High-energy ep/eA physics with the LHeC and FCC-eh

sustainable future colliders with impact

Jorgen D’Hondt

Vrije Universiteit Brussel

on behalf of the ep/eA Coordination Panel

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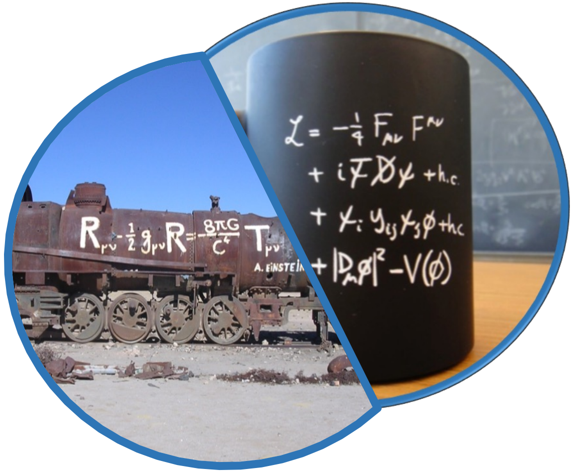
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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



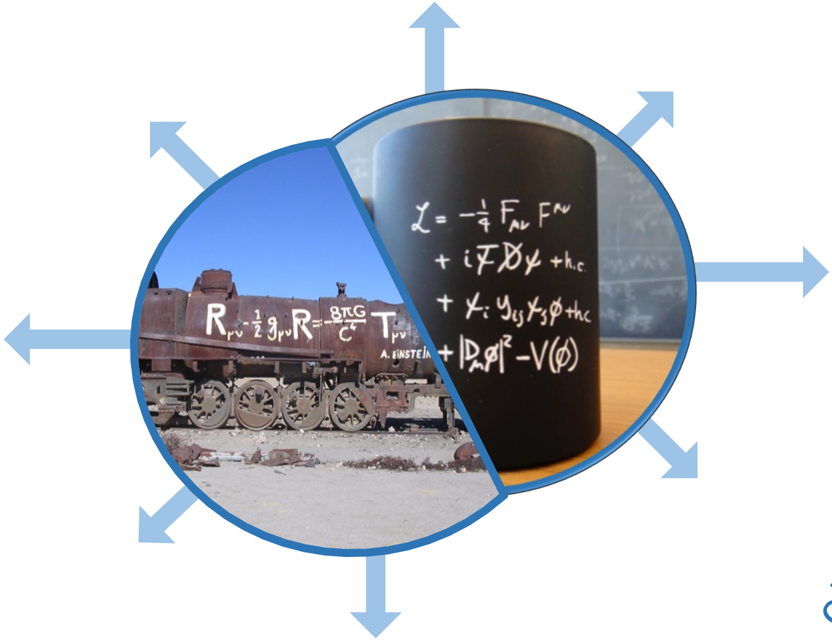
The Standard Model of particle physics has alarming symptoms… and at the same time it is perfectly healthy.

WHERE WILL WE FIND THE REMEDIES?

higher energy interactions
in the lab

earlier universe

rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

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The landscape of particle physics colliders

$e^{\pm}p$ (and $e^{\pm}A$)

ERL technology (E_e ~ 30-60 GeV)

E_{CMS} > 1 TeV

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

~1B EUR

~7-12B EUR

e^+e^-

RF technology

E_{CMS} ~ 10 GeV (flavour)

E_{CMS} ~ 90-360 GeV (Z/W/H/top)

E_{CMS} > 500 GeV

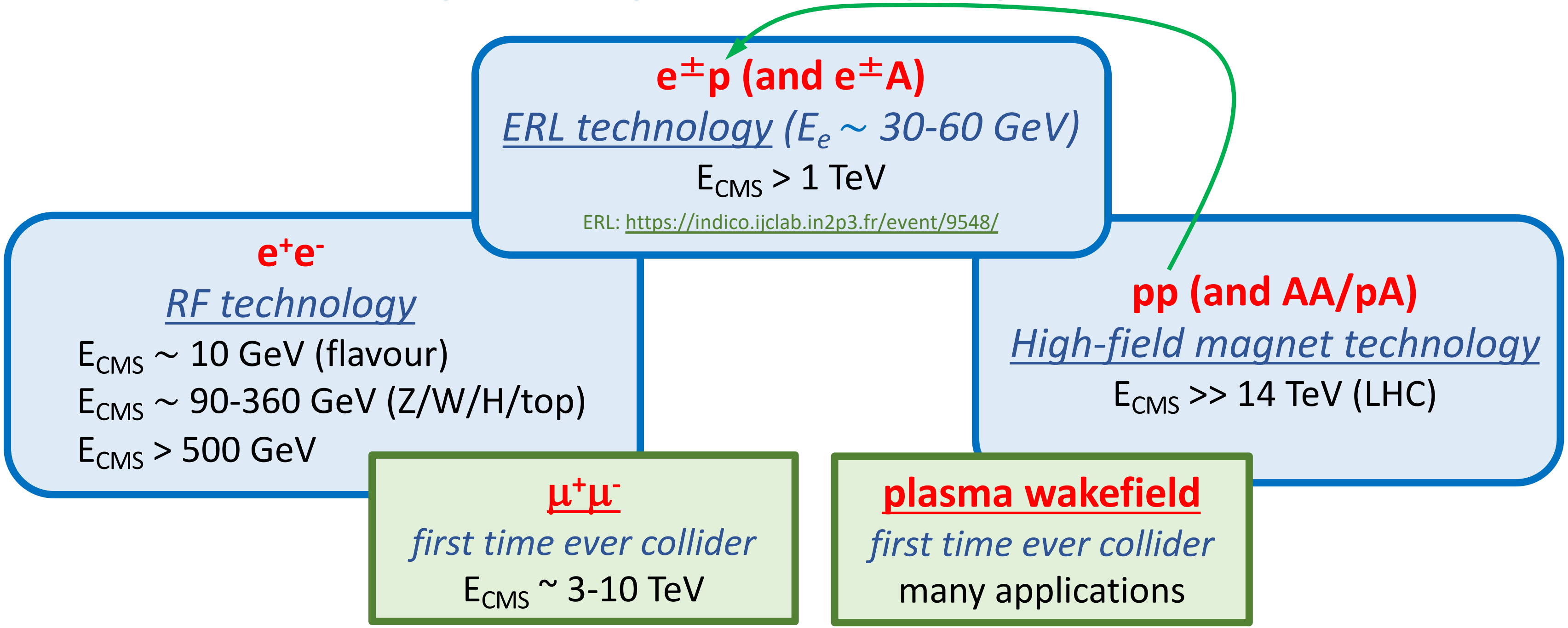
~15-20B EUR

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

The landscape of particle physics colliders



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

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FOCUS

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High-field magnet technology

$E_{CMS} \gg 14$ TeV (LHC)

$\mu^+\mu^-$

first time ever collider

$E_{CMS} \sim 3\text{-}10$ 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

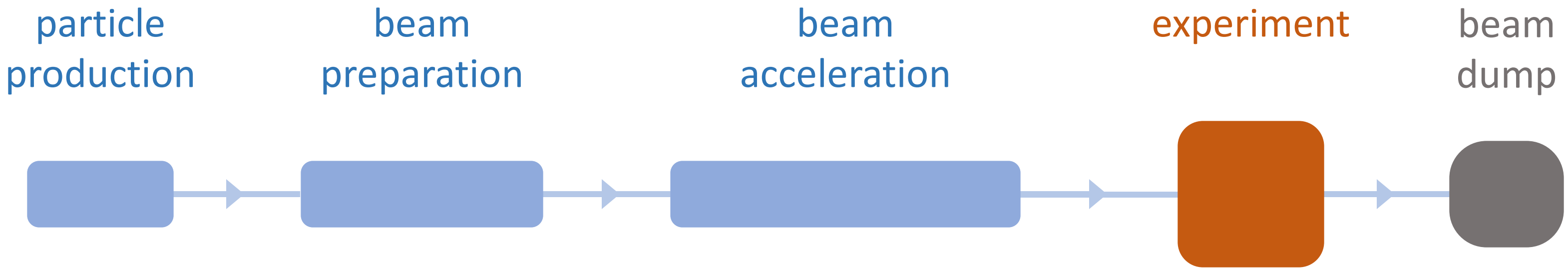
CERN Yellow Rep. Monogr. 1 (2022) 1-270, https://cds.cern.ch/record/2800190?ln=en

Caveat

power requirements of future colliders

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

Basic structures of a particle accelerator



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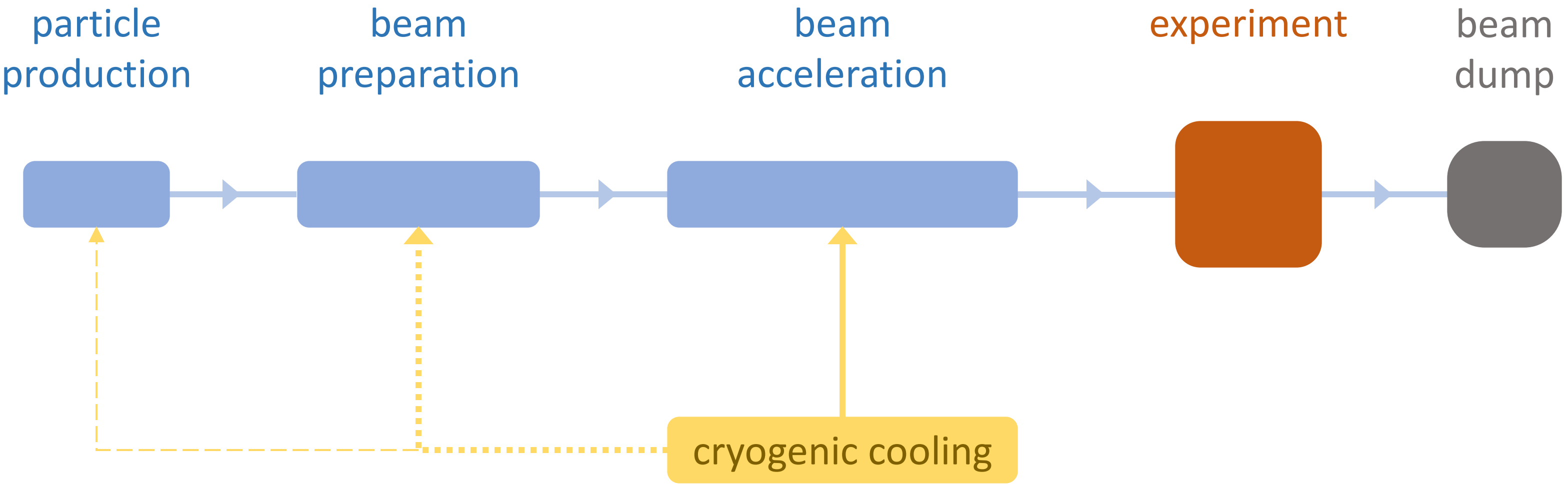

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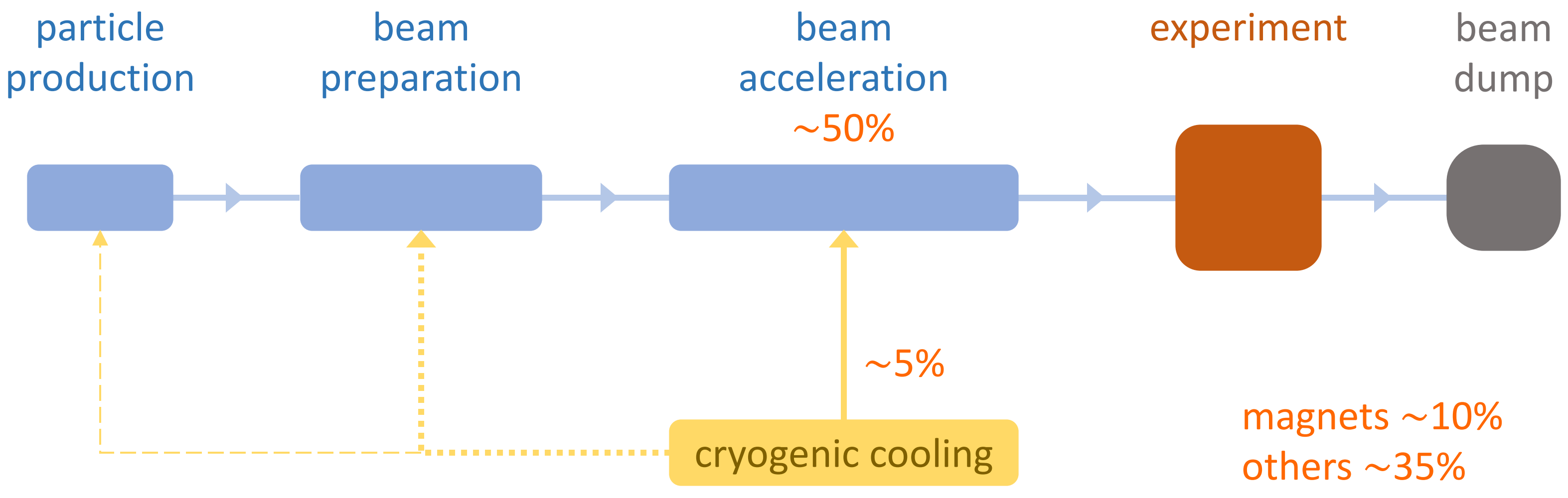


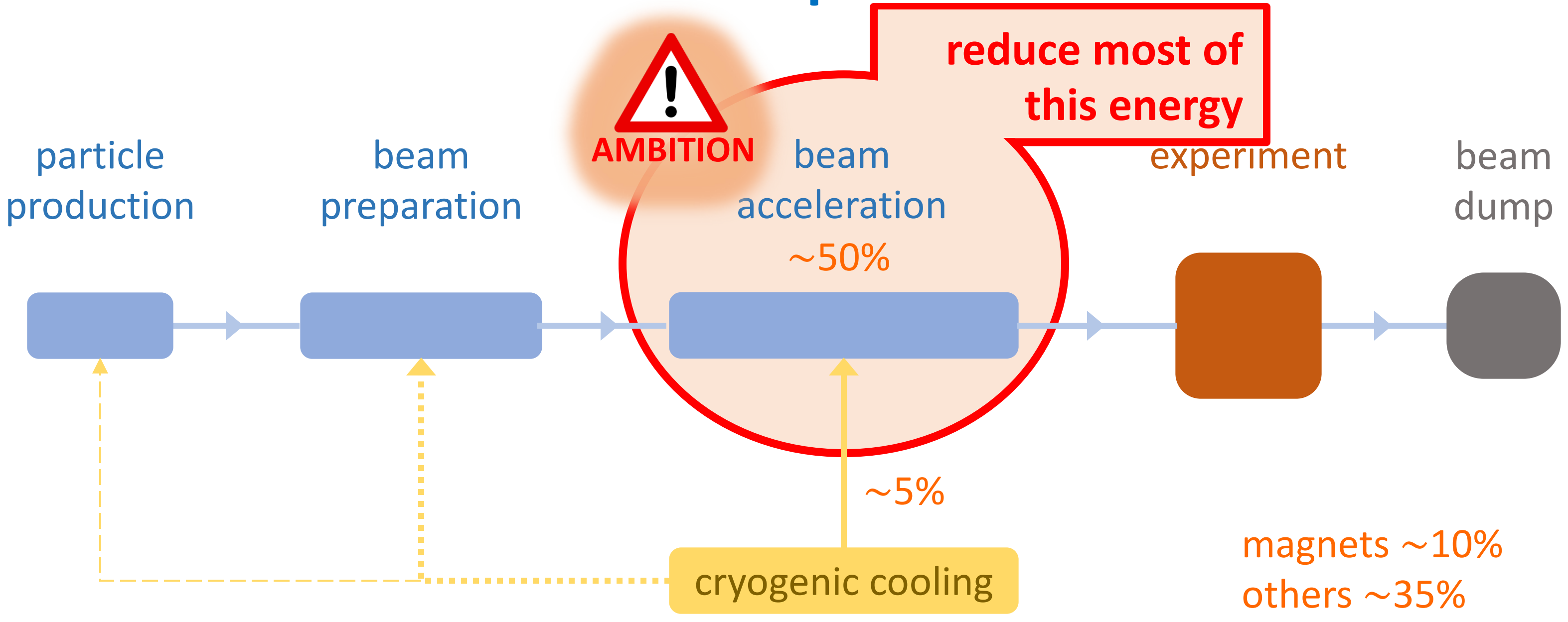
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

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

Basic structures of a particle accelerator



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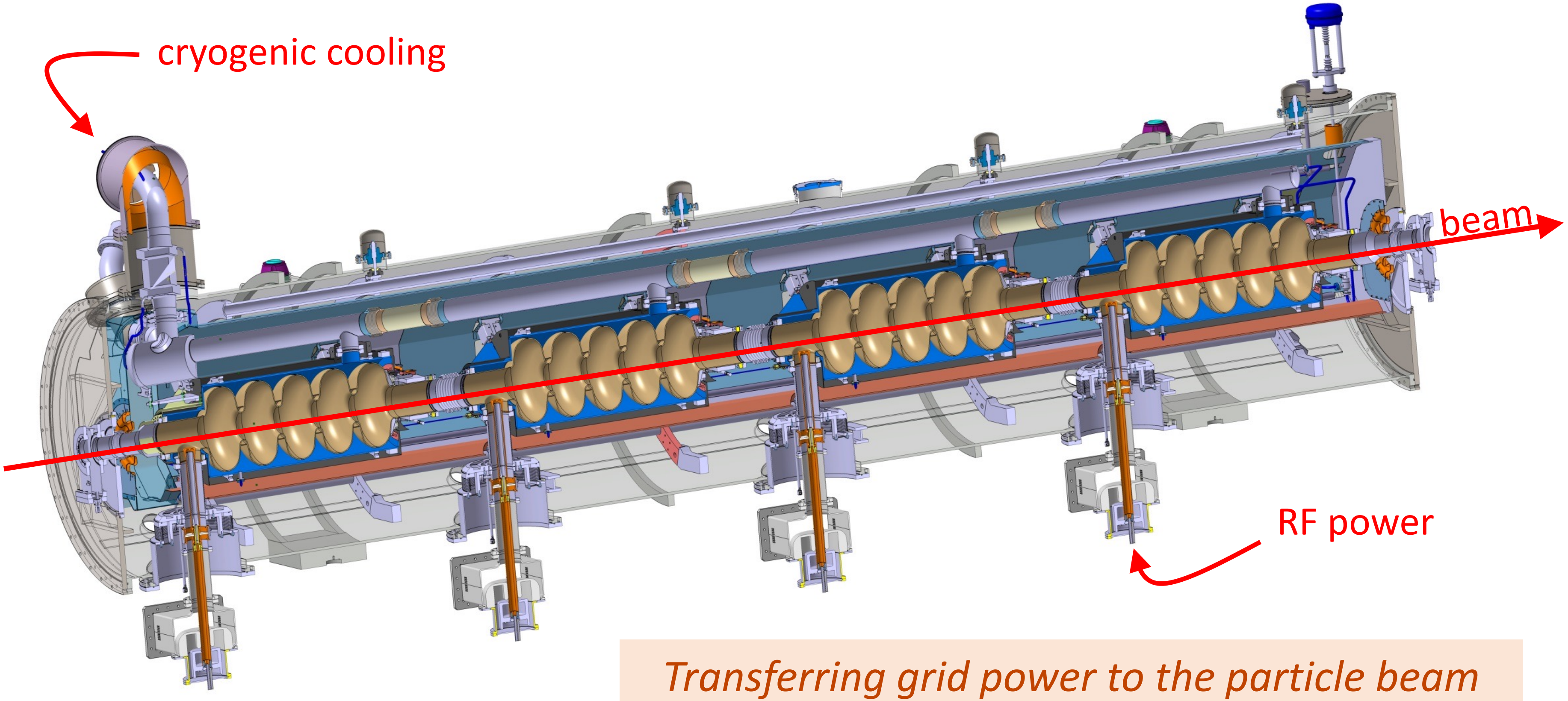
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency



Transferring grid power to the particle beam

Key building block for beam acceleration: the SRF cryomodule

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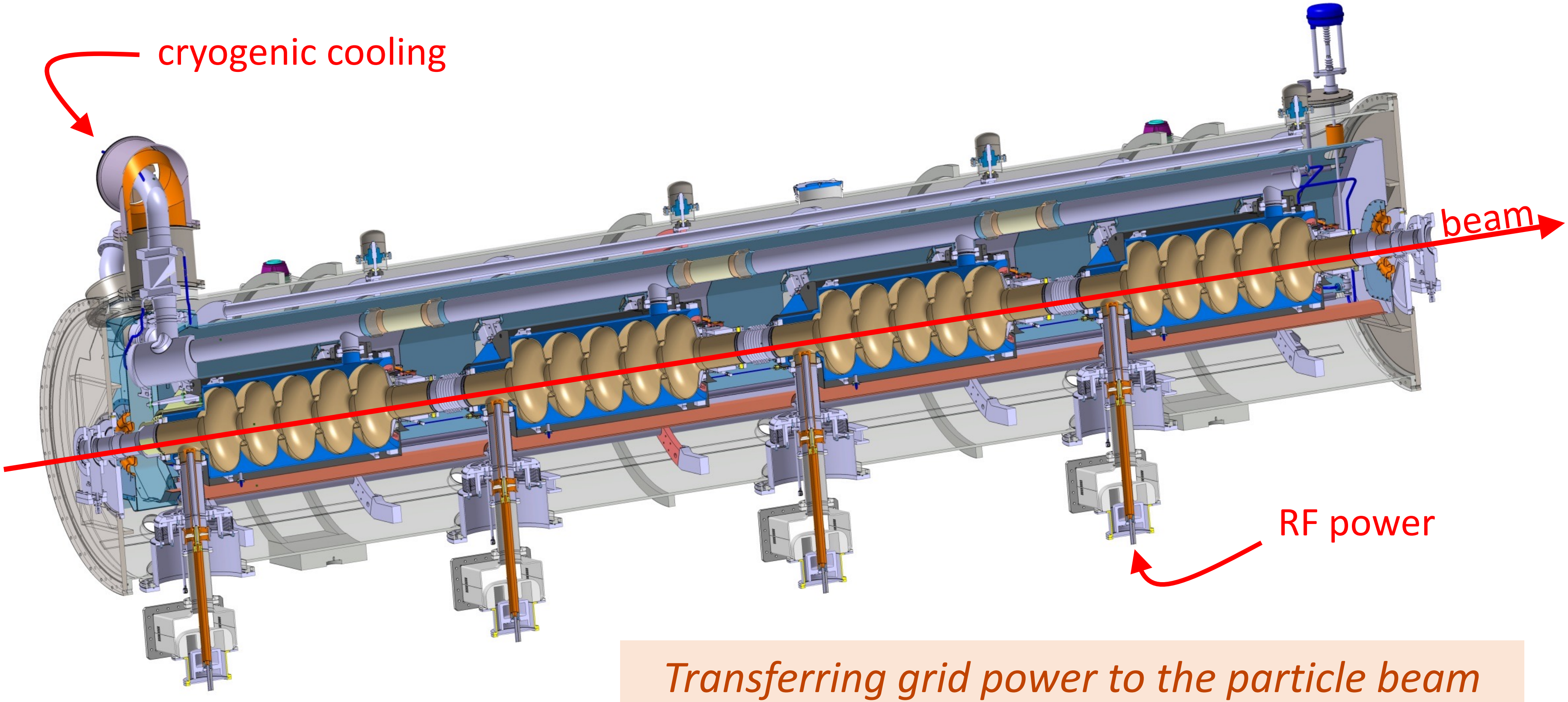

Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

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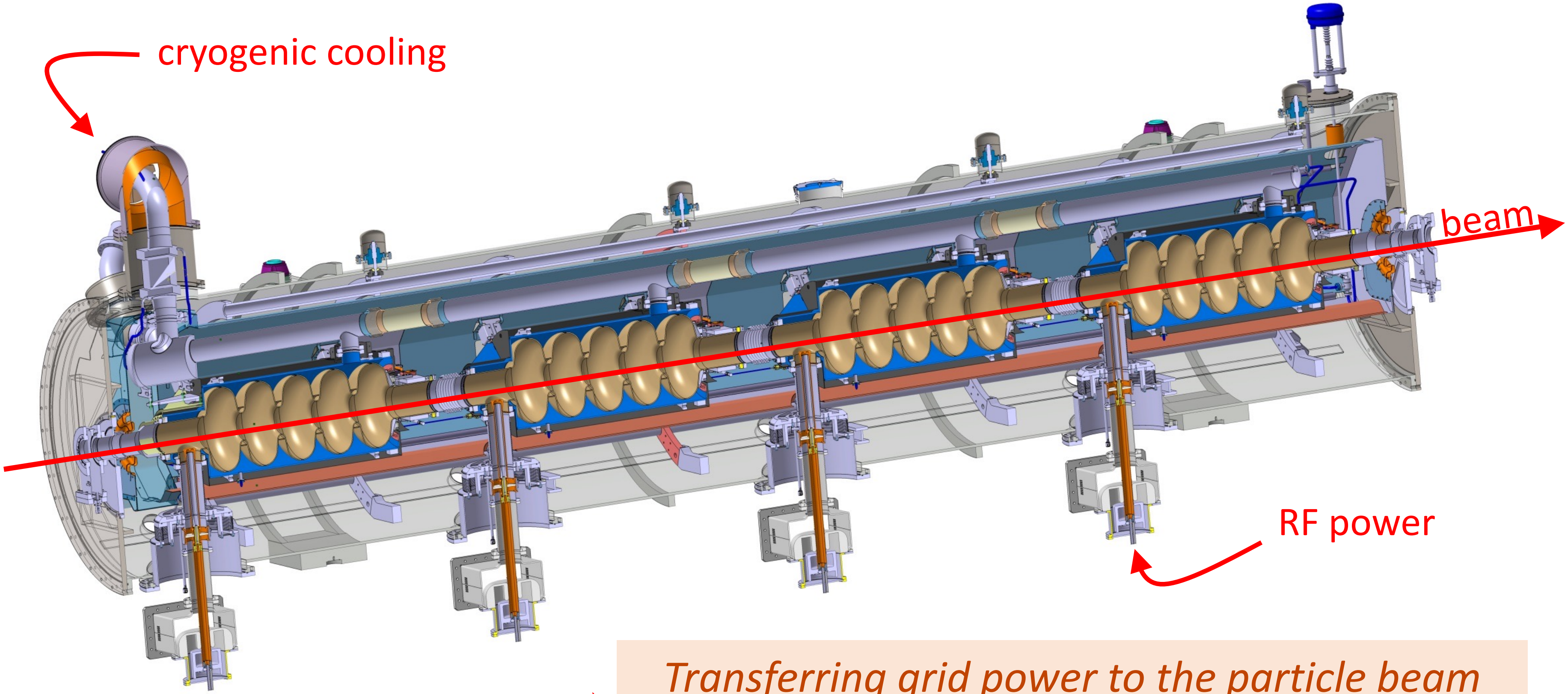
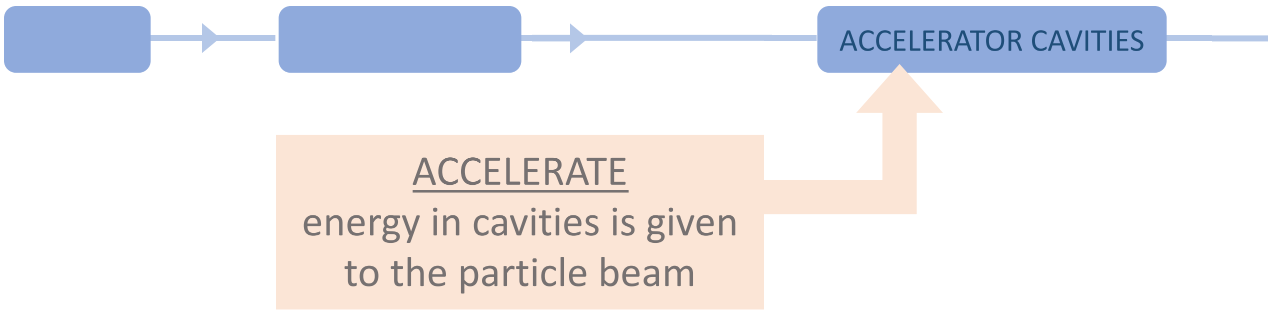


ENERGY RECOVERY →

Transferring grid power to the particle beam

RECOVER THE ENERGY FROM THE USED BEAM

The principle of Energy Recovery



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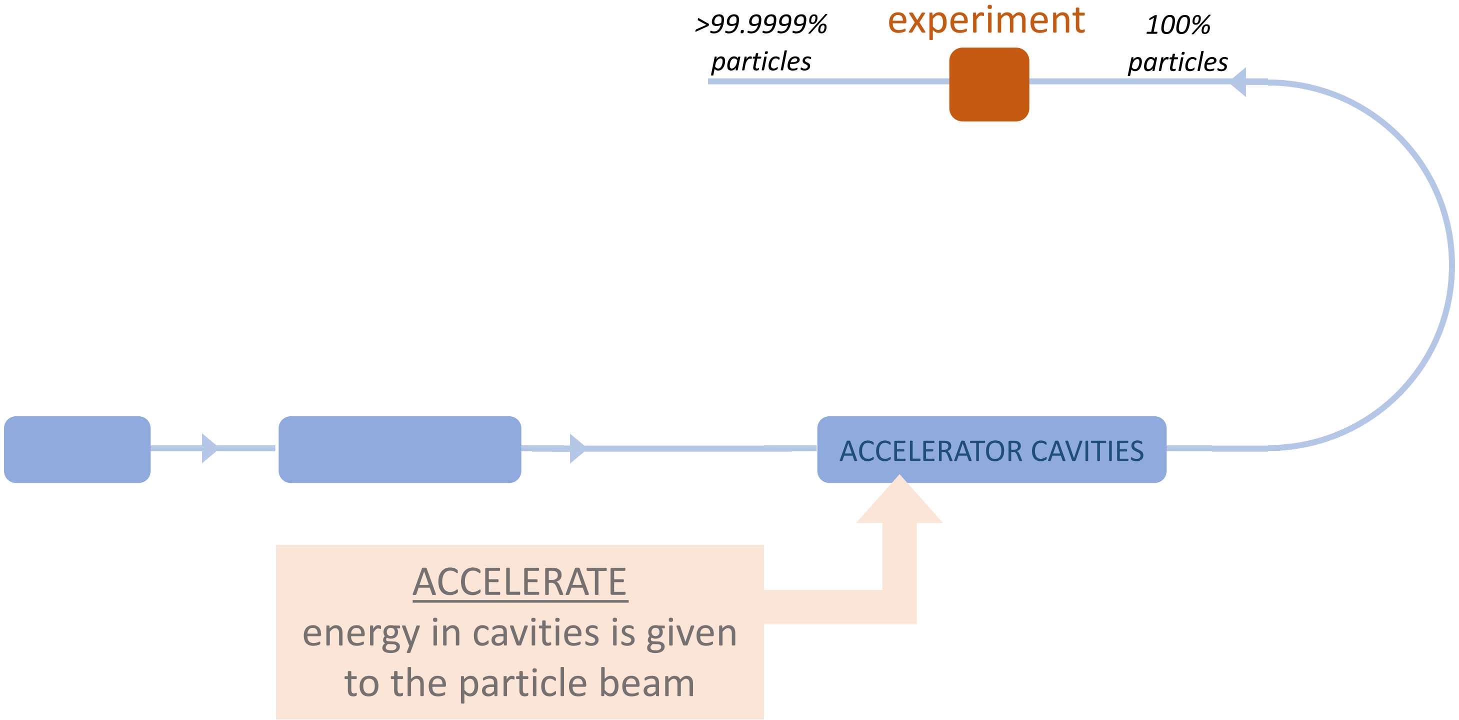

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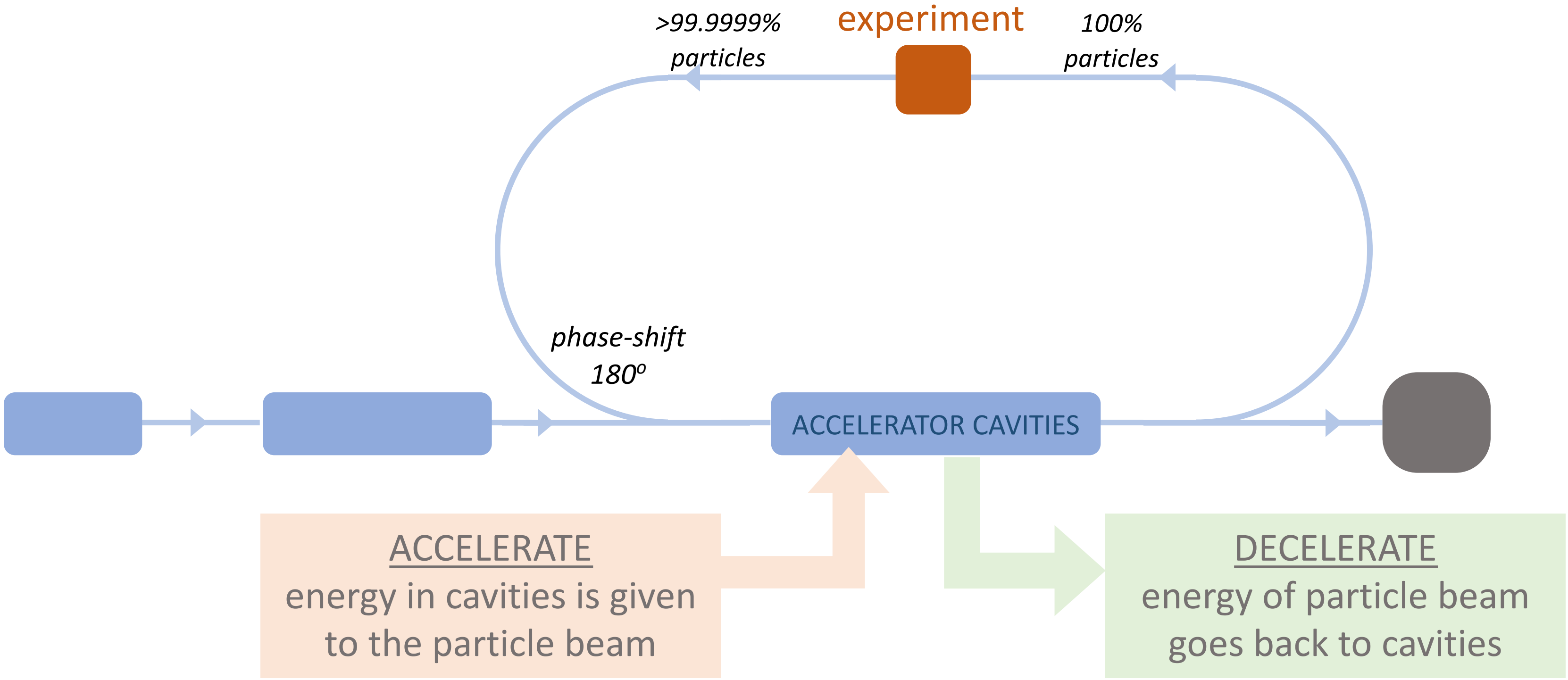

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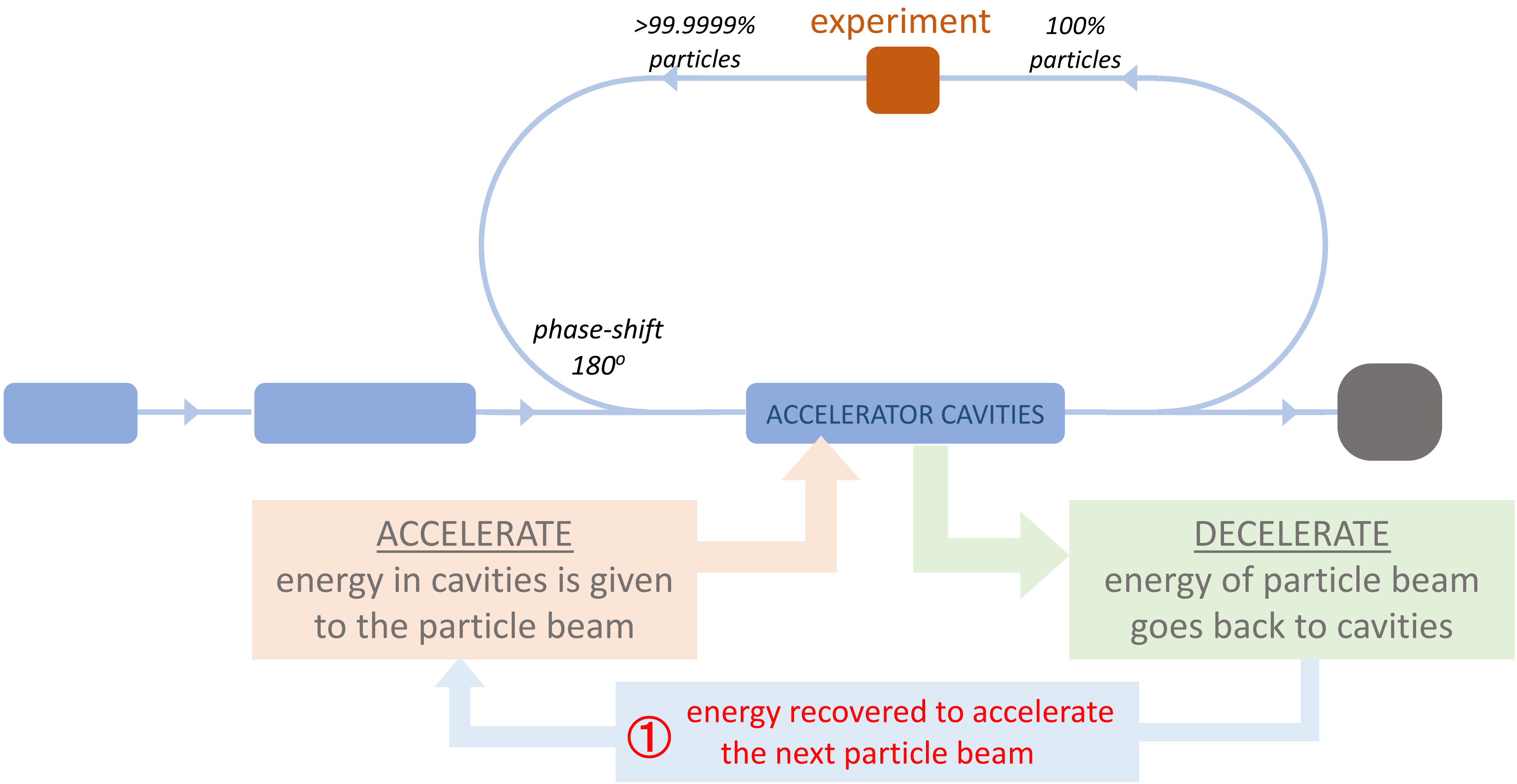

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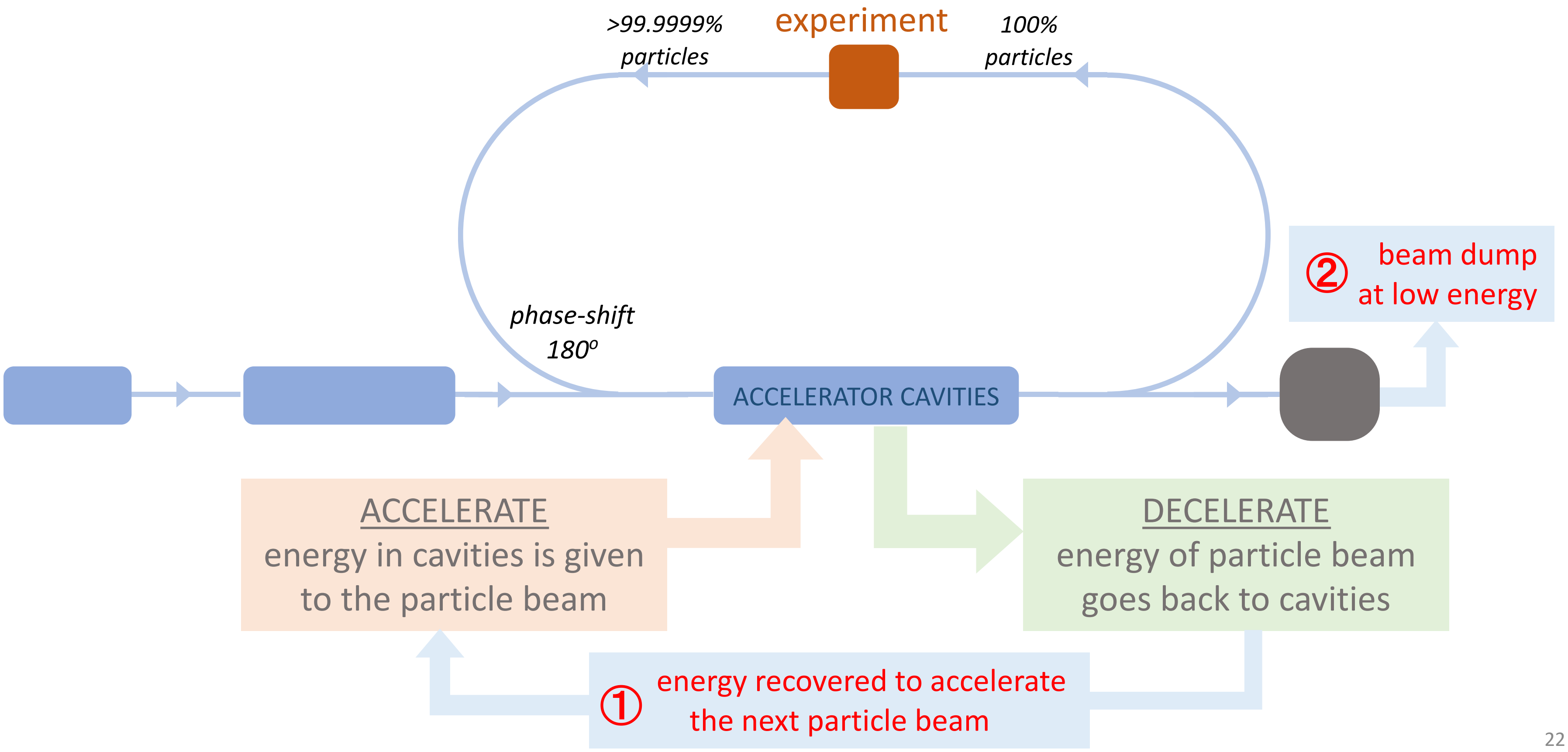

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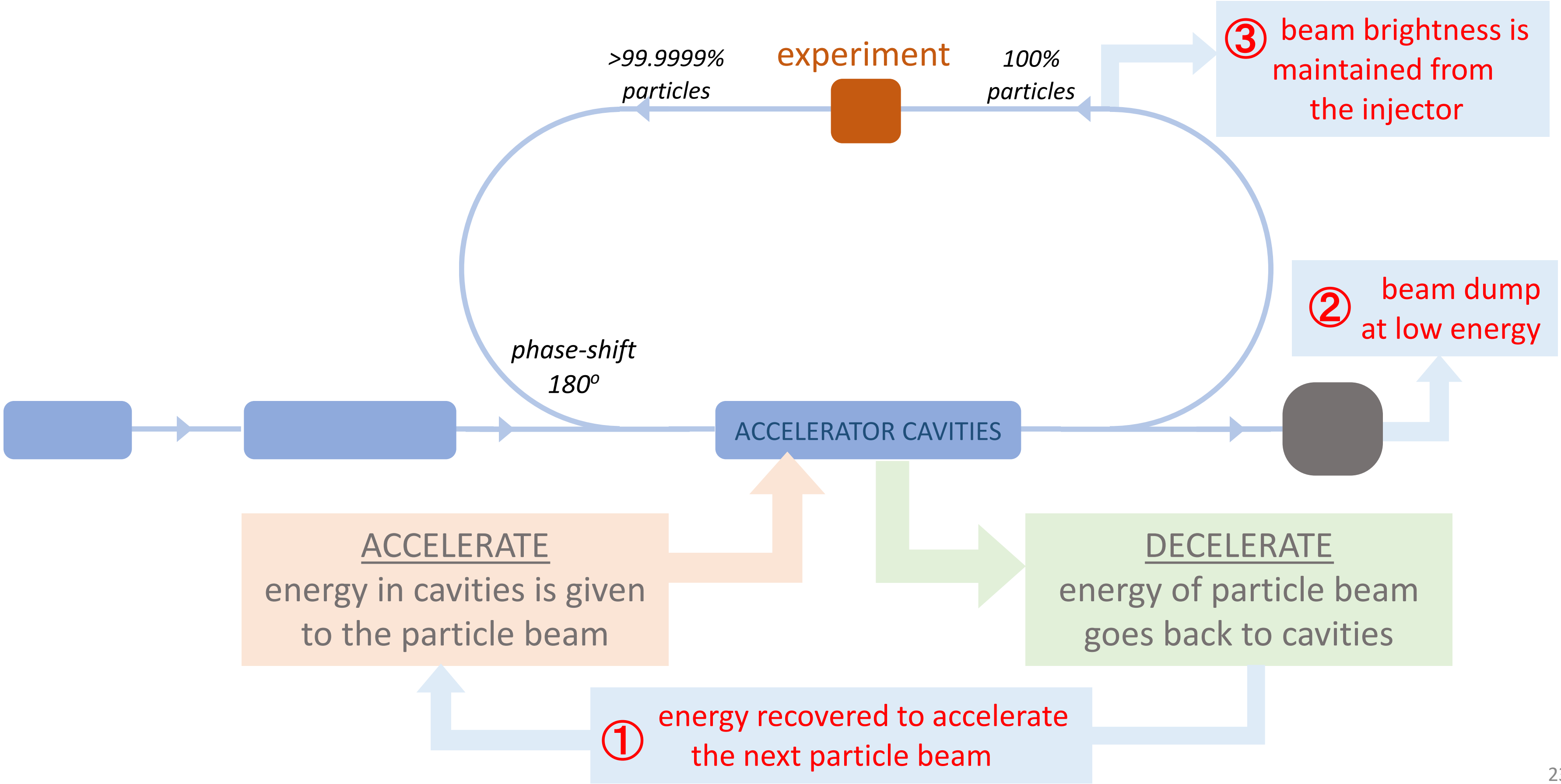

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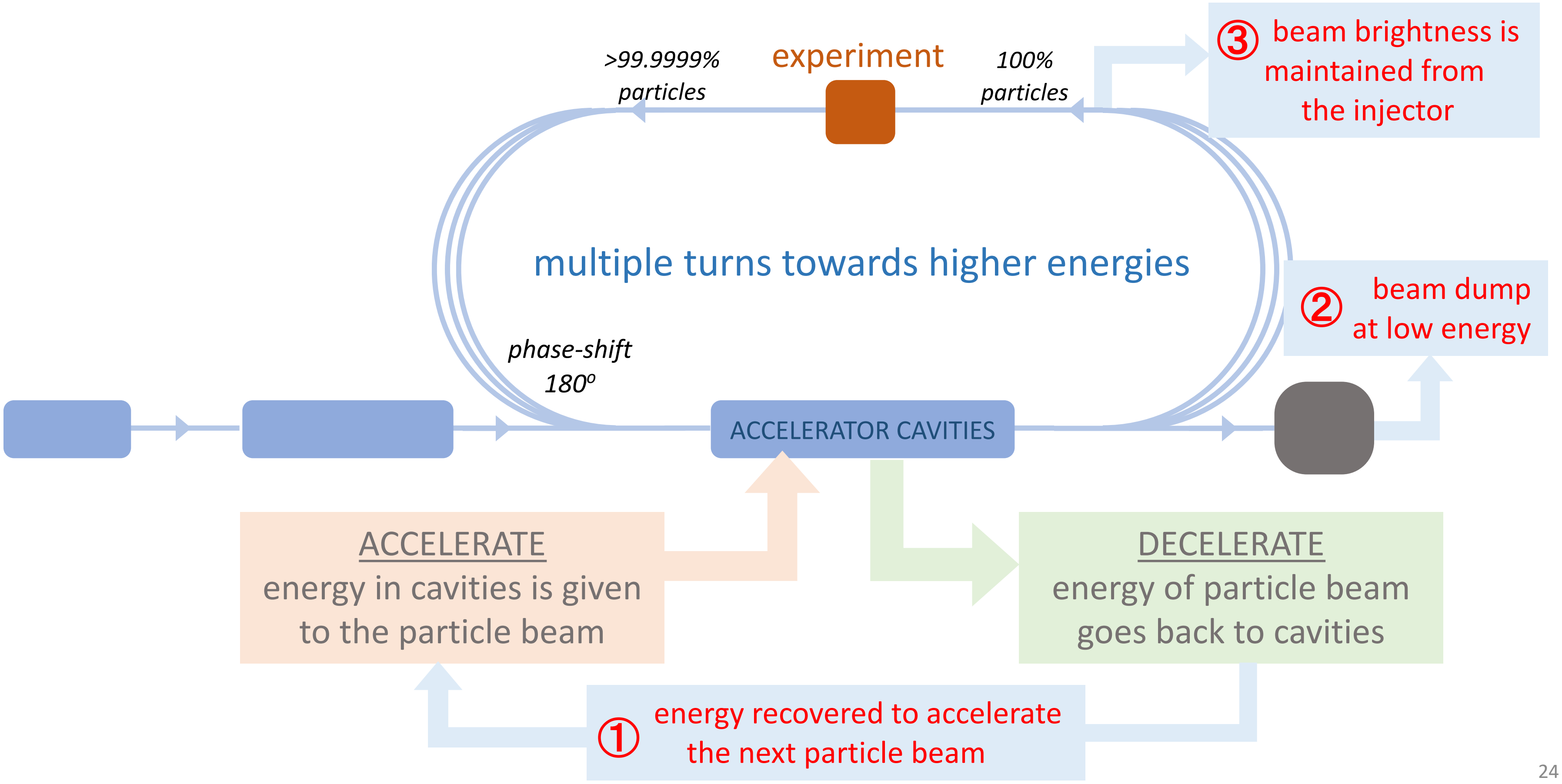

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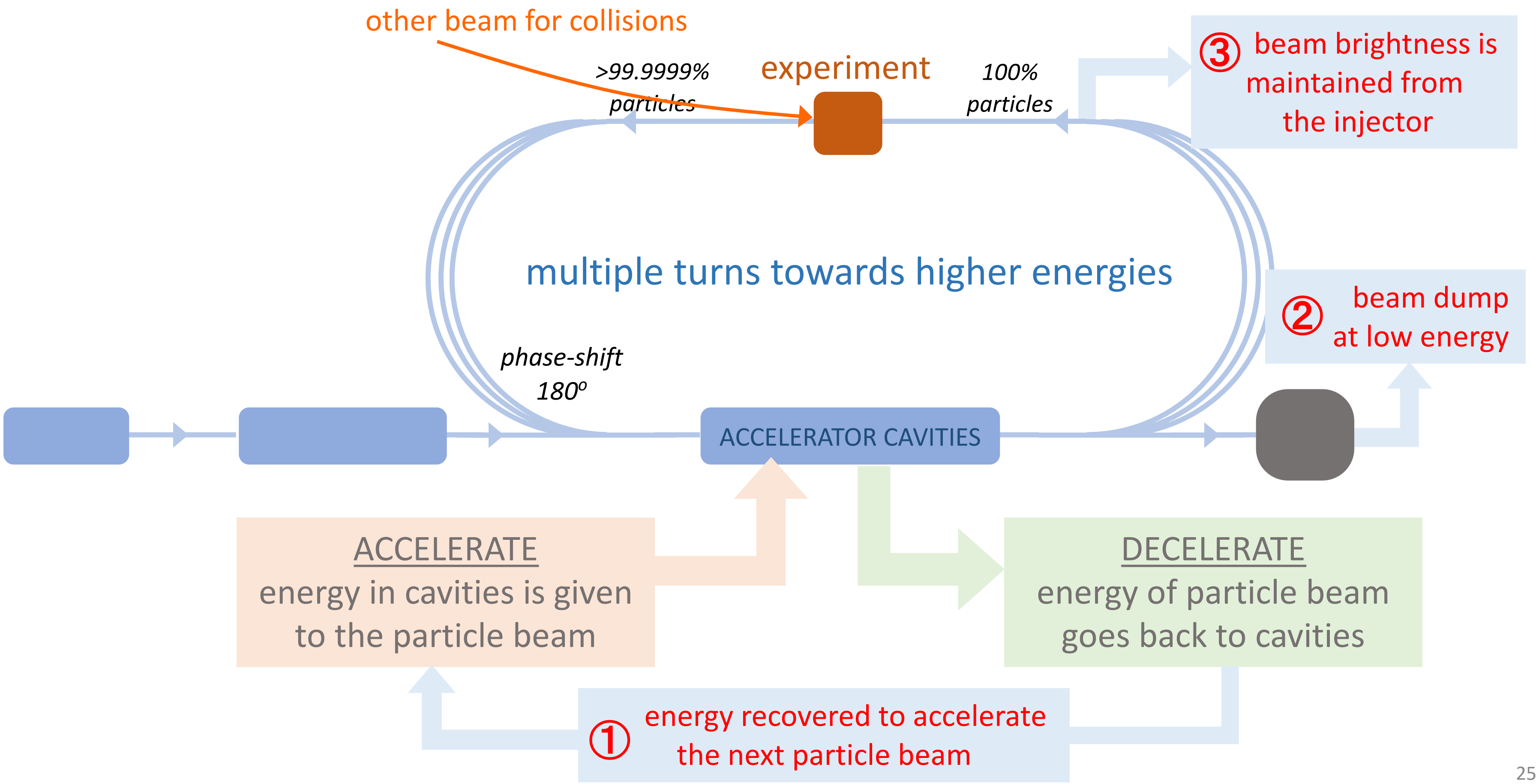

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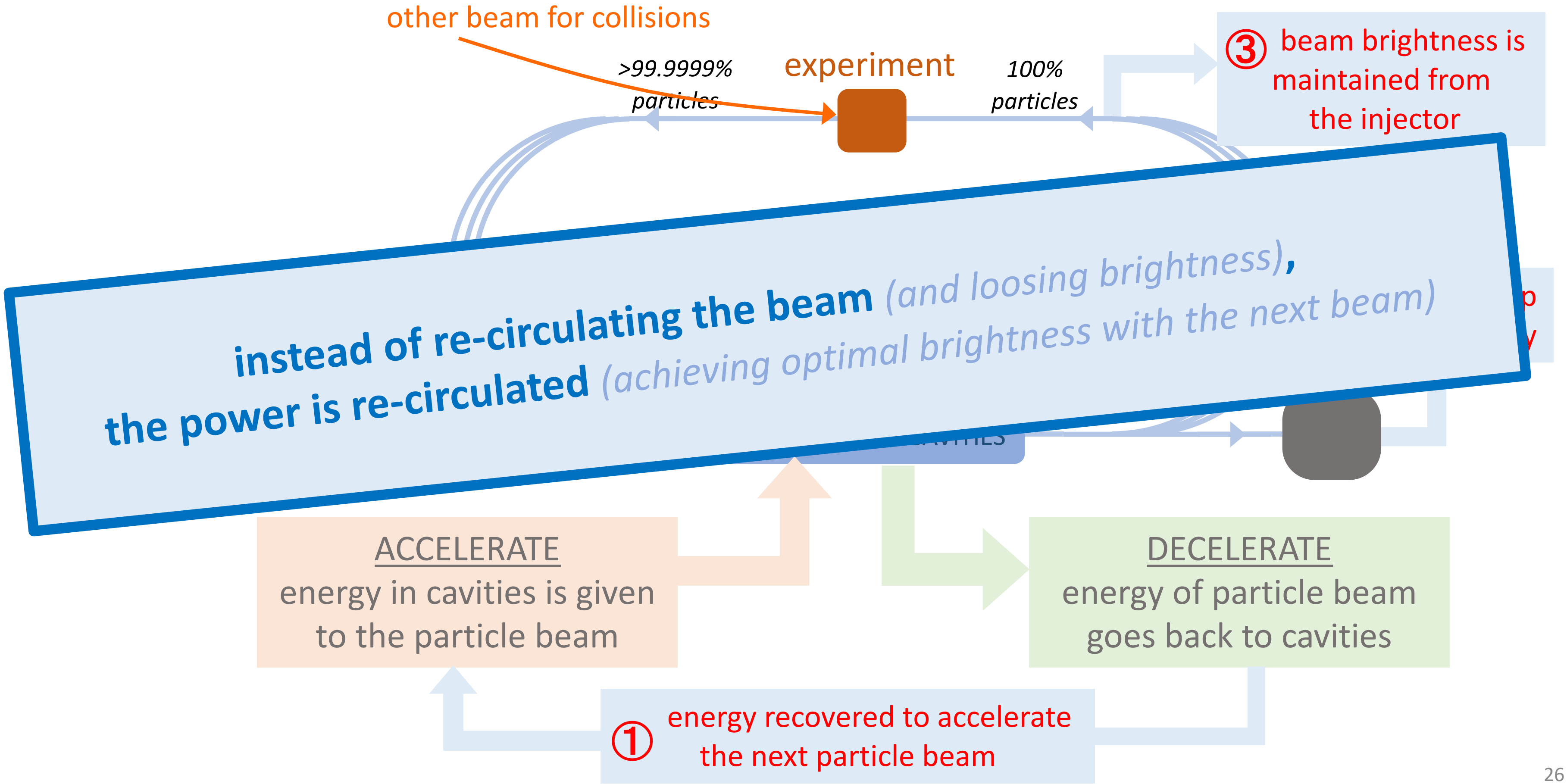

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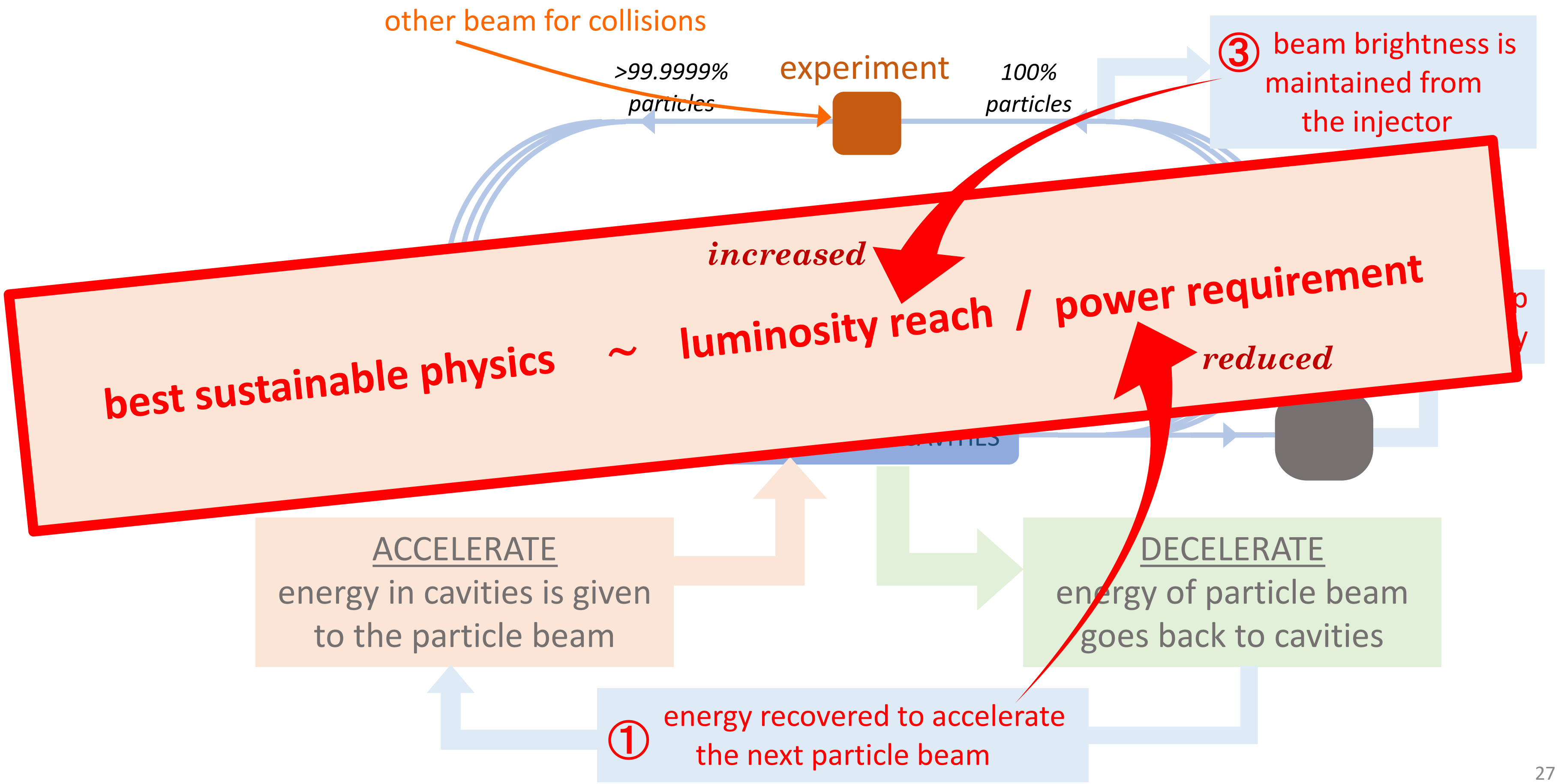
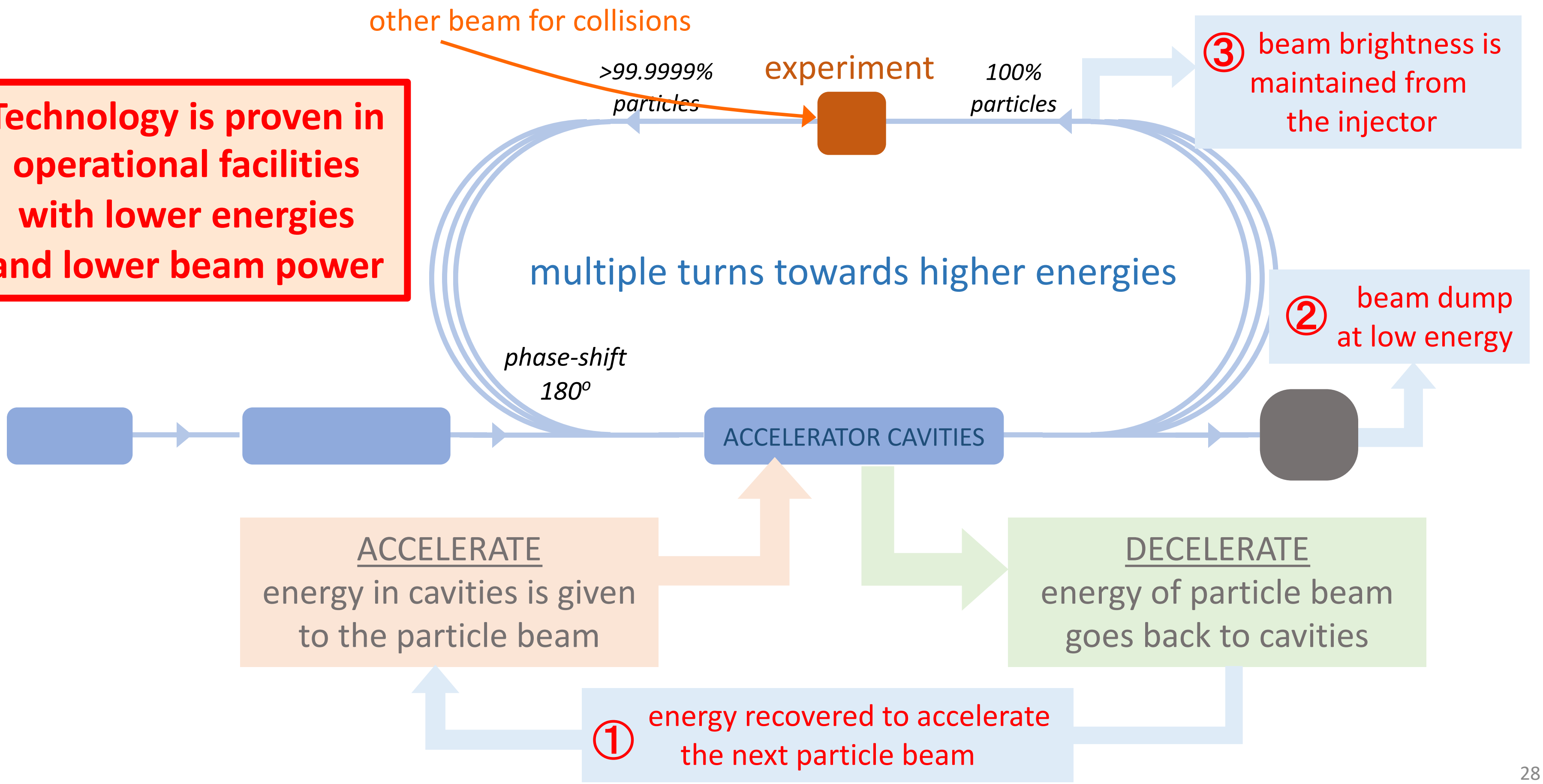
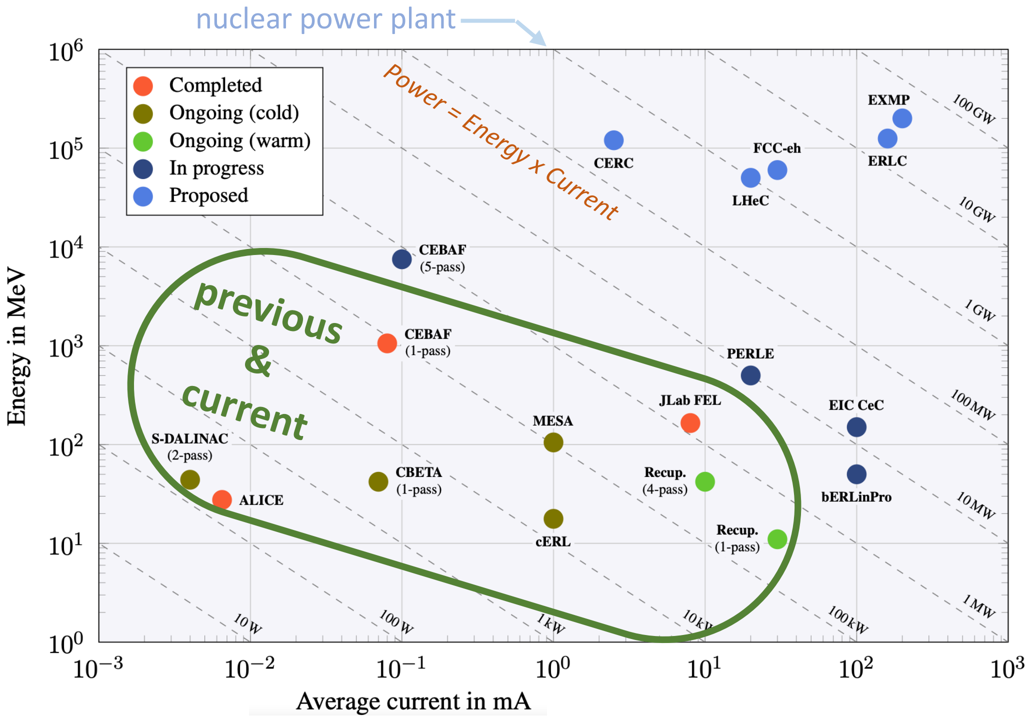


The principle of Energy Recovery

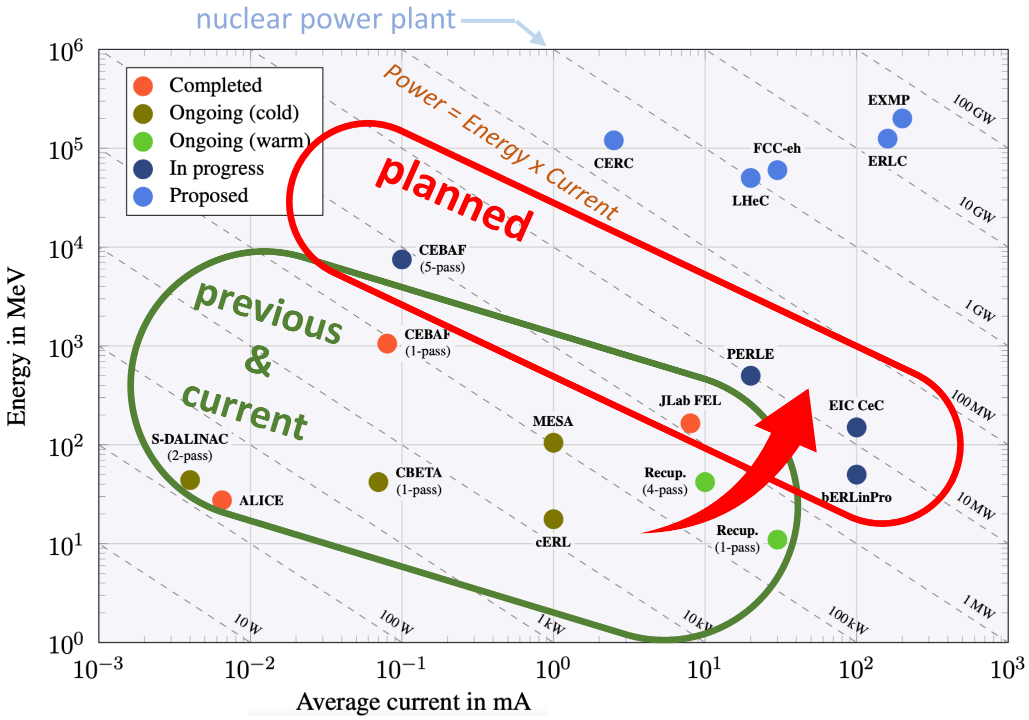
Technology is proven in operational facilities with lower energies and lower beam power





Energy Recovery demonstrated

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



bERLinPro & PERLE

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

towards high energy & high power

Energy Recovery demonstrated

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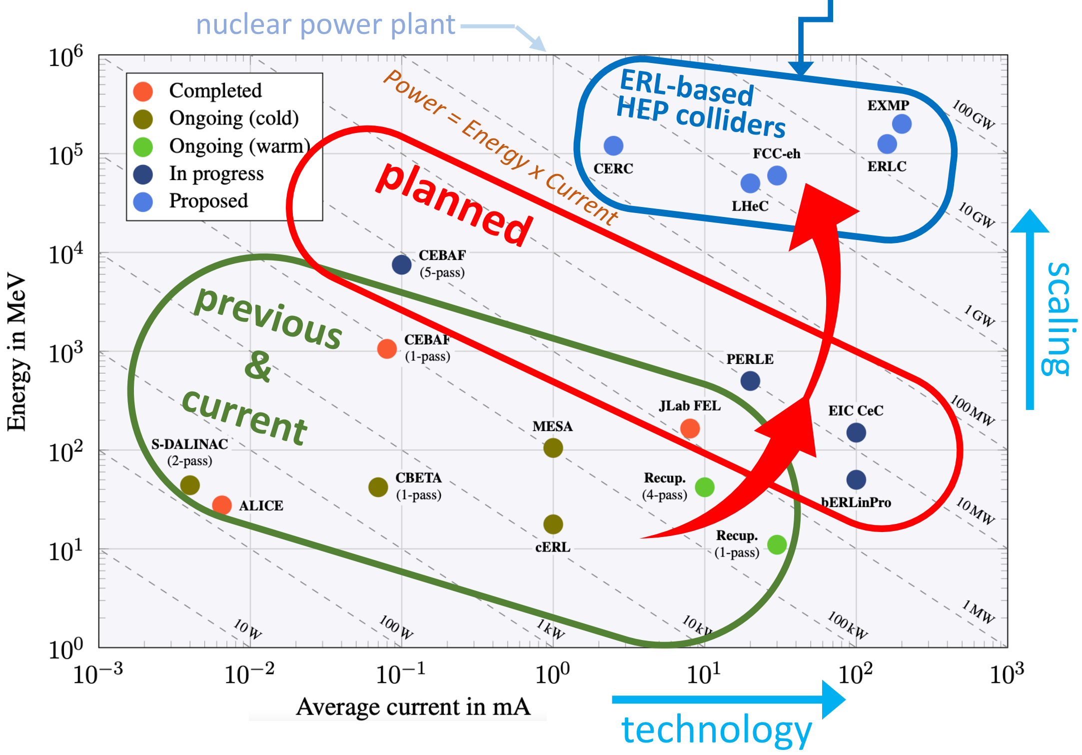
ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Future ERL-based Colliders

H, HH, ep/eA, muons, …

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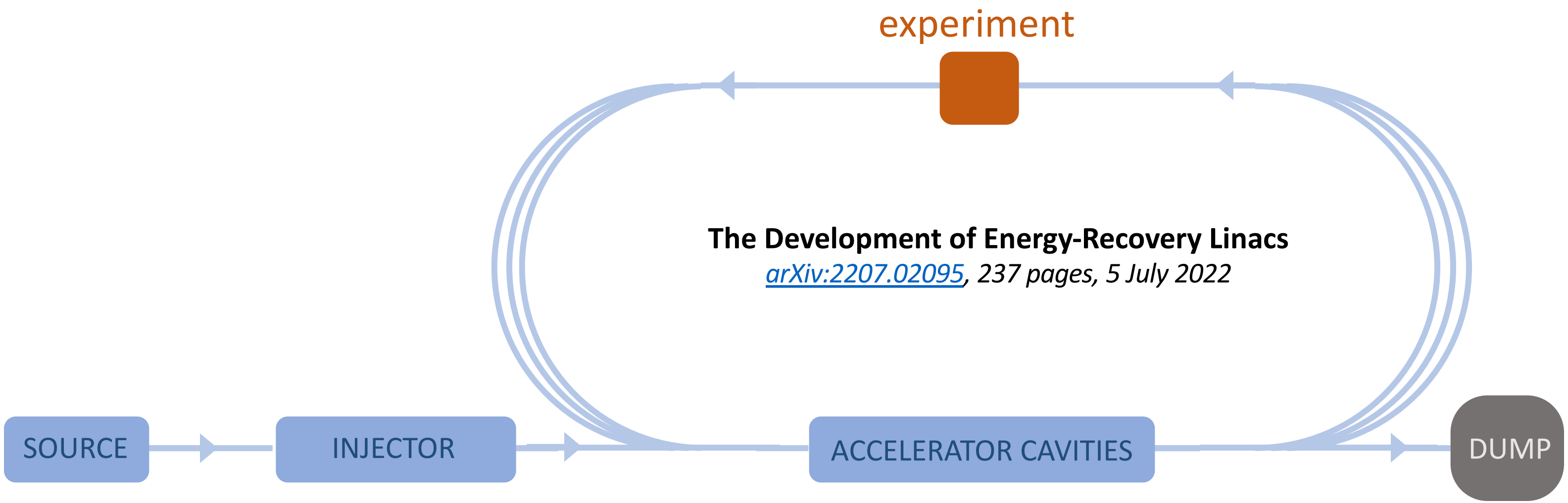
Identified the key R&D aspects for an ERL accelerator

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



The Development of Energy-Recovery Linacs

arXiv:2207.02095, 237 pages, 5 July 2022

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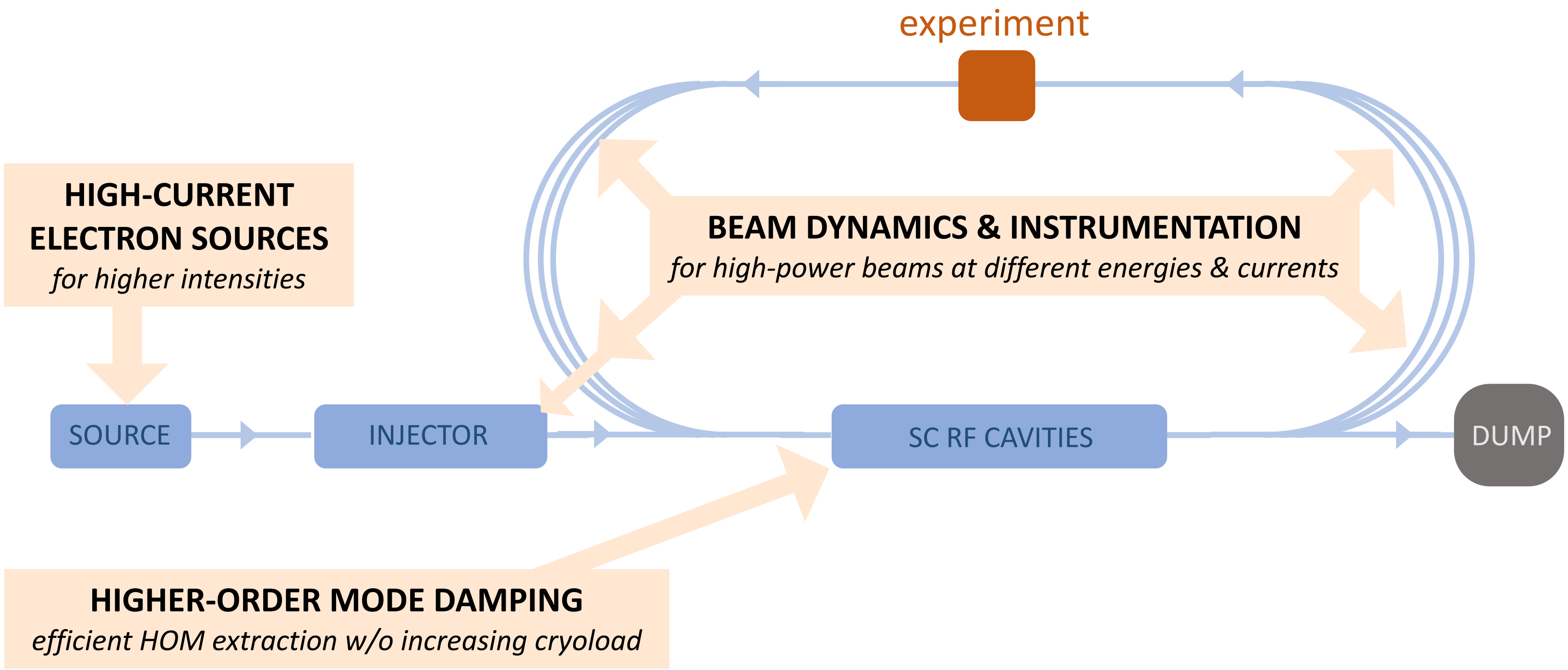

ENABLE EFFICIENT ENERGY RECOVERY

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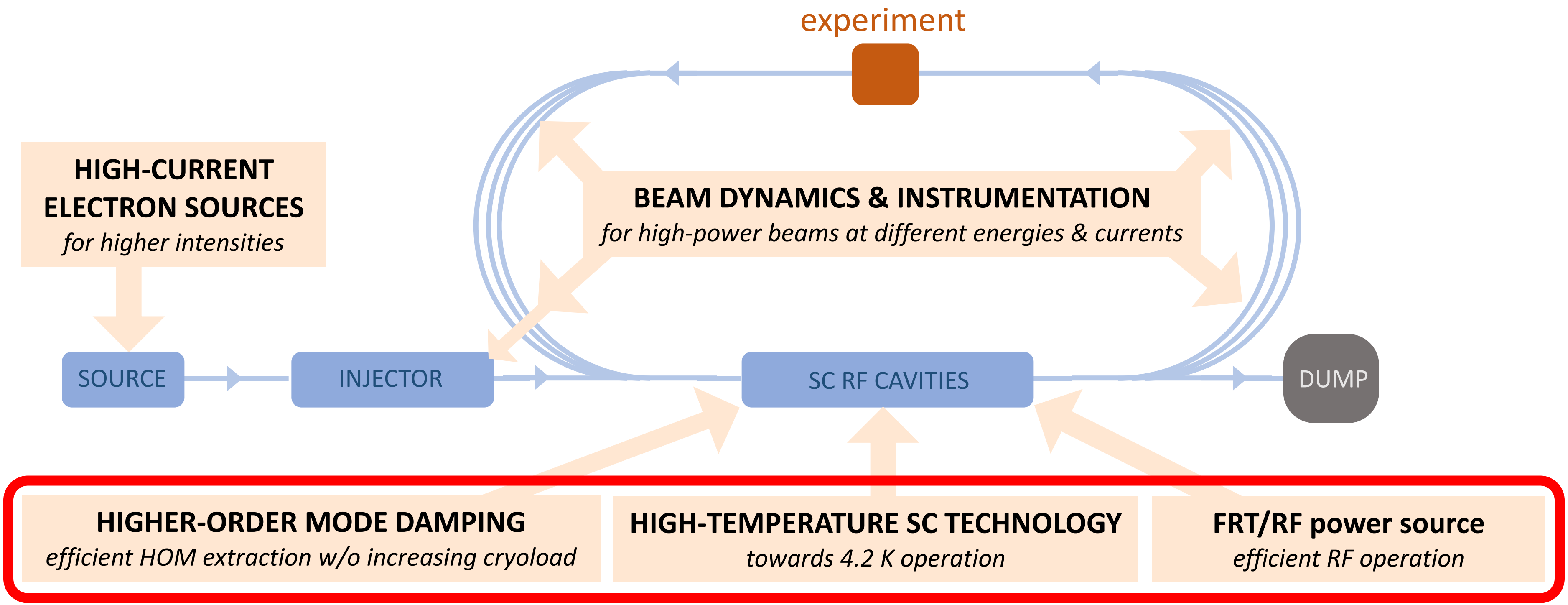

ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

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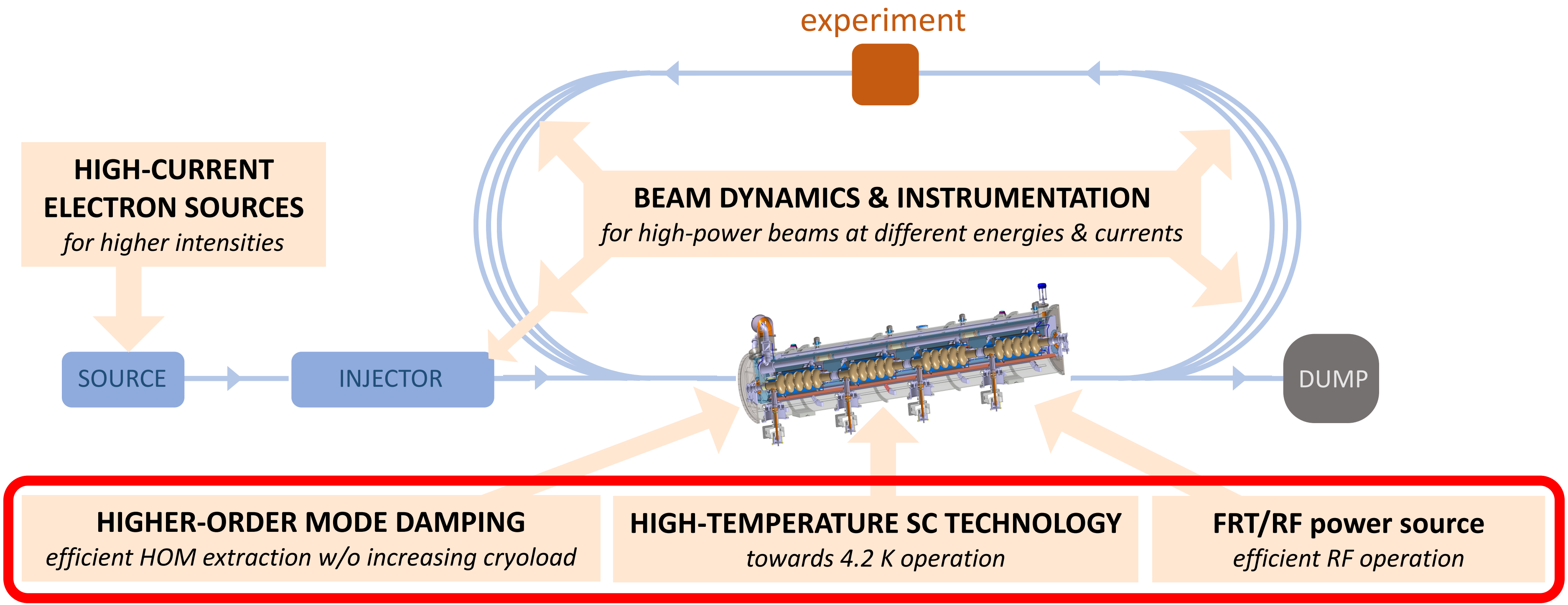


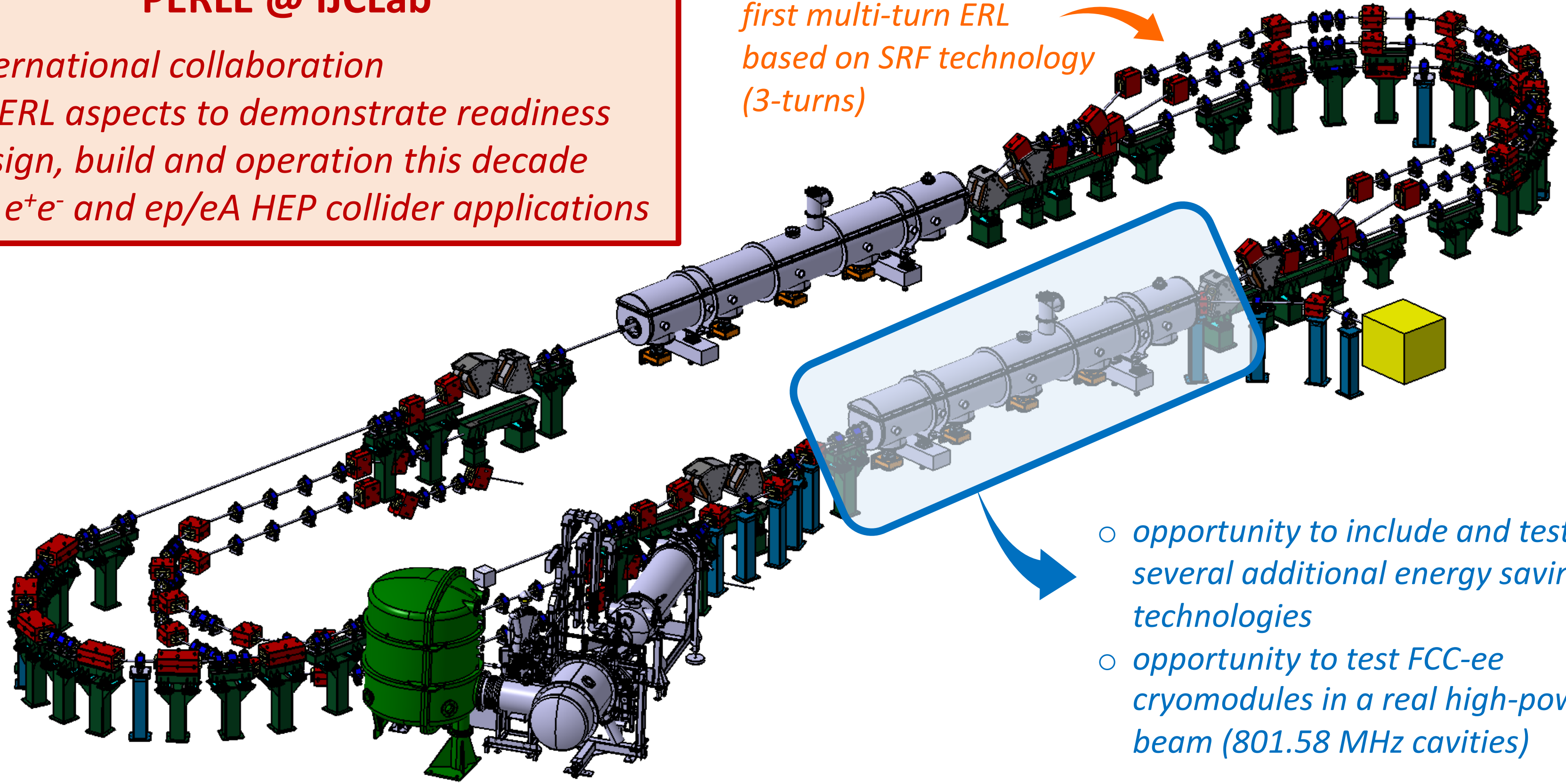
ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

Demonstrate readiness of ERL technology for high-power applications in HEP

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*

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



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

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

Accelerator R&D for Particle Physics
Energy Recovery Linacs

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

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

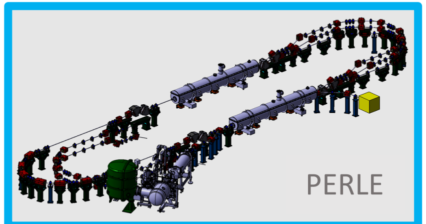
WHERE WILL WE FIND THE REMEDIES?

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

Potential impact of ERL technology

Potential impact of ERL technology

2020'ies

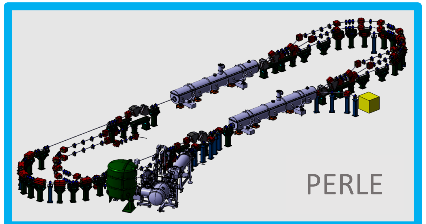


high-power ERL demonstrated

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies



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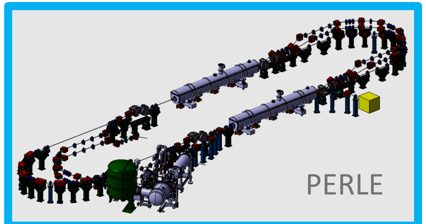

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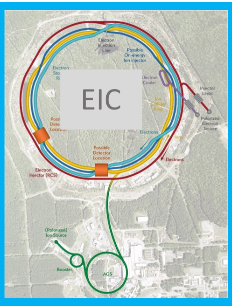

ERL application electron cooling

Potential impact of ERL technology

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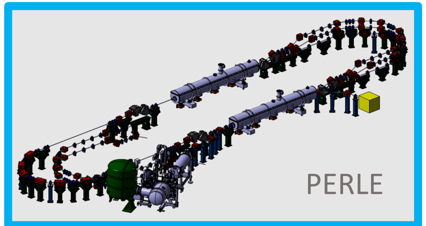

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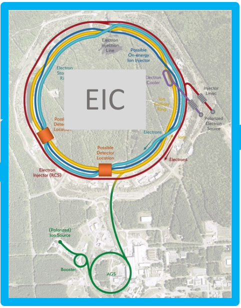
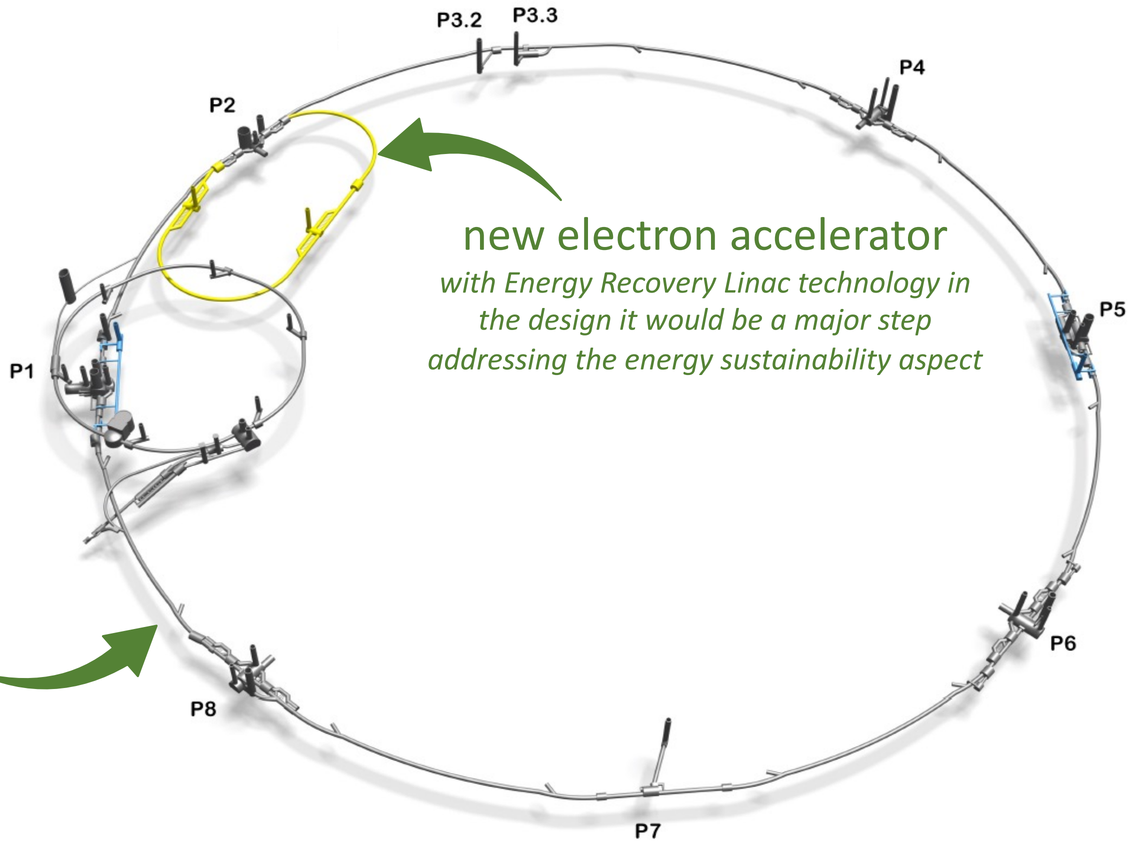


ERL application electron cooling

Ready for high-energy and high-luminosity ep/eA collisions

ERL-based ep/eA colliders at CERN

paradigm shift with ERL
high-energy & high-luminosity 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

(LHeC and/or FCC-eh)

The challenge

high-intensity electron beam

From HERA to LHeC/FCC-eh

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

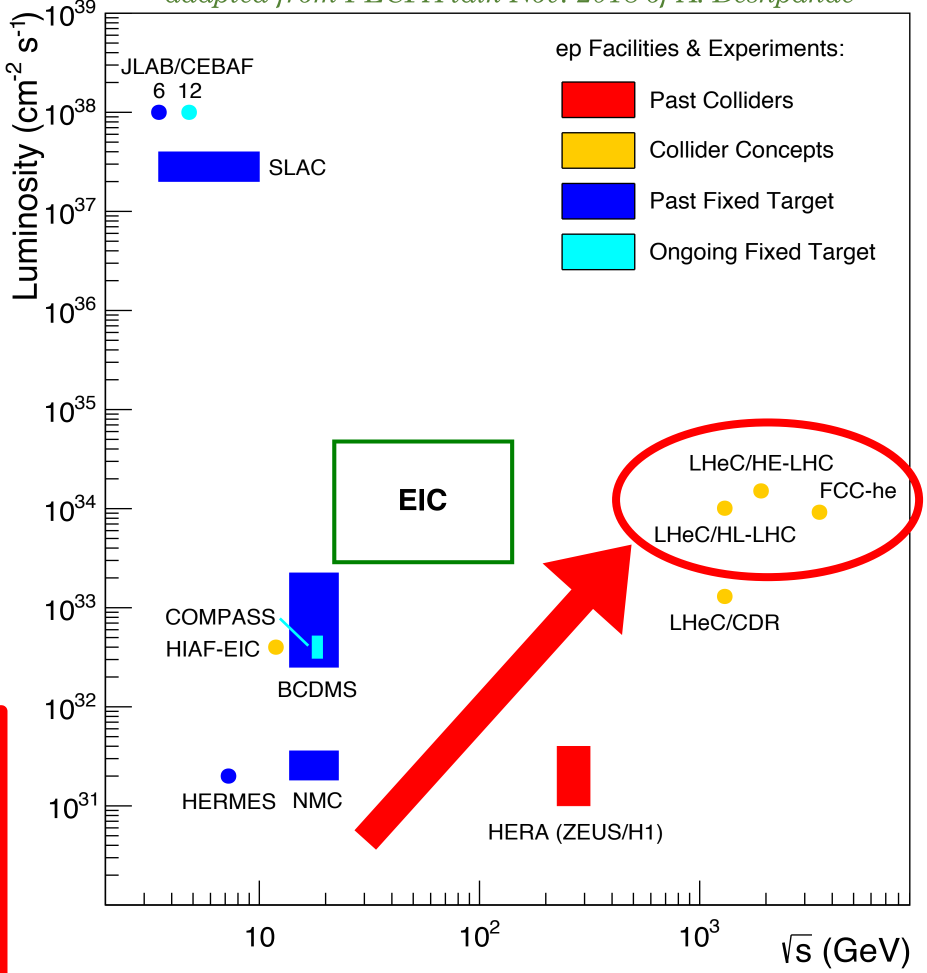
beam current × beam energy
= beam power

LHeC/FCC-eh ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant

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



Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

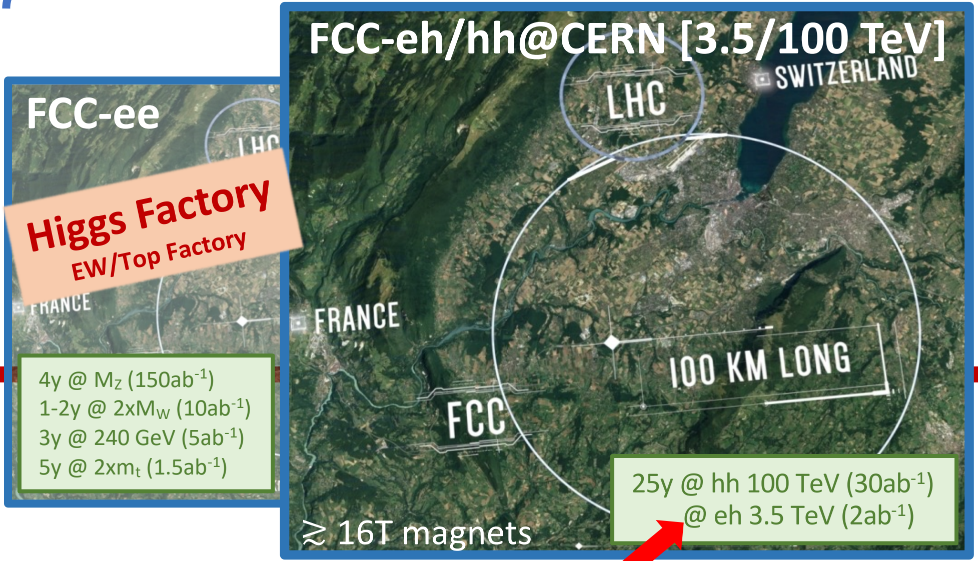
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

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

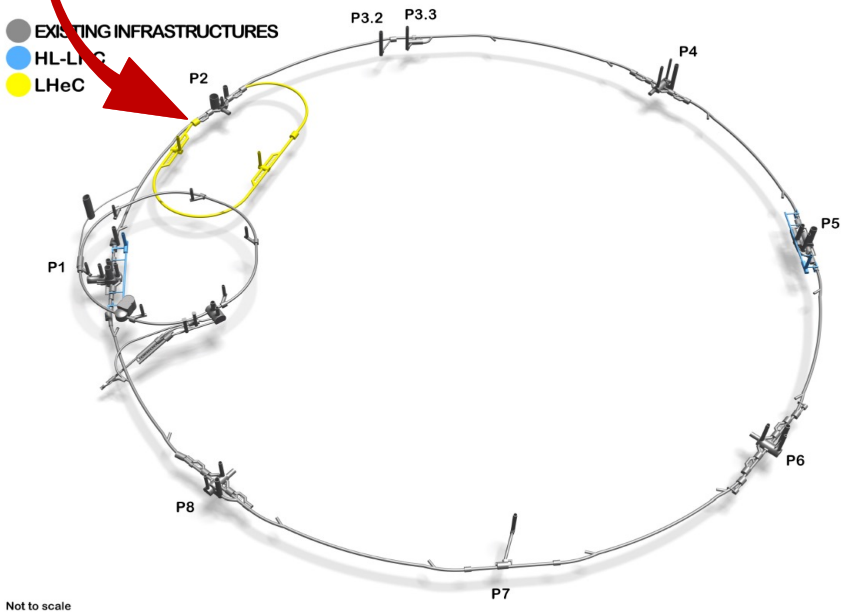
updated CDR: J.Phys.G 48 (2021) 11, 110501

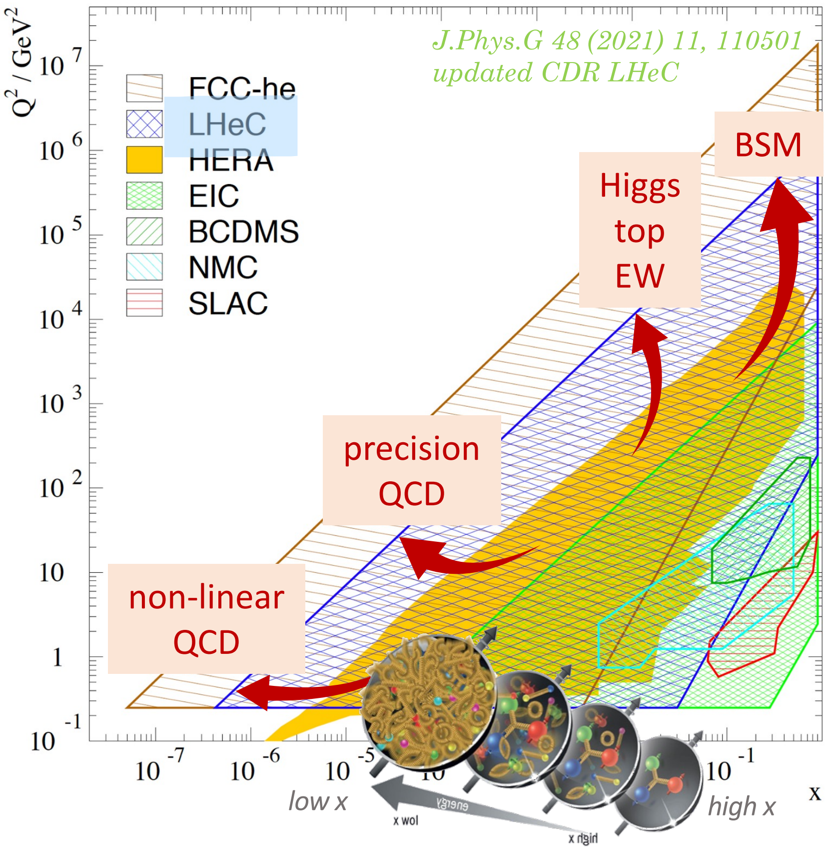


numbers assume 2 IPs for each collider (only one for FCC-eh)

The LHeC program

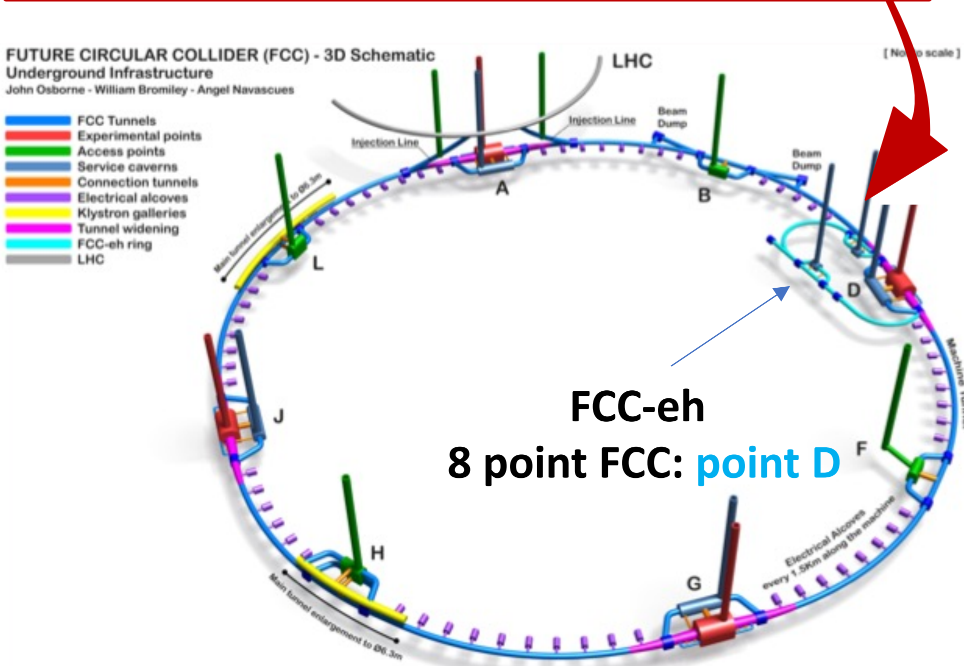
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



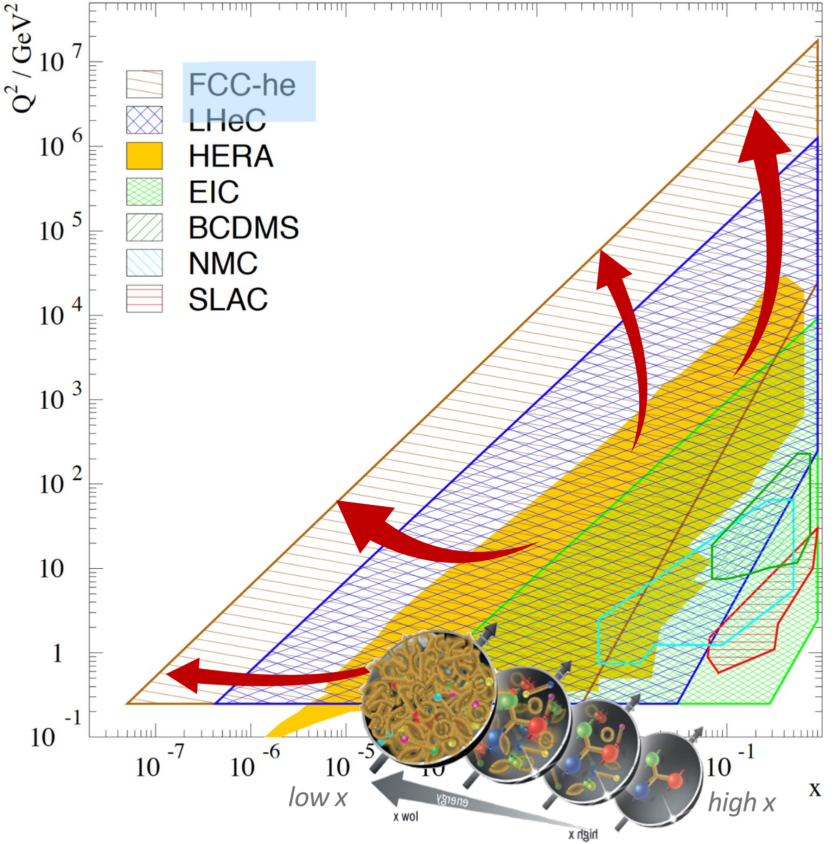


The FCC-eh program

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



Recent timeline

2005: first ideas for a concrete ep/eA study with the LHC (= LHeC)
2007: ECFA mandate to explore
2012: CDR of LHeC
2013: CERN mandate to further explore LHeC (M. Klein & H. Schopper)
2018: CDR for FCC, including FCC-eh
2020: updated CDR for LHeC (including ERL)
2021: publication updated CDR in Journal of Physics G, *J.Phys.G 48 (2021) 11, 110501*
2021: end of CERN mandate

picture from M. Klein

High-energy ep/eA physics with the LHeC and FCC-eh

Renewed mandate (Oct 2022): *“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.”*

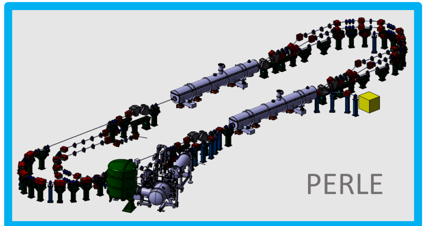
Coordination Panel members (May 2023): Nestor Armesto, Maarten Boonekamp, Oliver Brüning, Daniel Britzger, Jorgen D’Hondt (spokesperson), Monica D’Onofrio, Claire Gwenlan, Uta Klein, Paul Newman, Yannis Papaphilippou, Christian Schwanenberger, Yuji Yamazaki.

International Advisory Committee members (May 2023): Phil Allport, Diego Bettoni, Frederick Bordry (chair), Abhay Deshpande, Rohini Godbole, Beate Heinemann, Karl Jakobs, Young-Kee Kim, Max Klein, Eric Laenen, Jean-Philippe Lansberg, Tadeusz Lesiak, Dave Newbold, Vladimir Shiltsev, Johanna Stachel, Achille Stocchi.

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies



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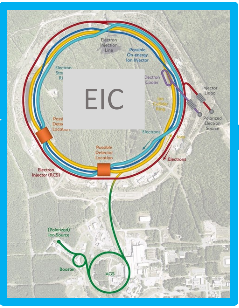


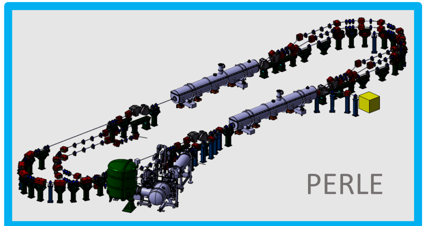
ERL application electron cooling

Potential impact of ERL technology

demonstrate multi-turn high-power ERL

enables the ultimate upgrade of the LHC program

2020'ies



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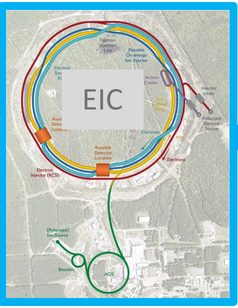
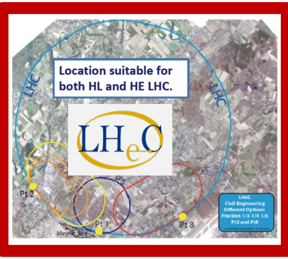


ERL application electron cooling

2030-2040'ies



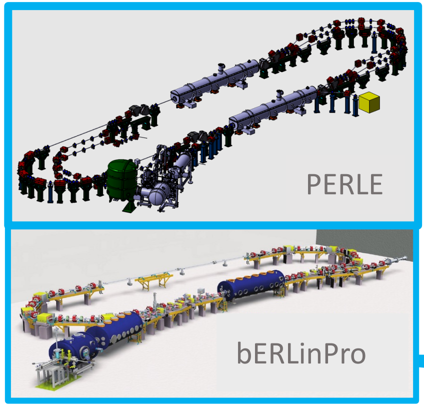
1 ERL beam

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

Potential impact of ERL technology

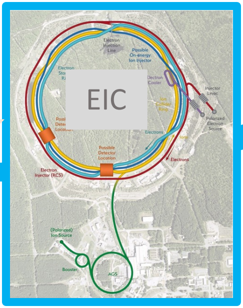
demonstrate multi-turn high-power ERL

2020'ies



high-power ERL demonstrated

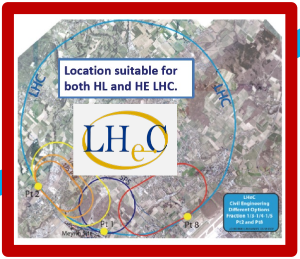
2030'ies



ERL application electron cooling

enables the ultimate upgrade of the LHC program

2030-2040'ies



1 ERL beam

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

2040-2050'ies

2070'ies

2 ERL beams

reuse ERL

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

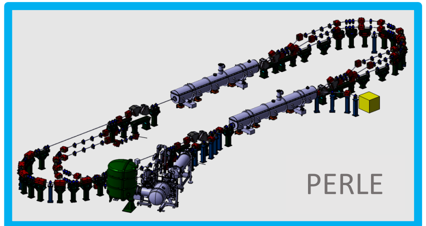
increases the performance of the next major colliders

Potential impact of ERL technology

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

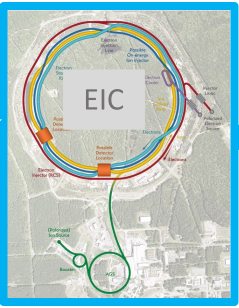
demonstrate multi-turn high-power ERL

2020'ies



high-power ERL demonstrated

2030'ies



ERL application electron cooling

enables the ultimate upgrade of the LHC program

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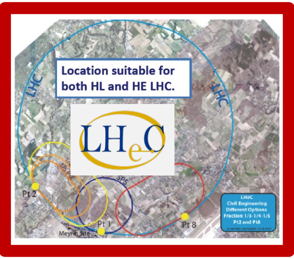

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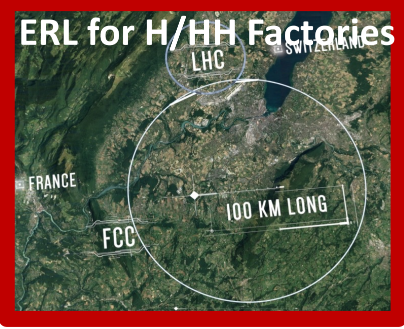

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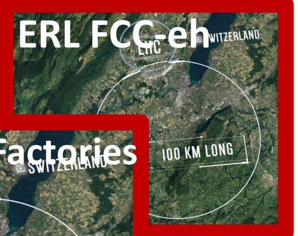
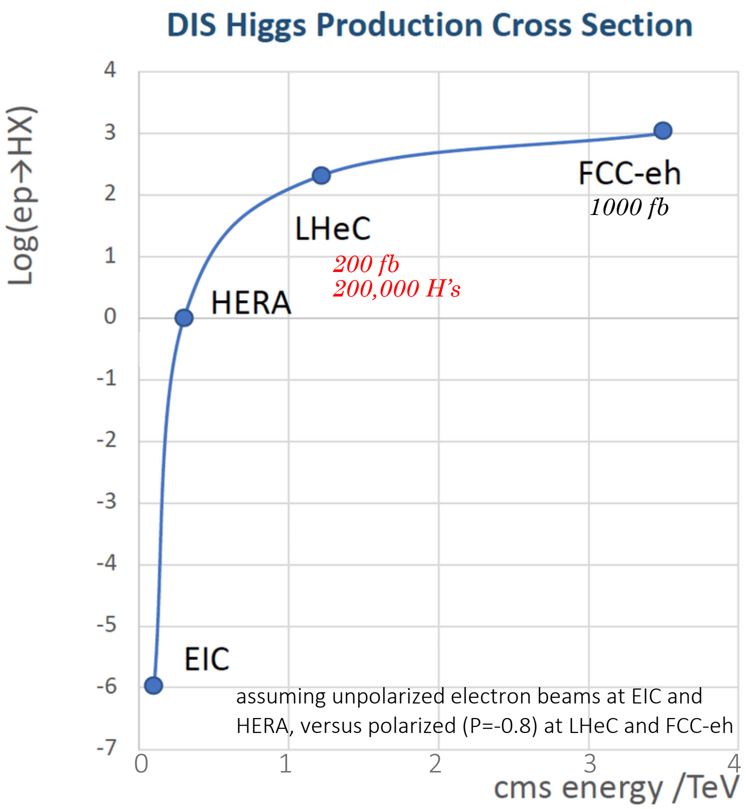


reuse ERL

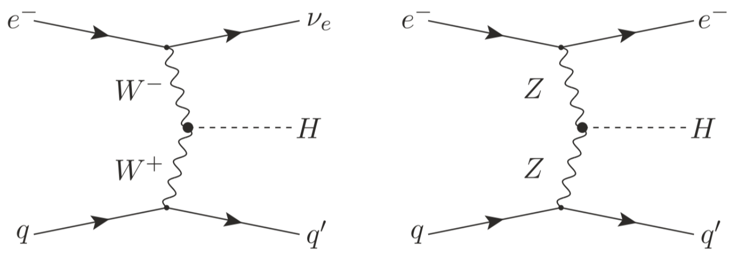
increases the performance of the next major colliders

the physics impact

Collision energy above the threshold for EW/Higgs/Top



The real game change between HERA and LHC/FCC

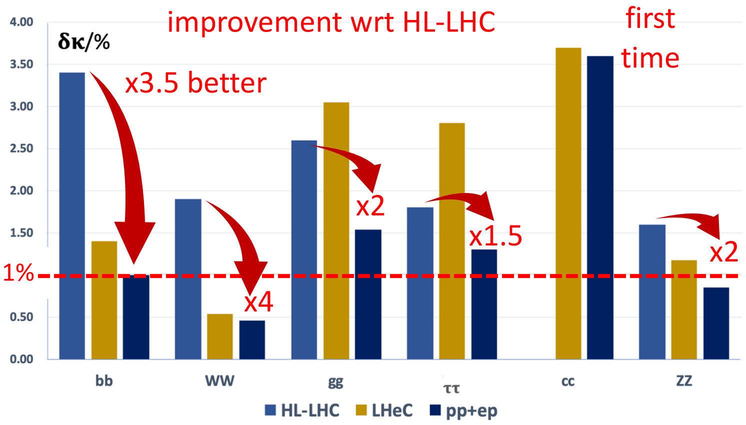


compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

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)

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

- **EW/Higgs/top physics: improvement from HL-LHC → LHeC similar to LHC → HL-LHC**

- **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

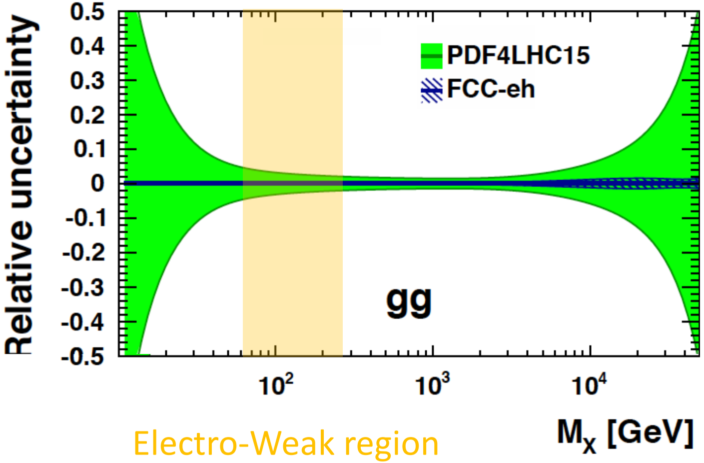
- **In addition, unique potential with LHeC/FCC-eh to search for new physics phenomena,** e.g. what if features appear in the interactions between leptons and quarks

The LHeC is a general-purpose experiment

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

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

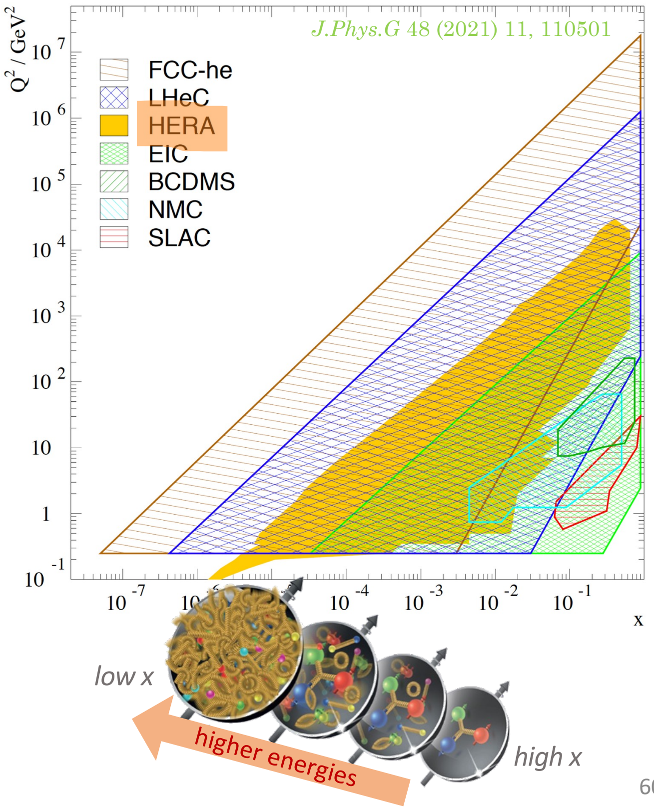


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

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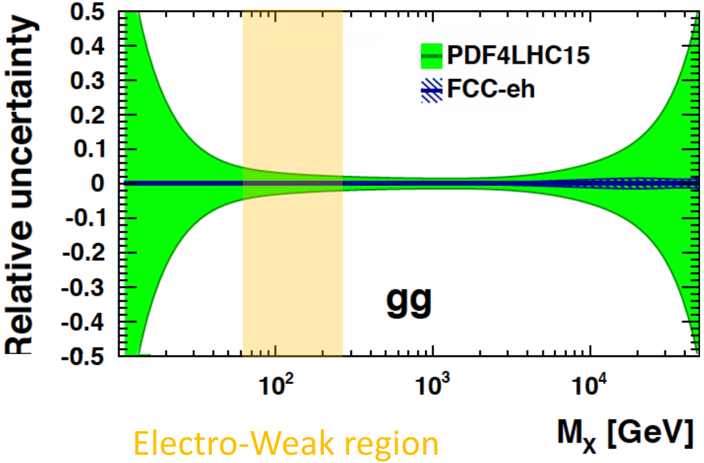


Electro-Weak region

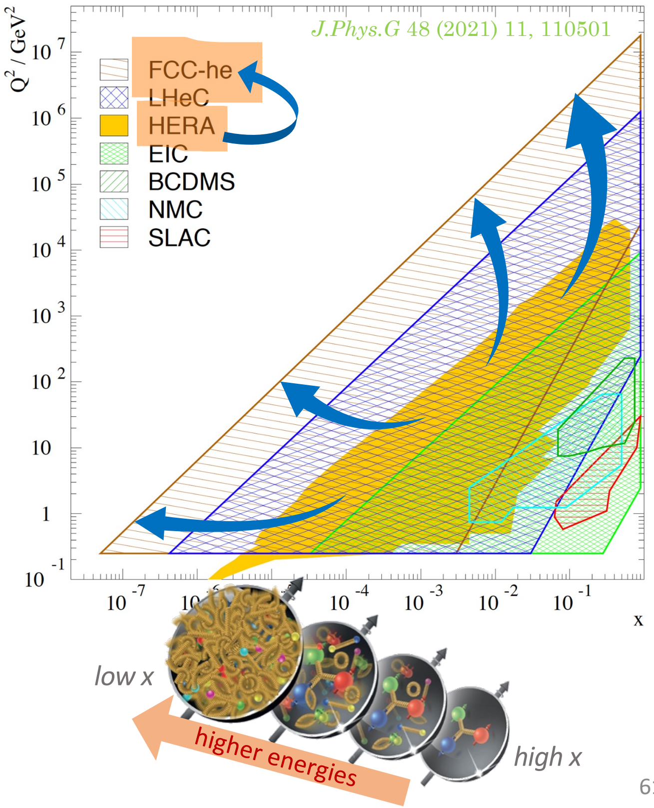
~5-7% uncertainty on the σ(W,Z,H)

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

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

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

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κ_g [%]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.42
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.61	1.3	0.44

Explore the physics opportunity of a joint ep/eA/pp/pA/AA/(ee) programme 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}

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

“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.”

While fostering continuous developments in the realm of ep/eA physics, the Coordination Panel in consultation with the International Advisory Committee proposes a coherent focus on five new physics and technology themes to provide impactful information at the time of the next European strategy discussions.

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

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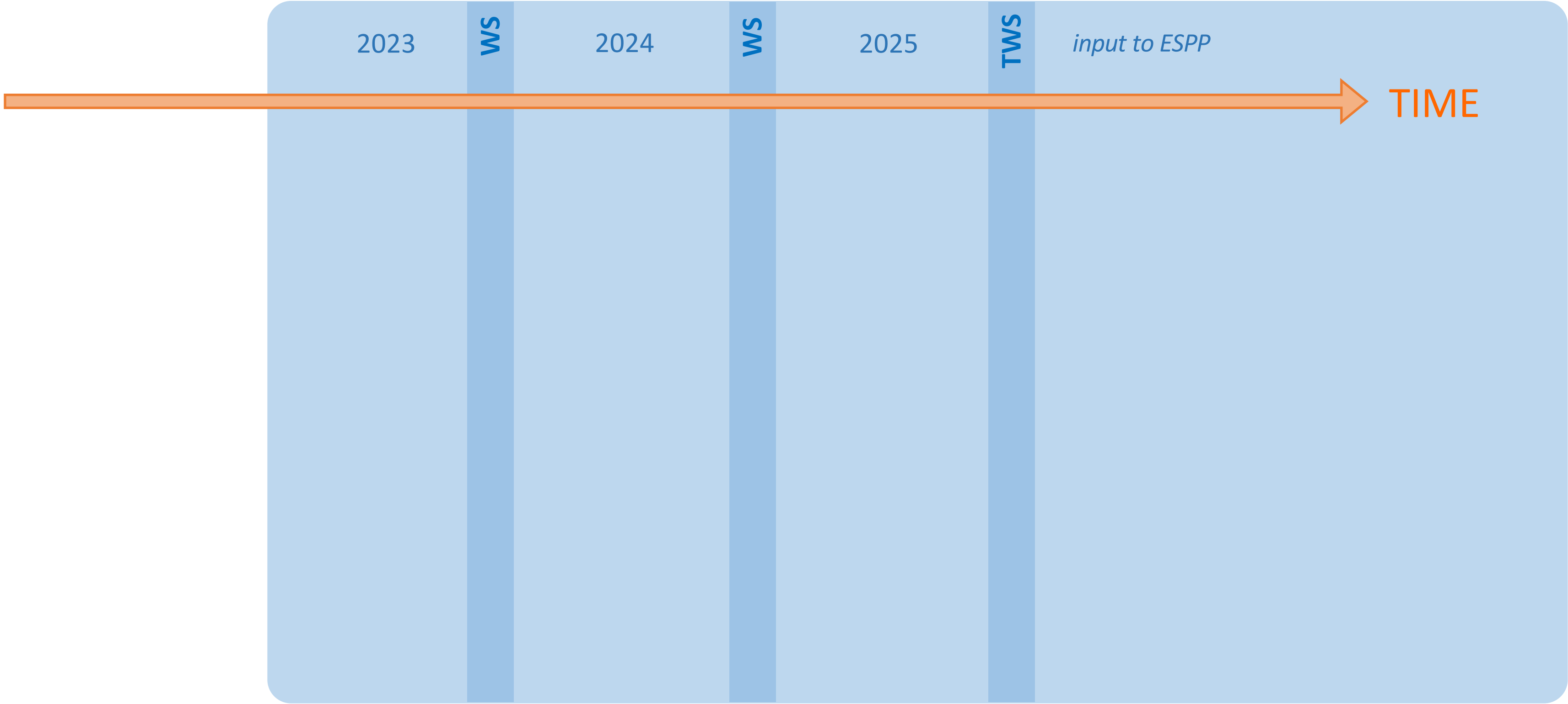

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The ep/eA study at the LHC and FCC – new impactful goals for the community

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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

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general-purpose high-energy physics programme: precision physics and searches
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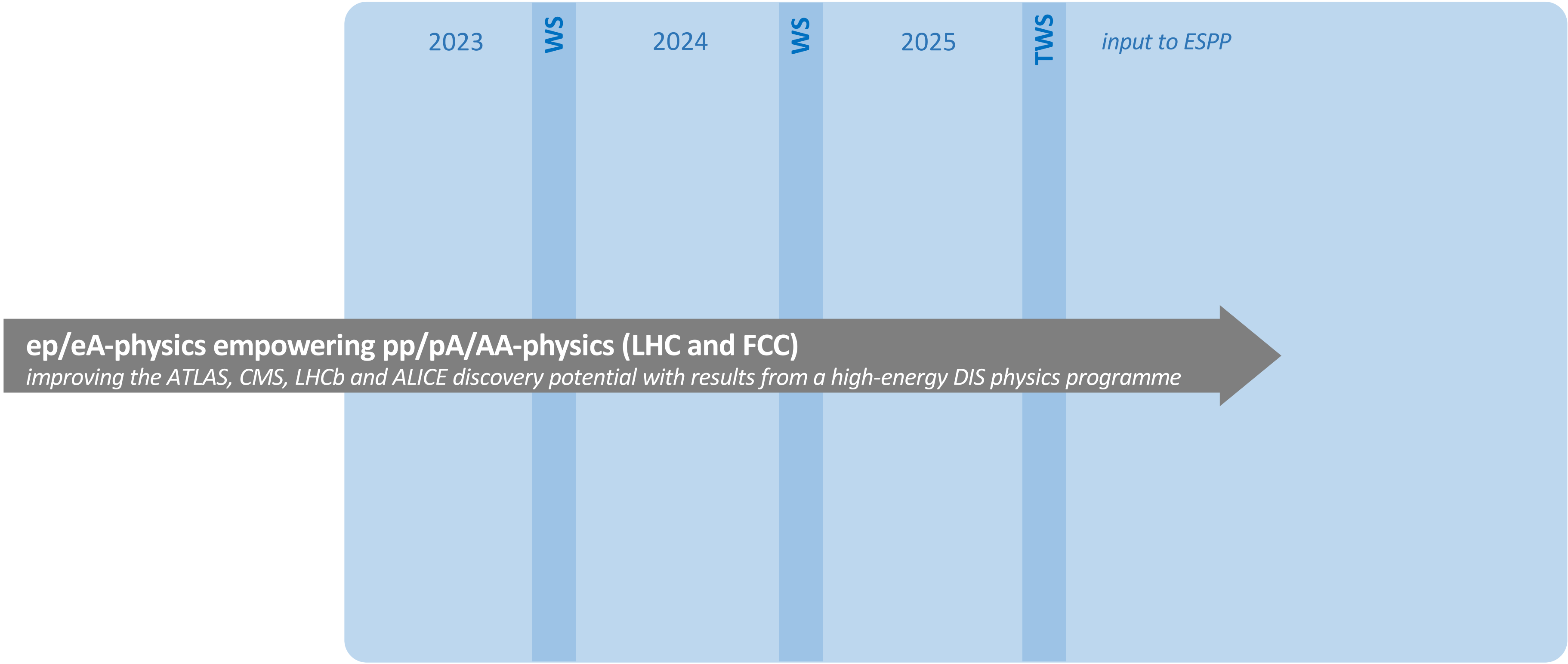

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critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics

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- 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

High-energy ep/eA physics with the LHeC and FCC-eh

- ERL is an enabling technology for our most prominent future ep/eA and e^+e^- colliders, delivering breakthrough performances on an interesting timeline
- The engine of our curiosity-driven exploration with particle physics is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize: ERL technology delivers on this front
- New impactful goals have been developed for the ep/eA study with a timeline to inform the next update of the European Strategy for Particle Physics
- The ep/eA collider programs at CERN address not only our most prominent physics ambitions, but also important sustainability and financial aspects

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- The potential physics and technology impact of ep/eA colliders at CERN is so appealing that we must foster this path for the future of the field

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