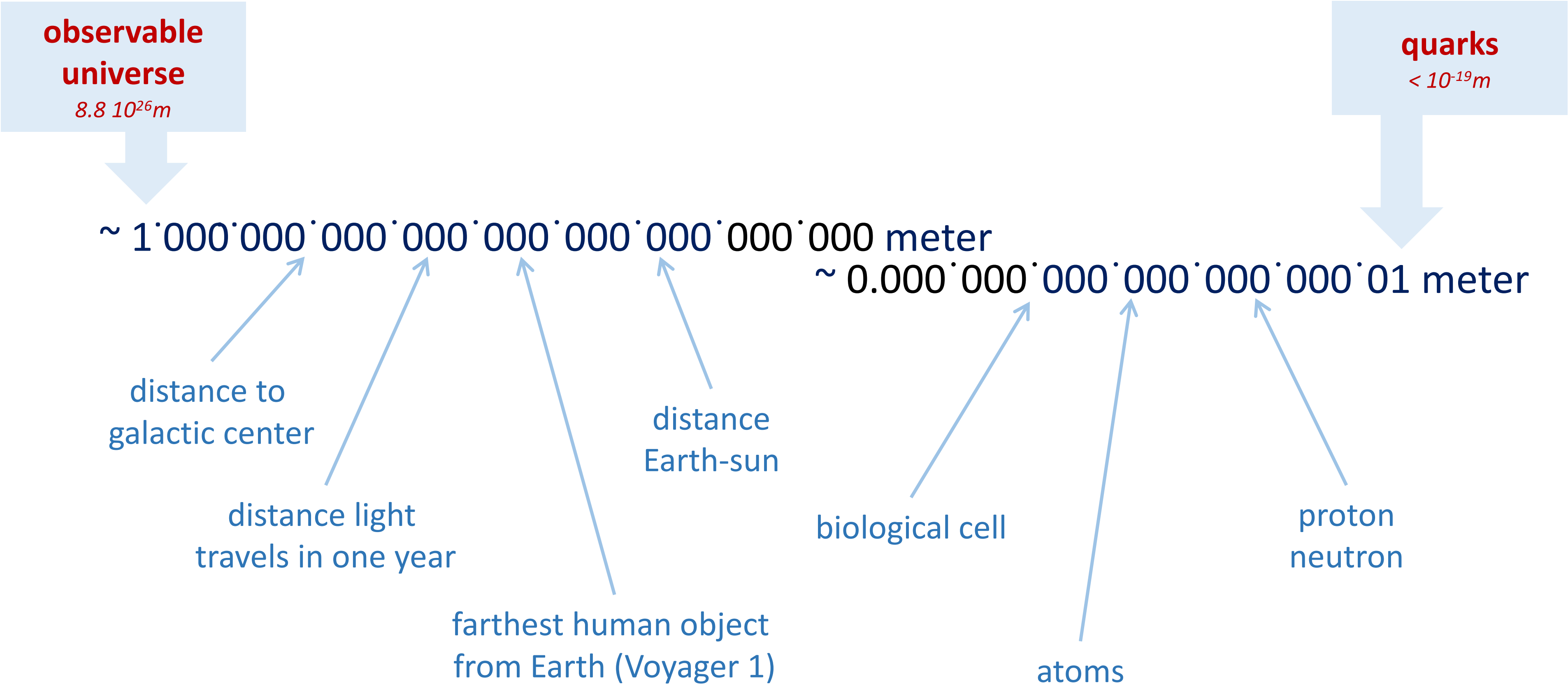
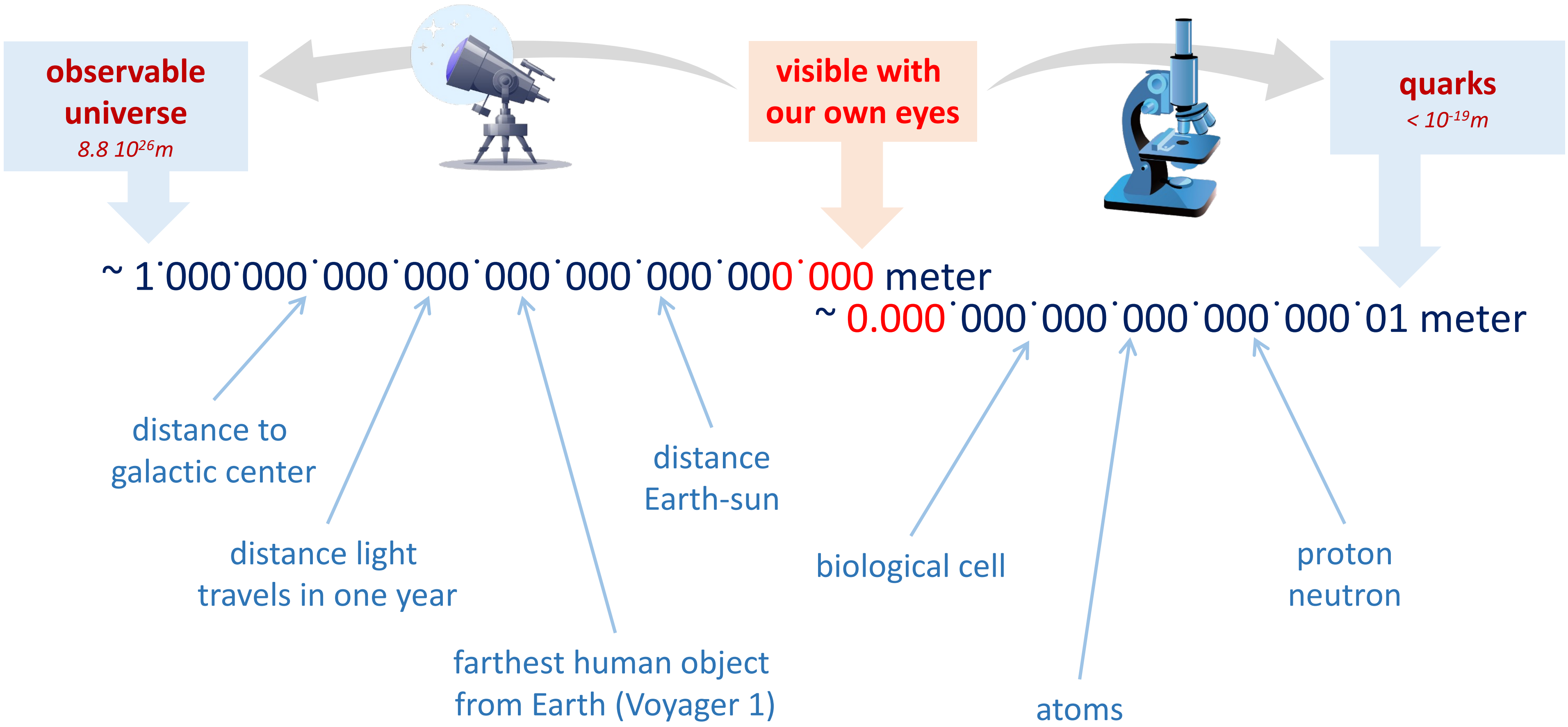
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

ERL Open Seminar, IJCLab
29 September 2023


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



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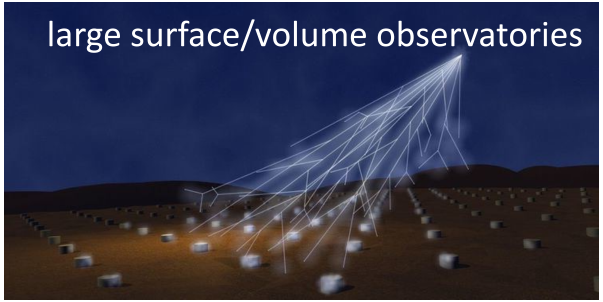

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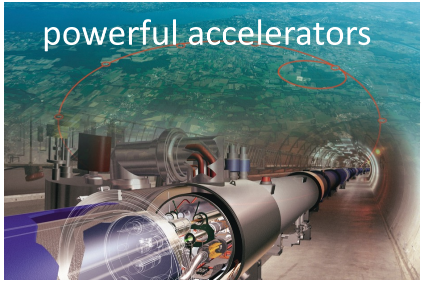

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distance to galactic center

distance light travels in one year

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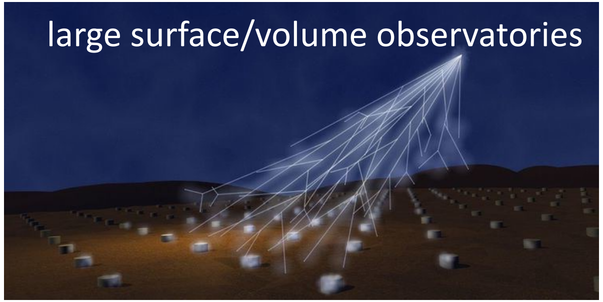
biological cell

atoms

proton neutron

age universe
4.4 10^{18} s

observable universe
8.8 10^{26}m



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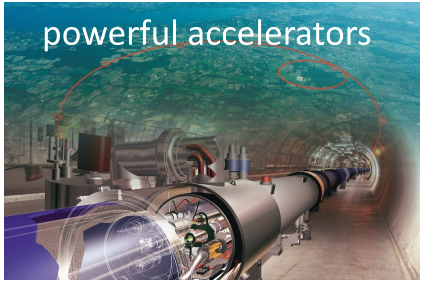

lifetime top quark
5 10^{-25} s

quarks
< 10 $^{-19}$m

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

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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

lifetime star
10^{13}-10^{16} s

duration supernova & GRB
0.1-100 s

lifetime proton
> 3 10^{41} s

lifetime kaon ($K^{\pm}$)
1.2 10^{-8} s

Develop a model to describe how objects behave in this space and time

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Basic Principles

FROM INTUITION

e.g. the locality principle:
all matter has the same set of constituents

e.g. the causality principle:
a future state depends only on the present state

e.g. the invariance principle:
space-time is homogeneous

FROM LONG-STANDING OBSERVATIONS

the wave-particle duality principle
the quantisation principle
the cosmological principle
the constant speed of light principle
the uncertainty principle
the equivalence principle

no obvious reason for these long-standing observations to be what they are…

Develop a model to describe how objects behave in this space and time

Basic Principles

Fundamental Theories

MATHEMATICAL FRAMEWORKS HOW OBJECTS BEHAVE

① ***General Relativity*** *(for gravity)*

② ***Quantum Mechanics + Special Relativity = Quantum Field Theory***
(for electromagnetic, weak and strong forces)

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Concrete Models

APPLY MATHEMATICAL FRAMEWORKS ON OBJECTS

① ***General Relativity → Standard Model of Cosmology***
② ***Quantum Field Theory → Standard Model of Particle Physics***

need to be valid into even the tiniest cracks of space and time
and for all energies or masses of the objects… even at the extremes

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

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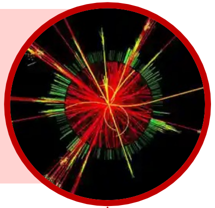
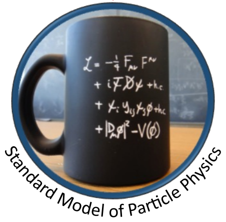
observations how small objects behave in our laboratories





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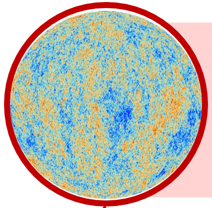
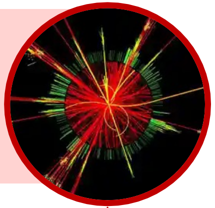


observations how large objects behave in our universe

Standard Model of Cosmology



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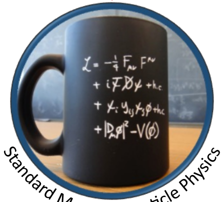

Standard Model of Particle Physics

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

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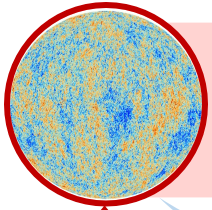
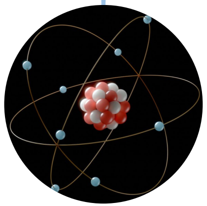
building blocks of life on the human scale



observations how large objects behave in our universe

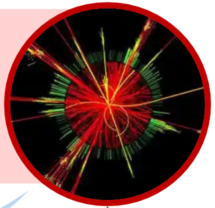
Standard Model of Cosmology

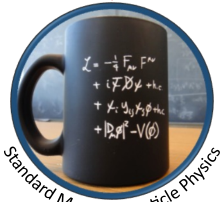
e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories





Standard Model of Particle Physics

A century of scientific revolutions

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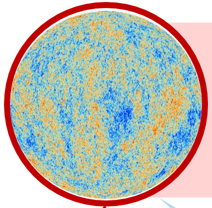
building blocks of life on the human scale



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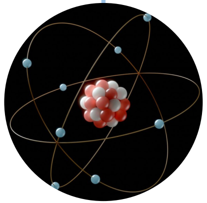

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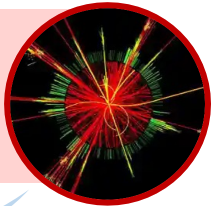
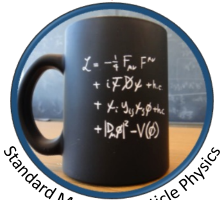
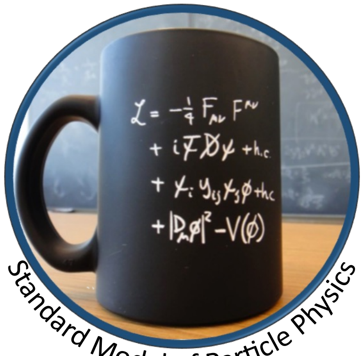




Standard Model of Particle Physics

The quest for understanding physics



Standard Model of Particle Physics

Standard Model of Cosmology

“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?

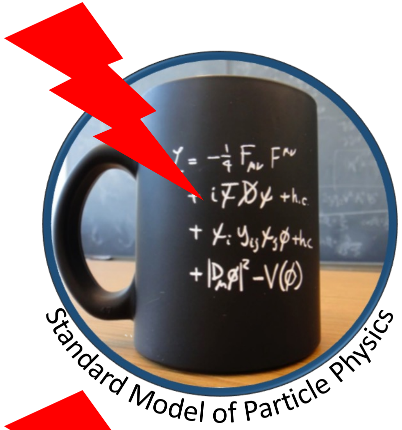
Scale of things (why do the numbers miraculously match)?

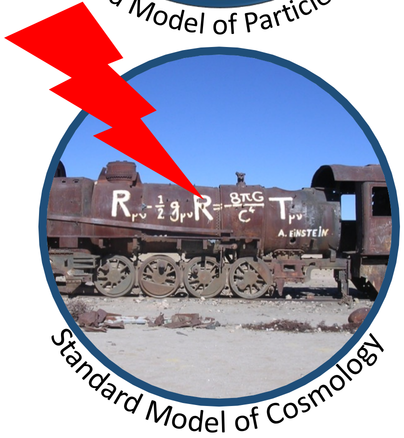
Pattern of particle masses and mixings?

Dynamics of Electro-Weak symmetry breaking?

How do quarks and gluons give rise to properties of nuclei?…

The quest for understanding physics





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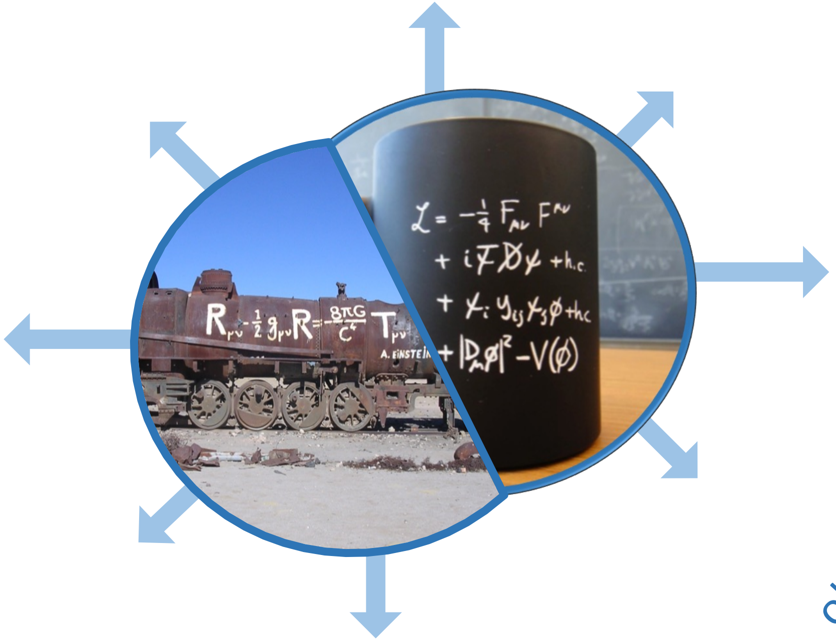
Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

higher energy interactions
in the lab

earlier universe

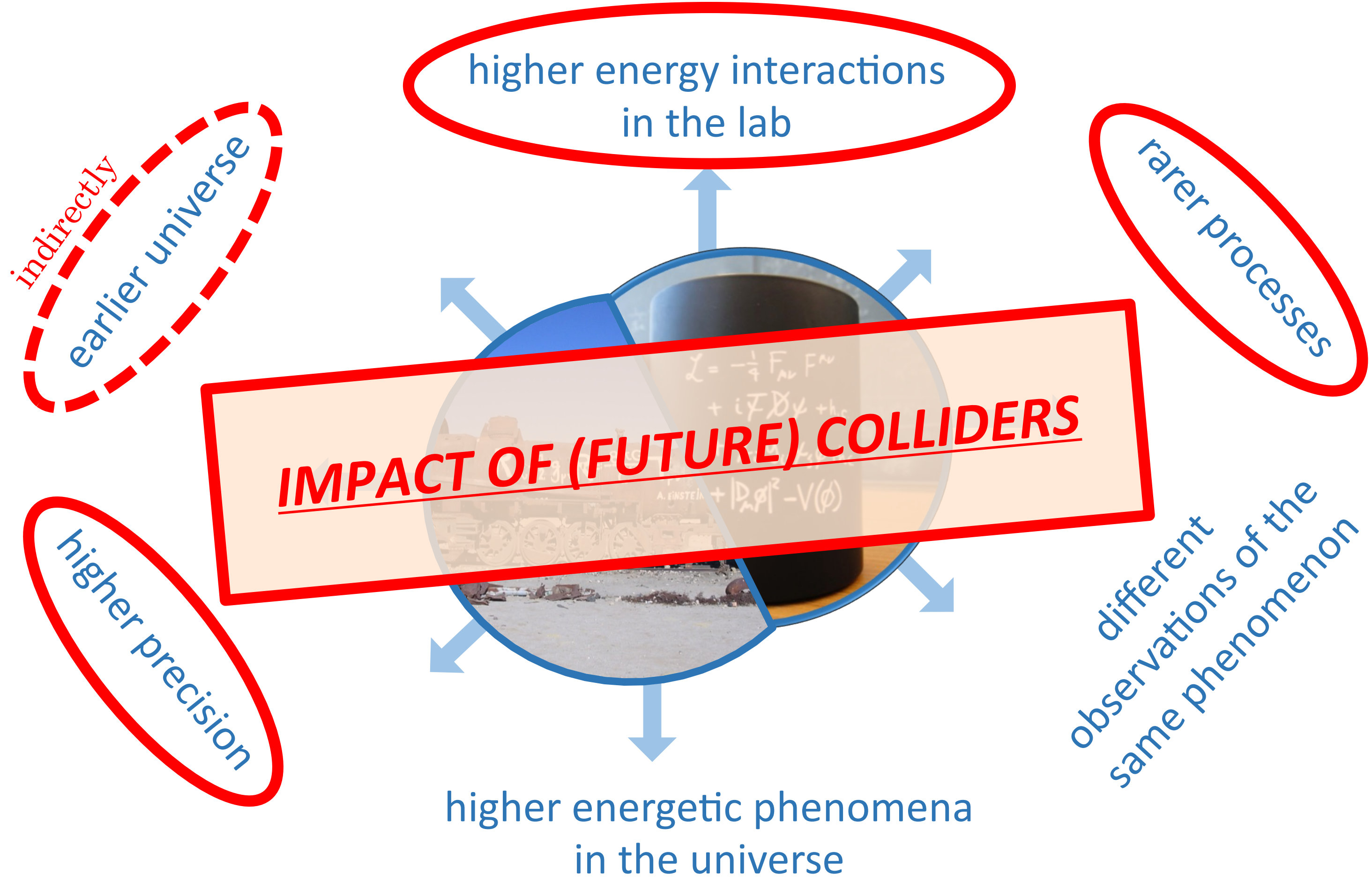
rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe


IMPACT OF (FUTURE) COLLIDERS
higher energy interactions in the lab
rarer processes
different observations of the same phenomenon
higher energetic phenomena in the universe
higher precision
indirectly
earlier universe

The landscape of particle physics colliders

~15-20B EUR

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

The landscape of particle physics colliders

$e^{\pm}p$ (and $e^{\pm}A$)

ERL technology ($E_e \sim$ 30-60 GeV)

E_{CMS} > 1 TeV

ERL: https://indico.ijclab.in2p3.fr/event/9548/

∼1B EUR

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~1B EUR

~7-12B EUR

e^+e^-

RF technology

E_{CMS} ~ 10 GeV (flavour)

E_{CMS} ~ 90-360 GeV (Z/W/H/top)

E_{CMS} > 500 GeV

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$\mu^+\mu^-$

first time ever collider

E_{CMS} ~ 3-10 TeV

plasma wakefield

first time ever collider

many applications

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

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

The landscape of particle physics colliders

This talk will focus on the Energy Recovery Linac technology to improve the performance of these colliders

FOCUS

$e^{\pm}p$ (and $e^{\pm}A$)

ERL technology ($E_e \sim$ 30-60 GeV)

E_{CMS} > 1 TeV

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particle physics ambition

high-energy & high-current beams

(energy x current = power)

particle physics ambition

high-energy & high-current beams

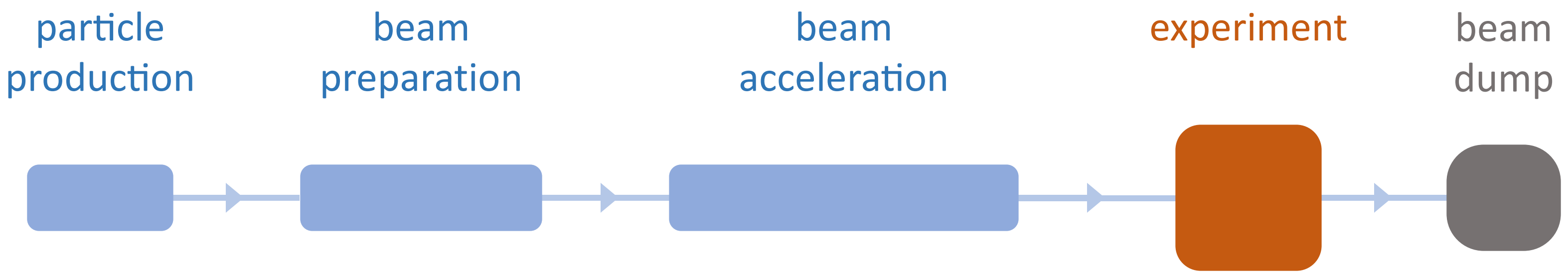
(energy x current = power)

caveat

power requirements of future colliders

focus on electron/positron accelerators

Basic structures of a particle accelerator



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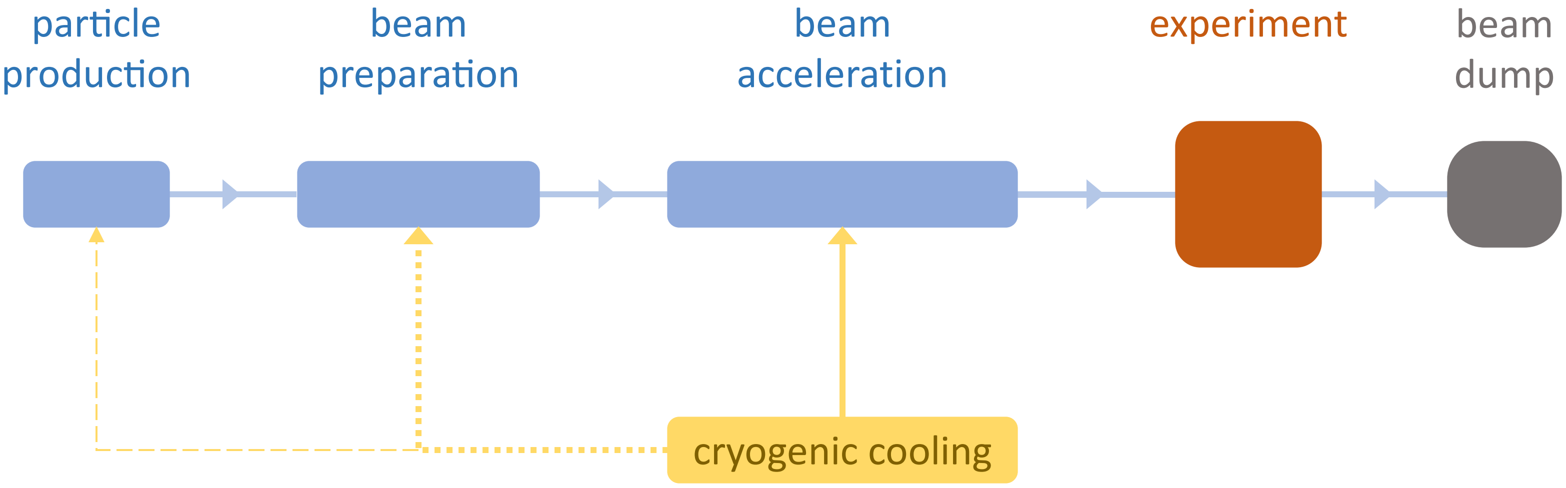

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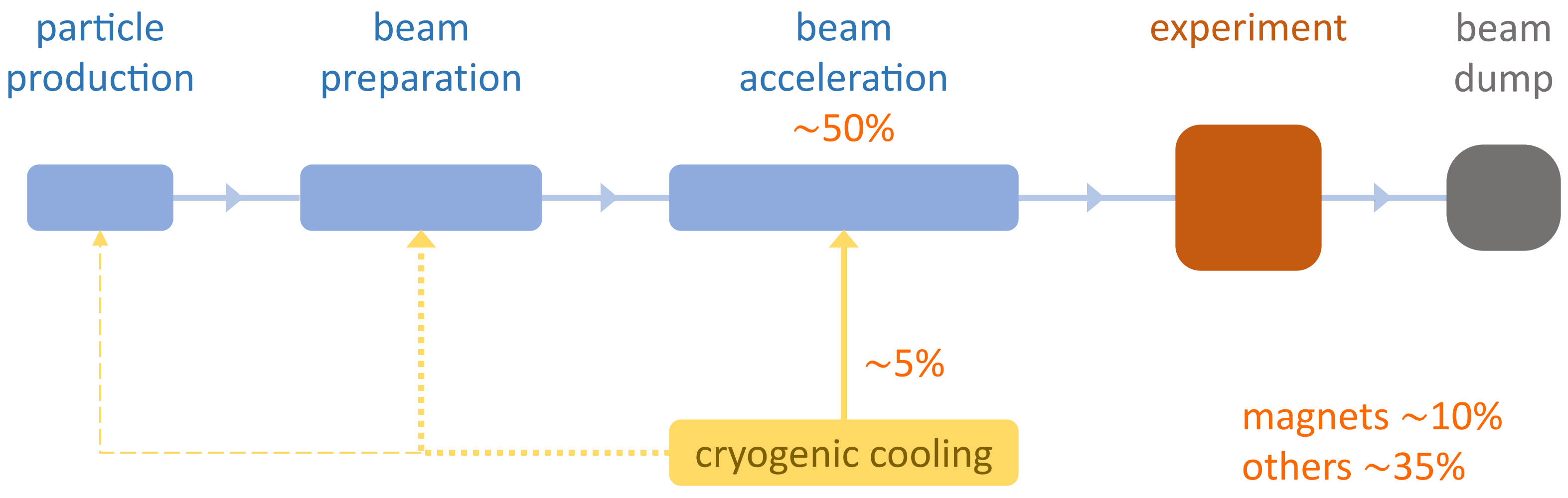


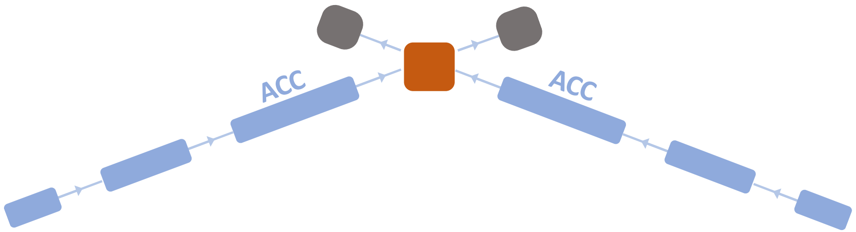
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC-ee@250GeV

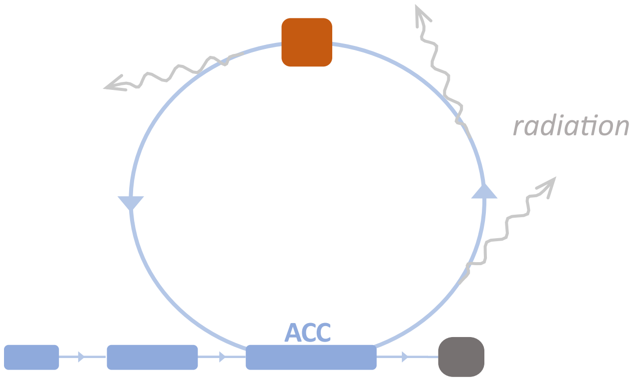
FCC CDR, Eur. Phys. J. Special Topics 228, 261–623 (2019)

Linear colliders



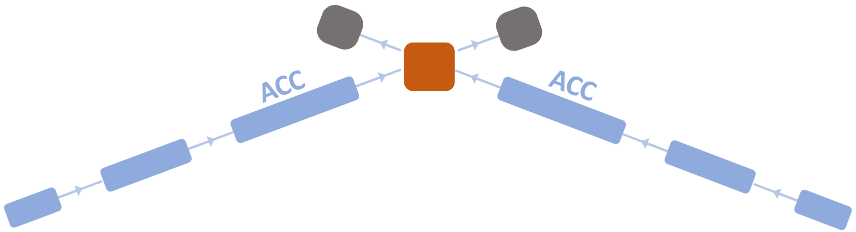
dump >99.9999% of
the beam power

Circular colliders



radiate away very quickly
the beam power

Linear colliders



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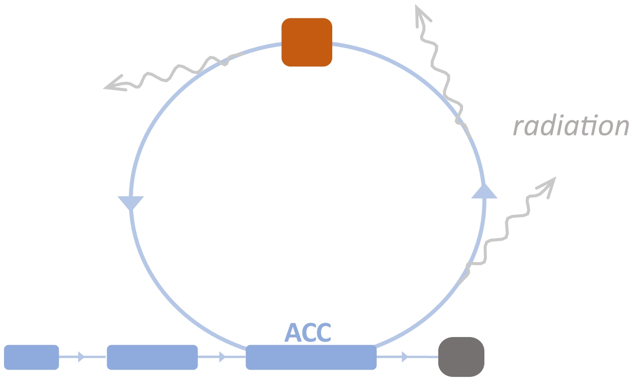
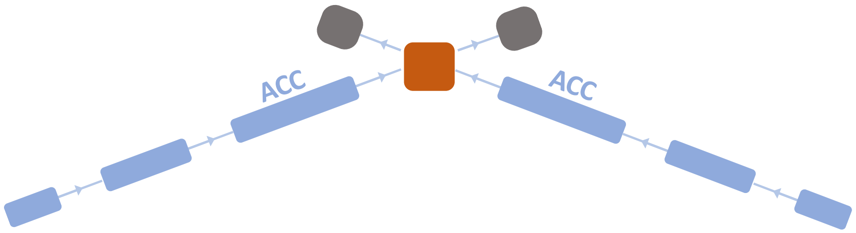


radiate away very quickly the beam power

FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

Linear colliders



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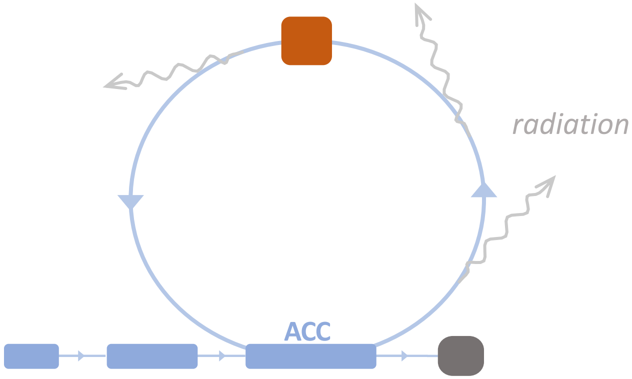


dump >99.9999% of the beam power

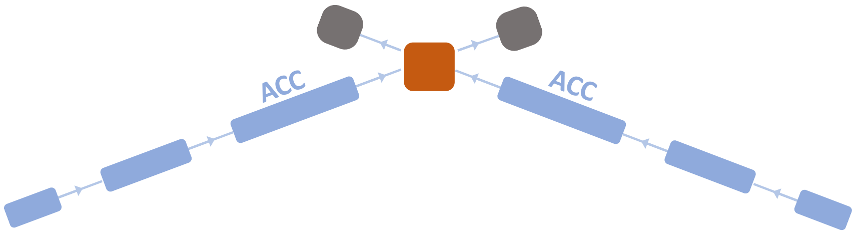
radiate away very quickly the beam power

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

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

Linear colliders



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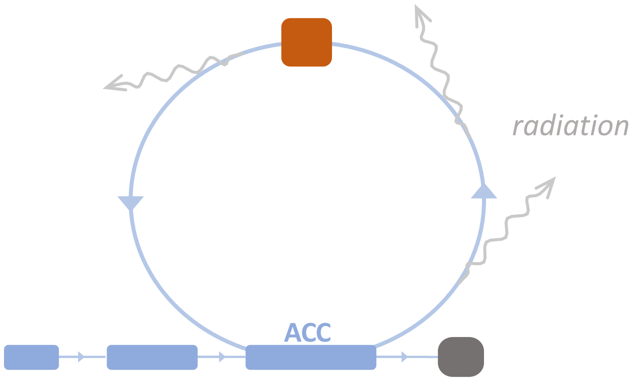


radiate away very quickly the beam power

FCC-ee@250 ≃ 300 MW

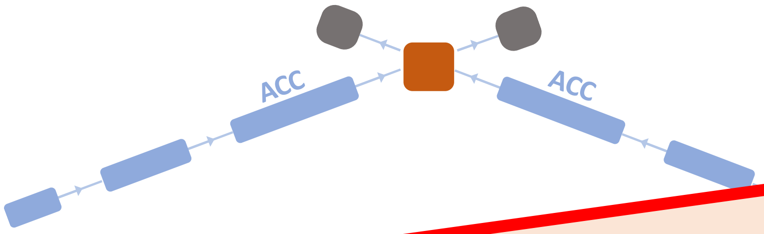
~4% of annual electricity consumption in Belgium

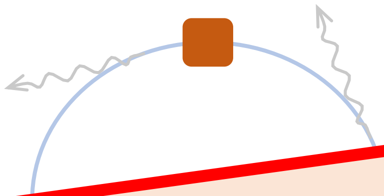
about half of this is dumped or lost due to radiation

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

Linear colliders

Circular colliders





To further increase the luminosity we would reach 1 GW power

equivalent to a nuclear power plant

away very quickly
the beam power

FCC-ee@250 $\simeq$ 300 MW

~4% of annual electricity consumption in Belgium

about half of this is dumped or lost due to radiation

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

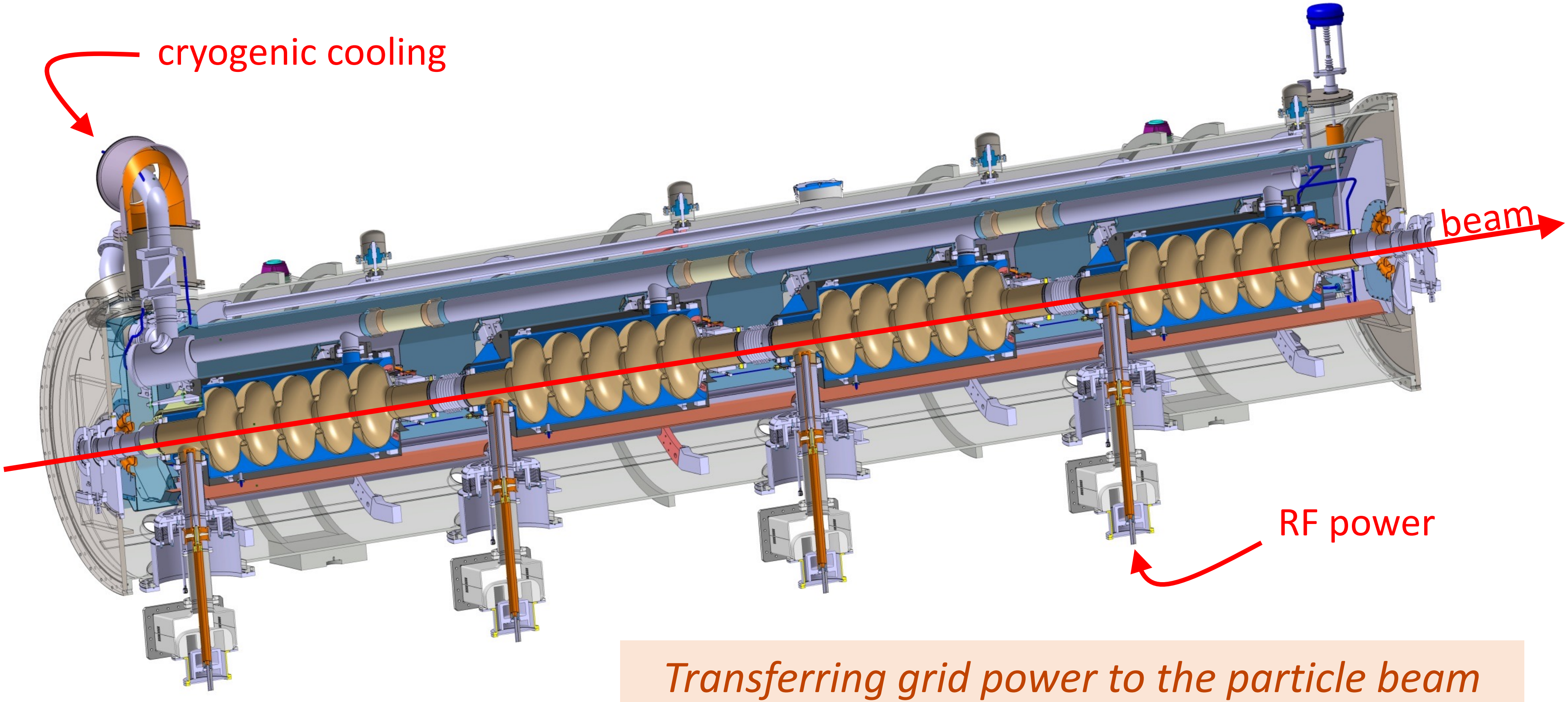
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

Key building block for beam acceleration: the SRF cryomodule

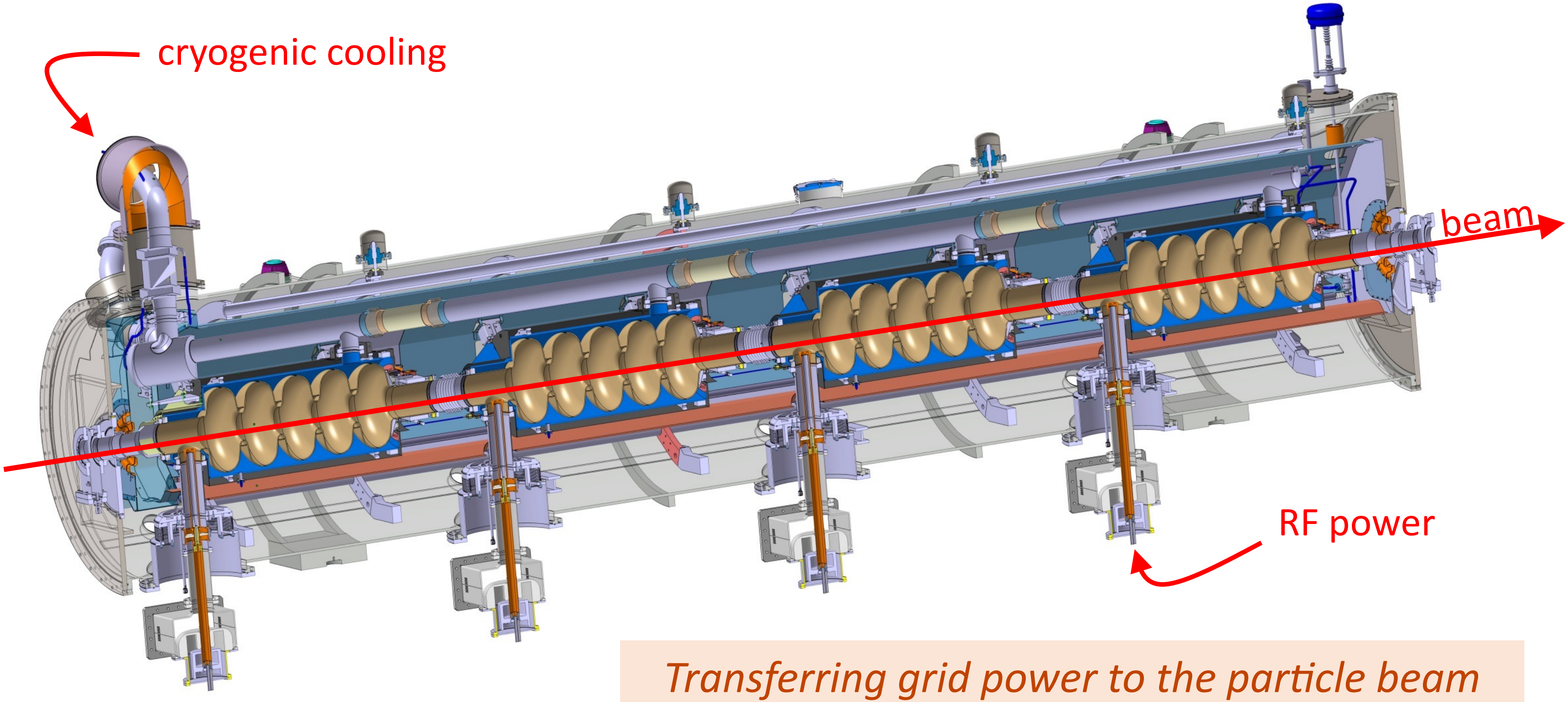
SRF: Superconducting Radio Frequency



Transferring grid power to the particle beam

Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

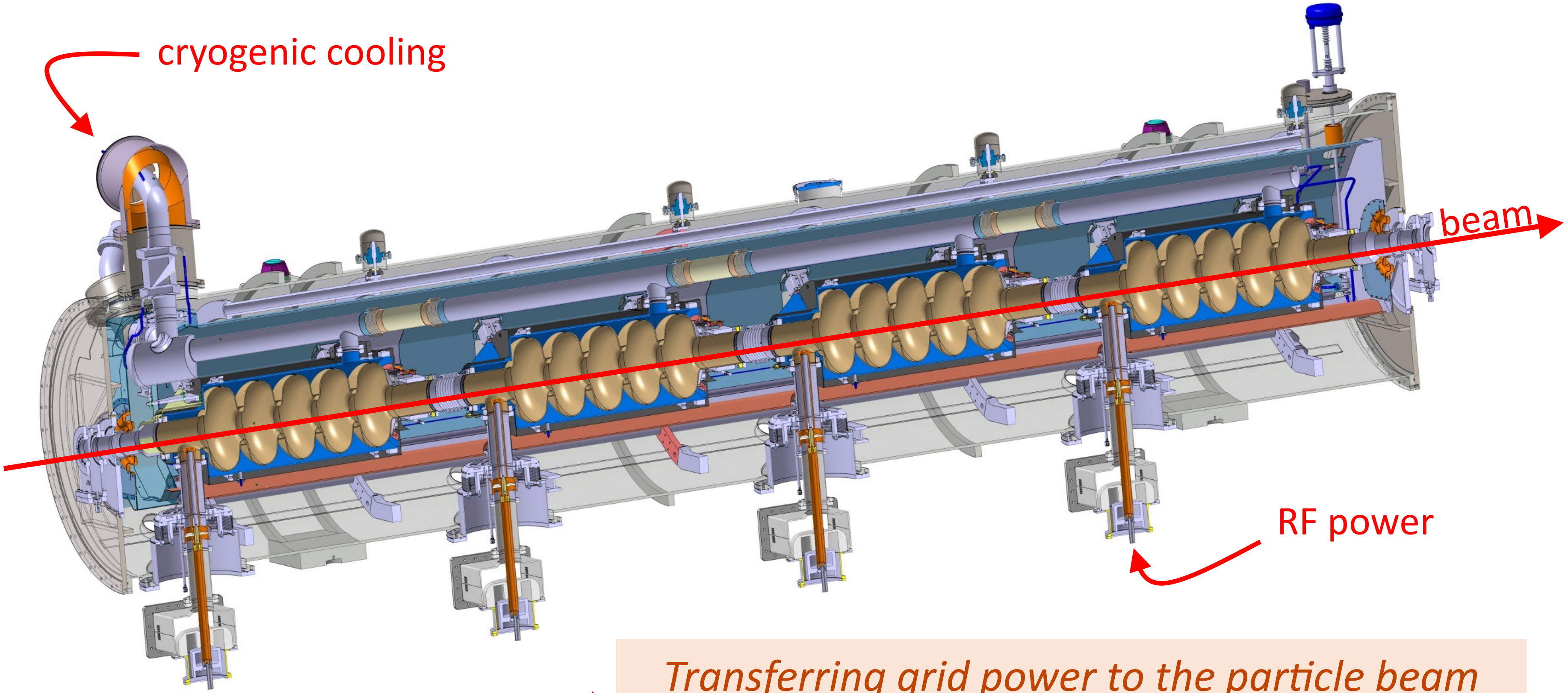


Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

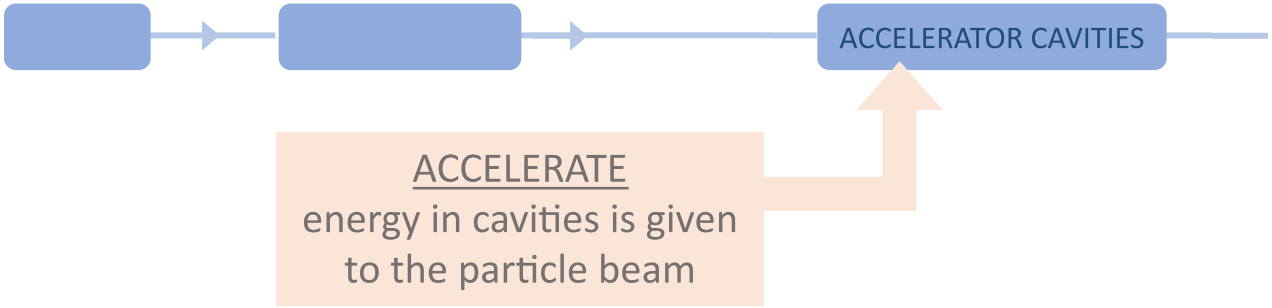


ENERGY RECOVERY →

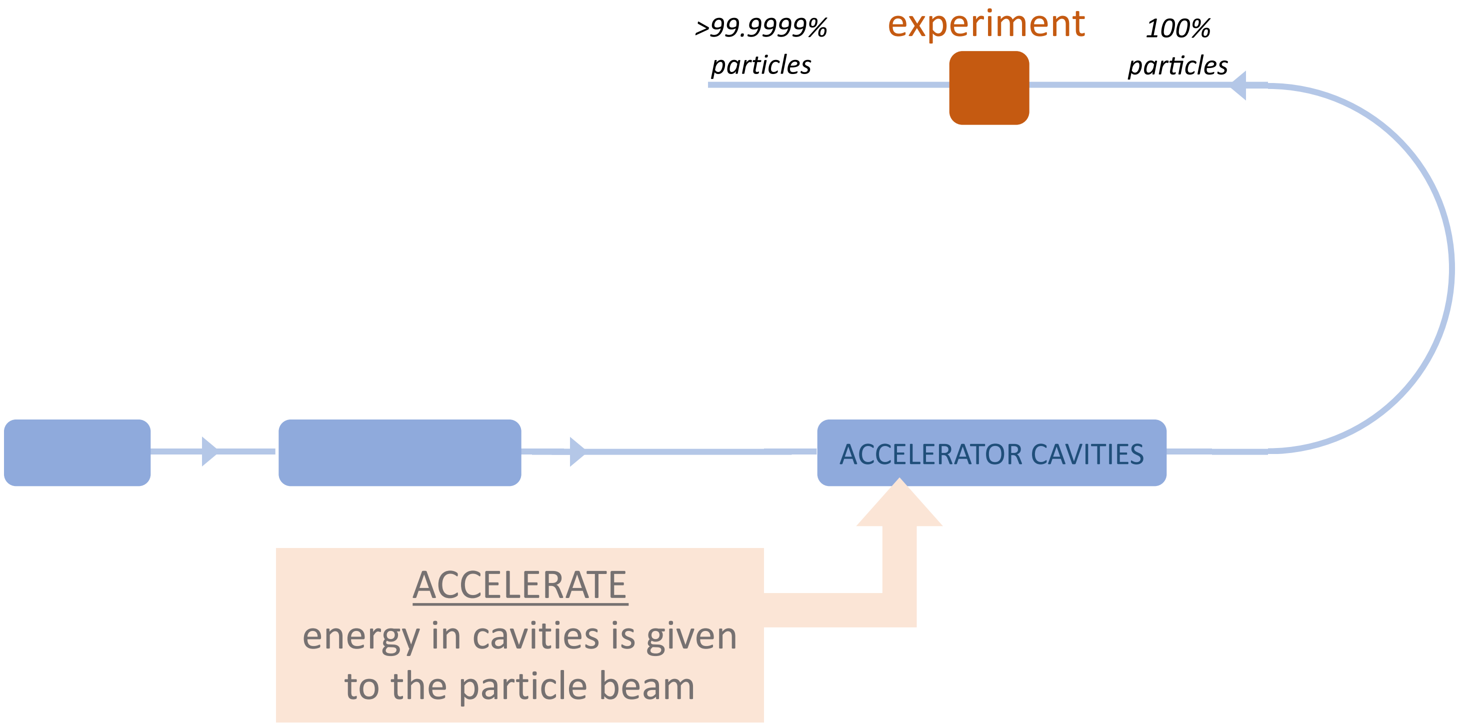
Transferring grid power to the particle beam

RECOVER THE ENERGY FROM THE USED BEAM

The principle of Energy Recovery



The principle of Energy Recovery



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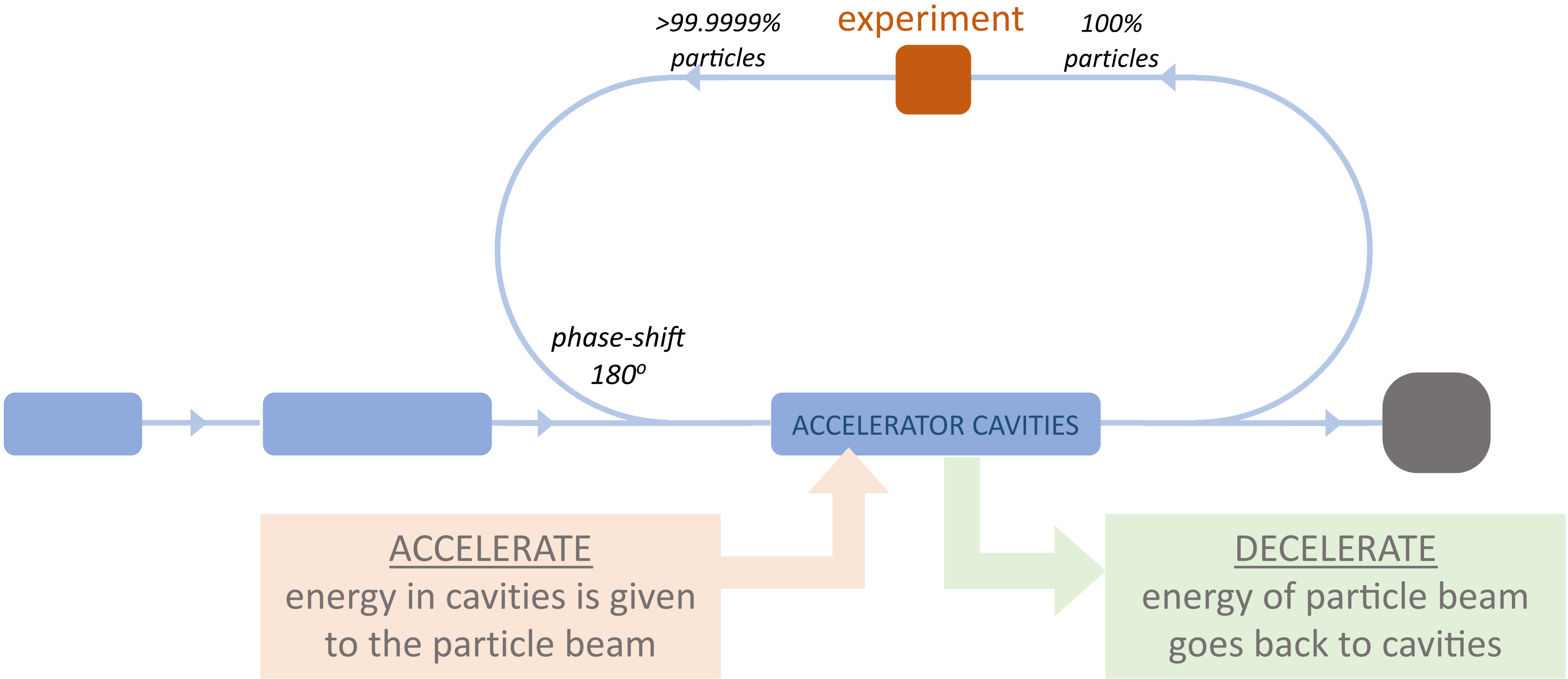

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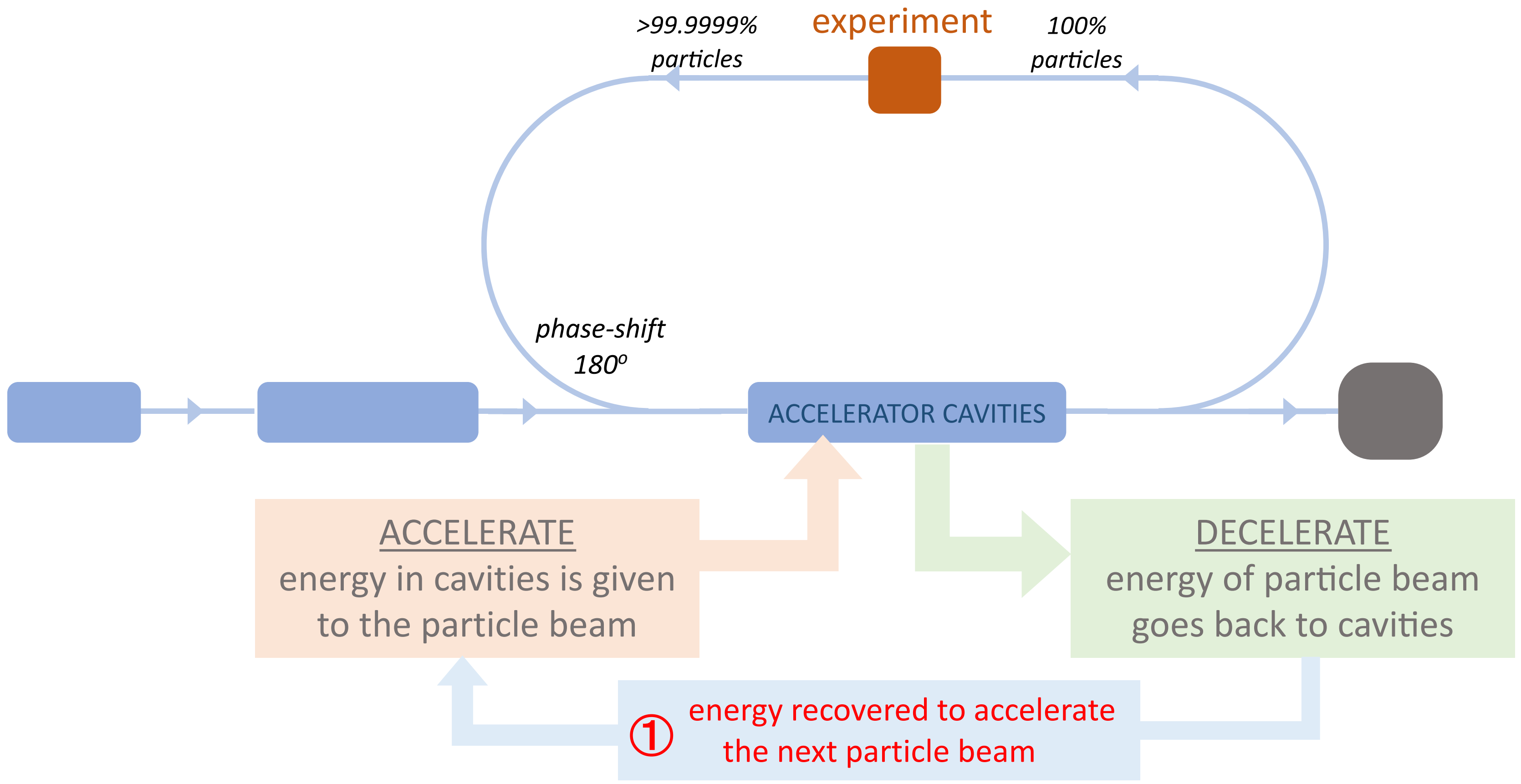
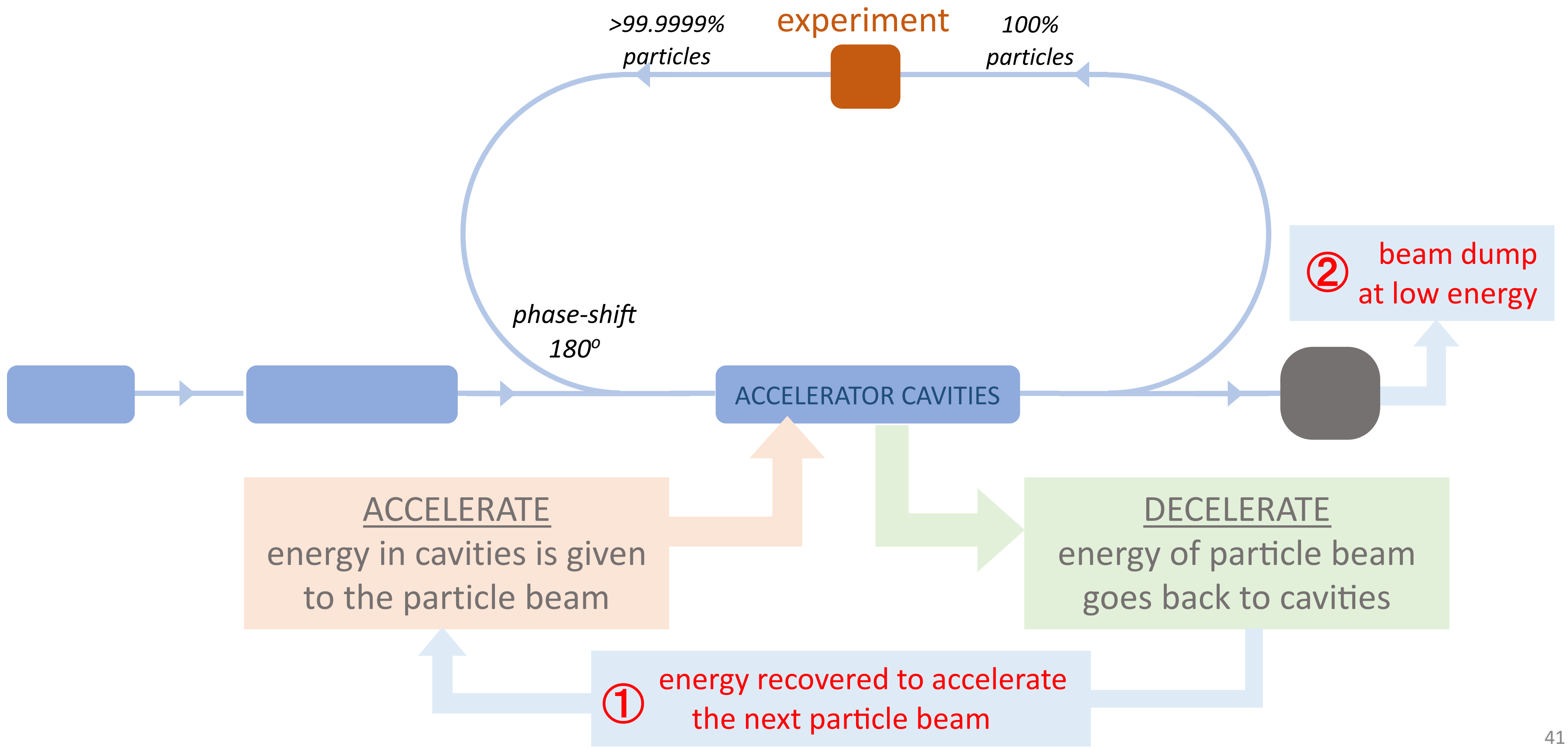


The principle of Energy Recovery



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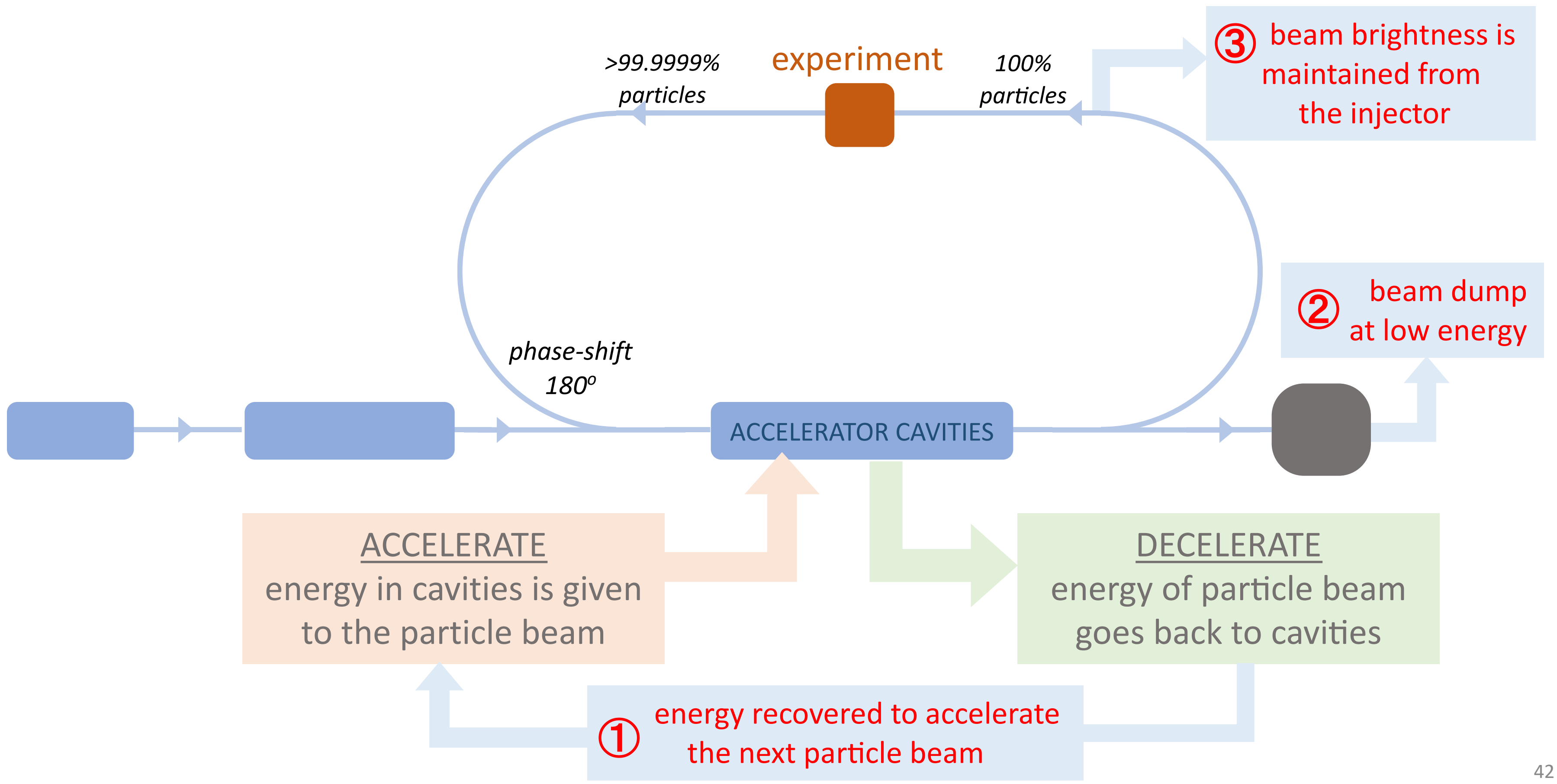
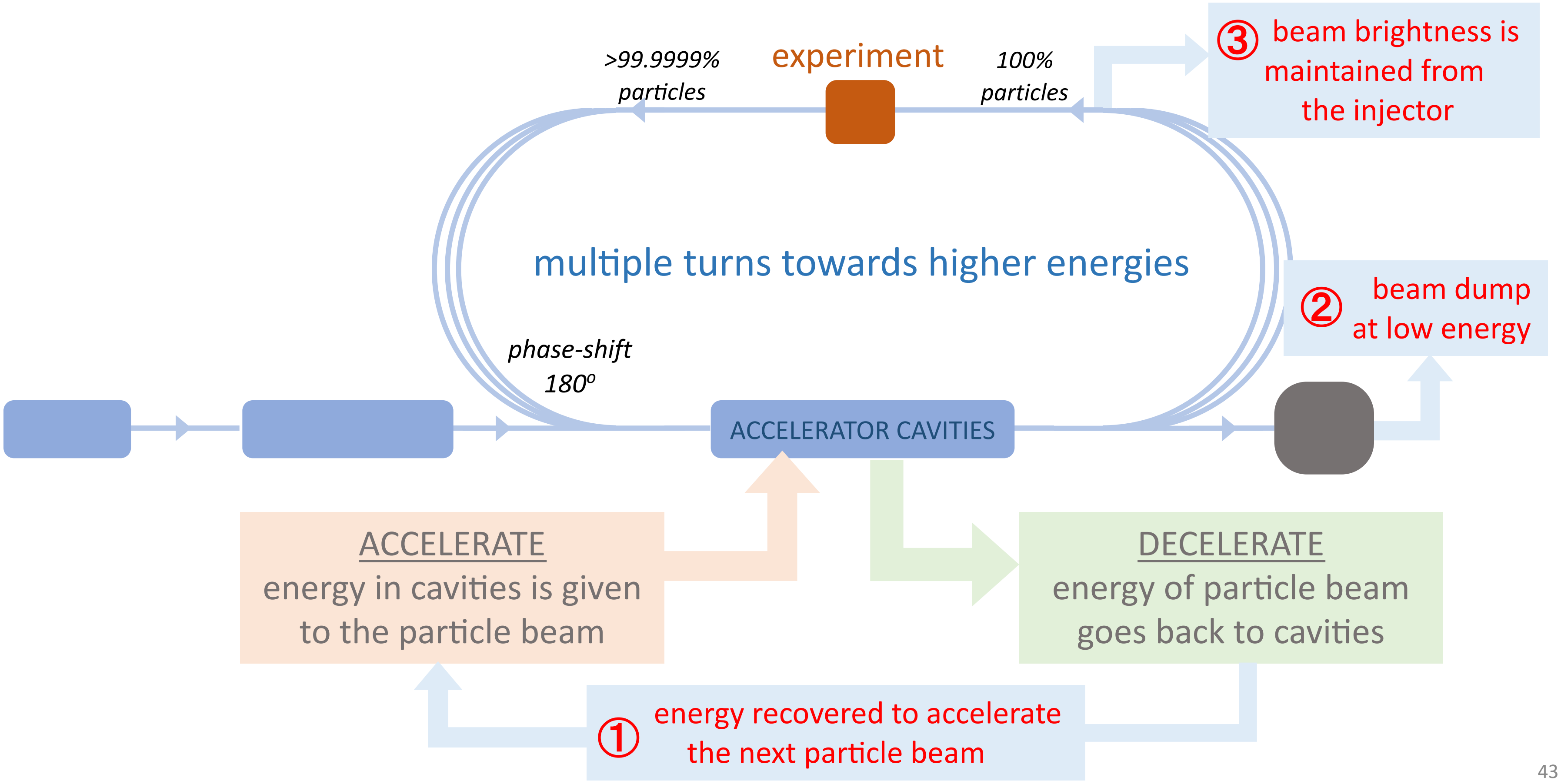
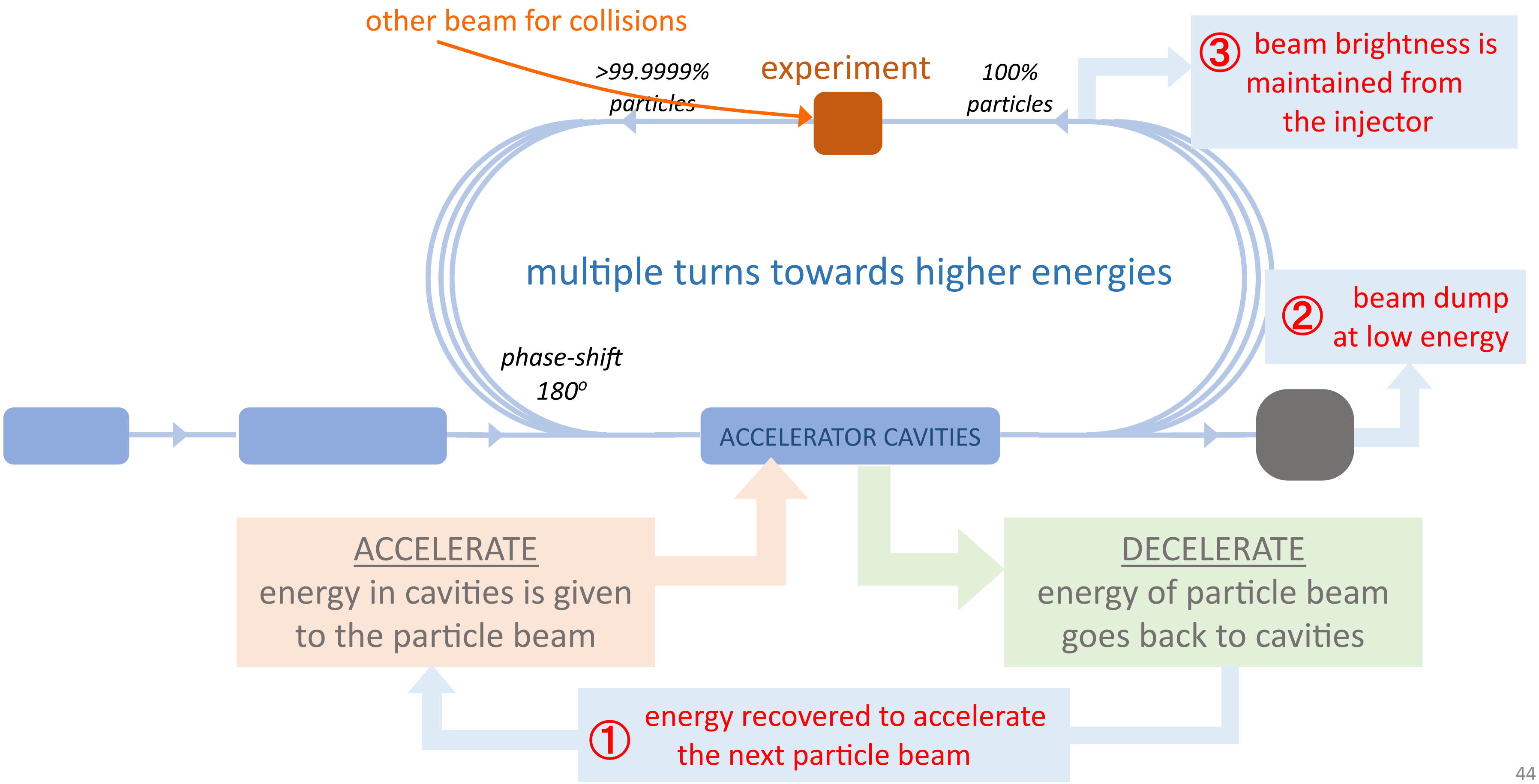


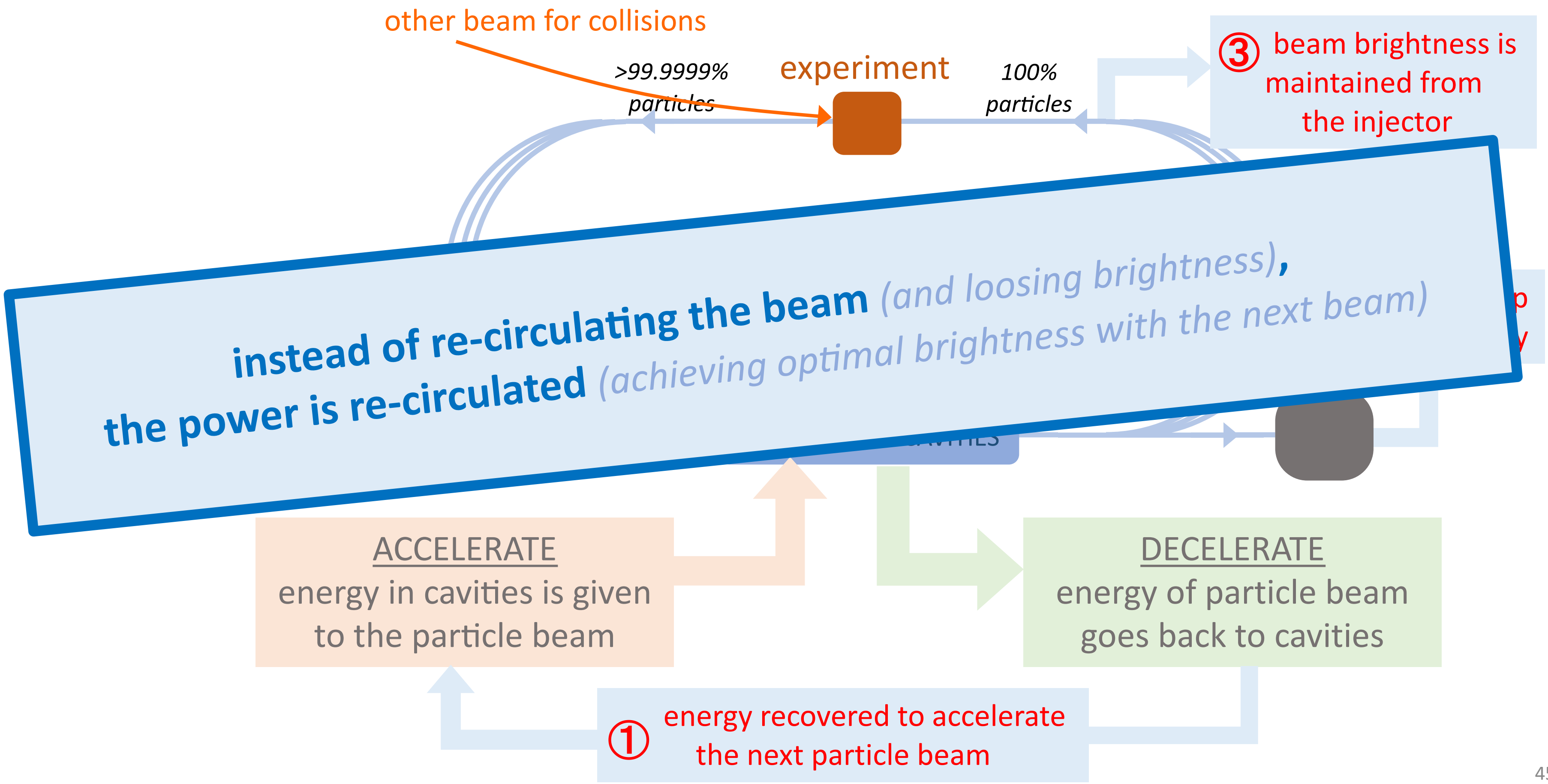
The principle of Energy Recovery



The principle of Energy Recovery

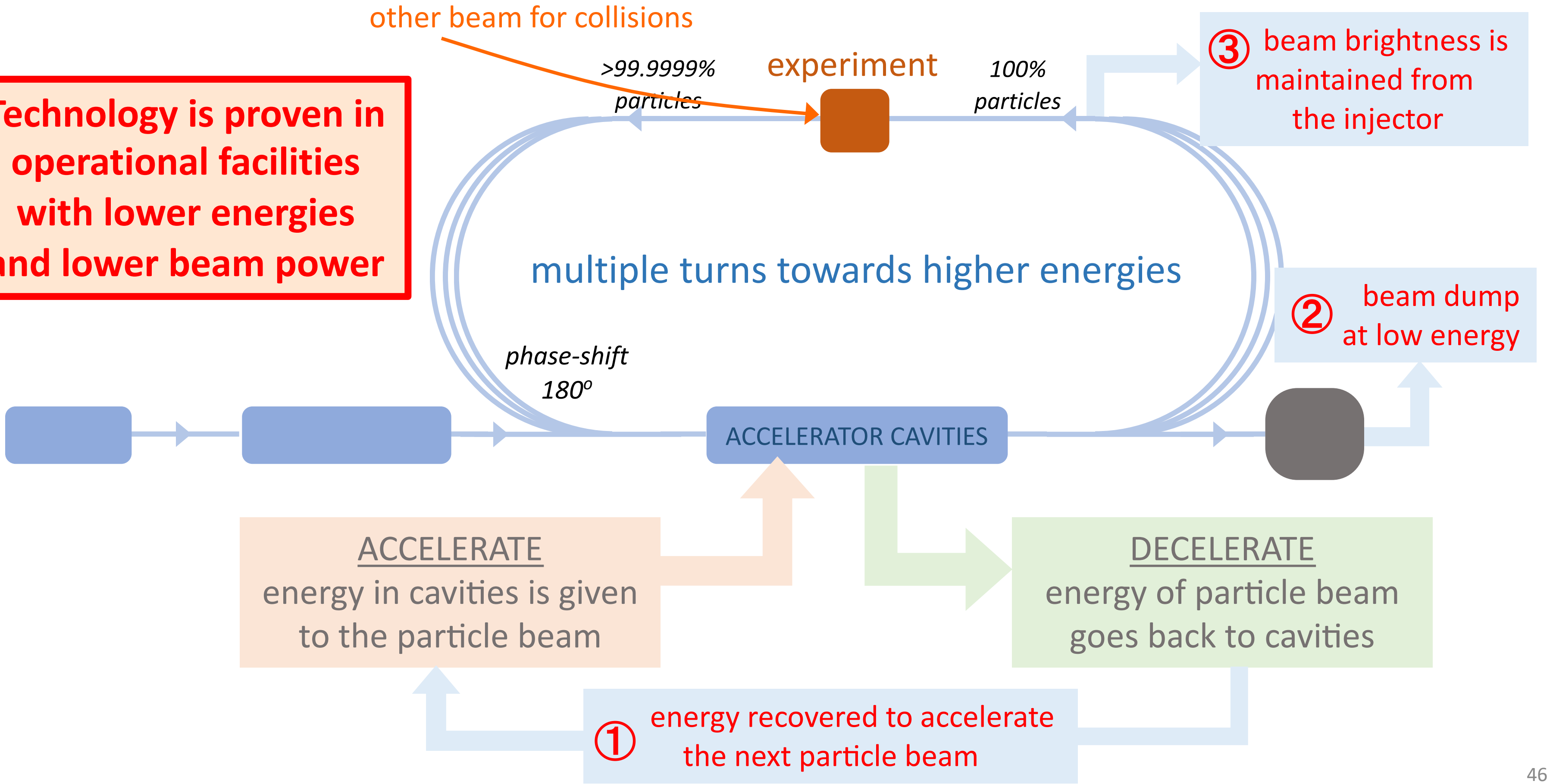


The principle of Energy Recovery



The principle of Energy Recovery

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



Ongoing & Upcoming facilities with ERL systems

worldwide several facilities are operational or are emerging

ongoing

s-DALINAC *TU Darmstadt. Germany*

two pass operation demonstrated

ongoing

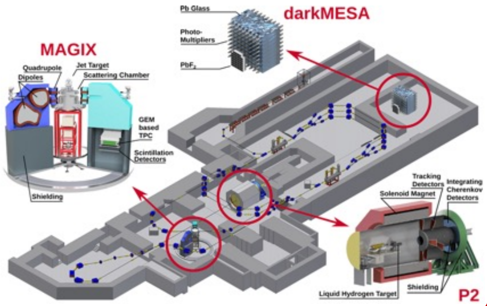
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

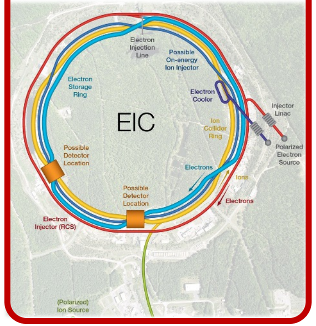
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

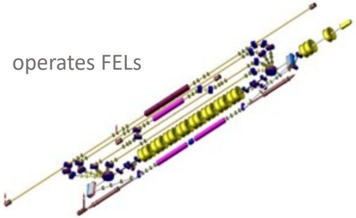
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

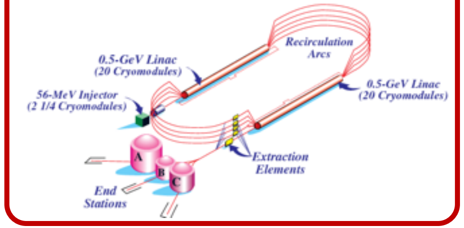
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes

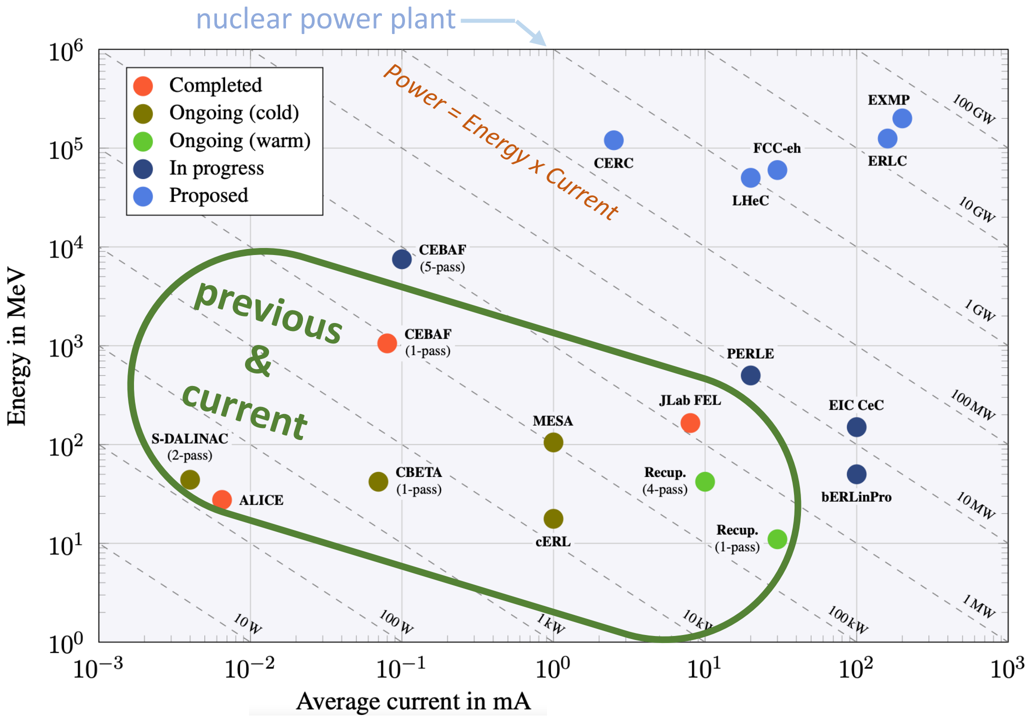


in progress

Upcoming: bERLinPro & PERLE

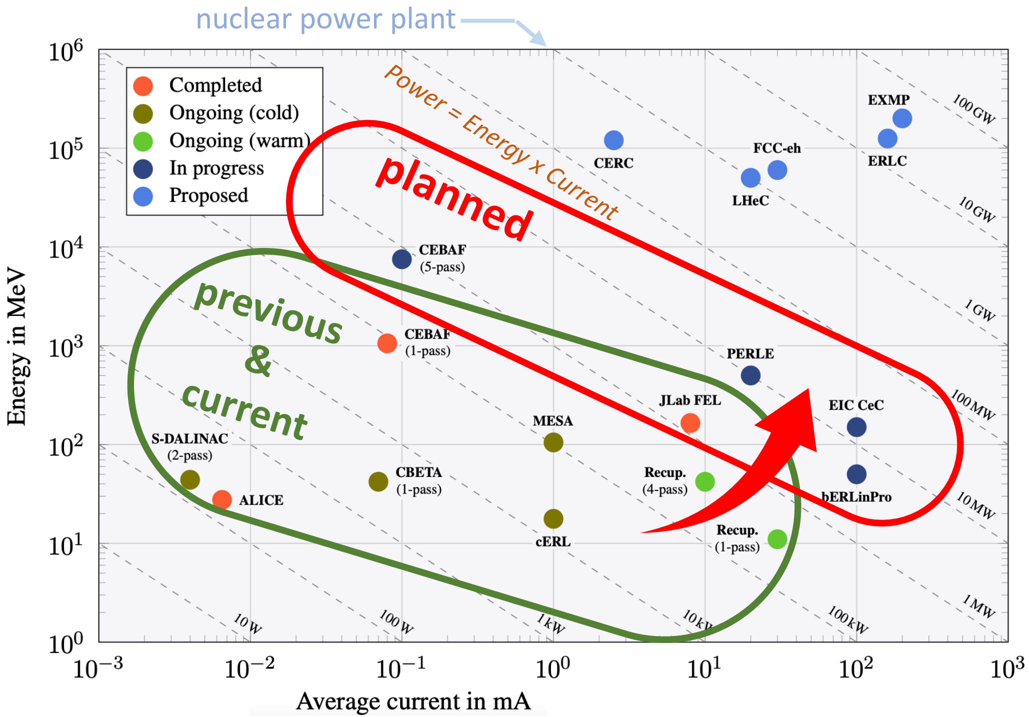
More facilities in design

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



Energy Recovery demonstrated

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



bERLinPro & PERLE

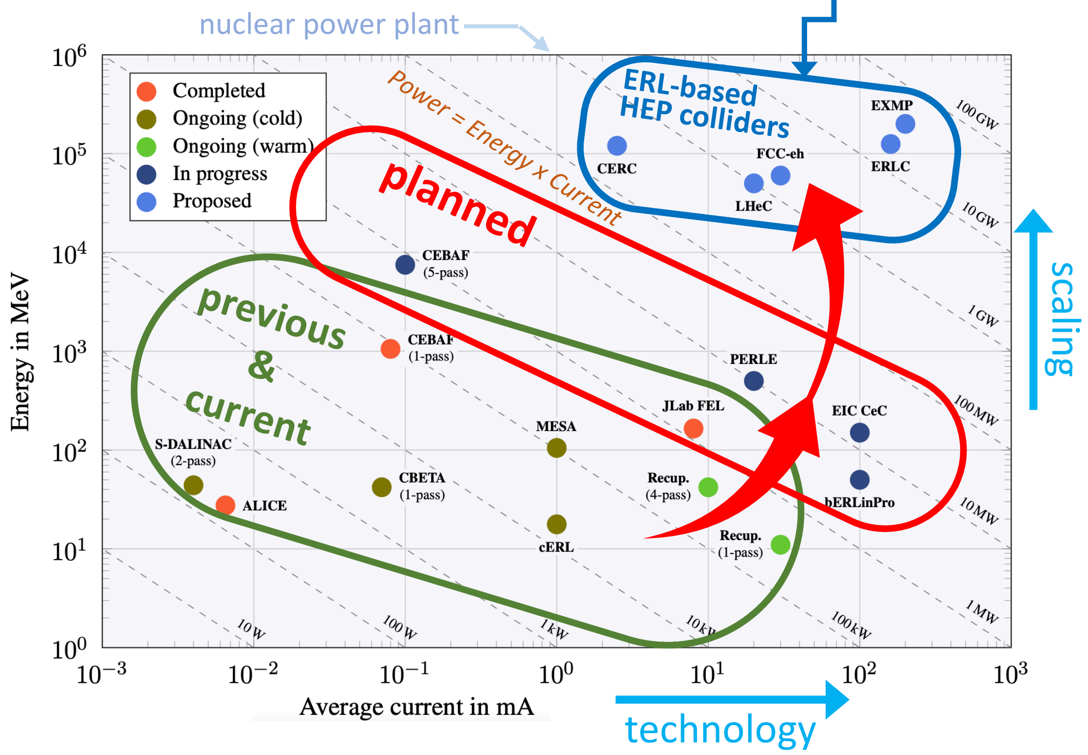
essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high energy & high power

Energy Recovery demonstrated

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

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



Future ERL-based Colliders

H, HH, ep/eA, muons, …

bERLinPro & PERLE

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

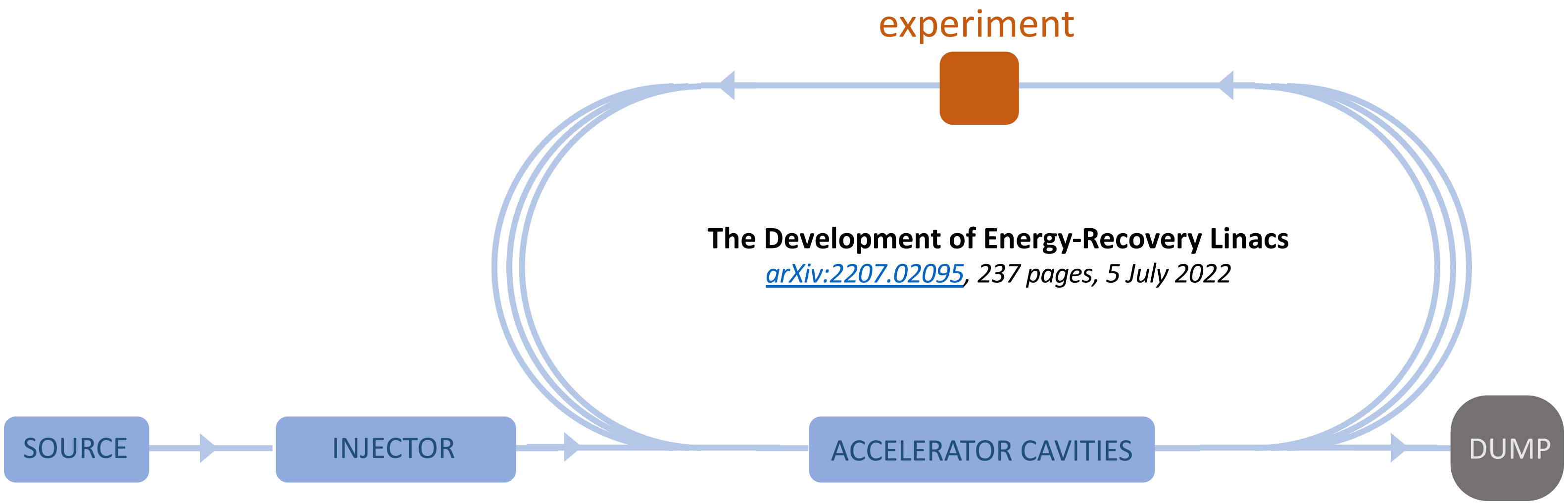
towards high energy & high power

Energy Recovery demonstrated

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

Identified the key aspects for an ERL accelerator

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



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

Identified the key aspects for an ERL accelerator

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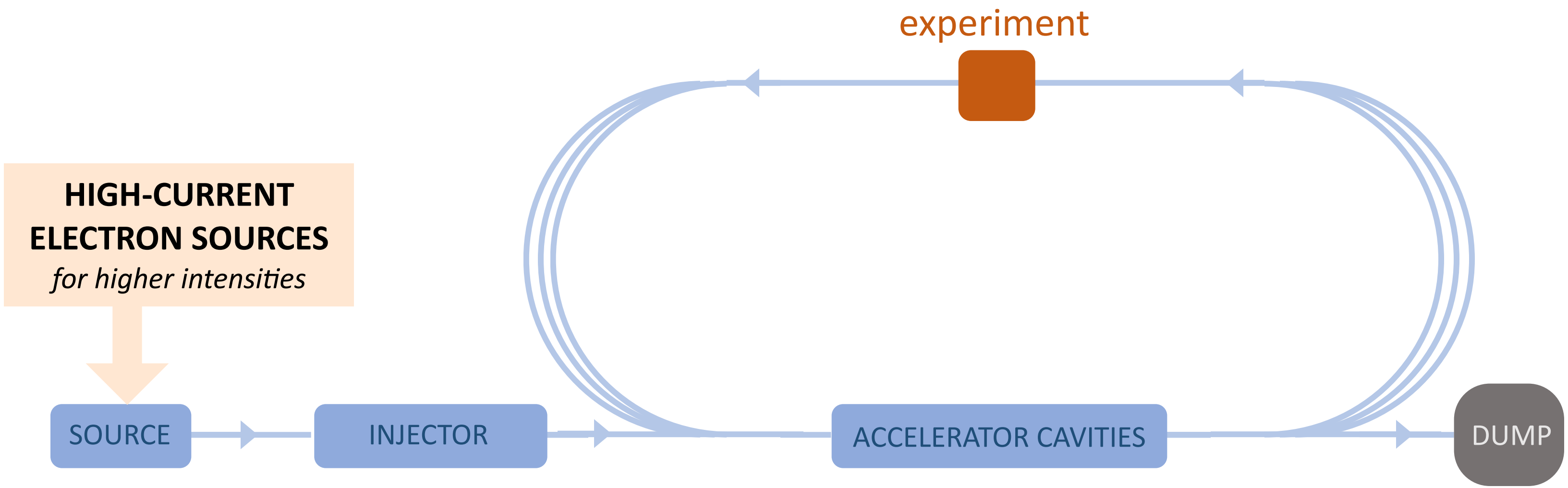


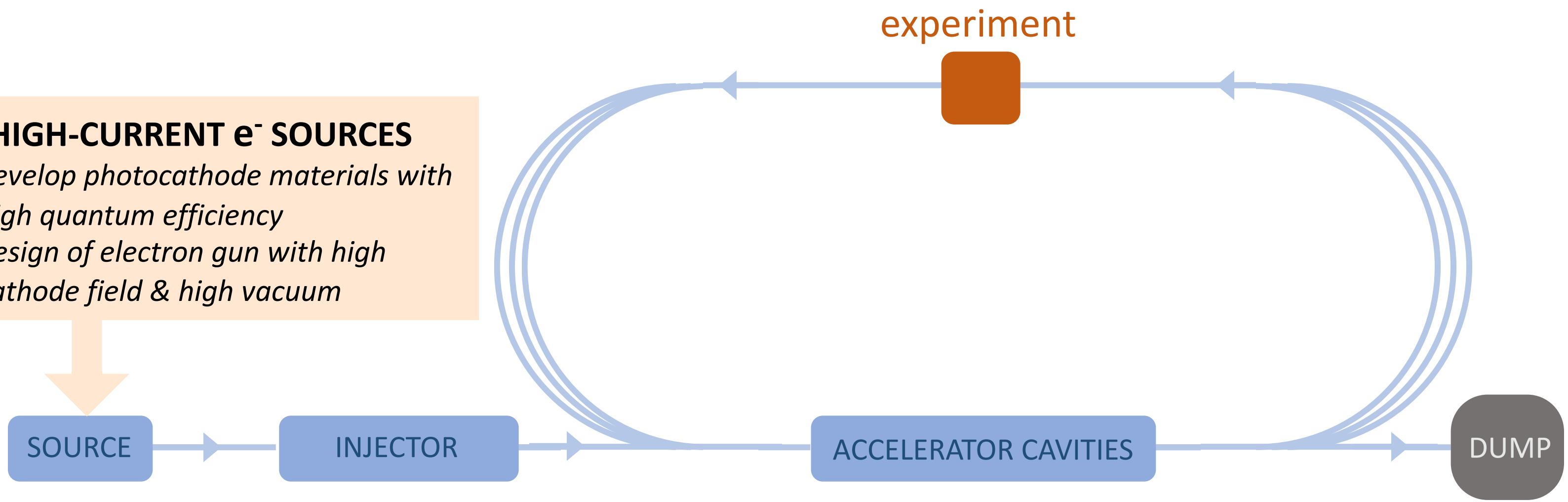
SRF photoinjectors have the greatest potential to generate high-brightness CW electron beams with a continuous reliable injection of high-charge, low-emittance bunches into a LINAC. Future systems must go more than an order of magnitude beyond the state-of-the-art.

Identified the key aspects for an ERL accelerator

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

HIGH-CURRENT e^- SOURCES

- *develop photocathode materials with high quantum efficiency*
- *design of electron gun with high cathode field & high vacuum*



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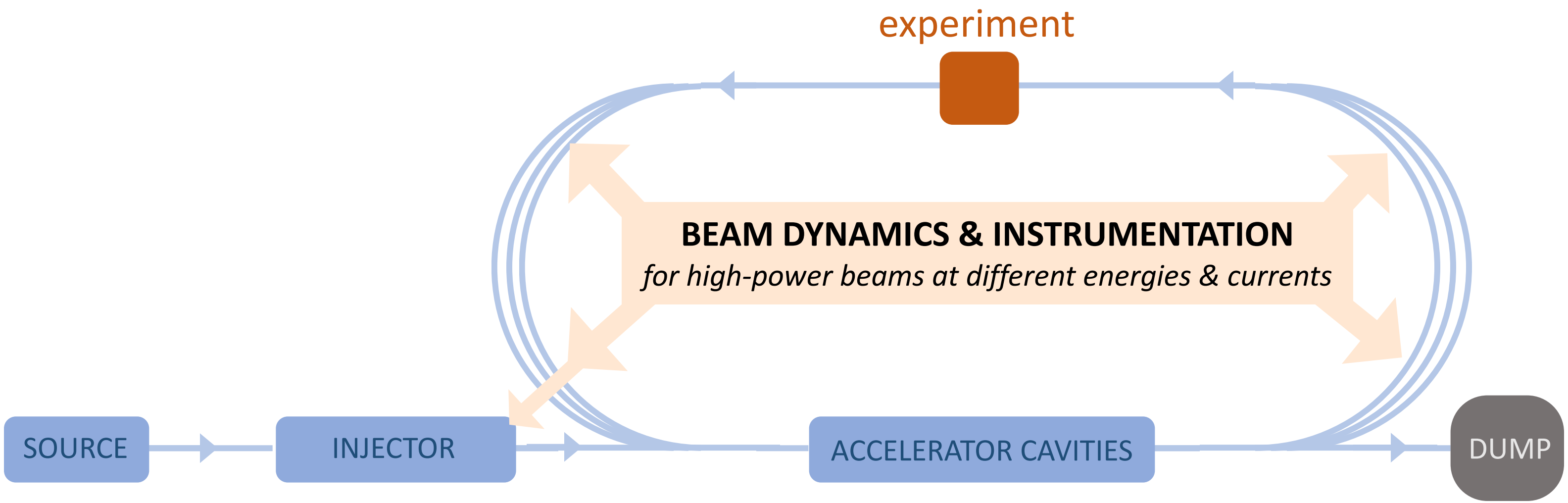

Very low levels of beam loss and a high degree of beam control will be essential for energy efficiency, radiation protection and machine protection. Here novel beam diagnostics are essential, with a dynamic range of many orders of magnitude for beam commissioning or to discern "wanted" beam from "unwanted" beam (such as beam halo).

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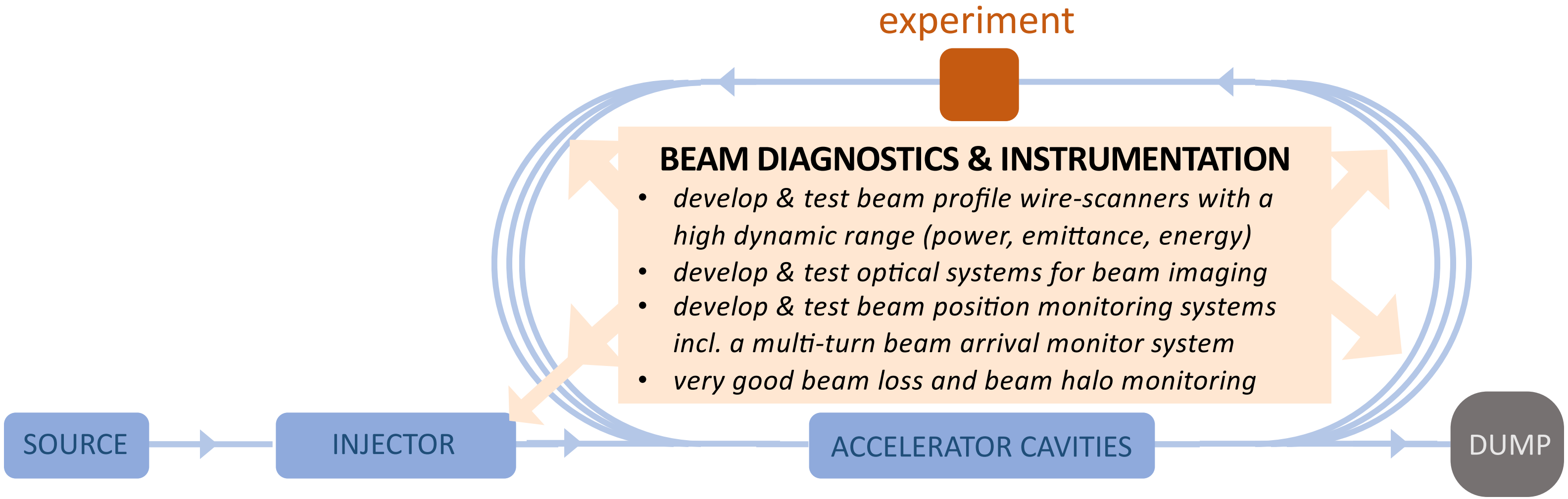

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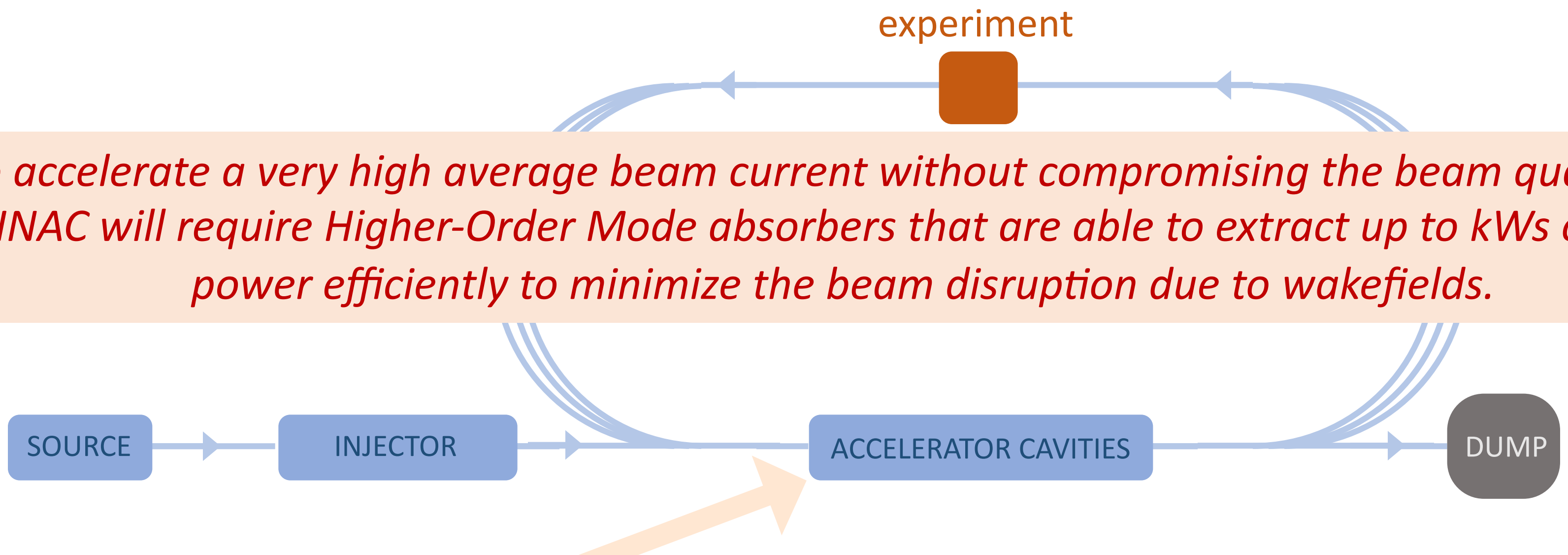


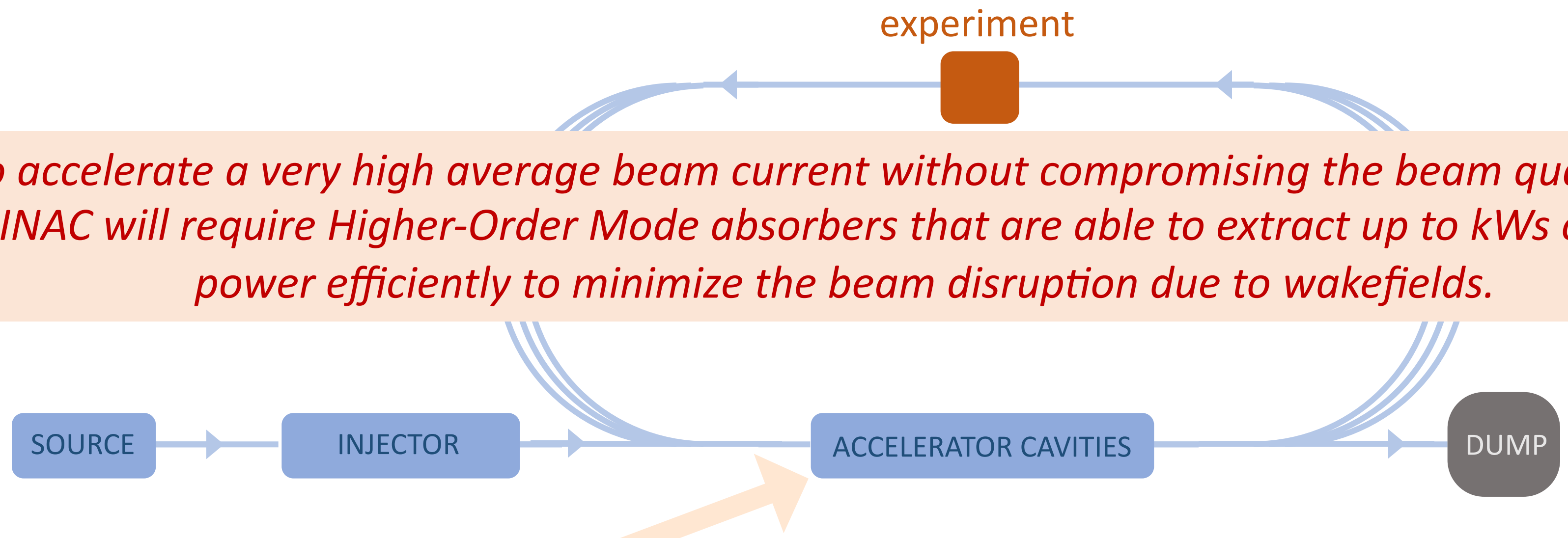
To accelerate a very high average beam current without compromising the beam quality, the LINAC will require Higher-Order Mode absorbers that are able to extract up to kWs of HOM power efficiently to minimize the beam disruption due to wakefields.

HIGHER-ORDER MODE DAMPING

efficient HOM extraction w/o increasing cryoload

Identified the key aspects for an ERL accelerator

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



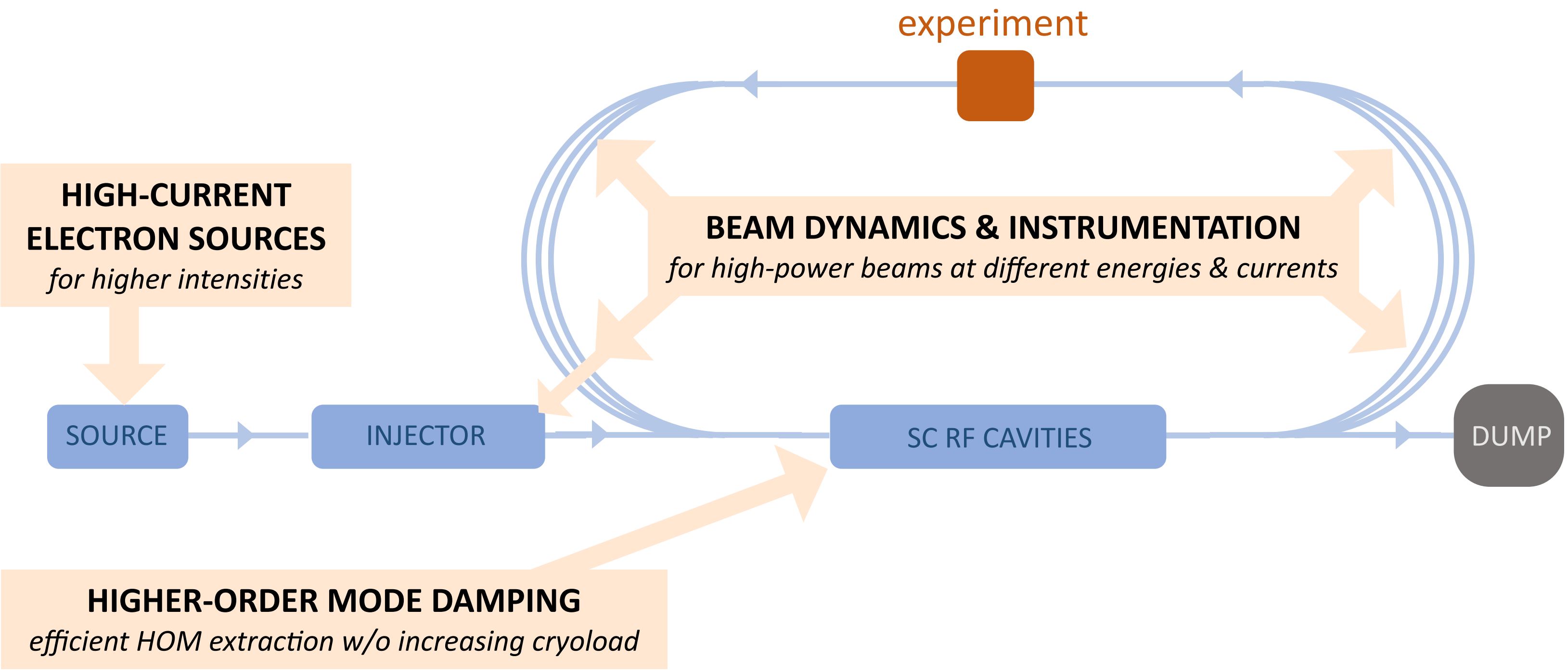
To accelerate a very high average beam current without compromising the beam quality, the LINAC will require Higher-Order Mode absorbers that are able to extract up to kWs of HOM power efficiently to minimize the beam disruption due to wakefields.

HIGHER-ORDER MODE DAMPING

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

Identified the key aspects for an ERL accelerator

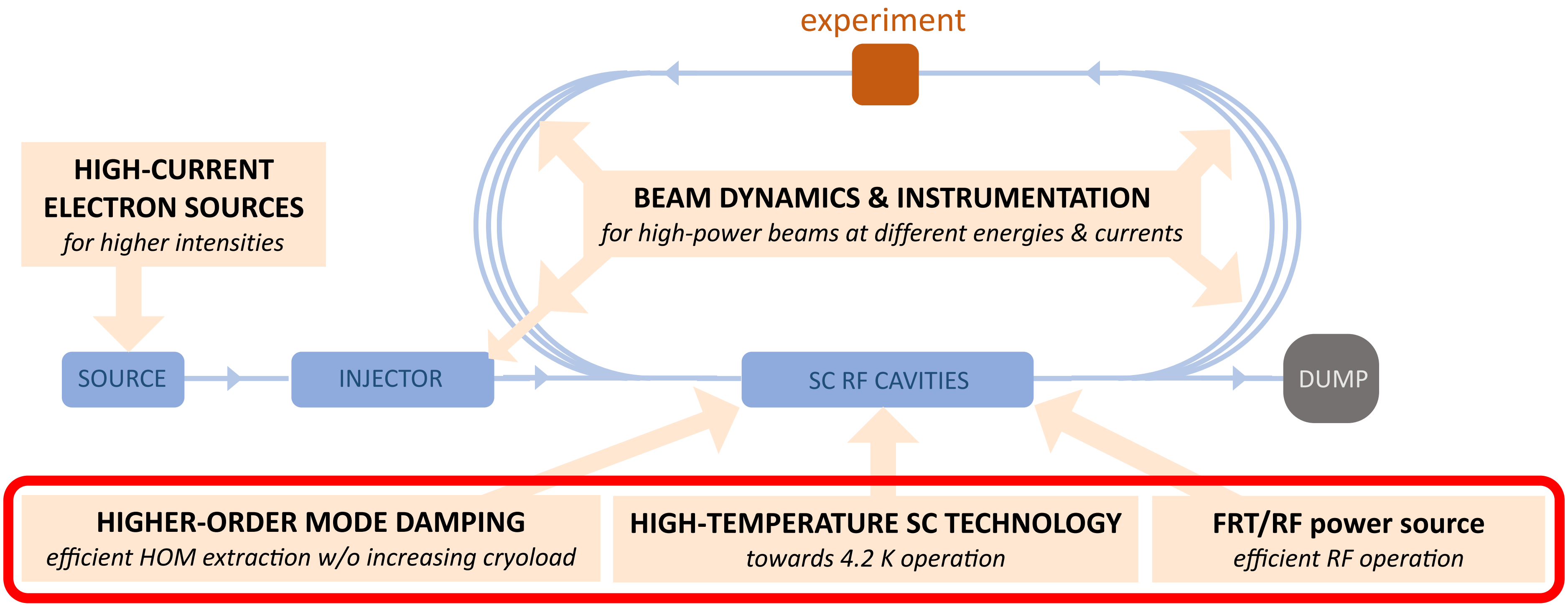
towards high-energy & high-intensity beams to be used at particle colliders



ENABLE EFFICIENT ENERGY RECOVERY

Identified the key aspects for an ERL accelerator

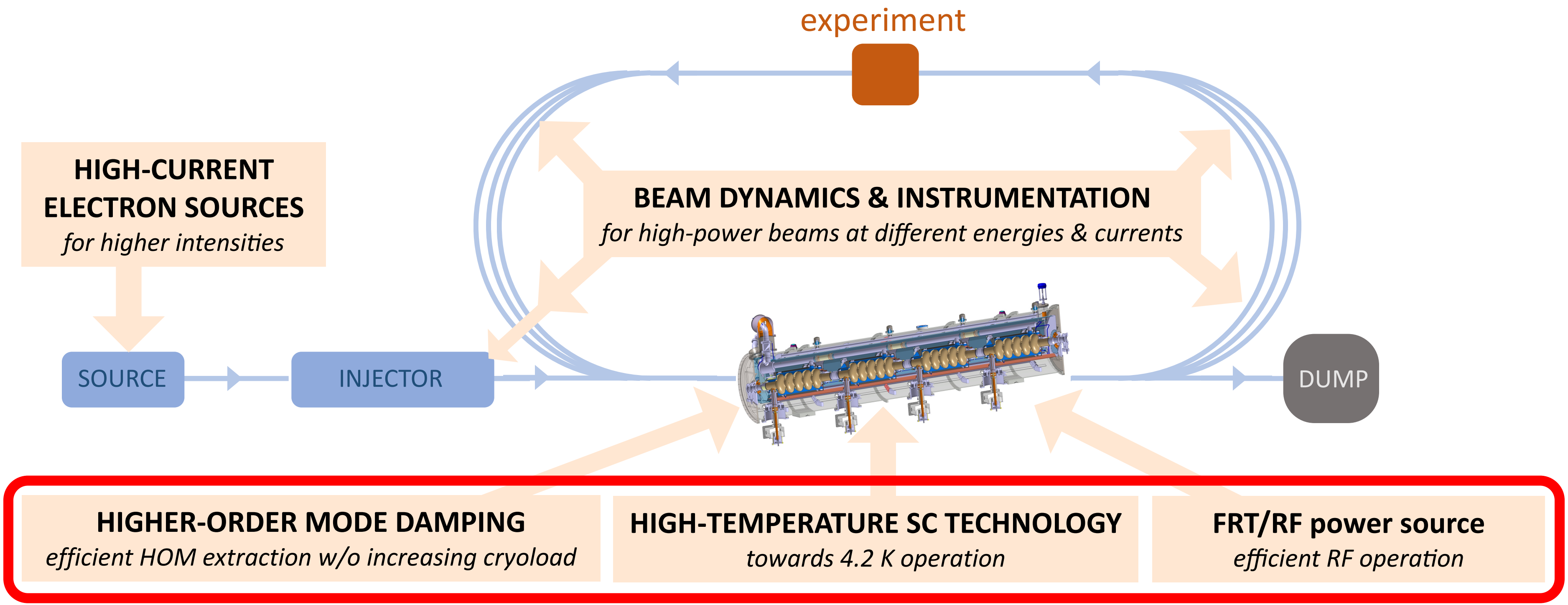
towards high-energy & high-intensity beams to be used at particle colliders



ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

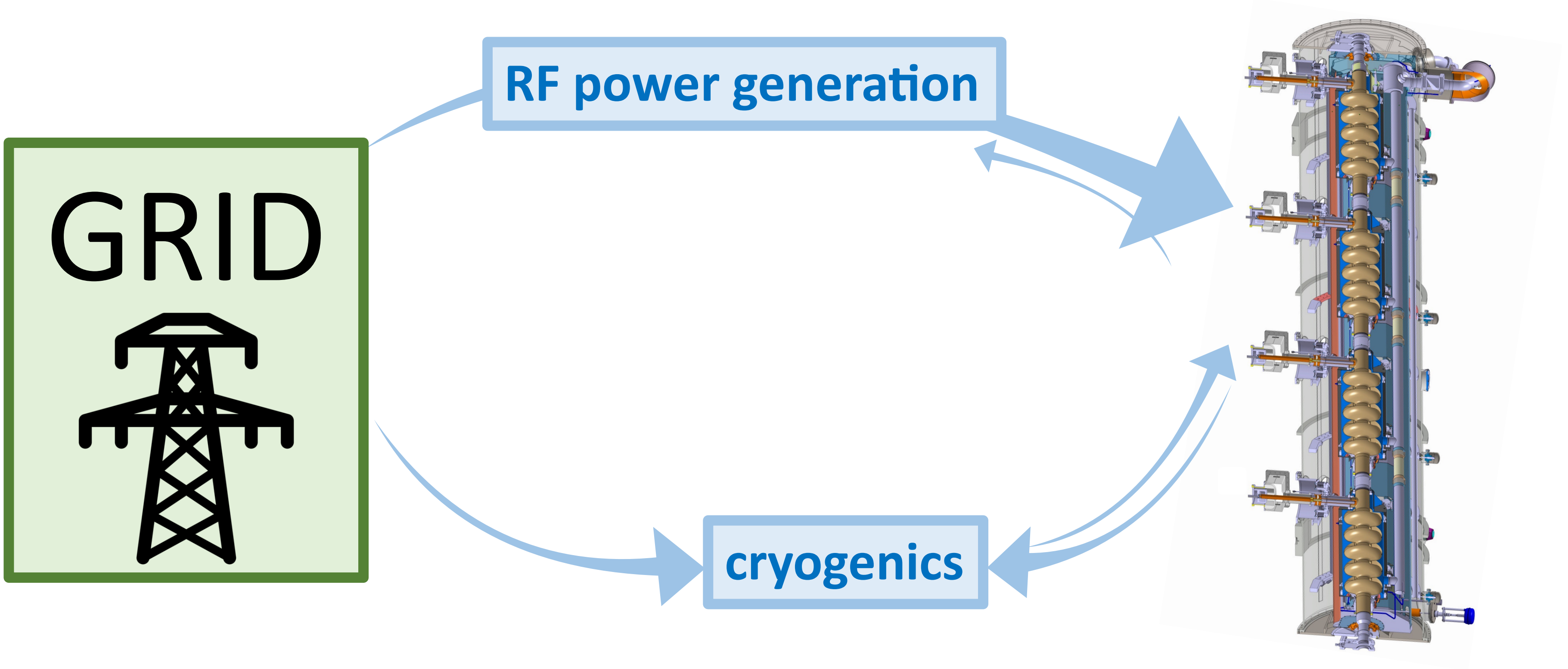
Identified the key aspects for an ERL accelerator

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



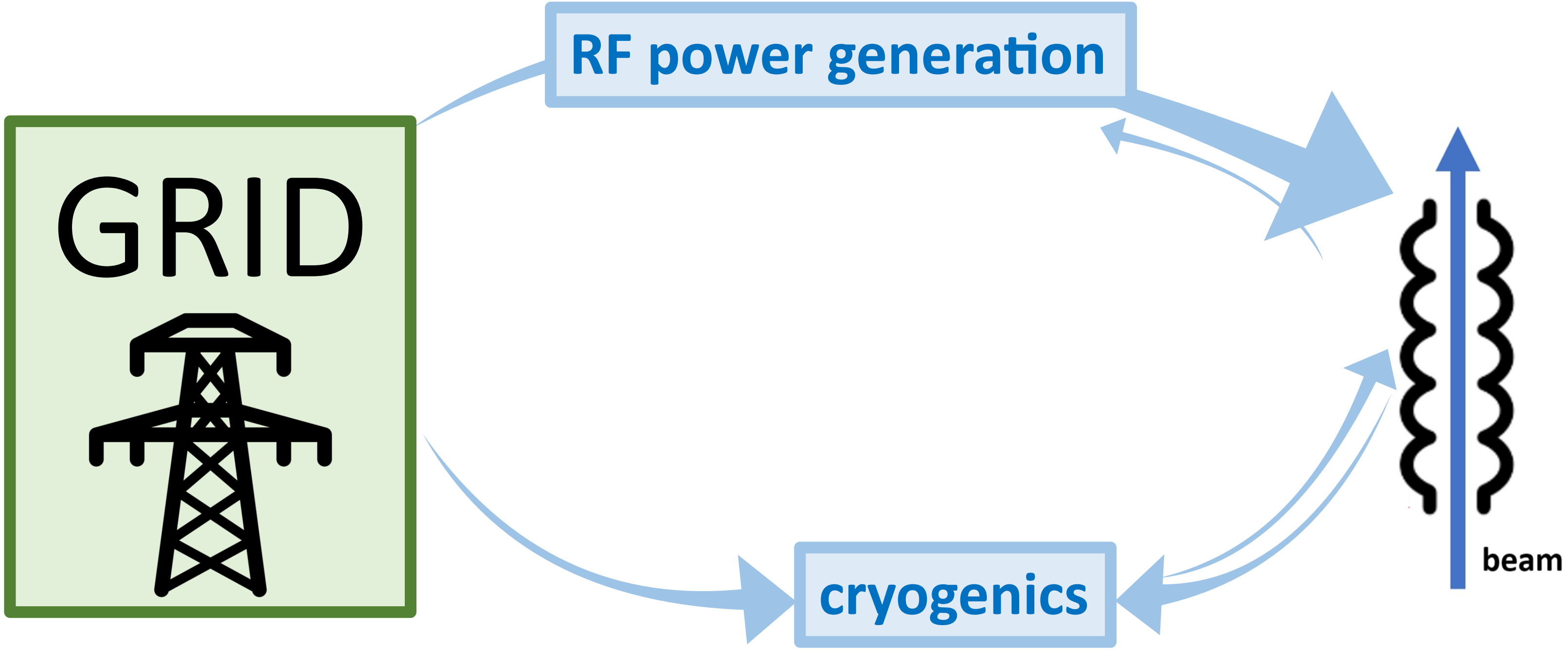
ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam



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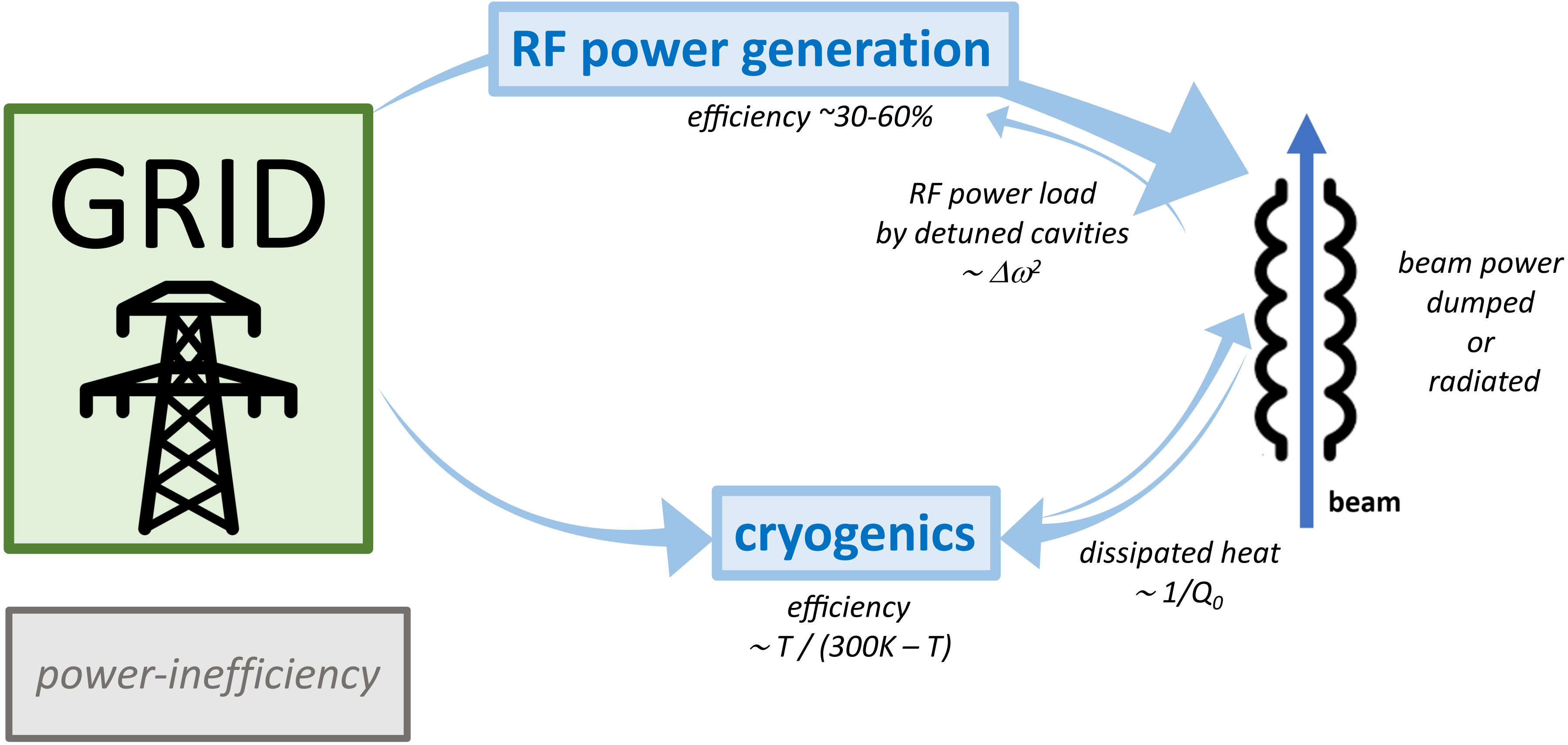

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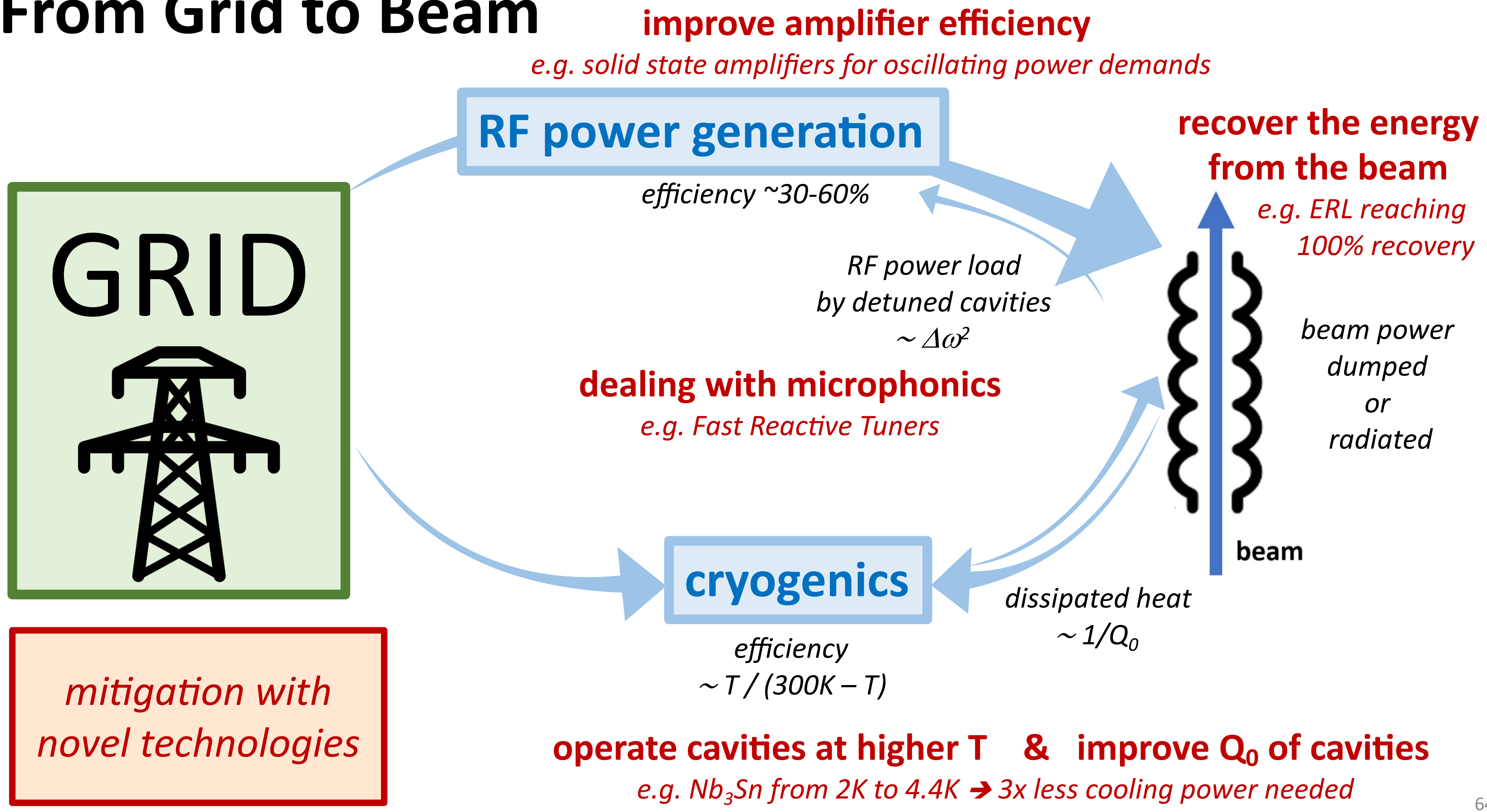
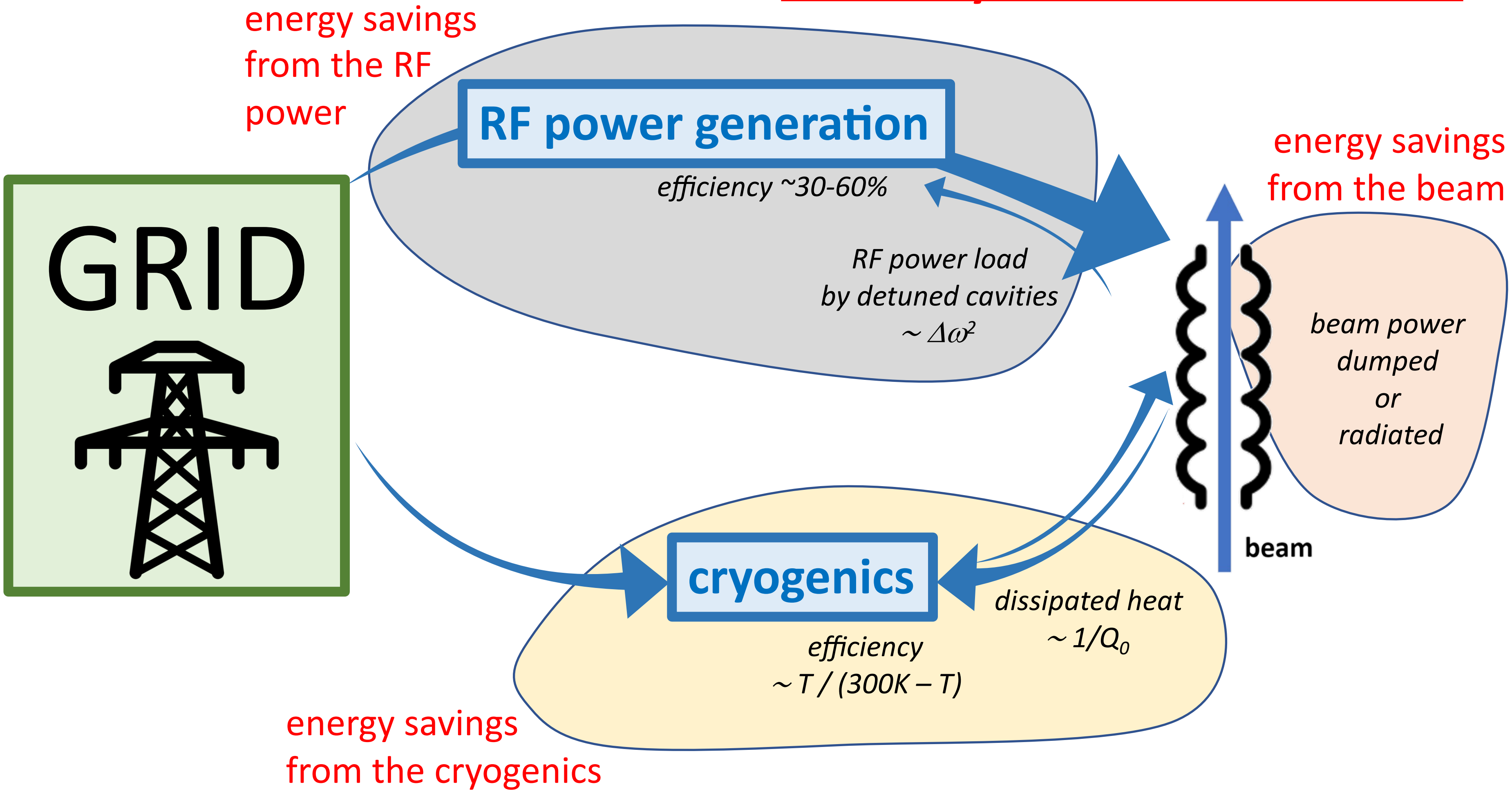


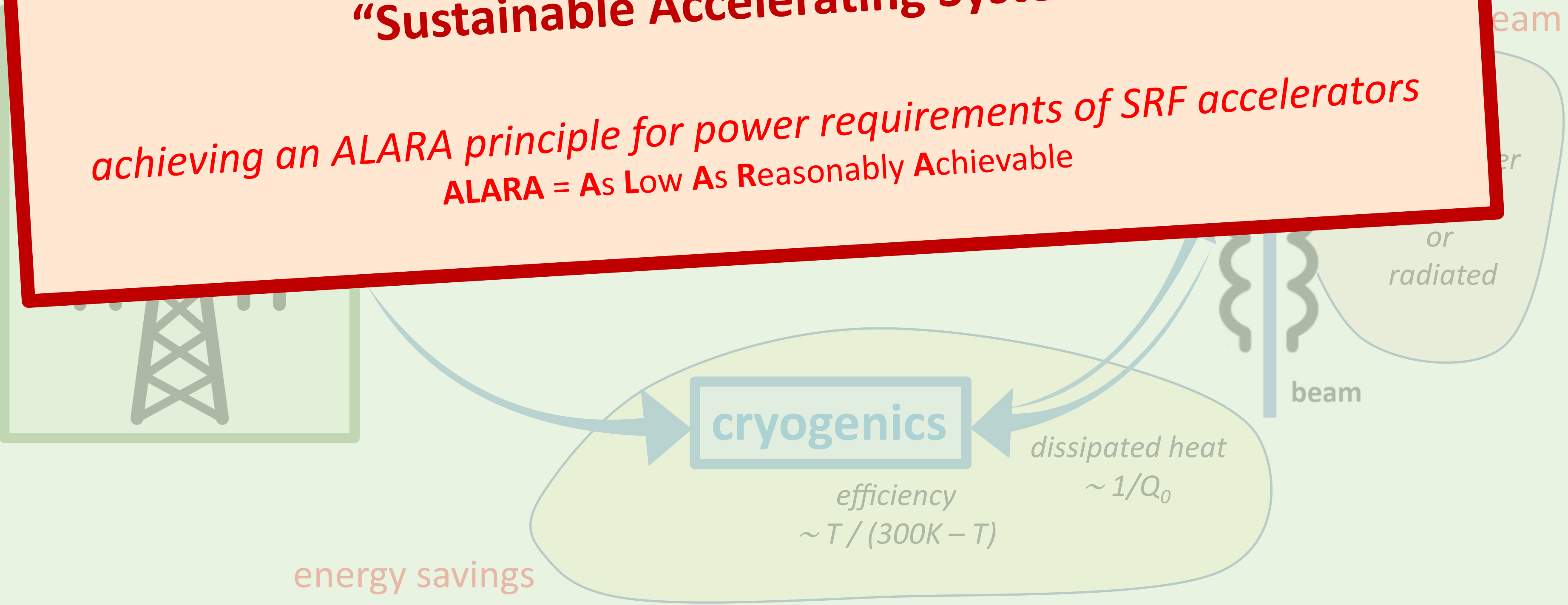
Three key innovation directions



Requires a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

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



energy savings
from the cryogenics

Requires a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

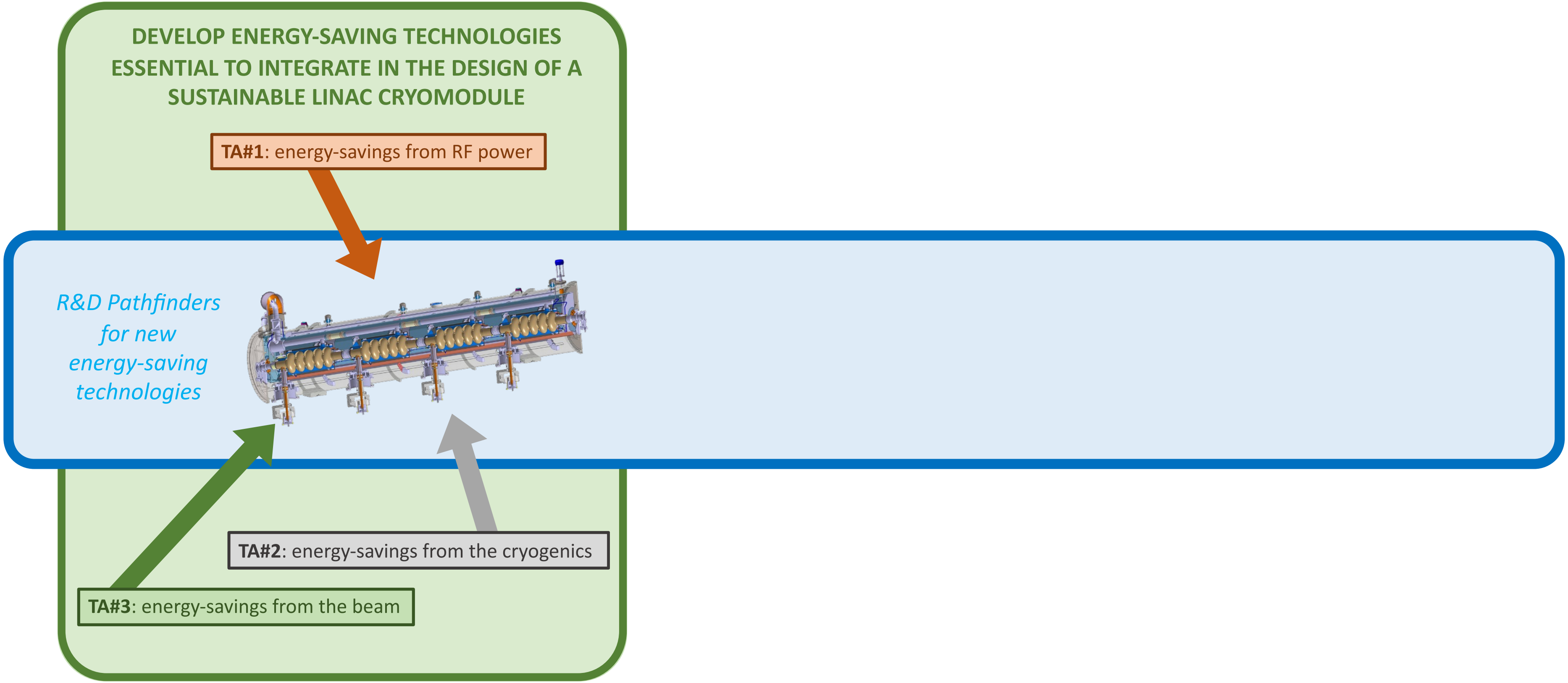
ALARA = **A**s **L**ow **A**s **R**easonably **A**chievable

Innovate for Sustainable Accelerating Systems (iSAS)

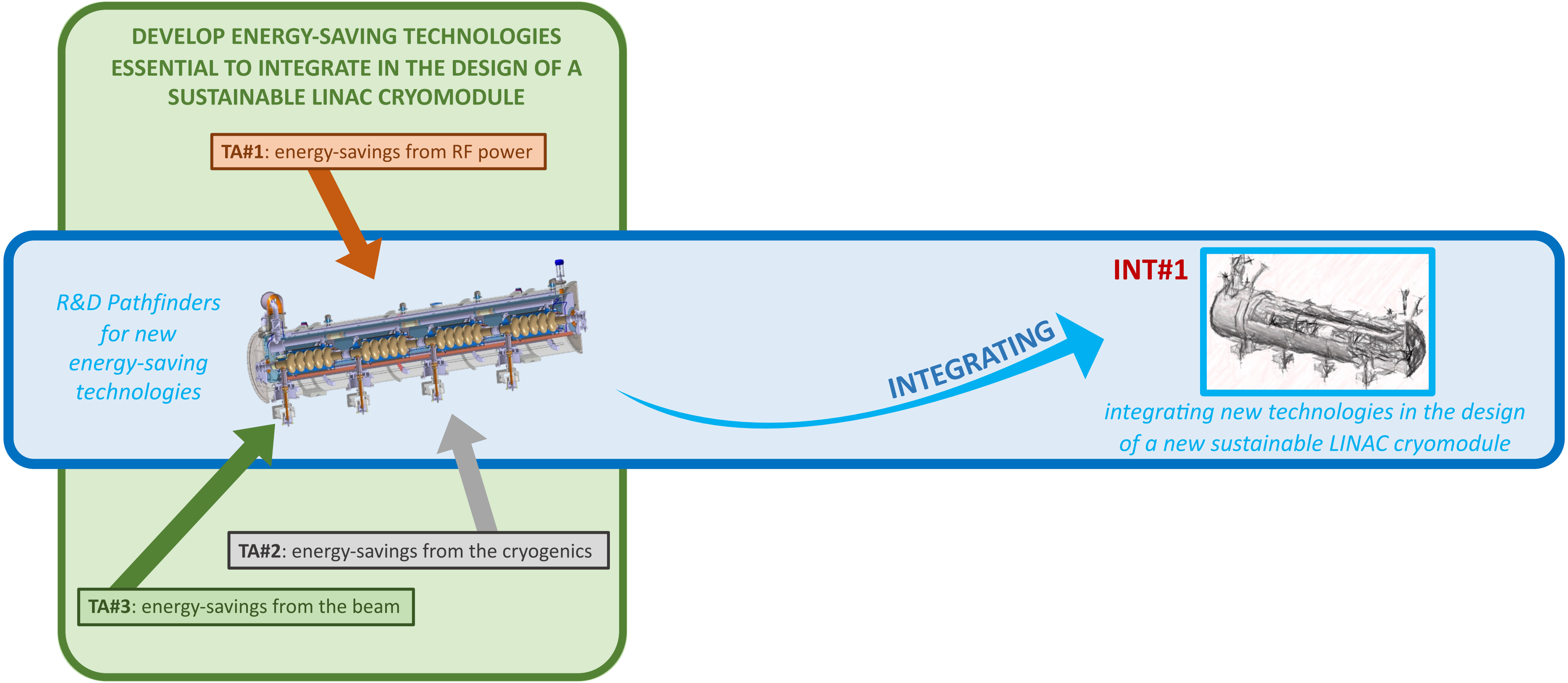
https://indico.ijclab.in2p3.fr/event/9521/

ambition: significantly reduce the energy footprint of SRF accelerators

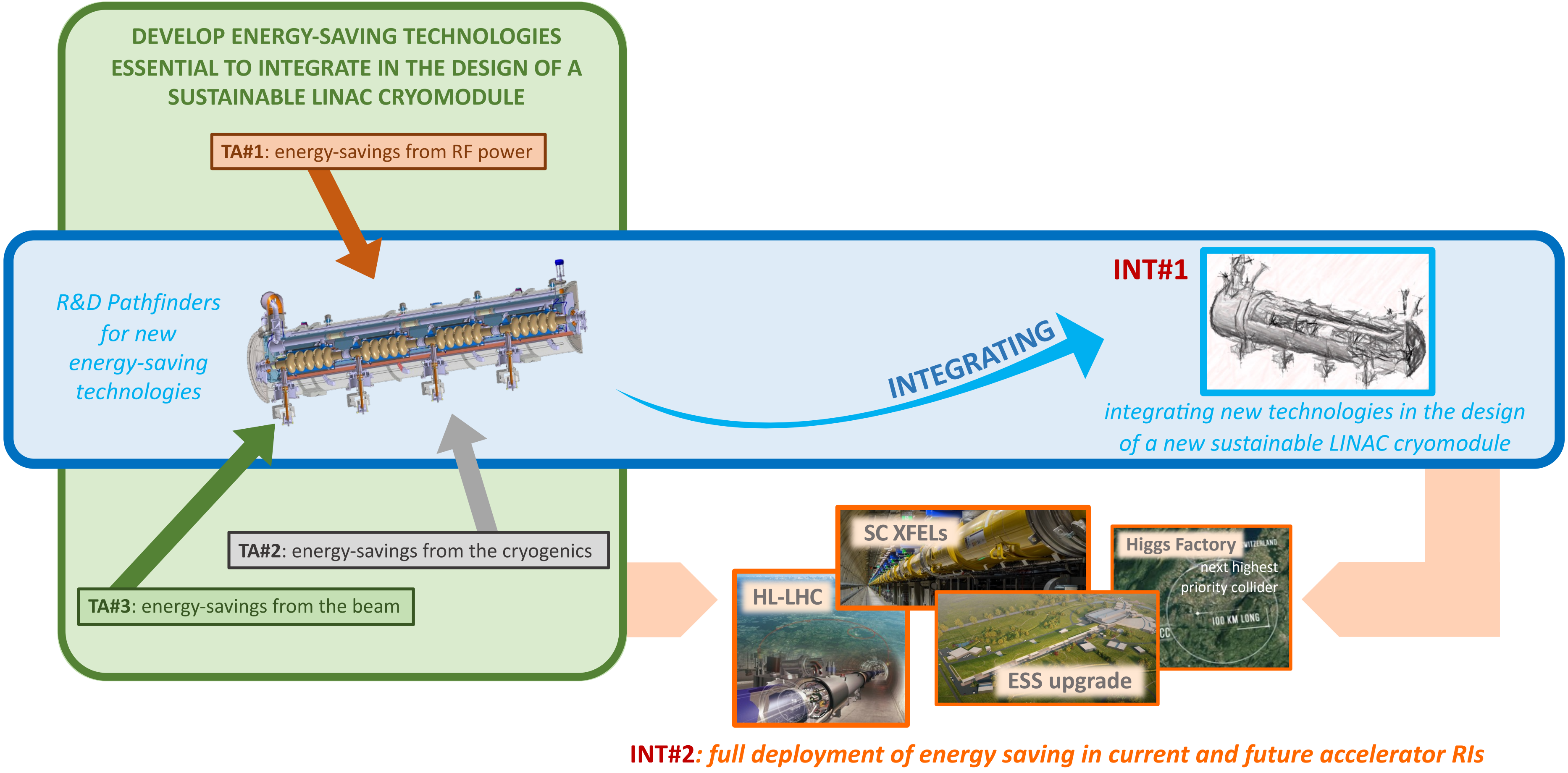
TODAY
INNOVATE TECHNOLOGIES TOWARDS
A SUSTAINABLE ACCELERATING SYSTEM
NEW DESIGN OF
SRF CRYOMODULE



TA: Technology Area

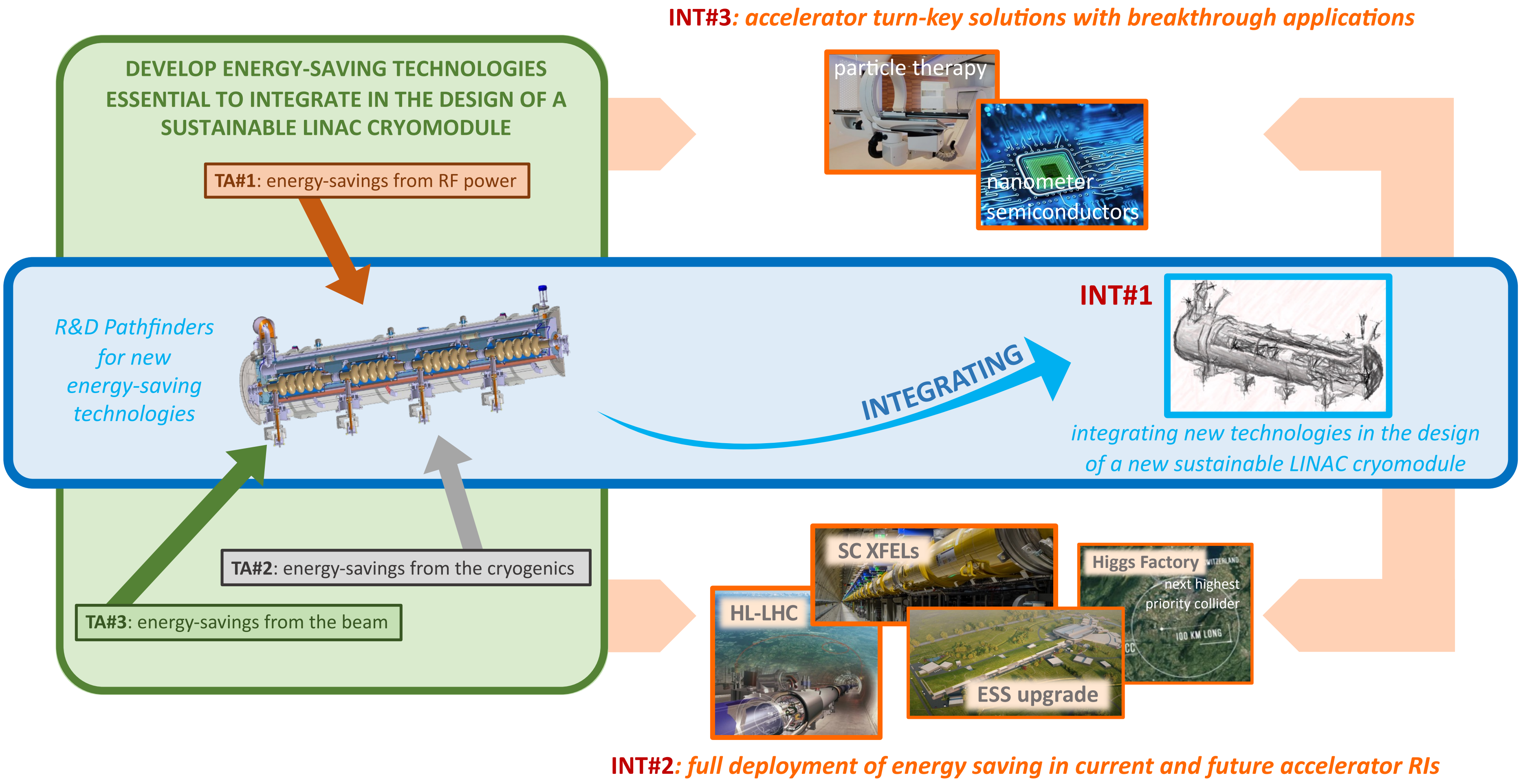


TA: Technology Area, INT: Integration Activities



TA: Technology Area, INT: Integration Activities

RIs: Research Infrastructures



INT#3: accelerator turn-key solutions with breakthrough applications
DEVELOP ENERGY-SAVING TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
TA#1: energy-savings from RF power
particle therapy
nanometer semiconductors
R&D Pathfinders for new energy-saving technologies
INTEGRATING
INT#1
integrating new technologies in the design of a new sustainable LINAC cryomodule
TA#2: energy-savings from the cryogenics
TA#3: energy-savings from the beam
SC XFELs
HL-LHC
Higgs Factory
next highest priority collider
100 KM LONG
ESS upgrade
INT#2: full deployment of energy saving in current and future accelerator RIs

iSAS organisation

Spread over 4 years: ~1000 person-months of researchers and ~12.6M EUR

DESY.

INFN

UKRI UK Research and Innovation

HZB Helmholtz Zentrum Berlin

ess EUROPEAN SPALLATION SOURCE

Lancaster University

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

cea

VUB VRIJE UNIVERSITEIT BRUSSEL

cnrs

IJCLab Irène Joliot-Curie

CERN

+ industrial companies: *ACS Accelerators and Cryogenic Systems* (France), *RI Research Instruments GmbH* (Germany), *Cryoelectra GmbH* (Germany), *TFE Thin Film equipment srl* (Italy), *Zanon Research* (Italy), *EuclidTechLab* (USA)

iSAS organisation

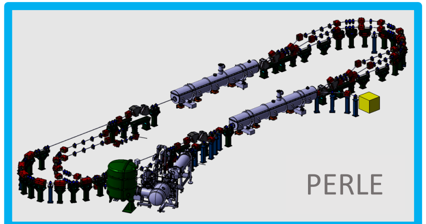
Spread over 4 years: ~1000 person-months of researchers and ~12.6M EUR

iSAS will have a catalyzing effect on implementing the European ERL and RF R&D Roadmap

+ industrial companies: *ACS Accelerators and Cryogenic Systems* (France), *RI Research Instruments GmbH* (Germany), *Cryoelectra GmbH* (Germany), *TFE Thin Film equipment srl* (Italy), *Zanon Research* (Italy), *EuclidTechLab* (USA)

High-power ERL technology timeline

2020'ies



high-power ERL demonstrated

Upcoming facilities for Energy Recovery Linac R&D

complementary in addressing the R&D objectives for ERL

bERLinPro @ Helmholtz Zentrum Berlin

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

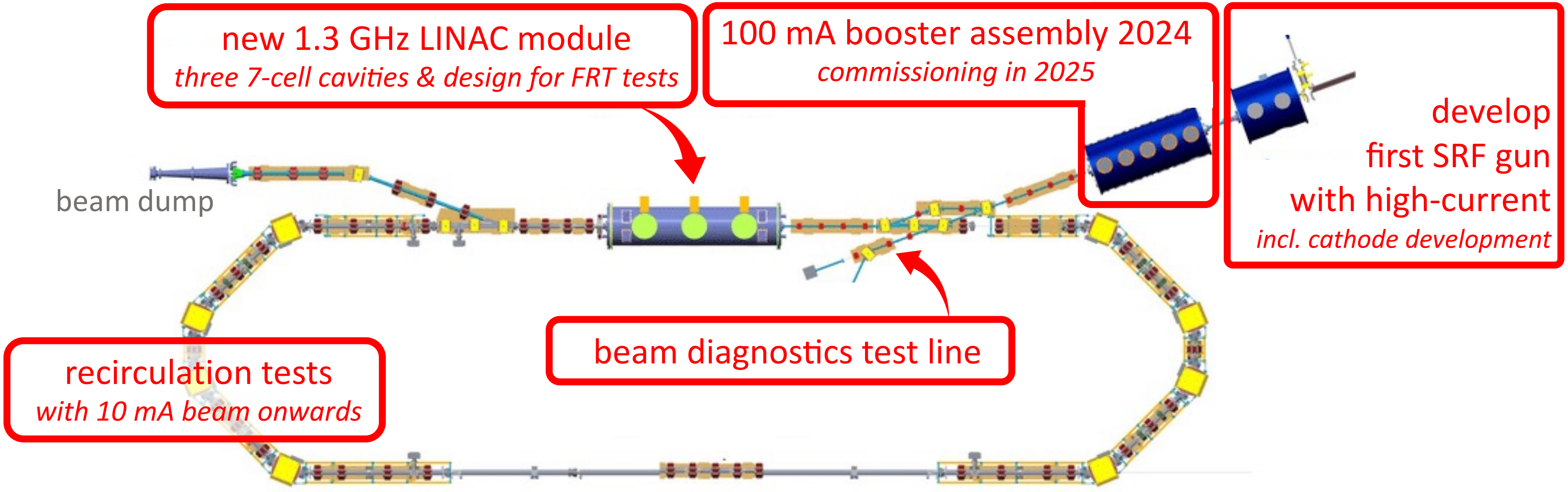
BERLinPro: Main Project Parameters	
Total beam energy, MeV	50
Maximum average current, mA	100
Bunch charge, pC	77
Bunch repetition rate, GHz	1.3
Emittance (normalized), π mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	$< 10^{-5}$

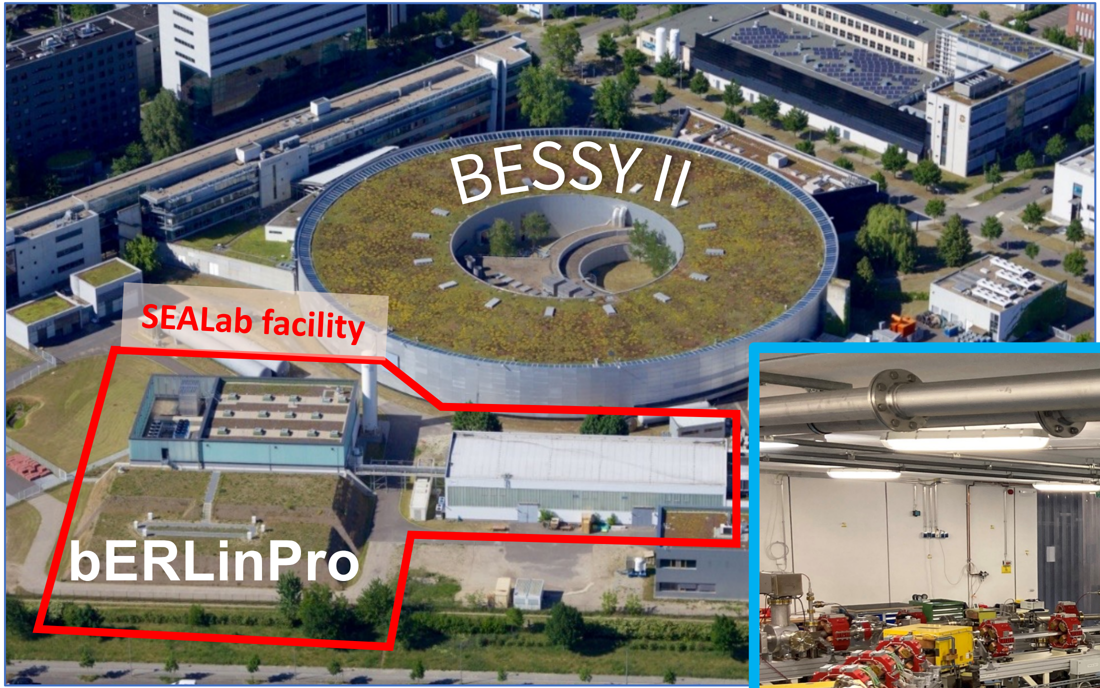
Upcoming facilities for Energy Recovery Linac R&D

complementary in addressing the R&D objectives for ERL

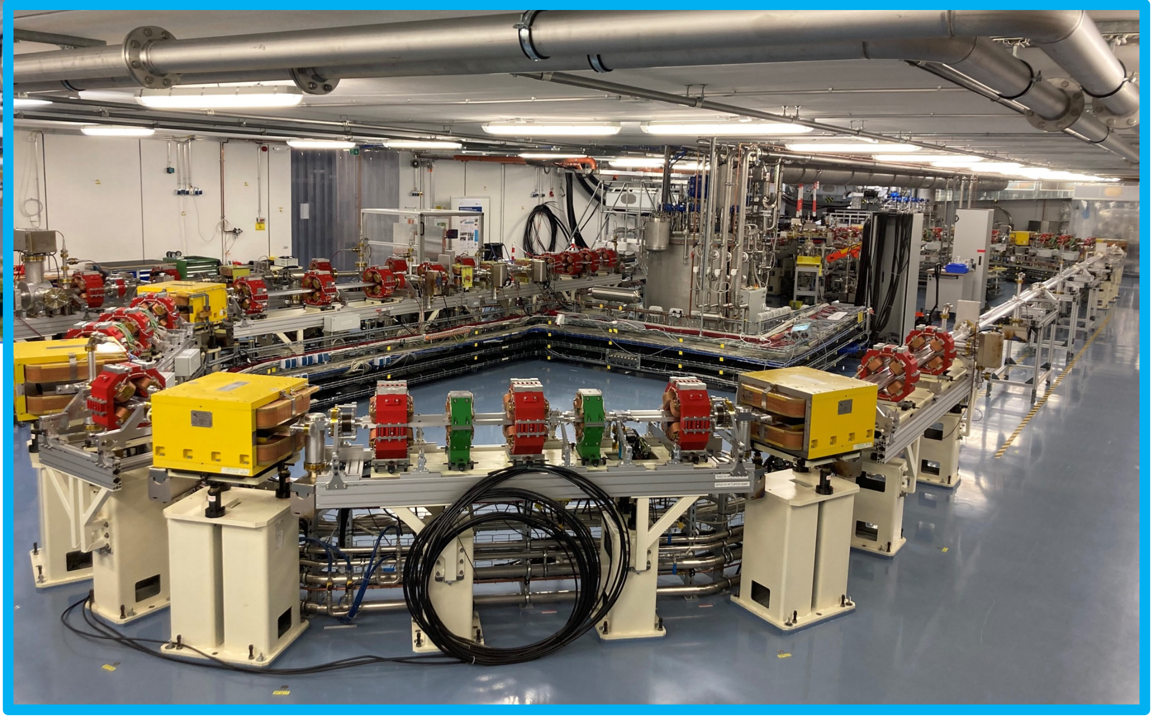
bERLinPro @ Helmholtz Zentrum Berlin
addressing HEP related challenges

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 in 2023

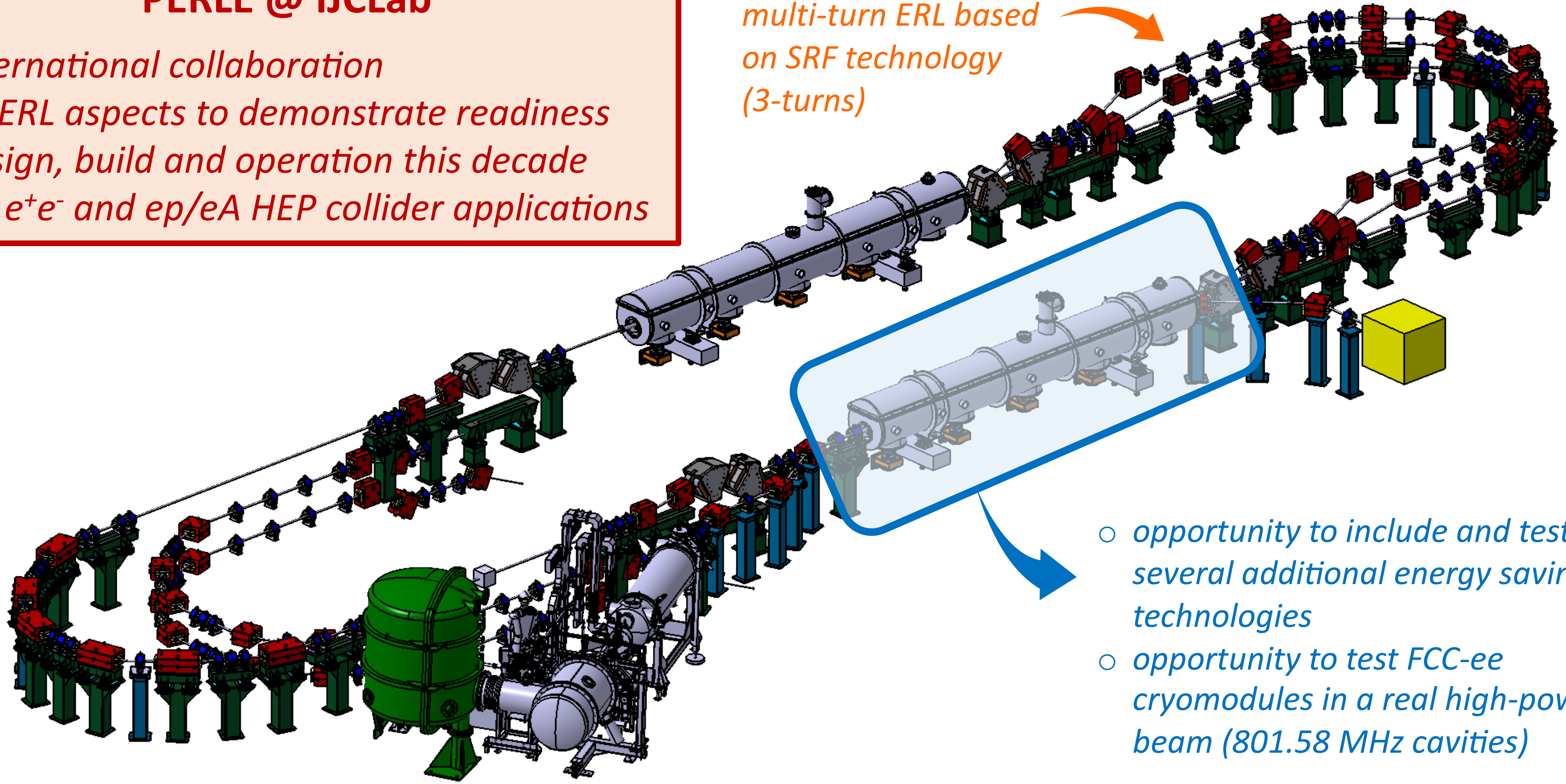


- focus on commissioning injector with SRF gun + diagnostic line
  (map out the reachable parameter space)
- installation of the Booster module
- recirculation, when LINAC funding is secured

Demonstrate readiness of ERL technology for high-power applications in HEP

PERLE @ IJCLab

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



- *opportunity to include and test several additional energy saving technologies*
- *opportunity to test FCC-ee cryomodules in a real high-power beam (801.58 MHz cavities)*

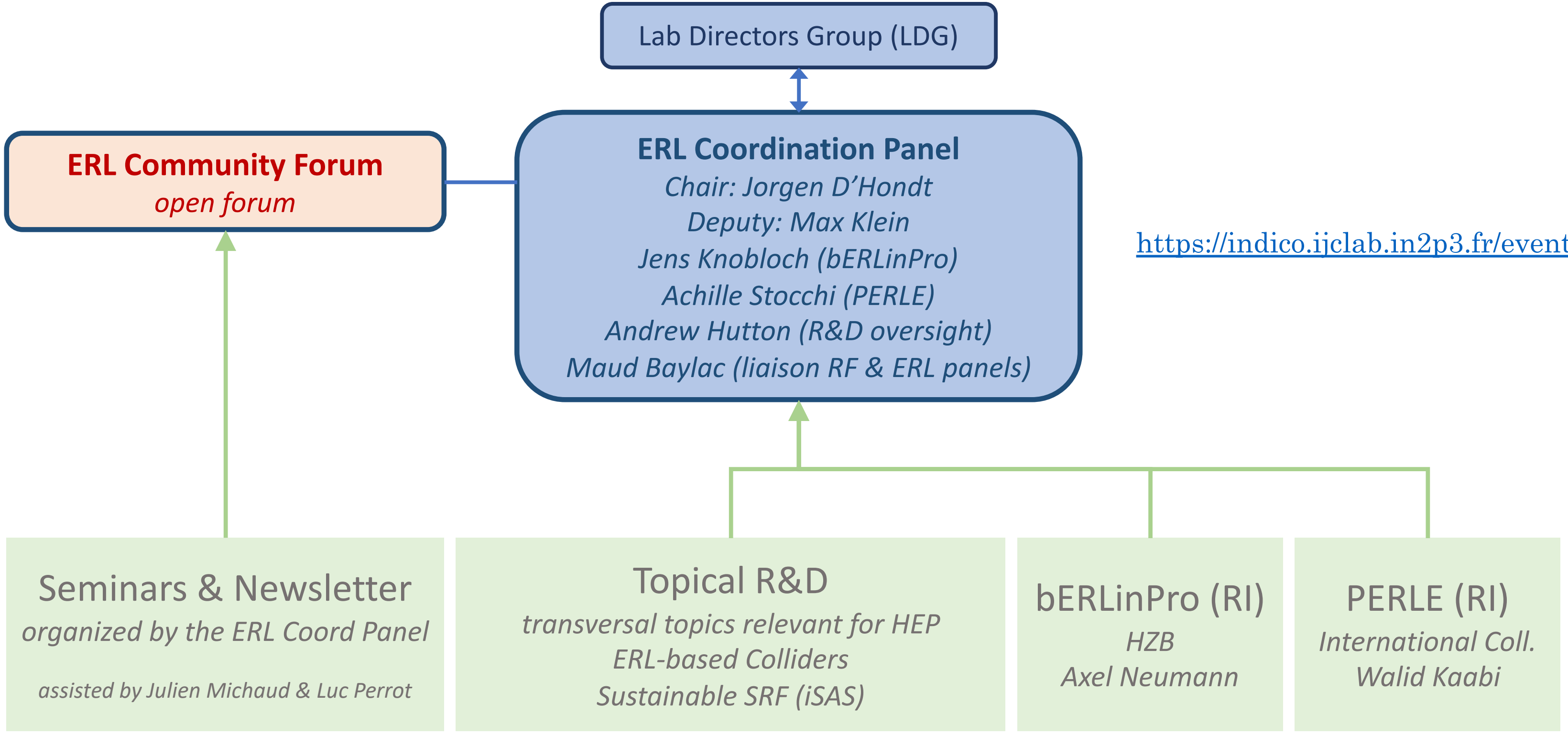
PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Organising the European R&D for ERL in HEP

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

Organising the European R&D for ERL in HEP

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



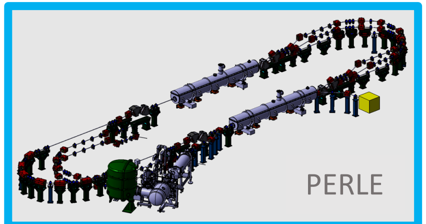
https://indico.ijclab.in2p3.fr/event/9548/

RI: Research Infrastructure

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies

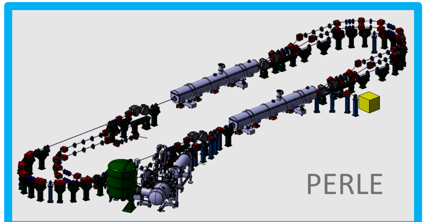


high-power ERL
demonstrated

Potential impact of ERL technology

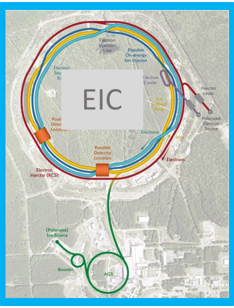
demonstrate
multi-turn high-power ERL

2020'ies



high-power ERL demonstrated

2030'ies

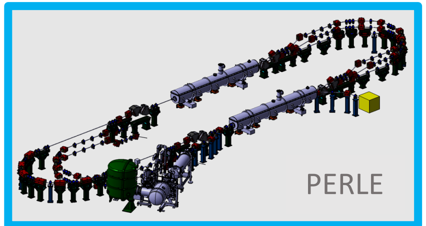


ERL application electron cooling

Potential impact of ERL technology

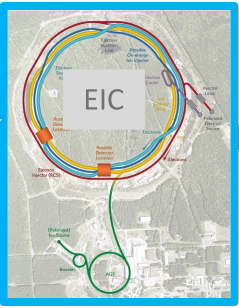
demonstrate
multi-turn high-power ERL

2020'ies



high-power ERL demonstrated

2030'ies

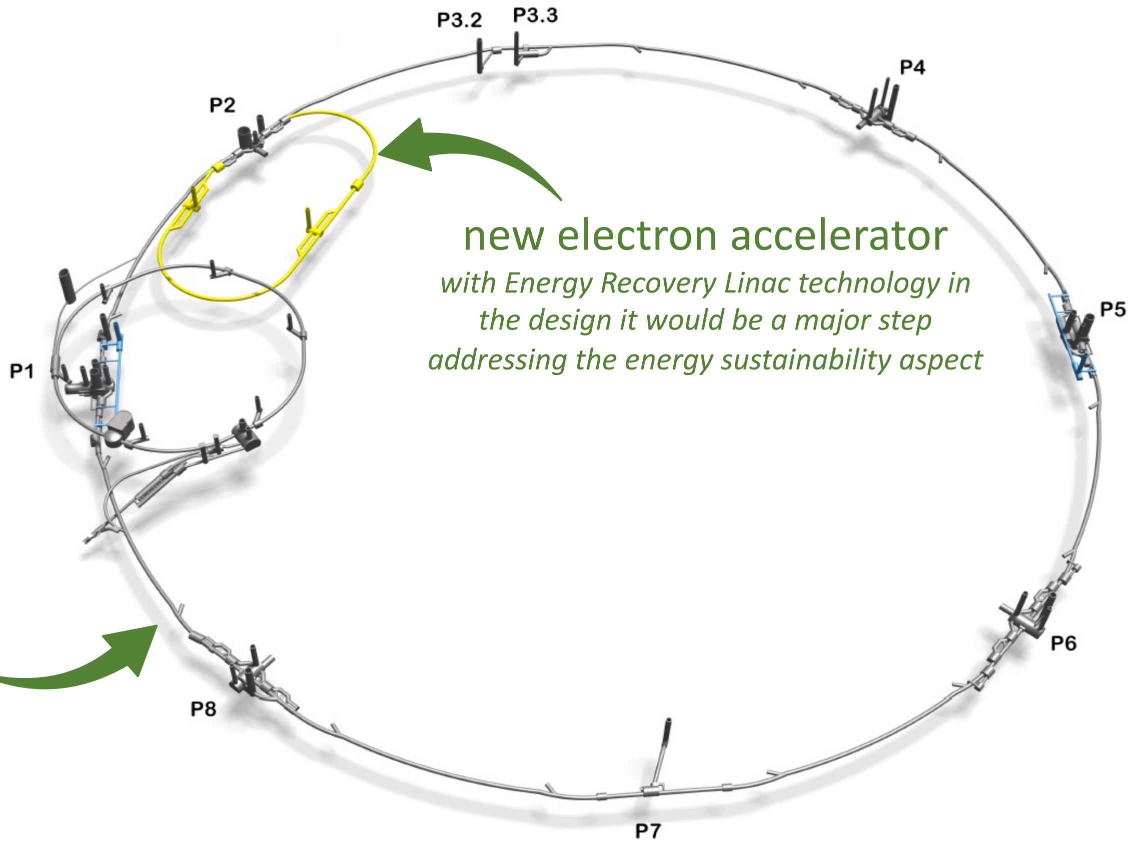


ERL application electron cooling

Ready for high-energy and high-luminosity ep/eA collisions

ERL-based ep/eA colliders at CERN

paradigm shift with ERL
high-energy & high-luminosity electron-proton collisions



new electron accelerator

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

existing/future proton accelerator

LHC and/or FCC

(LHeC and/or FCC-eh)

The challenge

High-intensity electron beam

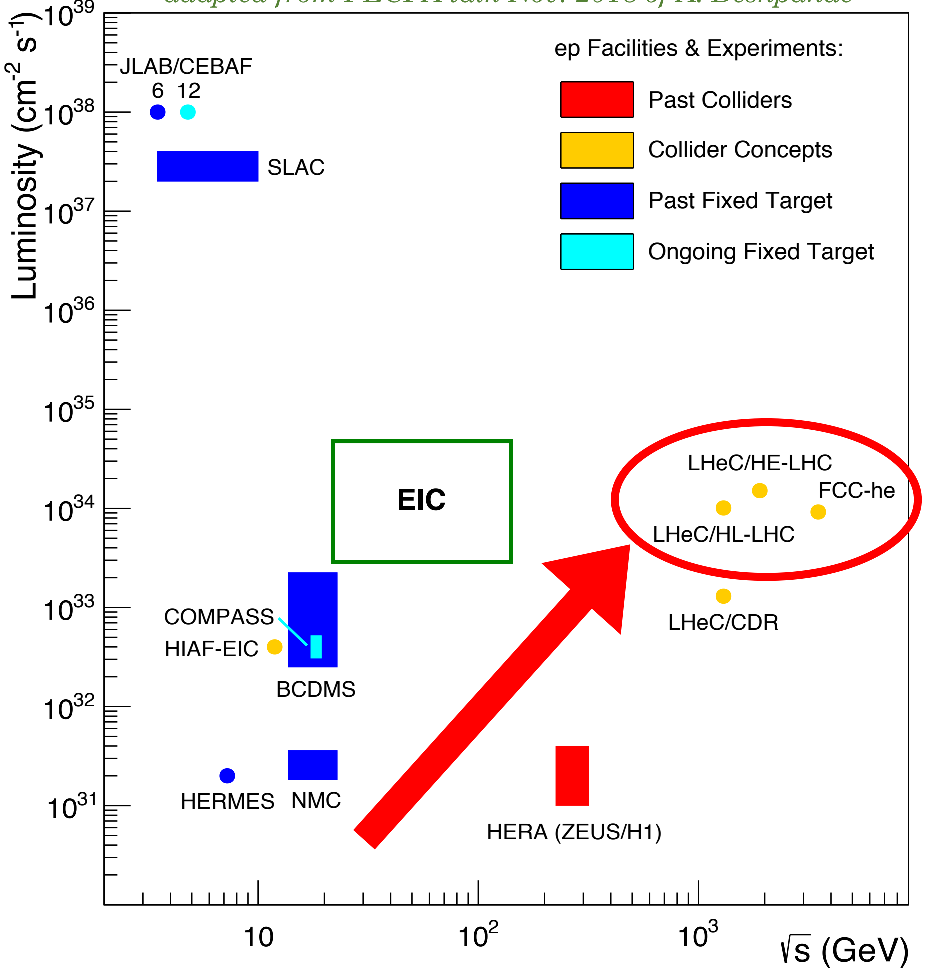
From HERA@DESY to LHeC@CERN

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

adapted from PECFA talk Nov. 2018 of A. Deshpande



The challenge

High-intensity electron beam

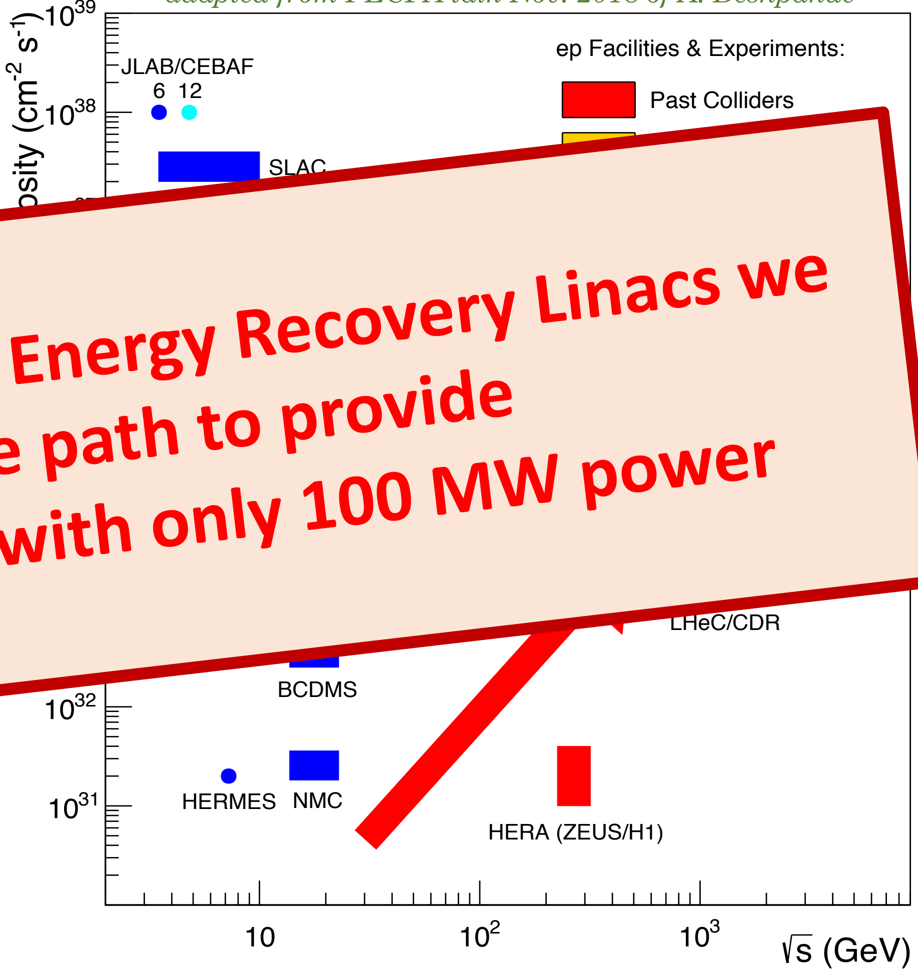
From HERA@DESY to LHeC@...

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 100 MW power

adapted from PECFA talk Nov. 2018 of A. Deshpande



Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to ~2040

ep-option with HL-LHC: LHeC

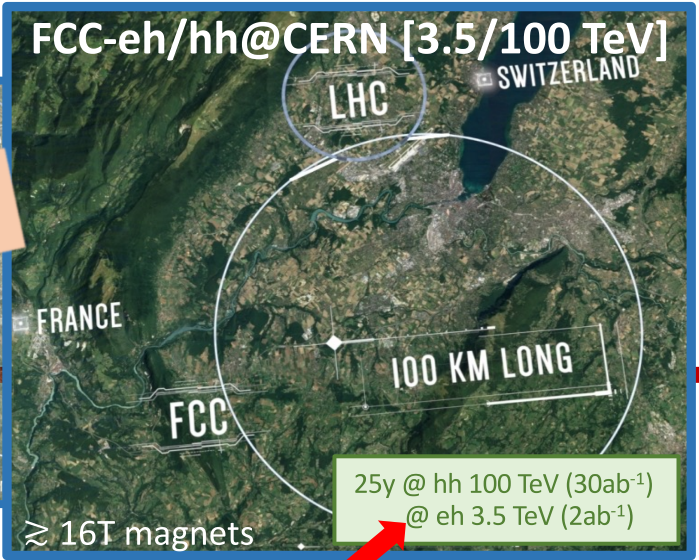
10y @ 1.2 TeV (1ab^{-1})

updated CDR: J.Phys.G 48 (2021) 11, 110501

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

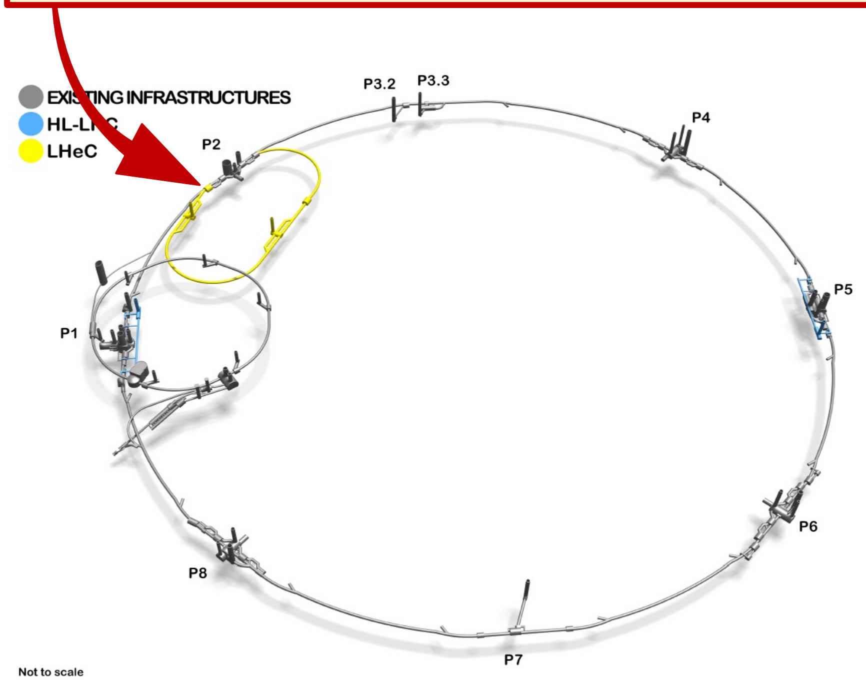
attractive combination of precision & energy frontier

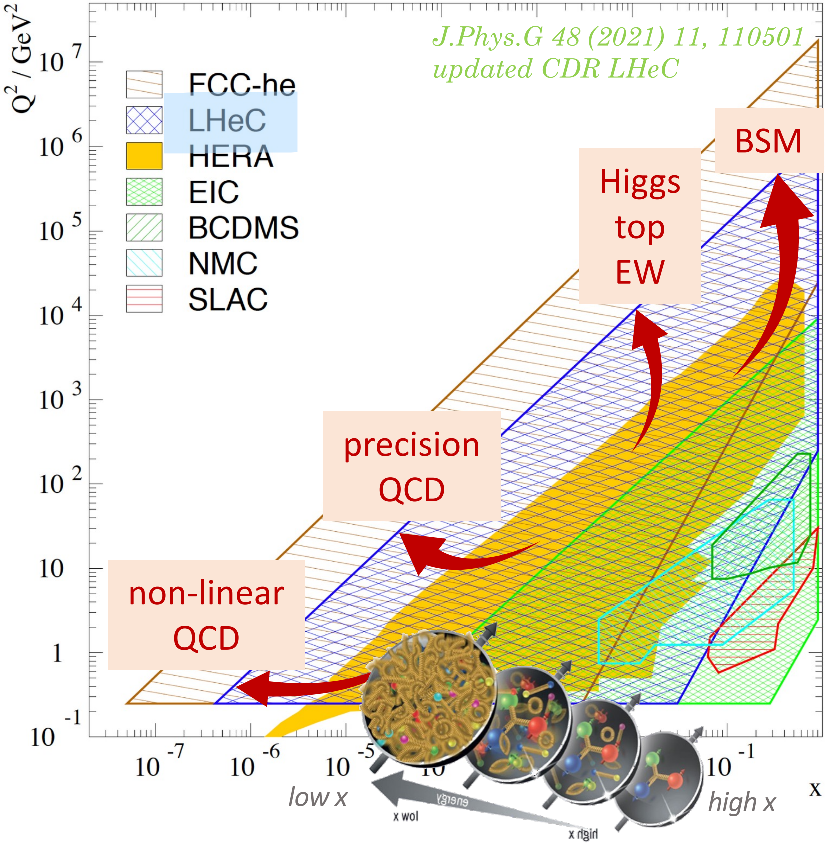


numbers assume 2 IPs for each collider (only one for FCC-eh)

The LHeC program

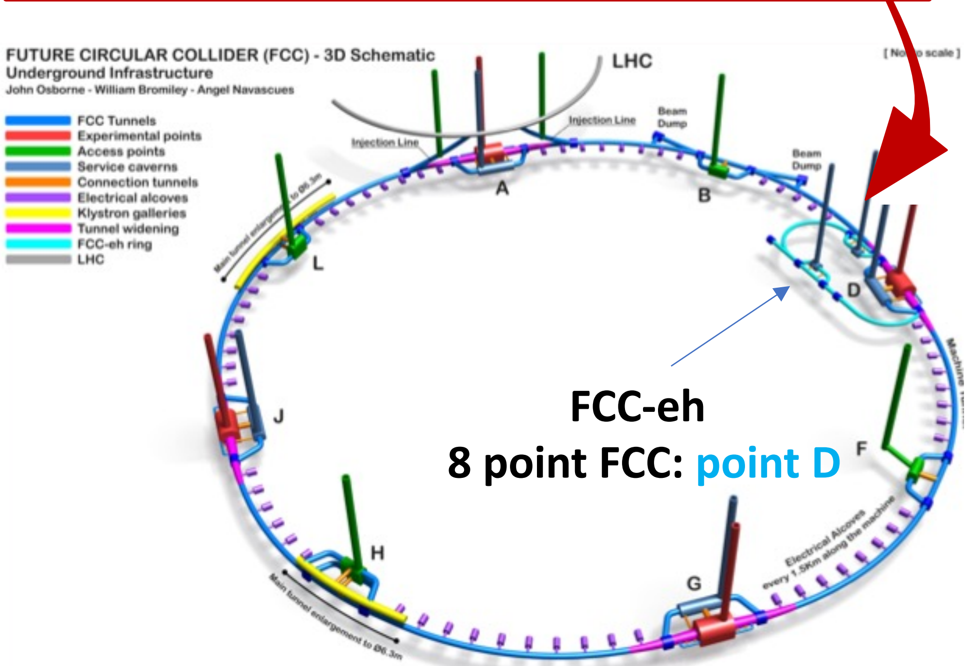
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



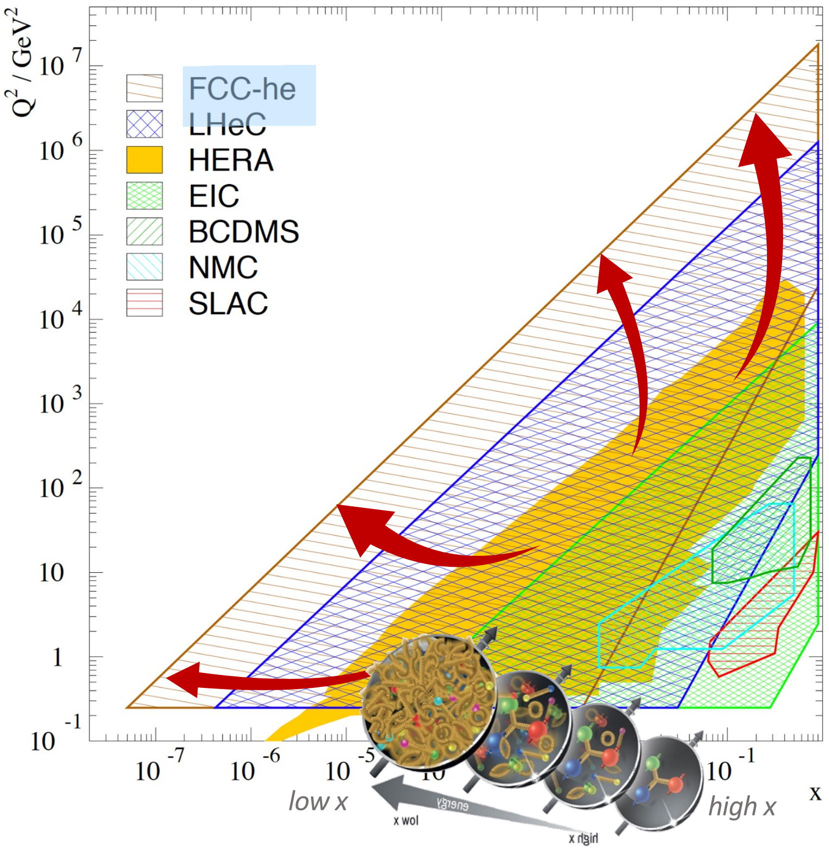


The FCC-eh program

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh

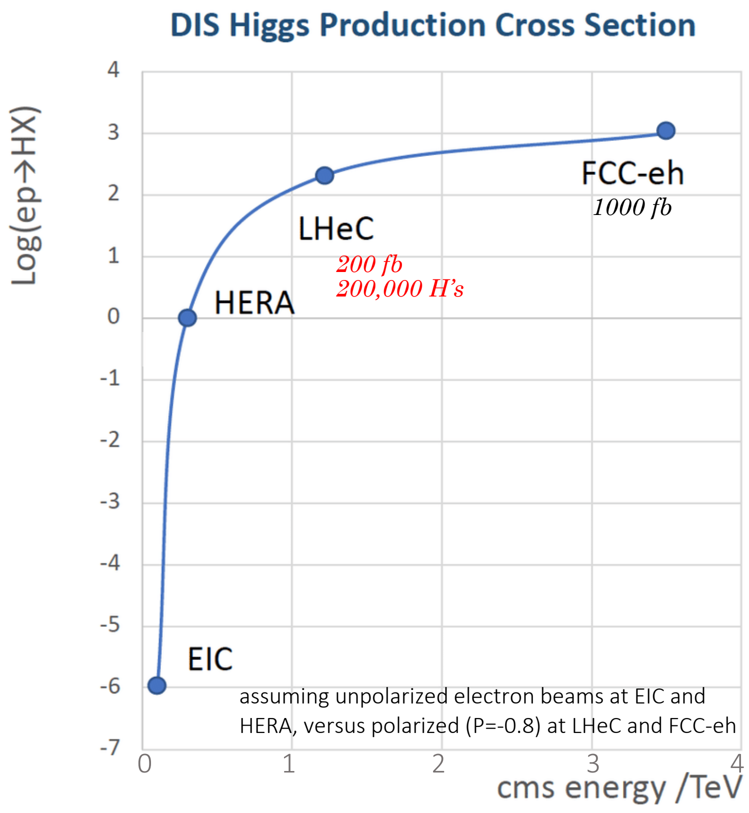


J. Osborne, W. Bromiley, A. Navascues

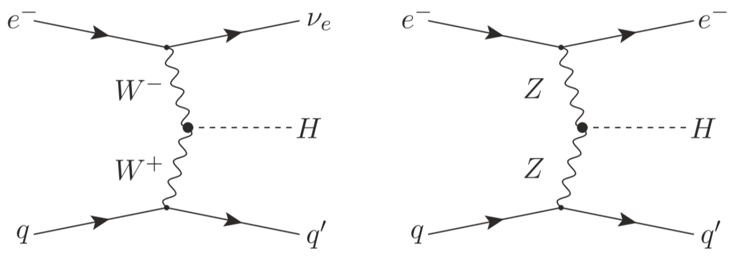


the physics impact

Collision energy above the threshold for EW/Higgs/Top



The real game change between HERA and LHC/FCC

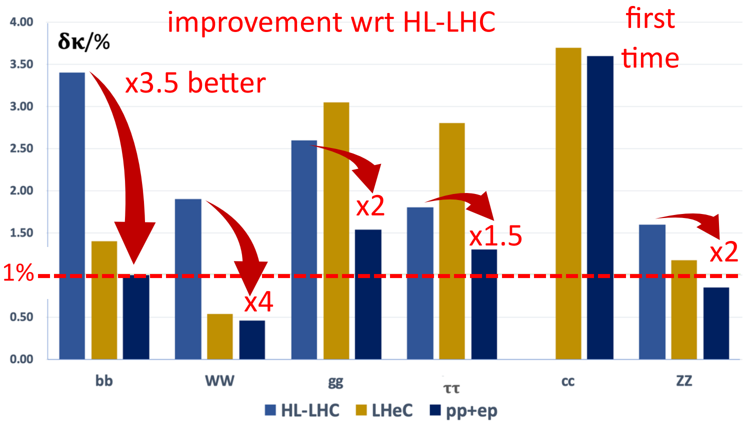


compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

at these energies and luminosities, interactions with all SM particles can be measured precisely

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

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 0.2%
- low-x: a new discovery frontier

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

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

Higgs physics

EW physics

The LHeC is a general-purpose experiment

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

EW/Higgs/top: improvement from LHC → HL-LHC similar to HL-LHC → LHeC

γ, W, Z couplings

DIS scattering cross sections

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

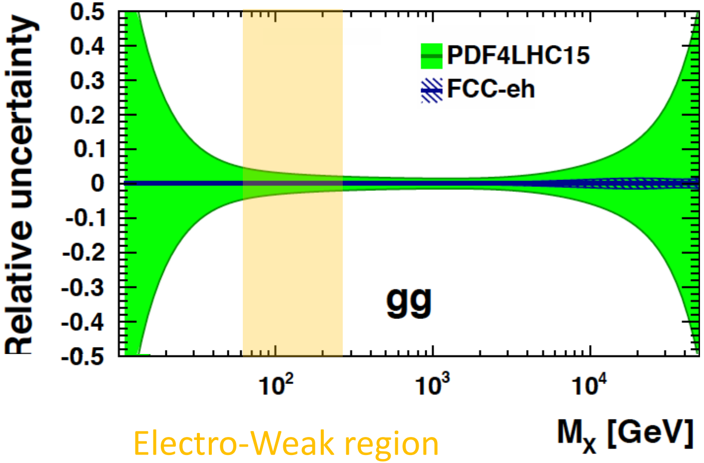
Strong interaction physics

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

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

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

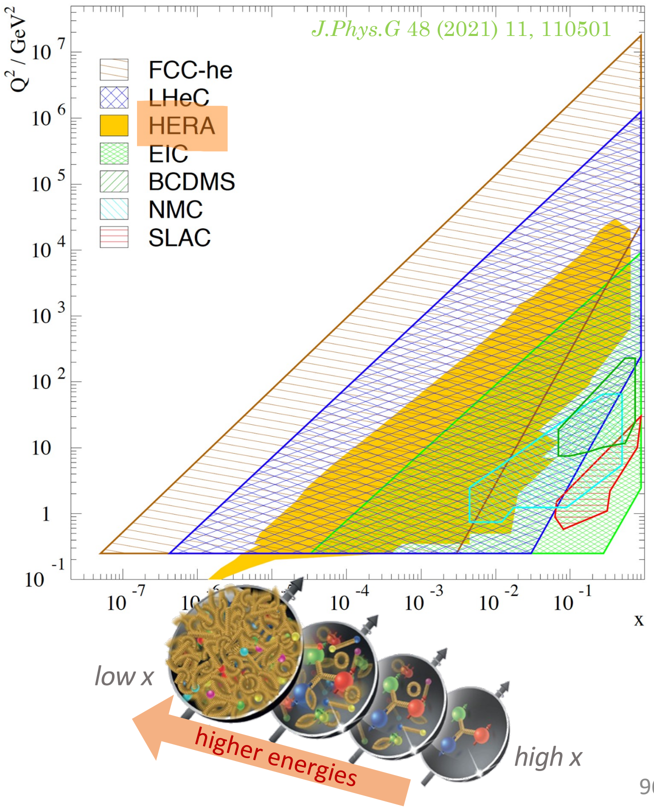


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

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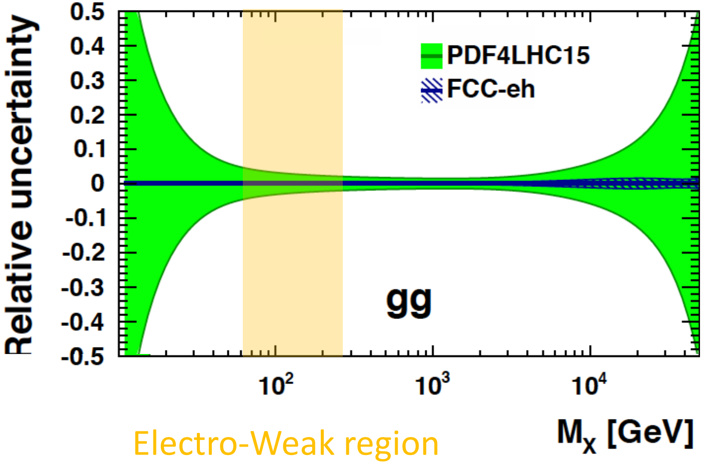


Electro-Weak region

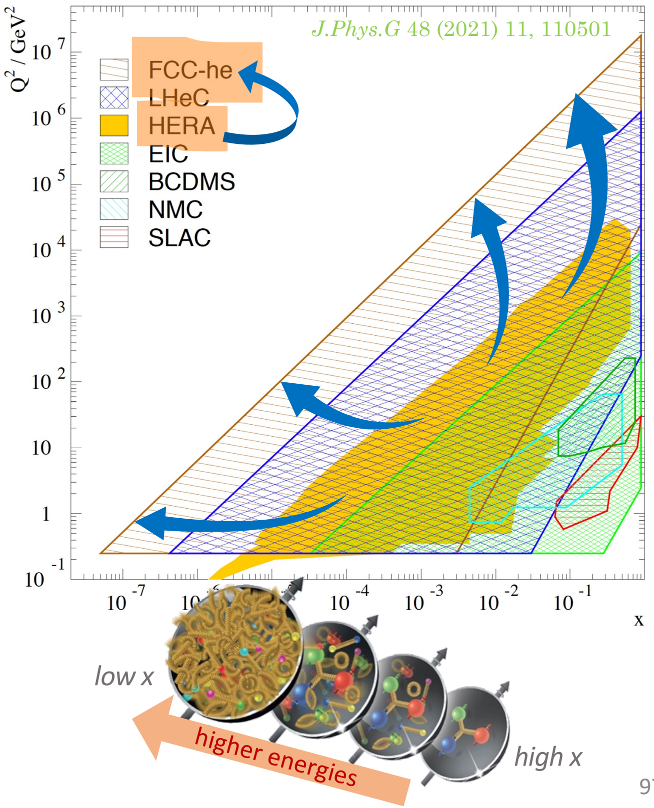
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



FCC-eh essential to unlock FCC-hh science potential

Complementarity for Higgs physics in the FCC program

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

J. de Blas et al., JHEP 01 (2020) 139

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

only FCC-ee@240GeV

FCC-ee prospect

FCC-hh/eh prospect

only FCC-hh

ALL COMBINED

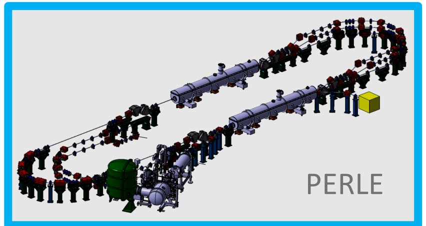
Ultimate Higgs Factory = {ee + eh + hh}

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

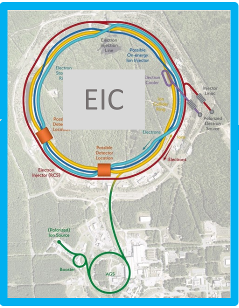
enables the ultimate upgrade of the LHC program

2020'ies



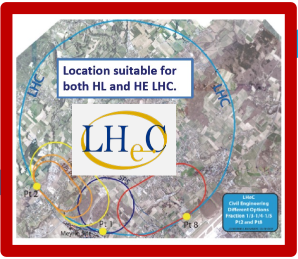
high-power ERL demonstrated

2030'ies



ERL application electron cooling

2030-2040'ies

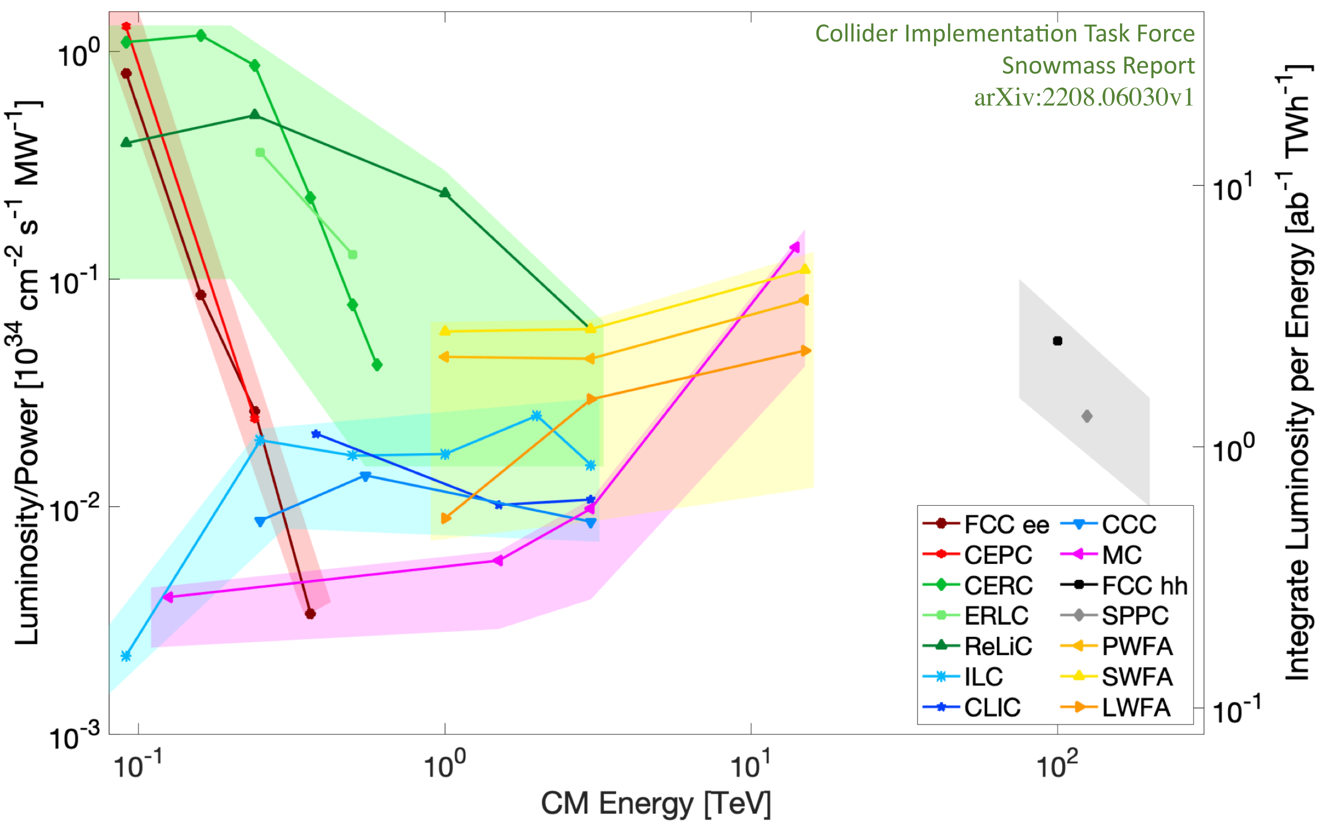


1 ERL beam

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

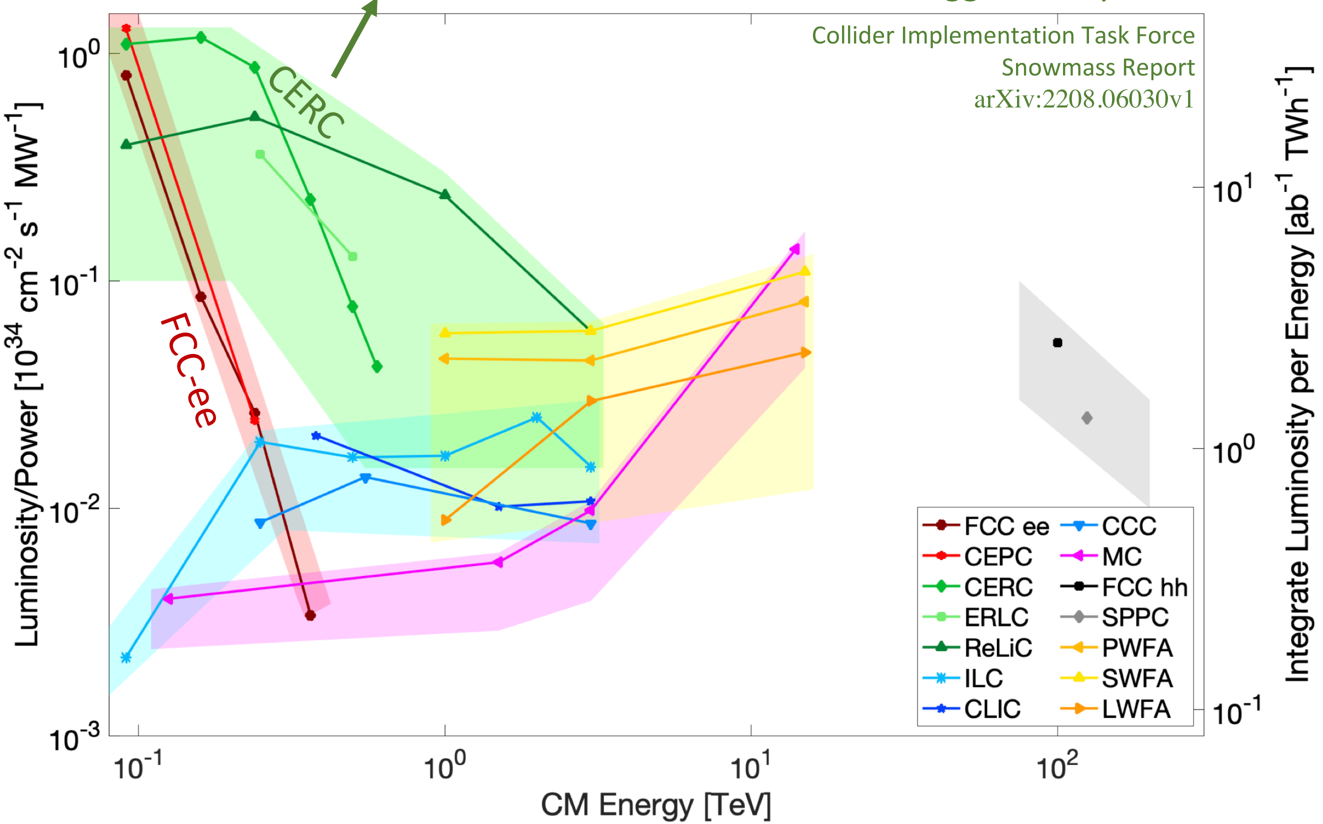
ERL-based H/HH Factories

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



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

CERC: ERL-based circular 100km e^+e^- Higgs Factory



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

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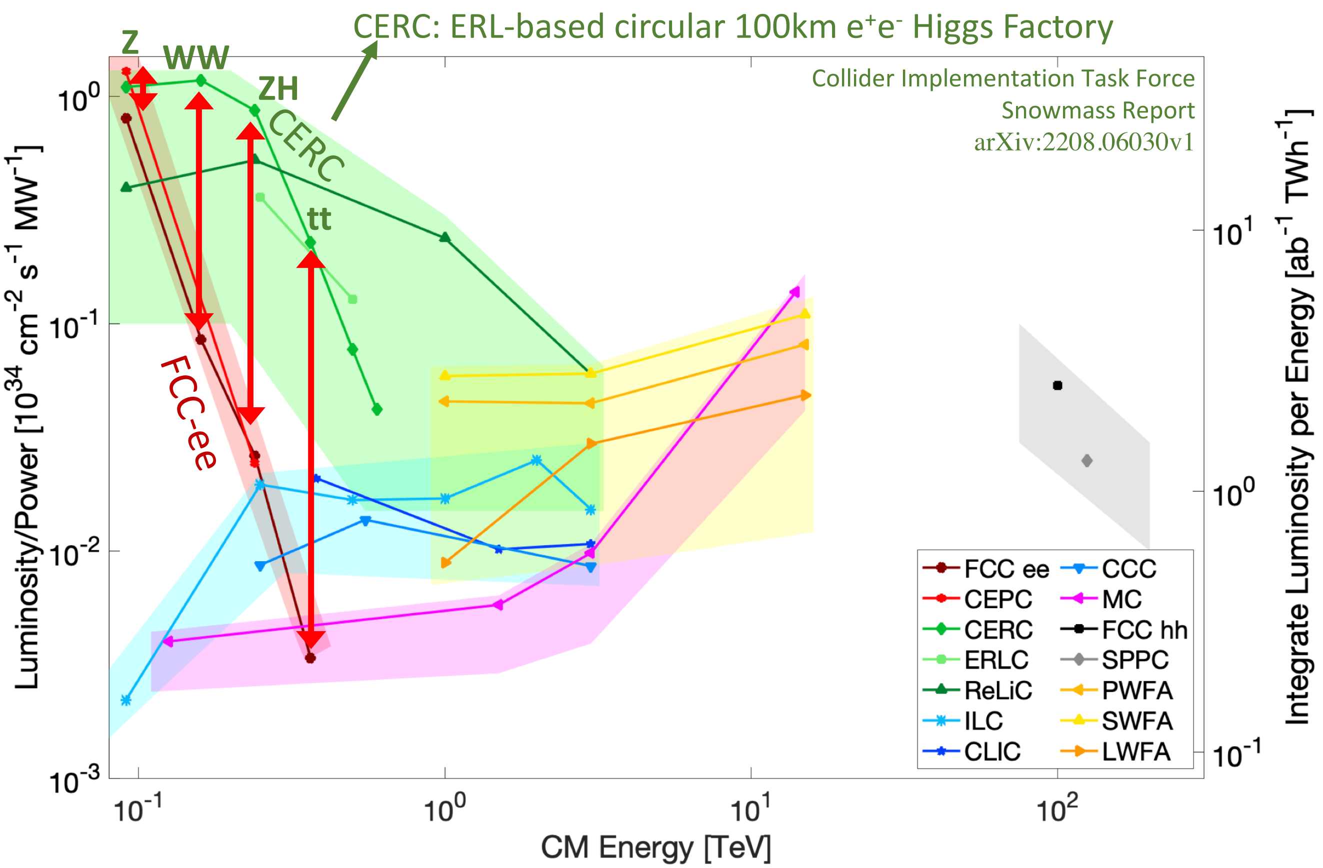

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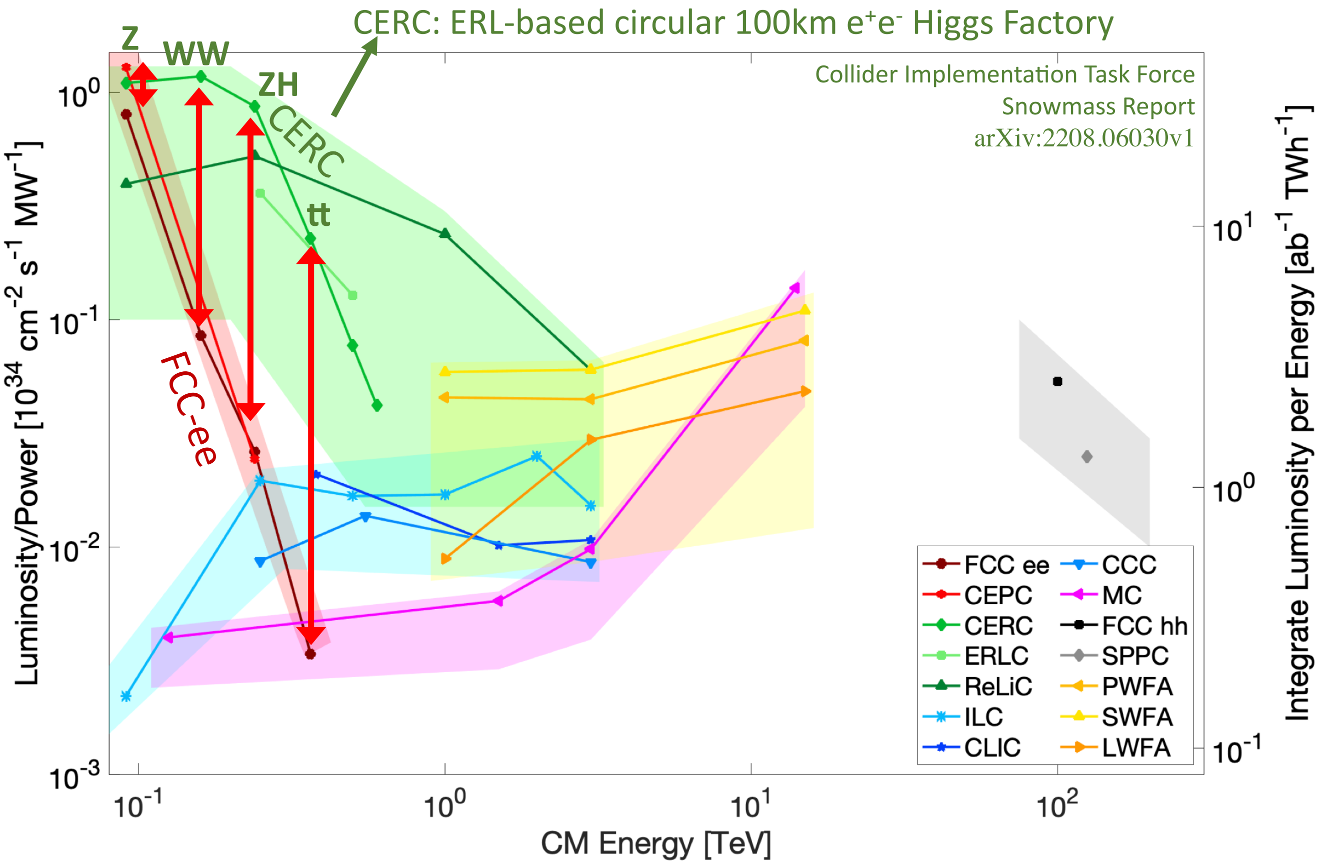
Energy Recovery applications for HEP e^+e^- colliders

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

x10 more H's

or

x10 less electricity costs



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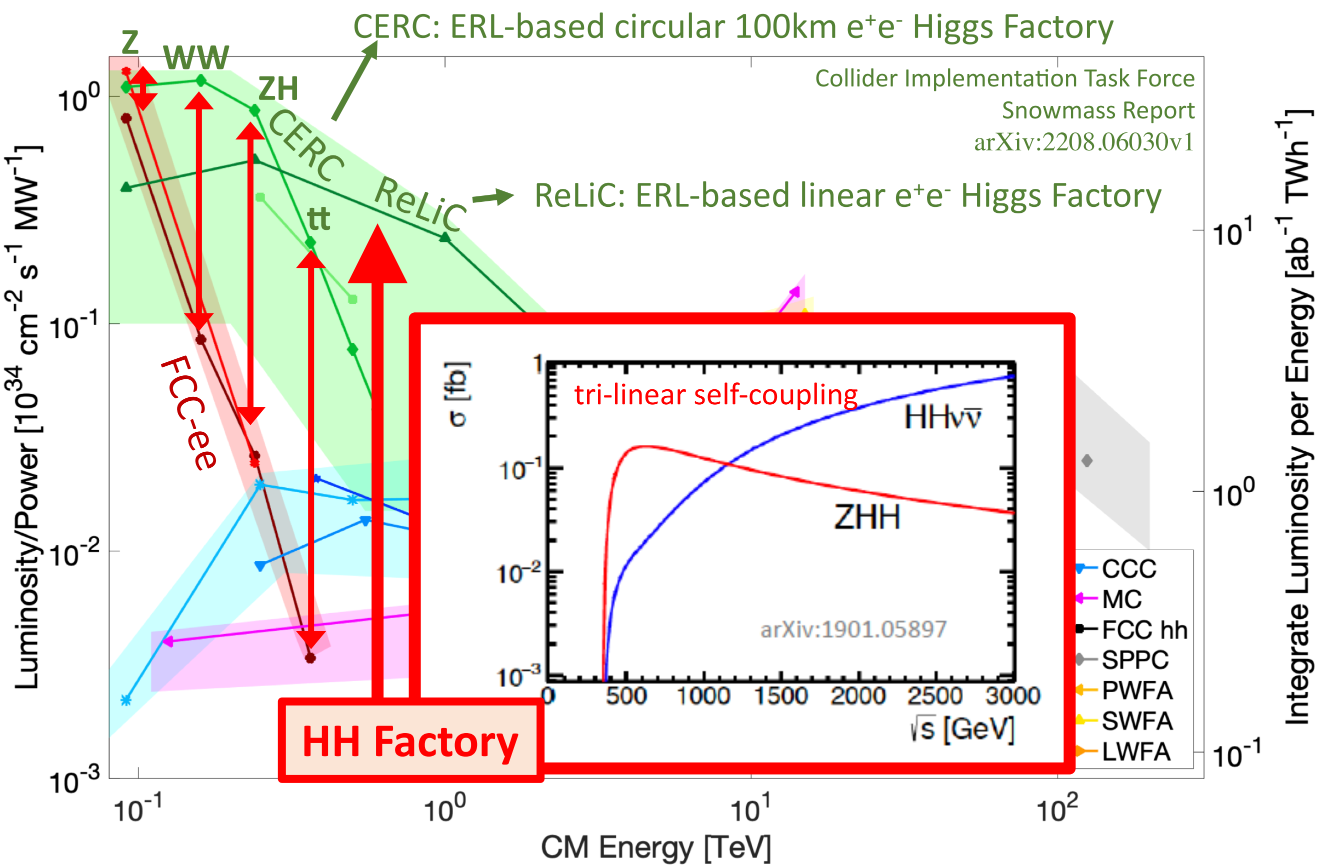

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Ref for ReLiC: arXiv:2203.06476

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

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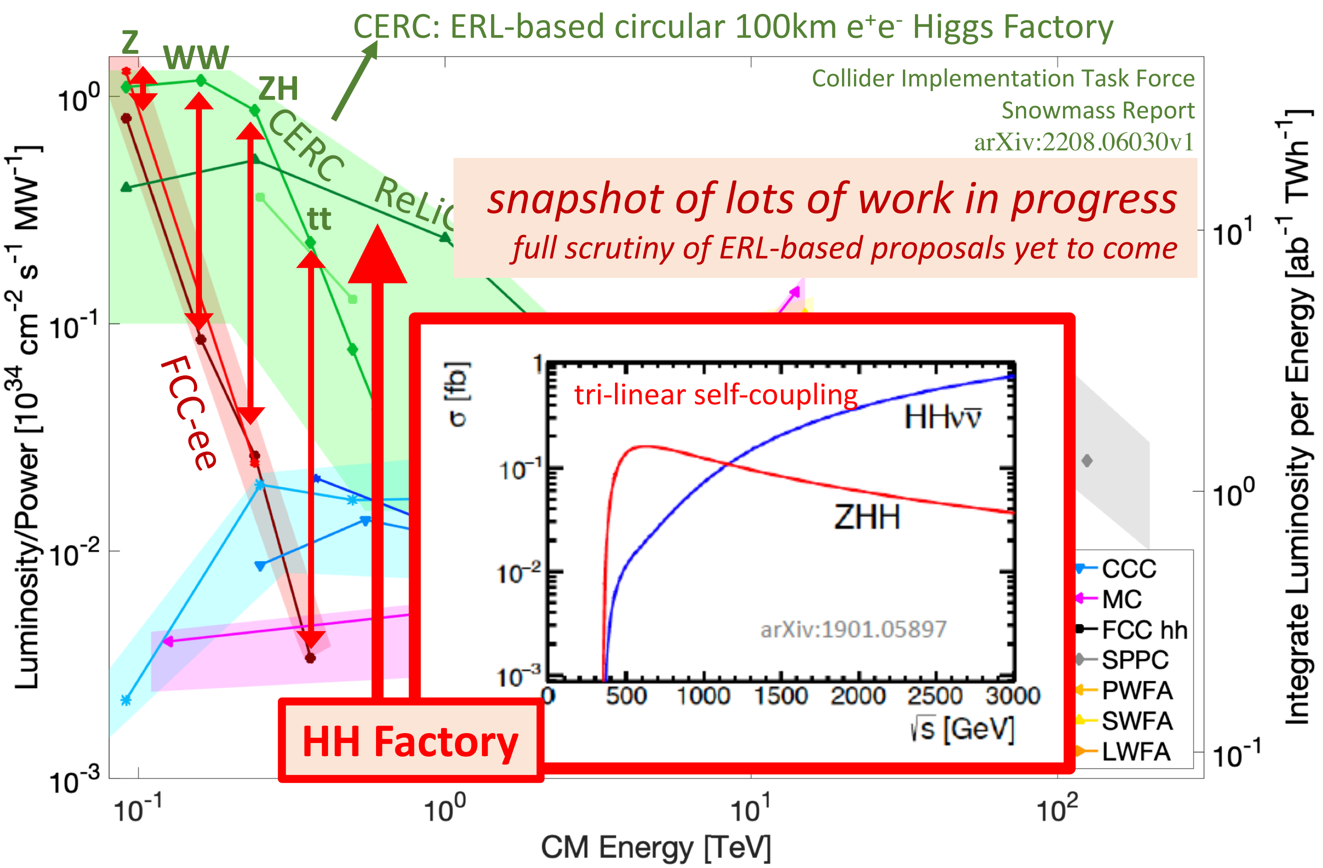
or

x10 less electricity costs

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



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Energy Recovery applications for HEP e^+e^- collid…

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x10…

NO…
challe…
these E… …ggs Factories

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

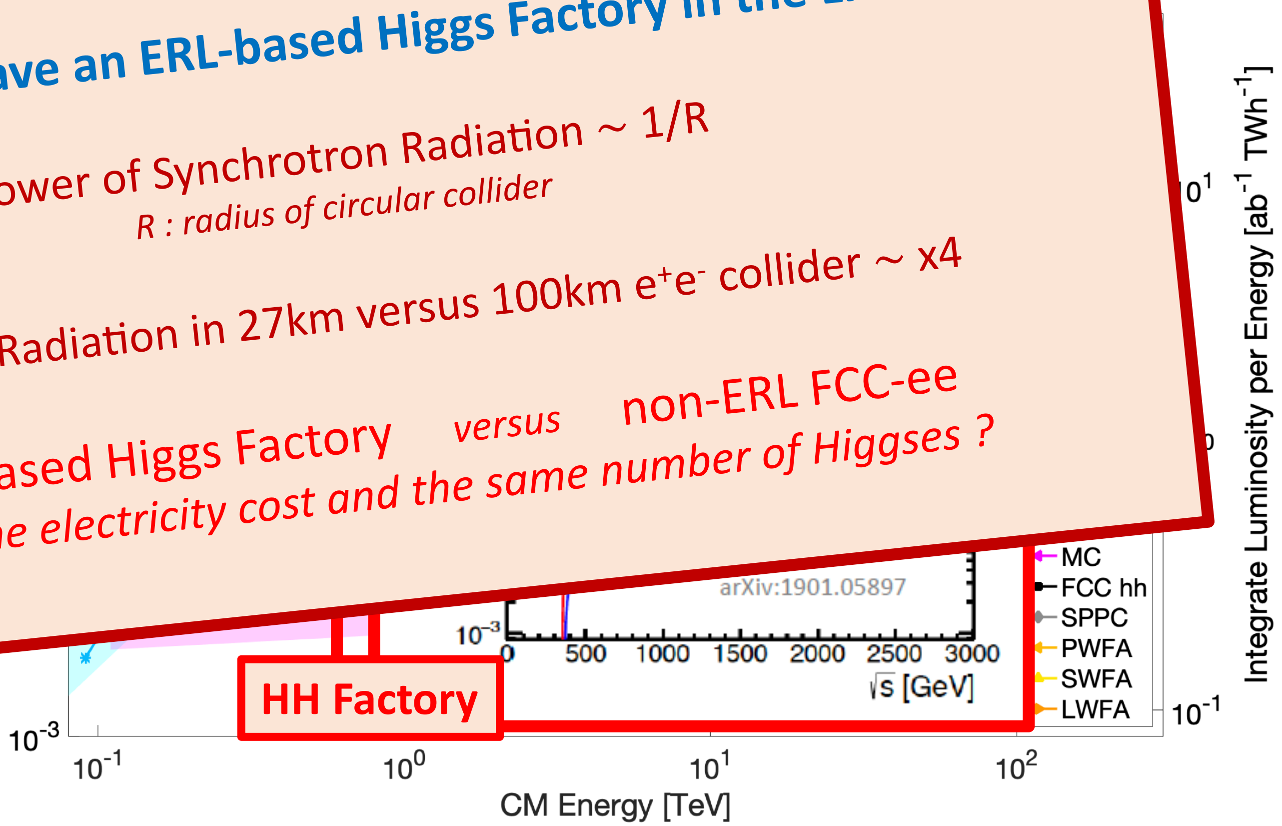
Power of Synchrotron Radiation ~ 1/R

R : radius of circular collider

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

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

with the same electricity cost and the same number of Higgses ?



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

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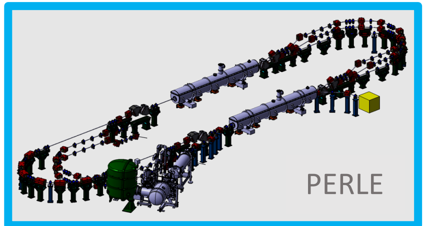
Potential impact of ERL technology

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

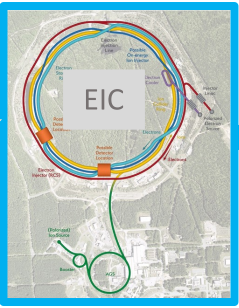
demonstrate multi-turn high-power ERL

2020'ies



high-power ERL demonstrated

2030'ies



ERL application electron cooling

enables the ultimate upgrade of the LHC program

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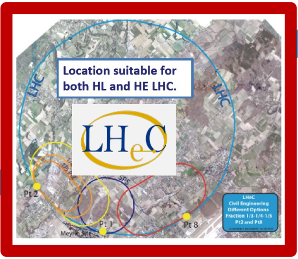
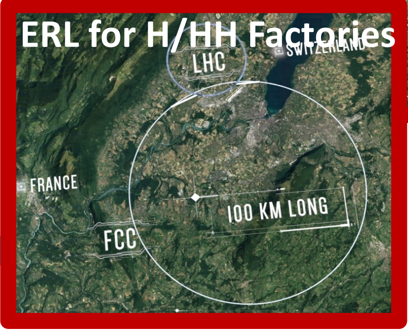


1 ERL beam

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

2040-2050'ies

ERL for H/HH Factories



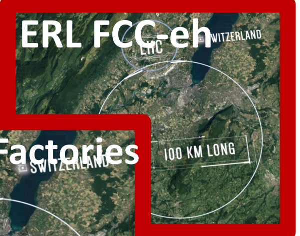
2 ERL beams

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

increases the performance of the next major colliders

2070'ies

ERL FCC-eh



reuse ERL

Energy Recovery Linacs (ERL): R&D plans and impact

- ERL is an enabling technology for our most prominent future ep/eA and e^+e^- colliders, delivering breakthrough performances on an interesting timeline
- The engine of our curiosity-driven exploration with particle physics is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize: ERL technology delivers on this front
- To achieve the best physics for the least power, we connect leading European institutions and industry to expedite the development of sustainable technologies that are essential to realize the ambition expressed in the European Strategy for Particle Physics

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https://indico.ijclab.in2p3.fr/event/9548/

The potential impact of ERL is so appealing that we must foster this R&D path

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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Thank you for your attention!

Jorgen.DHondt@vub.be