FCC-eh summary

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with input from O. Bruning, J. D'Hondt,
W. Kaabi,T. Von Witzleben,
Y. Yamazaki, M. Chamizo Llatas

FCC Week 2023, 09/06/2023

FCC-eh accelerator session

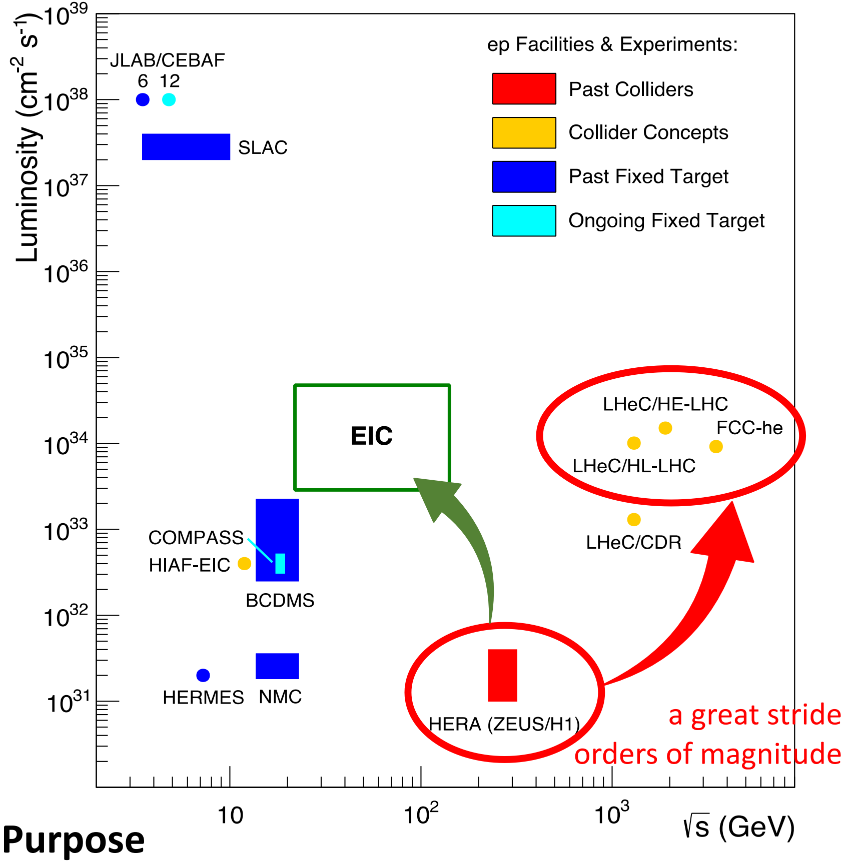
- FCC-eh and LHeC: Project overview and developments on ERL and sustainable technology, Jorgen D'Hondt
- PERLE: Status and prospects for high power ERL, Walid Kaabi
- Design and optimisation of the ep (and possibility joint ep/pp) Interaction Region, Tiziana Von Witzleben
- Physics and design of the eh detector, Yuji Yamazaki
- EIC-FCC synergies, Maria Chamizo Llatas

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 high-energy electron-proton programs represent great strides into uncharted territories

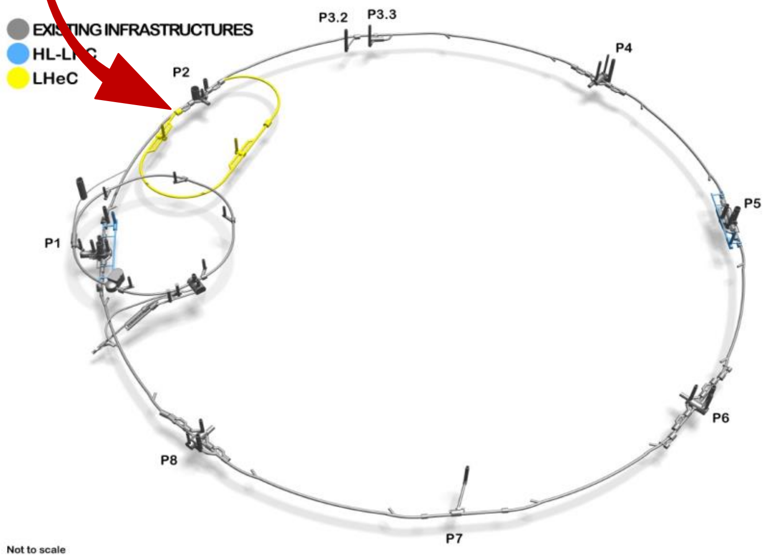


At high energies e-p colliders provide a General-Purpose experiment

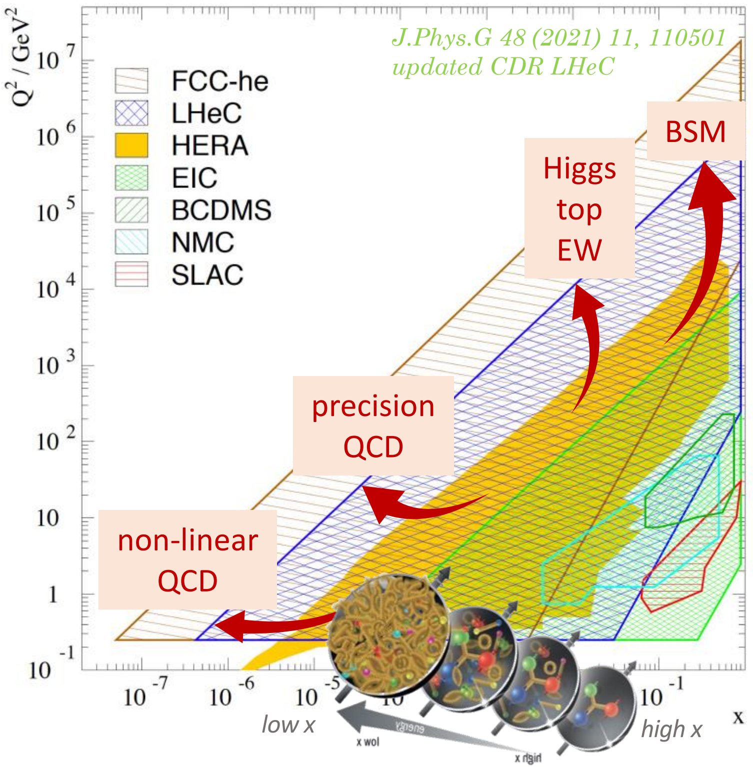
Jorgen D'Hondt

The LHeC program

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



Kinematic range Parton Distribution Functions



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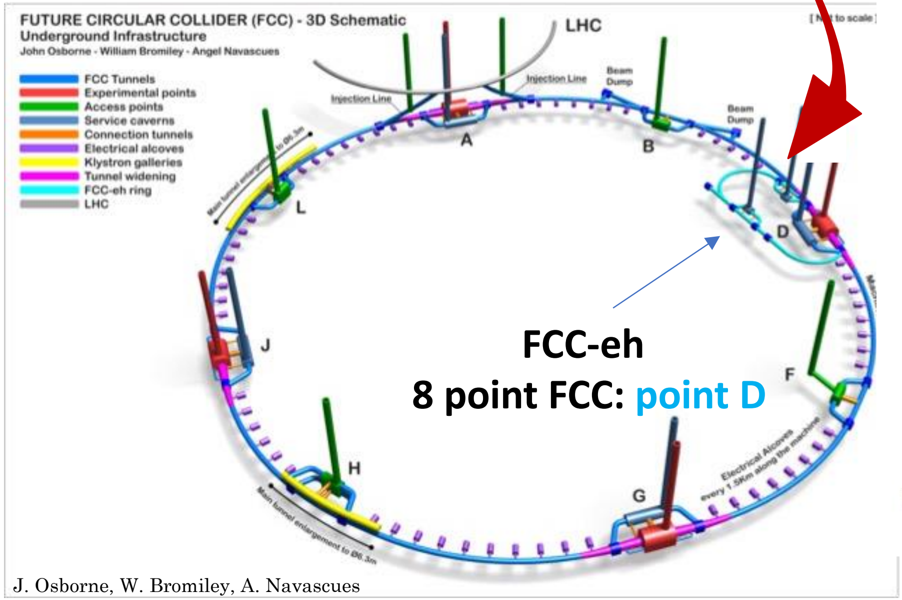
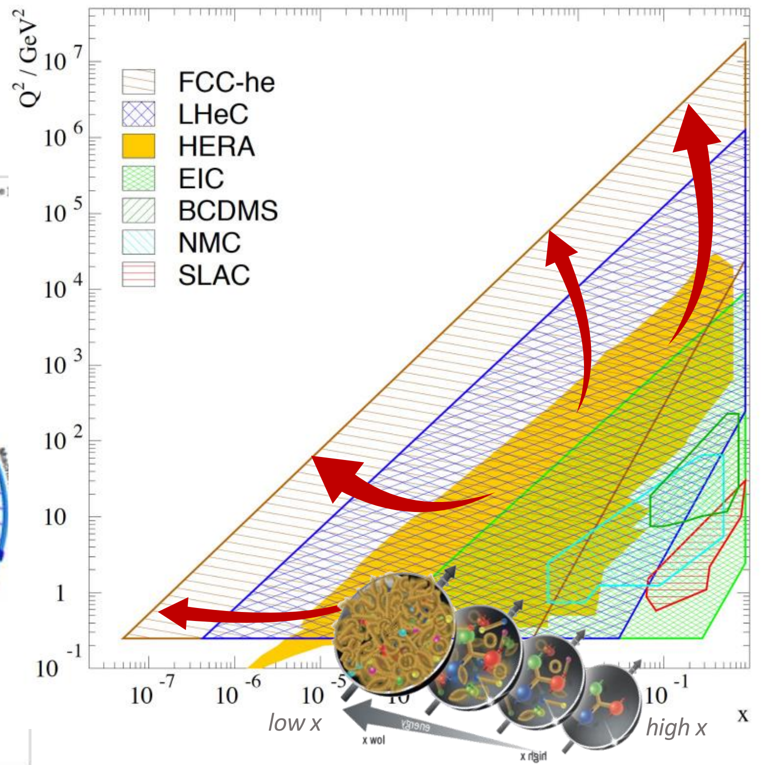
The FCC-eh program

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



Kinematic range Parton Distribution Functions



Jorgen D'Hondt

Complementarity for Higgs physics of ee/ep/pp in the FCC program

(Higgs coupling strength modifier parameters k_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

adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

Jorgen D'Hondt

The challenge

high-intensity electron beam

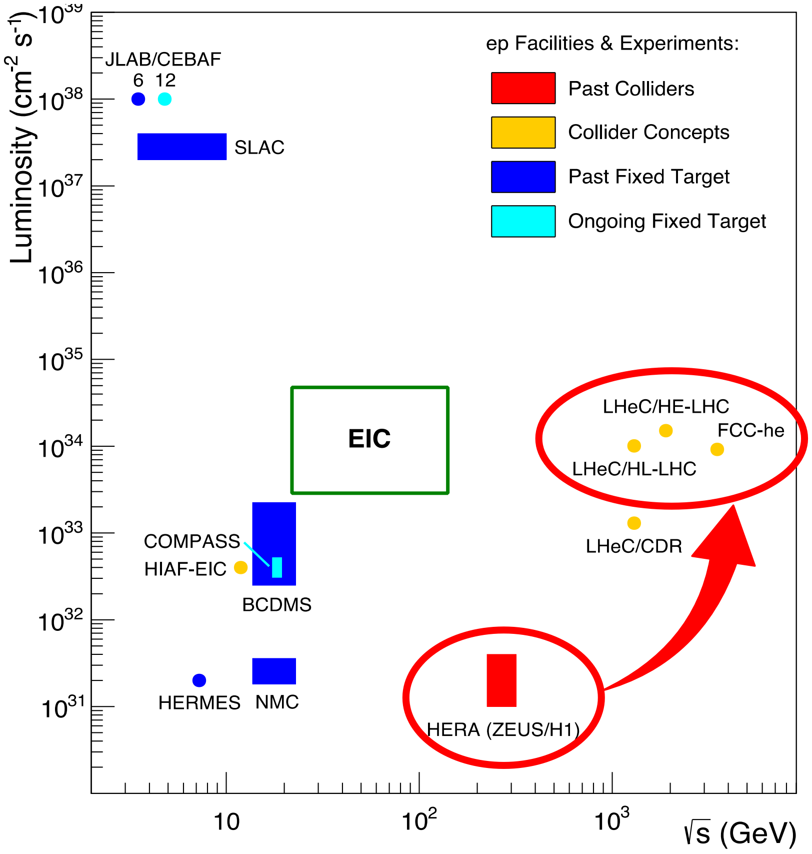
From HERA to LHeC/FCC-eh

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

Jorgen D'Hondt



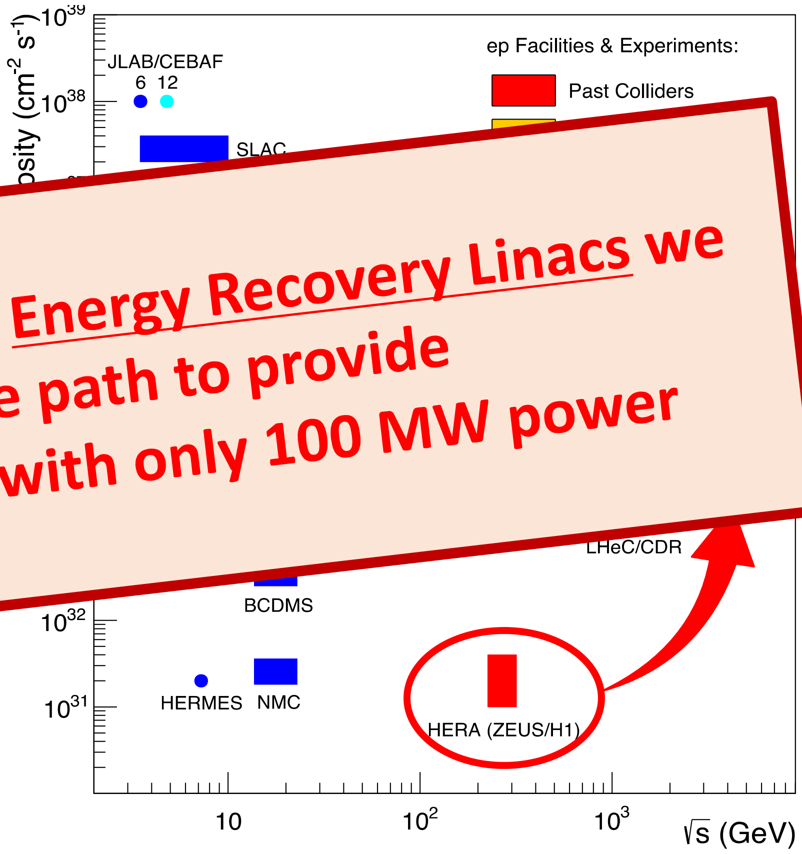
The challenge

high-intensity electron beam

From HERA to LHeC/FCC

1 GW beam power

equivalent to the power delivered by a nuclear power plant

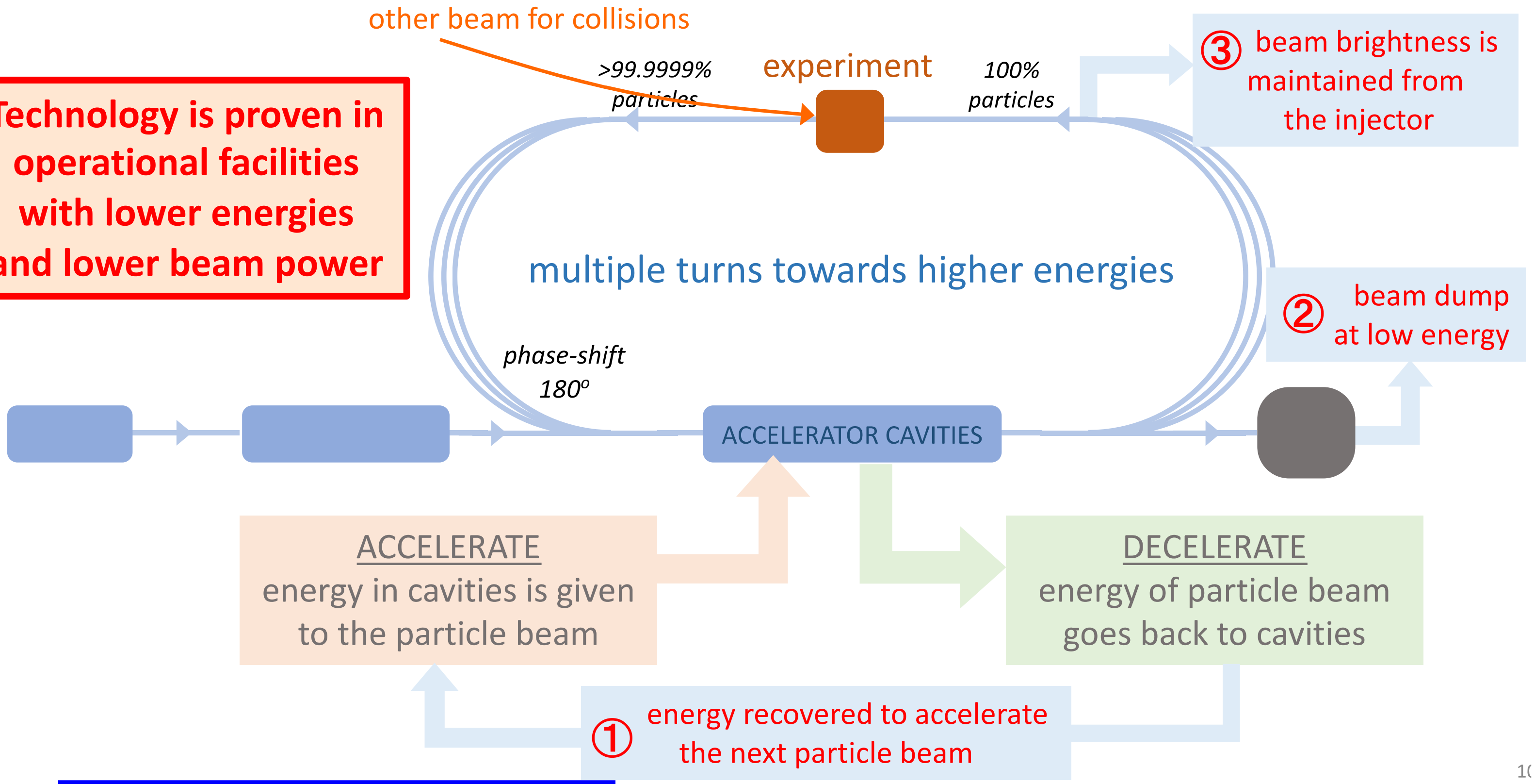


With the planned R&D on Energy Recovery Linacs we will prepare the path to provide a 1 GW electron beam with only 100 MW power

Jorgen D'Hondt

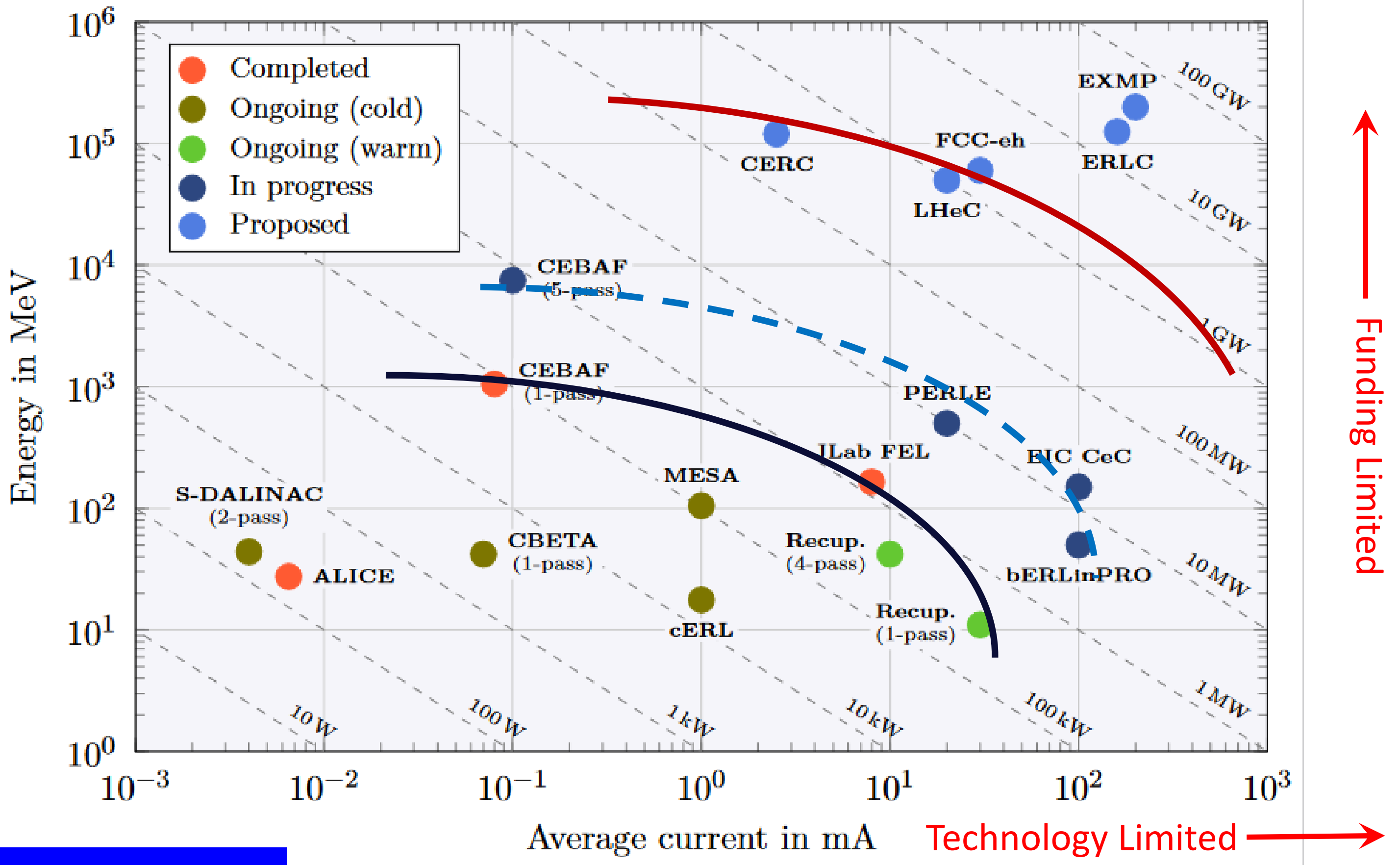
The principle of Energy Recovery

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



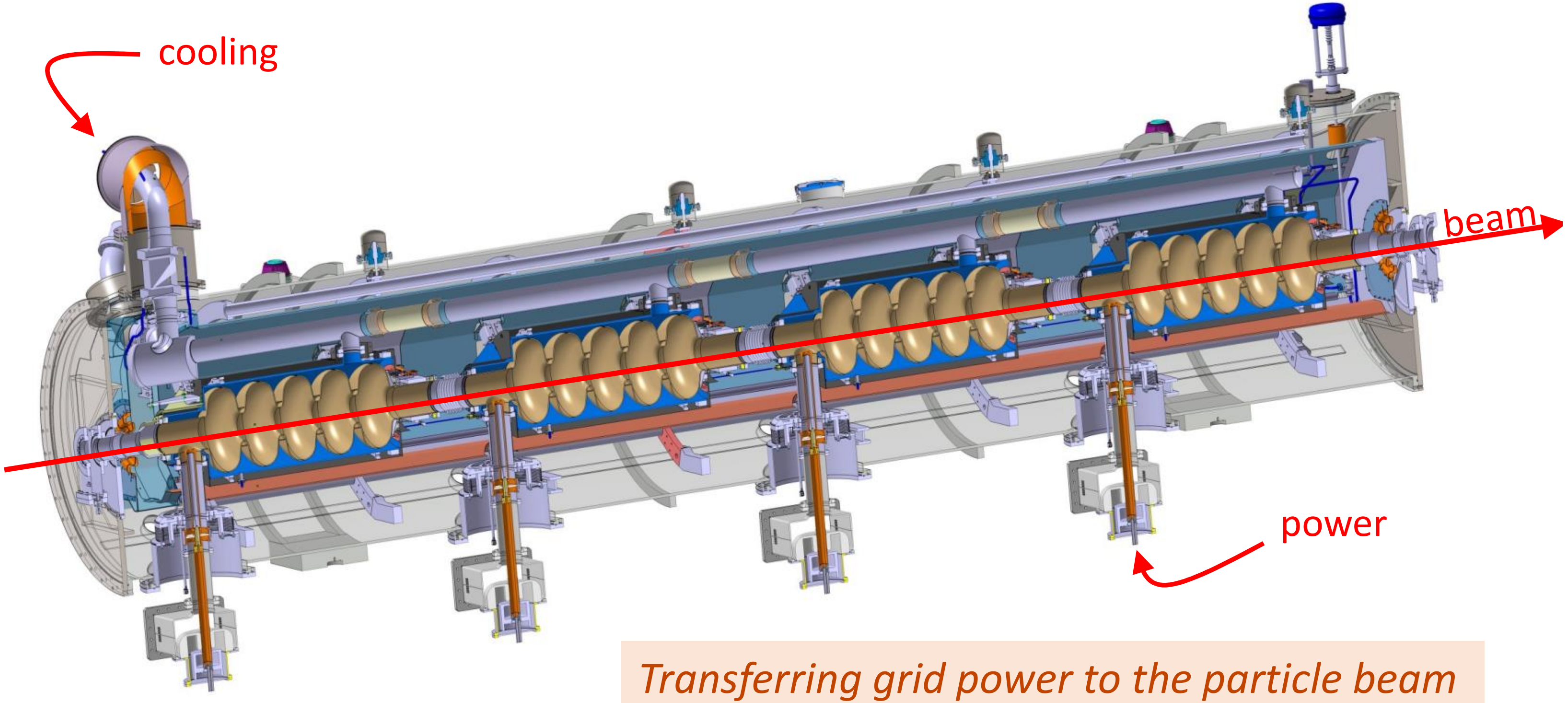
Jorgen D'Hondt

ERL - The global landscape



Key building block for beam acceleration: the SRF cryomodule

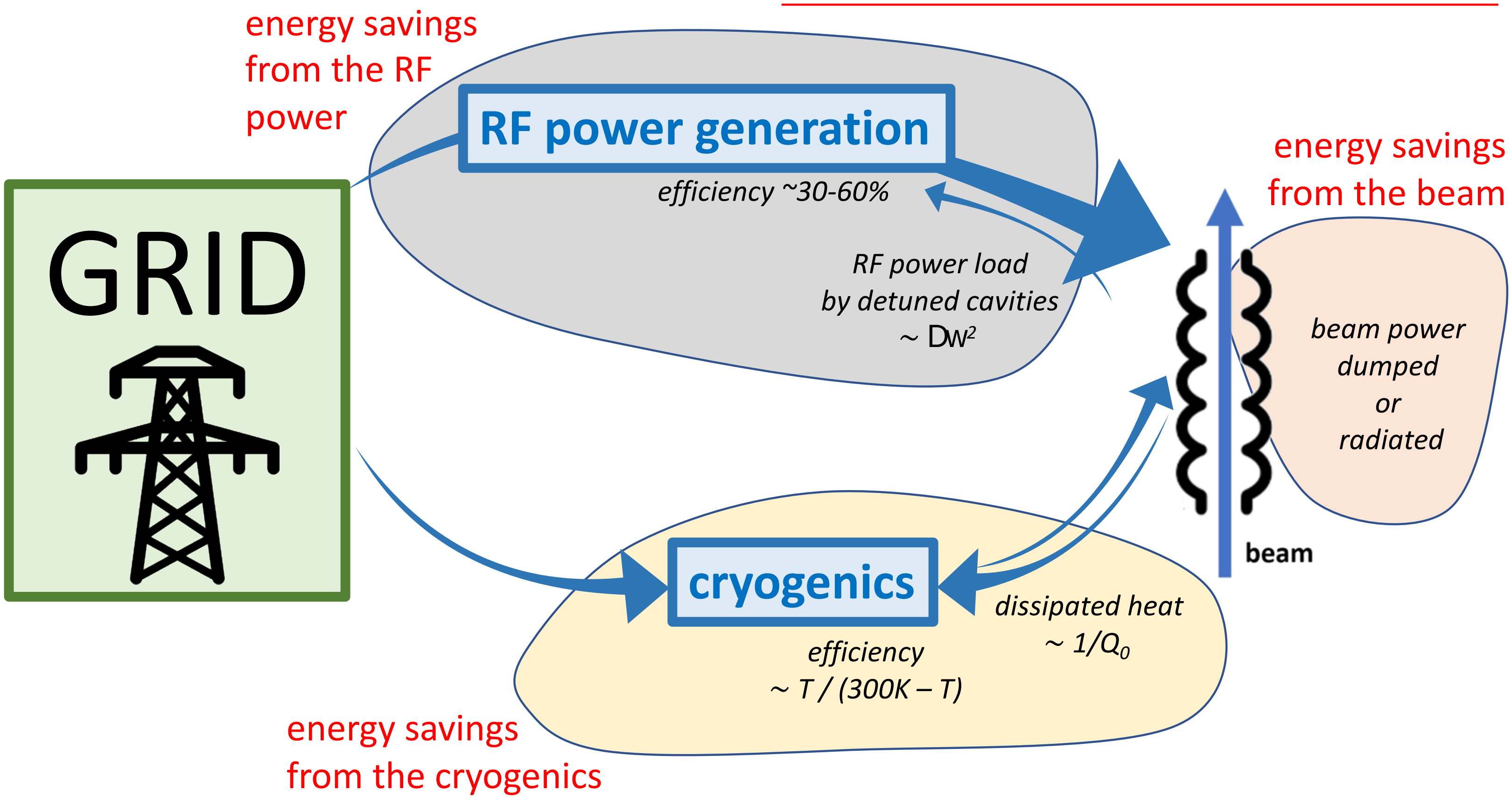
SRF: Superconducting Radio Frequency



Transferring grid power to the particle beam

Jorgen D'Hondt

Three main innovation directions



Jorgen D'Hondt

Three main innovation directions

energy savings from the RF power

Innovate for Sustainable Accelerating Systems (iSAS)

https://indico.ijclab.in2p3.fr/event/9521/

(ambition: significantly reduce the energy footprint of SRF accelerators)

Energy-saving technologies widely applicable in SRF cryomodules: synergies between R&D at PERLE/bERLinPro and implementation in FCC-ee/eh/hh

dissipated heat $\sim 1/Q_0$

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

energy savings from the cryogenics

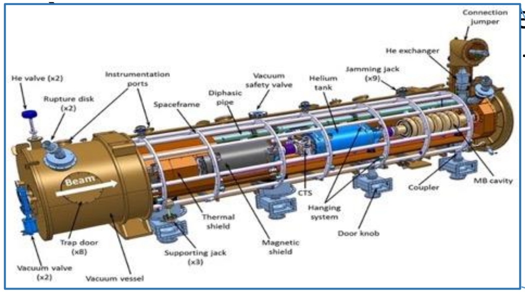
Jorgen D'Hondt

PERLE Configuration

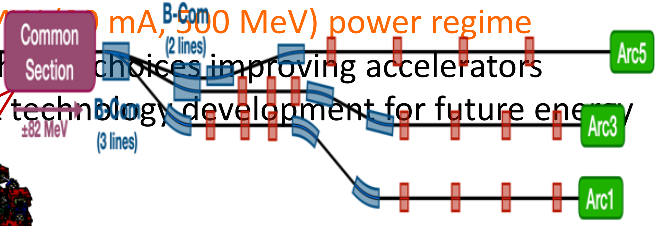
PERLE: first multi-turn ERL, based on SRF technology, designed to operate at 10M… mA, 500 MeV) power regime

…e of accelerator phenomena and to validate tec… choices improving accelerators

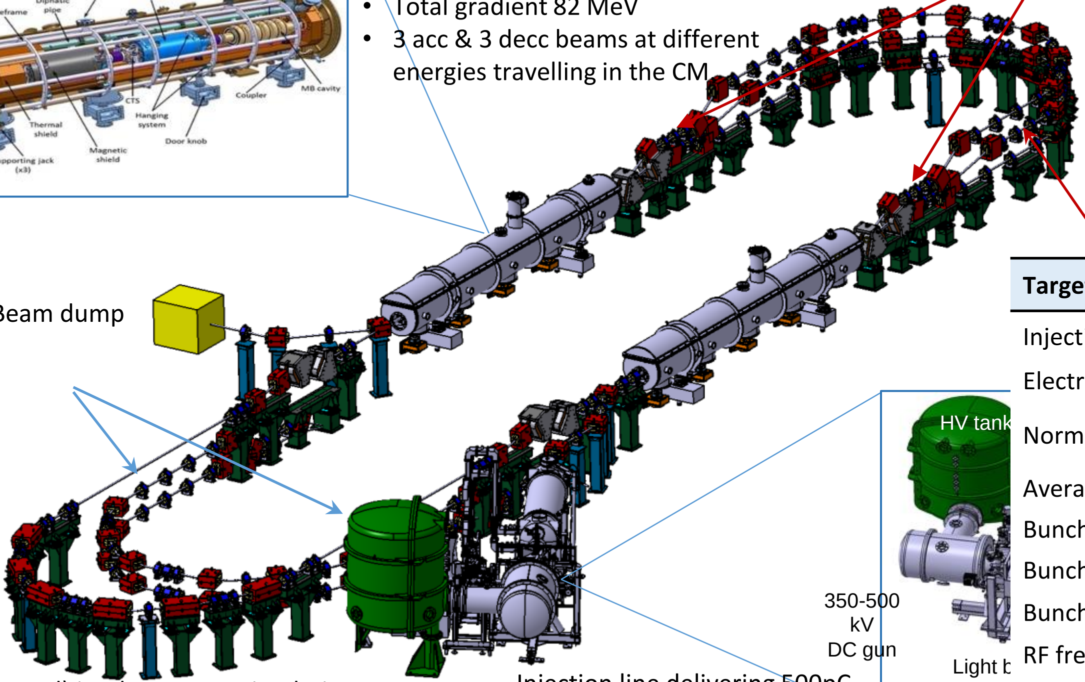
…tional power regime on the pathway of the ERL technology development for future ener…



- Cryomodule with 4 five-Cell cavities
- Total gradient 82 MeV
- 3 acc & 3 decc beams at different energies travelling in the CM



Switchyard: vertical separation/recombination of beams at different energies



Beam dump

Interaction Points

3 staked isochronous recirculation arcs for

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

HV tank

350-500 kV DC gun

Light b… Green laser

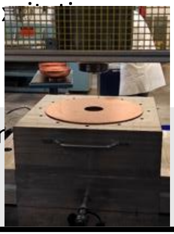
3 staked (& inversed) isochronous recirculation

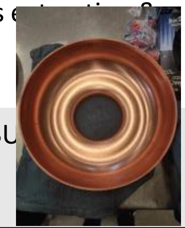
Injection line delivering 500pC bunches at 7 MeV.

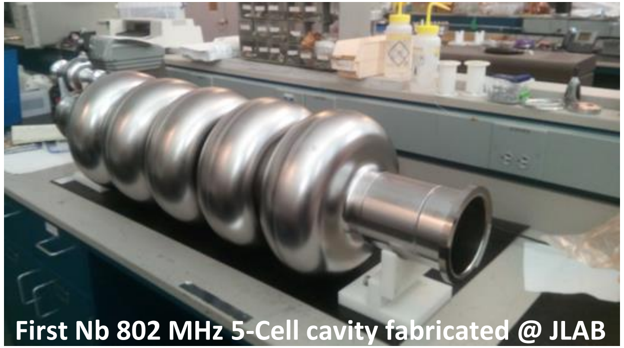
PERLE SRF cavity

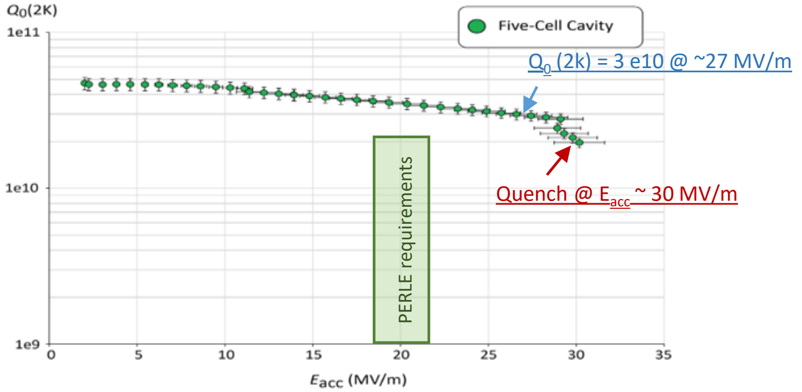
A 5-Cell copper cavity is under fabrication @Jlab to allow end group design optimisation and to test several HOM couplers combinations to assess the best HOM damping scheme.

PERLE R			
CW opera			
High current operation	High HOMs ex...	Efficient HOMs e...	A ... cavity desi... frequency cavity choice (< 1GHz), la... ...er... ...lls for the a given gradient, o... er...
Muti-bunches operation	...ear...	...BU...	R... ...g o... ...imisation of the bunch fi... ...ur... ...ign + BBU study after HOM o... ...cl... ...e effects).



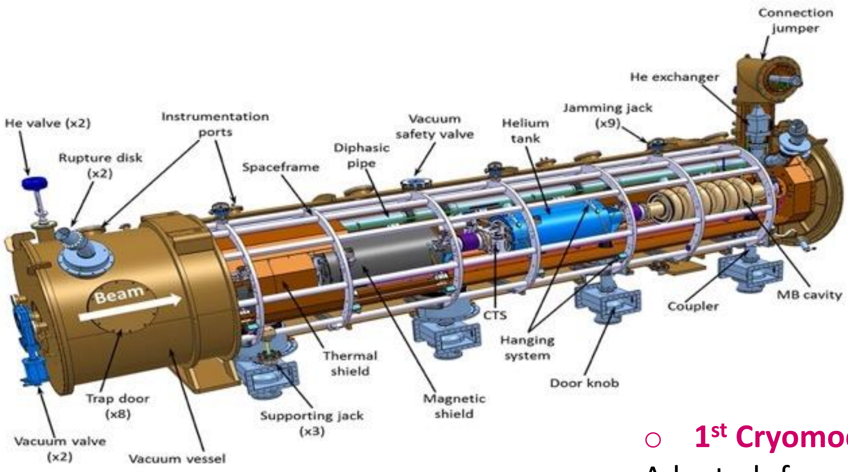

First Nb 802 MHz 5-Cell cavity fabricated @ JLAB

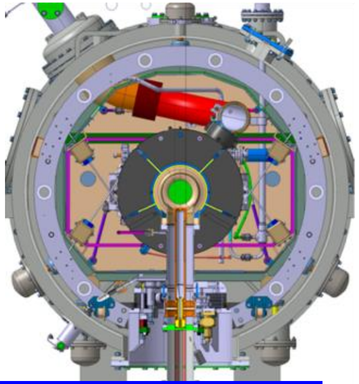


F. Marhauser et al. "802 MHz ERL cavity design and development"- IPAC2018 (Vancouver, BC, Canada)- doi:10.18429/JACoW-IPAC2018-

Walid Kaabi

Cryomodule design:





ESS Cryomodule design was selected:

- Intermediate supporting structure (spaceframe)
- Cavity string hung by rods
- Insertion of the cavity string by the extremity (rollers)
- Trap doors for tuner access
- Connexion to the valve box on the top of the vacuum vessel
- Important space available inside
- Design validated: series fab. & tests ongoing (Qty 30)

○ **1st Cryomodule: Foreseen for 2027**

Adapted from ESS design, it will be optimised for efficient high current ERL operation within the *European Infra-Tech program iSAS**. It will host cavities equipped with HOM couplers and FPC optimised and developed within the same program.

○ **2nd Cryomodule: Foreseen for 2030**

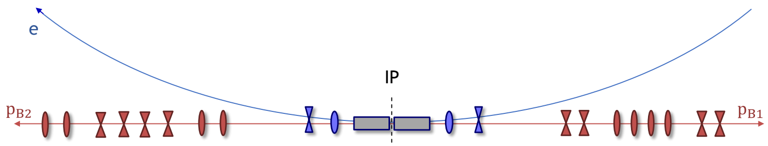
May include some/all the technologies studied within *iSAS program* to improve the efficiency of Cryomodules: Fast Reactive Tuner (FRT) for microphonics mitigation, LLRF managed by AI and 4.2 K Cavities operating.

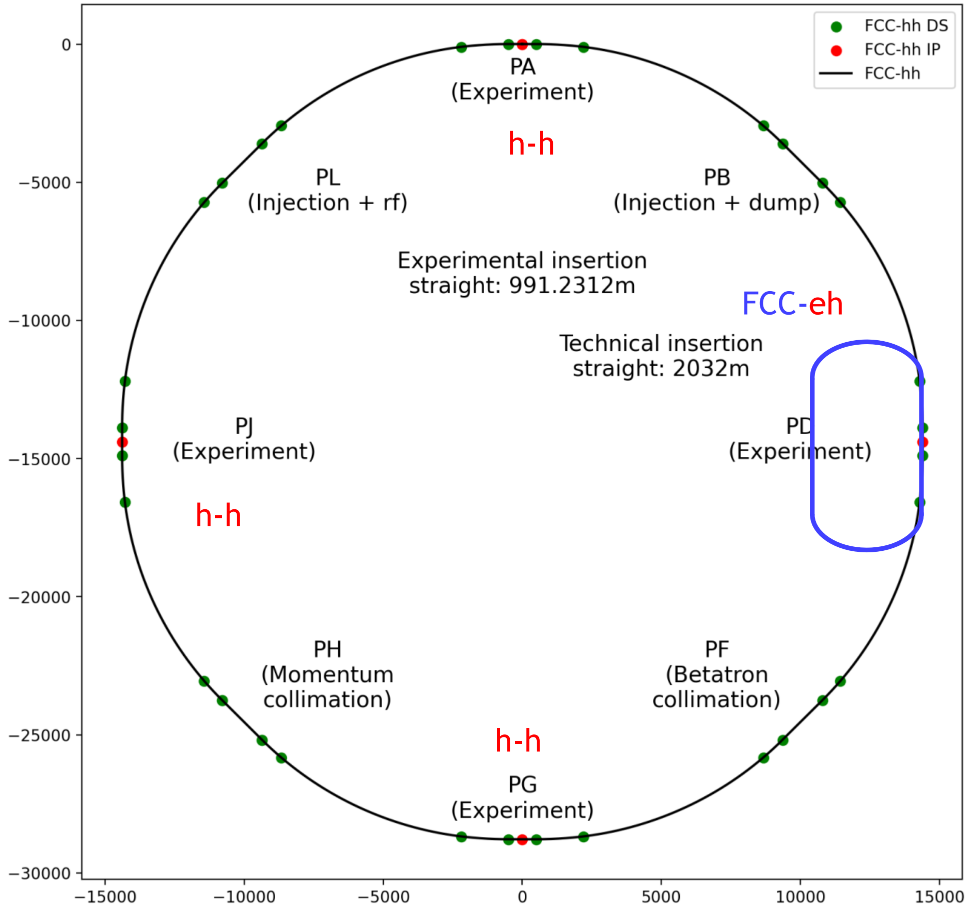
** More information on iSAS program: https://indico.ijclab.in2p3.fr/event/9521/*

Walid Kaabi

Concurrent Operation of e-h and h-h

- New FCC-hh lattice: talk Gustavo
- Optimized electron interaction region to minimize SR power Kevin's Thesis
- The impact of the electron magnets can be corrected locally for the proton beams
- Concurrent operation implies 3 beams at the IR
- The two protons need to be separated at the e-p interaction point





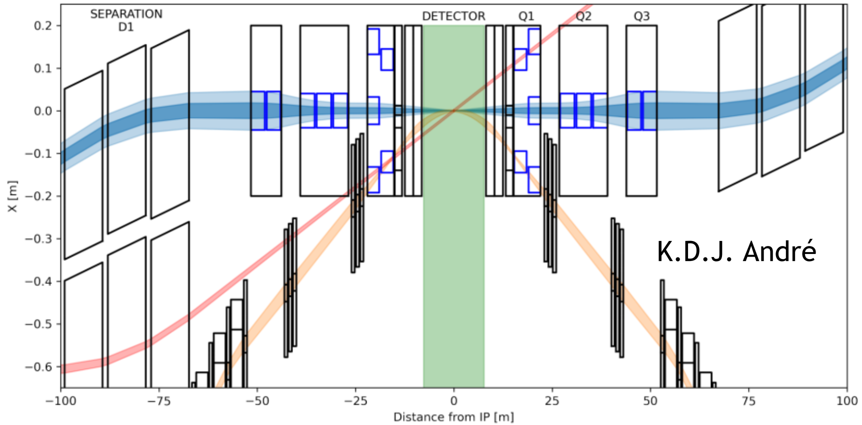
Possible layout of the FCC [1]

Tiziana Von Witzleben

FUTURE CIRCULAR COLLIDER

2 possible separation schemes for the h-h beams:

only e-h collisions



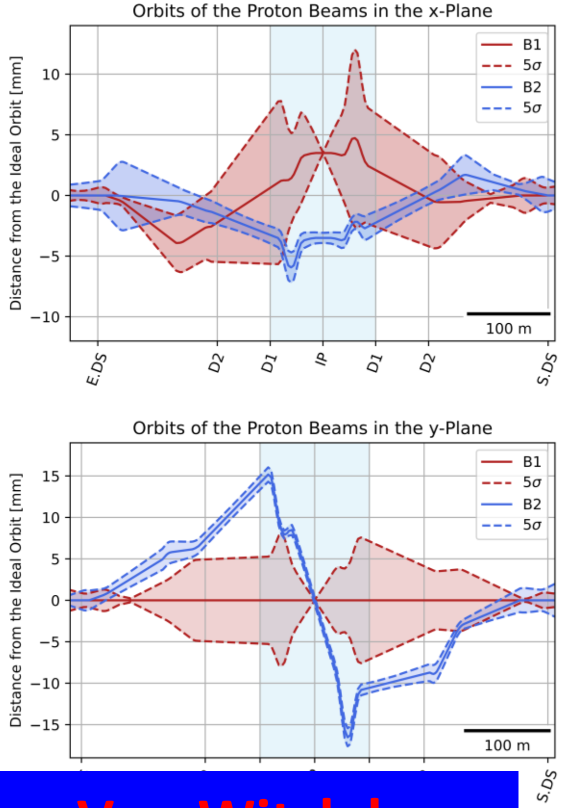
Colliding proton beam

Electron beam

Non-colliding proton beam

Separate apertures for the two proton beams

e-h and h-h collisions



Shared aperture for the two proton beams

Both schemes will be implemented a soon as the FCC-hh lattice is fully available

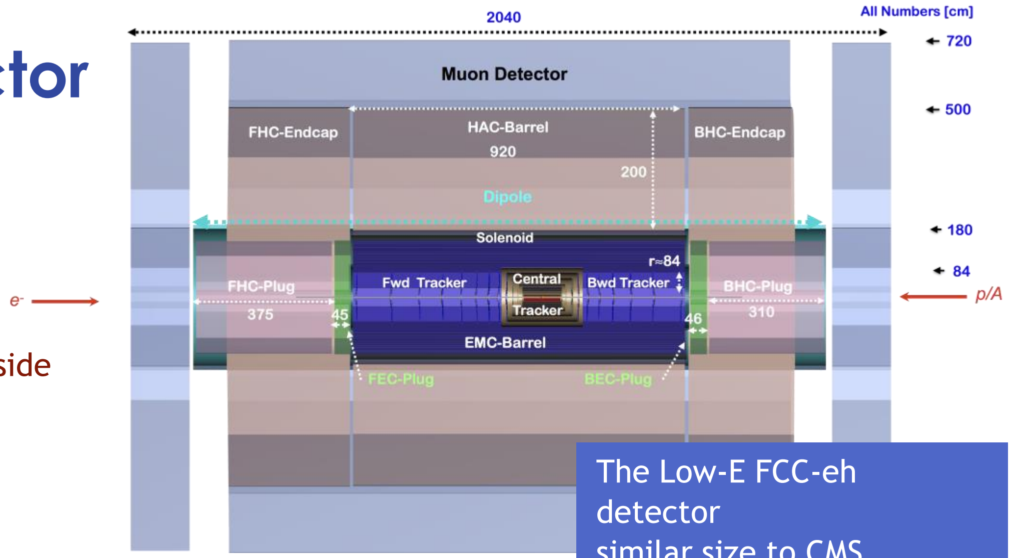
FUTURE CIRCULAR COLLIDER

Tiziana Von Witzleben

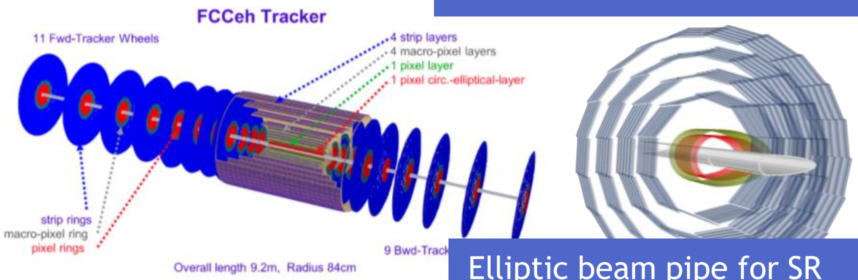
FCC-eh physics and detector

- Detector for DIS designed for LHeC extended to FCC-eh
  - similar E_e 50 ⇒ 60 GeV: similar e-side
  - proton 7 ⇒ 20 or 50 TeV: need to cope with stronger energy and denser particle flow on p/A side
    - Tracker and Calo extended to more forward
- Study item 1: machine-detector interface
  - weak dipole around IP for head-on collision as proposed for LHeC: detector needs to avoid SR fan
  - Need to optimise for FCC-eh design
- Study item 2: optimisation for higher energy h beam
  - cutting technologies for 2050 and beyond? in collaboration with ee/hh studies
- Possibility to run pp/AA for precision physics at eh IP
  - better calibrated by kinematic constraints of DIS events

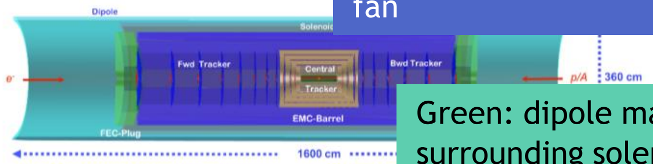
Yuji Yamazaki



The Low-E FCC-eh detector
similar size to CMS



Elliptic beam pipe for SR fan

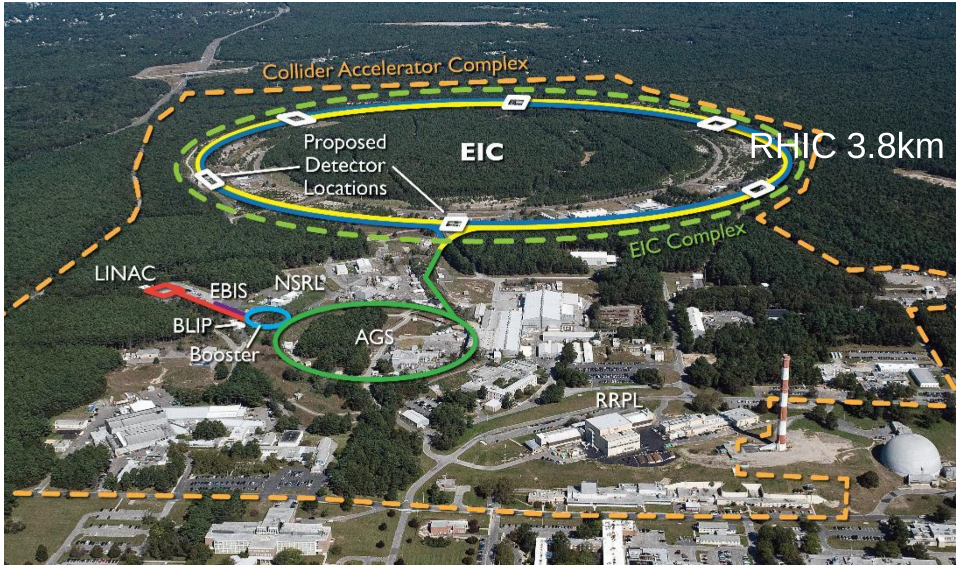


Green: dipole magnet surrounding solenoid/IP

EIC design

EIC Design based on existing RHIC facility

- **Hadron storage Ring (RHIC Rings) 40-275 GeV** (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - Strong hadron cooling
- **Electron storage ring 2.5–18 GeV** (**new**)
  - many bunches,
  - large beam current, 2.5 A ➔ 9 MW S.R. power
  - S.C RF cavities
  - Polarized bunches (up to 70%)
- **Electron rapid cycling synchrotron 0.4- 18GeV** (**new**)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (**new**)
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation



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EIC schedule

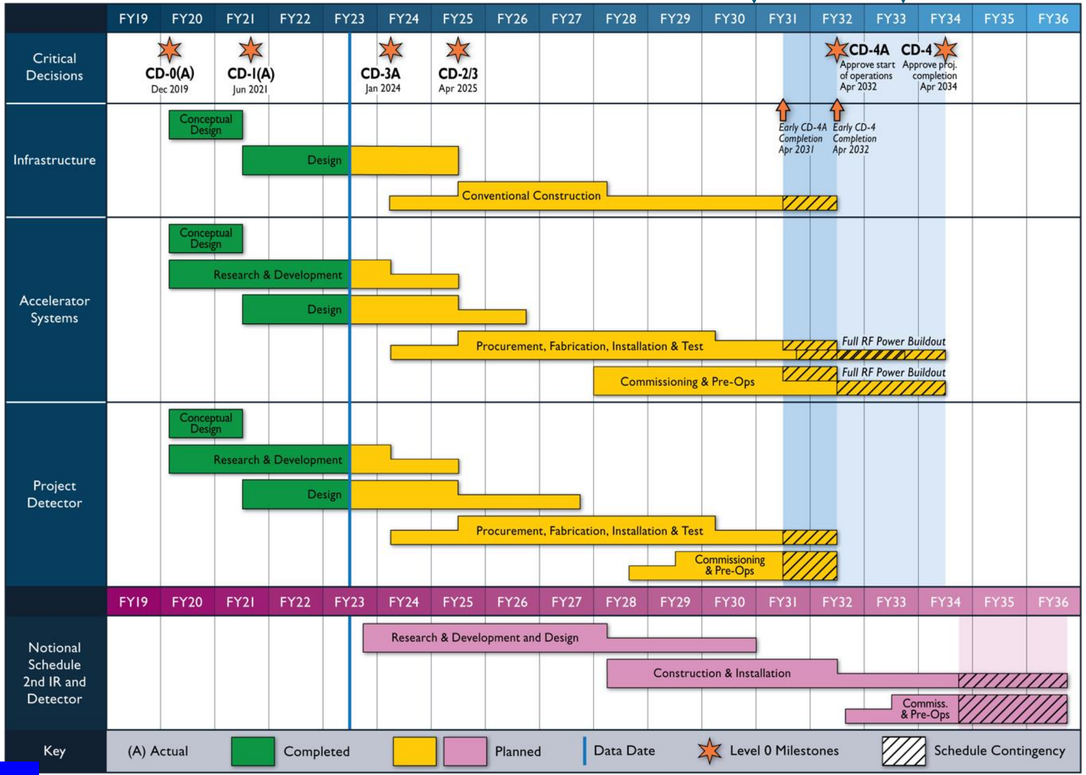
- The US Department Of Energy approved the **EIC accelerator and one detector** in Dec 2019 (CD-0)
- EIC is currently in the design and prototype phase
- Baseline/start of construction approval expected April 2025 **Start of operations ~2033**
- Second interaction region and second detector delayed by ~5 years

FCC approval by Council ~2028

FCC construction tunnel ~2030

FCC-ee construction 2033-2045

Operation FCC-ee 2048



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EIC-FCC parameters

The EIC electron beam features great similarities with the FCC-ee beam (EIC has higher beam currents, and shorter bunch spacing).

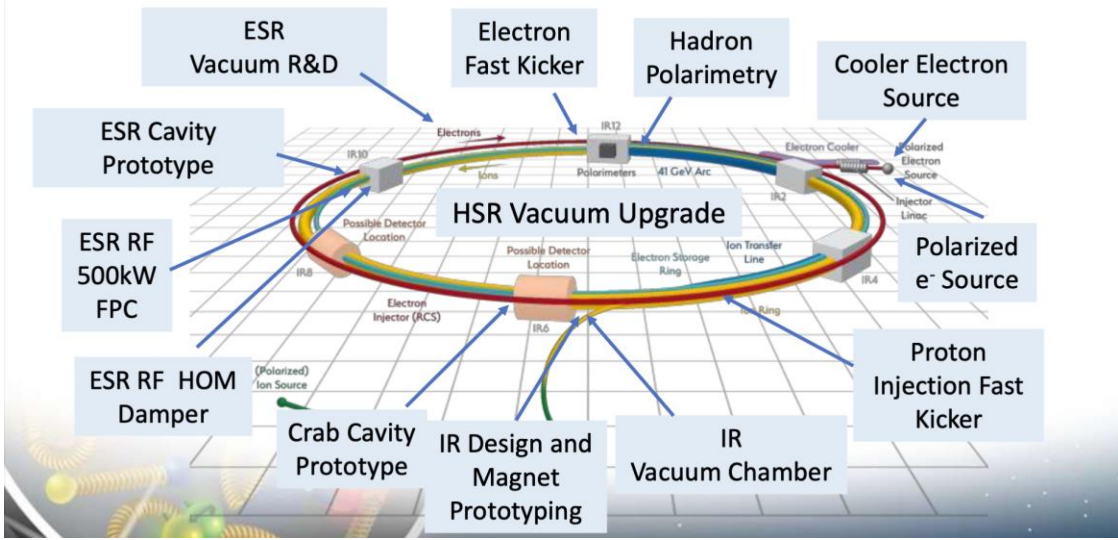
	EIC e beam	FCC-ee Z pole (W)
Beam energy [GeV]	10 (18)	45.6 (80)
Bunch population [10^{11}]	1.7	1.7
Bunch spacing [ns]	10	15, 17.5 or 20
Rms bunch length [mm]	2	3.5 from SR
Beam current [A]	2.5 (0.27)	1.39
SR power / beam / meter [W/m]	9000	600
Critical photon energy [keV]	9 (54)	19 (100)

Maria Chamizo Llatas

Key updates towards the EIC

ESR=Electron Storage Ring
HSR=Hadron Storage Ring

- EIC challenging design parameters require much accelerator R&D, prototyping, synergistic with other facilities.
- Areas of common interest between the EIC and FCC-ee have been identified and are being addressed through joint workshops



A few selected topics will be discussed in this presentation

FCC-EIC Joint & MDI Workshop (Oct 2022), FCC-EIC Beam Instrumentation Workshop, EIC Workshop Promoting Collaboration on the EIC (Oct 2020), First annual US FCC workshop (May 2023)

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Synergies EIC-FCC

Areas for mutually beneficial collaboration

- SRF cavities, electron gun (high current, high brightness beams)
- Beam instrumentation: SR monitors, BLM, BPMs, Beam feedback systems, crab angle measurements
- Vacuum systems
- IR region magnets, prototypes, production
- MDI, IR shielding
- Collimation
- Beam-beam interactions, beam-gas interactions
- Impedance model, instabilities, HOM, ion instability

Maria Chamizo Llatas