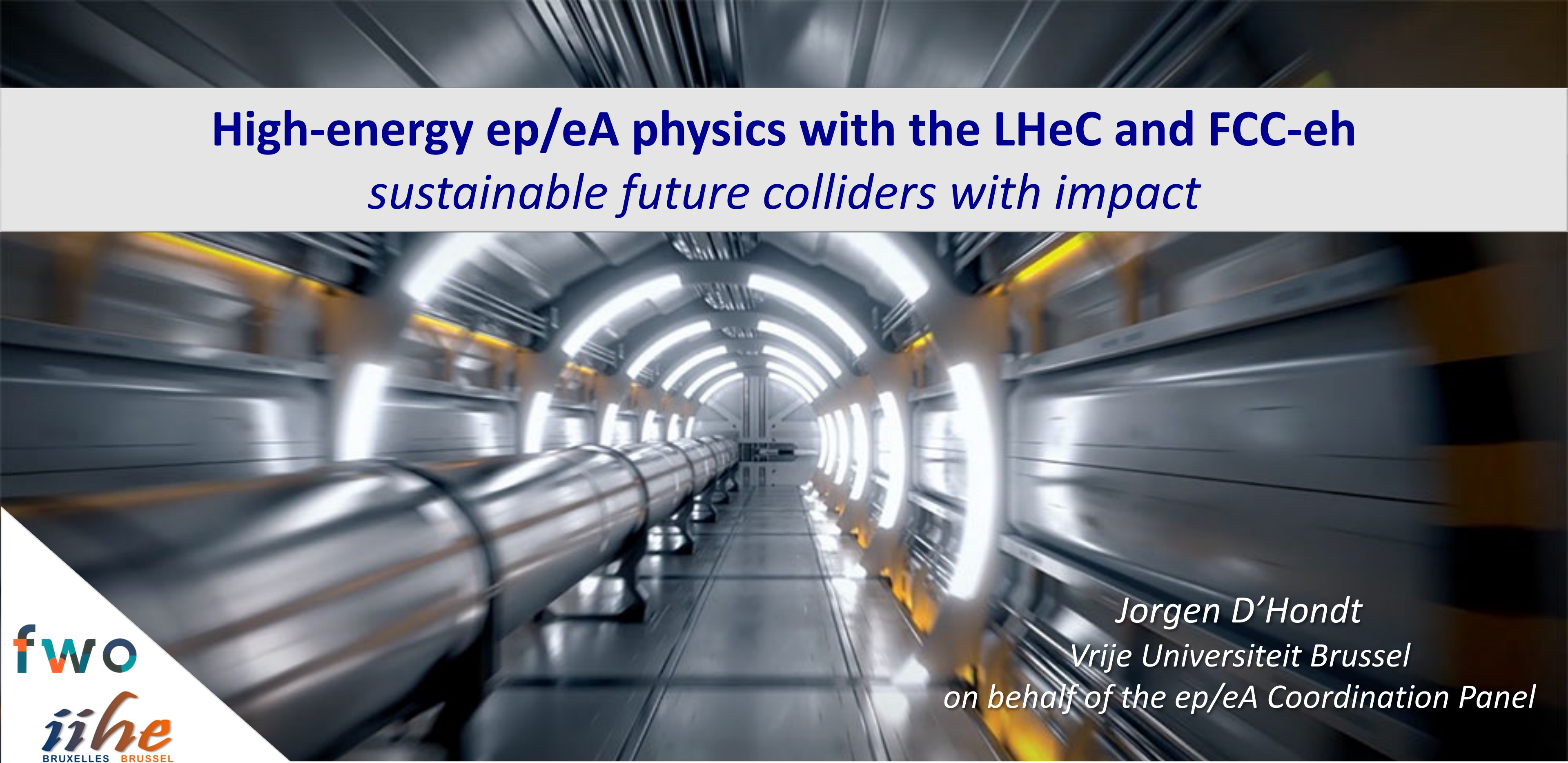
High-energy ep/eA physics with the LHeC and FCC-eh

sustainable future colliders with impact



Jorgen D’Hondt

Vrije Universiteit Brussel

on behalf of the ep/eA Coordination Panel

fwo

iihe BRUXELLES BRUSSEL

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

UK FCC meeting, November 2023

The landscape of particle physics colliders

at CERN

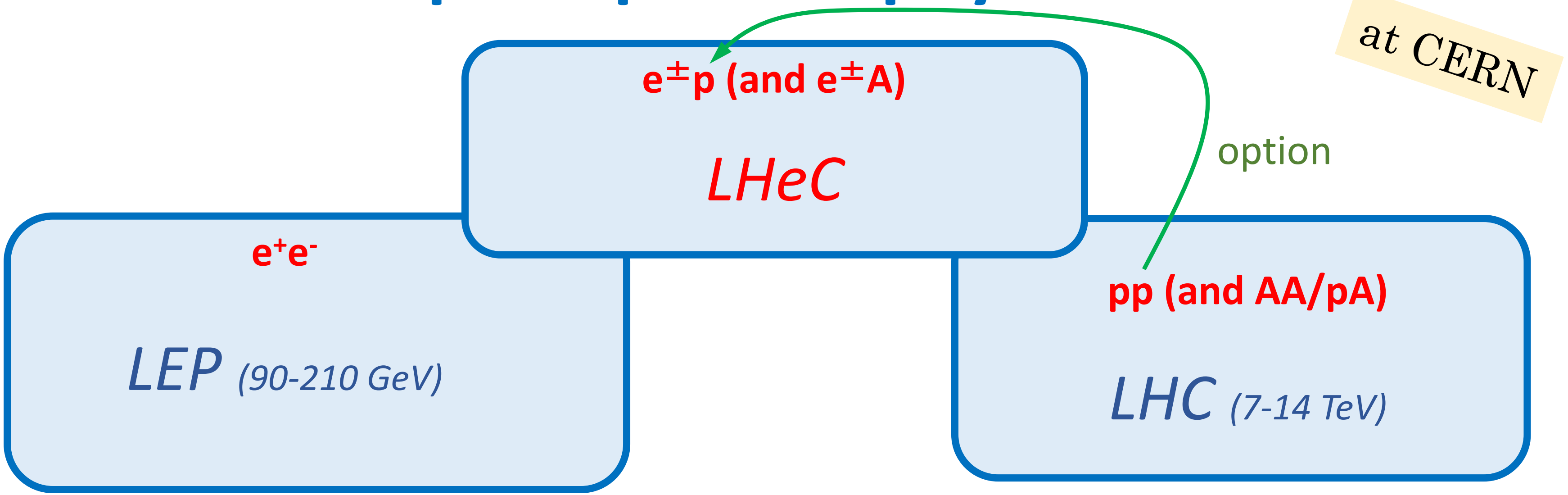
e^+e^-

LEP (90-210 GeV)

pp (and AA/pA)

LHC (7-14 TeV)

The landscape of particle physics colliders



Future options for particle physics colliders

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

$E_{CMS} > 1$ TeV

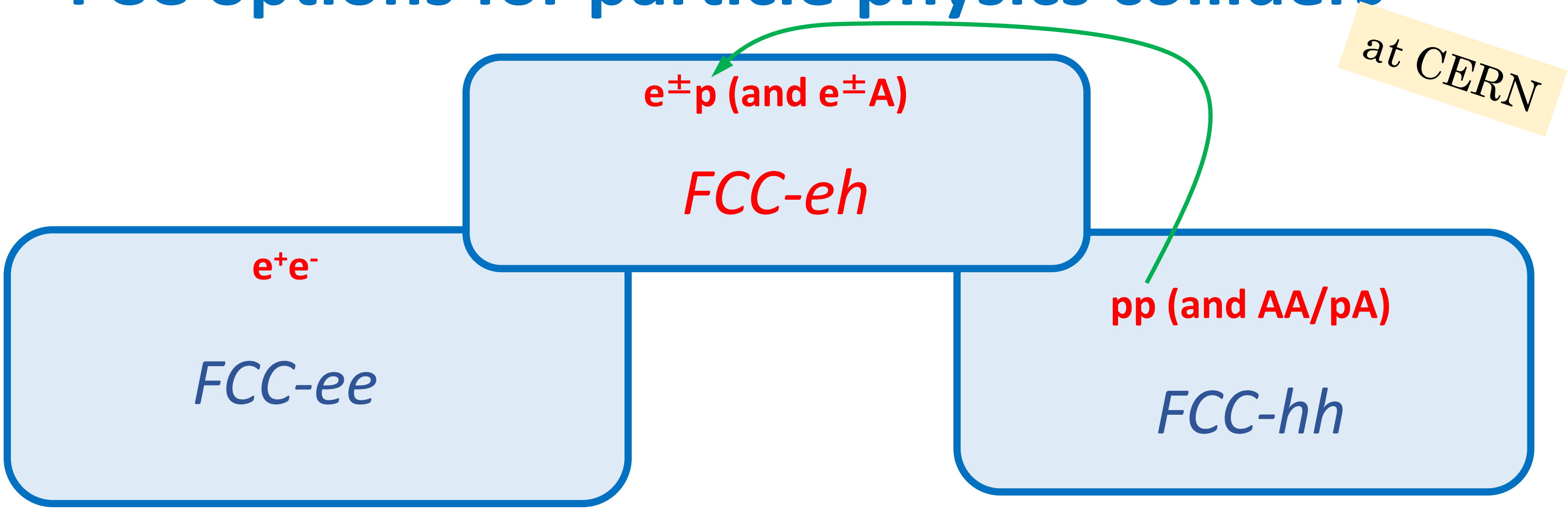
e^+e^-

$E_{CMS} \sim 10$ GeV (flavour)
$E_{CMS} \sim 90$-360 GeV (Z/W/H/top)
$E_{CMS} > 500$ GeV

pp (and AA/pA)

$E_{CMS} >> 14$ TeV (LHC)

FCC options for particle physics colliders



Future options for particle physics colliders

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

ERL technology ($E_e \sim$ 30-60 GeV)

E_{CMS} > 1 TeV

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

e^+e^-

RF technology

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

$E_{CMS} \sim$ 90-360 GeV (Z/W/H/top)

E_{CMS} > 500 GeV

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

$\mu^+\mu^-$

first time ever collider

E_{CMS} ~ 3-10 TeV

plasma wakefield

first time ever collider

many applications

Accelerator R&D Roadmap prioritizes progress on these technologies to enable future particle accelerators in a timely, affordable and sustainable way

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

Future options for particle physics colliders

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

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particle physics ambition

high-energy & high-current beams

(energy x current = power)

particle physics ambition

high-energy & high-current beams

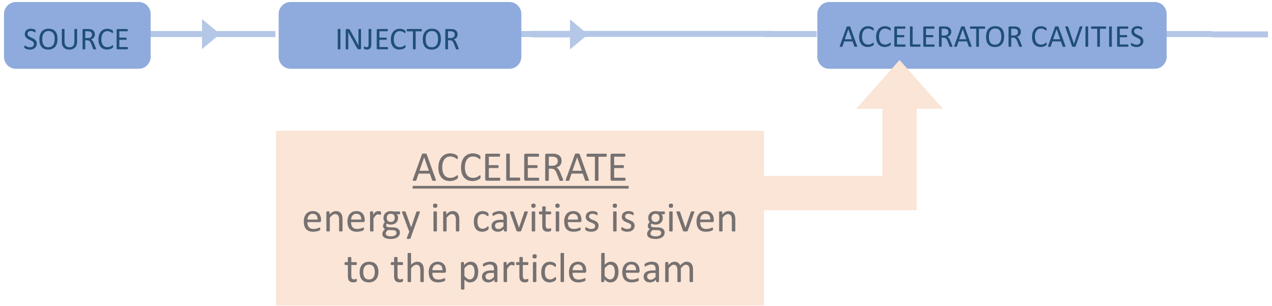
(energy x current = power)

caveat

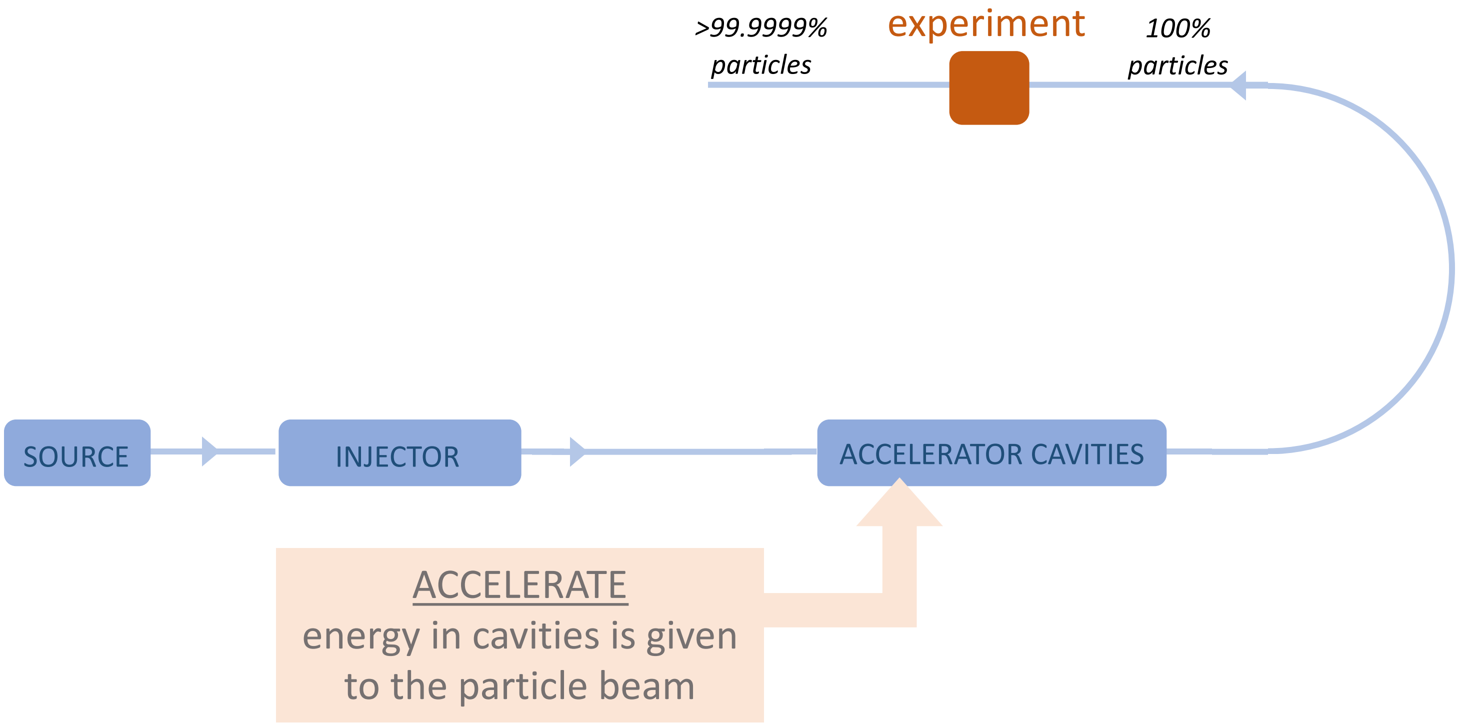
power requirements of future colliders

focus on electron/positron accelerators

The principle of Energy Recovery Linacs



The principle of Energy Recovery Linacs



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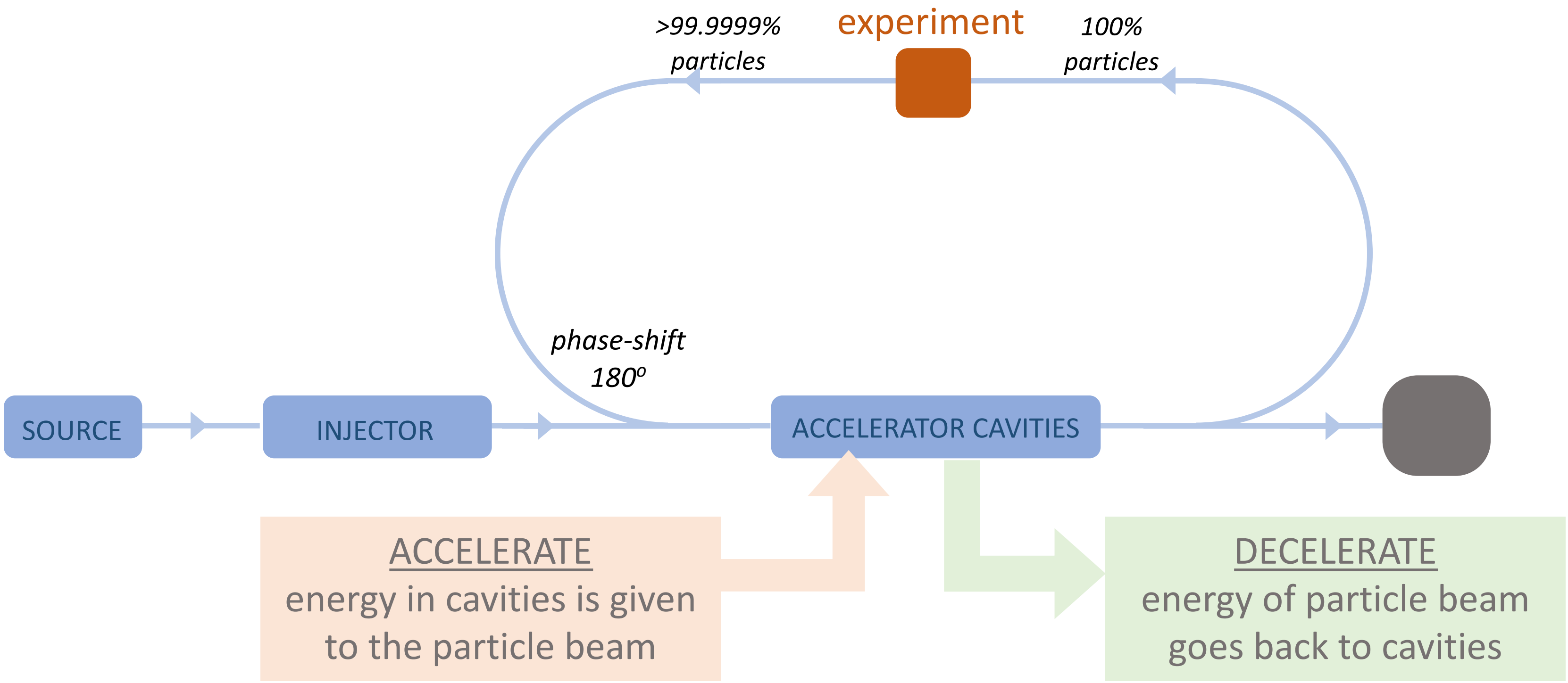

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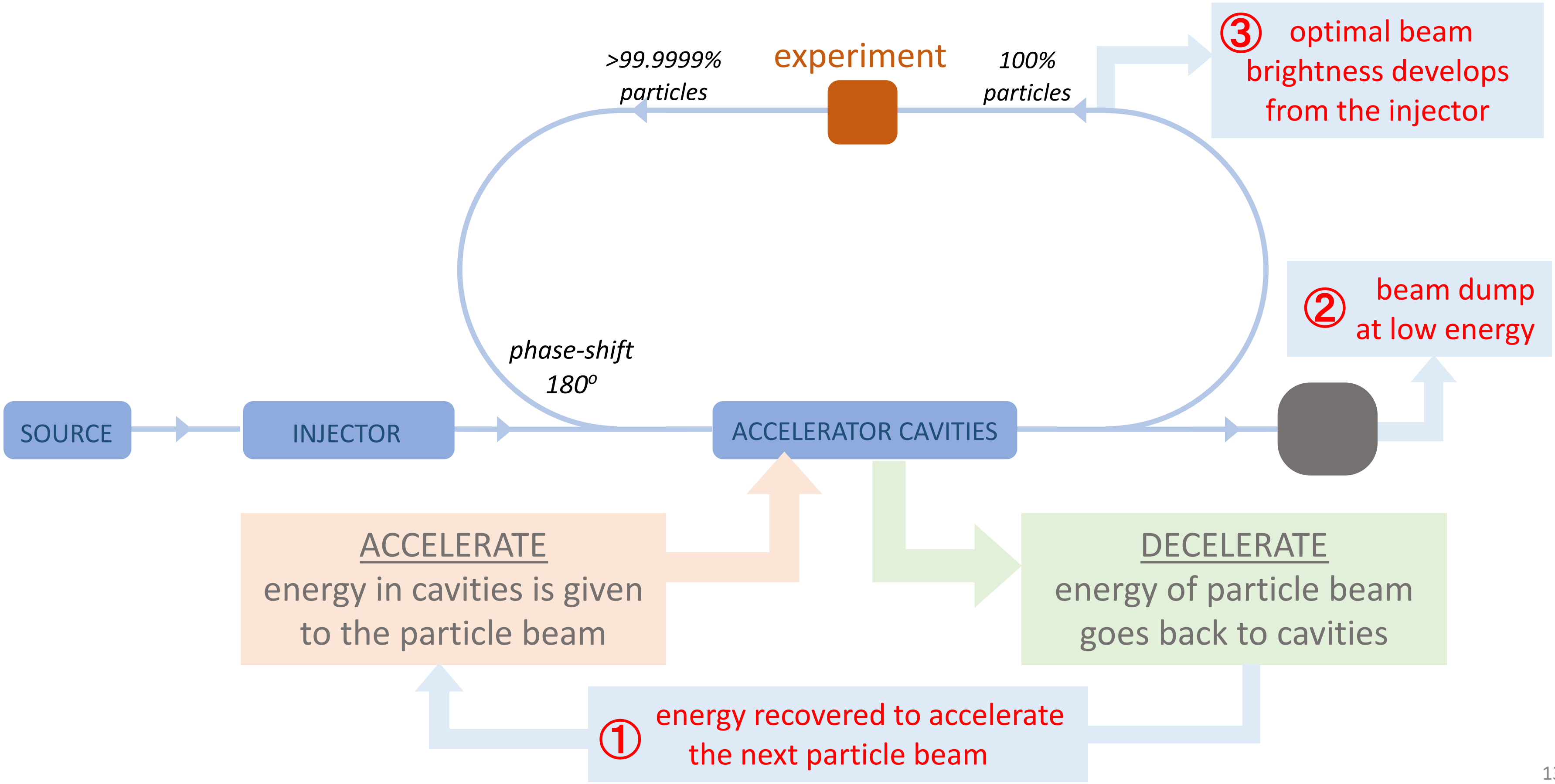

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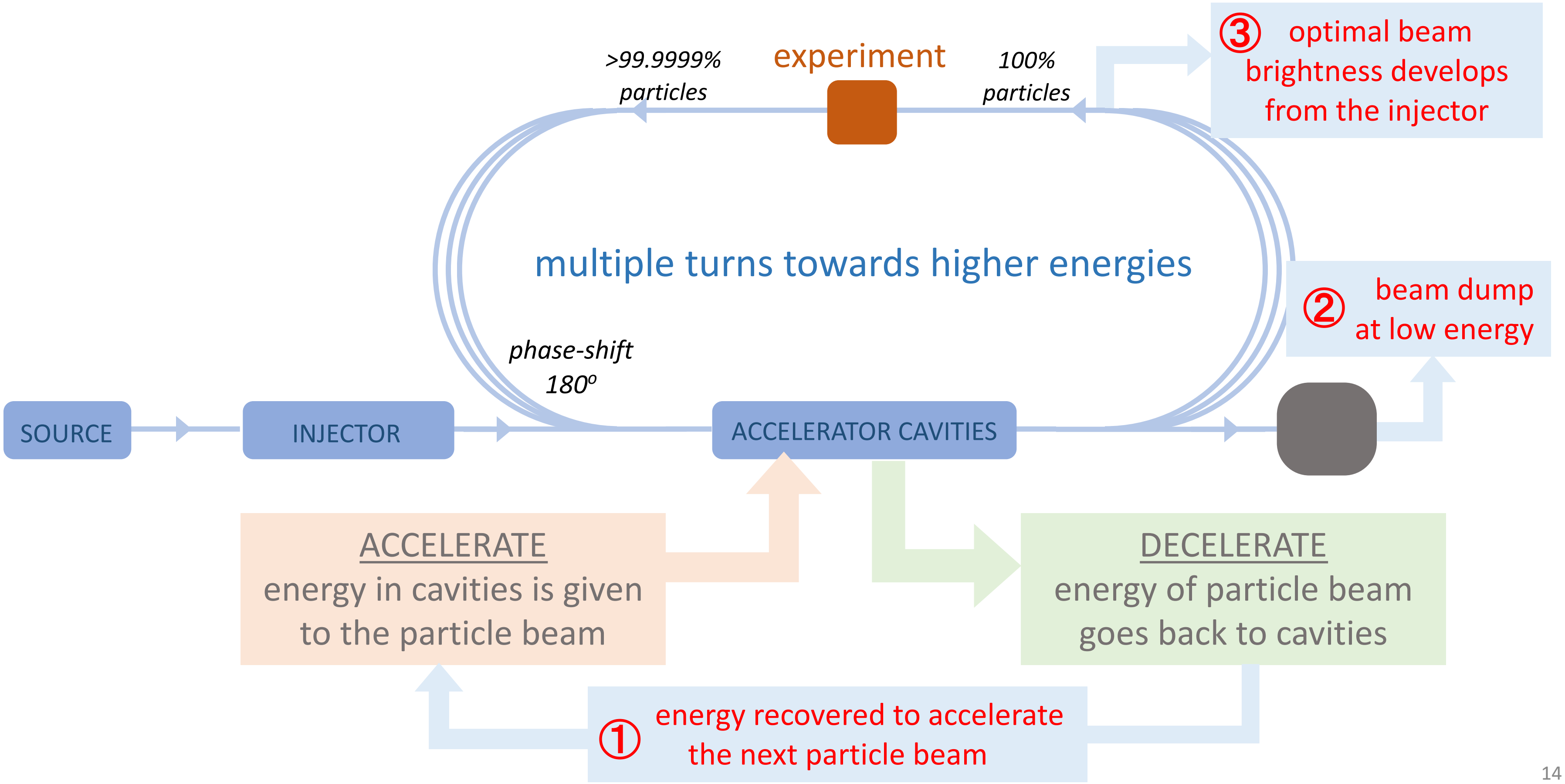

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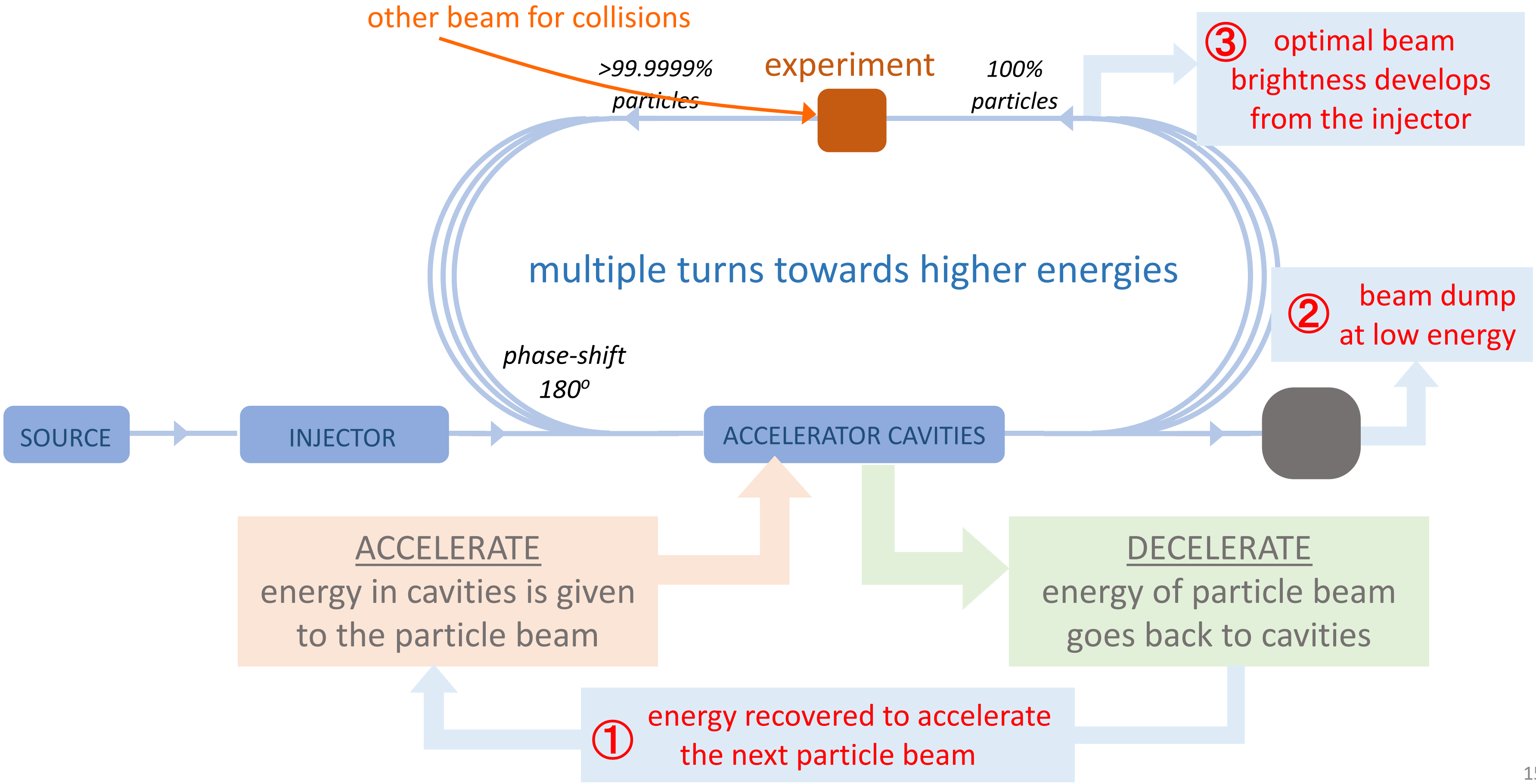

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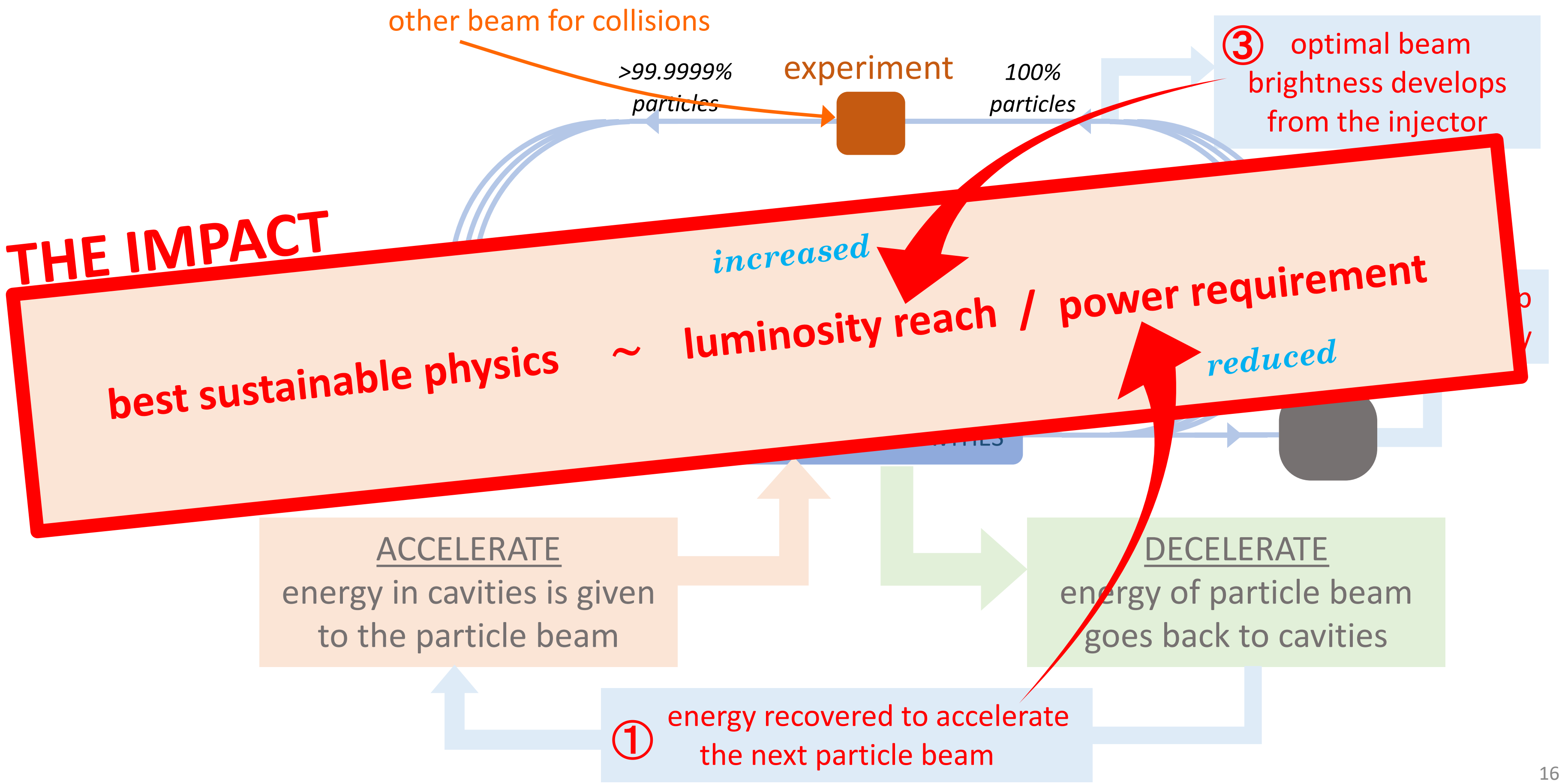
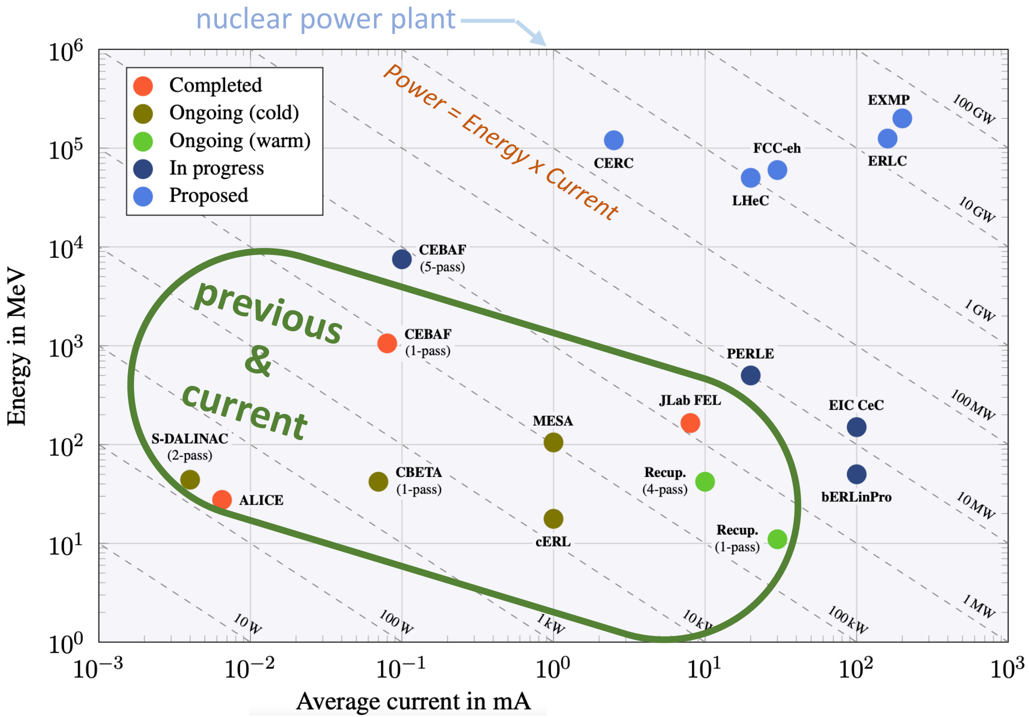
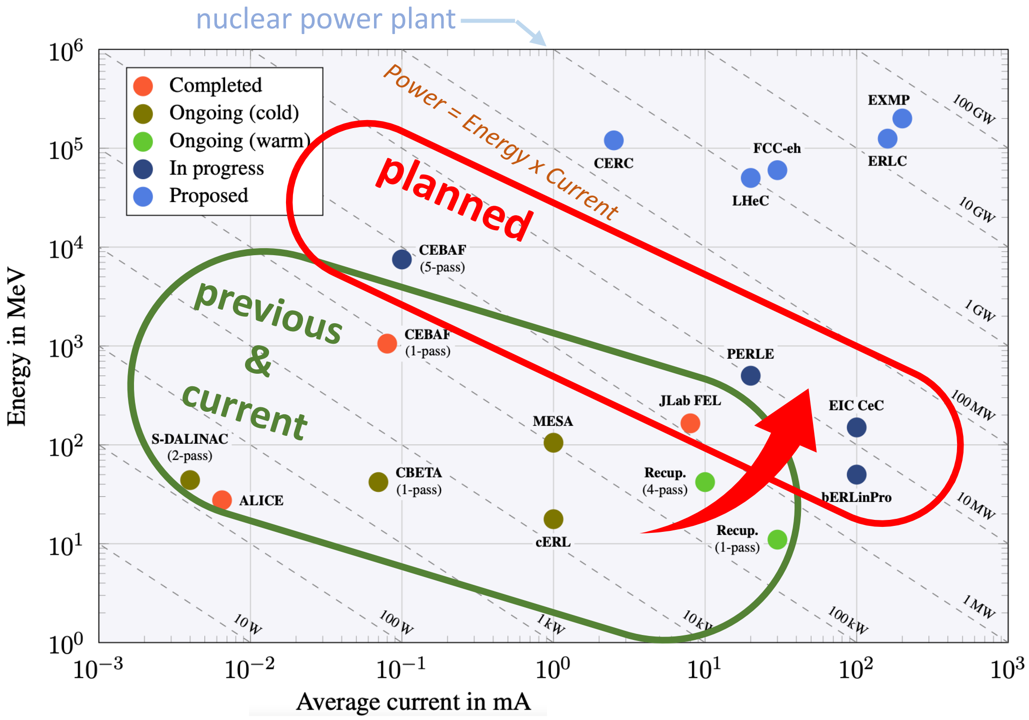




Energy Recovery demonstrated

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



bERLinPro & PERLE

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

towards high energy & high power

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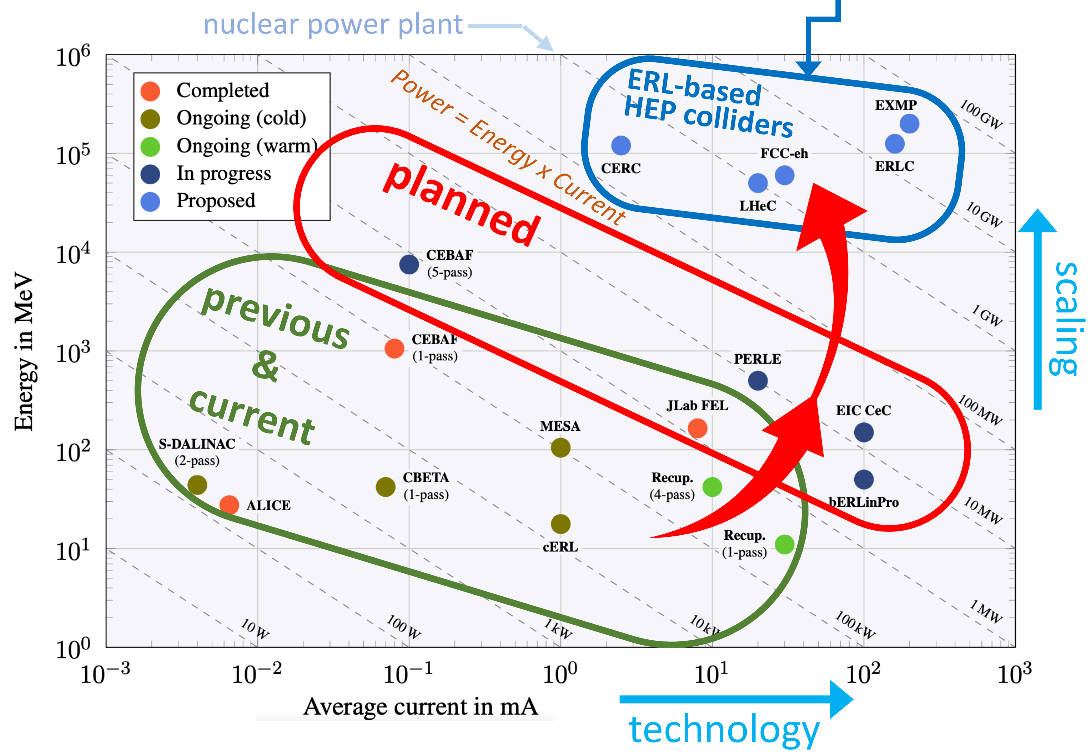
ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Future ERL-based Colliders

H, HH, ep/eA, muons, …

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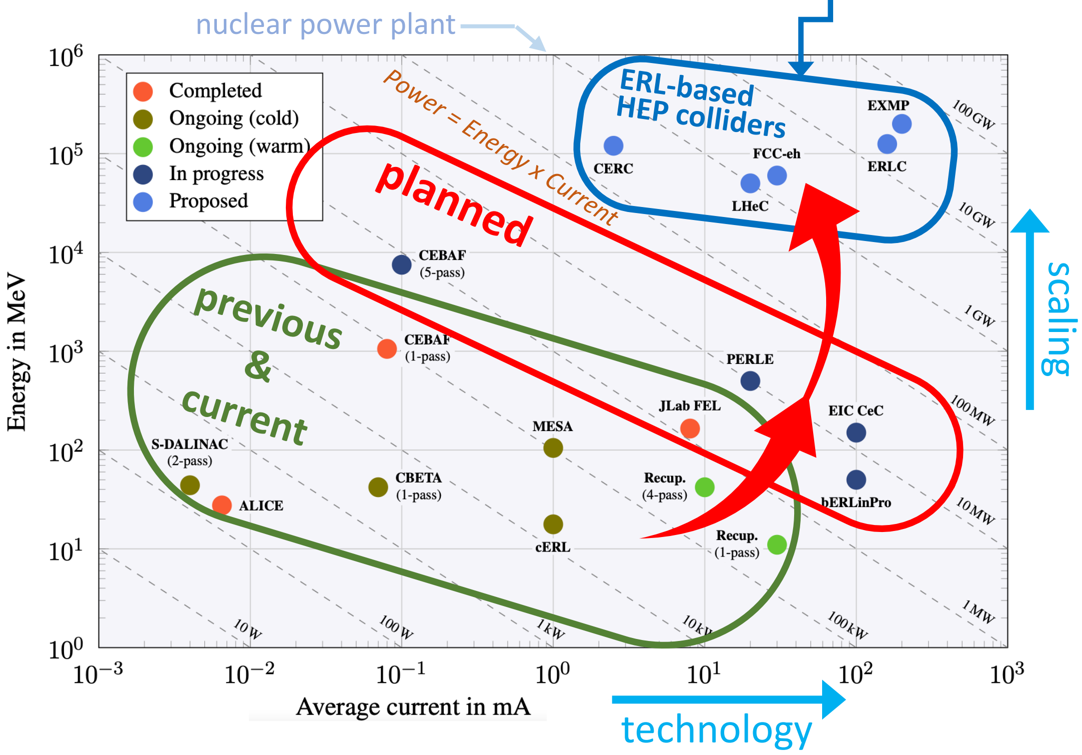

R&D Roadmap

Future ERL-based Colliders

H, HH, ep/eA, muons, …

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

towards high energy & 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

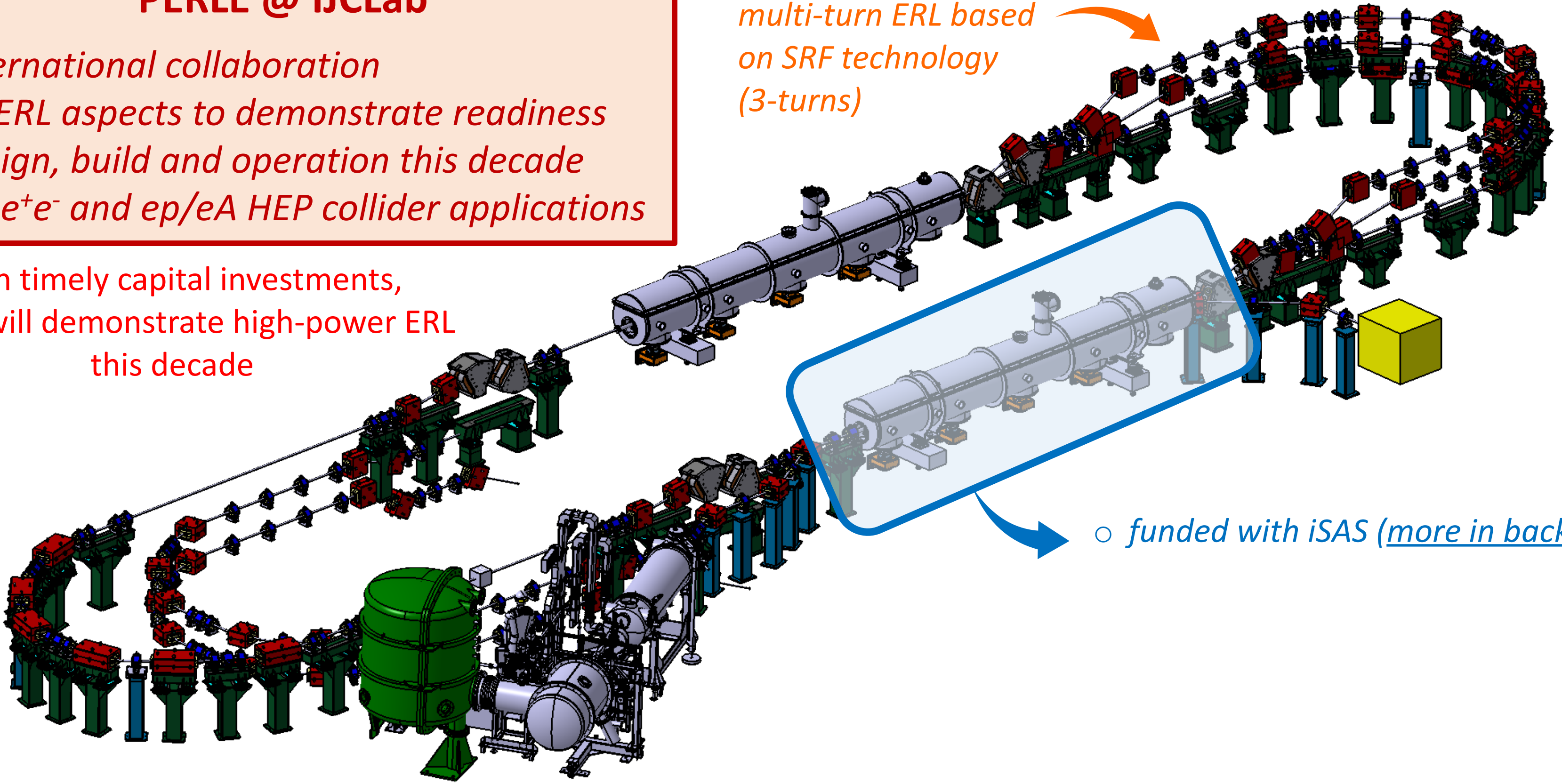
Upcoming facilities for Energy Recovery Linac R&D

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)



- *funded with iSAS (more in back-up)*

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

Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

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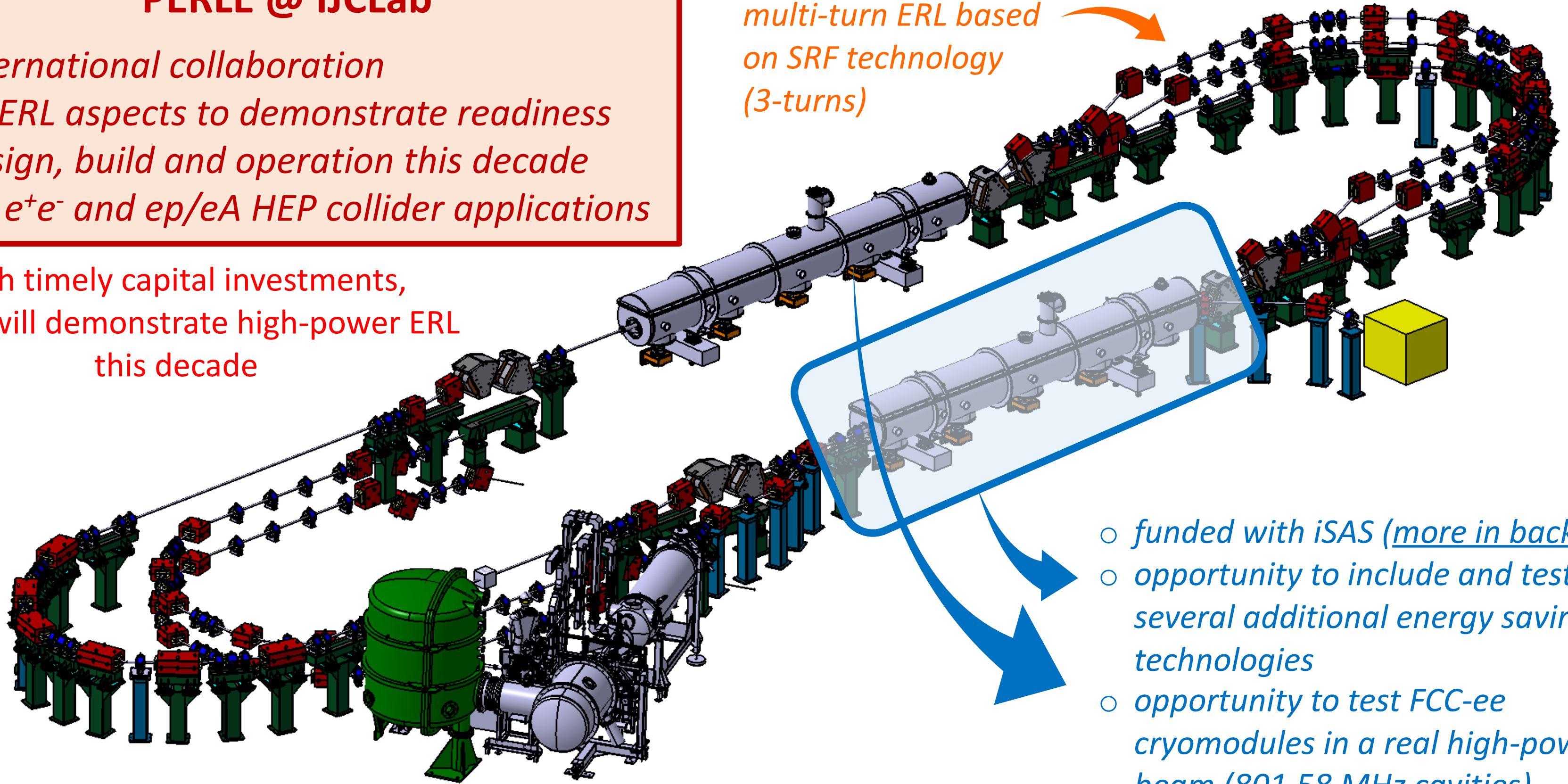


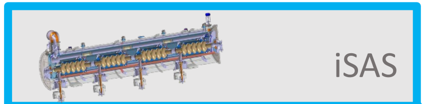
- *funded with iSAS (more in back-up)*
- *opportunity to include and test several additional energy saving technologies*
- *opportunity to test FCC-ee cryomodules in a real high-power beam (801.58 MHz cavities)*

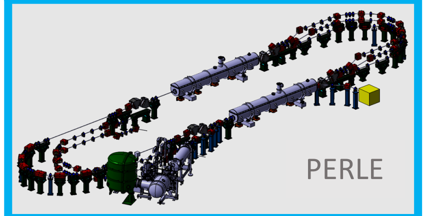
PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies





high-power ERL demonstrated

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

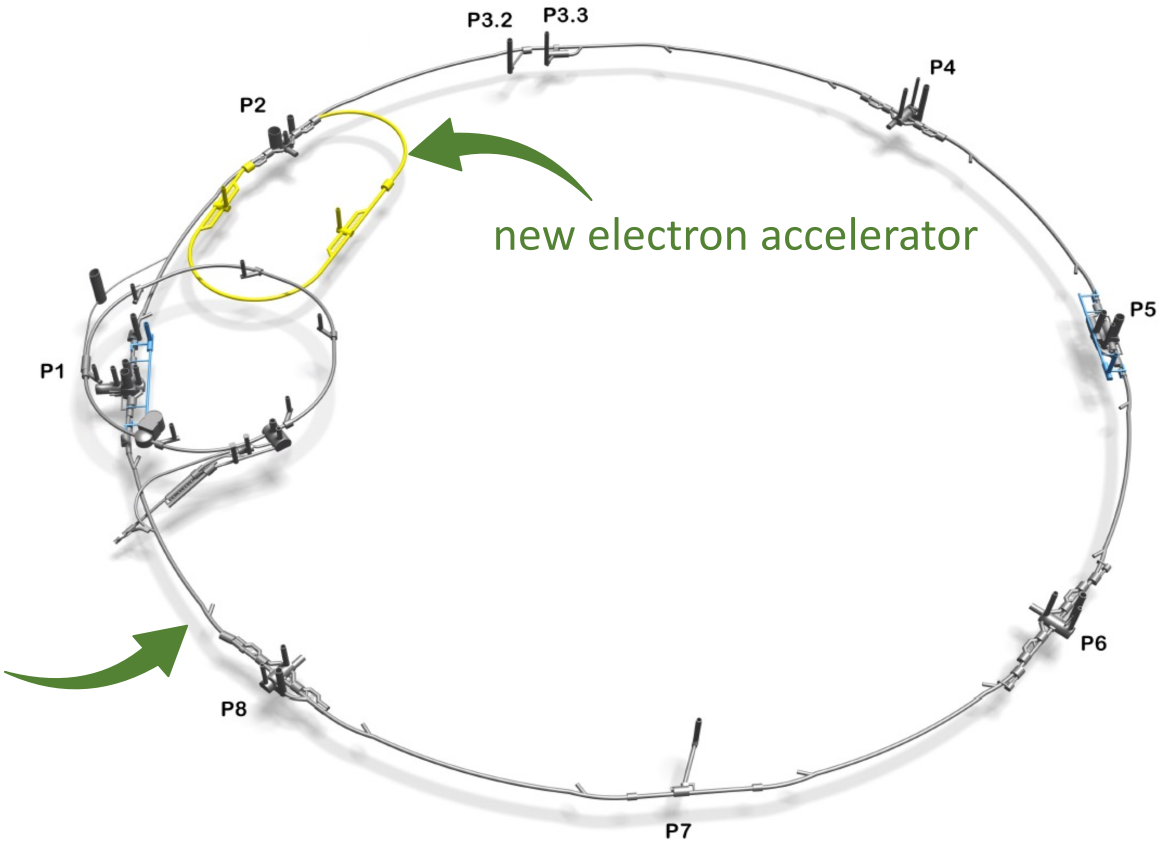
2020’ies

high-power ERL
demonstrated

ERL ready for high-energy and high-luminosity colliders

ERL-based ep/eA colliders at CERN

high-energy & high-luminosity electron-proton collions



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

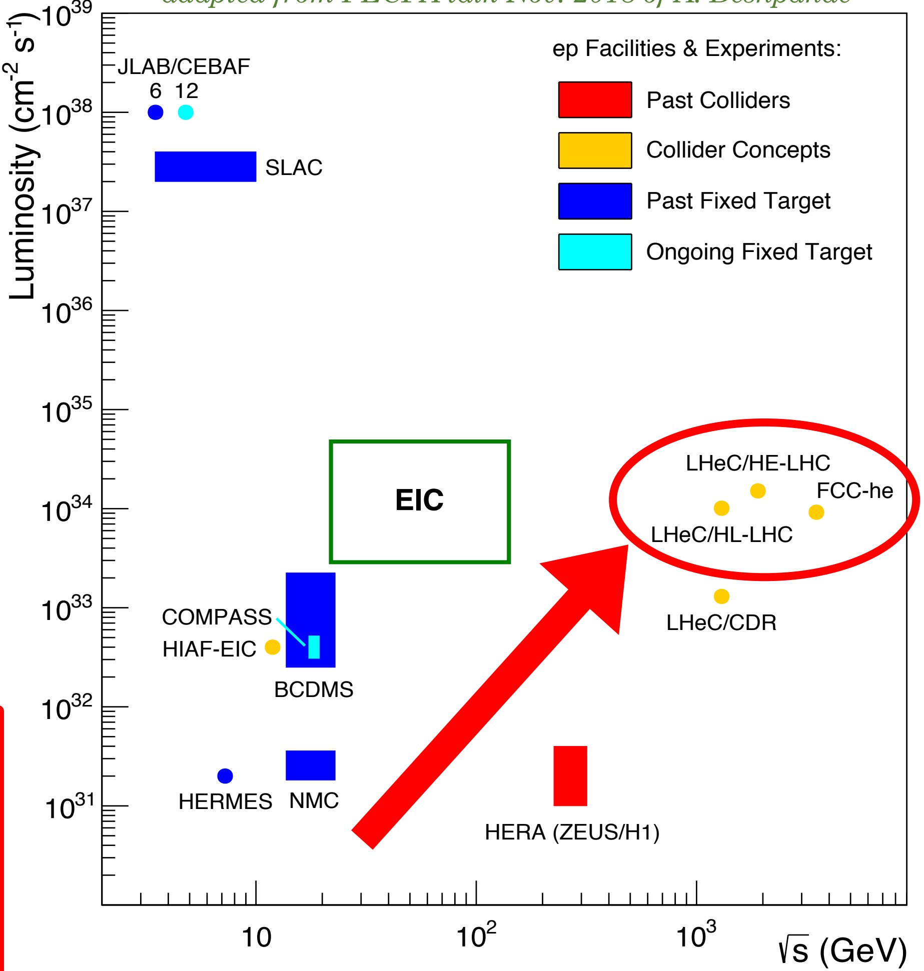
beam current × beam energy
= beam power

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 program up to ~2040

Future Circular Collider (FCC)

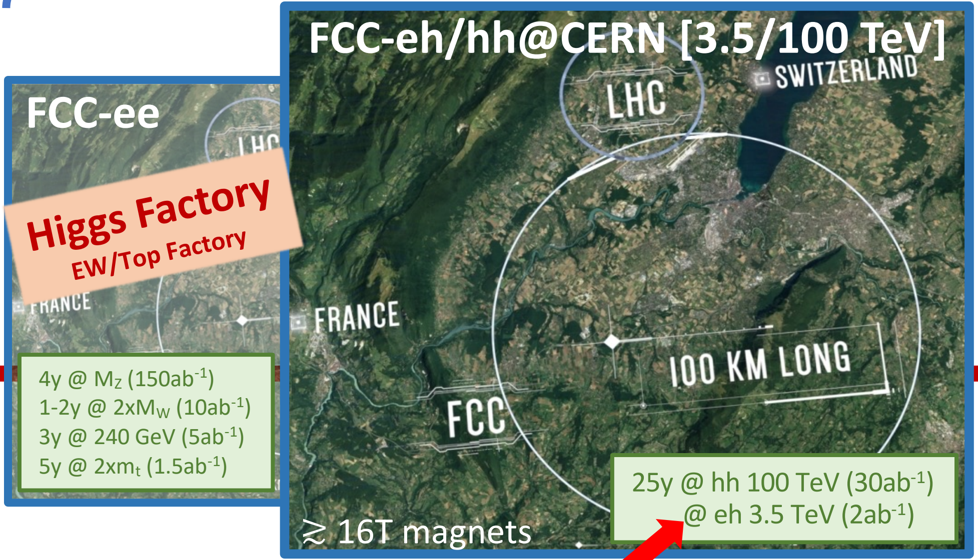
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

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

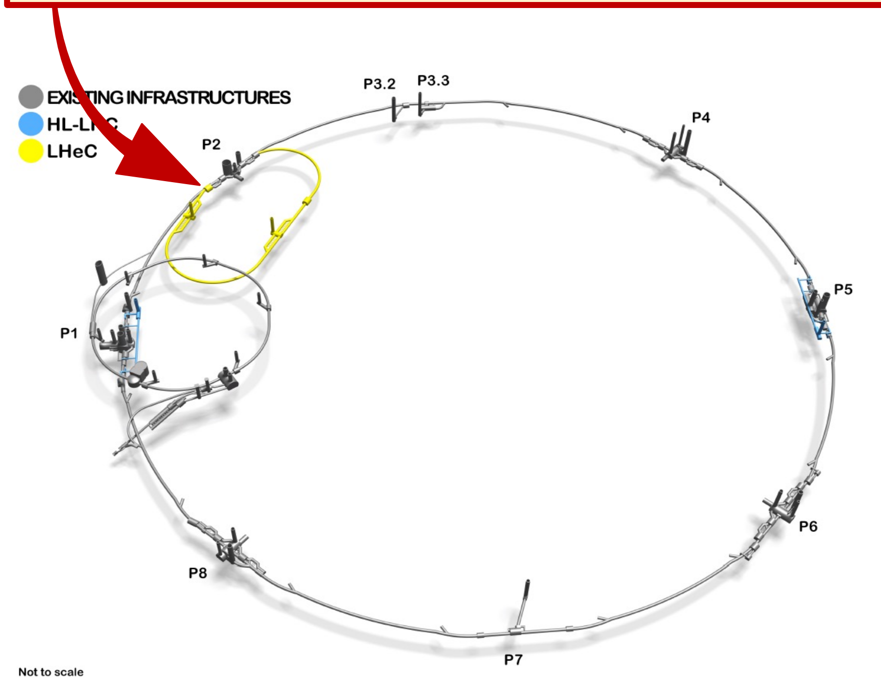
updated CDR: J.Phys.G 48 (2021) 11, 110501

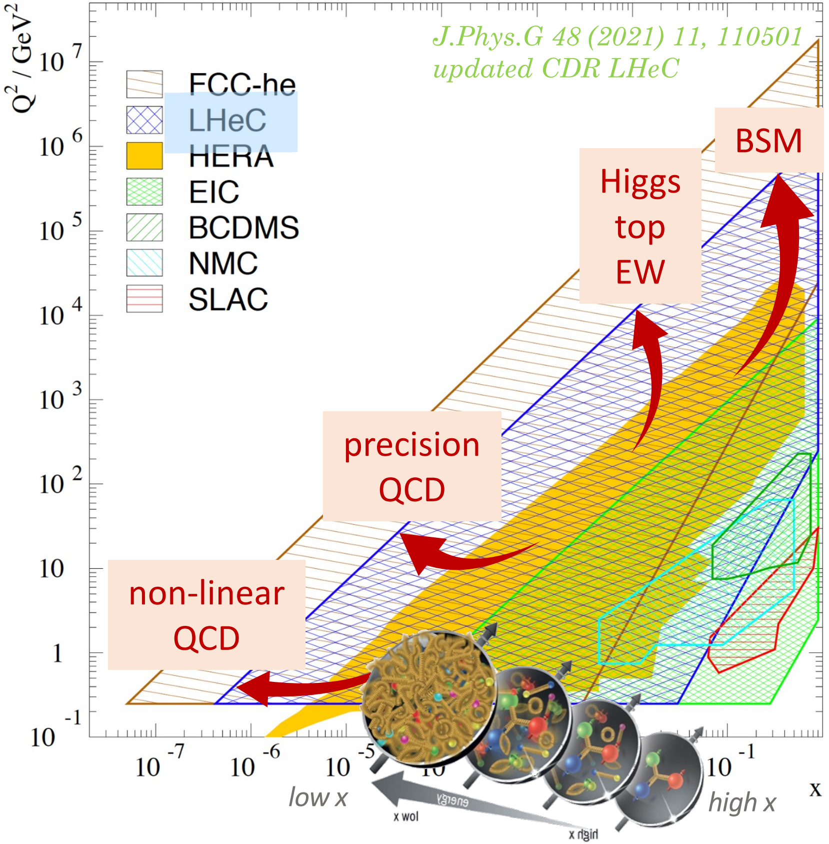


numbers assume 2 IPs for each collider (only one for FCC-eh)

The LHeC program

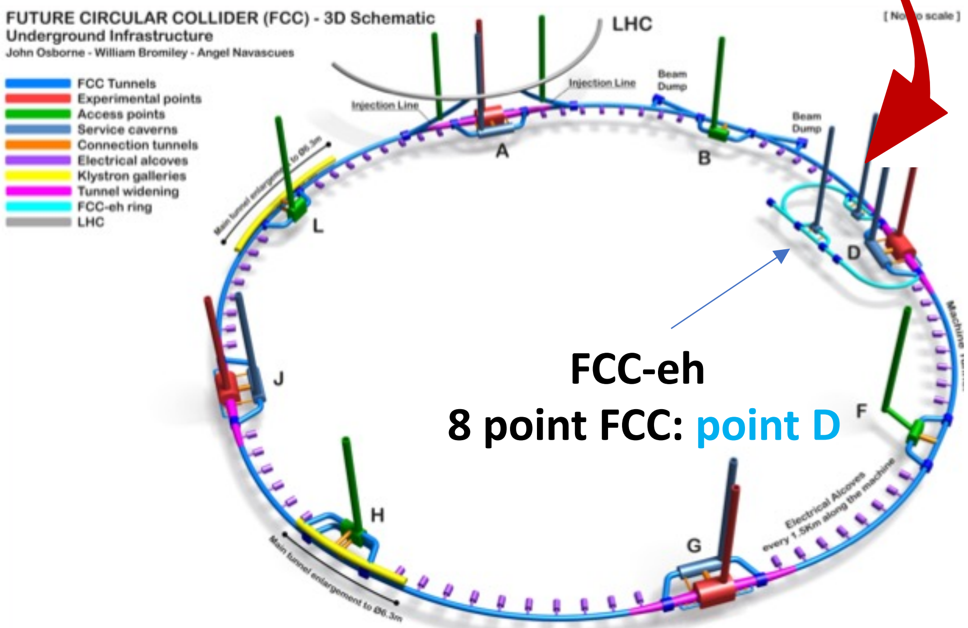
LHeC (>50 GeV ERL electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳Run5)



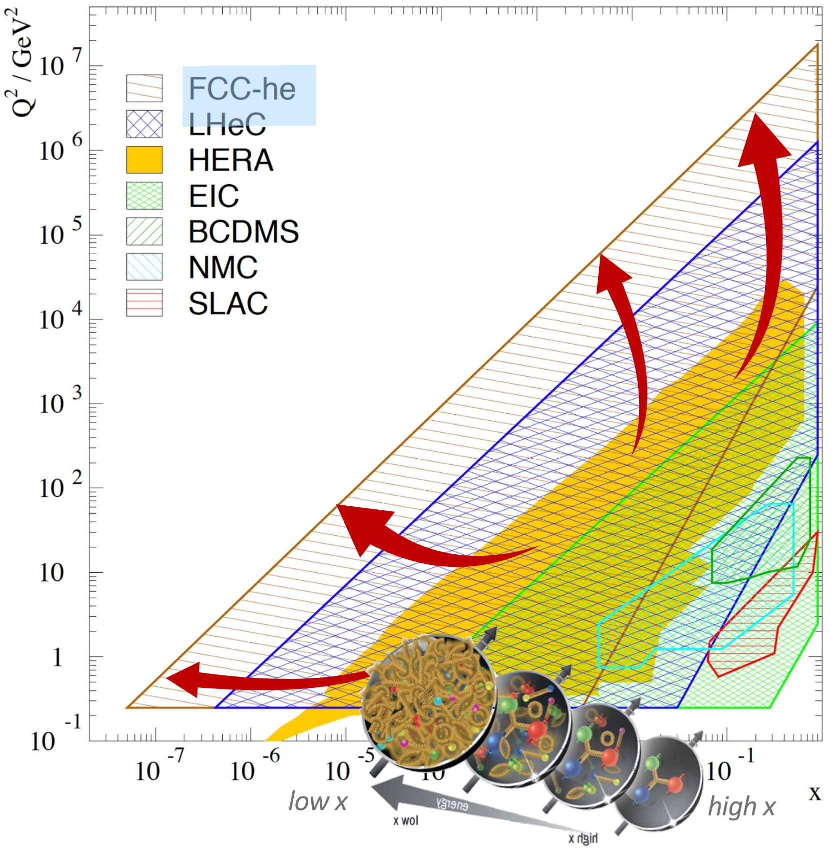


The FCC-eh program

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



J. Osborne, W. Bromiley, A. Navascues



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

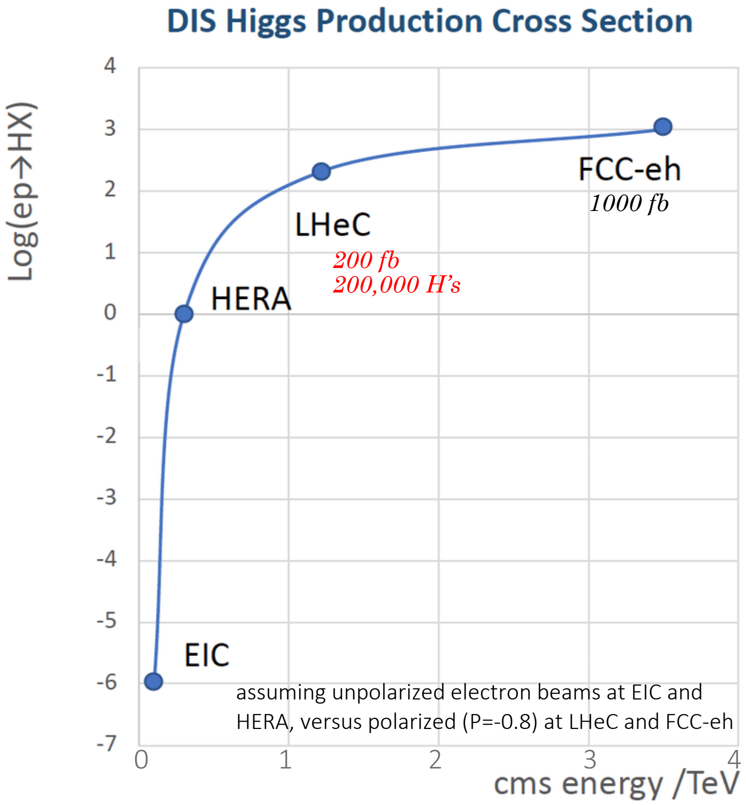
Renewed mandate (Oct 2022): *"CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics. The study is to further develop the scientific potential and possible technical realization 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.

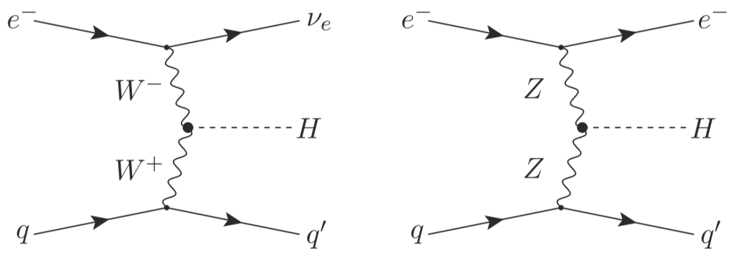
International Advisory Committee members (May 2023): Phil Allport, Diego Bettoni, Frederick Bordry (chair), Abhay Deshpande, Rohini Godbole, Beate Heinemann, Karl Jakobs, Young-Kee Kim, Max Klein, Eric Laenen, Jean-Philippe Lansberg, Tadeusz Lesiak, Dave Newbold, Vladimir Shiltsev, Johanna Stachel, Achille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

the physics impact

Collision energy above the threshold for EW/Higgs/Top



The real game change between HERA and LHC/FCC

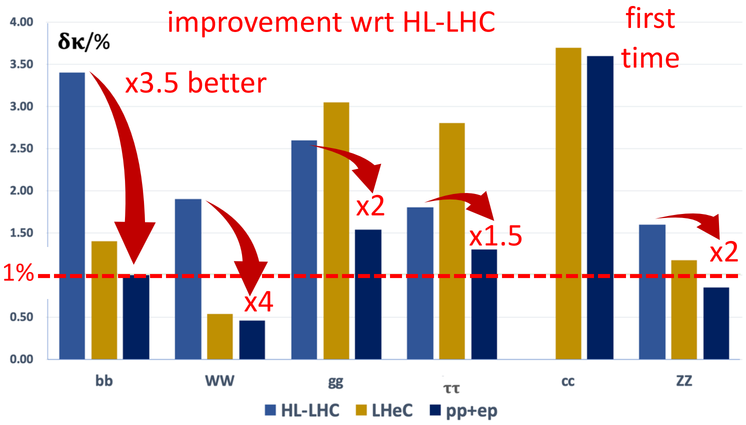


compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

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

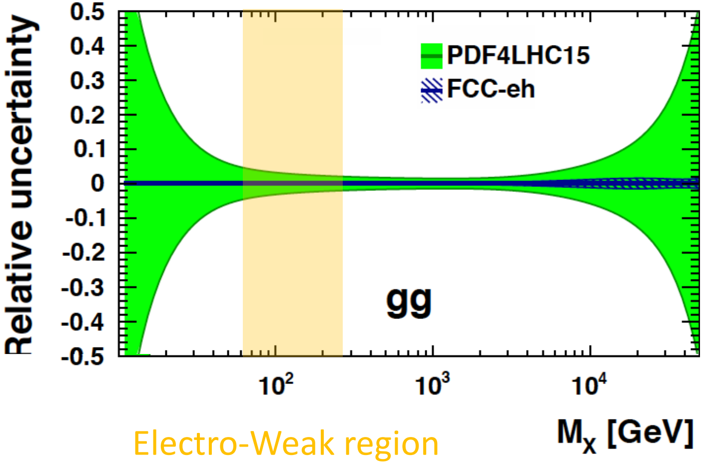
i.e. H/EW/top/QCD/search factory

Empowering the FCC-hh program with the FCC-eh

~5-7% uncertainty on the σ(W,Z,H)

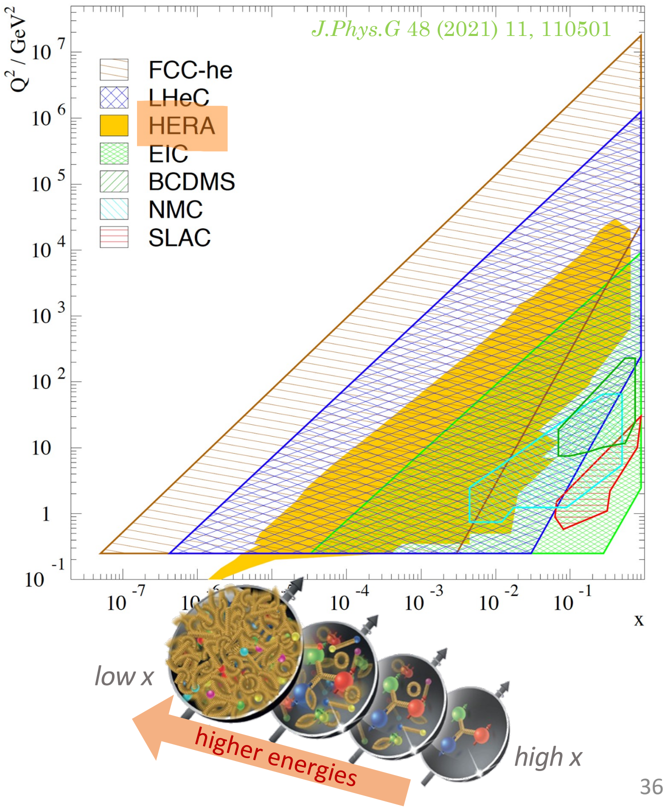
no FCC-eh

pp @ 100 TeV



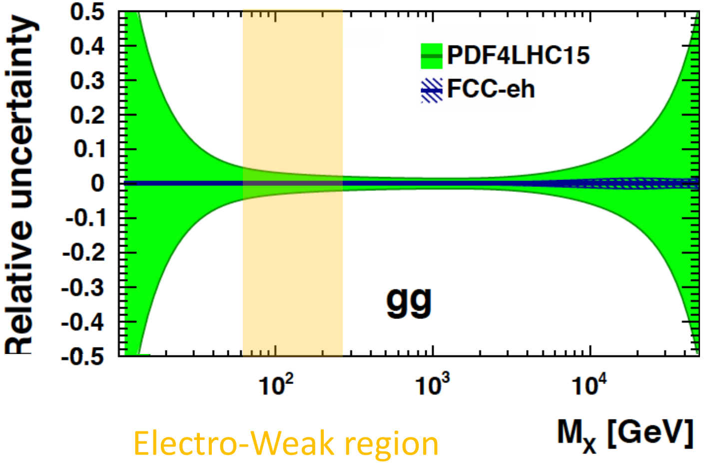
Electro-Weak region

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV



Electro-Weak region

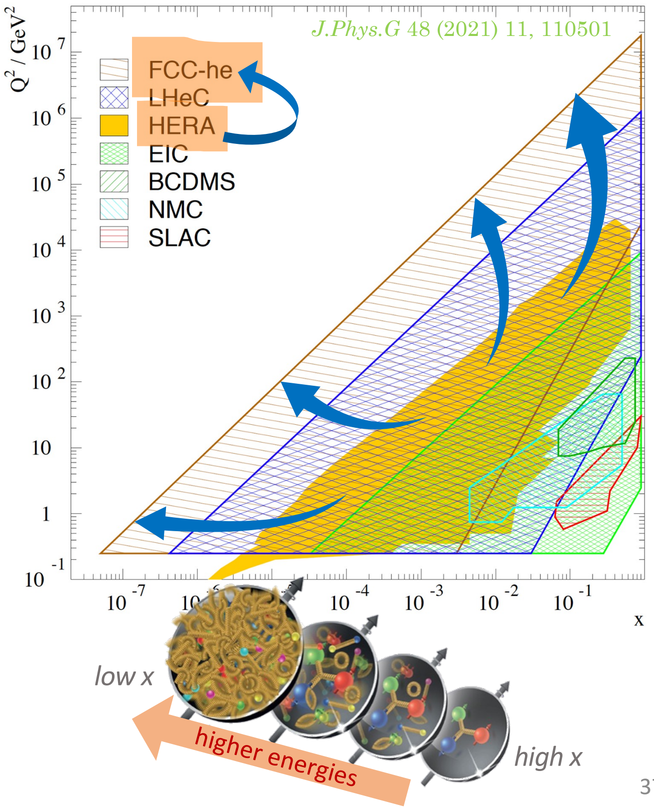
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

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)

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

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

only FCC-ee@240GeV

only FCC-hh

Complementarity for Higgs physics in the FCC program

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FCC-ee prospect

FCC-hh/eh prospect

only FCC-ee@240GeV

only FCC-hh

Complementarity for Higgs physics in the FCC program

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

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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}

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…	[illegible]	[illegible]	[illegible]
κ_W [%]	0.86	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
κ_Z [%]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.41
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.68	0.41
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.63	0.9	0.42
[illegible]	[illegible]	[illegible]	0.55	0.67	0.61	1.3	0.44

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

FCC-ee prospect

FCC-hh/eh prospect

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

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

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

While fostering continuous developments in the realm of ep/eA physics, a coherent focus on five new physics and technology themes is proposed to provide impactful information at the time of the next European strategy discussions.

more at the kick-off meeting of Oct 31, 2023: https://indico.cern.ch/event/1335332/
including self-registration to mailing lists

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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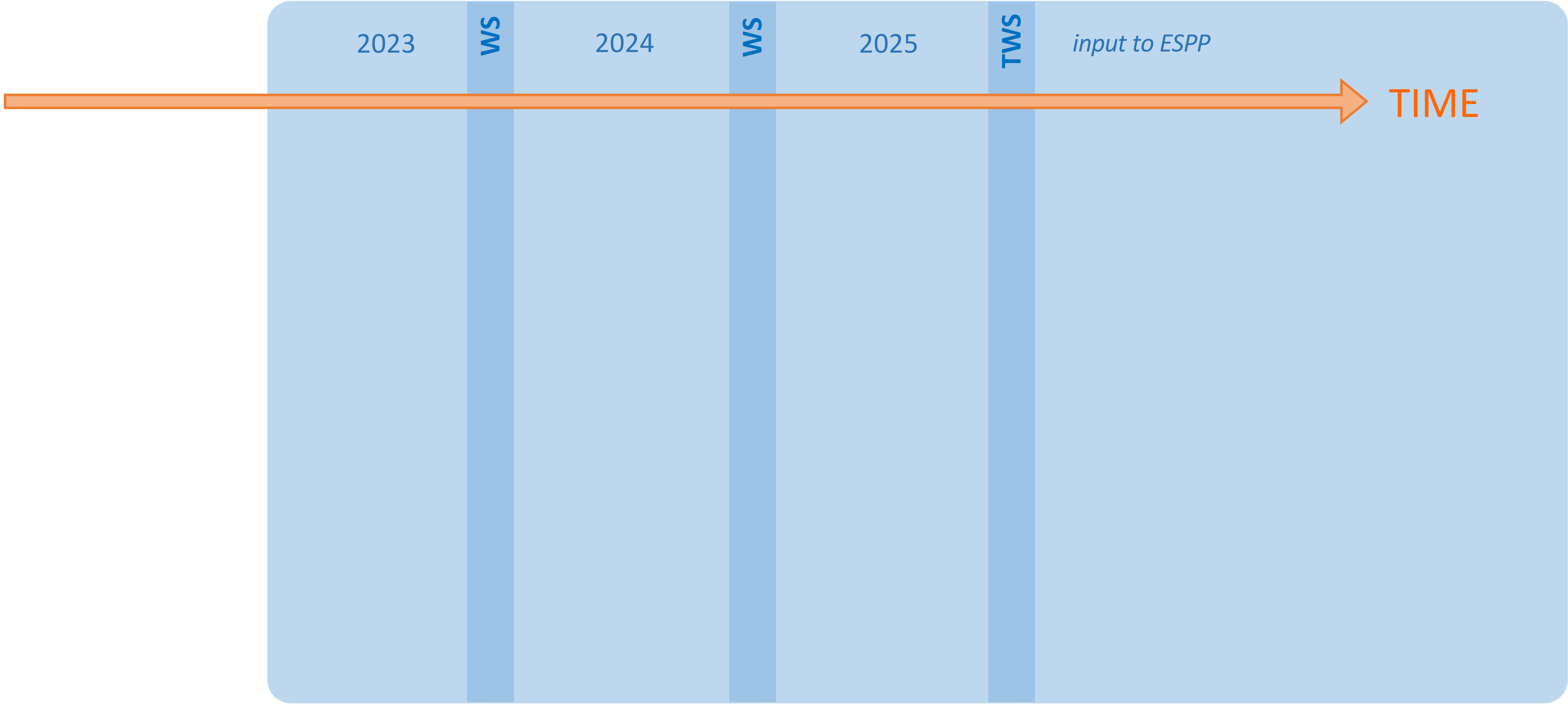

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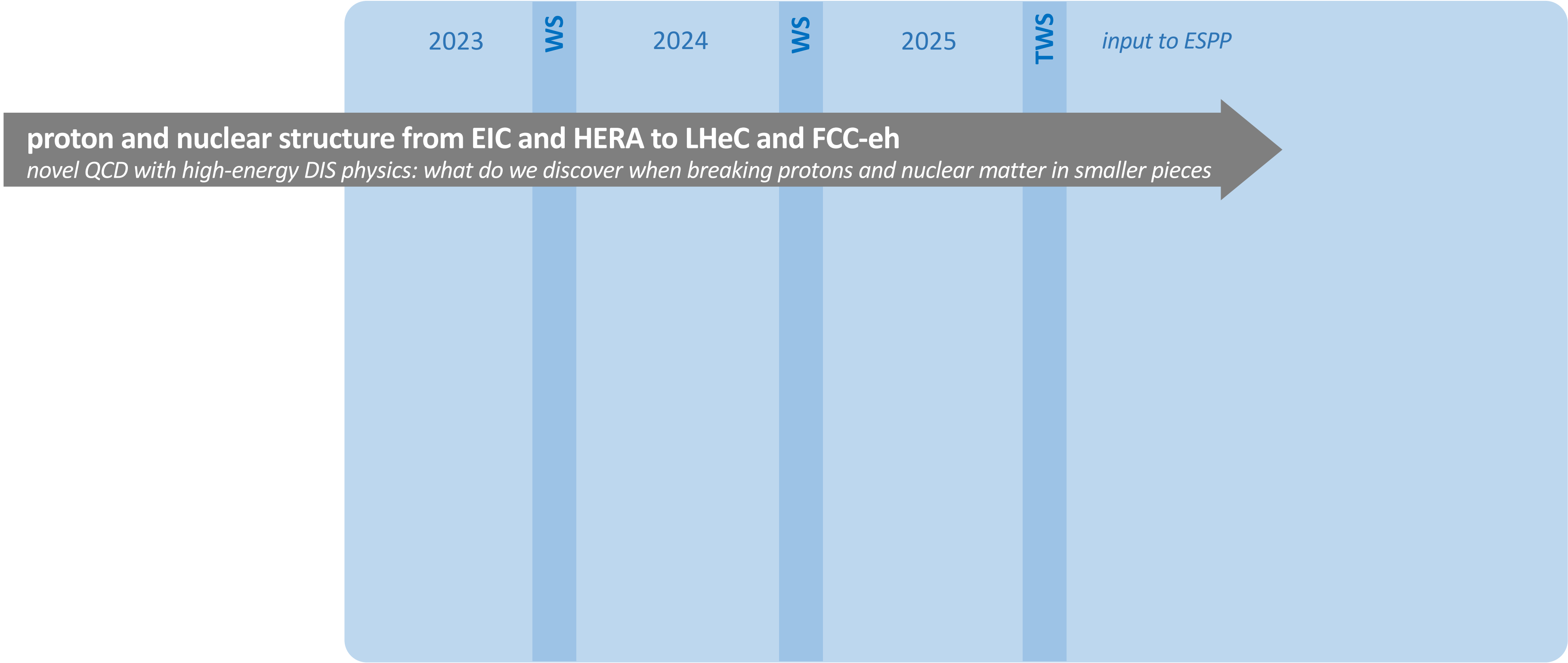

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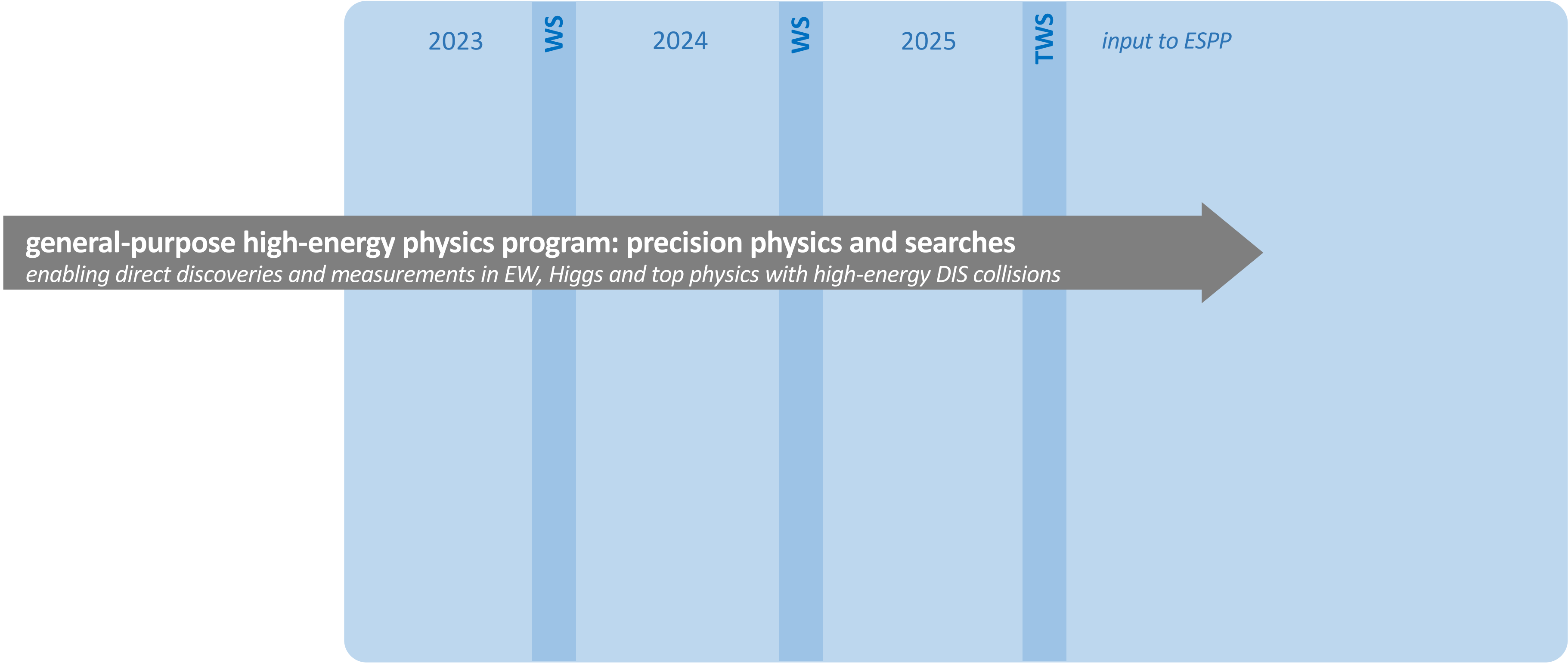

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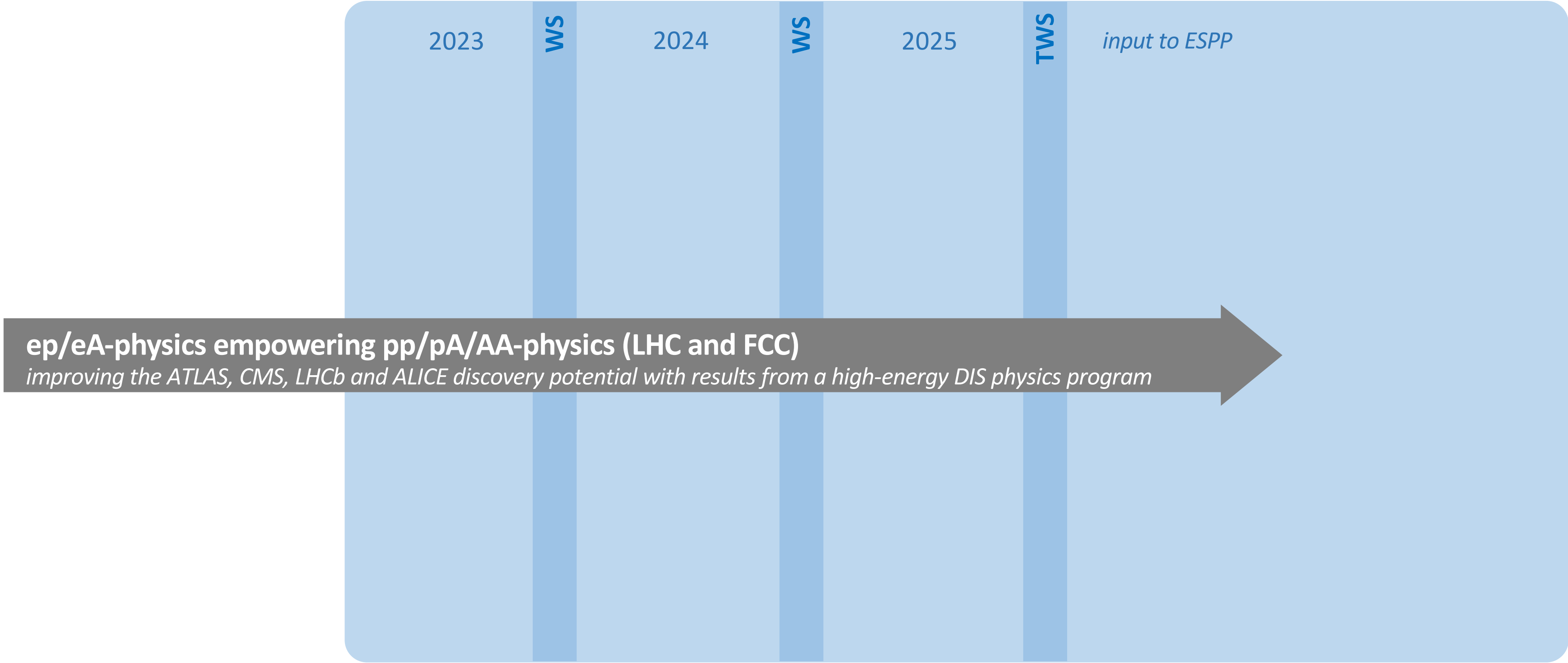

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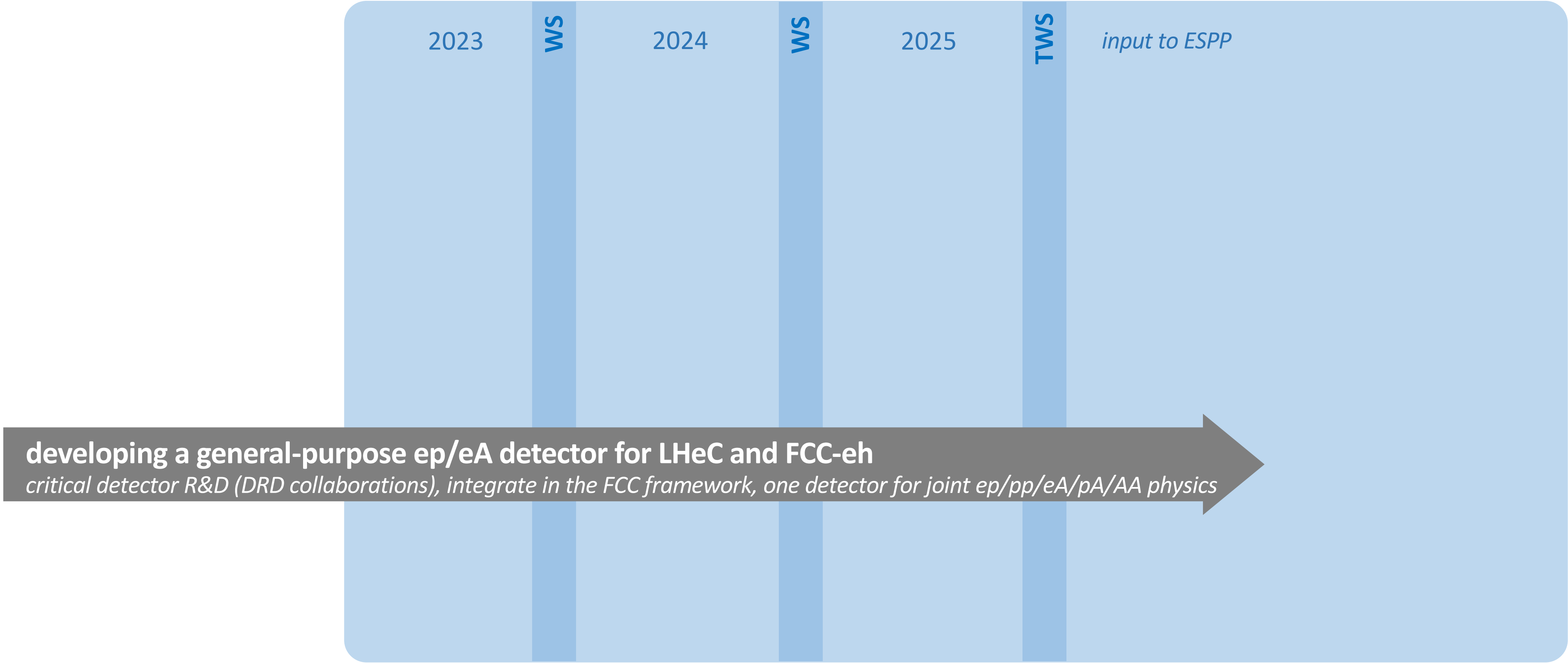

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The ep/eA study at the LHC and FCC – new impactful goals for the community

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

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

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

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

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

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

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design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

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

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

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very impactfull UK leadership
not to forget the leadership of Max Klein

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

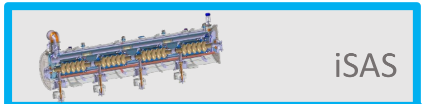
Potential impact of ERL technology

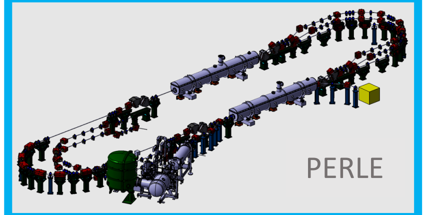
demonstrate multi-turn high-power ERL

enables the ultimate upgrade of the LHC/FCC programs

increases the performance of the next major colliders

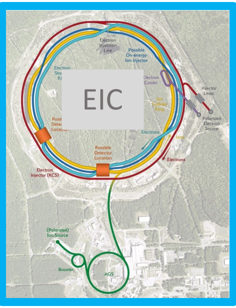
2020'ies





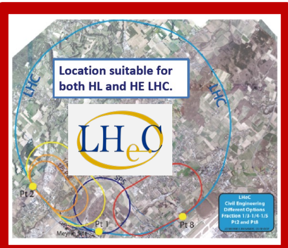
high-power ERL demonstrated

2030'ies



ERL application electron cooling

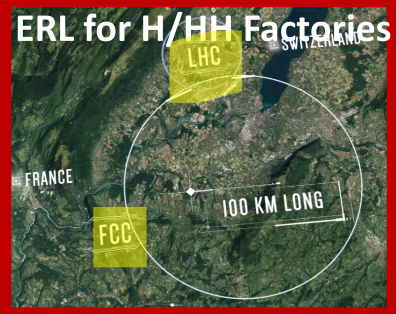
2030-2040'ies



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

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

- 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

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
- 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
- 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

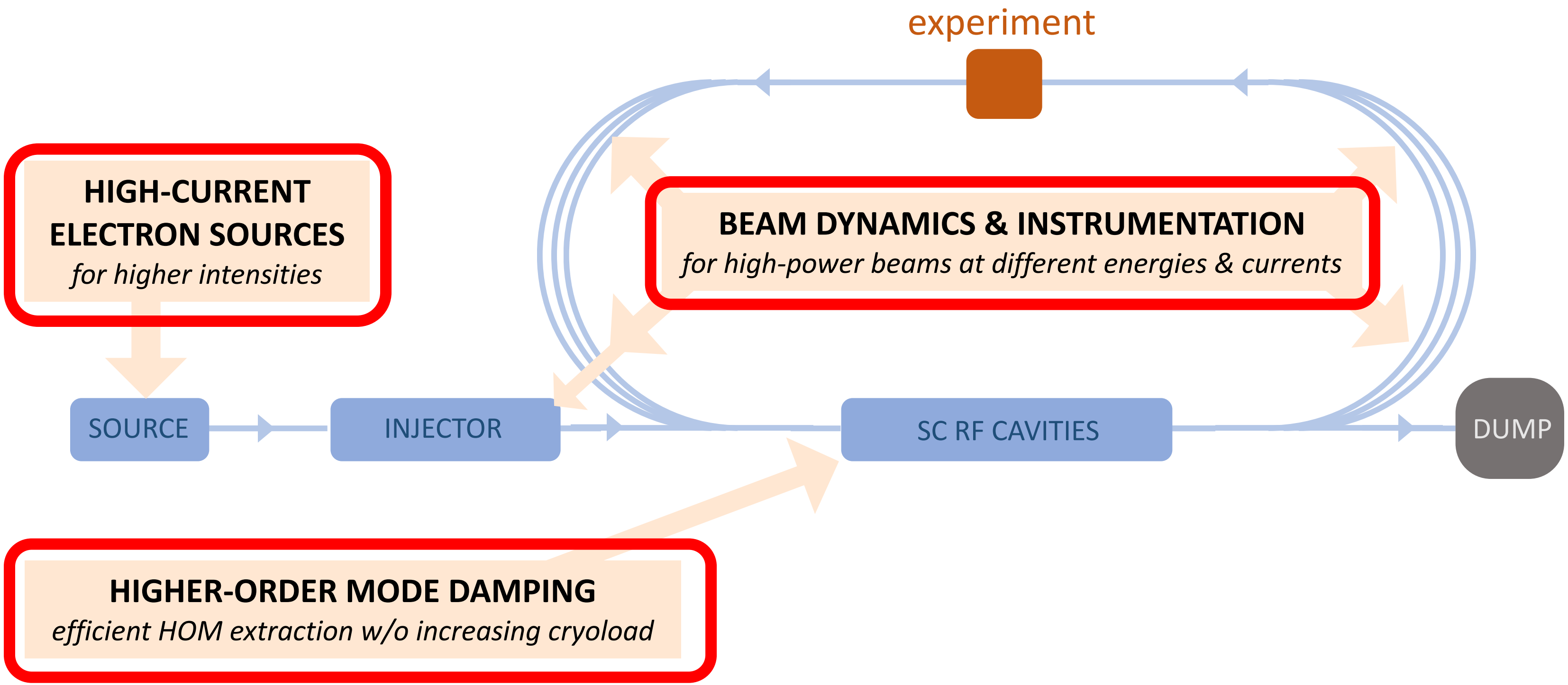
iihe BRUXELLES BRUSSEL

fwo

Thank you for your attention!

Jorgen.DHondt@vub.be

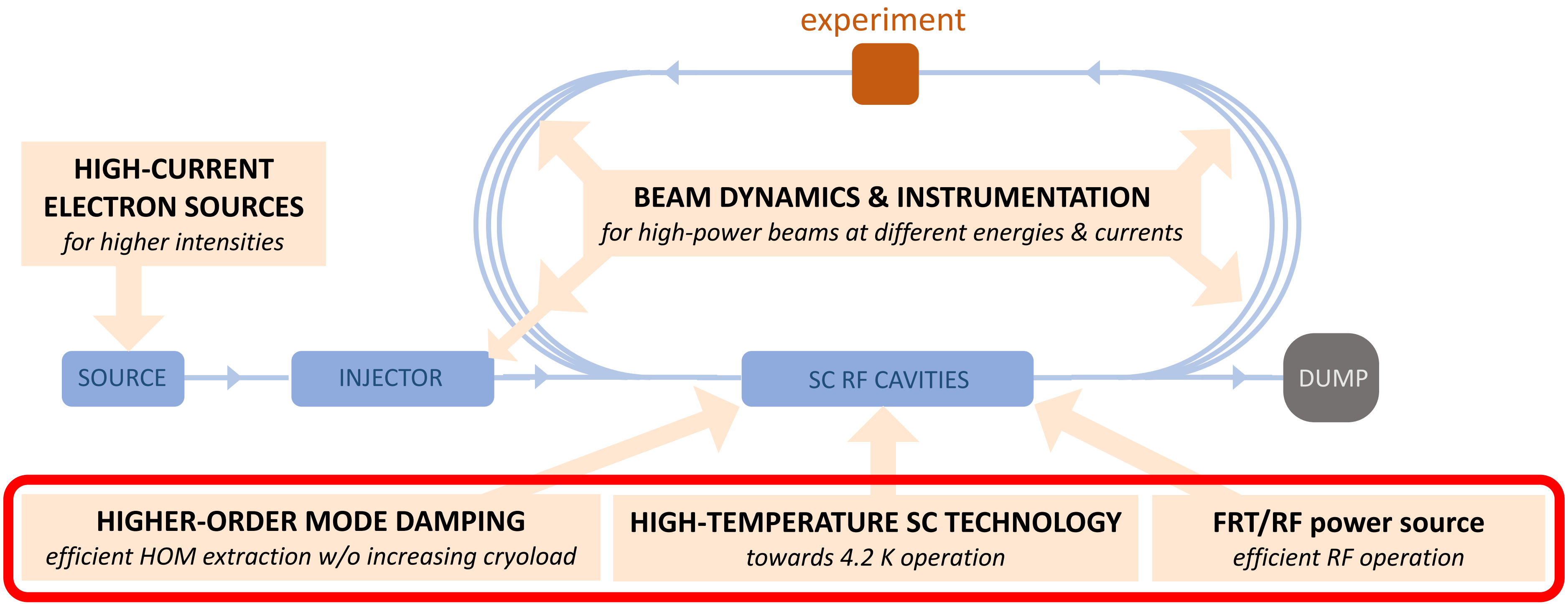
Sustainable Accelerating Systems



ENABLE EFFICIENT ENERGY RECOVERY

ERL

Sustainable Accelerating Systems



ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

ERL **RF**

Sustainable Accelerating Syst

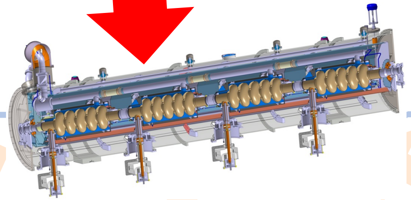
Innovate for Sustainable Accelerating Systems (iSAS)

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 … different energies & currents

SOURCE → INJECTOR →  → DUMP

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

ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

ERL **RF**

iSAS is now an approved Horizon Europe project

Grant Agreement has been signed this month – 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 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)

Potential impact of ERL technology

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2020'ies

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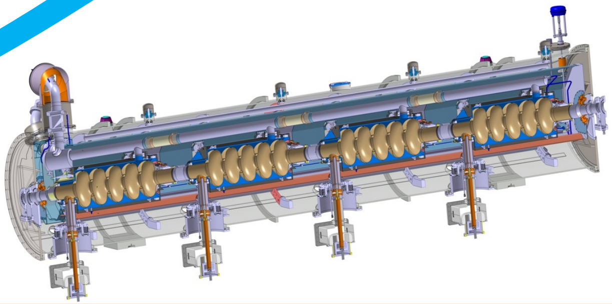

***iSAS**: new design including various energy-saving and energy-recovery technologies*

Potential impact of ERL technology

demonstrate
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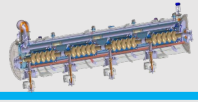
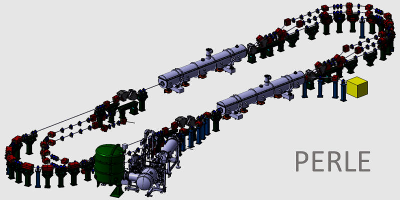
2020'ies



iSAS

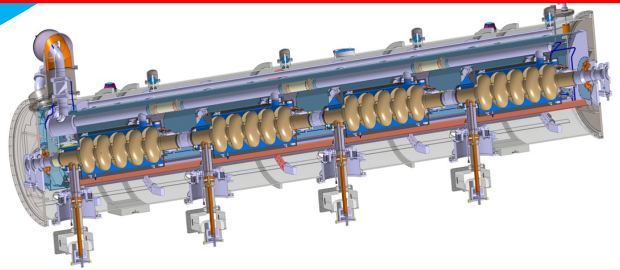


PERLE

bERLinPro

high-power ERL demonstrated

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

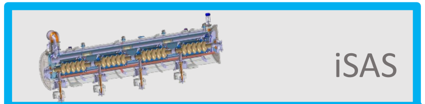


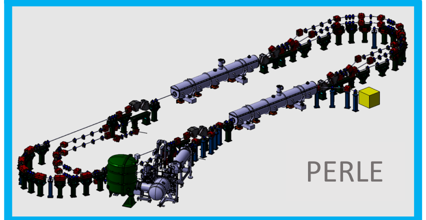
***iSAS**: new design including various energy-saving and energy-recovery technologies*

Potential impact of ERL technology

demonstrate multi-turn high-power ERL

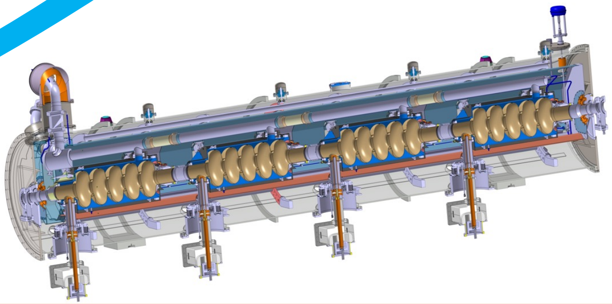
2020'ies





high-power ERL demonstrated

ERL ready for high-energy and high-luminosity colliders



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

Accelerator R&D for Particle Physics
Energy Recovery Linacs

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

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