### The FCC-eh program an essential part in the FCC portfolio

Jorgen D'Hondt Vrije Universiteit Brussel



Latest LHeC/FCC-eh/PERLE workshop: https://indico.ijclab.in2p3.fr/event/8623/timesable/#20221026.detailed

HIGH-ENERGY PHYSICS RESEARCH CENTRE

FCC Week, London, 5-9 June 2023

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

Great theory that matches all our observations related to fundamental interactions

Yet, we are puzzled with the dominance of matter over anti-matter, with the dominance of dark matter in the universe, with the flavour structure of our theory, with the fine-tuning of the parameters in the theory, ... and, it is not clear where we will find answers

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

# A paradigm shift: high-energy electron-proton collions

at high energies electron-proton colliders provide a General-Purpose experiment

# **Collision energy above the threshold for EW/Higgs/Top**

from mostly QCD-oriented physics to General-Purpose physics



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, interactions with all particles in the Standard Model can be measured precisely

# The ep/eA landscape

For ep/eA physics, the 2030'ies will be the decade of the EIC

The next ambition for the community will be to enable ep/eA physics both at higher luminosities and at higher energies

The LHeC and FCC-eh programs represent great strides into uncharted territories



# A paradigm shift: high-energy electron-proton collions



# A paradigm shift: high-energy electron-proton collions



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

# A paradigm shift: high-energy electron-proton collions



# The LHeC program



# The FCC-eh program



# 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



10y @ 1.2 TeV (1ab<sup>-1</sup>) updated CDR: J.Phys.G 48 (2021) 11, 110501

# Some physics highlights of the LHeC (ep/eA@LHC)

on several fronts comparable improvements between LHC  $\rightarrow$  HL-LHC as for HL-LHC  $\rightarrow$  LHeC



#### **EW physics**

- $\circ \Delta m_W$  down to 2 MeV (today at ~10 MeV)
- $\circ \Delta sin^2 \theta_W^{eff}$  to 0.00015 (same as LEP)

#### **Top quark physics**

- $\circ$  |V<sub>tb</sub>| precision better than 1% (today ~5%)
- $\circ$  top quark FCNC and  $\gamma$ , W, Z couplings

#### **DIS scattering cross sections**

PDFs extended in (Q<sup>2</sup>,x) by orders of magnitude

#### **Strong interaction physics**

- $\circ \alpha_s$  precision of 0.1%
- o low-x: a new discovery frontier





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# **Complementarity of different colliders in the FCC program**

#### Complementarity for Higgs physics between ee/eh/hh colliders

(Higgs coupling strength modifier parameters  $\kappa_i$  – assuming no BSM particles in Higgs boson decay) (expected relative precision)

kappa-0-HL	HL+FCC-ee <sub>240</sub>	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
$\kappa_W[\%]$	0.86	0.38	0.23	0.27	0.17	0.39	0.14
$\kappa_Z[\%]$	0.15	0.14	0.094	0.13	0.27	0.63	0.12
$\kappa_{g}[\%]$	1.1	0.88	0.59	0.55	0.56	0.74	0.46
$\kappa_{\gamma}[\%]$	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
$\kappa_c[\%]$	1.5	1.3	0.88	1.2	1.2	-	0.94
$\kappa_t$ [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
$\kappa_b[\%]$	0.94	0.59	0.44	0.5	0.52	0.99	0.41
$\kappa_{\mu}[\%]$	4.	3.9	3.3	0.41	0.45	0.68	0.41
$\kappa_{\tau}[\%]$	0.9	0.61	0.39	0.49	0.63	0.9	0.42
$\Gamma_H[\%]$	1.6	0.87	0.55	0.67	0.61	1.3	0.44
ALL COMBI							
only FCC-ee@240GeV					only FCC-hh		

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

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# **Empowering the FCC-hh program with the FCC-eh**



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# **Empowering the FCC-hh program with the FCC-eh**



# New mandate from the CERN Directorate (Oct 2022)

Following the publication of the updated LHeC CDR, <u>CERN continues to support</u> <u>studies for the LHeC and the FCC-eh</u> 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.

# The challenge

high-intensity electron beam

From HERA to LHeC/FCC-eh

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

#### LHeC/FCC-eh ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant






















# The principle of Energy Recovery



# European Accelerator R&D Roadmap for particle physics

### ERL one of five impactful avenues for Accelerator R&D

CERN Yellow Rep. Monogr. 1 (2022) 1-270 and arXiv:2201.07895 Extensive ERL report: arXiv:2207.02095

First Community Report of the implementation of the Accelerator R&D Roadmap Frascati, 12-13 July <u>https://agenda.infn.it/event/35579/</u>

# 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



<sup>(\*)</sup> 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



#### **Energy Recovery**

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

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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

### **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

#### **BERLinPro: 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), $\pi$ mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	< 10 <sup>-5</sup>

bERLinPro – Berlin Energy Recovery Linac Project



### First beam of bERLinPro@SEALab to be expected in 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



## **Upcoming facilities for Energy Recovery R&D**

complementary in addressing the R&D objectives for Energy Recovery

3-turn ERL

### 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

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

Target Parameter	Unit	Value			
Injection energy	MeV	7			
Electron beam energy	MeV	500			
Normalised Emittance	mm	6			
γε <sub>x,y</sub>	mrad	U			
Average beam current	mA	20			
Bunch charge	рС	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 – Powerful Energy Recovery Linac for Experiments [CDR: J.Phys.G 45 (2018) 6, 065003]

Technology synergies emerge between the R&D for ERL at PERLE and bERLinPro and the ambition for high-performant e<sup>+</sup>e<sup>-</sup> Higgs Factories

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

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

European Strategy for Particle Physics 2020

# Where do SRF H-factories use power?

### **Basic structures of a particle accelerator**



### **Basic structures of a particle accelerator**



### **Basic structures of a particle accelerator**



Typical power consumption for an electron-positron Higgs Factory the highest priority next collider for particle physics



Typical power consumption for an electron-positron Higgs Factory the highest priority next collider for particle physics

## Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency









### improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands



## **Three main innovation directions**



## **Three main innovation directions**



## iSAS develops, prototypes & validates SRF energy-saving technologies

### TA#1: energy-savings from RF power

The objective is to significantly reduce the RF power sources and wall plug power for all SRF accelerators with ferro-electric fast reactive tuners (FE-FRTs) for control of transient beam loading and detuning by microphonics, and with optimal low level radio frequency (LLRF) and detuning control with legacy piezo based systems. iSAS will demonstrate operation of a superconducting cavity with FE-FRTs coherently integrated with AI-smart digital control systems to achieve low RF-power requirements.



Schematic overview to compensate detuning with new FE-FRTs avoiding large power overhead and to compensate with AI-smart control loop countermeasures via the LLRF steering of the RF amplifier the disturbances in SRF cavities that impact field stability

## iSAS develops, prototypes & validates SRF energy-saving technologies

#### TA#2: energy-savings from cryogenics

*The objective is focused on the development of* thin-film cavities and aims to transform conventional superconducting radio-frequency technology based on off-shelf bulk niobium operating at 2 K, into a technology operating at 4.2 K using a highly functionalized material, where individual functions are addressed by different layers. iSAS will optimize the coating recipe for Nb<sub>3</sub>Sn on copper to optimize tunability and flux trapping of thin-film superconducting cavities and to validate a prototype beyond the achievements of the ongoing Horizon Europe I.FAST project.



The higher critical temperature ( $T_c$ ) of Nb<sub>3</sub>Sn allows for the maximum value of quality factor  $Q_0$  for 1.3 GHz cavities to be achieved at operating temperatures of about 4 K compared to 2 K for Nb (left figure). The graph on the right shows the efficiency of a cryogenic plant (COP) as a function of temperature achieving about 3 times higher COP efficiency when operating at a temperature of 4.2 K than at 2 K. This suggests that operating a cryogenic plant at 4.2 K with Nb<sub>3</sub>Sn SRF cavities, can lead to significant better performances and energy savings.

## iSAS develops, prototypes & validates SRF energy-saving technologies

### TA#3: energy-savings from the beam

The objective is to reduce the total power deposited into the cryogenics circuits of the cryomodule of the Higher-Order Mode (HOM) couplers and fundamental power couplers (FPCs) leading to a significant reduction of the heat loads and the overall power consumption. iSAS will improve the energy efficiency of the FPCs and HOM couplers by designing and building prototypes that will be integrated into a LINAC cryomodule capable of energy-recovery operations and to be tested in accelerator-like conditions.



towards full high-power energy recovery

## iSAS organisation

Spread over 4 years: ~1000 person-months of researchers and ~12.6M EUR (of which 5M EUR is requested to Horizon Europe)



+ 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)

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### **Electron-proton collisions at the core of particle physics**

- The high-energy electron-hadron programme at the LHC and FCC are <u>truely</u> <u>general-purpose experiments</u> reaching beyond current knowledge in QCD, Higgs, EW and top quark physics and with its own BSM discovery potential
- At the same time, these programmes empower the current research in ATLAS and CMS, and are vital to <u>unlock the full physics potential of the FCC program</u>
- And surely, when we look deeper into the proton we <u>significantly move the</u> <u>low-x frontier</u> and in this terra incognita we do not know what to discover
- The engine of our curiosity-driven exploration is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize: <u>Energy Recovery Linac systems deliver on this technology front</u>

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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 <sup>31</sup>	1 × 10 <sup>34</sup>	$2.3 \times 10^{34}$	1.5 × 10 <sup>34</sup>	
epton	Electrons, positrons	Electrons	Electrons	Electrons	
	polarized	polarized	unpolarized	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	Protons	Protons	Protons	
	unpolarized	polarized	unpolarized	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	-	-	

## **Organising the European R&D for Energy Recovery in HEP**

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



## Timeline

2005: first ideas for an 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), arXiv:2007.14491
2021: publication updated CDR in Journal of Physics G
2021: end of CERN mandate



picture from M. Klein

## Timeline

2022 (Aug): J. D'Hondt invited to become the new LHeC/FCC-eh Spokesperson 2022 (Oct): new CERN mandate received from CERN DG and DRC

Following the publication of the updated CDR, 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.

### Mandate of the LHeC/FCC-eh Coordinator (Jorgen D'Hondt)

The coordinator convenes the Coordination Panel. The coordinator provides visible leadership, organization, and advocacy for the work towards an ep/eA collider programme at CERN. The coordinator acts as the Spokesperson of the study to the international community and represents the FCC-eh towards the FCC feasibility study. The coordinator can assign a deputy.

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### Mandate of the LHeC/FCC-eh Coordination Panel

The panel has the task to assist the coordinator (and deputy). The panel organizes, coordinates, oversees, and steers an appropriate long-term organizational structure and programme plan. The panel will report to CERN's Director for Research and Computing through the Coordinator and will receive advice from the International Advisory Committee. It includes an international representation and acts as a decision-making and prioritization body for the study.
## Timeline

2022 (Aug): J. D'Hondt invited to become the new LHeC/FCC-eh Spokesperson 2022 (Oct): new CERN mandate received from CERN DG and DRC

## Mandate of the International Advisory Committee

The IAC advises the Coordination Panel and the CERN Directorate by following the development of options of an ep/eA collider at the LHC and at the FCC. Advice may relate to the scientific and technical direction for the physics potential of the ep/eA collider, with emphasis on the FCC, depending on the machine parameters and a realistic detector design. The IAC assists the Coordination Panel build the international case for the accelerator and detector developments, and advises on the resource, infrastructure and science policy aspects of the ep/eA collider.

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**Coordination Panel members**: Nestor Armesto, Maarten Boonekamp, Oliver Brüning, Daniel, Britzger, Monica D'Onofrio, Claire Gwenlan, Uta Klein, Paul Newman, Yannis Papaphilippou, Christian Schwanenberger, Yuji Yamazaki.

**IAC members**: Frederick Bordry (chair), Phil Allport, Diego Bettoni, 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.