Innovate for Sustainable Accelerating Systems (iSAS)

reducing the energy footprint of SRF accelerators

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Vrije Universiteit Brussel

on behalf of the iSAS consortium

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iihe BRUXELLES BRUSSEL

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

iSAS

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101131435

ESSRI workshop

Madrid, September 2024

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
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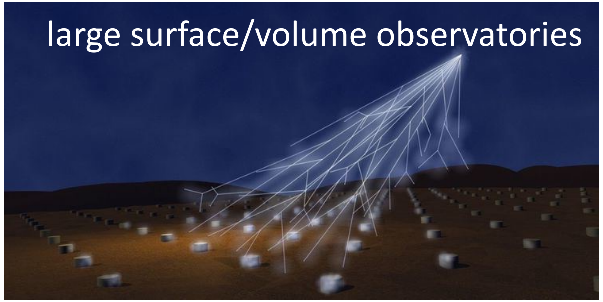
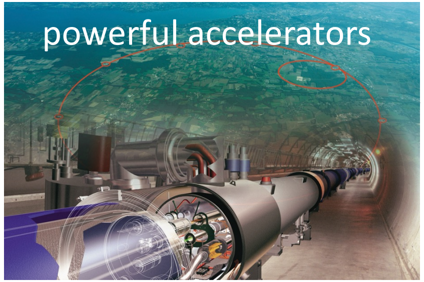


visible with our own eyes



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distance to galactic center

distance light travels in one year

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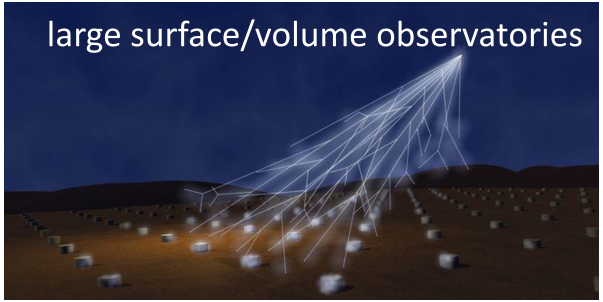
biological cell

atoms

proton neutron

age universe
4.4 10^{18} s

observable universe
8.8 10^{26}m



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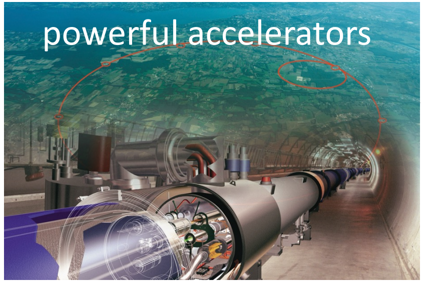


lifetime top quark
5 10^{-25} s

quarks
< 10^{-19}m

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

~ 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

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

duration supernova & GRB
0.1-100 s

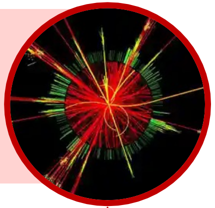
lifetime proton
> 3 10^{41} s

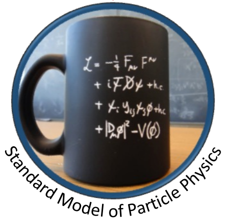
lifetime kaon ($K^{\pm}$)
1.2 10^{-8} s

~ 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





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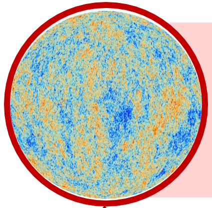
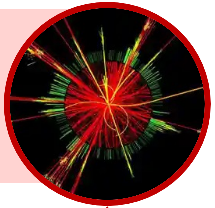
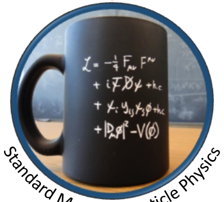


observations how large objects behave in our universe

Standard Model of Cosmology

observations how small objects behave in our laboratories





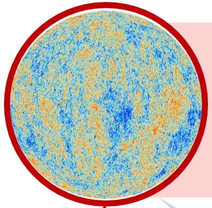
Standard Model of Particle Physics

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



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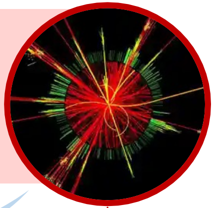

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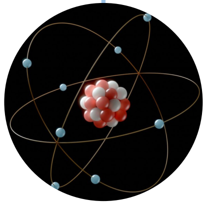
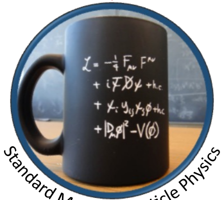


Standard Model of Cosmology

e.g. creation of chemical elements

e.g. nuclei built from quarks and gluons



Standard Model of Particle Physics

A century of scientific revolutions

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

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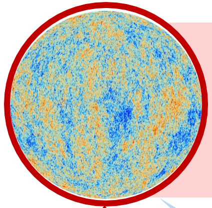

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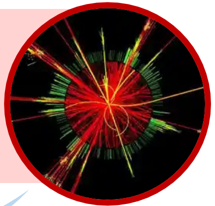

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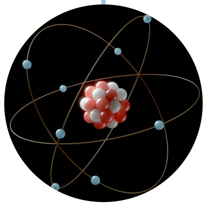

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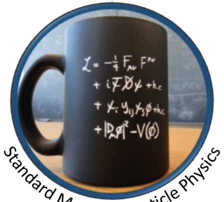
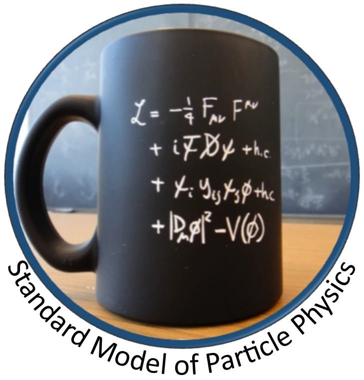


Standard Model of Particle Physics

very large Research Infrastructures and concerted efforts have been the enabling factor

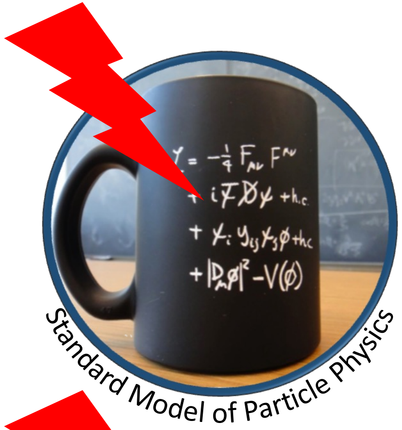
The quest for understanding physics

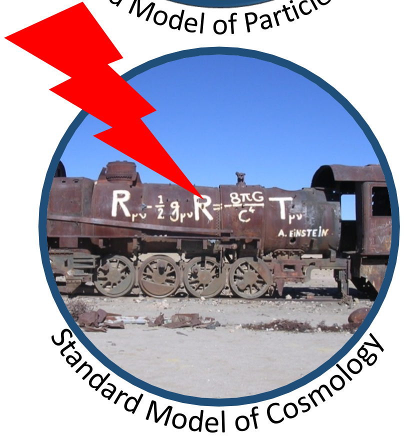


"Problems and Mysteries"

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?...

The quest for understanding physics





"Problems and Mysteries"

e.g. Abundance of dark matter?
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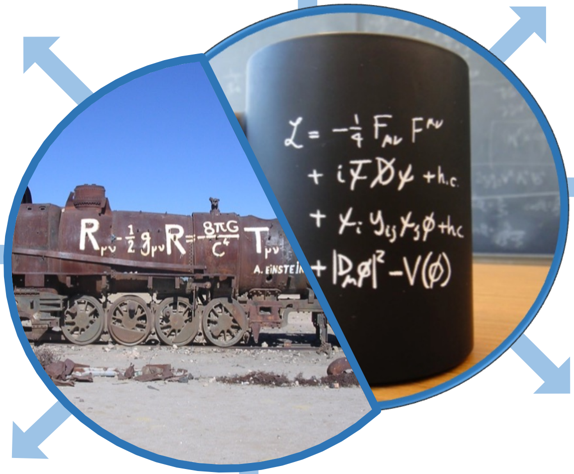
- How do quarks and gluons give rise to properties of nuclei?…

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

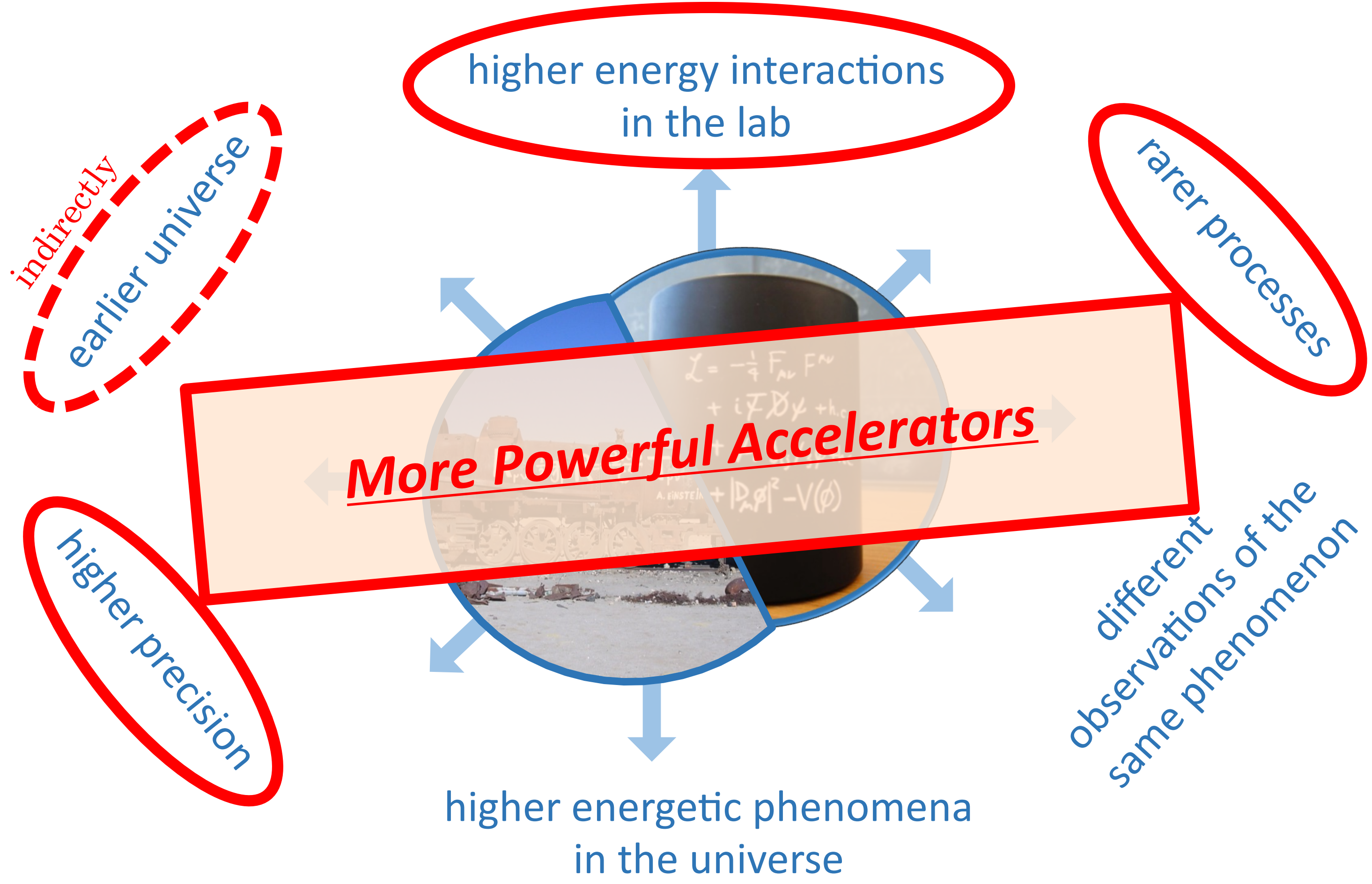
rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe


higher energy interactions
in the lab
indirectly
earlier universe
rarer processes
More Powerful Accelerators
higher precision
different
observations of the
same phenomenon
higher energetic phenomena
in the universe

particle physics ambition

high-energy & high-current beams

particle physics ambition

high-energy & high-current beams

an ambition shared with other fields enabled by SRF accelerators
e.g., XFELs and high-intensity proton beams (ESS, MYRRHA, …)

particle physics ambition

high-energy & high-current beams

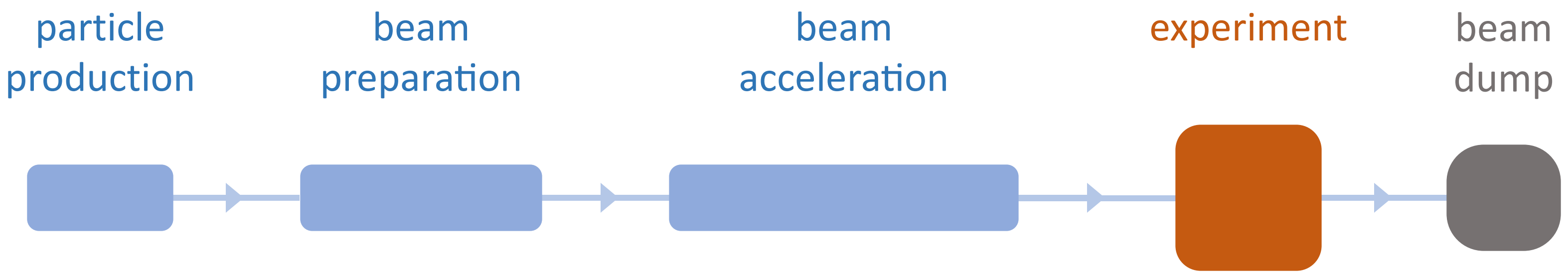
caveat

energy x current = power

power requirements of future colliders

focus on electron/positron accelerators

Basic structures of a particle accelerator



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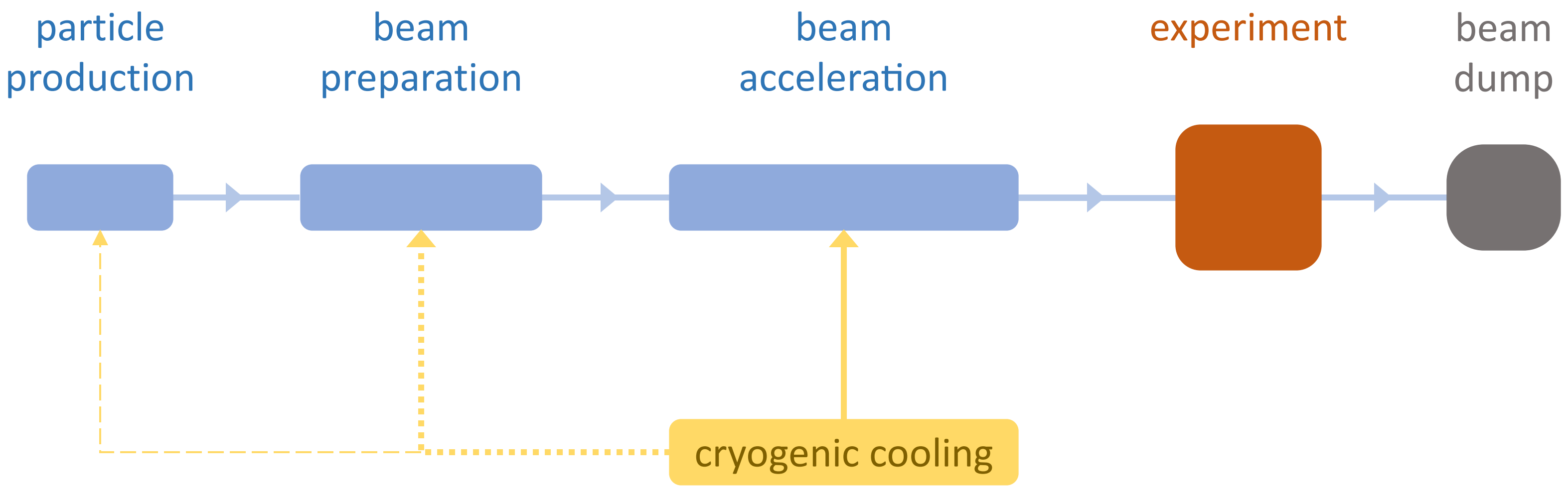

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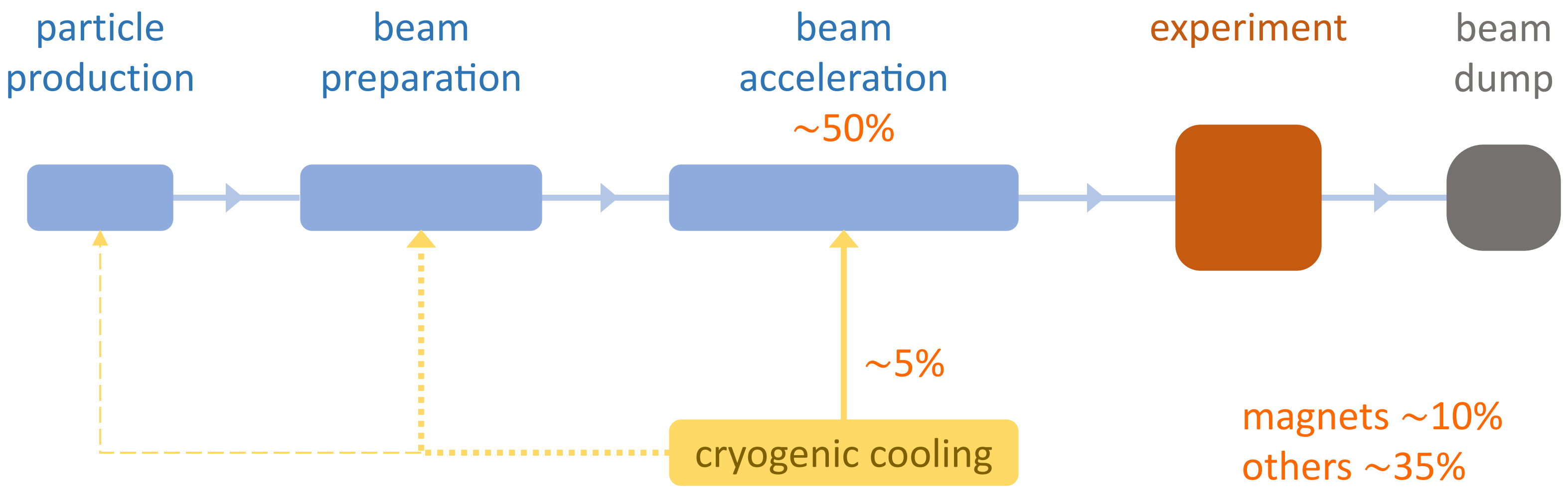


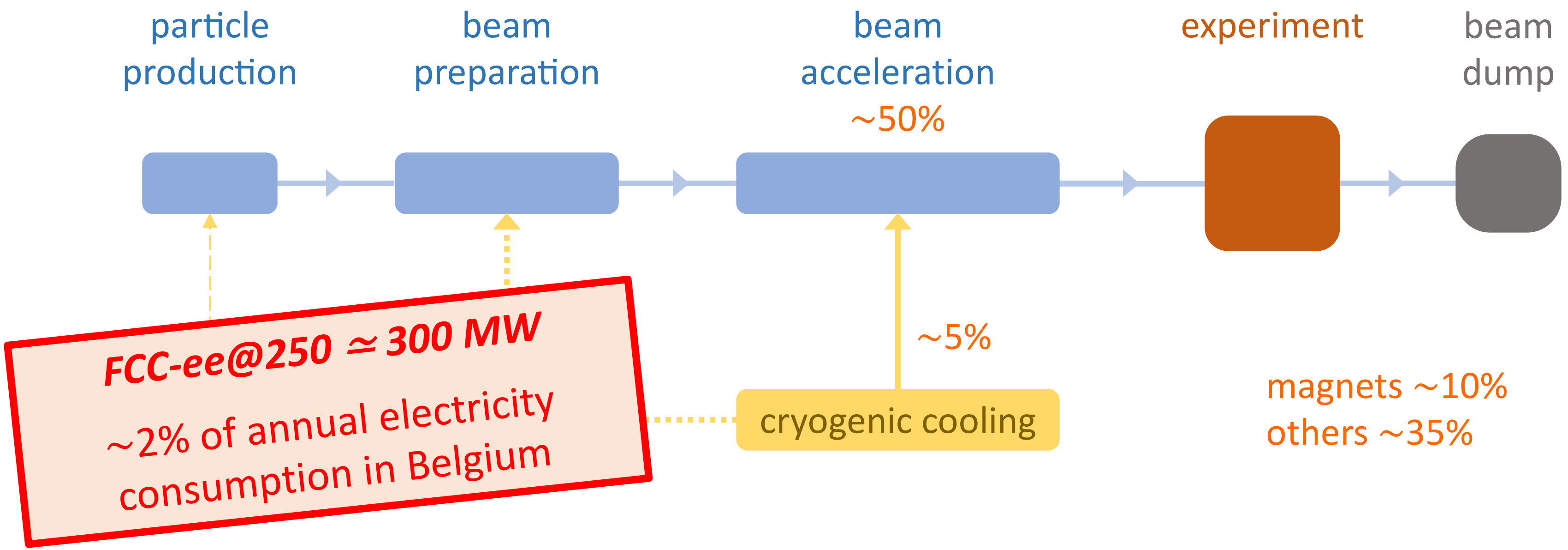
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC-ee@250GeV

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

Basic structures of a particle accelerator



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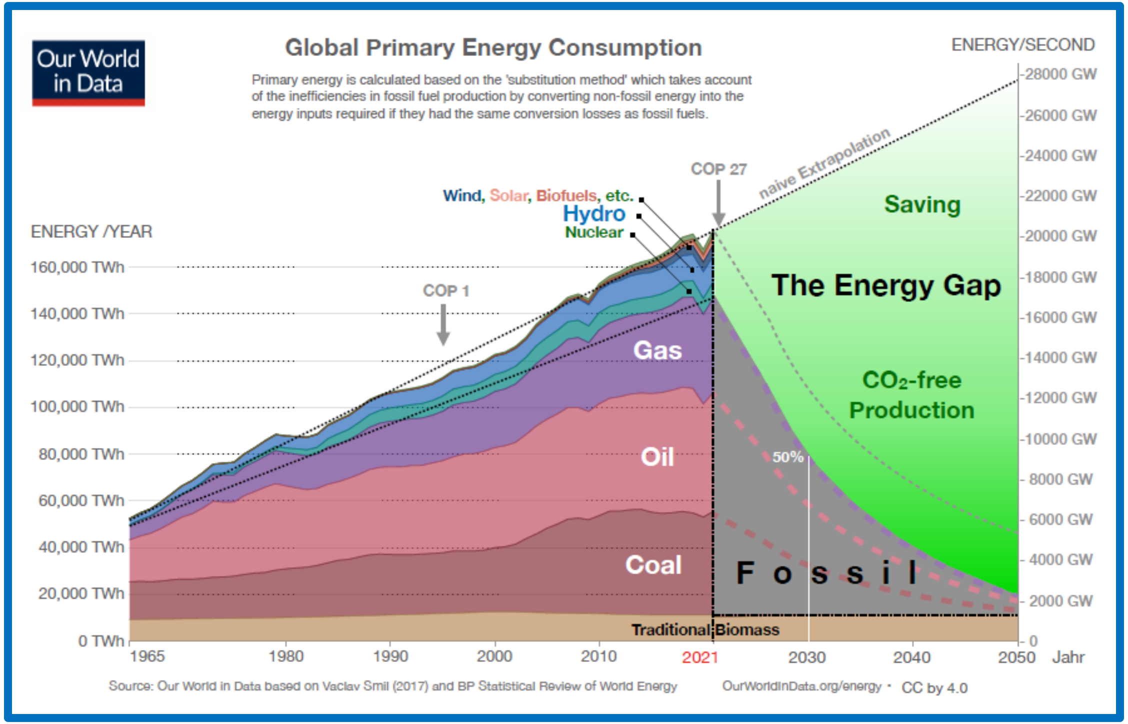
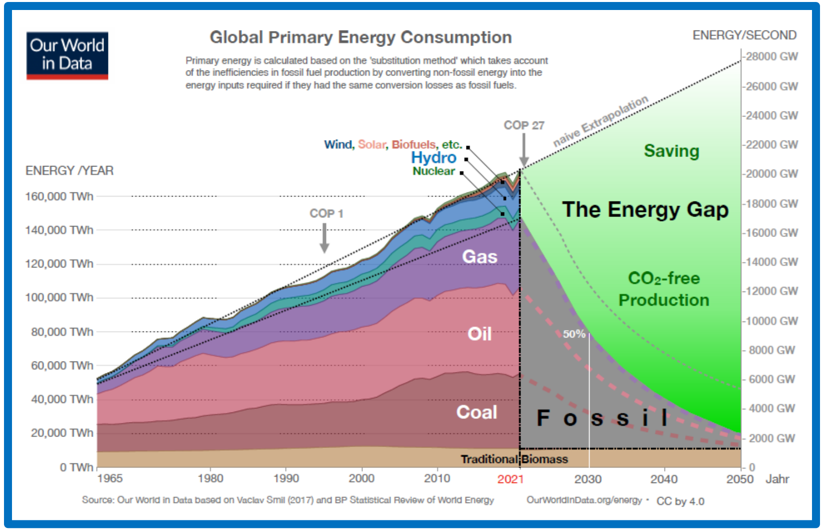

Our World in Data
Global Primary Energy Consumption
Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.
ENERGY/SECOND
ENERGY /YEAR
160,000 TWh
140,000 TWh
120,000 TWh
100,000 TWh
80,000 TWh
60,000 TWh
40,000 TWh
20,000 TWh
0 TWh
28000 GW
26000 GW
24000 GW
22000 GW
20000 GW
18000 GW
16000 GW
14000 GW
12000 GW
10000 GW
8000 GW
6000 GW
4000 GW
2000 GW
0
COP 1
COP 27
naive Extrapolation
Wind, Solar, Biofuels, etc.
Hydro
Nuclear
Gas
Oil
Coal
Traditional Biomass
Saving
The Energy Gap
CO2-free Production
50%
F o s s i l
1965
1980
1990
2000
2010
2021
2030
2040
2050
Jahr
Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy
OurWorldInData.org/energy • CC by 4.0

OVERALL OBJECTIVE
dramatically improving energy efficiency by 2050



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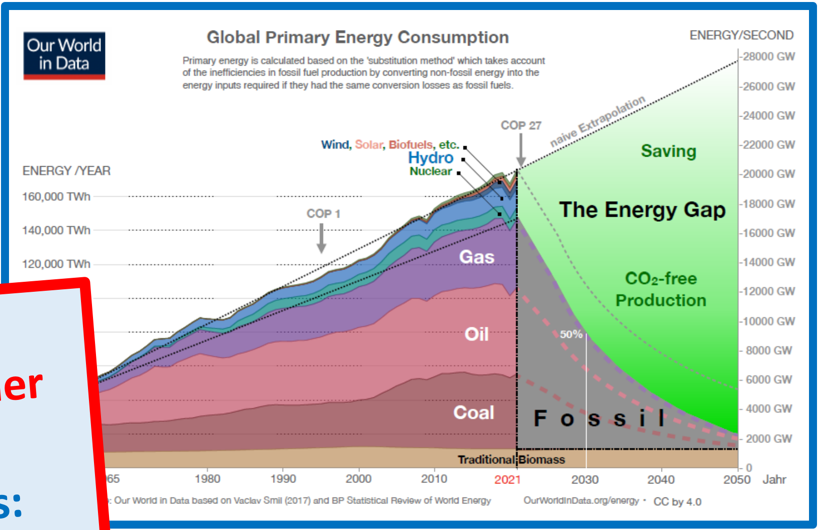


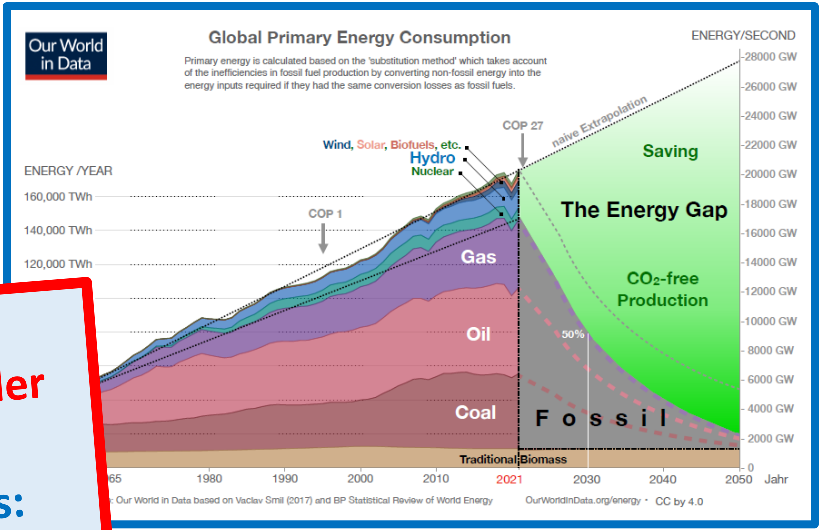
2050 might be the timescale for a new major collider

potential future requirements for future colliders:
zero emission & drastically reduce energy footprint

my opinion:
If you are part of the problem,
you should be part of the solution

OVERALL OBJECTIVE

dramatically improving energy efficiency by 2050



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If you are part of the problem,
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along the lines of F. Bordry (opening ESSRI 2024)
from dreams to concrete actions

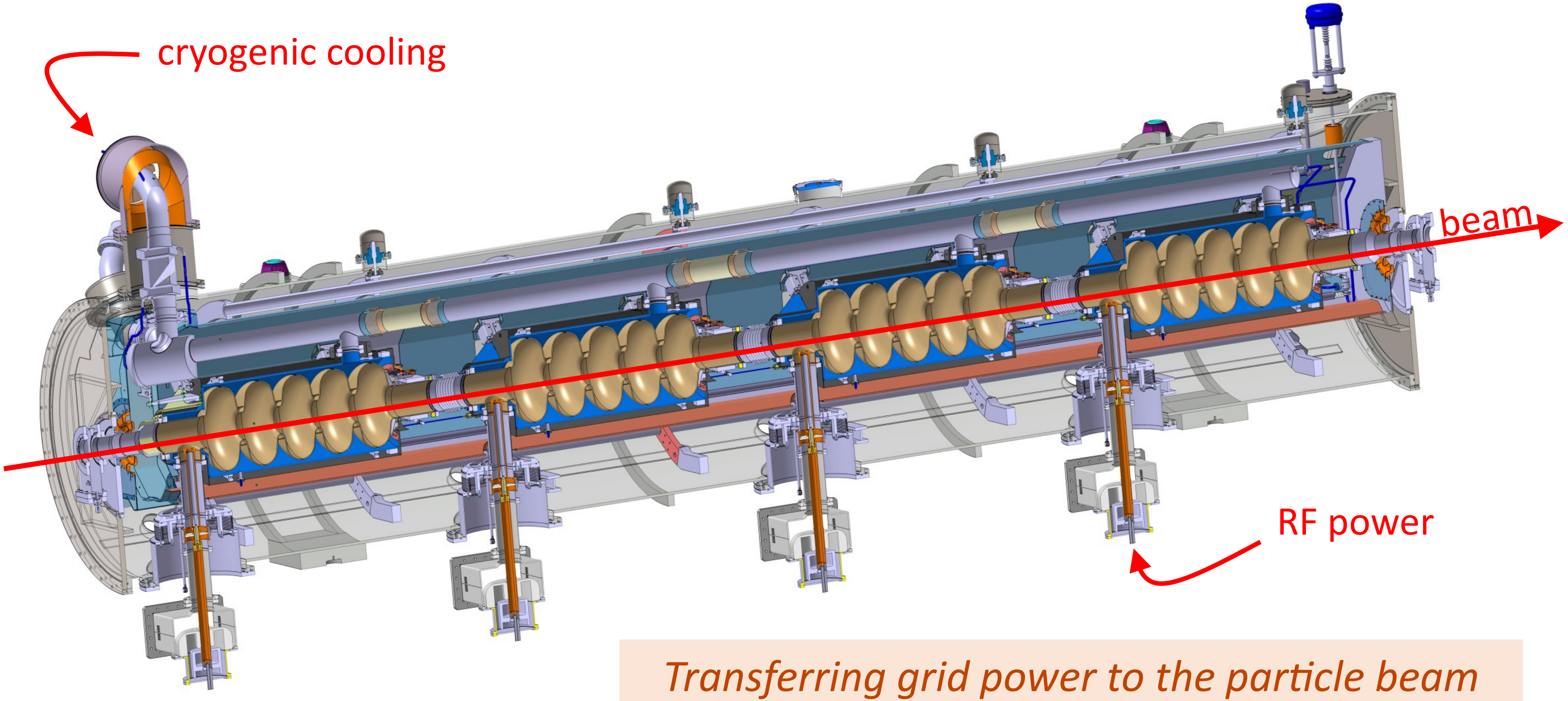
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

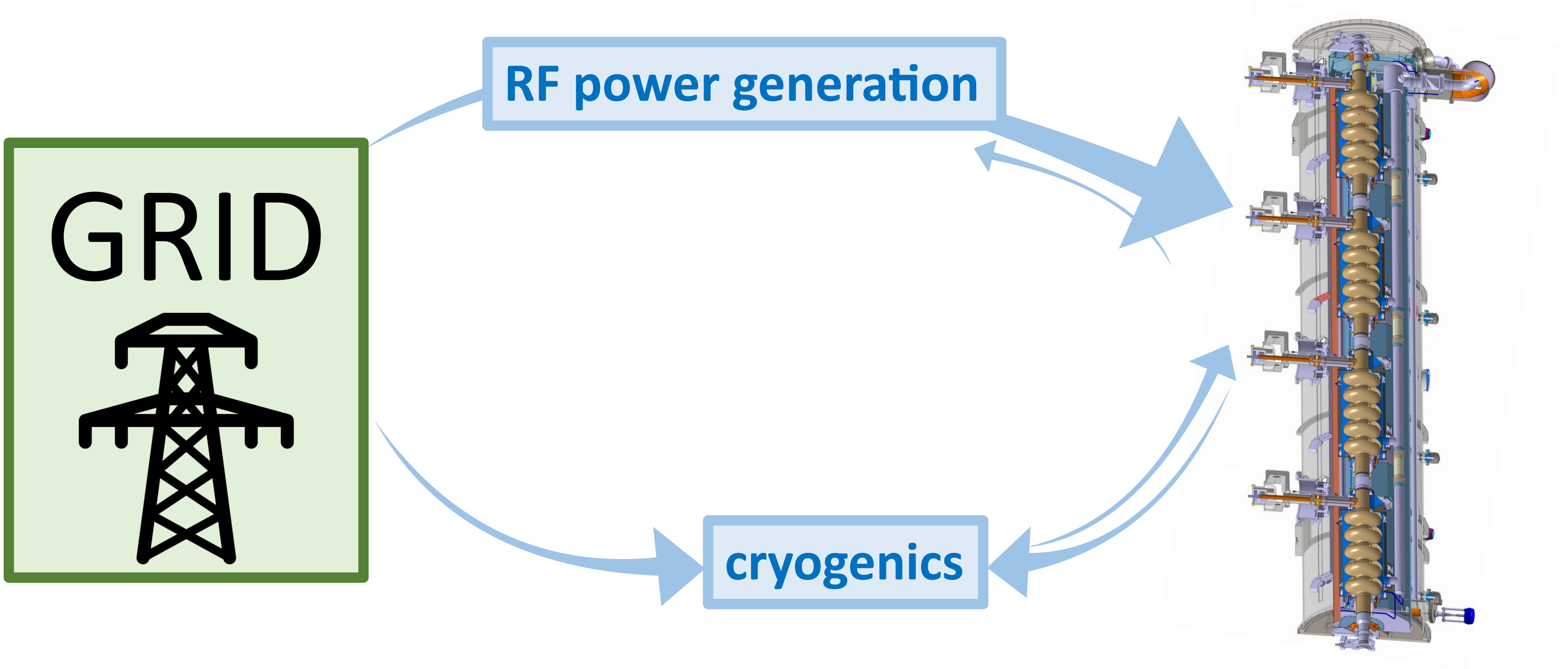
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

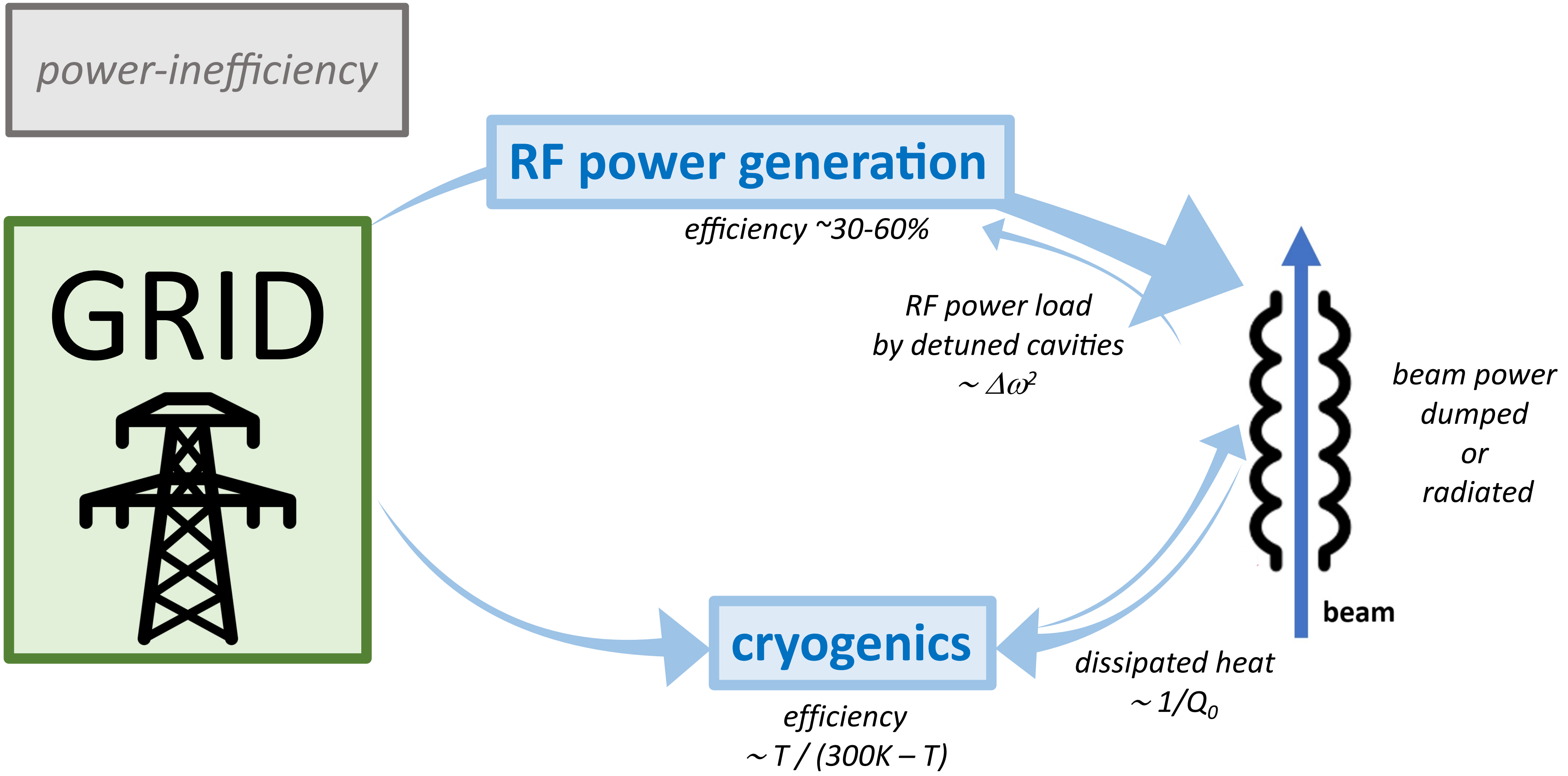


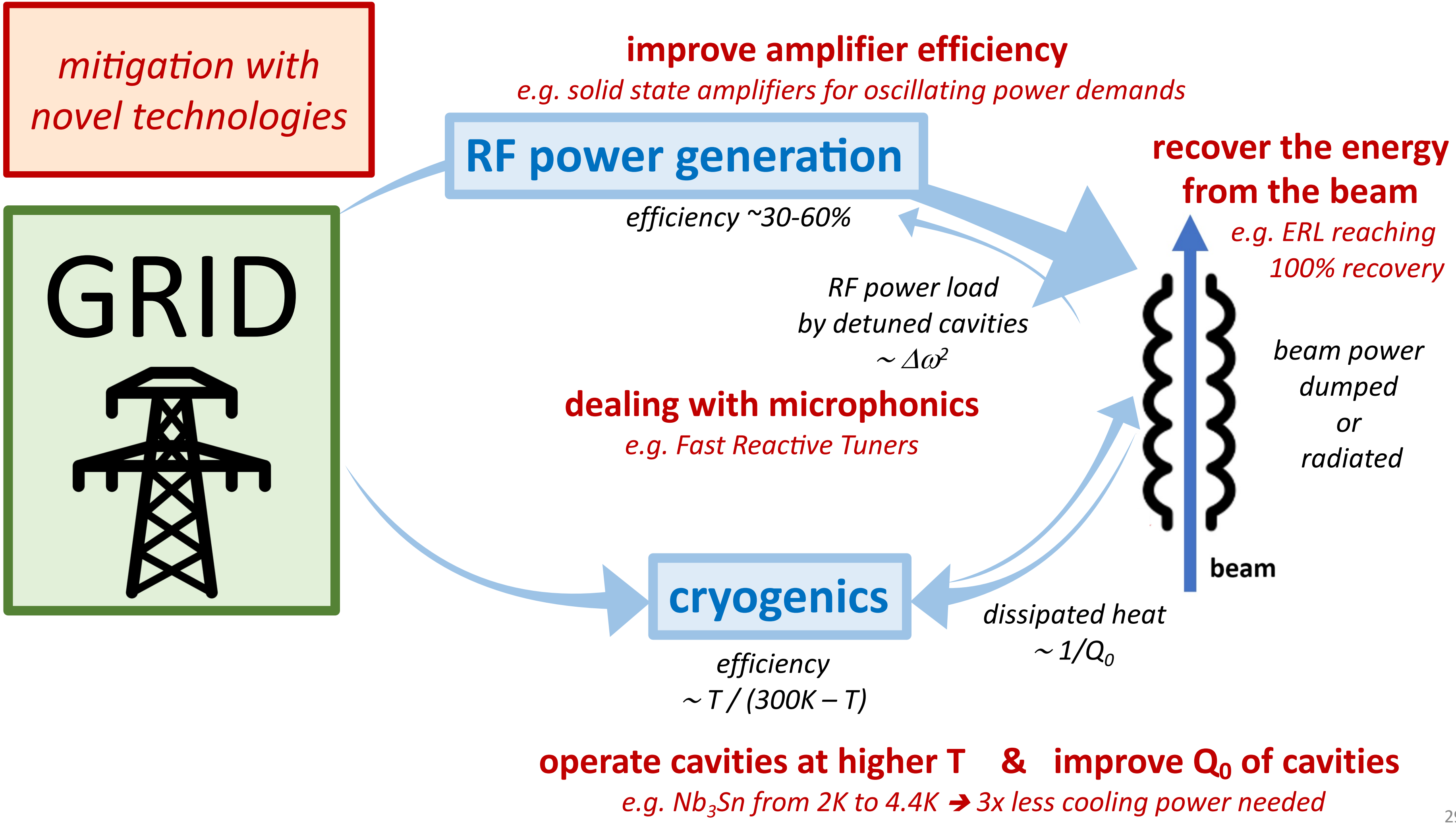
Transferring grid power to the particle beam

SRF accelerator – from Grid to Beam

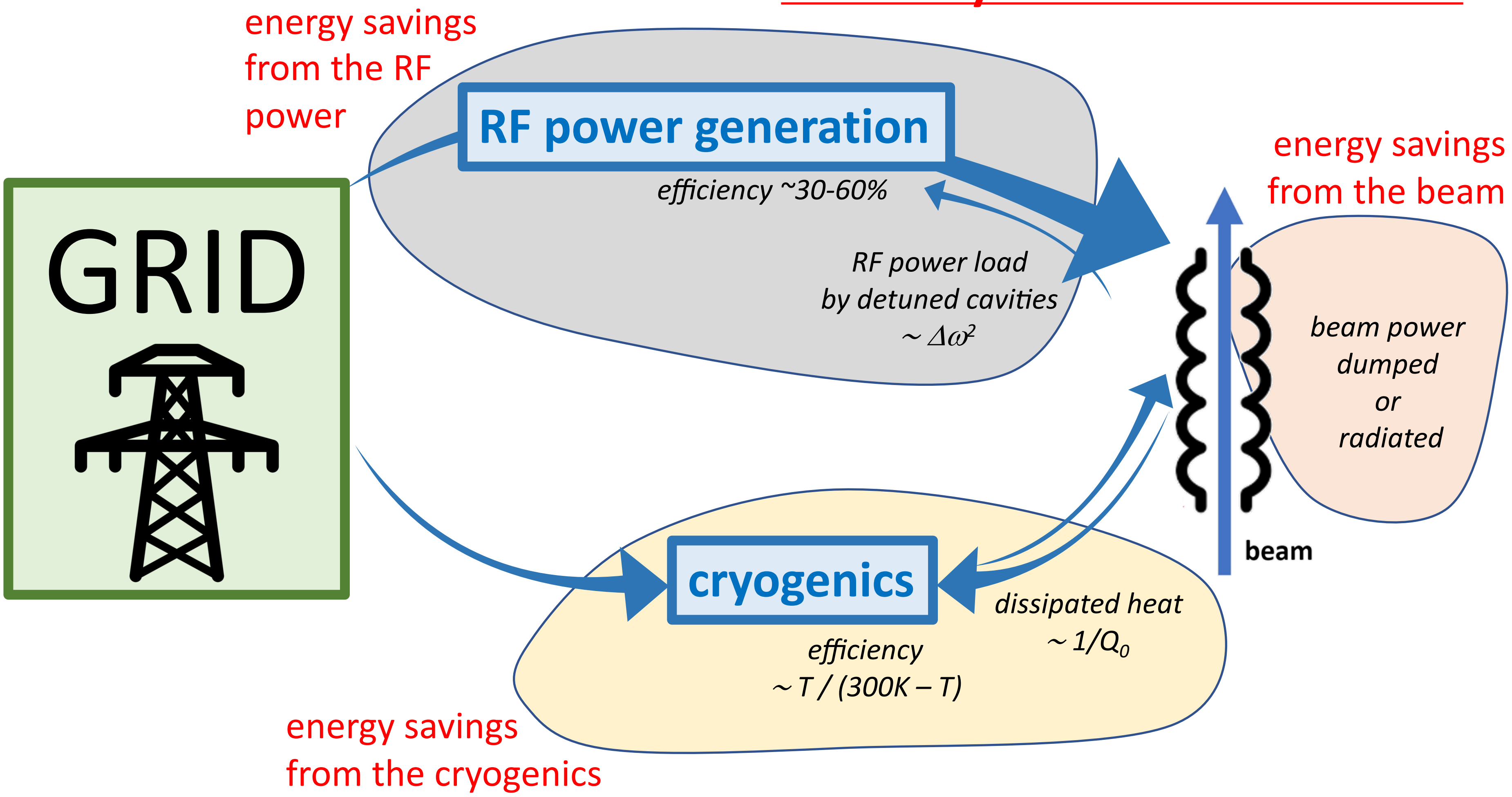


Picture adopted from M. Seidel (IPAC 2022)

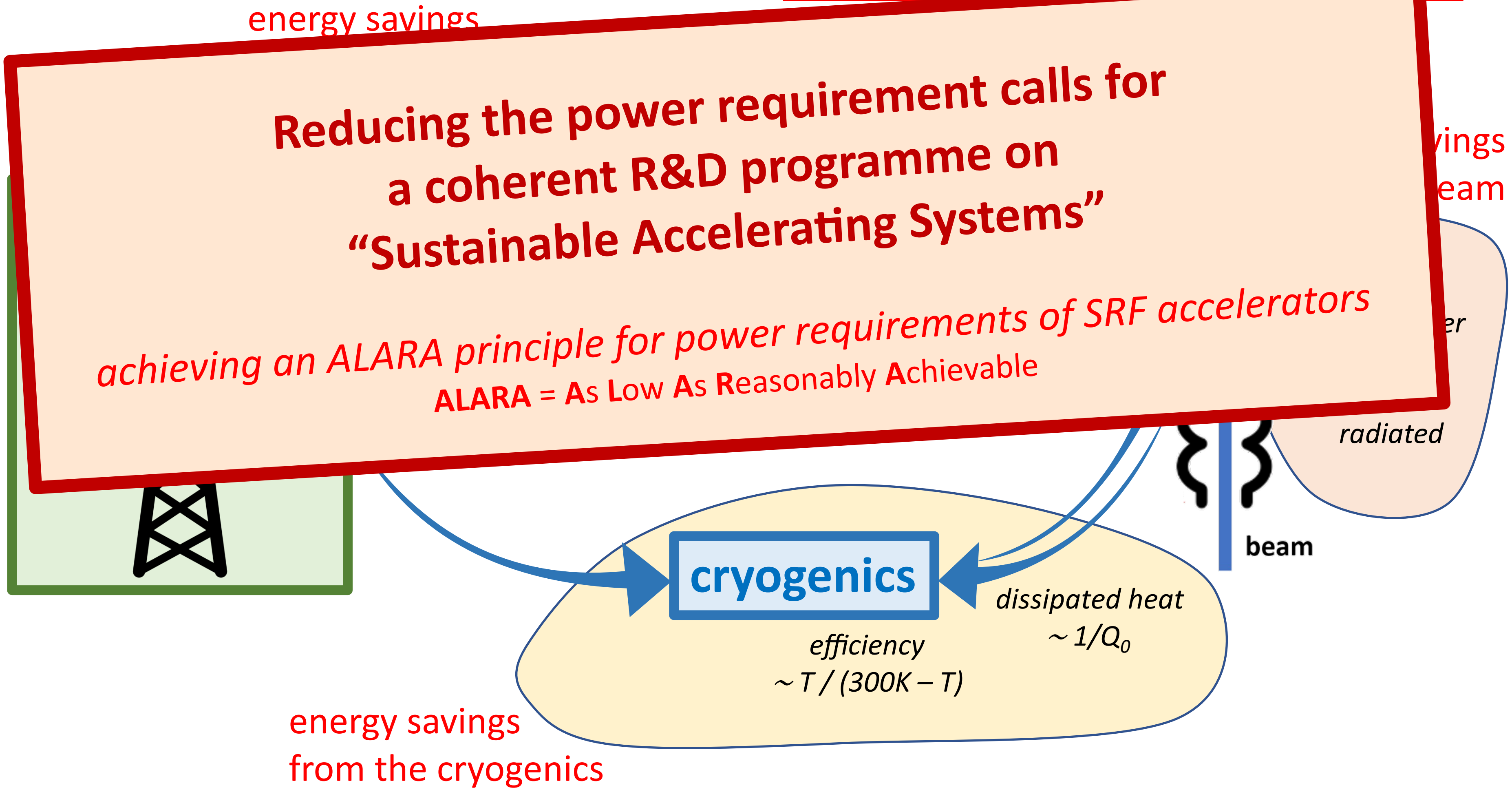

power-inefficiency
GRID
RF power generation
efficiency ~30-60%
RF power load
by detuned cavities
$\sim \Delta\omega^2$
beam power
dumped
or
radiated
beam
cryogenics
efficiency
$\sim T / (300K - T)$
dissipated heat
$\sim 1/Q_0$


mitigation with novel technologies
improve amplifier efficiency
e.g. solid state amplifiers for oscillating power demands
RF power generation
efficiency ~30-60%
recover the energy from the beam
e.g. ERL reaching 100% recovery
GRID
RF power load by detuned cavities $\sim \Delta\omega^2$
beam power dumped or radiated
dealing with microphonics
e.g. Fast Reactive Tuners
beam
cryogenics
dissipated heat $\sim 1/Q_0$
efficiency $\sim T / (300K - T)$
operate cavities at higher T & improve Q_0 of cavities
e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

Three key innovation directions



Three key innovation directions



Reducing the power requirement calls for 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

Three key innovation directions

energy savings

…vings
…eam
…er

Reducing the power requirement calls for a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

ALARA = **As** **Low** **As** **Reasonably** **Achievable**

Innovate for Sustainable Accelerating Systems (iSAS)

develop a new design of an SRF cryomodule

integrating the most impactful energy-saving technologies (incl. RF & ERL aspects)

Kick-off meeting 15-16 April 2024 @ IJCLab: https://indico.ijclab.in2p3.fr/event/10302/

https://isas.ijclab.in2p3.fr

Horizon Europe

…from the cryogenics

iSAS is now an approved and ongoing Horizon Europe project

Spread over 4 years (2024-2028): ~1000 person-months of researchers and ~12.6M EUR

(of which 5M EUR is provided through 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)

ACS ACCELERATORS AND CRYOGENIC SYSTEMS Cryoelectra RF Technology for Particle Accelerators euclid TECHLABS research instruments TFE THIN FILM EQUIPMENT Zanon RESEARCH & INNOVATION SRL

iSAS

Innovate for Sustainable Accelerating Systems

Kick-Off Meeting / 15-16 april 2024

IJCLab Orsay

cnrs université PARIS-SACLAY Université Paris Cité

Innovate for Sustainable Accelerating Systems

Kick-Off Meeting / 15-16 april 2024

IJCLab Orsay

“Innovate for Sustainable Accelerating Systems”

AMBITION – Innovate those technologies related to the cryomodule that have been identified as being a common core of SRF accelerating systems and that have the largest leverage for energy savings with a view to minimizing the intrinsic energy consumption in all phases of operation.

METHODOLOGY – Several interconnected technologies will be developed, prototyped, and tested, each enabling significant energy savings. The new energy-saving technologies will be coherently integrated into the parametric design of a new accelerating system, a LINAC SRF cryomodule, optimised to achieve high beam-power in accelerators with an as low as reasonably possible energy consumption.

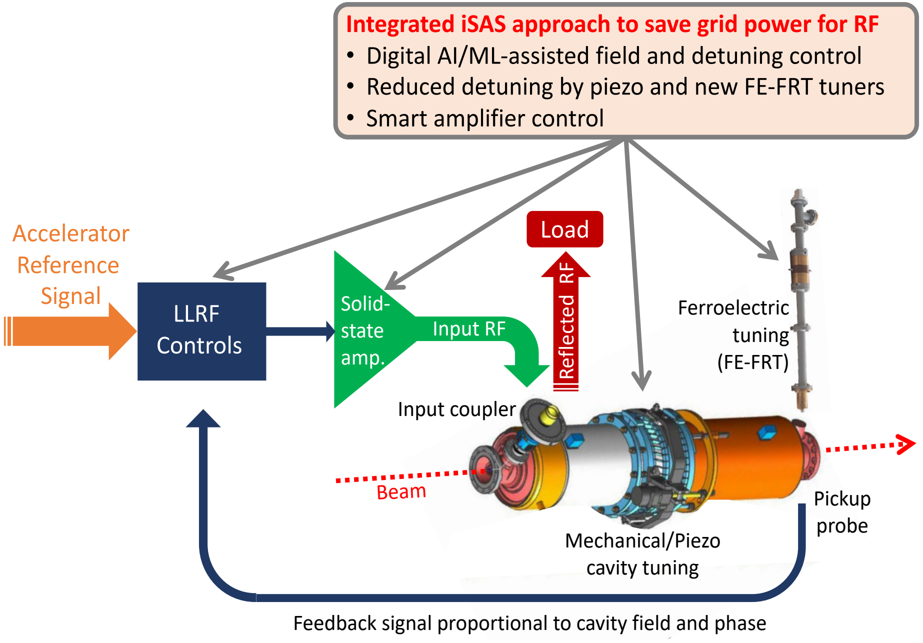
IMPACT – The long-term ambition is to reduce the energy footprint of SRF accelerators in future research infrastructures by half, and even more when the systems are integrated in Energy-Recovery LINACs.

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*

very concrete

energy-savings from RF power (HZB, CERN, CNRS, Uni.Lancaster, DESY)

FE-FRT

- *FE-FRT for Transient Beam Loading: design & performance tests for an LHC 400 MHz cavity in an existing cryomodule.*
- *FE-FRT for Microphonics: design, fabricate and validate in a cryomodule like setup for 1.3 GHz cavities, single-cell and multi-cell (TESLA/XFEL).*
- *FE-FRT for Microphonics compensation in Energy-Recovery LINAC (ERL) mode: for 800 MHz cavities and study the requirements for integration in a cryomodule.*

LLRF

- *Efficient field control for high loaded-quality factor (Q_L>5e7) cavities in CW and long pulse operation (incl. a ML-based feedback controller).*
- *Vibration analysis and detuning control of cavities (incl. ML-based control).*
- *Integrate a FE-FRT with a digital LLRF system & demonstrate operation in a horizontal test stand.*
- *Energy efficient supervisory control and fault diagnosis (incl. ML-based diagnosis).*

potential to reduce the power requirements up to a factor of 3

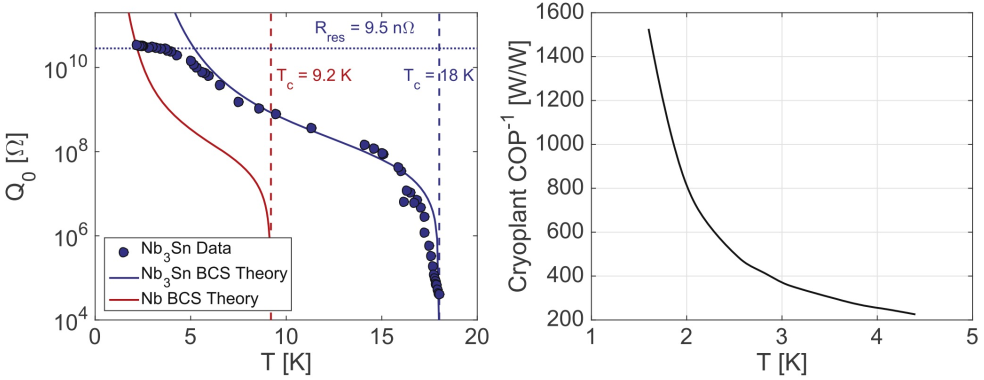
iSAS *develops, prototypes & validates SRF energy-saving technologies*

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, and the various US-based achievements (e.g., GARD).

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*

very concrete

energy-savings from cryogenics (INFN, CEA, HZB, UKRI)

- *Flux trapping: study how trapped magnetic flux may affect the superconducting properties of the thin film and its RF surface resistance.*
- *RF tunability: study and improve mechanical properties of superconducting thin films to assess the impact of future cavity tuning during normal 4.2 K operation.*
- *Adaptive layers: developing suitable adaptative layers on Cu for subsequent Nb_3Sn deposition to reduce the detrimental effect of mechanical deformation on the superconducting properties of Nb_3Sn.*
- *Working cavity @ 4.2K: optimize the superconducting coating procedure of 1.3 GHz cavities including an adaptive layer and demonstrate suitability for 4.2 K operation (using Cu cavities originally produced for I.FAST).*

potential to reduce the grid-power to operate the cryogenic system by a factor of 3

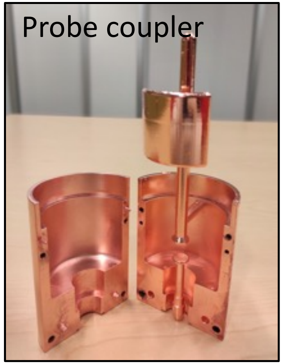
iSAS develops, prototypes & validates SRF energy-saving technologies

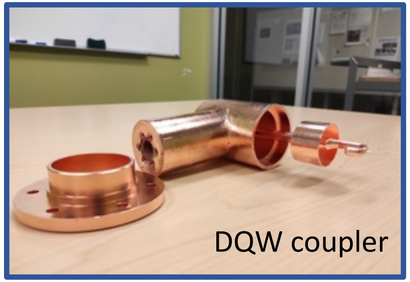
pictures from W. Kaabi

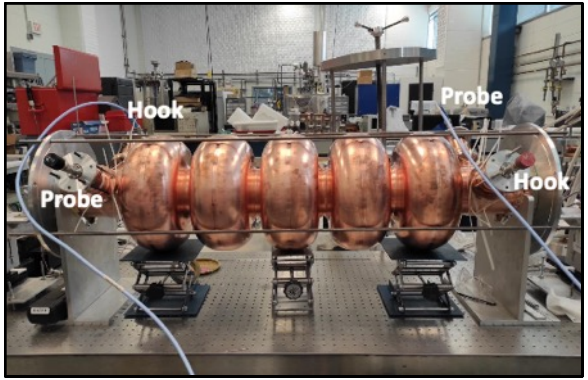
TA#3: energy-savings from the beam

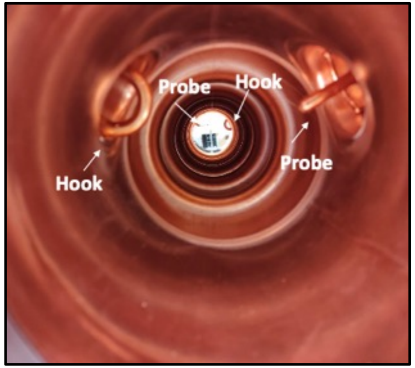
The objective is to reduce the total power deposited into the cryogenics circuits of the cryomodule of the Higher-Order Mode (HOM) couplers and fundamental power couplers (FPCs) leading to a significant reduction of the heat loads and the overall power consumption.

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.









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

very concrete

energy-savings from the beam (CNRS, INFN, CERN)

HOM

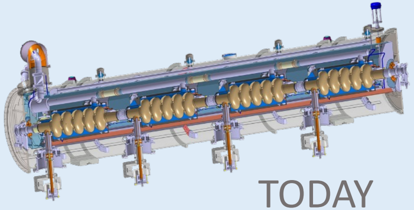
- *HOM coupler design: with simulations for various models and mechanical integration issues in a cryomodule*
- *Fabrication of HOM couplers: R&D on fabrication strategy for prototypes at 800 MHz and 1.3 GHz*
- *Test of the HOM couplers: performance validation of the design with RF measurements on mock-up cavities*

FPC

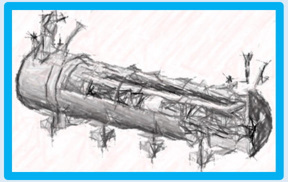
- *RF coupler design: optimize cost, cooling, heat loads, fabrication time, and mechanical integration issues in a cryomodule*
- *Fabrication of RF couplers: build 4 prototypes*
- *Test of the RF couplers: performance validation of the design with RF conditioning in CW mode (50kW)*

ERL could reduce the power requirements for high-power accelerators by a factor of 10

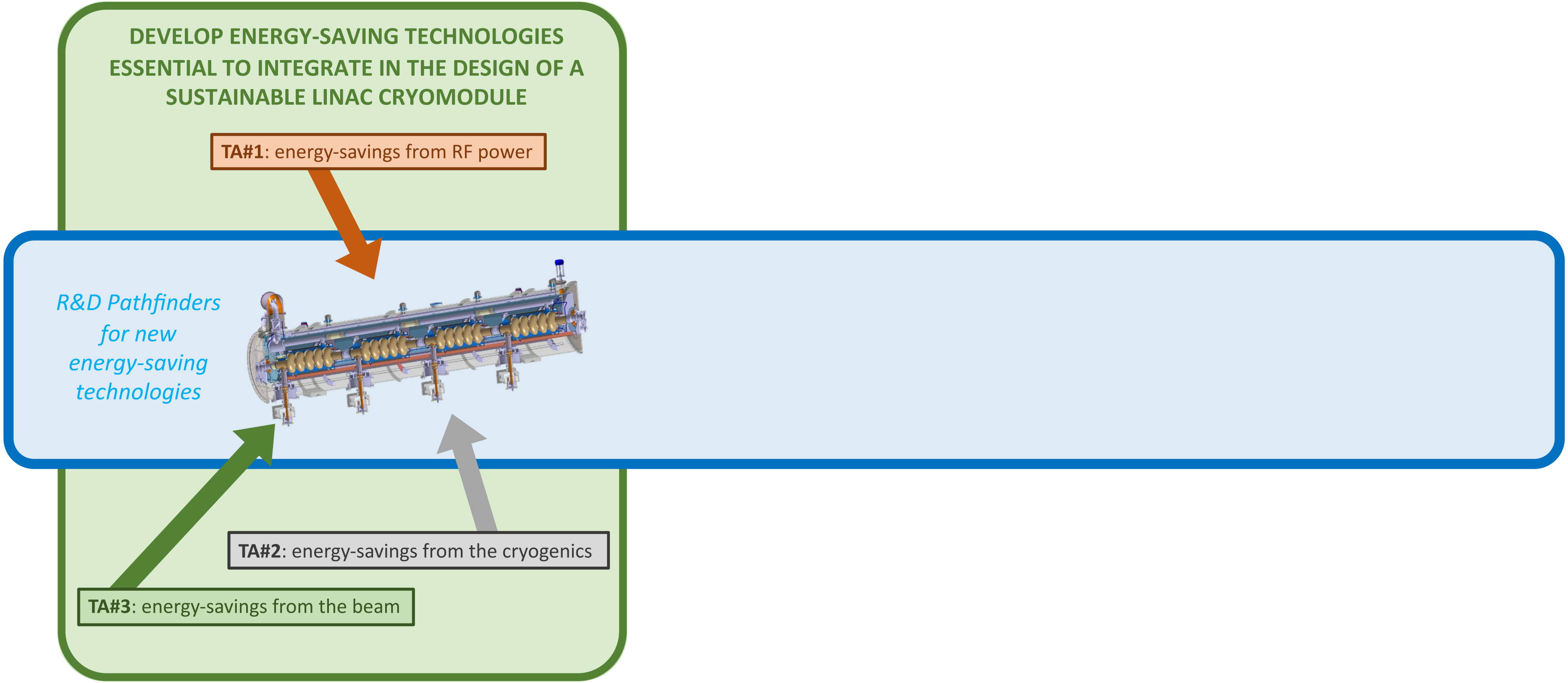
INNOVATE TECHNOLOGIES TOWARDS A SUSTAINABLE ACCELERATING SYSTEM



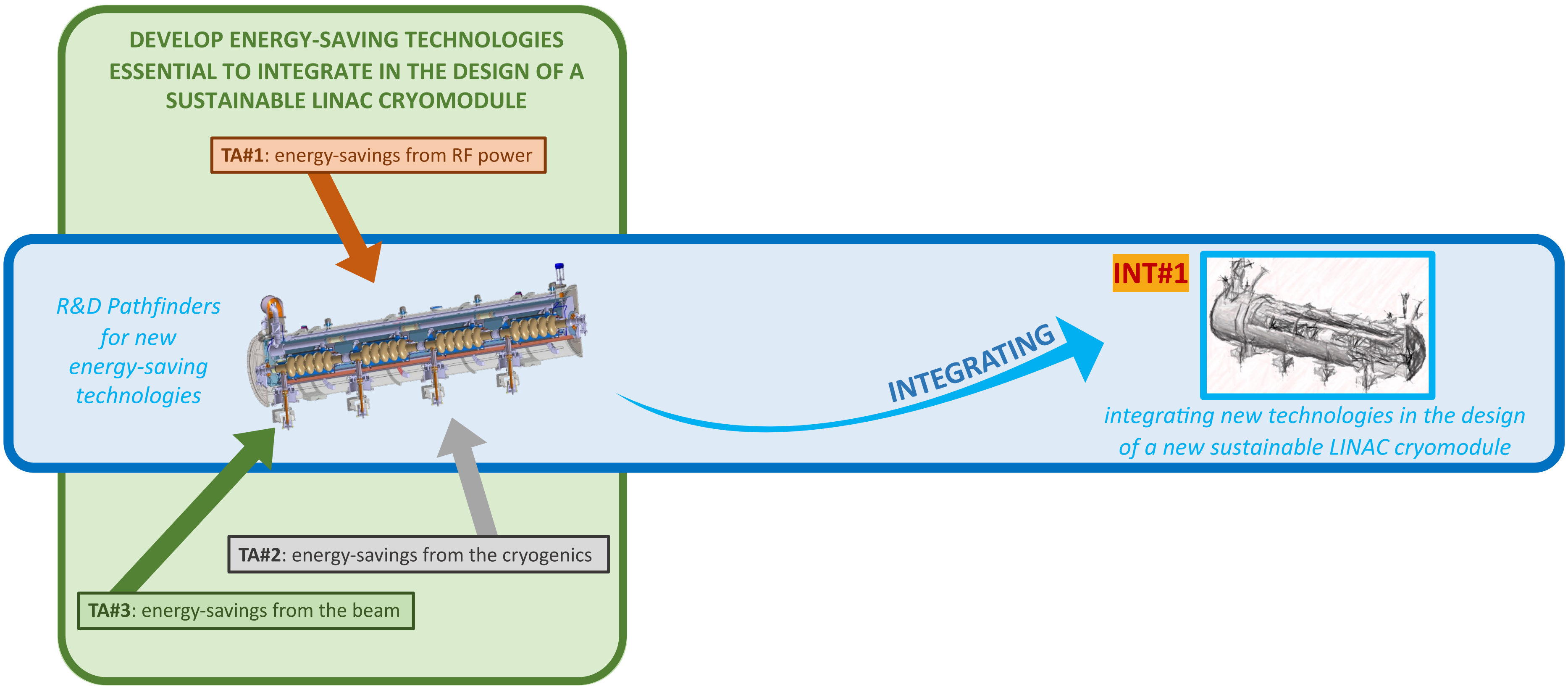
TODAY



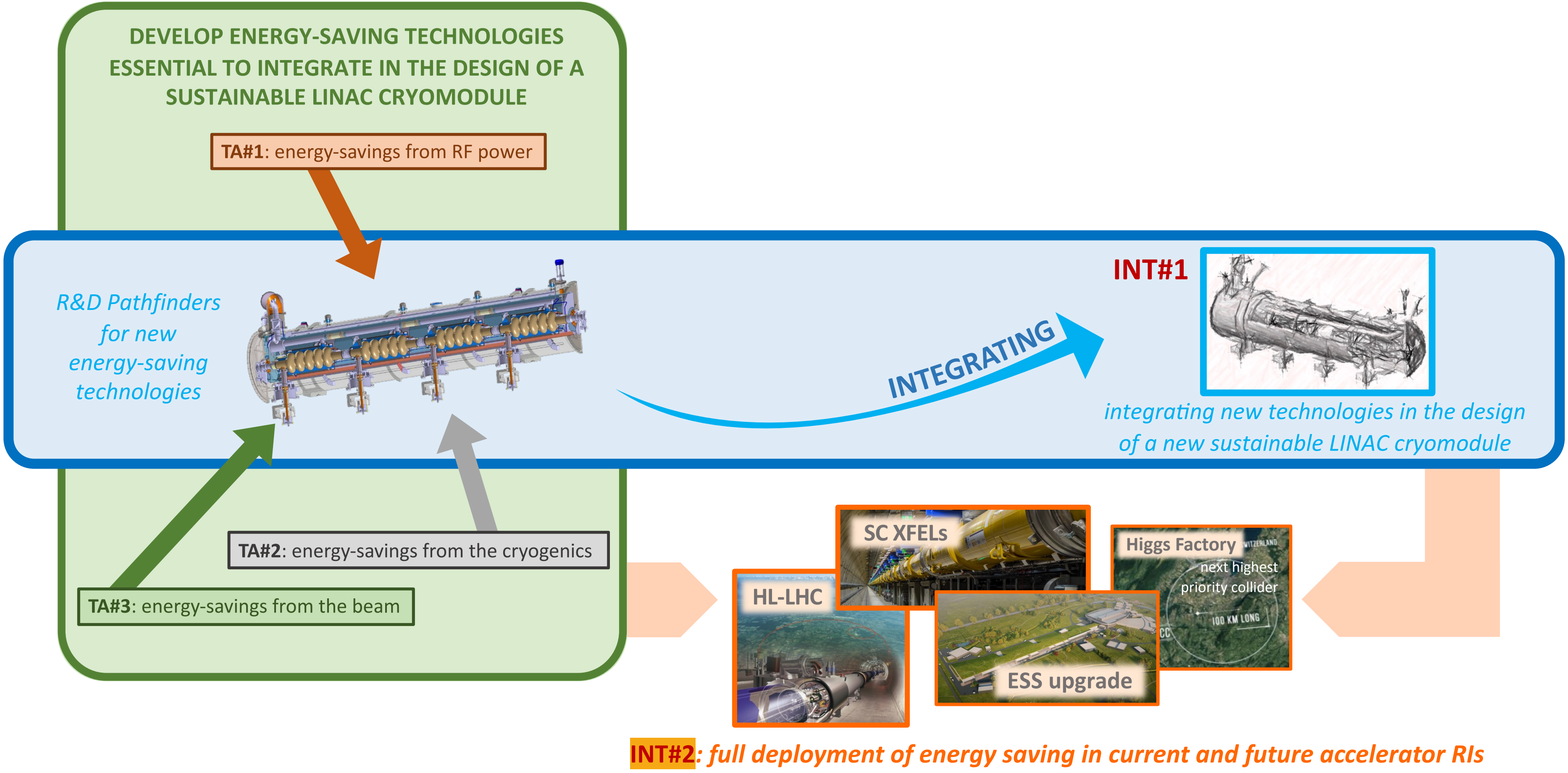
NEW DESIGN



TA: Technology Area

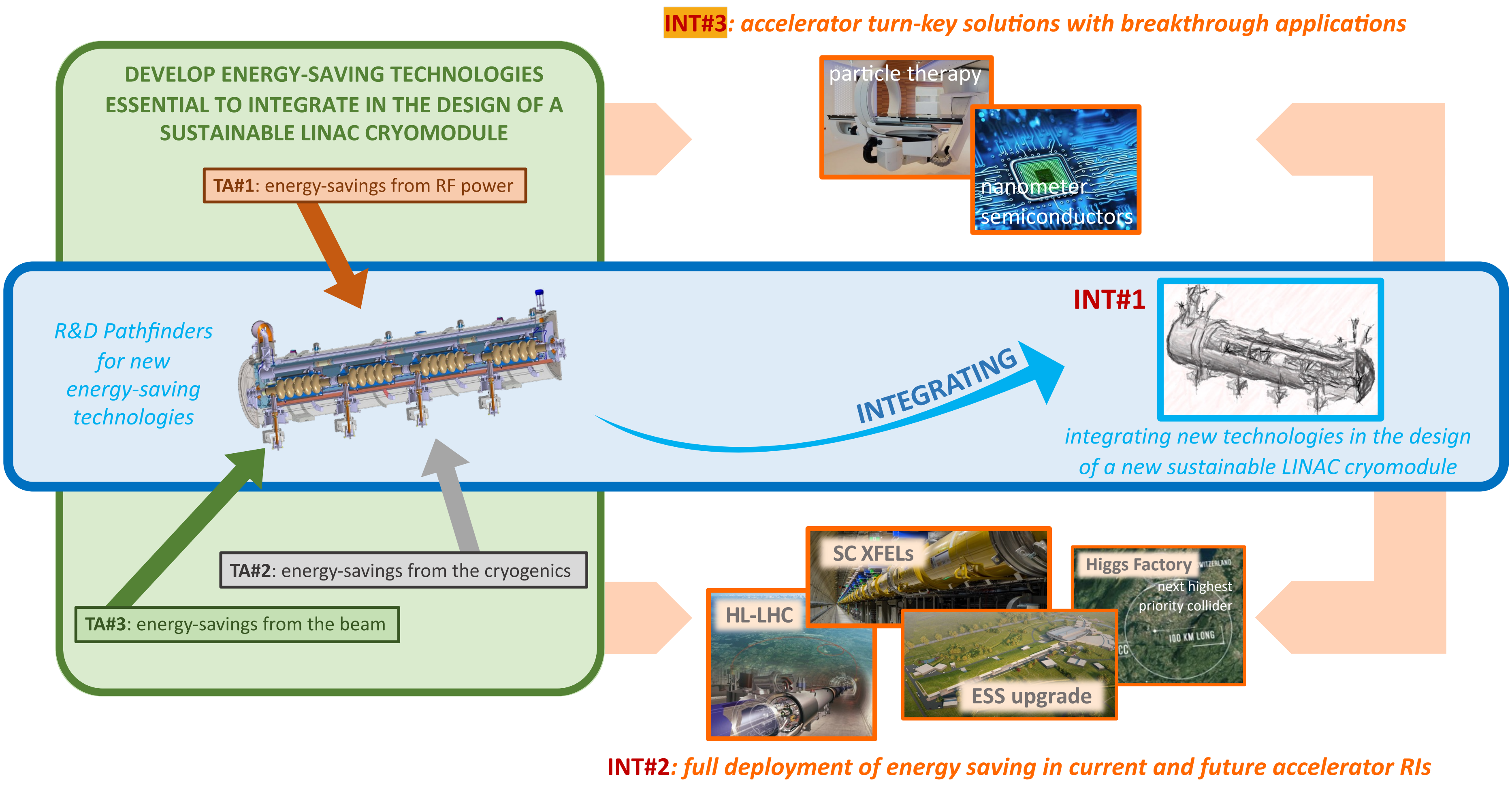


TA: Technology Area, INT: Integration Activities



TA: Technology Area, INT: Integration Activities

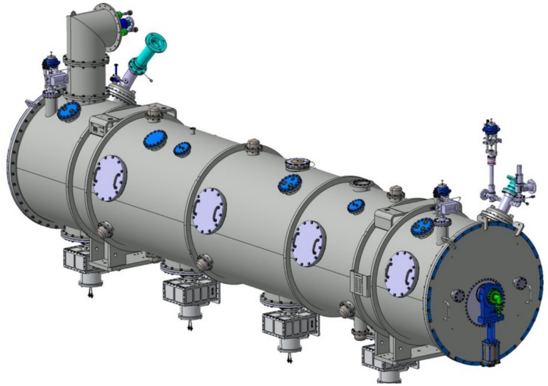
RIs: Research Infrastructures



INT#3: accelerator turn-key solutions with breakthrough applications
particle therapy
nanometer semiconductors
DEVELOP ENERGY-SAVING TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
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: full deployment of energy saving in current and future accelerator RIs

iSAS Objectives – *Integration Activities*

- **integration into the design of a LINAC cryomodule** – *While LINAC cryomodules are designed for specific accelerators, the objective of iSAS is to address the common engineering challenges of integrating iSAS energy-saving technologies into a parametric design of a new sustainable accelerator system.*



- **integration into existing RIs** – *While various RIs envisage upgrades, the objective of iSAS is to expedite the technical integration of energy-saving technologies by retrofitting existing accelerating systems. An existing cryomodule will be adapted, ready to demonstrate energy recovery of high-power recirculating beams in the PERLE research facility, paving the way for high-energy, high-intensity electron beams with minimal energy consumption.*

- **integration into industrial solutions** – *While iSAS technologies are emerging, the objective of iSAS is to plan for concrete co-developments with industry to expedite reaching a Technology Readiness Level (TRL) sufficiently advanced towards largescale deployment of the new energy-saving solutions at current and future RIs as well as to prepare the path for industrial applications. For many future RIs and industrial applications SRF is the enabling technology.*

iSAS *integration objectives*

very concrete

- **integration into the design of a LINAC cryomodule** **(ESS, CNRS, CERN, INFN, CERN, EPFL)**
  - *Lessons learned with ESS cryomodules and benchmarking with other recent facilities will be compiled, and a roadmap will be developed towards a new sustainable CM design.*
  - *Sustainable criteria for LINAC cryomodule design will be developed.*
  - *Beam dynamics will be developed for ERL-based accelerators with the energy-efficient iSAS technologies.*

- **integration into existing RIs** **(CNRS, Uni.Lanc., CEA, ESS, INFN)**
  - *Retrofitting FE-FRT into existing cryomodules, HL-LHC oriented.*
  - *Adapt an existing ESS cryomodule to integrate new HOM couplers and FPC.*
  - *Fabrication and validation of cryomodule components (e.g., cavities).*
  - *Assembly and (cryogenic and RF) tests of adapted cryomodule.*

- **integration into industrial solutions** **(INFN, CNRS)**
  - *<u>Relations with industries</u>: engagement to expedite the evolution from low to higher TRL (involving an Industry Board involved in design reviews with a view on industrialization).*
  - *<u>Business opportunities</u>: develop an iSAS project repository and disseminate the innovative technologies.*

iSAS *integration objectives*

very concrete

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ready to demonstrate energy recovery of high-power recirculating beams with PERLE

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PERLE – Powerful Energy Recovery Linac for Experiments

[CDR: *J.Phys.G* 45 (2018) 6, 065003]

PERLE @ IJCLab (Orsay/Paris, France)

- *growing international collaboration with impactful in-kind contributions*
- *all ERL aspects to demonstrate readiness*
- *for e^+e^- and ep/eA HEP collider applications*

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

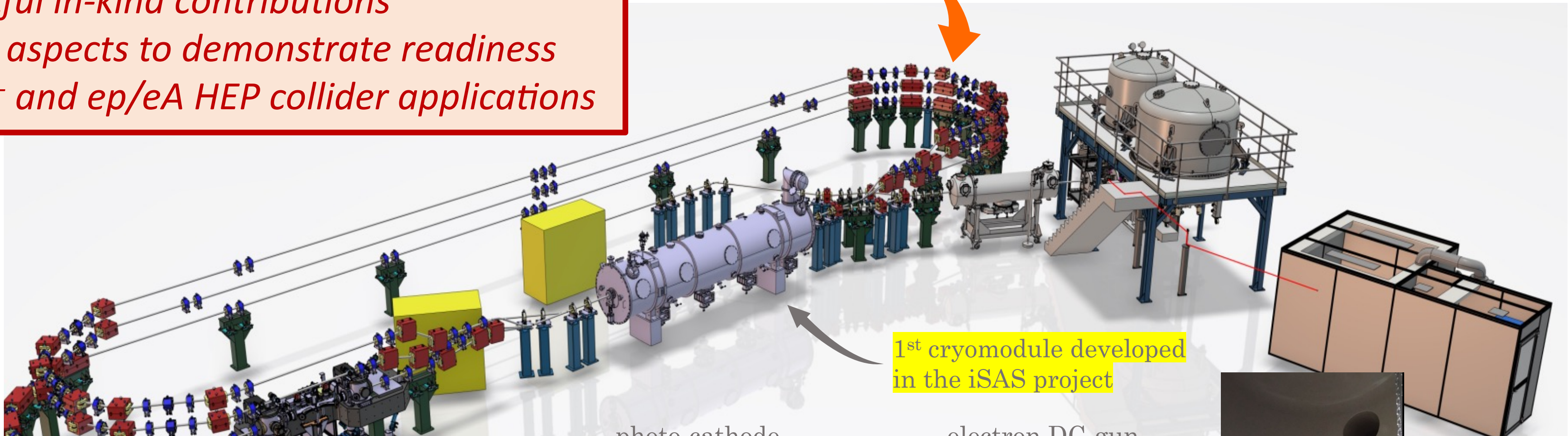


photo-cathode

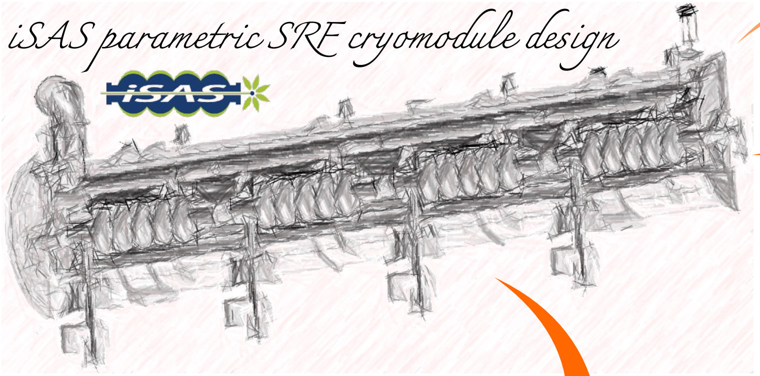
electron DC-gun

First stage: one-turn by 2028

(pending some budget requests and additional in-kind contributions)

implementation started

iSAS will have a catalyzing effect to realize the European Accelerator R&D Roadmap for particle physics and high-power SRF accelerators in general



an many more of the thousands of accelerators worldwide

Innovate for Sustainable Accelerating Systems (iSAS)

https://isas.ijclab.in2p3.fr

- **Enabling technologies for our most prominent future accelerator programs delivering breakthrough performances, i.e. best physics for least power**
- **Connects leading European institutions and industry to expedite the development of sustainable technologies essential to realise our ambitions**
- **The energy saving technologies further developed in iSAS will enable industrial applications with SRF accelerators**

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https://isas.ijclab.in2p3.fr

- Enabling technologies for our most prominent future accelerator programs delivering breakthrough performances, i.e. best physics for least power
- Connects leading European institutions and industry to expedite the development of sustainable technologies essential to realise our ambitions
- The energy saving technologies further developed in iSAS will enable industrial applications with SRF accelerators

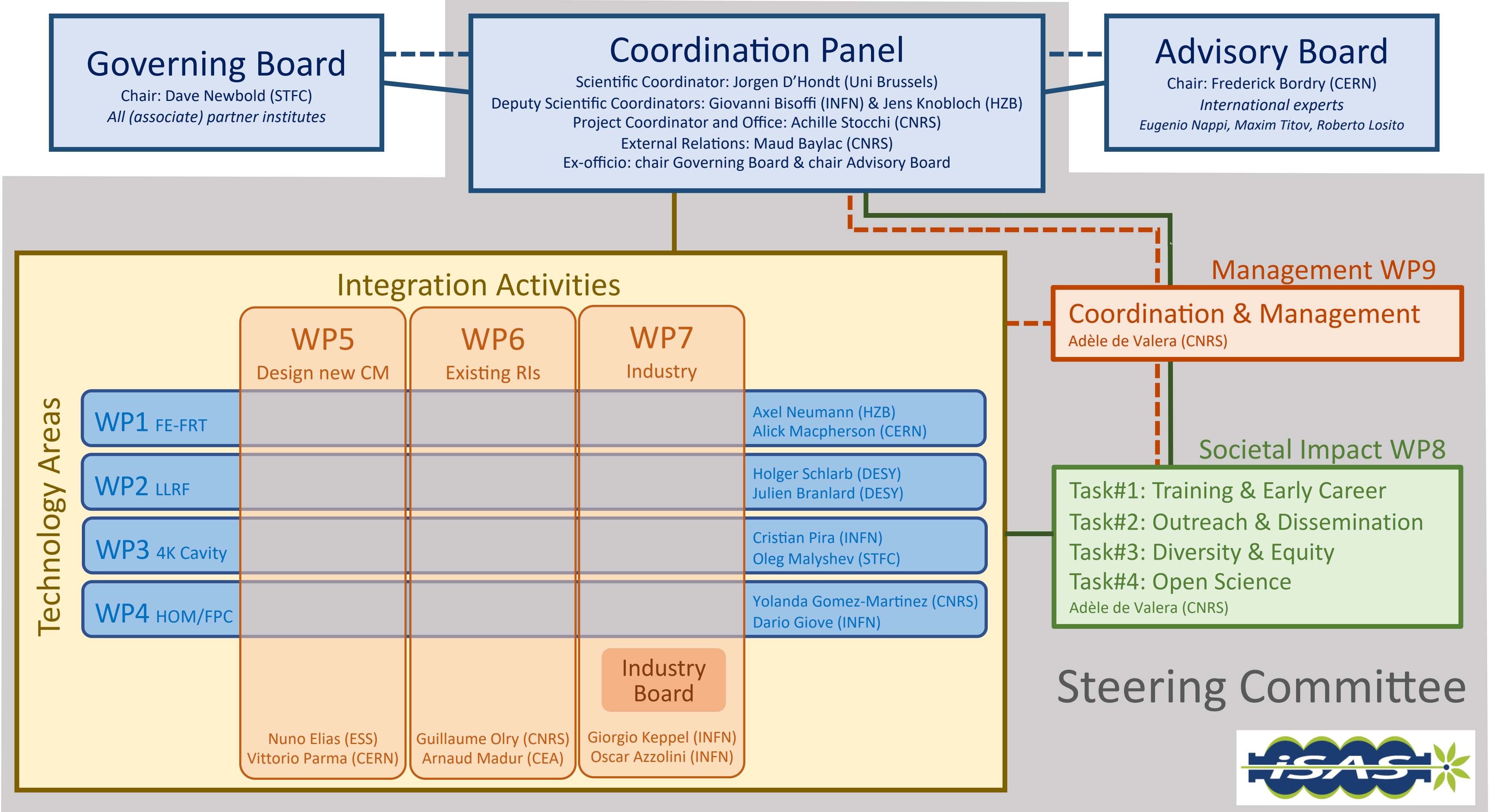
the potential risk is so dramatic that we must foster this R&D path

addressing sustainability is not the easiest path, but a strategic choice & responsibility

HIGH-ENERGY PHYSICS RESEARCH CENTRE

Thank you for your attention!

Jorgen.DHondt@vub.be



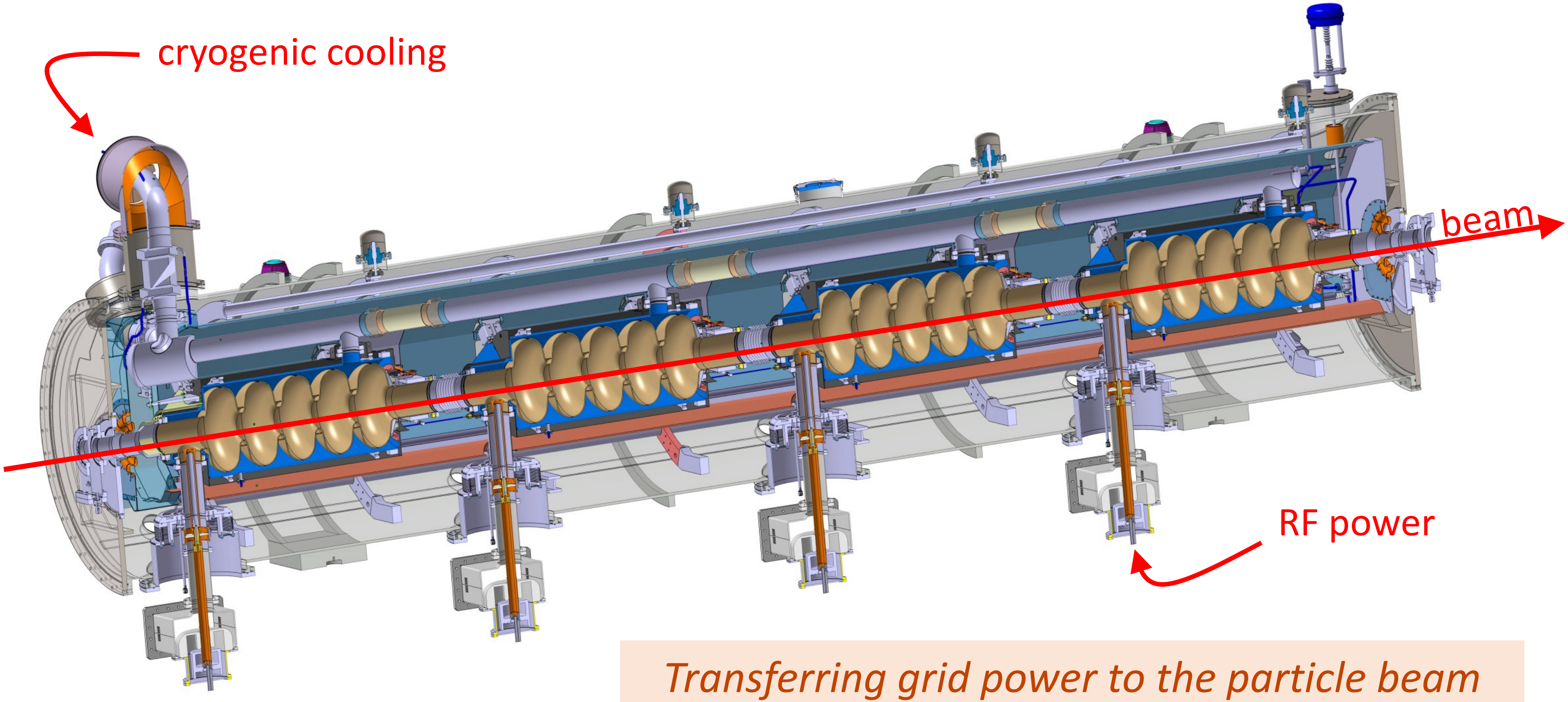
Governing Board
Chair: Dave Newbold (STFC)
All (associate) partner institutes
Coordination Panel
Scientific Coordinator: Jorgen D'Hondt (Uni Brussels)
Deputy Scientific Coordinators: Giovanni Bisoffi (INFN) & Jens Knobloch (HZB)
Project Coordinator and Office: Achille Stocchi (CNRS)
External Relations: Maud Baylac (CNRS)
Ex-officio: chair Governing Board & chair Advisory Board
Advisory Board
Chair: Frederick Bordry (CERN)
International experts
Eugenio Nappi, Maxim Titov, Roberto Losito
Integration Activities
WP5
Design new CM
WP6
Existing RIs
WP7
Industry
Technology Areas
WP1 FE-FRT
Axel Neumann (HZB)
Alick Macpherson (CERN)
WP2 LLRF
Holger Schlarb (DESY)
Julien Branlard (DESY)
WP3 4K Cavity
Cristian Pira (INFN)
Oleg Malyshev (STFC)
WP4 HOM/FPC
Yolanda Gomez-Martinez (CNRS)
Dario Giove (INFN)
Industry Board
Nuno Elias (ESS)
Vittorio Parma (CERN)
Guillaume Olry (CNRS)
Arnaud Madur (CEA)
Giorgio Keppel (INFN)
Oscar Azzolini (INFN)
Management WP9
Coordination & Management
Adèle de Valera (CNRS)
Societal Impact WP8
Task#1: Training & Early Career
Task#2: Outreach & Dissemination
Task#3: Diversity & Equity
Task#4: Open Science
Adèle de Valera (CNRS)
Steering Committee

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

European Strategy for Particle Physics 2020

Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

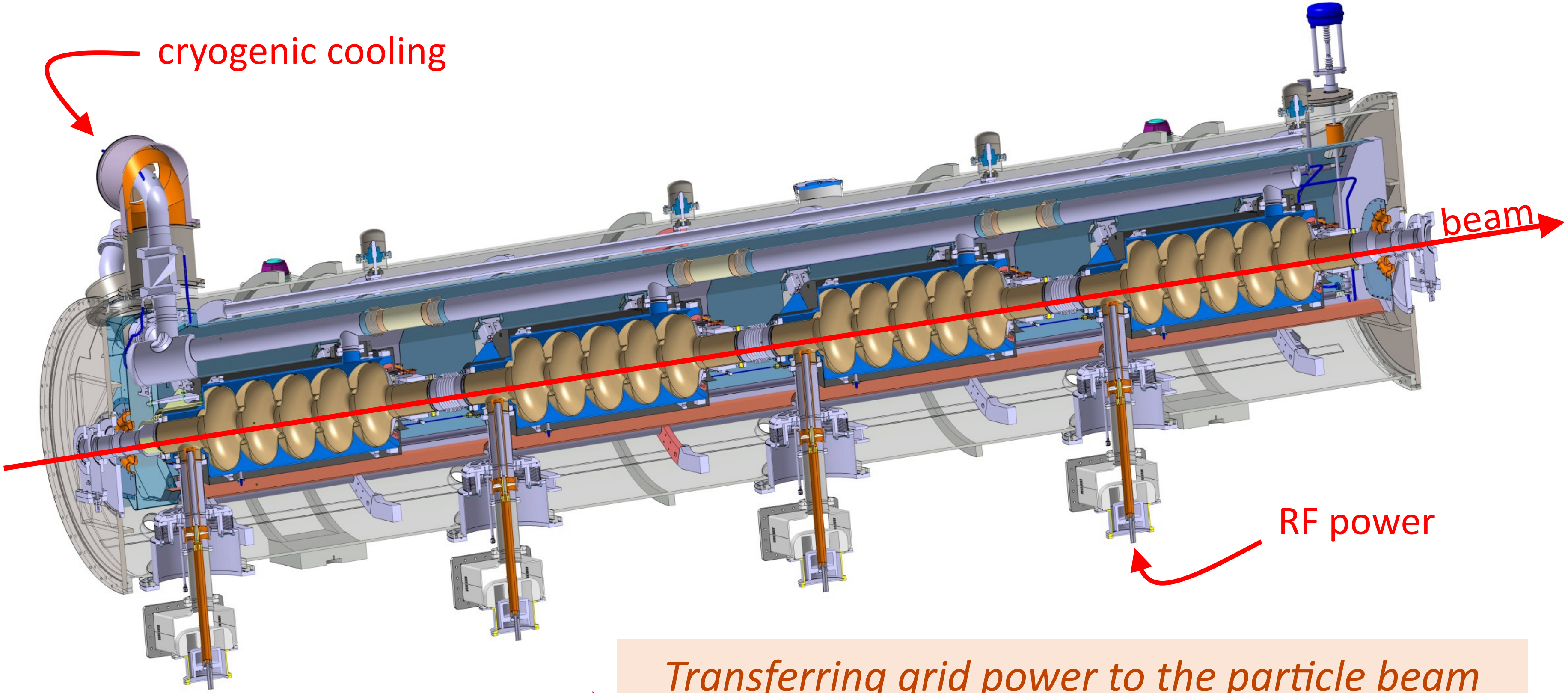


Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

Key building block for beam acceleration: the SRF cryomodule

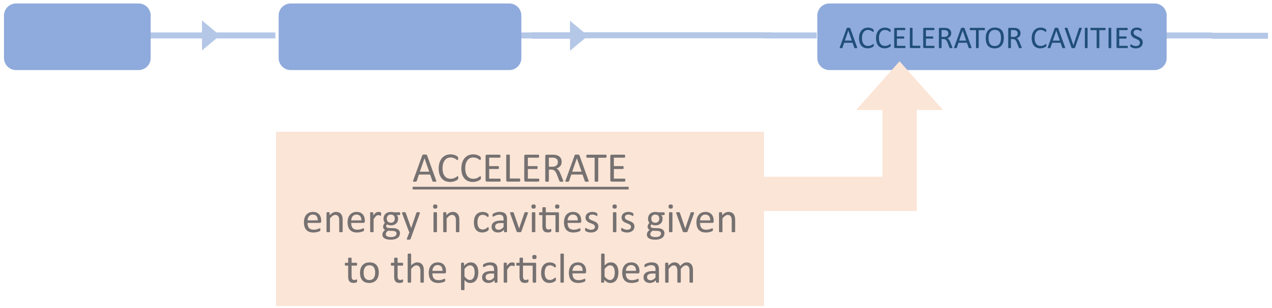
SRF: Superconducting Radio Frequency



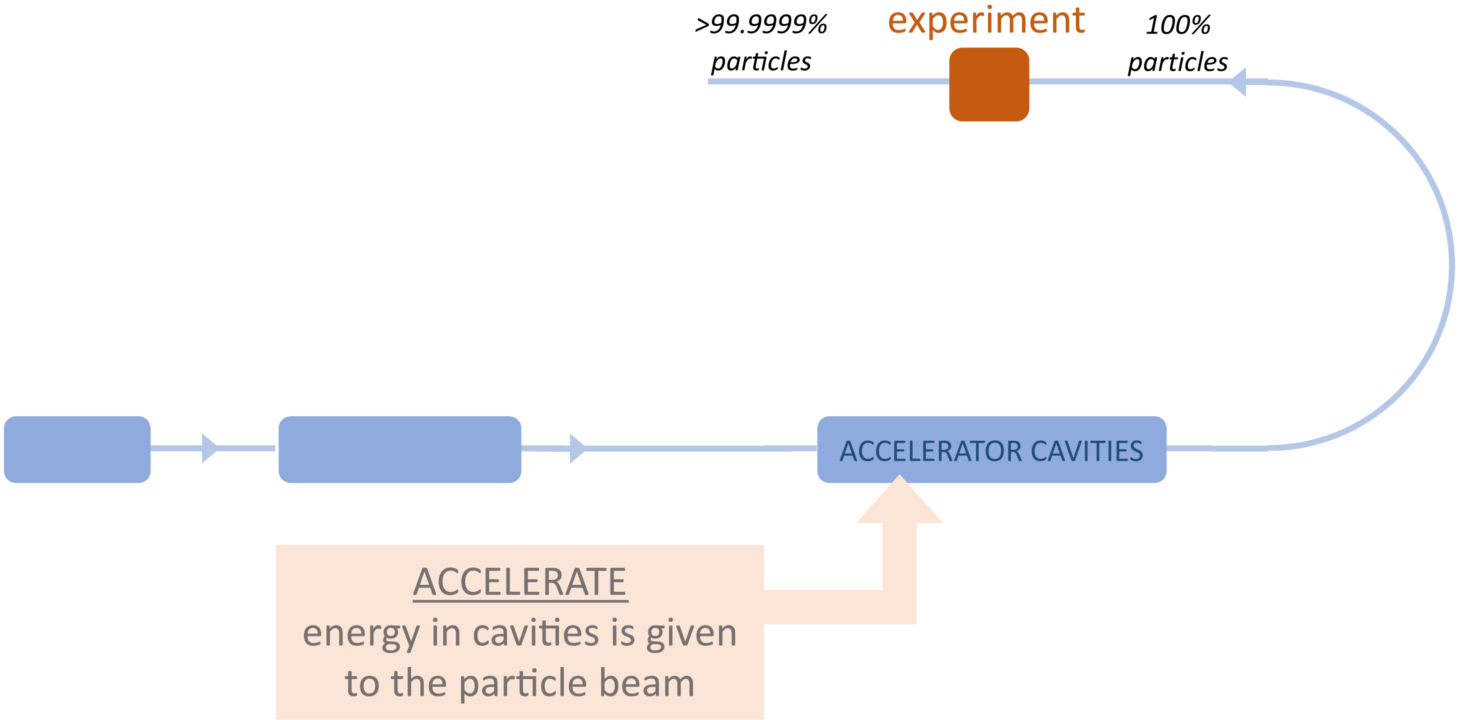
ENERGY RECOVERY →

Transferring grid power to the particle beam
RECOVER THE ENERGY FROM THE USED BEAM

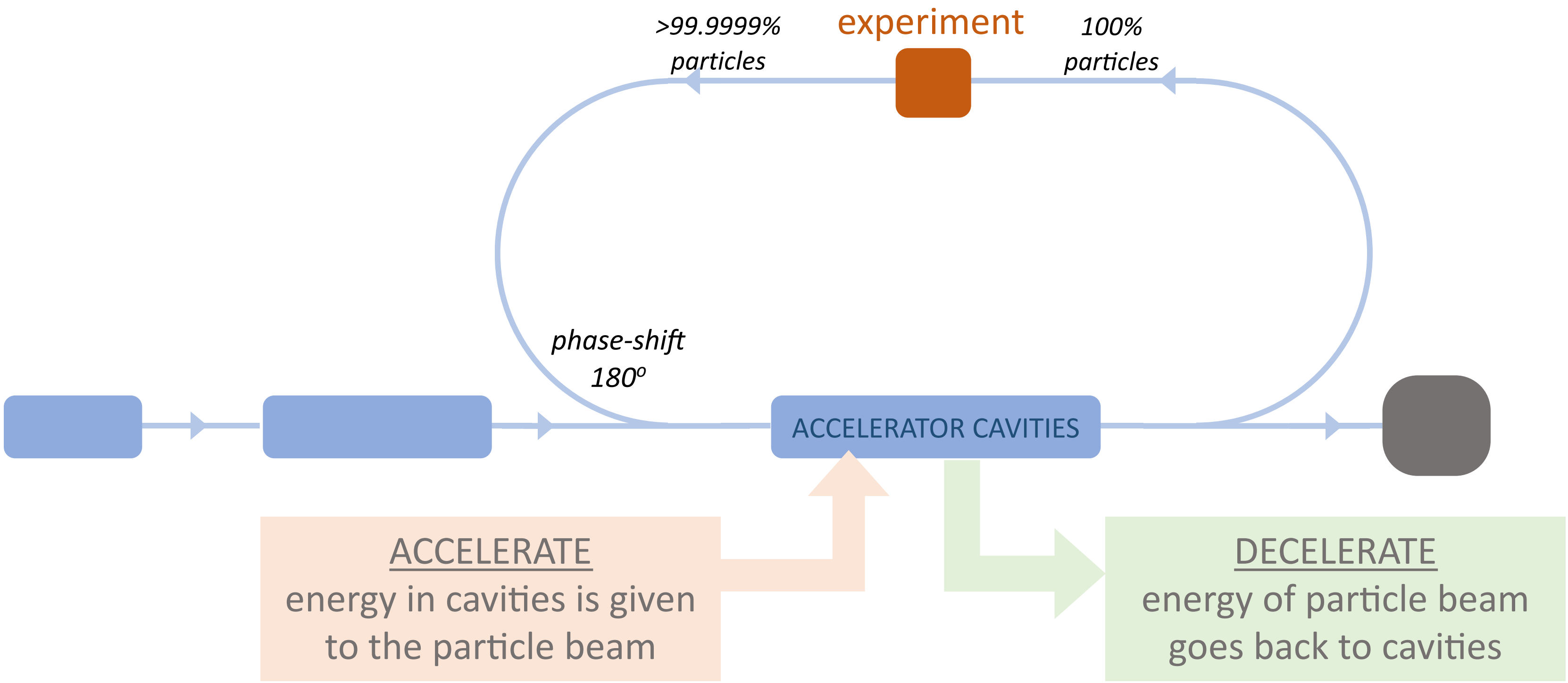
The principle of Energy Recovery



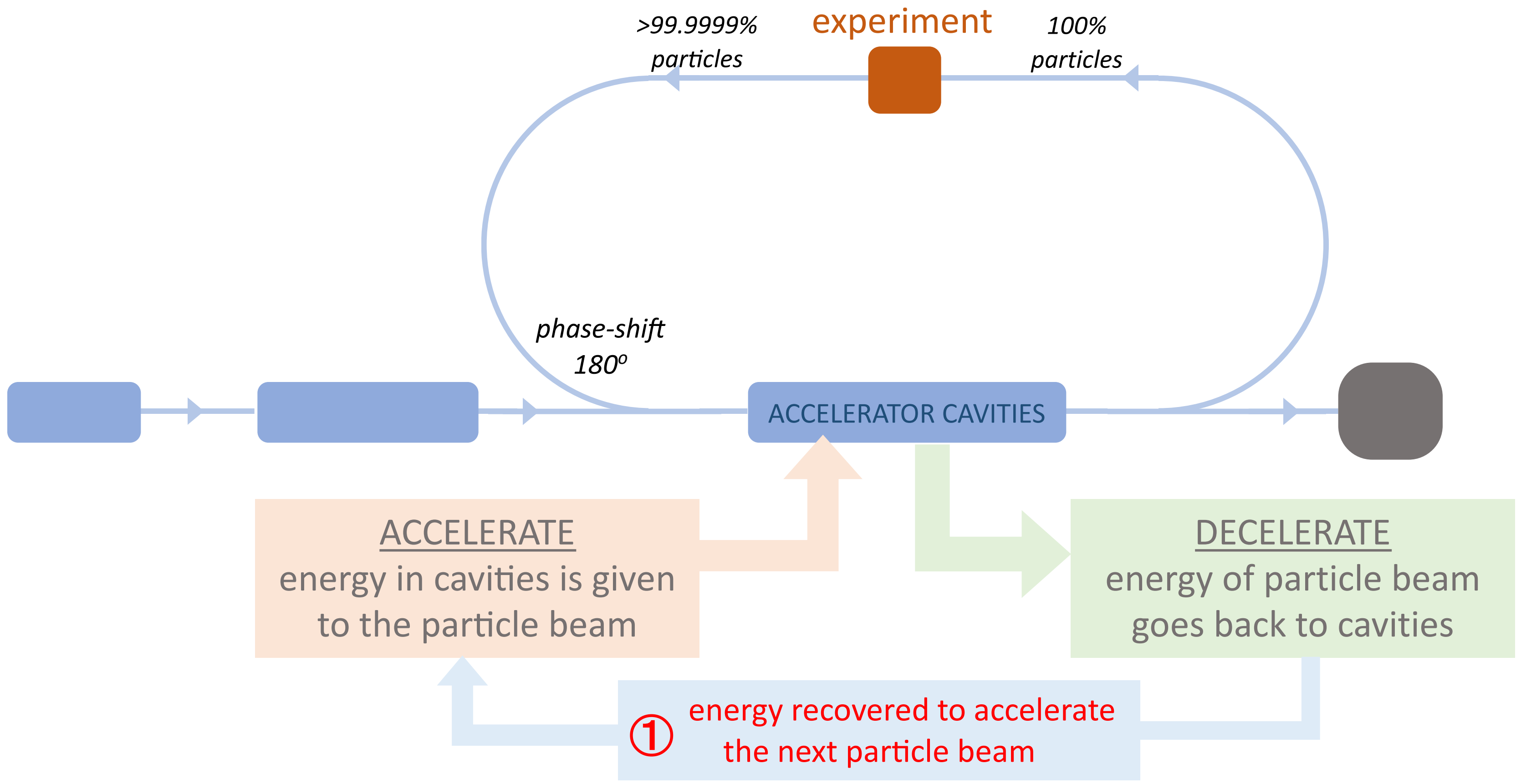
The principle of Energy Recovery



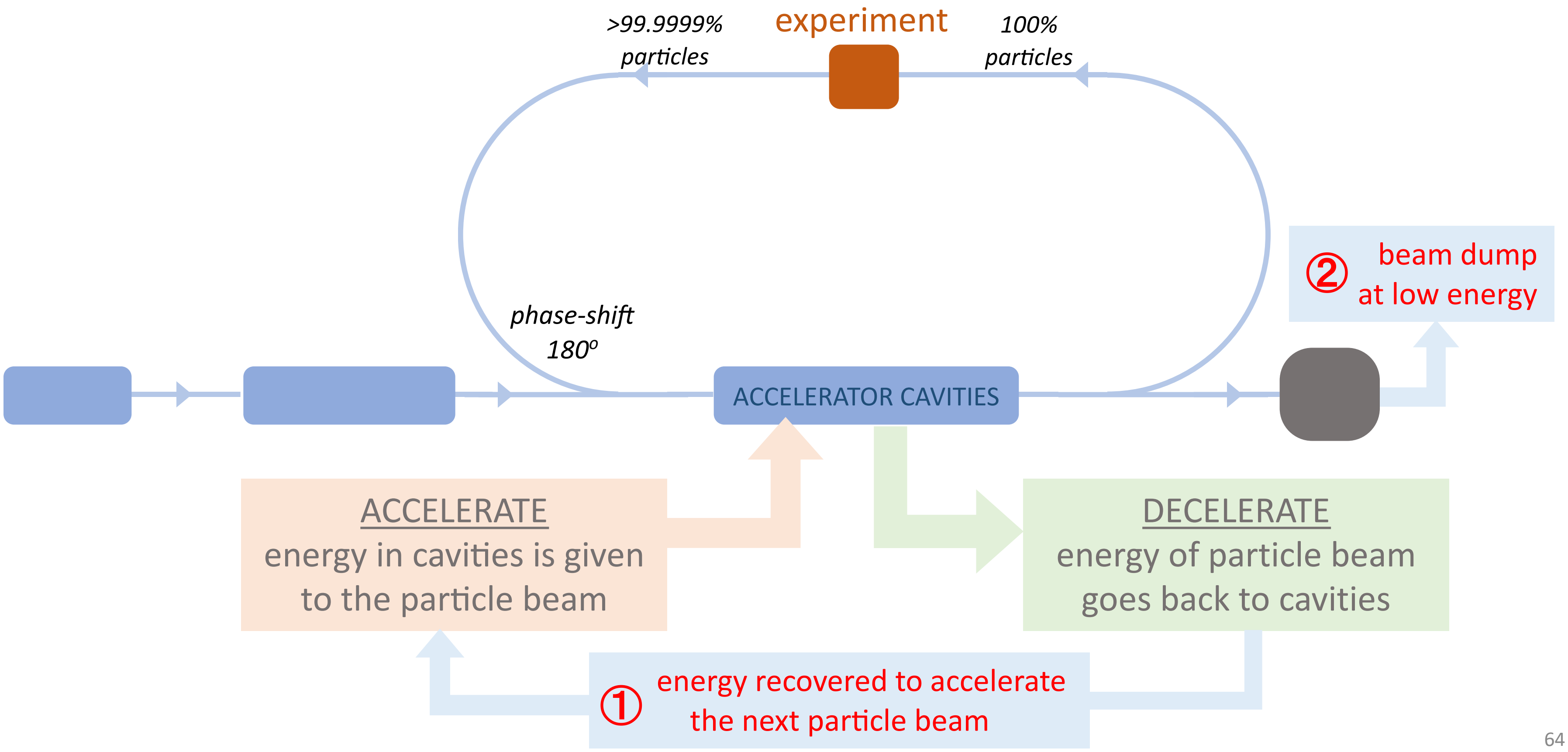
The principle of Energy Recovery



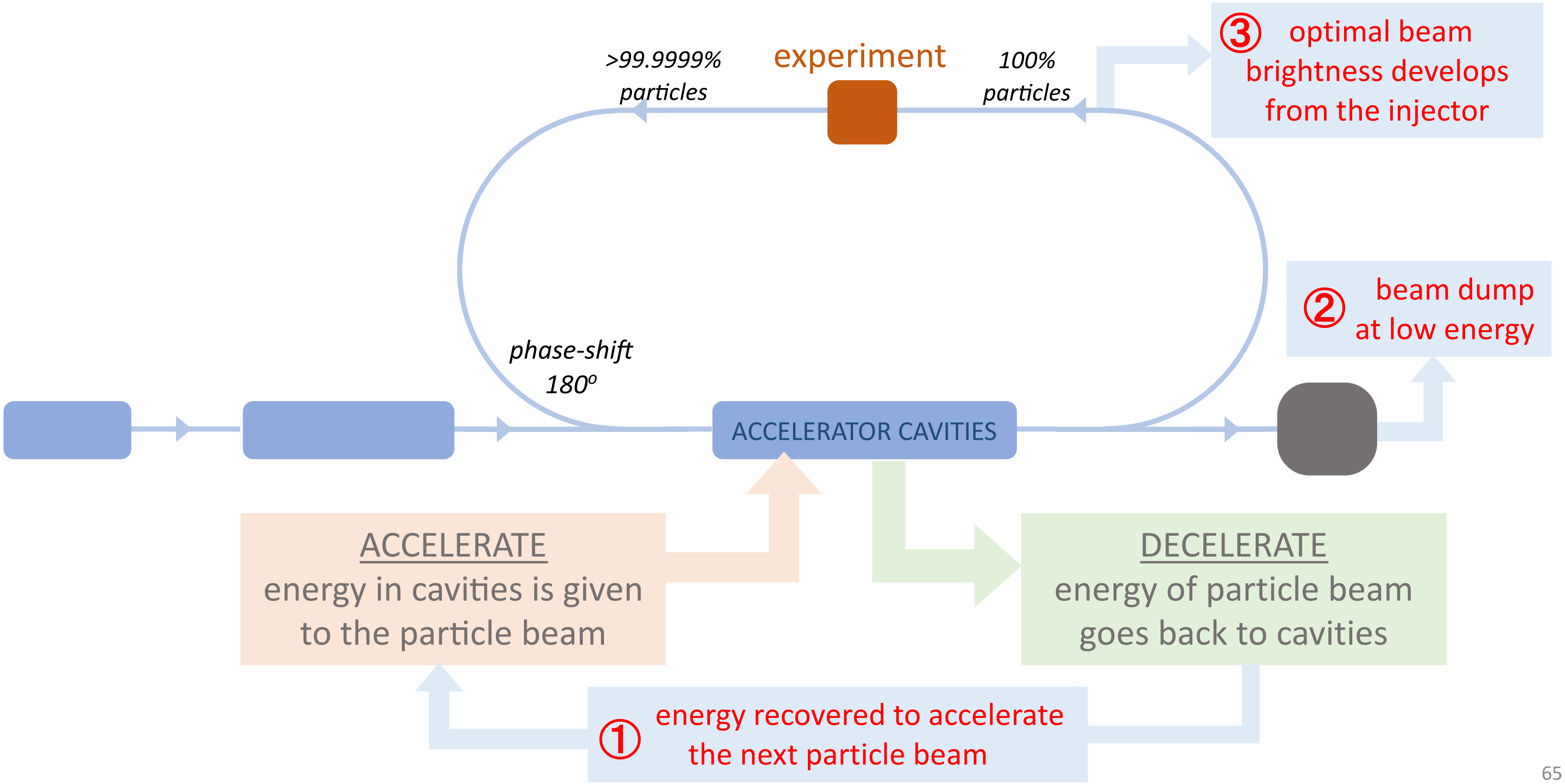
The principle of Energy Recovery



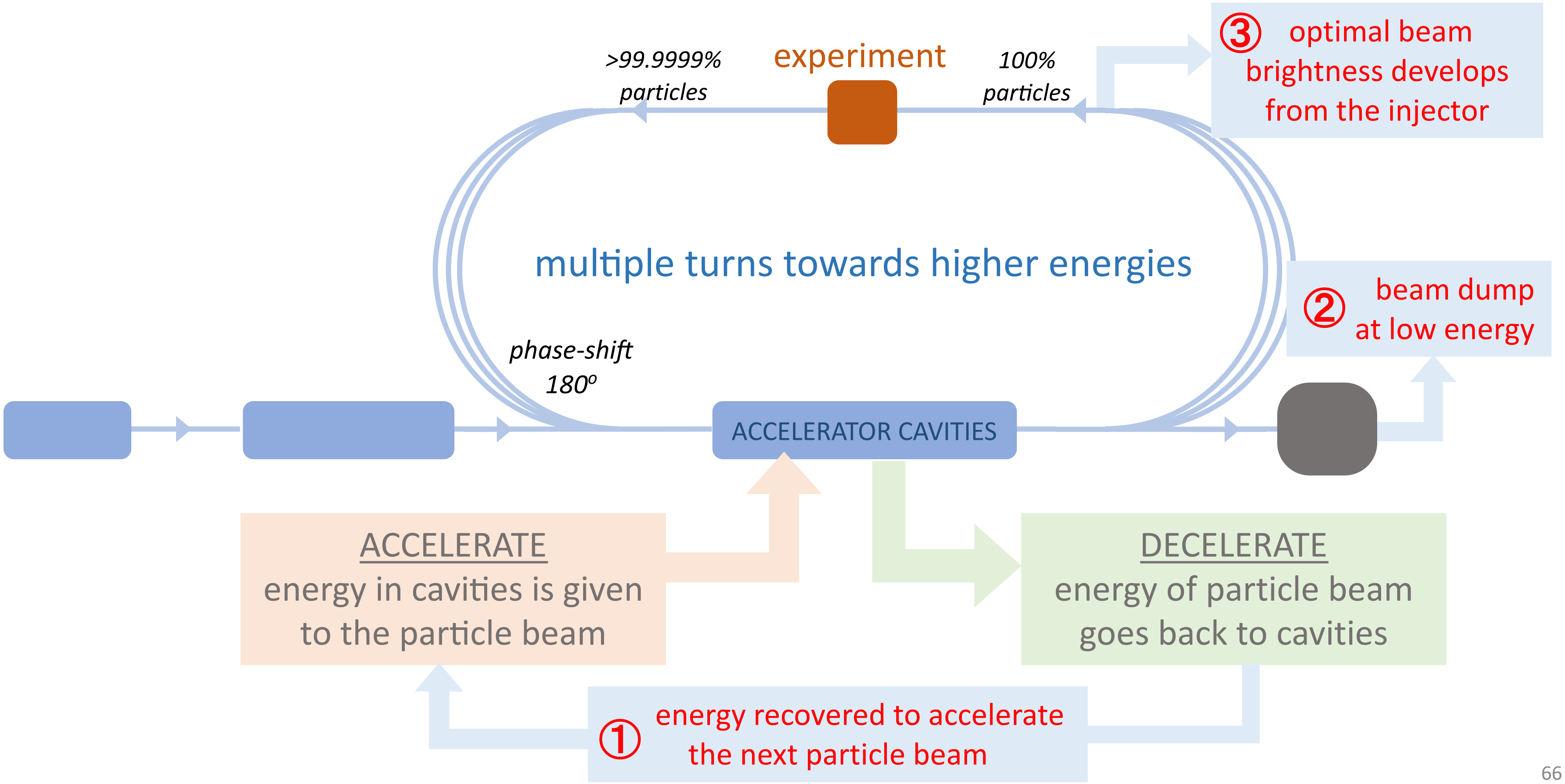
The principle of Energy Recovery



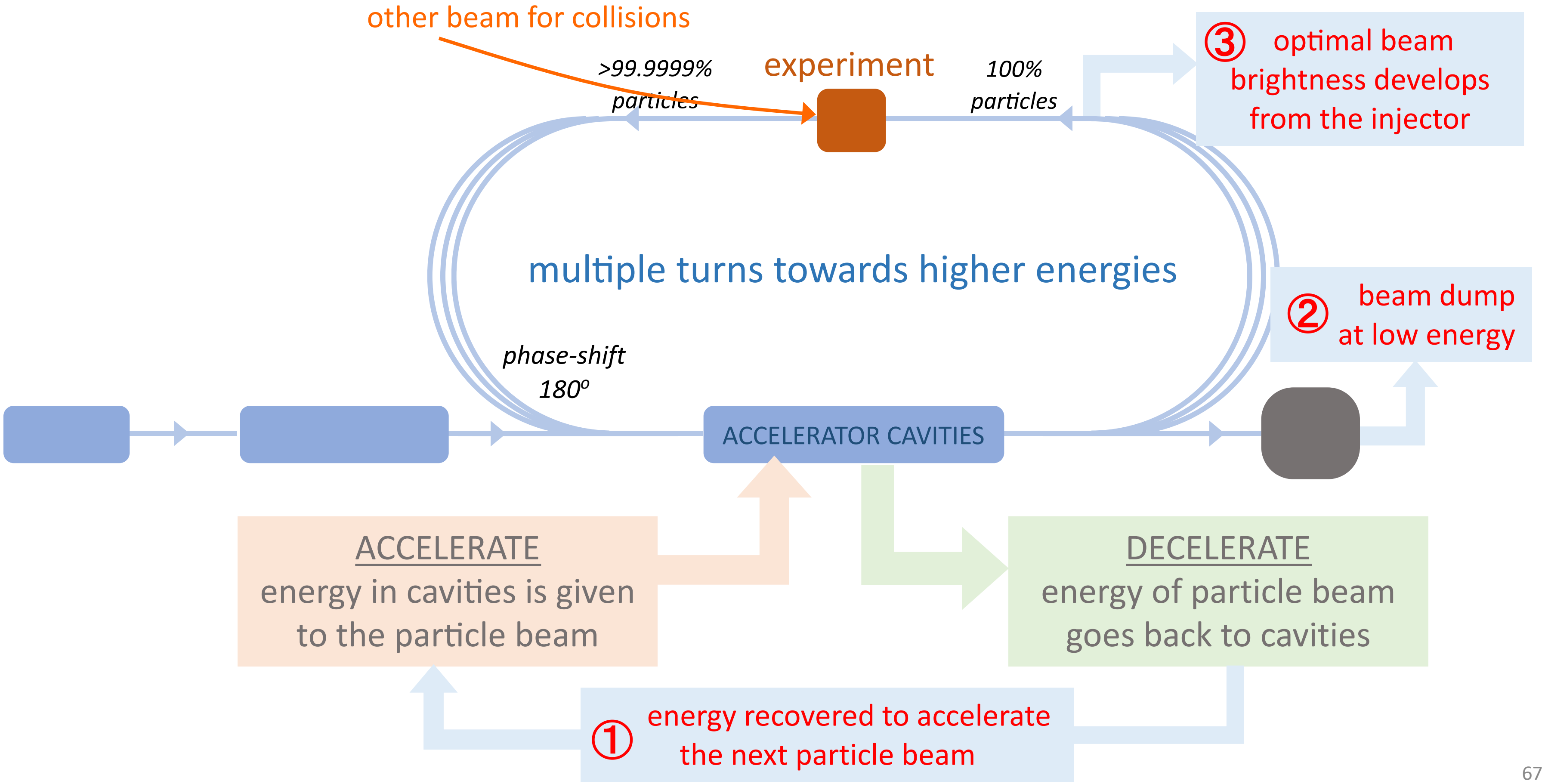
The principle of Energy Recovery



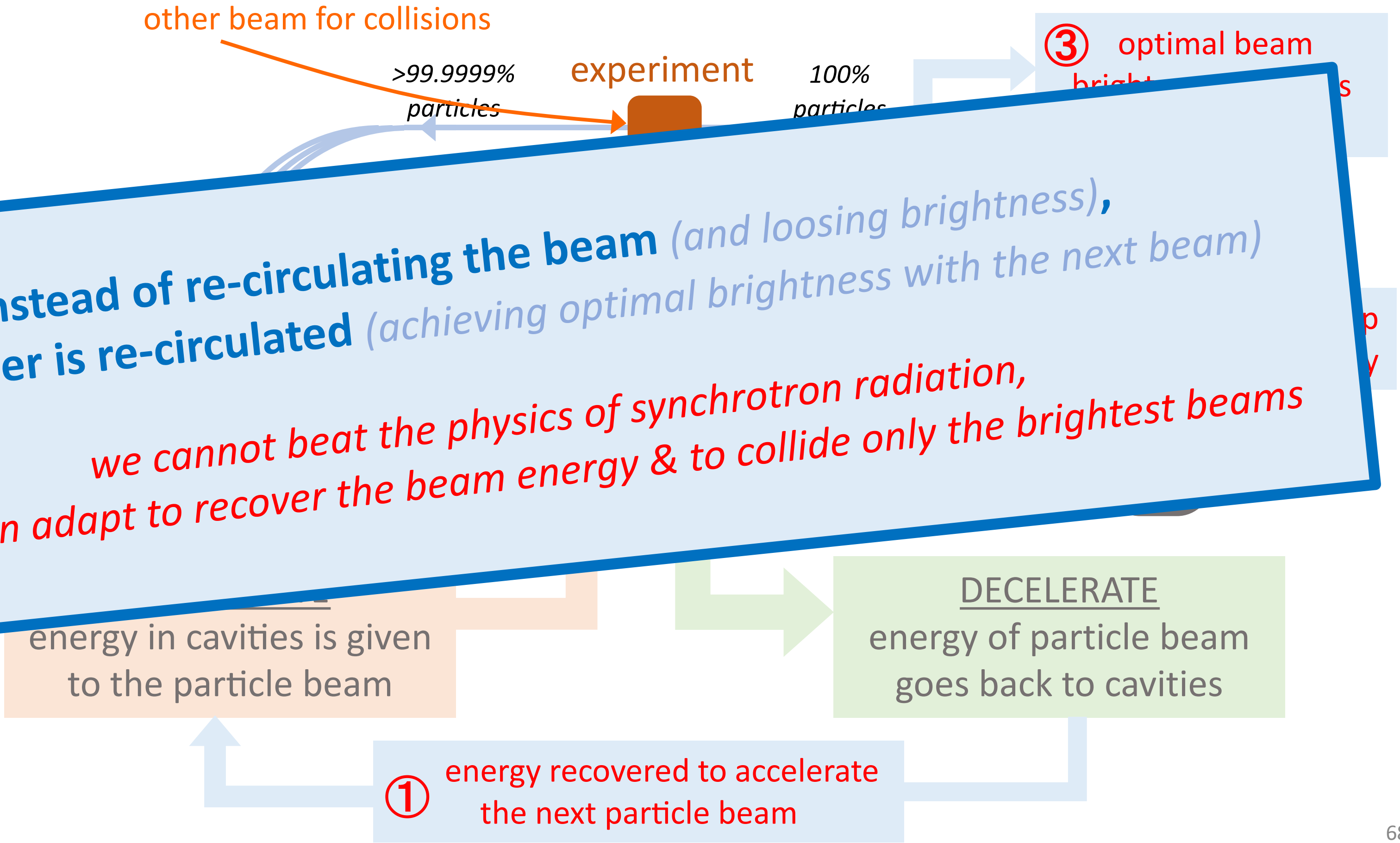
The principle of Energy Recovery



The principle of Energy Recovery



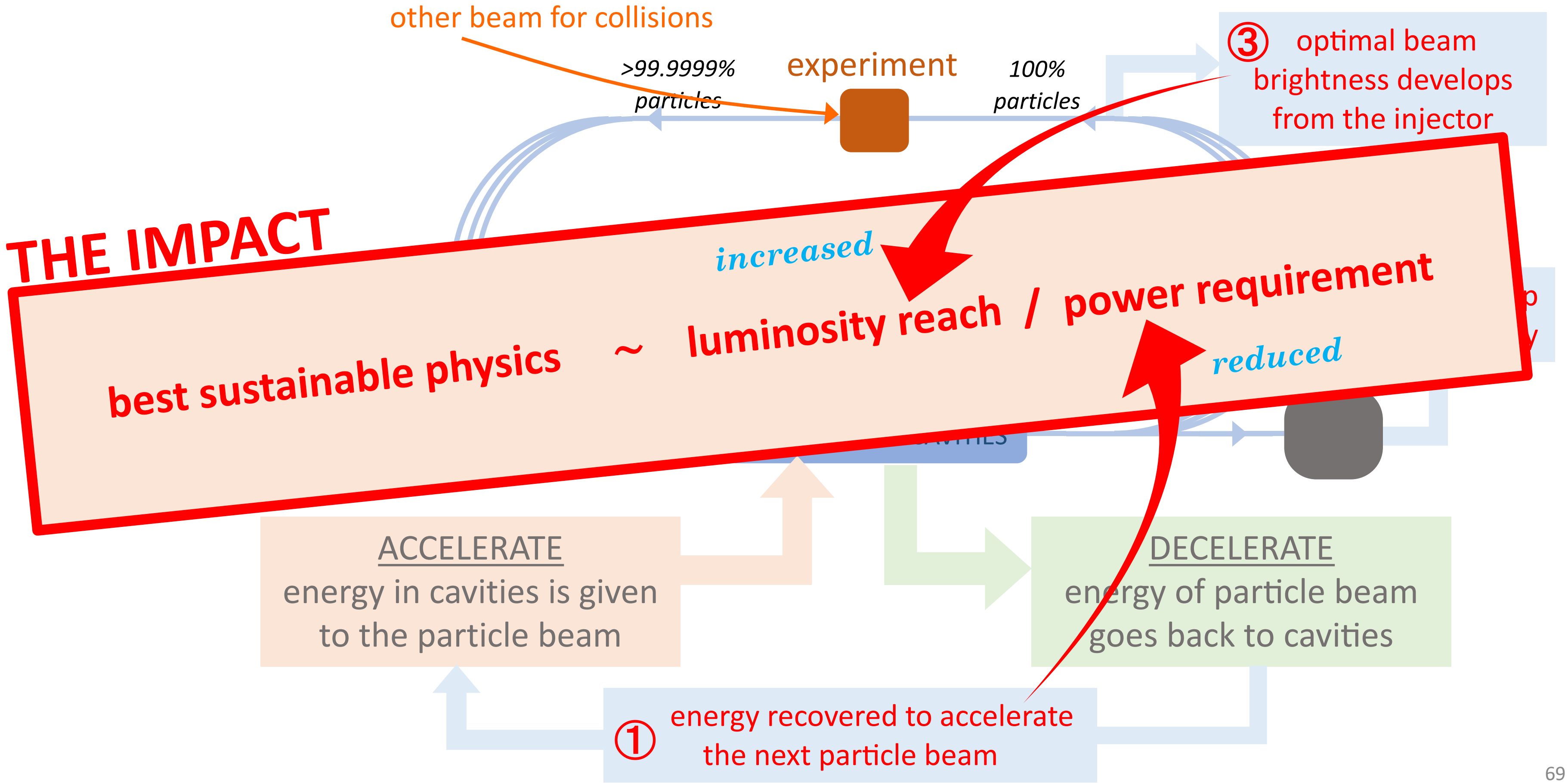
The principle of Energy Recovery



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

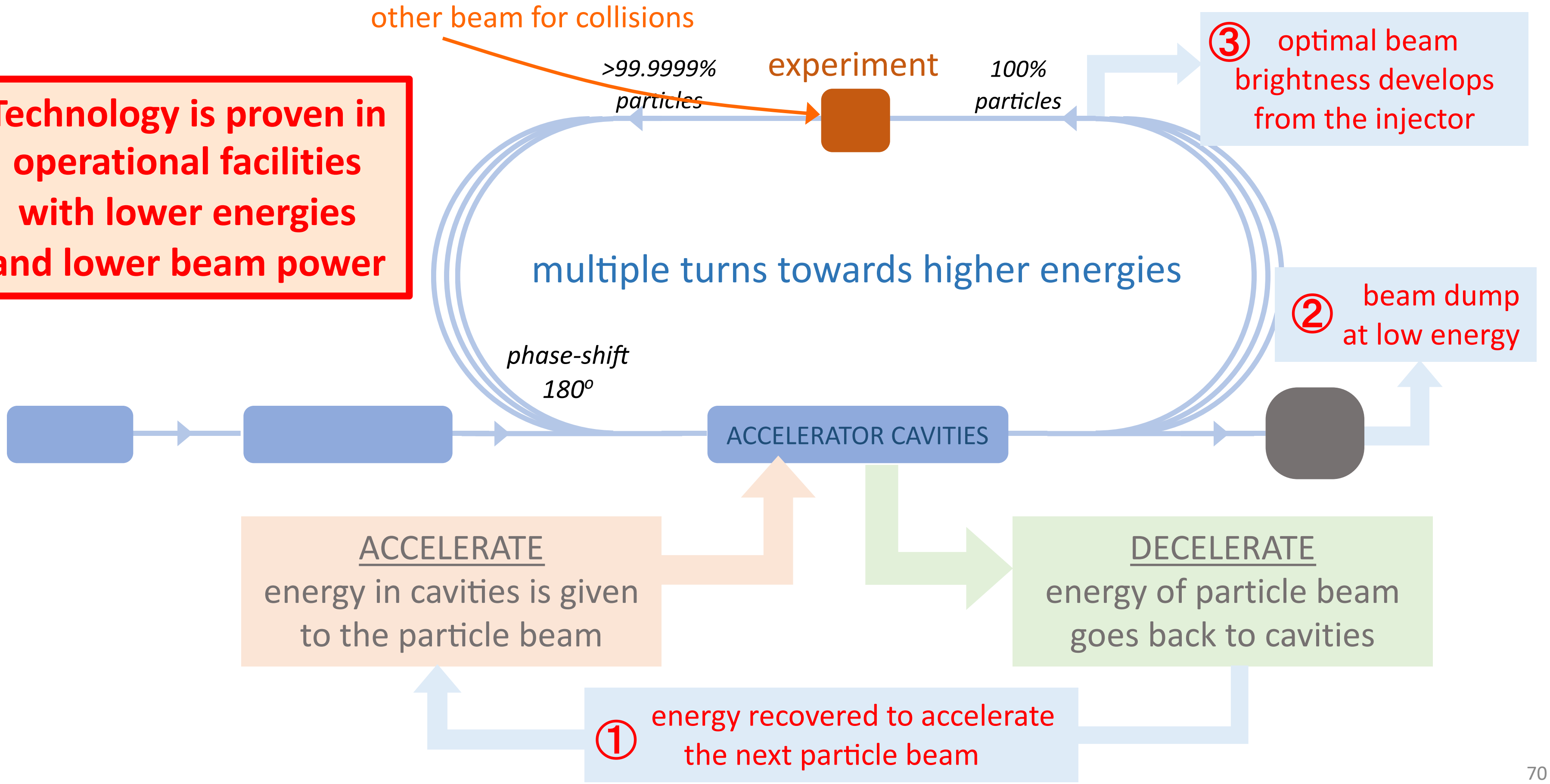
we cannot beat the physics of synchrotron radiation,
but we can adapt to recover the beam energy & to collide only the brightest beams

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

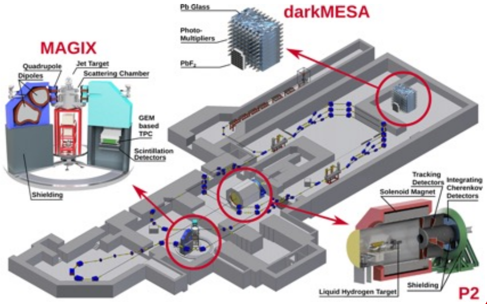
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

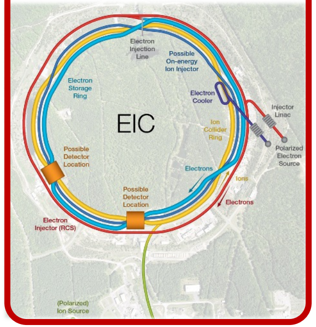
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

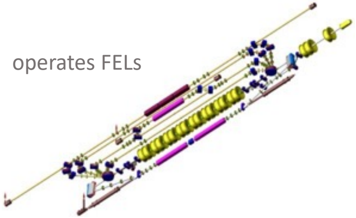
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

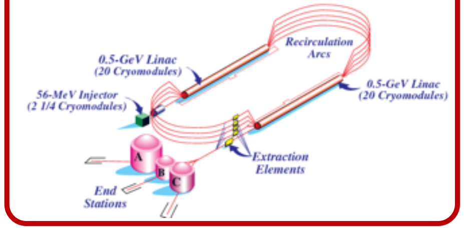
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes

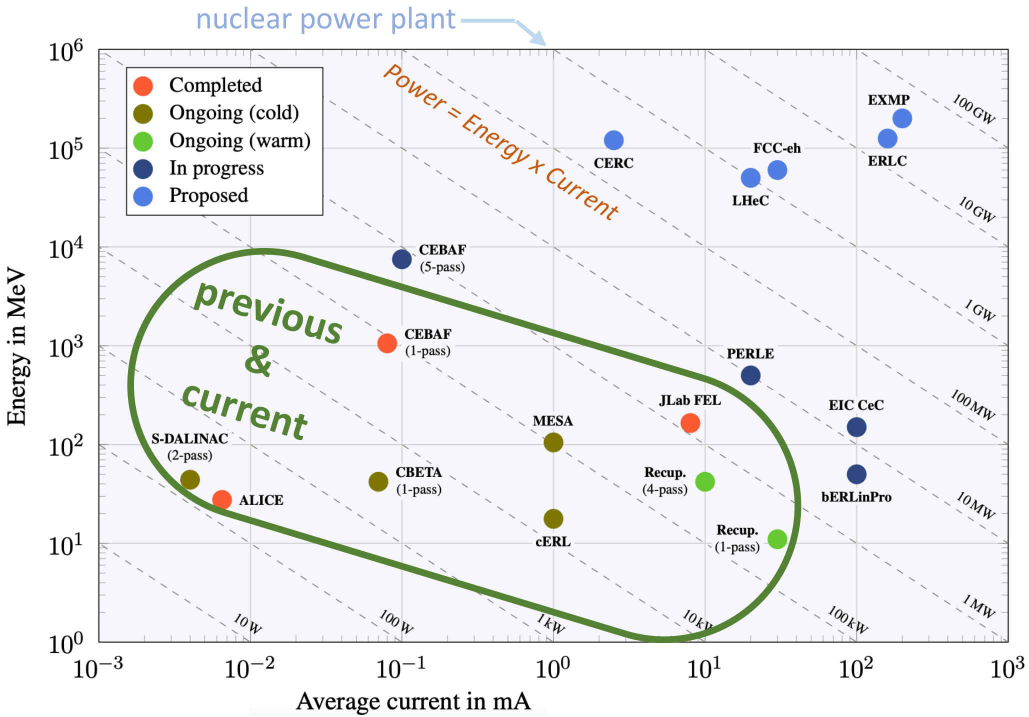


in progress

Upcoming: bERLinPro & PERLE

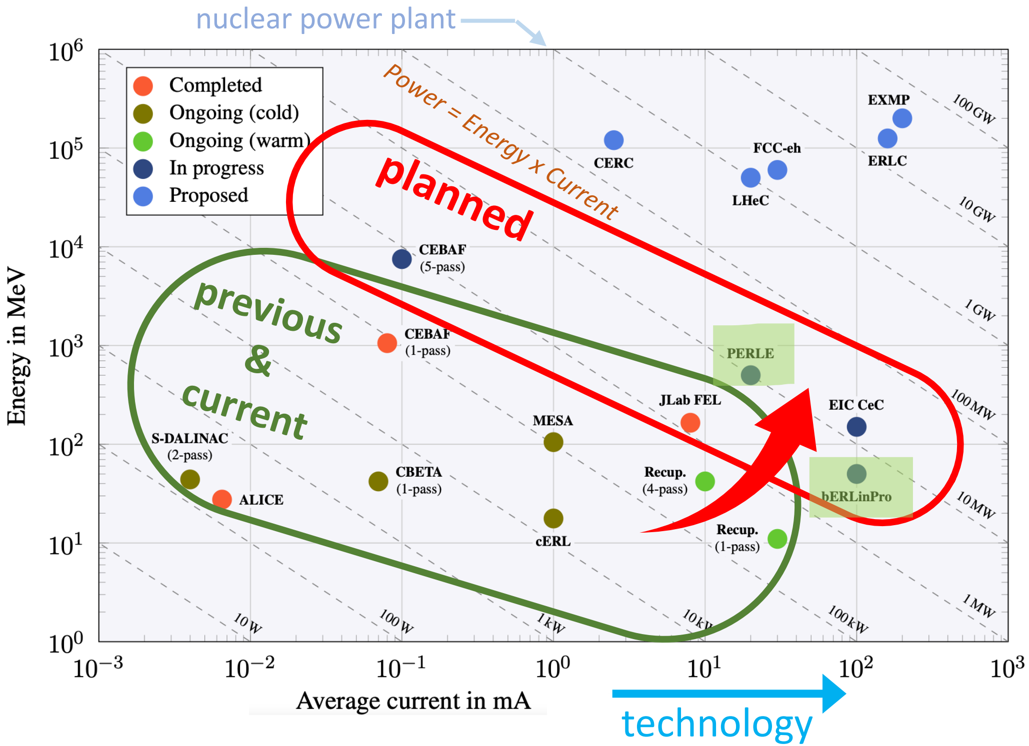
More facilities in design

- **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

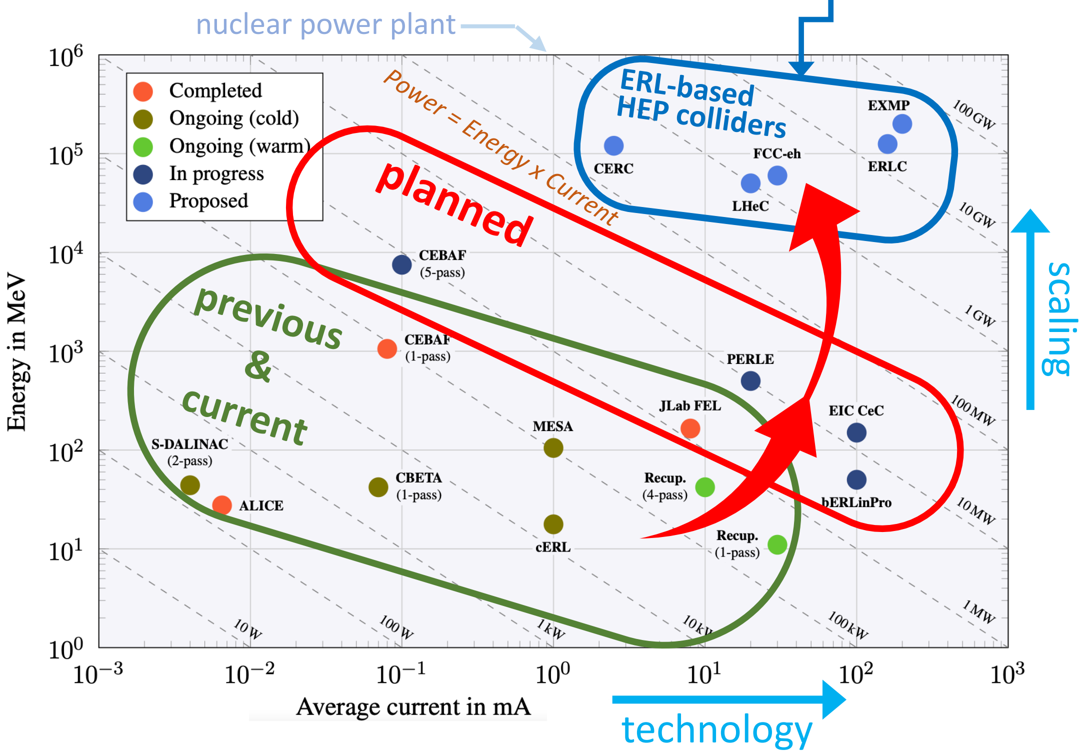
essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high 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 power

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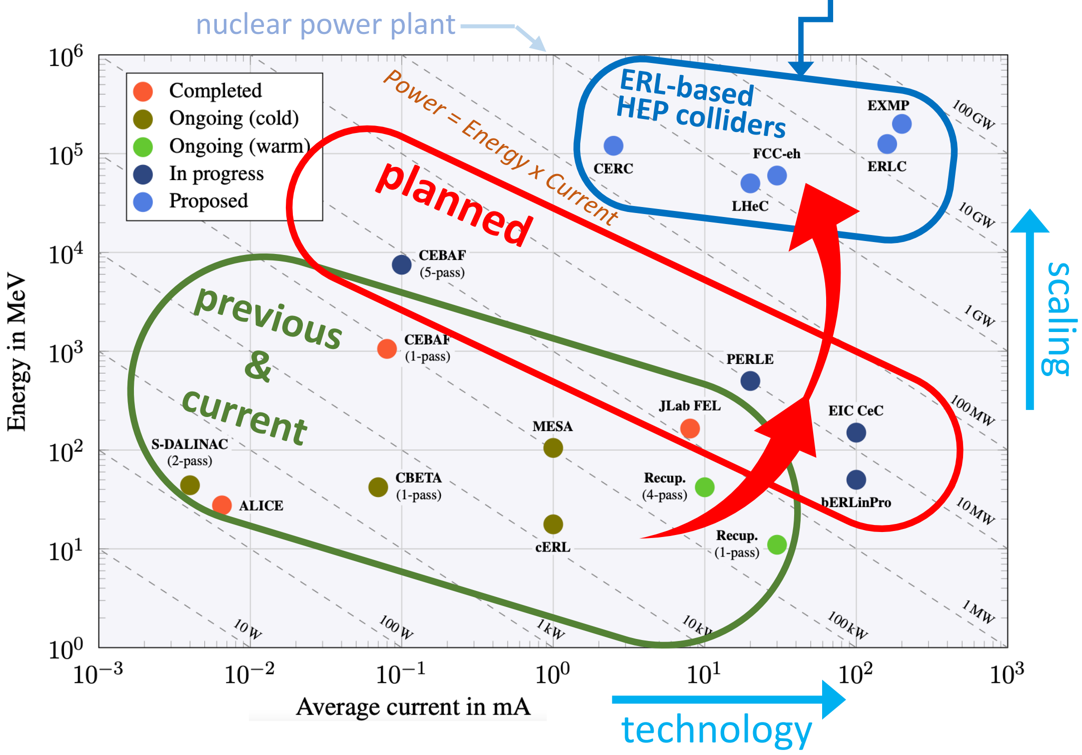

Future ERL-based Colliders

H, HH, ep/eA, muons, …

R&D Roadmap

bERLinPro & PERLE

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

towards high power

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Energy Recovery Linacs (ERL): reaching higher luminosities with less power requirements