

# Impact of Technological Innovation

Sustainable Accelerating Systems for Particle Physics



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*Vrije Universiteit Brussel*



Colloquium to honour 50 years of Max Klein in Particle Physics  
*MaxFest*, Liverpool, 9 December 2022

**observable universe**

$8.8 \cdot 10^{26} m$



**visible with our own eyes**



**quarks**

$< 10^{-19} m$

~ 1'000'000'000'000'000'000'000'000'000'000'000 meter

~ 0.000'000'000'000'000'000'000'01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

biological cell

atoms

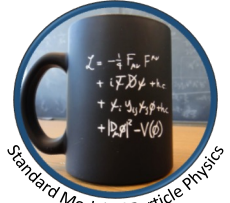
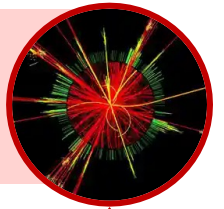
proton  
neutron



~ 1'000'000'000'000'000'000'000'000'000'000 meter

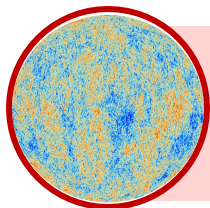
~ 0.000'000'000'000'000'000'000'01 meter

observations how  
small objects  
behave in our  
laboratories



$\sim 1.000'000'000'000'000'000'000'000'000'000'000$  meter

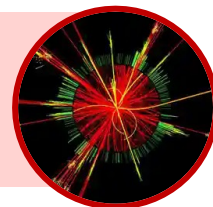
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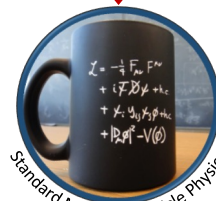
observations how large objects behave in our universe



Standard Model of Cosmology



observations how small objects behave in our laboratories

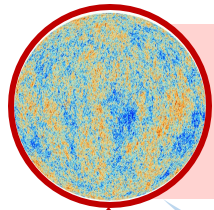


Standard Model of Particle Physics

$\sim 1\,000\,000\,000\,000\,000\,000\,000\,000\,000\,000$  meter

$\sim 0.000\,000\,000\,000\,000\,000\,000\,01$  meter

building blocks of life on the human scale

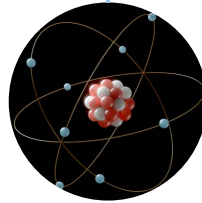


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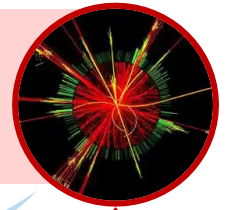


Standard Model of Cosmology

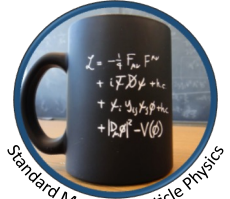
e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons



observations how small objects behave in our laboratories

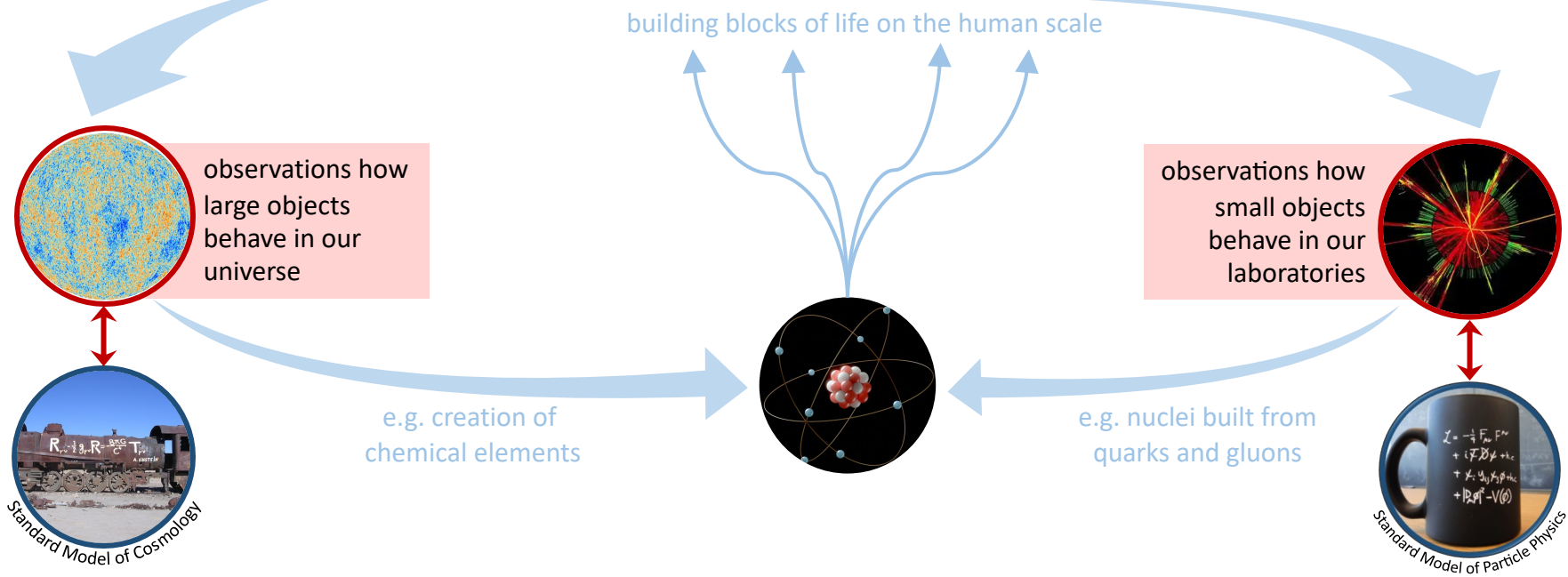


Standard Model of Particle Physics

# A century of scientific revolutions

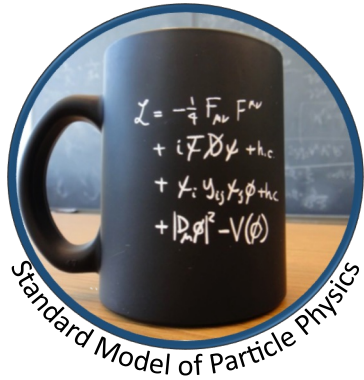
$\sim 1'000'000'000'000'000'000'000'000'000'000$  meter

$\sim 0.000'000'000'000'000'000'000'01$  meter



# The quest for understanding physics

## “Problems and Mysteries”



Standard Model of Particle Physics



Standard Model of Cosmology

e.g. Abundance of dark matter?

Abundance of matter over antimatter?

What is the origin and engine for high-energy cosmic particles?

Dark energy for an accelerated expansion of the universe?

What caused (and stopped) inflation in the early universe?

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

Pattern of particle masses and mixings?

Dynamics of Electro-Weak symmetry breaking?

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

Resolution of the structure and dynamics inside hadrons? ...



# The quest for understanding physics

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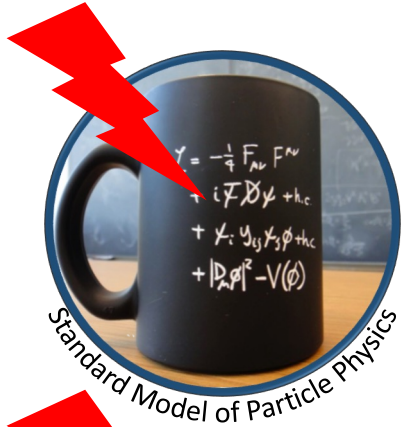
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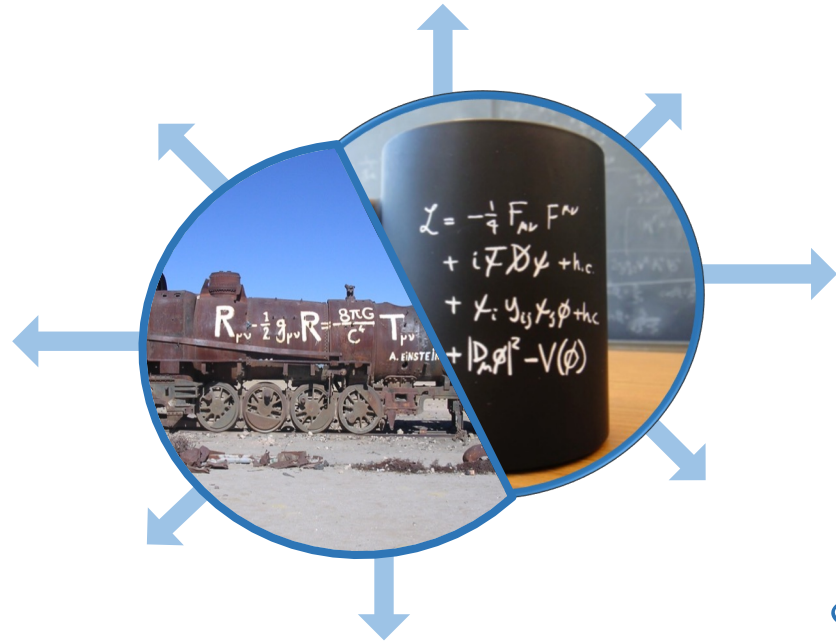


Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

earlier universe

higher energy interactions  
in the lab

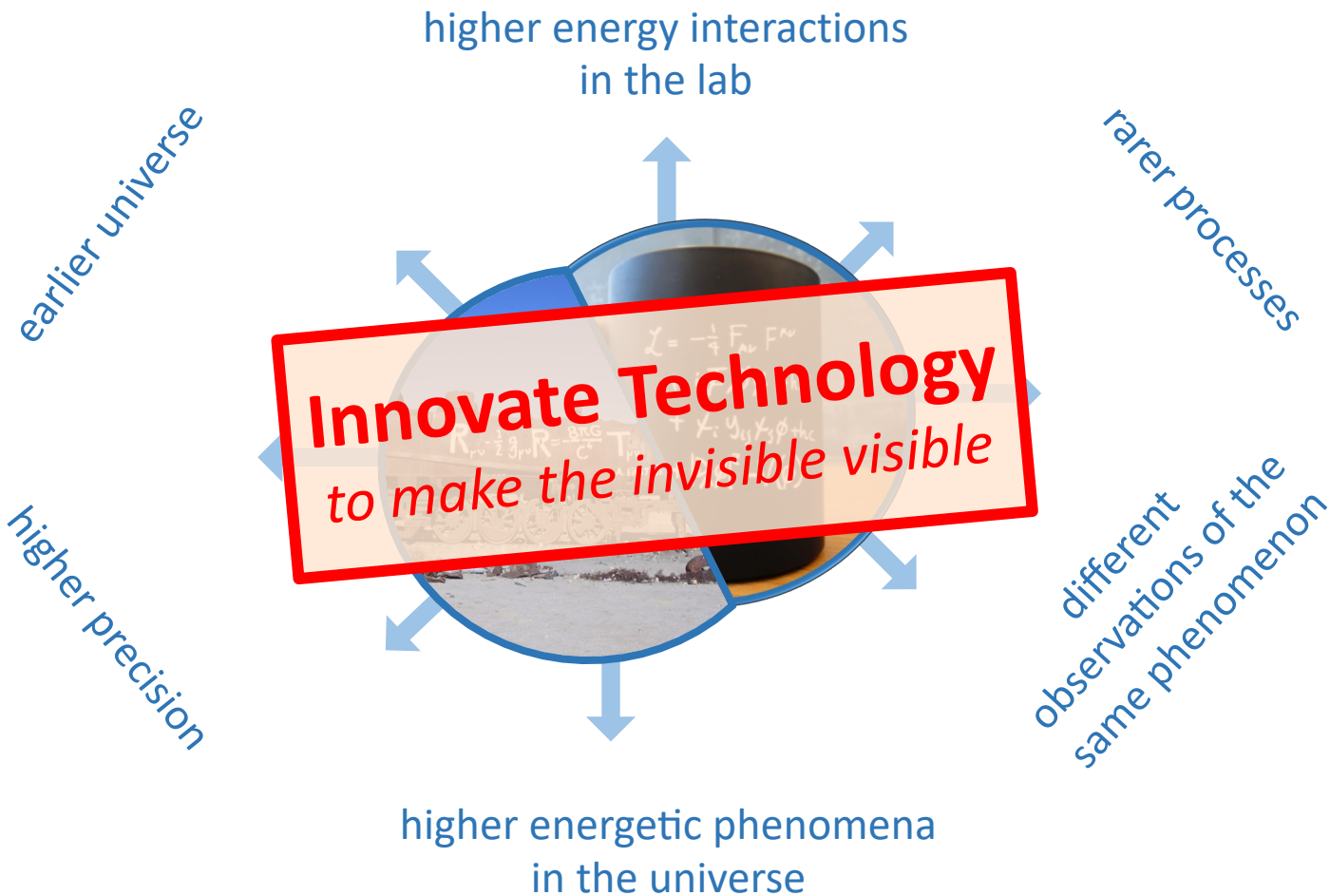
rarer processes



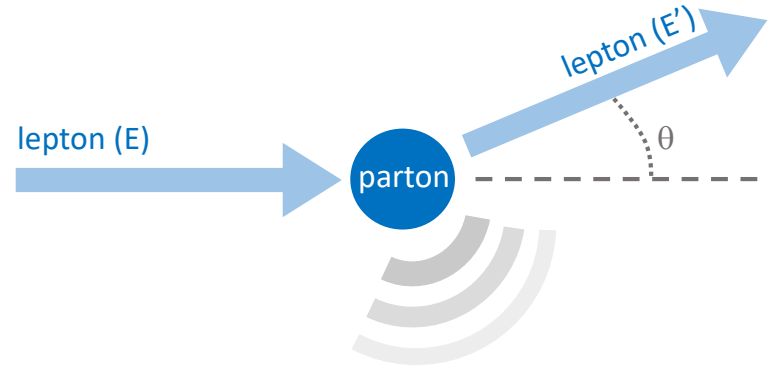
higher precision

different  
observations of the  
same phenomenon

higher energetic phenomena  
in the universe



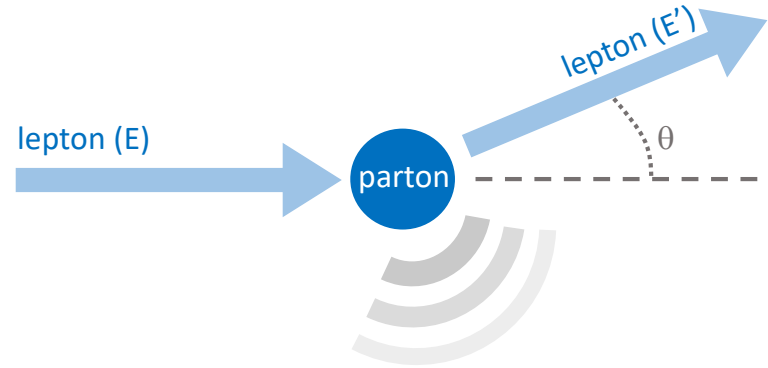
# Key exploration to answers: the structure of matter



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From the legacy of HERA to  
high-energy electron-proton collisions

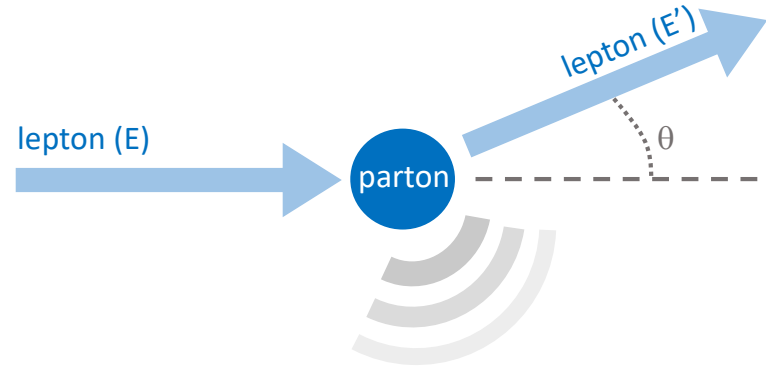
*when DIS physics becomes  
general-purpose physics*






# Key exploration to answers: the structure of matter

From the legacy of HERA to high-energy electron-proton collisions

*when DIS physics becomes general-purpose physics*



	 <b>HERA</b>	<b>EIC</b>	 <b>LHeC</b>	 <b>FCC-eh</b>
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 <sup>-2</sup> s <sup>-1</sup> )	$5 \times 10^{31}$	$1 \times 10^{34}$	$2.3 \times 10^{34}$	$1.5 \times 10^{34}$

# High-intensity electron beam

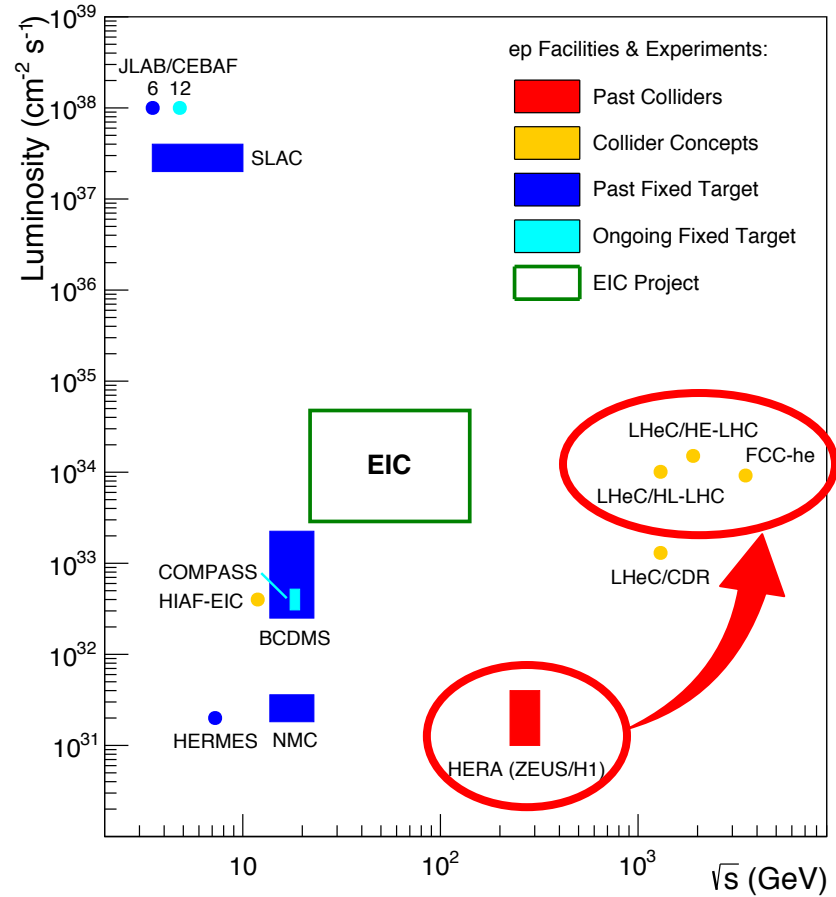
## From HERA to LHeC

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

beam current  $\times$  beam energy = beam power

**LHeC  $\sim$  1 GW beam power**

*equivalent to the power delivered by a nuclear power plant*



# High-intensity electron beam

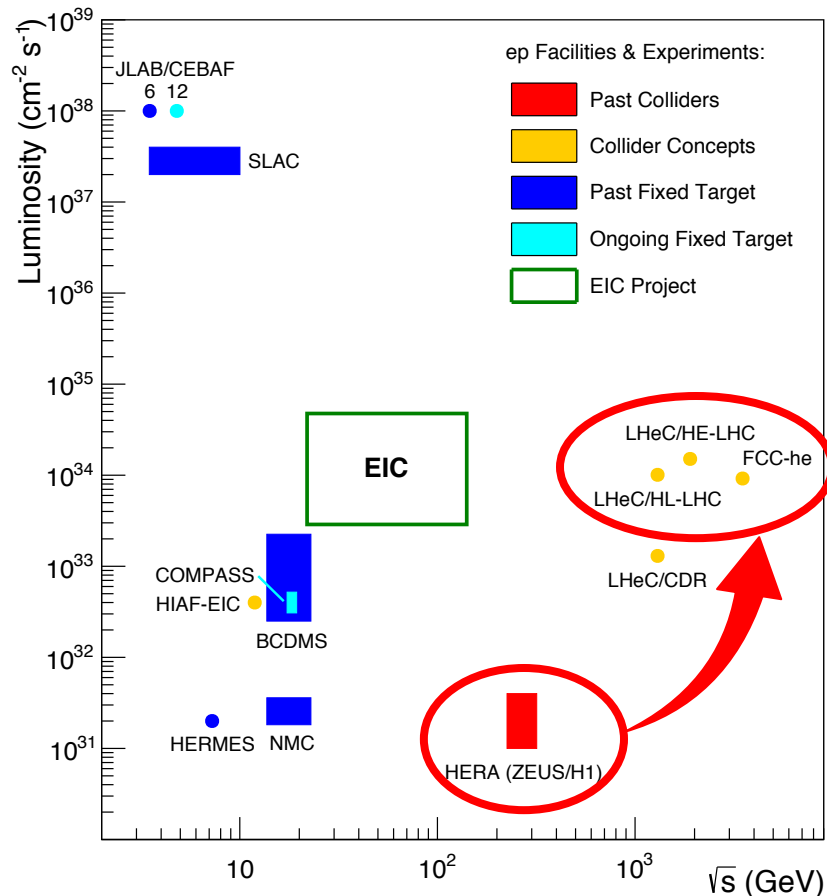
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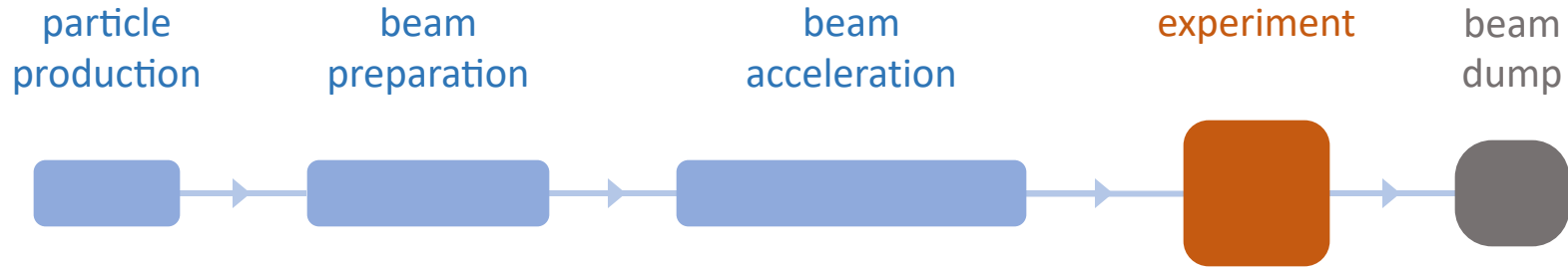
*equivalent to the power delivered by a nuclear power plant*



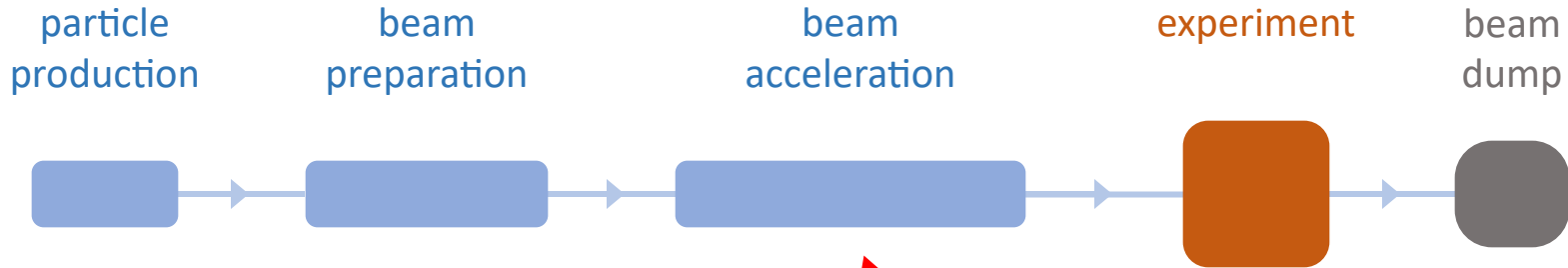


*where do we use power*  
*where do we lose power*

# Basic structures of a particle accelerator



# Basic structures of a particle accelerator



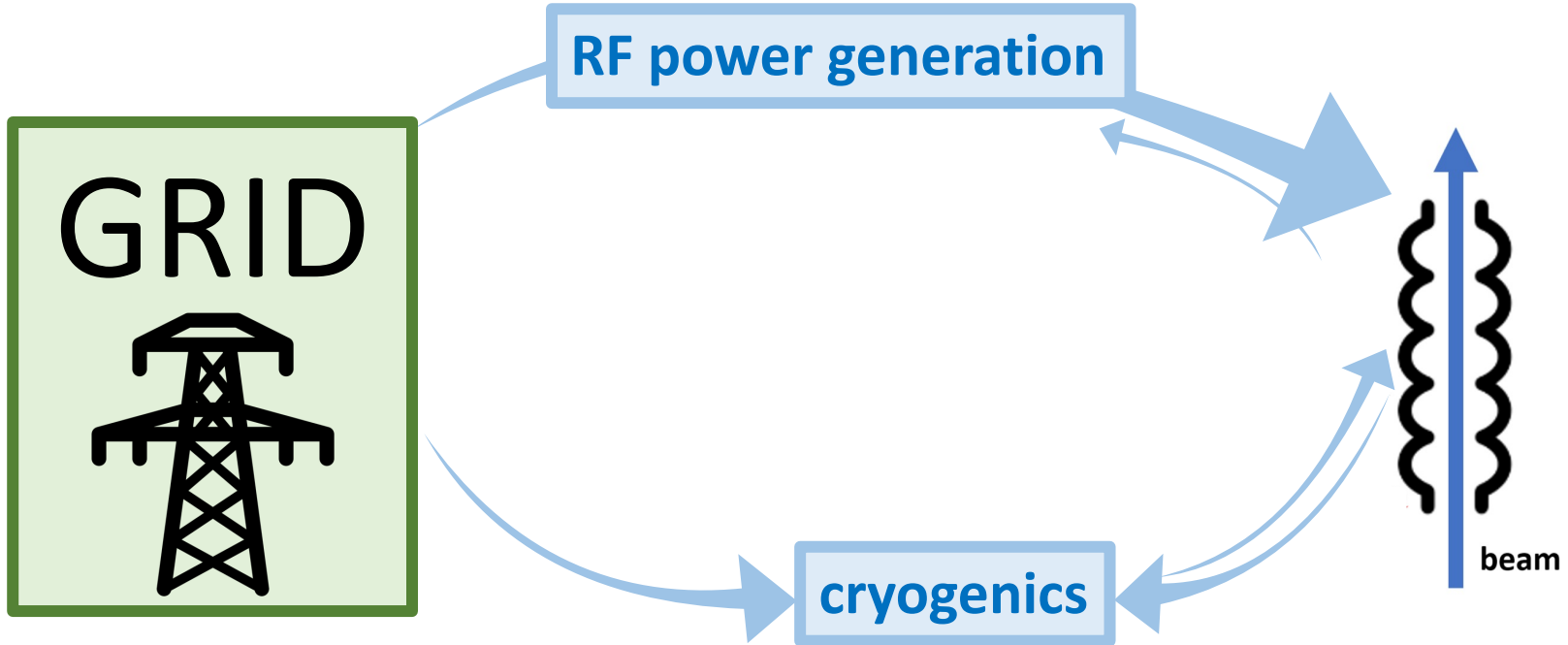
**most of the power consumption**  
*from the power-grid provide power to the beam*  
*(for lepton accelerators)*

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

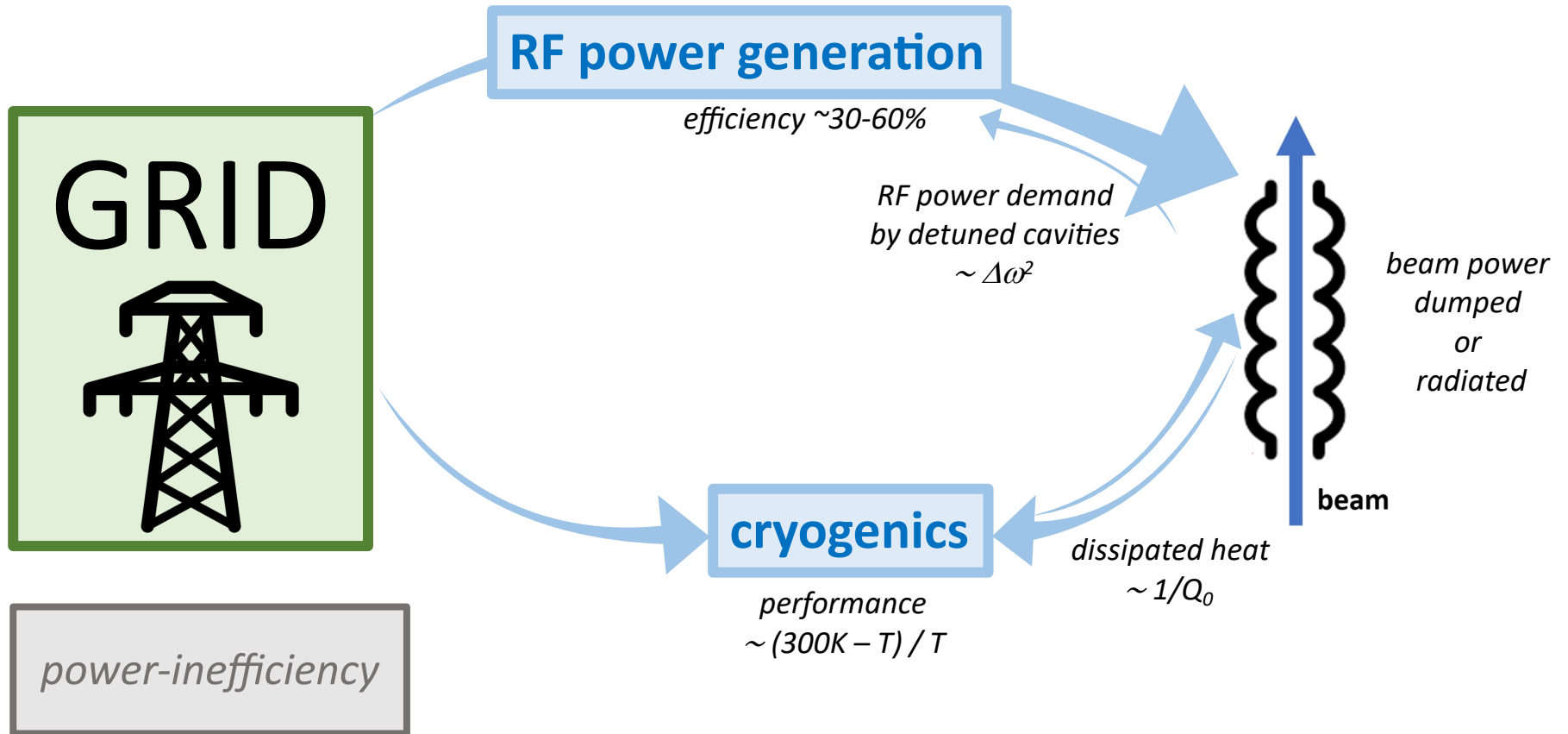
***A detailed plan for the [...] saving and re-use of energy should be part of the approval process for any major project.***

*European Strategy for Particle Physics 2020*

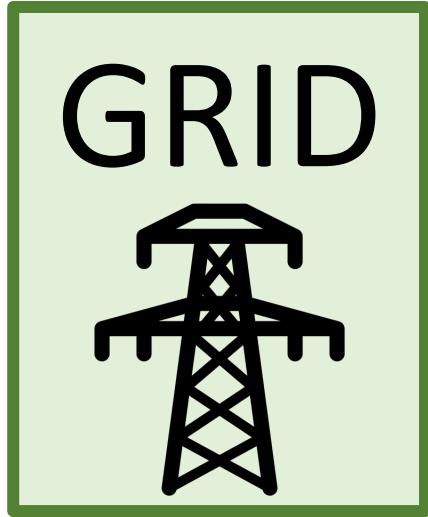
# From Grid to Beam



# From Grid to Beam



# From Grid to Beam



*mitigation with novel technologies*

**improve amplifier efficiency**

*e.g. solid state amplifiers for oscillating power demands*

**RF power generation**

*efficiency ~30-60%*

*RF power demand  
by detuned cavities  
 $\sim \Delta\omega^2$*

**dealing with microphonics**

*e.g. Fast Reactive Tuners*

**recover the energy from the beam**

*e.g. ERL reaching  
100% recovery*



*beam power  
dumped  
or  
radiated*

**beam**

**cryogenics**

*performance  
 $\sim (300K - T) / T$*

*dissipated heat  
 $\sim 1/Q_0$*

**operate cavities at higher T & improve  $Q_0$  of cavities**

*e.g.  $Nb_3Sn$  from 2K to 4.4K  $\rightarrow$  3x less cooling power needed*

# From Grid to Beam

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*

**ALARA = As Low As Reasonable Achievable**  
*principle enforced for nuclear safety,  
also for energy consumption ?*

*e.g. Nb<sub>3</sub>Sn from 2K to 4.4K → 3x less cooling power needed*

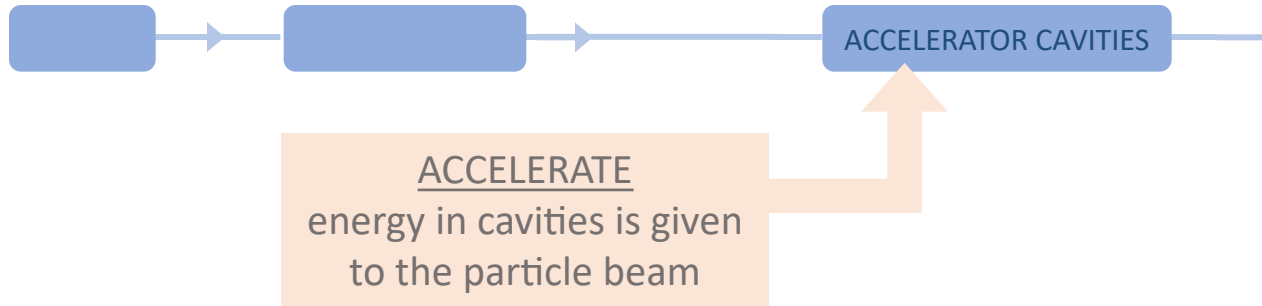


# European Accelerator R&D Roadmap

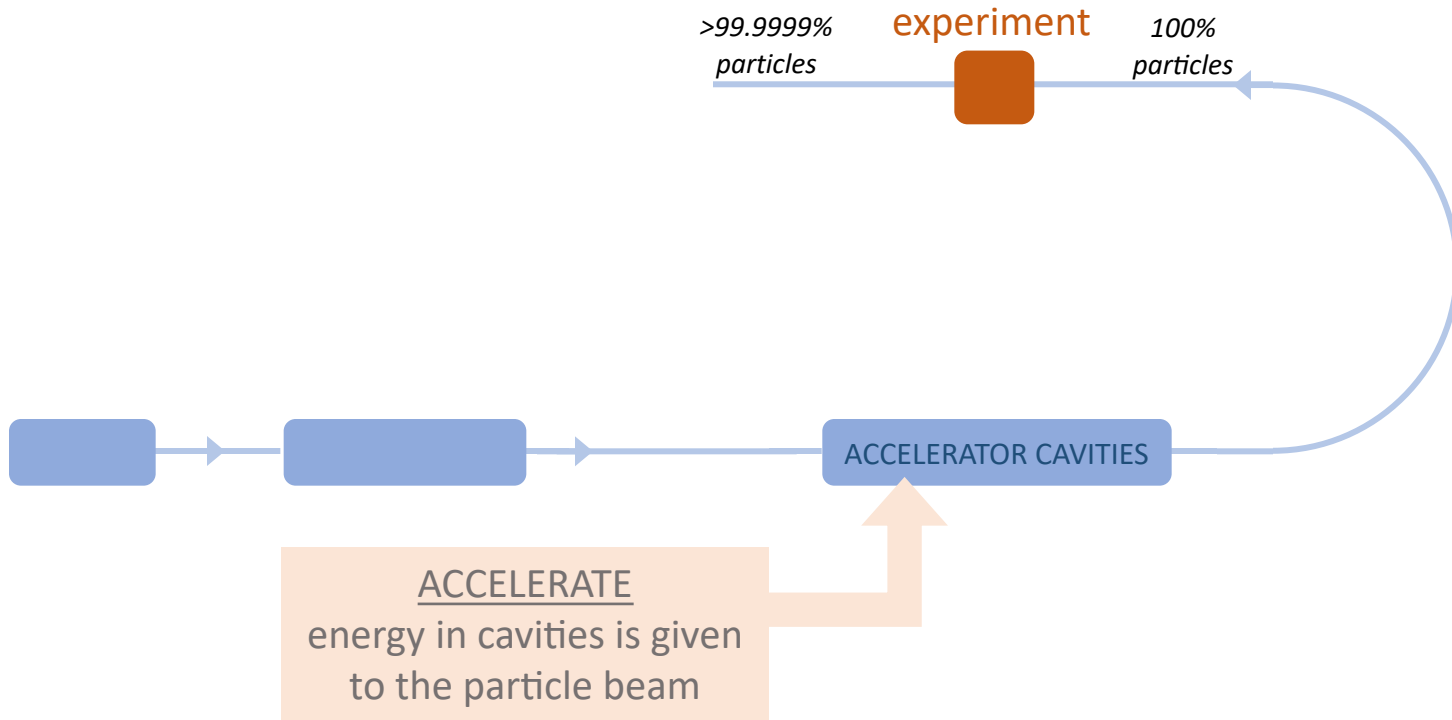
*for particle physics*



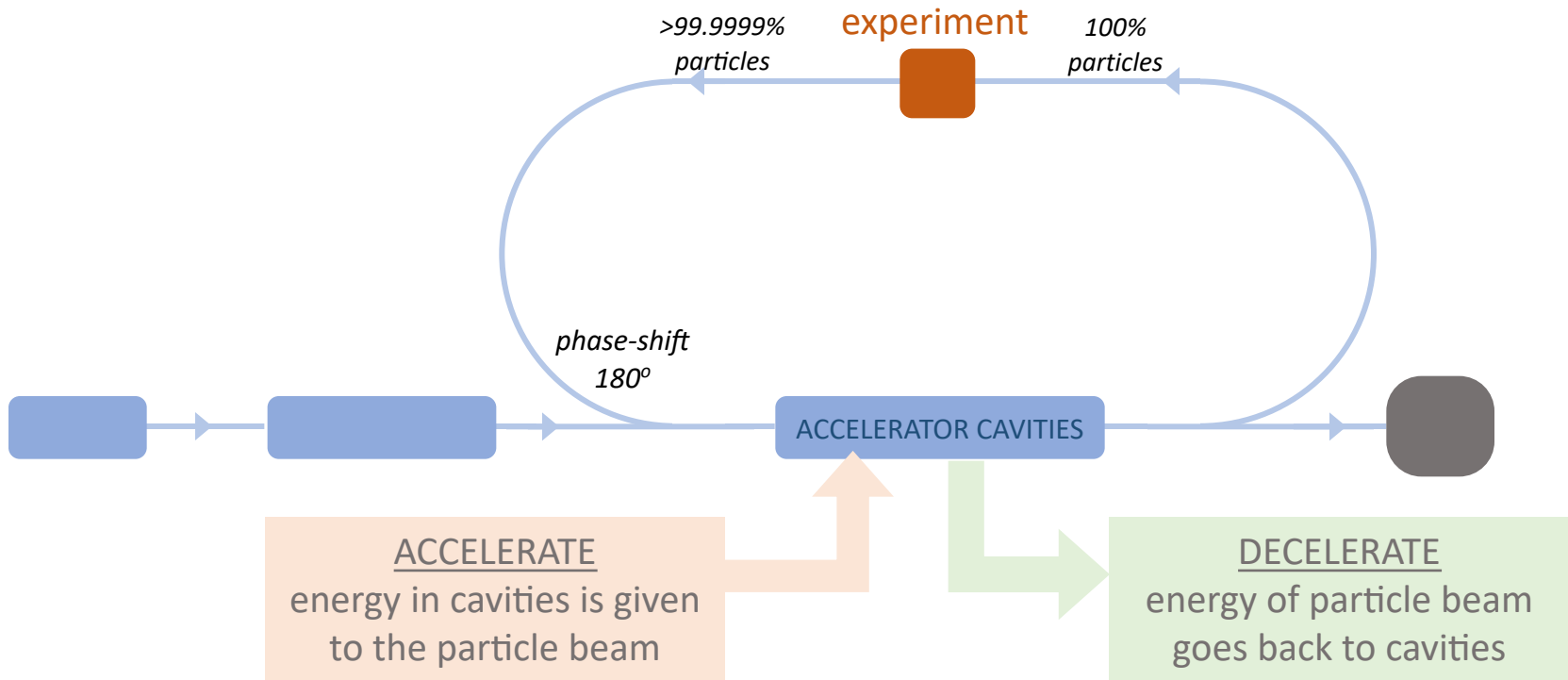
# The principle of Energy Recovery



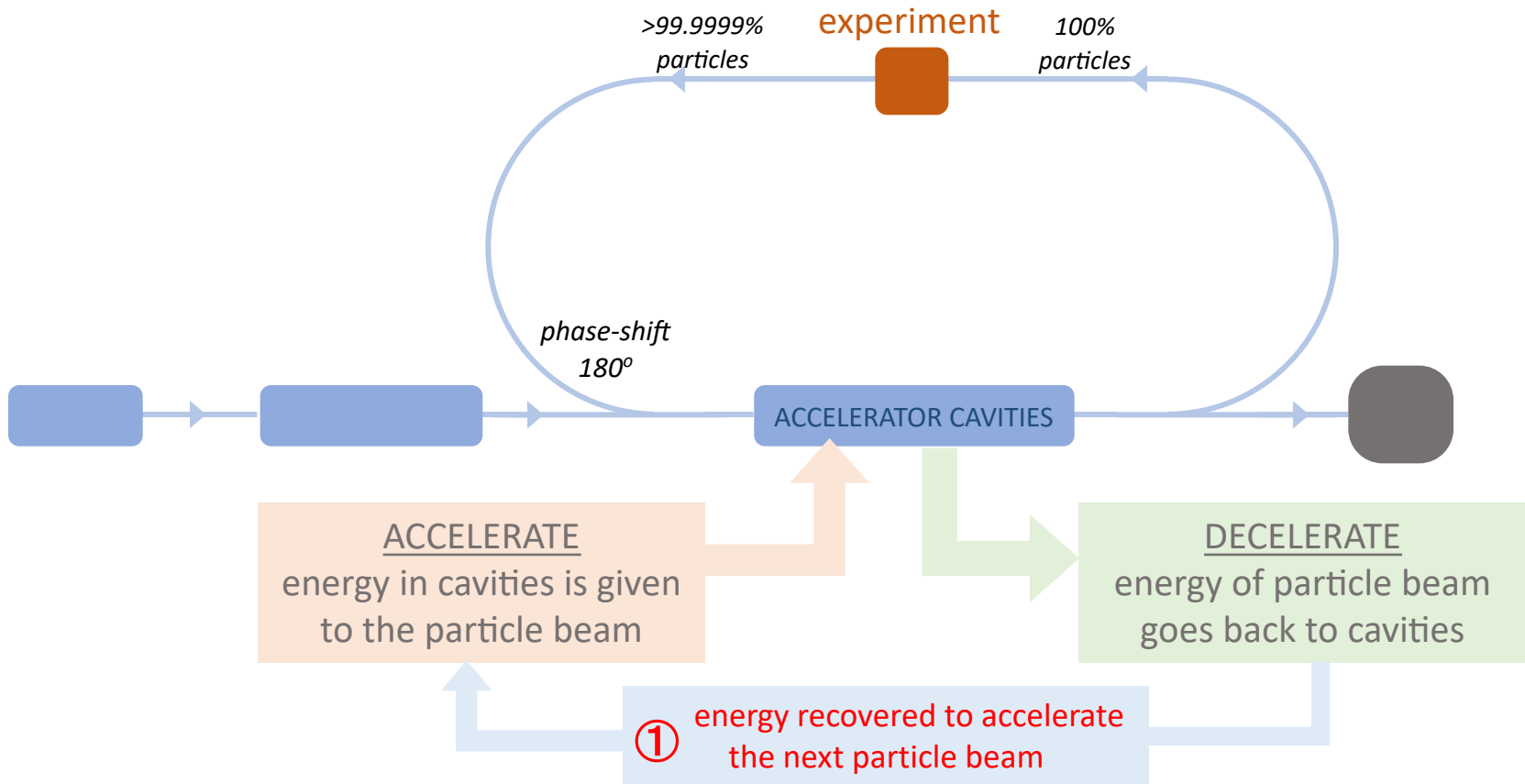
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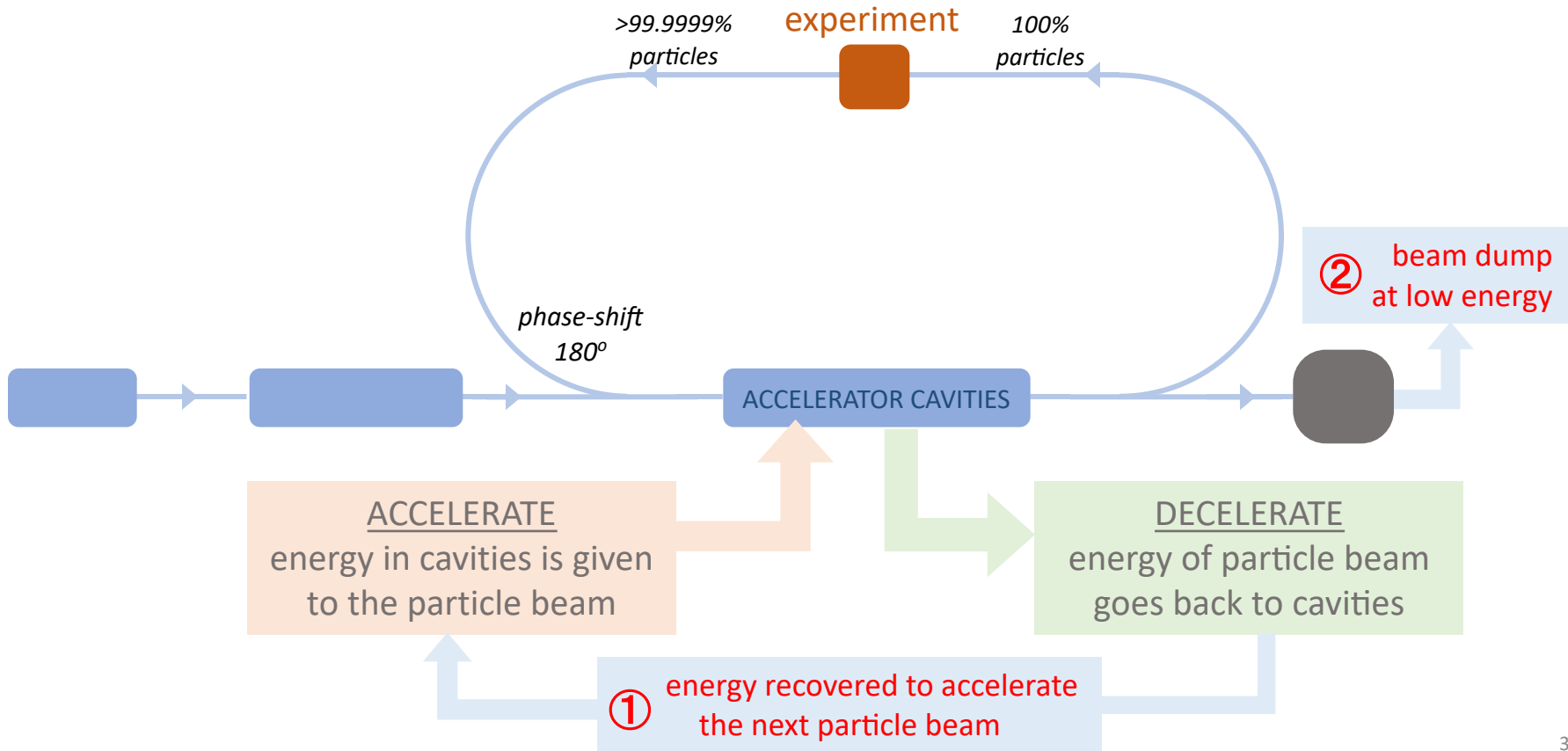
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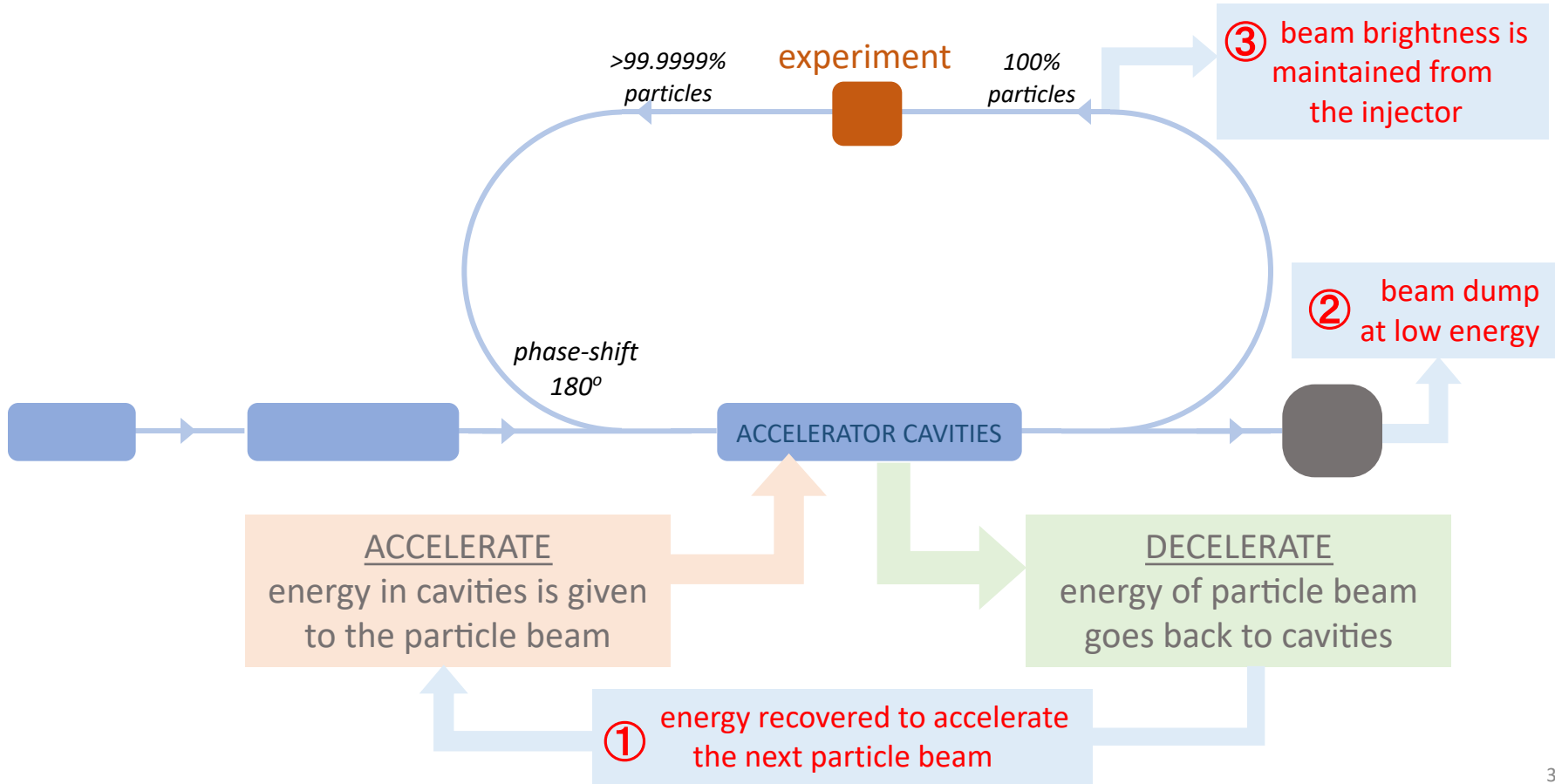
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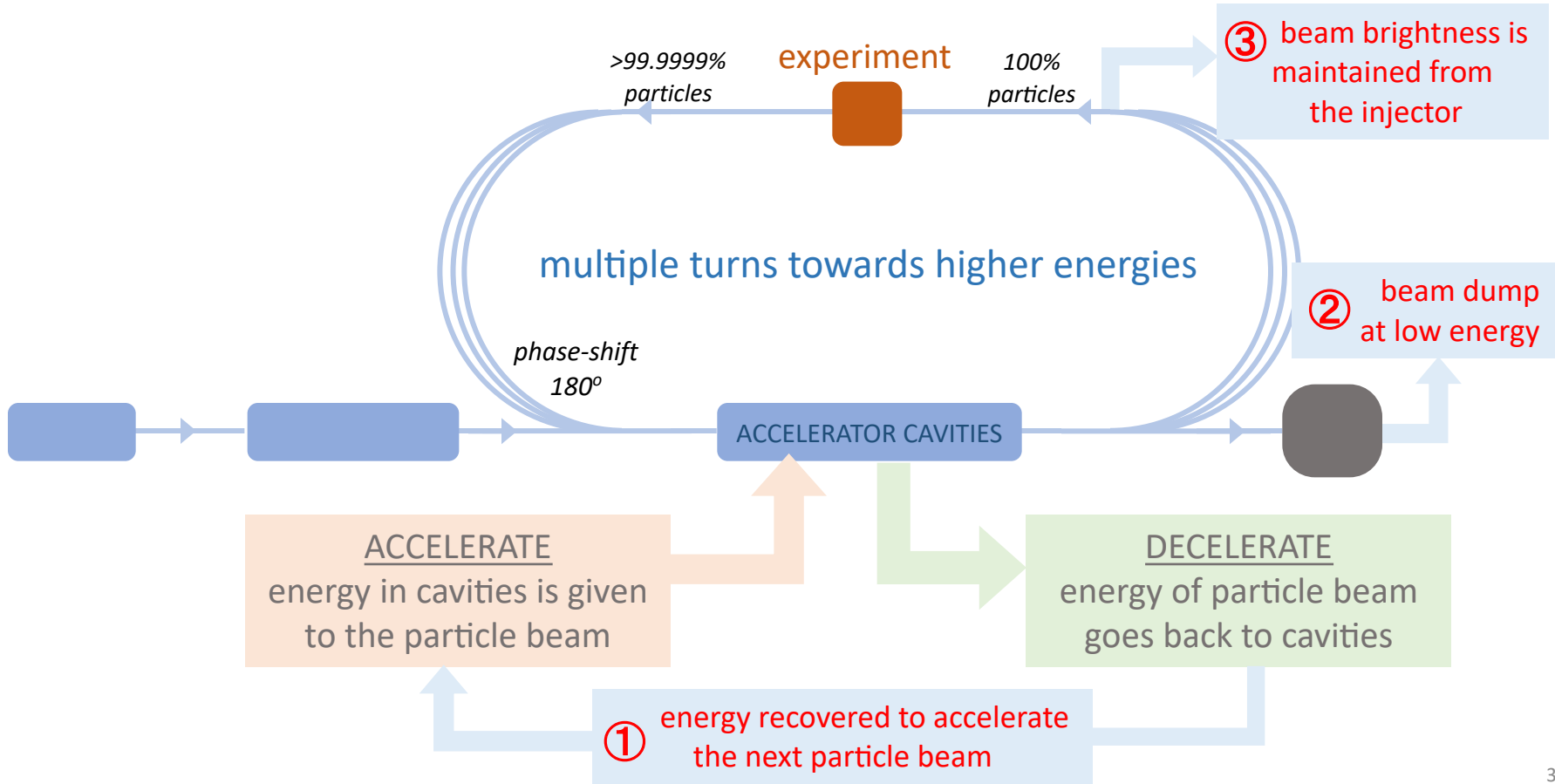
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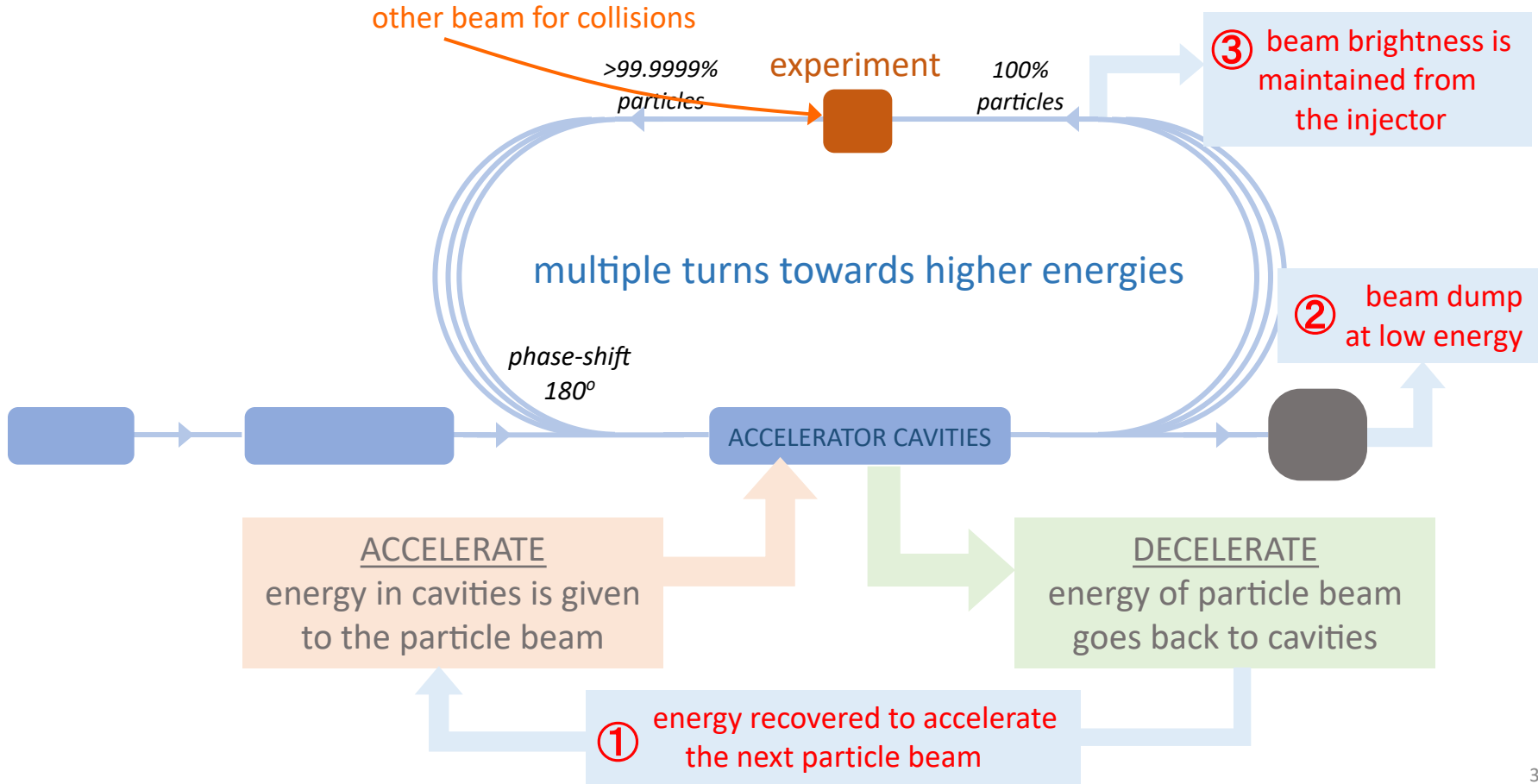


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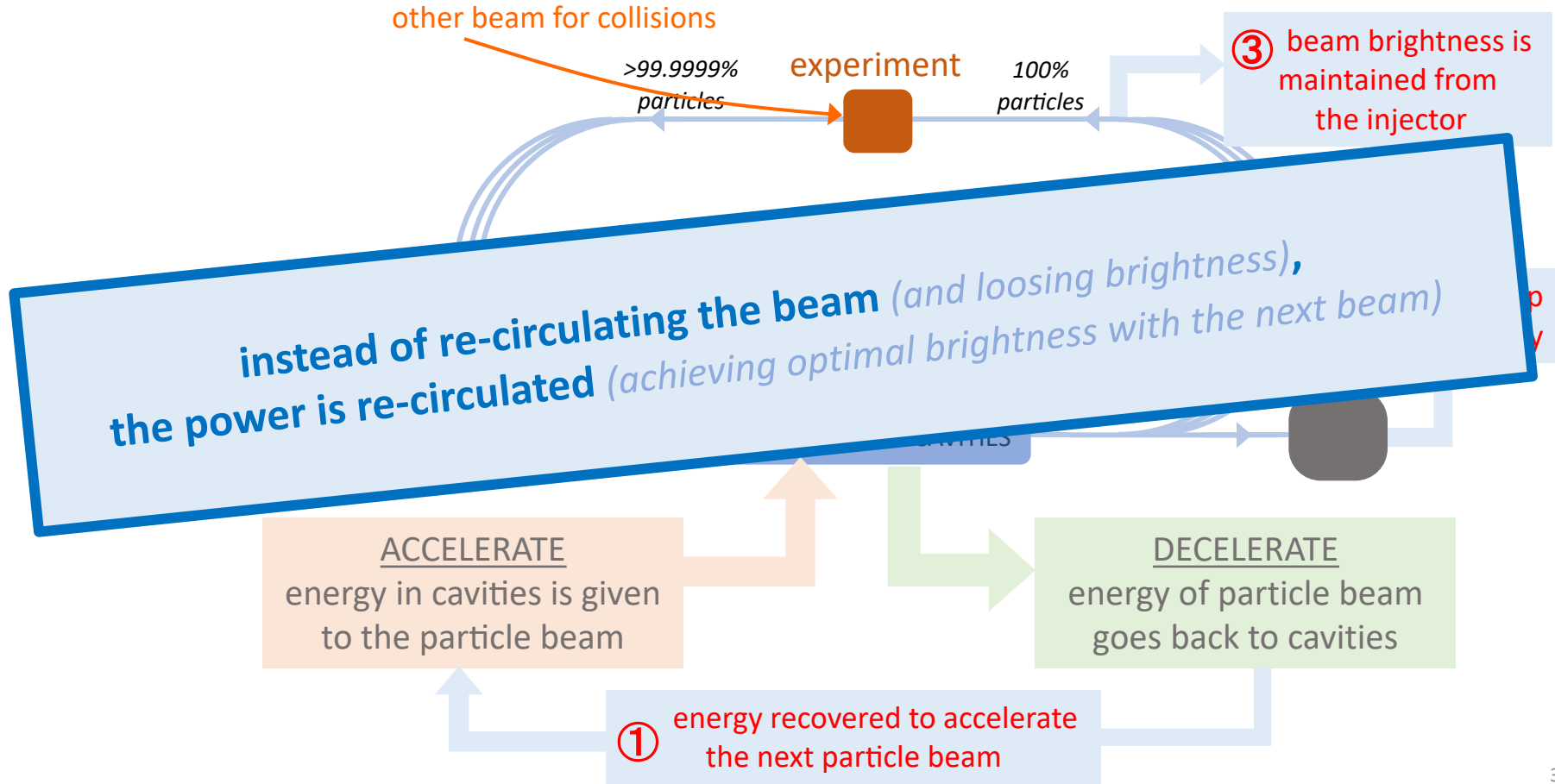




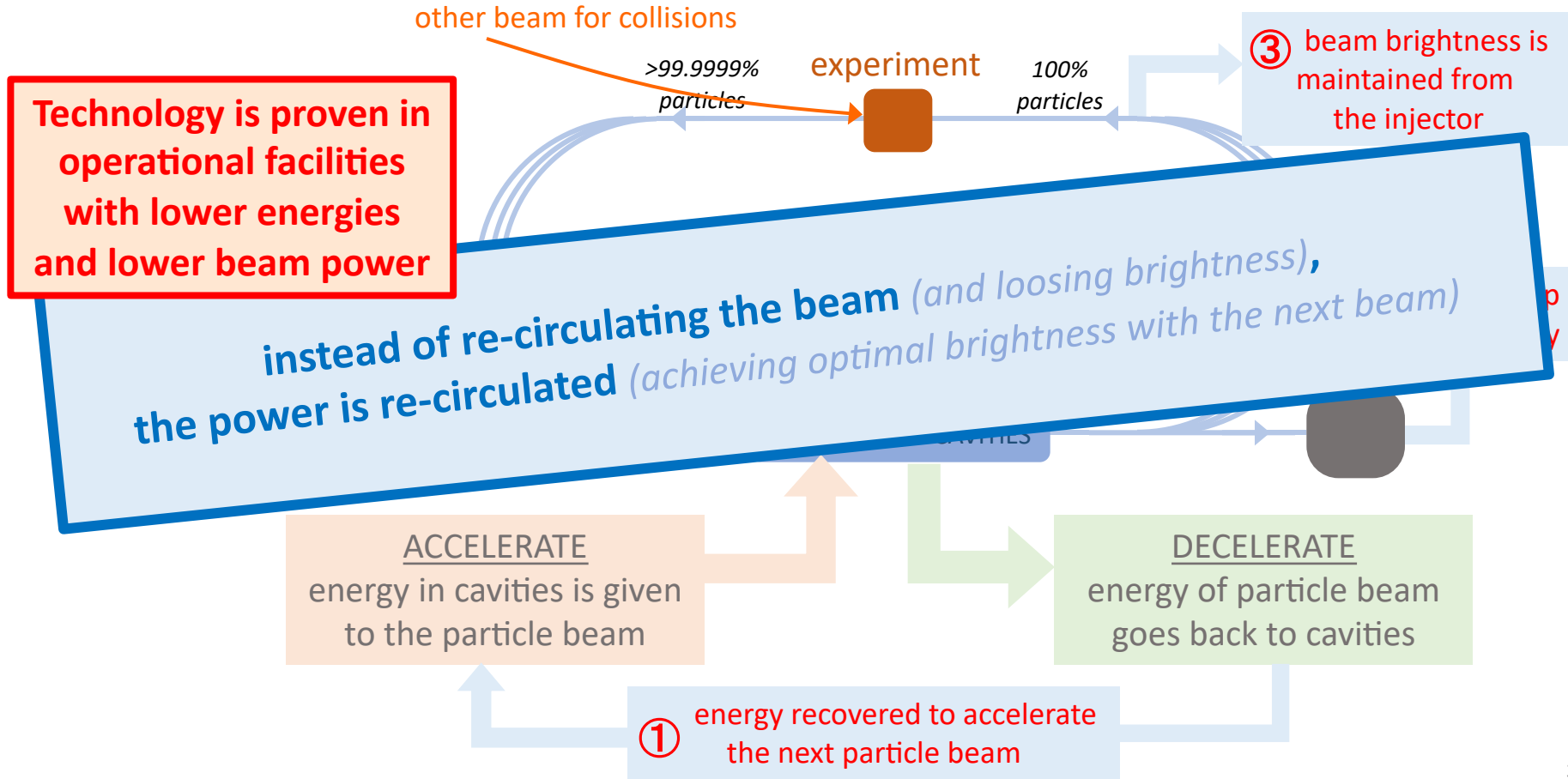
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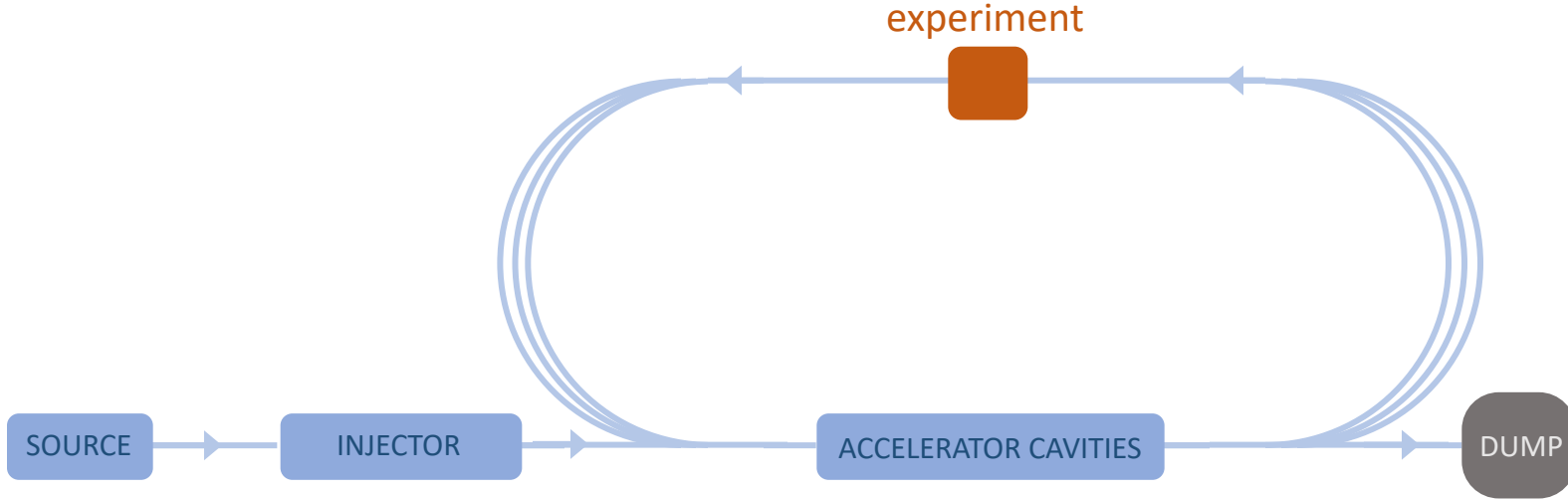
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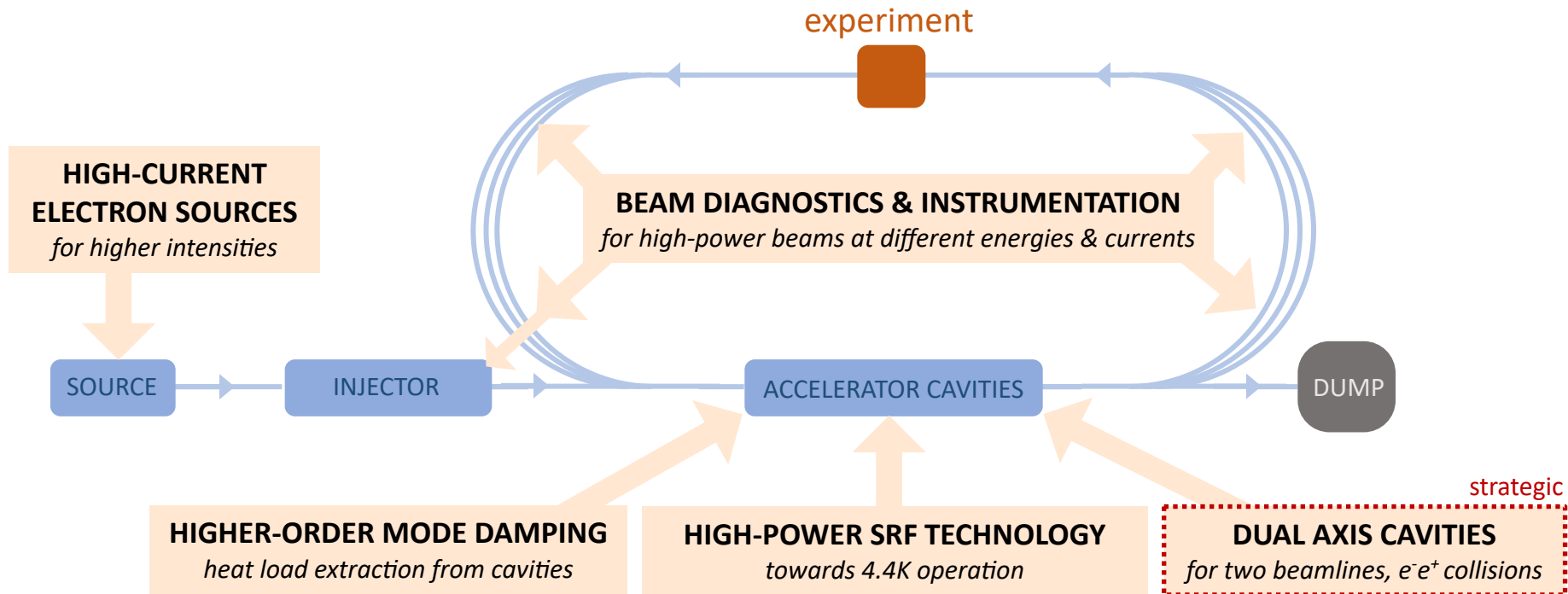
# The principle of Energy Recovery



# Identified the key aspects for an Energy Recovery accelerator *towards high-energy & high-intensity beams to be used at particle colliders*

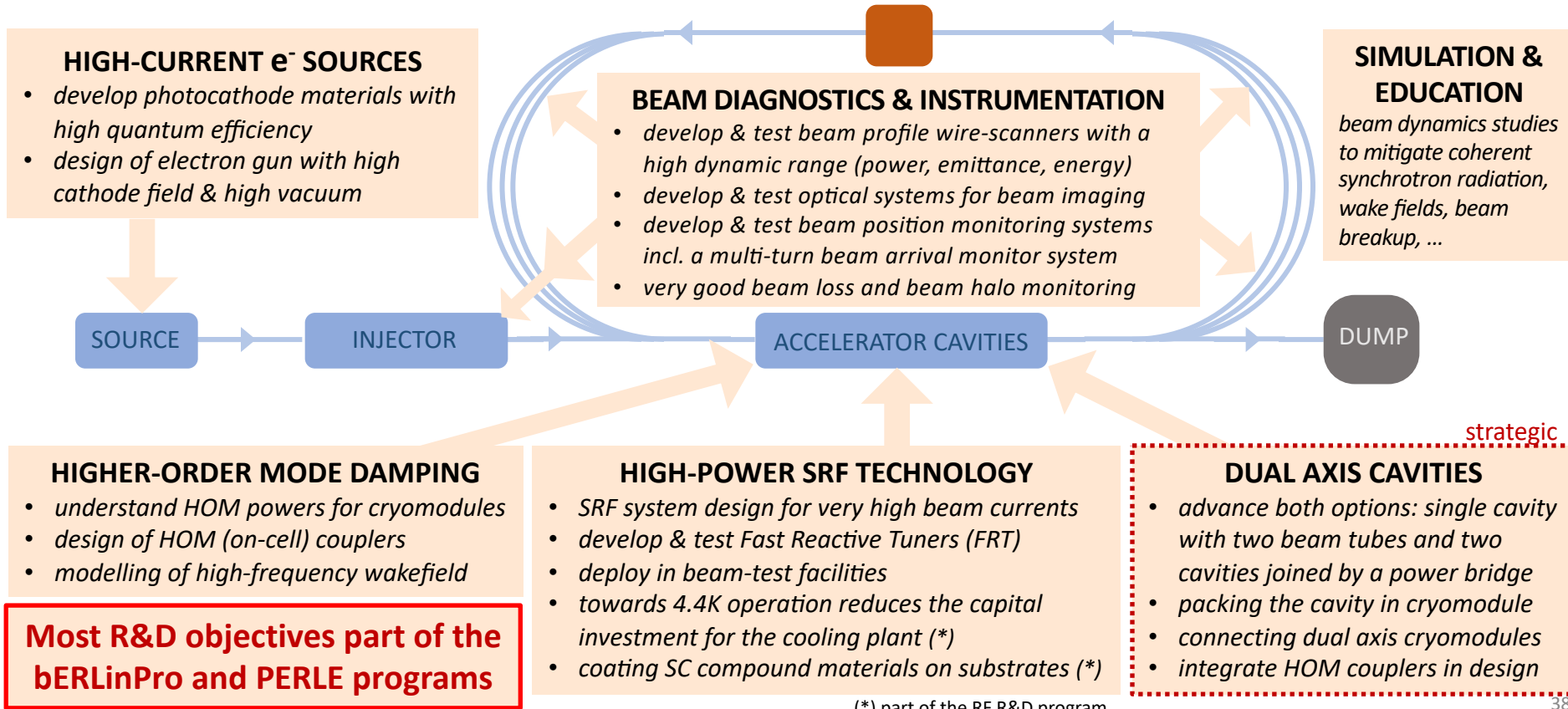


# Identified the key aspects for an Energy Recovery accelerator towards high-energy & high-intensity beams to be used at particle colliders



# Translated into the main R&D objectives for Energy Recovery

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



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## HIGH-CURRENT $e^-$ SOURCES

- develop photocathode materials
- high-current

With the planned R&D we should be able to demonstrate Energy Recovery for high-power beams and prepare the path to provide a 1 GW electron beam with 50 MW power 

- 
- 
- 

**Most R&D objectives part of the BERLinPro and PERLE programs**

- 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 (\*)

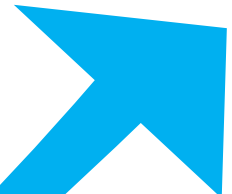
## DUAL AXIS CAVITIES

- 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

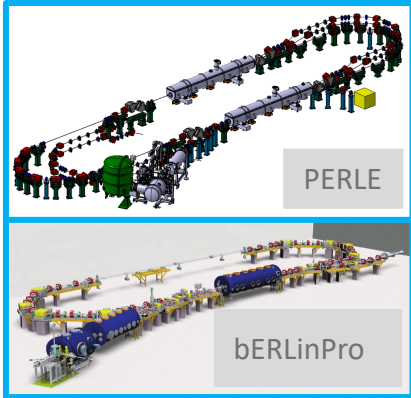
(\*) part of the RF R&D program

# The future of ERL-based colliders

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

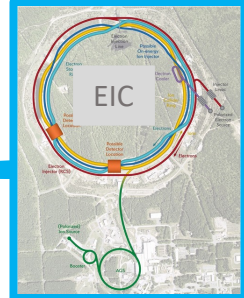


2020'ies



*high-power ERL demonstrated*

2020-2030'ies



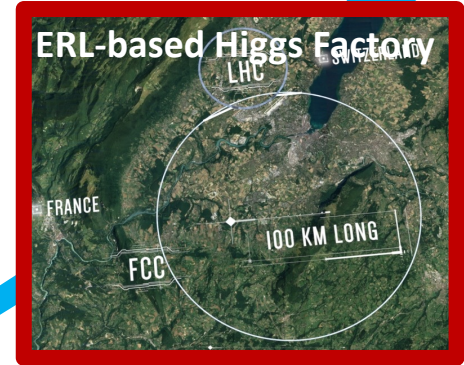
*ERL application electron cooling*

2030-2040'ies



*high-power ERL  
e<sup>-</sup> beam in collision  
(ep/eA @ LHC program)*

2040-2050'ies



*with high-power ERL  
e<sup>+</sup>e<sup>-</sup> Higgs Factory  
(Z/W/H/top program)*

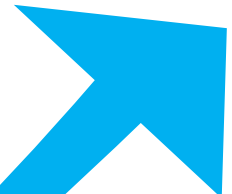
2 ERL beams

1 ERL beam

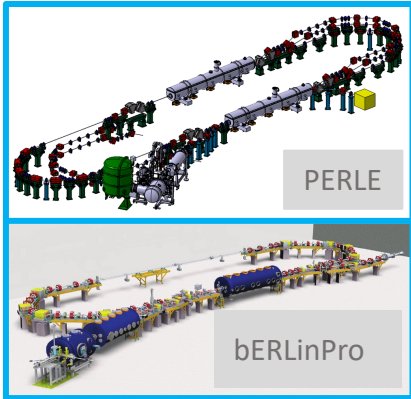


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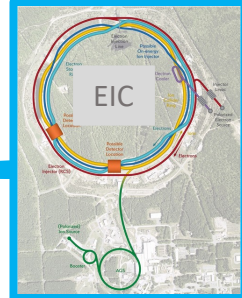


2020'ies



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2020-2030'ies



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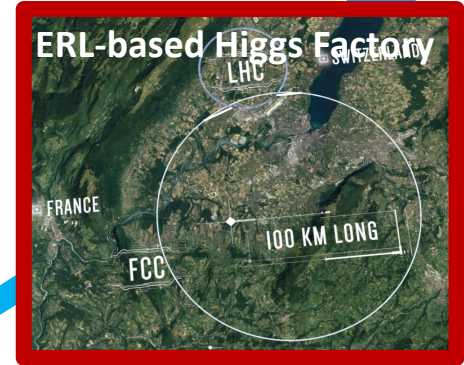
2030-2040'ies



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

1 ERL beam

2040-2050'ies



2 ERL beams

*with high-power ERL  
 $e^+e^-$  Higgs Factory  
(Z/W/H/top program)*



*a roadmap developed  
on the shoulders of giants*

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I was not aware that in 2022, I would be invited to walk in his footsteps

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Today, I am grateful for his leadership as scientist and friend

A photograph of three men walking outdoors on a grassy path. The man on the left is wearing a blue button-down shirt, glasses, and a backpack, and is smiling. The man in the middle is wearing a dark blazer over a red sweater and is also smiling. The man on the right is wearing a dark suit jacket and is looking towards the camera. The background features trees with some autumn-colored leaves and a building in the distance.

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Big thanks to Max Klein for his leadership

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