Energy Recovery Linacs for high-energy physics

sustainably enabling high-power beam

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Vrije Universiteit Brussel

First Community Report on the Accelerator R&D Roadmap, Frascati, July 2023

The Standard Model of particle physics has alarming symptoms…

and at the same time it is perfectly healthy.

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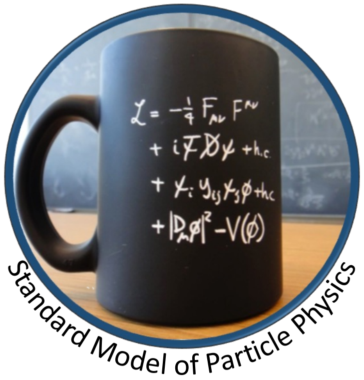
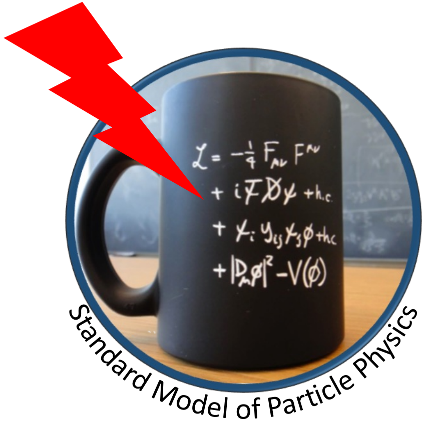
and at the same time it is perfectly healthy.



Great theory that matches all our observations related to fundamental interactions

The Standard Model of particle physics has alarming symptoms… and at the same time it is perfectly healthy.



Great theory that matches all our observations related to fundamental interactions

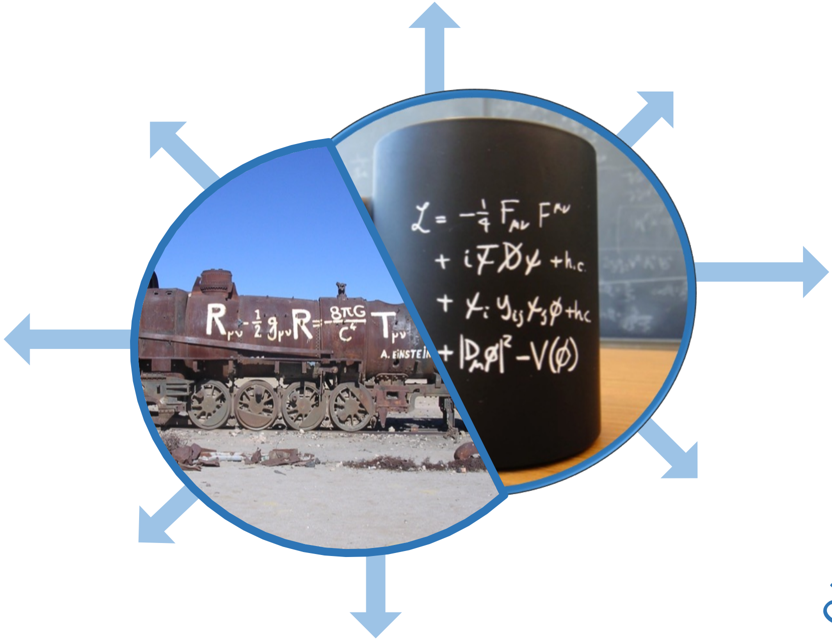
Yet, we are puzzled with the dominance of matter over anti-matter, with the dominance of dark matter in the universe, with the flavour structure of our theory, with the fine-tuning of the parameters in the theory, … and, it is not clear where we will find answers

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

higher energy interactions
in the lab

earlier universe

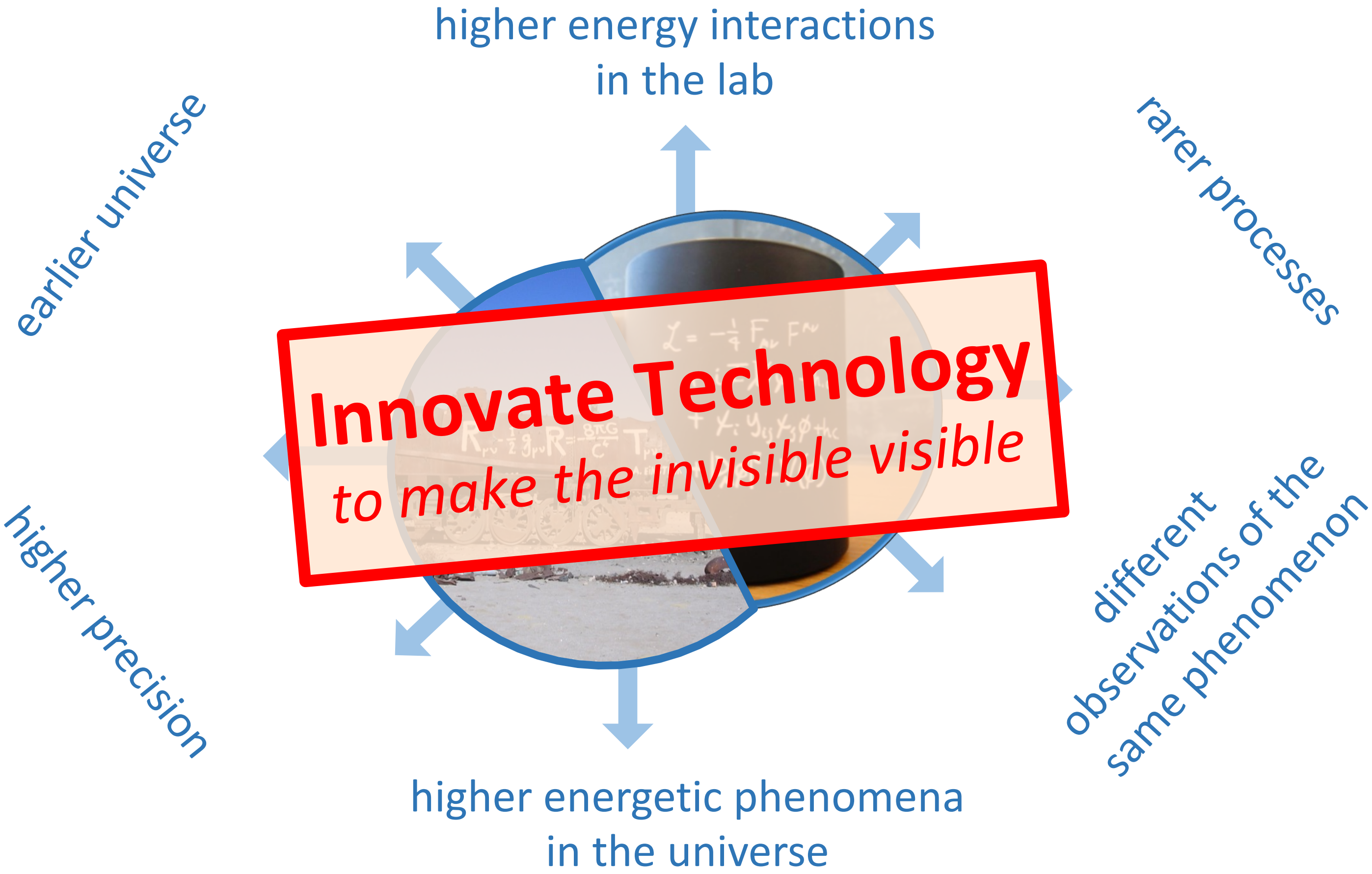
rarer processes



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
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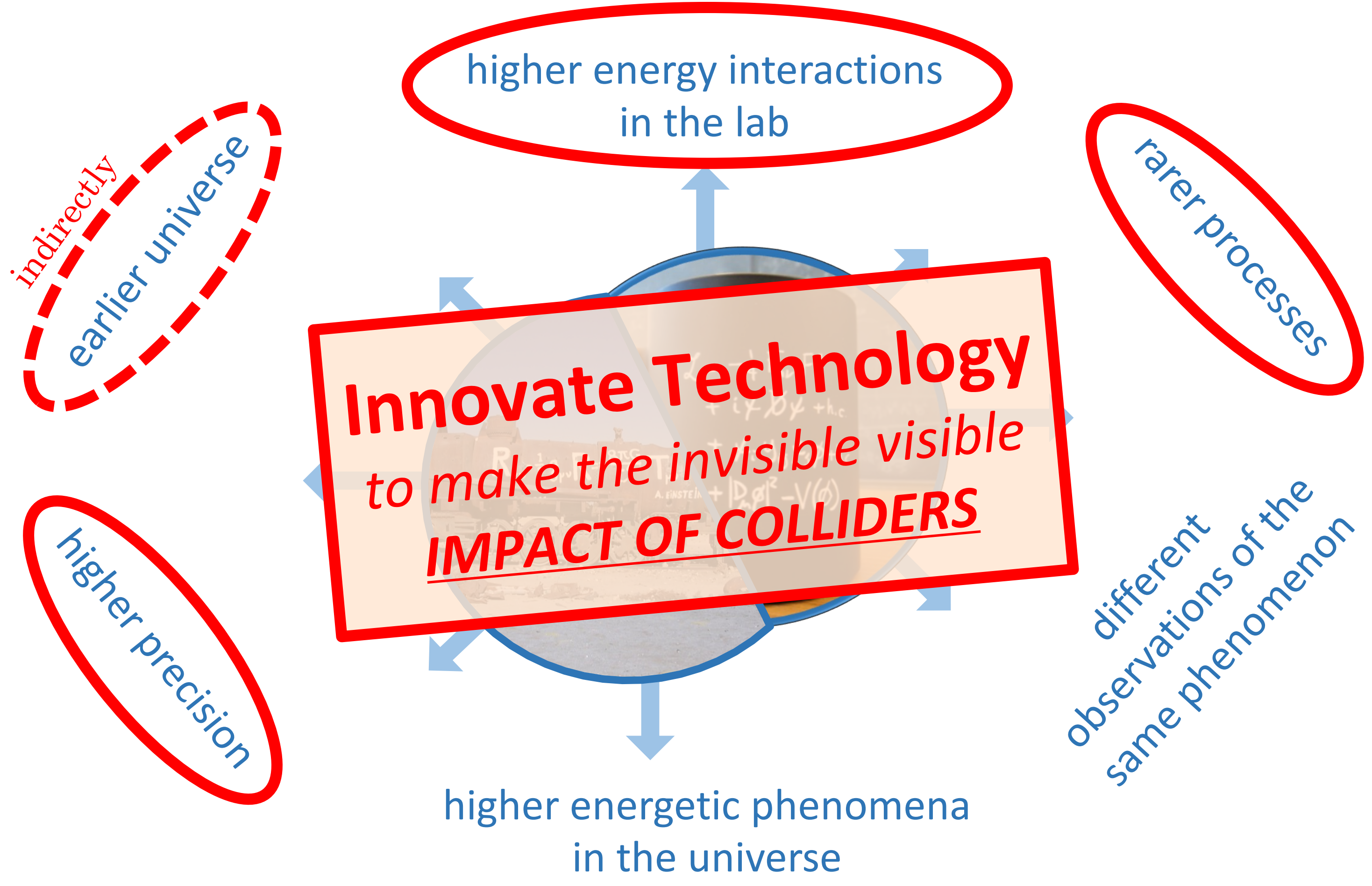
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IMPACT OF COLLIDERS

Particle beams required at high energy and high current = high power

!! ENERGY CONSUMPTION !!

higher energetic phenomena
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IMPACT OF COLLIDERS

higher precision

different observations of the same phenomenon

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in the universe

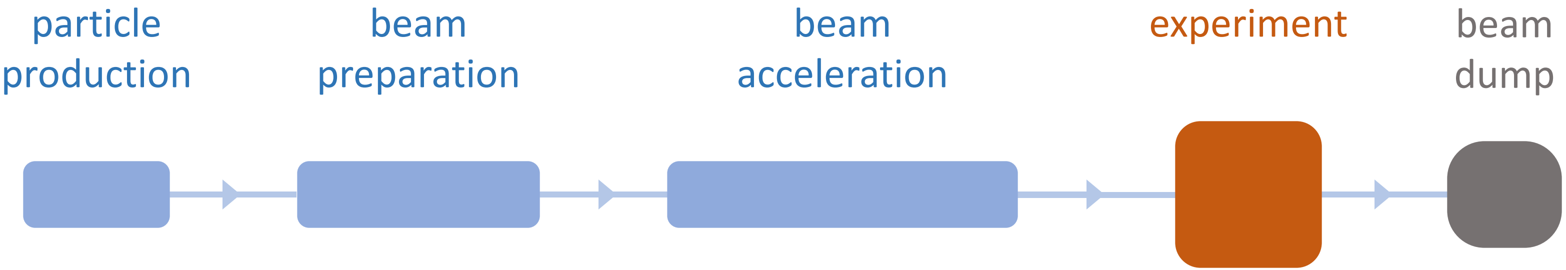
Particle beams required at high energy and high current = high power

!! ENERGY CONSUMPTION !!

A paradigm shift: sustainable high-power particle beams

Where our <u>lepton</u> accelerators use power ?

Basic structures of a particle accelerator



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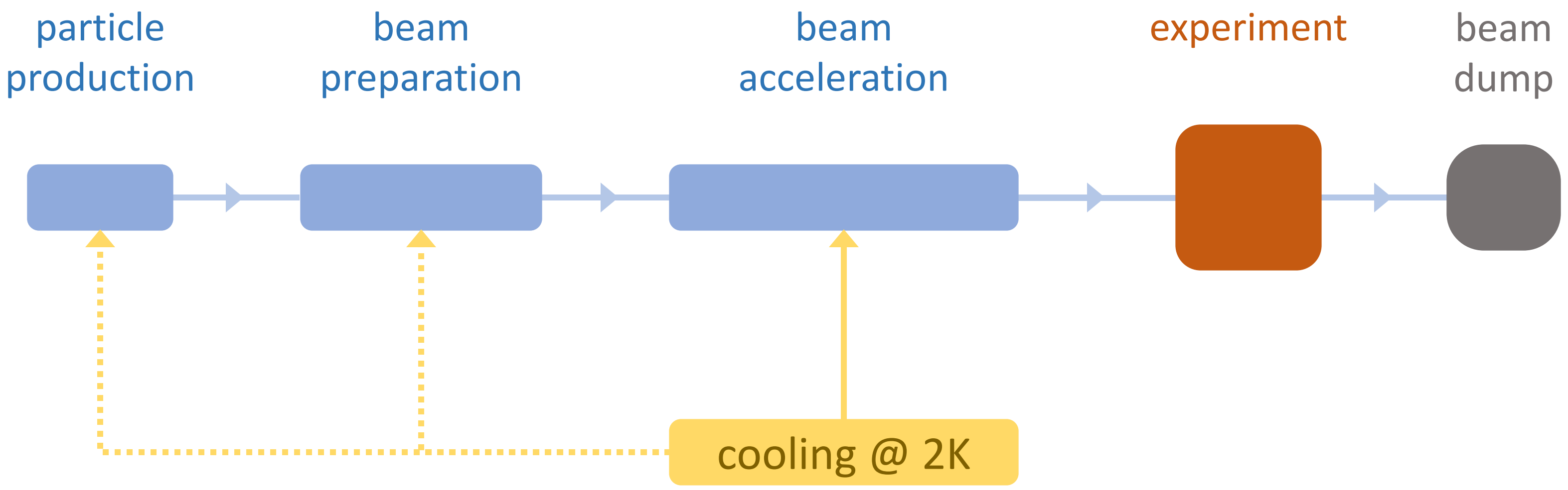

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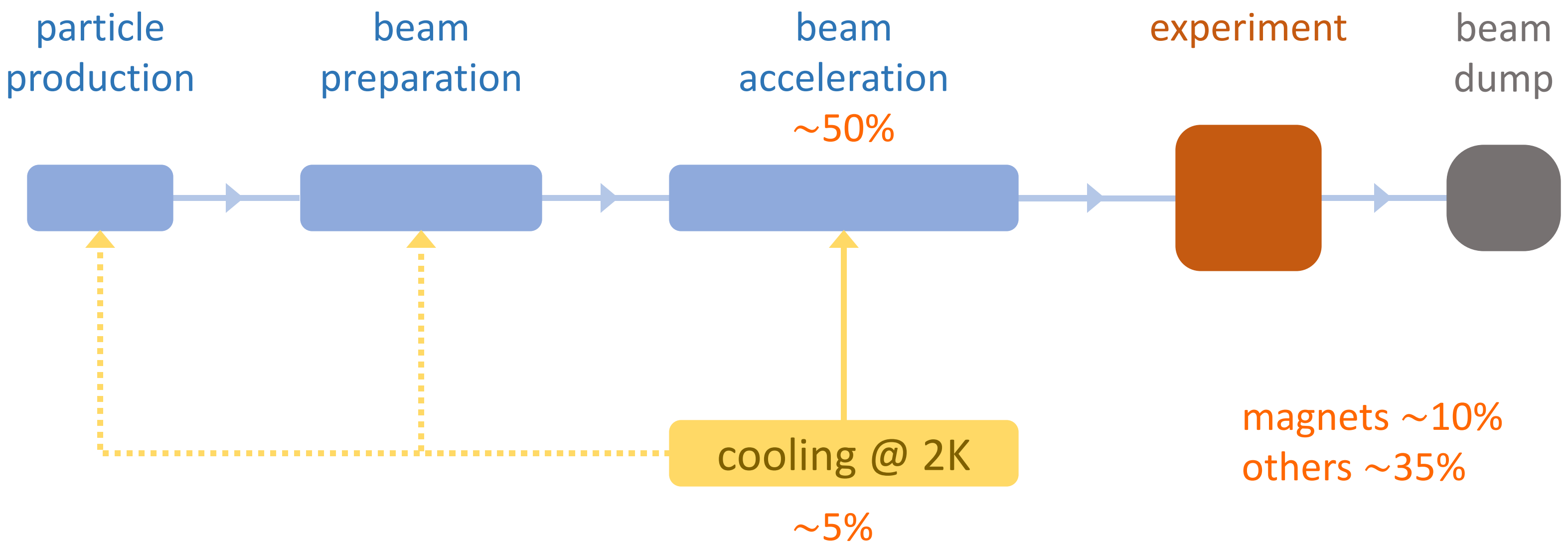
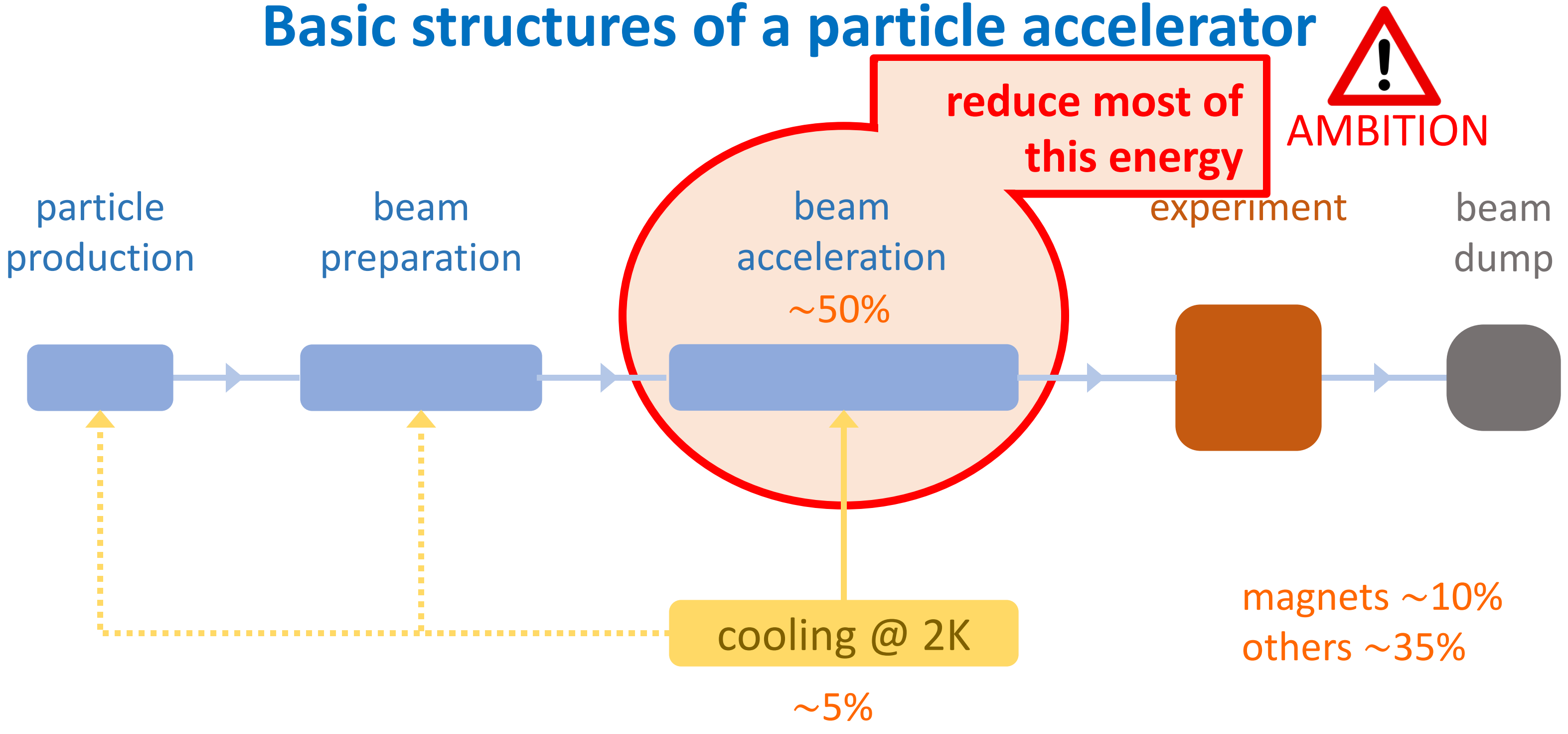


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator



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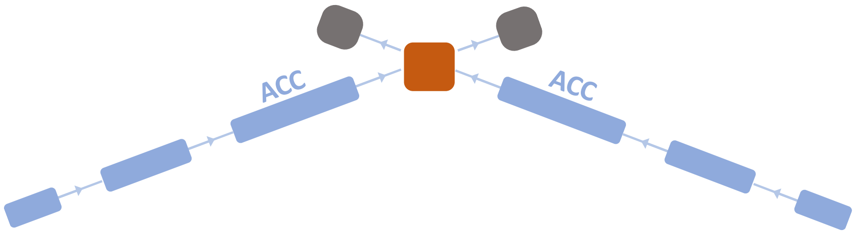
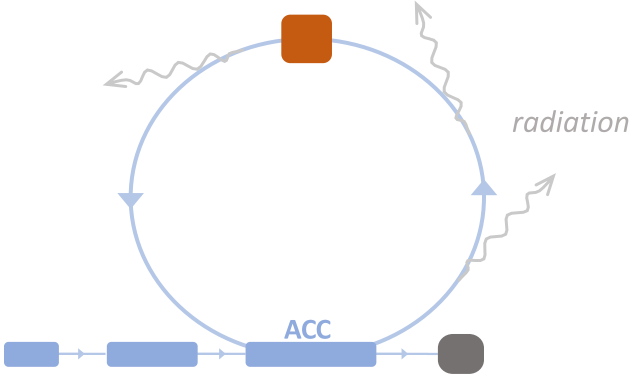
Impact for the current designs of e^+e^- Higgs Factories

Linear colliders



dump >99.9999% of
the beam power

Circular colliders



radiate away very quickly
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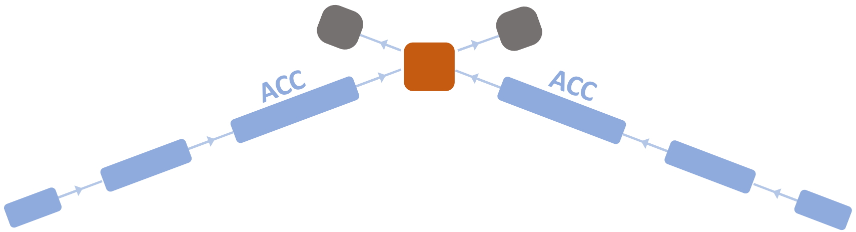

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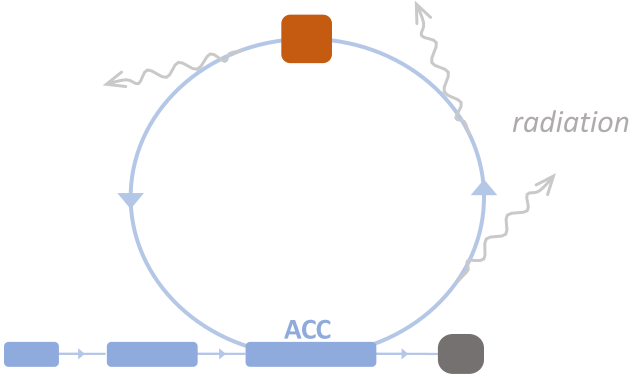


dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

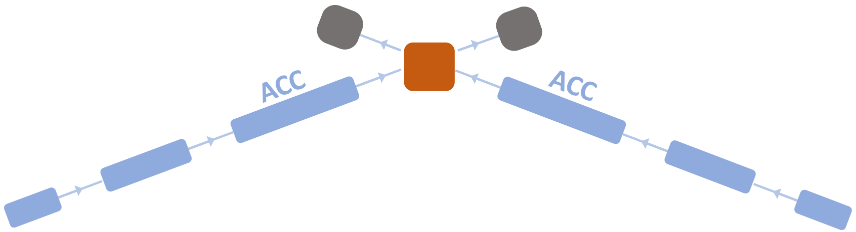
radiate away very quickly the beam power

about half of this is dumped or lost due to radiation

OBJECTIVE: develop new accelerating systems that save power with an impact of saving ~1% of Belgium's electricity

Impact for the current designs of e^+e^- Higgs Factories

Linear colliders



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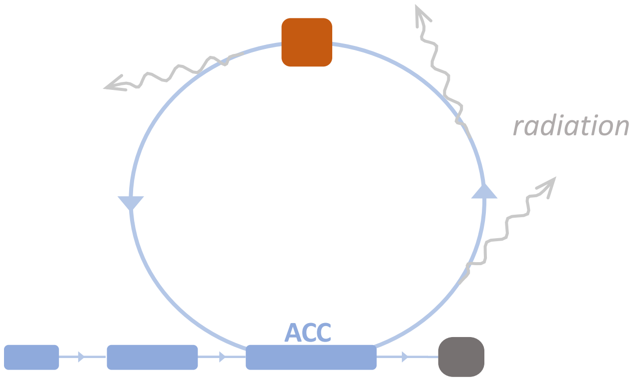


dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

radiate away very quickly the beam power

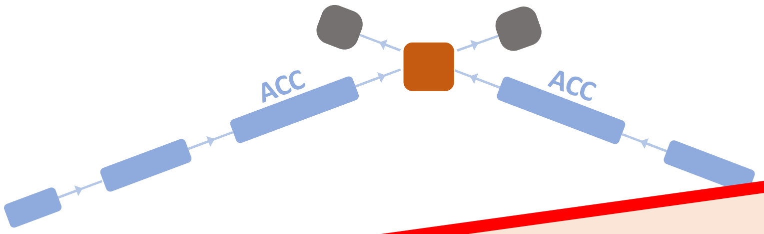
Energy consumption is reducing in Europe, not excluded with ½ by 2050-2060

about half of this is dumped or lost due to radiation

OBJECTIVE: develop new accelerating systems that save power with an **impact of saving ~2% of Belgium's electricity**

Impact for the current designs of e^+e^- Higgs Factories

Linear colliders



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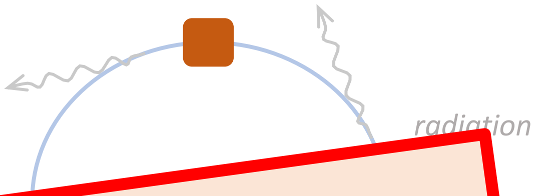


To further increase the luminosity we reach 1 GW power

equivalent to a nuclear power plant

... away very quickly
the beam power

Energy ... is reduc... not excluded with ½ by 2050-2060

... of annual electricity consumption in Belgium

about half of this is dumped or lost due to radiation

OBJECTIVE: develop new accelerating systems that save power with an **impact of saving ~2% of Belgium's electricity**

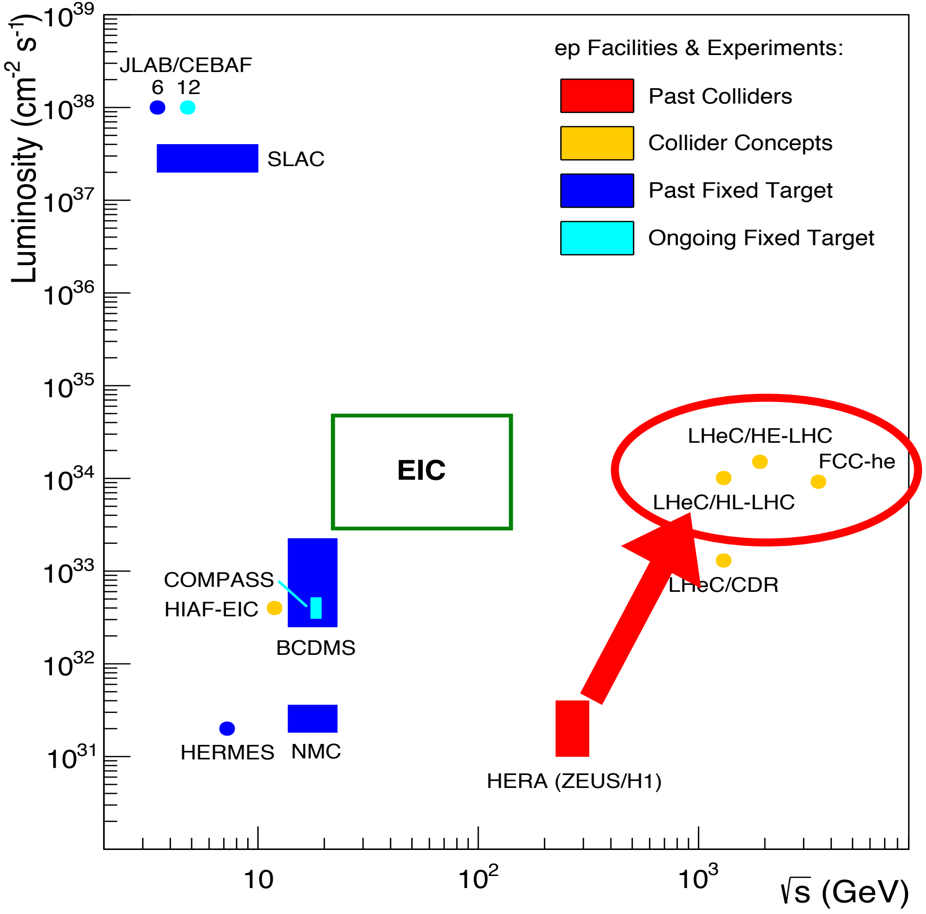
The high-energy and high-luminosity ep/eA frontier

From HERA to LHeC/FCC-eh

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

beam current × beam energy
= beam power

LHeC/FCC-eh ~ 1 GW beam power
equivalent to the power delivered by a nuclear power plant



adapted from PECFA talk Nov. 2018 of A. Deshpande

The high-energy and high-luminosity ep/eA frontier

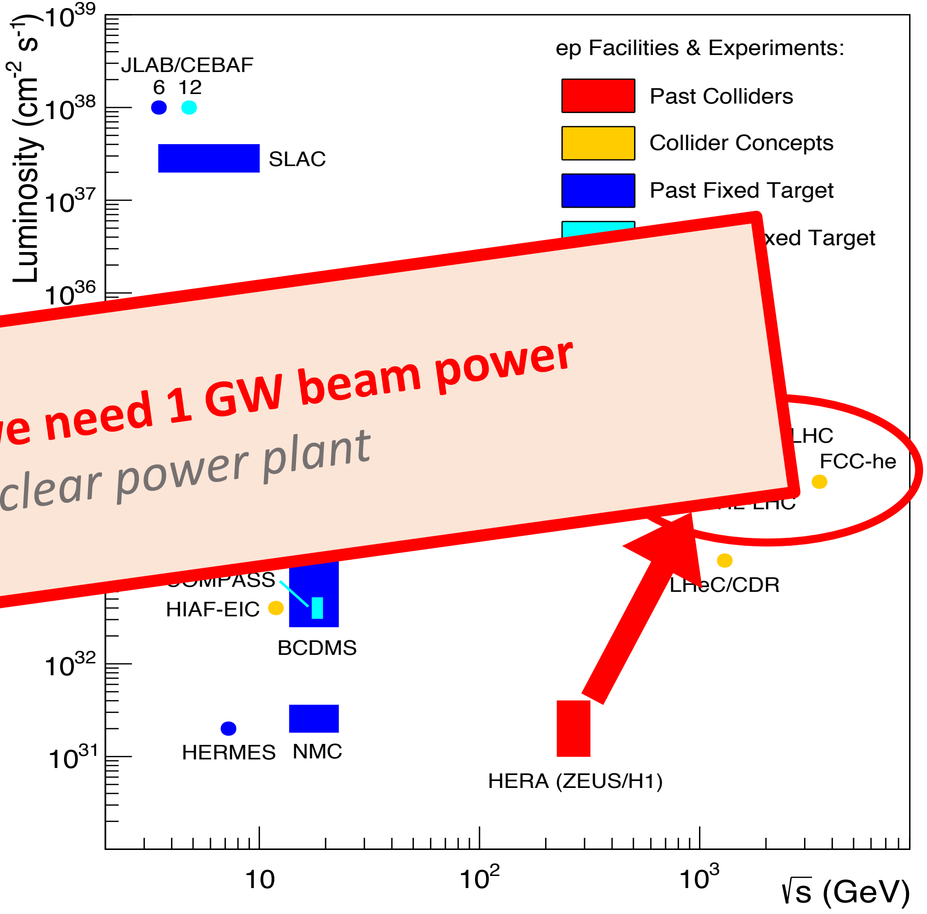
From HERA to LHeC/FCC-eh

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

beam current × ...

To enable this ep/eA path we need 1 GW beam power
equivalent to a nuclear power plant

LH... power
equ... power delivered by a nuclear power plant



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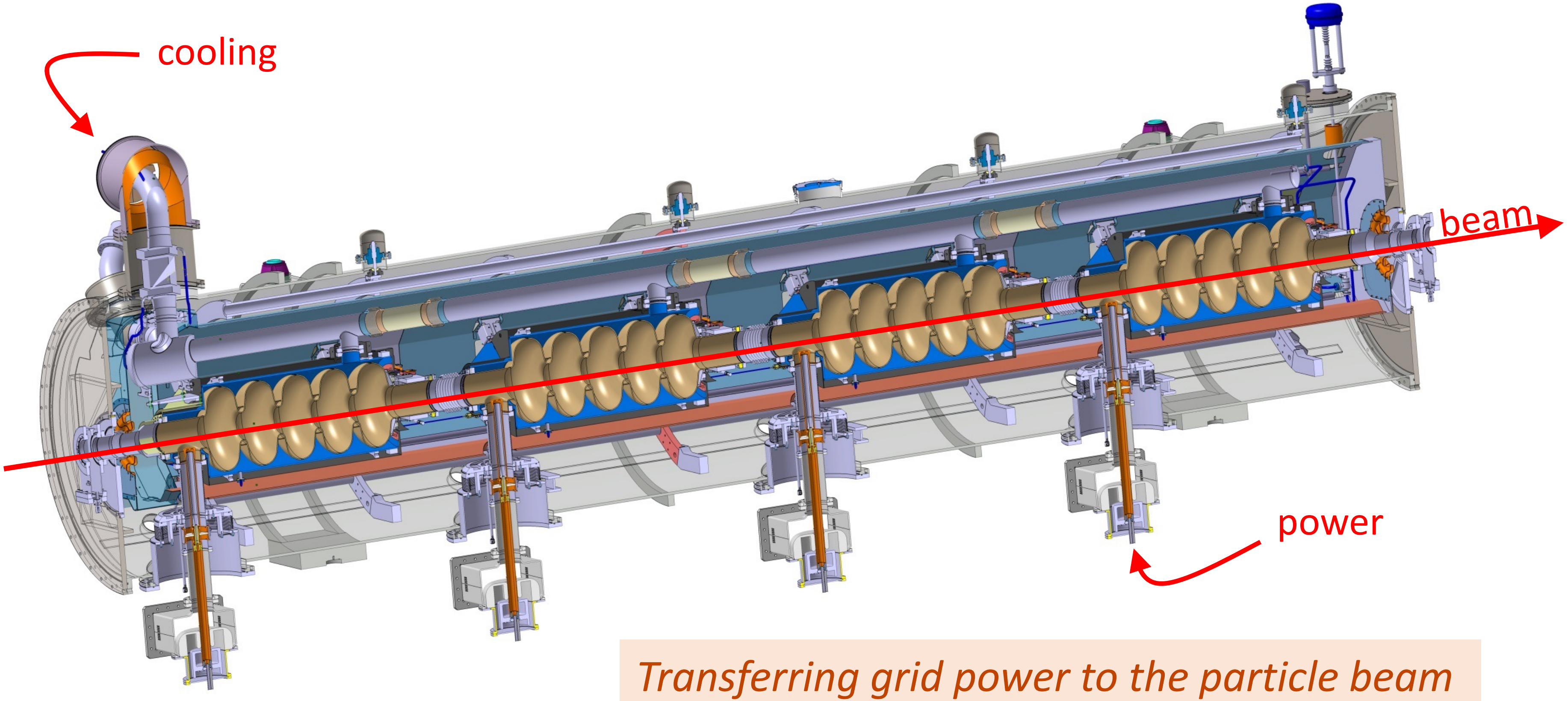
The energy efficiency of present and future accelerators [...] is and should remain an area requiring constant attention.

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

European Strategy for Particle Physics 2020

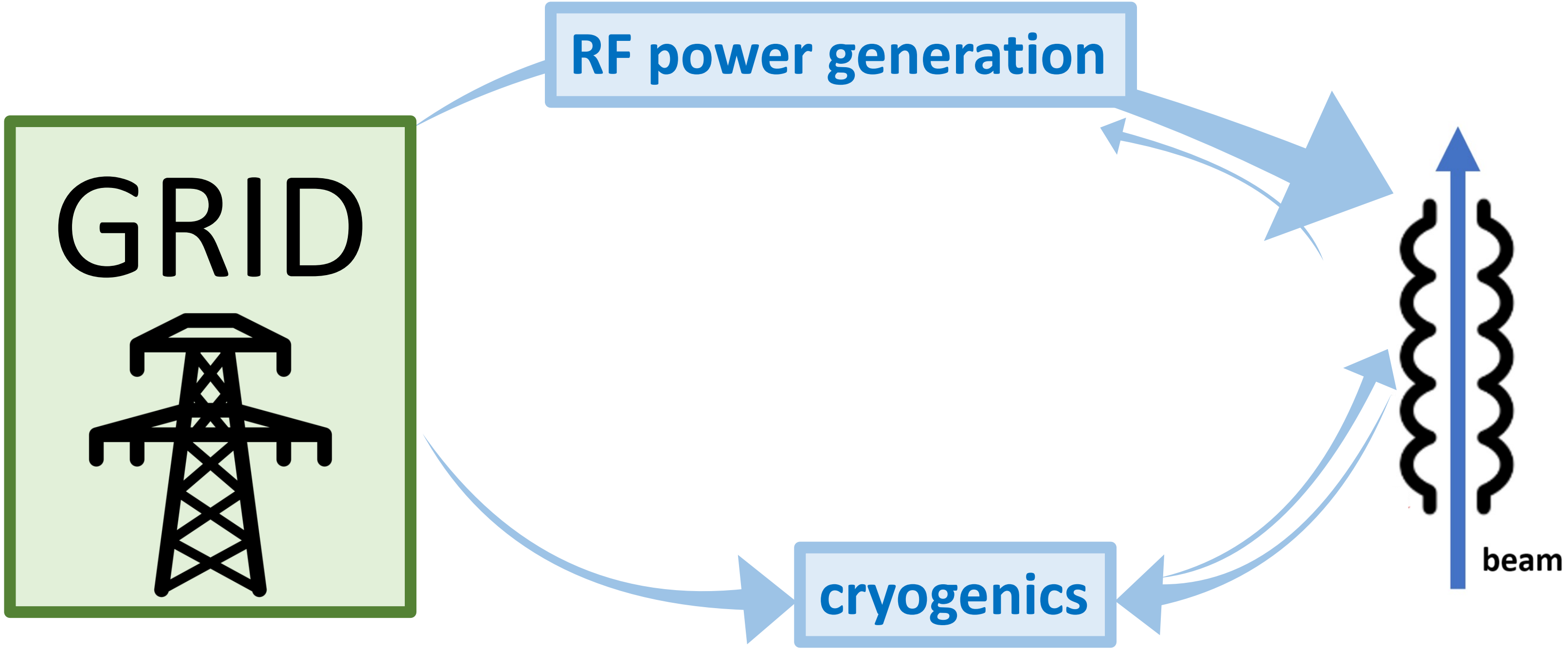
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency



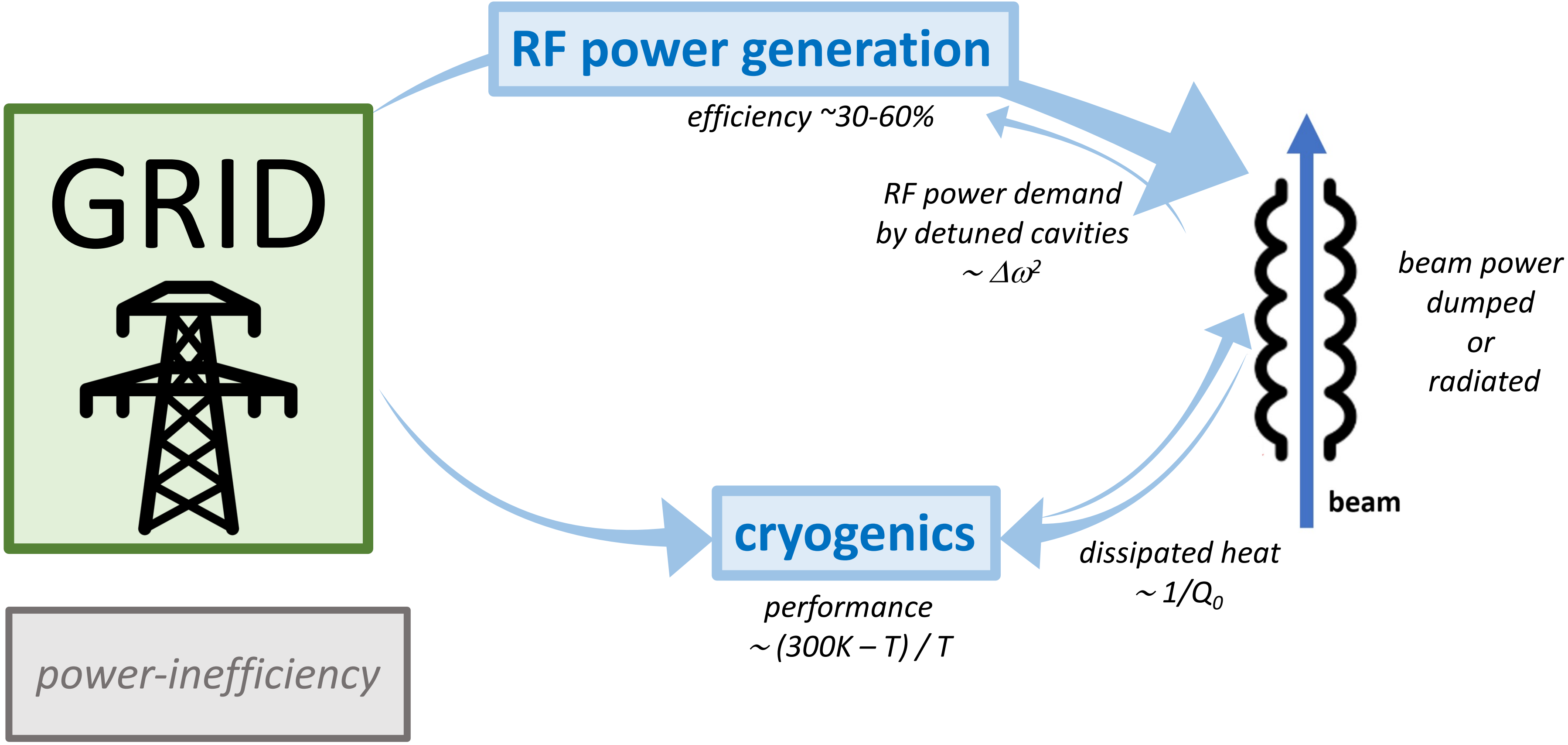
Transferring grid power to the particle beam

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam



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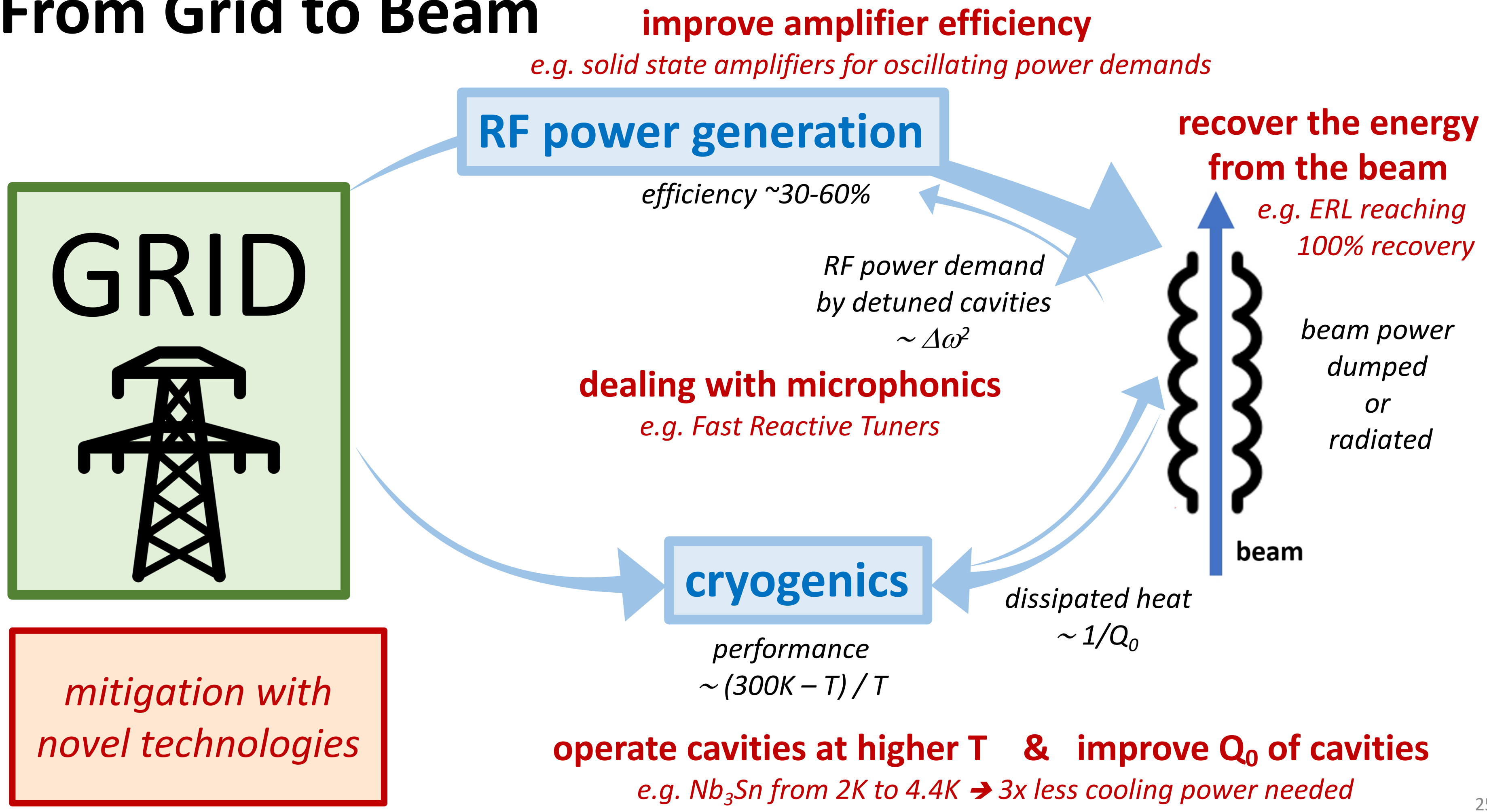

From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscill...

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

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

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

beam

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

From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscill...

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

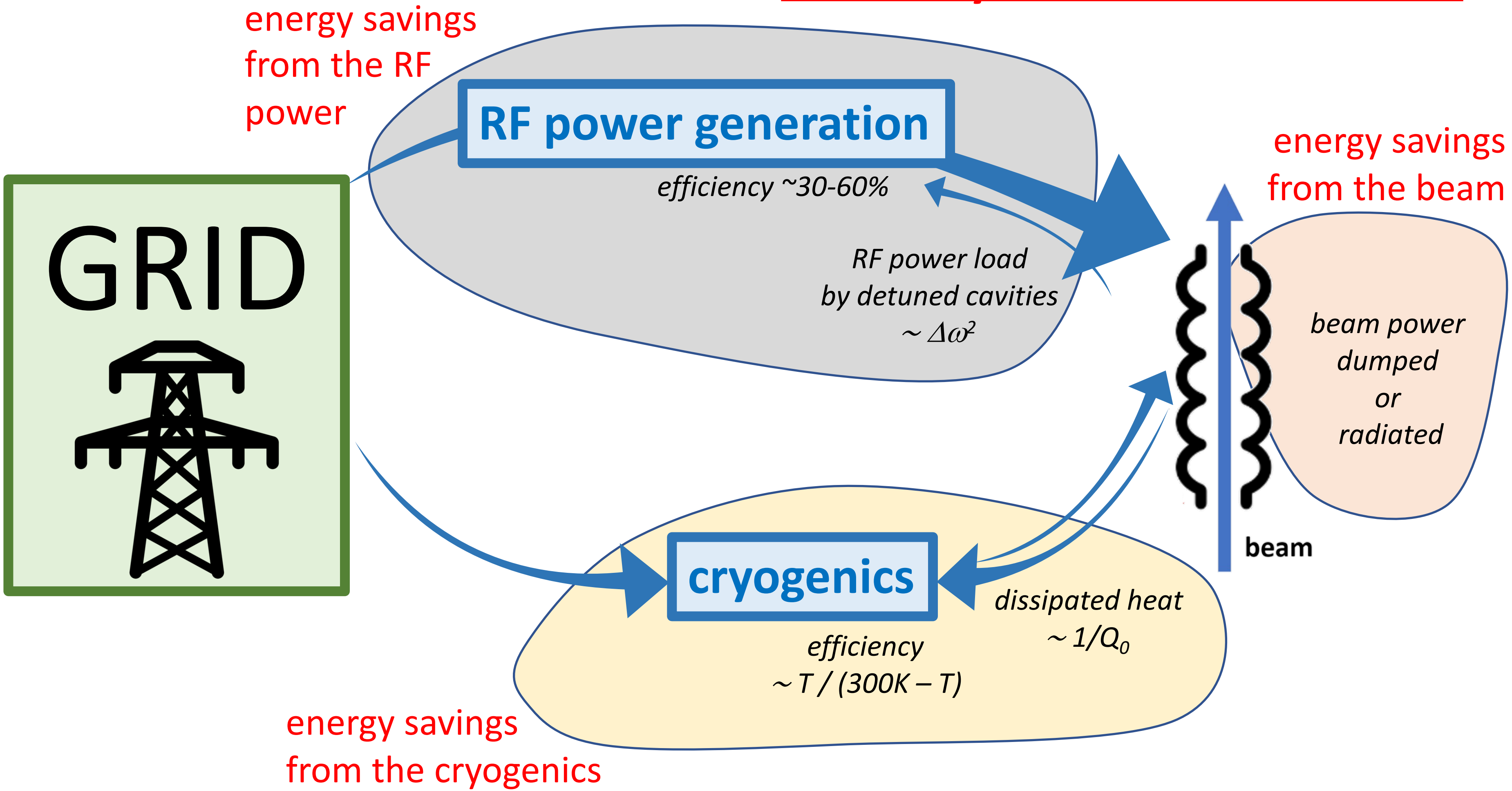
ALARA = **A**s **L**ow **A**s **R**easonable **A**chievable

principle enforced for nuclear safety,
also for energy consumption ?

operate...

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

Three key innovation directions



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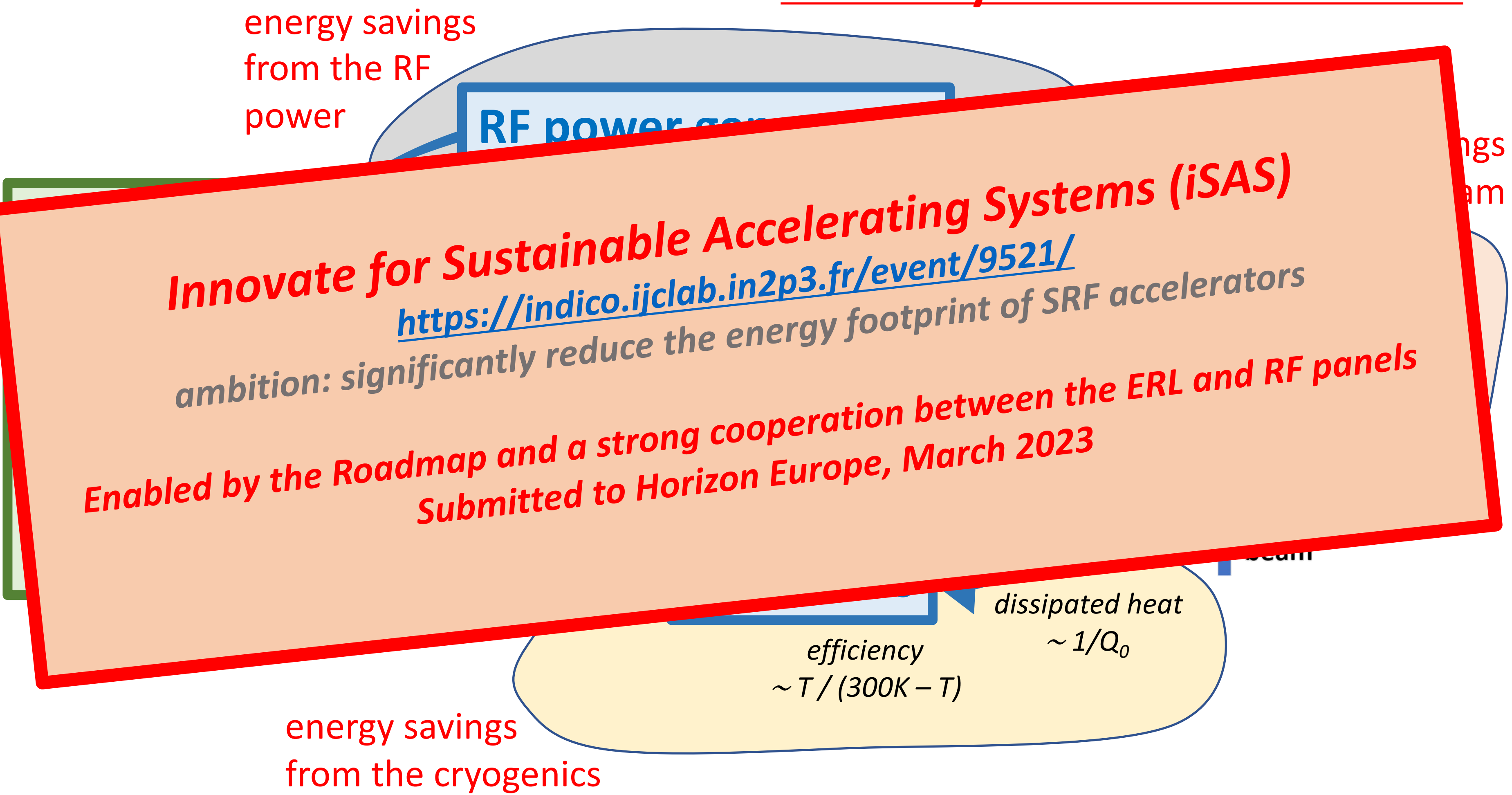

Innovate for Sustainable Accelerating Systems (iSAS)

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

ambition: significantly reduce the energy footprint of SRF accelerators

Enabled by the Roadmap and a strong cooperation between the ERL and RF panels

Submitted to Horizon Europe, March 2023

Three key innovation directions

energy savings from the RF power

RF power gen...

...ngs ...am

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Enabled by the Roadmap and a strong cooperation between the ERL and RF panels

Submitted to Horizon...

PROJECT GRANTED

10 July 2023

energy savings from the cryogenics

iSAS organisation

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

(of which 5M EUR is requested to Horizon Europe)

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

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

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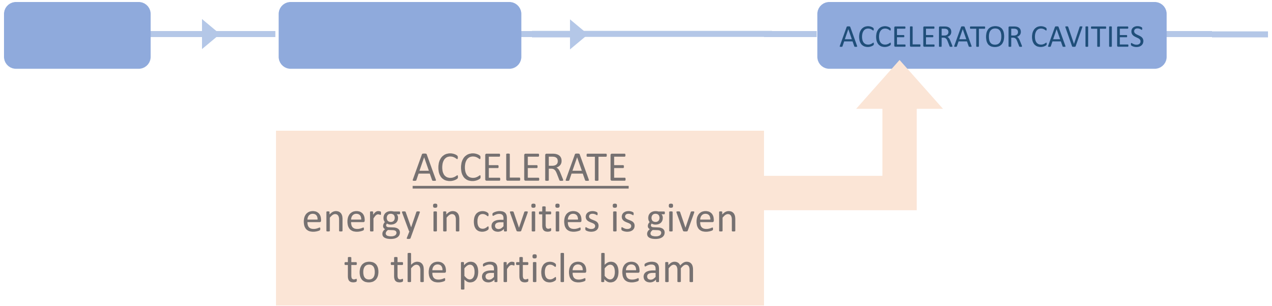
The principle of Energy Recovery



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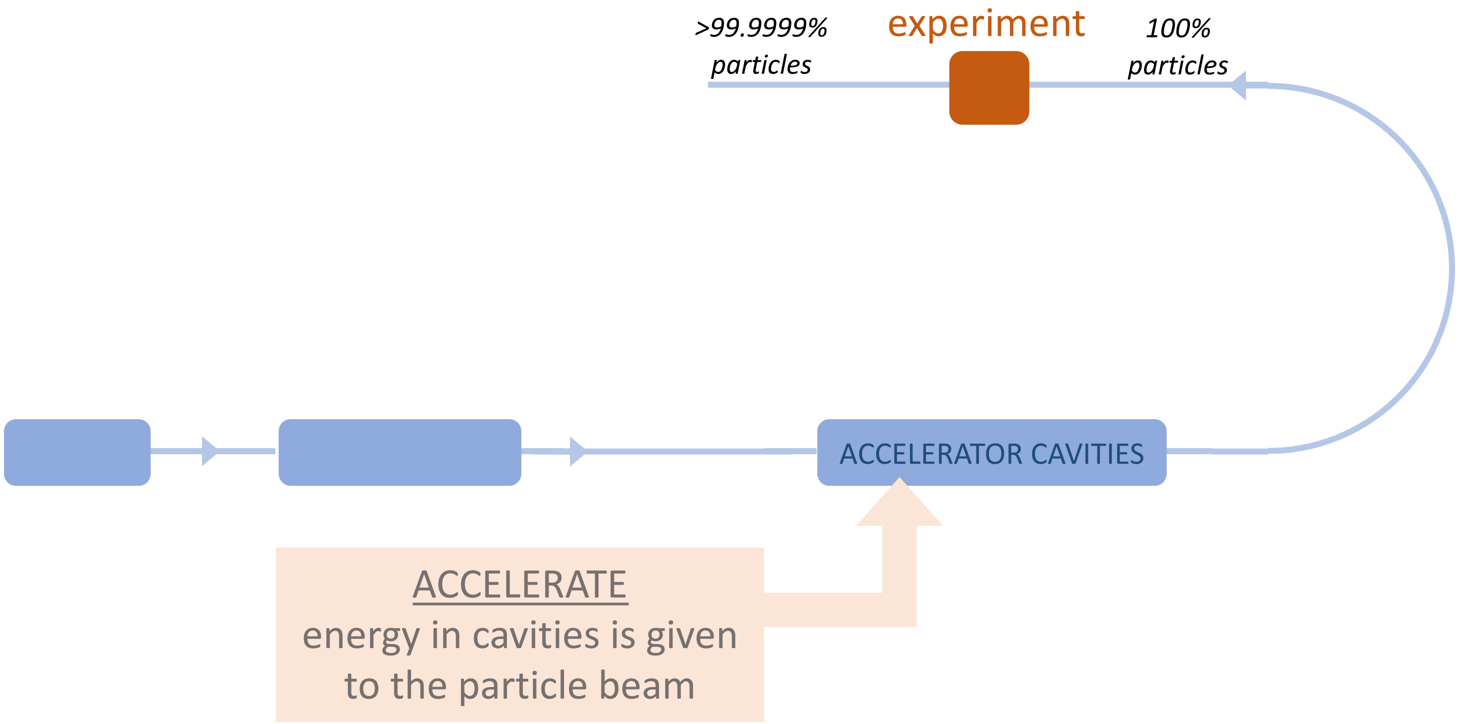

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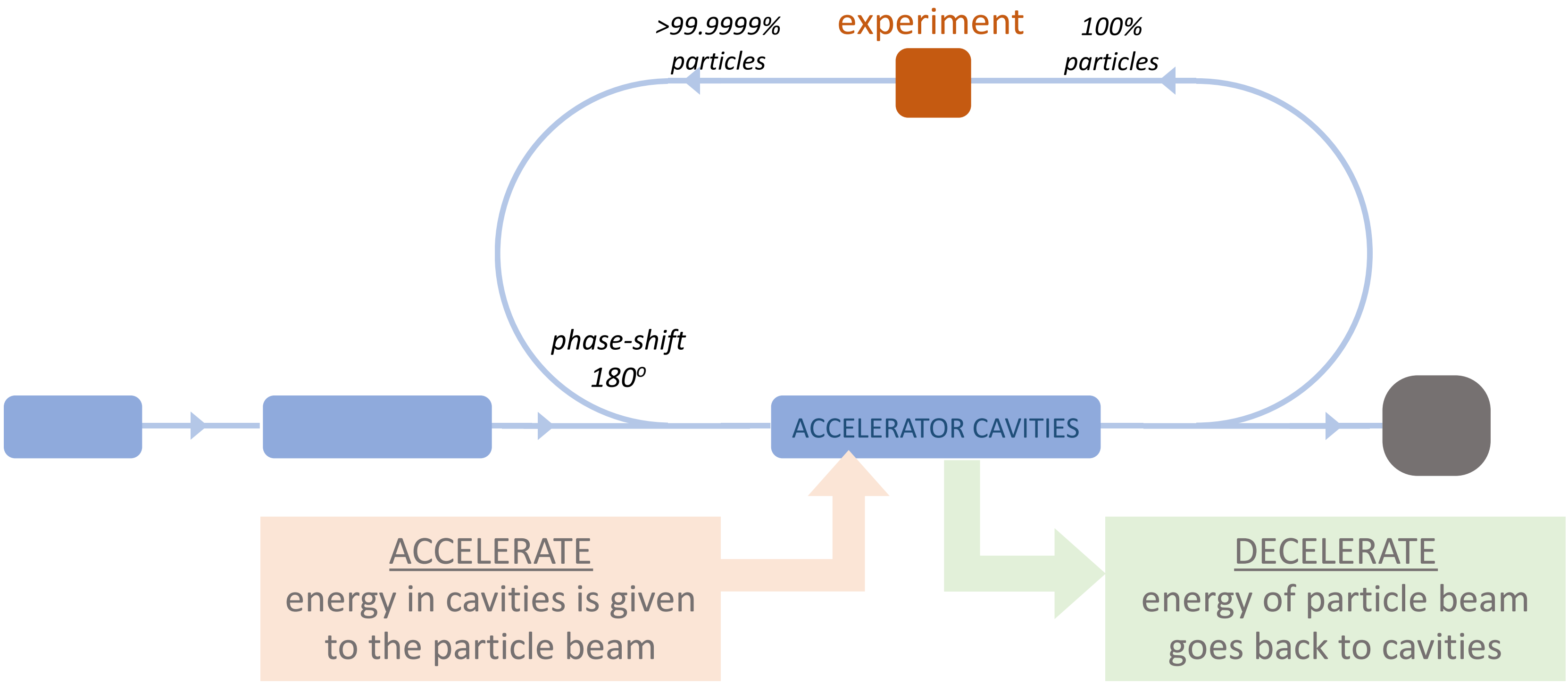

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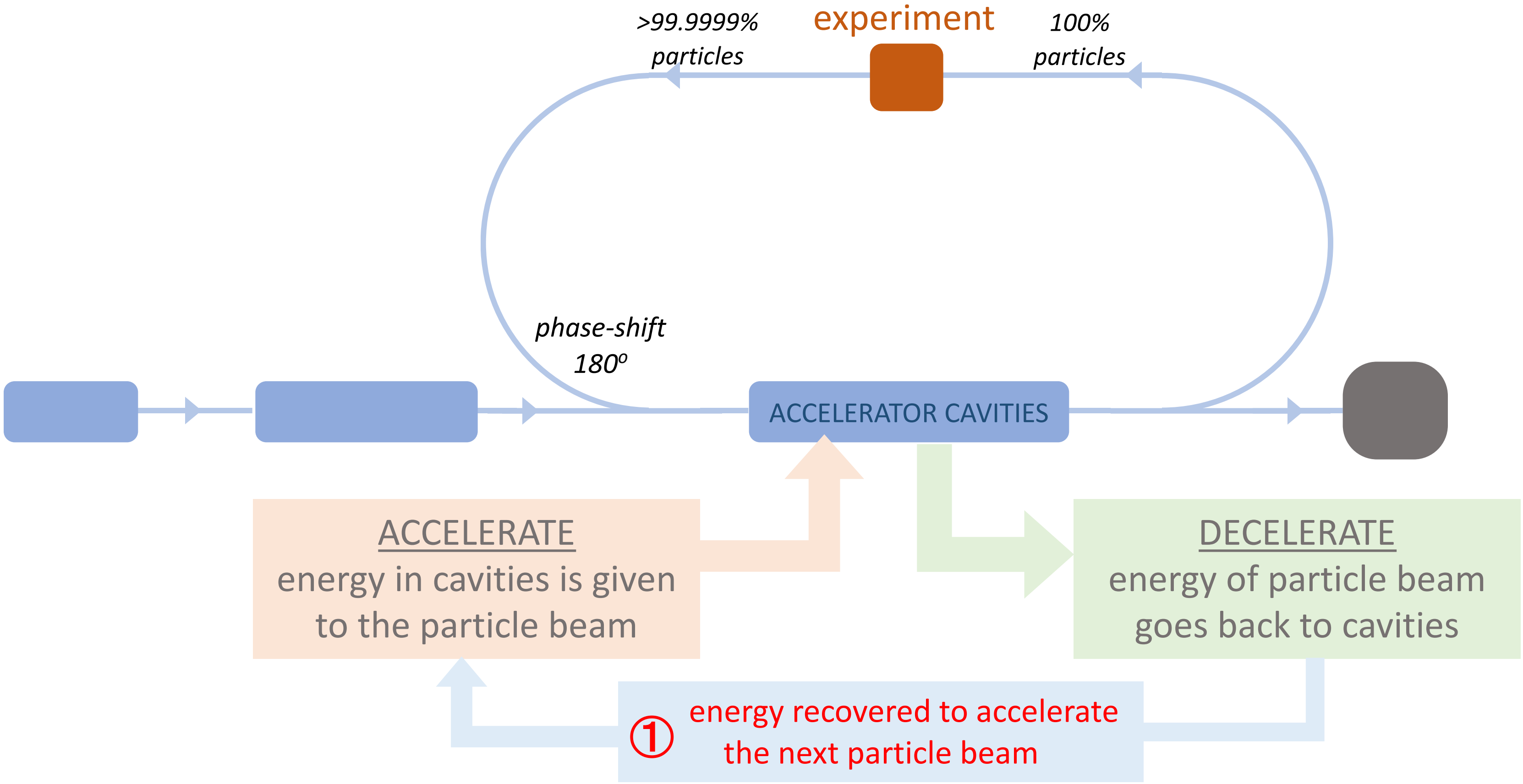

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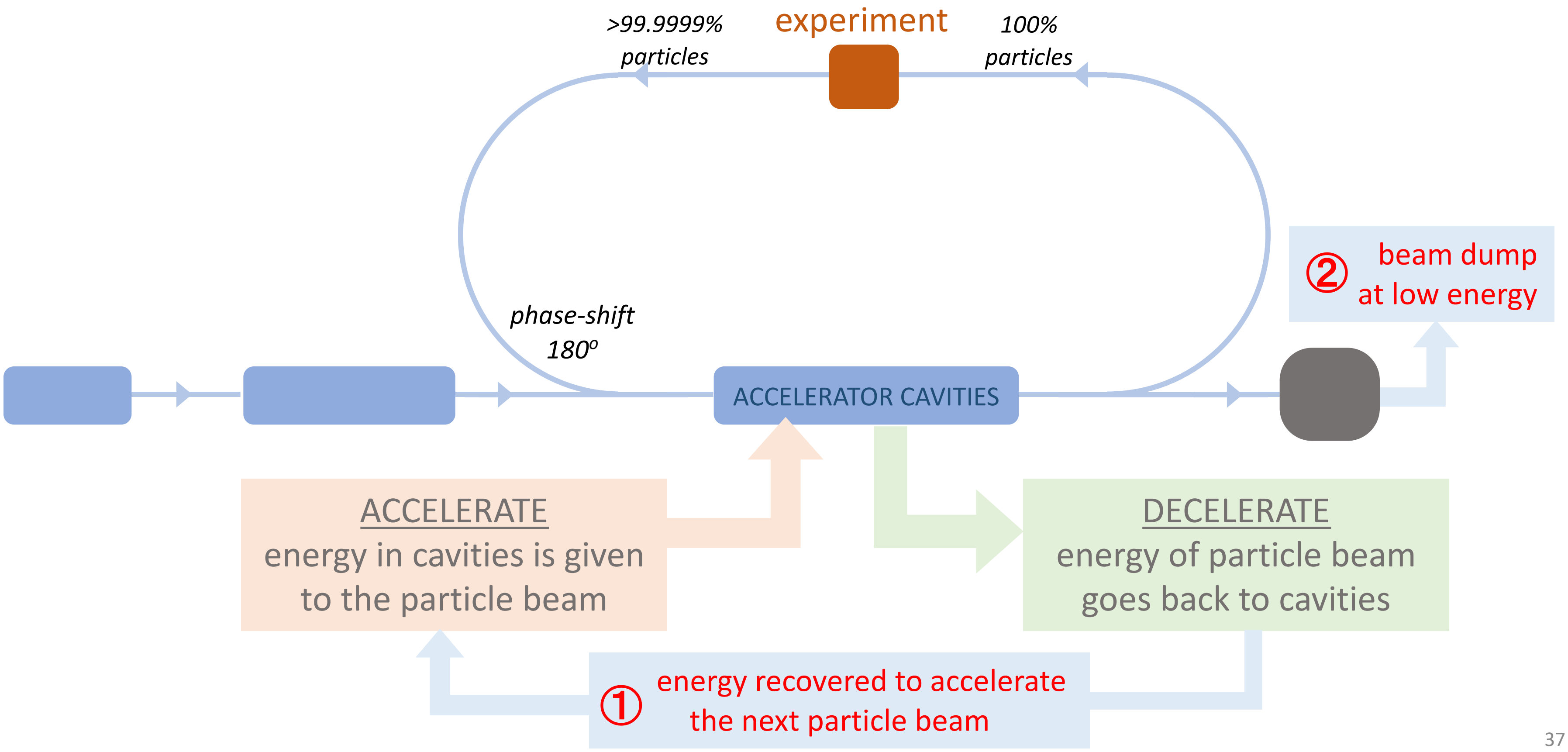

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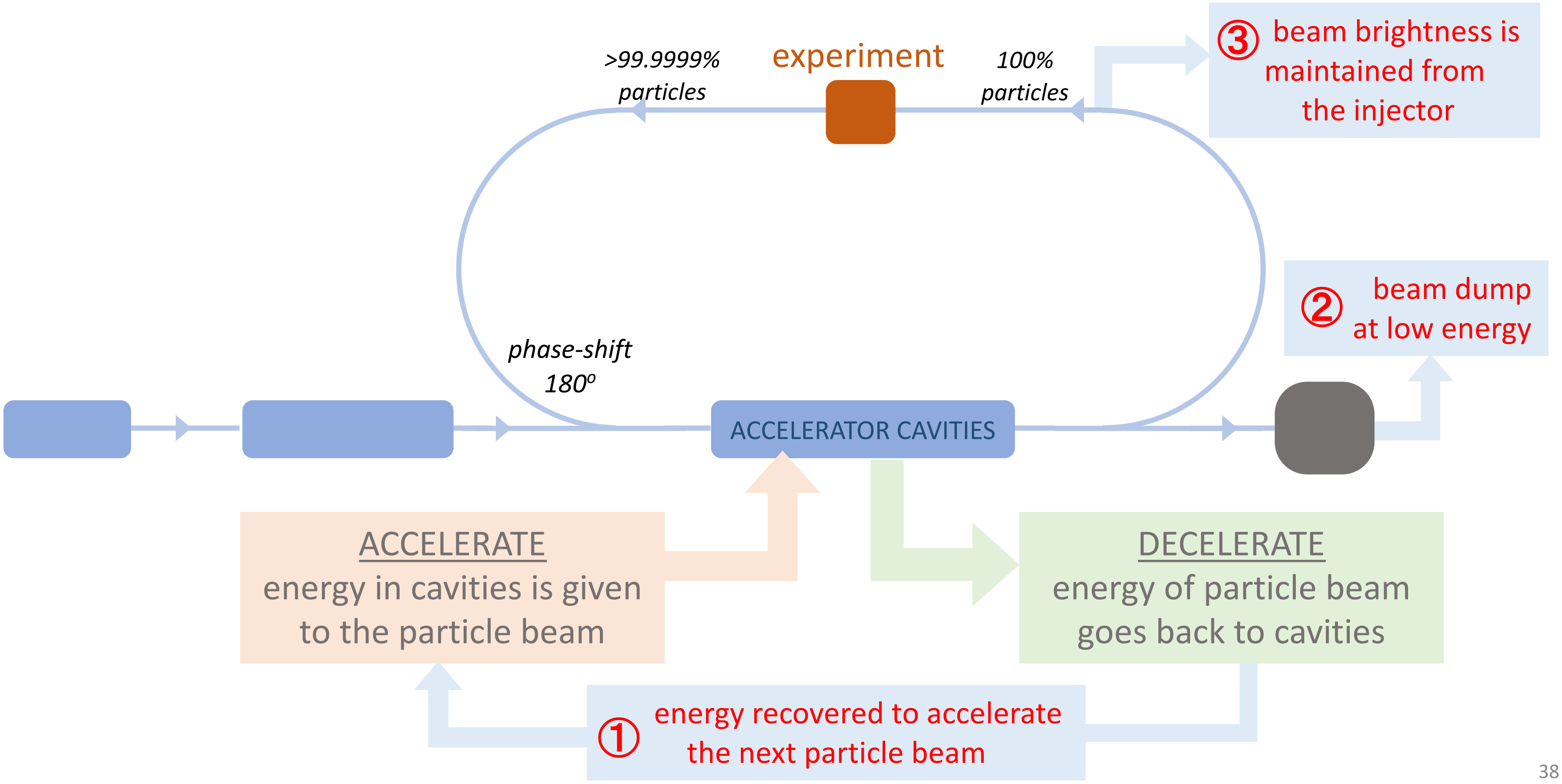

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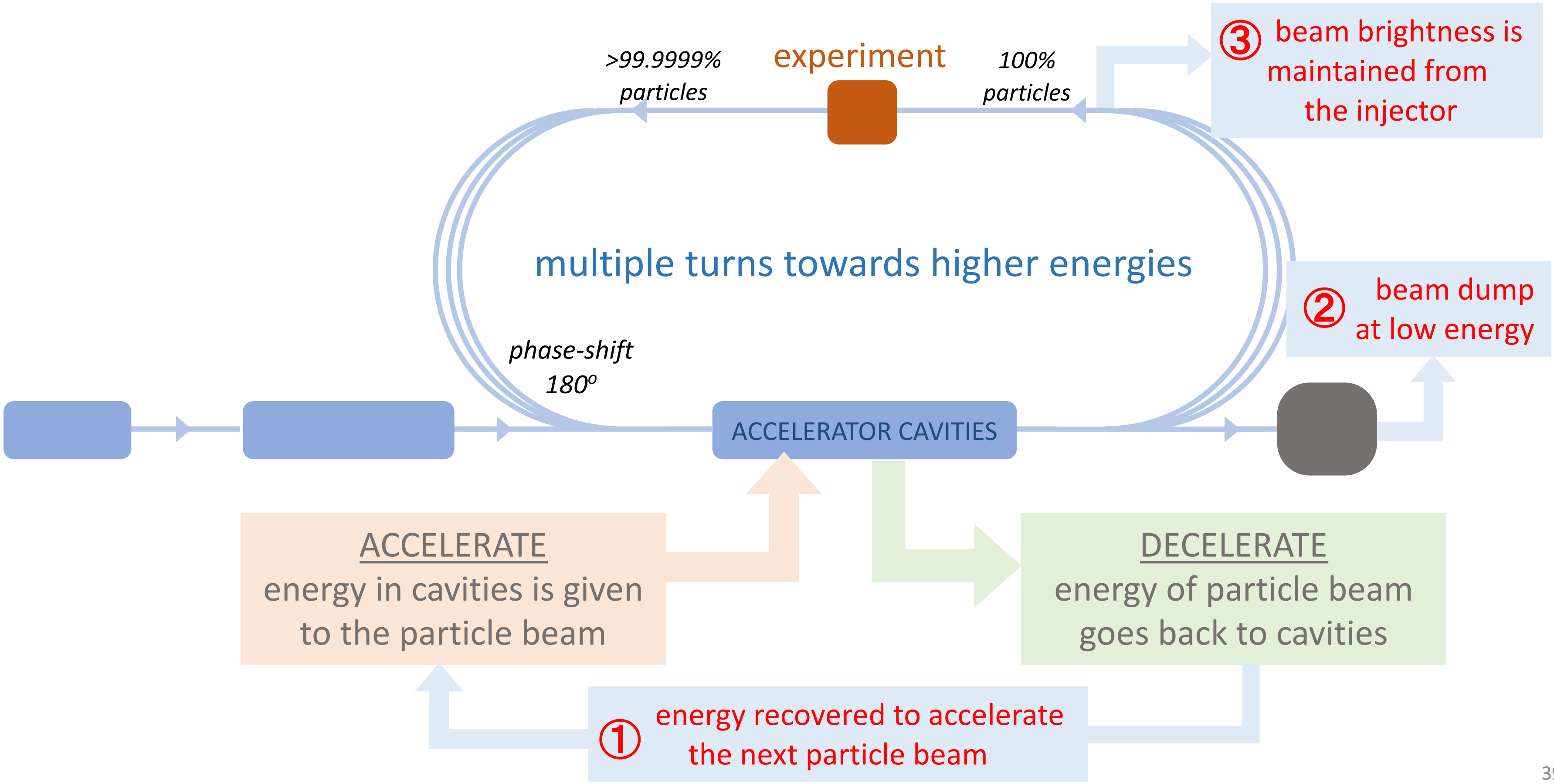

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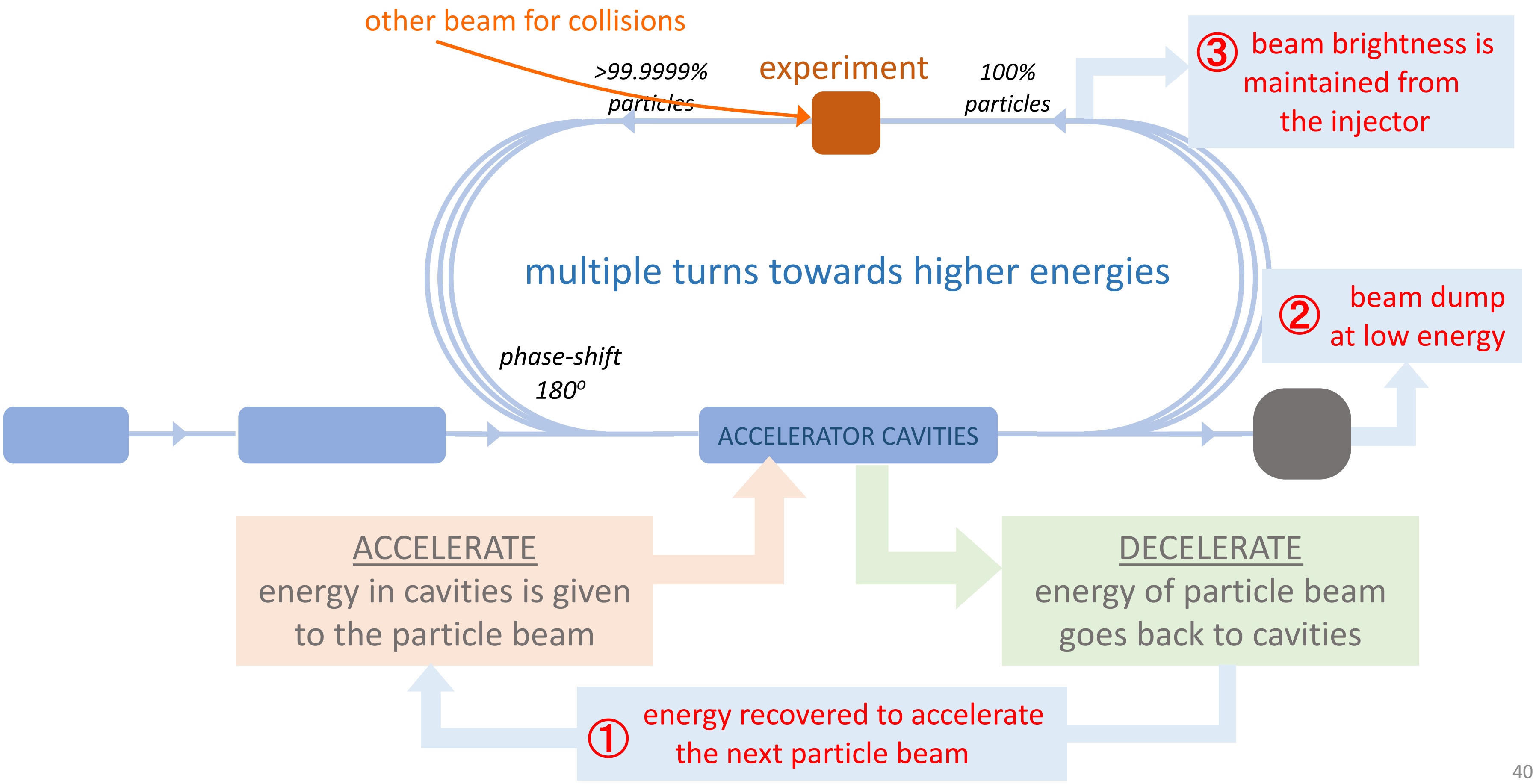

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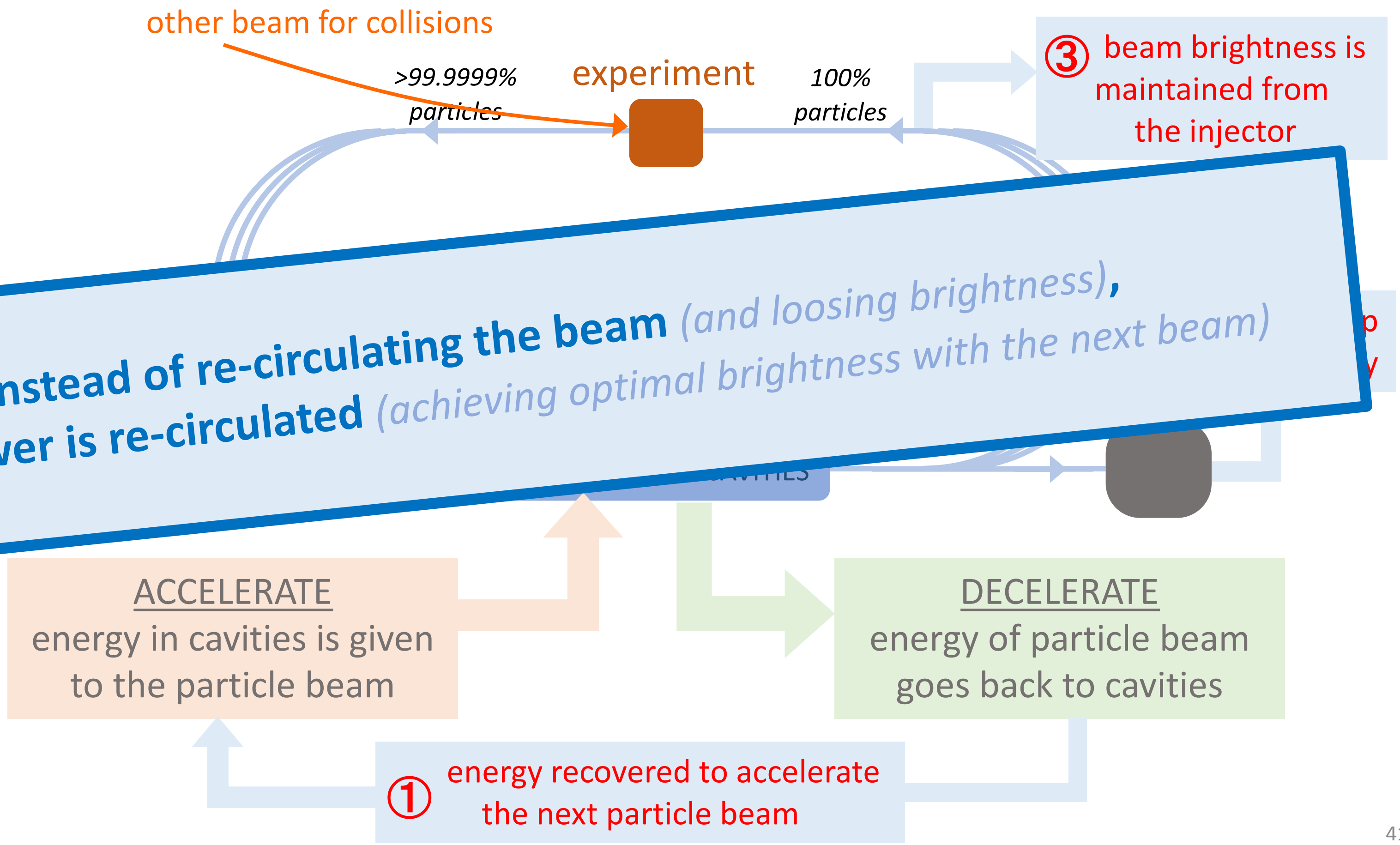
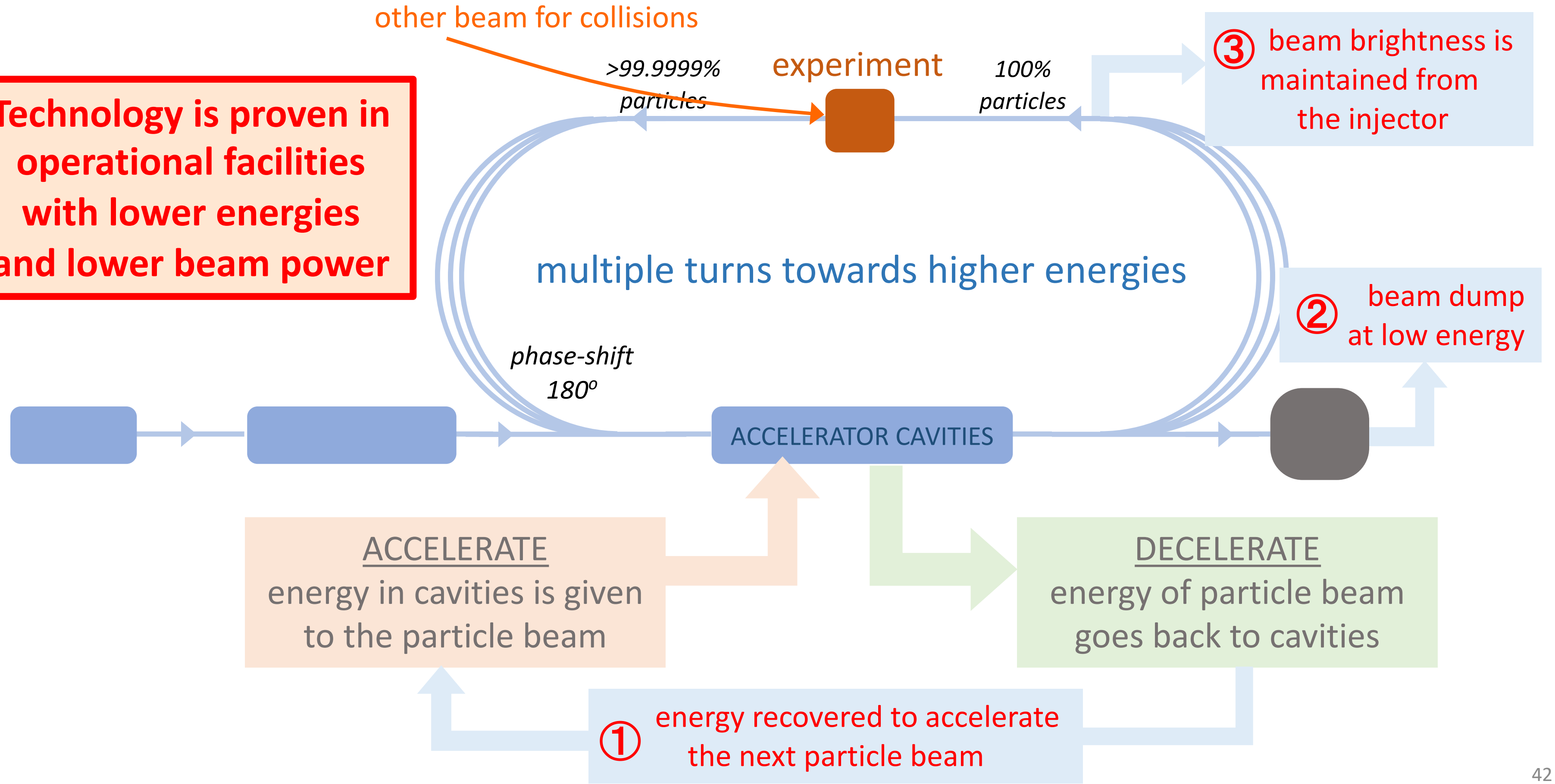


instead of re-circulating the beam *(and loosing brightness)*,
the power is re-circulated *(achieving optimal brightness with the next beam)*

The principle of Energy Recovery

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



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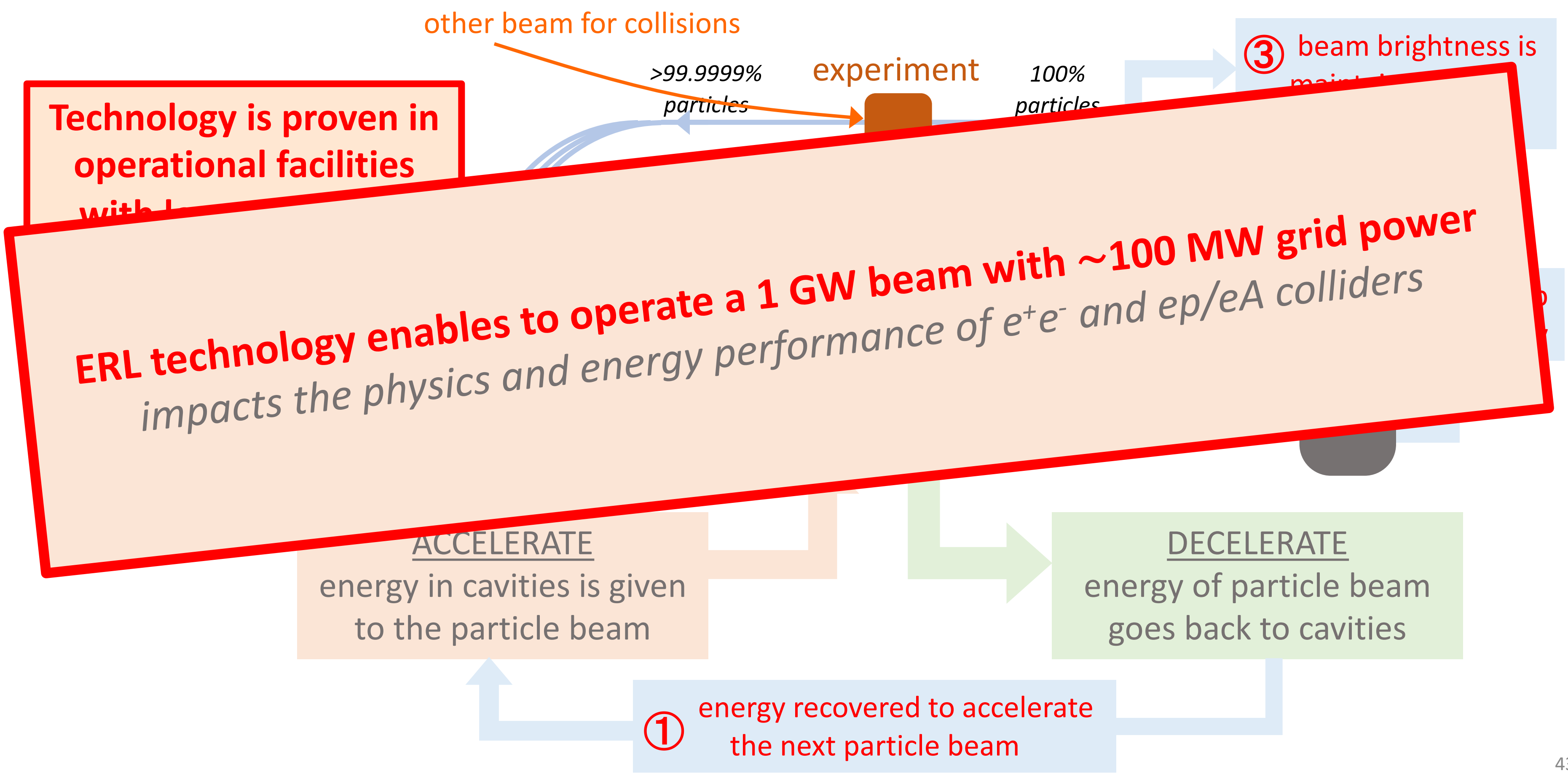
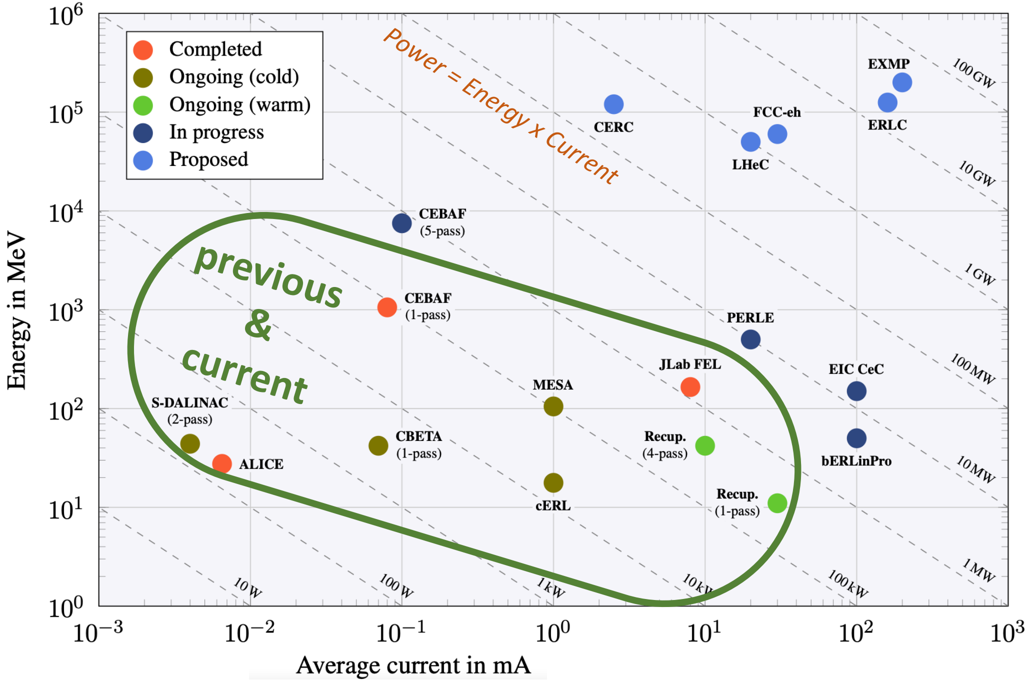
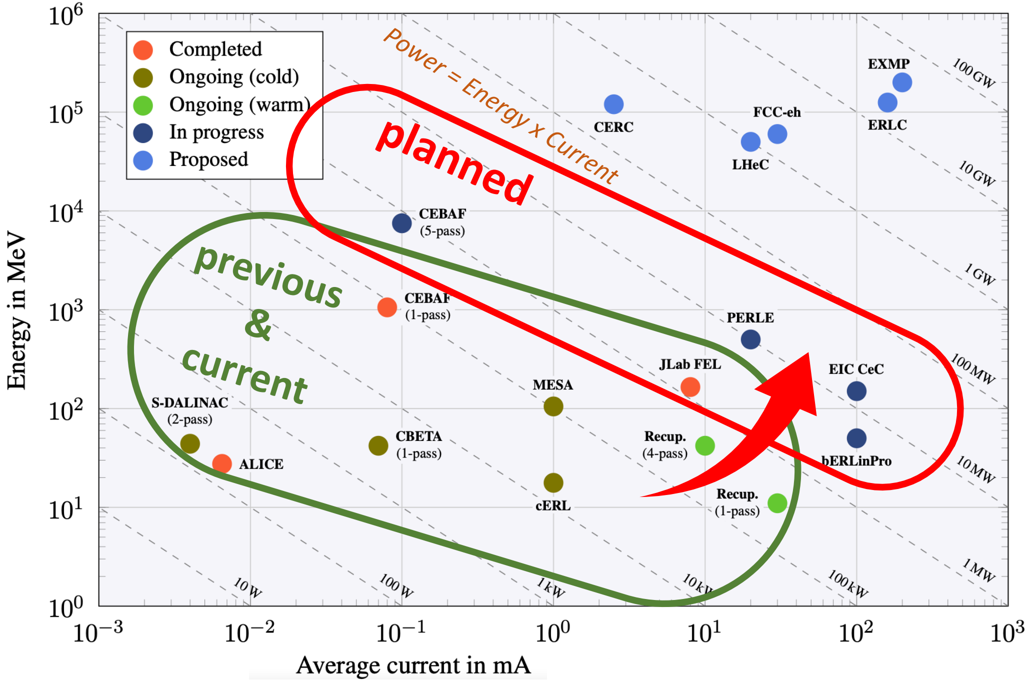




Energy Recovery demonstrated

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

next two presentations

Energy Recovery demonstrated

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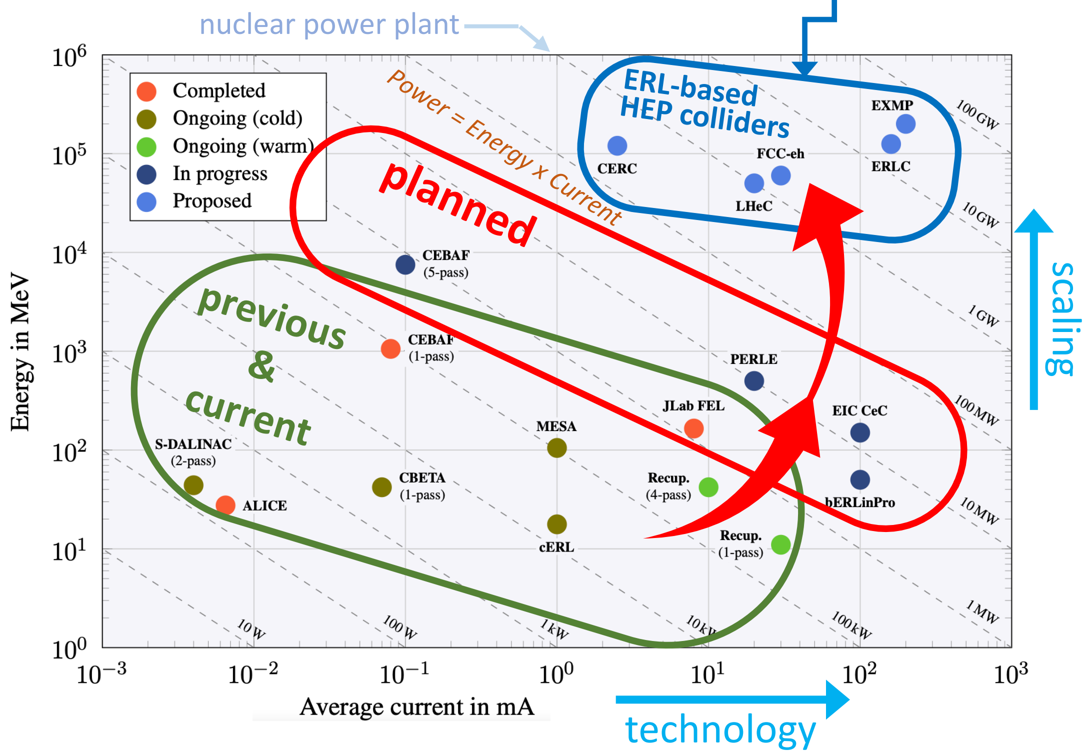
ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Future ERL-based Colliders

H, HH, ep/eA, muons, …

the presentation thereafter

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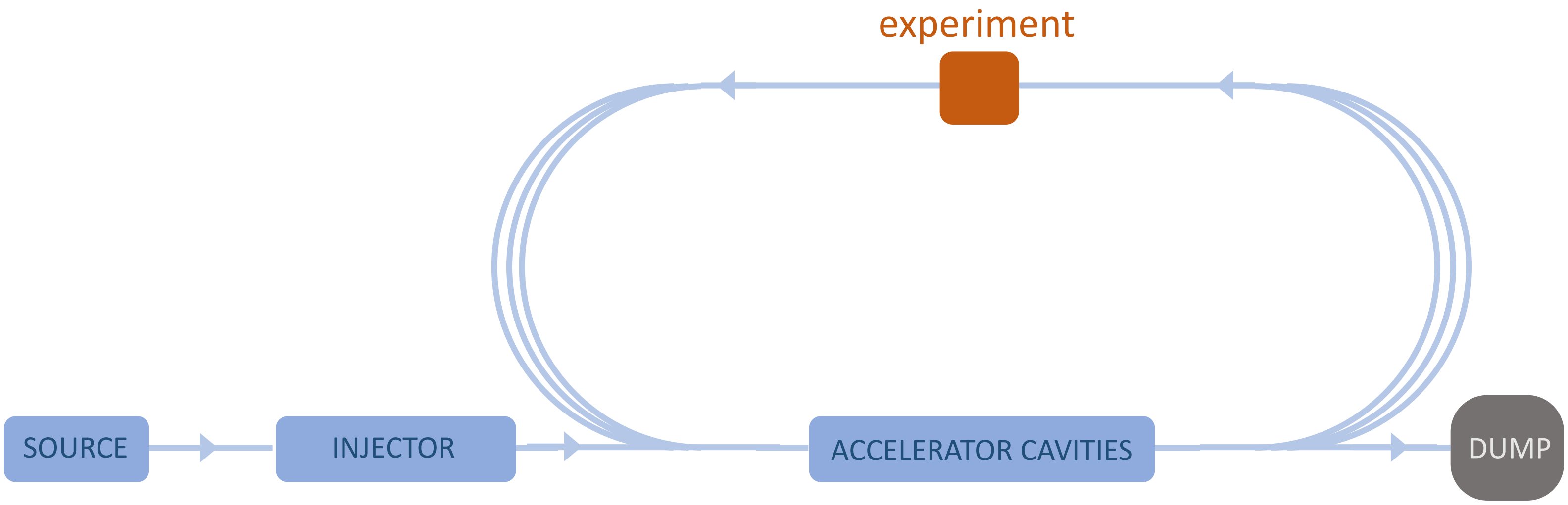
Identified the key aspects for an Energy Recovery accelerator

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



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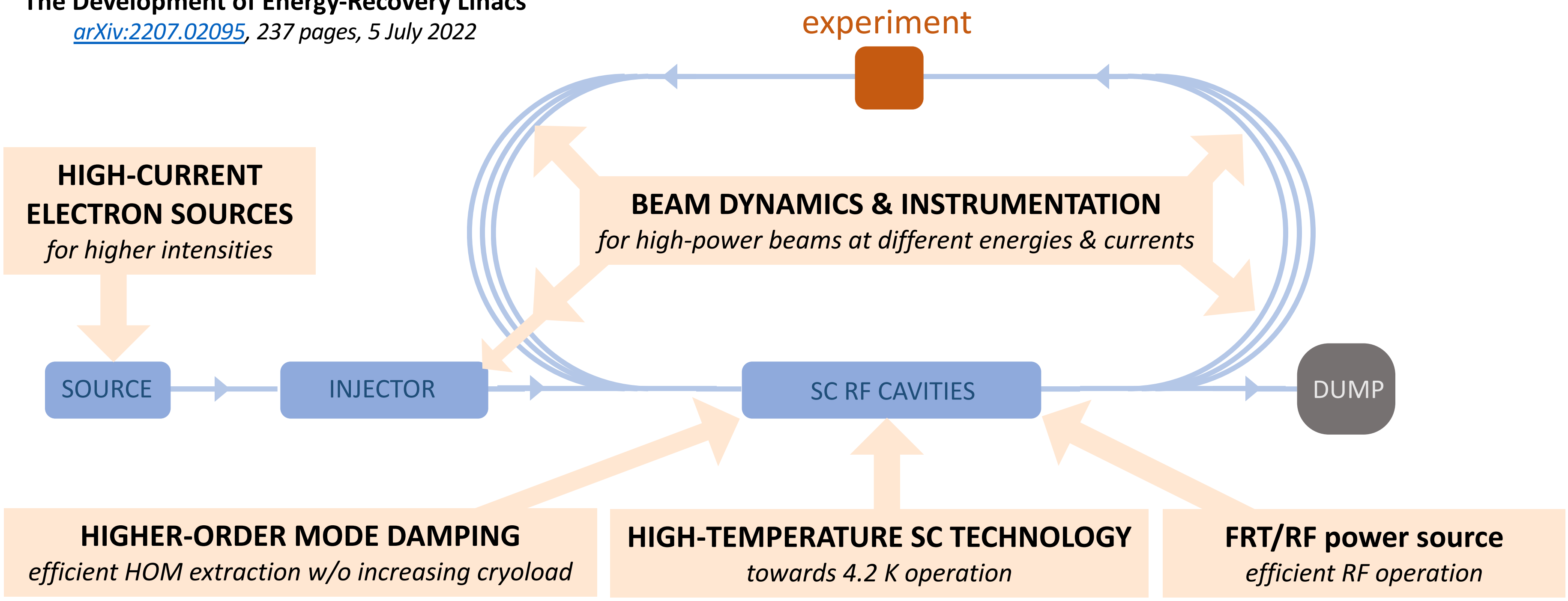
The Development of Energy-Recovery Linacs
arXiv:2207.02095, 237 pages, 5 July 2022

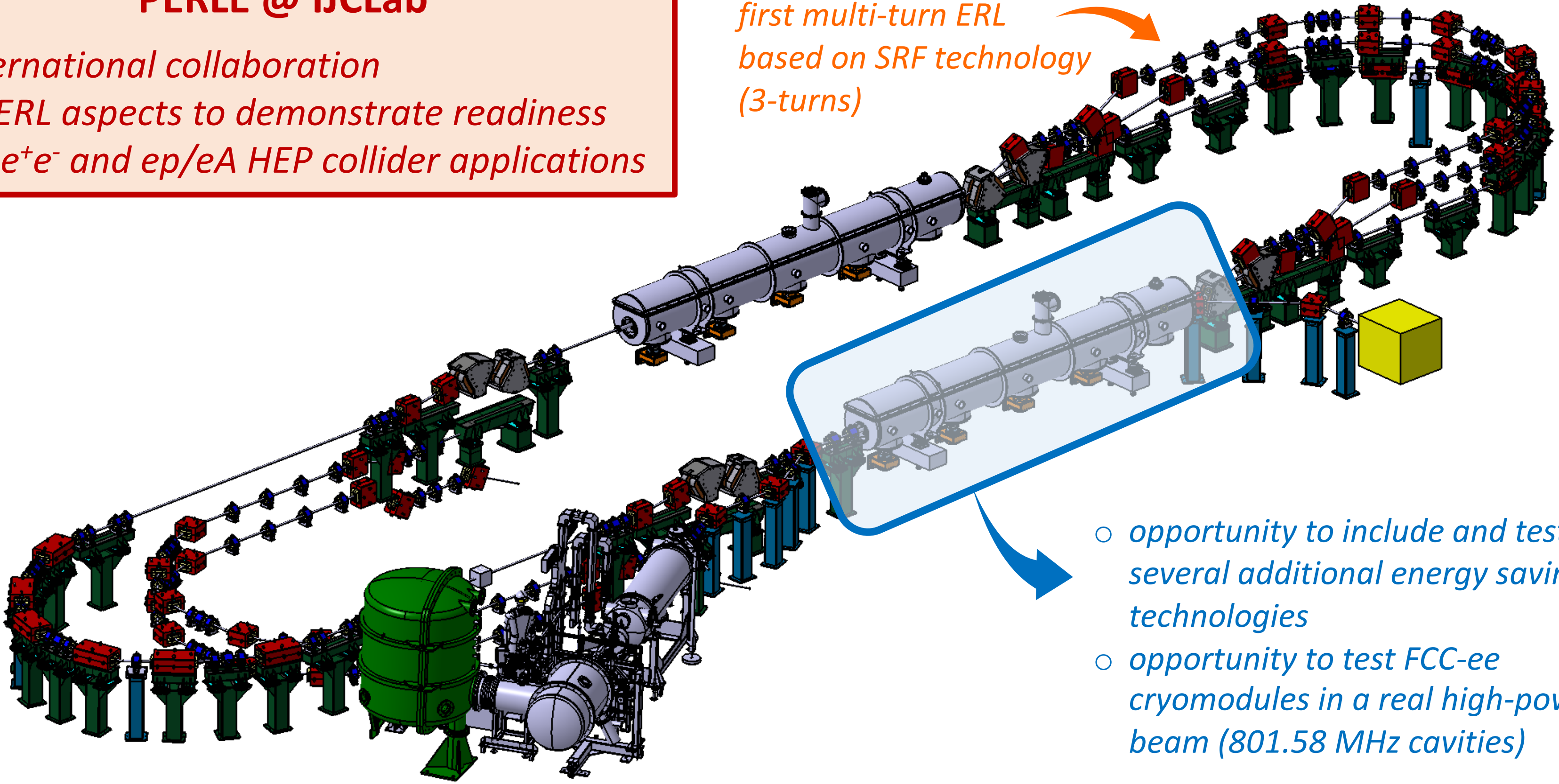


Upcoming facilities for Energy Recovery R&D

PERLE @ IJCLab

- *international collaboration*
- *all ERL aspects to demonstrate readiness*
- *for e^+e^- and ep/eA HEP collider applications*

first multi-turn ERL based on SRF technology (3-turns)



- *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]

Upcoming facilities for Energy Recovery R&D

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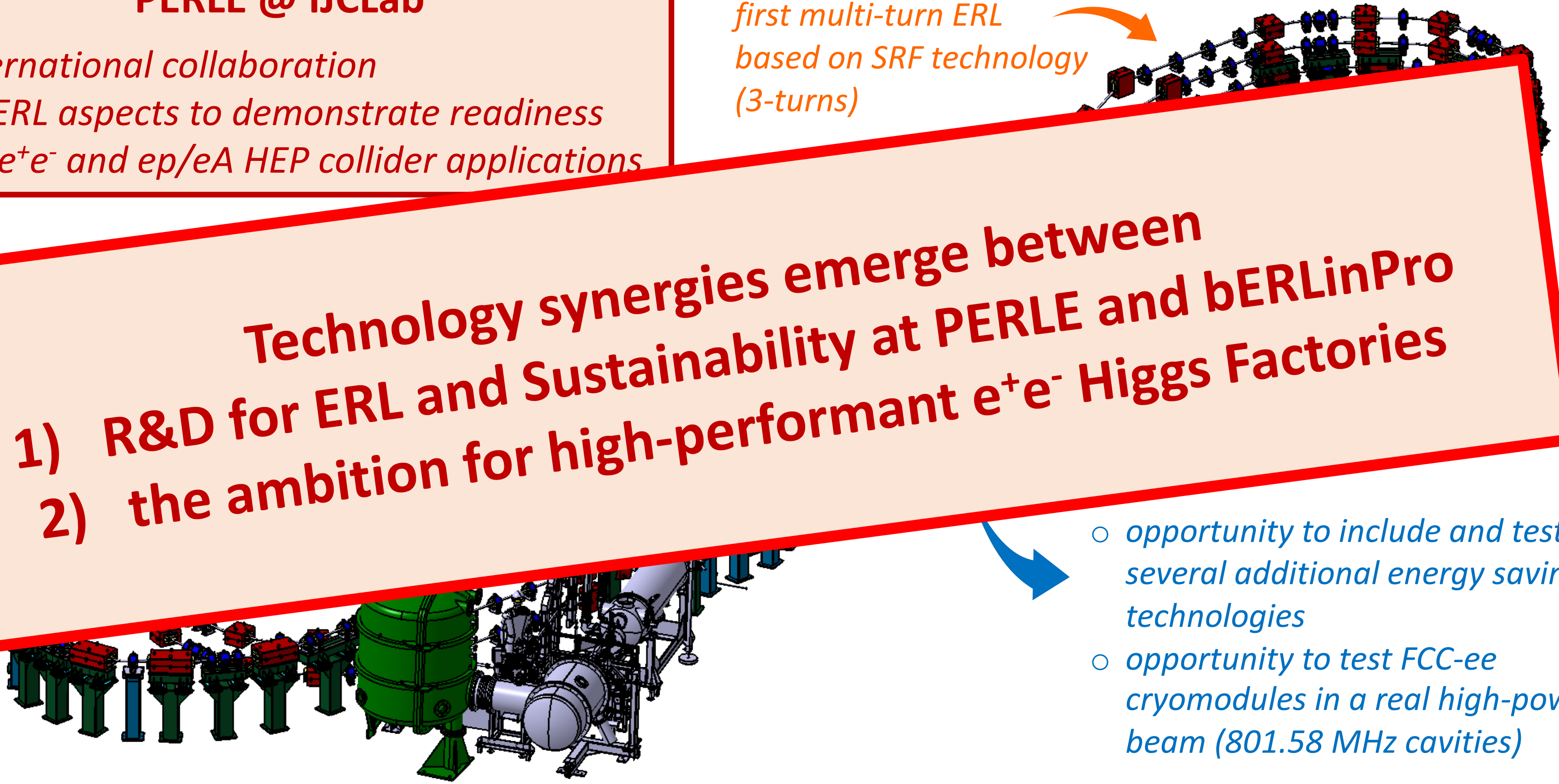


Technology synergies emerge between

1) R&D for ERL and Sustainability at PERLE and bERLinPro

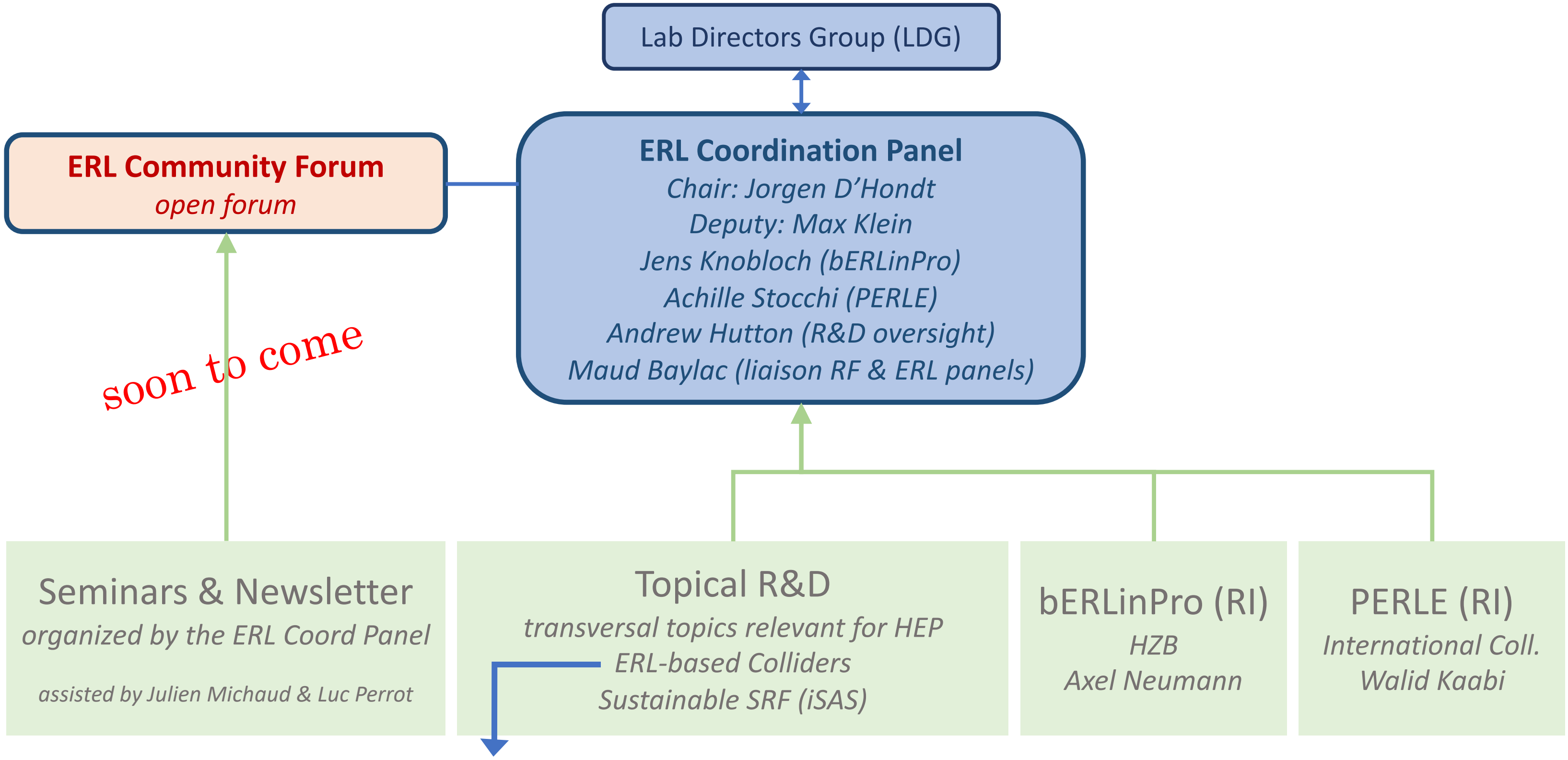
2) the ambition for high-performant e^+e^- Higgs Factories

- *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 Energy Recovery in HEP

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



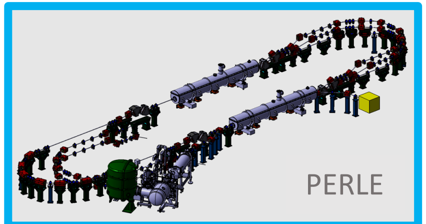
first thoughts for workshops dedicated on the design of ERL-based colliders

RI: Research Infrastructure

Potential impact of ERL technology

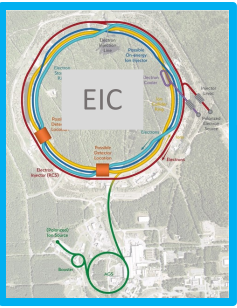
With stepping stones for innovations in technology to boost our physics reach

2020’ies



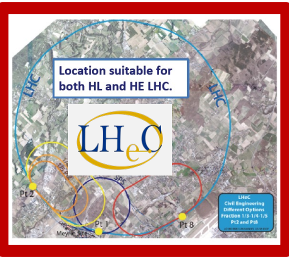
high-power ERL demonstrated

2030’ies



ERL application electron cooling

2030-2040’ies

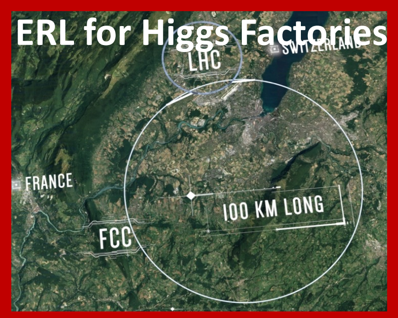


1 ERL beam

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

2040-2050’ies

ERL for Higgs Factories

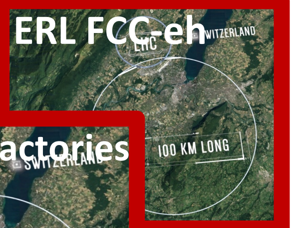


2 ERL beams

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

2070’ies

ERL FCC-eh



reuse ERL

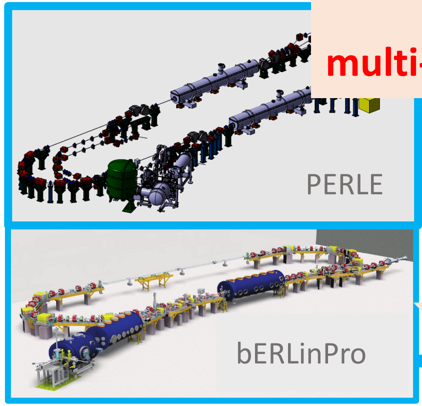
Potential impact of ERL technology

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

enables the ultimate upgrade of the LHC program

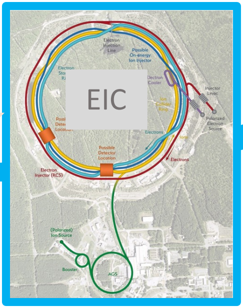
2020'ies

demonstrate multi-turn high-power ERL



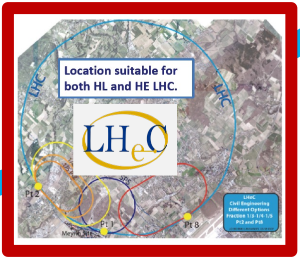
high-power ERL demonstrated

2030'ies



ERL application electron cooling

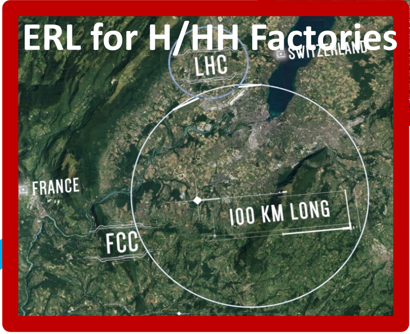
2030-2040'ies



1 ERL beam

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

2040-2050'ies



2 ERL beams

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

2070'ies

reuse ERL

increases the performance of the next major colliders

High-power particle beams enabled by Energy Recovery Linacs

- An enabling technology for our most prominent future e^+e^- and ep/eA collider programs delivering breakthrough performances
- The emerging high-power ERL demonstrators provide synergetic laboratories for energy savings technologies for all SRF accelerators
- 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 systems deliver on this front
- The potential impact of ERL on e^+e^- and ep colliders is so great that not exploring this technology in our strategy is not an option

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- The potential impact of ERL on e^+e^- and ep colliders is so great that not exploring this technology in our strategy is not an option

HIGH-ENERGY PHYSICS
RESEARCH CENTRE

Thank you for your attention!

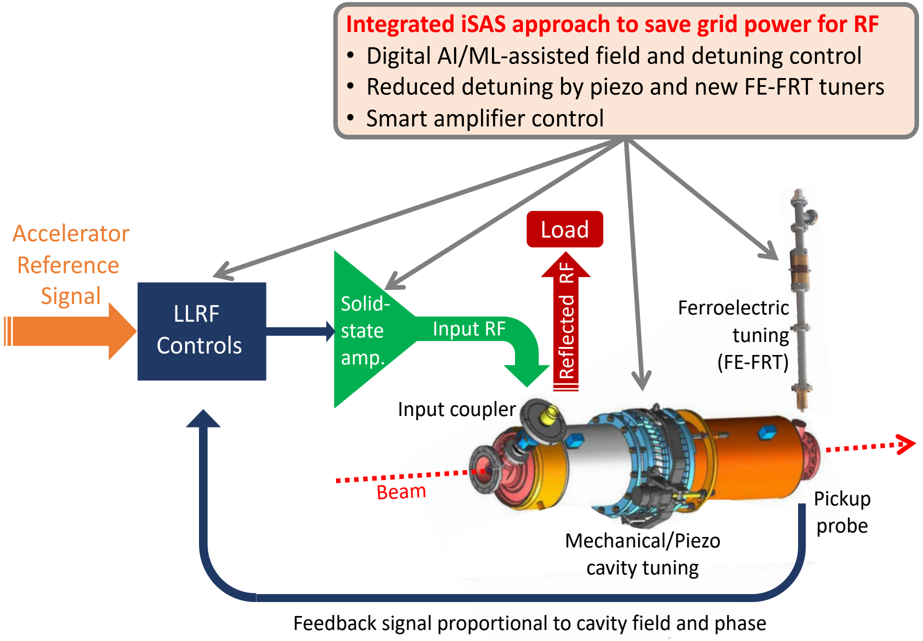
Jorgen.DHondt@vub.be

more on iSAS

iSAS develops, prototypes & validates SRF energy-saving technologies

TA#1: energy-savings from RF power

The objective is to significantly reduce the RF power sources and wall plug power for all SRF accelerators with ferro-electric fast reactive tuners (FE-FRTs) for control of transient beam loading and detuning by microphonics, and with optimal low level radio frequency (LLRF) and detuning control with legacy piezo based systems. iSAS will demonstrate operation of a superconducting cavity with FE-FRTs coherently integrated with AI-smart digital control systems to achieve low RF-power requirements.



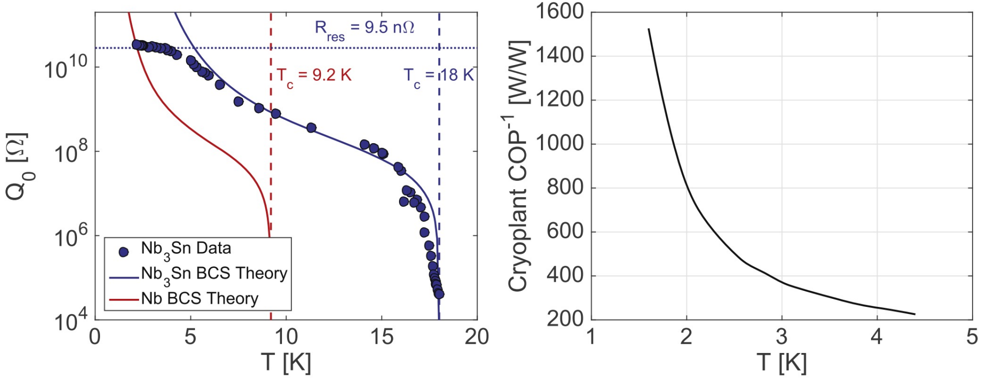
Schematic overview to compensate detuning with new FE-FRTs avoiding large power overhead and to compensate with AI-smart control loop countermeasures via the LLRF steering of the RF amplifier the disturbances in SRF cavities that impact field stability

iSAS *develops, prototypes & validates SRF energy-saving technologies*

TA#2: energy-savings from cryogenics

The objective is focused on the development of thin-film cavities and aims to transform conventional superconducting radio-frequency technology based on off-shelf bulk niobium operating at 2 K, into a technology operating at 4.2 K using a highly functionalized material, where individual functions are addressed by different layers. iSAS will optimize the coating recipe for Nb_3Sn on copper to optimize tunability and flux trapping of thin-film superconducting cavities and to validate a prototype beyond the achievements of the ongoing Horizon Europe I.FAST project.

Supercond. Sci. Technol. 30 (2017) 033004

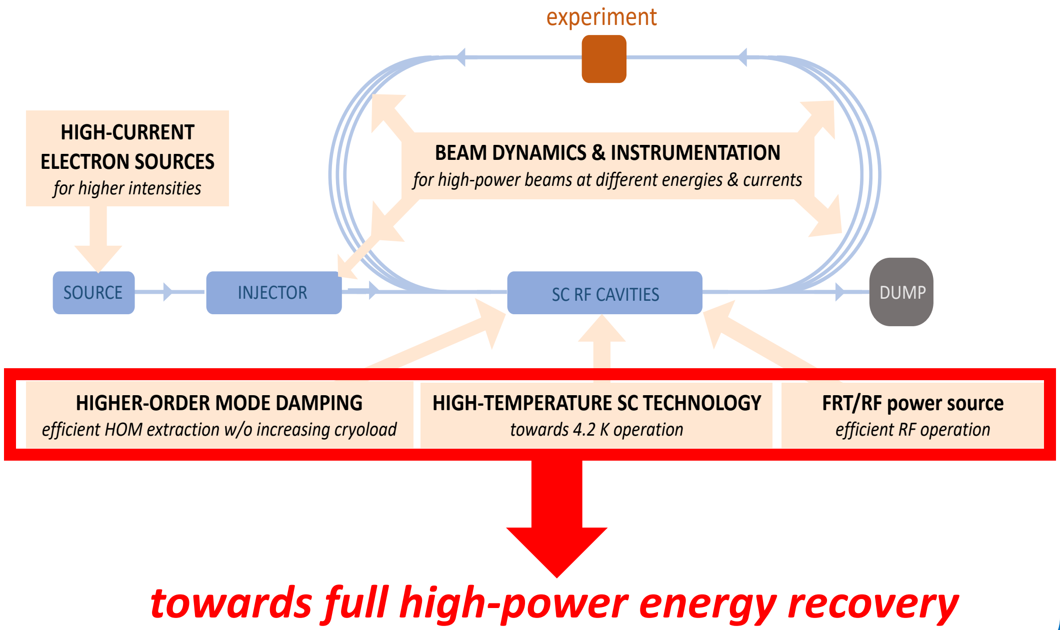


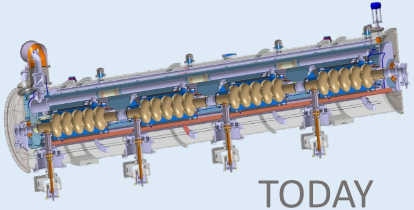
The higher critical temperature (T_c) of Nb_3Sn allows for the maximum value of quality factor Q_0 for 1.3 GHz cavities to be achieved at operating temperatures of about 4 K compared to 2 K for Nb (left figure). The graph on the right shows the efficiency of a cryogenic plant (COP) as a function of temperature achieving about 3 times higher COP efficiency when operating at a temperature of 4.2 K than at 2 K. This suggests that operating a cryogenic plant at 4.2 K with Nb_3Sn SRF cavities, can lead to significant better performances and energy savings.

iSAS *develops, prototypes & validates SRF energy-saving technologies*

TA#3: energy-savings from the beam

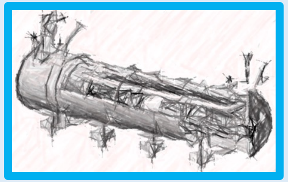
The objective is to reduce the total power deposited into the cryogenics circuits of the cryomodule of the Higher-Order Mode (HOM) couplers and fundamental power couplers (FPCs) leading to a significant reduction of the heat loads and the overall power consumption. iSAS will improve the energy efficiency of the FPCs and HOM couplers by designing and building prototypes that will be integrated into a LINAC cryomodule capable of energy-recovery operations and to be tested in accelerator-like conditions.



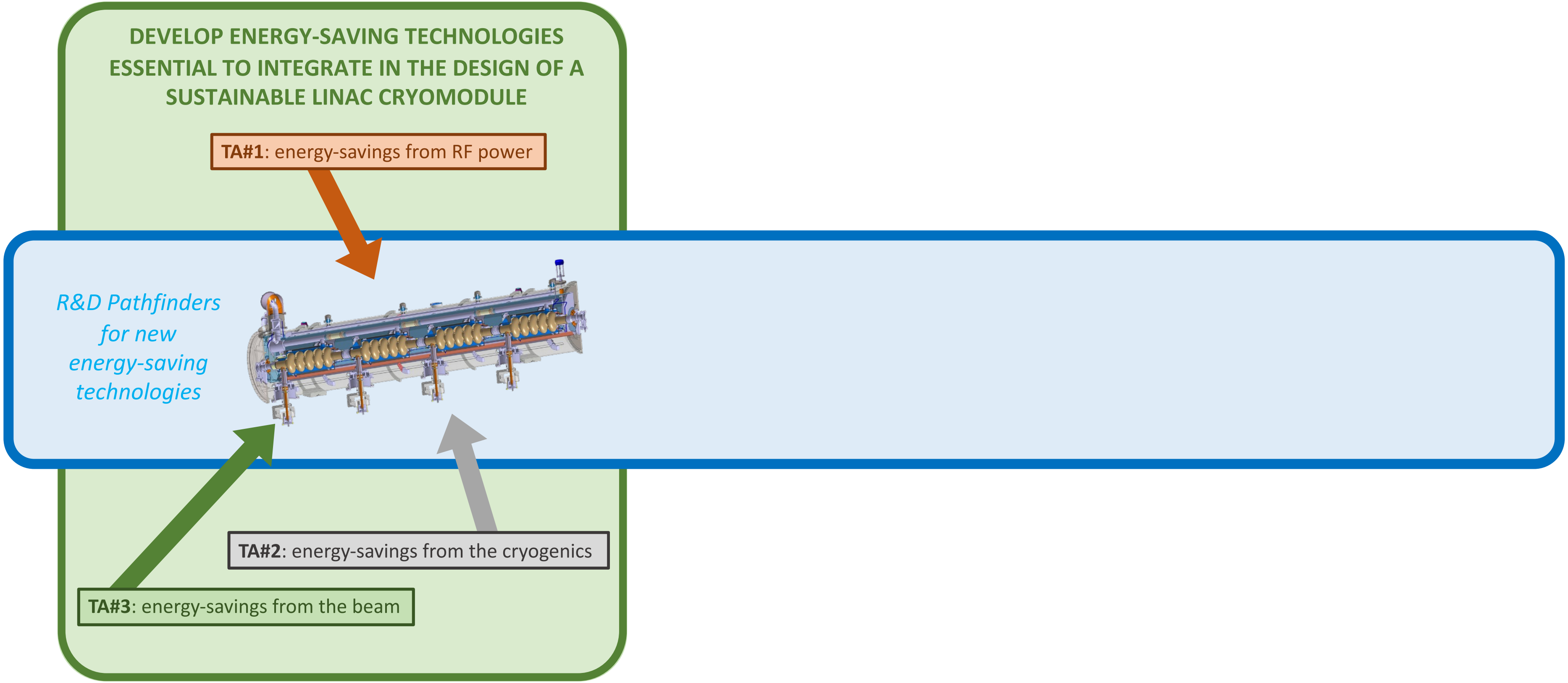


TODAY

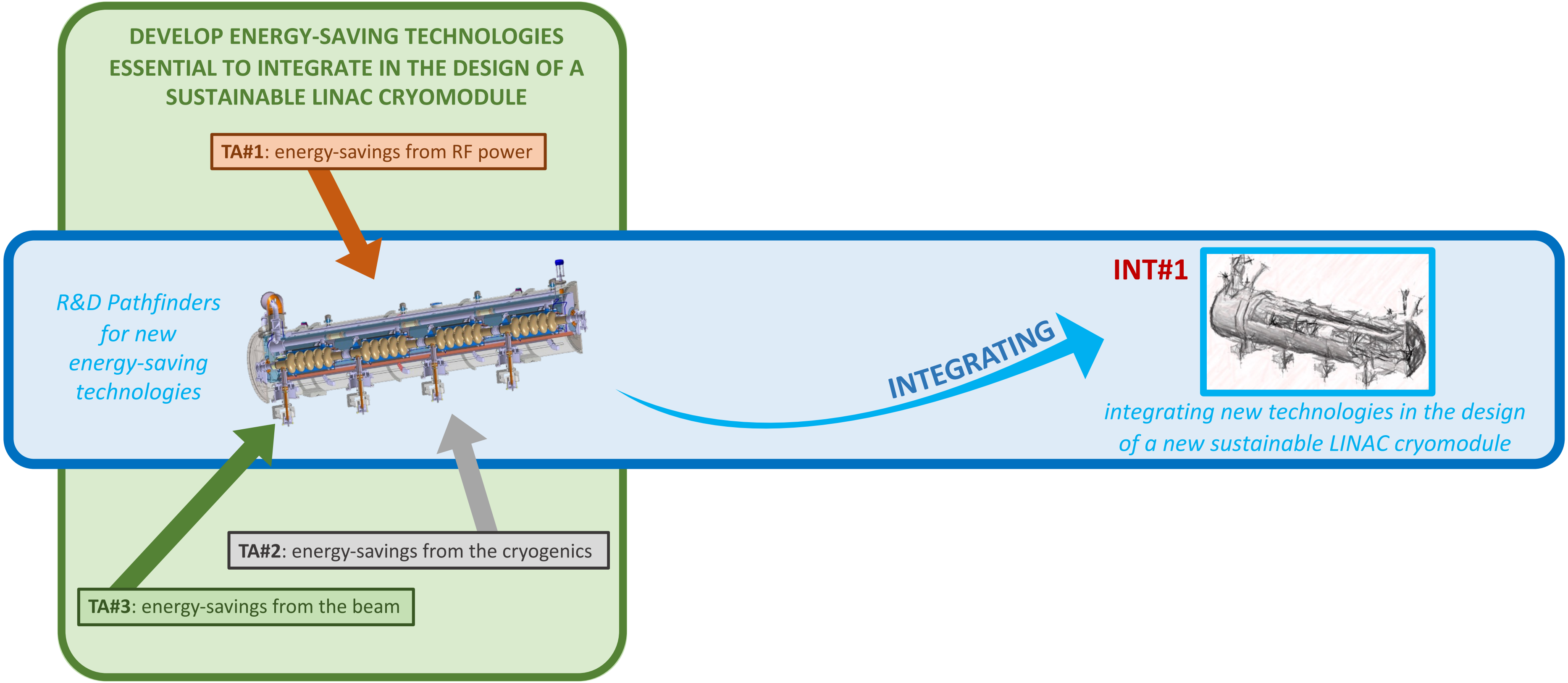
INNOVATE TECHNOLOGIES TOWARDS
A SUSTAINABLE ACCELERATING SYSTEM



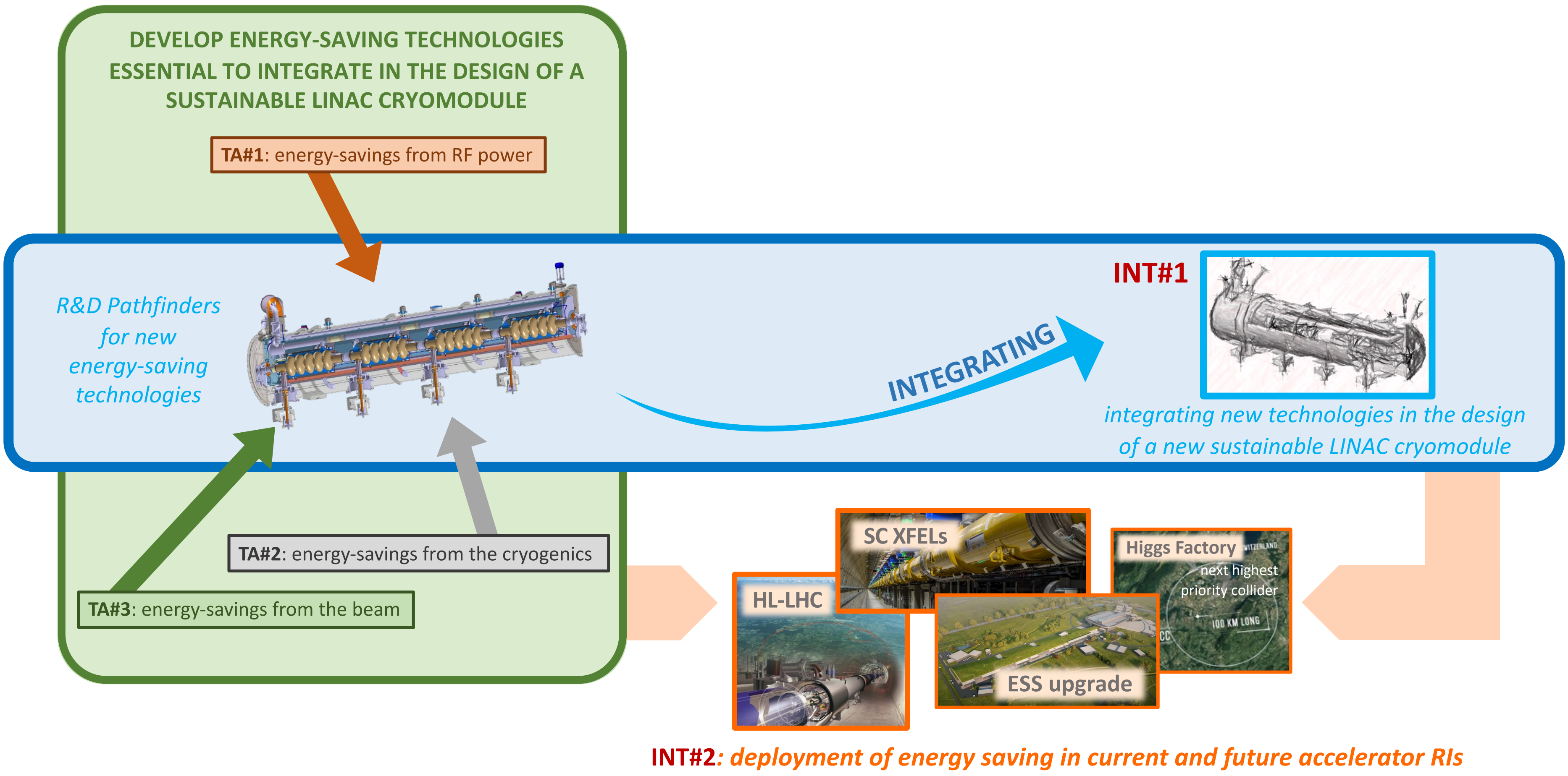
NEW DESIGN



TA: Technology Area

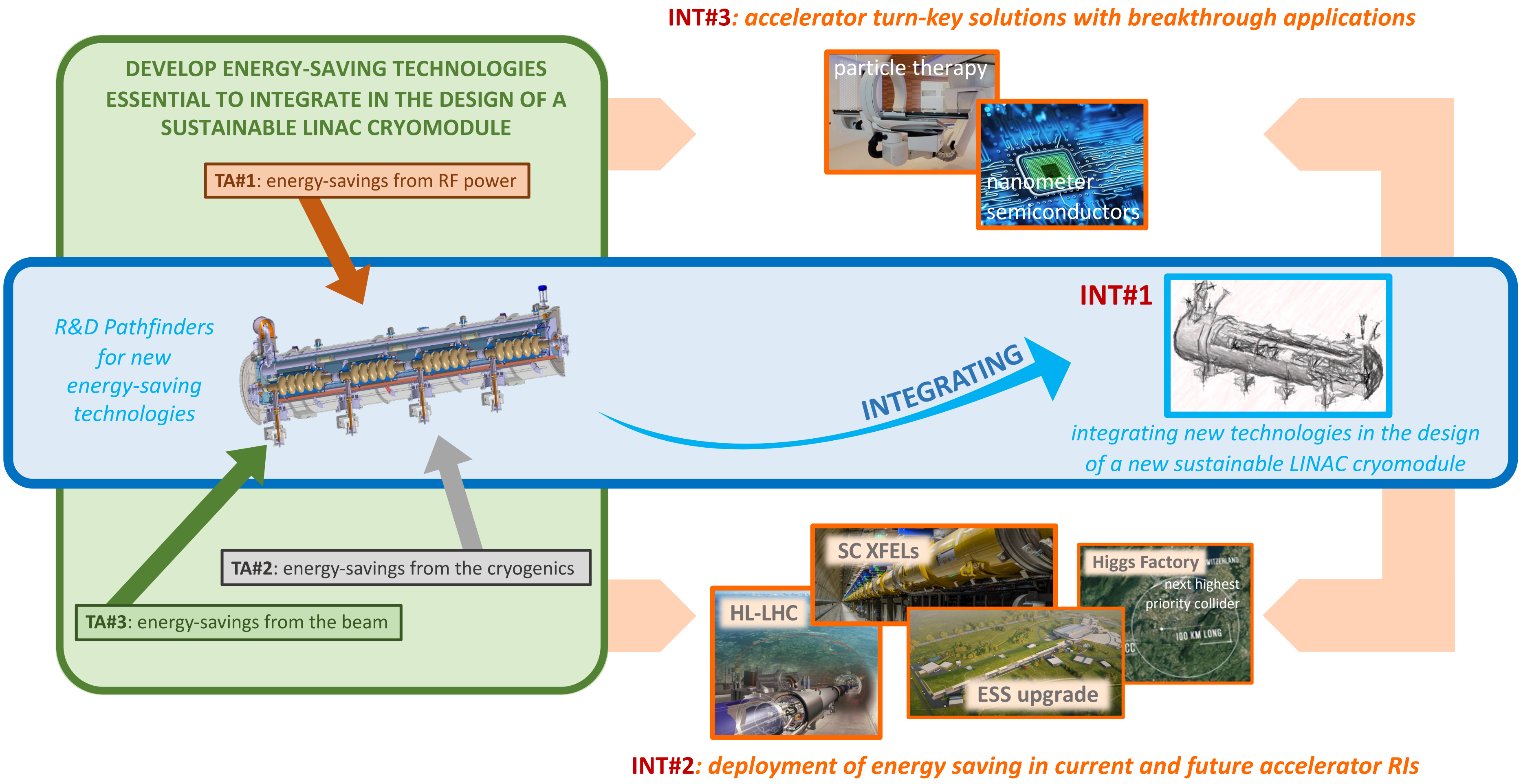


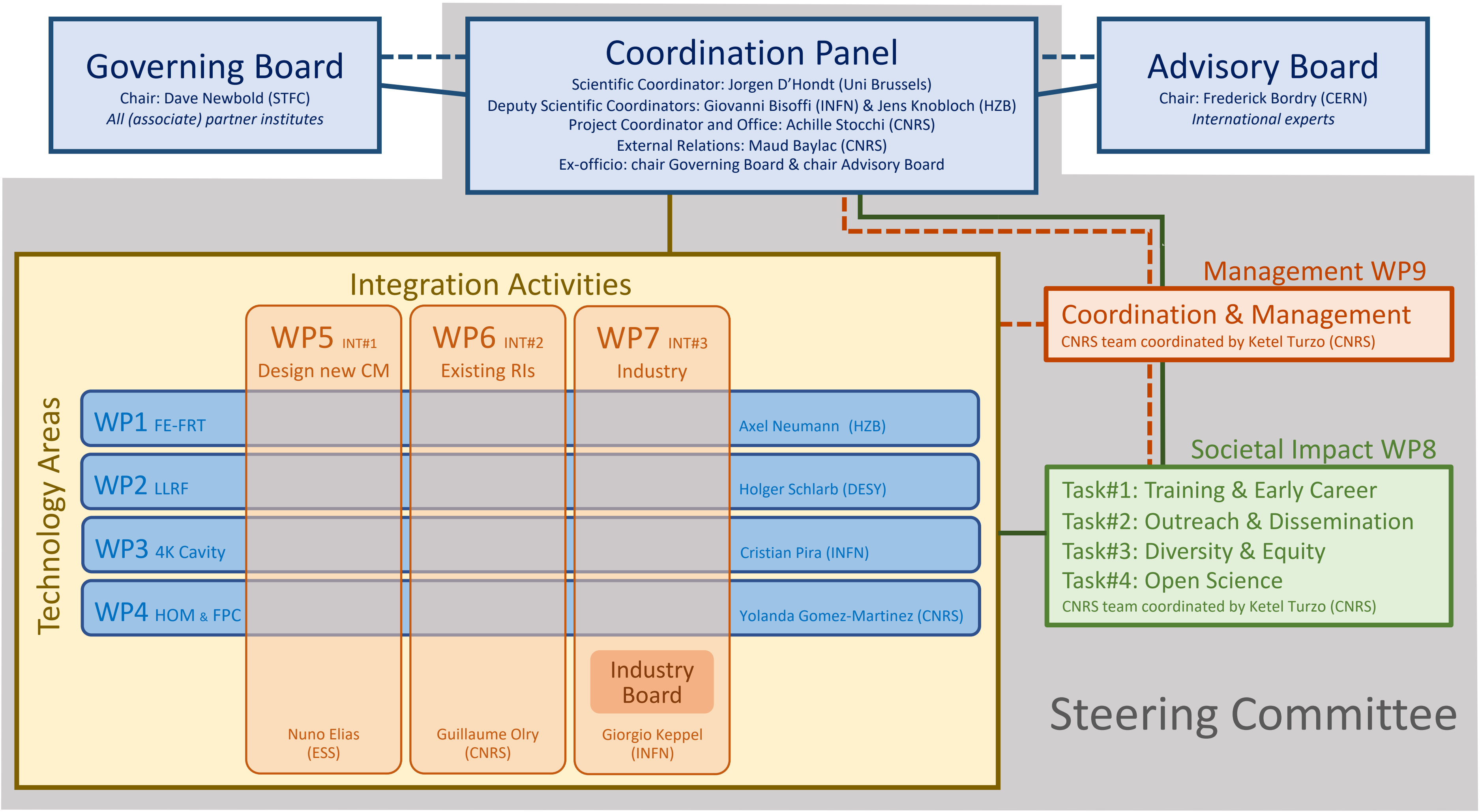
TA: Technology Area, INT: Integration Activities



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
particle therapy
nanometer semiconductors
TA#1: energy-savings from RF power
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: deployment of energy saving in current and future accelerator RIs


Governing Board
Chair: Dave Newbold (STFC)
All (associate) partner institutes
Coordination Panel
Scientific Coordinator: Jorgen D'Hondt (Uni Brussels)
Deputy Scientific Coordinators: Giovanni Bisoffi (INFN) & Jens Knobloch (HZB)
Project Coordinator and Office: Achille Stocchi (CNRS)
External Relations: Maud Baylac (CNRS)
Ex-officio: chair Governing Board & chair Advisory Board
Advisory Board
Chair: Frederick Bordry (CERN)
International experts
Integration Activities
WP5 INT#1
Design new CM
WP6 INT#2
Existing RIs
WP7 INT#3
Industry
Technology Areas
WP1 FE-FRT
Axel Neumann (HZB)
WP2 LLRF
Holger Schlarb (DESY)
WP3 4K Cavity
Cristian Pira (INFN)
WP4 HOM & FPC
Yolanda Gomez-Martinez (CNRS)
Industry Board
Nuno Elias (ESS)
Guillaume Olry (CNRS)
Giorgio Keppel (INFN)
Management WP9
Coordination & Management
CNRS team coordinated by Ketel Turzo (CNRS)
Societal Impact WP8
Task#1: Training & Early Career
Task#2: Outreach & Dissemination
Task#3: Diversity & Equity
Task#4: Open Science
CNRS team coordinated by Ketel Turzo (CNRS)
Steering Committee

more on ERL

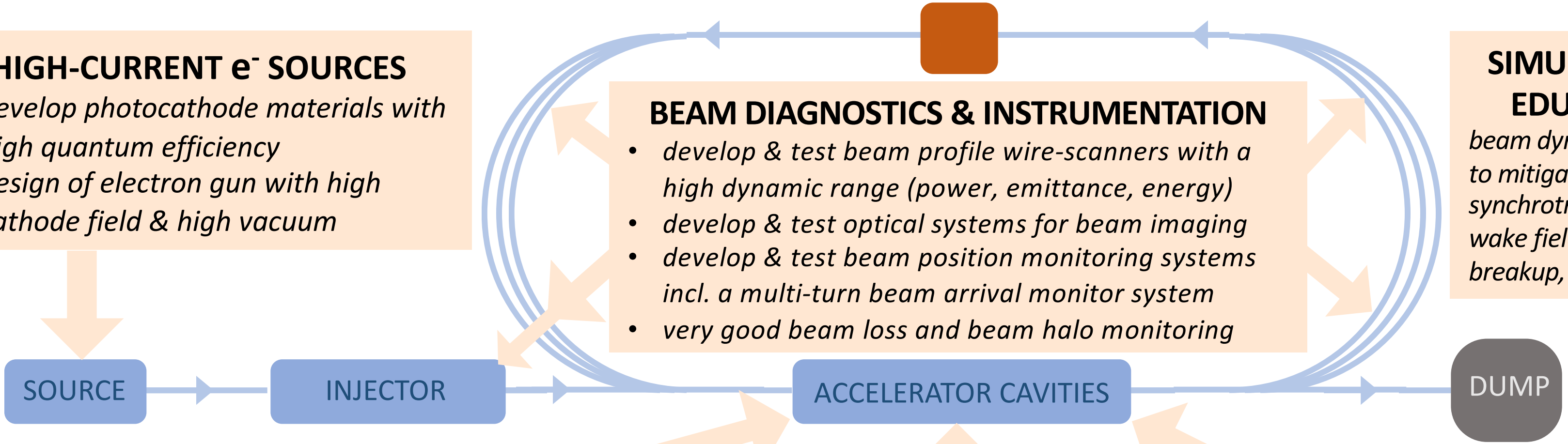
Translated into the main R&D objectives for Energy Recovery

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

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

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

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



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

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

strategic

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

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

(*) part of the RF R&D program

Ongoing & Upcoming facilities with ERL systems

worldwide several facilities are operational or are emerging

ongoing

s-DALINAC *TU Darmstadt, Germany*

two pass operation in progress

ongoing

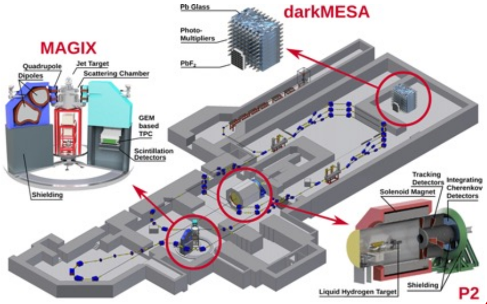
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

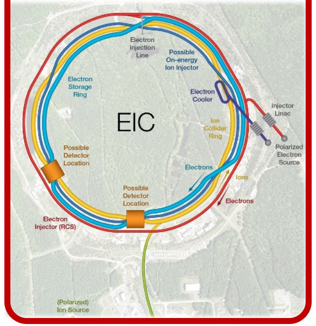
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

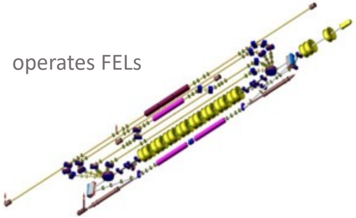
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

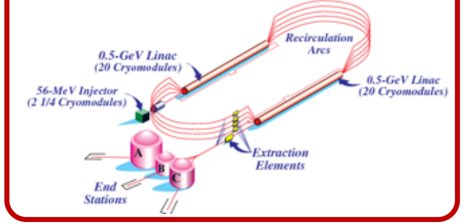
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes



in progress

Upcoming: bERLinPro & PERLE

More facilities in design

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

more on ep/eA colliders

The ultimate microscope in hadronic matter: a high-energy electron-hadron collider

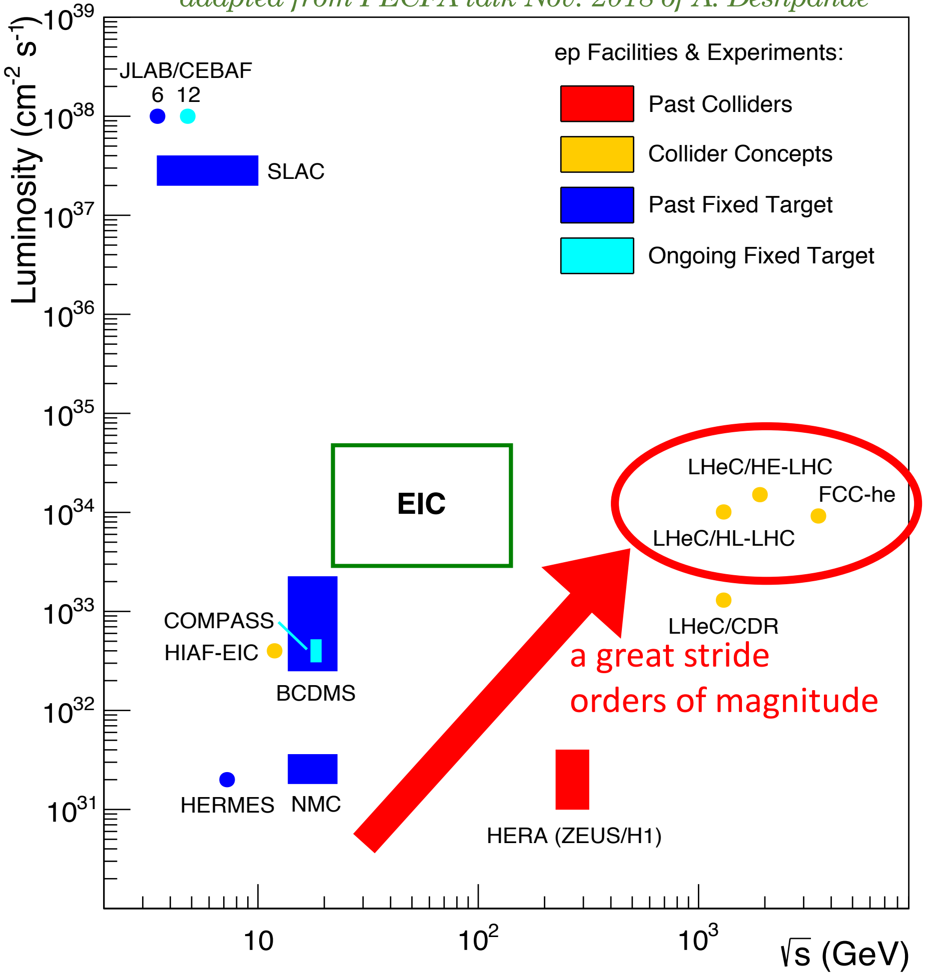
The scope

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

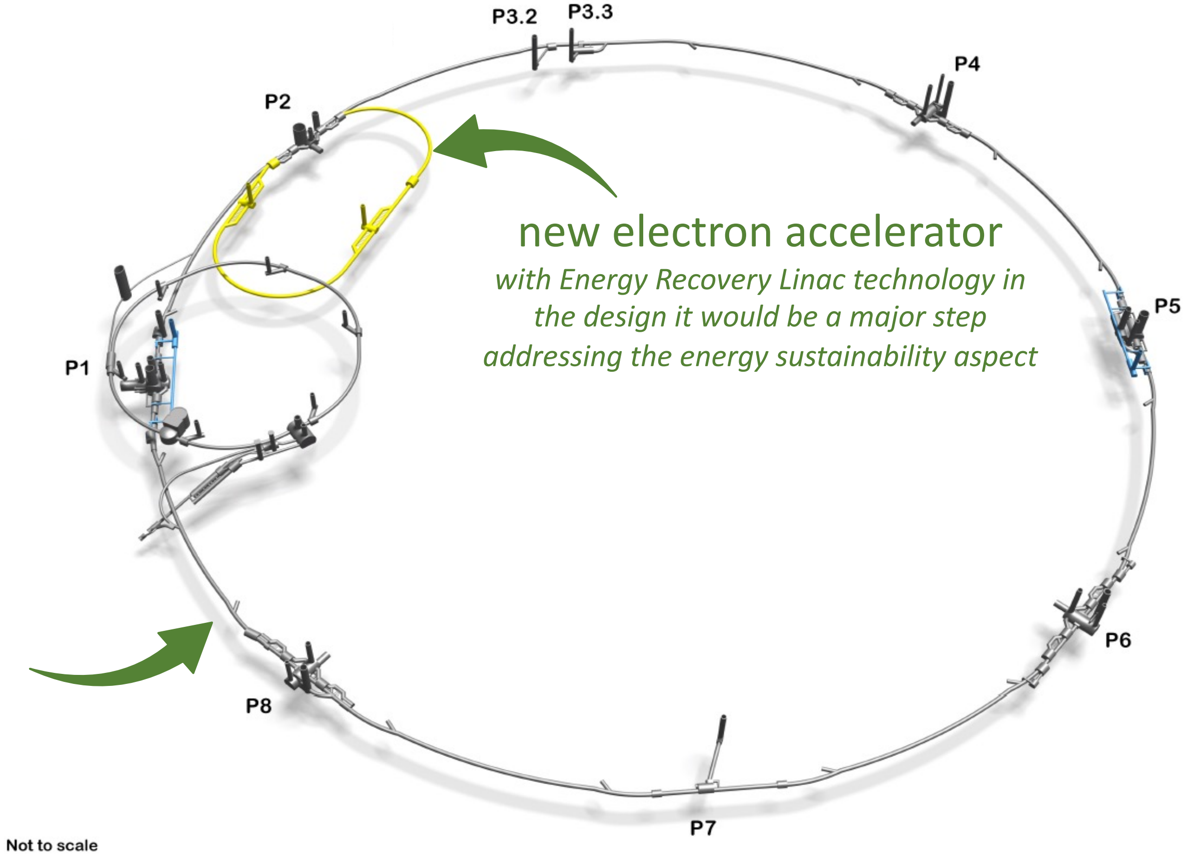
The next ambition for the community will be to enable ep/eA physics both at higher luminosities and at higher energies

Reaching deep into the hadronic matter has the potential to unlock new discoveries and insights to help addressing the puzzles of the SM

adapted from PECFA talk Nov. 2018 of A. Deshpande



A paradigm shift: high-energy electron-proton collions



new electron accelerator

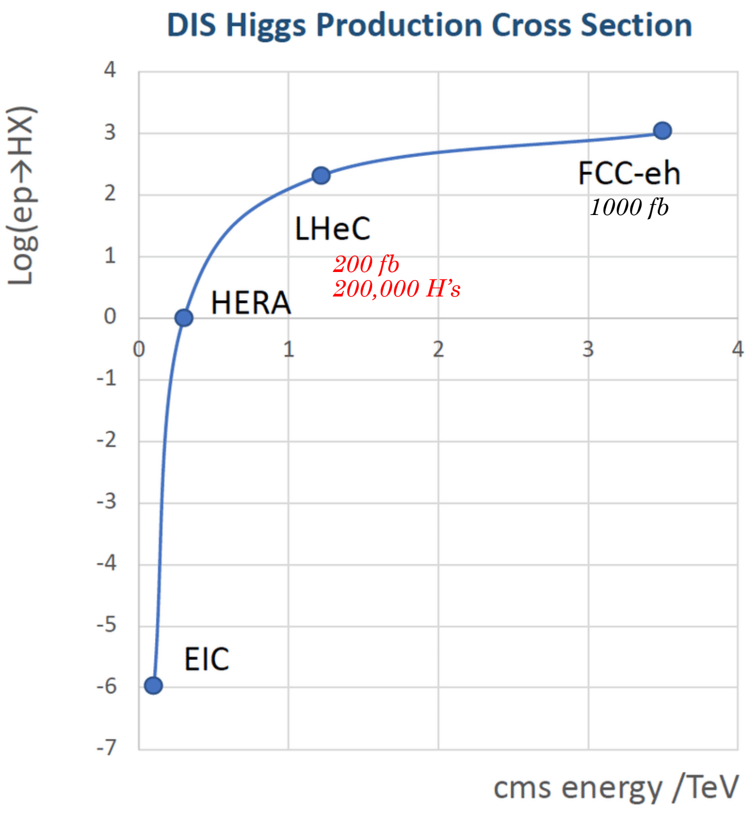
with Energy Recovery Linac technology in the design it would be a major step addressing the energy sustainability aspect

existing/future proton accelerator

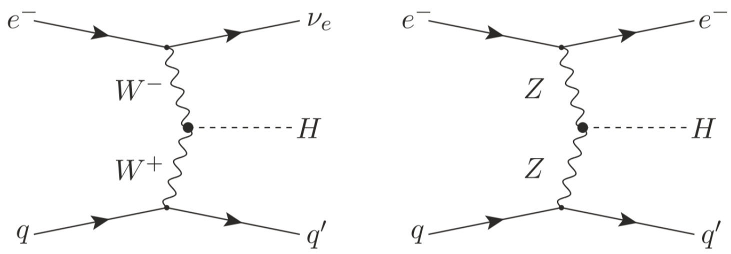
LHC and/or FCC

Collision energy above the threshold for EW/Higgs/Top

from mostly QCD-oriented physics to General-Purpose physics



The real game change between HERA and LHC/FCC

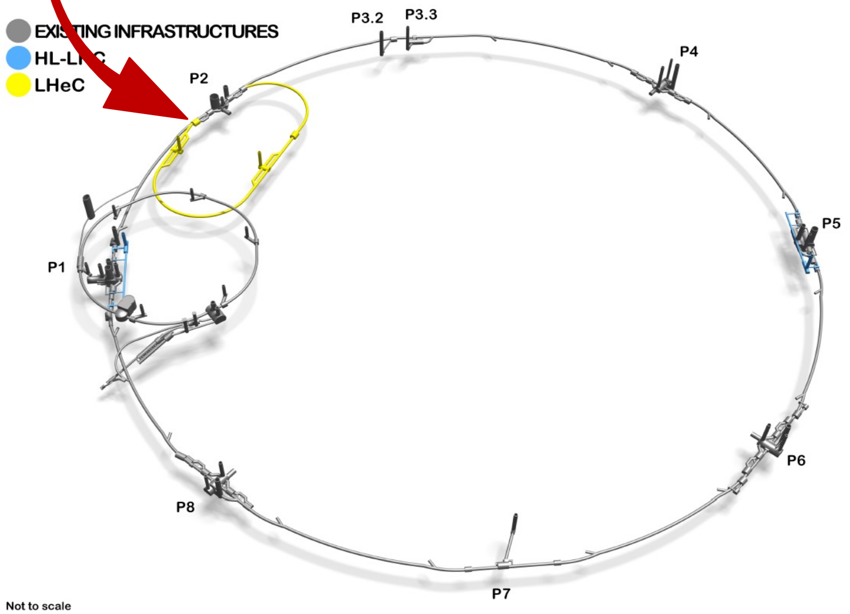


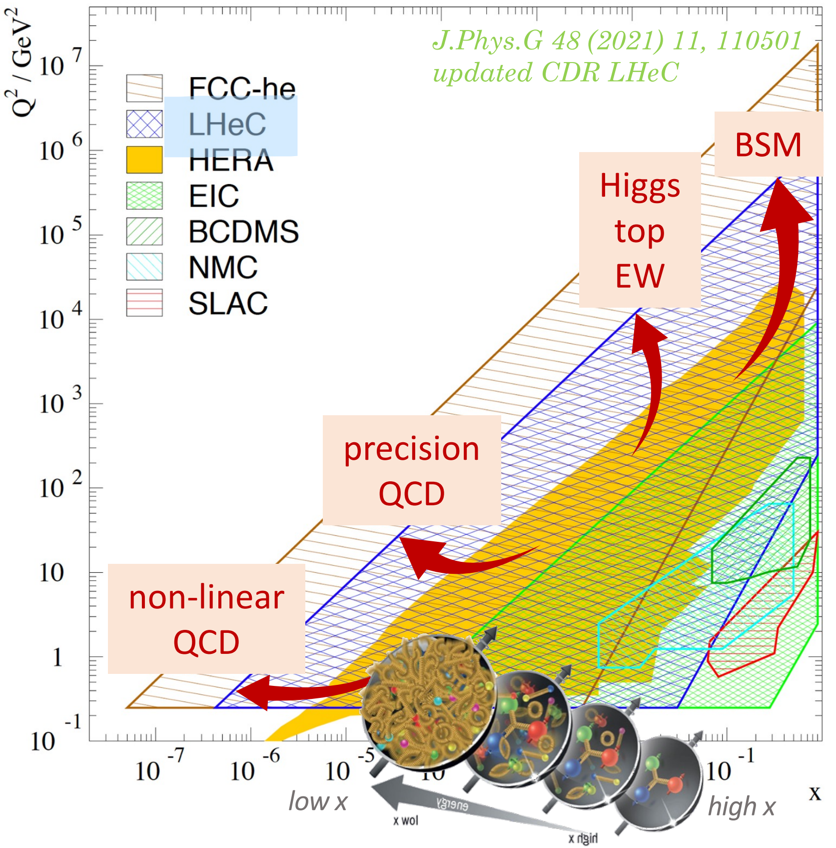
compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

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

The LHeC program

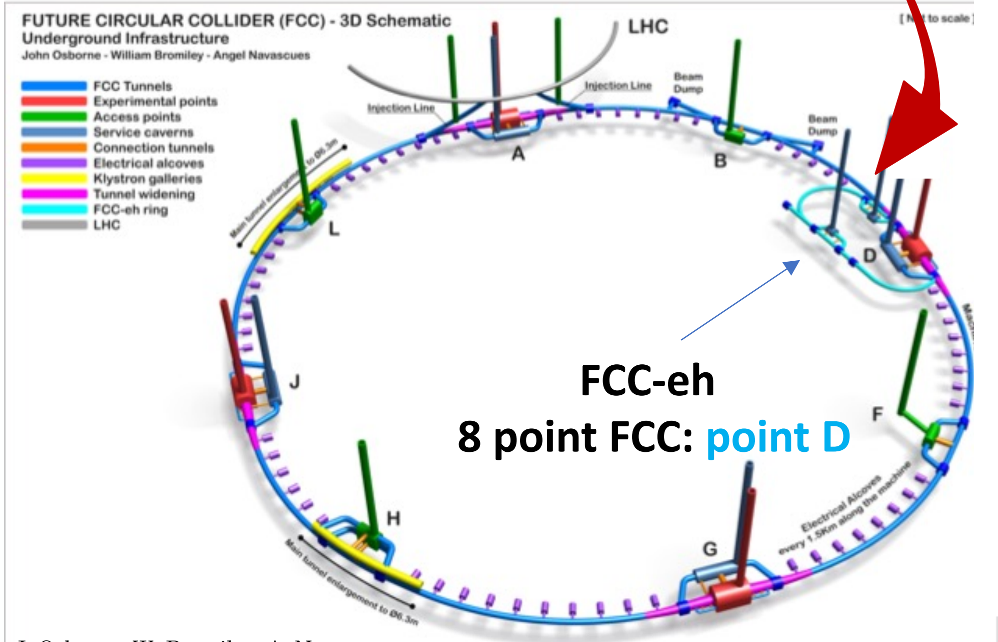
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳Run5)



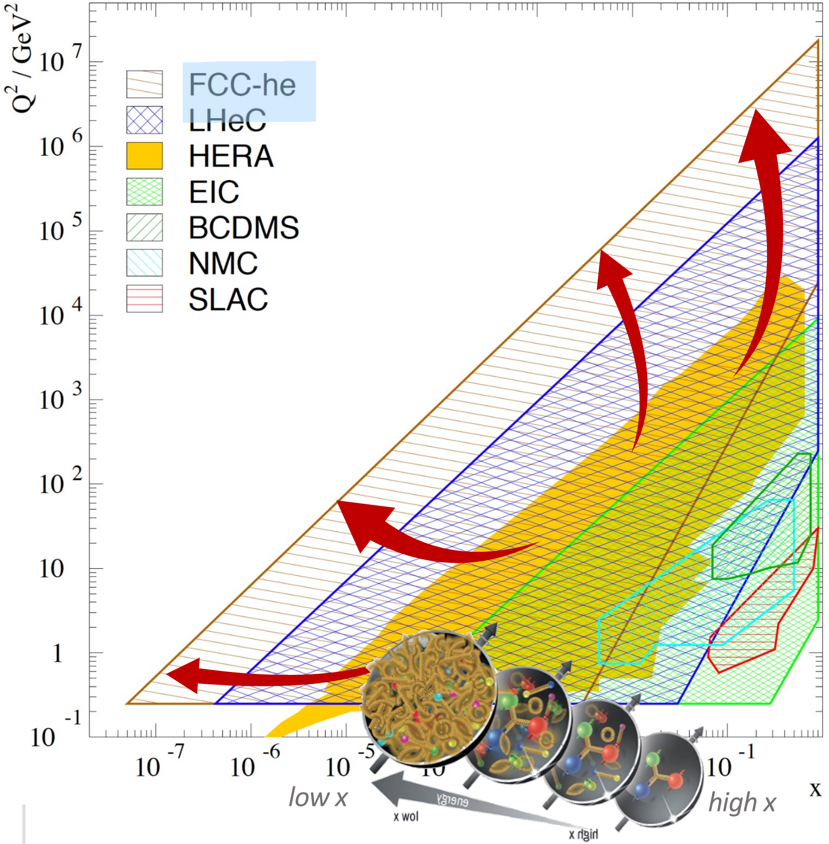


The FCC-eh program

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



Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

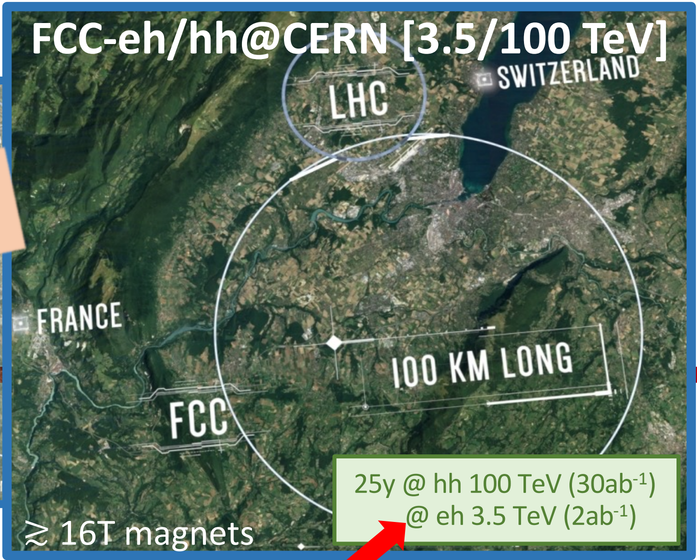
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

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

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

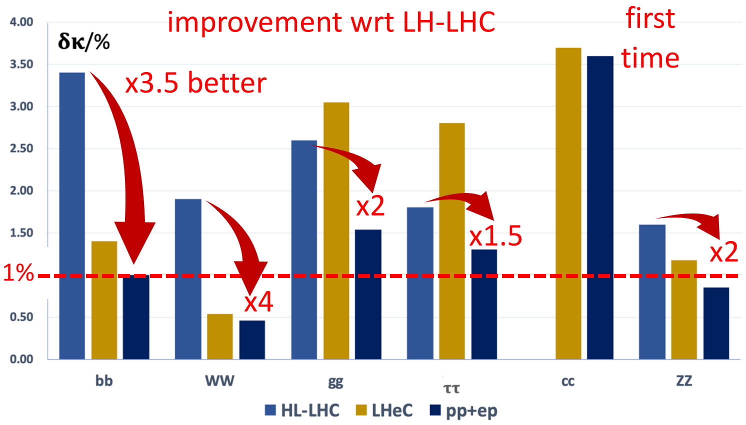


numbers assume 2 IPs for each collider (only one for FCC-eh)

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 0.2%
- 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)

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

- **EW/Higgs/top physics: improvement from LHC → HL-LHC similar to HL-LHC → LHeC**
- **Joint ep/pp interaction region with the same detector: correlate results and reach the ultimate precision,** e.g. $\Delta m_W \sim 1$ MeV might be within reach *Eur.Phys.J.C* 82 (2022) 1, 40
- **In addition, unique potential with LHeC/FCC-eh to search for new physics phenomena,** e.g. what if features appear in the interactions between leptons and quarks

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

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

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

adding 365 GeV runs

adding FCC-ep

ALL COMBINED

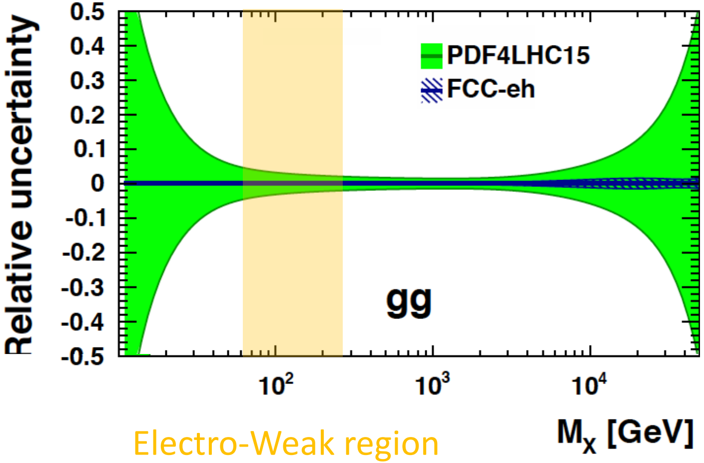
only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

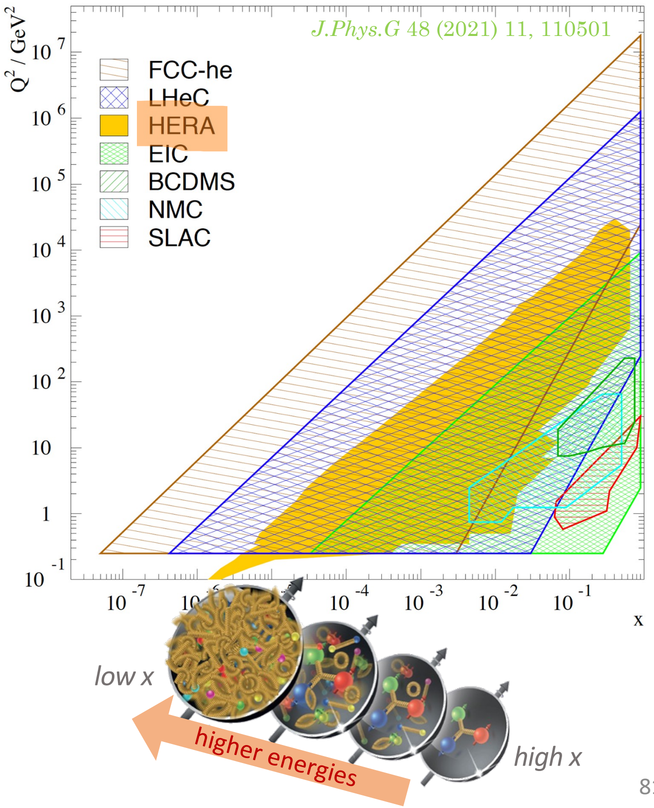


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

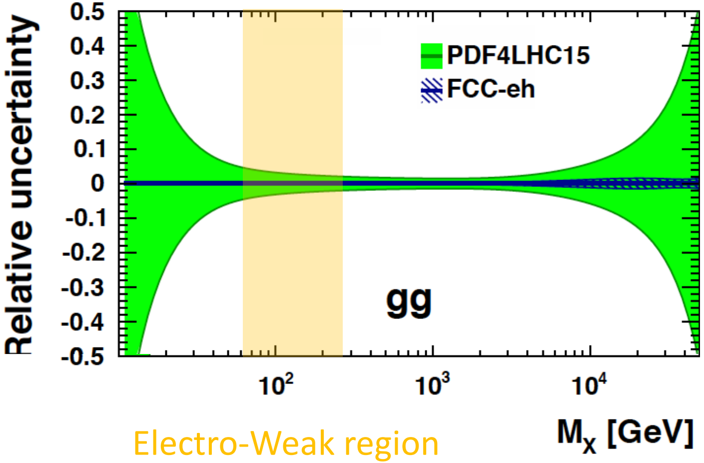
no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV



Electro-Weak region

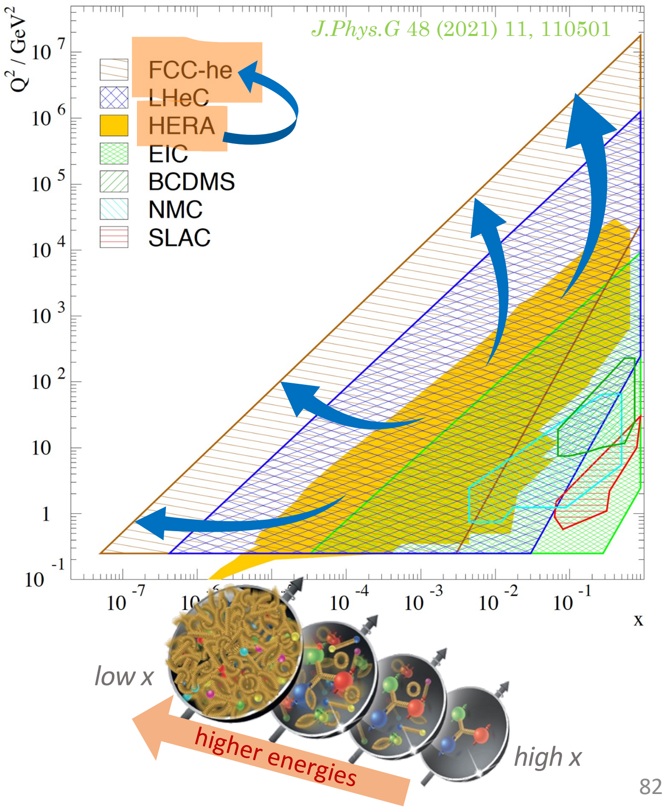
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



FCC-eh essential to unlock FCC-hh science potential