Energy Recovery Linacs for high-energy physics

sustainable particle accelerators

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PERLE Collaboration meeting, CERN, June 2023

The Standard Model of particle physics has alarming symptoms…

and at the same time it is perfectly healthy.

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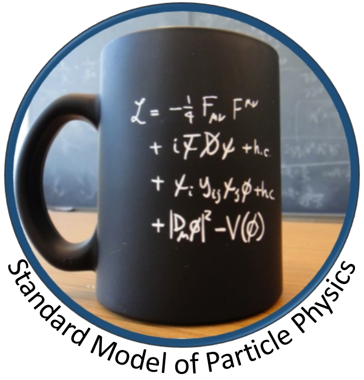

Great theory that matches all our observations related to fundamental interactions

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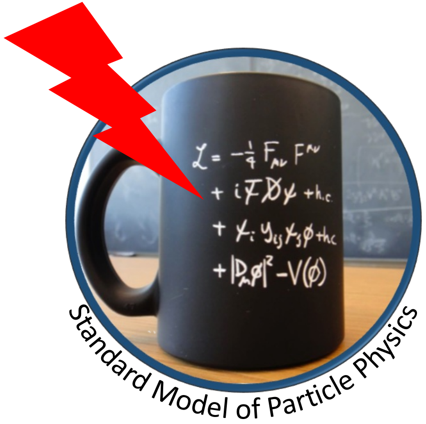

Great theory that matches all our observations related to fundamental interactions

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

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

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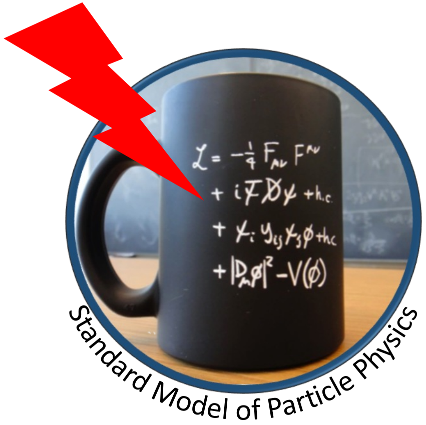

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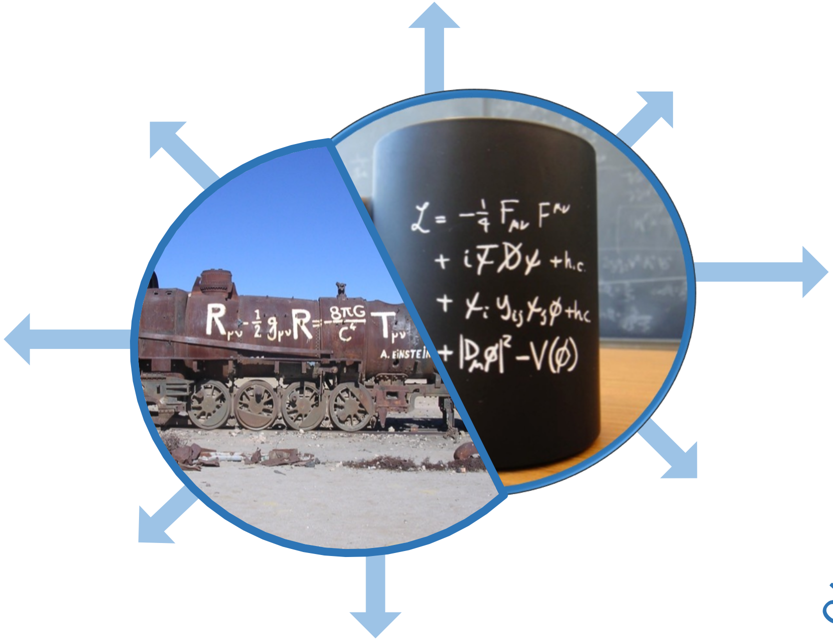
A paradigm shift: <u>sustainable</u> high-power particle beams

higher energy interactions
in the lab

earlier universe

rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

RF cavities, high-field magnets, plasma wakefield acceleration, …

squeezed-light sources to deal with quantum noise in gravitational-wave detectors

solid-state devices with fast read-out electronics

higher energy interactions in the lab

earlier universe

rarer processes

Innovate Technology

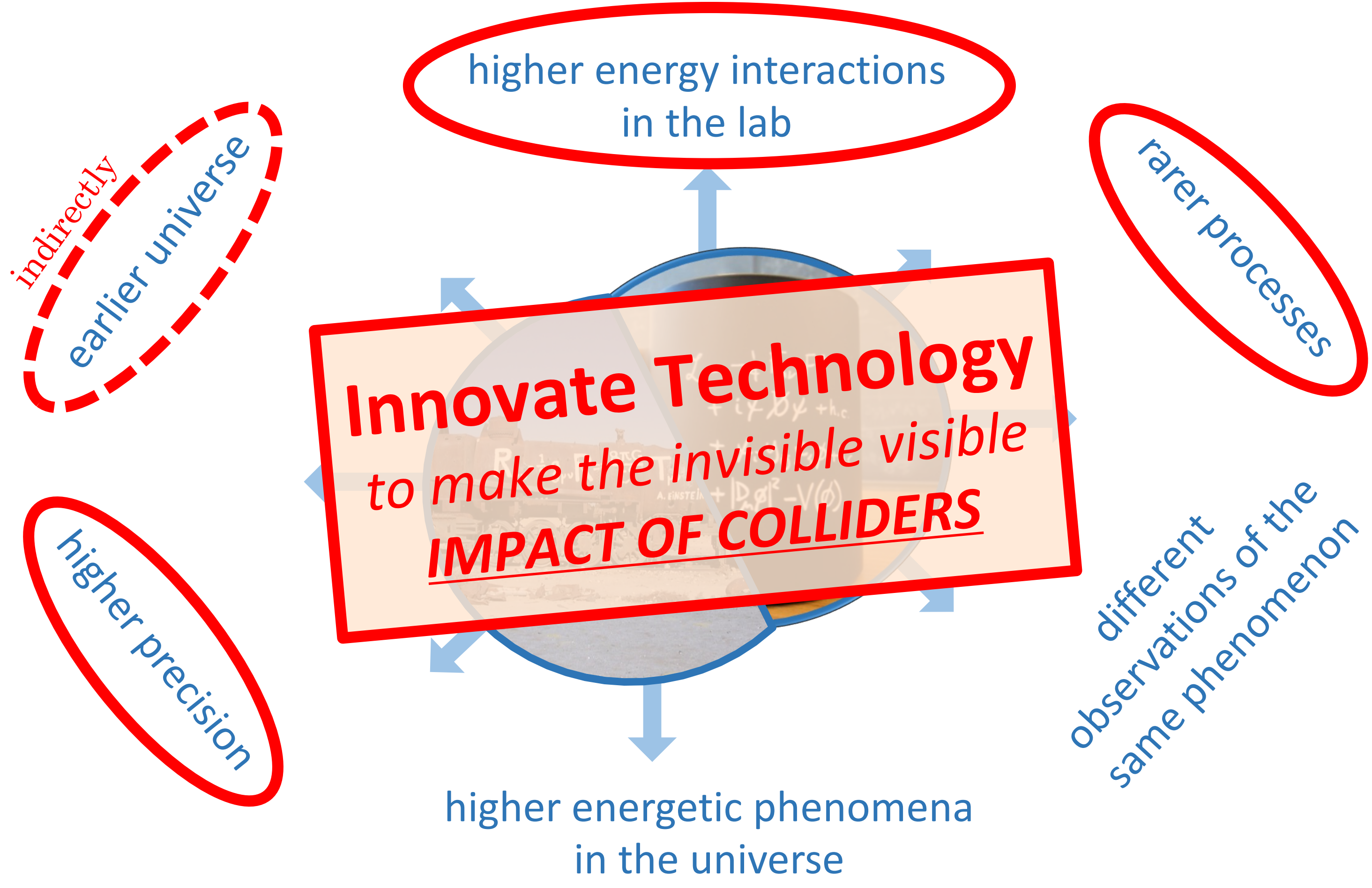
to make the invisible visible

higher precision

different observations of the same phenomenon

higher energetic phenomena in the universe

computing and software challenge for Multi-Exabyte Data Infrastructures


higher energy interactions
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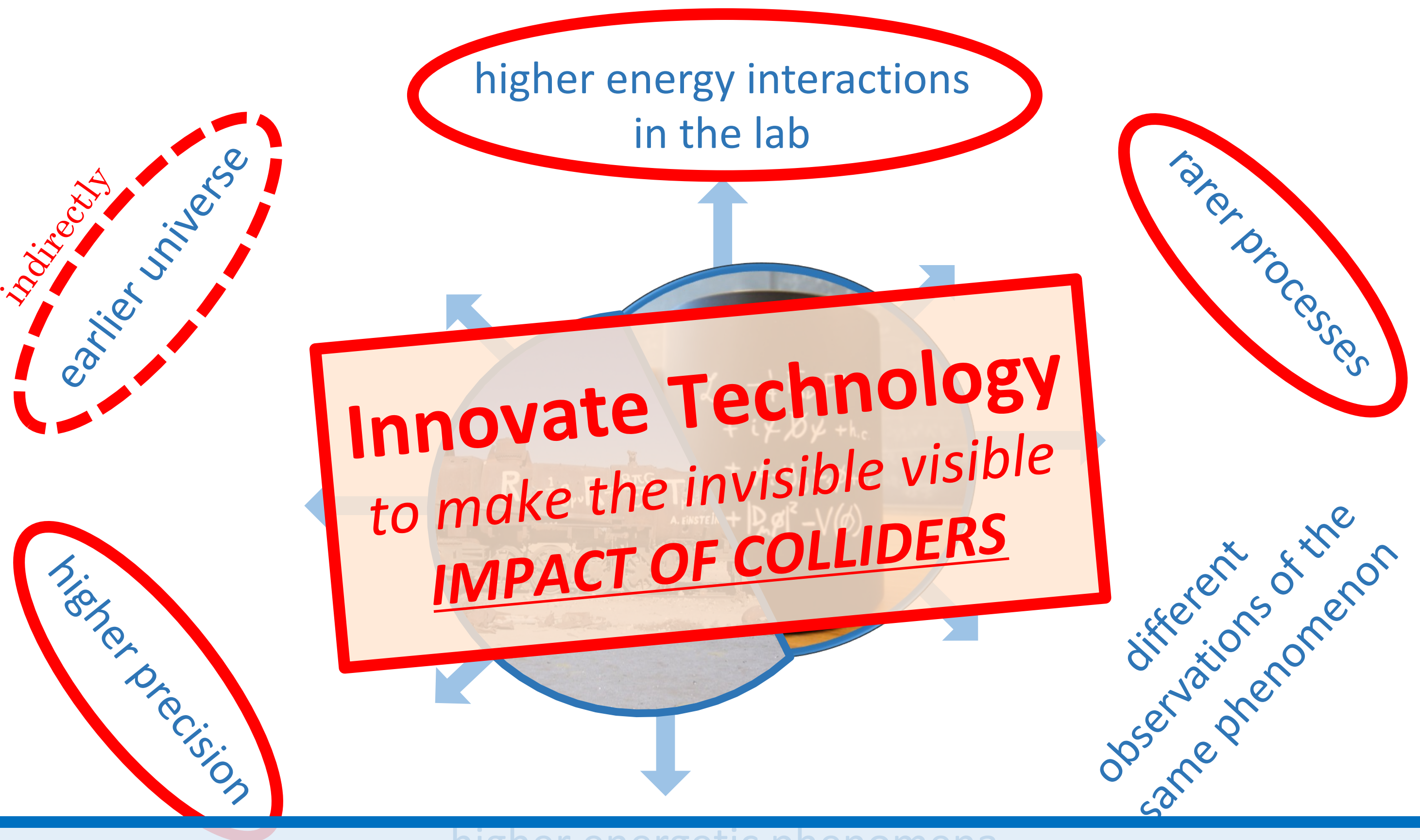


Particle beams required at high energy and high current = high power

!! ENERGY CONSUMPTION !!

<u>EXAMPLE</u>

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

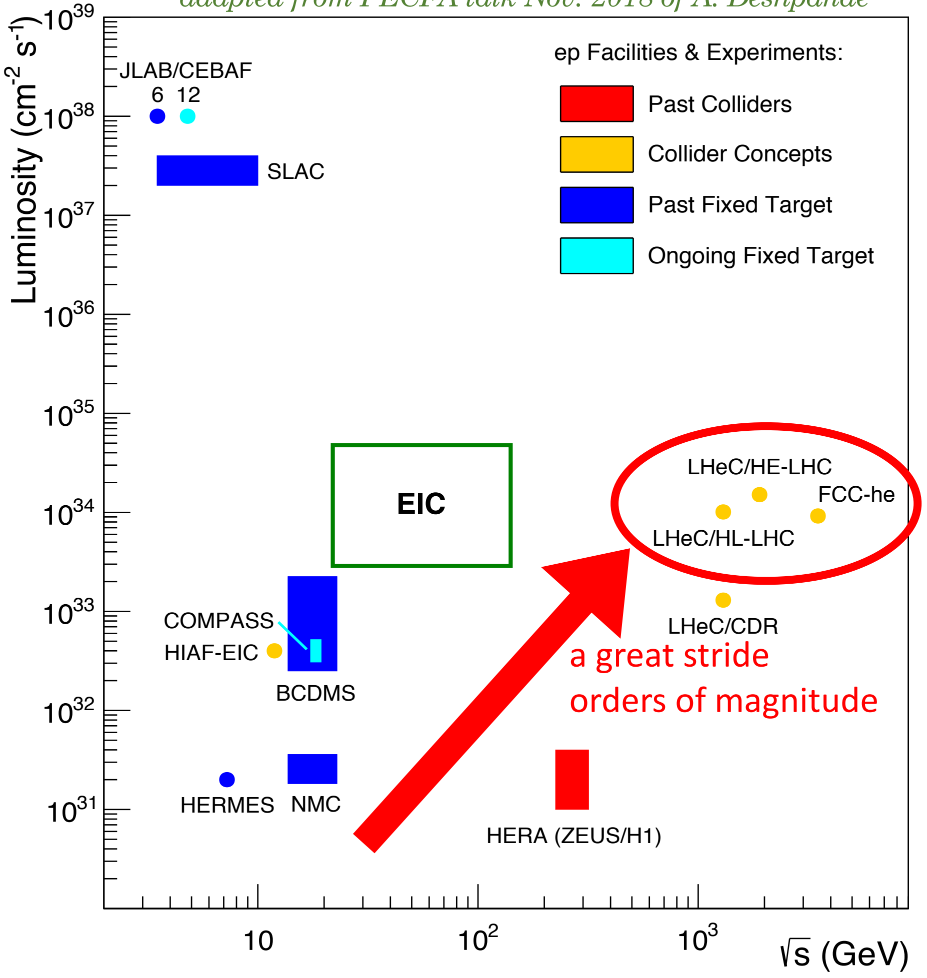
The scope

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

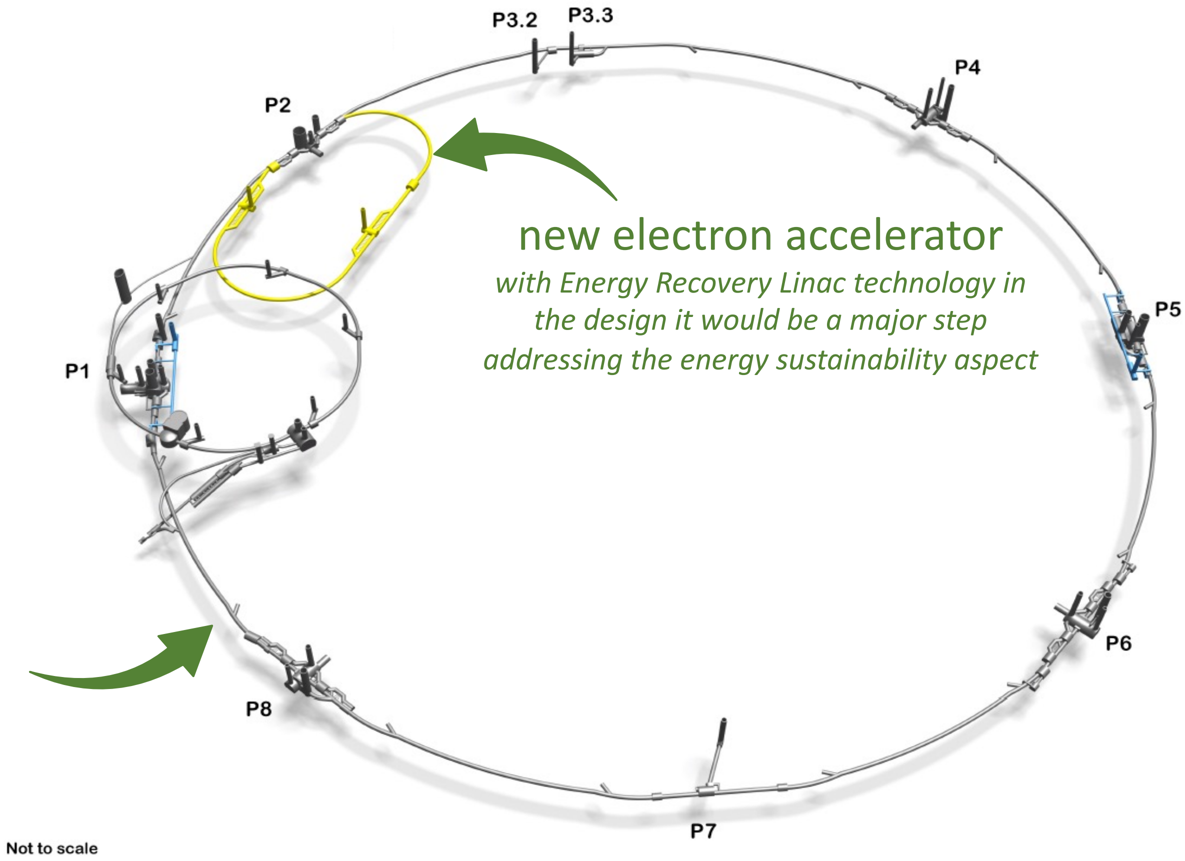
The next ambition for the community will be to enable ep/eA physics both at higher luminosities and at higher energies

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

adapted from PECFA talk Nov. 2018 of A. Deshpande



A paradigm shift: high-energy electron-proton collions



new electron accelerator

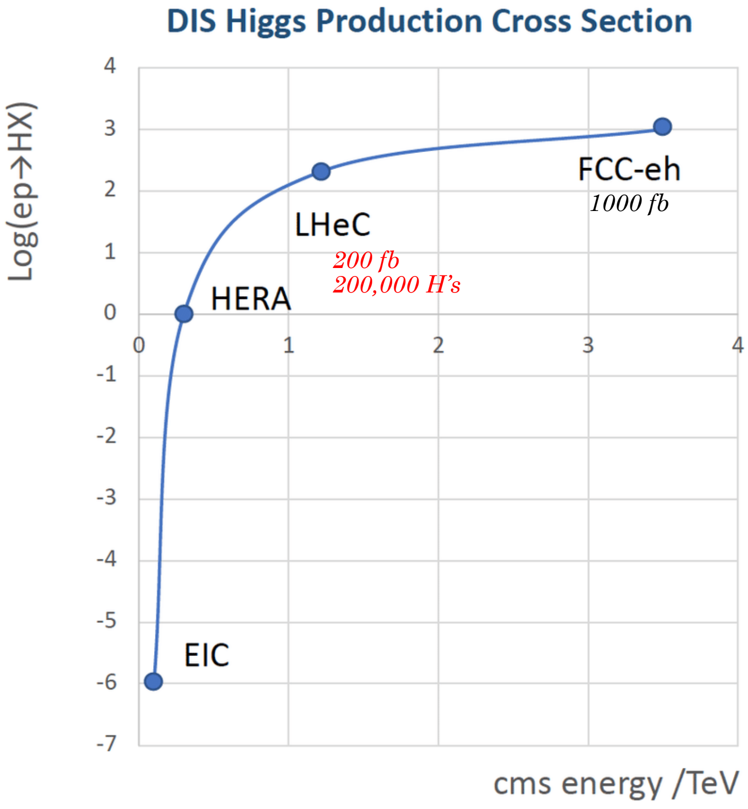
with Energy Recovery Linac technology in the design it would be a major step addressing the energy sustainability aspect

existing/future proton accelerator

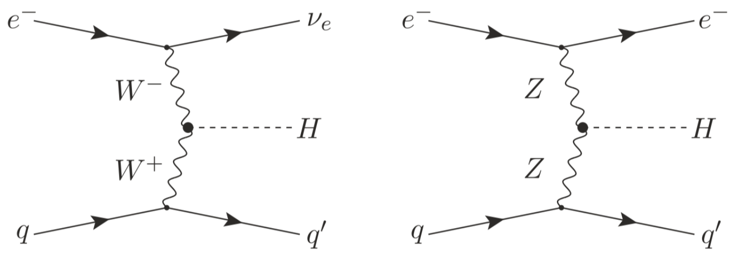
LHC and/or FCC

Collision energy above the threshold for EW/Higgs/Top

from mostly QCD-oriented physics to General-Purpose physics



The real game change between HERA and LHC/FCC

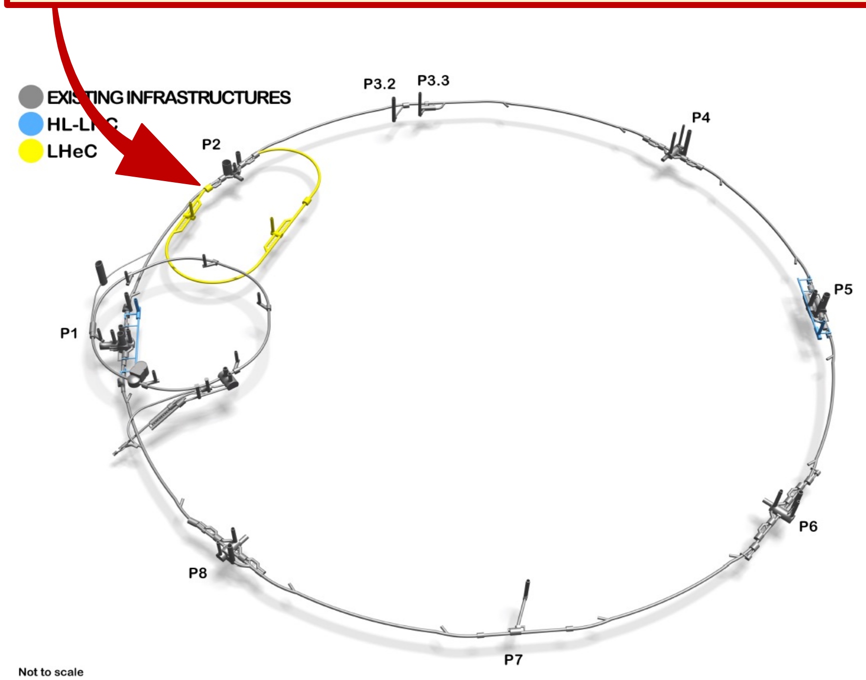


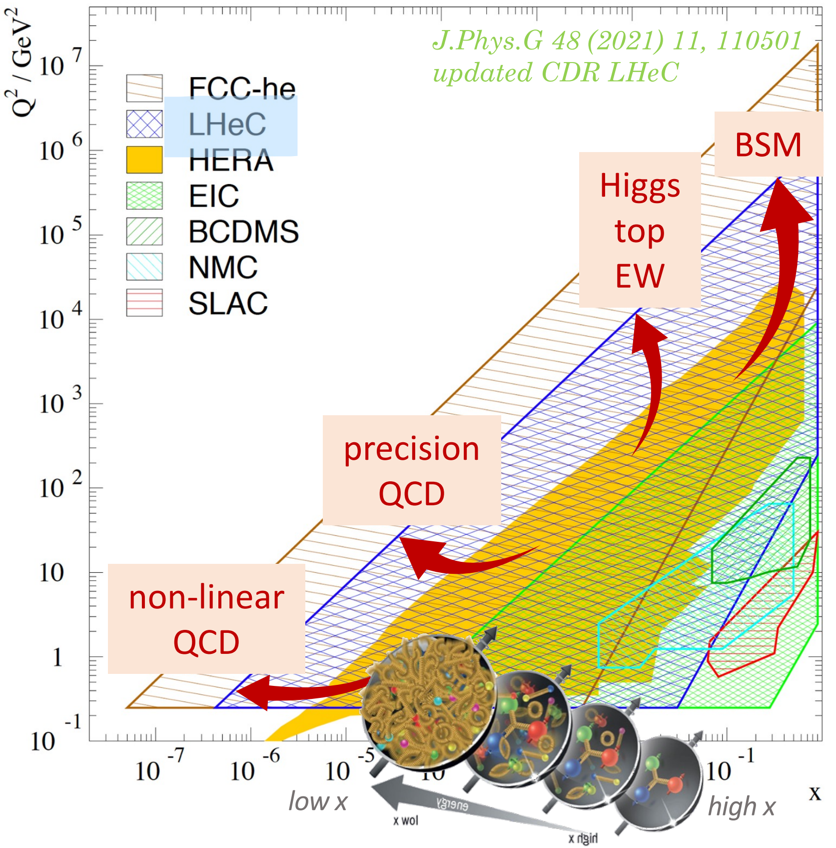
compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

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

The LHeC program

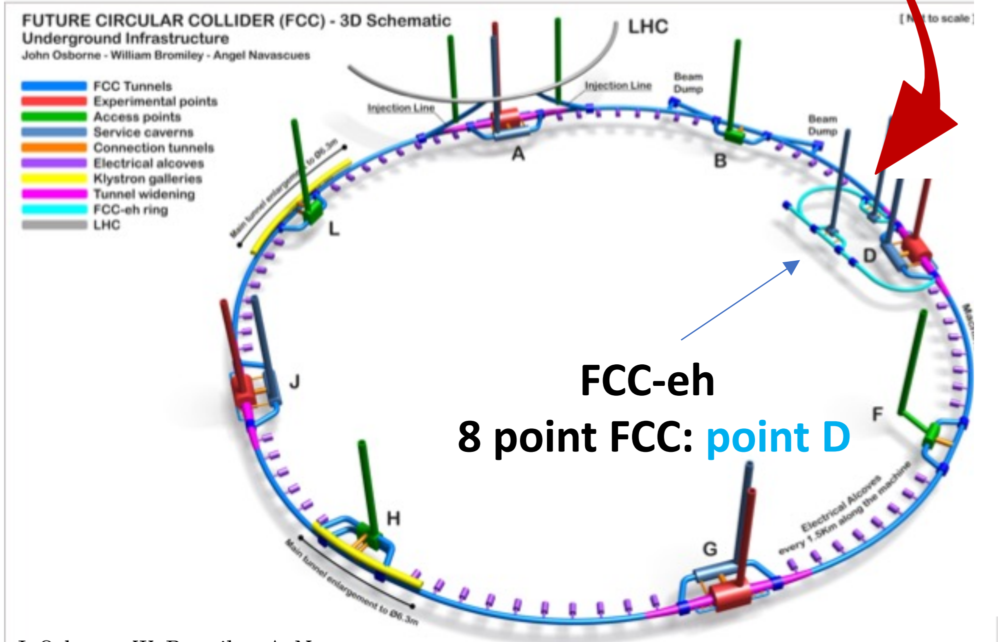
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



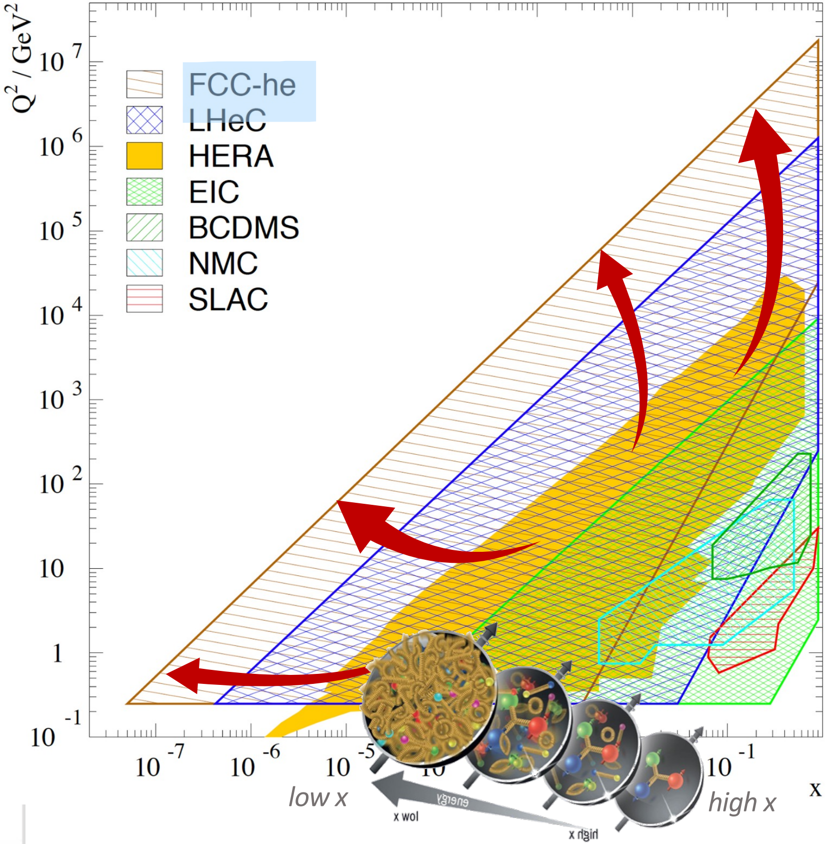


The FCC-eh program

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



J. Osborne, W. Bromiley, A. Navascues



Future flagship at the energy & precision frontier

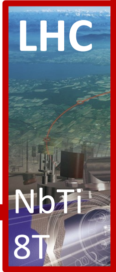
Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

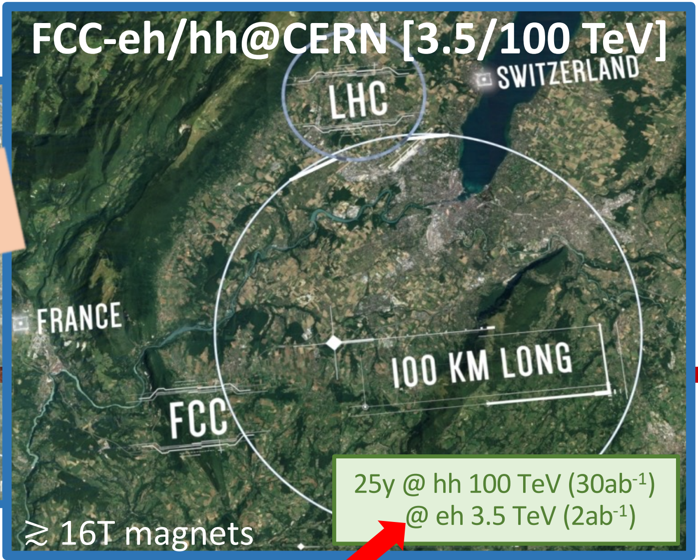
attractive combination of precision & energy frontier



ep-option with HL-LHC: LHeC

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

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

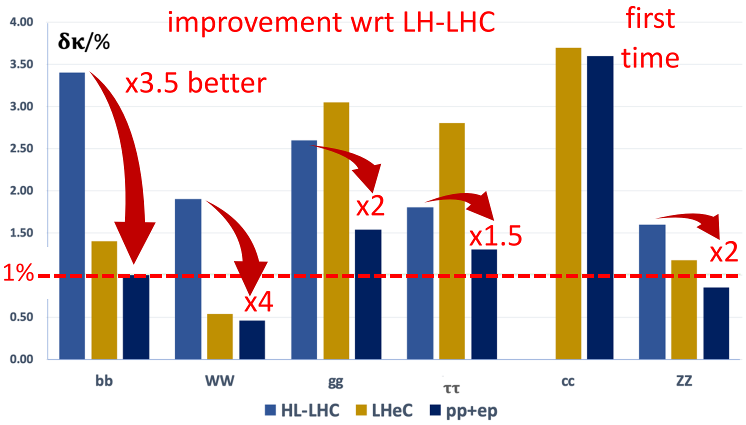


numbers assume 2 IPs for each collider (only one for FCC-eh)

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

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

Higgs physics



EW physics

- Δm_W down to 2 MeV (today at ~10 MeV)
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP)

Top quark physics

- $|V_{tb}|$ precision better than 1% (today ~5%)
- top quark FCNC and γ, W, Z couplings

DIS scattering cross sections

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

Strong interaction physics

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

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

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

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

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

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

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

Complementarity for Higgs physics in the FCC program

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

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]

adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

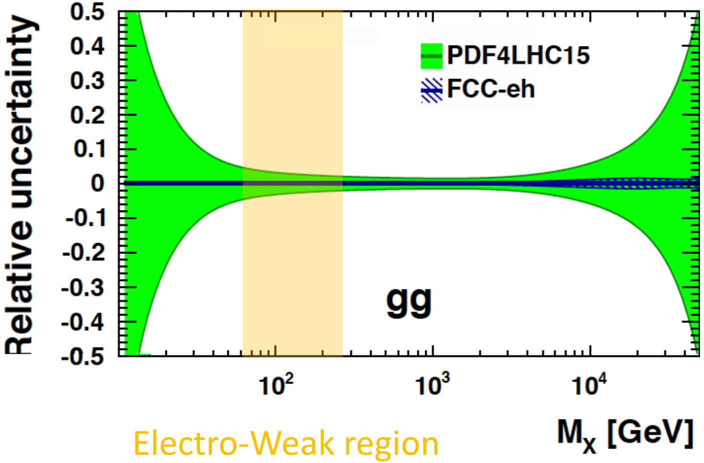
only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

Empowering the FCC-hh program with the FCC-eh

~5-7% uncertainty on the σ(W,Z,H)

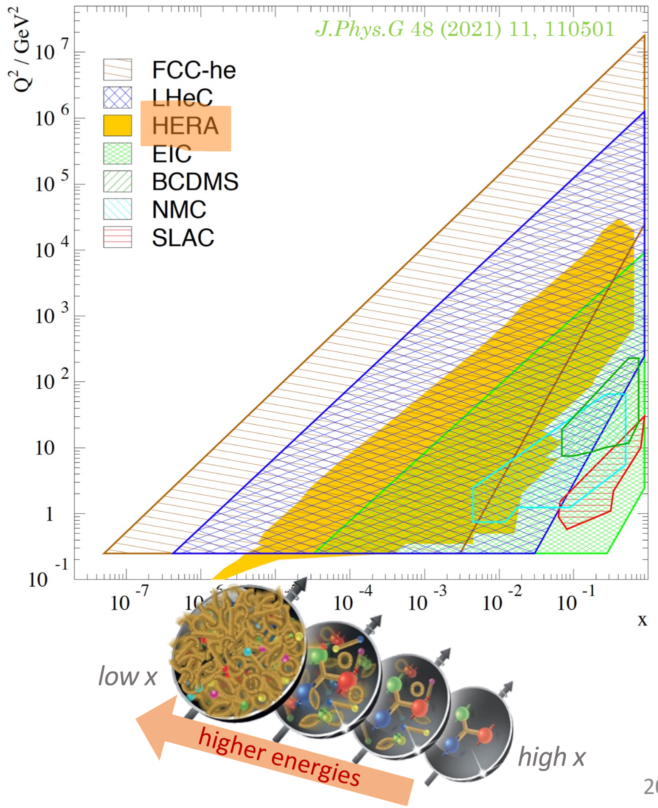
pp @ 100 TeV



Electro-Weak region

no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

~5-7% uncertainty
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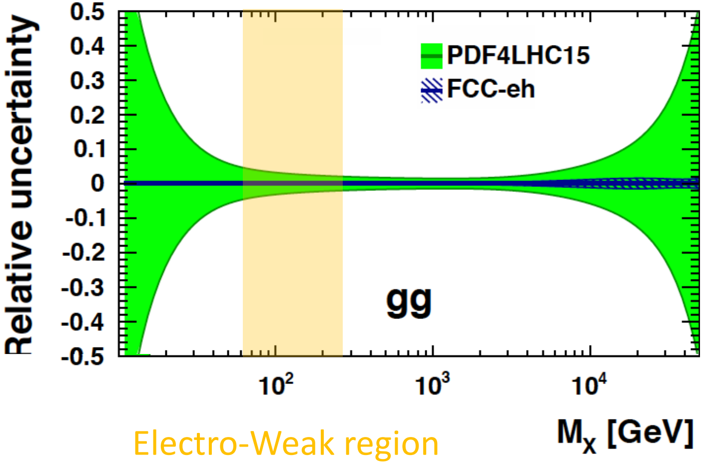


Electro-Weak region

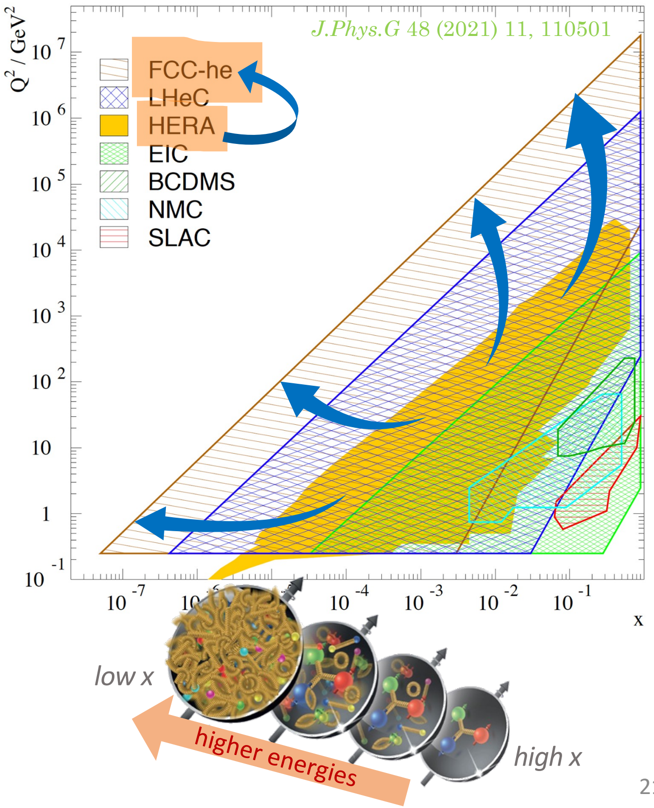
no FCC-eh

with FCC-eh

~1% uncertainty
on the σ(W,Z,H)

FCC-eh essential to unlock FCC-hh science potential

Kinematic range Parton Distribution Functions



The challenge

High-intensity electron beam

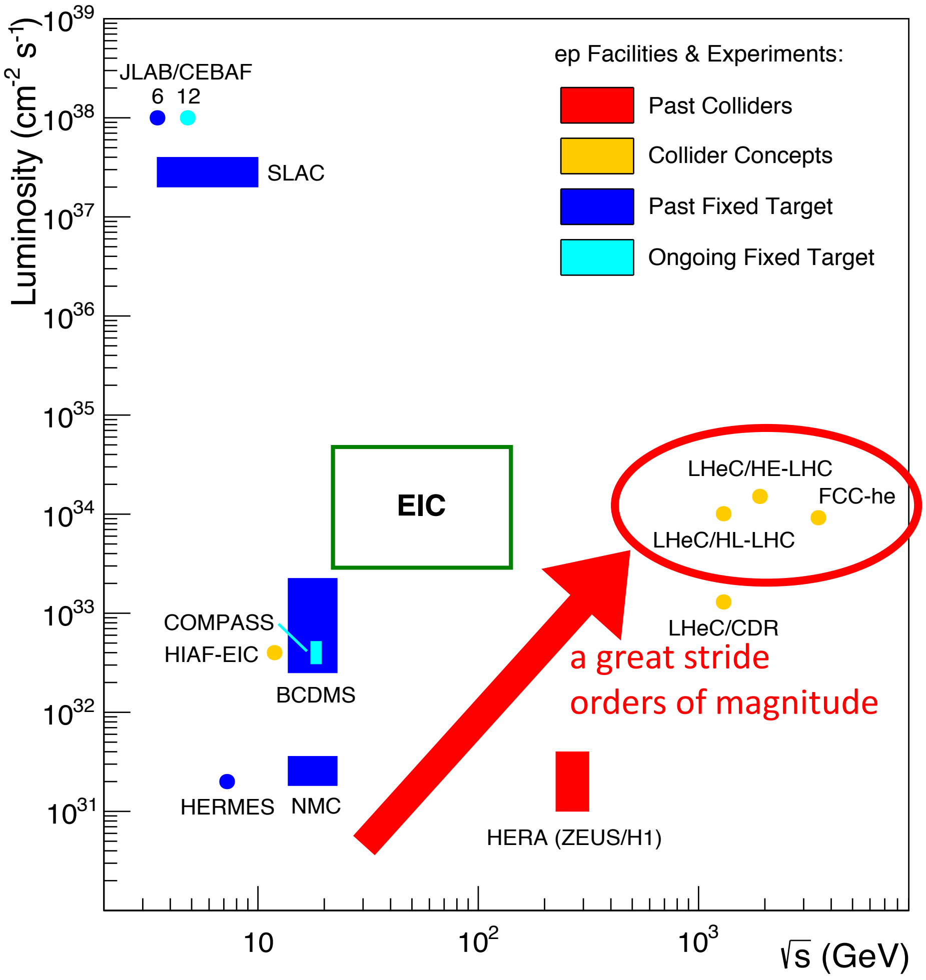
From HERA@DESY to LHeC@CERN

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



The challenge

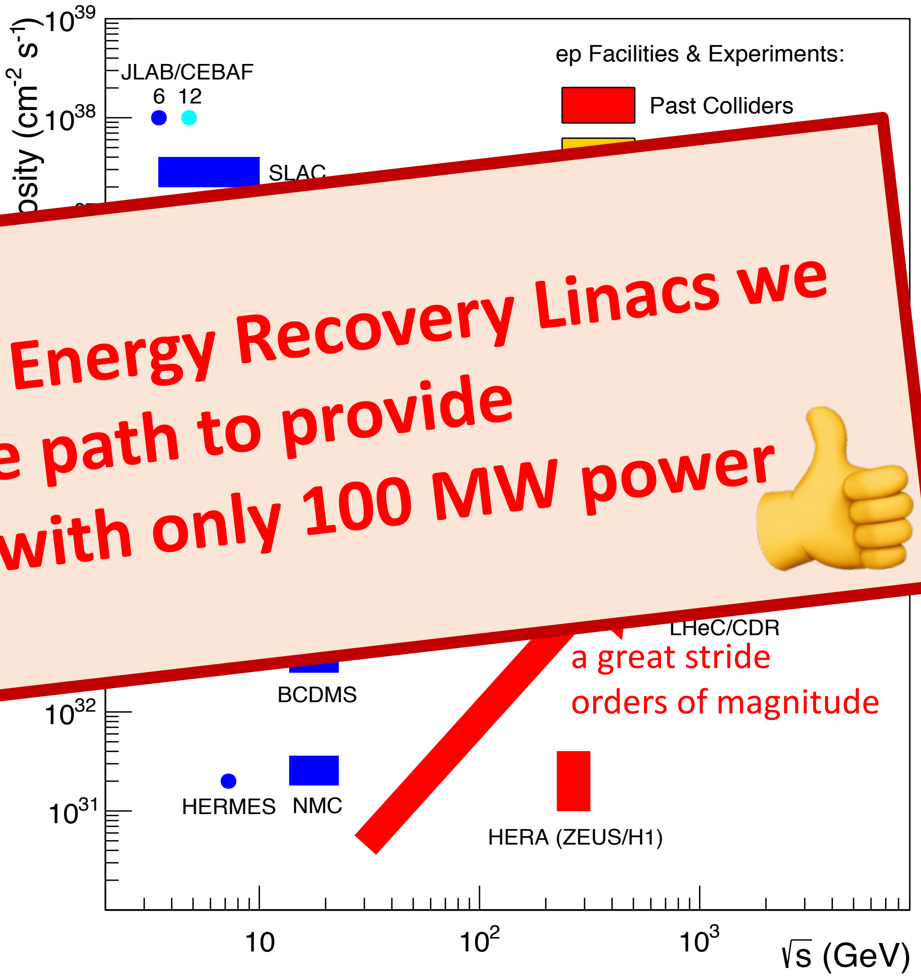
High-intensity electron beam

From HERA@DESY to LHeC@

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

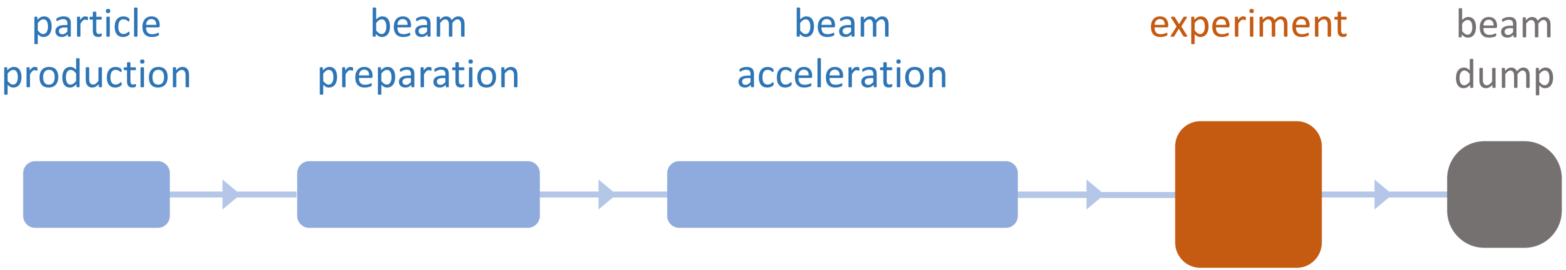
1 GW beam power

equivalent to the power delivered by a nuclear power plant



Where our lepton accelerators use power ?

Basic structures of a particle accelerator



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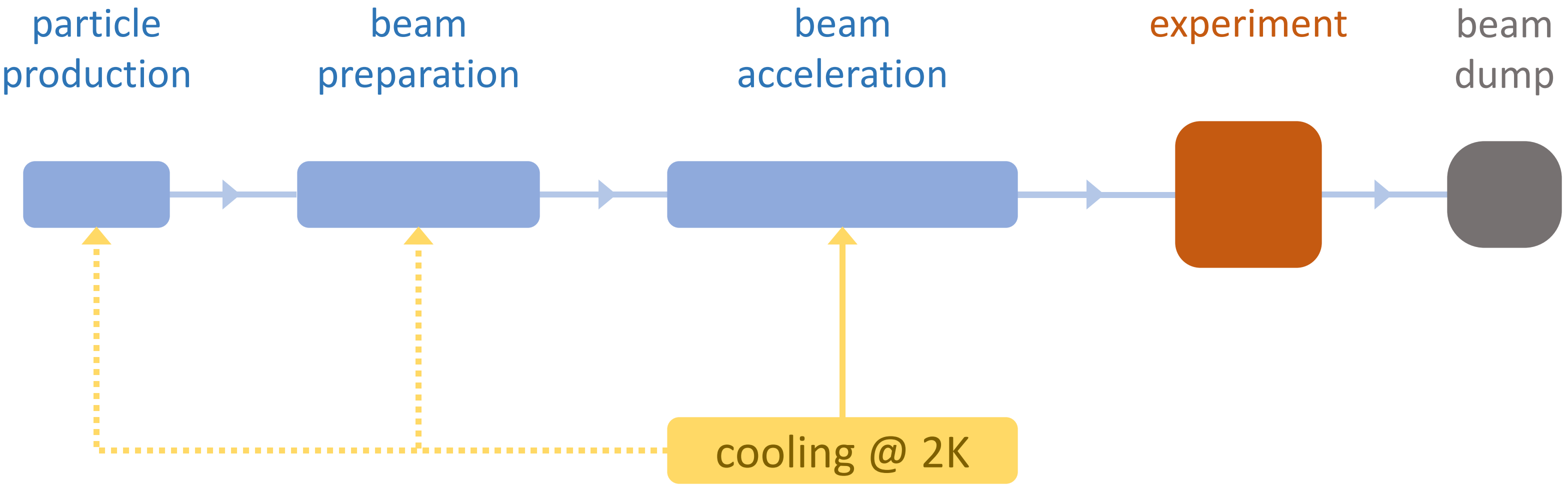

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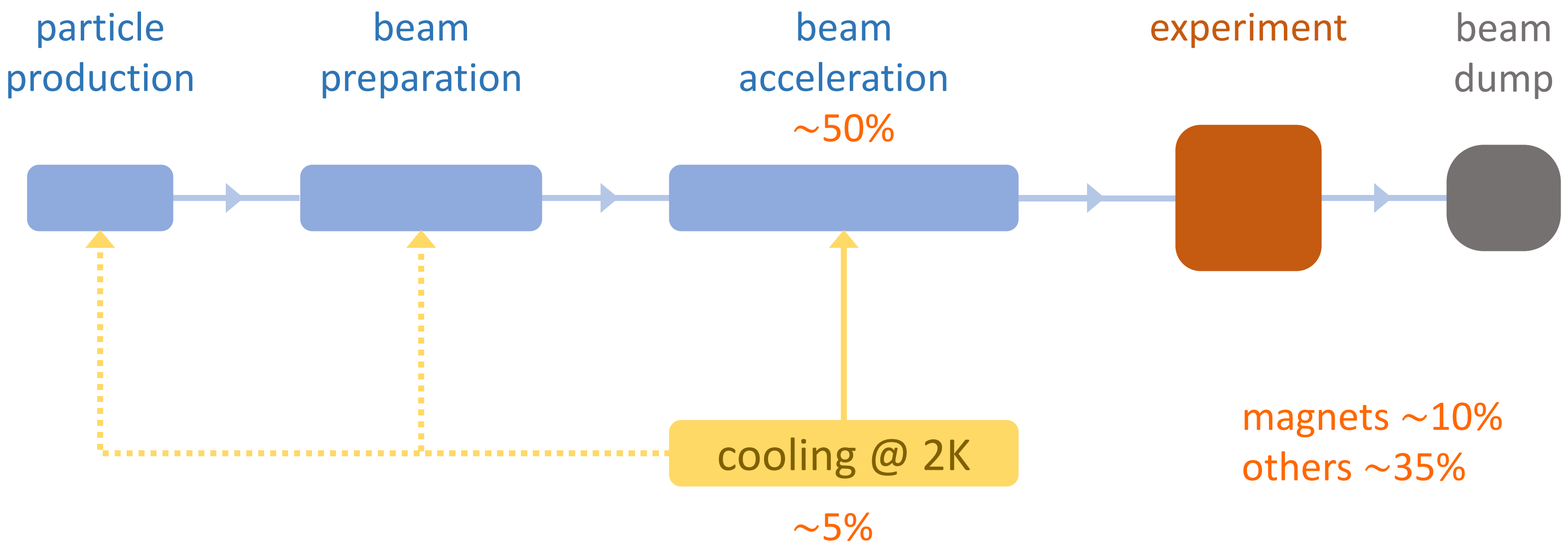
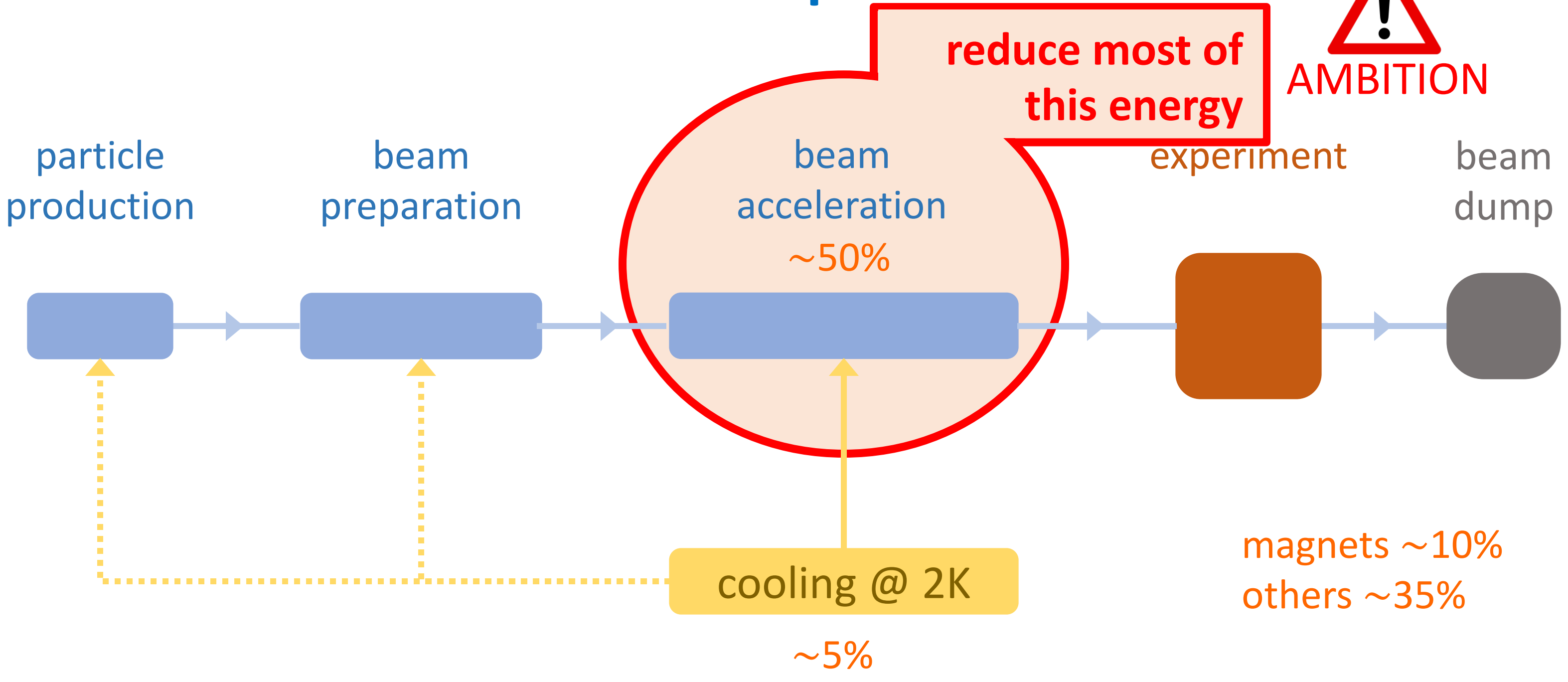


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator



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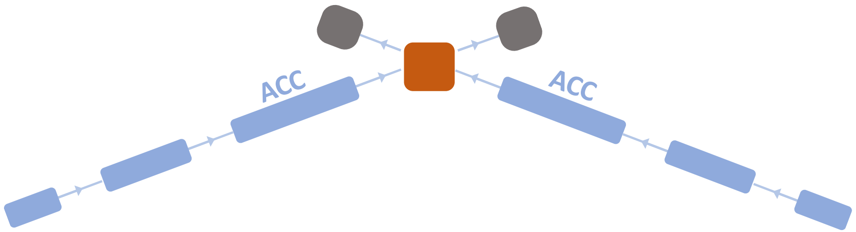
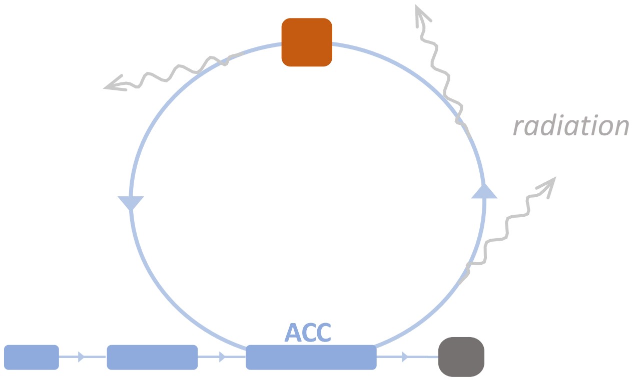
Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

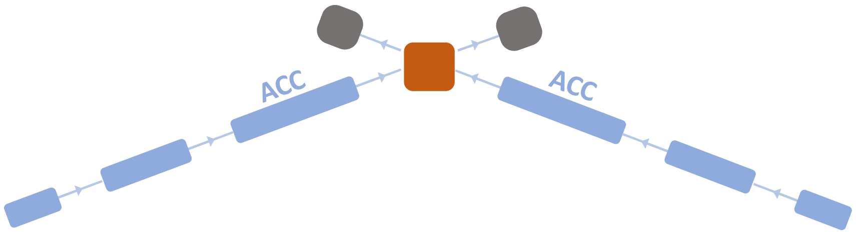
radiate away very quickly the beam power

about half of this is dumped or lost due to radiation

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

Impact for the current designs of Higgs Factories

Linear colliders



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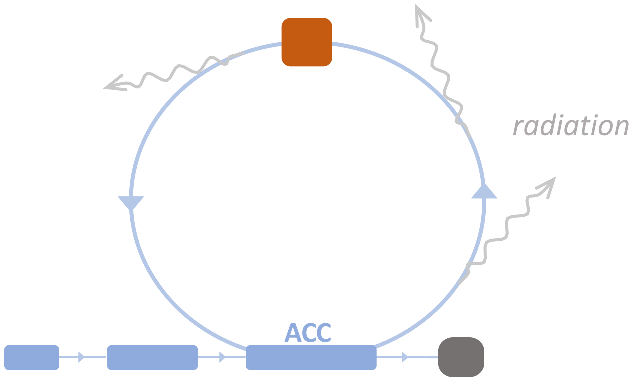


dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

radiate away very quickly the beam power

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

about half of this is dumped or lost due to radiation

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

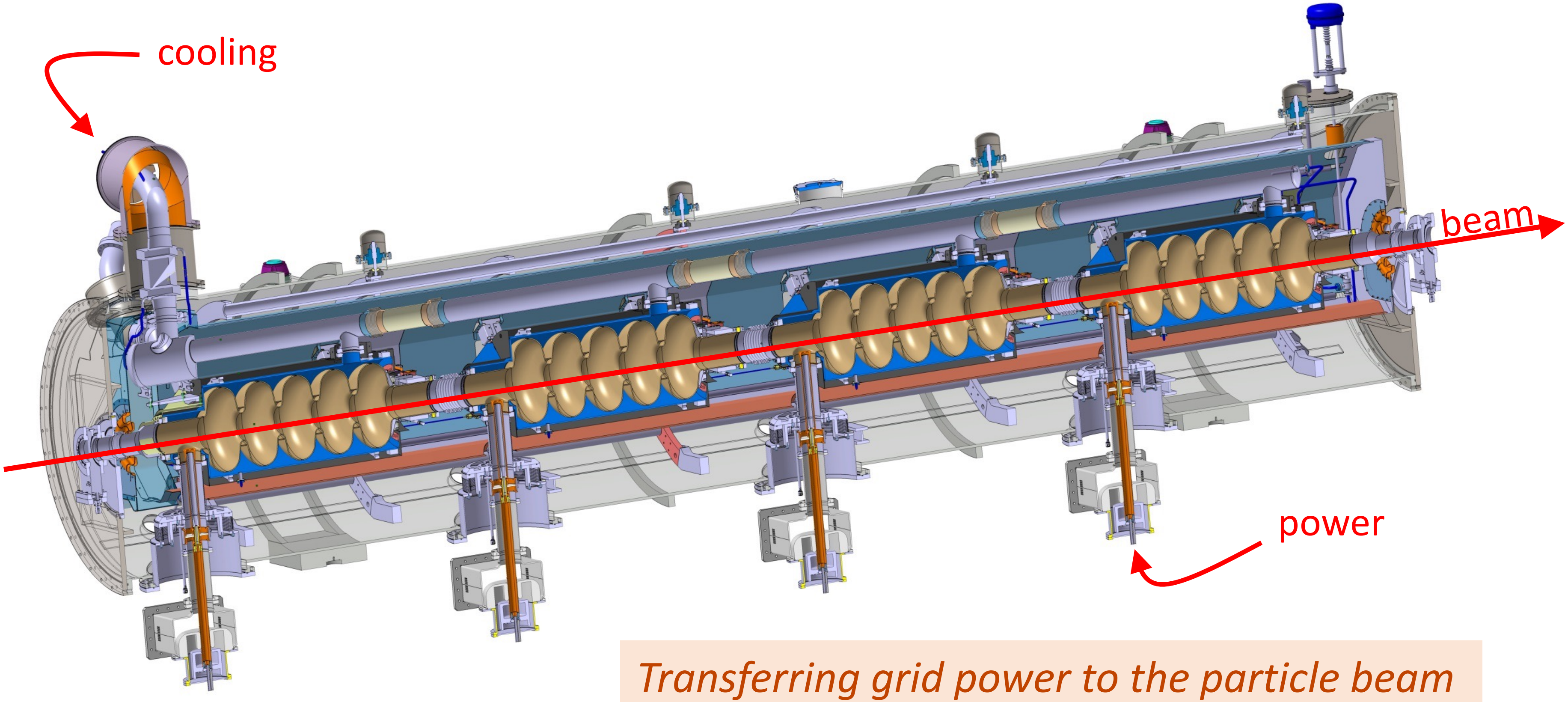
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

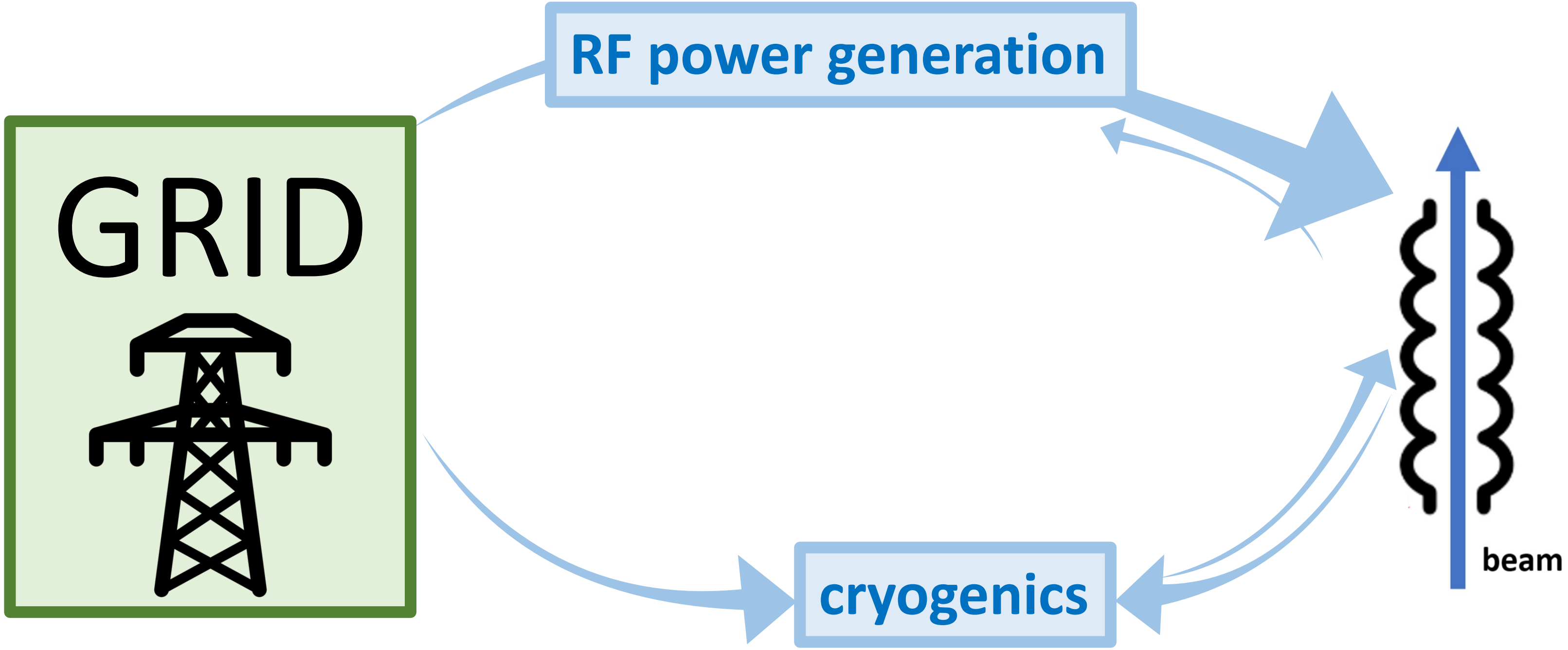
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency



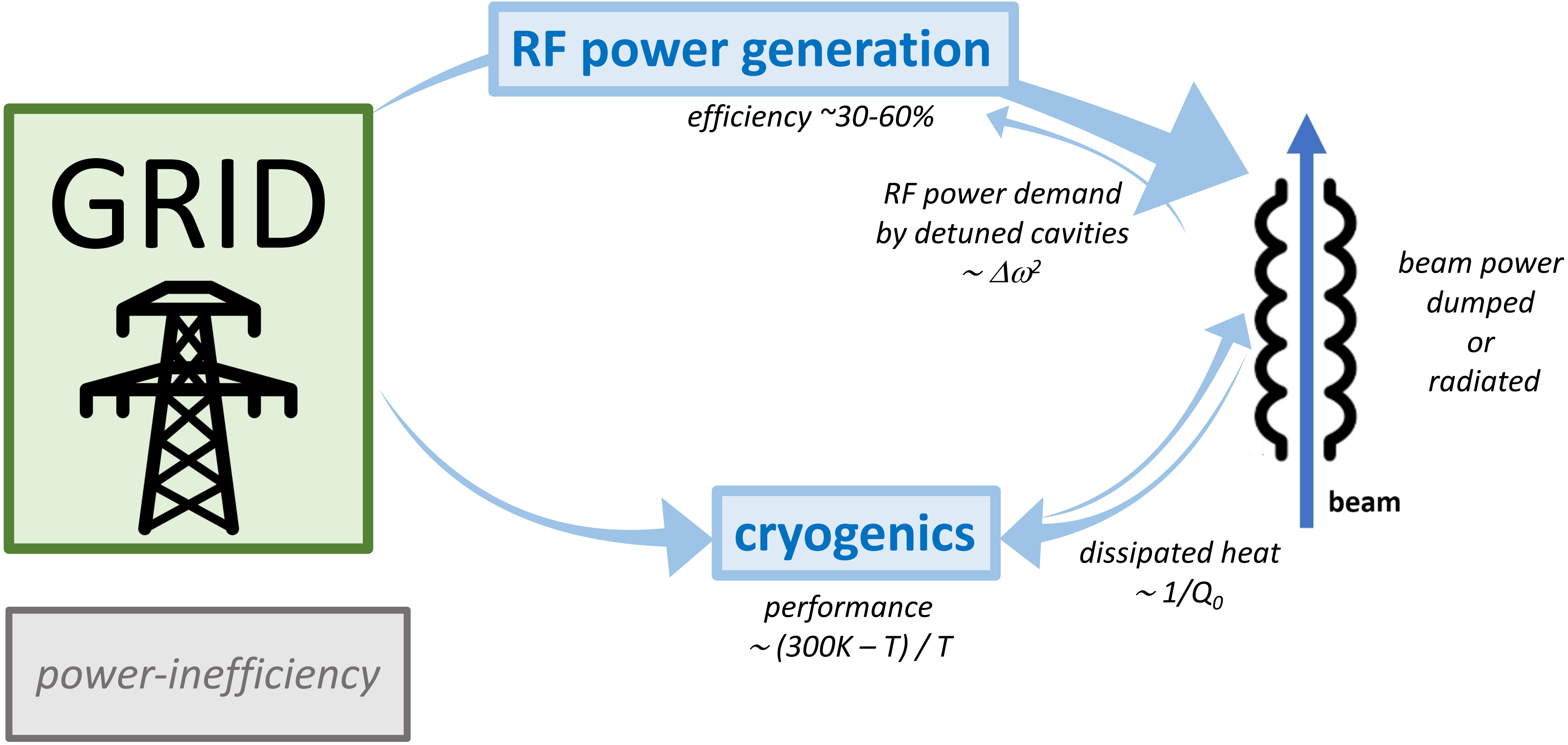
Transferring grid power to the particle beam

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

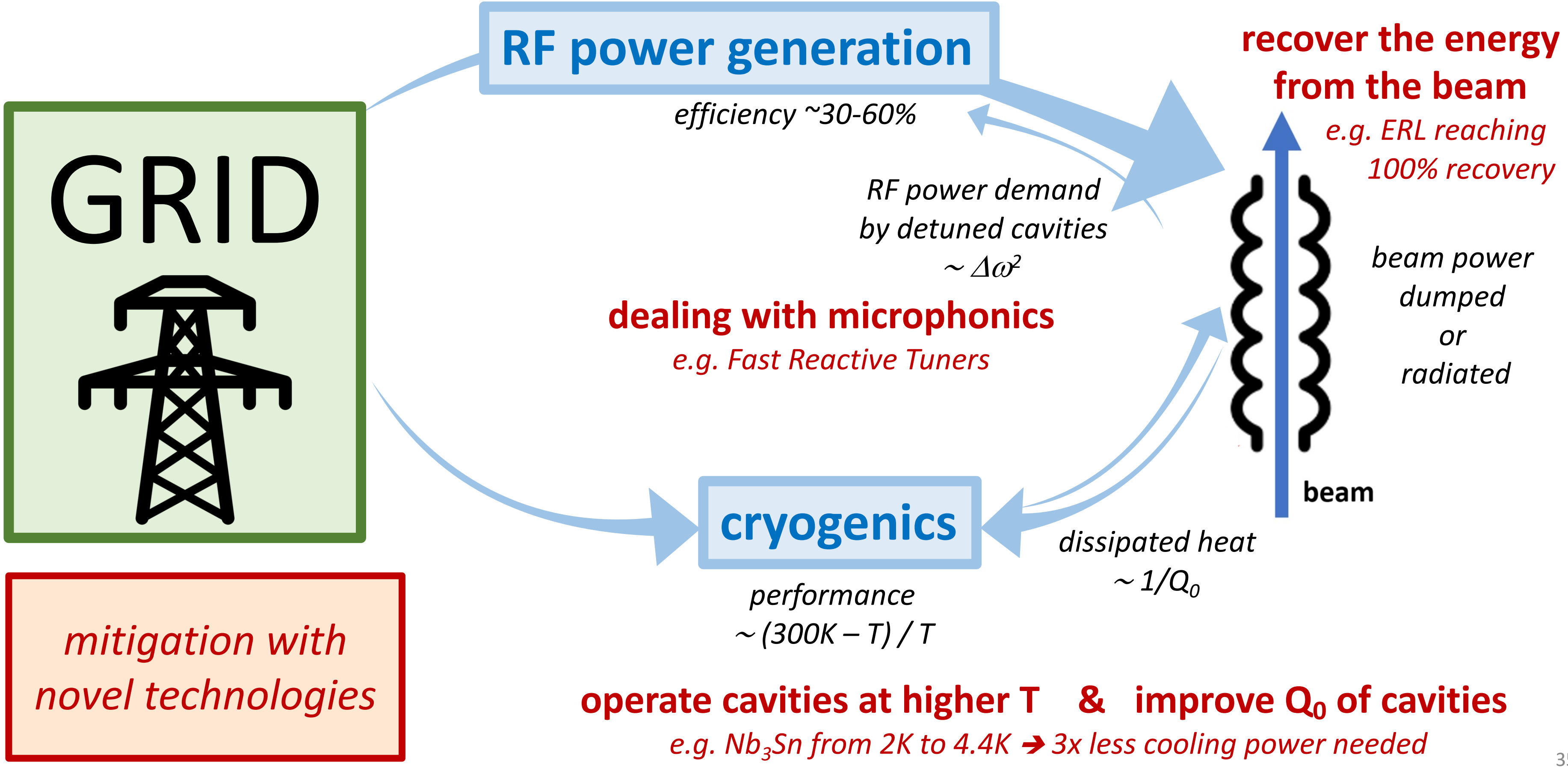
From Grid to Beam



From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands



From Grid to Beam

improve amplifier efficiency

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

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

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

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

beam

dissipated heat
~ 1/Q_0

performance
~ (300K – T) / T

operate cavities at higher T & improve Q_0 of cavities

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

From Grid to Beam

improve amplifier efficiency

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

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

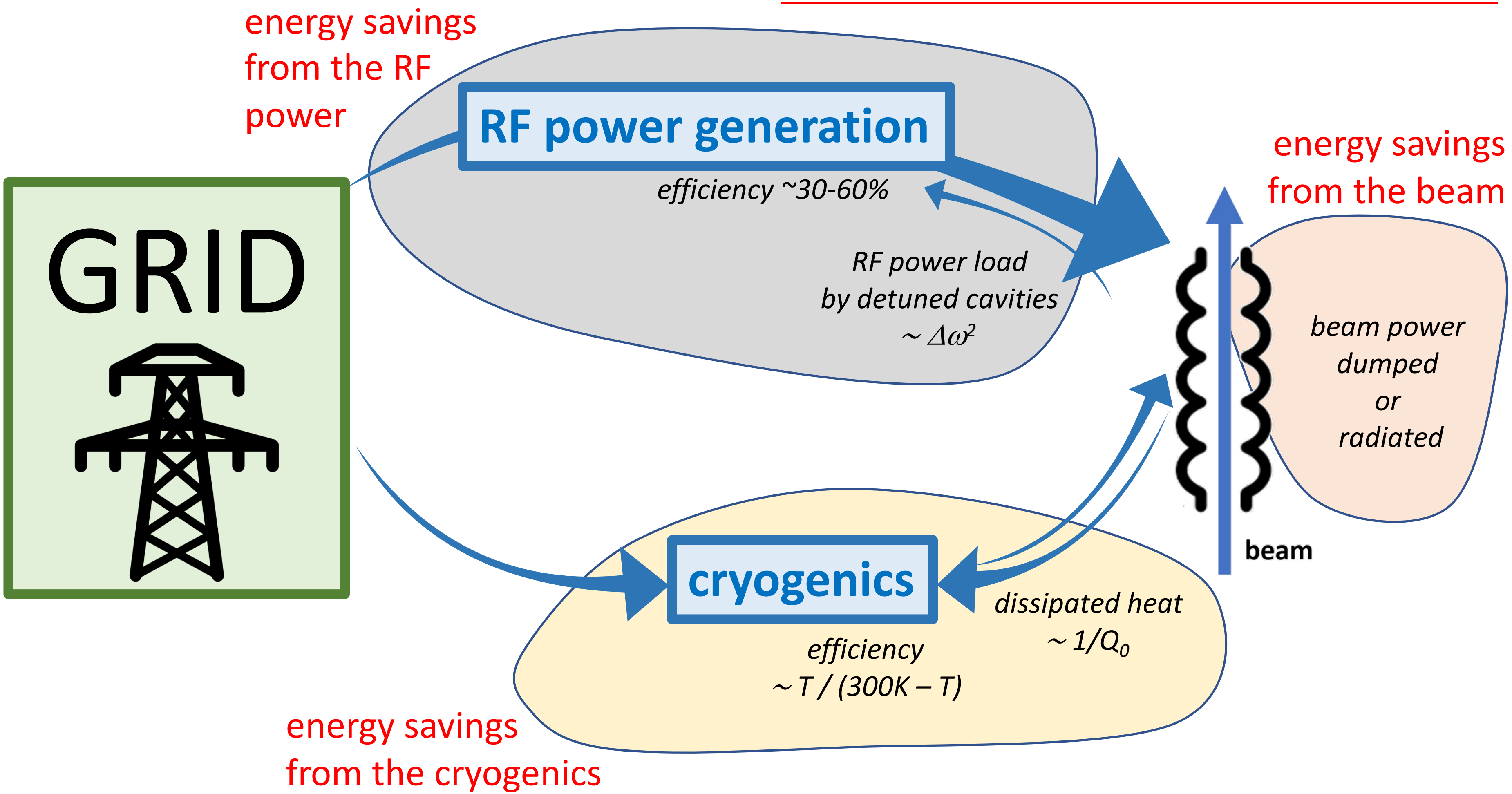
ALARA = **A**s **L**ow **A**s **R**easonable **A**chievable

principle enforced for nuclear safety,
also for energy consumption ?

operate...

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

Three main innovation directions



Three main innovation directions

energy savings from the RF power

Innovate for Sustainable Accelerating Systems (iSAS)

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

(ambition: significantly reduce the energy footprint of SRF accelerators)

Energy-saving technologies are widely applicable in SRF cryomodules: synergies between R&D at PERLE/bERLinPro and implementation in major colliders, e.g. FCC-ee/eh/hh

dissipated heat $\sim 1/Q_0$

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

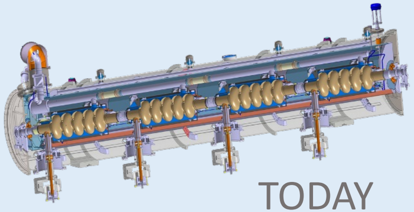
energy savings from the cryogenics

“Innovate for Sustainable Accelerating Systems” (iSAS)

AMBITION – With the ambition to maintain the attractiveness and competitiveness of European research infrastructures and to enable Europe’s Green Deal, we propose to Innovate for Sustainable Accelerating Systems (iSAS) by establishing enhanced collaboration in the field to broaden, expedite and amplify the development and impact of novel energy-saving technologies to accelerate particles. The objective of iSAS is to 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.

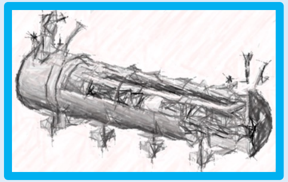
METHODOLOGY – Based on a recently established European R&D Roadmap for accelerator technology and based on a collaboration between leading European research institutions and industry, several interconnected technologies will be developed, prototyped, and tested, each enabling significant energy savings on their own in accelerating particles. The collection of energy-saving technologies will be developed with a portfolio of forthcoming applications in mind and to explore energy-saving improvements of existing research infrastructures on the ESFRI Roadmap, for example the ESFRI Landmarks HL-LHC, ESS and EuXFEL. Considering the developments realised, 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 – Through inter- and multidisciplinary research that delivers and combines various technologies, it is the long-term ambition of iSAS technologies 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.

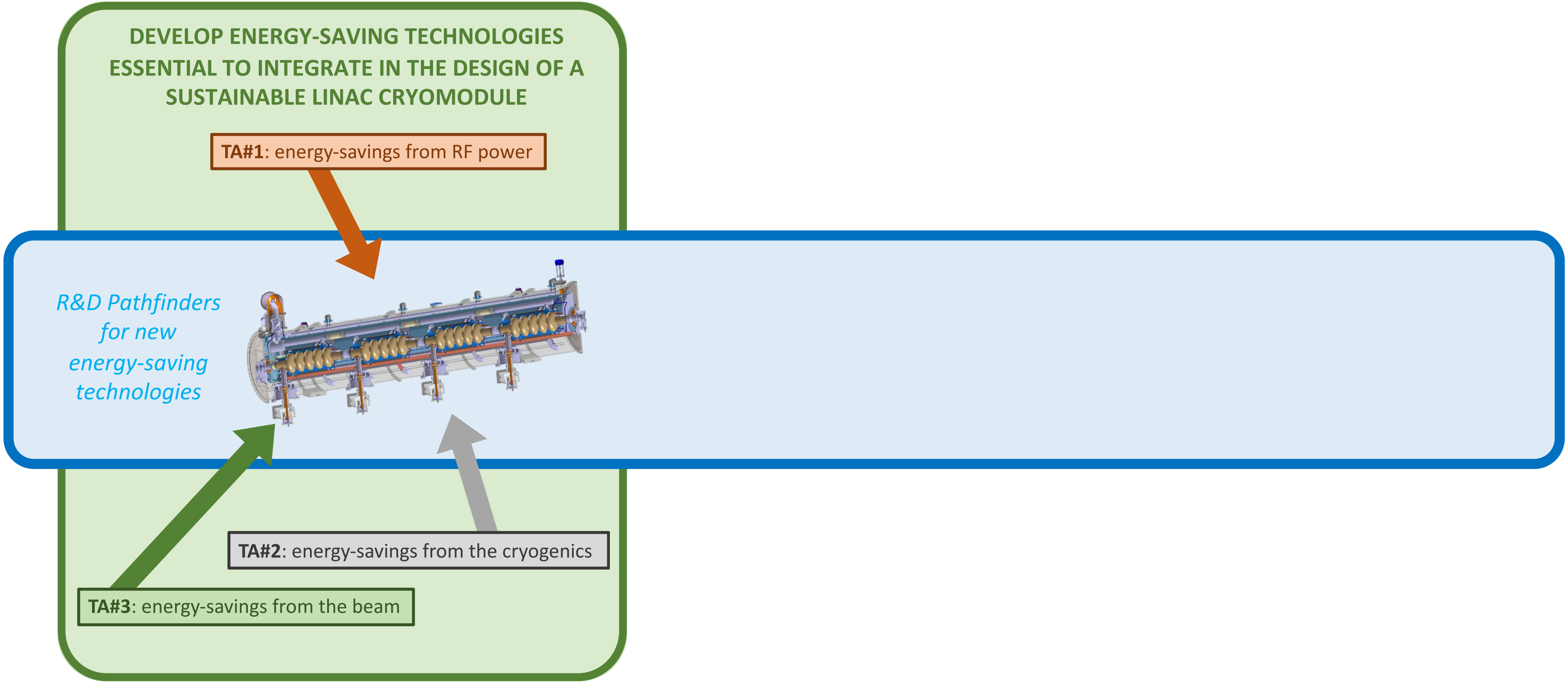


TODAY

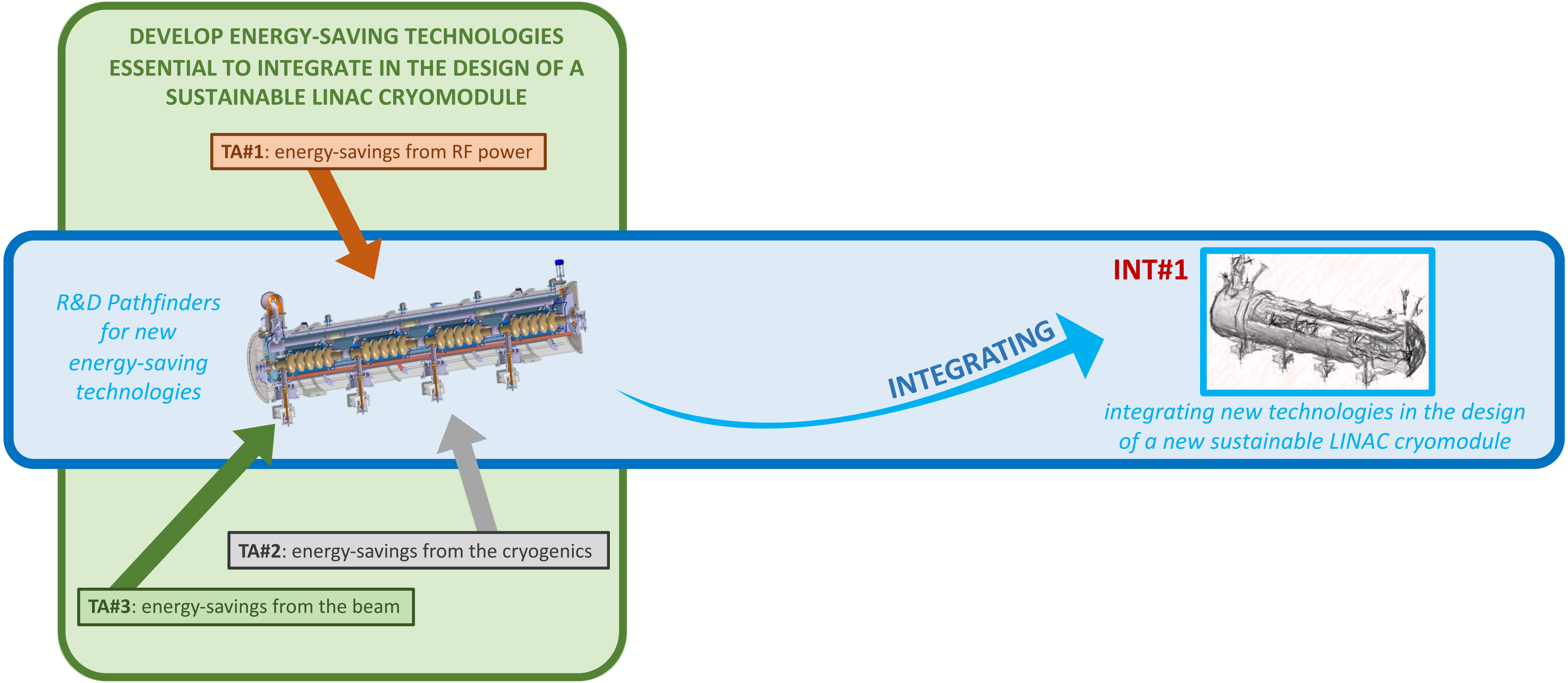
INNOVATE TECHNOLOGIES TOWARDS A SUSTAINABLE ACCELERATING SYSTEM



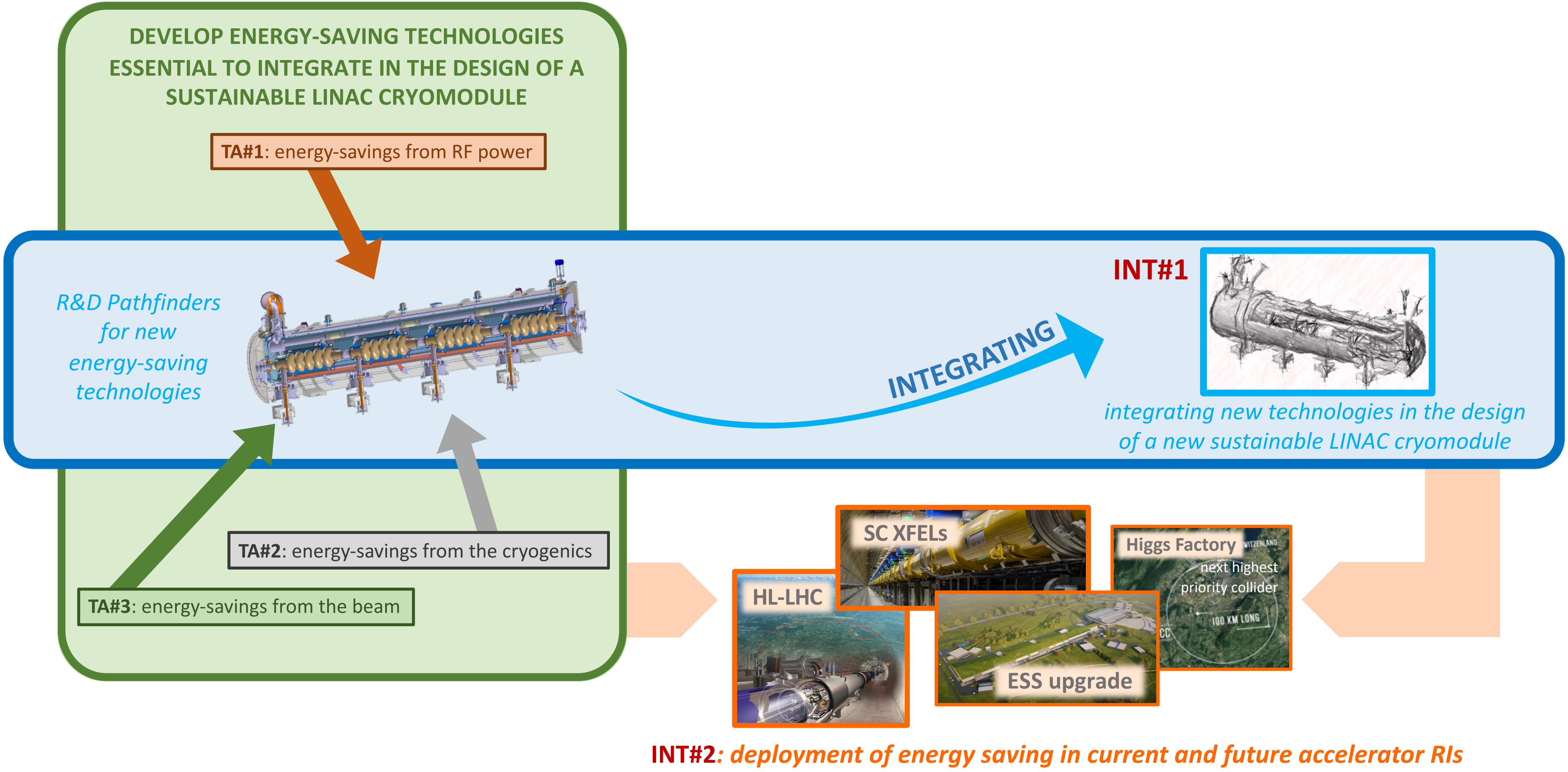
NEW DESIGN



TA: Technology Area

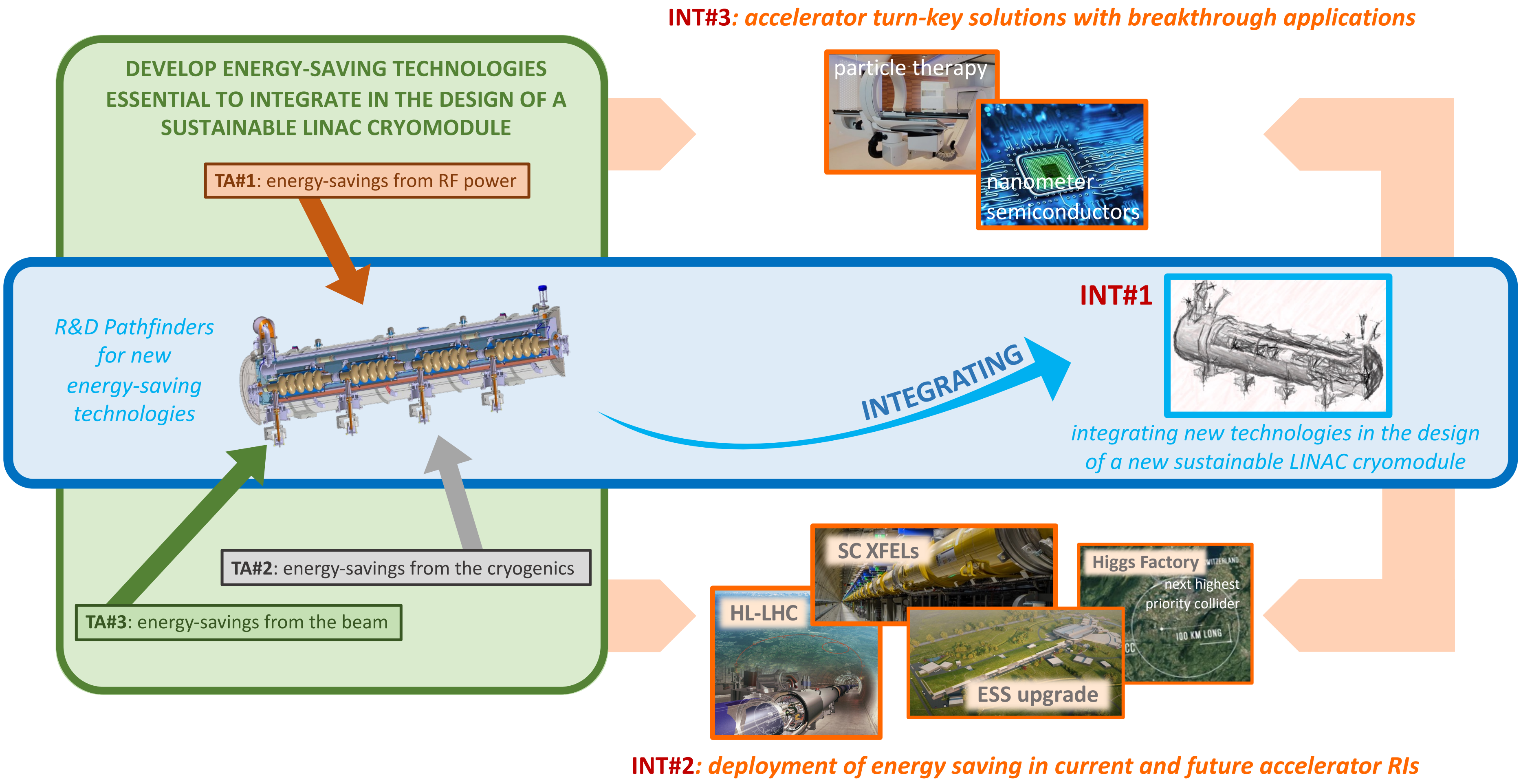


TA: Technology Area, INT: Integration Activities



TA: Technology Area, INT: Integration Activities

RIs: Research Infrastructures



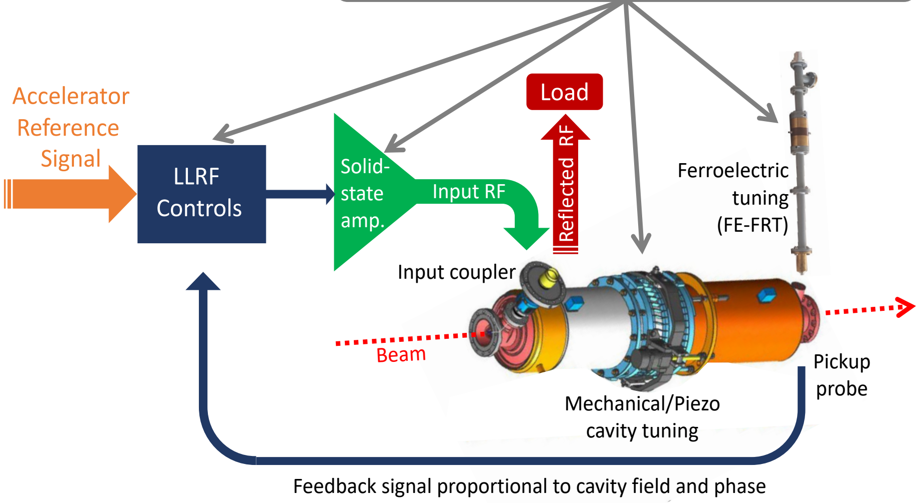
INT#3: accelerator turn-key solutions with breakthrough applications
DEVELOP ENERGY-SAVING TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
TA#1: energy-savings from RF power
particle therapy
nanometer semiconductors
R&D Pathfinders for new energy-saving technologies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

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.

Integrated iSAS approach to save grid power for RF
- Digital AI/ML-assisted field and detuning control
- Reduced detuning by piezo and new FE-FRT tuners
- Smart amplifier control



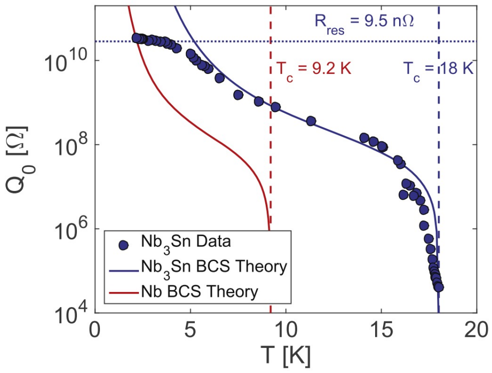
Schematic overview to compensate detuning with new FE-FRTs avoiding large power overhead and to compensate with AI-smart control loop countermeasures via the LLRF steering of the RF amplifier the disturbances in SRF cavities that impact field stability

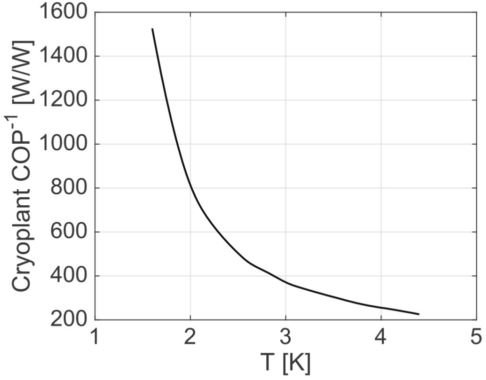
iSAS *develops, prototypes & validates SRF energy-saving technologies*

TA#2: energy-savings from cryogenics

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

Supercond. Sci. Technol. 30 (2017) 033004



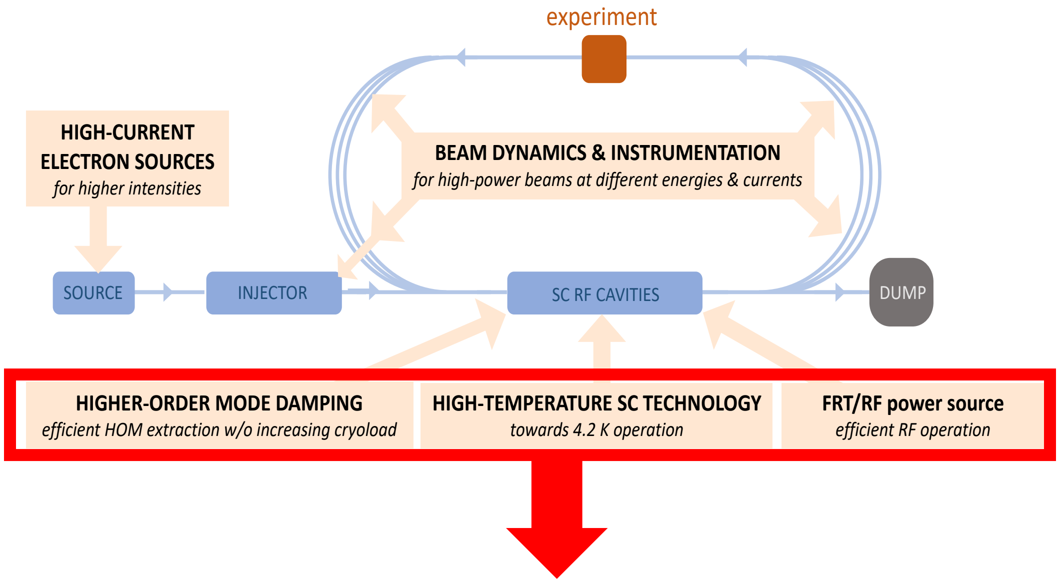


The higher critical temperature (T_c) of Nb_3Sn allows for the maximum value of quality factor Q_0 for 1.3 GHz cavities to be achieved at operating temperatures of about 4 K compared to 2 K for Nb (left figure). The graph on the right shows the efficiency of a cryogenic plant (COP) as a function of temperature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

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

TA#3: energy-savings from the beam

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



towards full high-power energy recovery

iSAS organisation

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

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

DESY.

INFN

UKRI UK Research and Innovation

HZB Helmholtz Zentrum Berlin

ess EUROPEAN SPALLATION SOURCE

Lancaster University

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

cea

VUB VRIJE UNIVERSITEIT BRUSSEL

cnrs

IJCLab Irène Joliot-Curie

CERN

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

iSAS organisation

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

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

Innovate for Sustainable Accelerating Systems (iSAS)

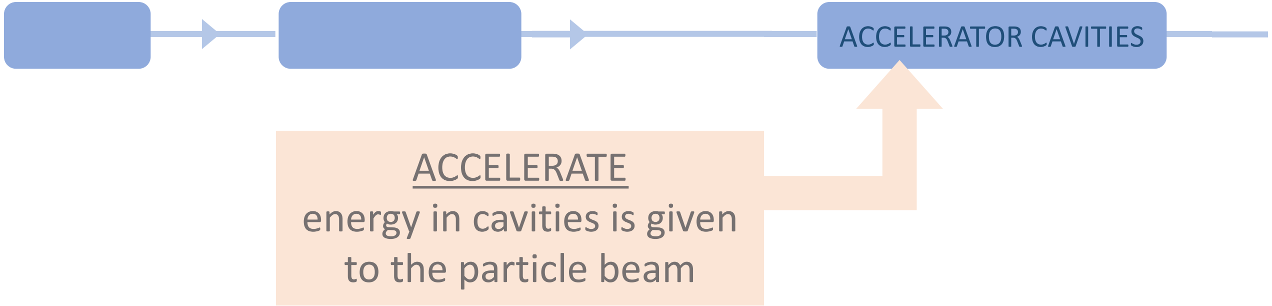
https://indico.ijclab.in2p3.fr/event/9521/

News from Horizon Europe is expected in July-August 2023

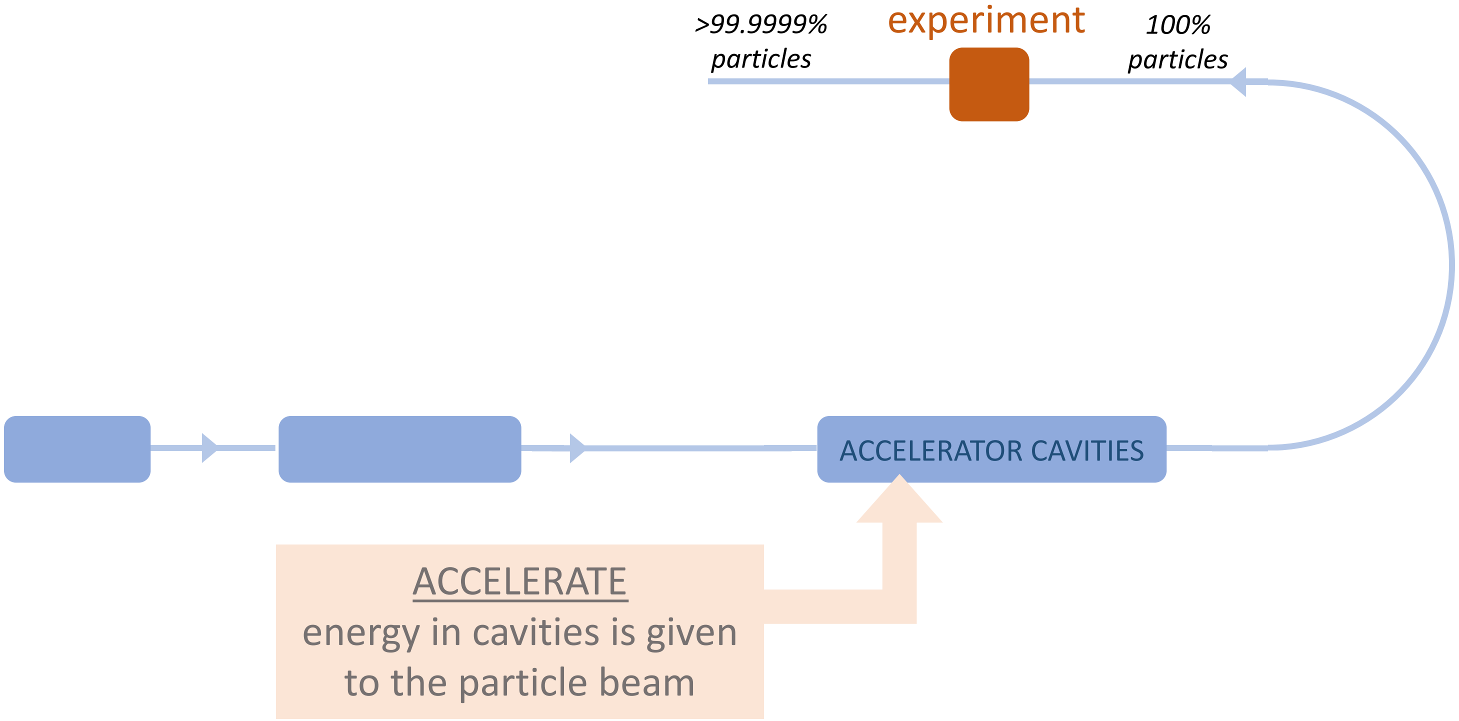
iSAS would have a catalyzing effect on implementing the European ERL R&D Roadmap

+ in

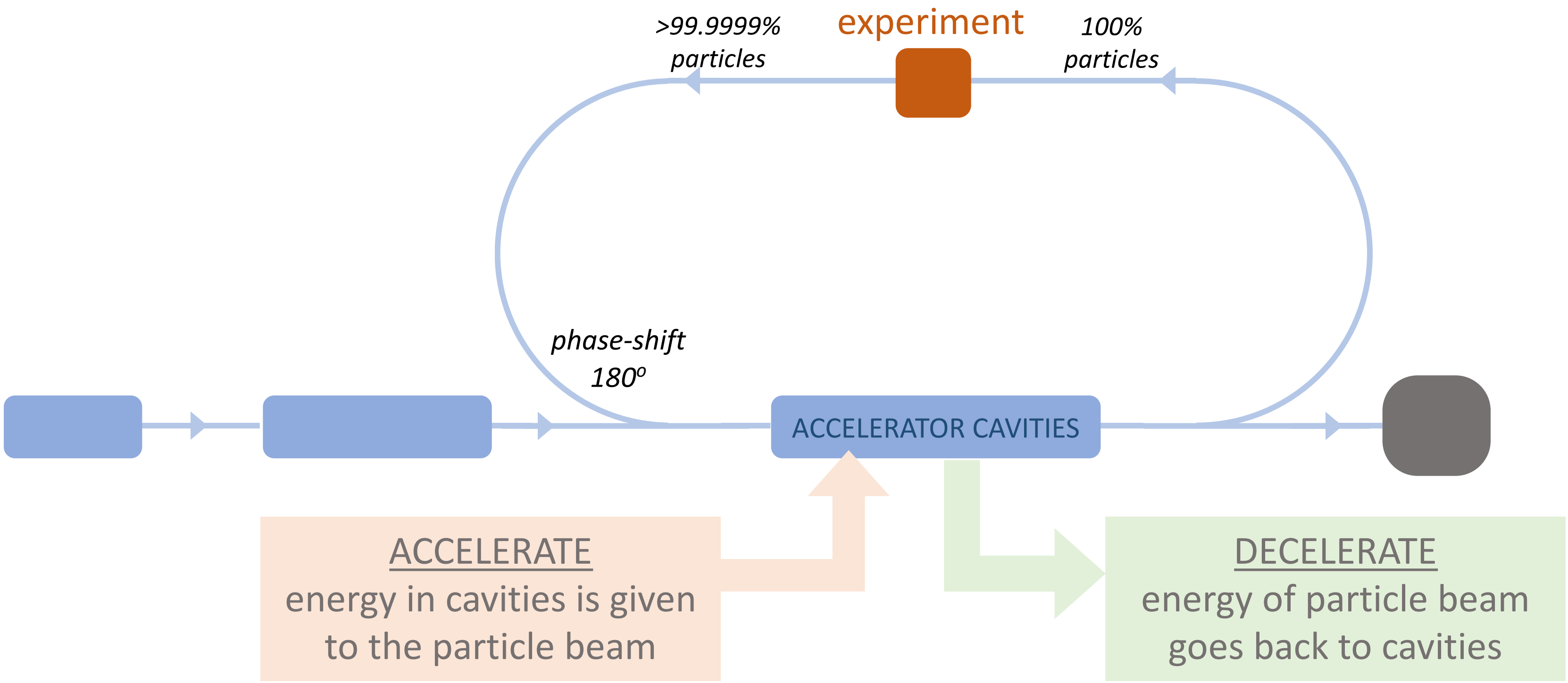
The principle of Energy Recovery



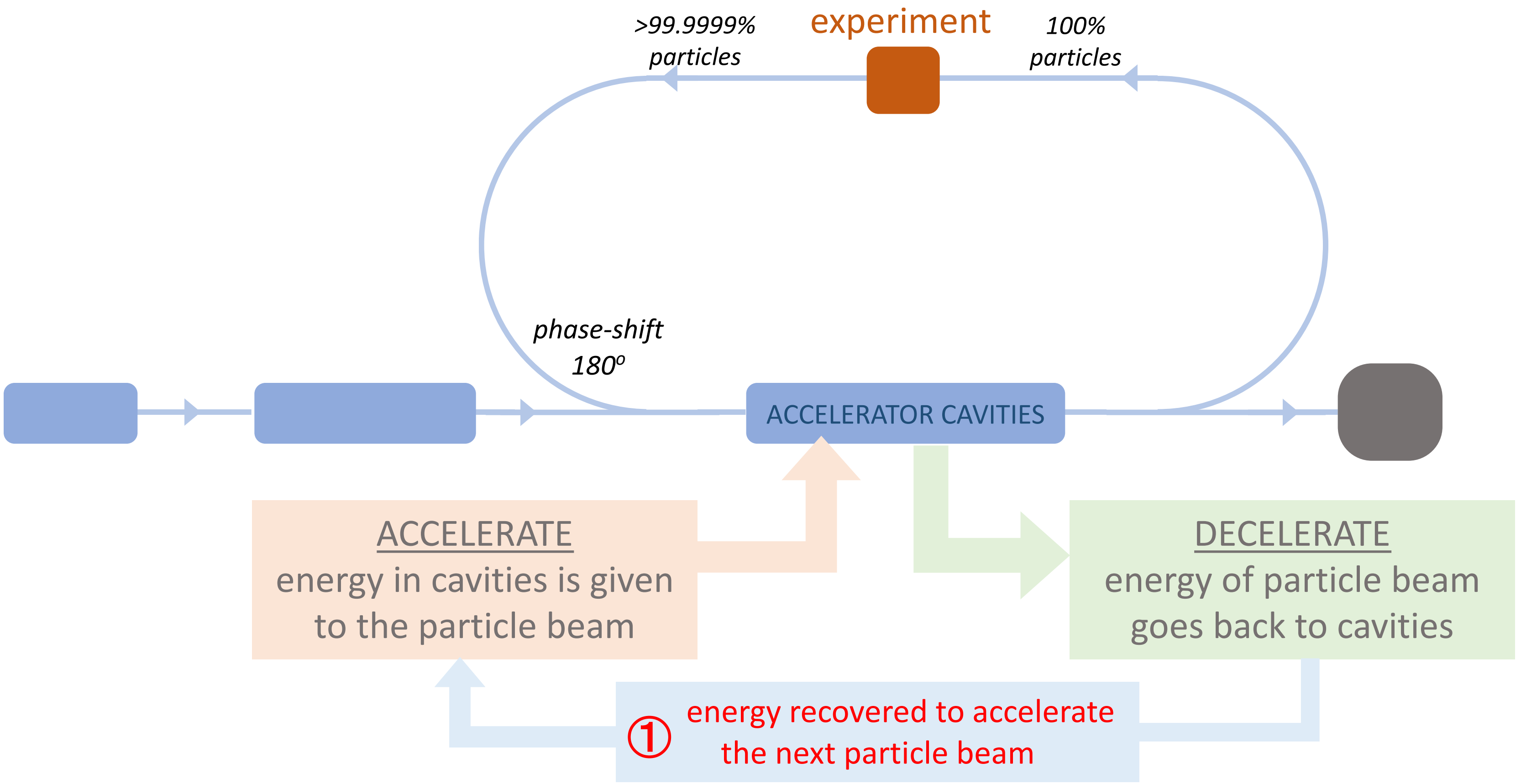
The principle of Energy Recovery



The principle of Energy Recovery



The principle of Energy Recovery



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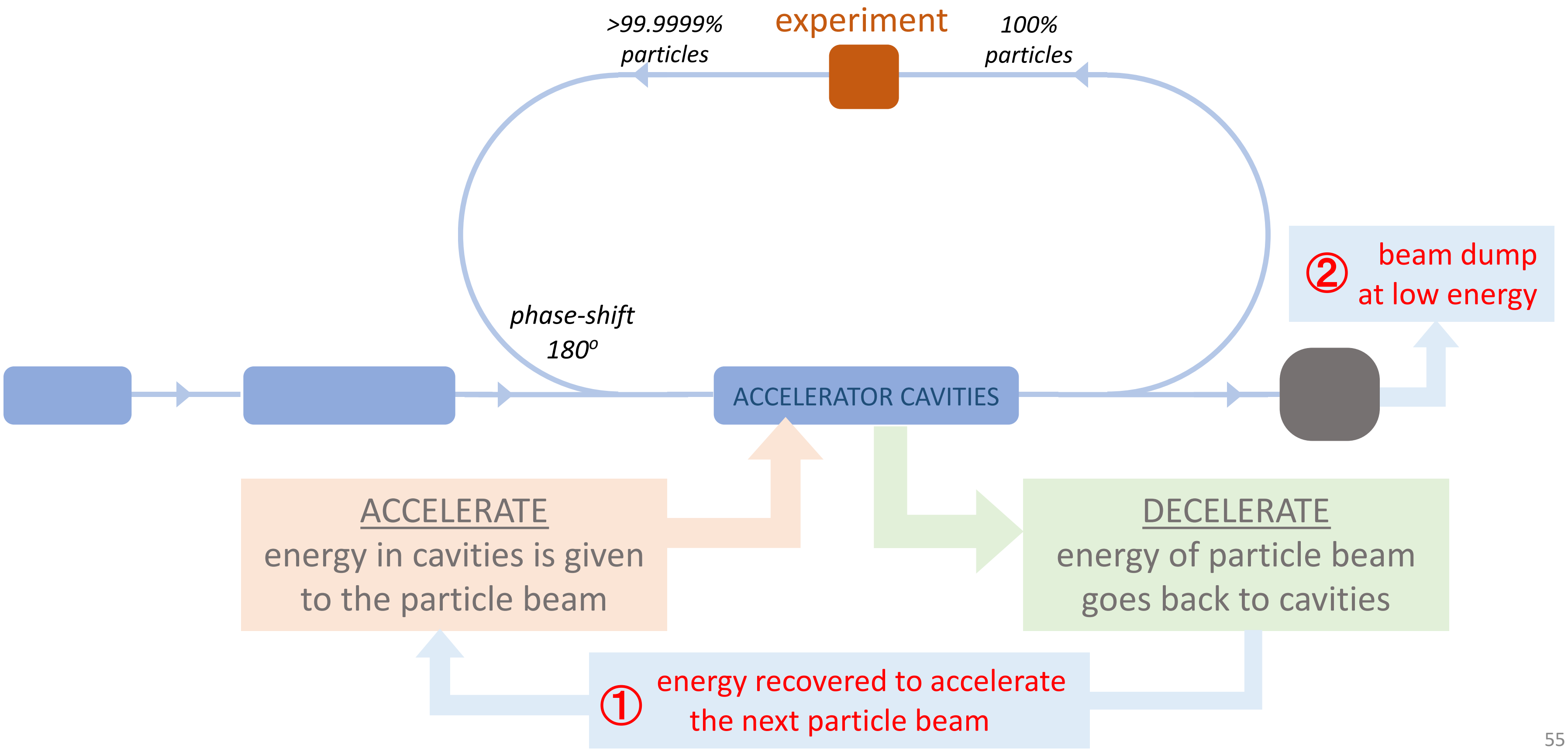

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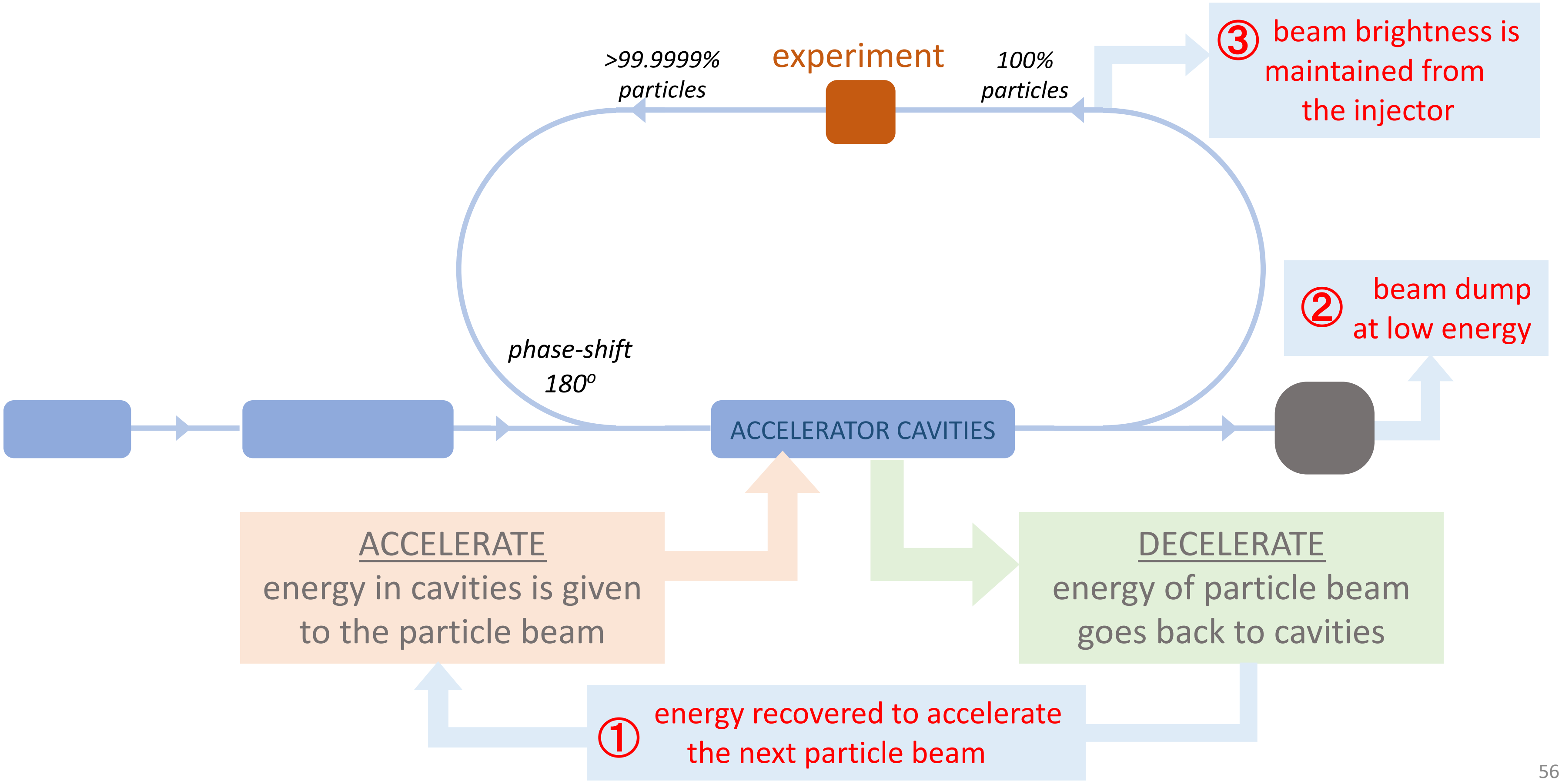

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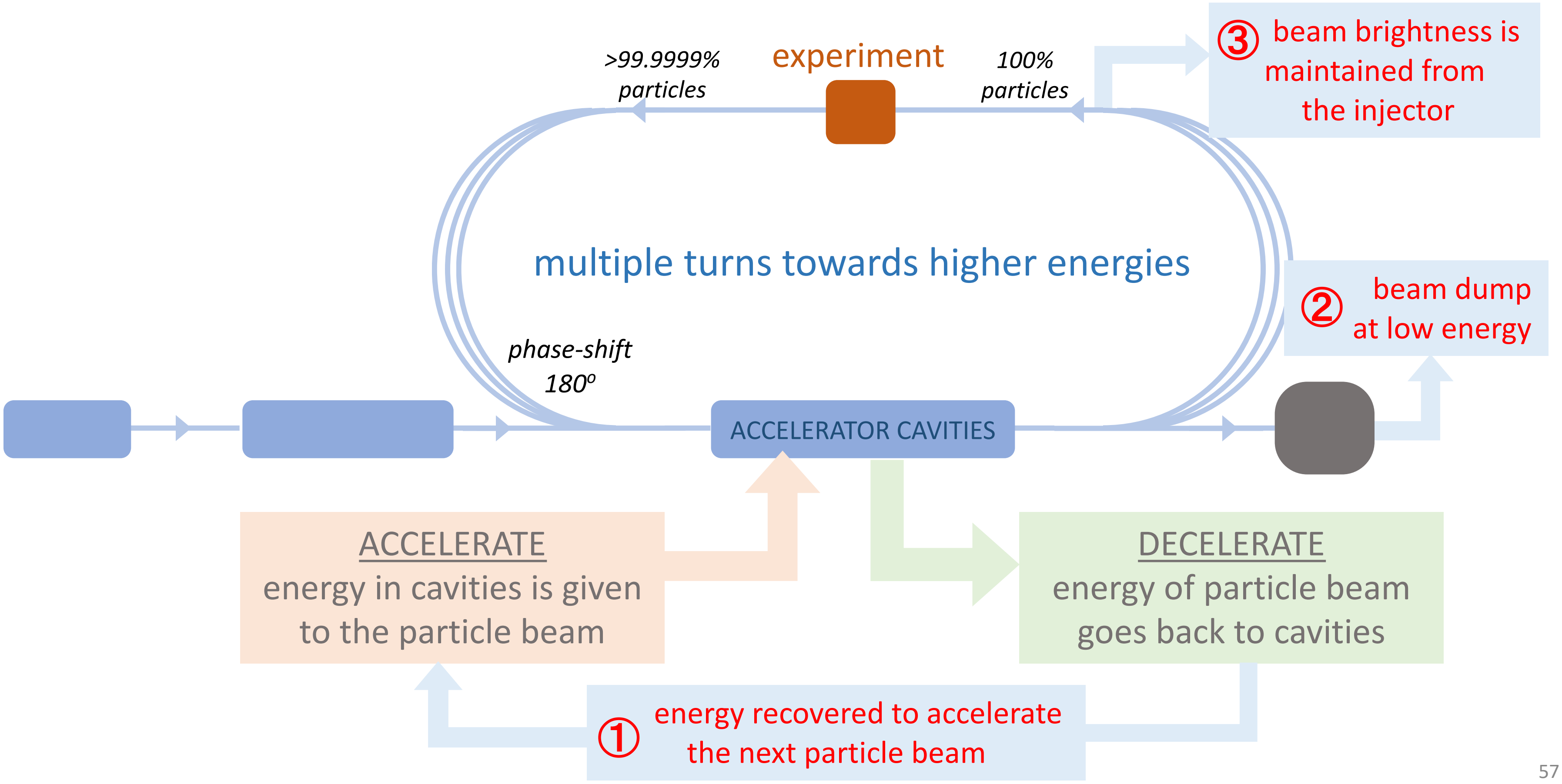
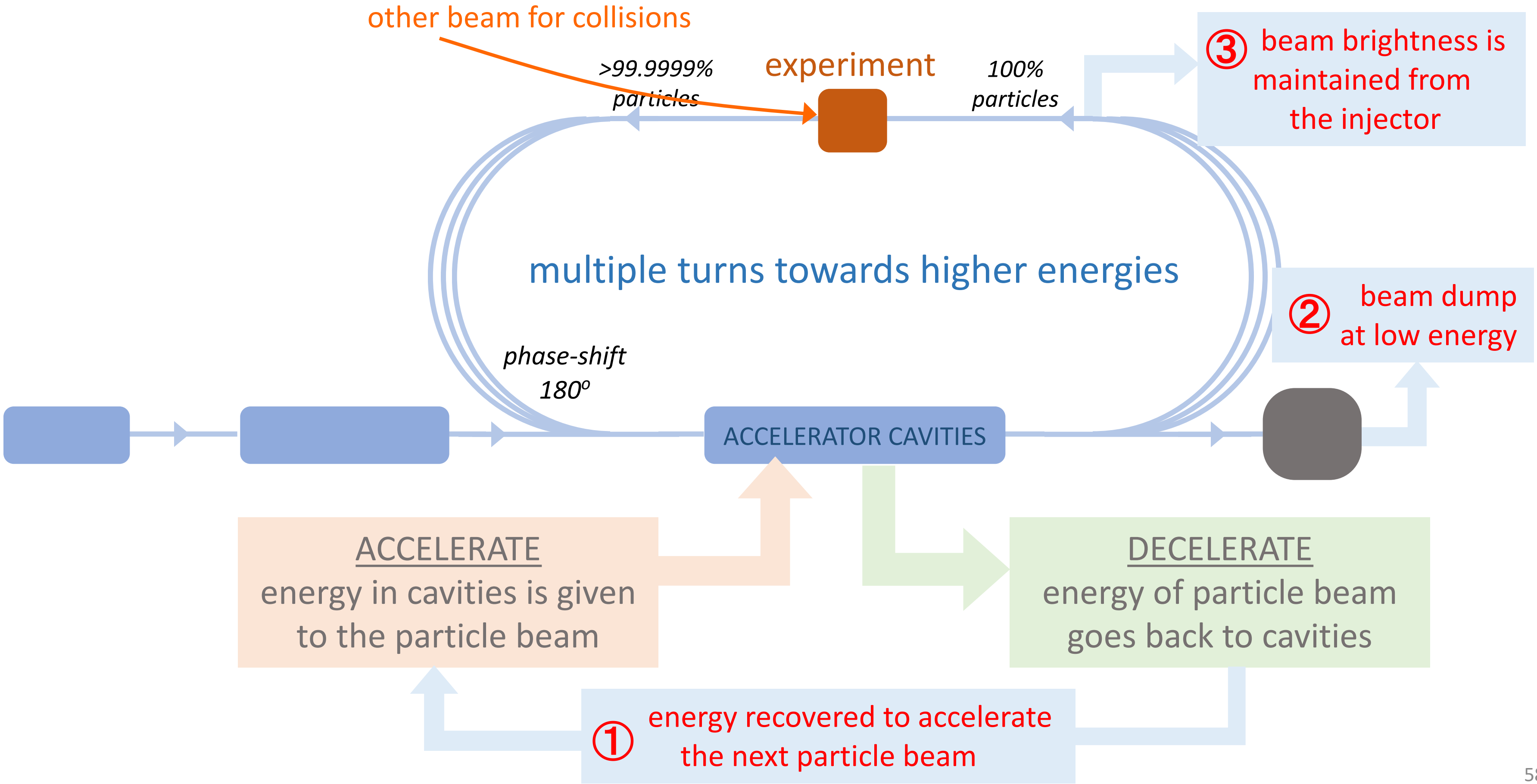
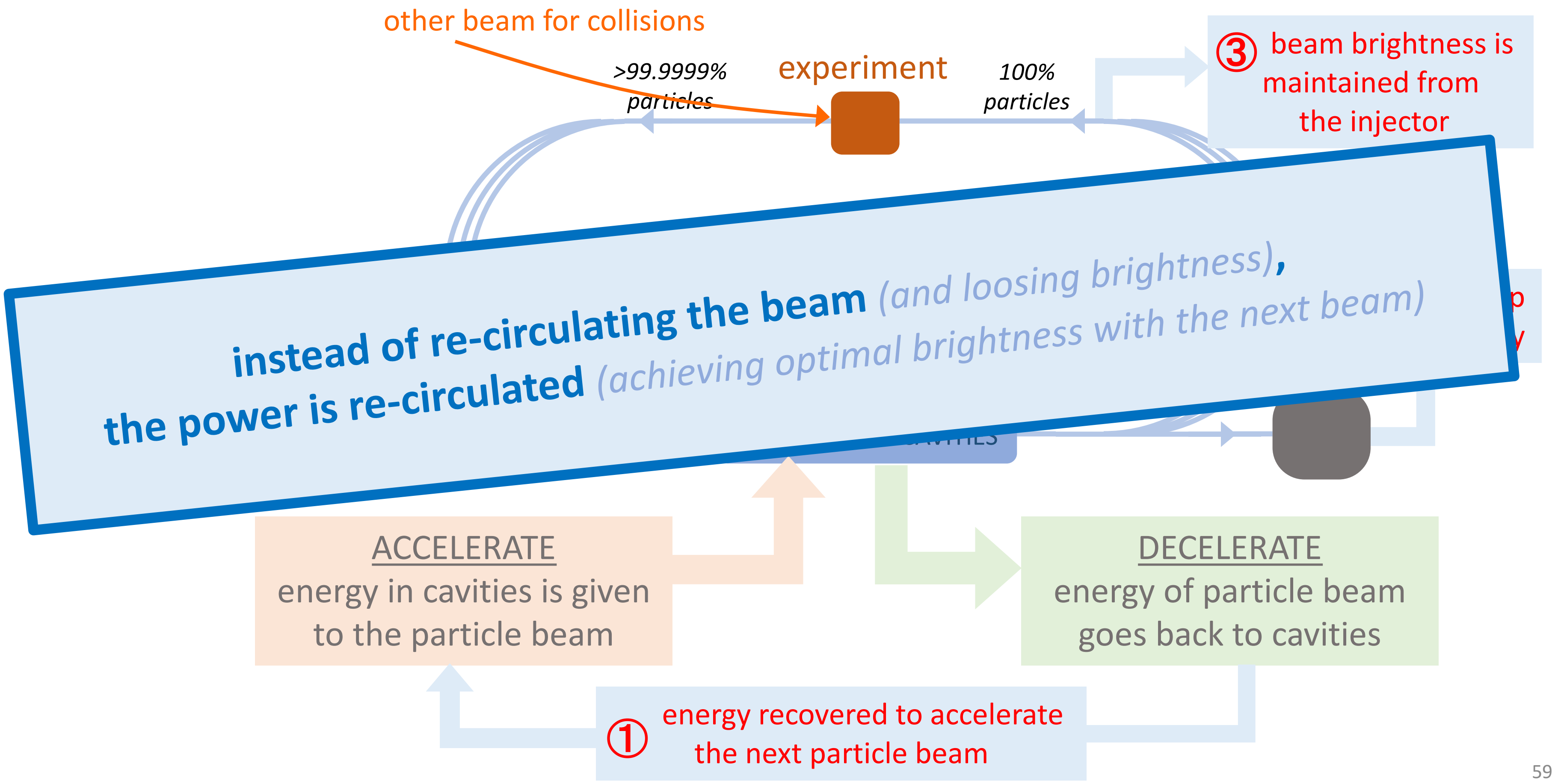


The principle of Energy Recovery

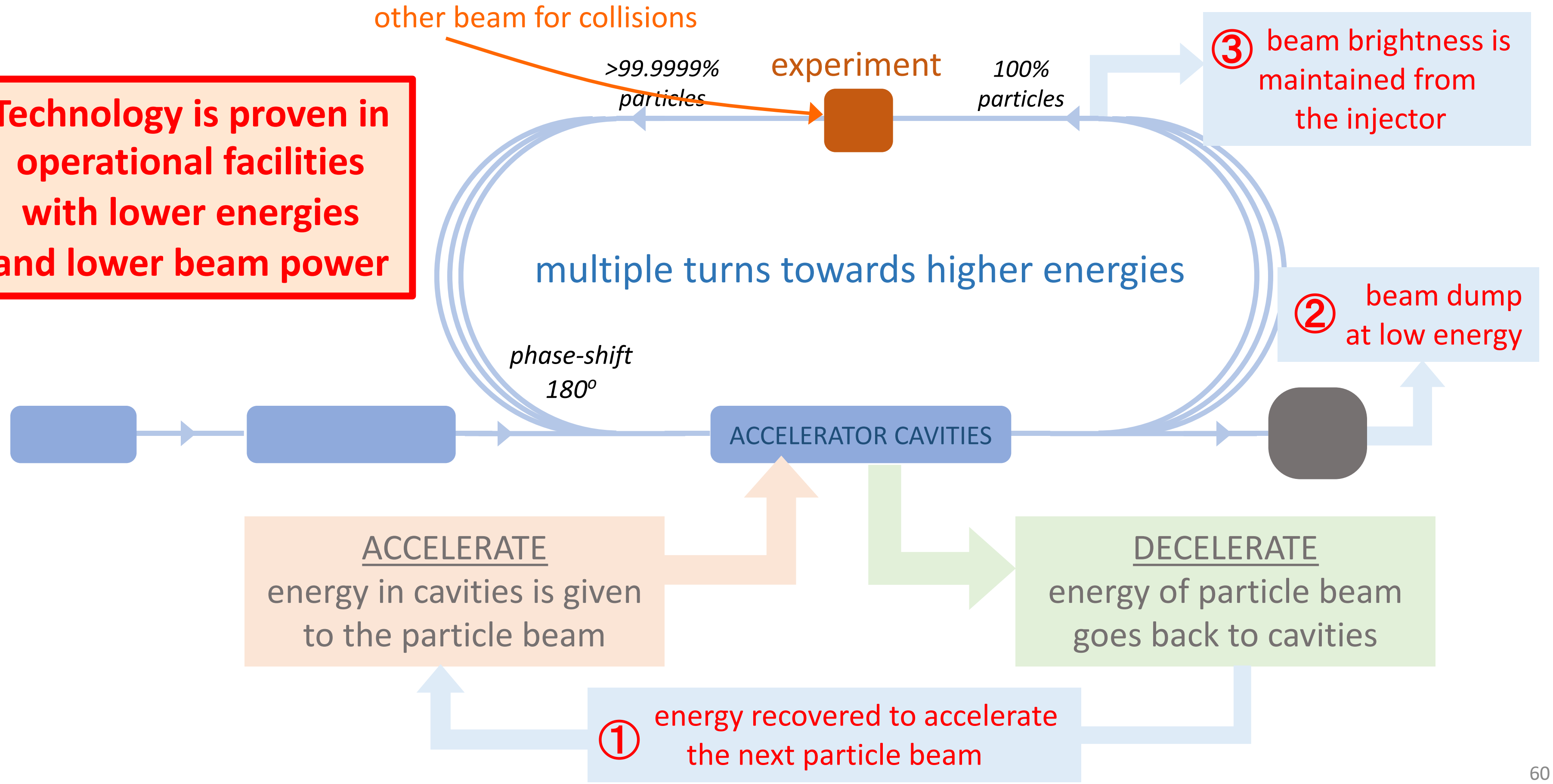


The principle of Energy Recovery



The principle of Energy Recovery

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



Ongoing & Upcoming facilities with ERL systems

worldwide several facilities are operational or are emerging

ongoing

s-DALINAC *TU Darmstadt, Germany*

two pass operation in progress

ongoing

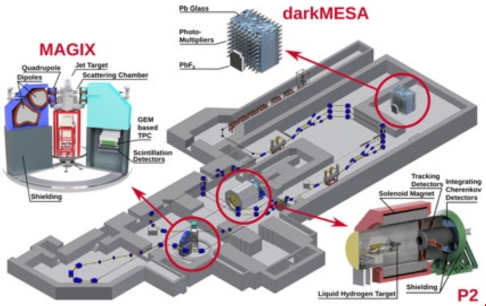
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

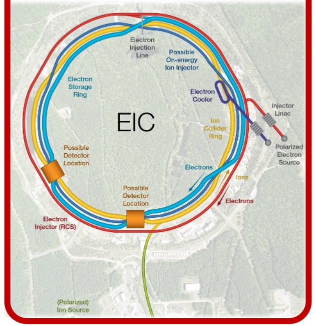
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

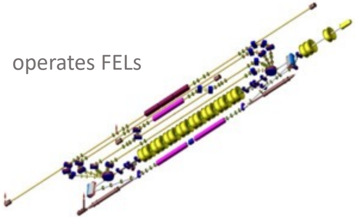
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

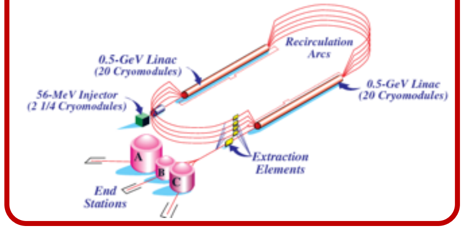
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes



in progress

Upcoming: bERLinPro & PERLE

More facilities in design

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

European Accelerator R&D Roadmap

for particle physics

ERL one of five impactful avenues for Accelerator R&D

CERN Yellow Rep. Monogr. 1 (2022) 1-270 and *arXiv:2201.07895*

Extensive ERL report: arXiv:2207.02095

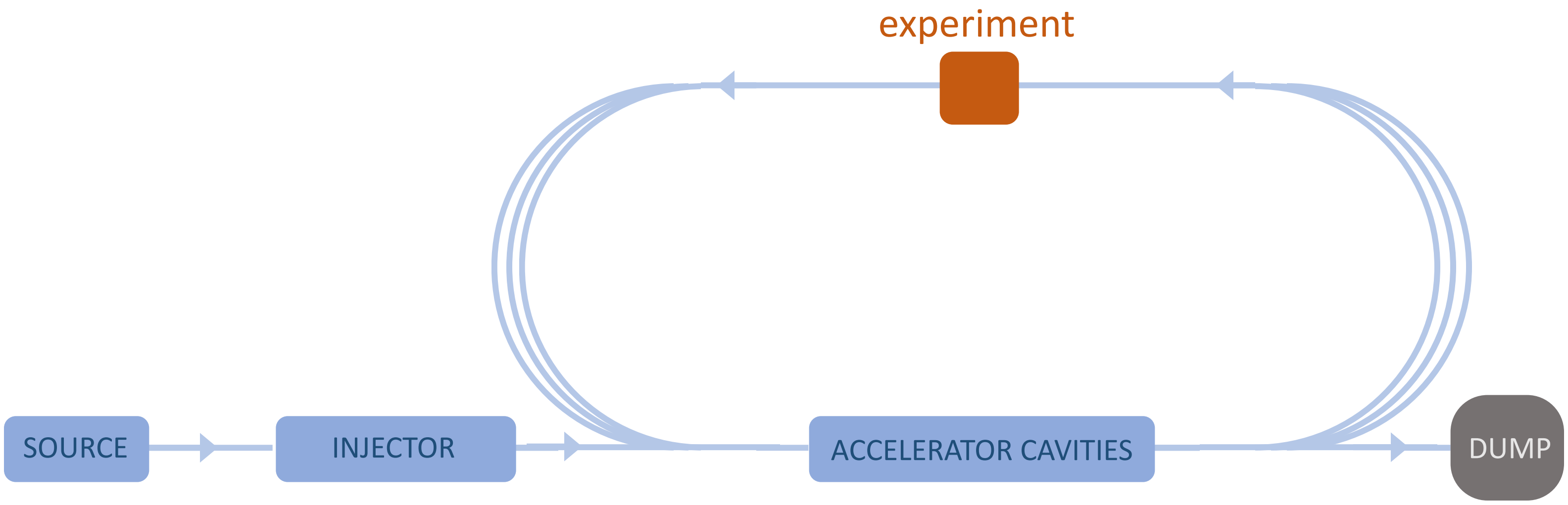
First Community Report of the implementation of the Accelerator R&D Roadmap

Frascati, 12-13 July

https://agenda.infn.it/event/35579/

Identified the key aspects for an Energy Recovery accelerator

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



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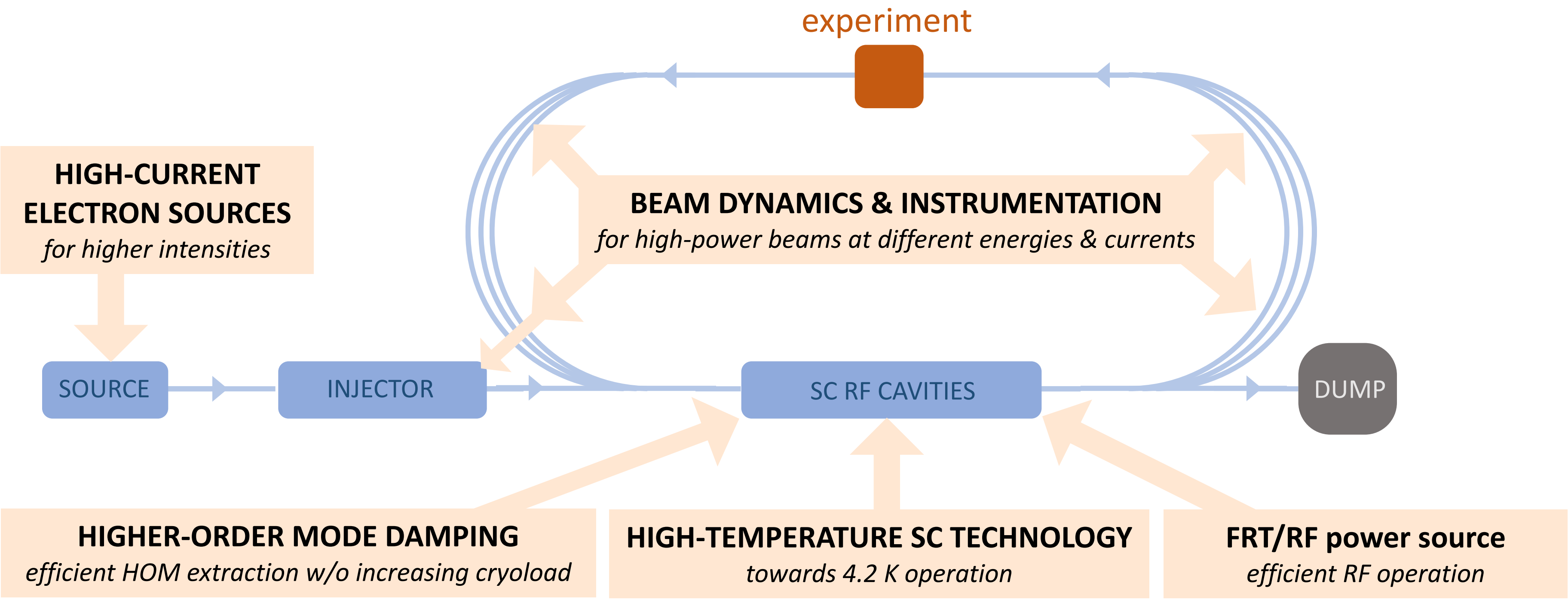


Translated into the main R&D objectives for Energy Recovery

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

HIGH-CURRENT e⁻ SOURCES

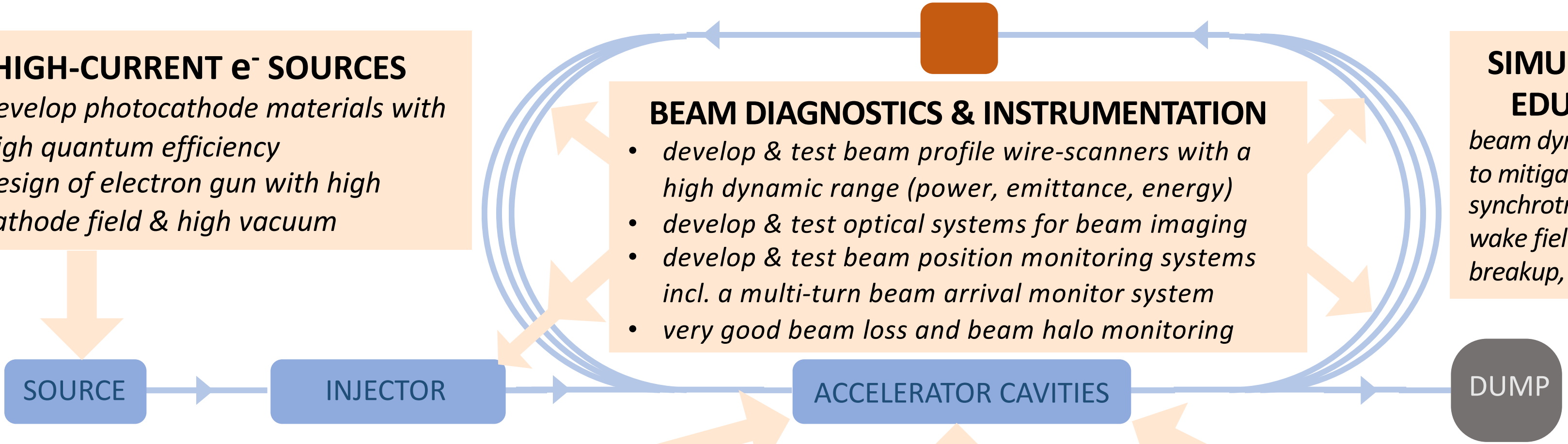
- *develop photocathode materials with high quantum efficiency*
- *design of electron gun with high cathode field & high vacuum*

BEAM DIAGNOSTICS & INSTRUMENTATION

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

SIMULATION & EDUCATION

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



HIGHER-ORDER MODE DAMPING

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

HIGH-POWER SRF TECHNOLOGY

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

strategic

DUAL AXIS CAVITIES

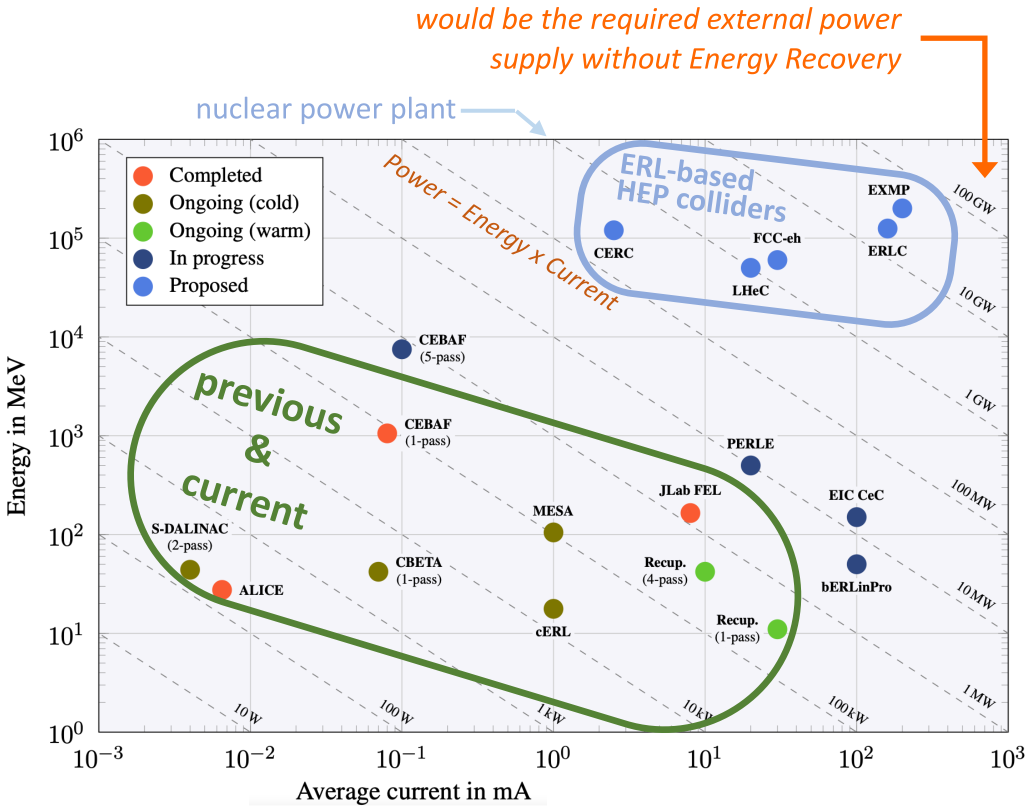
- *advance both options: single cavity with two beam tubes and two cavities joined by a power bridge*
- *packing the cavity in cryomodule*
- *connecting dual axis cryomodules*
- *integrate HOM couplers in design*

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

(*) part of the RF R&D program

Energy Recovery – 50 years of innovation

from previous to current and future facilities as stepping stones for R&D



Energy Recovery

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

Energy Recovery – 50 years of innovation

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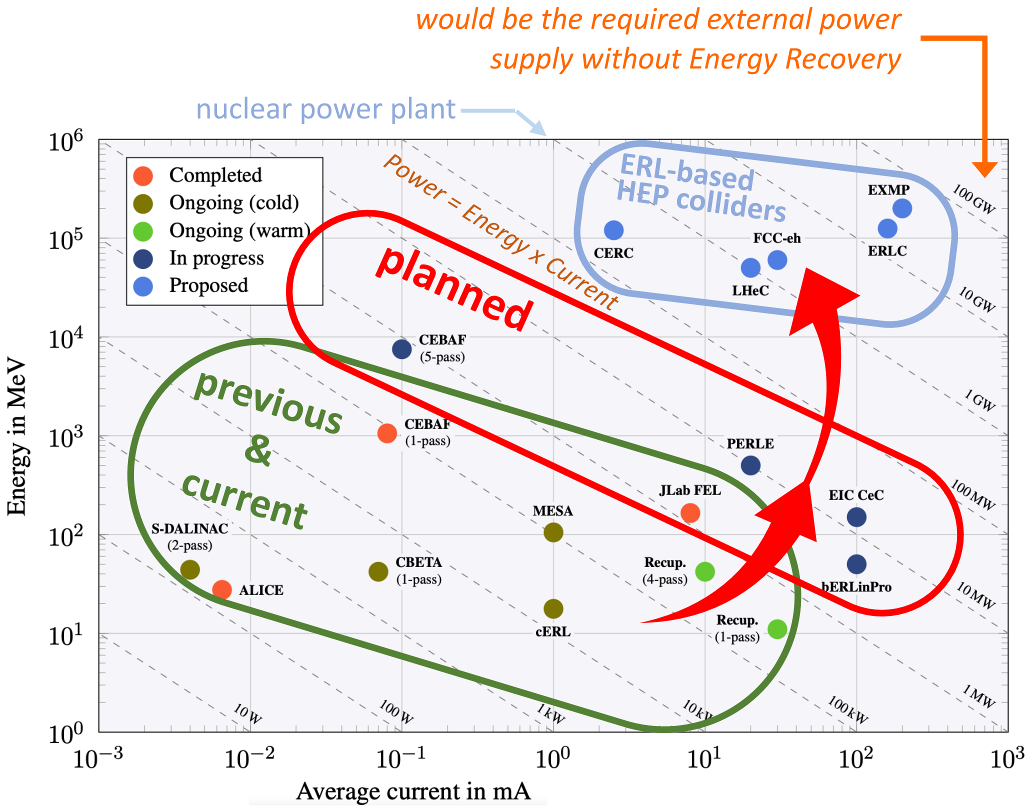

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bERLinPro & PERLE

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

towards high energy & high power

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

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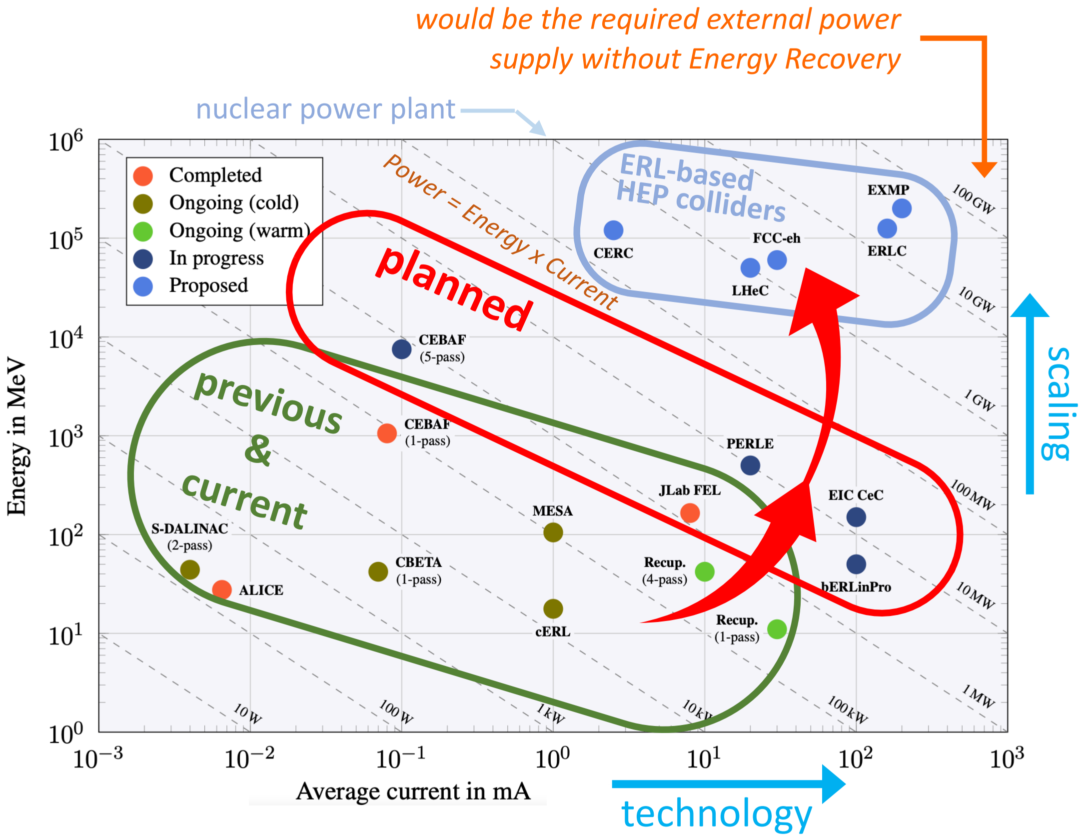

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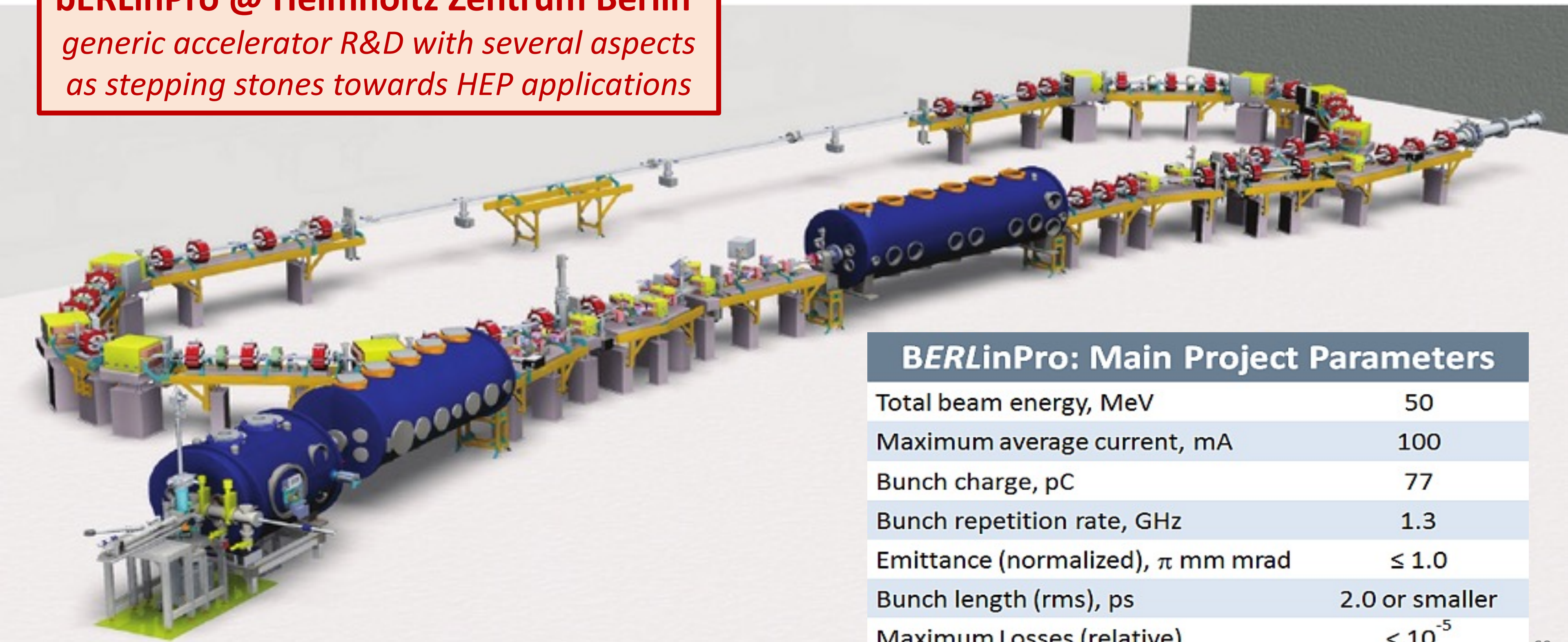
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

bERLinPro @ Helmholtz Zentrum Berlin

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



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

bERLinPro – Berlin Energy Recovery Linac Project

Upcoming facilities for Energy Recovery R&D

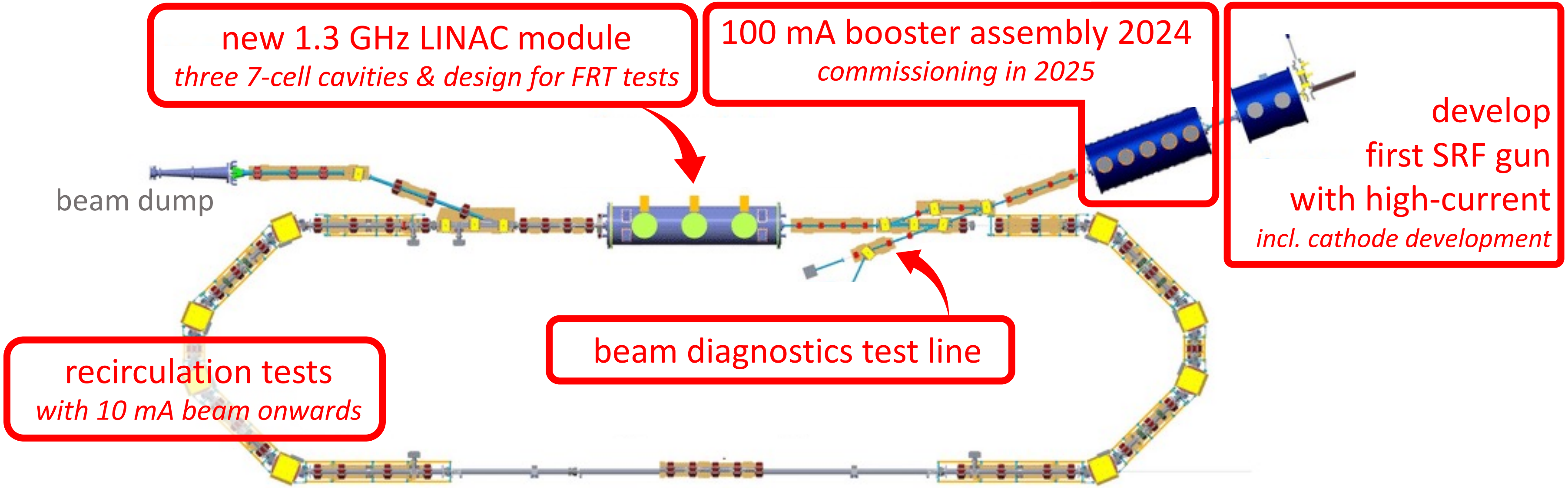
complementary in addressing the R&D objectives for Energy Recovery

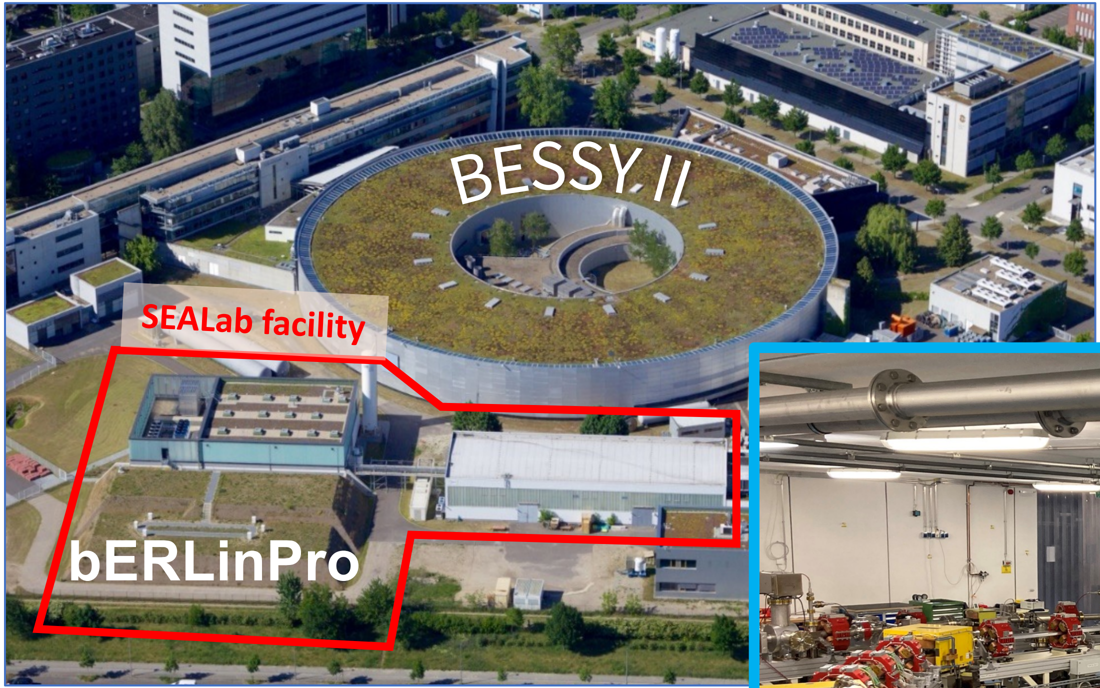
bERLinPro @ Helmholtz Zentrum Berlin

addressing HEP related challenges

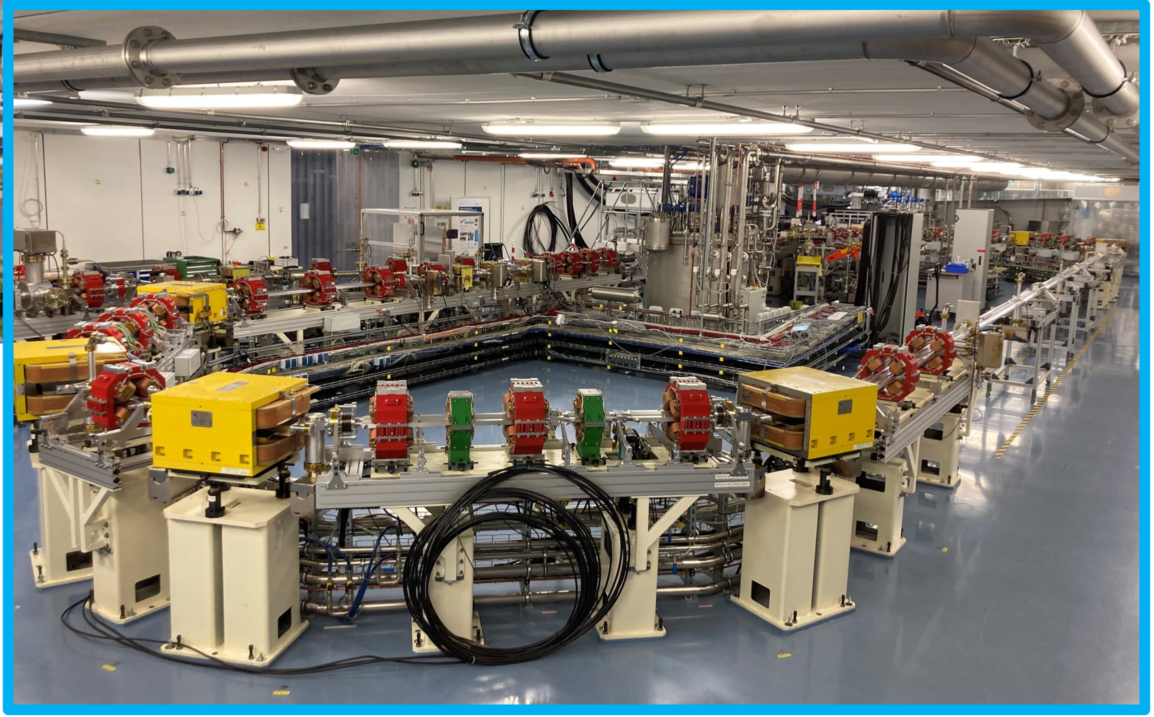
bERLinPro ready for operation at 10 mA

contingent on additional budgets upgrades to 100 mA and ERL at 50 MeV can be planned to be operational by 2028





First beam of bERLinPro@SEALab to be expected in 2023



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

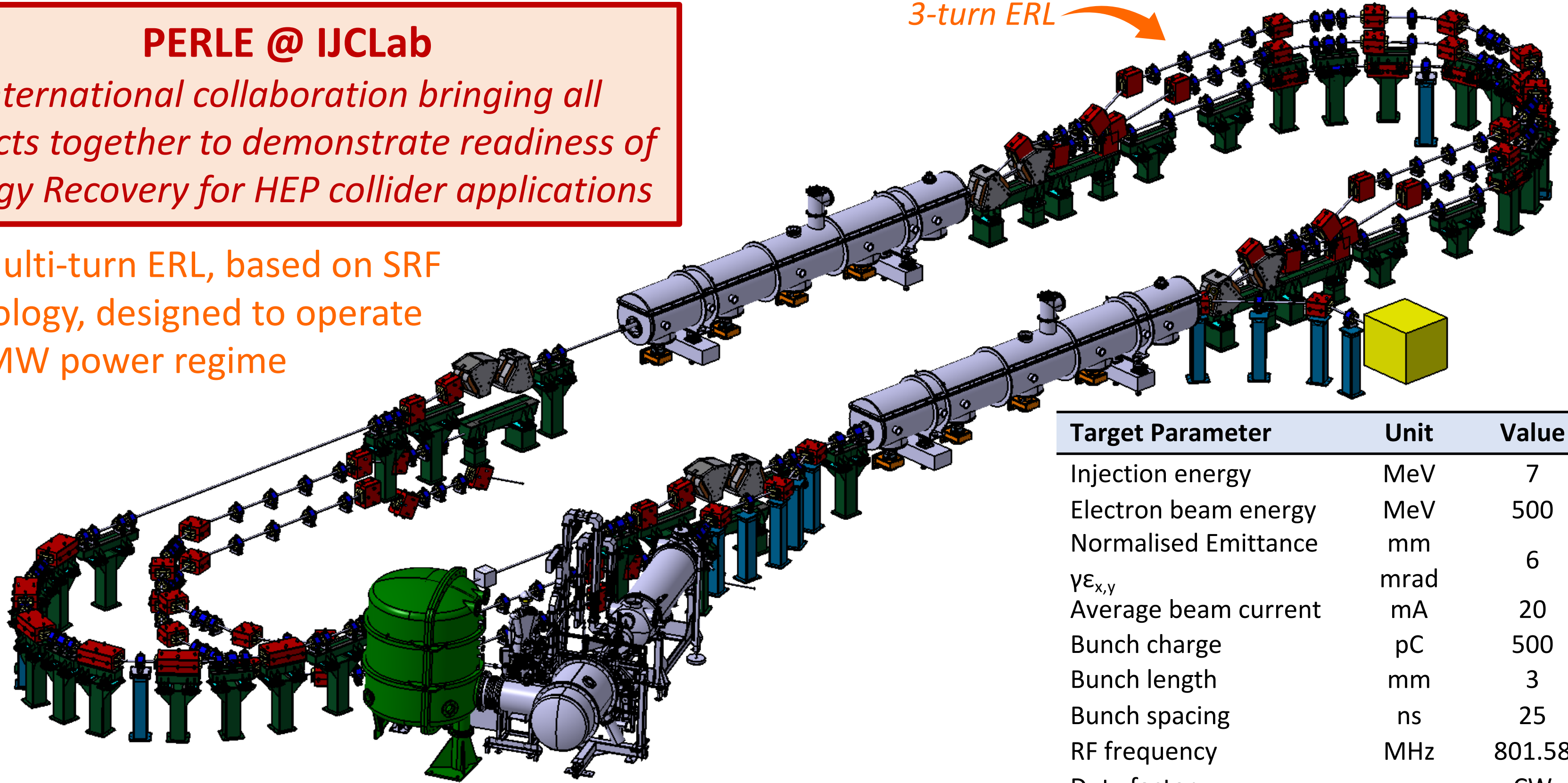
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

PERLE @ IJCLab

international collaboration bringing all aspects together to demonstrate readiness of Energy Recovery for HEP collider applications

first multi-turn ERL, based on SRF technology, designed to operate at 10MW power regime



Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

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

Technology synergies emerge between the R&D for ERL at PERLE and bERLinPro and the ambition for high-performant e^+e^- Higgs Factories

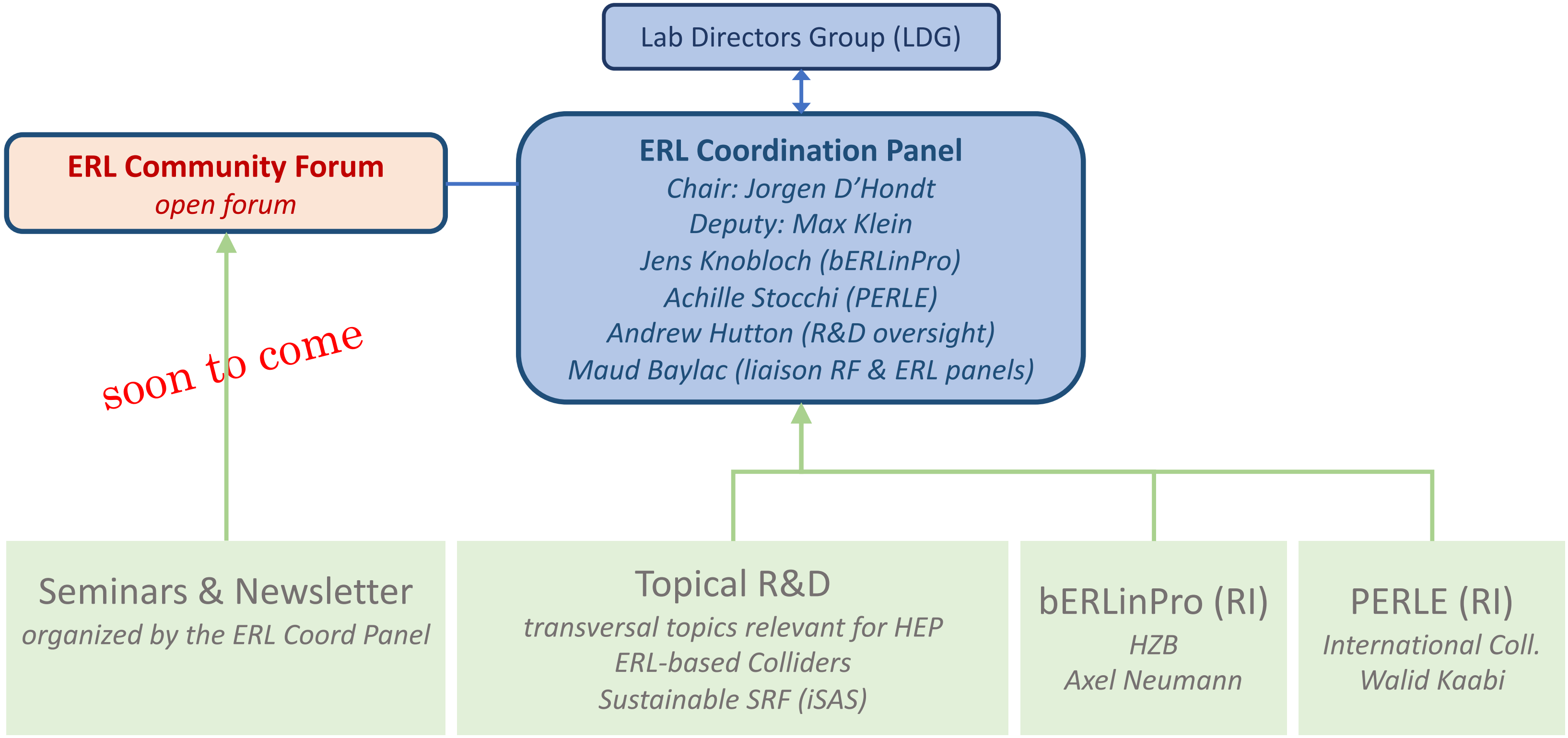
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

Organising the European R&D for Energy Recovery in HEP

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



RI: Research Infrastructure

In addition, thoughts for ERL-based colliders:

Sustainable Accelerating Systems with Energy Recovery at future HEP colliders

example of Higgs Factories

Addressing with ERL the European Strategy for Particle Physics 2020

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

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

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European Strategy for Particle Physics 2020

ERL

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

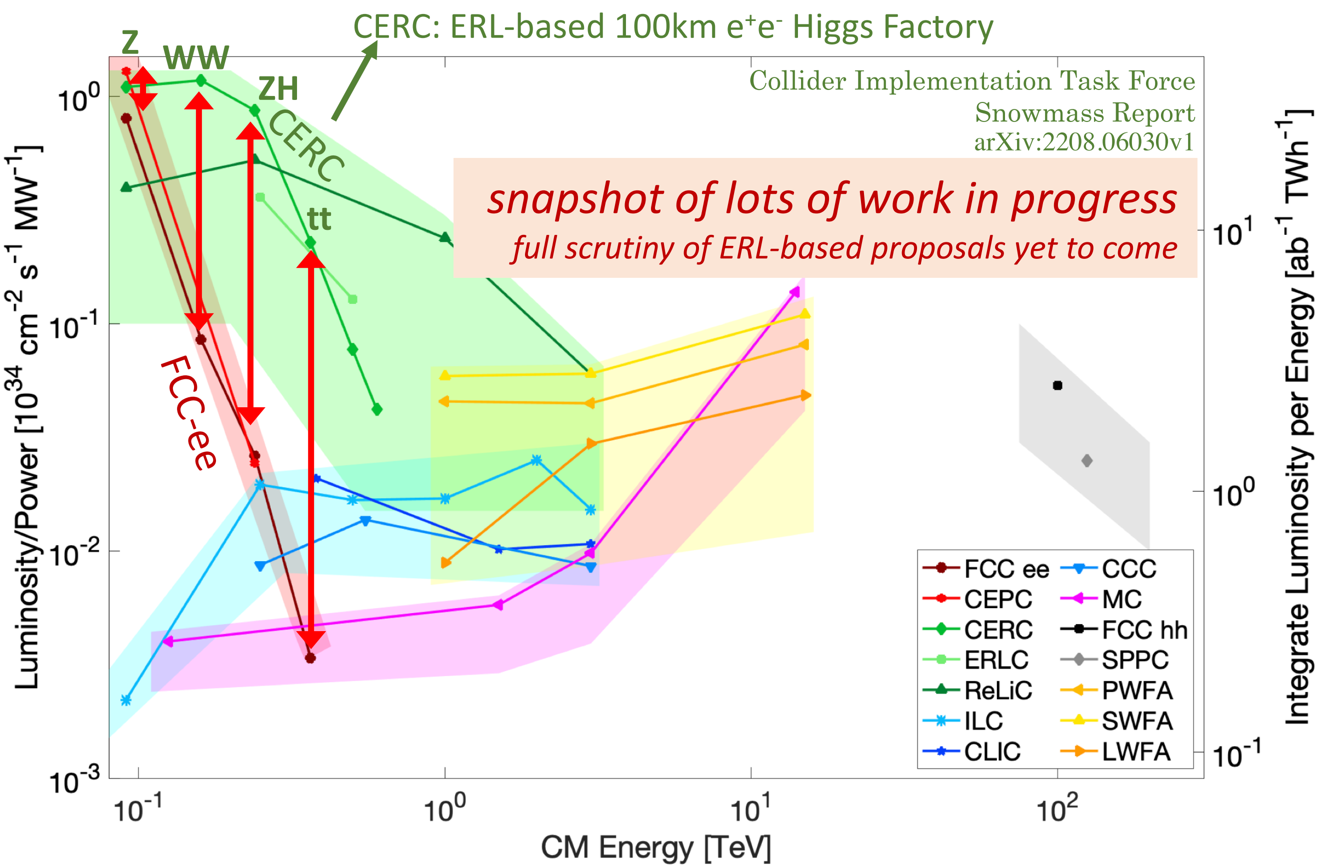
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

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



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

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

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next slide: what would be the concrete impact

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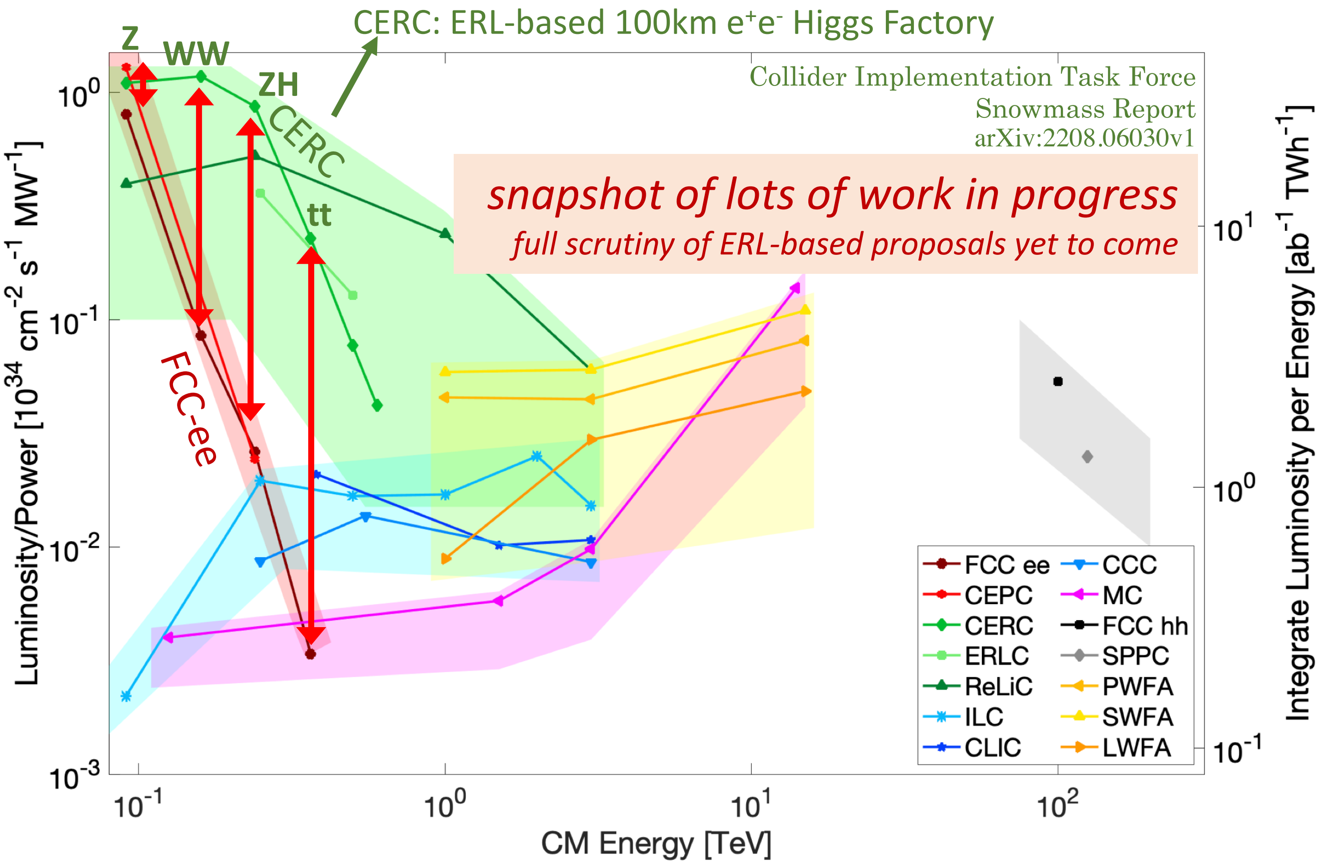


Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Energy Recovery applications for HE[...]

invest today an additional R&D budget to avoid a 100x larger spending on electricity bills

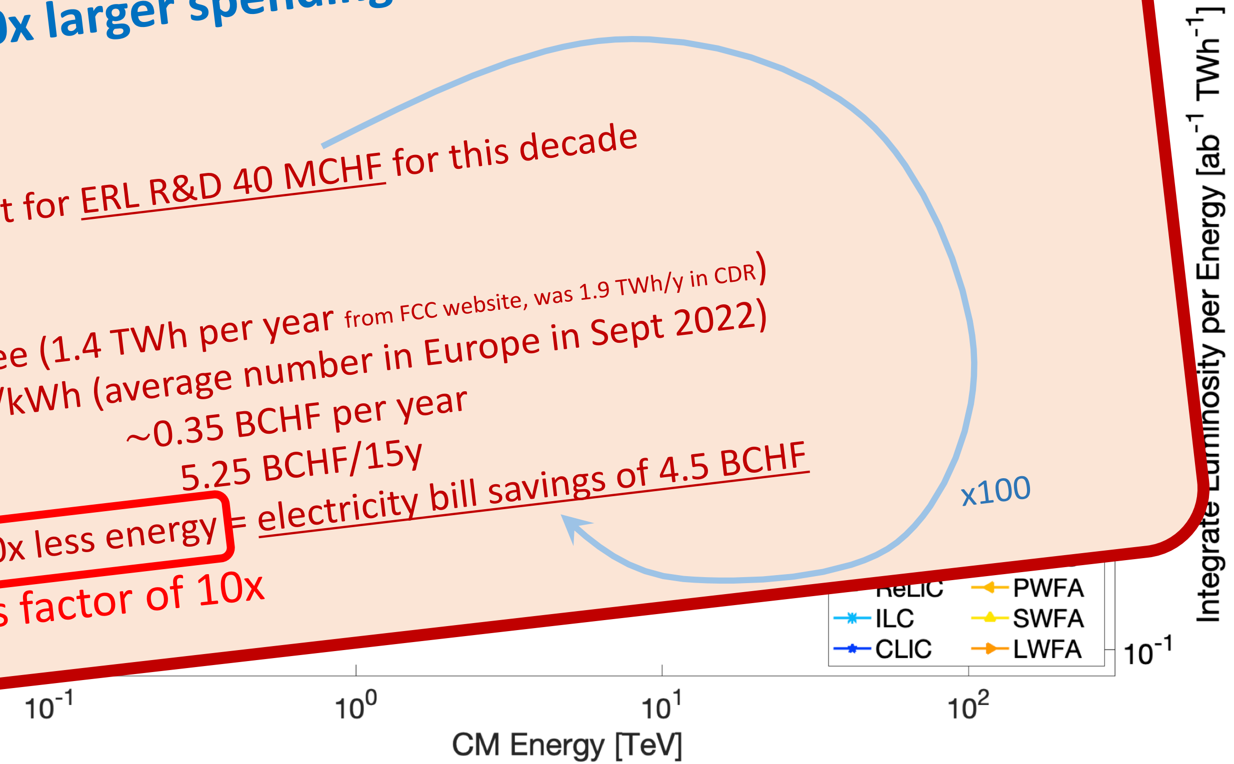
budget for ERL R&D 40 MCHF for this decade

15y of FCC-ee (1.4 TWh per year from FCC website, was 1.9 TWh/y in CDR)
~0.25 EUR/kWh (average number in Europe in Sept 2022)
~0.35 BCHF per year
5.25 BCHF/15y

With ERL 10x less energy = electricity bill savings of 4.5 BCHF

the previous factor of 10x

x100



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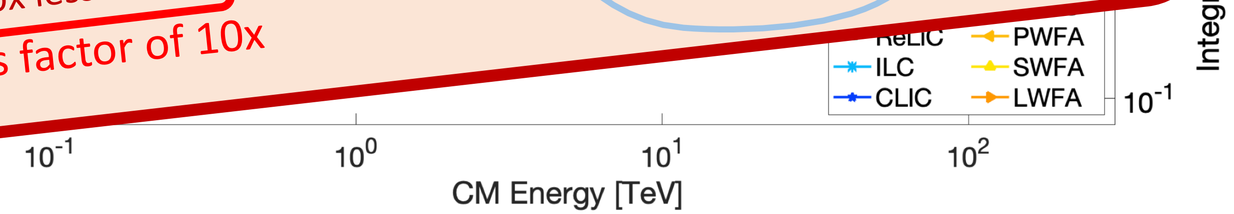
x100

the previous factor of 10x

even with only a factor of 2x
the impact is huge, >2.5 BCHF



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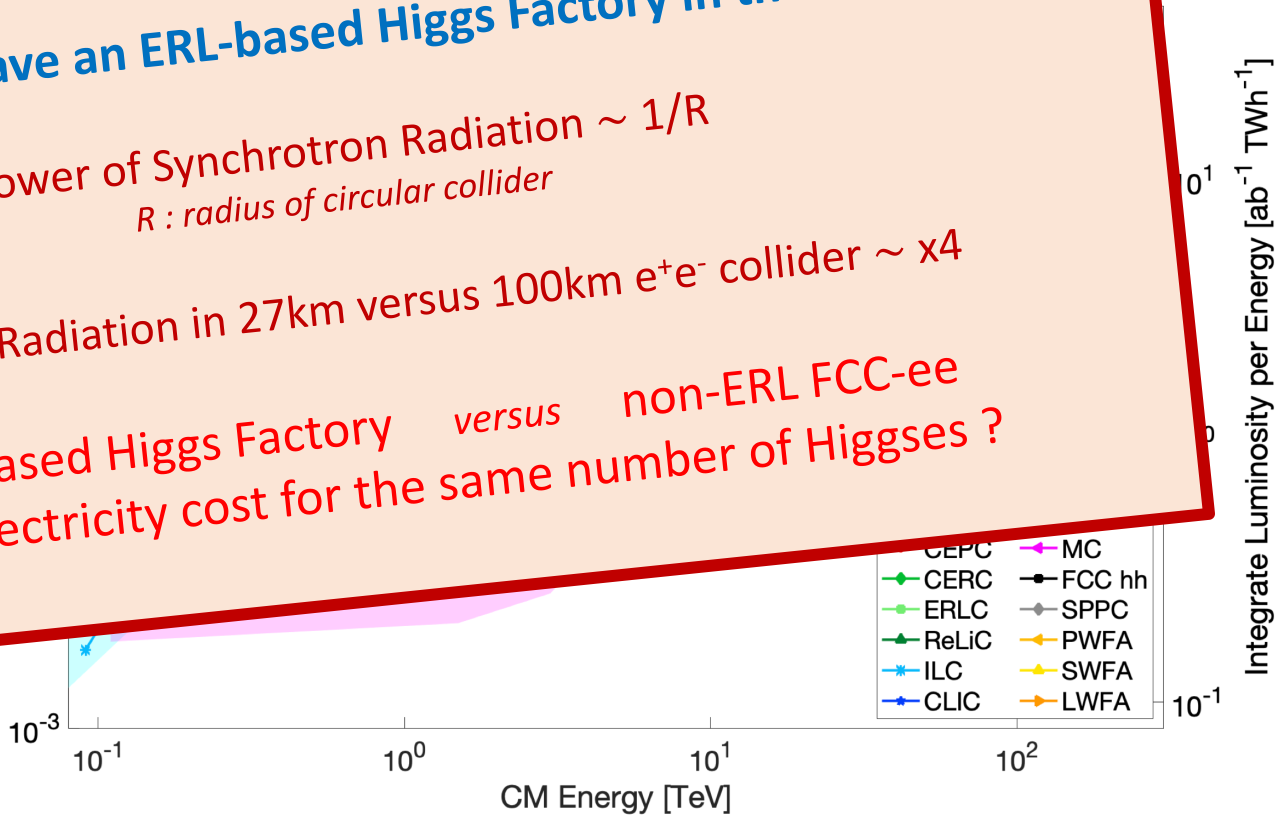
Energy Recovery applications for HEP

This

an

Fac

x10



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

the same electricity cost for the same number of Higgses ?

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

Energy Recovery applications for HEP

This an Fac

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

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R : radius of circular collider

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

Higgs Factory *versus* non-ERL FCC-ee

...er of Higgses ?

10^1

10^0

...osity per Energy [ab^{-1} TWh^{-1}]

Several aspects are to be verified in these initial thoughts, but it demonstrates the potential impact of ERL, and motivates R&D support for ERL and sustainable accelerating systems to further explore

Additional Energy Recovery applications for HEP

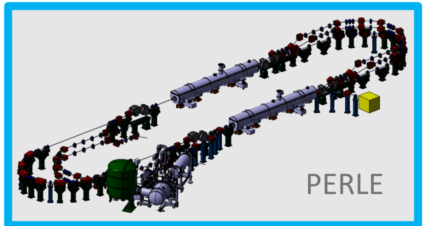
- Within a society that acts urgently on sustainability, additional thoughts for ERL-based colliders for particle physics are emerging
    - ERL-based e^+e^- colliders reaching 500 GeV to study directly the Higgs boson self-coupling (H→HH)
    - ERL-based muon colliders, e.g. EXMP *[Appl.Sciences 12 (2022) 6, 3149]*

There is no doubt that upon a demonstration of the technical capability of ERL enabling high-power beams, the portfolio of applications is large

Potential future of ERL technology

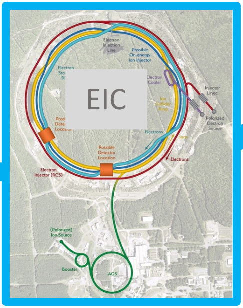
With stepping stones for innovations in technology
to boost our physics reach

2020'ies



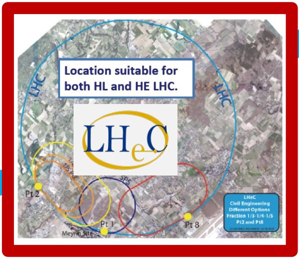
high-power ERL demonstrated

2030'ies



ERL application electron cooling

2030-2040'ies



1 ERL beam

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

2040-2050'ies

2 ERL beams

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

2070'ies

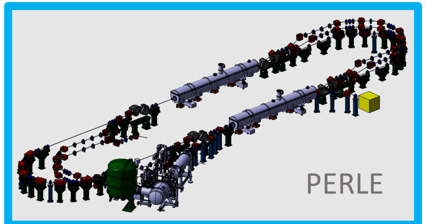
reuse ERL

Potential future of ERL technology

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

the ultimate upgrade of the LHC program

2020'ies



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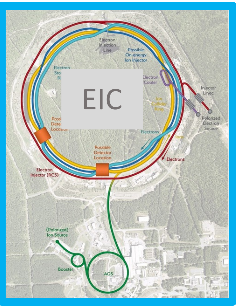
2030'ies



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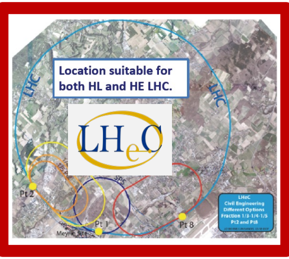

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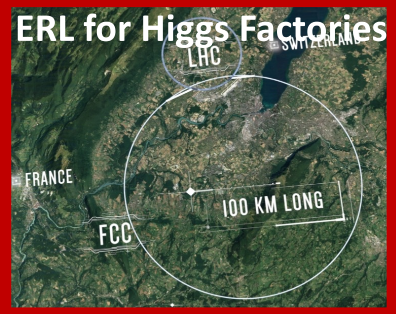

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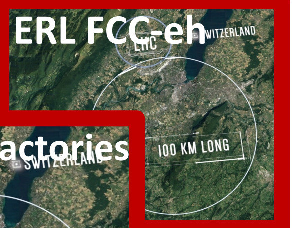

reuse ERL

next major colliders

High-power particle beams at the core of particle physics

- The high-energy electron-hadron programme at the LHC and FCC are truely general-purpose experiments reaching beyond current knowledge in QCD, Higgs, EW and top quark physics and with its own BSM discovery potential
- At the same time, these programmes empower the current research in ATLAS and CMS, and are vital to unlock the full physics potential of the FCC program
- The engine of our curiosity-driven exploration is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize: Energy Recovery Linac systems deliver on this technology front
- A demonstration of the capability of high-power ERL will enable a portfolio of impactful applications in particle physics and industry

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VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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Thank you for your attention!

Jorgen.DHondt@vub.be

From HERA onwards to high-energy proton beams

	HERA	EIC	LHeC	FCC-eh
Host site	DESY	BNL	CERN	CERN
Layout	ring-ring	ring-ring	ERL linac-ring	ERL linac-ring
Circumference hadron/lepton (km)	6.3/6.3	3.8/3.8	26.7/[5.3–8.9]	100/[5.3–8.9]
Number of IRs/IPs	4/2	6/1–2	1	1
Max. CM energy (TeV)	0.32	0.14	1.2	3.5
Crossing angle (mrad)	0	22	0	0
Max. peak luminosity (cm^{-2} s^{-1})	5×10^{31}	1×10^{34}	2.3×10^{34}	1.5×10^{34}
Lepton	Electrons, positrons polarized	Electrons polarized	Electrons unpolarized	Electrons unpolarized
Max. average current (A)	0.058	2.5	0.02	0.02
Max. SR power (MW)	7.2	10	45	45
Main RF frequency (MHz)	500	591	802	802
No. main RF cavities/cryomodules	28	17–18/9–18	448/112	448/112
No. crab RF cavities	–	2	–	–
Hadron	Protons unpolarized	Protons polarized	Protons unpolarized	Protons unpolarized
Max. average current (A)	0.163	1.0	1.1	1.1
Main RF frequency (MHz)	208	591	400	400
No. crab RF cavities/cryomodules	–	12/6	8/4	8/4
No. ERL RF cavities	–	13	–	–

Front. Phys. 10 (2022) 886473