Future particle physics colliders with Sustainable Accelerating Systems

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John Adams Institute for Accelerator Science, Oxford
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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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visible with our own eyes

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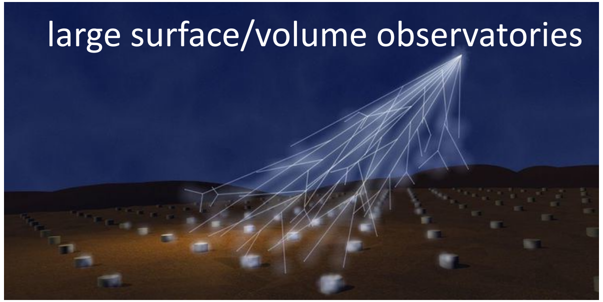

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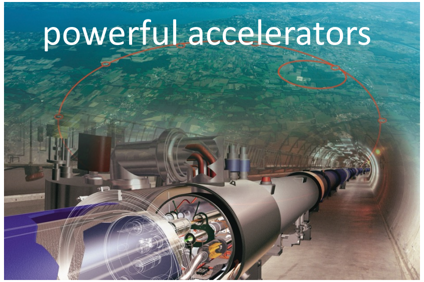

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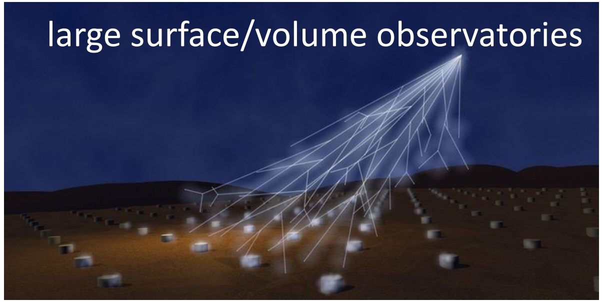
age universe
$4.4\ 10^{18}$ s

observable universe
$8.8\ 10^{26}$m



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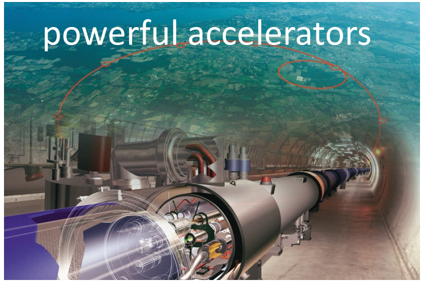

lifetime top quark
$5\ 10^{-25}$ s

quarks
< 10^{-19}m

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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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(for electromagnetic, weak and strong forces)

Concrete Models

APPLY MATHEMATICAL FRAMEWORKS ON OBJECTS

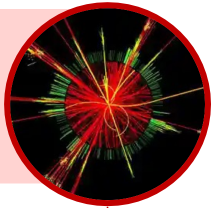
① ***General Relativity → Standard Model of Cosmology***
② ***Quantum Field Theory → Standard Model of Particle Physics***

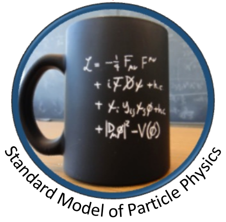
need to be valid into even the tiniest cracks of space and time and for all energies or masses of the objects… even at the extremes

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

~ 0.000˙000˙000˙000˙000˙000˙01 meter

observations how small objects behave in our laboratories





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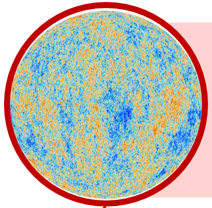
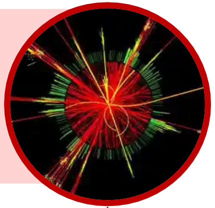
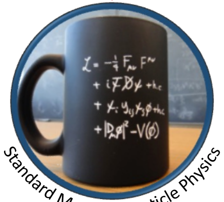


observations how large objects behave in our universe

Standard Model of Cosmology

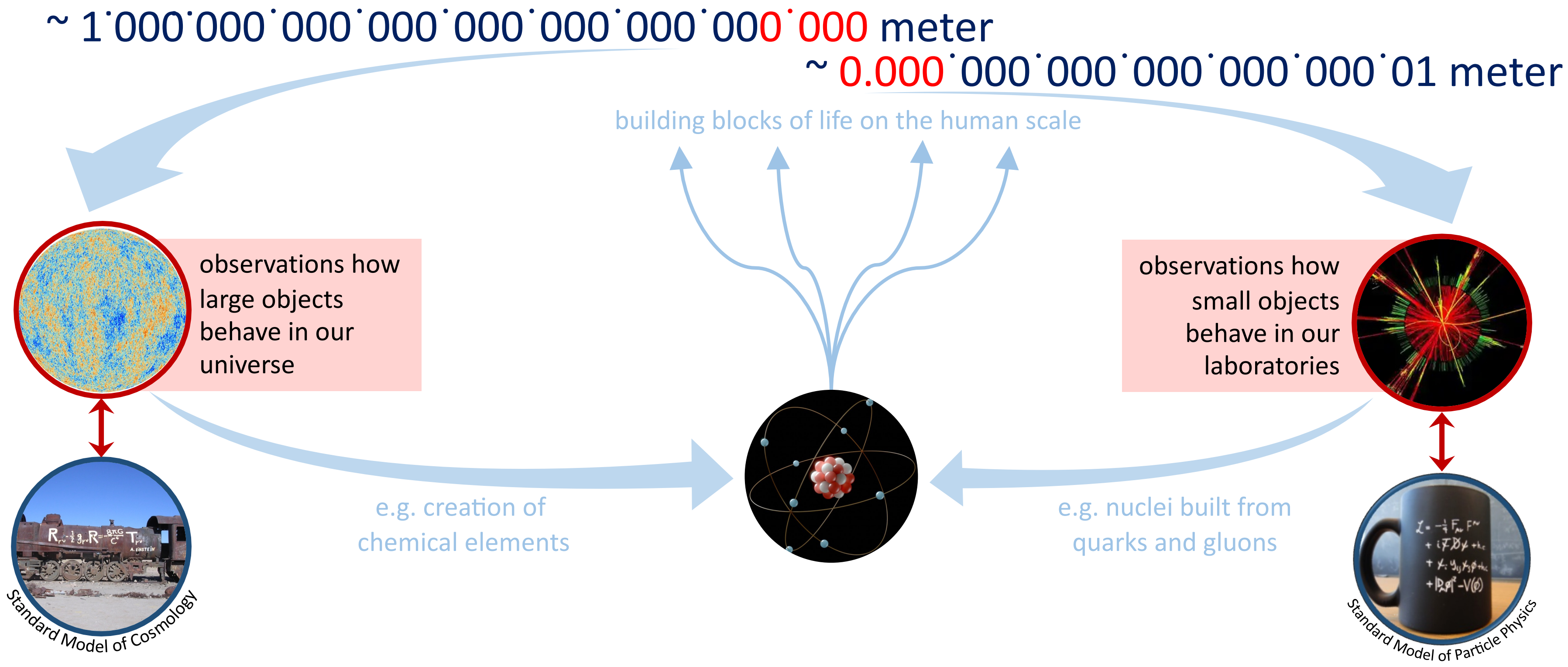
observations how small objects behave in our laboratories





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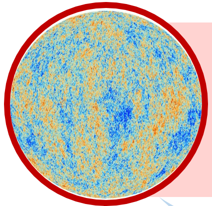
building blocks of life on the human scale
observations how large objects behave in our universe
observations how small objects behave in our laboratories
e.g. creation of chemical elements
e.g. nuclei built from quarks and gluons
Standard Model of Cosmology
Standard Model of Particle Physics

A century of scientific revolutions

~ 1·000·000·000·000·000·000·000·000·000 meter

~ 0.000·000·000·000·000·000·01 meter

building blocks of life on the human scale



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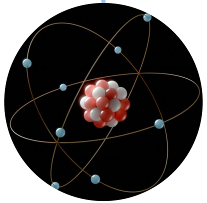
Standard Model of Cosmology



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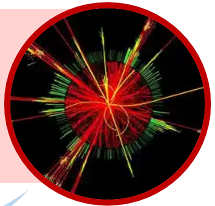
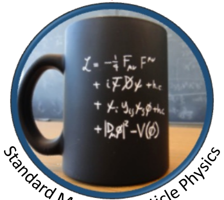
e.g. nuclei built from quarks and gluons

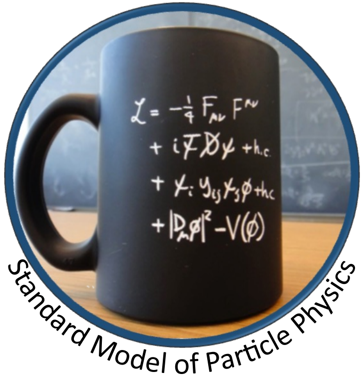


observations how small objects behave in our laboratories



Standard Model of Particle Physics

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?

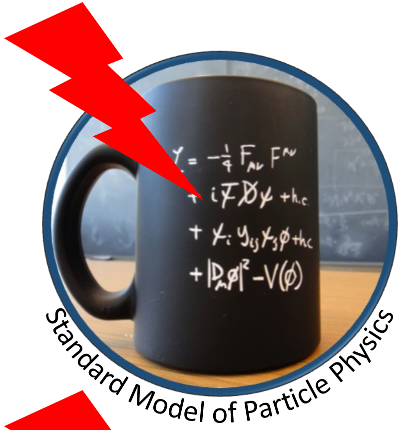
Scale of things (why do the numbers miraculously match)?

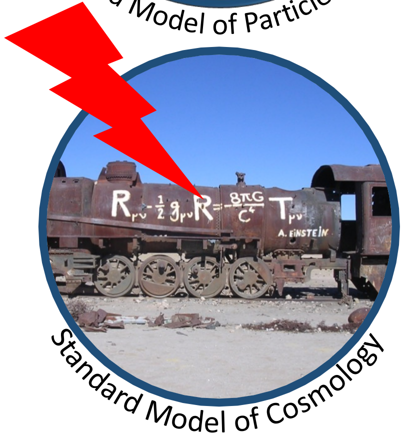
Pattern of particle masses and mixings?

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”

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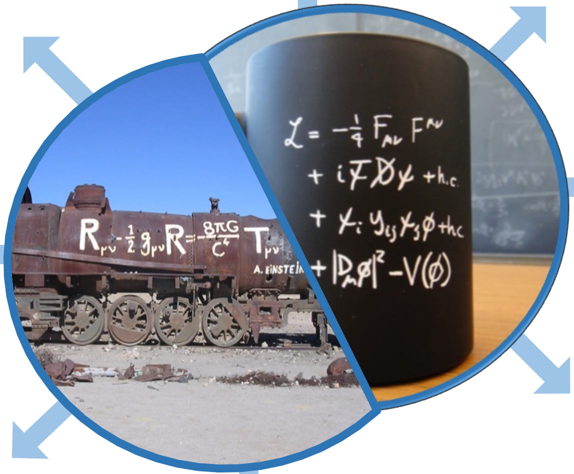
- How do quarks and gluons give rise to properties of nuclei?…

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

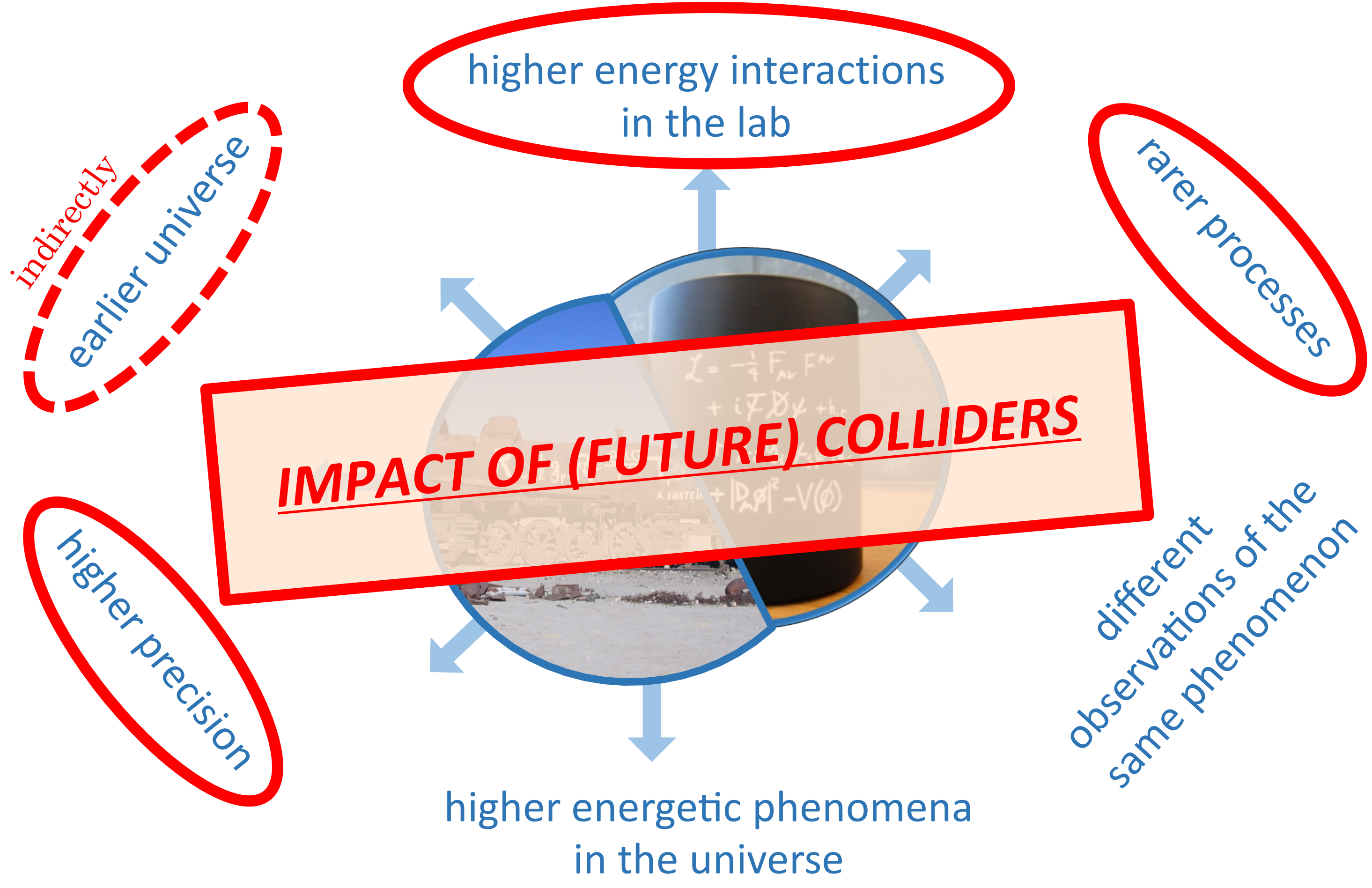
rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe


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 future particle physics colliders

~15-20B EUR

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

The landscape of future 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

$E_{CMS} \sim$ 10 GeV (flavour)

$E_{CMS} \sim$ 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 future particle physics colliders

This talk will focus on improving 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
ERL: https://indico.ijclab.in2p3.fr/event/9548/

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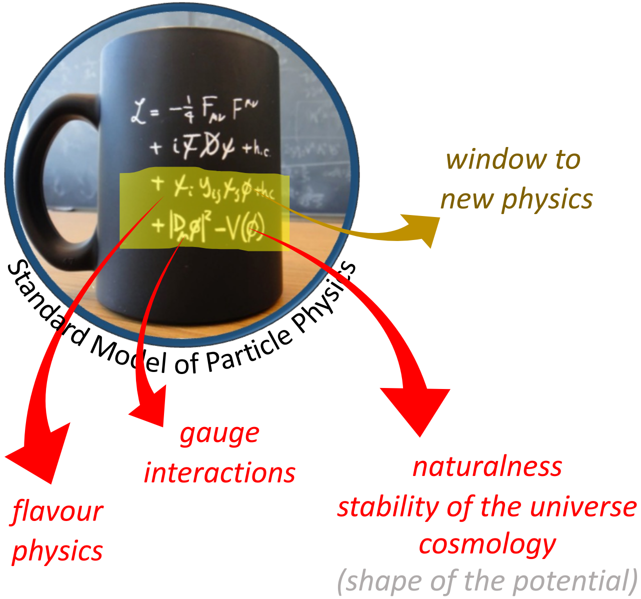
An electron-positron Higgs factory is the highest-priority next collider.

European Strategy for Particle Physics 2020

The Higgs field fills the vacuum as a scalar field



The particle fields in this vacuum feel an interaction with the H field and the particle acquires a mass.
(≠ Newton, not slowing down by inertia)

The scalar H field is home to the scalar H boson which is deeply intertwined with the vacuum structure throughout space-time and its mass is wildly sensitive to quantum fluctuations emerging from new physics phenomena at higher energies.

Essentially all problems of the Standard Model are related to the dynamics and couplings of the scalar field, and we do not know very much about them.

Breakthroughs with more precise observations

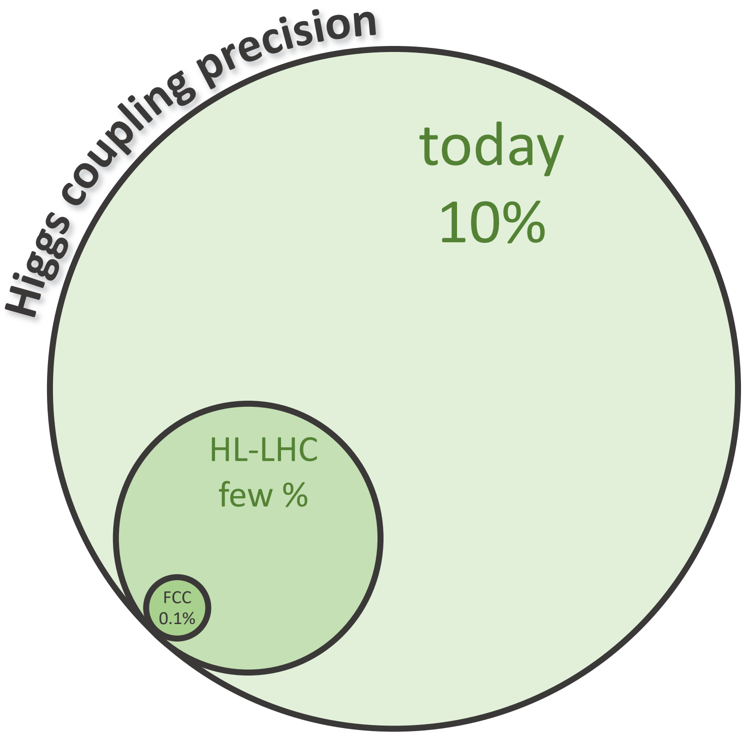
e.g., a more precise analysis of measured UV light reaching Earth revealed the ozone hole

e.g., with improved interferometers gravitational waves were finally directly observed

e.g., more precise measurements of the nature of the CMB unlocked early universe cosmology

Unless dramatic new insights appear, we might have to built a Higgs Factory to ever be able to answer our open fundamental questions.

i.e. finding our ozone hole, our missing link, the true nature of fundamental interactions, …



Surely, future collider programmes go beyond only precision Higgs physics

Future flagship at the energy & precision frontier

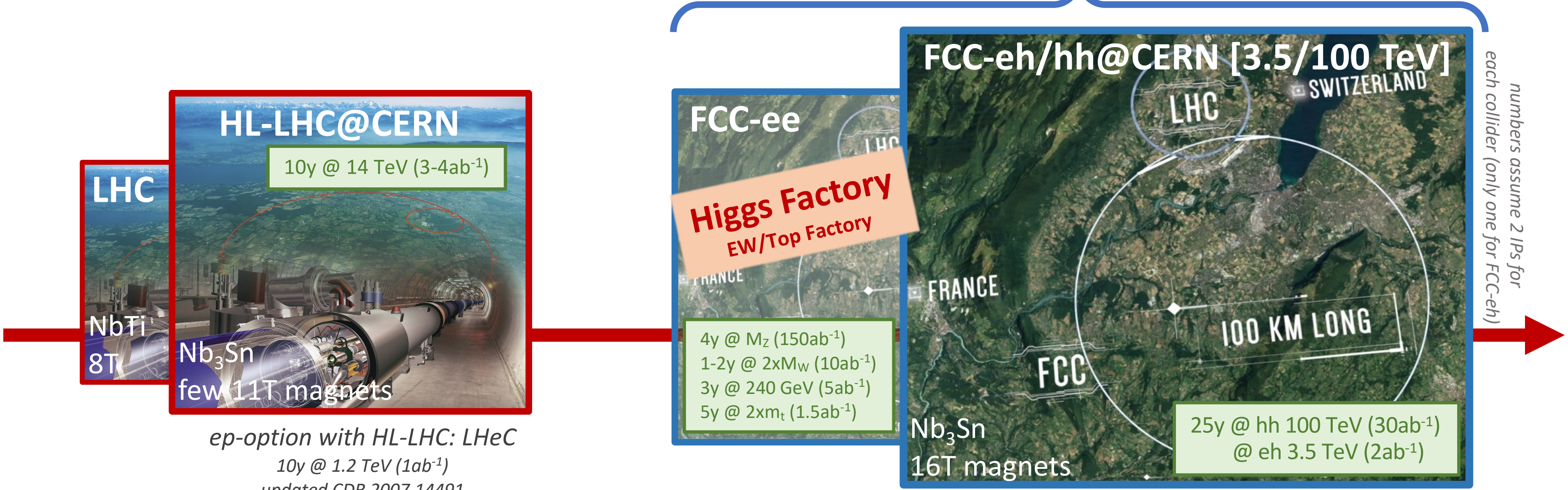
Current flagship (27km)

impressive programme up to 2042

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2048

attractive combination of precision & energy frontier



ep-option with HL-LHC: LHeC

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

updated CDR 2007.14491

by around 2026, verify if it is feasible to plan for success (techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider

particle physics ambition

high-energy & high-current beams

(energy x current = power)

particle physics ambition

high-energy & high-current beams

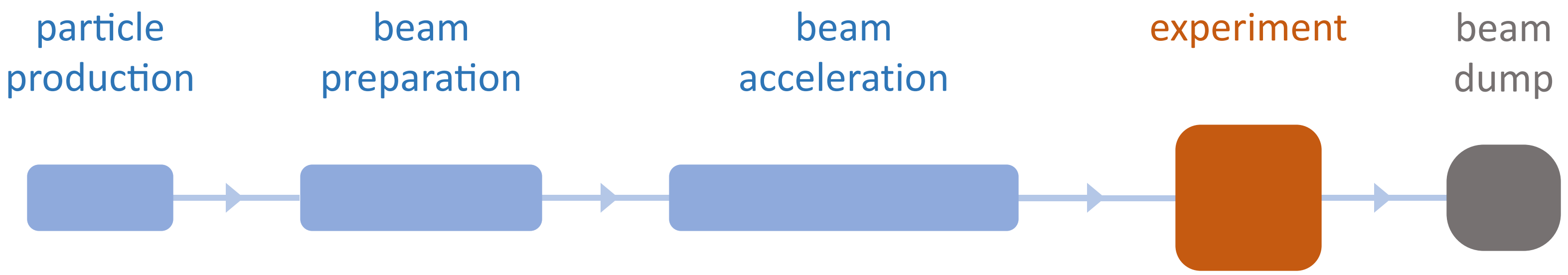
(energy x current = power)

caveat

power requirements of future colliders

focus on electron/positron accelerators

Basic structures of a particle accelerator



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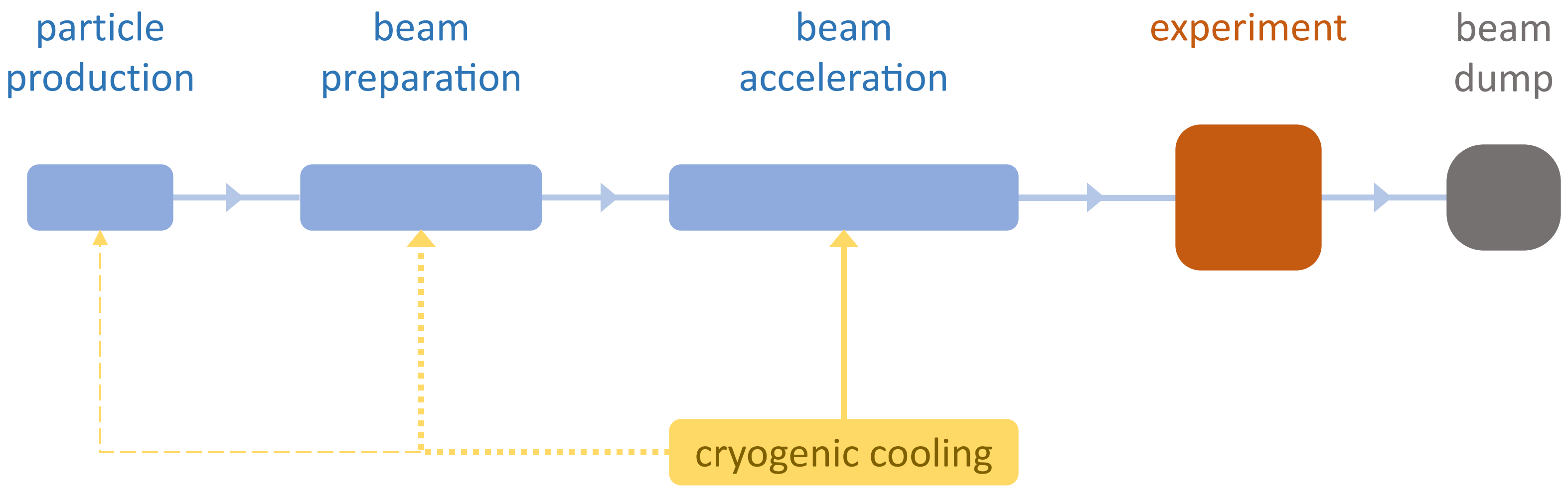

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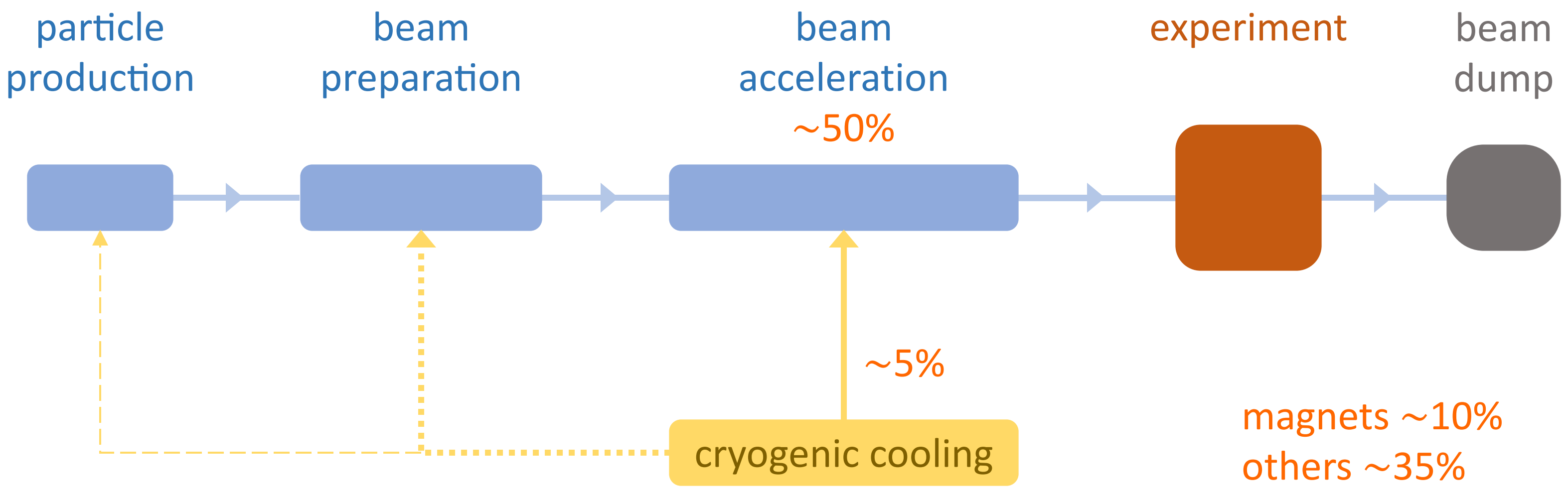

Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC-ee@250GeV

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

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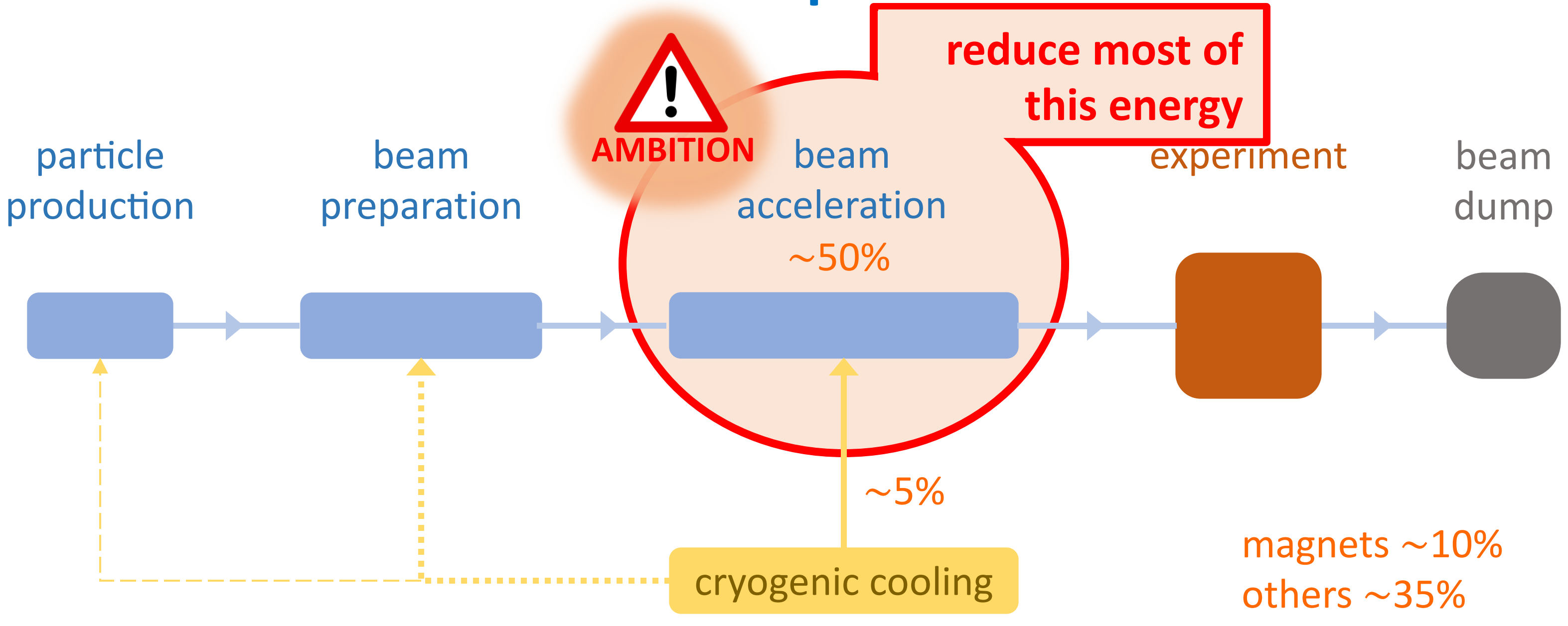

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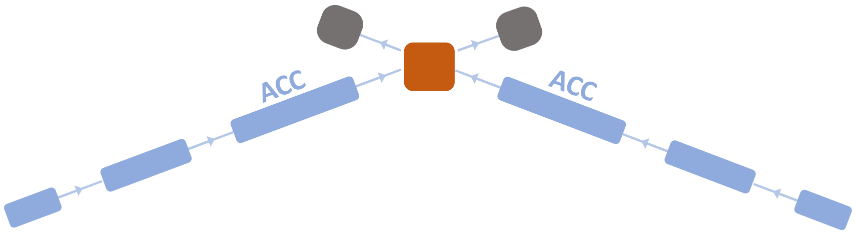
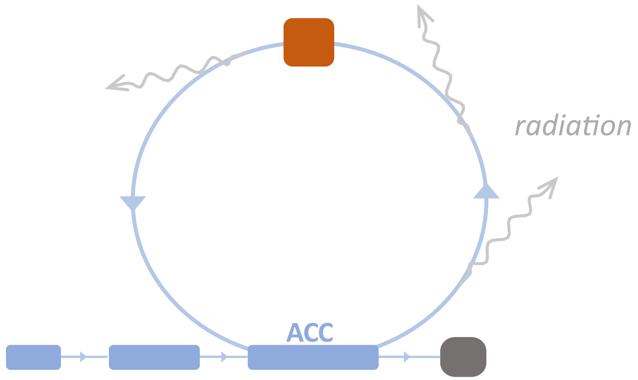
Linear colliders



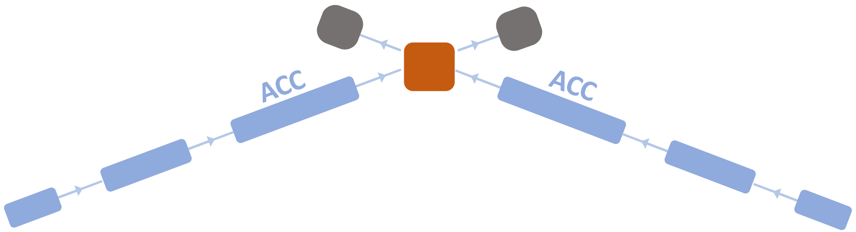
dump >99.9999% of
the beam power

Circular colliders



radiate away very quickly the beam power
& loose beam quality

Linear colliders



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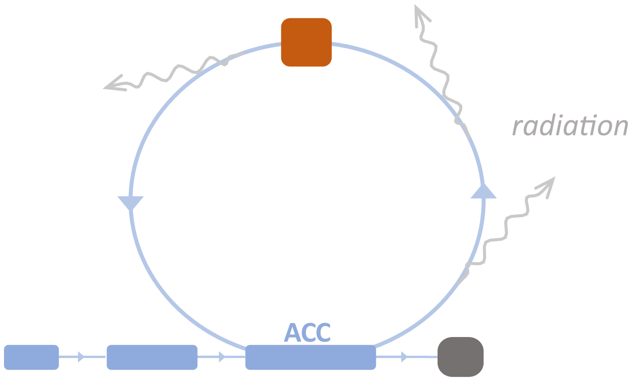
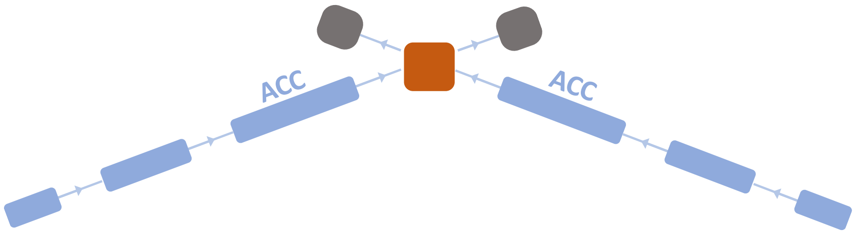


radiate away very quickly the beam power & loose beam quality

FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

Linear colliders



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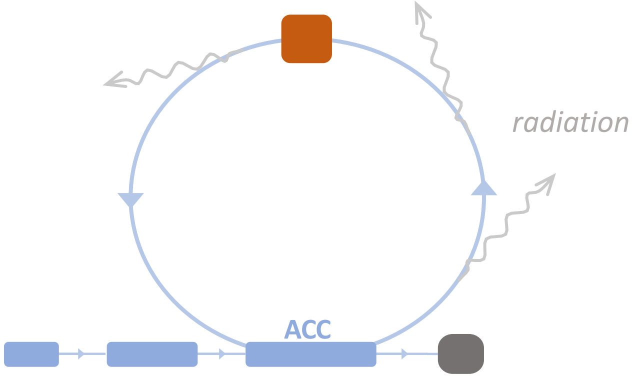

radiate away very quickly the beam power
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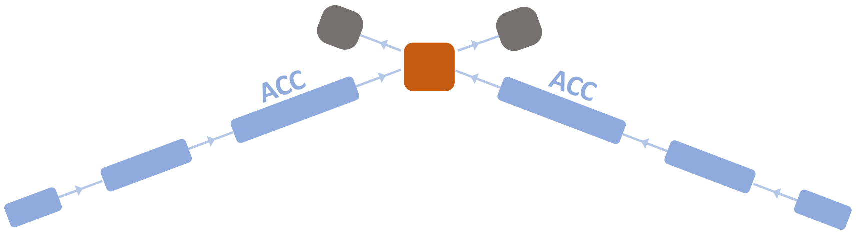
FCC-ee@250 ≃ 300 MW

~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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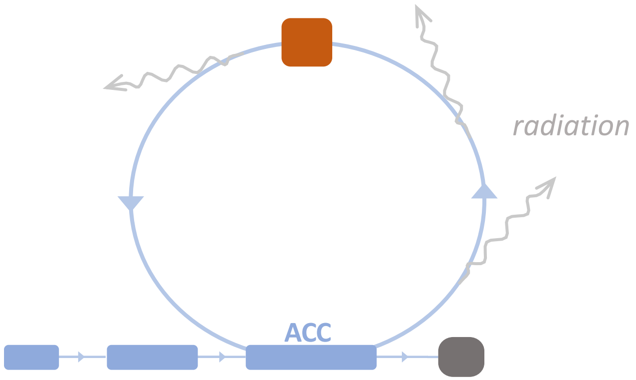


dump >99.9999% of the beam power

radiate away very quickly the beam power & loose beam quality

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

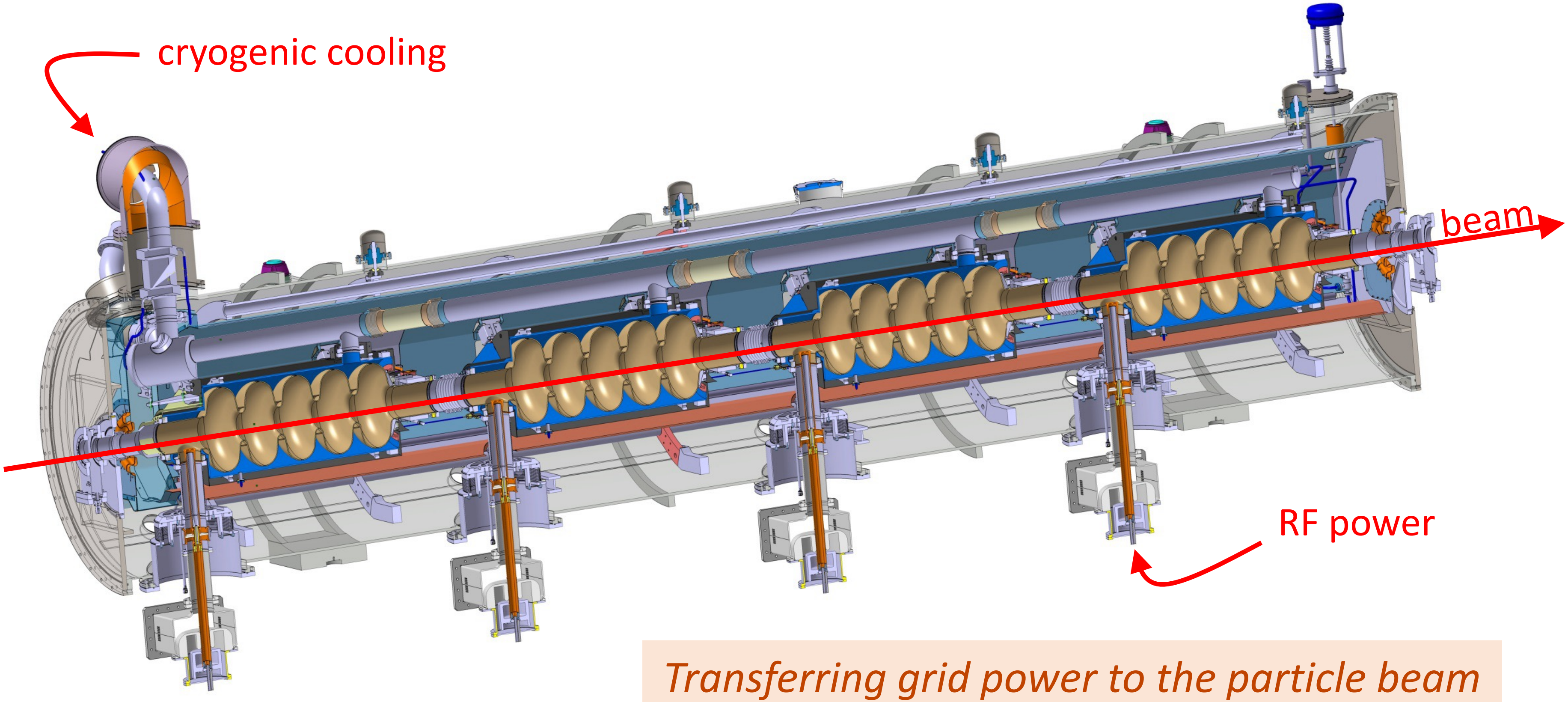
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

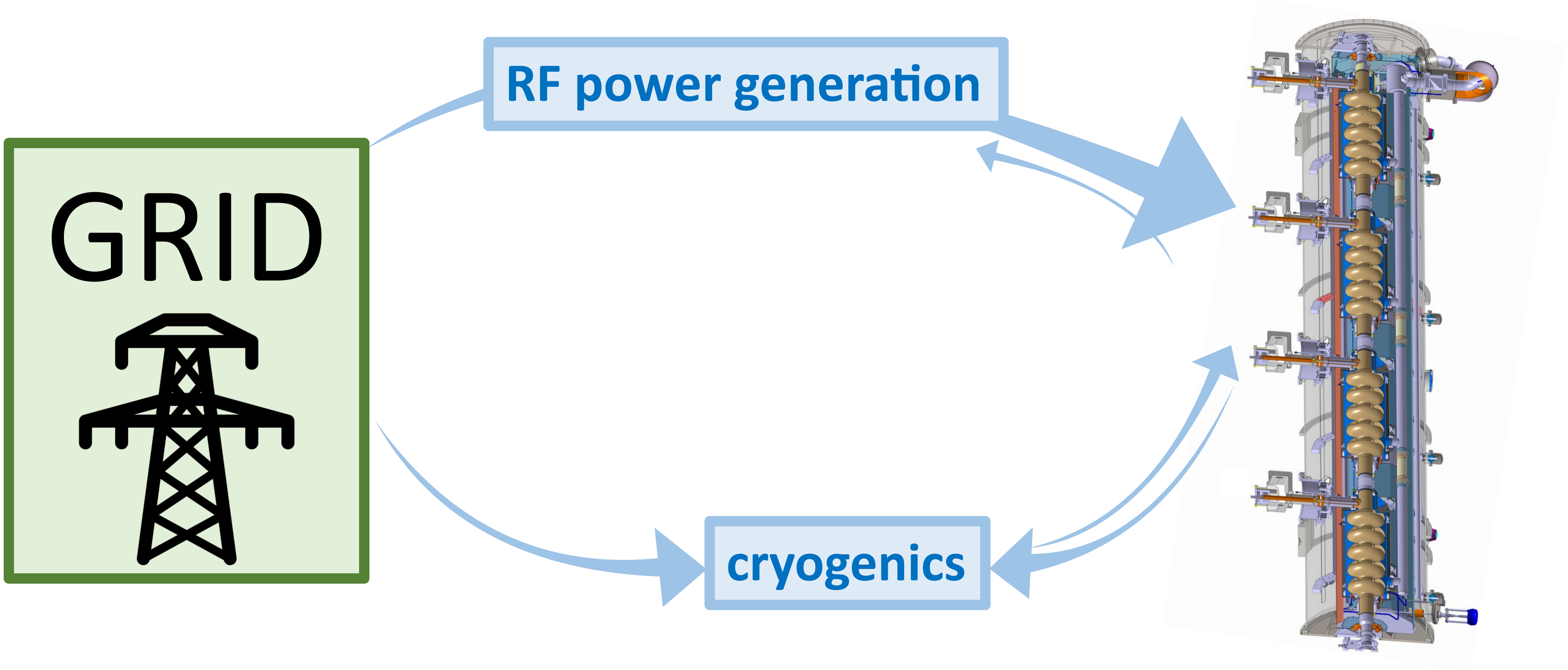
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

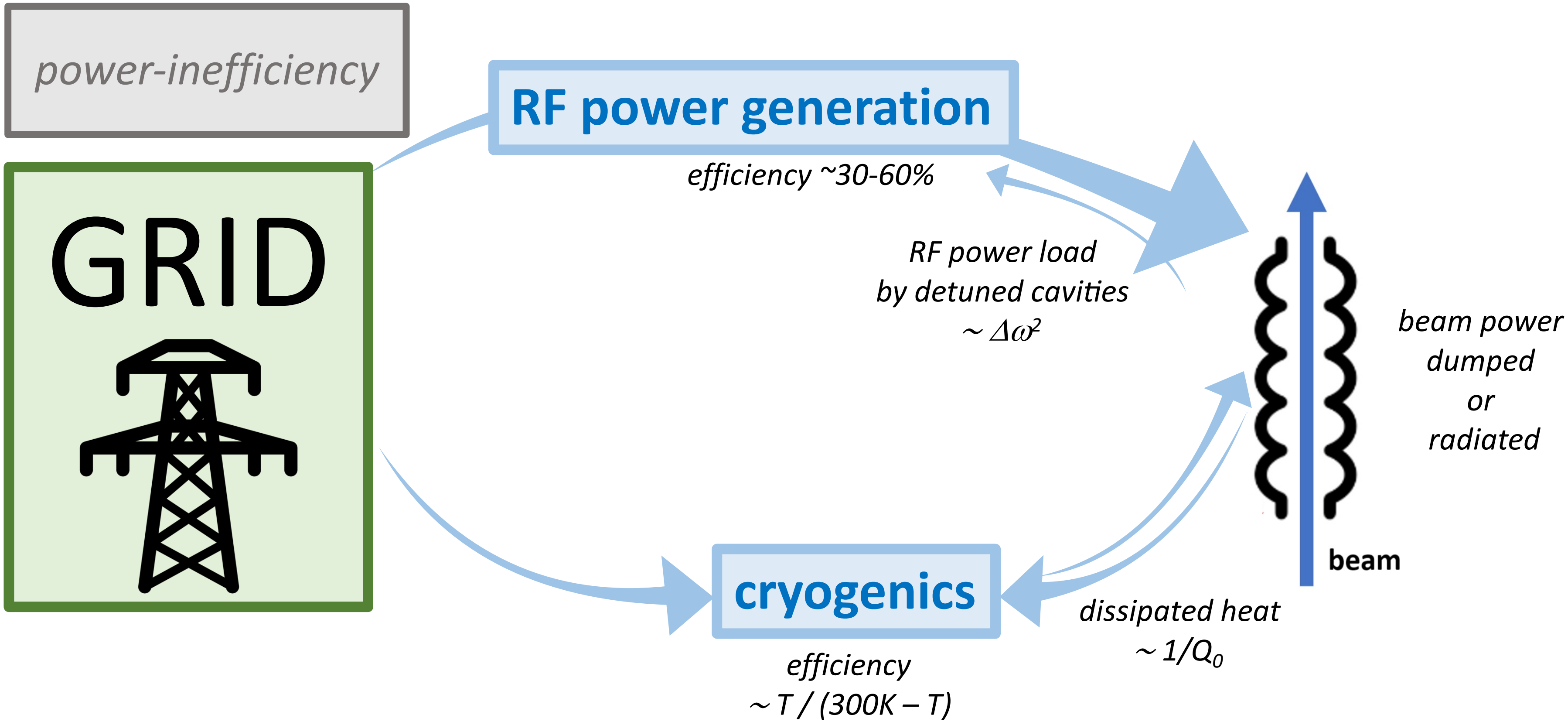


Transferring grid power to the particle beam

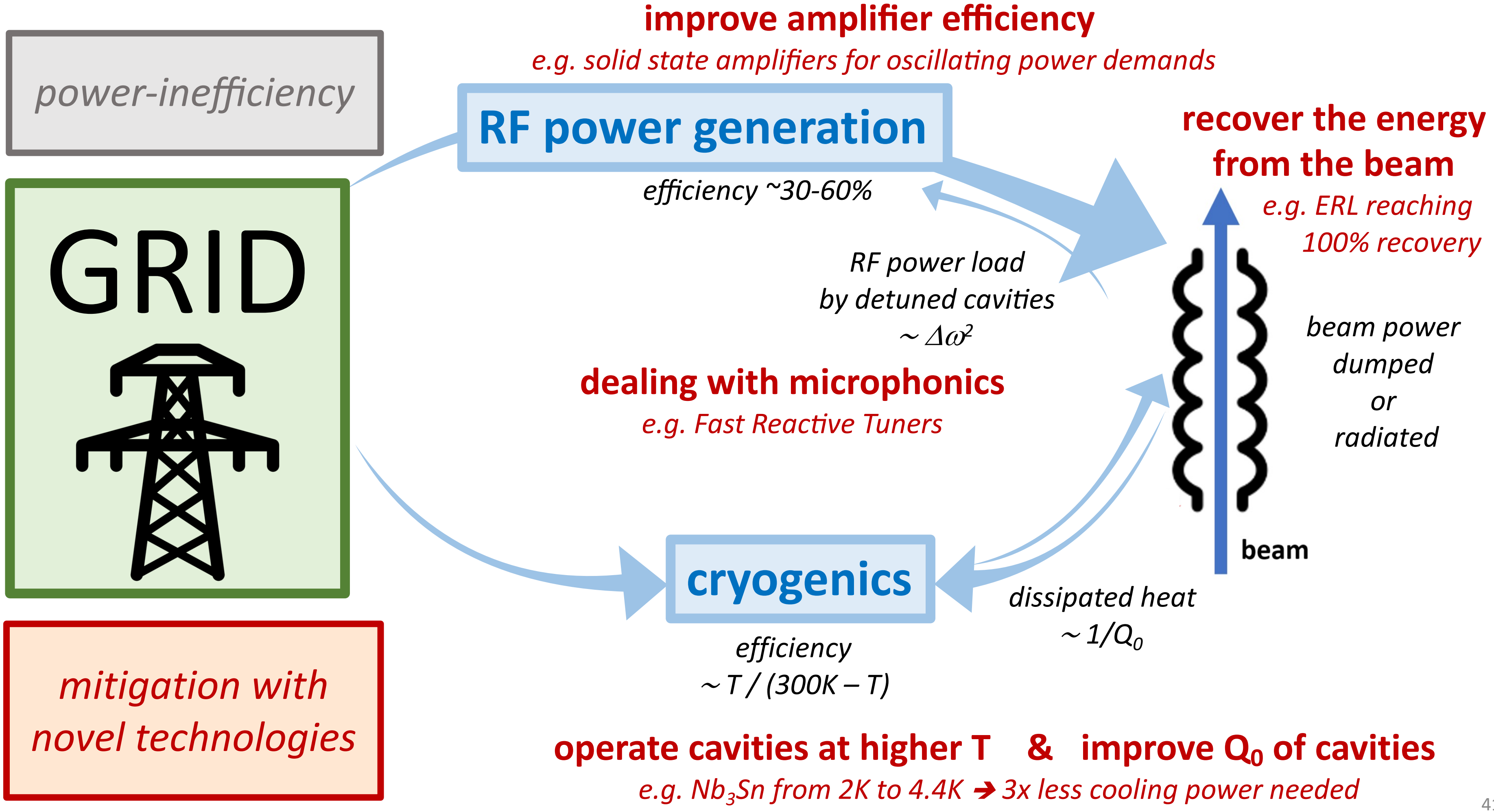
Sustainable Accelerating Systems – from Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

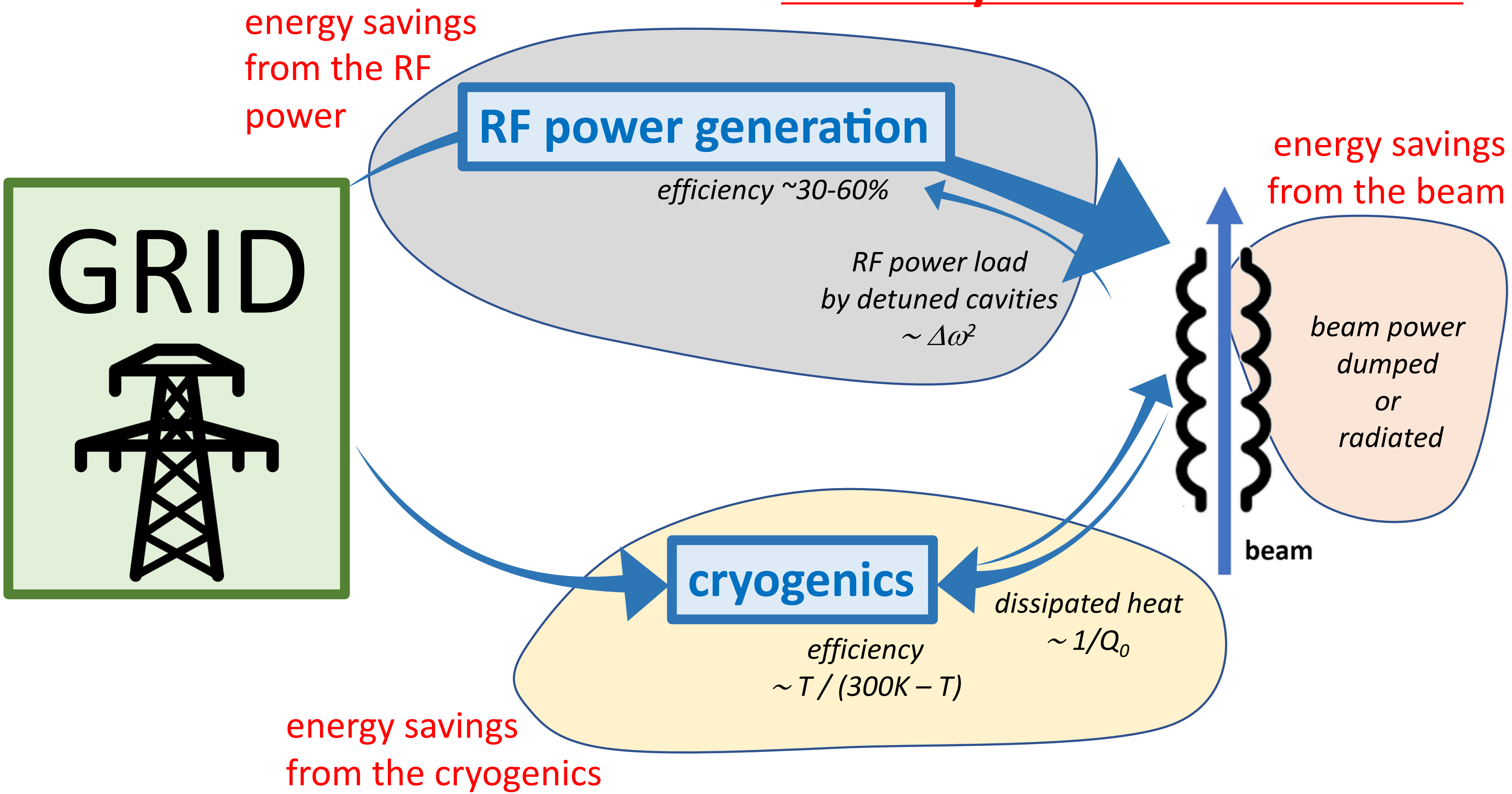


power-inefficiency
RF power generation
efficiency ~30-60%
RF power load
by detuned cavities
~ $\Delta\omega^2$
GRID
beam power
dumped
or
radiated
beam
cryogenics
dissipated heat
~ $1/Q_0$
efficiency
~ T / (300K – T)



improve amplifier efficiency
e.g. solid state amplifiers for oscillating power demands
power-inefficiency
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 $\sim T / (300K – T)$
mitigation with novel technologies
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

energy savings from the RF power

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

$1/Q_0$

$\sim T\,/\,(300K - T)$

energy savings from the cryogenics

from the overall Accelerator R&D Roadmap
and responding to a Horizon Europe call, we

Innovate for Sustainable Accelerating Systems (iSAS)

with focus on these three main iSAS Technology Areas (TAs)
to develop energy-saving solutions
for cryomodules of modern SRF accelerators

with support from
TIARA, Enterprise Europe Network (EEN), EuXFEL GmbH, I.FAST, LEAPS, LDG

from the overall Accelerator R&

Innovate for Sustainable Accelerating Systems (iSAS)

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

ambition: significantly reduce the energy footprint of SRF accelerators

Approved in Horizon Europe, July 2023
Grant Agreement signed, November 2023
Project starts on March 1, 2024

Kick-Off Meeting, April 15-16, 2024: https://indico.ijclab.in2p3.fr/event/10302/

…I.FAST, LEAPS, LDG

iSAS is now an approved Horizon Europe project

Grant Agreement has been signed in Nov 2023 – project starts on March 1, 2024

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

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

DESY. INFN UK Research and Innovation HZB Helmholtz Zentrum Berlin

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 Objectives – *Technology Areas*

- **TA#1: energy-savings from RF power** – *While great strides are being made in the energy efficiency of various RF power generators, the objective of iSAS is to ensure additional impactful energy savings through coherent integration of the RF power source with smart digital control systems and with novel tuners that compensate rapidly cavity detuning from mechanical vibrations, resulting in a further reduction of power demands by up to a factor of 3.*

- **TA#2: energy-savings from cryogenics** – *While major progress is being made in reusing the heat produced in cryogenics systems, the objective of iSAS is to develop superconducting cavities that operate with high performance at 4.2 K (i.e., up to 4.5 K depending on the cryogenic overpressure) instead of 2 K, thereby reducing the grid-power to operate the cryogenic system by a factor of 3 and requiring less capital investment to build the cryogenic plant.*

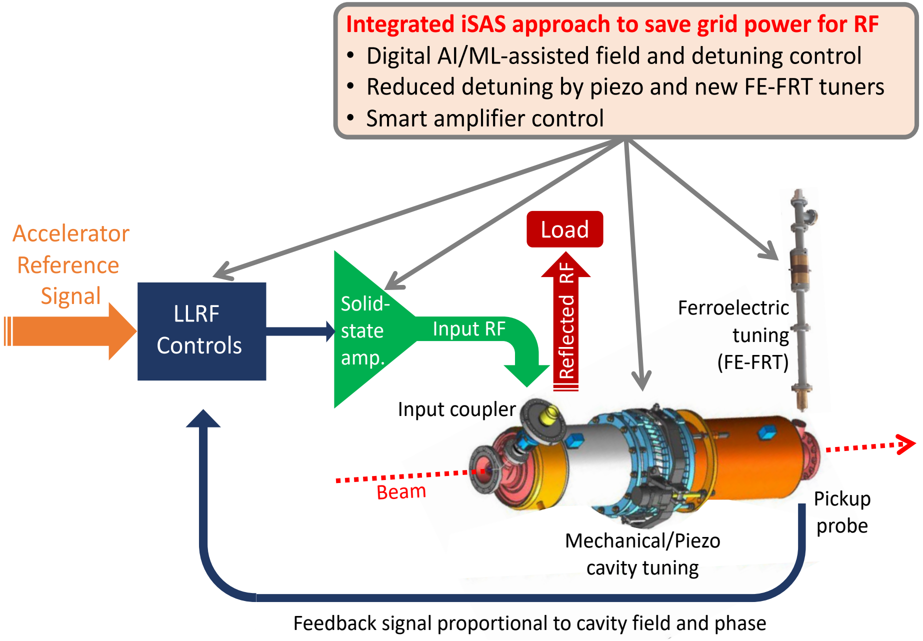
- **TA#3: energy-savings from the beam** – *Significant progress has been achieved in maintaining the brightness of recirculating beams to provide high-intensity collisions to experiments, but most of the particles lose their power through radiation or in the beam dump system. The objective of iSAS is to develop dedicated power couplers for damping the so-called Higher-Order Modes (HOMs) excited by the passage of high-current beams in the superconducting cavities, enabling efficient recovery of the energy of recirculating beams back into the cavities before it is dumped, resulting in energy reduction for operating, high-energy, high-intensity accelerators by a factor ten.*

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

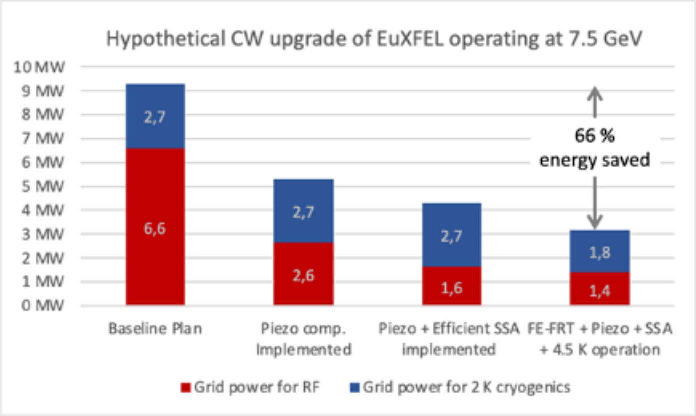
- *FE-FRT for Transient Beam Loading: design & performance tests for an LHC 400 MHz cavity in an existing cryomodule.*
- *FE-FRT for Microphonics: design, fabricate and validate in a cryomodule like setup for 1.3 GHz cavities, single-cell and multi-cell (TESLA/XFEL).*
- *FE-FRT for Microphonics compensation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

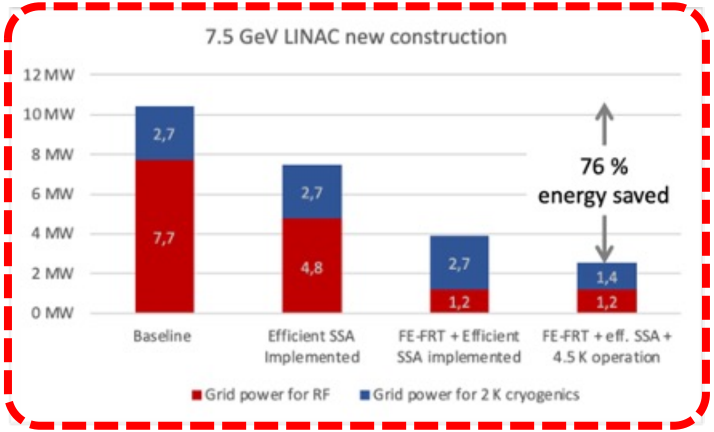
LLRF

- *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).*

Impact of iSAS technologies on FELs

example EuXFEL





For an upgrade of EuXFEL to CW, a refurbishment of the injection LINAC cavities is being considered. This could provide the opportunity to retrofit some iSAS technology developments as well. The figure (left) depicts the expected energy savings if various iSAS developed technologies are implemented (assumption: 0.1 mA beam current), the degree of modifications, but also the benefits, are increasing from left to right. The achievable total energy savings amounts to 66%, more than 6 MW, avoiding 2.9 tons CO_2 per hour of operation for Germany's electrical energy mix (485 g CO_2/kWh). Future LINACs can be optimally designed to take full advantage of the iSAS technologies, as integrated in the cryomodule being designed in iSAS. The right figure shows that the full savings for a 7.5-GeV LINAC is of the order of 76% (RF + cryogenics cavity cooling). Not included here are the additional potential savings by optimizing the heat load from HOM and FPC couplers – for the Cornell system their load accounts for nearly 4 MW – or any scheme to recover the beam power (750 kW in these examples).

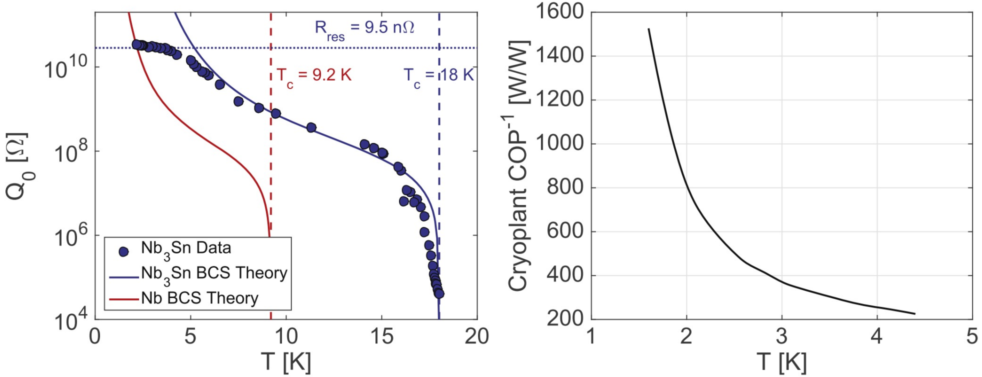
iSAS *develops, prototypes & validates SRF energy-saving technologies*

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*

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.*

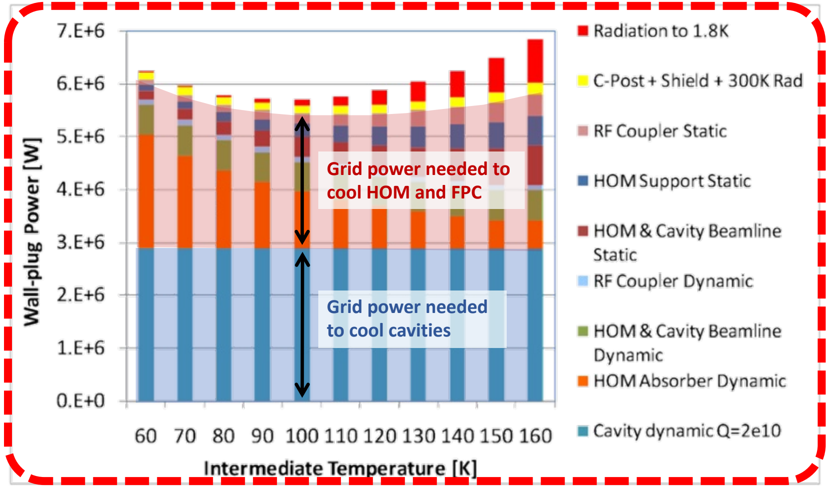
- *Working cavity @ 4.2K: optimize the superconducting coating procedure of 1.3 GHz cavities including an adaptive layer and demonstrate suitability for 4.2 K operation (using Cu cavities originally produced for I.FAST).*

Impact of iSAS technologies on SRF accelerators

example Cornell ERL LINAC

iSAS develops new designs for both fundamental power couplers and HOM couplers dedicated to beam operation at very high currents while minimizing their static and dynamic heat loads in the cryogenic system. The reduction in the required cryogenic power will depend on the final design but the energy savings potential is expected to be large. As an example, the adjacent figure shows the grid power required to cool various parts of the cryomodules in the 5-GeV Cornell ERL LINAC design for different configurations of the cryogenics. The HOM and fundamental power couplers account for nearly half of the full cryogenic load. Even a moderate improvement can thus save powers in the MW range. The required cooling power scales linearly with the beam energy, so for the most ambitious future SRF accelerators, the savings in wall-plug power can be in the tens of MW and more range.

"Cornell Energy Recovery LINAC Project Definition Design Report"
G. Hoffstatter, S. Gruner, M. Tigner, eds. (2013)



Grid power for cooling the Cornell ERL LINAC.
(figure adapted from reference)

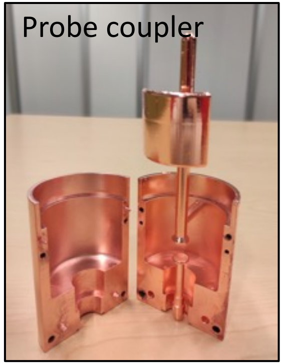
iSAS develops, prototypes & validates SRF energy-saving technologies

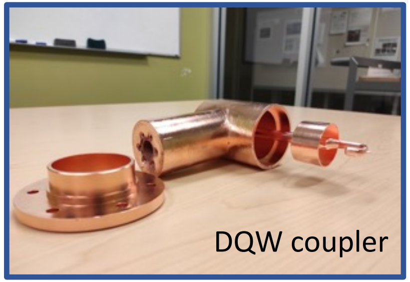
pictures from W. Kaabi

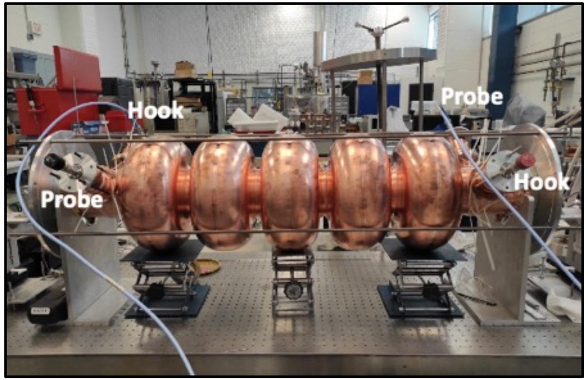
TA#3: energy-savings from the beam

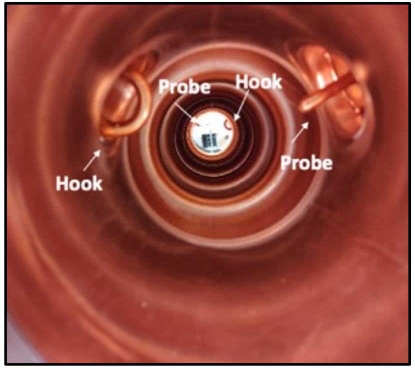
The objective is to reduce the total power deposited into the cryogenics circuits of the cryomodule of the Higher-Order Mode (HOM) couplers and fundamental power couplers (FPCs) leading to a significant reduction of the heat loads and the overall power consumption.

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)*

Technology Readiness Level (TRL)

The readiness of the energy-saving iSAS technologies will be improved to prepare them towards industrialisation and cost-effective mass production for current and future RIs.

iSAS Technologies		initial TRL	target TRL
TA#1	FE-FRT for transient detuning @ 400 MHz	4	6
	FE-FRT for transient detuning @ 800 MHz	1-2	4
	FE-FRT for microphonics @ 400 MHz	3	5-6
	FE-FRT for microphonics @ 800-1300 MHz	1-2	5-6
	LLRF controls	3-4	7
	LLRF + FE-FRT controls	2-3	6
TA#2	Nb3Sn-on-Cu films for 4.2-K cavity operation	2-3	4-5
TA#3	Higher-Order Mode couplers	2-3	5
	Fundamental Power Couplers	2-3	5

up to fully functional prototypes in relevant environment

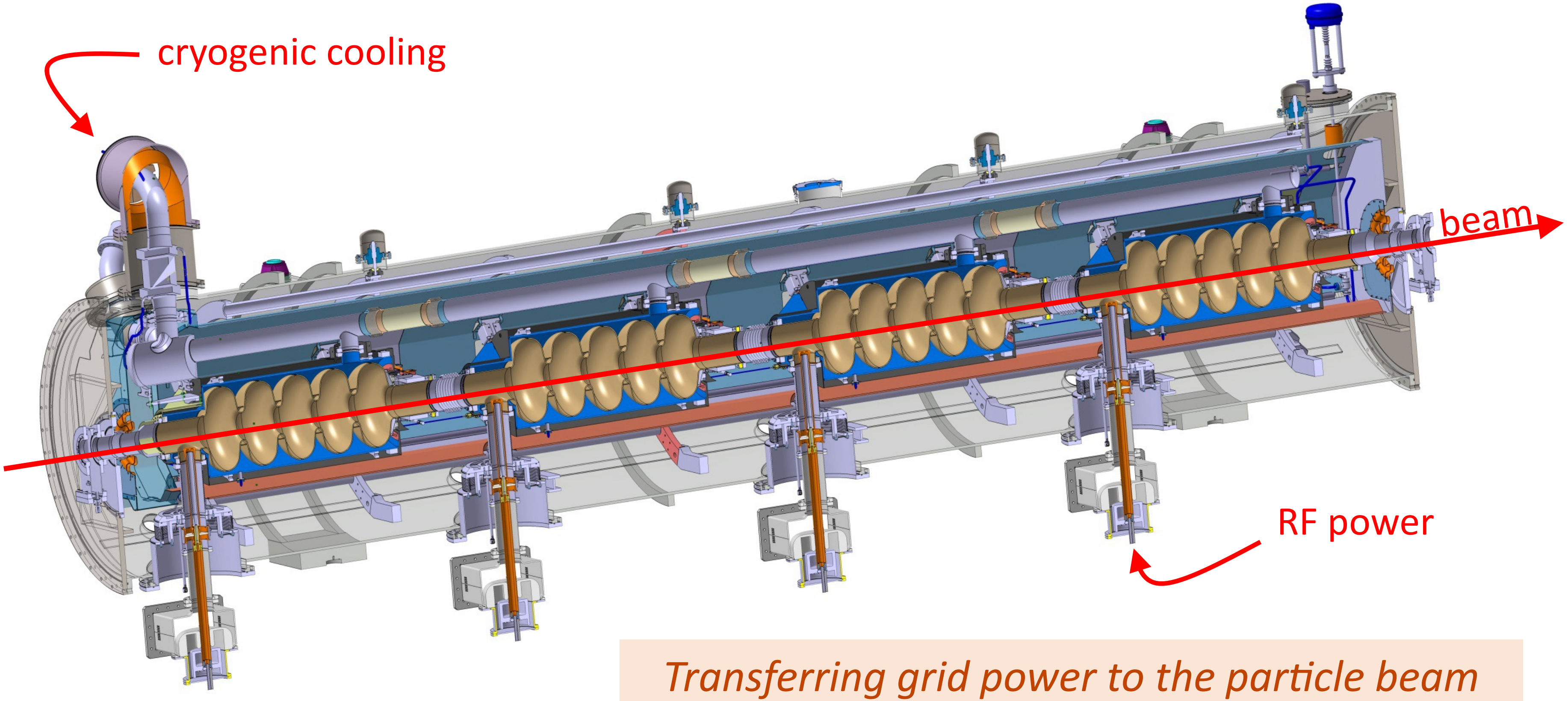
The objective of iSAS is for RIs and European industry to co-develop industrial solutions for energy-savings technologies in accelerators, delivering applications that can be implemented across various accelerator-driven research and non-research infrastructures.

The iSAS project is a catalyzer towards full high-power energy recovery

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

Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

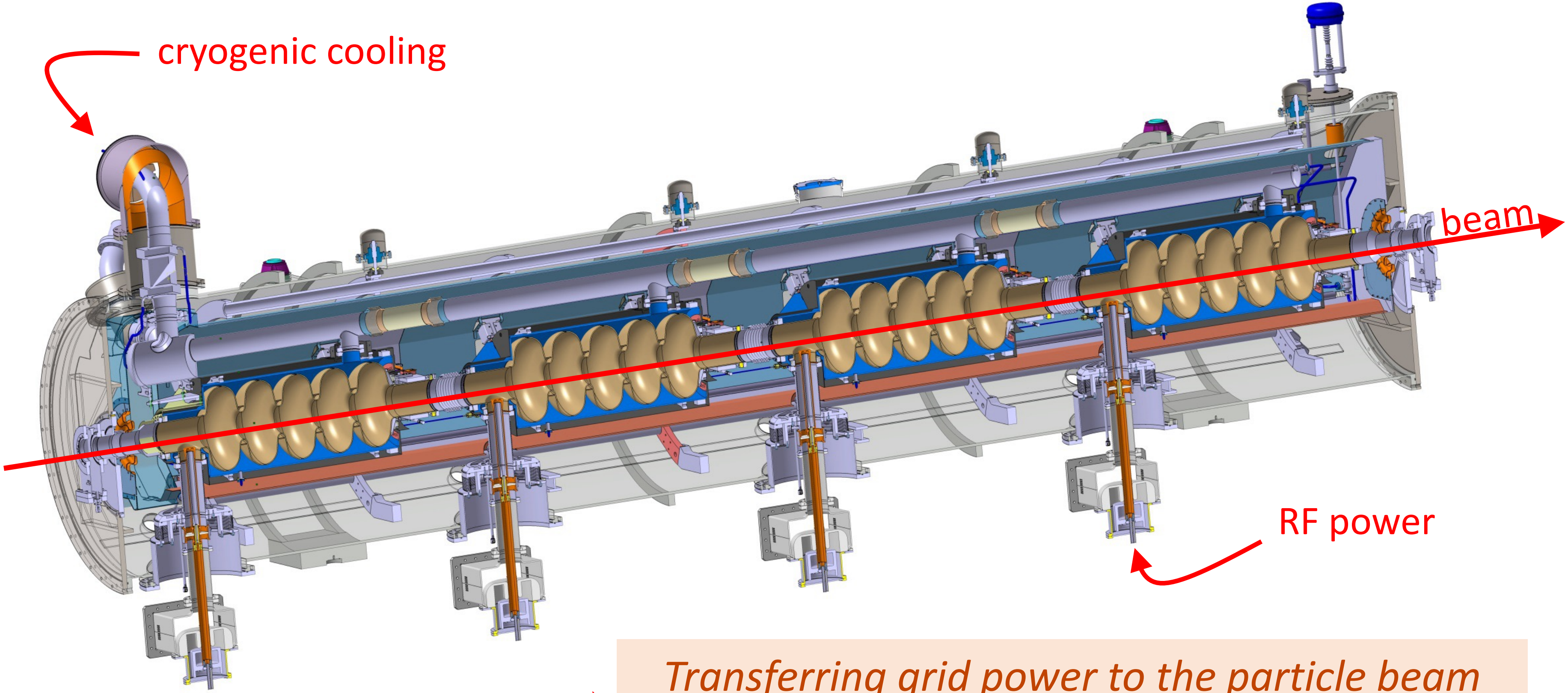


Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

Key building block for beam acceleration: the SRF cryomodule

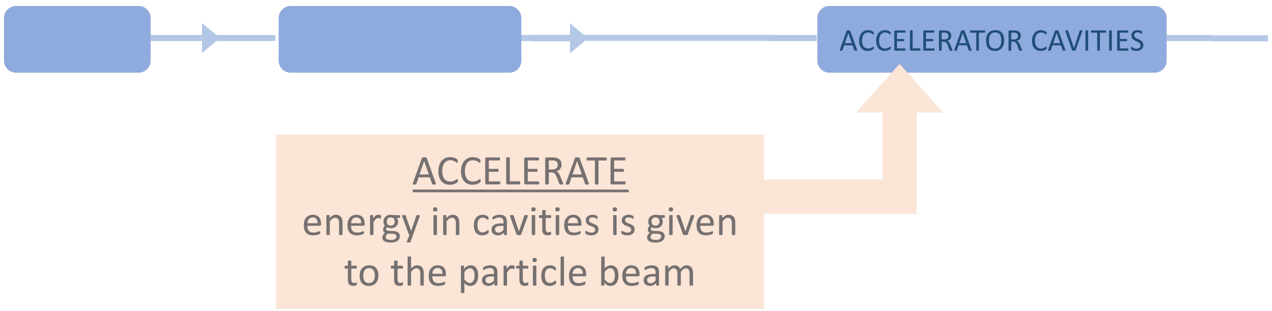
SRF: Superconducting Radio Frequency



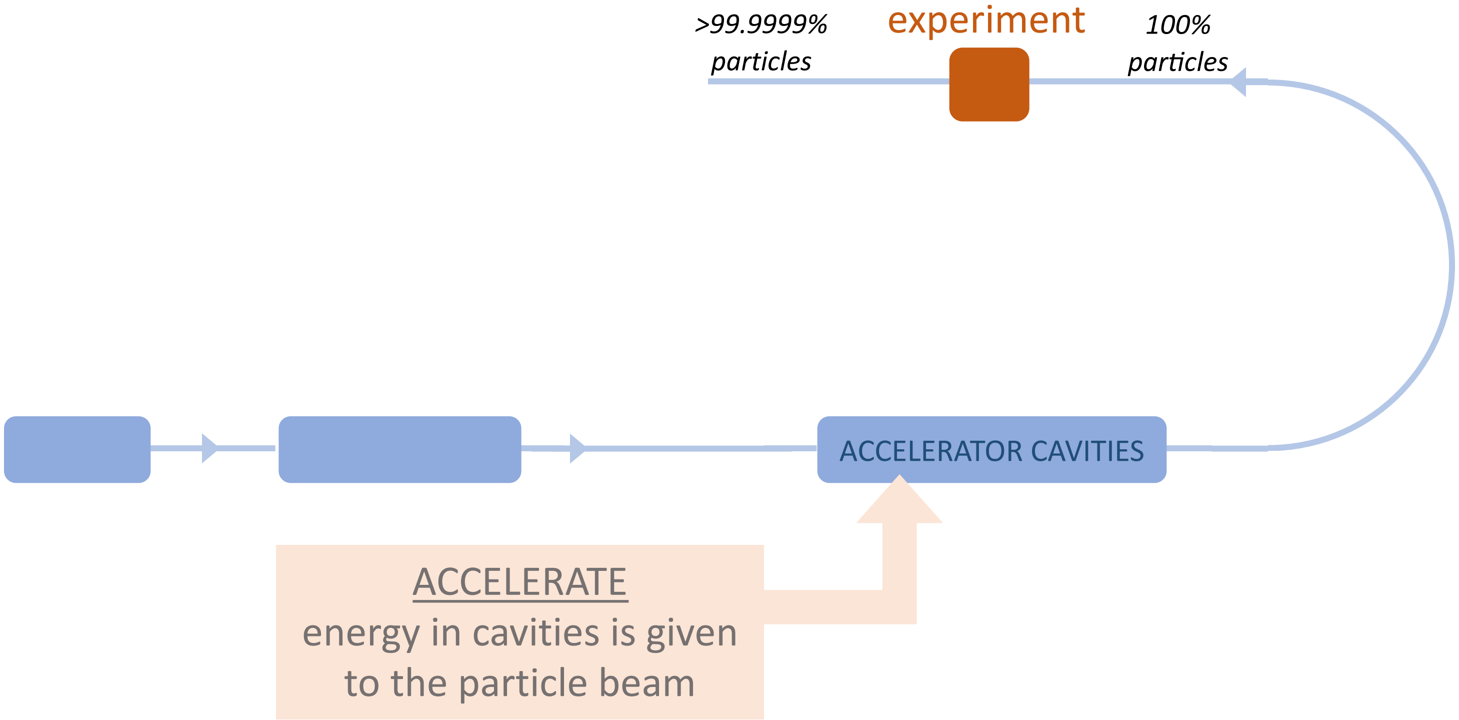
Transferring grid power to the particle beam

ENERGY RECOVERY → ***RECOVER THE ENERGY FROM THE USED BEAM***

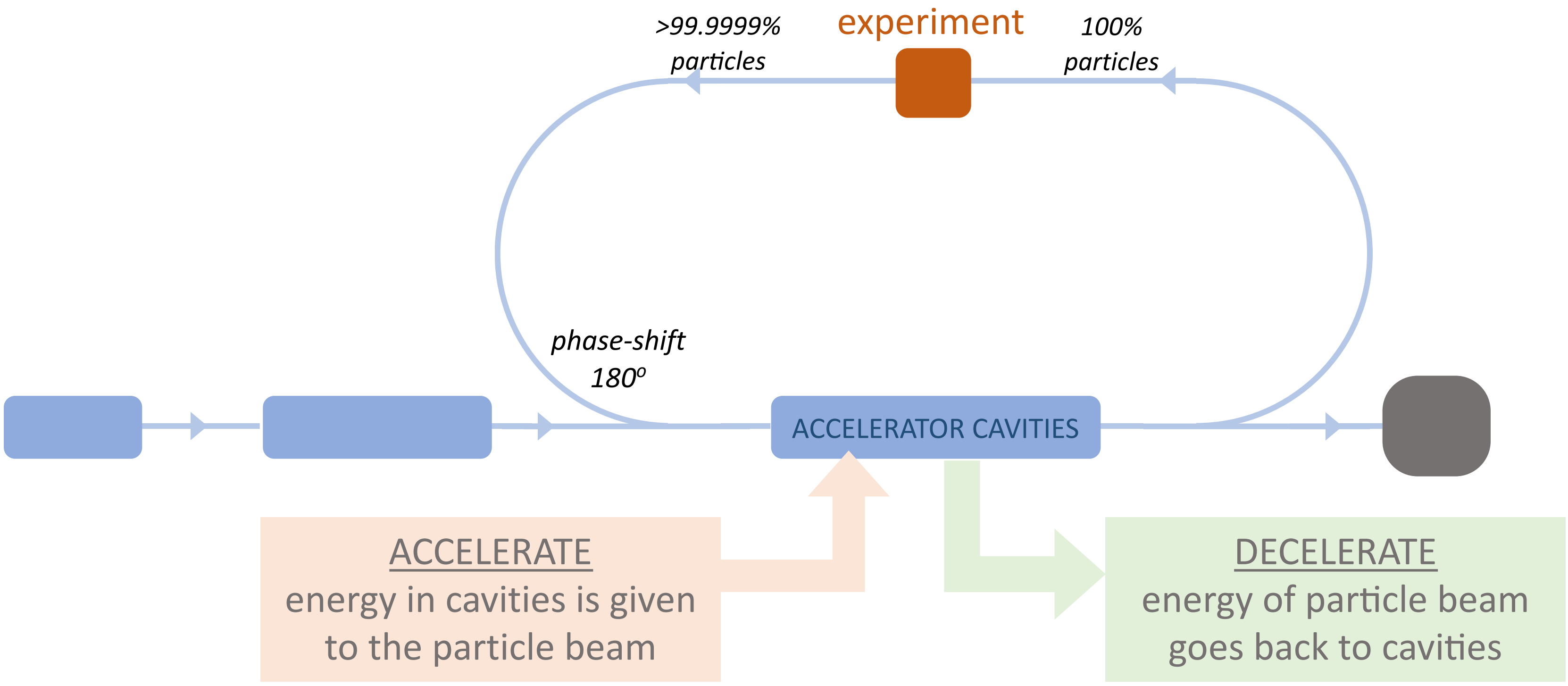
The principle of Energy Recovery



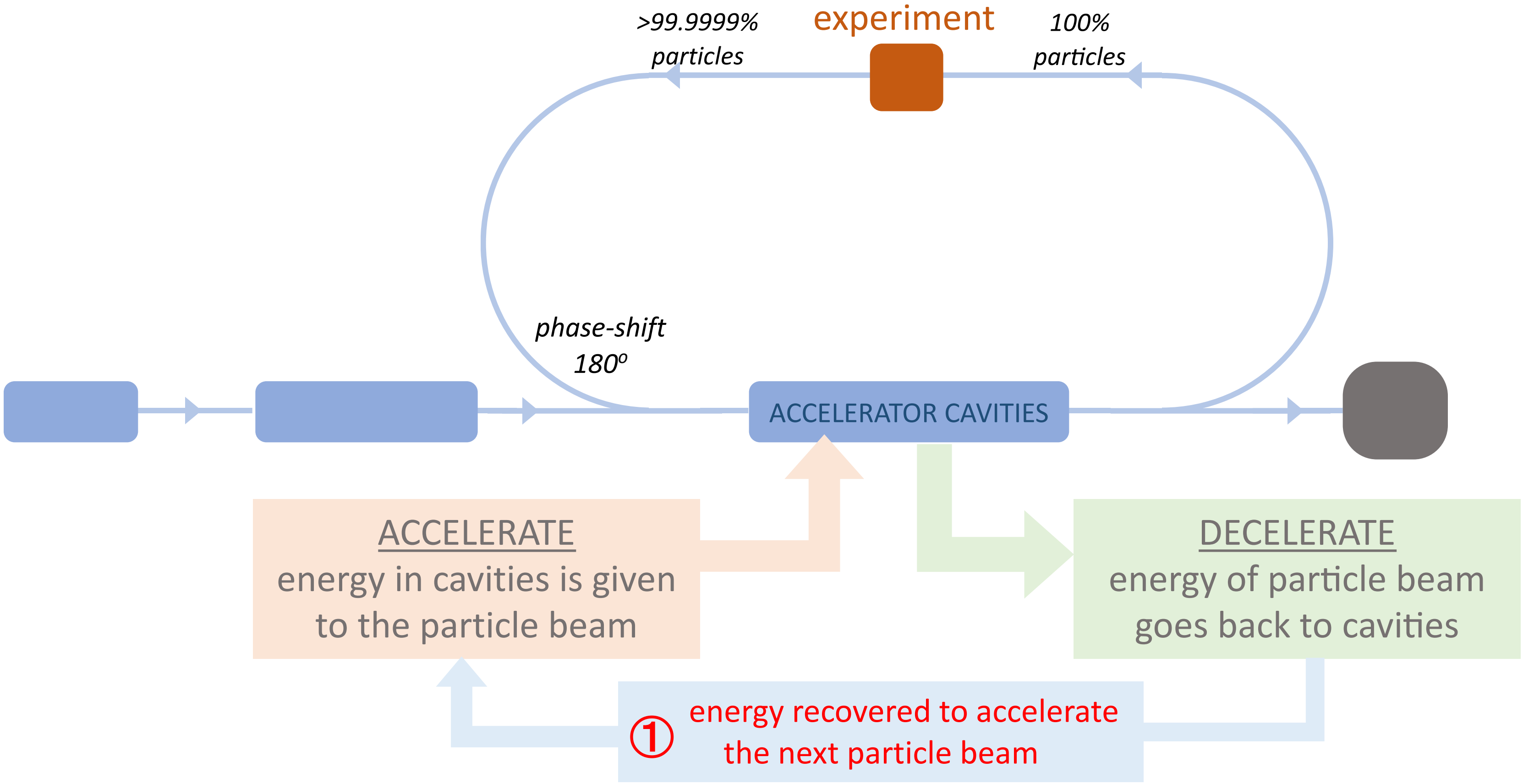
The principle of Energy Recovery



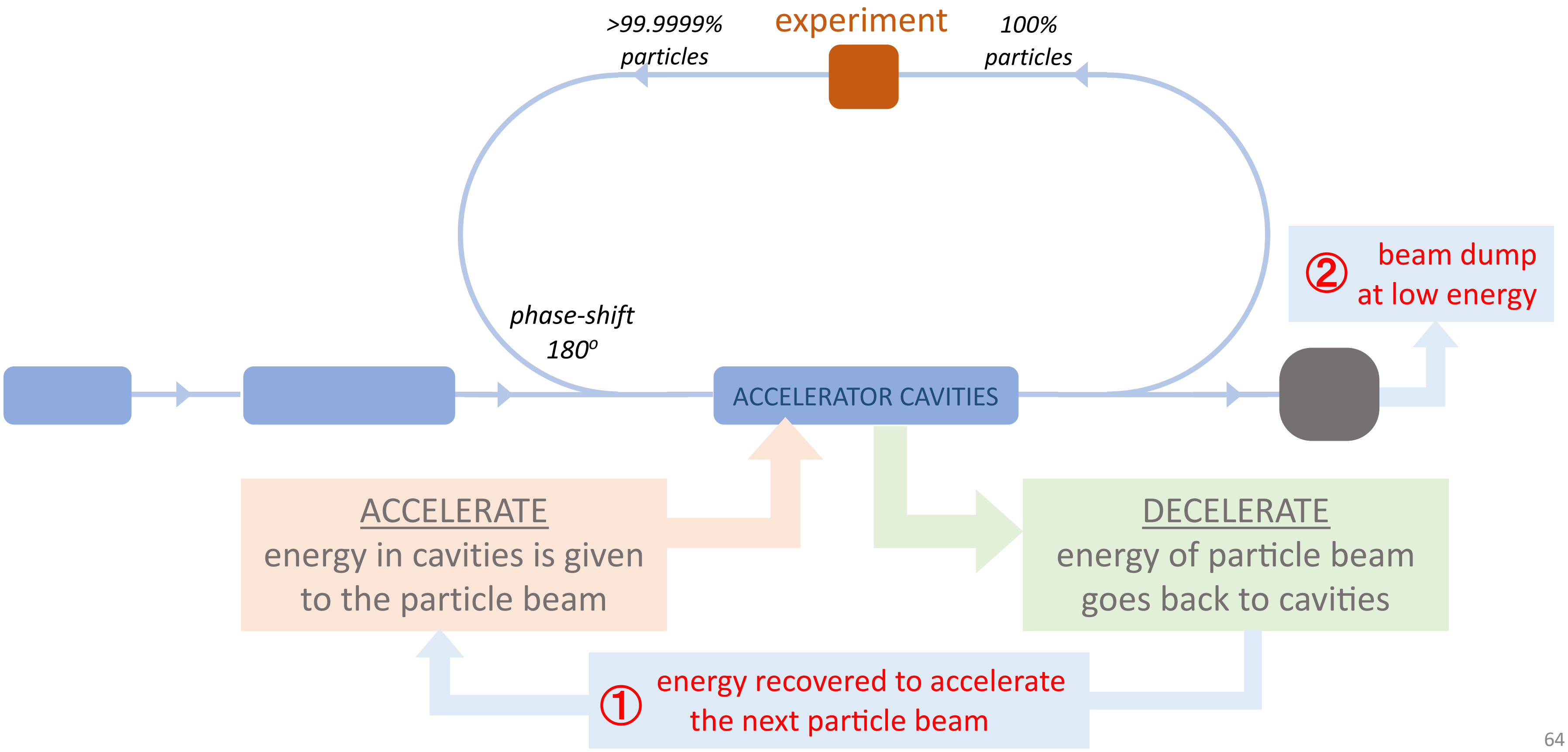
The principle of Energy Recovery



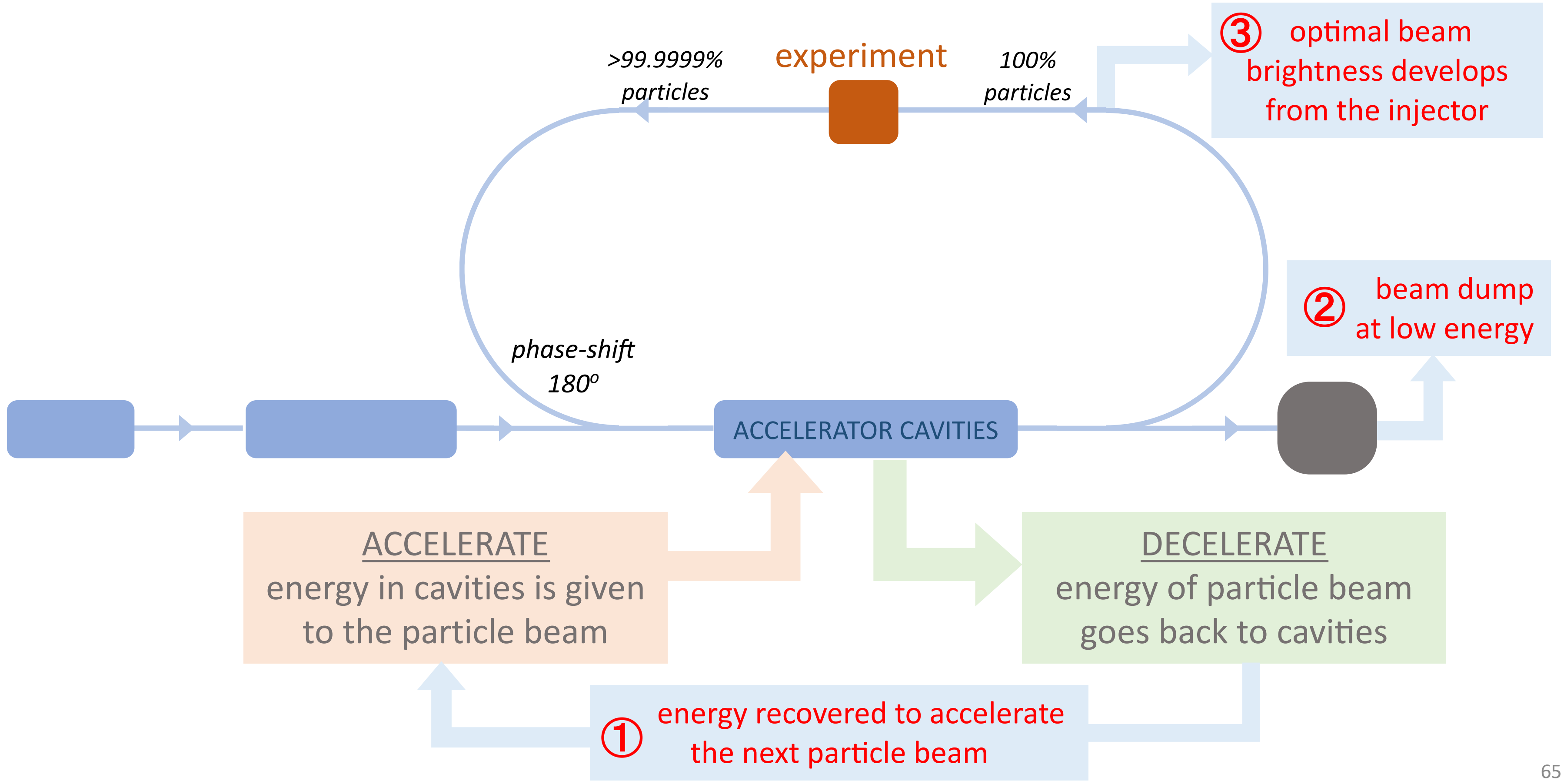
The principle of Energy Recovery



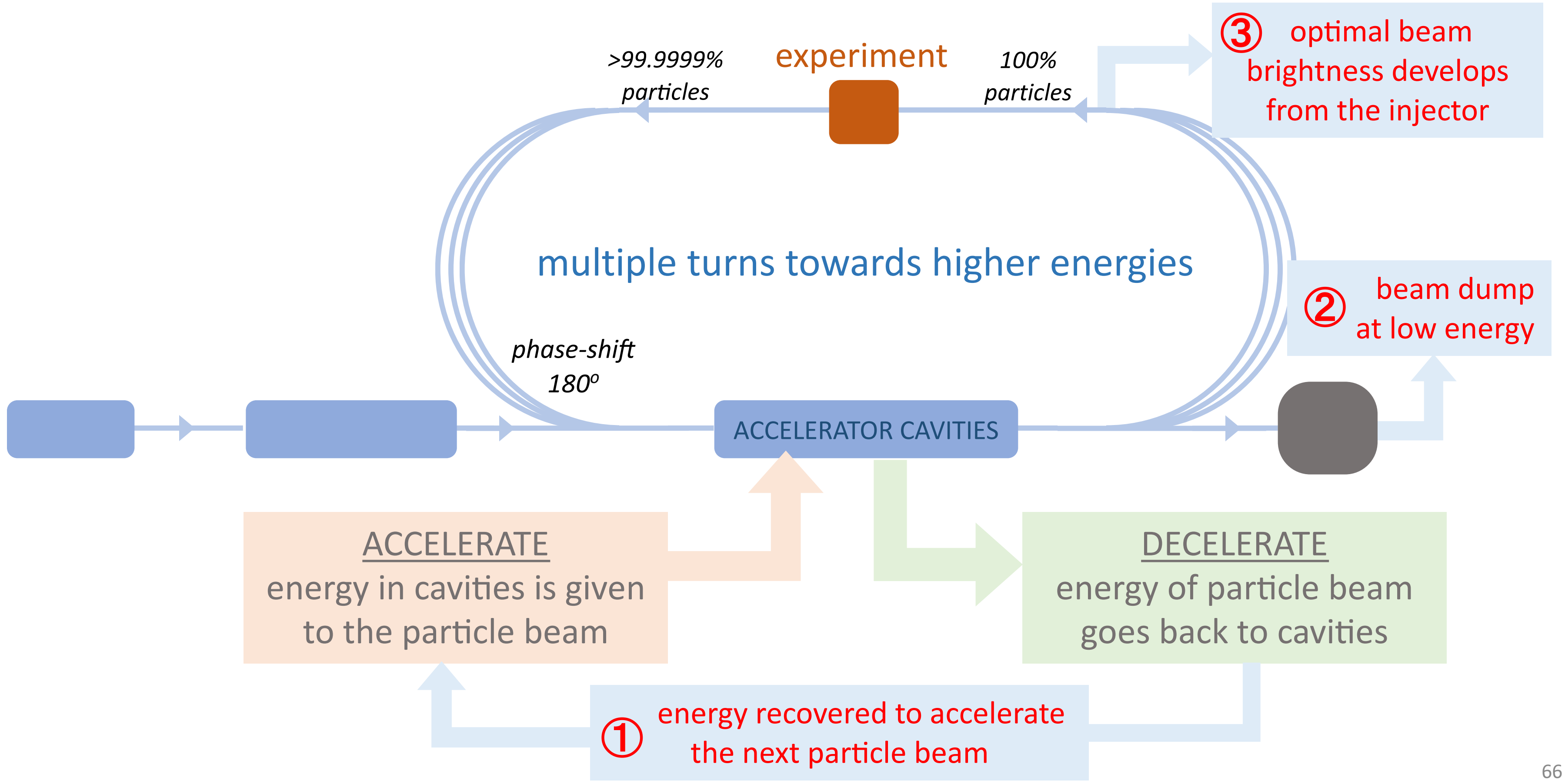
The principle of Energy Recovery



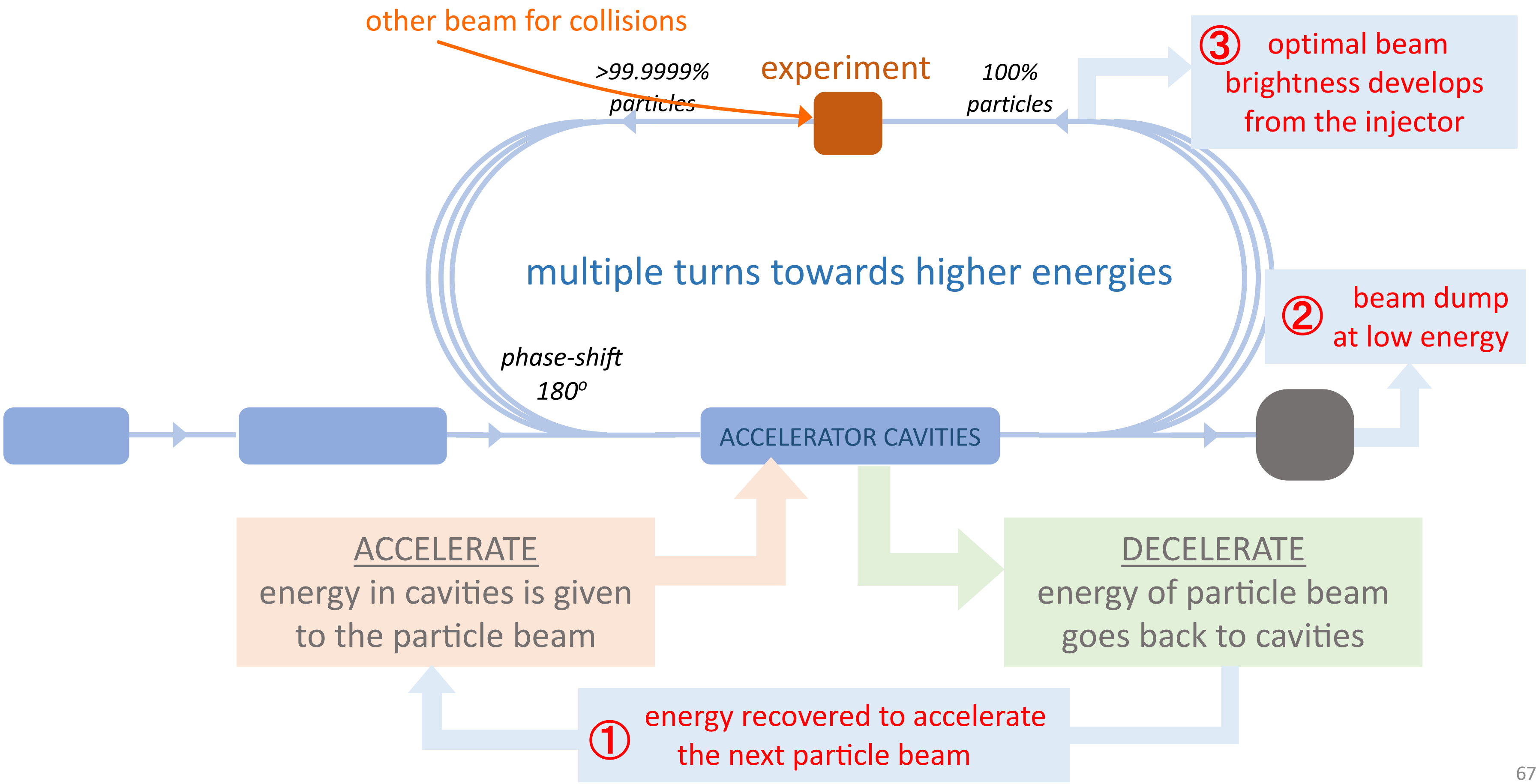
The principle of Energy Recovery



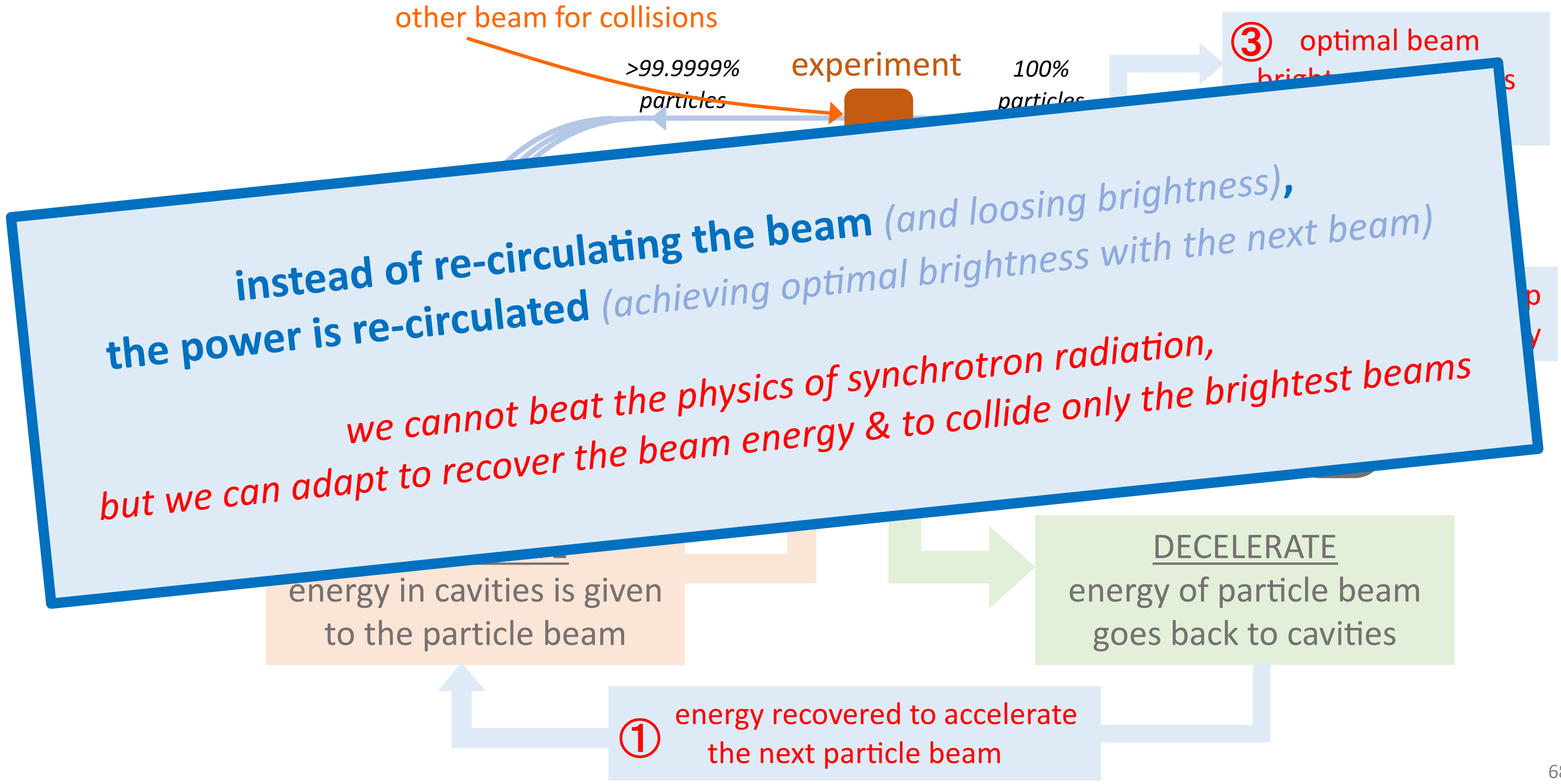
The principle of Energy Recovery



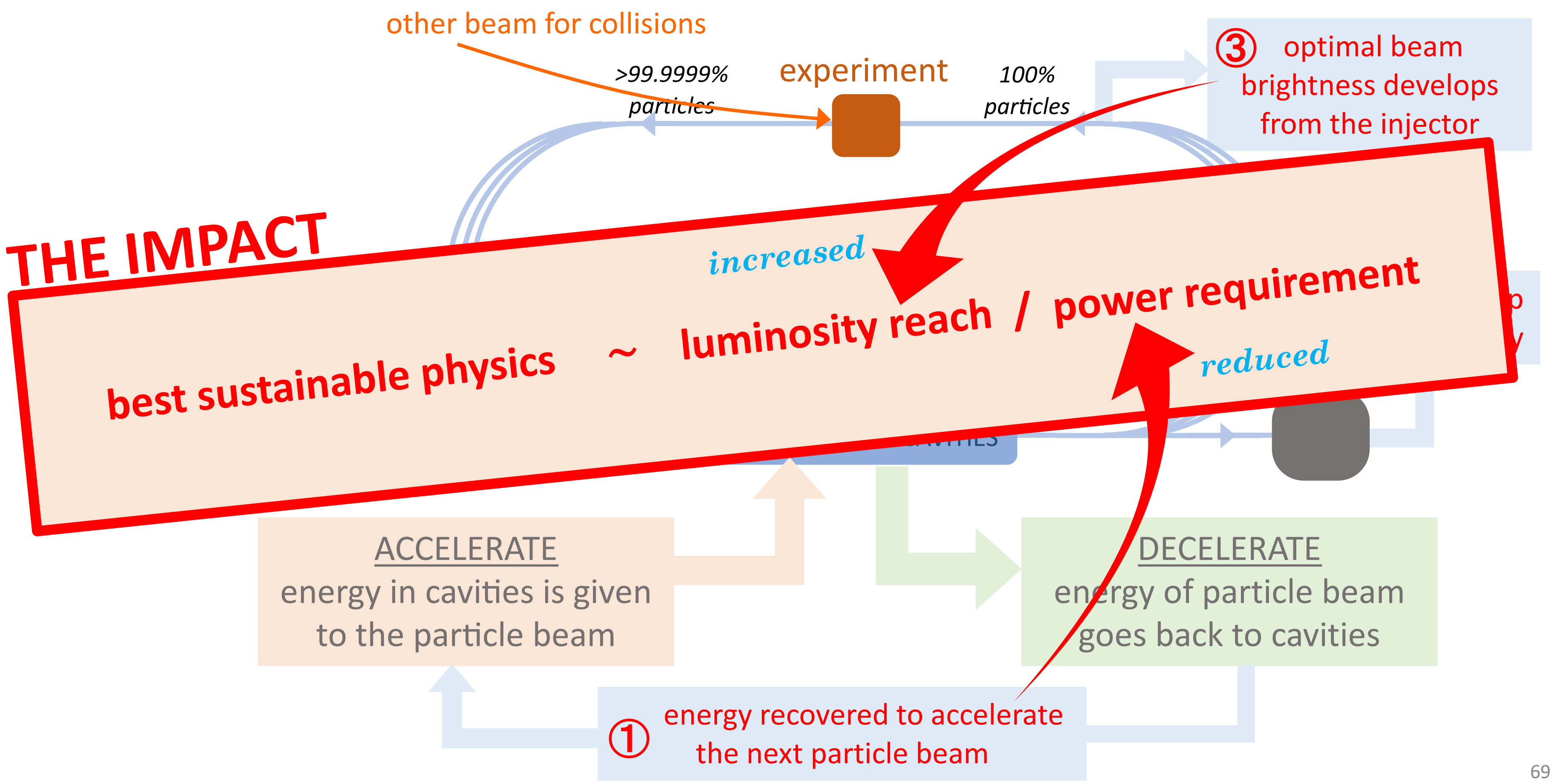
The principle of Energy Recovery



The principle of Energy Recovery

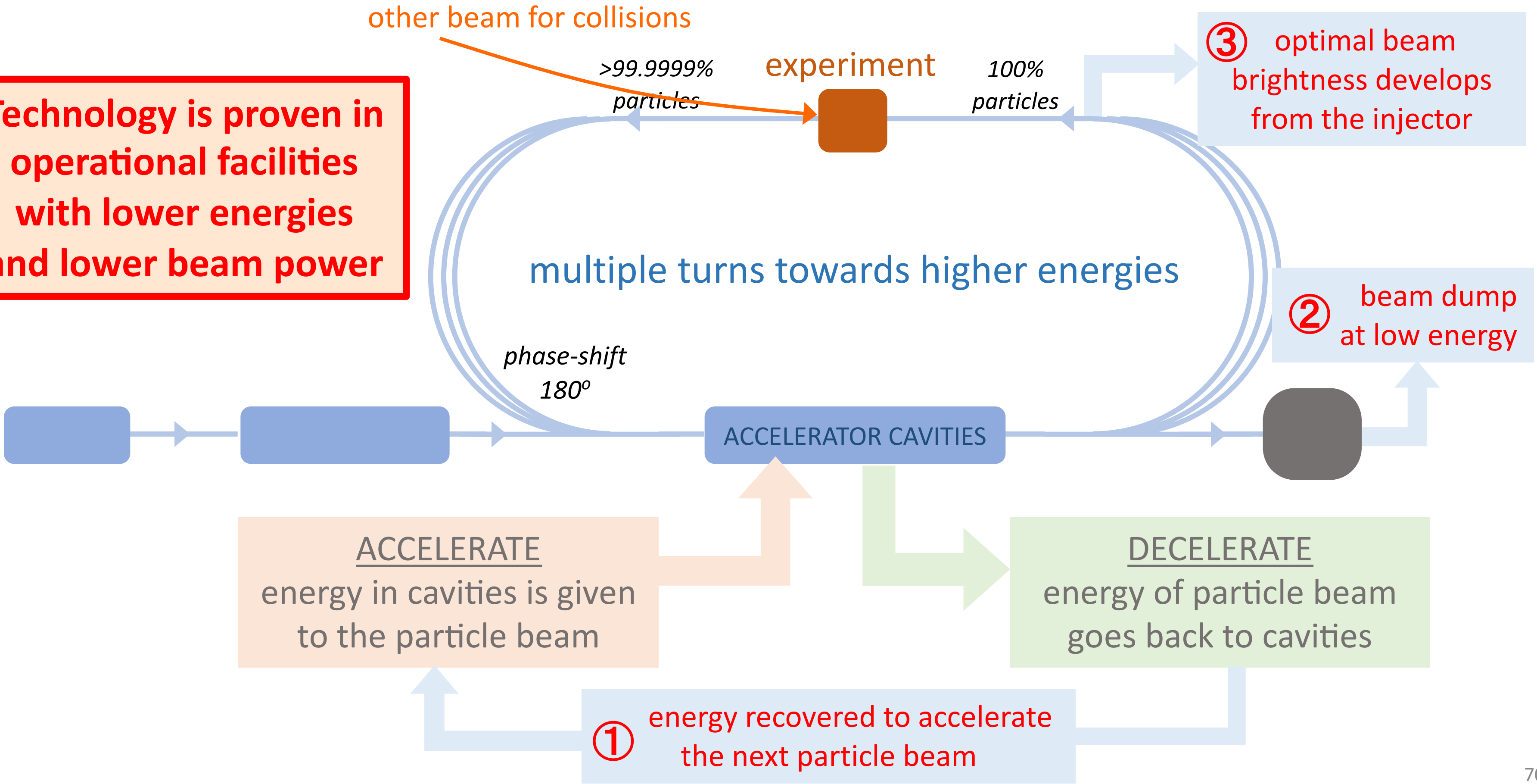


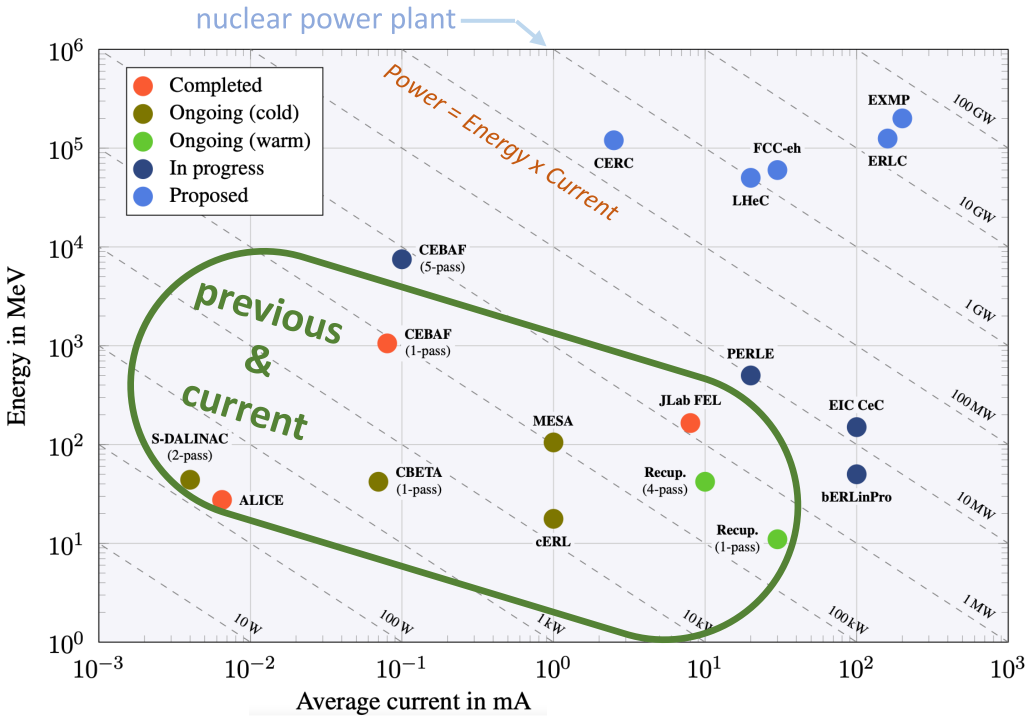
The principle of Energy Recovery



The principle of Energy Recovery

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

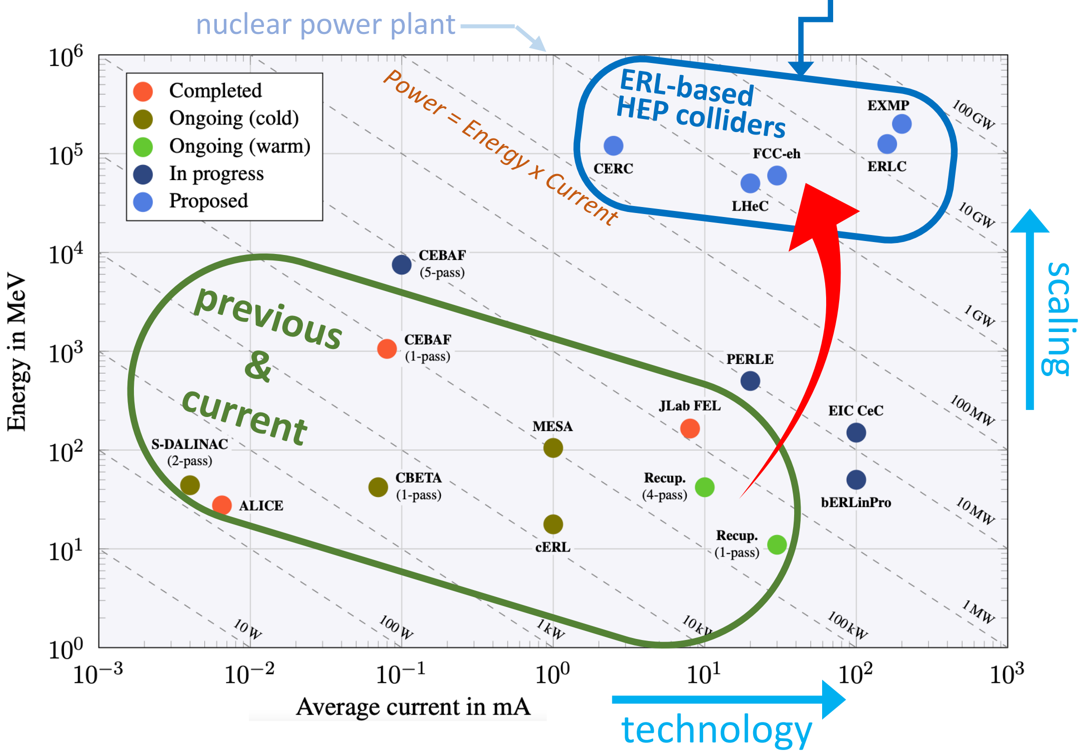




Energy Recovery demonstrated

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, …

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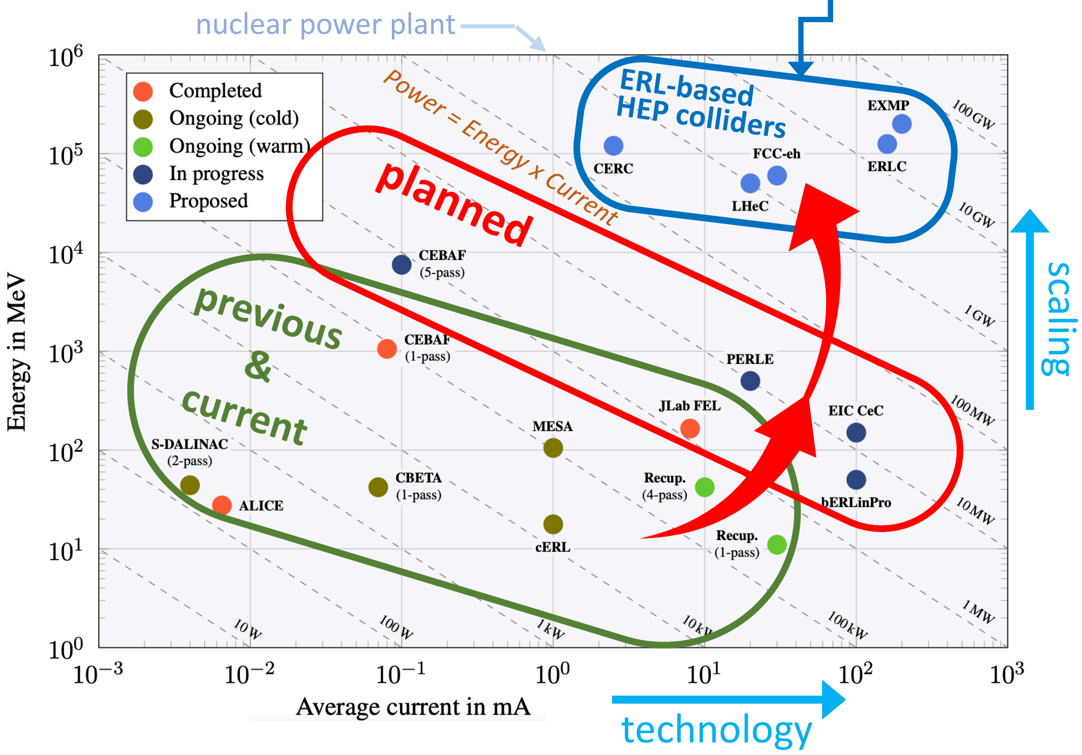

Future ERL-based Colliders

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

Energy Recovery demonstrated

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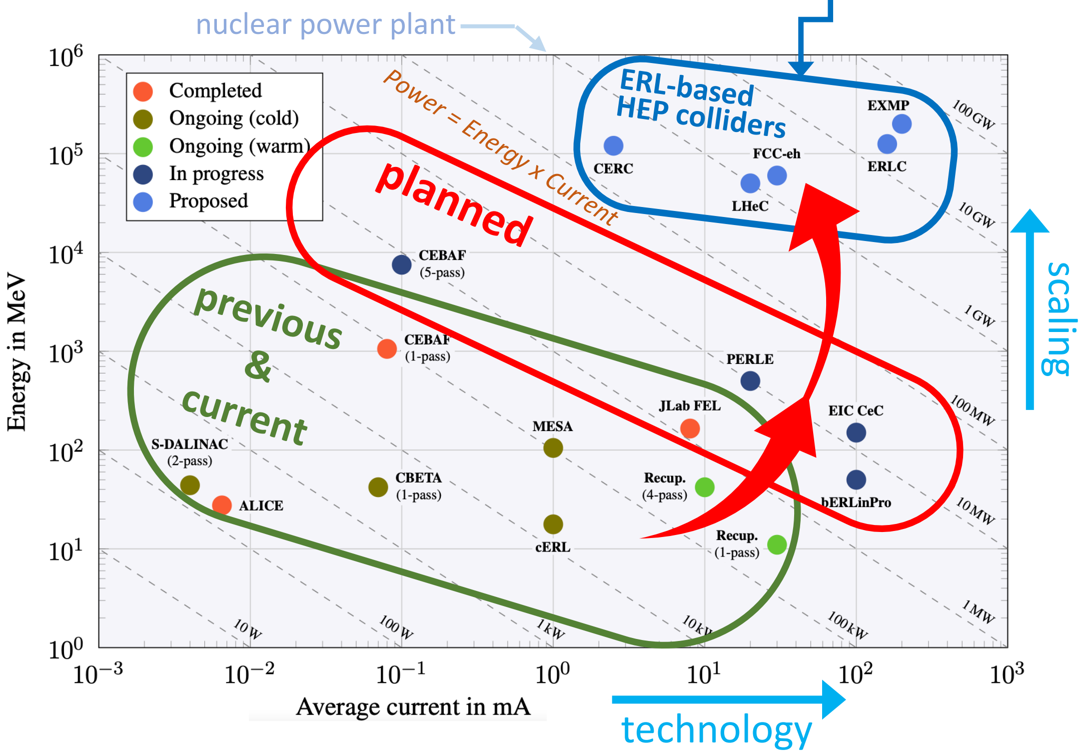


Future ERL-based Colliders

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

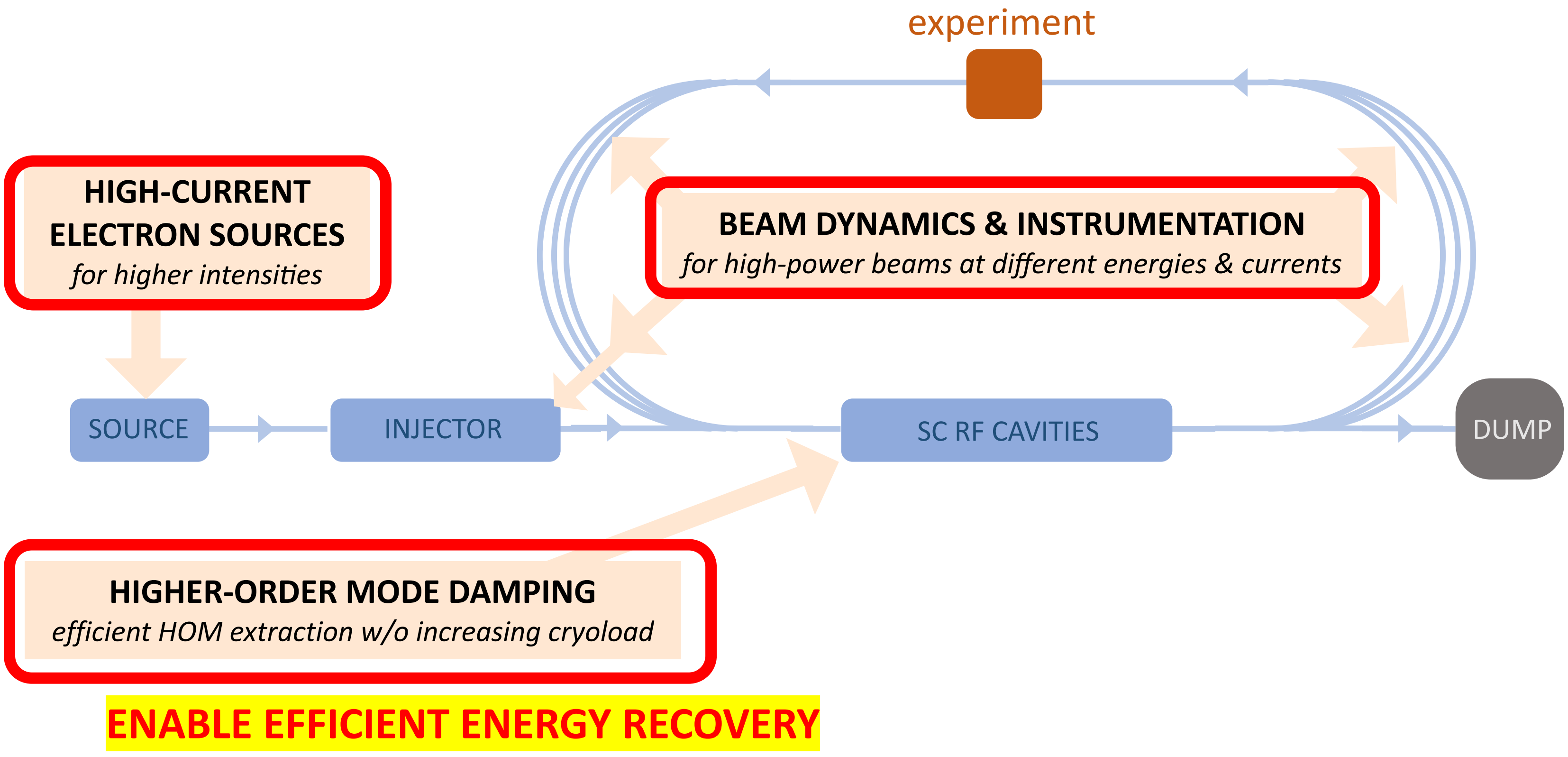
towards high power

Energy Recovery demonstrated

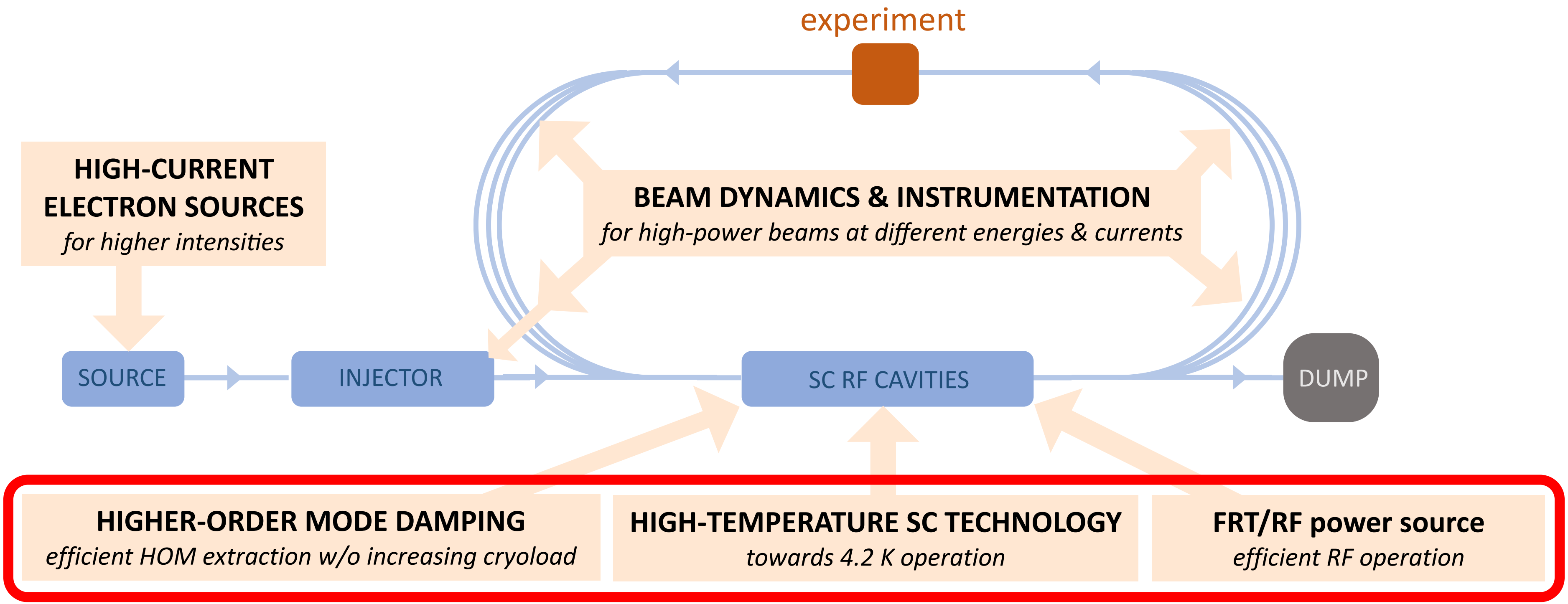
great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

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

Sustainable Accelerating Systems



Sustainable Accelerating Systems



ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

Sustainable Accelerating Syst

Innovate for Sustainable Accelerating Systems (iSAS)

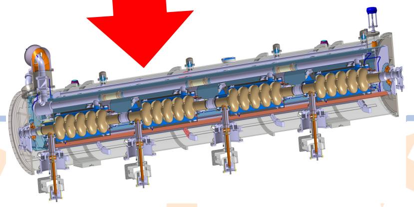
https://indico.ijclab.in2p3.fr/event/9521/

develop a new design of an SRF cryomodule

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

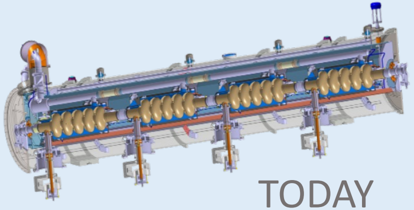
UMENTATION

for high-power beam different energies & currents

SOURCE → INJECTOR →  → DUMP

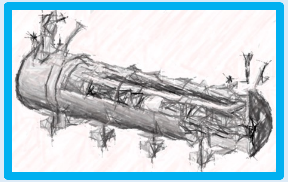
HIGHER-ORDER MODE DAMPING	**HIGH-TEMPERATURE SC TECHNOLOGY**	**FRT/RF power source**
efficient HOM extraction w/o increasing cryoload	*towards 4.2 K operation*	*efficient RF operation*

ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

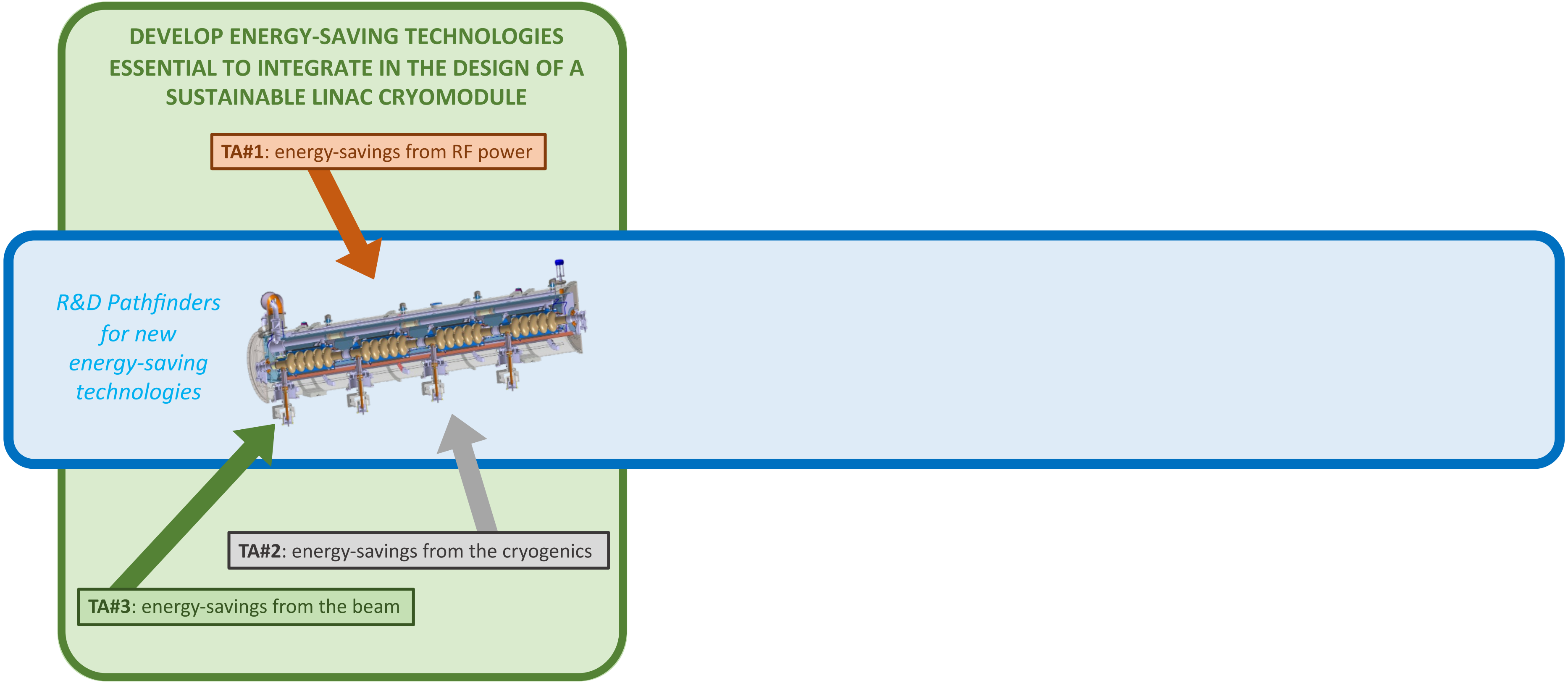


TODAY

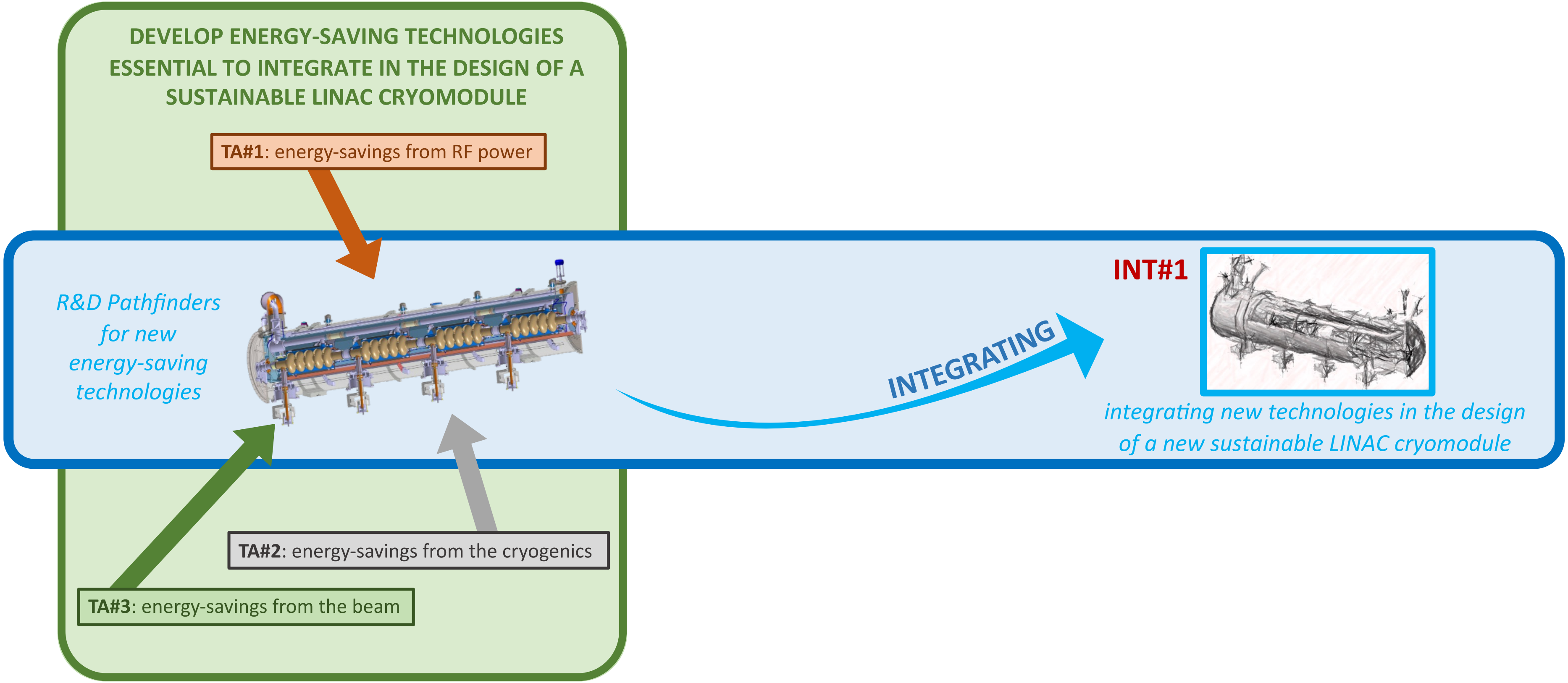
INNOVATE TECHNOLOGIES TOWARDS
A SUSTAINABLE ACCELERATING SYSTEM



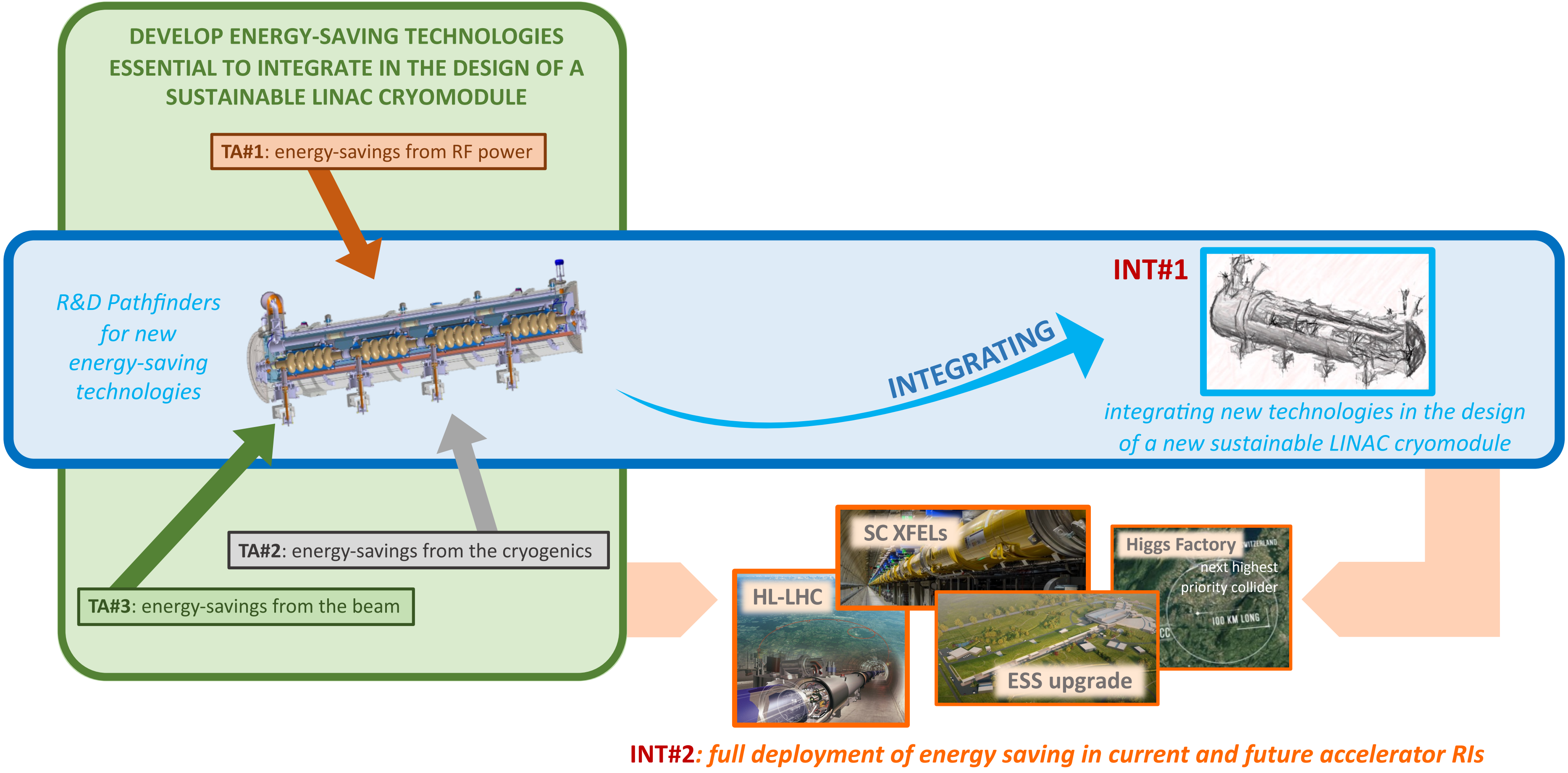
NEW DESIGN



TA: Technology Area

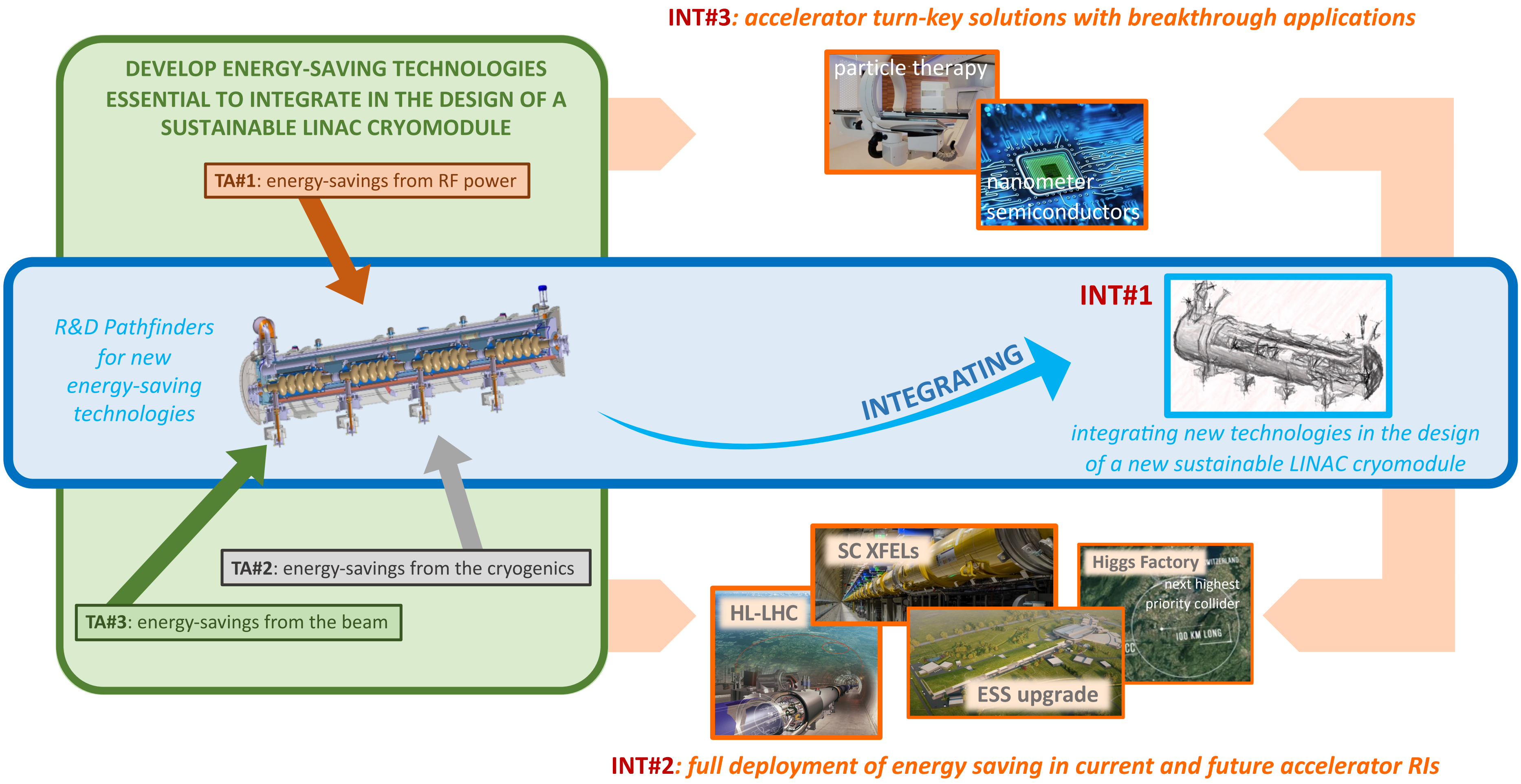


TA: Technology Area, INT: Integration Activities



TA: Technology Area, INT: Integration Activities

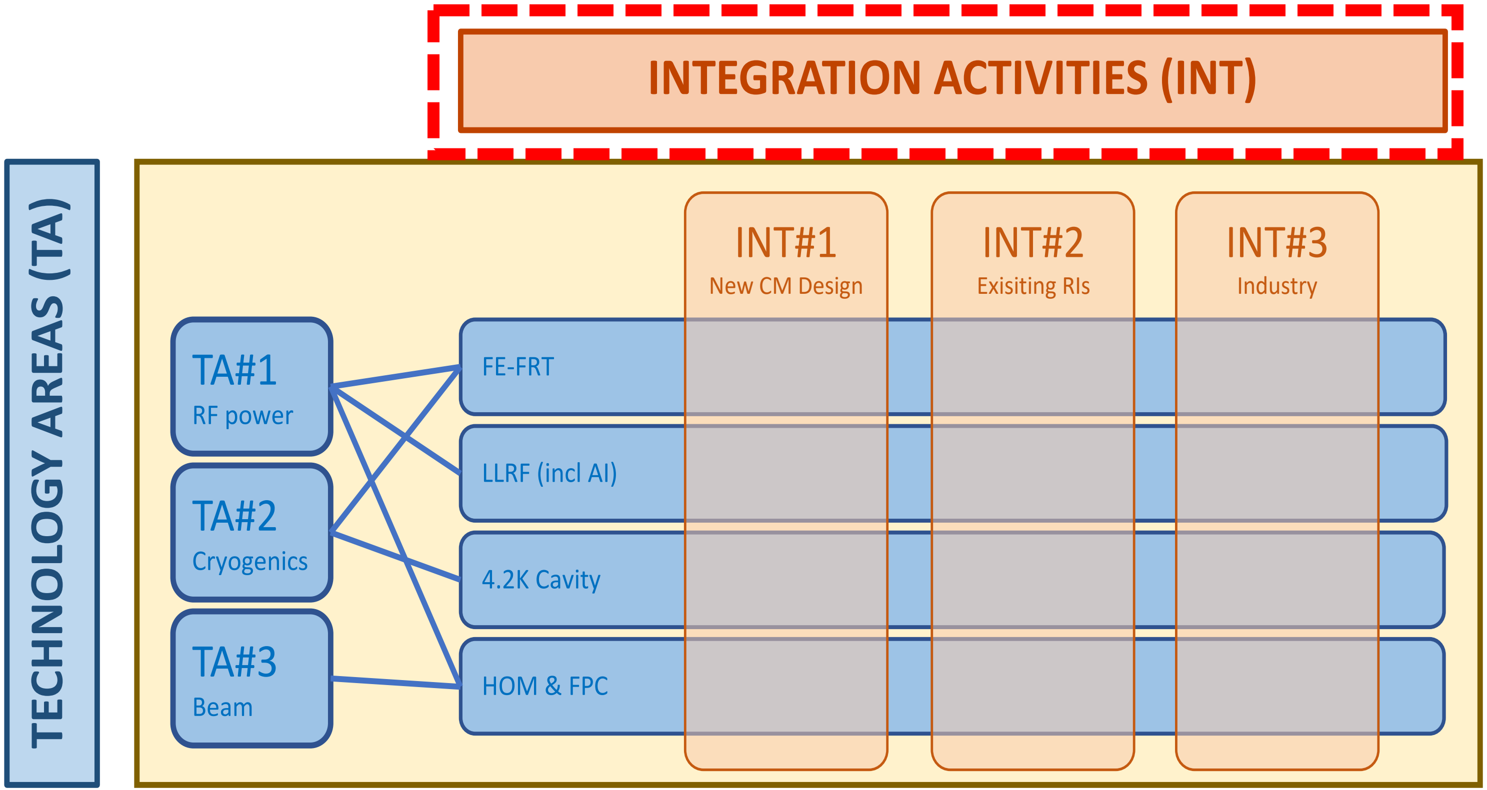
RIs: Research Infrastructures



INT#3: accelerator turn-key solutions with breakthrough applications
DEVELOP ENERGY-SAVING TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
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
Higgs Factory
next highest priority collider
100 KM LONG
HL-LHC
ESS upgrade
INT#2: full deployment of energy saving in current and future accelerator RIs

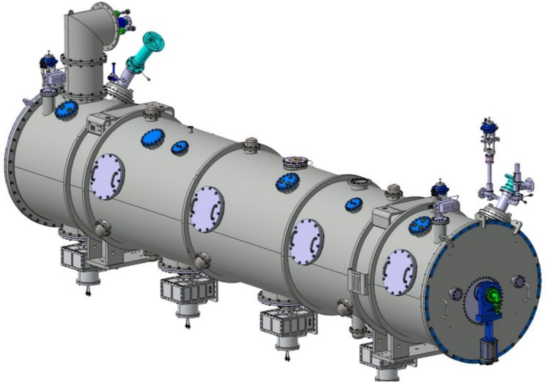
iSAS cross coordination

The ambition of iSAS is to pave the way by developing common solutions for the engineering and industrial challenges to expedite the integration of energy-saving solutions.



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 Objectives – *Integration Activities*

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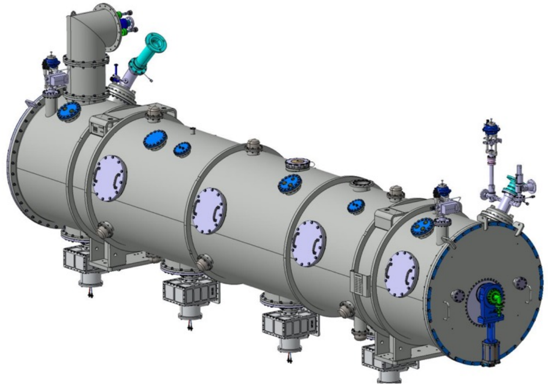

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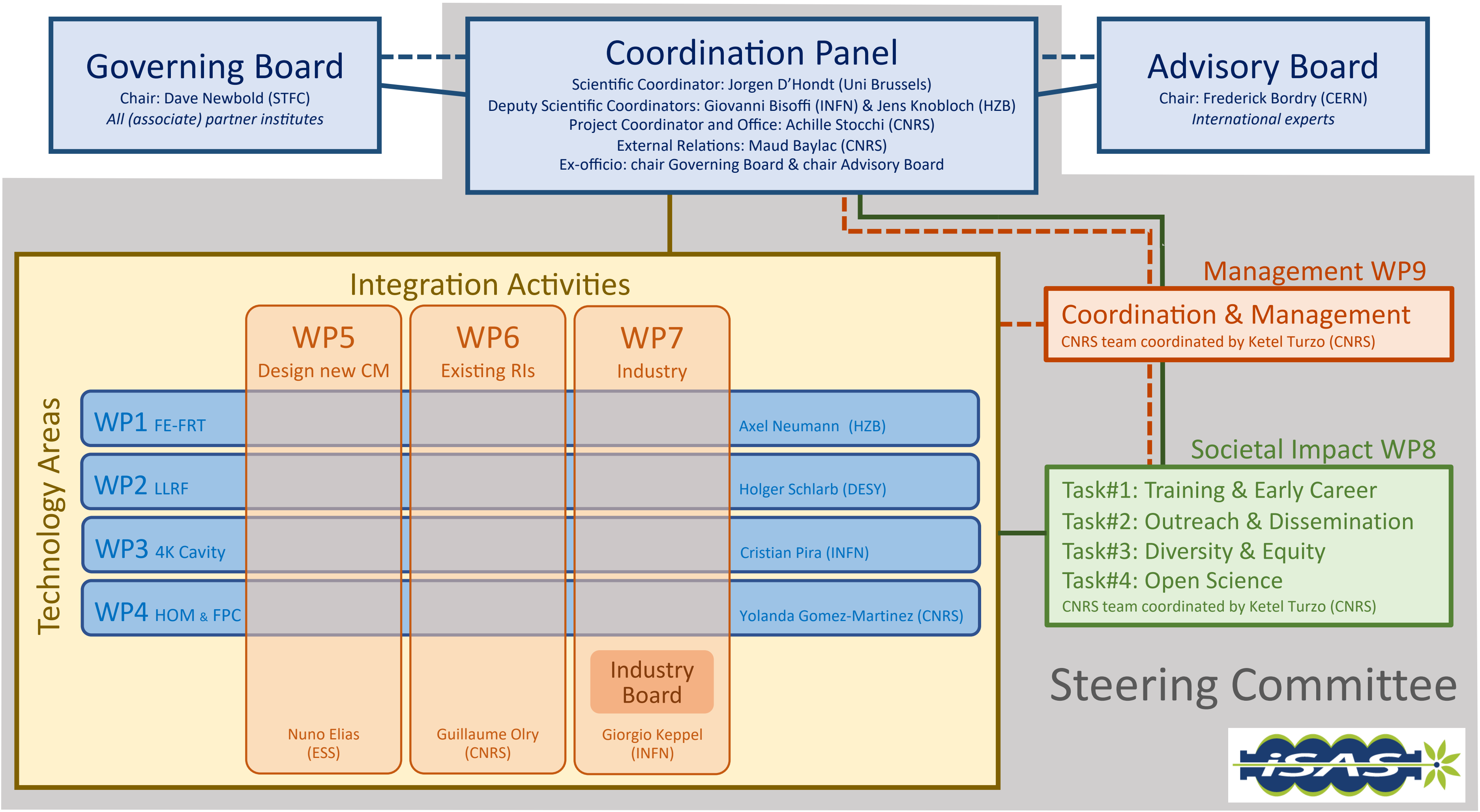
iSAS Objectives – *Integration Activities*

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.*

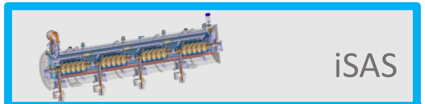
- **integration into existing RIs** (CNRS, Uni.Lanc., CEA, ESS, INFN)
  - *Retrofitting FE-FRT into existing cryomodules, HL-LHC oriented.*
  - *Adapt an existing ESS cryomodule to integrate new HOM couplers and FPC.*
  - *Fabrication and validation of cryomodule components (e.g., cavities).*
  - *Assembly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

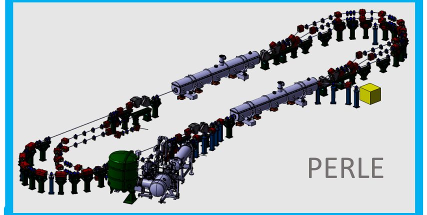
- **integration into industrial solutions** (INFN, CNRS)
  - *Relations with industries: engagement to expedite the evolution from low to higher TRL (involving an Industry Board involved in design reviews with a view on industrialization).*
  - *Business opportunities: develop an iSAS project repository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


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
Design new CM
WP6
Existing RIs
WP7
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

High-power ERL technology timeline

2020'ies





high-power ERL demonstrated

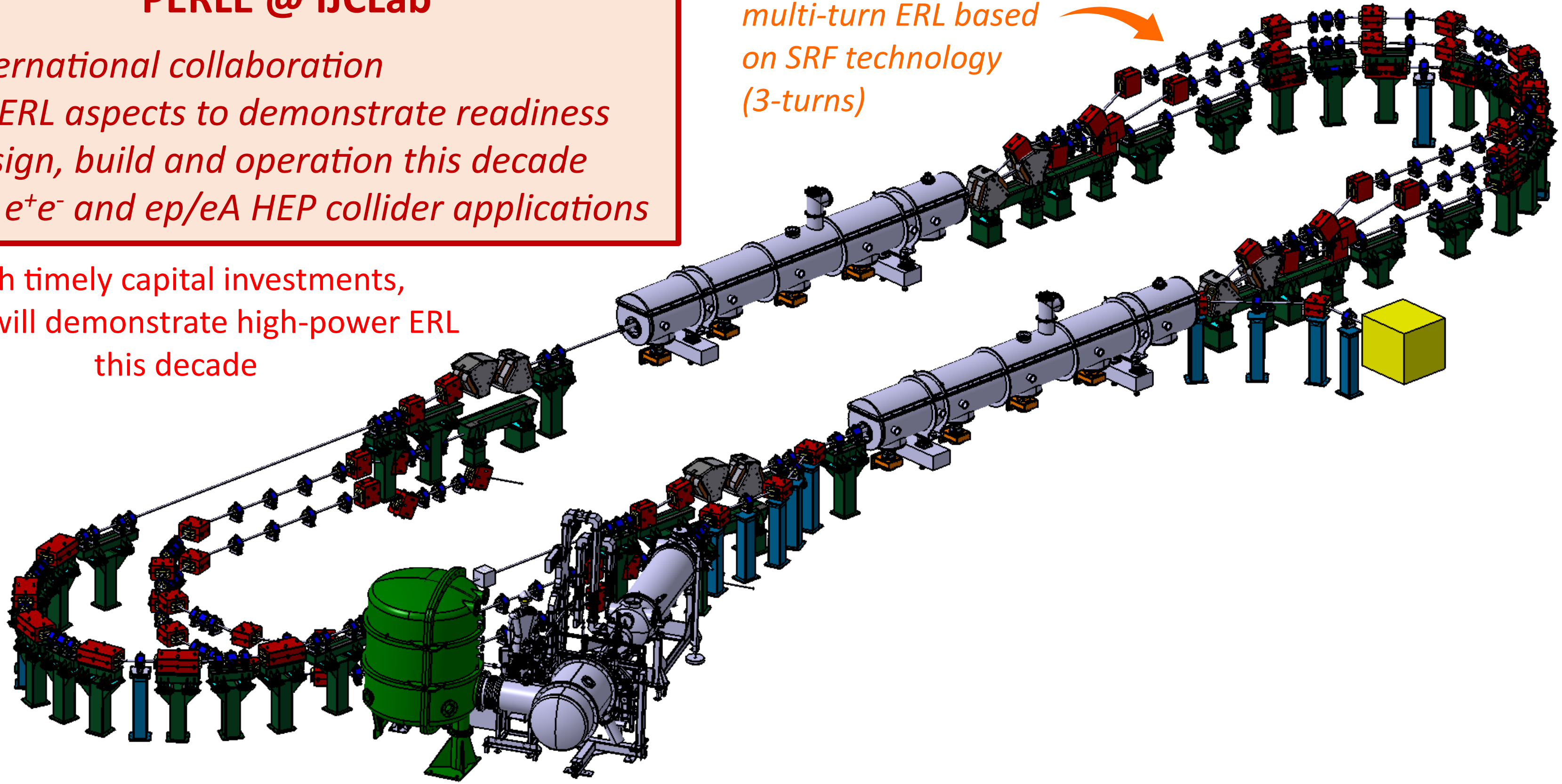
Upcoming facilities for Energy Recovery Linac R&D

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*

With timely capital investments,
PERLE will demonstrate high-power ERL
this decade

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



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

Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

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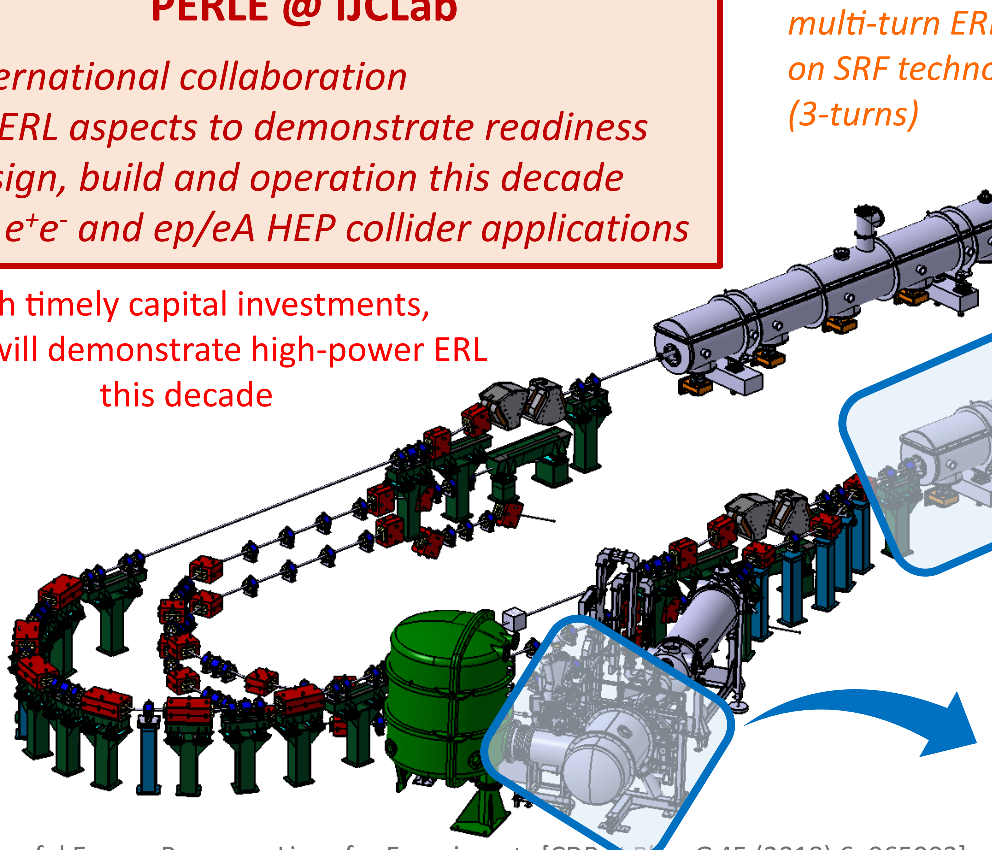

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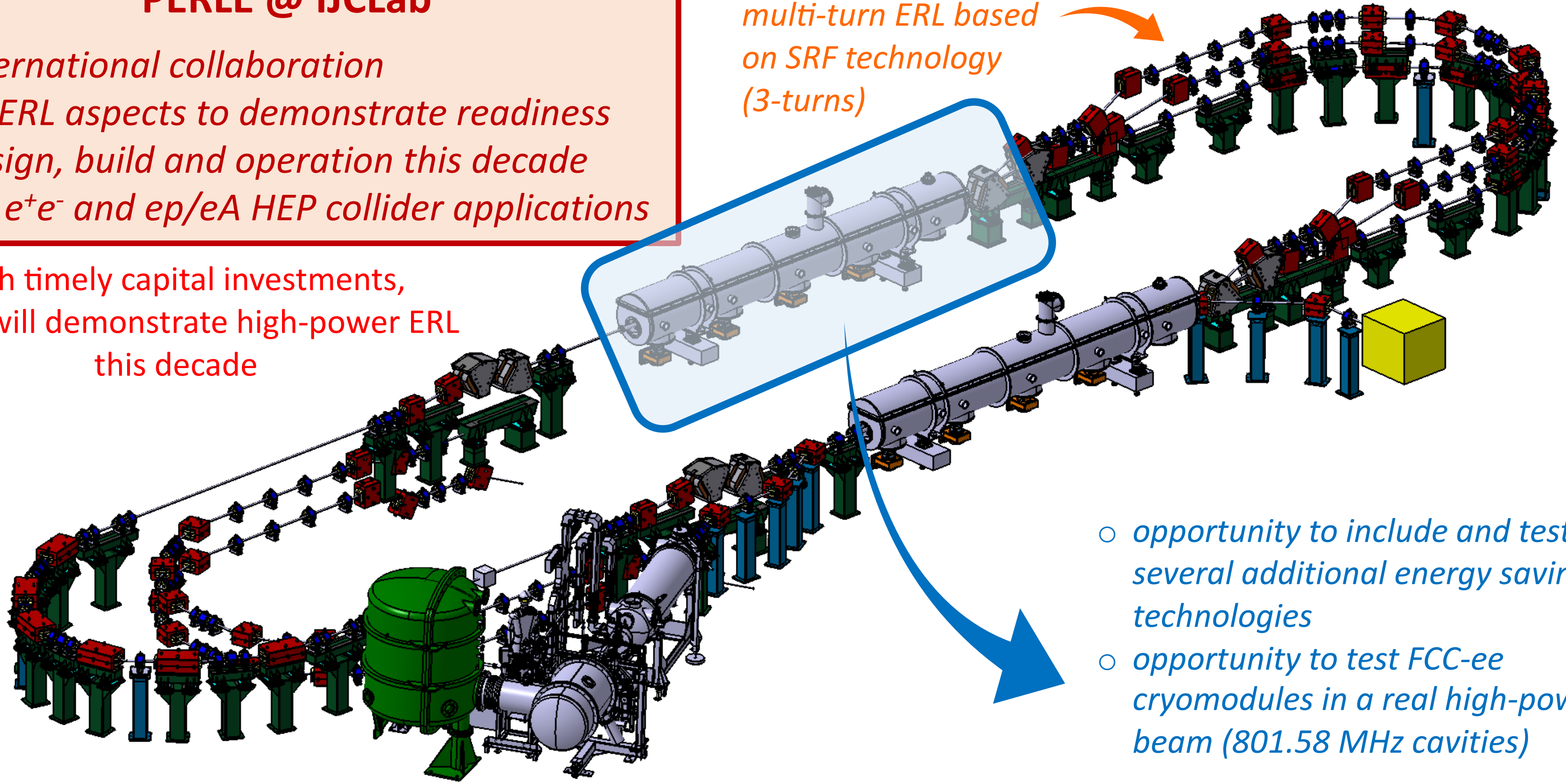


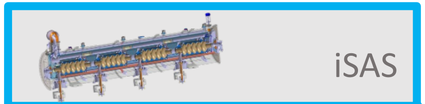
- *opportunity to include and test several additional energy saving technologies*
- *opportunity to test FCC-ee cryomodules in a real high-power beam (801.58 MHz cavities)*

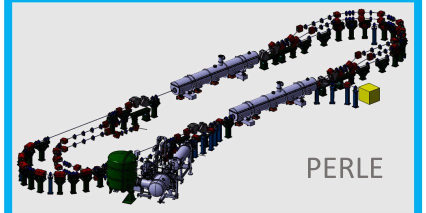
PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies





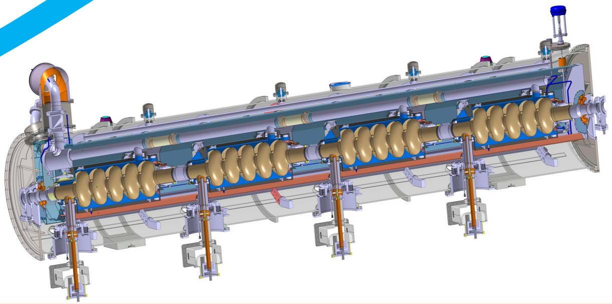
high-power ERL demonstrated

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies

high-power ERL demonstrated



***iSAS**: new design including various energy-saving and energy-recovery technologies*

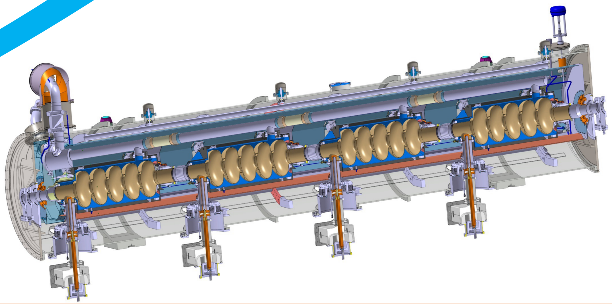
Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies

high-power ERL
demonstrated

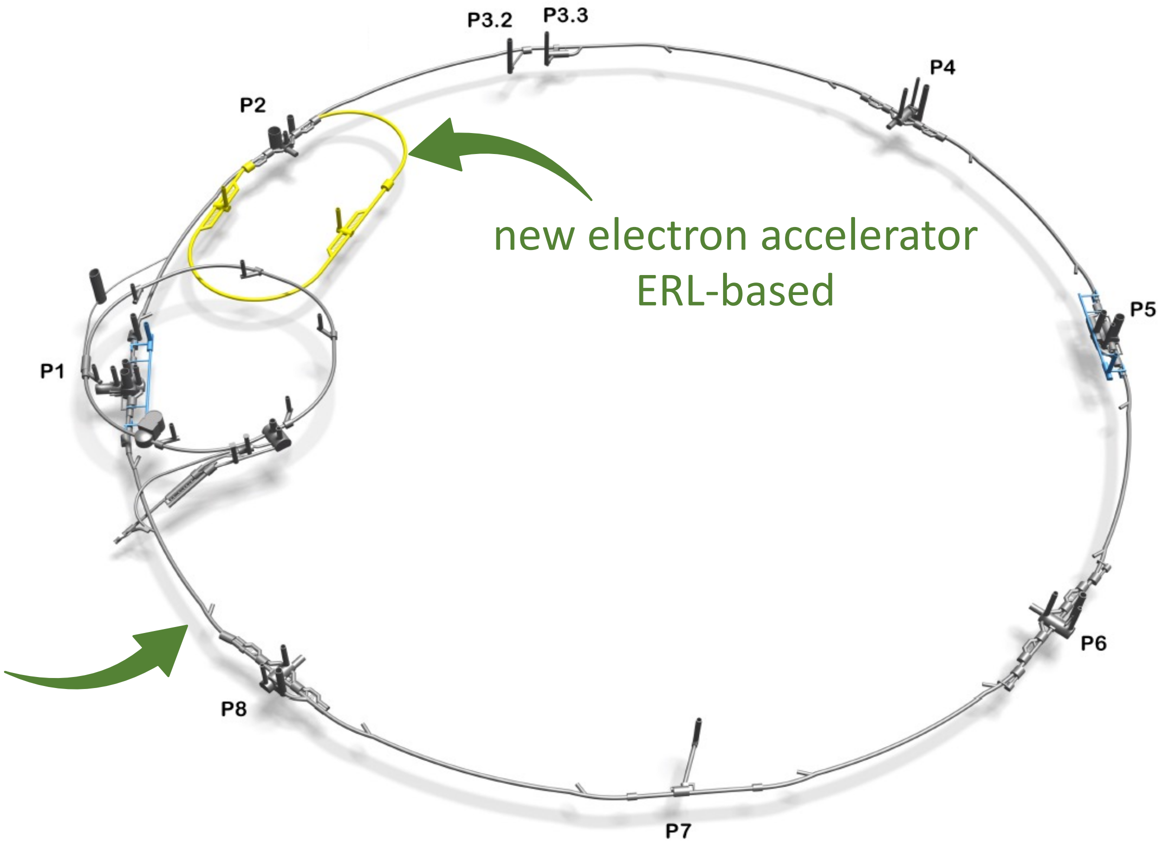
ERL ready for high-energy and high-luminosity colliders



iSAS*: new design including various energy-saving and energy-recovery technologies*

ERL-based ep/eA colliders at CERN

high-energy & high-luminosity electron-proton collisions



new electron accelerator
ERL-based

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

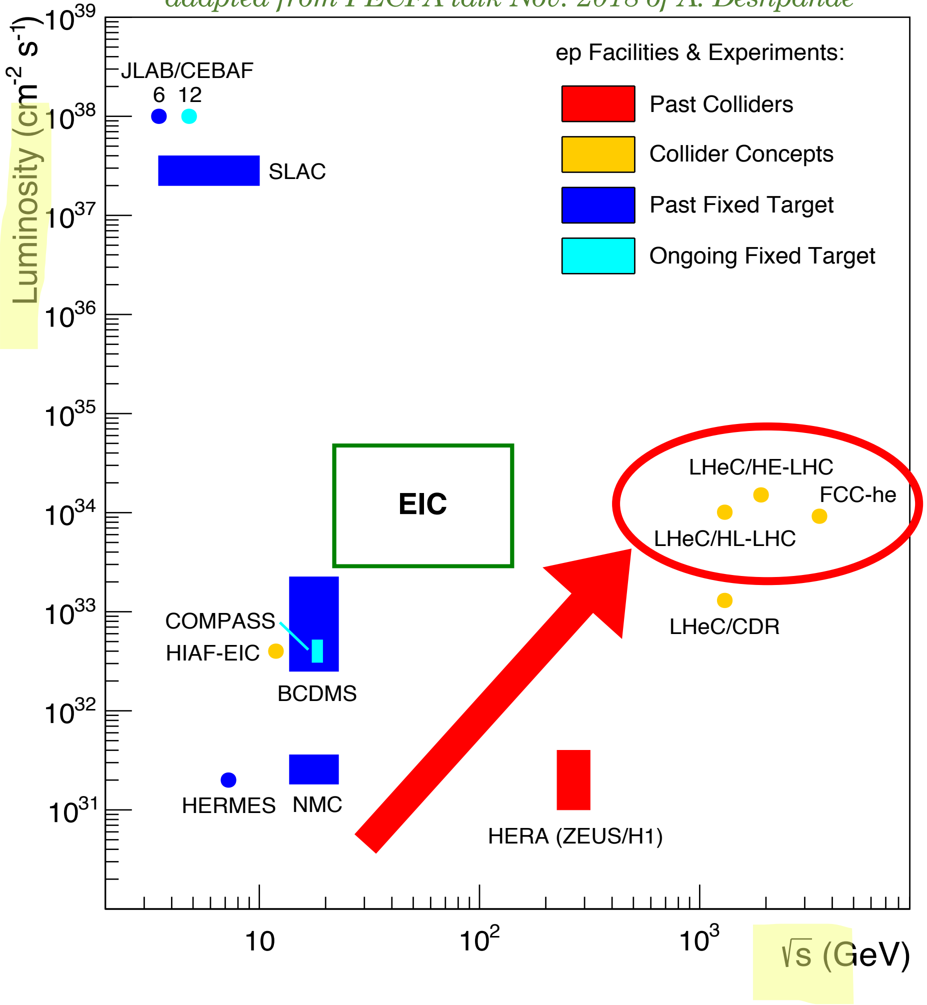
3 orders in magnitude in luminosity
1 order in magnitude in energy

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

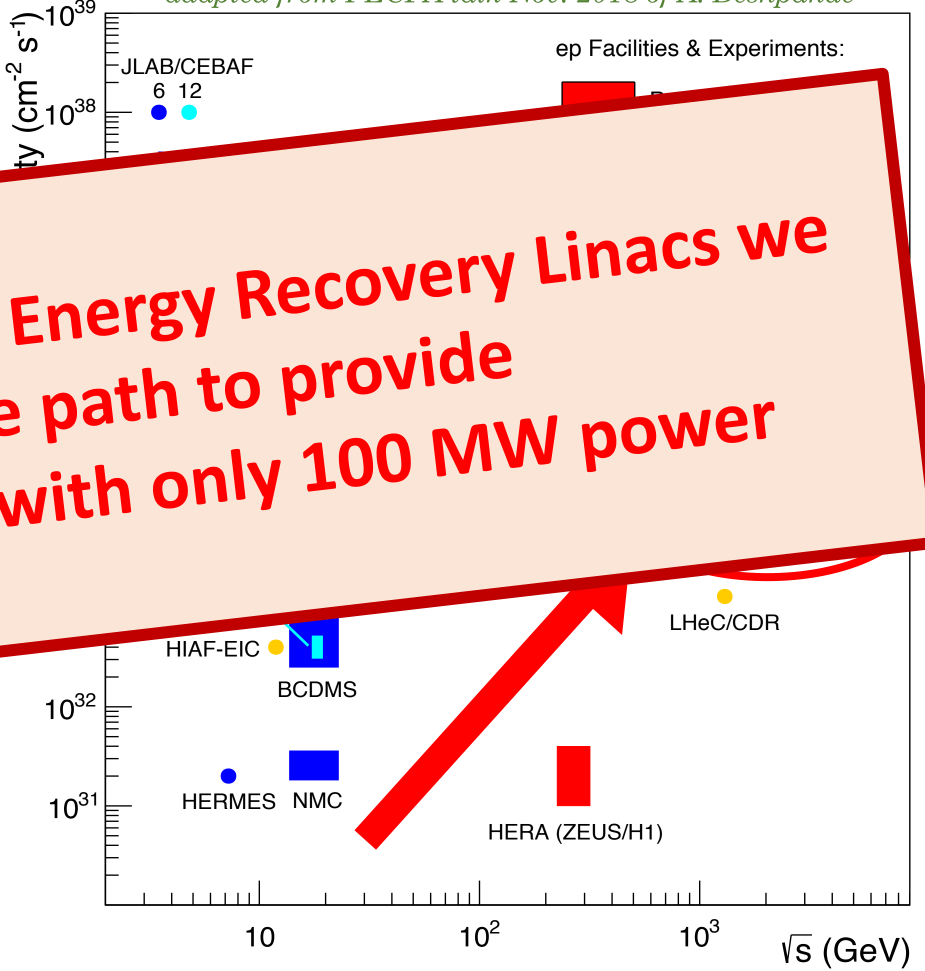
From HERA ...

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

LHeC ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant

adapted from PECFA talk Nov. 2018 of A. Deshpande



Future flagship at the energy & precision frontier

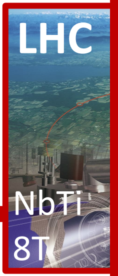
Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

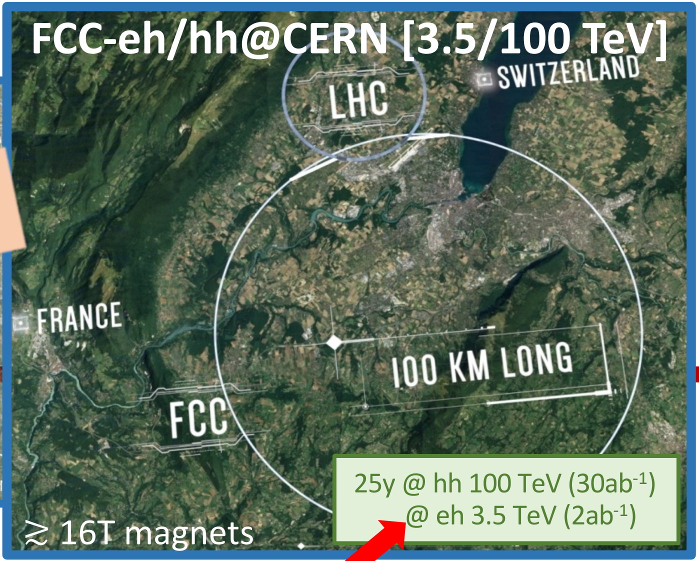
attractive combination of precision & energy frontier



ep-option with HL-LHC: LHeC

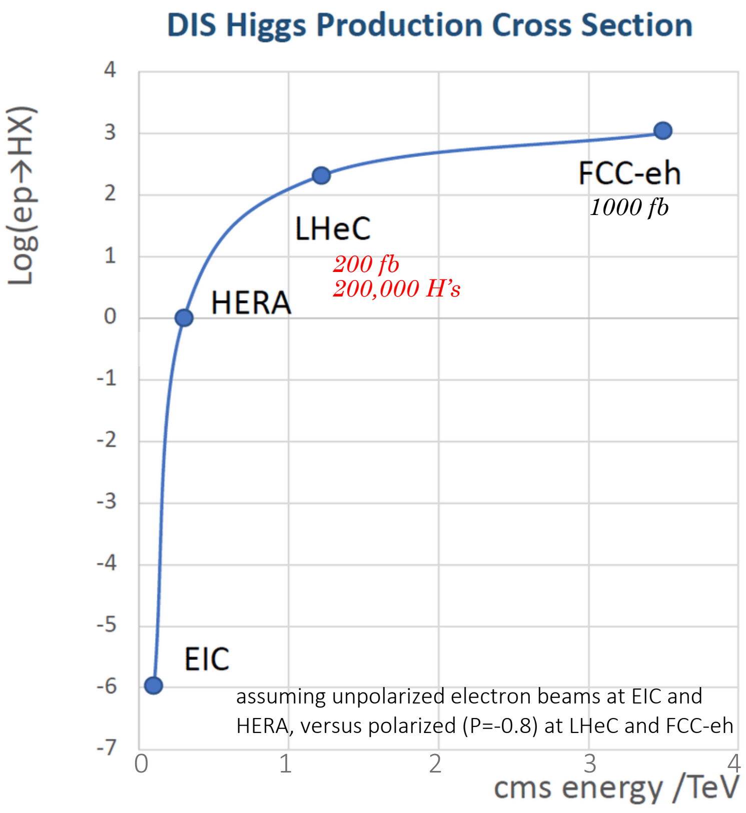
10y @ 1.2 TeV (1ab^{-1})

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

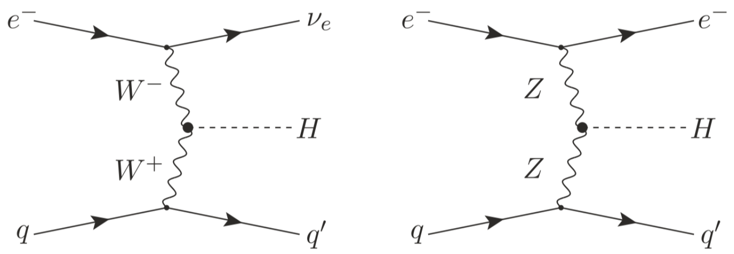


numbers assume 2 IPs for each collider (only one for FCC-eh)

Collision energy above the threshold for EW/Higgs/Top



The real game change between HERA and LHC/FCC

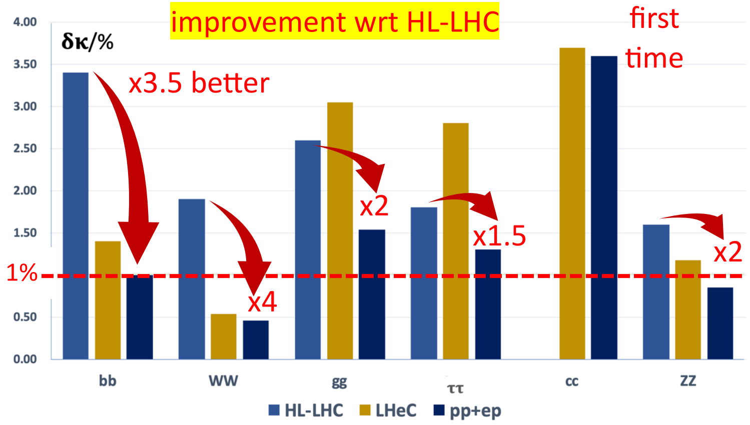


compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

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)

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

Open Kick-Off meeting on Oct 31, 2023: https://indico.cern.ch/event/1335332/

Workshop on ep vs pp synergies, Febr 29 – Mar 1, 2024: https://indico.cern.ch/event/1367865/overview

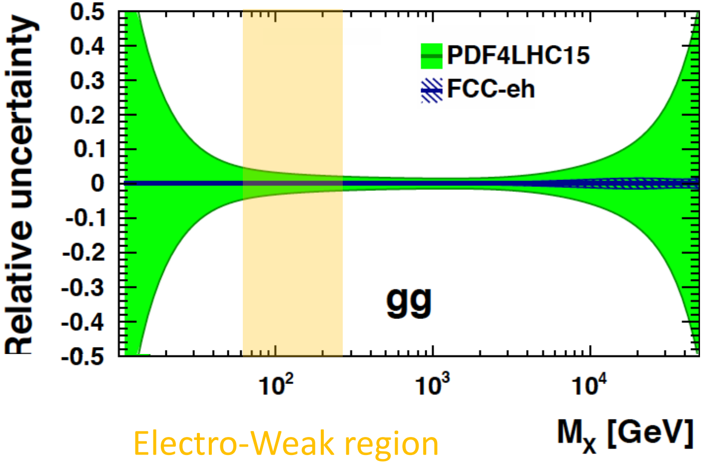
... extended in (Q^2,x) by
orders of magnitude

... physics

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

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

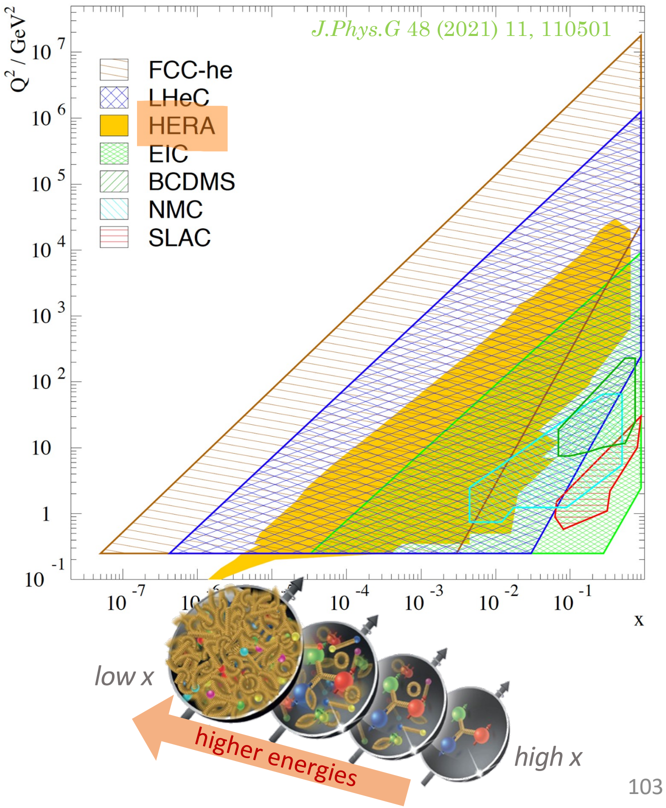


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

Kinematic range Parton Distribution Functions



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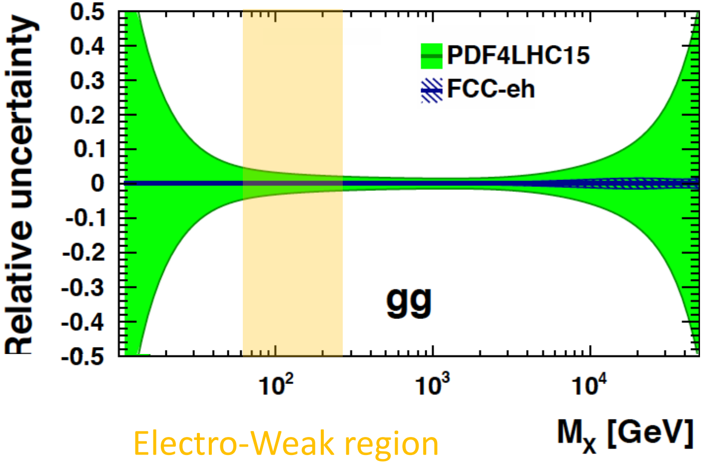


Electro-Weak region

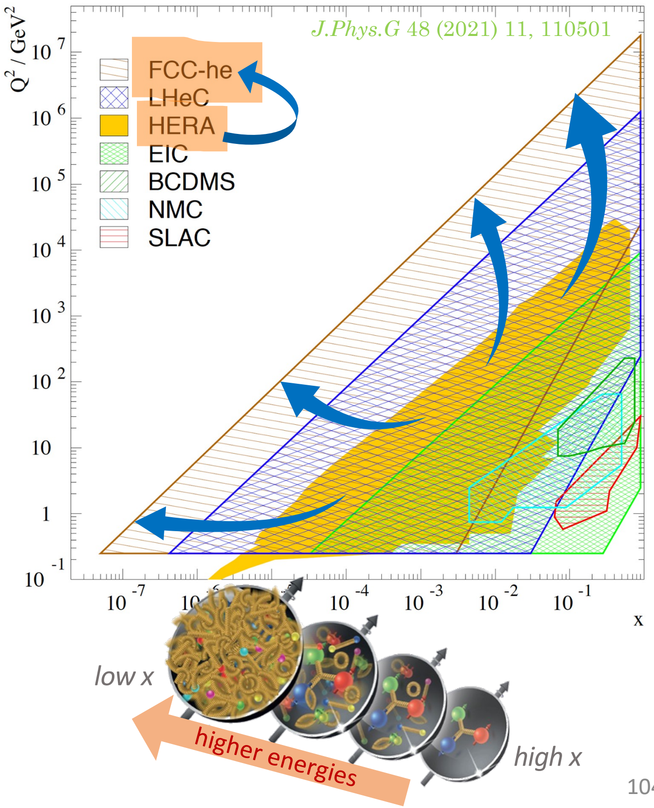
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



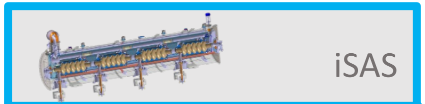
FCC-eh essential to unlock FCC-hh science potential

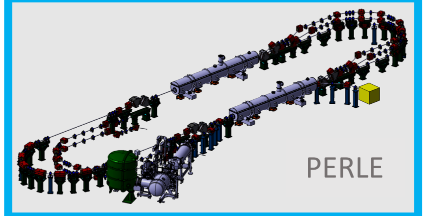
Potential impact of ERL technology

demonstrate multi-turn high-power ERL

enables the ultimate upgrades of the LHC/FCC programs

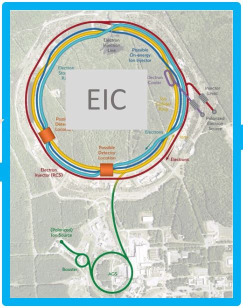
2020'ies





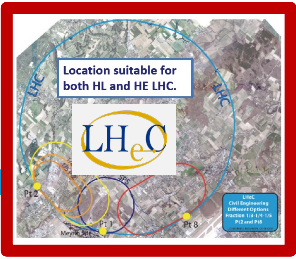
high-power ERL demonstrated

2030'ies



ERL application electron cooling

2030-2040'ies



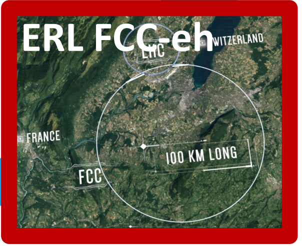
1 ERL beam

high-power ERL

e⁻ beam in collision

(ep/eA @ LHC program)

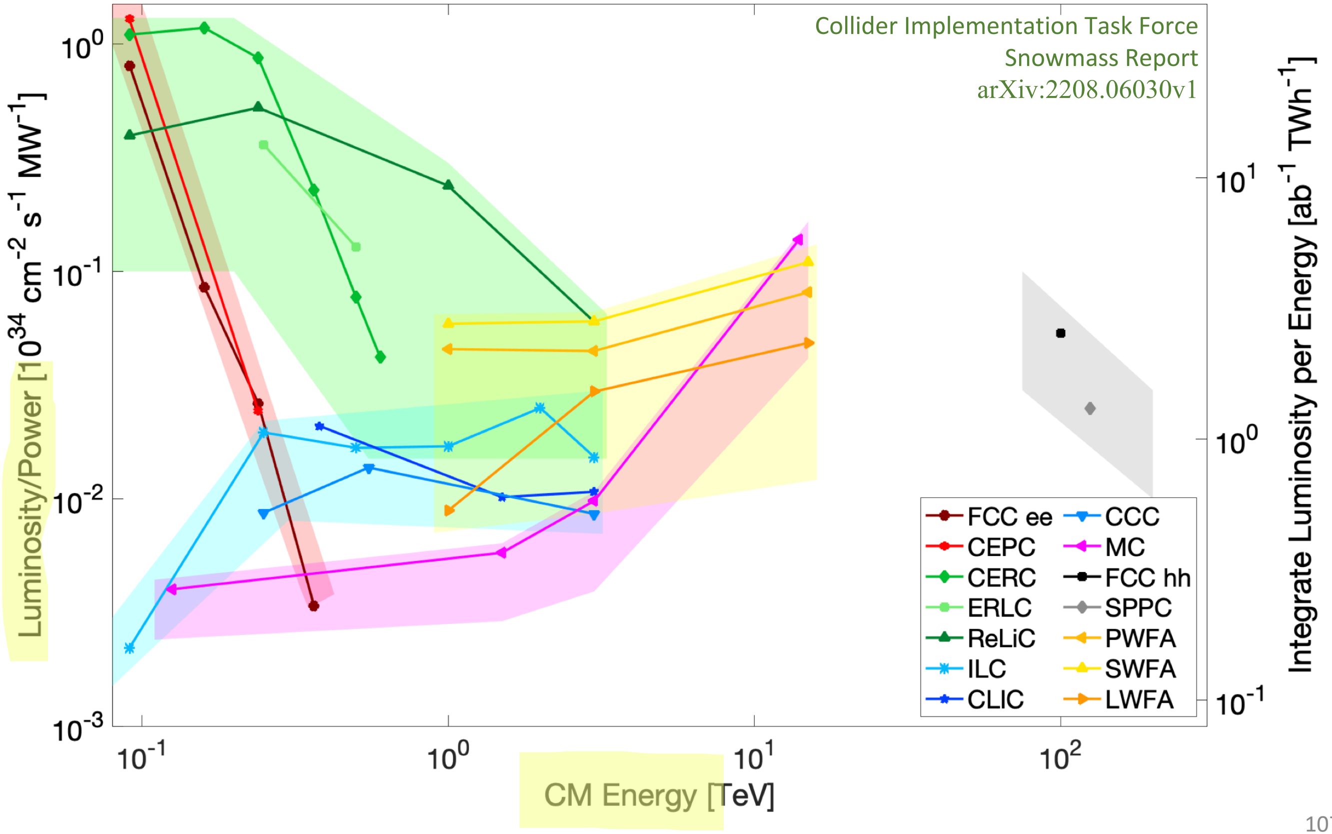
2070'ies



1 ERL beam

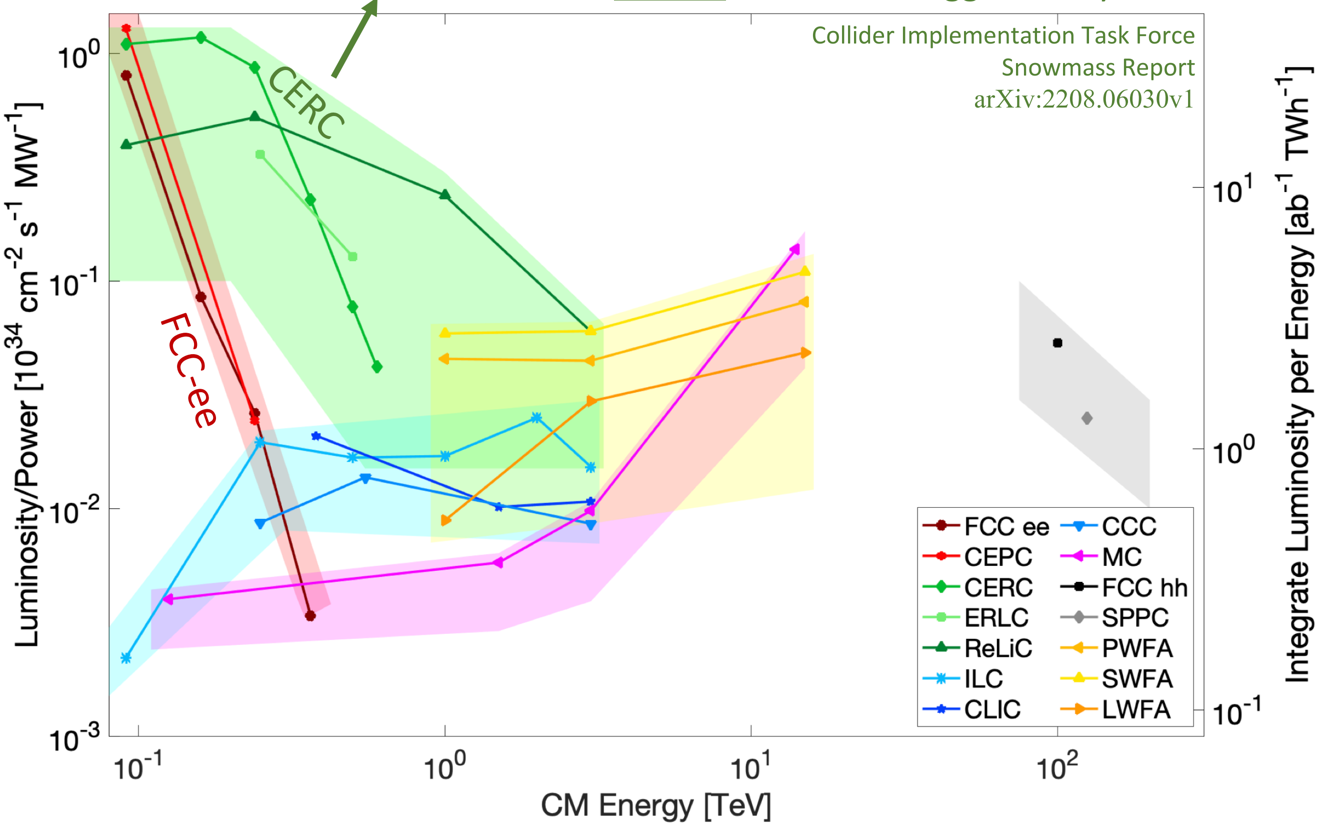
ERL-based e^+e^- H/HH Factories

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



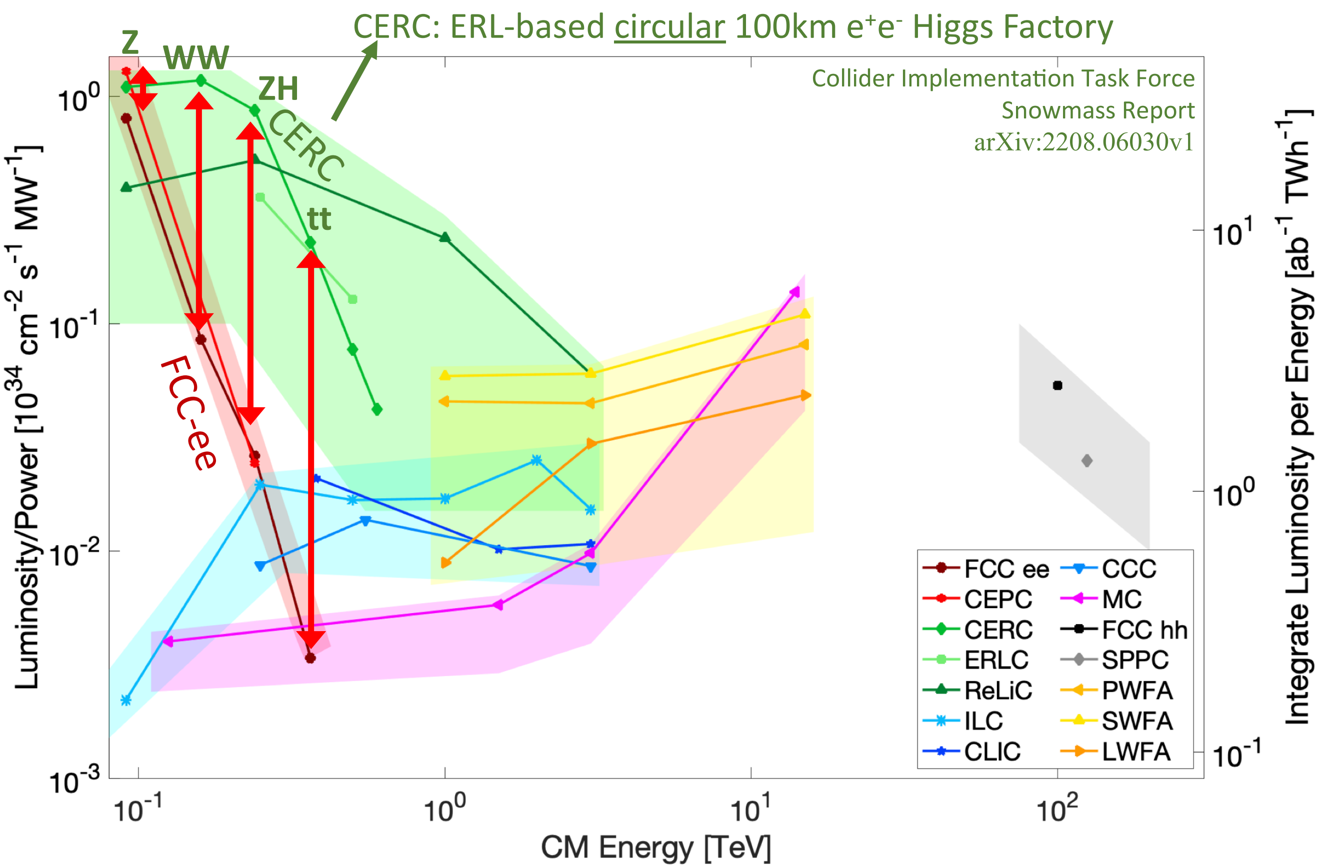
Energy Recovery applications for HEP e^+e^- colliders

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



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

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



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

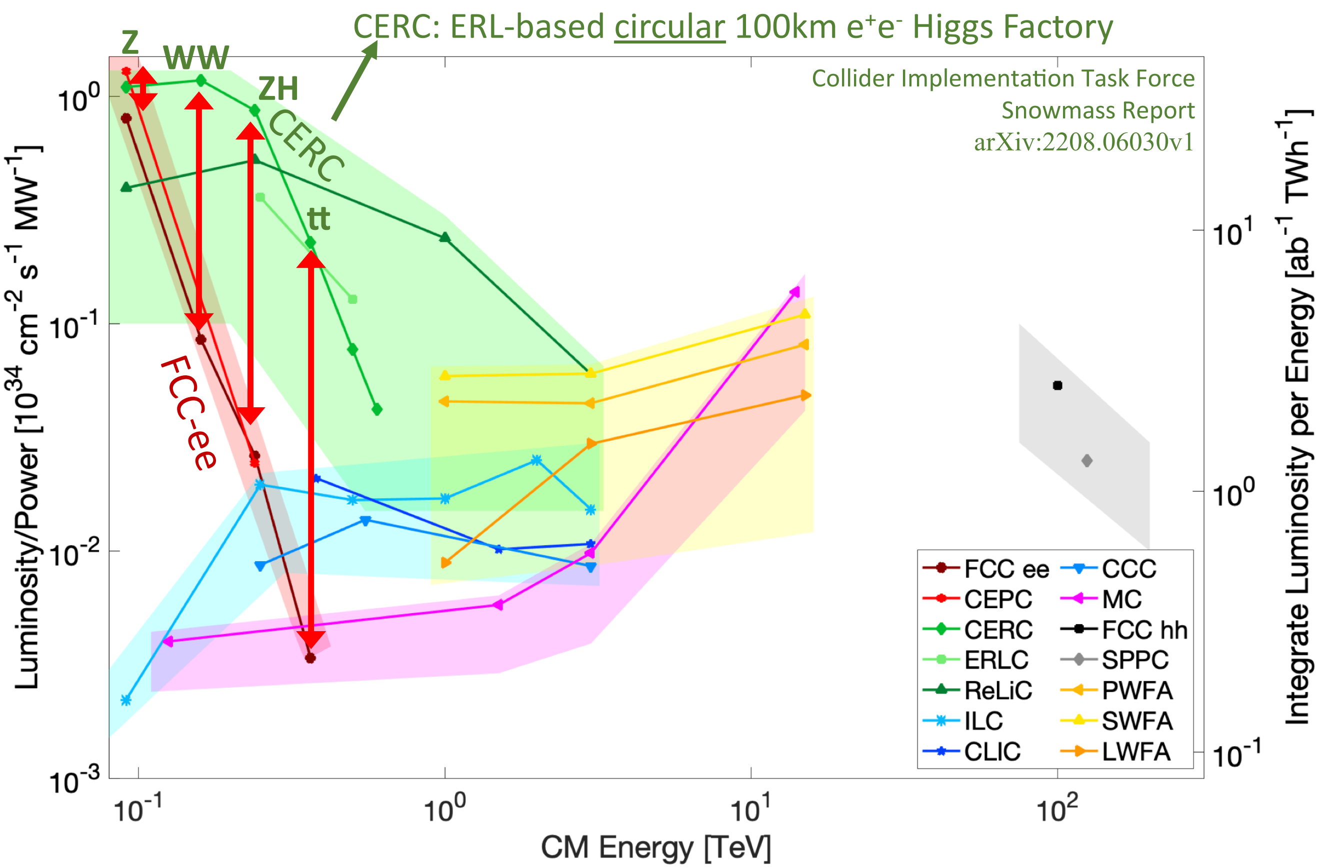
Energy Recovery applications for HEP e^+e^- colliders

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

x10 more H's

or

x10 less electricity costs



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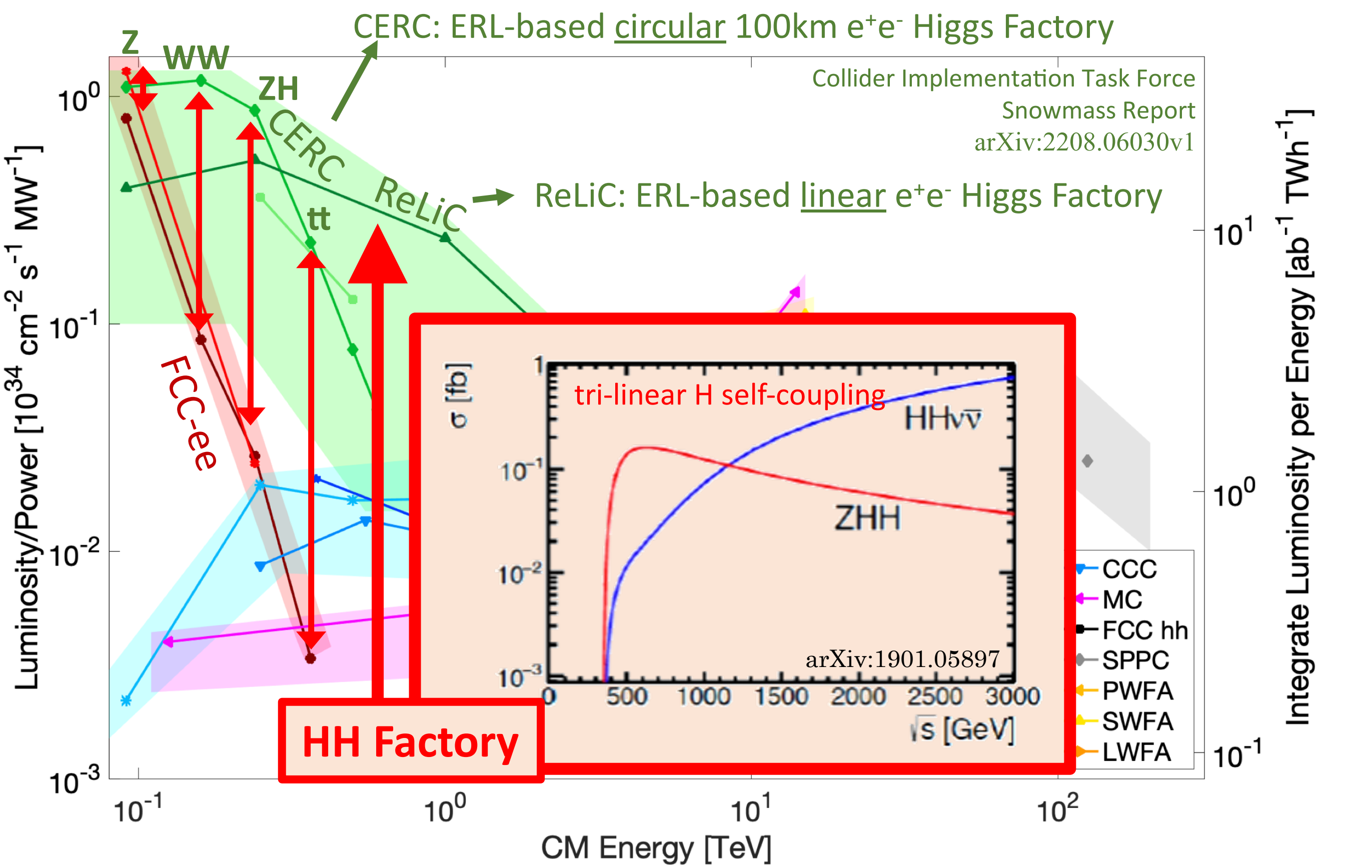

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Ref for ReLiC: arXiv:2203.06476

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

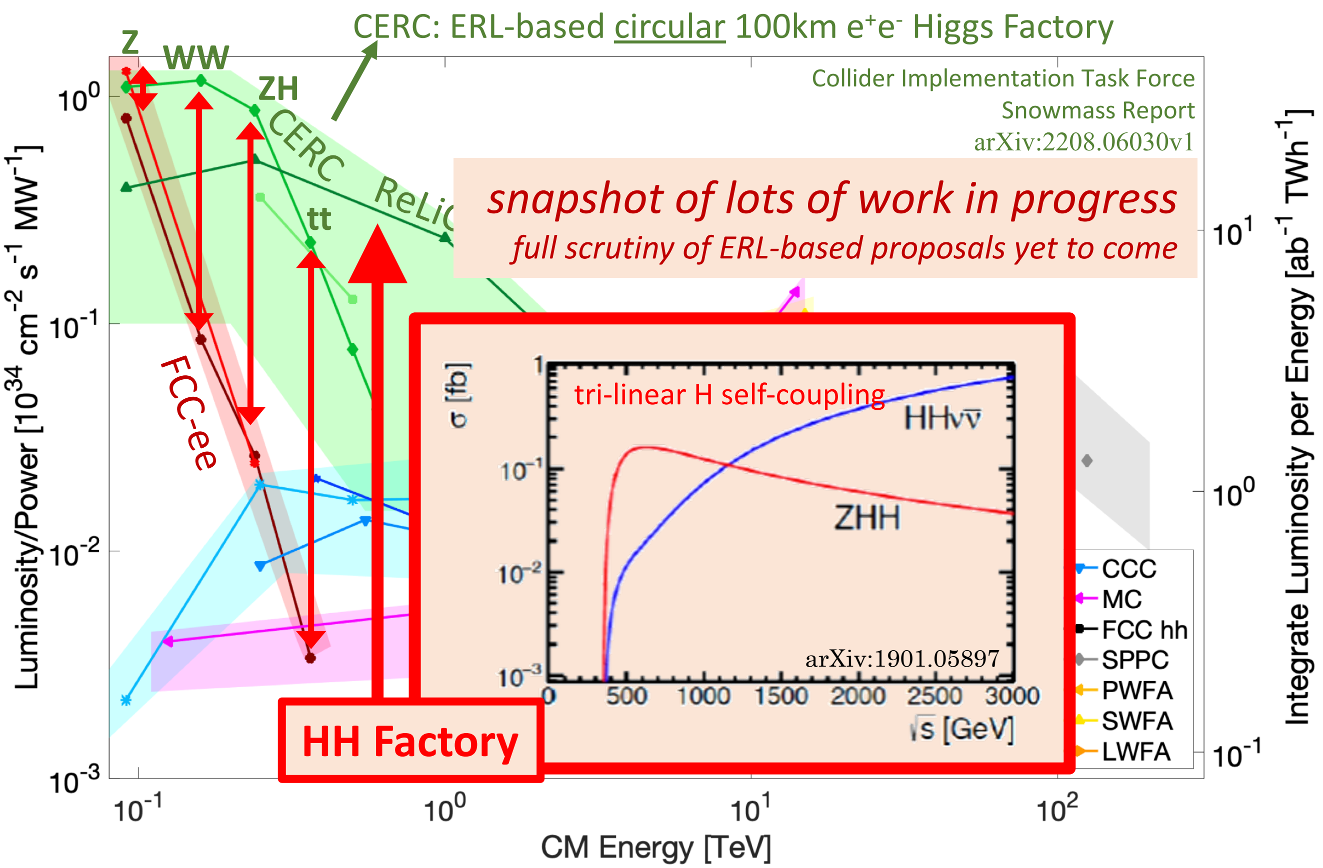
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories
(hence the large uncertainty band in the plot)



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

Ref for ReLiC: arXiv:2203.06476

Energy Recovery applications for HEP

Th

a

F

x10

NO
challe
these E
(hence the ... uncertainty band in the plot)

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

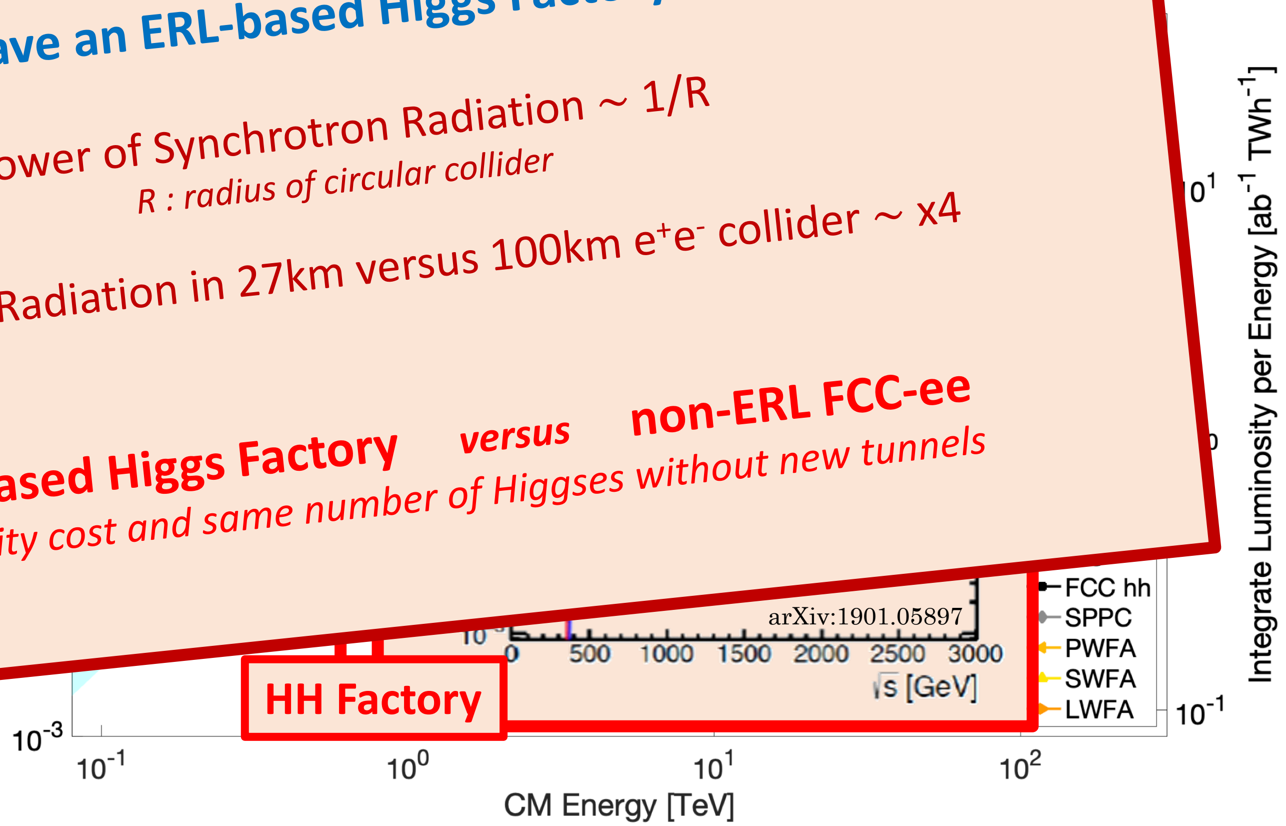
Power of Synchrotron Radiation ~ 1/R

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**

same electricity cost and same number of Higgses without new tunnels



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

Ref for ReLiC: arXiv:2203.06476

Energy Recovery applications for HEP

Th

Through beam dynamics studies develop a self-consistent set of operating parameters with associated achievable luminosity and power requirements.

Reduce uncertainties on performance indicators

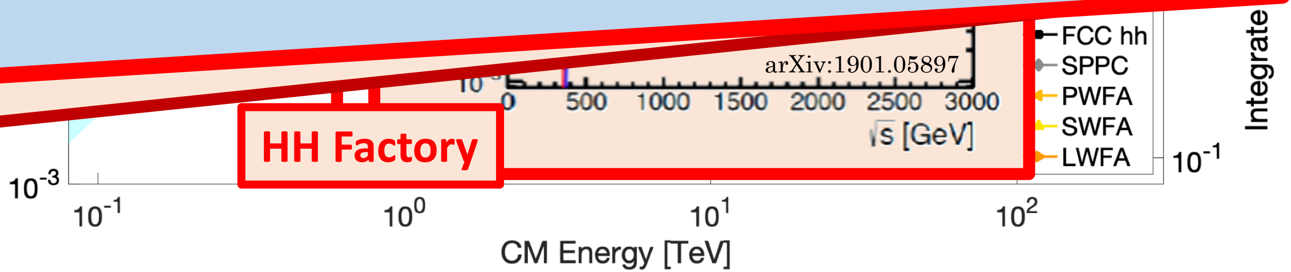
&

Develop confidence for the feasibility of ERL-based H/HH factories

cl

these E

(hence the ... ertainty band in the plot)



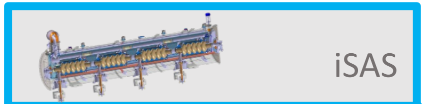
Potential impact of ERL technology

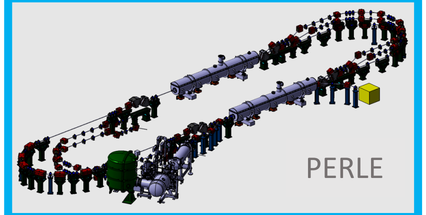
With stepping stones for innovations in technology to boost our physics reach

demonstrate multi-turn high-power ERL

enables the ultimate upgrades of the LHC/FCC programs

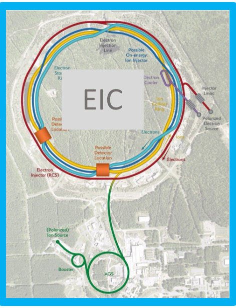
2020'ies





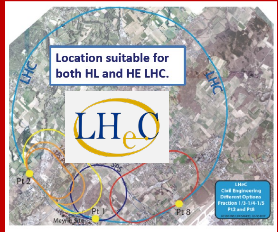
high-power ERL demonstrated

2030'ies



ERL application electron cooling

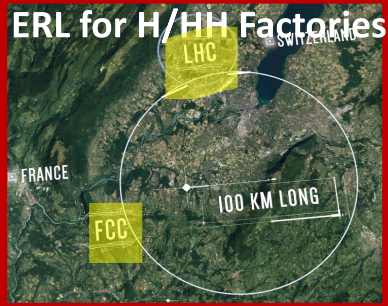
2030-2040'ies



1 ERL beam

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

2040-2050'ies



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

Potential impact of ERL technology

With stepping stones for innovations in tech…
to boost our physics reach

enables …

demonstrat…

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

European Strategy for Particle Physics 2020

An ERL-route towards an e^+e^- Higgs Factory

potentially enabling additional (ep/eA) and more (e^+e^-) physics
with less impact on the environment and less power requirements
with a timely and affordable realisation

…creases the performance of the next major colliders

…pplication
electron cooling

Potential impact of ERL technology

With stepping stones for innovations in techn...
to boost our physics reach

enables ...

demonstrat...

> An electron-positron Higgs factory is the highest-priority next collider.
>
> *European Strategy for Particle Physics 2020*

An ERL-route towards an e^+e^- Higgs Factory

potentially enabling additional (ep/eA) and more (e^+e^-) physics
with less impact on the environment and less power requirements
with a timely and affordable realisation
requires additional support to complete the R&D program (e.g. PERLE, bERLinPro, iSAS)
requires enhanced interest and resources for design efforts of ERL-based colliders

Not without challenges!

...pplication
electron cooling

...program)

...creases the performance of
the next major colliders

Future particle physics colliders with Sustainable Accelerating Systems

- 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: power requirements are on the minds now
- To achieve the best physics for the least power, with iSAS we connect leading European institutions and industry to expedite the development of various sustainable technologies that are essential to realize the ambition expressed in the European Strategy for Particle Physics
- ERL is an enabling technology for our most prominent future ep/eA and e^+e^- colliders, delivering breakthrough performances on an interesting timeline

Future particle physics colliders with Sustainable Accelerating Systems

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- ERL is an enabling technology for our most prominent future ep/eA and e^+e^- colliders, delivering breakthrough performances on an interesting timeline

The potential impact of energy-saving technologies on accelerators and colliders is so appealing that we must foster this R&D path

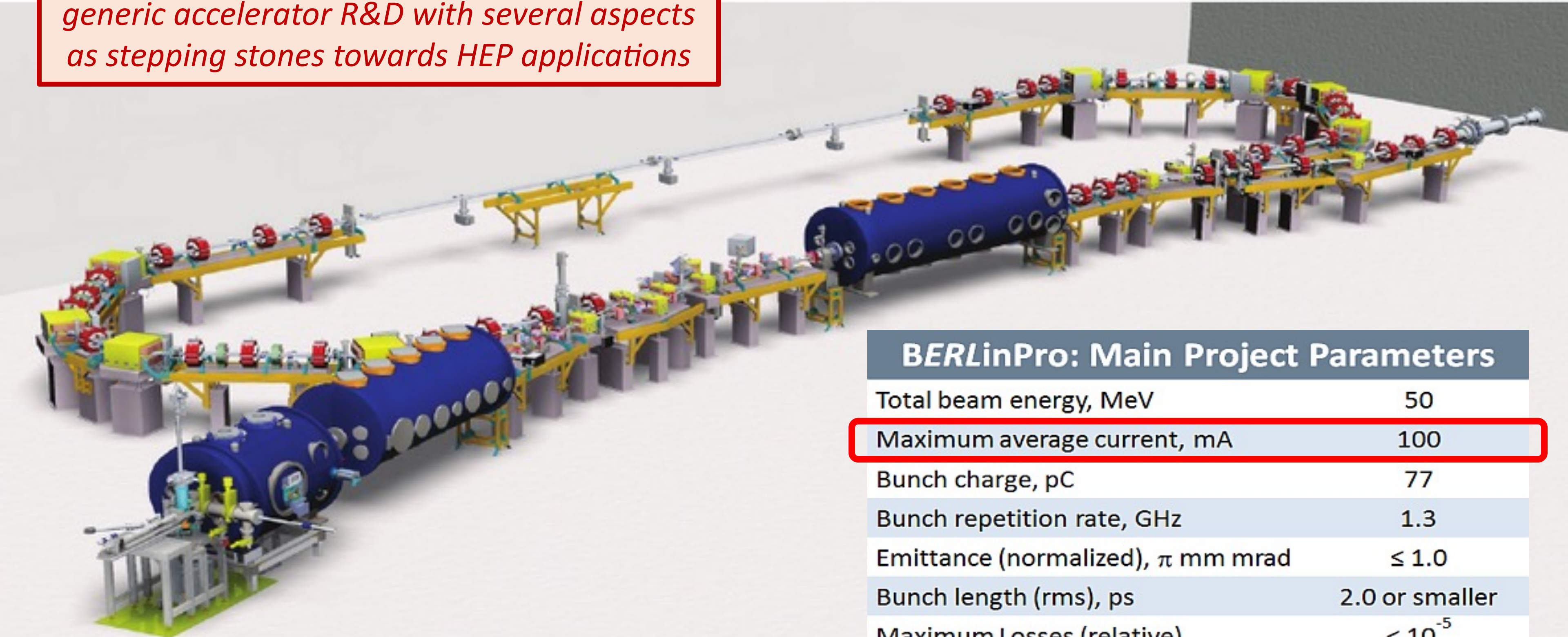
HIGH-ENERGY PHYSICS RESEARCH CENTRE

Thank you for your attention!

Jorgen.DHondt@vub.be

Upcoming facilities for Energy Recovery Linac R&D

bERLinPro @ Helmholtz Zentrum Berlin
generic accelerator R&D with several aspects as stepping stones towards HEP applications

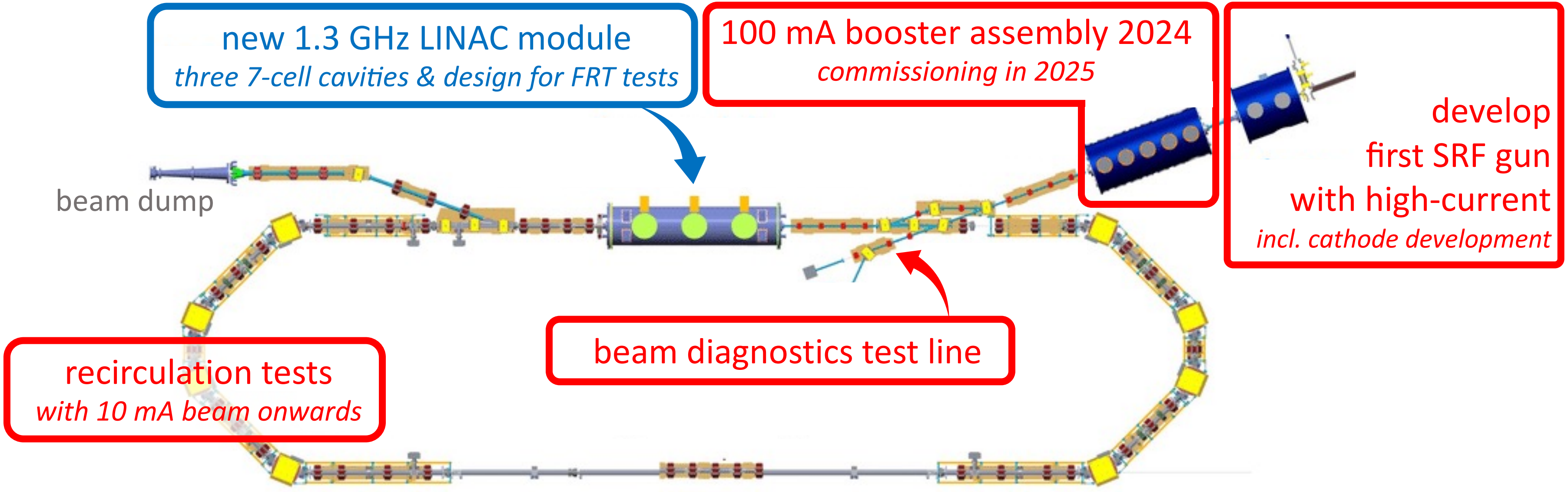


BERLinPro: Main Project Parameters	
Total beam energy, MeV	50
Maximum average current, mA	100
Bunch charge, pC	77
Bunch repetition rate, GHz	1.3
Emittance (normalized), π mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	$< 10^{-5}$

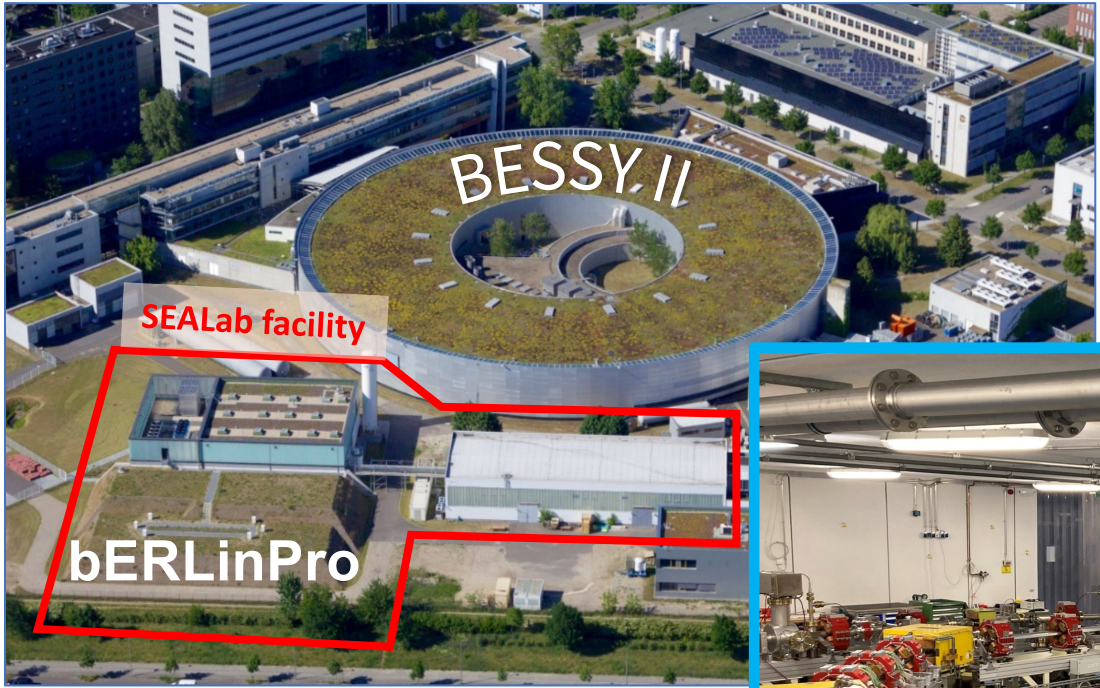
Upcoming facilities for Energy Recovery Linac R&D

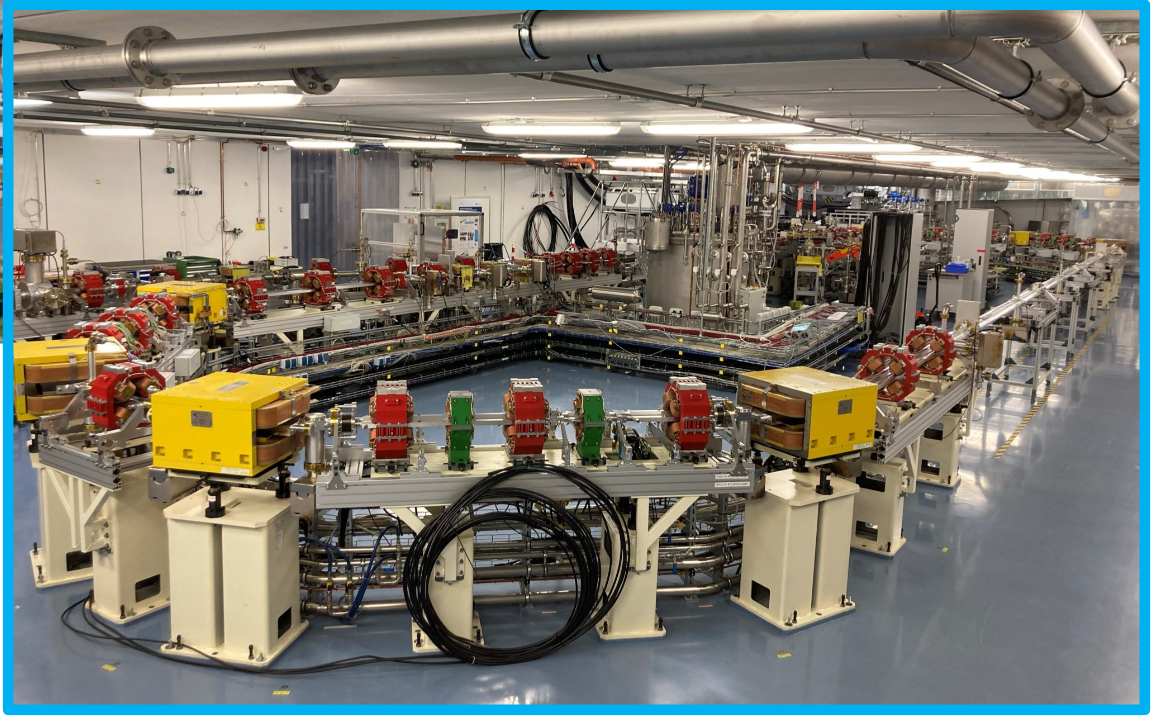
bERLinPro @ Helmholtz Zentrum Berlin
addressing HEP related challenges

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 2024

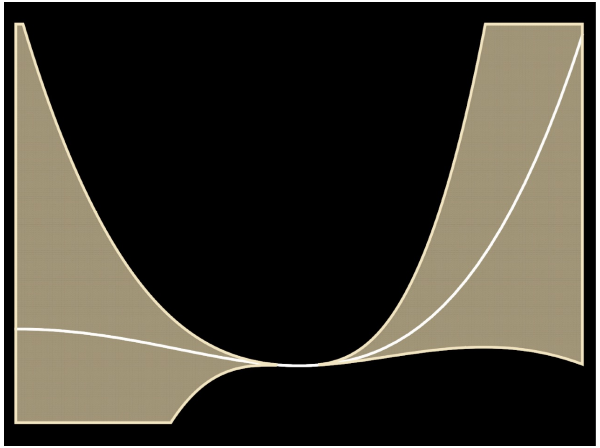




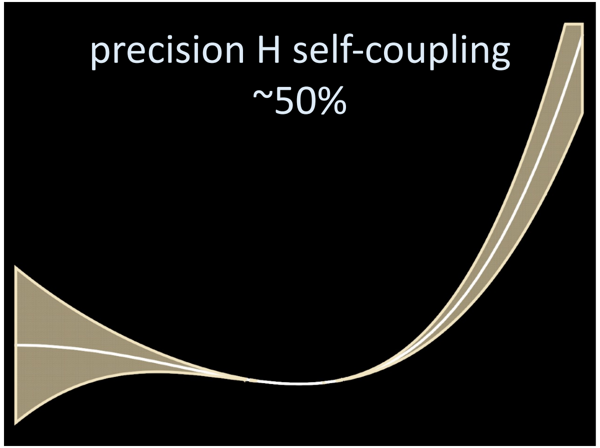
- focus on commissioning injector with SRF gun + diagnostic line
  (map out the reachable parameter space)
- installation of the Booster module
- recirculation, when LINAC funding is secured

Ultimate Higgs Factory = {ee + eh + hh}

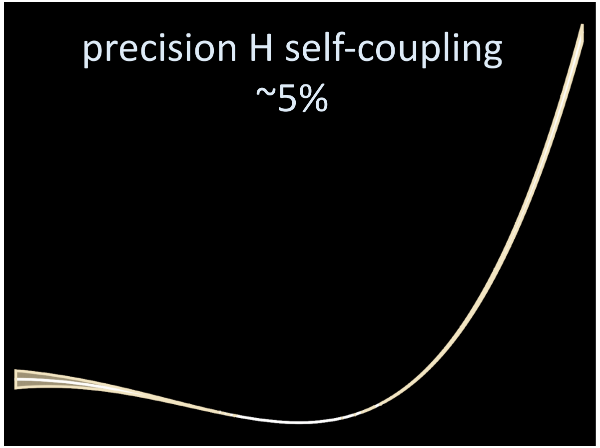
NOW



HL-LHC



FCC

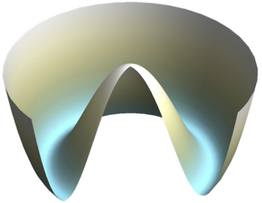


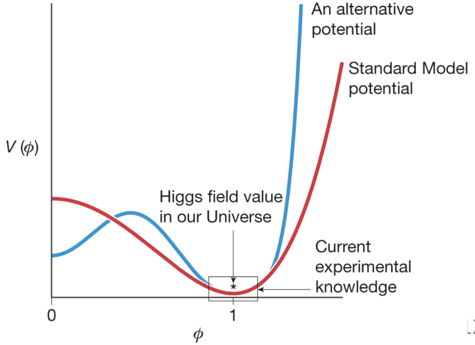
Adapted from Nathanial Craig

Is the H-field indeed represented by the standard model H-potential?

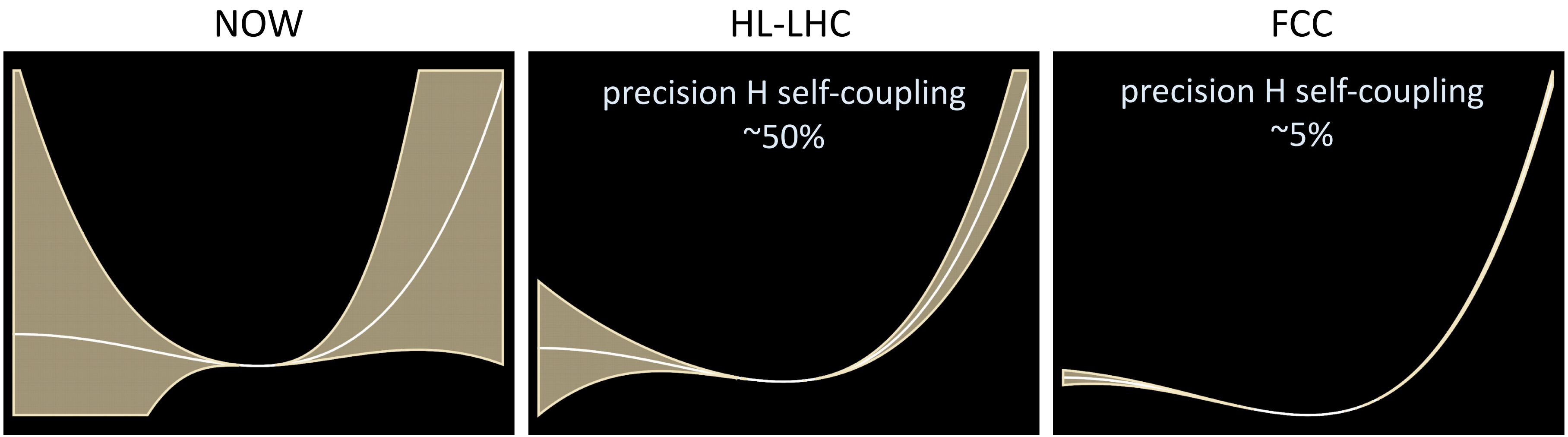
$$V_{higgs} = -\frac{1}{2}m^2|\varphi|^2 + \frac{\lambda}{4}|\varphi|^4$$

m_H *H self-coupling*





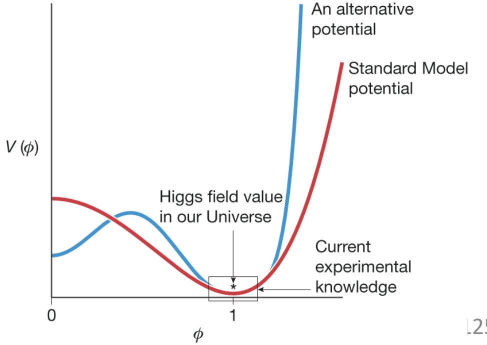
Ultimate Higgs Factory = {ee + eh + hh}



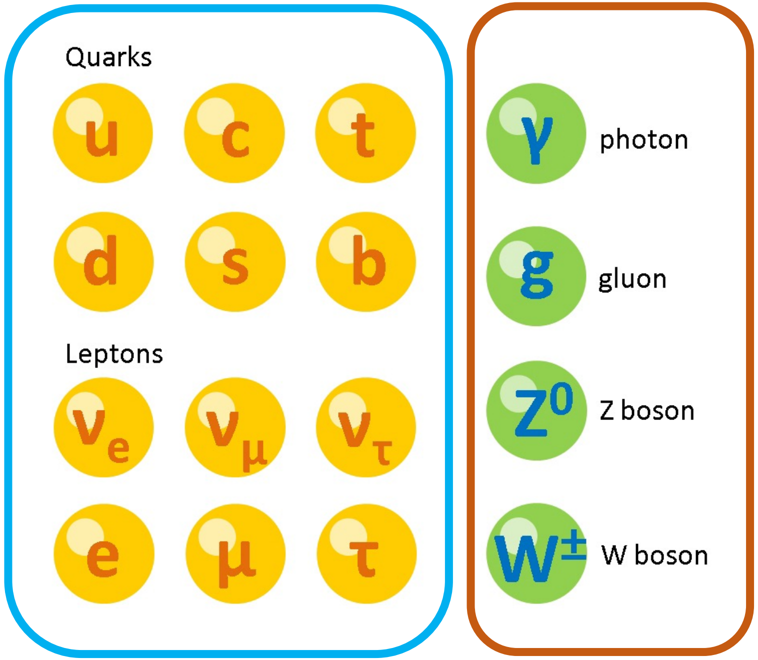
Adapted from Nathanial Craig

Is the H-field indeed represented by the standard model H-potential?

Was the electro-weak symmetry broken (from ϕ=0 to ϕ≠0) via a smooth transition or via a tunneling effect where two vacuum states emerge together with potentially lots of new physics?



Higgs couplings



building blocks of matter (fermions *f*)

forces between them (bosons *V*)

Theory prediction

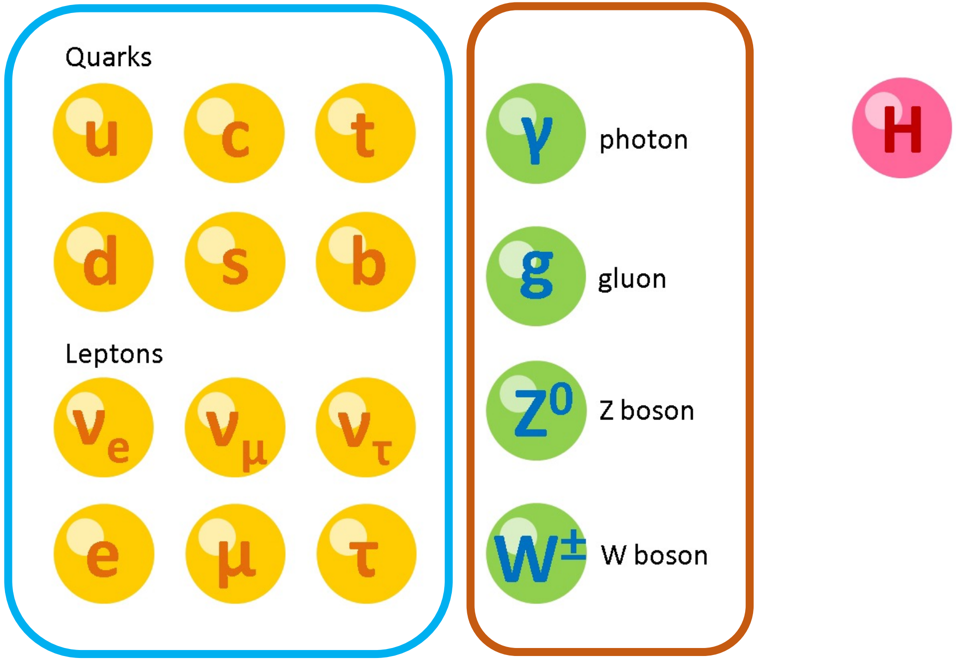
The particle mass depends on the coupling strength with the H field

$$y_f \propto m_f$$

$$g_V^2 \propto m_V^2$$

be aware, only the relation is predicted, and both sides of the relation are to be measured

Higgs couplings



building blocks of matter (fermions *f*)

forces between them (bosons *V*)

Theory prediction

The particle mass depends on the coupling strength with the H field

$y_f \propto m_f$ → **impact**

$g_V^2 \propto m_V^2$

be aware, only the relation is predicted, and both sides of the relation are to be measured

Higgs couplings

Quarks

Leptons

building block
(fermio

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field

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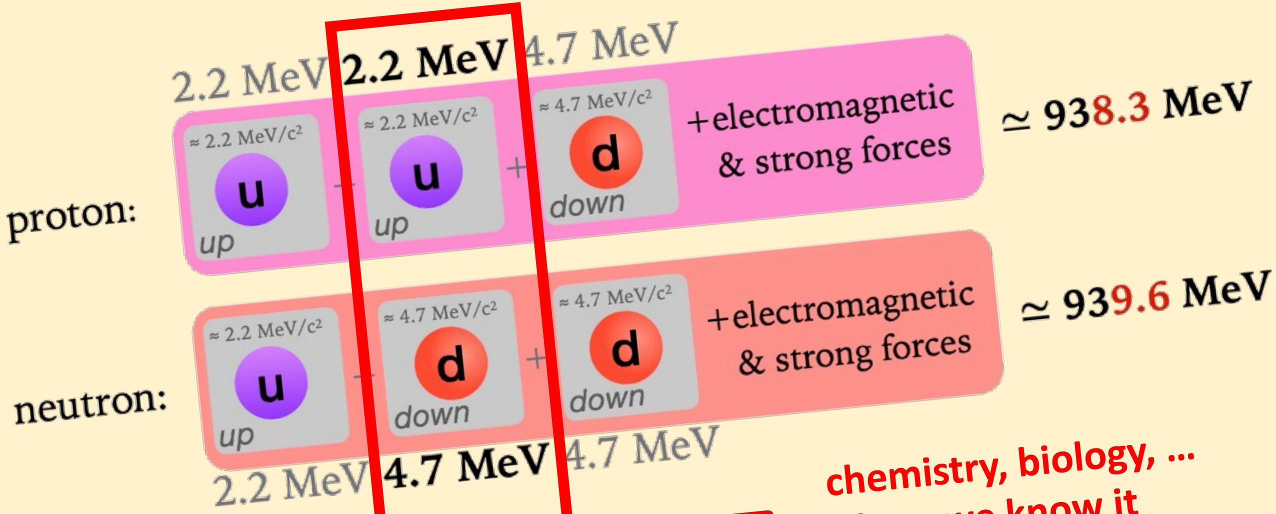
Why do hydrogen atoms exist?

Because the proton is stable!

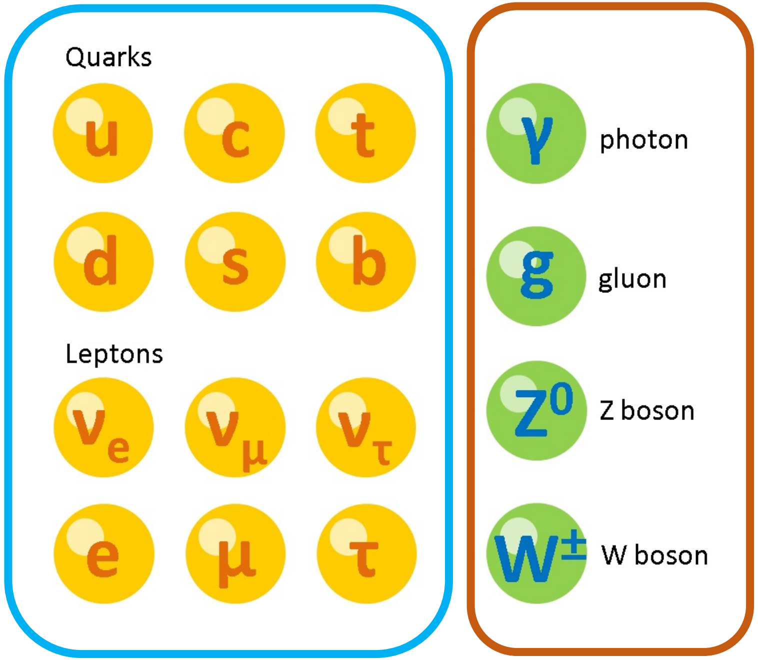


hypothesis: because $y_u < y_d$

chemistry, biology, …
life as we know it
depends on this hypothesis

adapted from G. Salam

Higgs couplings



building blocks of matter
(fermions *f*)

forces between them
(bosons *V*)

Theory prediction

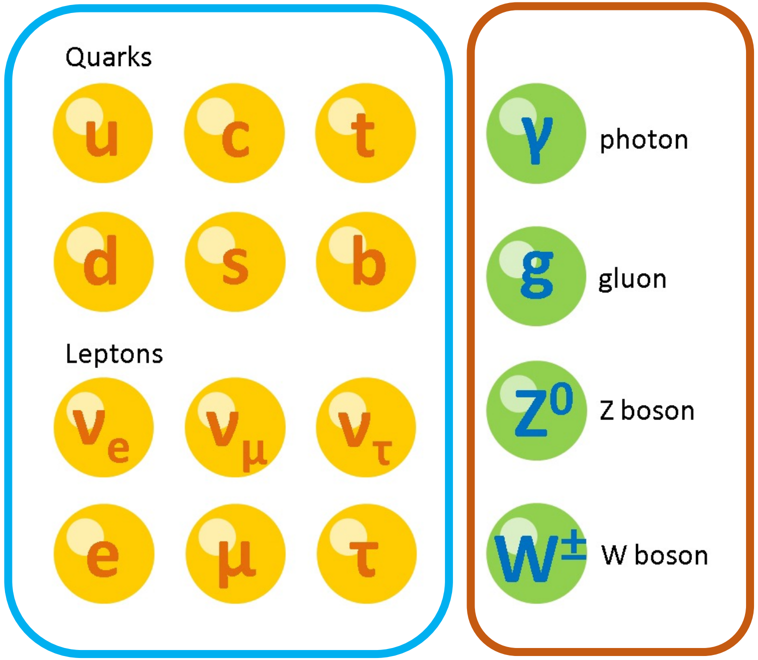
The particle mass depends on the coupling strength with the H field

$y_f \propto m_f$ → **impact**

$g_V^2 \propto m_V^2$

Is it so beautifully simple, or does the interaction include a more complex structure beyond the standard model?

Higgs couplings



building blocks of matter
(fermions *f*)

forces between them
(bosons *V*)

Theory prediction

The particle mass depends on the coupling strength with the H field

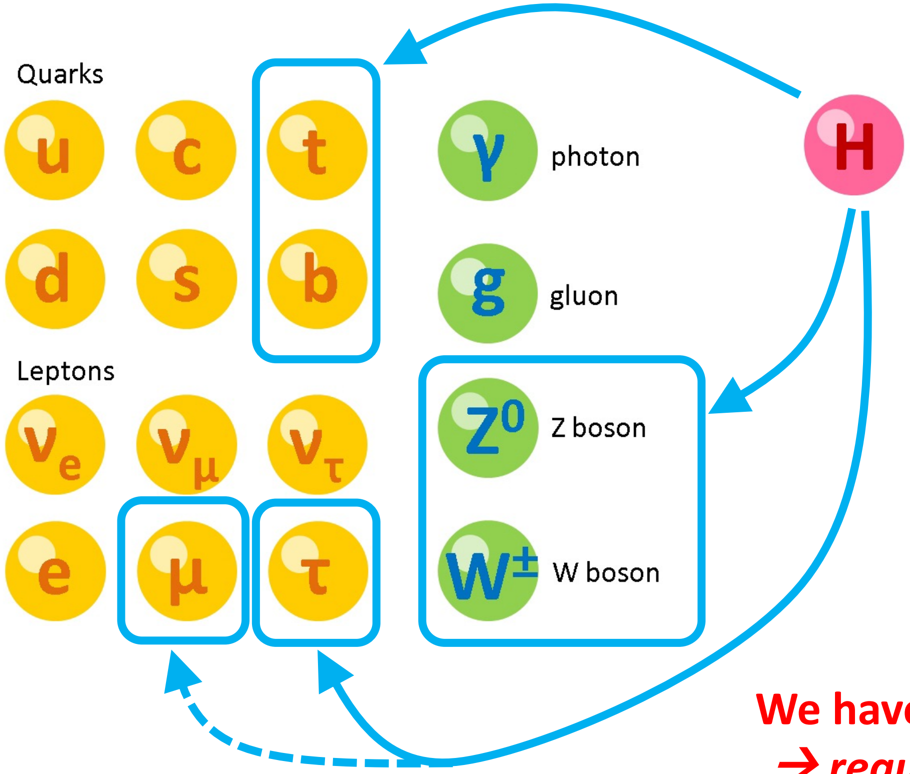
$$y_f \propto \kappa_f \, m_f \oplus \text{others}$$

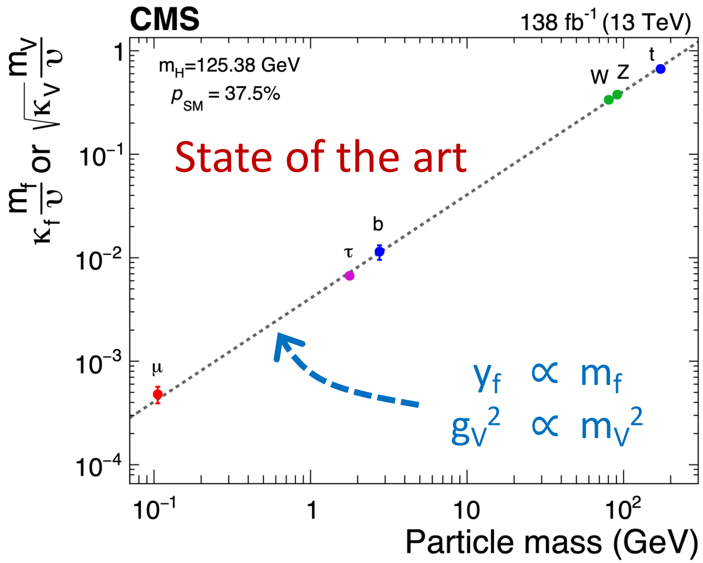
$$g_V^2 \propto \kappa_V \, m_V^2 \oplus \text{others}$$

simple coupling modifiers

involving new particles and/or new interactions

Higgs couplings





We have only seen a first glimpse of the H sector

→ *require more observations & more precision*

Breakthroughs with more precise observations

e.g., a more precise analysis of measured UV light reaching Earth revealed the ozone hole

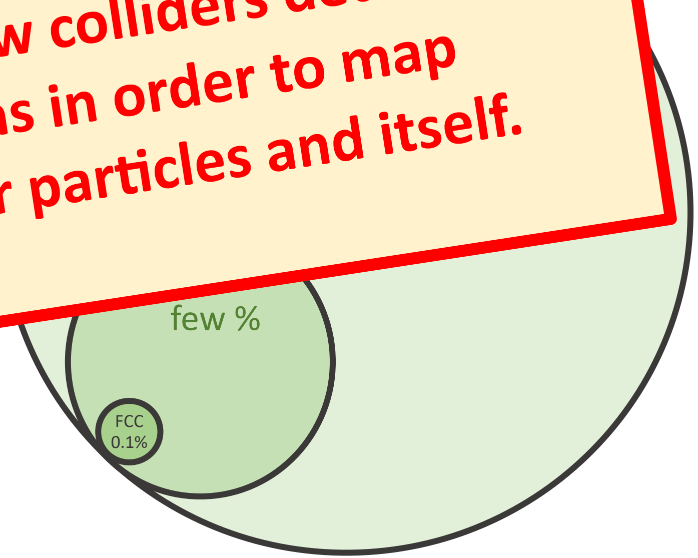
e.g., with improved i

Numerous arguments for building new colliders dedicated to produce copiously Higgs bosons in order to map precisely its interactions with other particles and itself.

U

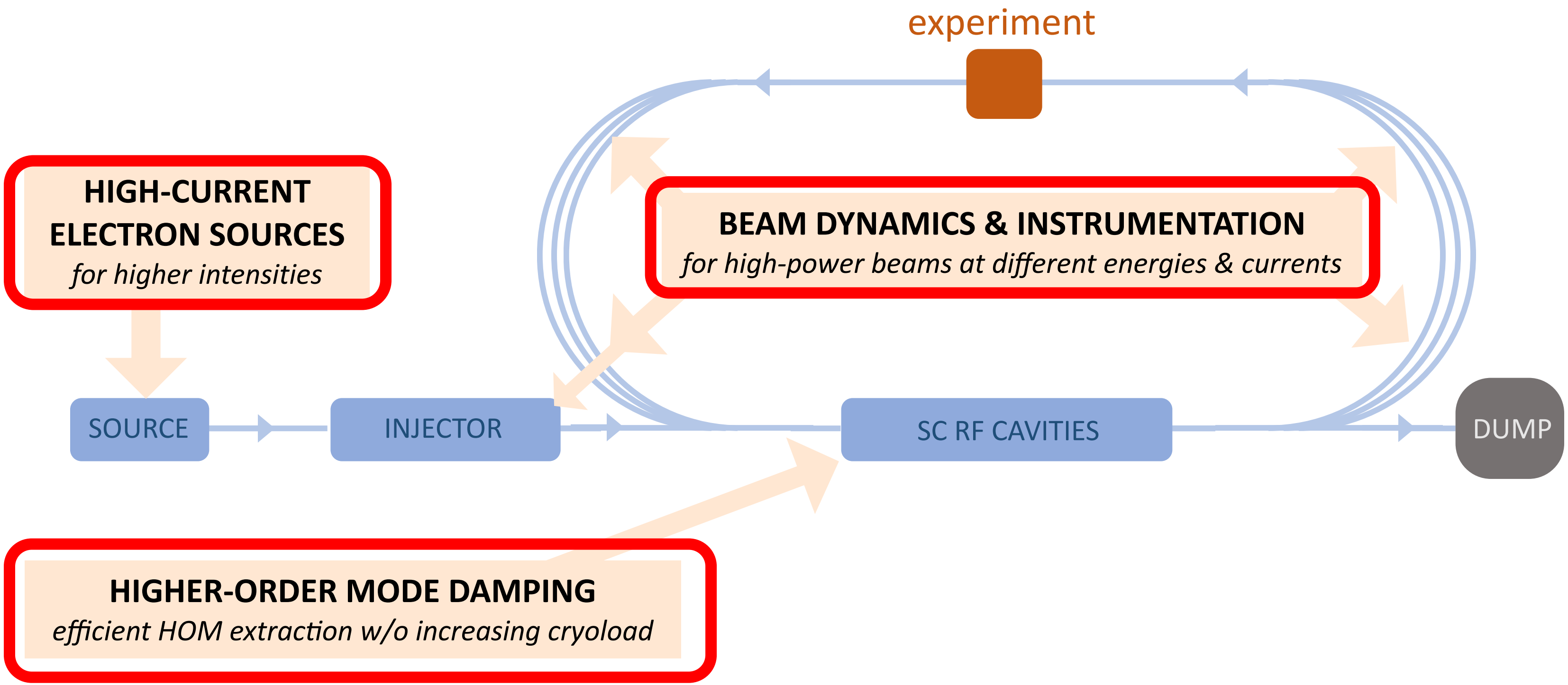
w **o built a Higgs Factory to ever be able to answer our open fundamental questions.**

i.e. finding our ozone hole, our missing link, the true nature of fundamental interactions, …



Surely, future collider programmes go beyond only precision Higgs physics

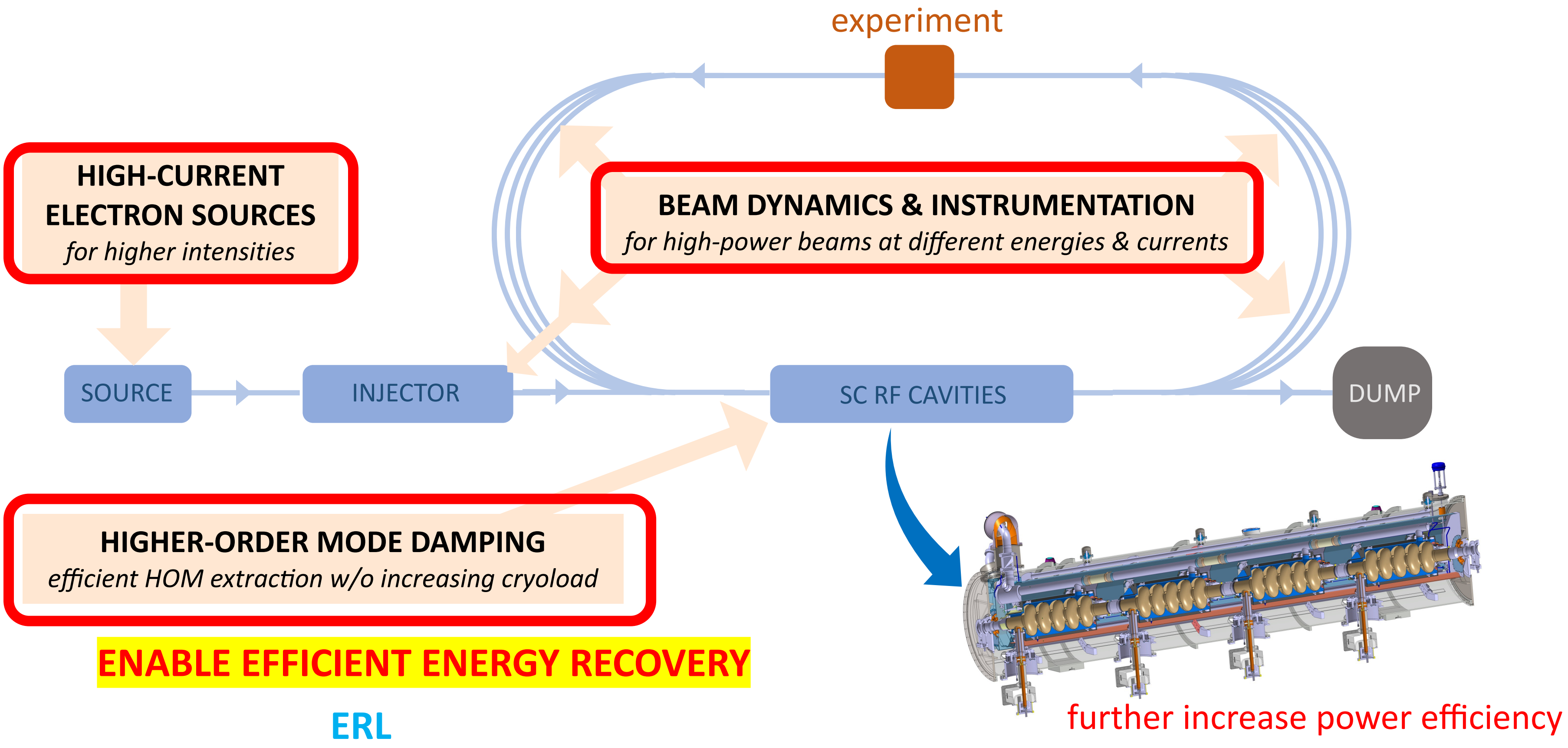
Sustainable Accelerating Systems



ENABLE EFFICIENT ENERGY RECOVERY

ERL

Sustainable Accelerating Systems



The ep/eA study at the LHC and FCC – new impactful goals for the community

More information:
https://indico.cern.ch/event/1335332/

2023 | WS | 2024 | WS | 2025 | TWS | *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces

general-purpose high-energy physics programme: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions

ep/eA-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics programme

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics

developing a sustainable LHeC and FCC-eh collider programme
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

- typically 2-3 conveners per theme
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)
- inform the community with regular ep/eA Newsletters
- everybody is welcome to join

Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

The ep/eA study at the LHC and FCC – new impactful goals for the community

More information:
https://indico.cern.ch/event/1335332/

2023 | WS | 2024 | WS | 2025 | WS

proton and nuclear st

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

pp/eA/pA/AA physics

d... LHeC and FCC-eh collider programme
de... the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

- ... community with regular ep/eA Newsletters
- everybody is welcome to join

Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

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

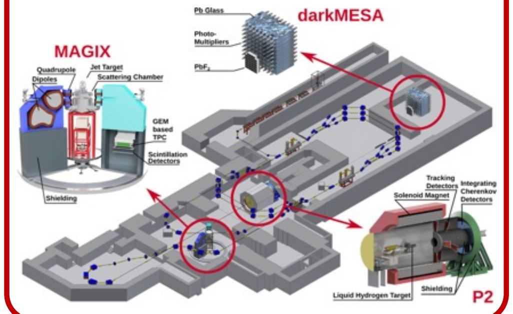
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

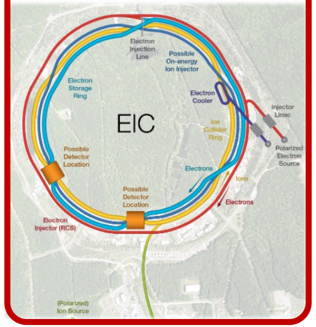
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

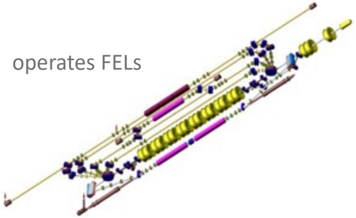
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

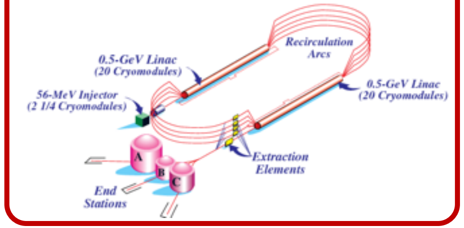
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes



in progress

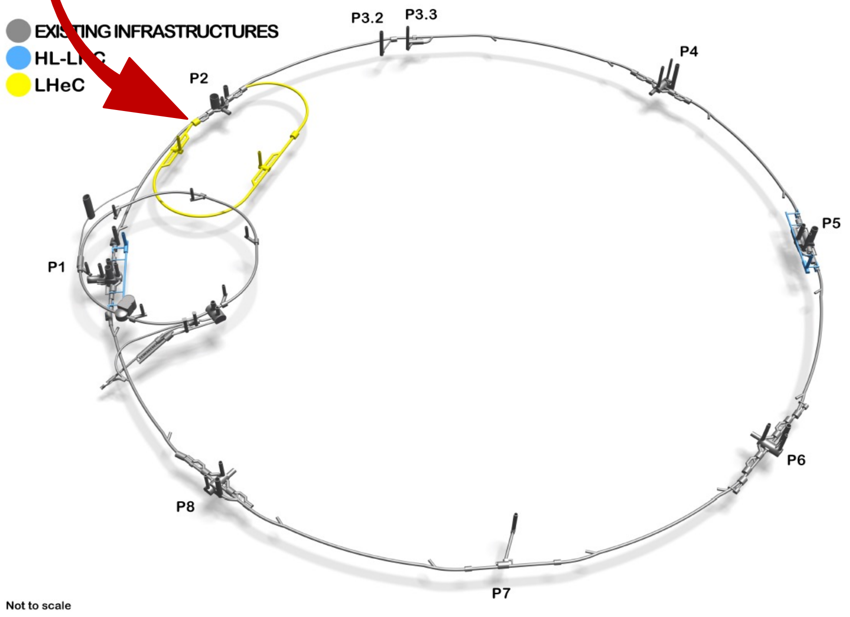
Upcoming: bERLinPro & PERLE

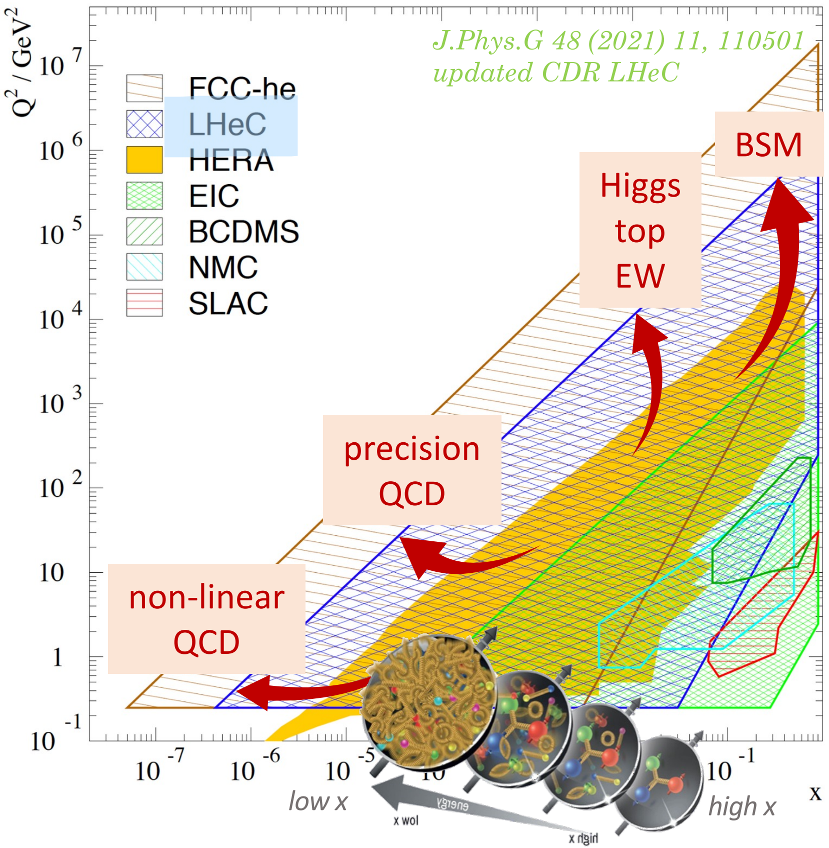
More facilities in design

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

The LHeC program

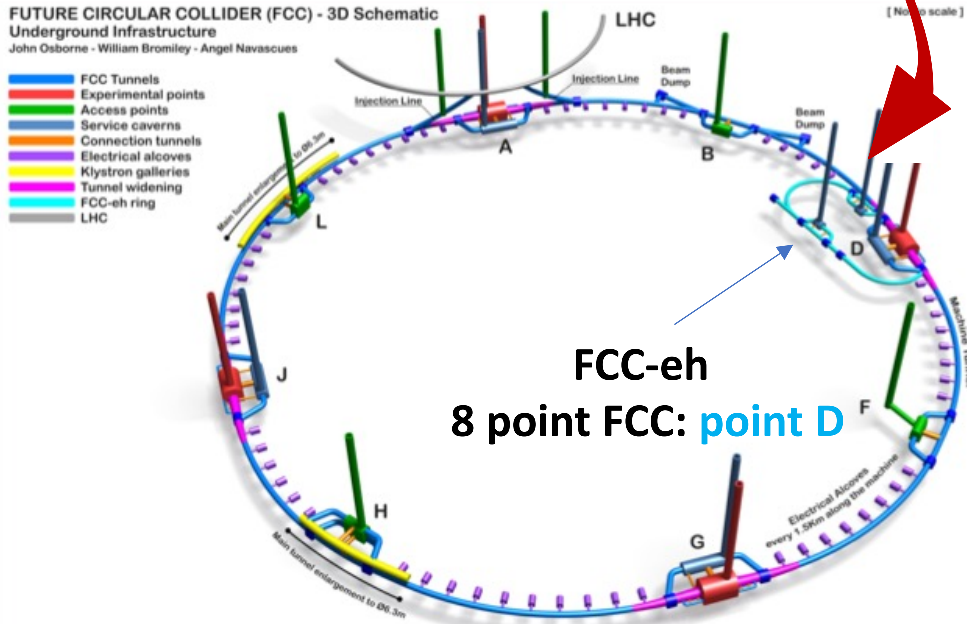
LHeC (>50 GeV ERL electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



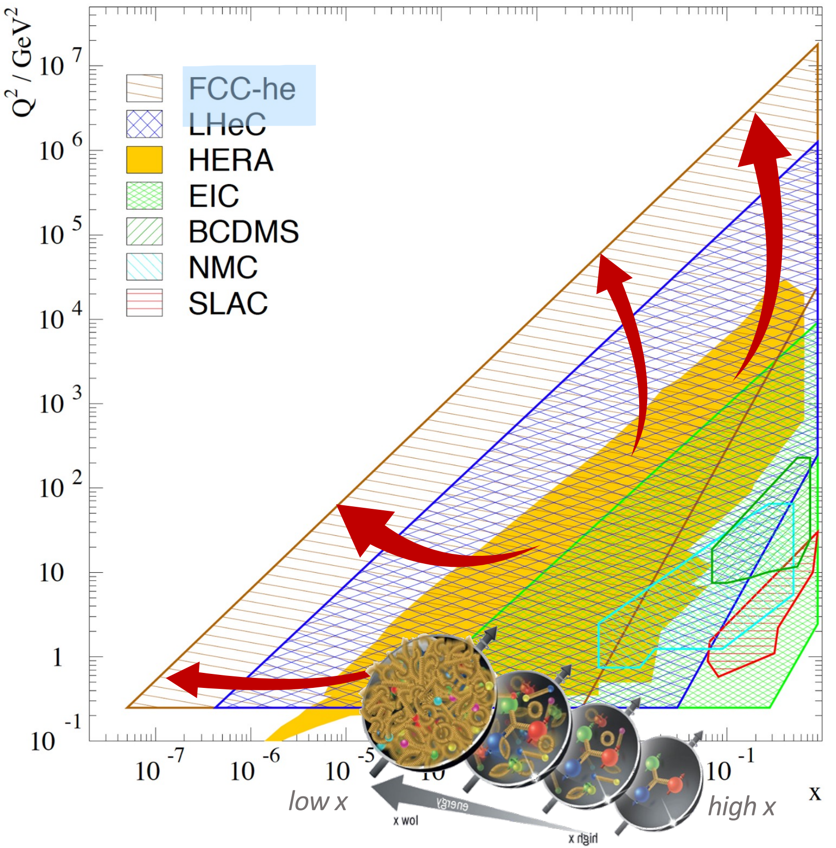


The FCC-eh program

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



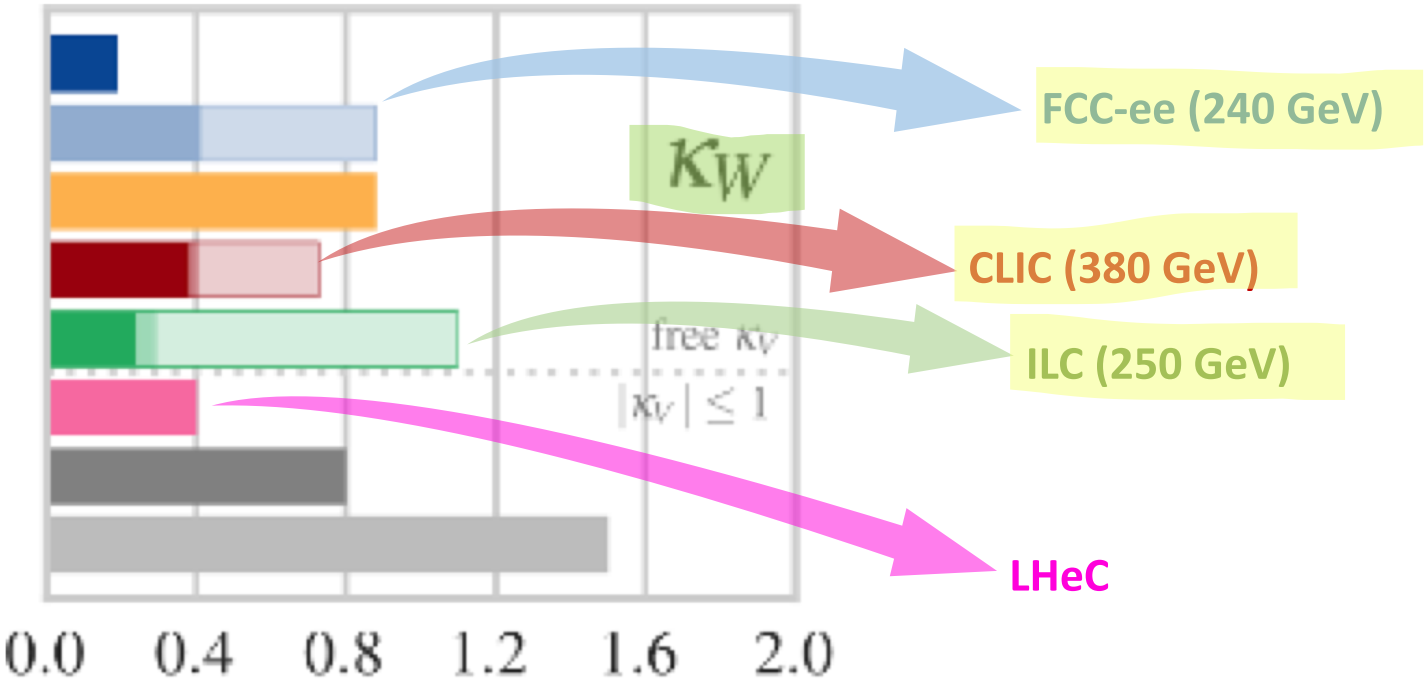
J. Osborne, W. Bromiley, A. Navascues



the physics impact

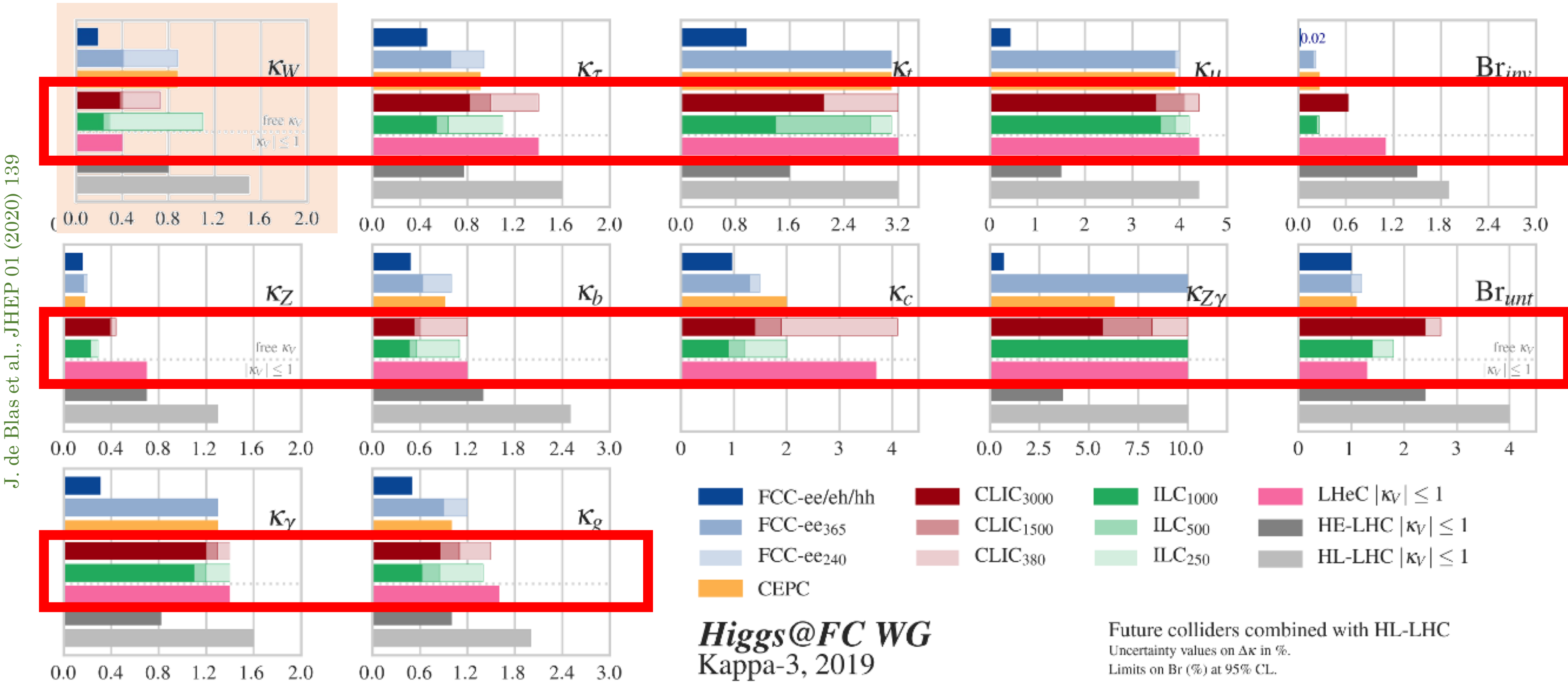
Higgs physics precision: LHeC versus e^+e^- colliders

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



LHeC: assumption is $|\kappa_V| \leq 1$ (V = W, Z), which is theoretically motivated as it holds in a wide class of BSM models albeit with some exceptions

Higgs physics precision: LHeC versus e^+e^- colliders



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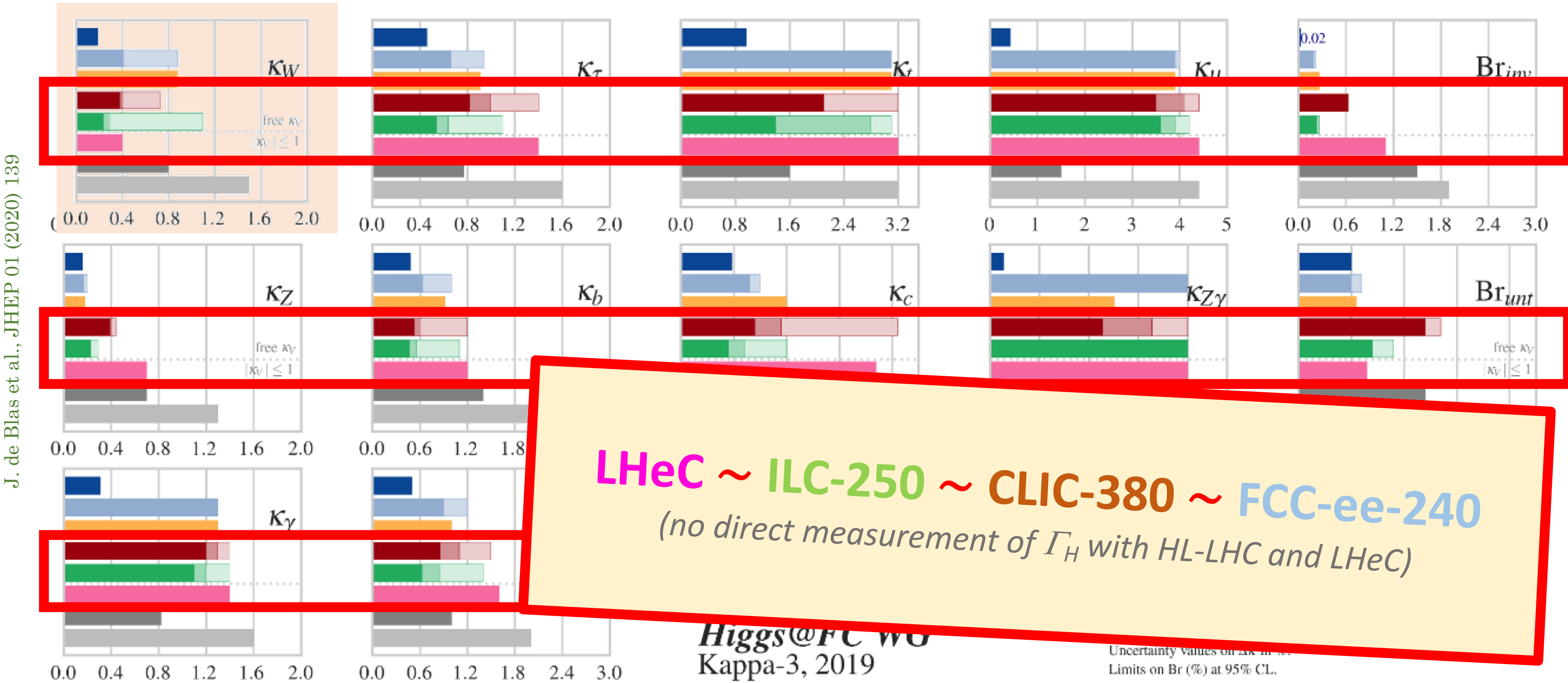

LHeC ~ ILC-250 ~ CLIC-380 ~ FCC-ee-240

(no direct measurement of Γ_H with HL-LHC and LHeC)

LHeC: assumption is $|\kappa_V| \leq 1$ (V = W, Z), which is theoretically motivated as it holds in a wide class of BSM models albeit with some exceptions

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

only FCC-hh

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)

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

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

FCC-ee prospect

FCC-hh/eh prospect

only FCC-ee@240GeV

only FCC-hh

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)

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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

FCC-ee prospect

FCC-hh/eh prospect

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

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)

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL...			
κ_W [%]	0.86						
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							0.41
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			0.55	0.67	0.61	1.3	0.44

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Explore the physics opportunity of a joint ep/eA/pp/pA/AA/(ee) program at the LHC and/or the FCC

FCC-ee prospect

FCC-hh/eh prospect

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

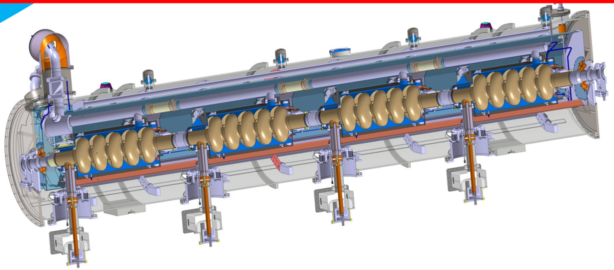
Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies

high-power ERL
demonstrated

Beyond the iSAS timescale and resources:
build and test this new cryomodule
(applications, e.g. FCC, LHeC, XFEL, ESS, ...)



***iSAS**: new design including various energy-saving*
and energy-recovery technologies