Power-efficient powerful beams

accelerator R&D for energy recovery for HEP

Jorgen D'Hondt
Vrije Universiteit Brussel

Max Klein
University of Liverpool

fwo

iihe BRUXELLES BRUSSEL

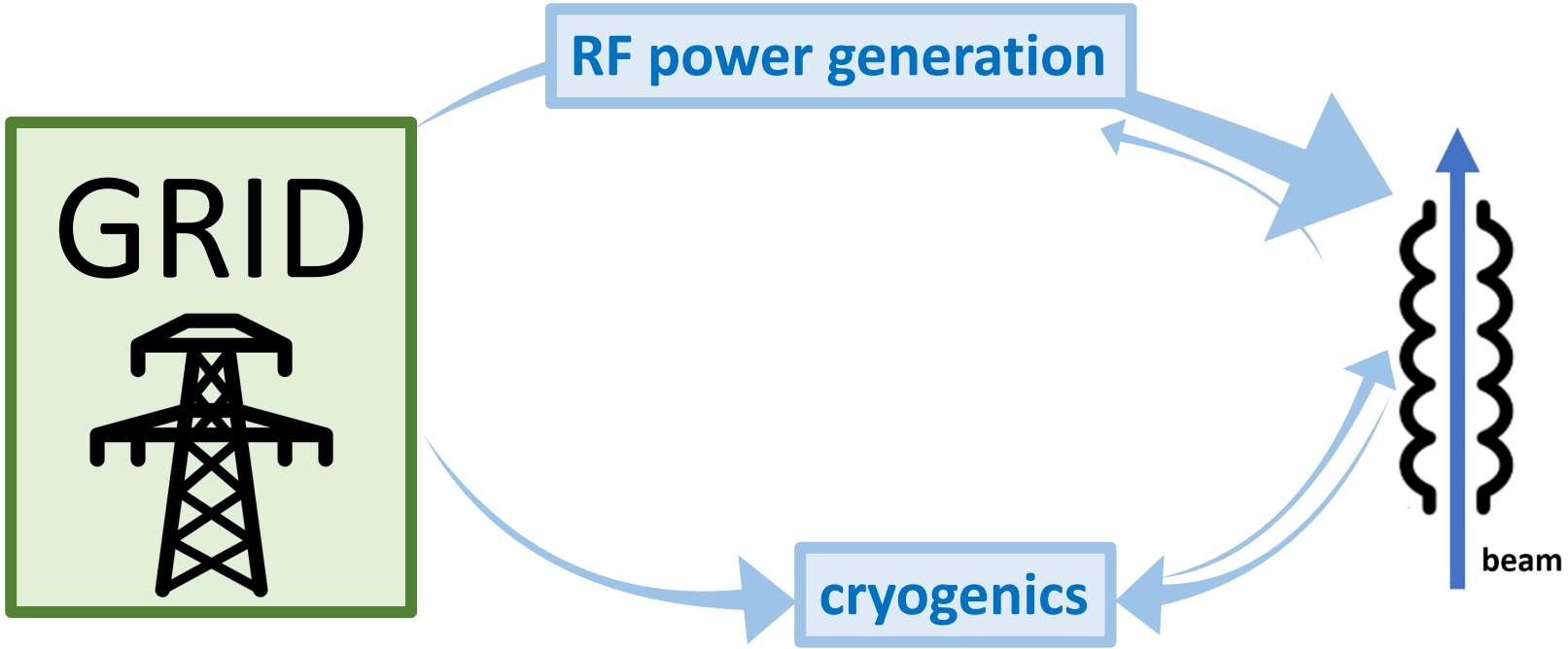
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

belle

UNIVERSITY OF LIVERPOOL

LDG meeting, 21 November 2022

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

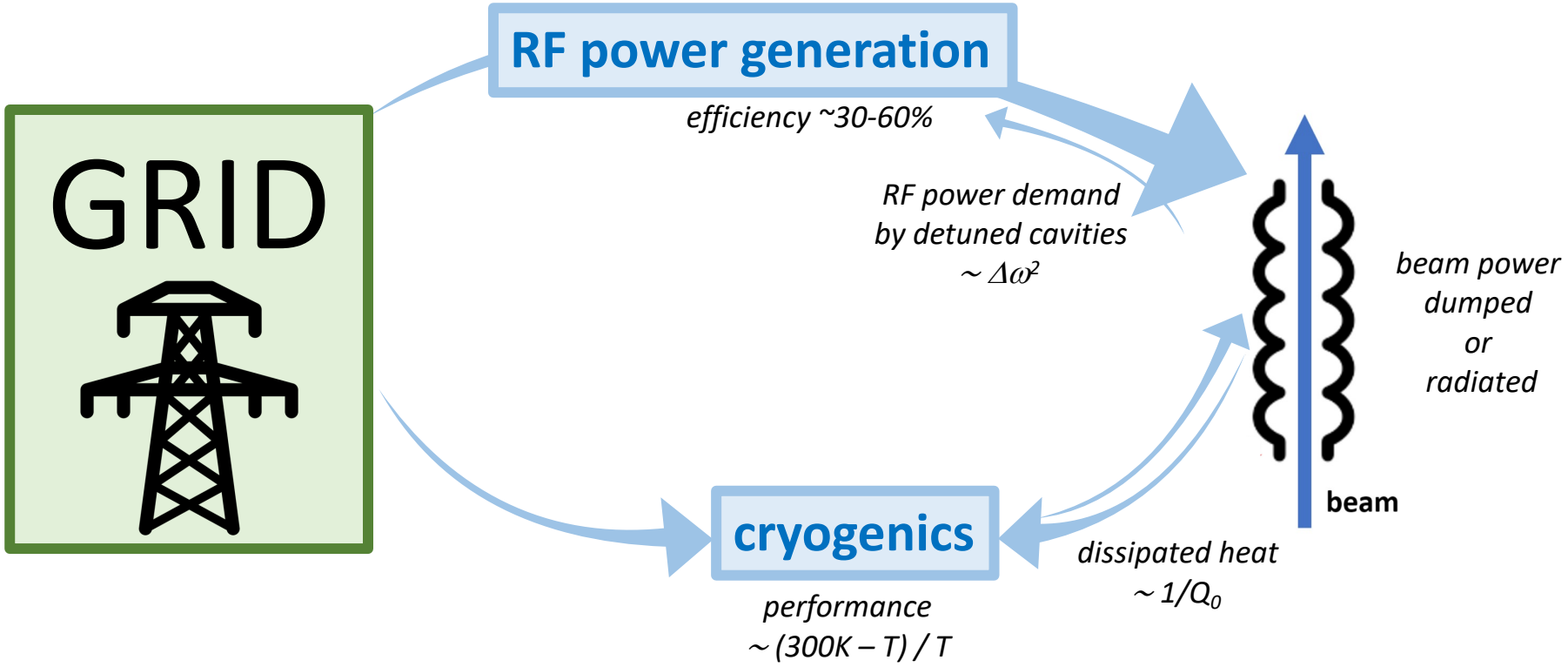
From Grid to Beam

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



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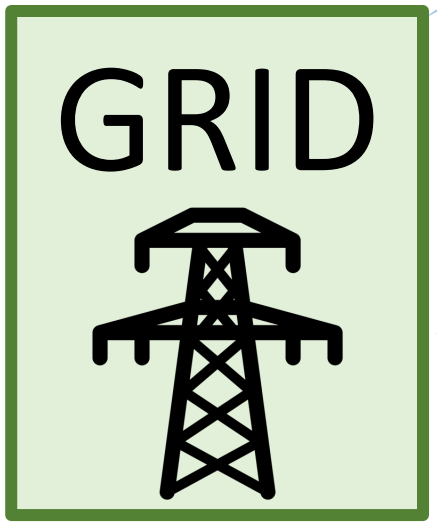


improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

RF power generation

efficiency ~30-60%

recover the energy from the beam

e.g. ERL reaching 100% recovery

RF power demand by detuned cavities

$\sim \Delta\omega^2$

dealing with microphonics

e.g. Fast Reactive Tuners

beam power dumped or radiated

beam

cryogenics

dissipated heat

$\sim 1/Q_0$

performance

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

operate cavities at higher T & improve Q_0 of cavities

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

From Grid to Beam

Accelerating particles will always require a large amount of energy, hence an optimal use of this energy is an unavoidable challenge for future (H) colliders

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

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

e.g. 4.4K SRF in the ERL world is equivalent to HTS in the magnet world

improve amplifier efficiency

e.g. solid state amplifi

energy

beam

reaching

recovery

power

ped

ted

beam

dissipated heat

~ 1/Q_0

performance

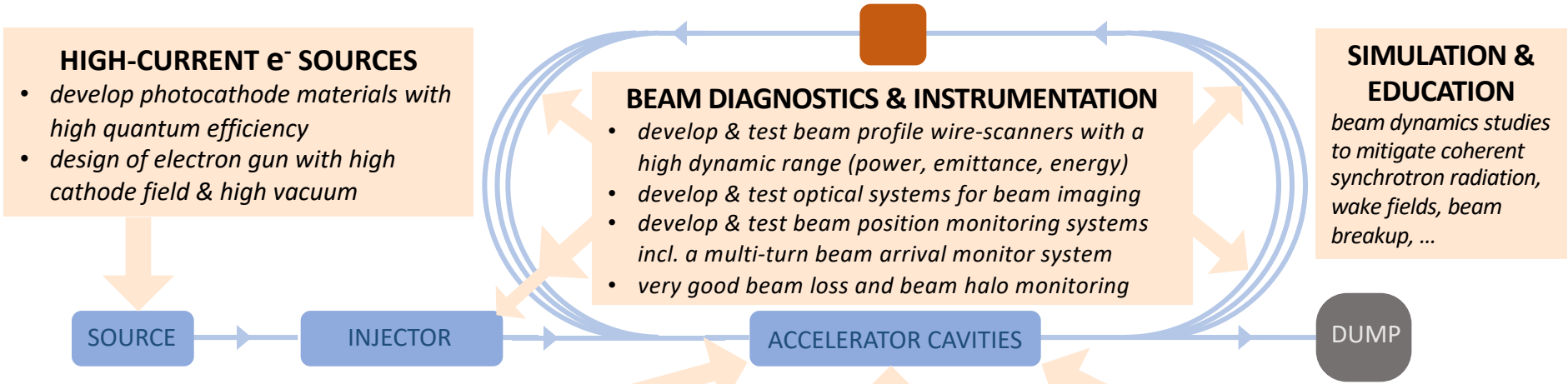
~ (300K – T) / T

operate cavities at higher T & improve Q_0 of cavities

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

Translated into the main R&D objectives for Energy Recovery

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



HIGHER-ORDER MODE DAMPING

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

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

HIGH-POWER SRF TECHNOLOGY

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

strategic

DUAL AXIS CAVITIES

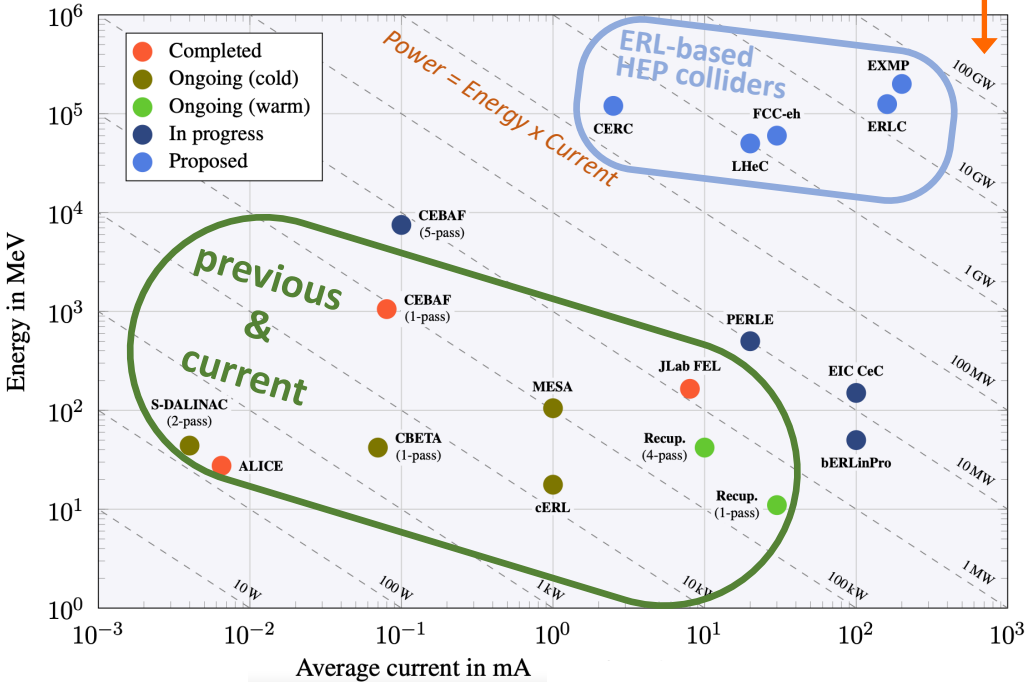
- *advance both options: single cavity with two beam tubes and two cavities joined by a power bridge*
- *packing the cavity in cryomodule*
- *connecting dual axis cryomodules*
- *integrate HOM couplers in design*

(*) part of the RF R&D program

Energy Recovery – 50 years of innovation

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

would be the required external power supply without Energy Recovery



Energy Recovery

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

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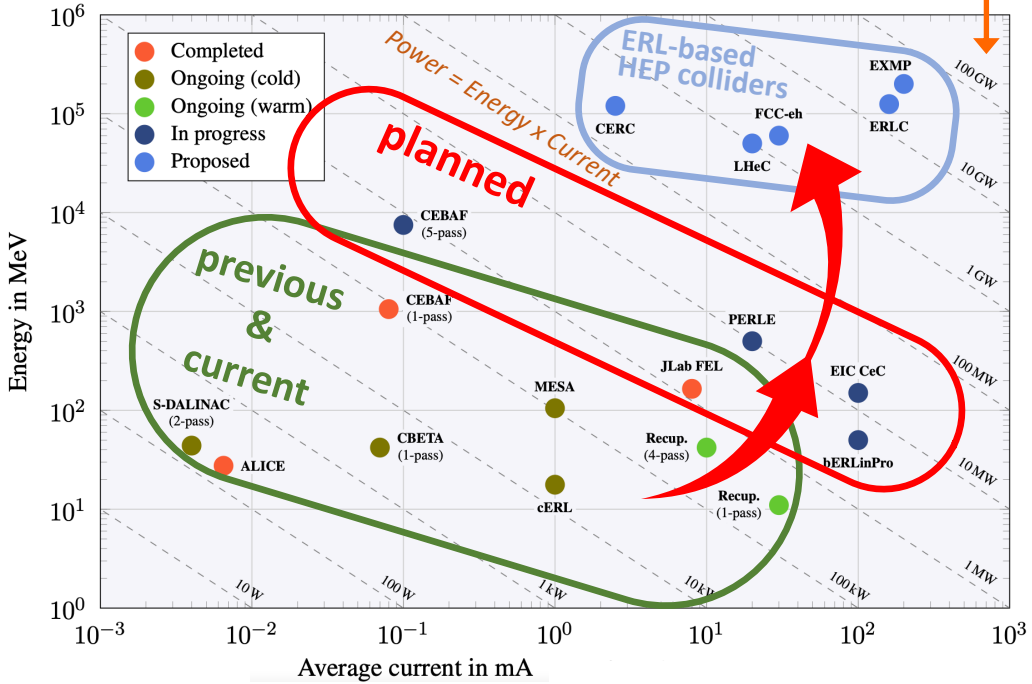

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bERLinPro & PERLE

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

towards high energy & high power

The Development of Energy-Recovery Linacs

arXiv:2207.02095, 237 pages, 5 July 2022

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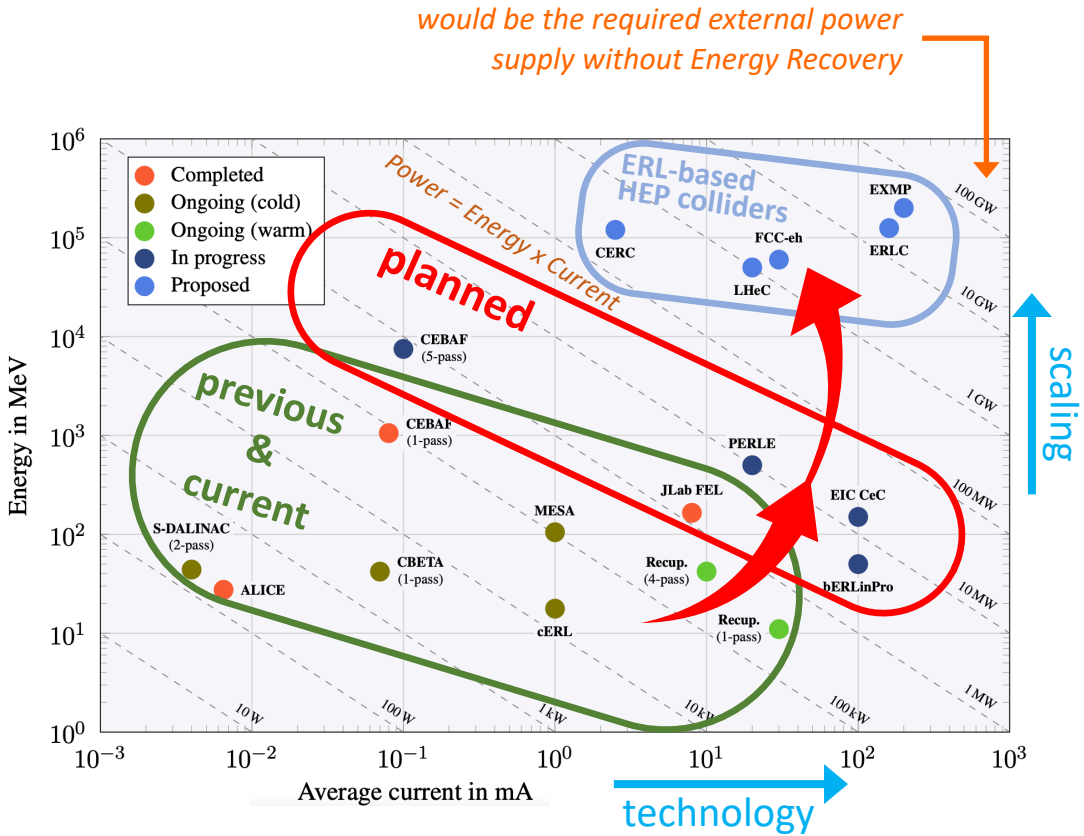

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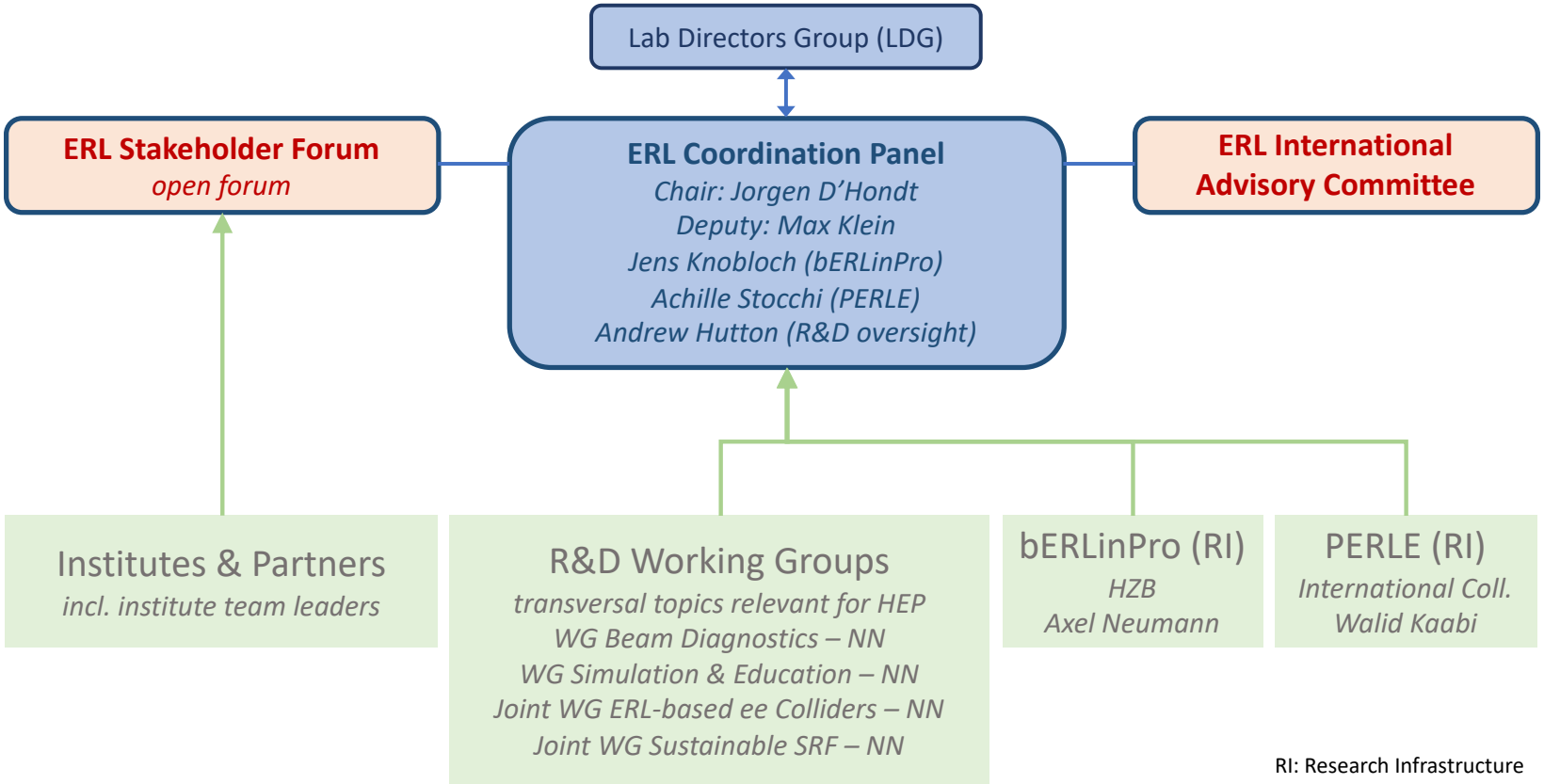
Organising the European R&D for Energy Recovery in HEP

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



RI: Research Infrastructure

Organising the European R&D for Energy Recovery in HEP

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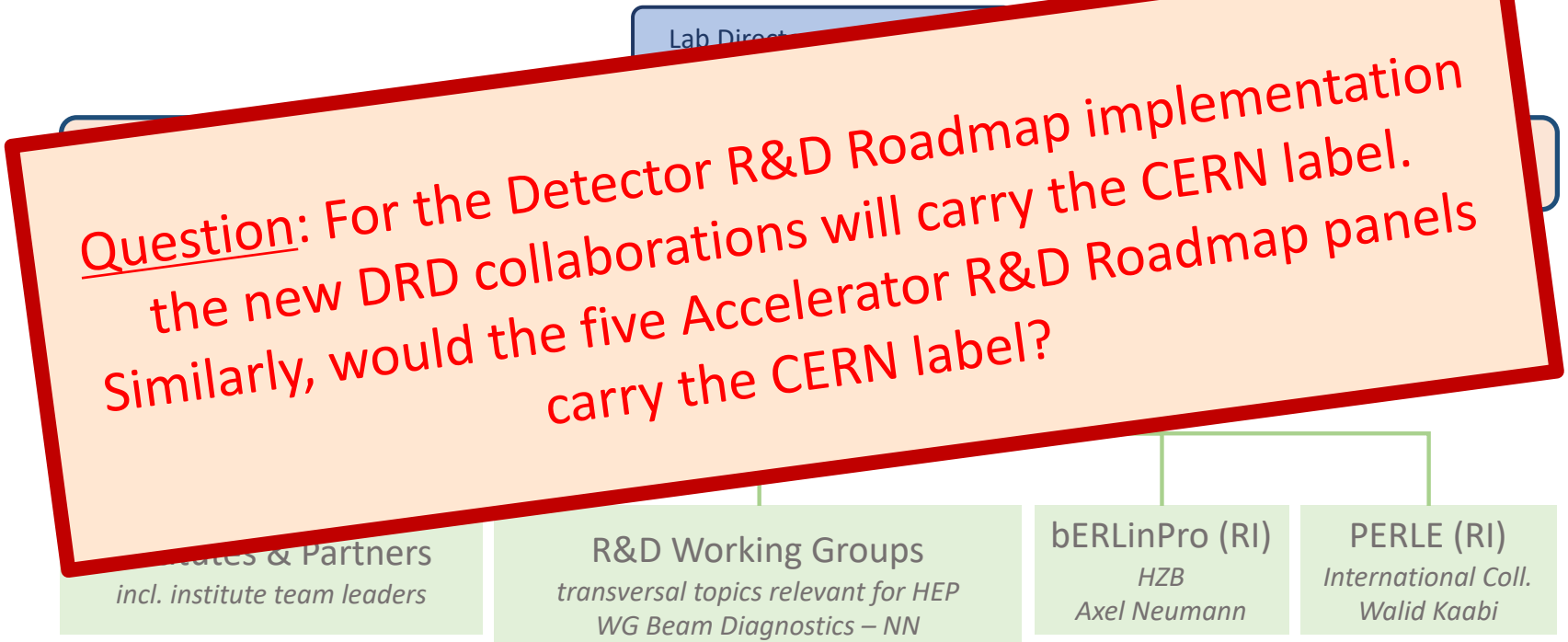

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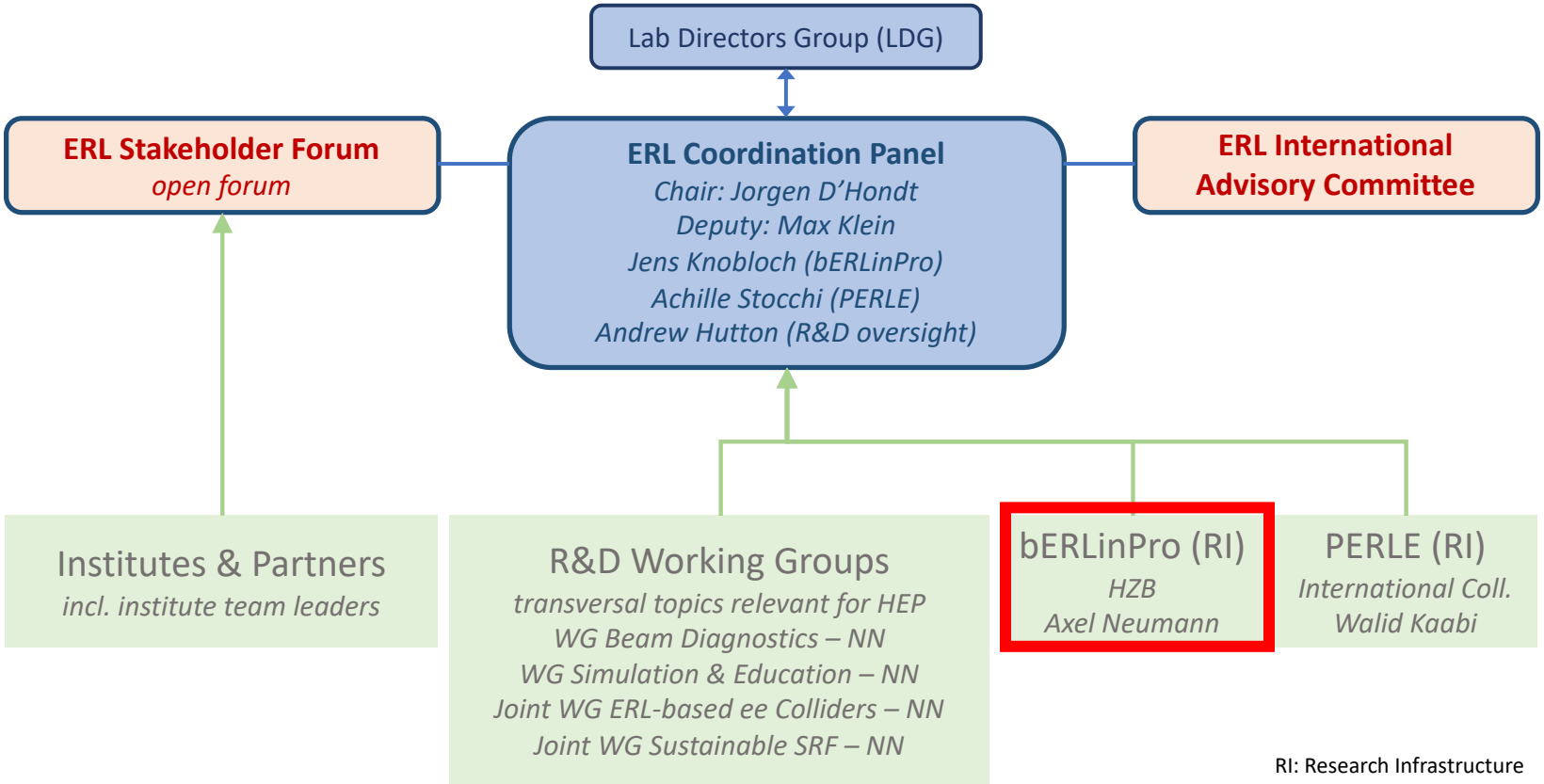


RI: Research Infrastructure

Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

bERLinPro @ Helmholtz Zentrum Berlin

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

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

Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

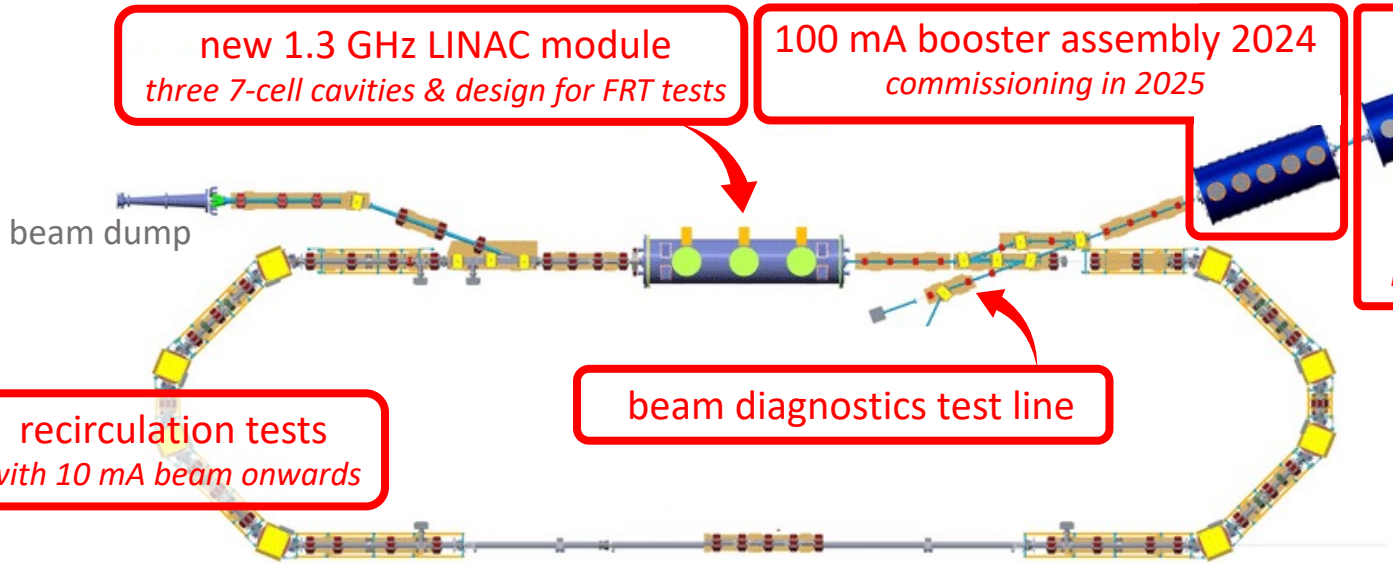
bERLinPro @ Helmholtz Zentrum Berlin
addressing HEP related challenges

bERLinPro ready for operation at 10 mA
contingent on additional budgets upgrades to 100 mA and ERL at 50 MeV can be planned to be operational by 2028

new 1.3 GHz LINAC module
three 7-cell cavities & design for FRT tests

100 mA booster assembly 2024
commissioning in 2025

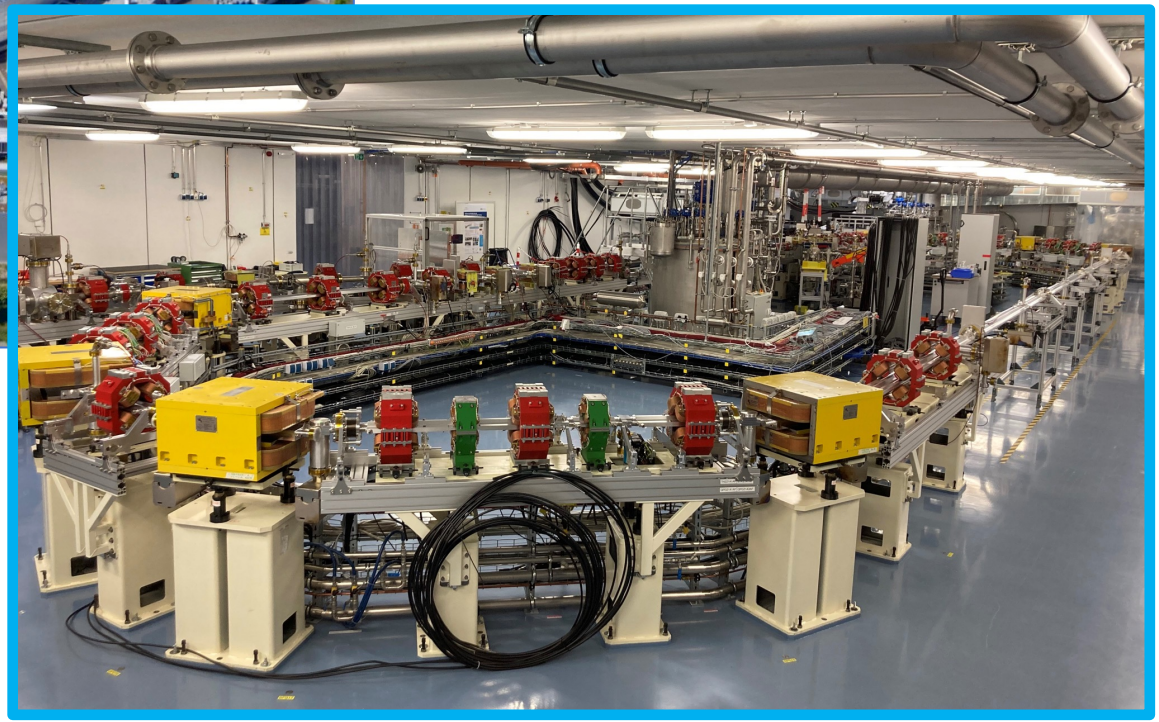
develop
first SRF gun
with high-current
incl. cathode development



recirculation tests
with 10 mA beam onwards

beam diagnostics test line

First beam of bERLinPro@SEALab to be expected around late Spring to Summer 2023



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

Status bERLinPro@SEALab

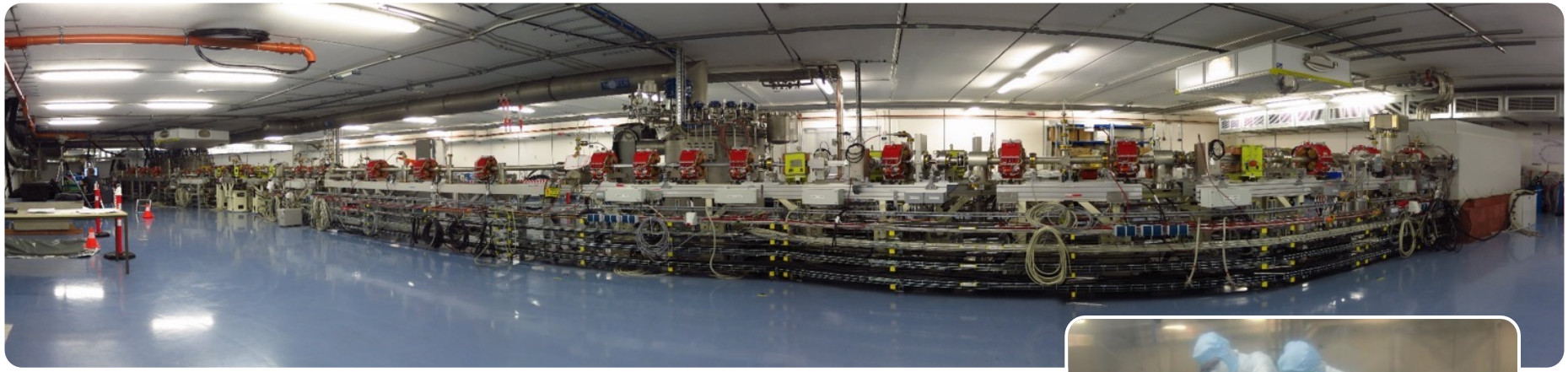
Support Infrastructure: Cryogenics & High-Power RF

Installed and commissioned

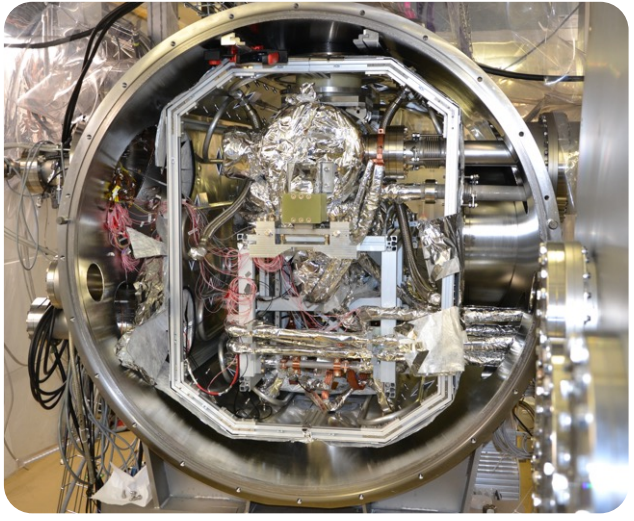
Status bERLinPro@SEALab

Beam transport / vacuum system / diagnostics

ISO-5 installed for SRF compatibility, ready for beam



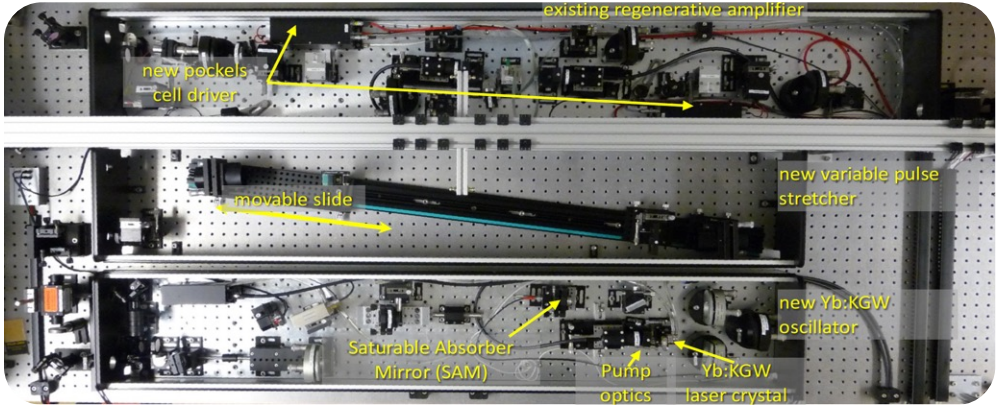
Status bERLinPro@SEALab

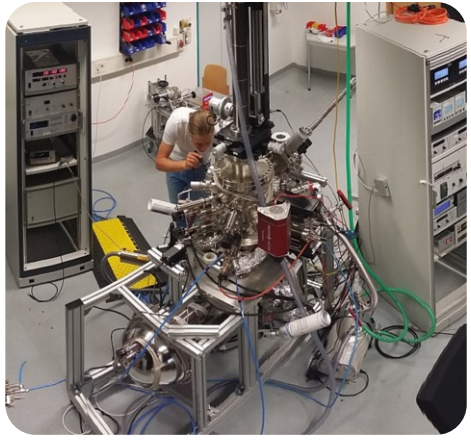


SRF Injector (10 mA CW limited by couplers)

Funded and part of baseline activities

- Beam operation with SRF gun (2 systems) in the past
- Re-Installation in cryomodule under way, complete 2022
- Laser system and beam transport installed / ready for operation
- Cathode production ready





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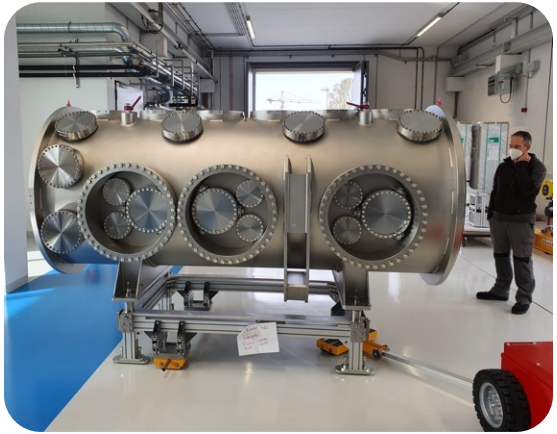


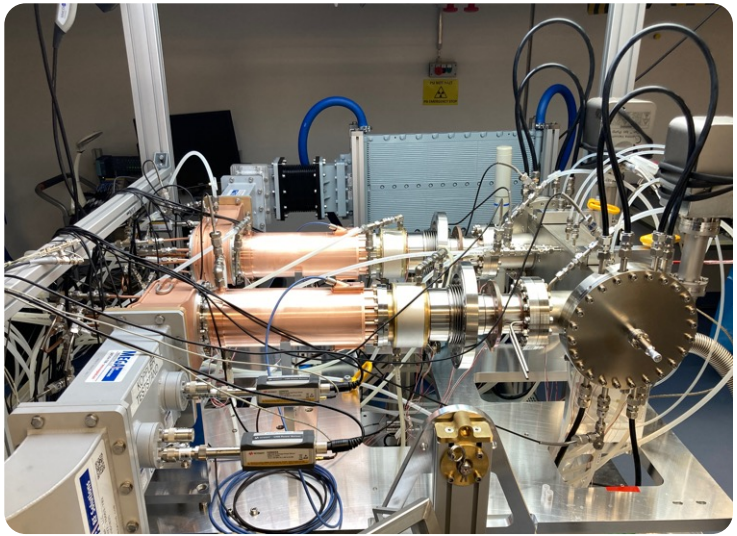
SRF Booster

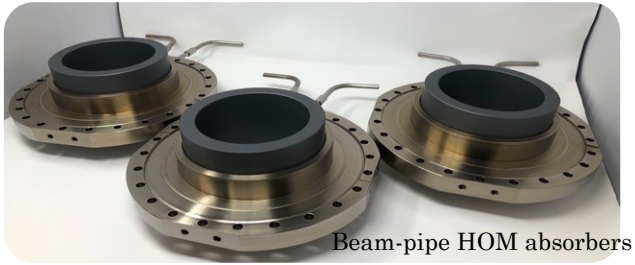
Funded and part of baseline activities

- All components in-house
- Critical couplers tested to 60 kW CW / 120 kW pulsed
- Installation planned to begin 2023

SRF LINAC

- Module design essentially finished





Beam-pipe HOM absorbers

Baseline plans for bERLinPro@SEALab (ARD)

Presently planned resource-loaded activities

Accelerator Research Development topic in Matter and Technology program of Helmhotz

2023

- Commission <10mA (CW) SRF gun & beam characterization
- Ultra-fast Electron Diffraction (UED) pilot experiment to demonstrate advantages of SRF injector for UED-type user applications
- Begin booster module assembly
- Design FRT system for HoBiCaT (Horizontal Bi-Cavity Testing)

2024

- Installation / commission booster module for <10mA CW operations
- Investigation of > 10mA SRF gun operation in macro-pulse mode.
- Continuation of UED-type experiments with flexibility afforded by booster.
- HoBiCaT and QPR (quadrupole resonator) testing of FRT system at 1.3 GHz (proof-of-concept)

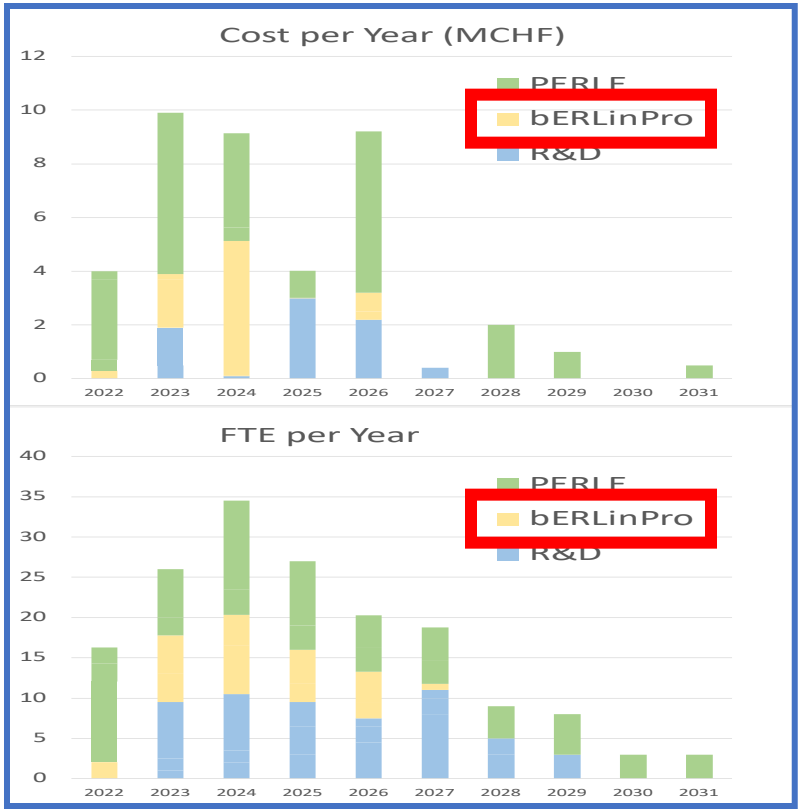
- Part of the programme not resources-loaded (the ERL part):
  - Adapt design of LINAC module with 4K cavity option and FRT and simplify HOM damping, and built the LINAC module (5.9M CHF & 17 FTEy)
  - Towards 100mA operations (2.4 MCHF & 16 FTEy)

Required resources for the R&D program for Energy Recovery

demonstrate a ready-to-go-path for high-energy colliders by the next Strategy Update

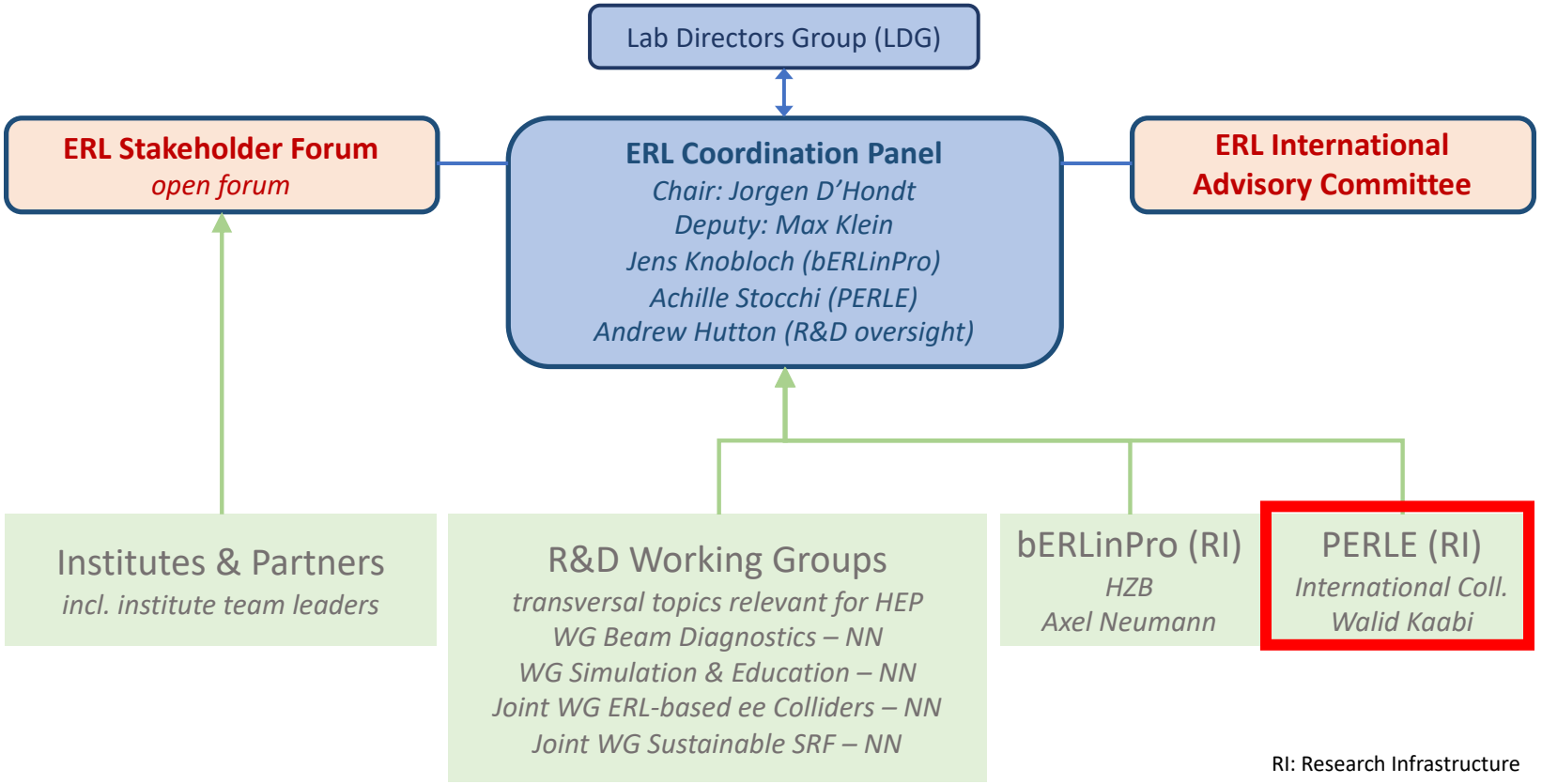
from the endorsed Accelerator R&D Roadmap

	R&D Working Groups						bERLinPro		PERLE		
	Beam Diagnostics	Simulations & Education	Sustainable SRF (HOM Damping part)	ERL-based ee Colliders	Electron Source	ERL-based ep-collider	Phase-1 100mA beam	Phase-2 Recirculation	Phase-1 250 MeV	Phase-2 500 MeV	
2022											
2023											
2024											
2025											
2026											
2027											
2028											
2029											
2030											
2031											
Cost (MCHF 2021)	1,4			2,7	3,5			2,4	5,9	14,6	9,6	**40,1**
FTEy	19			24,5	12,5			16	17	64	23	**176**



Organising the European R&D for Energy Recovery in HEP

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



RI: Research Infrastructure

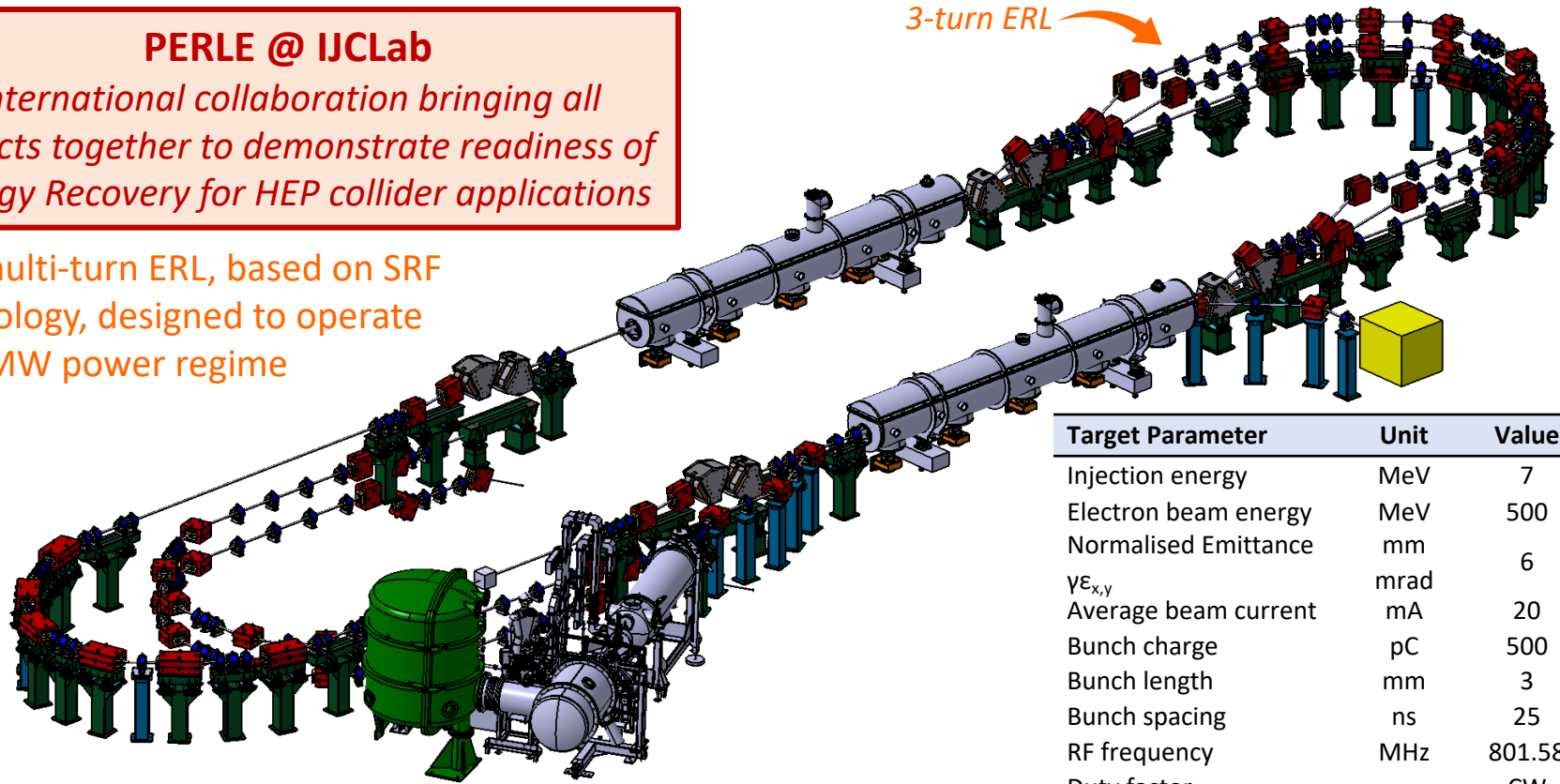
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

PERLE @ IJCLab

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

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



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

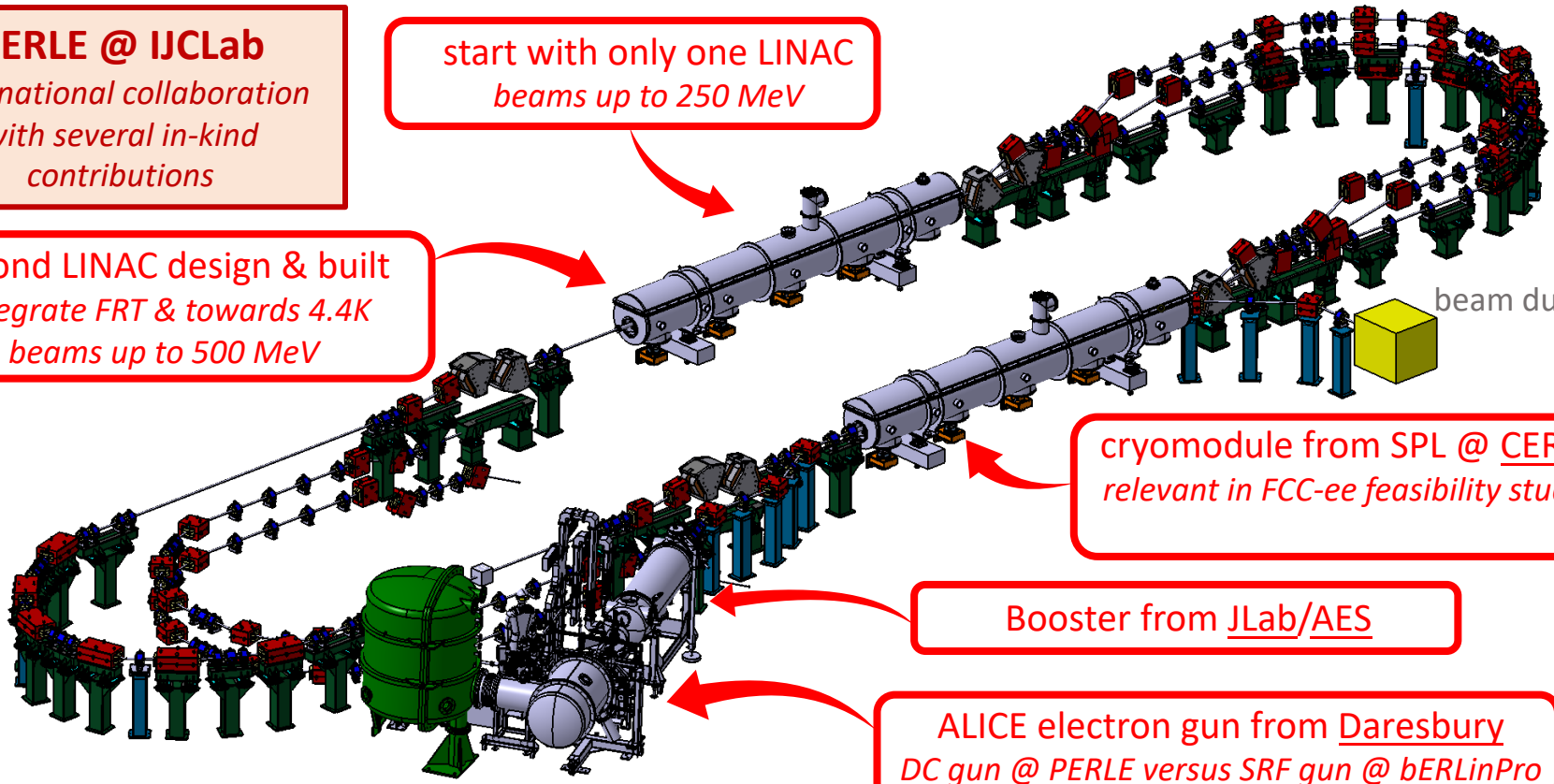
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

PERLE @ IJCLab
international collaboration with several in-kind contributions

start with only one LINAC
beams up to 250 MeV

second LINAC design & built
integrate FRT & towards 4.4K
beams up to 500 MeV



cryomodule from SPL @ CERN
relevant in FCC-ee feasibility study

Booster from JLab/AES

ALICE electron gun from Daresbury
DC gun @ PERLE versus SRF gun @ bERLinPro

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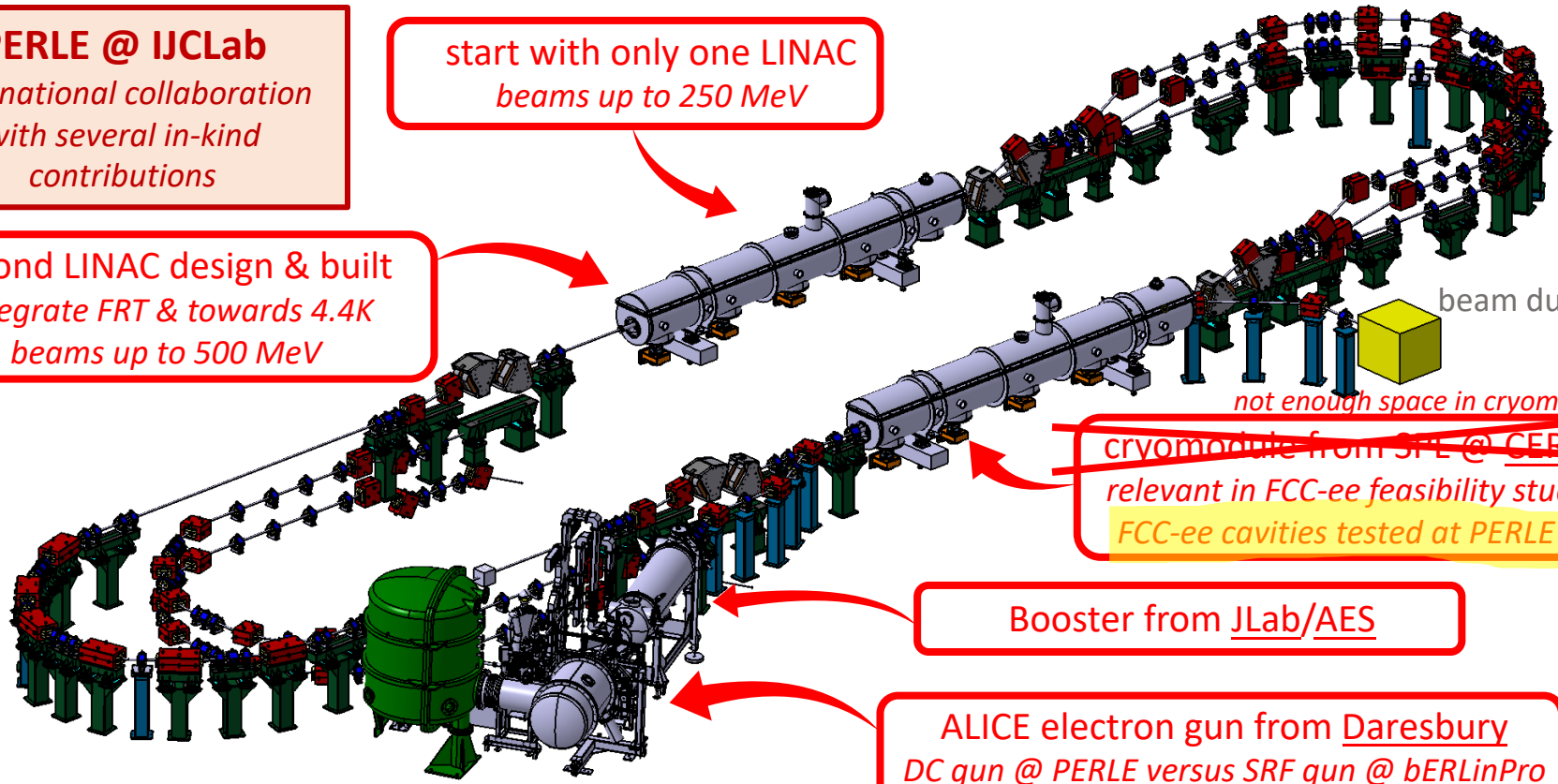


not enough space in cryomodule

cryomodule from SRF @ CERN
relevant in FCC-ee feasibility study
FCC-ee cavities tested at PERLE ?

Booster from JLab/AES

ALICE electron gun from Daresbury
DC gun @ PERLE versus SRF gun @ bERLinPro

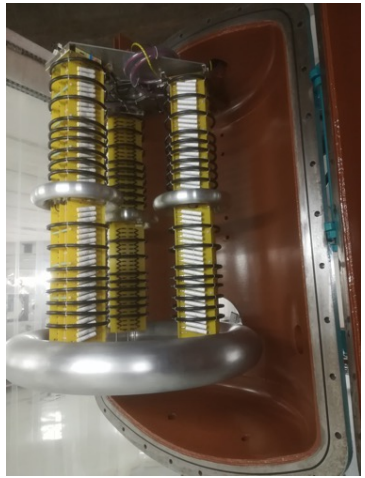
The “igloo”: equipped experimental hall to host the DC gun

progress with PERLE

Connecting cathode tank (Nov 22)

Checking HV vessel tightness (Sept 22)

HV vessel installation (June 22)

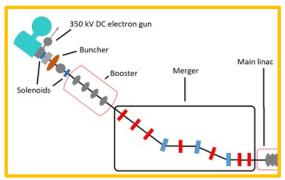


HV power supply assembly (July 22)

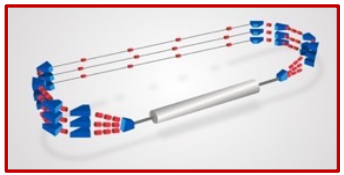
Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

2025
End Phase 0: Injection line



2030
End Phase 2: PERLE @ 500MeV



2023
PERLE TDR

2028
End Phase 1: PERLE @ 250MeV

Required resources for the R&D program for Energy Recovery

demonstrate a ready-to-go-path for high-energy colliders by the next Strategy Update

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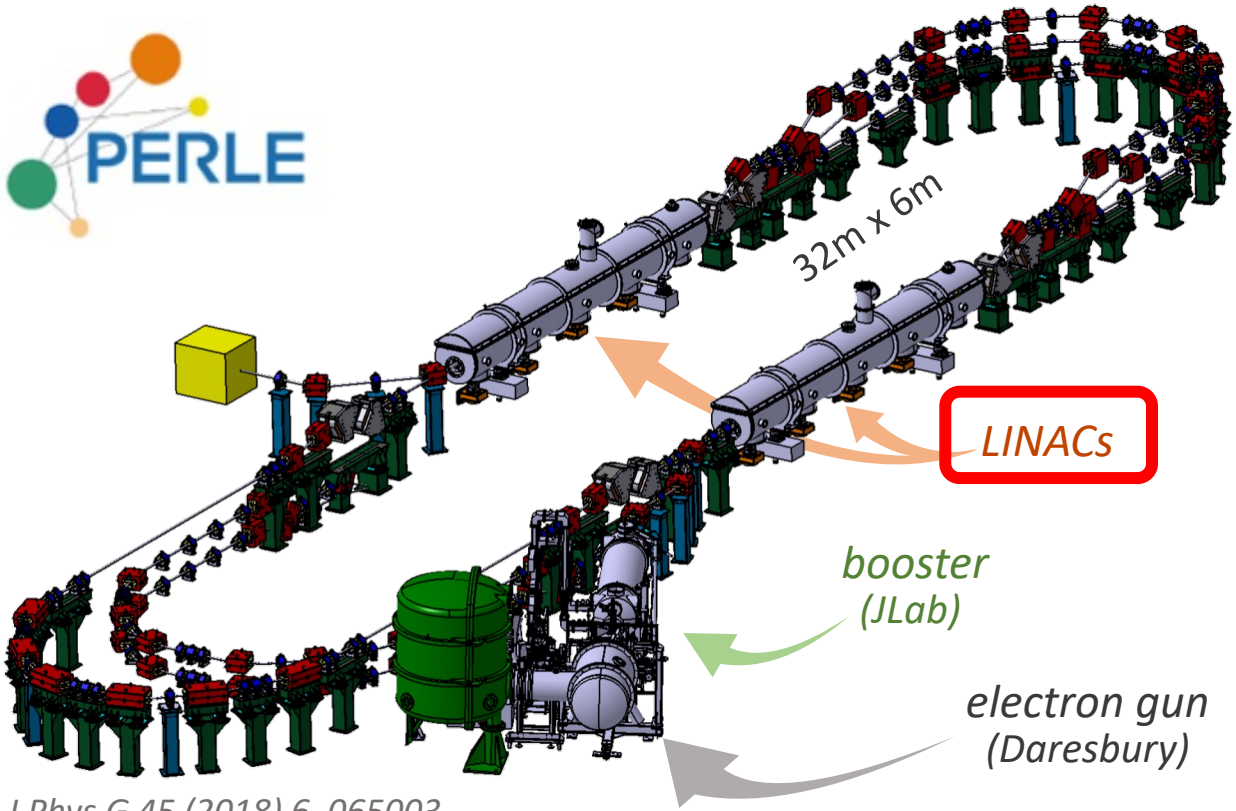

J.Phys.G 45 (2018) 6, 065003

Required resources for the R&D program f…

PERLE is mostly not resources loaded

- *International collaboration: Gun from Daresbury & Booster from JLab*
- ***Main challenge*: two LINAC blocks** *(cryomodule & cavities),* ***2 x 4MCHF***
- *SPL cryomodule from CERN is not possible (not enough space in cryomodule)*
- *Obtaining commitments for these LINACs would bring PERLE beyond the point-of-no-return for successful implementation, and on track to attract remaining funds*
- *Demonstrating high-power multi-turn ERL this decade is on the critical path due to the lack of resources for the LINACs*
- ***The timeline of PERLE is perfect for testing FCC-ee LINACs*** *(to be discussed)*
- *The PERLE collaboration seeks partnerships to join the ERL part of the programme and/or to join a broader R&D programme for "sustainable accelerating systems"*

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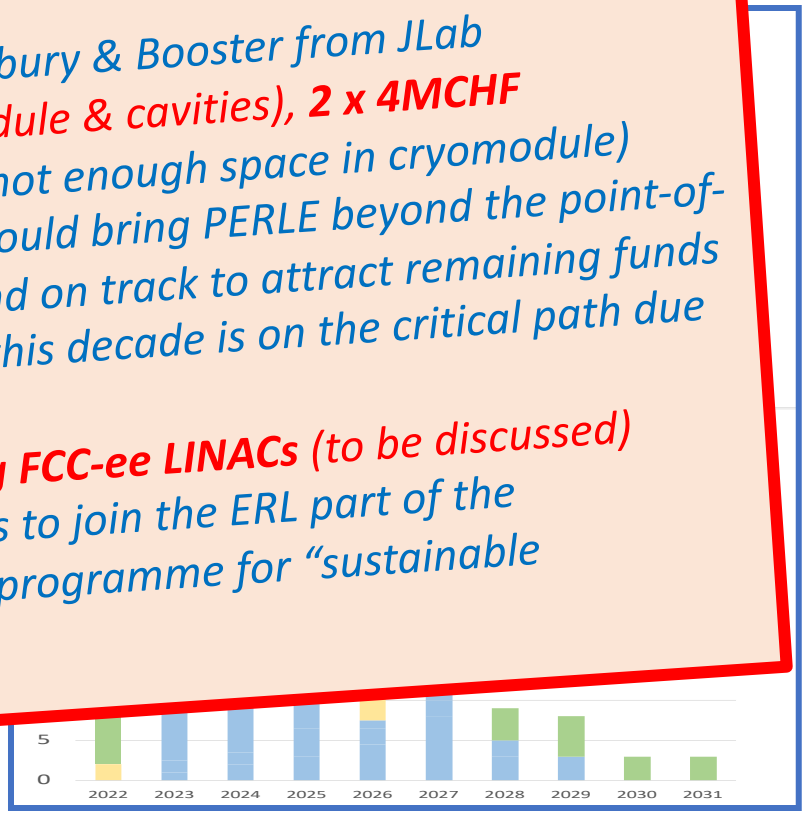

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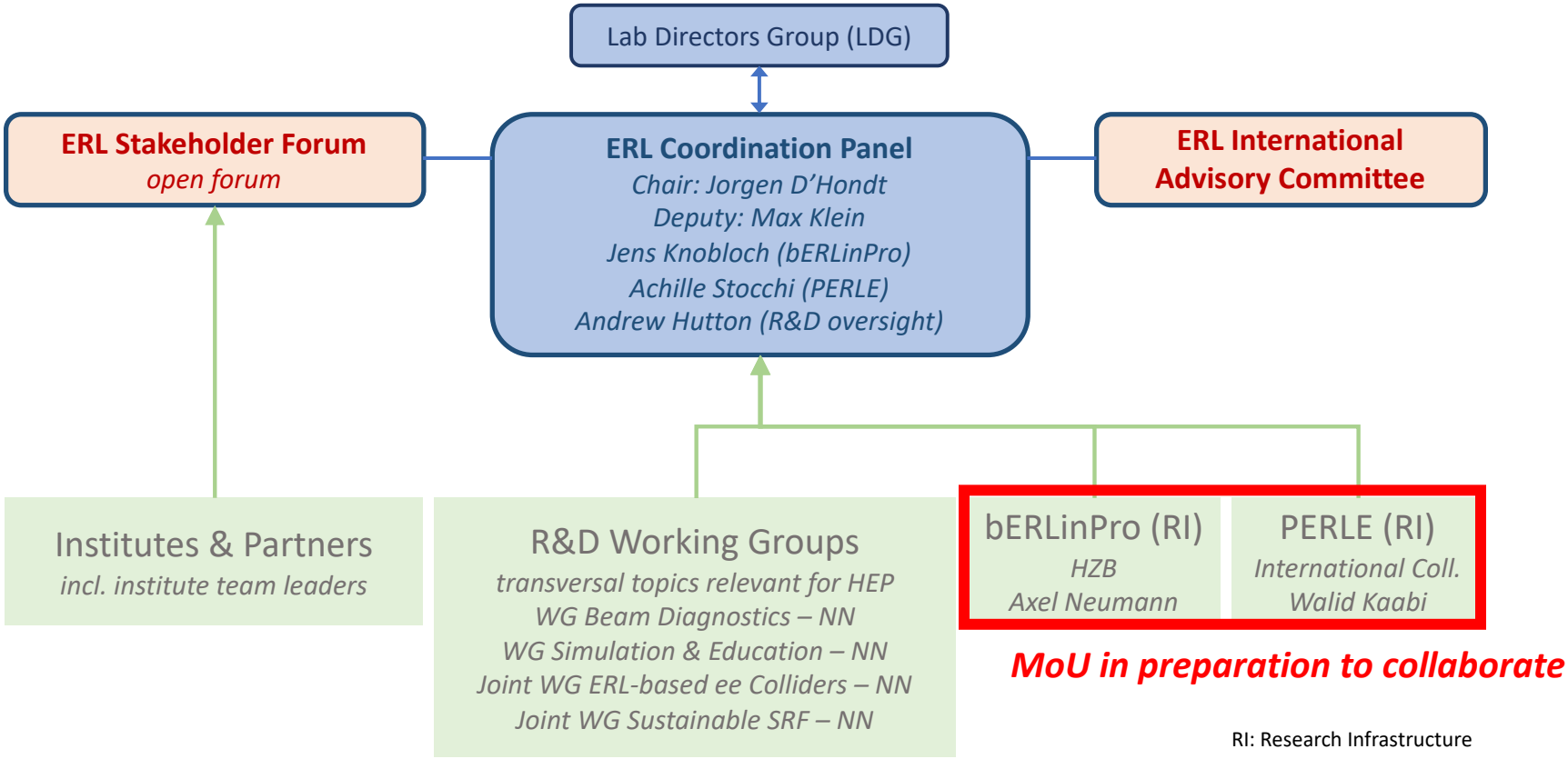

MoU in preparation to collaborate

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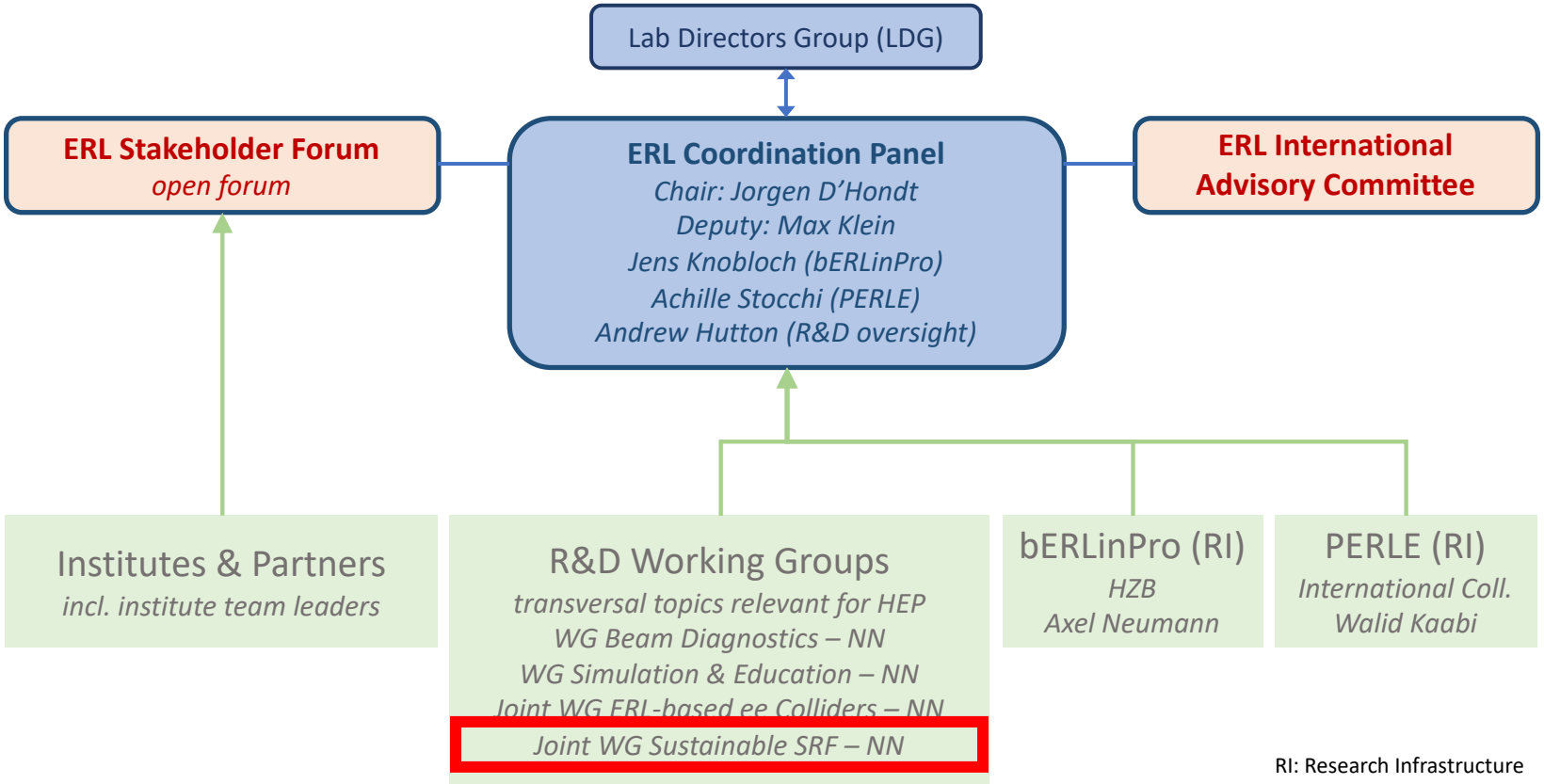

RI: Research Infrastructure

Organising the European R&D f… HEP

strengt… … together

bERLinPro and PERLE
can become European R&D centres for
"Sustainable Accelerating Systems"
for future HEP colliders

(incl. ERL, high-T SRF, materials, injectors, FRT, HOM damping, …)

- *develop a coherent R&D programme on power-efficiency for future electron/positron accelerating systems*
- *promote engagement to this broad R&D theme across panels and countries*
- *explore to resource-load the programme (EU?)*

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Organising the European R&D for Energy Recovery in HEP

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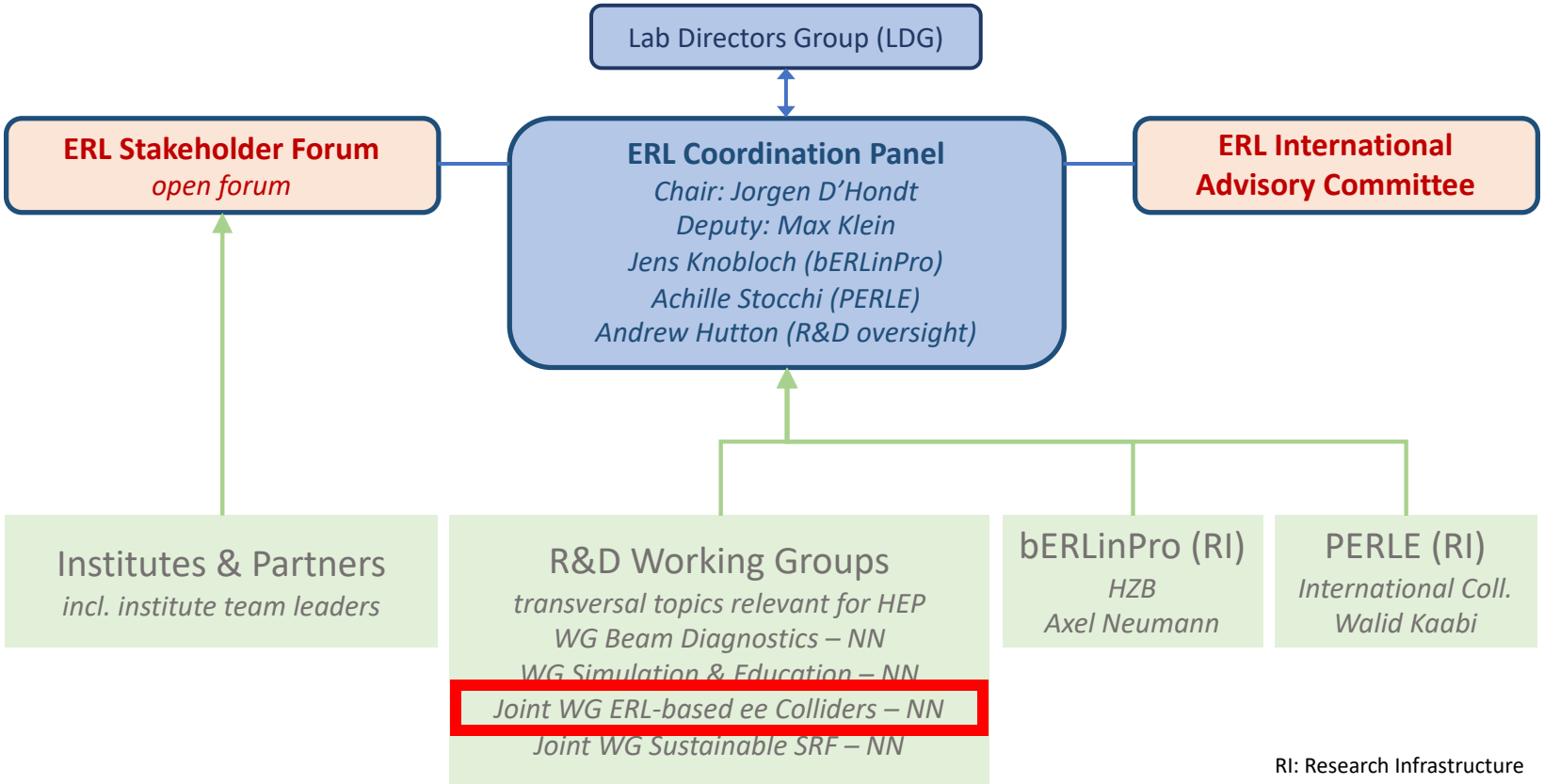
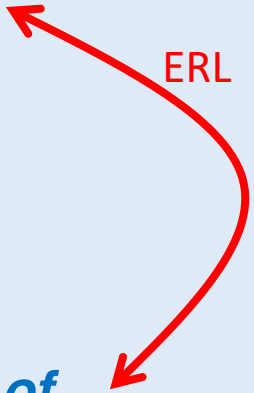


RI: Research Infrastructure

Addressing with ERL the European Strategy for Particle Physics 2020

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



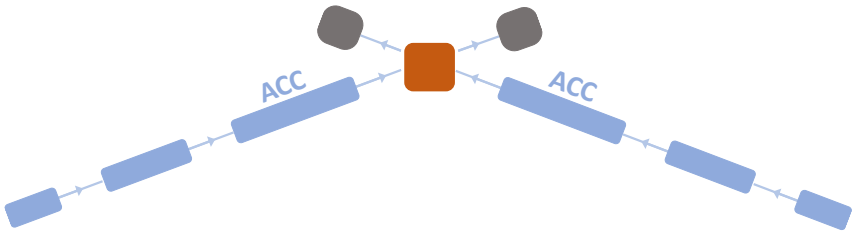
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

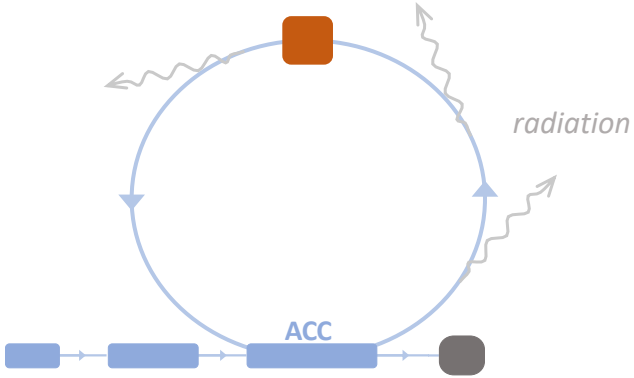
European Strategy for Particle Physics 2020

Current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

radiate away very quickly the beam power

about half of this is dumped or lost due to radiation

OBJECTIVE: develop an accelerator technology that recovers the beam energy with an impact of saving ~1% of Belgium's electricity

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

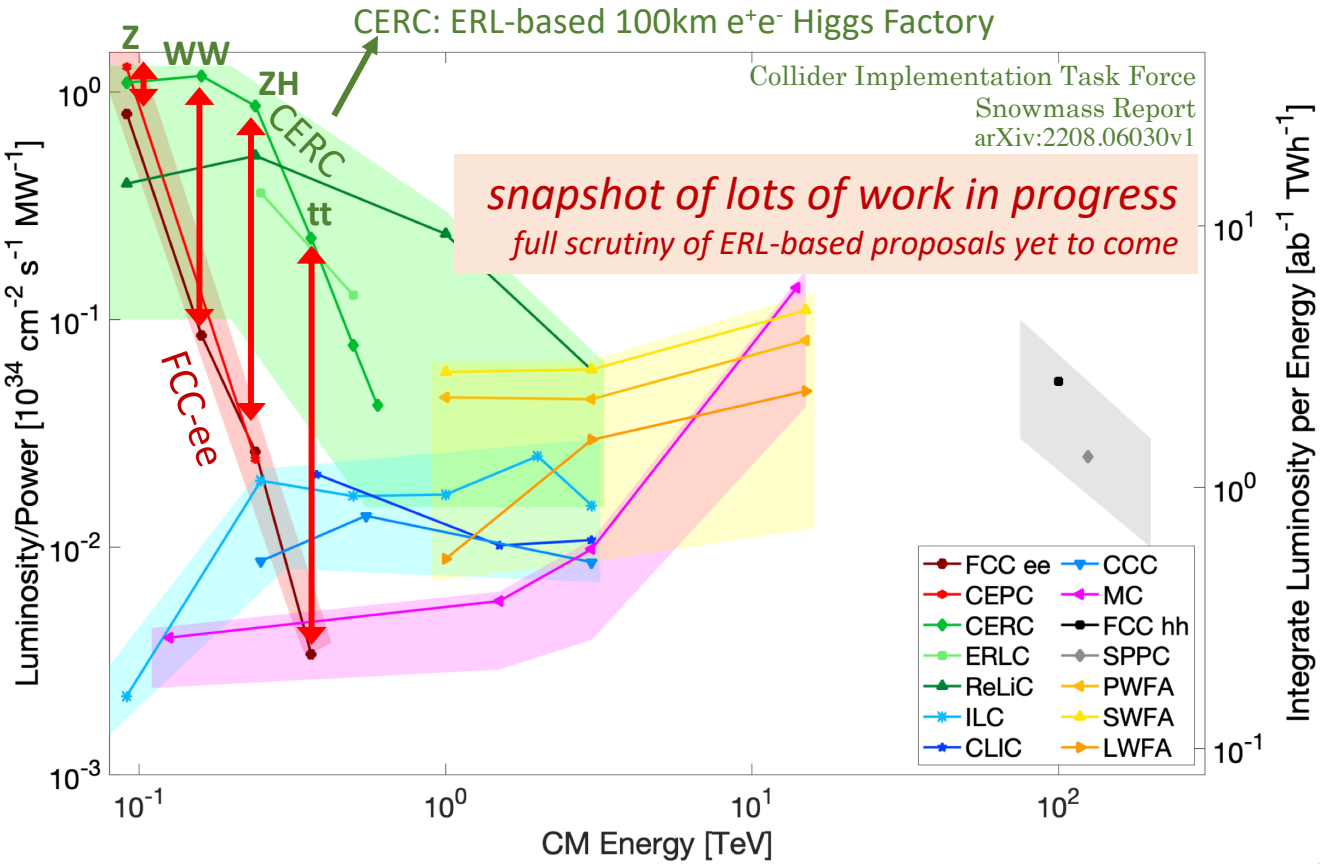
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

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



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

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

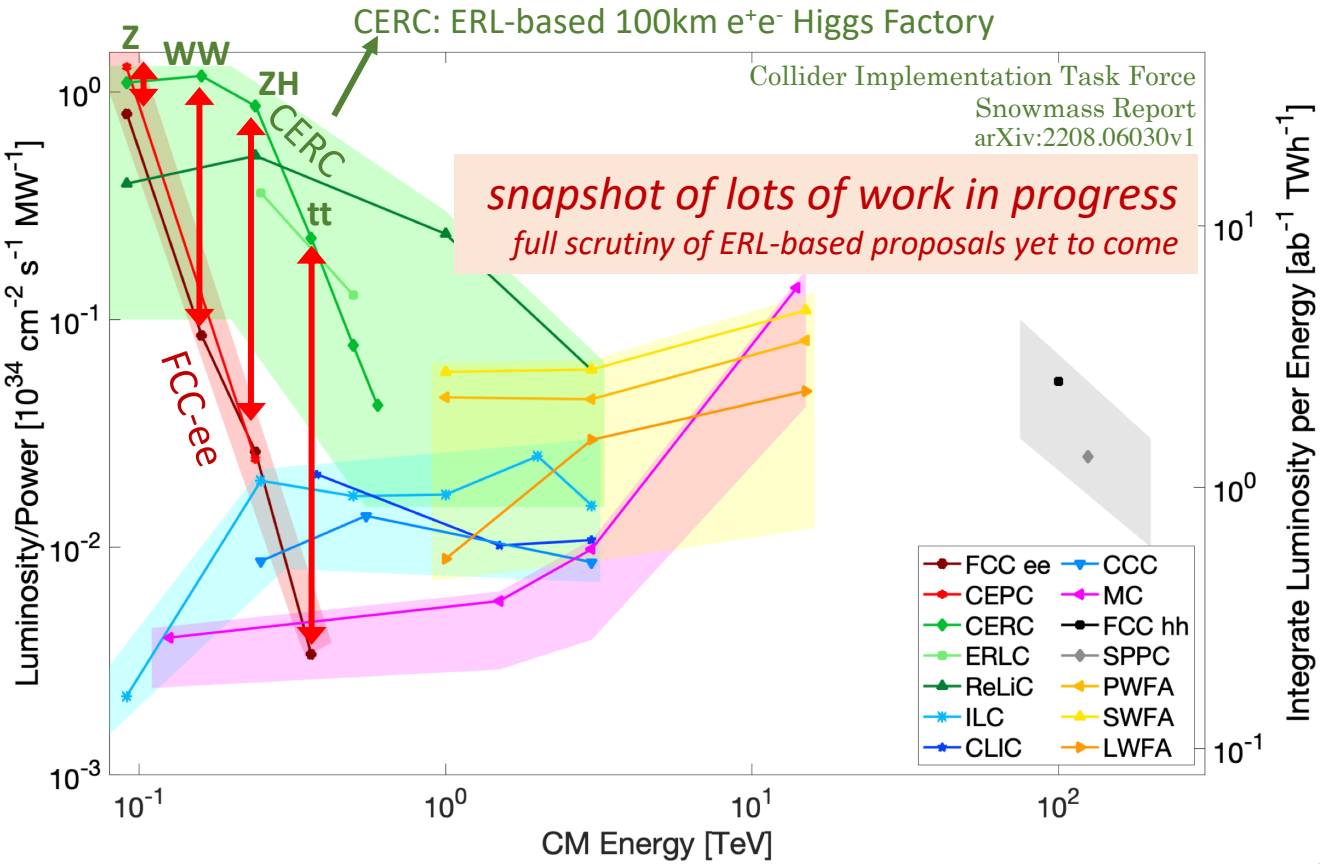
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs
next slide: what would be the concrete impact

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



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Energy Recovery applications for HEP

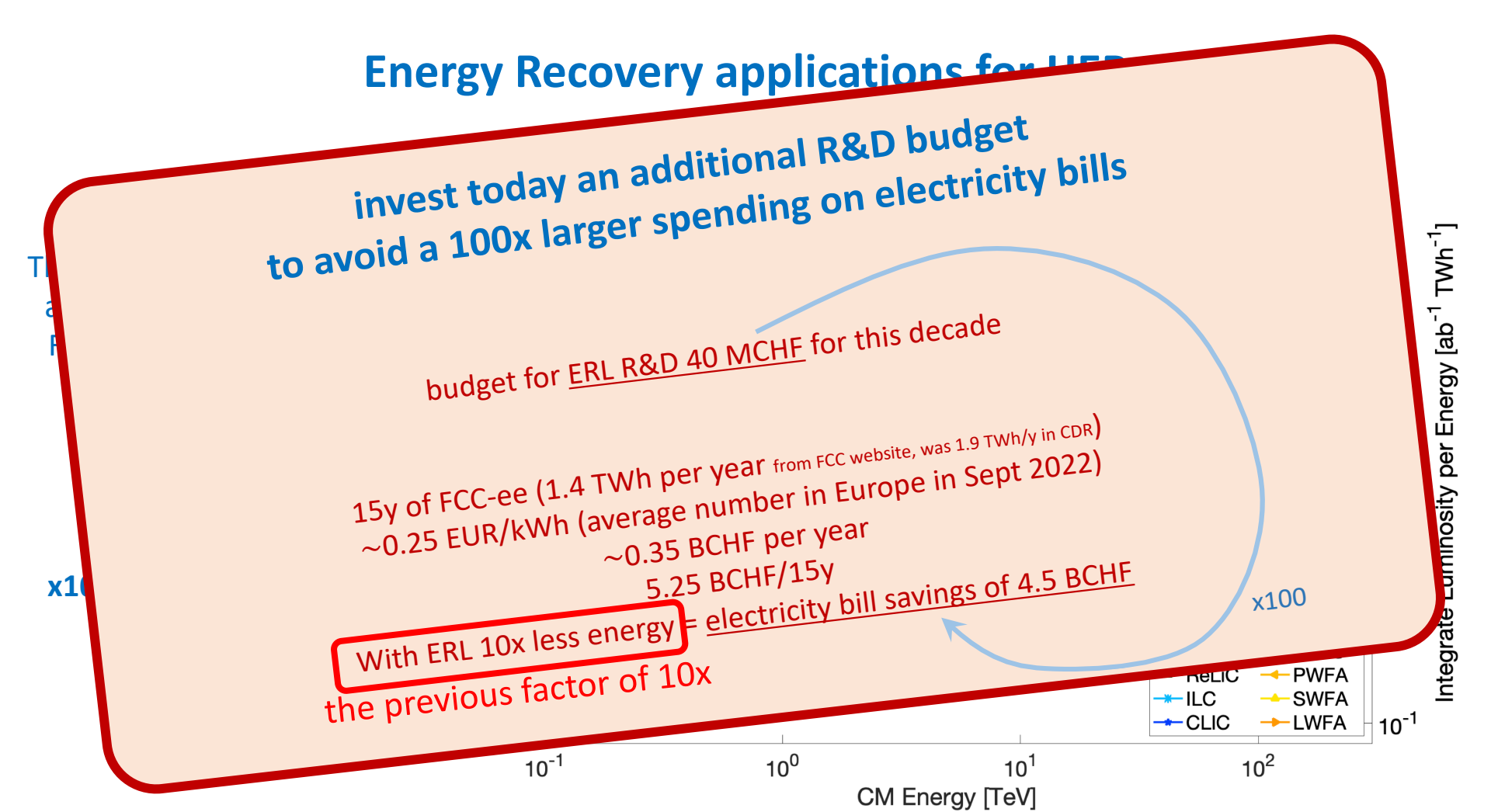
invest today an additional R&D budget
to avoid a 100x larger spending on electricity bills

budget for ERL R&D 40 MCHF for this decade

15y of FCC-ee (1.4 TWh per year from FCC website, was 1.9 TWh/y in CDR)
~0.25 EUR/kWh (average number in Europe in Sept 2022)
~0.35 BCHF per year
5.25 BCHF/15y
= electricity bill savings of 4.5 BCHF

With ERL 10x less energy
the previous factor of 10x

x100



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Energy Recovery applications for HEP

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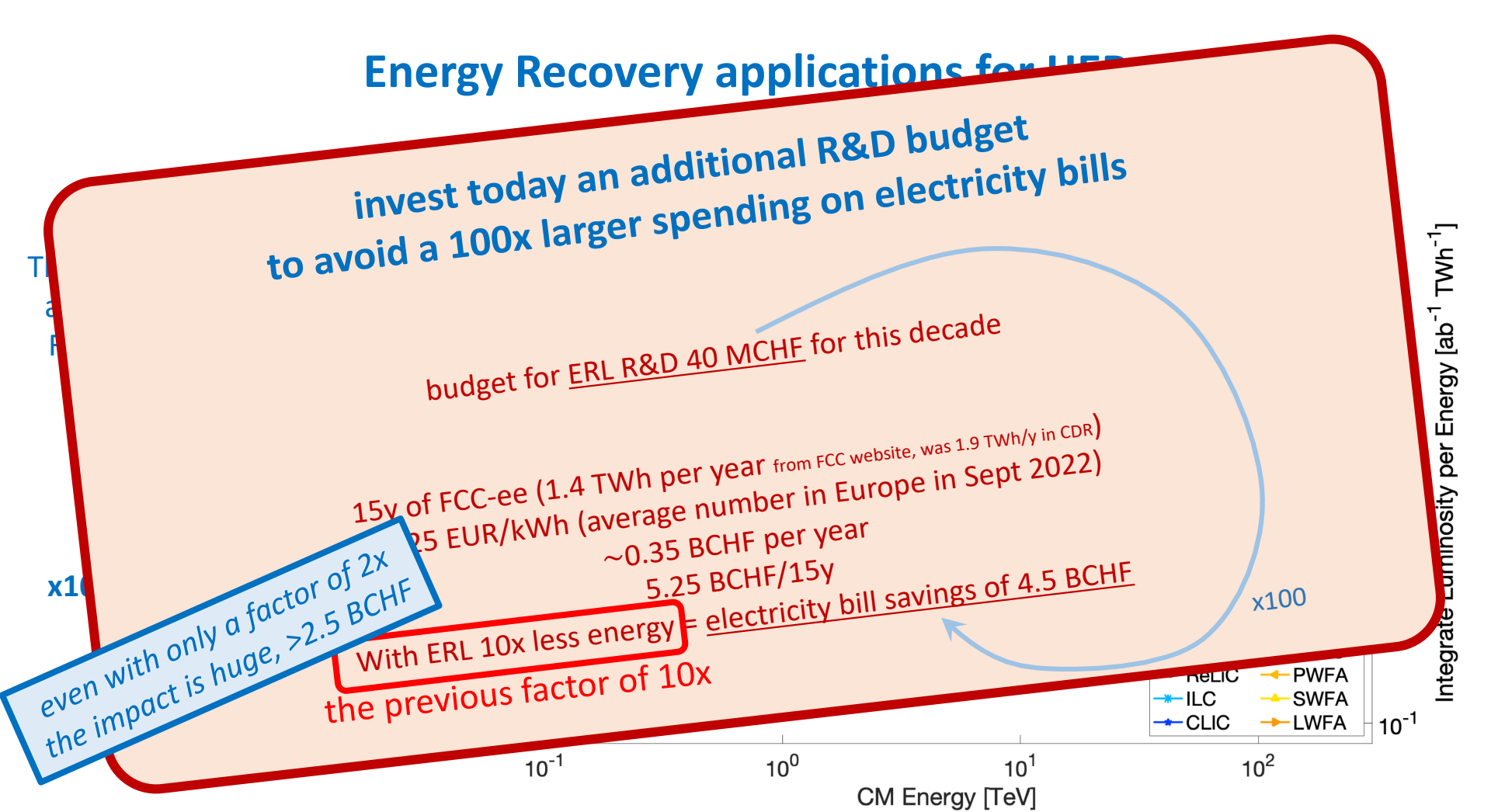
budget for ERL R&D 40 MCHF for this decade

15y of FCC-ee (1.4 TWh per year from FCC website, was 1.9 TWh/y in CDR)
25 EUR/kWh (average number in Europe in Sept 2022)
~0.35 BCHF per year
5.25 BCHF/15y
= electricity bill savings of 4.5 BCHF

x100

With ERL 10x less energy
the previous factor of 10x

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



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Energy Recovery applications for HEP

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

Power of Synchrotron Radiation ~ 1/R

R : radius of circular collider

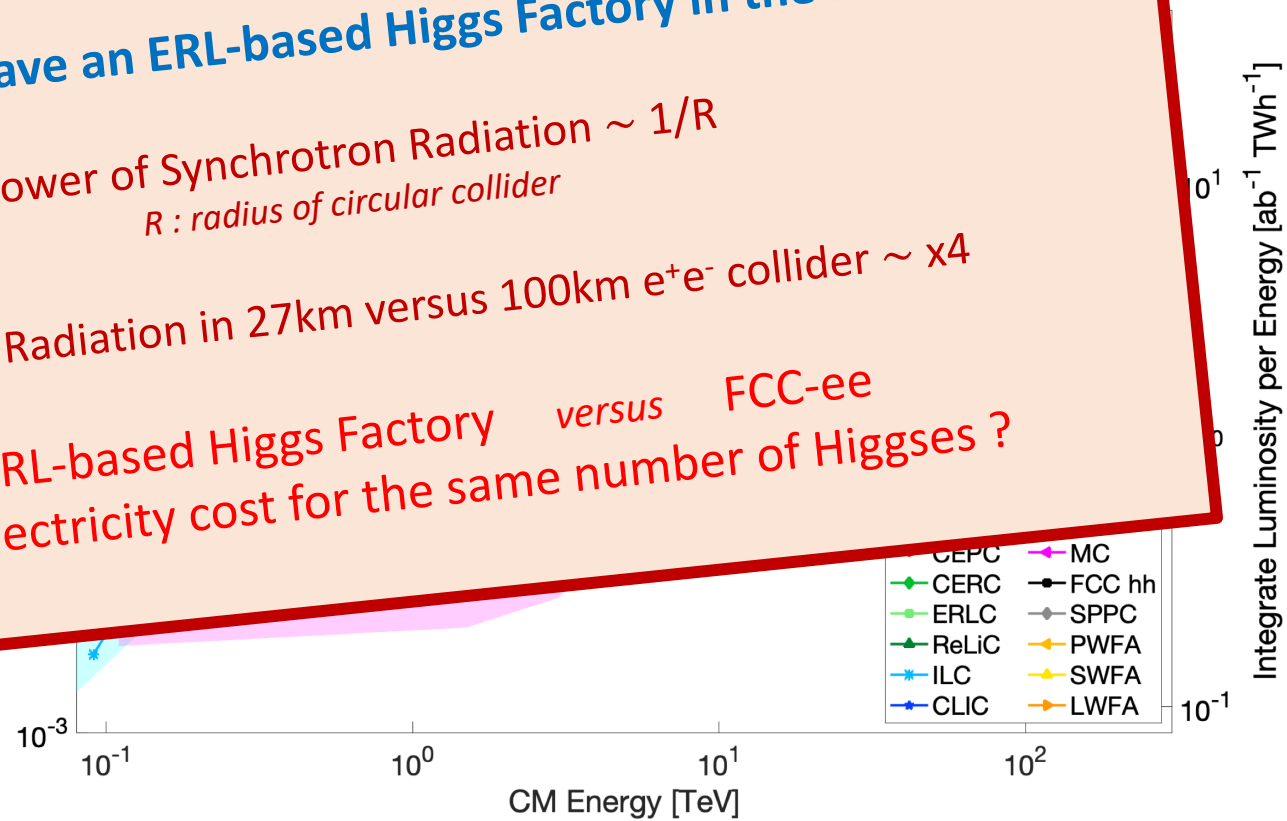
Synchrotron Radiation in 27km versus 100km e^+e^- collider ~ x4

LHC ERL-based Higgs Factory *versus* FCC-ee

the same electricity cost for the same number of Higgses ?

This
an
Fac

x10 I



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Energy Recovery applications for HEP

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

Power of Synchrotron Radiation ~ 1/R

R : radius of circular collider

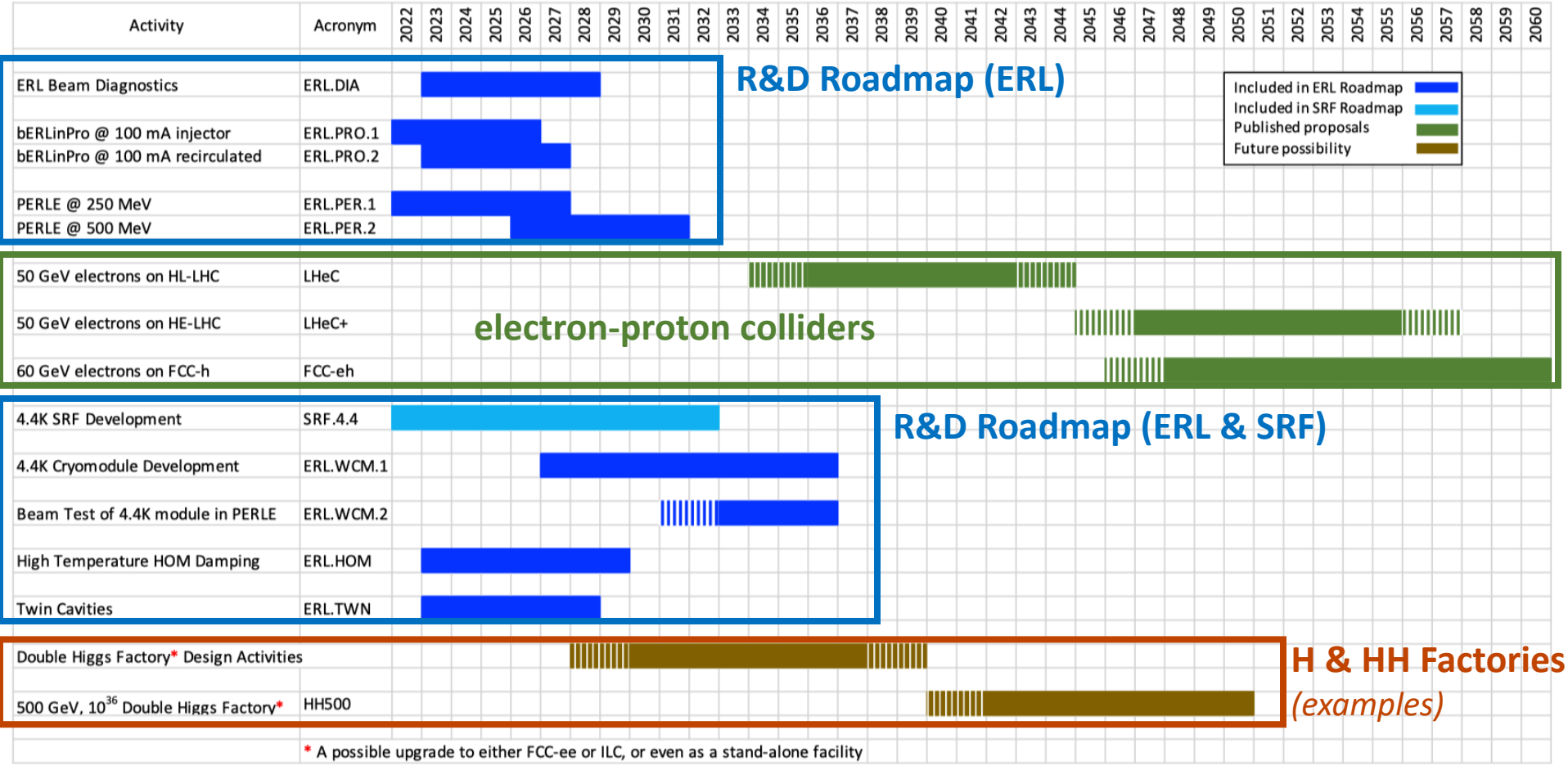
Synchrotron Radiation in 27km versus 100km e^+e^- collider ~ x4

ERL-based Higgs Factory *versus* FCC-ee

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

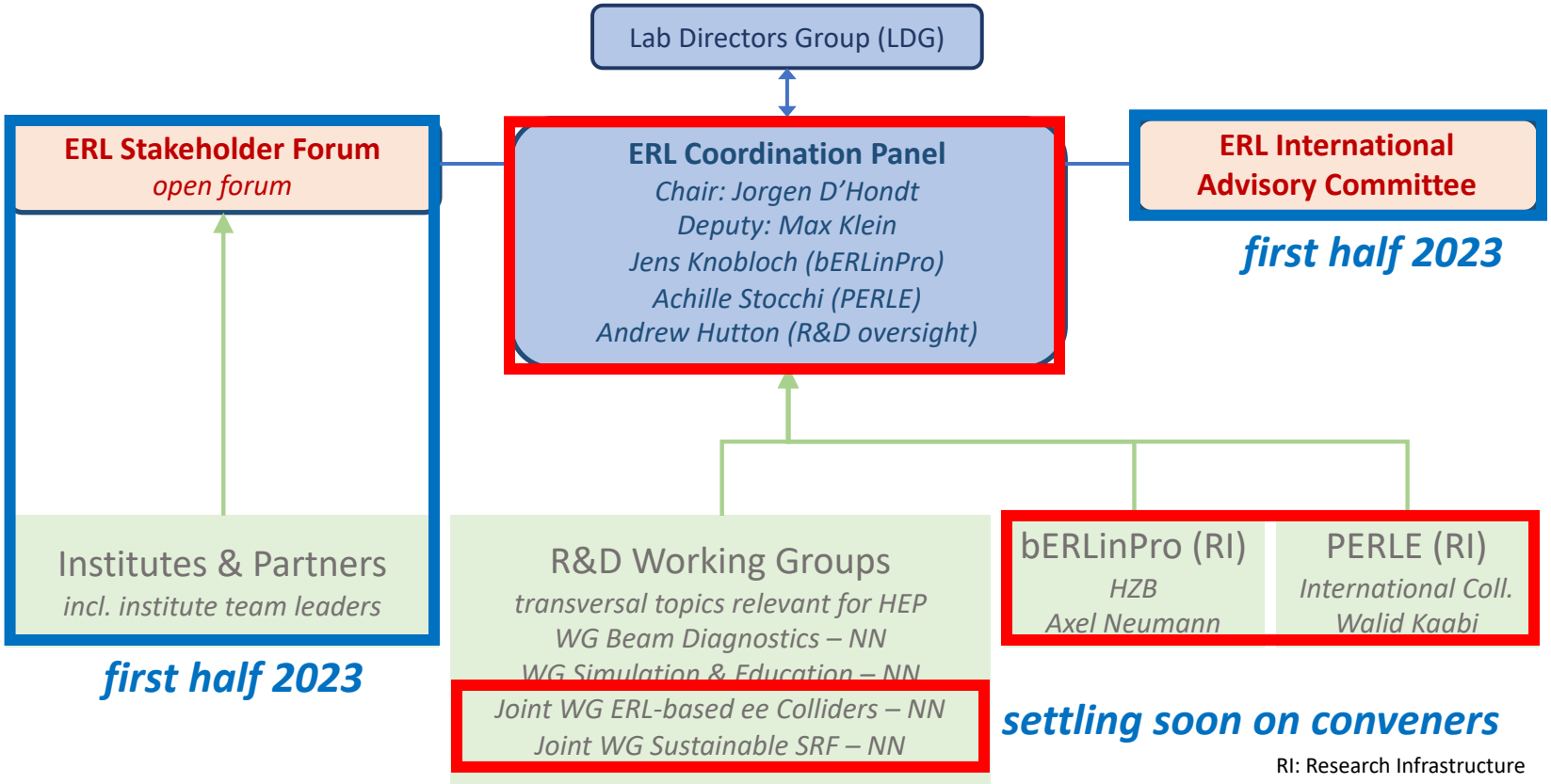
Workshops for “ERL-based Higgs Factories”

- **New conceptual ideas are welcome, focus on ERL-based H- or HH-Factories**
- **New workshop series “ERL-based Higgs Factories” to get experts together**
- **With a very broad programme committee led by our Coordination Panels**
  (together with the RF Coordination Panel, because e.g. 4.4K SRF is key for these colliders)
- **Initial objectives:**
  - **discuss the portfolio of options (all sizes and geometries)**
  - **verify the feasibility and identify challenges**
  - **peer-reviewed comparison of performances** (e.g. via ICFA panel on sustainability)
- **Frequent collective reports to the HEP community (e.g. ECFA, LDG, …)**
- **Prepare a written report as input to the next ESPP update**


Activity
Acronym
2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060
ERL Beam Diagnostics
ERL.DIA
bERLinPro @ 100 mA injector
ERL.PRO.1
bERLinPro @ 100 mA recirculated
ERL.PRO.2
PERLE @ 250 MeV
ERL.PER.1
PERLE @ 500 MeV
ERL.PER.2
R&D Roadmap (ERL)
Included in ERL Roadmap
Included in SRF Roadmap
Published proposals
Future possibility
50 GeV electrons on HL-LHC
LHeC
50 GeV electrons on HE-LHC
LHeC+
60 GeV electrons on FCC-h
FCC-eh
electron-proton colliders
4.4K SRF Development
SRF.4.4
4.4K Cryomodule Development
ERL.WCM.1
Beam Test of 4.4K module in PERLE
ERL.WCM.2
High Temperature HOM Damping
ERL.HOM
Twin Cavities
ERL.TWN
R&D Roadmap (ERL & SRF)
Double Higgs Factory* Design Activities
500 GeV, 10^36 Double Higgs Factory*
HH500
H & HH Factories
(examples)
* A possible upgrade to either FCC-ee or ILC, or even as a stand-alone facility

Organising the European R&D for Energy Recovery in HEP

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



Challenges for implementing the ERL R&D roadmap

- Reaching out for additional budgets is not trivial at this stage, i.e. today we are in an overconstrained system … we need to strategically promote our objectives
- It is relevant to soon promote a very clear statement that our community is committed to strong R&D contributions to realize “Sustainable Accelerating Systems” (incl. ERL) for the future HEP colliders it is studying
- The realization of bERLinPro and PERLE during this decade is crucial to potentially integrate innovative Sustainable Accelerating Systems into the design of future HEP colliders next decade
- In the absence of clear initial funding commitments from HEP funding bodies, the timelines for the implemention of bERLinPro and PERLE are jeopardised, i.e. first-stage commitments above the “we-gear-up-for-success” threshold are essential as a stepping stone and in order to have a catalyser for additional resources
- In particular, the PERLE international collaboration should be promoted as a priority R&D facility for our field and large laboratories should explore to join the efforts
- As the principle community driver, through promoting and with first-stage resources, a strong initial commitment from CERN could trigger a wider engagement and timely launch the R&D programme (e.g. win-win by potentially testing FCC-ee cryomodule LINACs with PERLE)

Additional slides

Expression of Interest to join this R&D program for Energy Recovery

with a view to demonstrate its applicability in high-energy particle physics colliders

Institute	R&D Working Groups						bERLinPro	PERLE
	Beam Diagnostics	Simulations & Education	Sustainable SRF	ERL-based ee Colliders	Electron Source	ERL-based ep-collider		
Univ. NN (names individuals)	x					x	x	x

ERL R&D is at the crossroad between different disciplines.

The successful and timely realisation of the ERL R&D plan for particle physics depends on the interest and involvement of leading experts and their institutions.

In addition, and as a prerequisite, it requires the particle physics funding bodies to timely resource load the plan in order to cover the material costs and activate the concrete implementation plan.

Contact: Jorgen D'Hondt (chair, Jorgen.DHondt@vub.be) and Max Klein (deputy, mklein@hep.ph.liv.ac.uk)

Organising the European R&D for Energy Recovery in HEP

① connecting the ERL R&D community with the HEP steering and funding bodies
② synergies with ongoing ERL R&D towards implementations in HEP applications
③ strengthen collaboration across the field to reach the HEP-related R&D objectives

Coordination Panel

Jorgen D'Hondt (chair), Max Klein (deputy)
Jens Knobloch (bERLinPro), Achille Stocchi (PERLE), Andrew Hutton (R&D oversight)

Working Groups

1. Beam Diagnostics & Instrumentation
2. Simulations (incl. education)

being explored

3. Designs of e^+e^- colliders with Energy Recovery (incl. Dual Axis R&D) – joint with RF Coordination Panel
4. Sustainable SRF (incl. HOM damping, FRT, >4K operation) – joint with RF Coordination Panel

Joint WG as a stepping stone for generic R&D towards potential integration in the PERLE and bERLinPro programmes

Additional

- Electron Source — *work integrated in the bERLinPro & PERLE programmes*
- Design of ep collider — *ongoing in the realm of the LHeC and FCC-eh programmes*