The ep/eA@CERN Study enabled by Energy Recovery Linacs (ERL)

Jorgen D'Hondt
Vrije Universiteit Brussel

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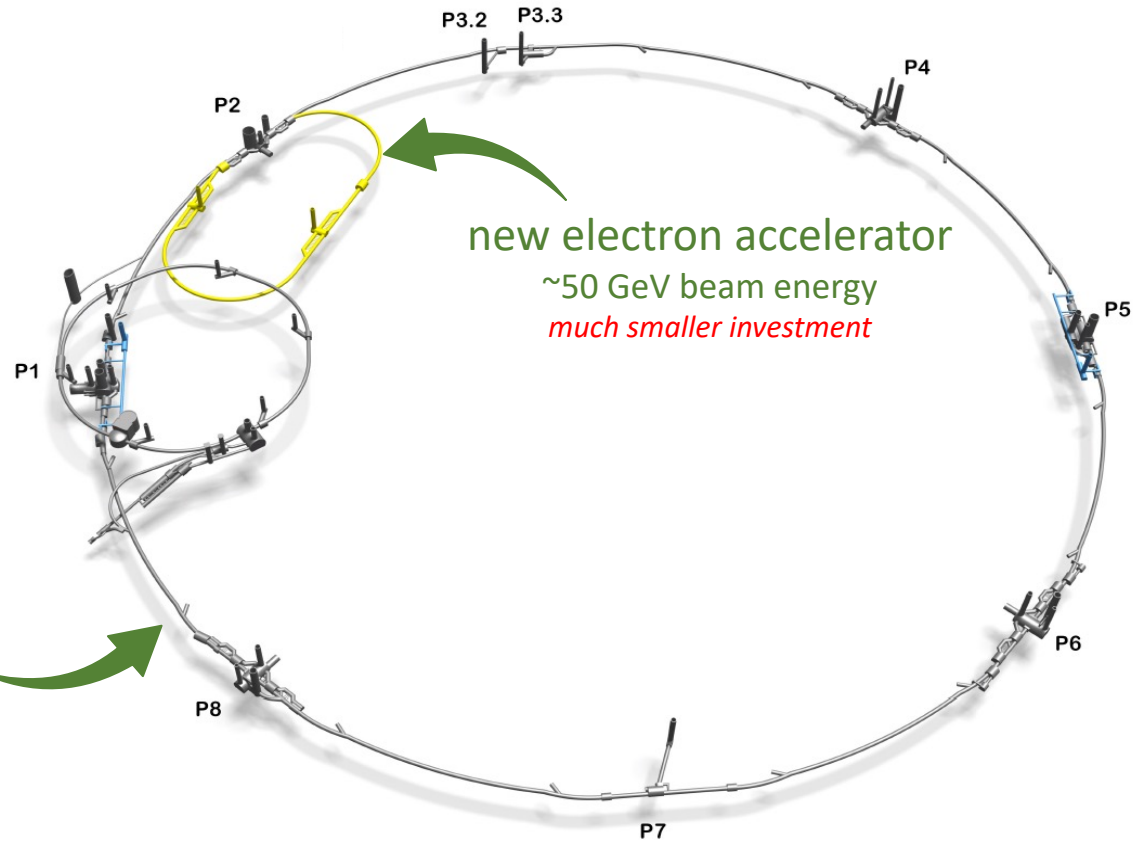
iihe BRUXELLES BRUSSEL

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

ep/eA versus pp/pA/AA synergy workshop, CERN
February 29 and March 1, 2024

high-energy & high-luminosity electron-proton collisions



new electron accelerator

~50 GeV beam energy

much smaller investment

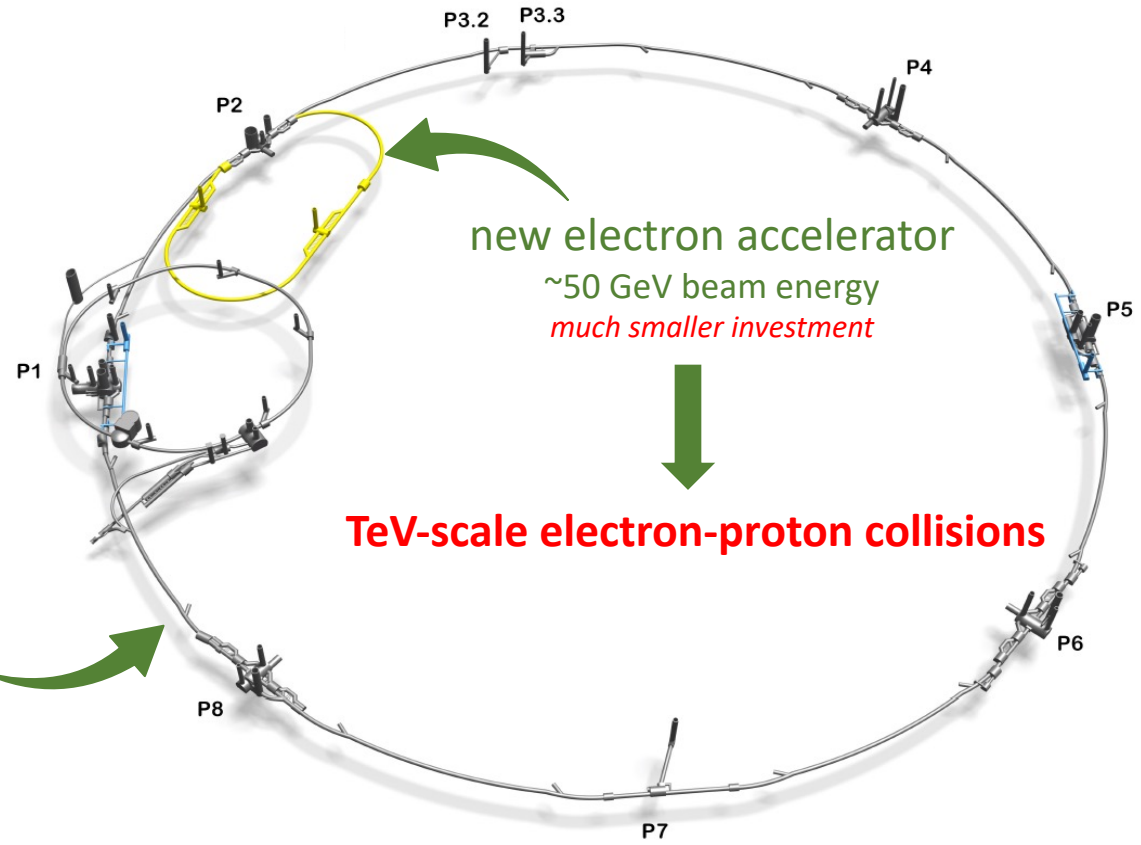
existing/future proton accelerator

LHC and/or FCC

(LHeC and/or FCC-eh)

major investment

high-energy & high-luminosity electron-proton collisions



new electron accelerator

~50 GeV beam energy

much smaller investment

TeV-scale electron-proton collisions

existing/future proton accelerator

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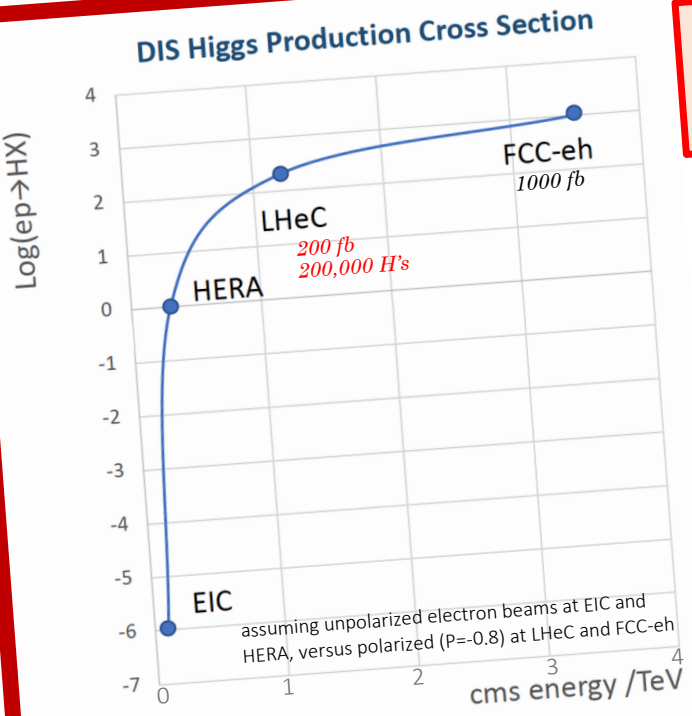
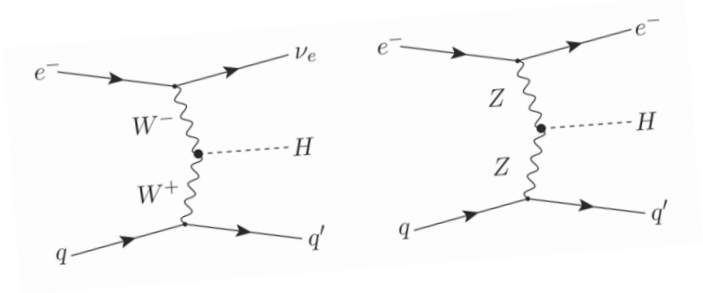
high-energy & high-luminosity electron-proton collisions



These electron-proton collisions enable a general-purpose experiment



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

major investment

P7

The ep/eA programs: at current & future hadron colliders

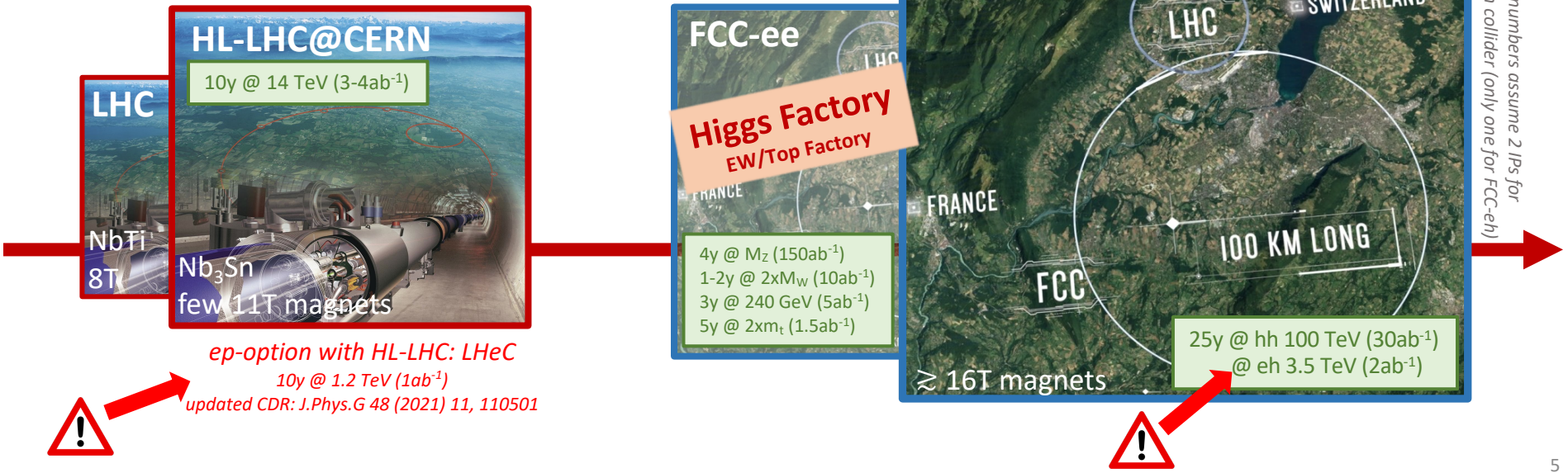
Current flagship (27km)

impressive programme up to ~2042

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2048

attractive combination of precision & energy frontier



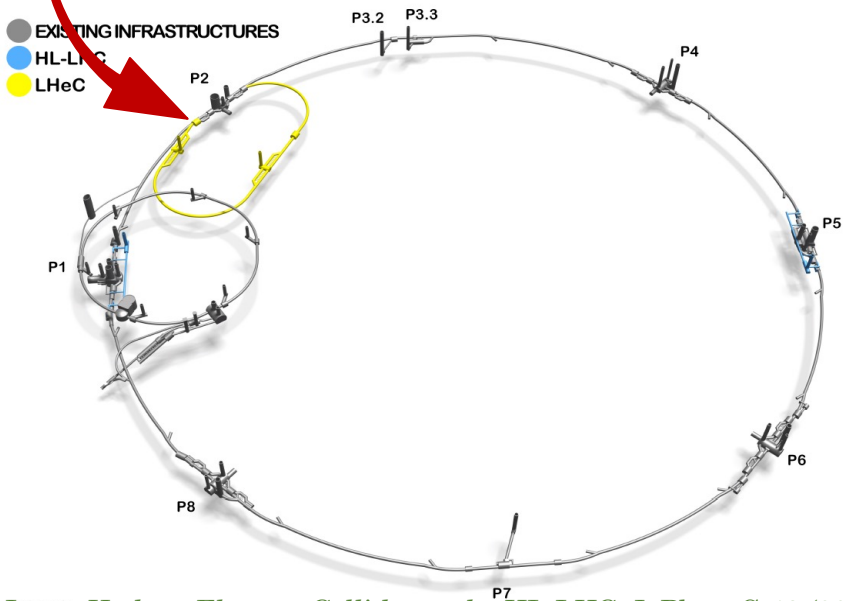
ep-option with HL-LHC: LHeC

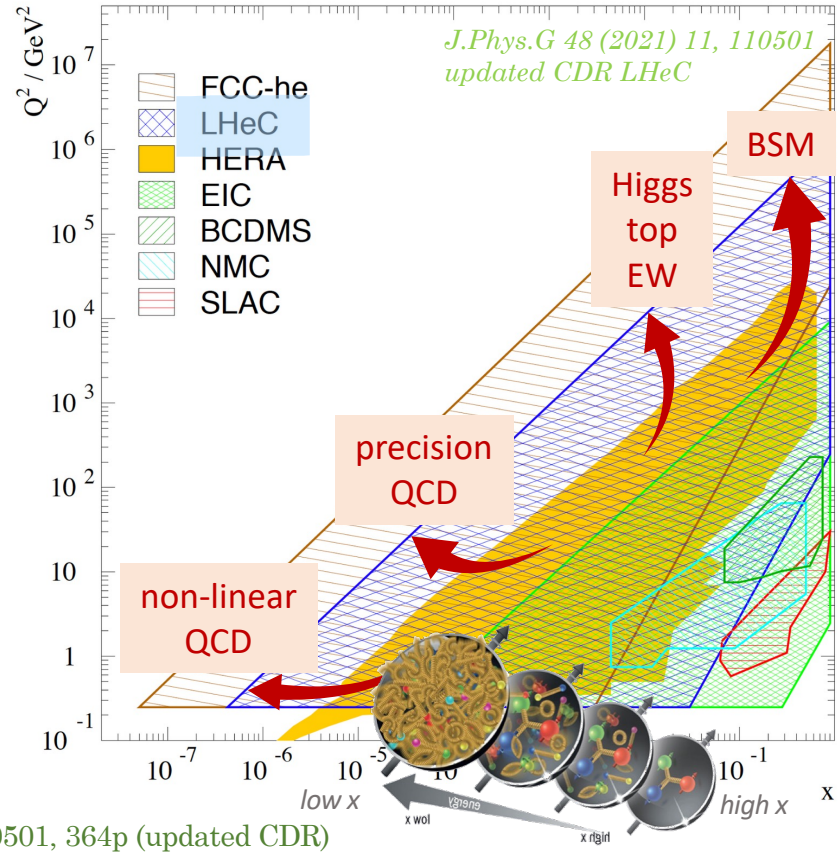
10y @ 1.2 TeV (1ab^{-1})

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

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)

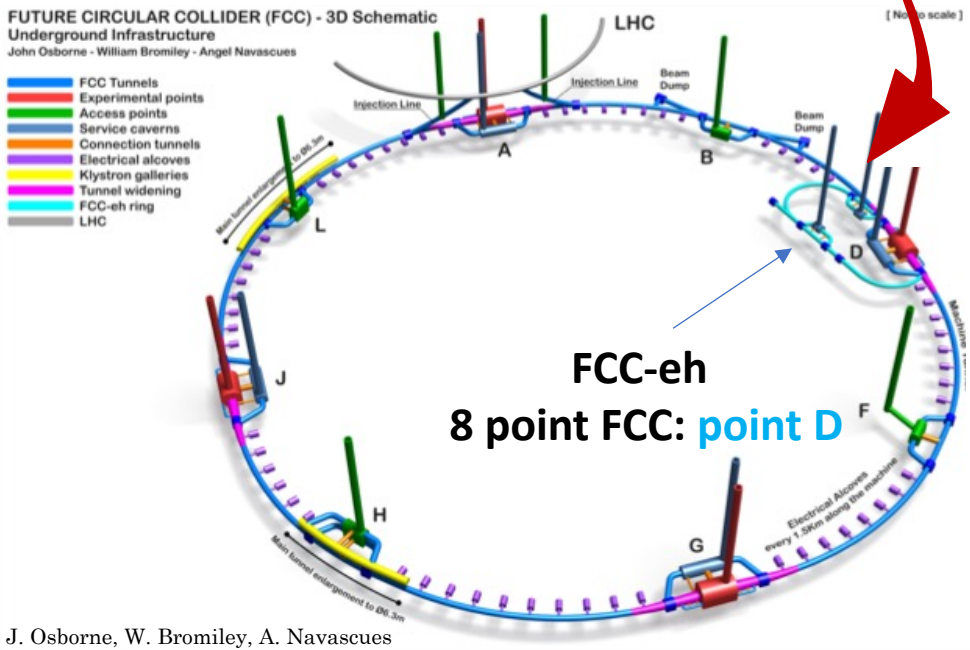


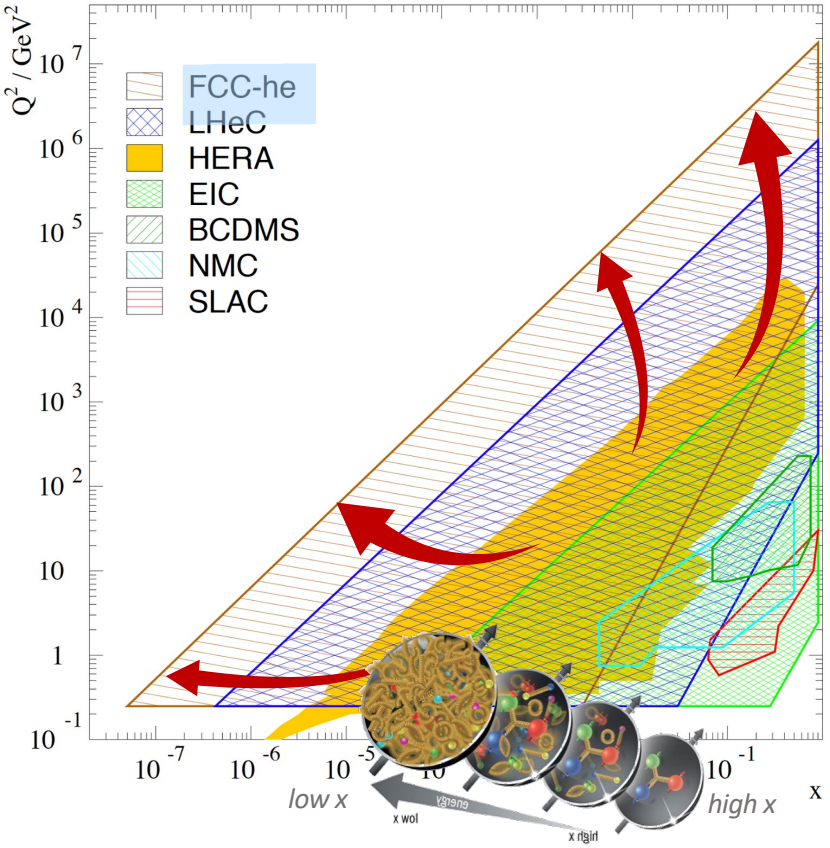


The Large Hadron-Electron Collider at the HL-LHC, J. Phys. G 48 (2021) 110501, 364p (updated CDR)

The FCC-eh program

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





J. Osborne, W. Bromiley, A. Navascues

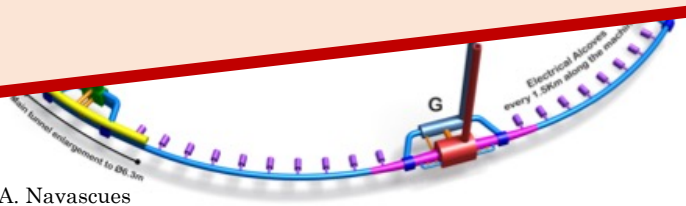
The FCC-hh

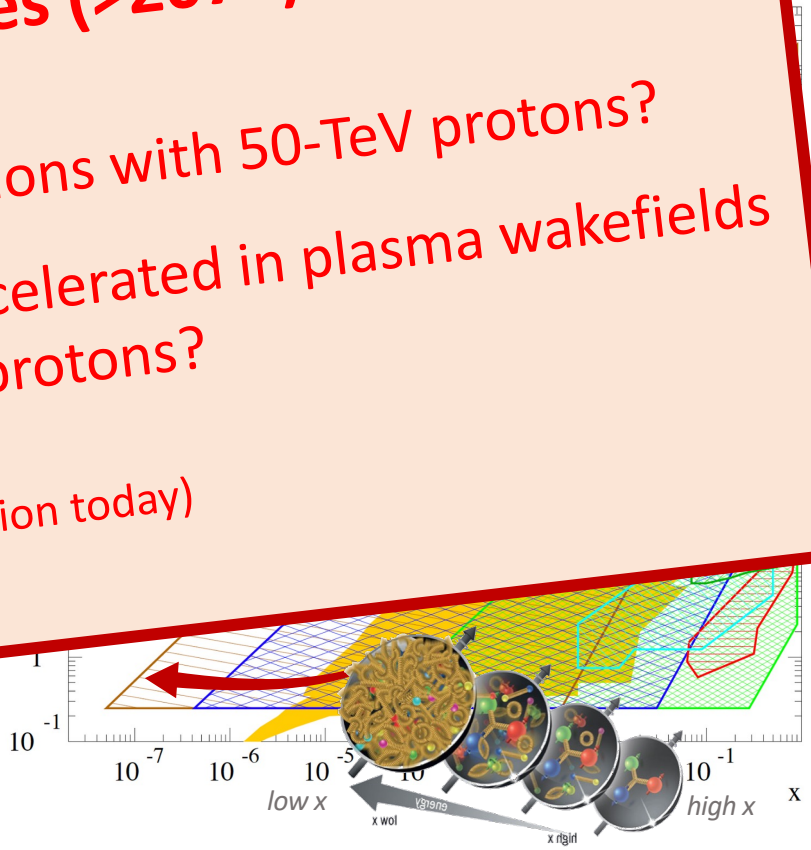
On FCC-hh timelines (>2070)…

Could we collide high-energy muons with 50-TeV protons?

Could we collide 5-TeV electrons accelerated in plasma wakefields with 50-TeV protons?

(not for discussion today)





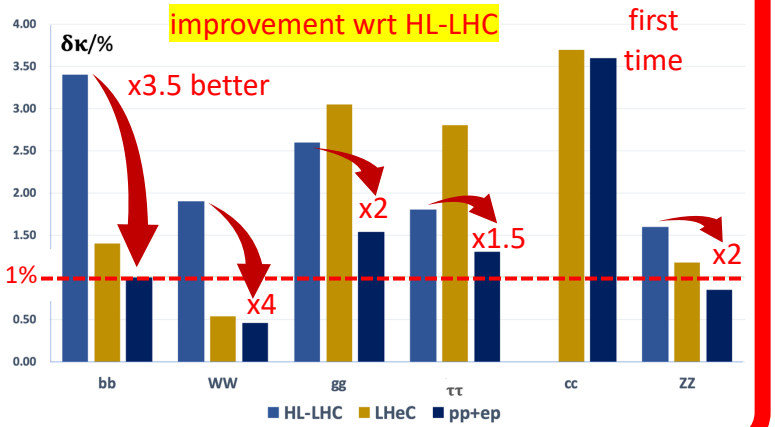
J. Osborne, W. Bromiley, A. Navascues

the synergistic physics impact

(briefly some highlights)

Some LHeC physics highlights achievable by ~2045

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

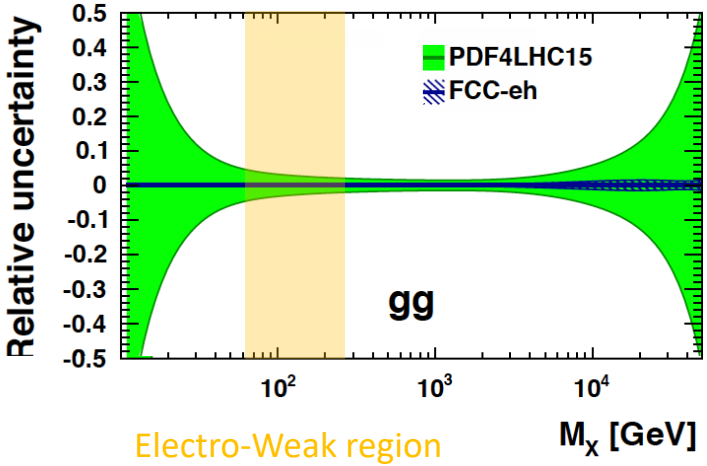
Strong interaction physics

- 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)

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

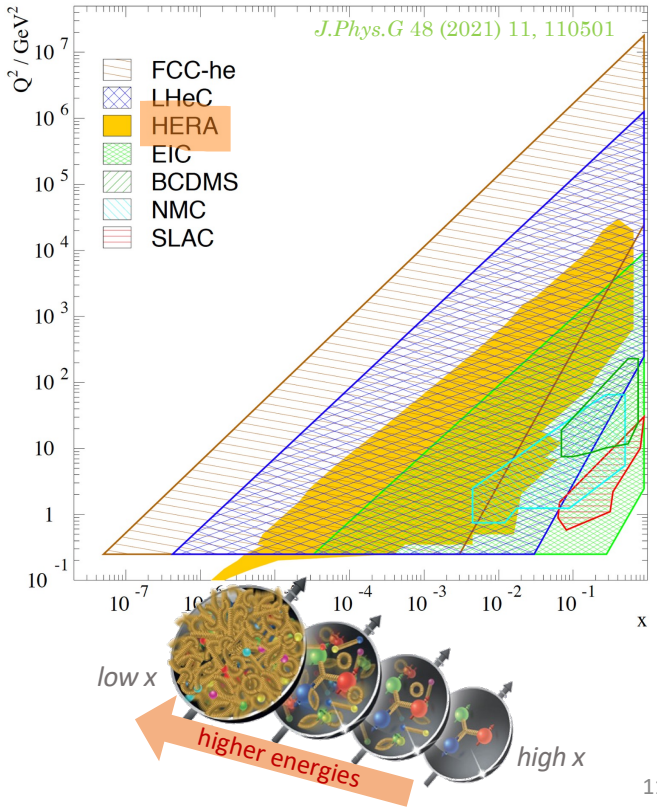


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-*eh*

Kinematic range Parton Distribution Functions



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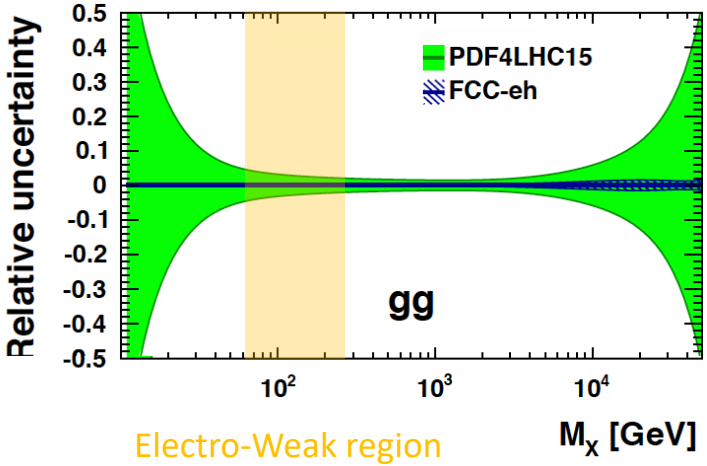


Electro-Weak region

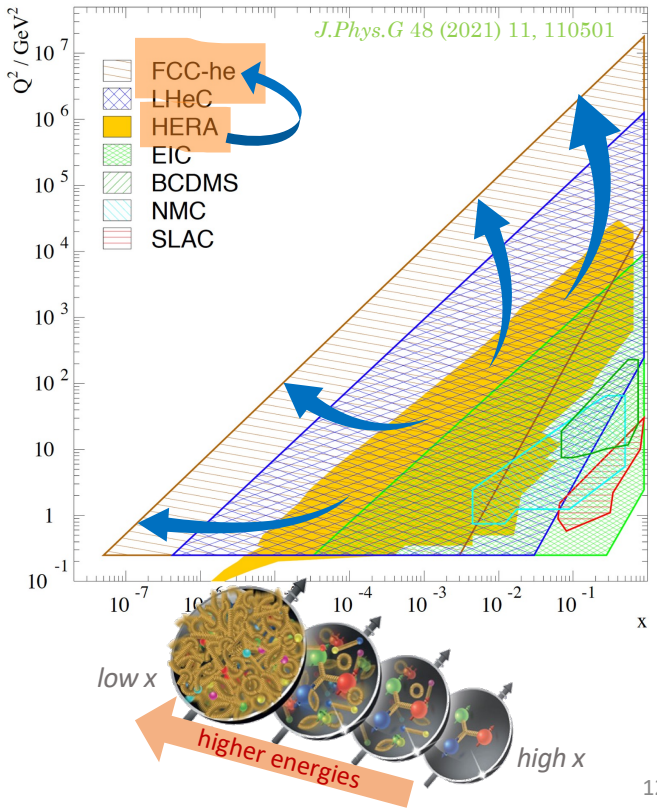
~5-7% uncertainty on the σ(W,Z,H)

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

The ESPP 2020 noted the synergy in its deliberation document

- "**Other essential scientific activities for particle physics …** An independent determination of the proton structure would be desirable to fully exploit the precision achievable with present and future hadron colliders. Detailed measurements of proton structure complement the investment in theoretical calculations and add sensitivity to searches for novel phenomena. A programme based on fixed-target experiments and on dedicated electron-proton machines, such as LHeC and FCC-ep, has been advocated in Europe."

The ESPP 2020 noted the synergy in its deliberation document

***The mandate of the ep/eA@CERN Study**: "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."*

Exploration of synergies between pp/pA/AA and ep/eA physics

- How to maximally exploit these synergies to advance the knowledge of the proton structure?
- How to maximally empower the HL-LHC/FCC-hh measurements and searches with additional knowledge of TeV-scale ep/eA collisions?
- Which flagship measurements and searches in ep/eA collisions could be most impactful and complementary in the field?
- Exploring synergies in detector R&D with other experiments on a similar timeline.

Exploration of synergies between pp/pA/AA and ep/eA physics

- How t…

In order to unlock the physics & detector opportunities, advancements on accelerator R&D are required.

…field?

…detector R&D with other experiments on a similar timeline.

particle physics ambition

high-energy & high-current beams

(energy x current = power)

caveat

power requirements of future colliders

The challenge

High-intensity electron beam

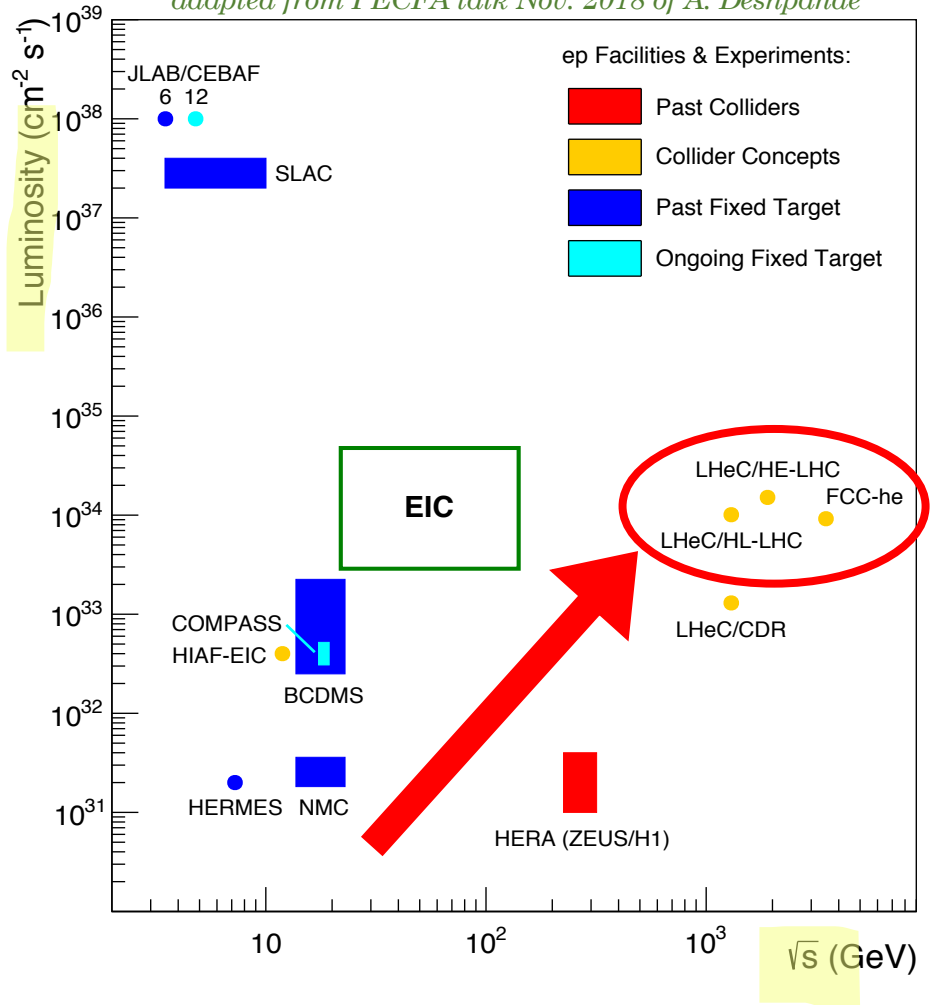
From HERA@DESY to LHeC@CERN

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

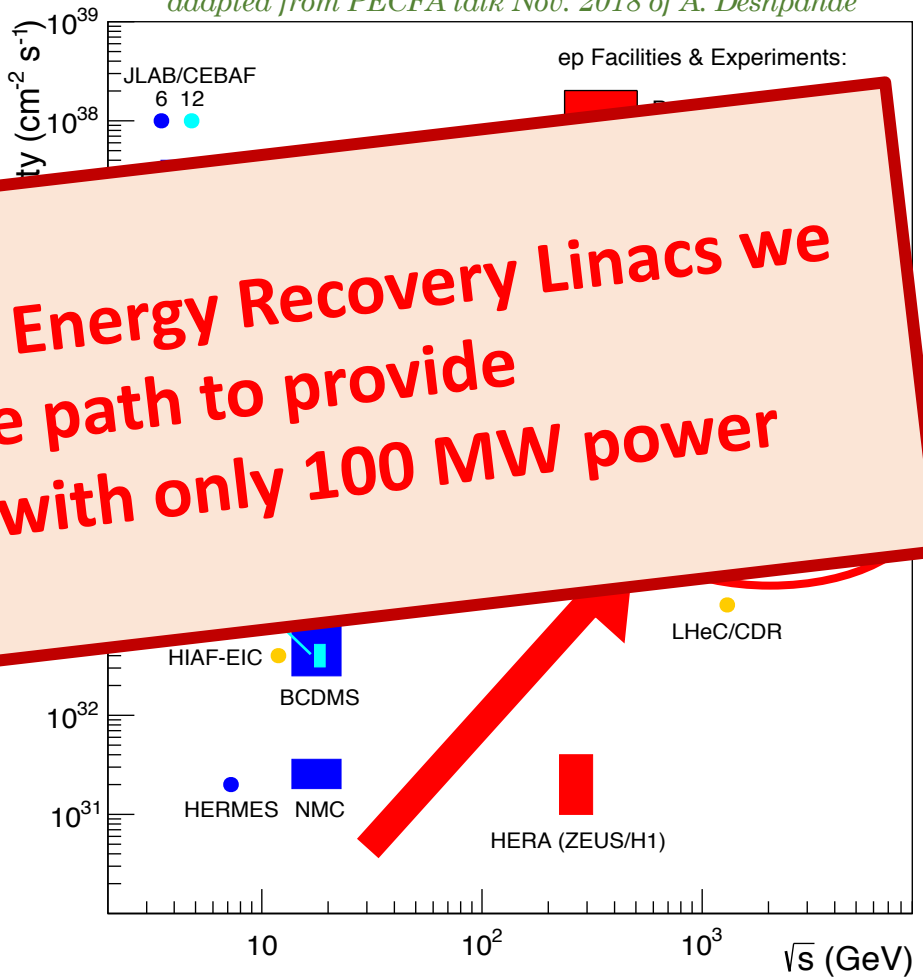
From HERA ...

LHeC ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant

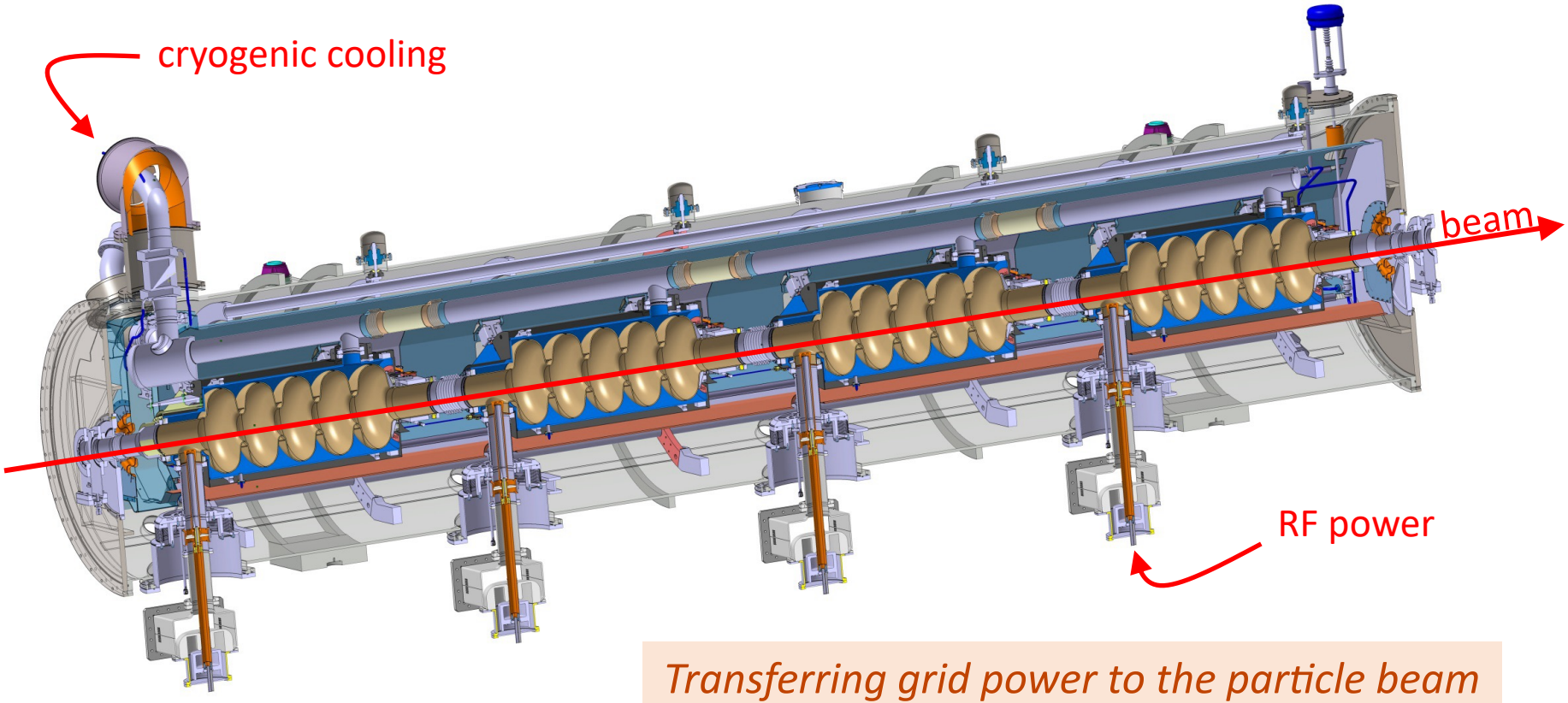
With the planned R&D on Energy Recovery Linacs we will prepare the path to provide a 1 GW electron beam with only 100 MW power

adapted from PECFA talk Nov. 2018 of A. Deshpande



Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency



Transferring grid power to the particle beam

Key building block for beam acceleration: the SRF cryomodule

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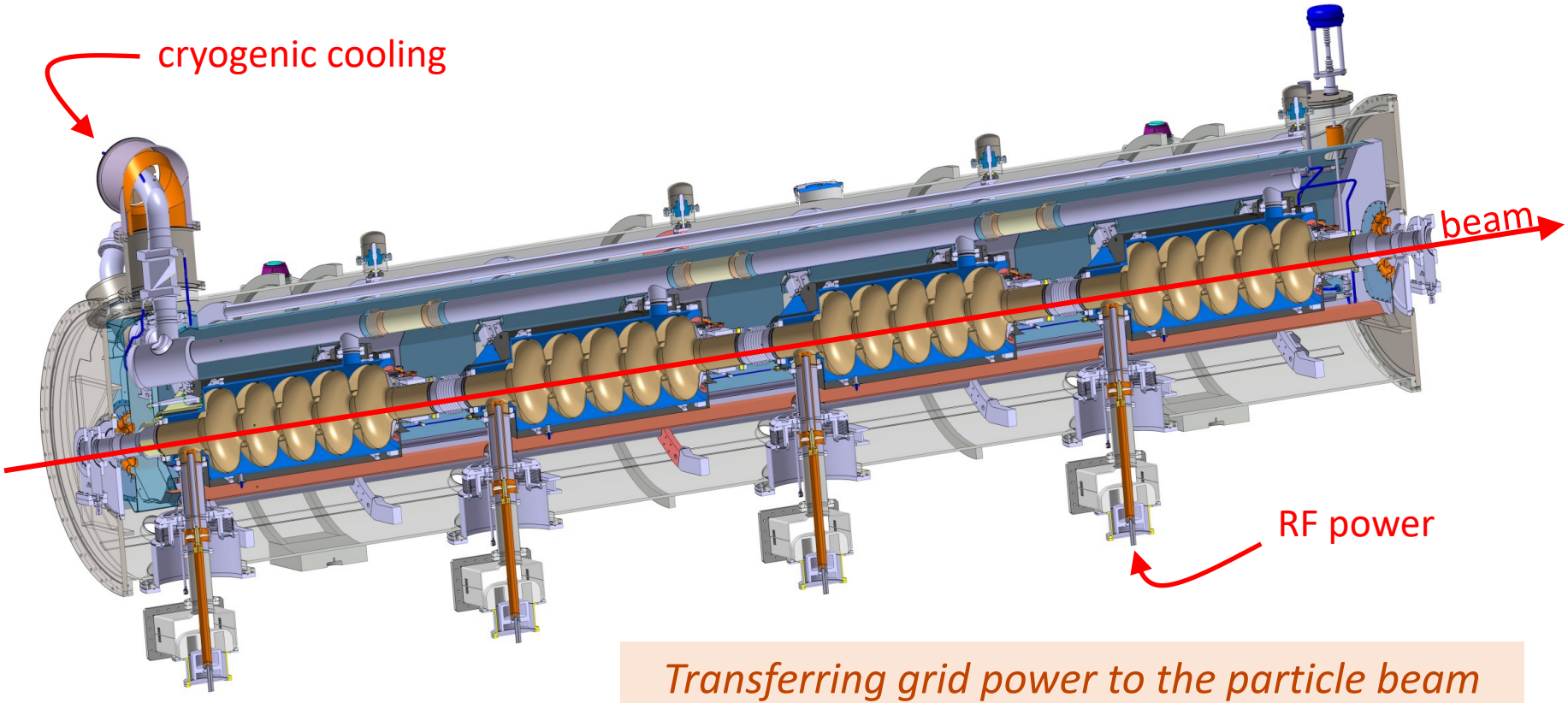

Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

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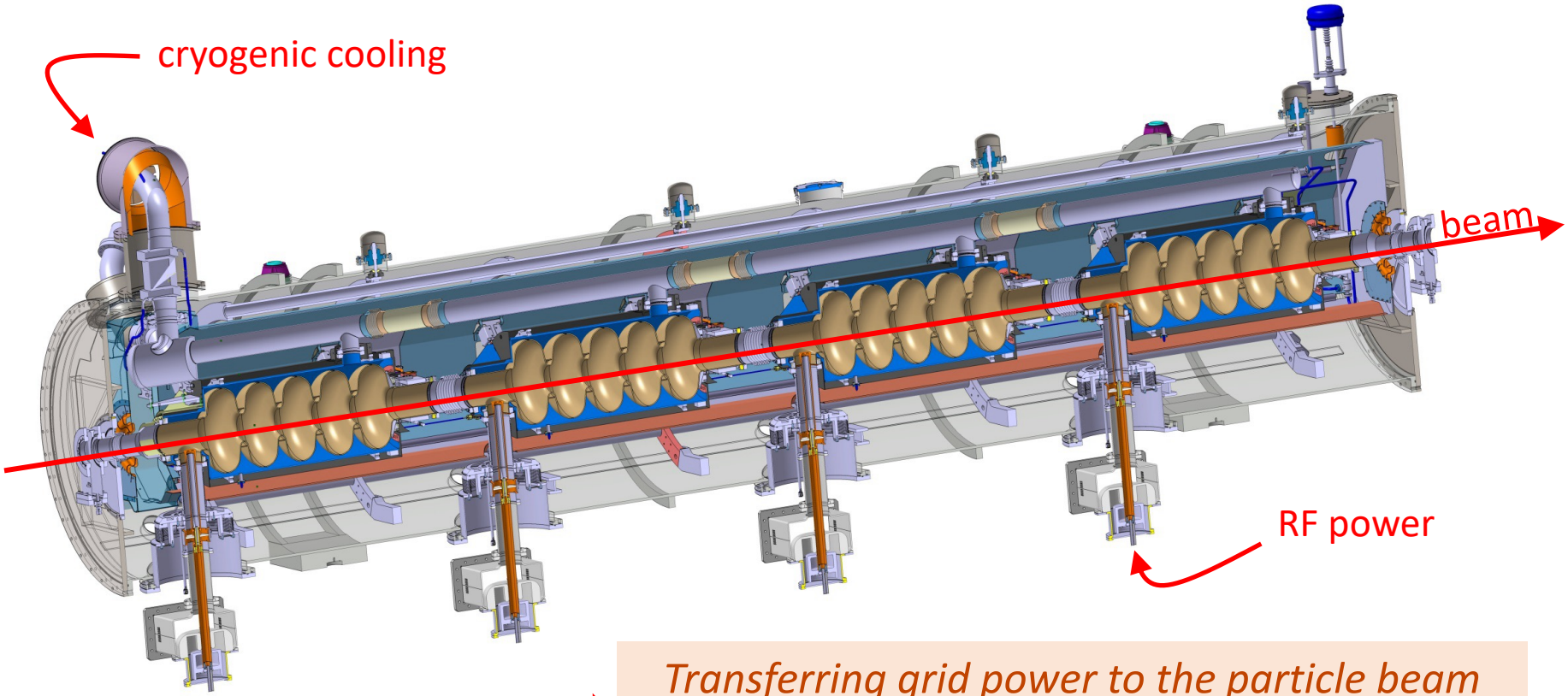
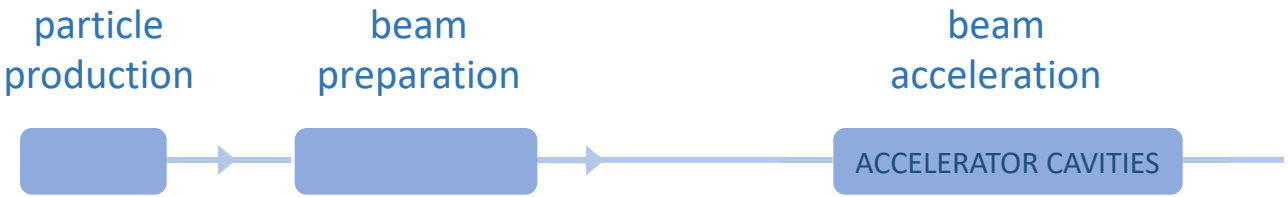


ENERGY RECOVERY → *Transferring grid power to the particle beam*

RECOVER THE ENERGY FROM THE USED BEAM

The principle of Energy Recovery



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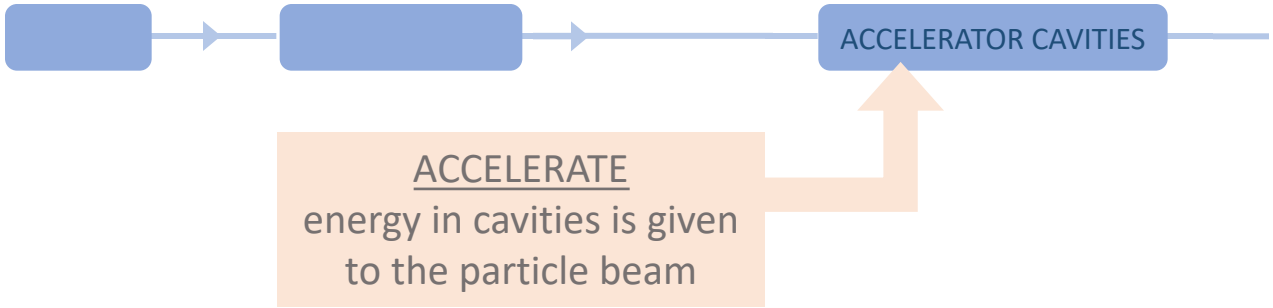

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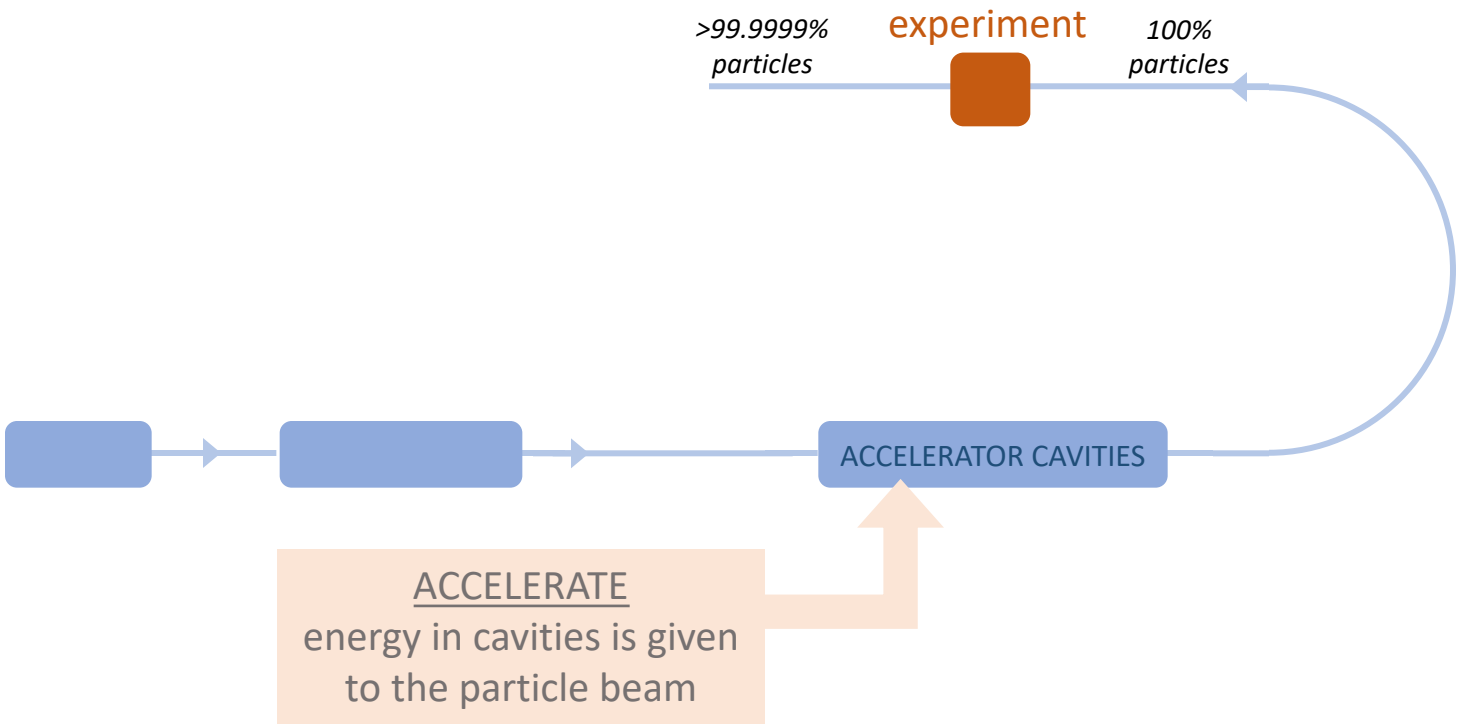

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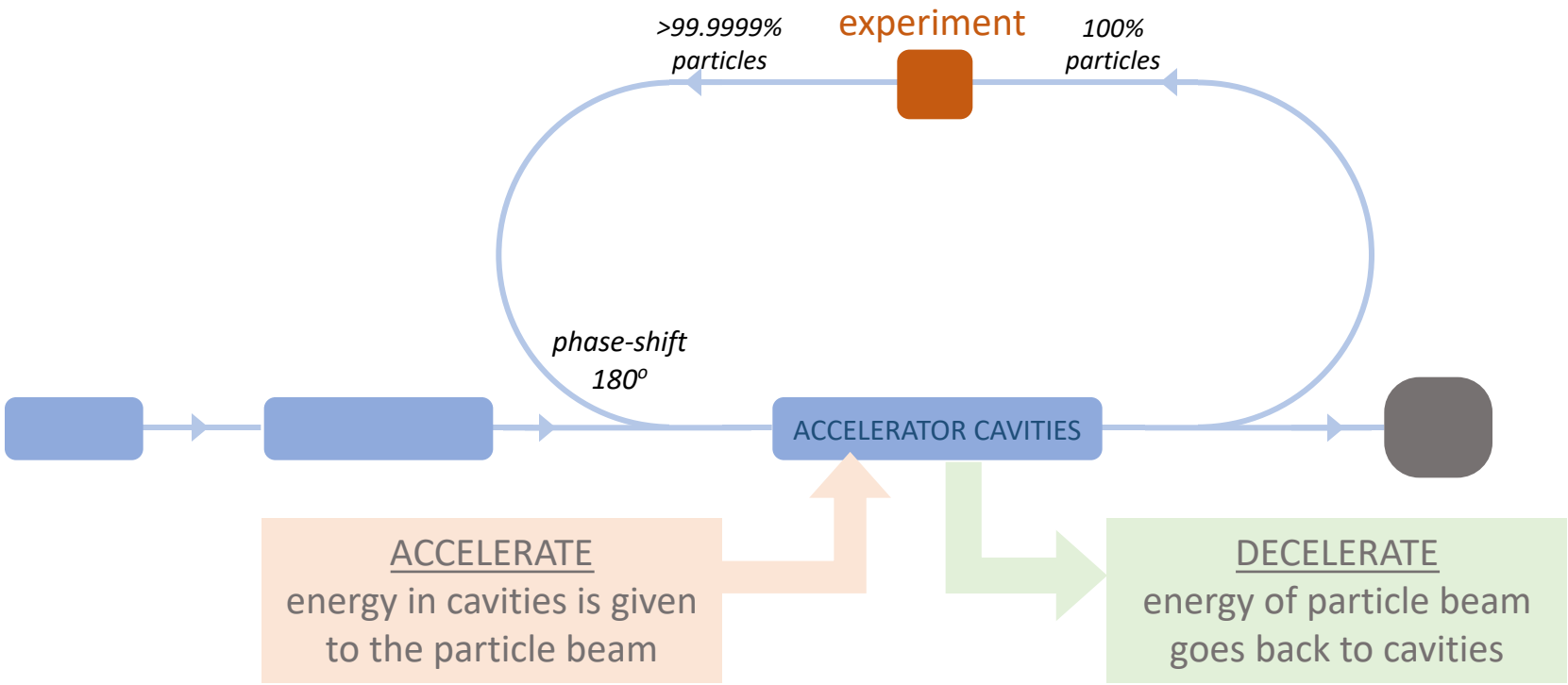

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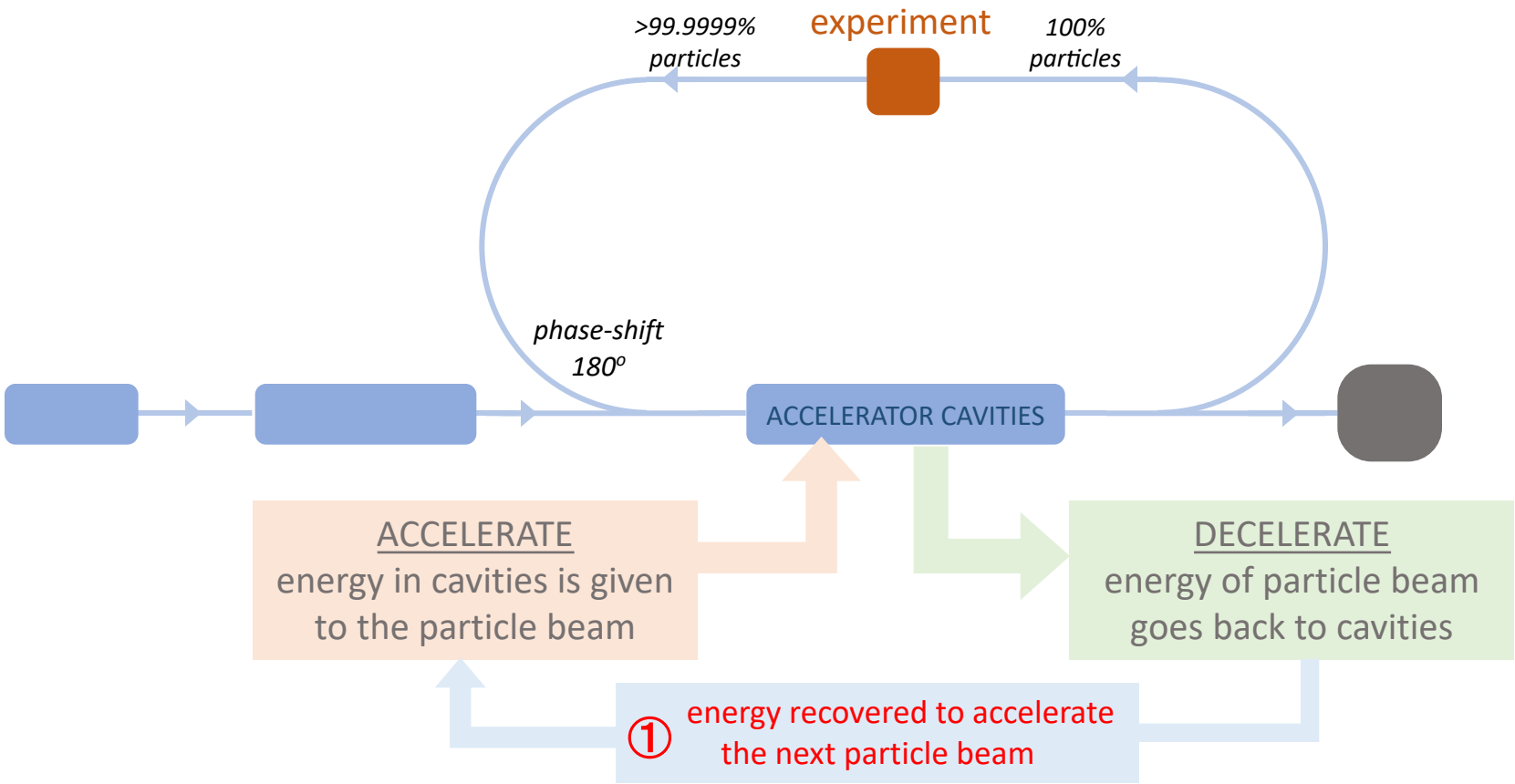

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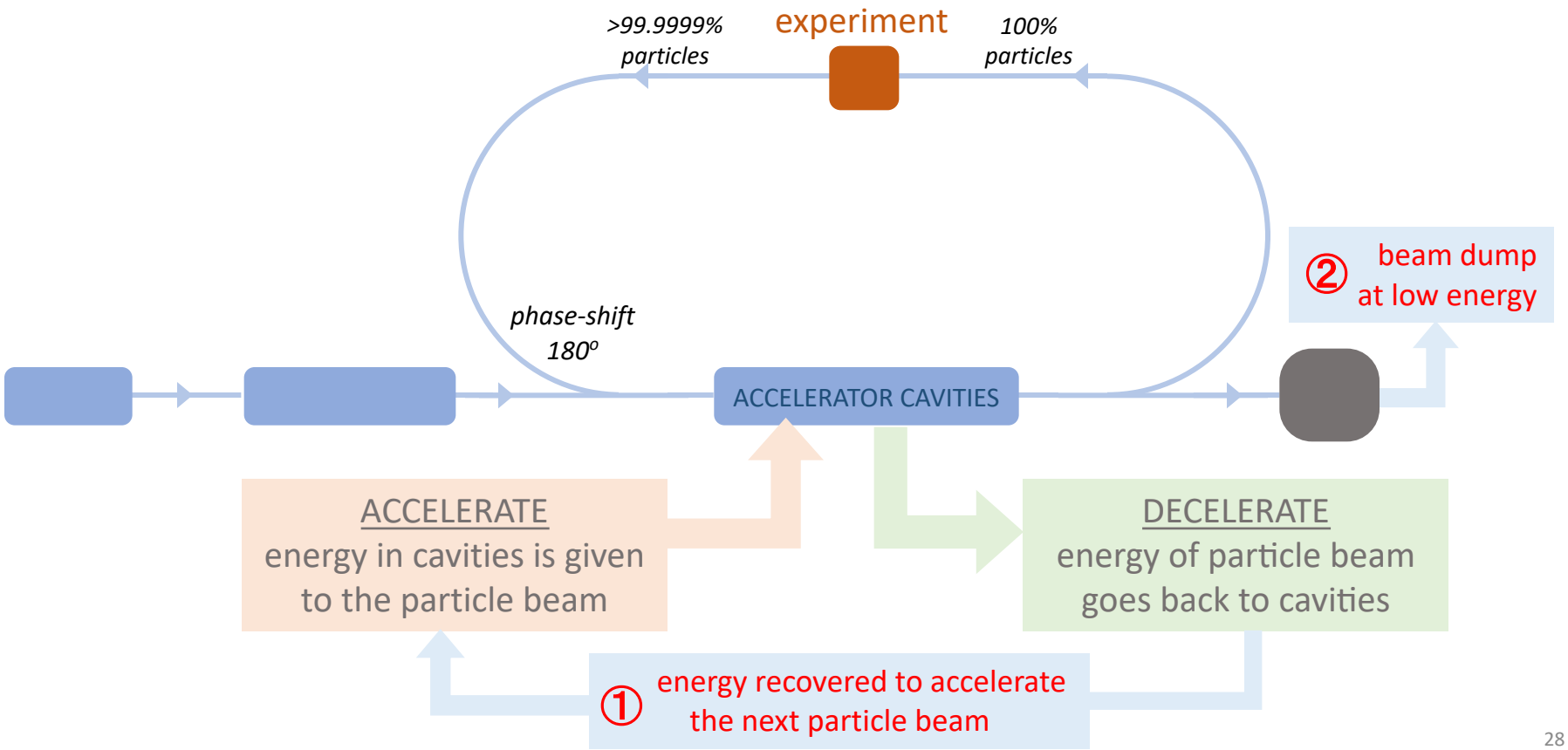

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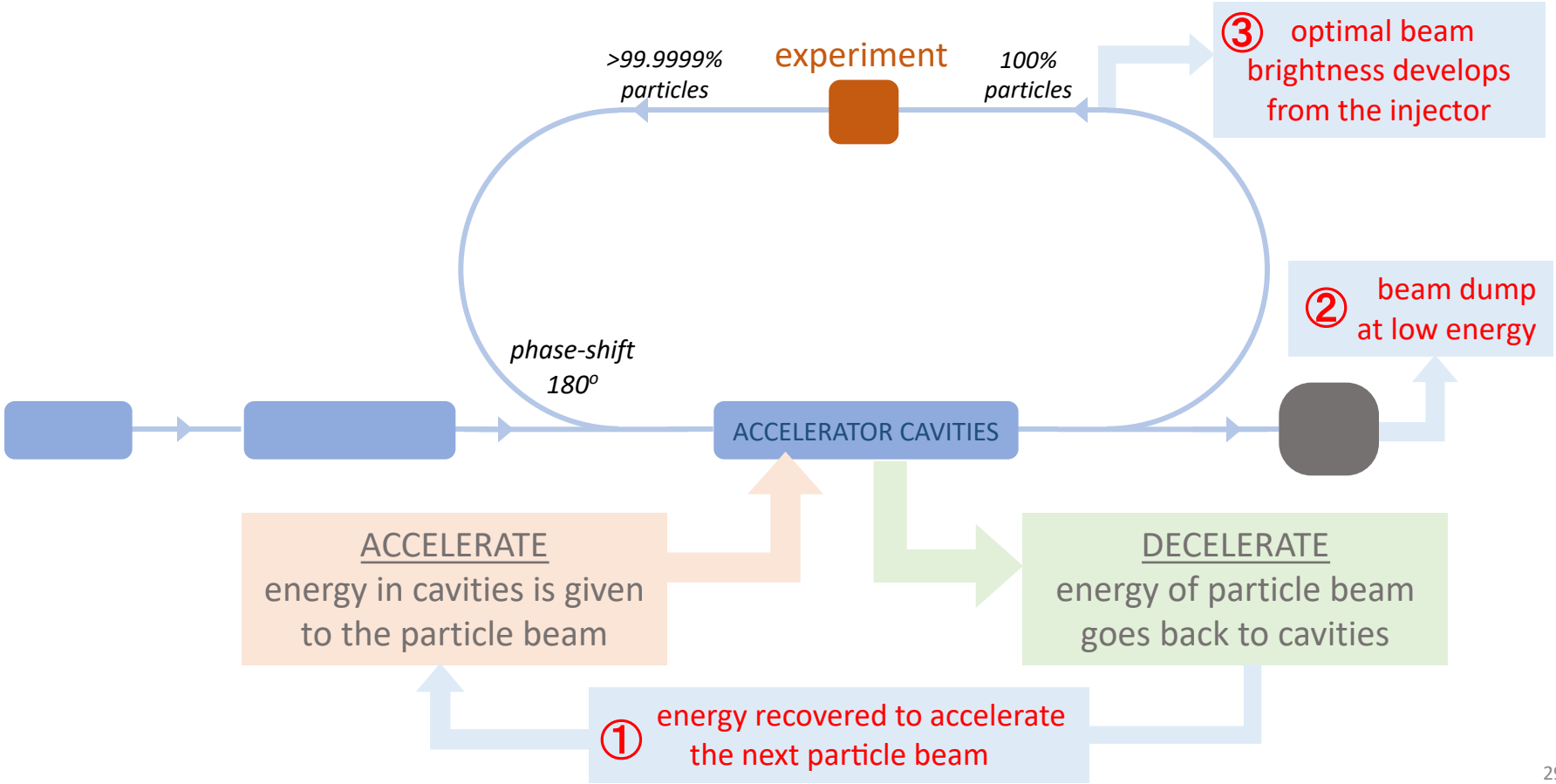

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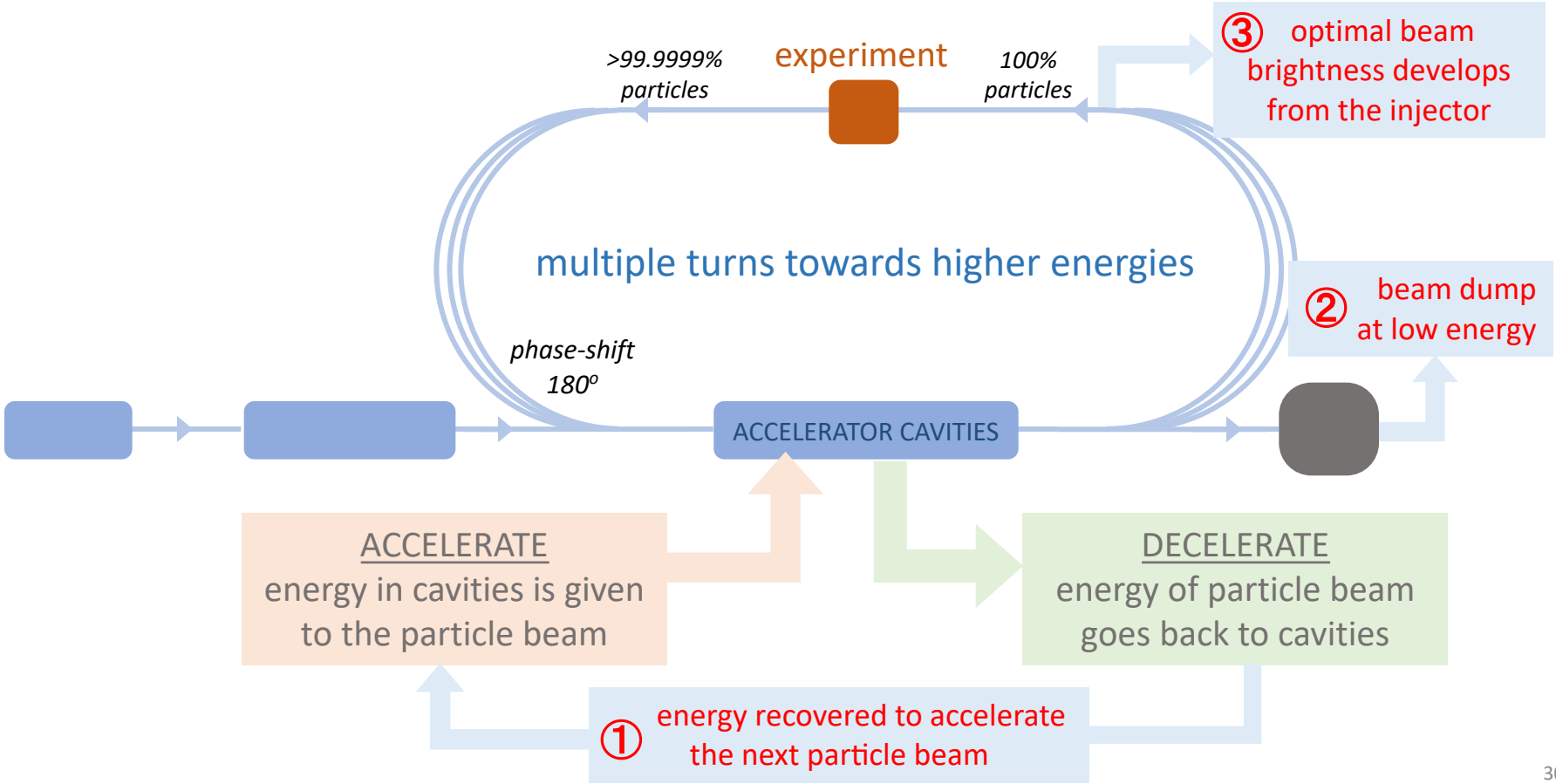

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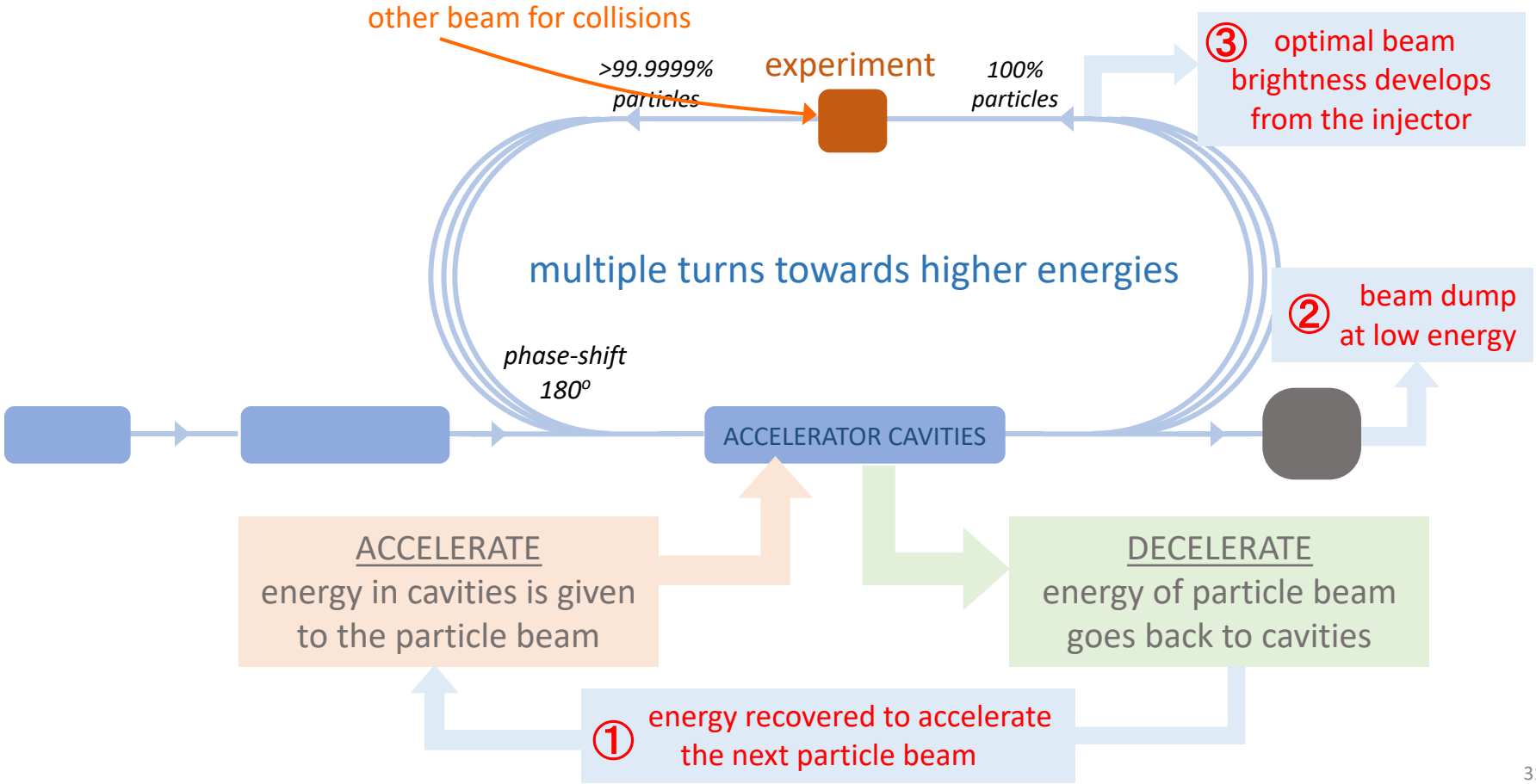

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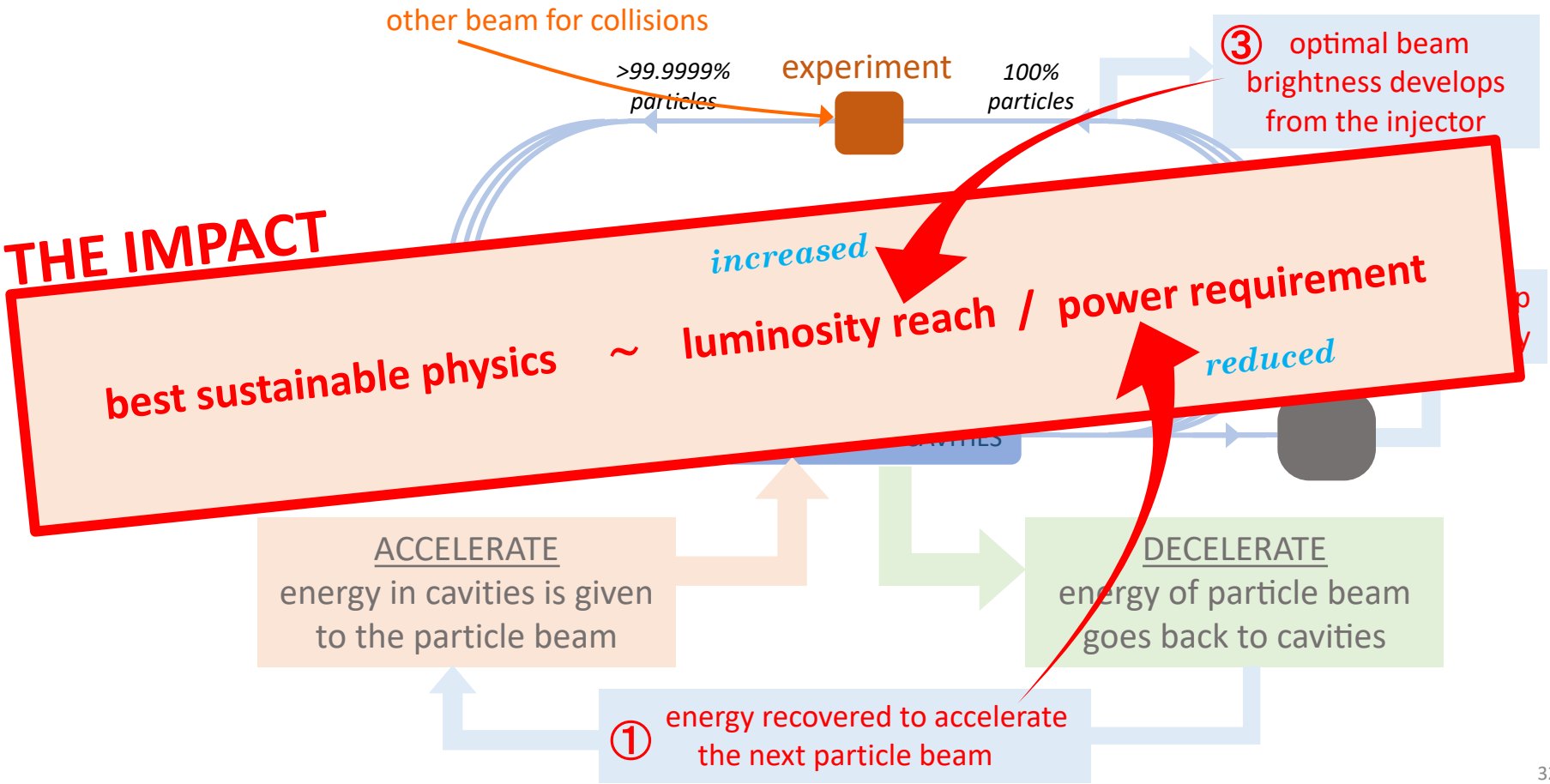

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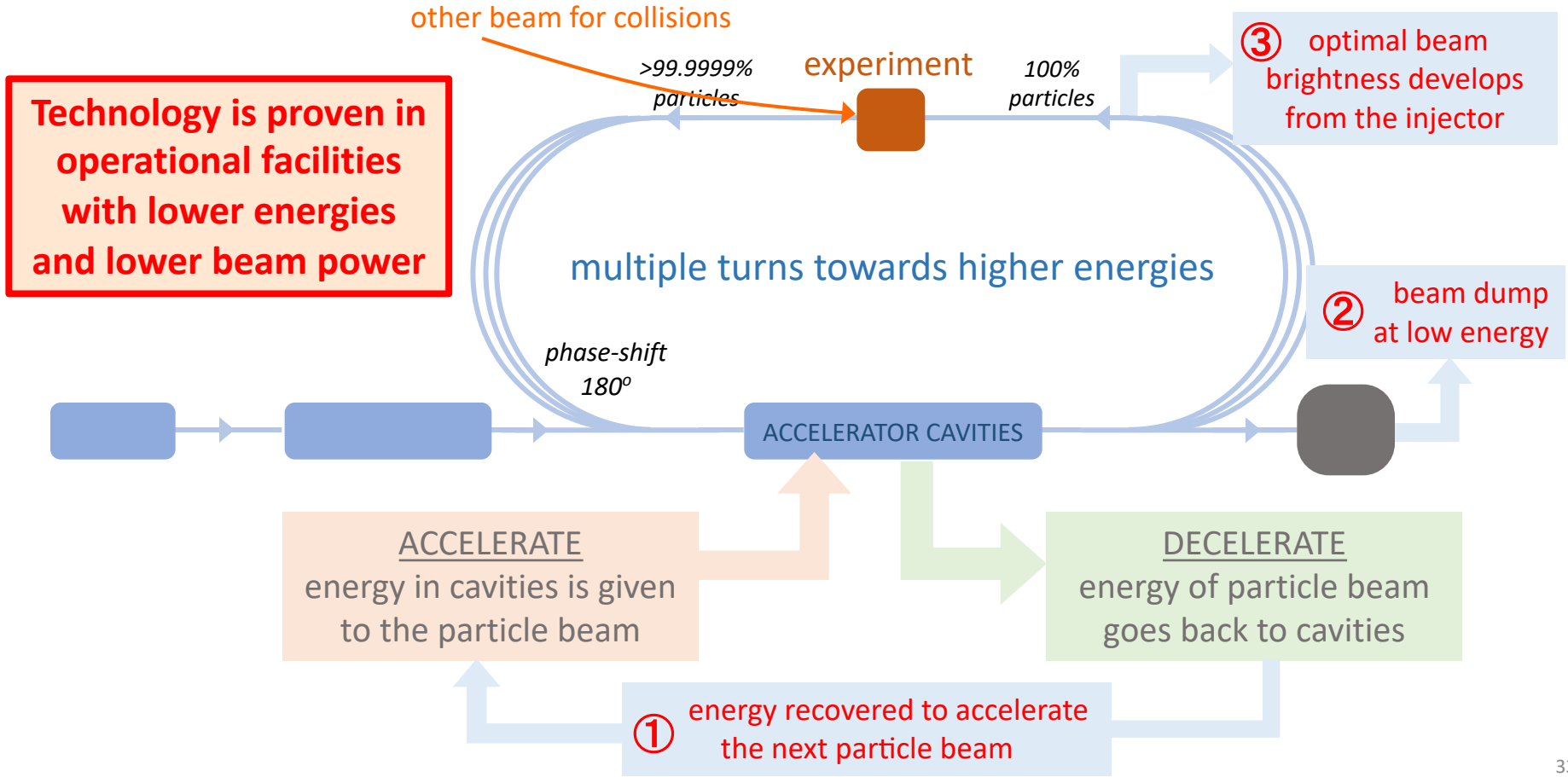
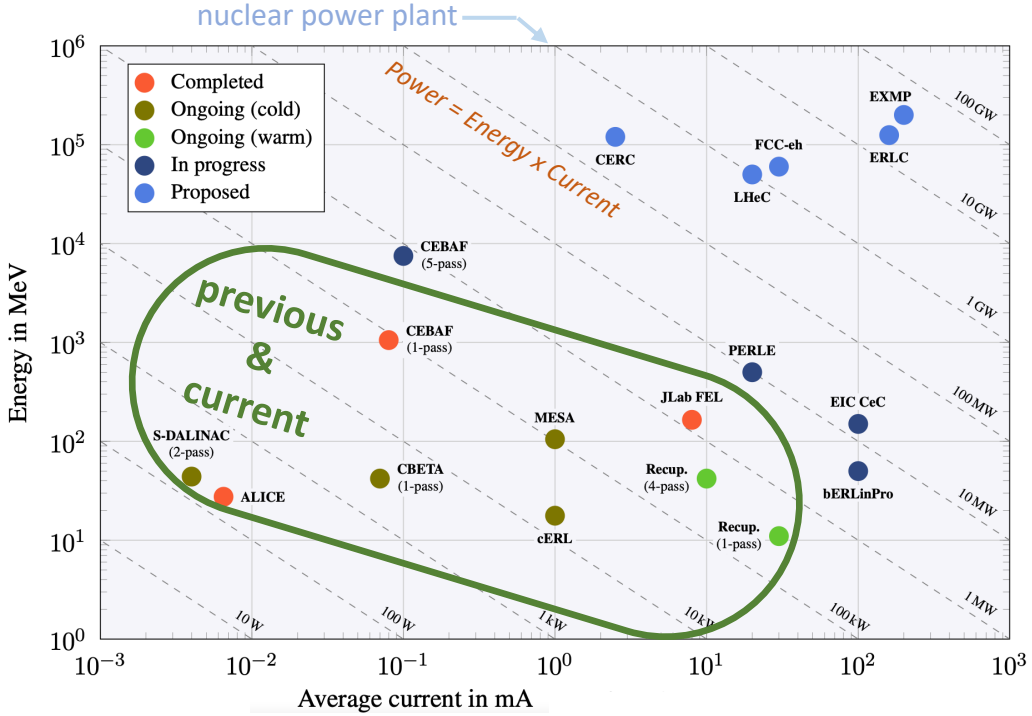
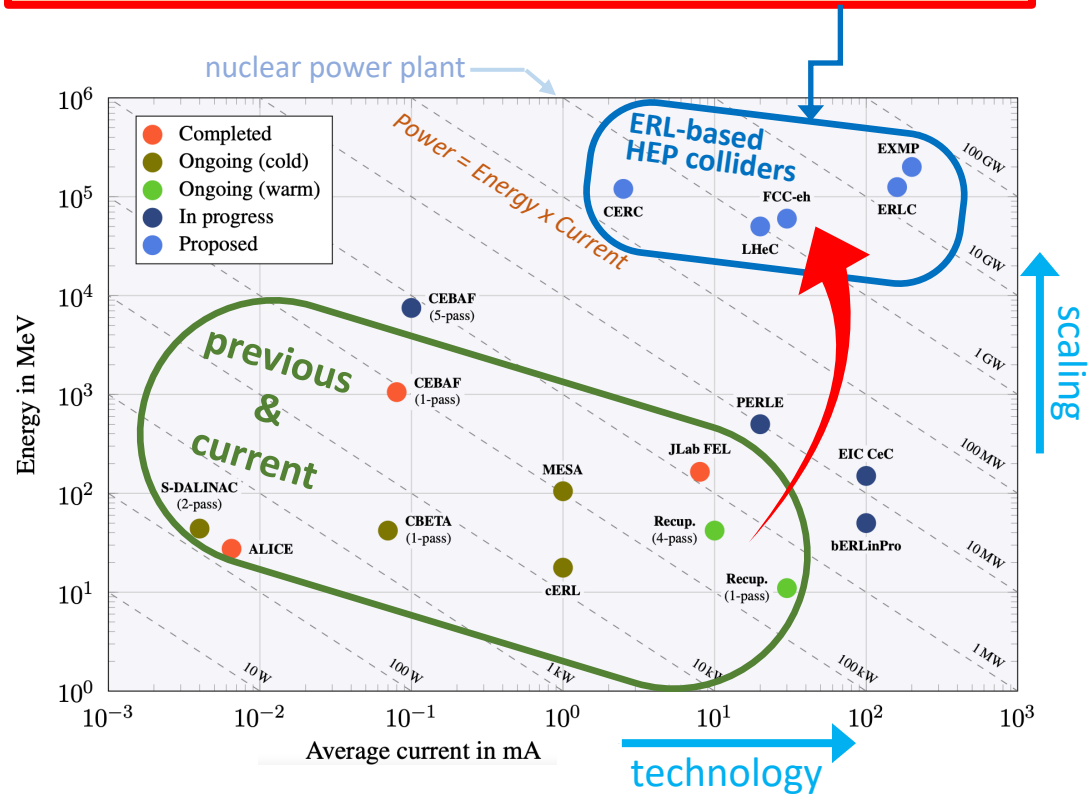




Energy Recovery demonstrated

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

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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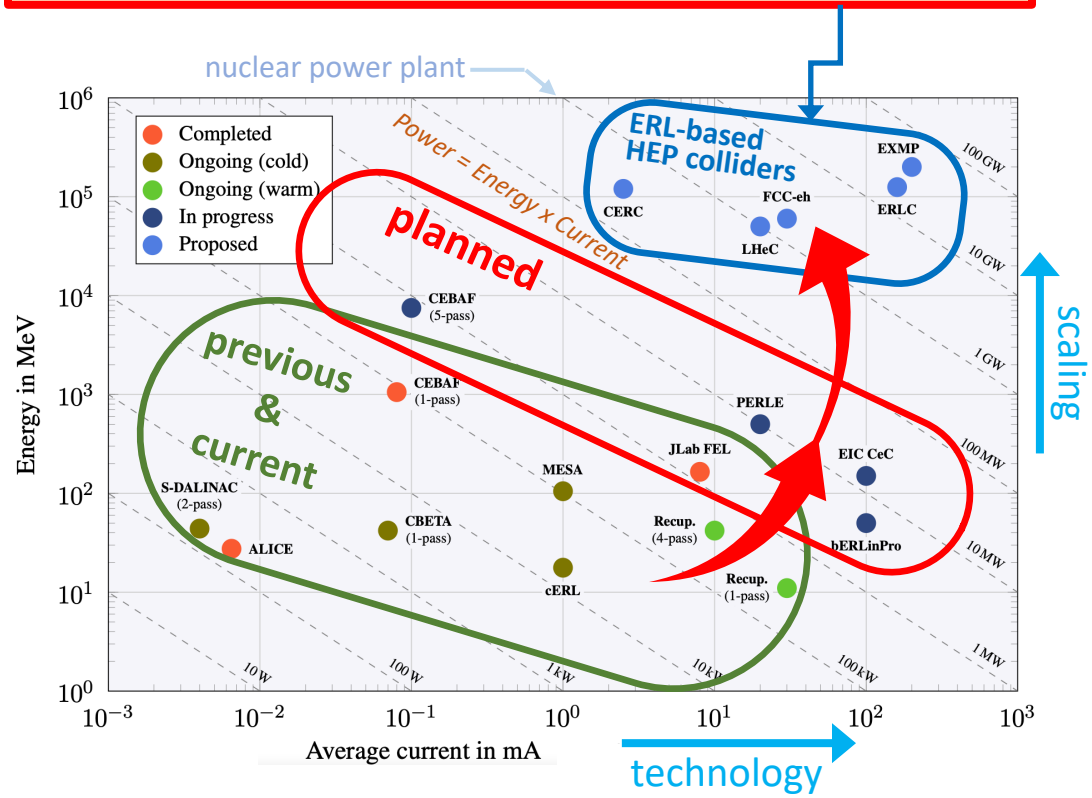

Future ERL-based Colliders

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

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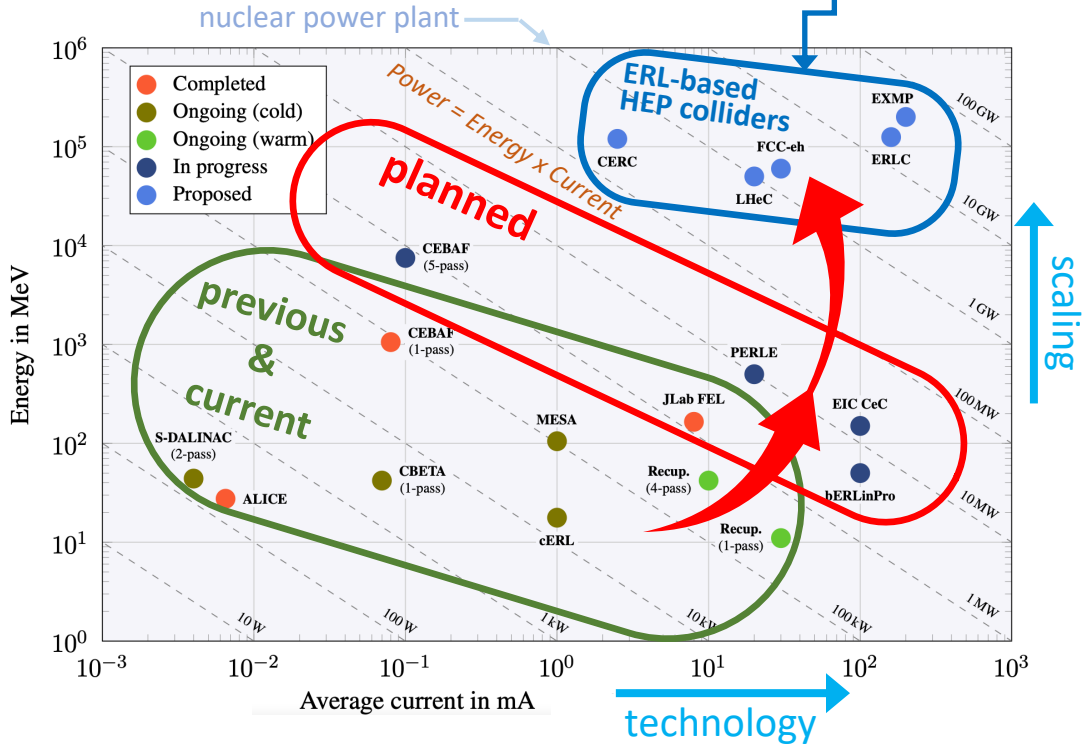


Future ERL-based Colliders

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

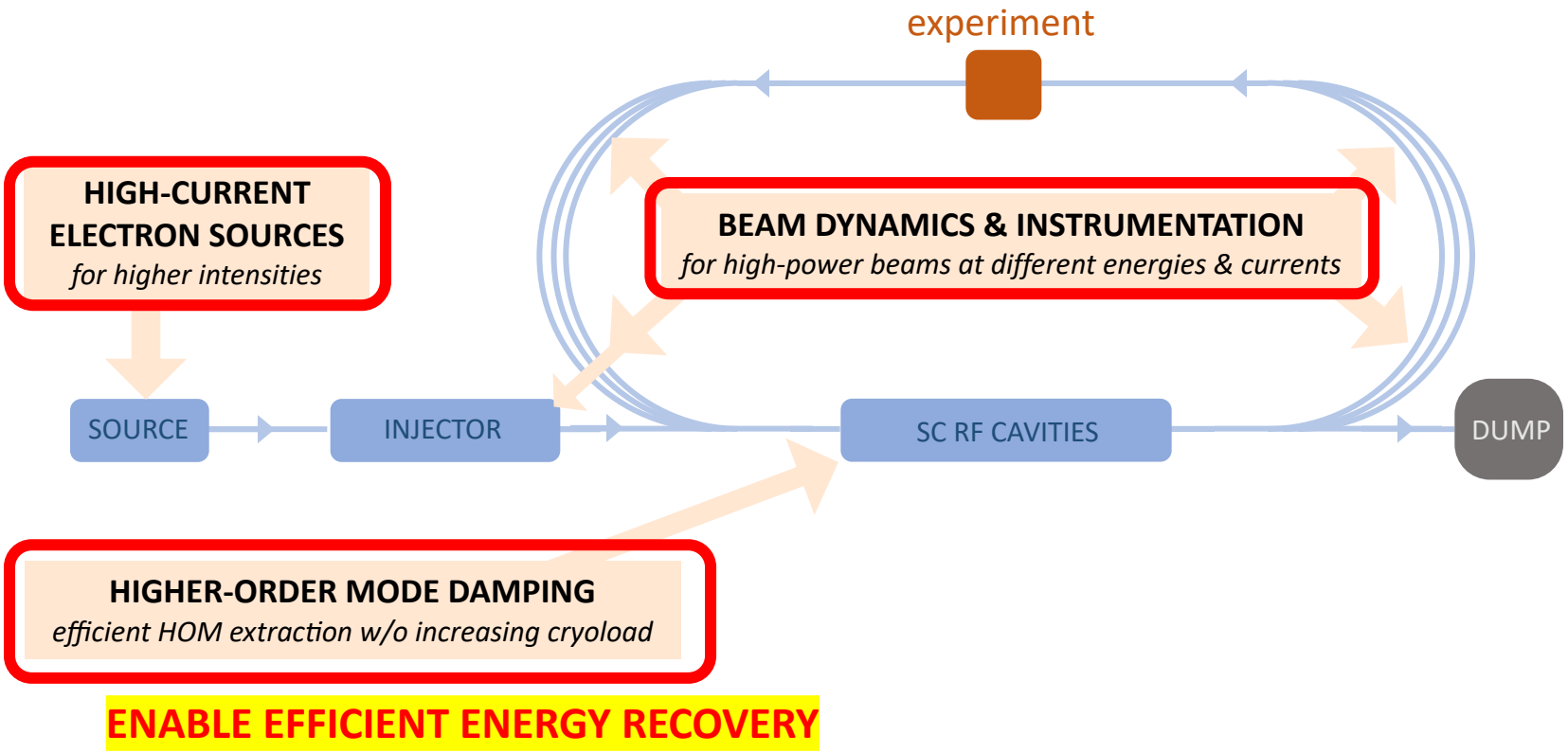
towards high power

Energy Recovery demonstrated

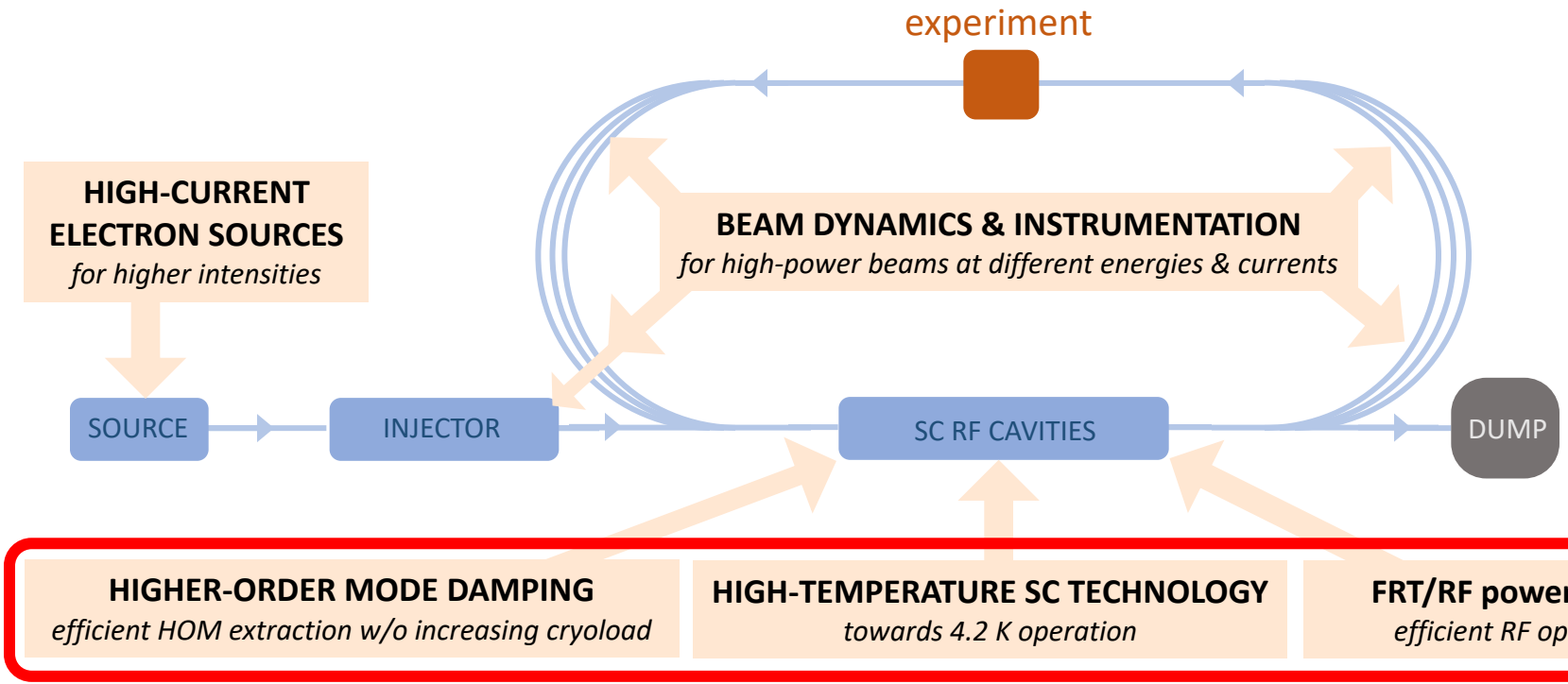
great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

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

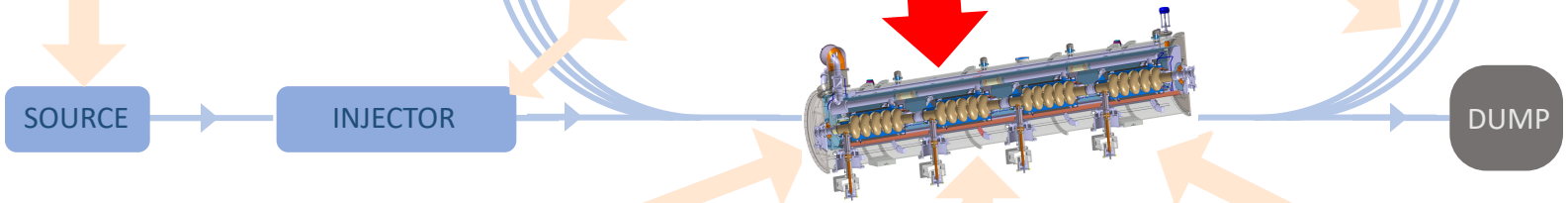
Innovate for Sustainable Accelerating Systems (iSAS)

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)

for high-power beam[illegible] different energies & currents



HIGHER-ORDER MODE DAMPING
efficient HOM extraction w/o increasing cryoload

HIGH-TEMPERATURE SC TECHNOLOGY
towards 4.2 K operation

FRT/RF power source
efficient RF operation

ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

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/

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

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)

High-power ERL technology timeline

2020'ies

high-power ERL demonstrated

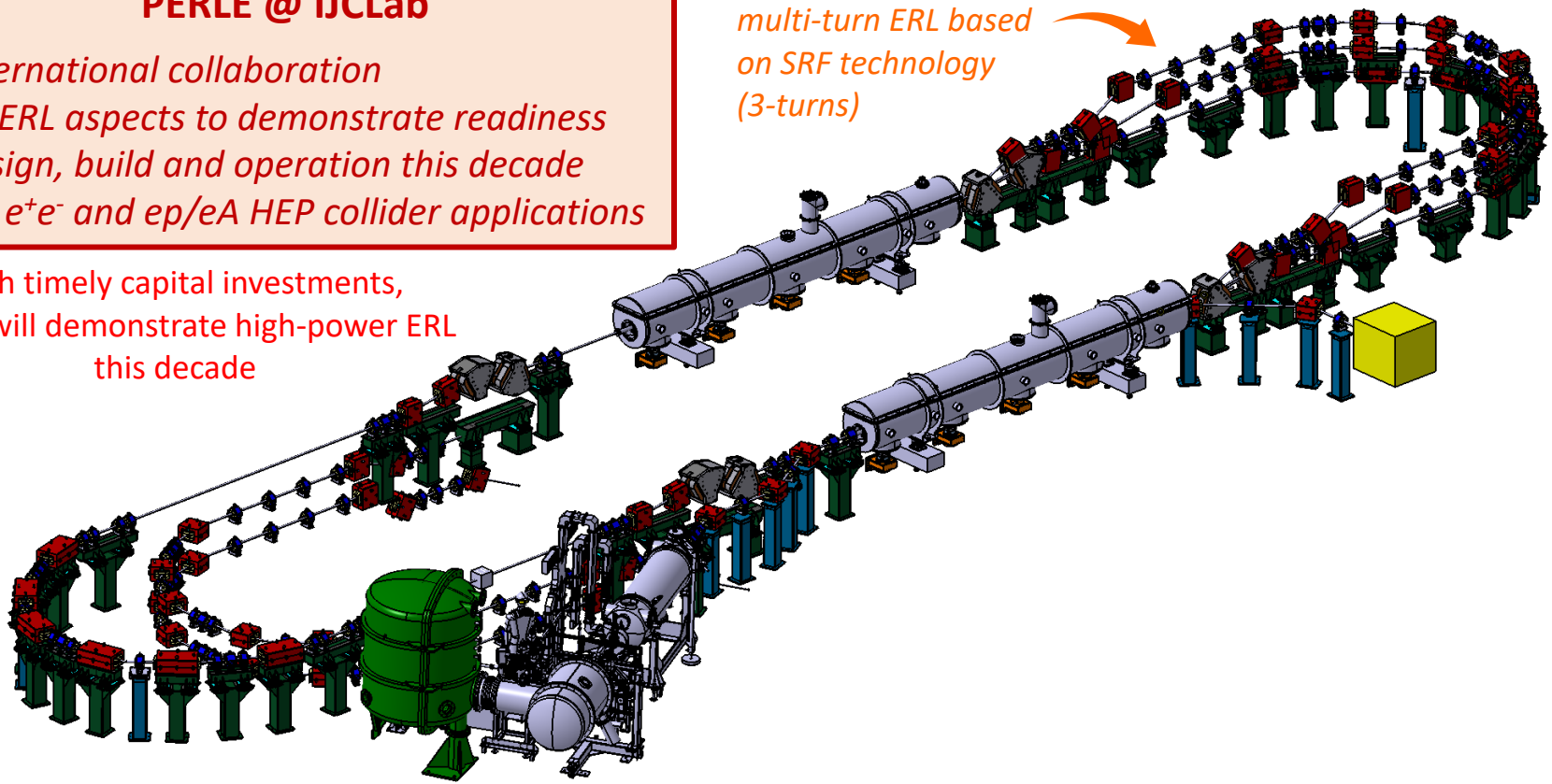
Upcoming facilities for Energy Recovery Linac R&D

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

- *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)

developed within the iSAS project

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

- *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

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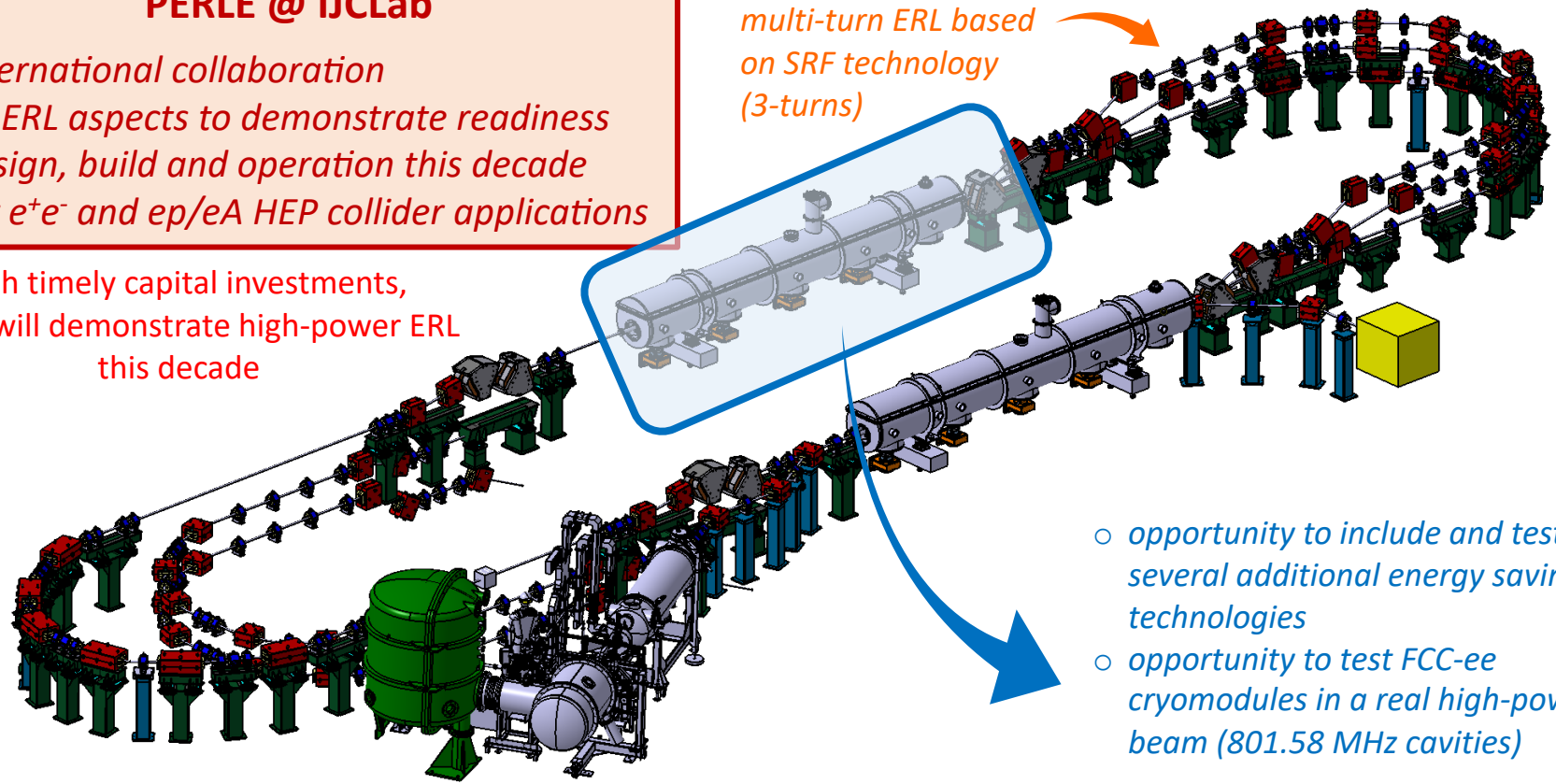

- *opportunity to include and test several additional energy saving technologies*
- *opportunity to test FCC-ee cryomodules in a real high-power beam (801.58 MHz cavities)*

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

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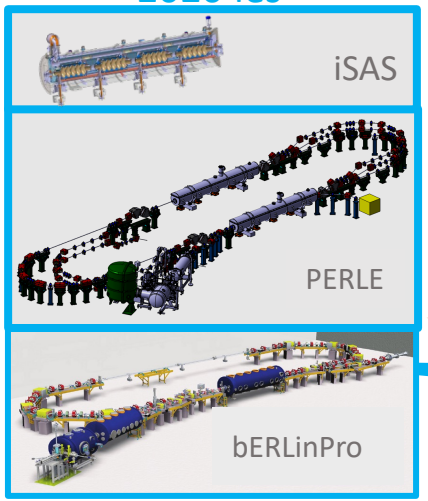
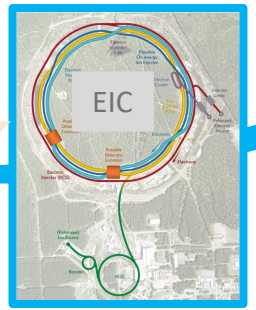


high-power ERL demonstrated

2030'ies



ERL application electron cooling

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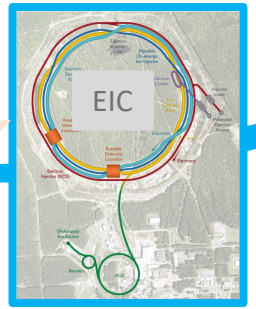
demonstrate multi-turn high-power ERL

enables the ultimate upgrades of the LHC/FCC programs

2020'ies

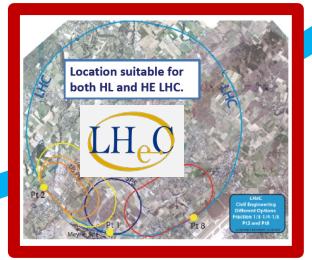
high-power ERL demonstrated

2030'ies



ERL application electron cooling

2030-2040'ies



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

1 ERL beam

2070'ies

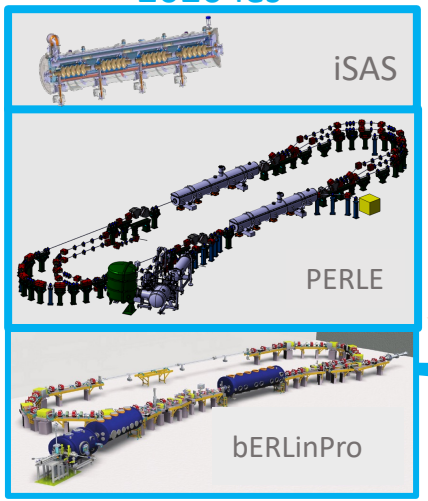
reuse ERL

Potential impact of ERL technology

demonstrate multi-turn high-power ERL

enables the ultimate upgrades of the LHC/FCC programs

2020'ies



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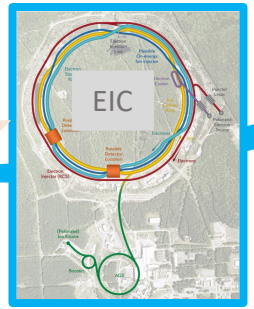

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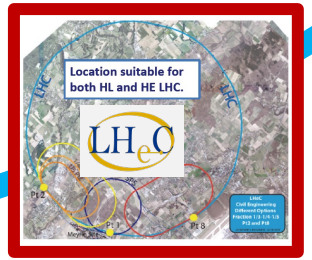

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Options for ERL-based H/HH factories

2070'ies

reuse ERL

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
Nestor Armesto, Claire Gwenlan, Paul Newman

general-purpose high-energy physics program: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions
Monica D'Onofrio, Uta Klein, Christian Schwanenberger

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 program
Maarten Boonekamp, Daniel Britzger, Christian Schwanenberger

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
Paul Newman, Yuji Yamazaki

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

- five thematic physics and technology working groups
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)

Subscribe to mailing lists via https://e-groups.cern.ch/ : use the search option, and search for "lhec-fcceh-all" or "ep-eA-WG" in all e-groups

The ep/eA study at the LHC and FCC – Energy Recovery Linacs (ERL)

- The ESPP emphasizes the importance of studying the Higgs boson sector with improved precision and diversifying our search for new physics phenomena.
- Guided by these strategic objectives, we study how high-energy, high-luminosity ep/eA physics can empower pp/pA/AA physics at the LHC and FCC.
- This workshop will explore the synergistic impact and identify where further research is required to fully reveal the synergistic benefits on topics such as proton structure, EW/H/top physics, Hidden Sector searches and Detector R&D.
- Meanwhile, impactful progress is being made in developing an ERL-based electron accelerator that will enable these ep/eA collisions in an affordable and sustainable way, and on an interesting timeline.

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The potential impact of ep/eA physics is so appealing that we must foster this study

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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Thank you for your attention!

Jorgen.DHondt@vub.be

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

only FCC-ee@240GeV

only FCC-hh

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FCC-ee prospect

FCC-hh/eh prospect

only FCC-ee@240GeV

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FCC-ee prospect

FCC-hh/eh prospect

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}