XXIX Cracow EPIPHANY Conference

on Physics at the Electron-Ion Collider and Future Facilities

16-19 January 2023

PERLE: The development of a multi-turn, high current ERL

Achille Stocchi
IJCLab / Université Paris-Saclay, IN2P3/CNRS

on behalf of PERLE Collaboration

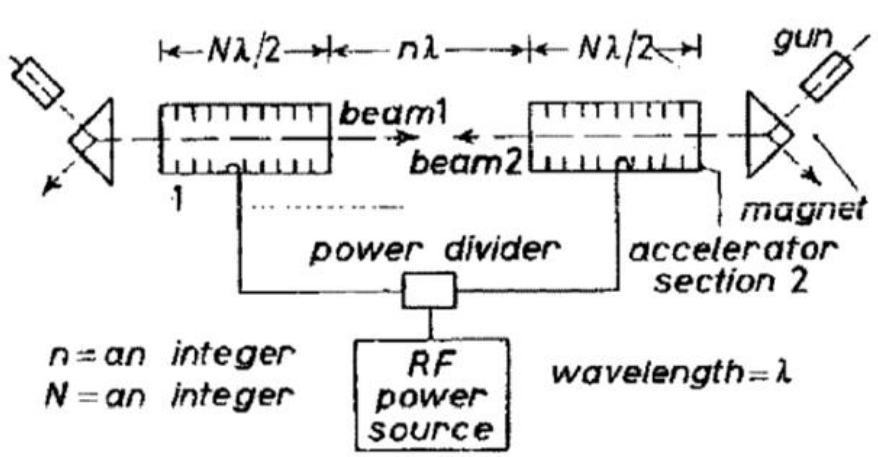
- Introduction.
  - The ERL concept
  - How an ERL works. Why an ERL today

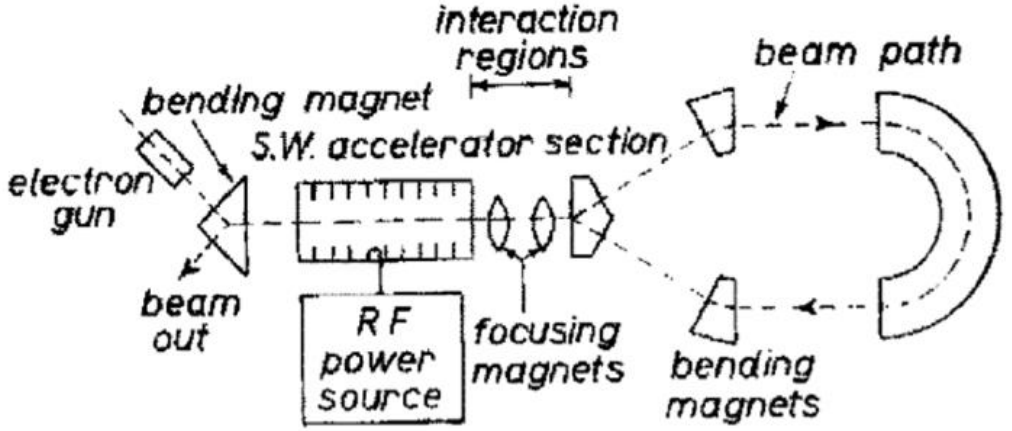
5’ to introduce the subject !

***Jorgen D’Hondt** has already explained the ERL concept*

ERL. The original Idea.

- ERL concept was proposed first in 1965 by Maury Tigner [1]

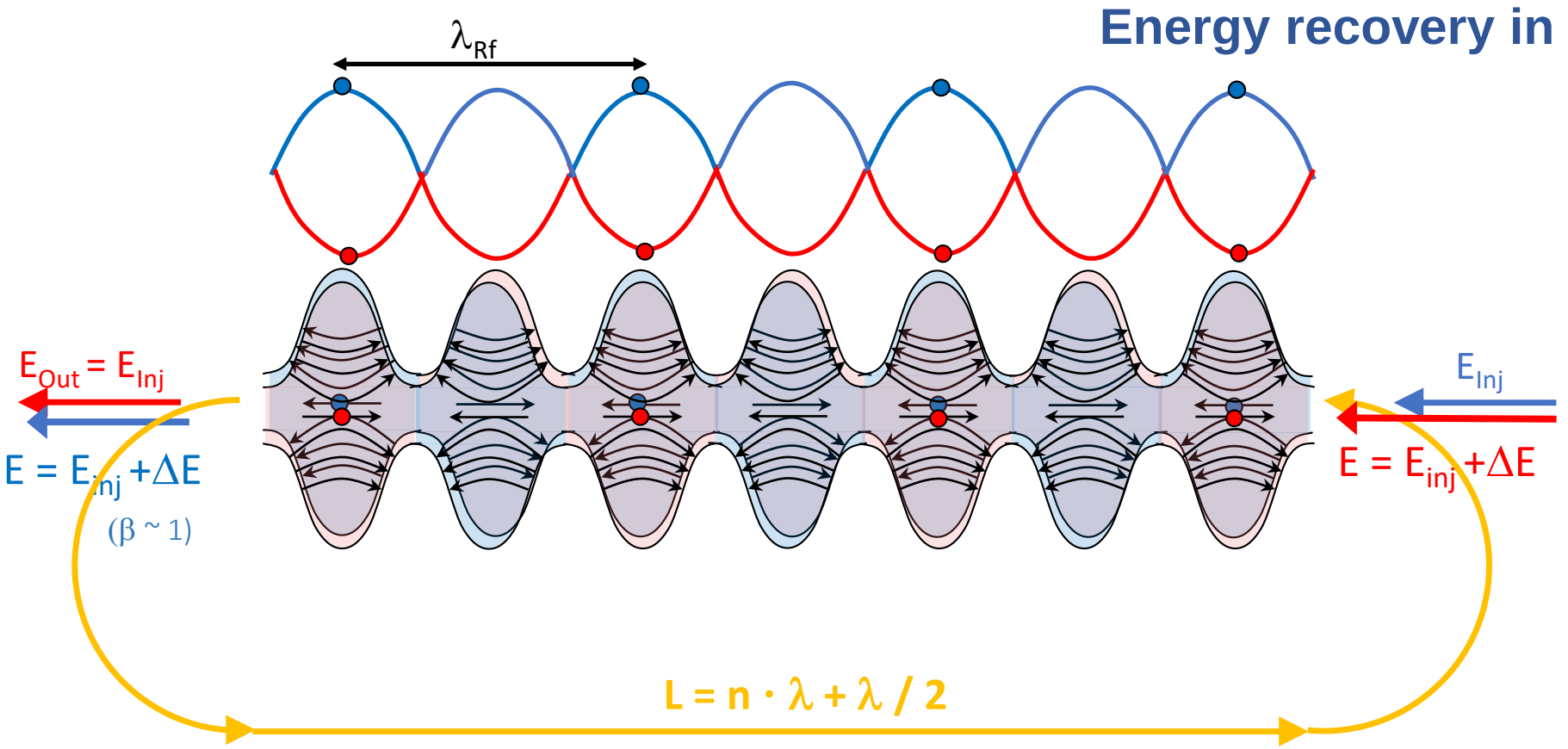




[1] M. Tigner: "A Possible Apparatus for Electron Clashing-Beam Experiments", Il Nuovo Cimento Series 10, Vol. 37, issue 3, pp 1228-1231,1 Giugno 1965

- First test was done at Stanford in 1986 (interesting concept for FELs, Compton light sources and high current electron cooler)
- Concept become only viable with recent advances in SRF technology.

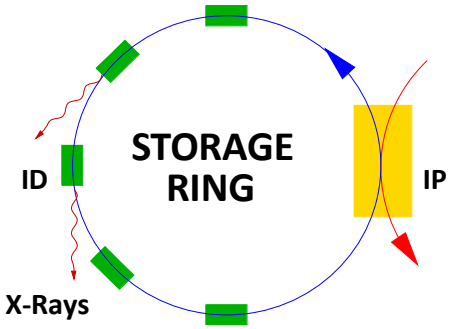
ERL how it works



- Energy supply → acceleration
- Deceleration = “loss free” energy storage (in the beam) → Energy recovery

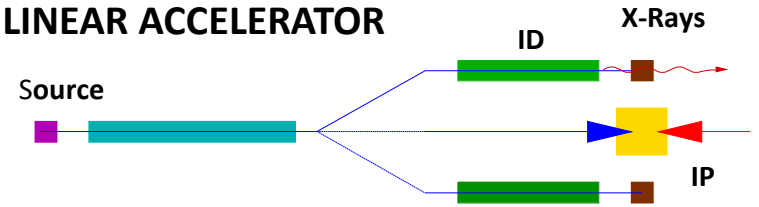
ERL WHY ? : The Best of Two Worlds

Limitation : syncrotron radiation



- Beam parameters defined by equilibrium
- Limited flexibility – multi-pass
- High average beam power (A, multi GeV)
- Typically long bunches (20 ps – 200 ps)
- Many user stations

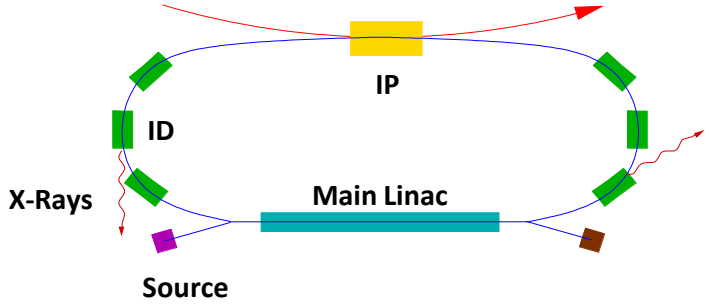
LINEAR ACCELERATOR



- Beam parameters defined by the source
- High flexibility – single pass
- Limited average beam power (<< mA)
- Possible short bunches (sub psec)
- Low number of user stations

- Linac-like beam quality
- Easy to upgrade (add linac section or recirculation passes)
- Tolerate more “damage” to the beam from collisions with another beam (the beam is dumped soon after)

ENERGY RECOVERY LINAC



- **High beam current possible (RF power limit removed)**
- **Reduced power bill (RF power recovered)**
- Reduced cost of RF amplifiers (smaller RF power amplifiers)
- Reduced beam power and energy in beam dump (less shielding / activation issues)

High average beam power in compact machine, excellent beam parameters with high flexibility

The short story of the PERLE Genesis

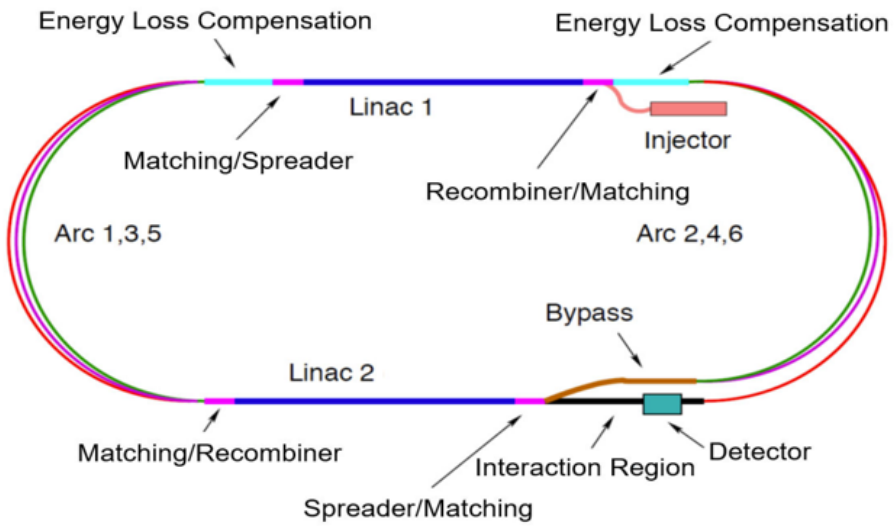
- Future **particle physics imposes strong challenges on accelerators** and requires a variety of **accelerator R&D programs** not only to meet the foreseen performances, but also to **lower their energetic consumption and enhance their efficiency**.
  → Energy Recovery Linacs offer one of the main options for energy frontier colliders

- To probe **deep inelastic scattering at high energy** and to study the **Higgs boson**, LHeC proposes a high luminosity collider using the HL-LHC protons and an intense electron beam.

- For the electron beam, the ERL scenario has many advantages :
  - High luminosity, low interference for installation next to LHC, machine size, energy consumption
  - Concept also applied to the FCC-eh design

- **The ERL-ring collider concept of LHeC based on**
  - synchronous operation of HL-LHC and 50 GeV electron beams
  - circumference of e- loop about 1/5 of that of LHC (5.3 km)
  - luminosity of 10^{34} $cm^{-2}.s^{-1}$

  → Multi-turn ERL (3+3 passes), 50 GeV, RF frequency: 801 MHz, 20 mA beam current (6 x 20 = 120mA load in the cavities).

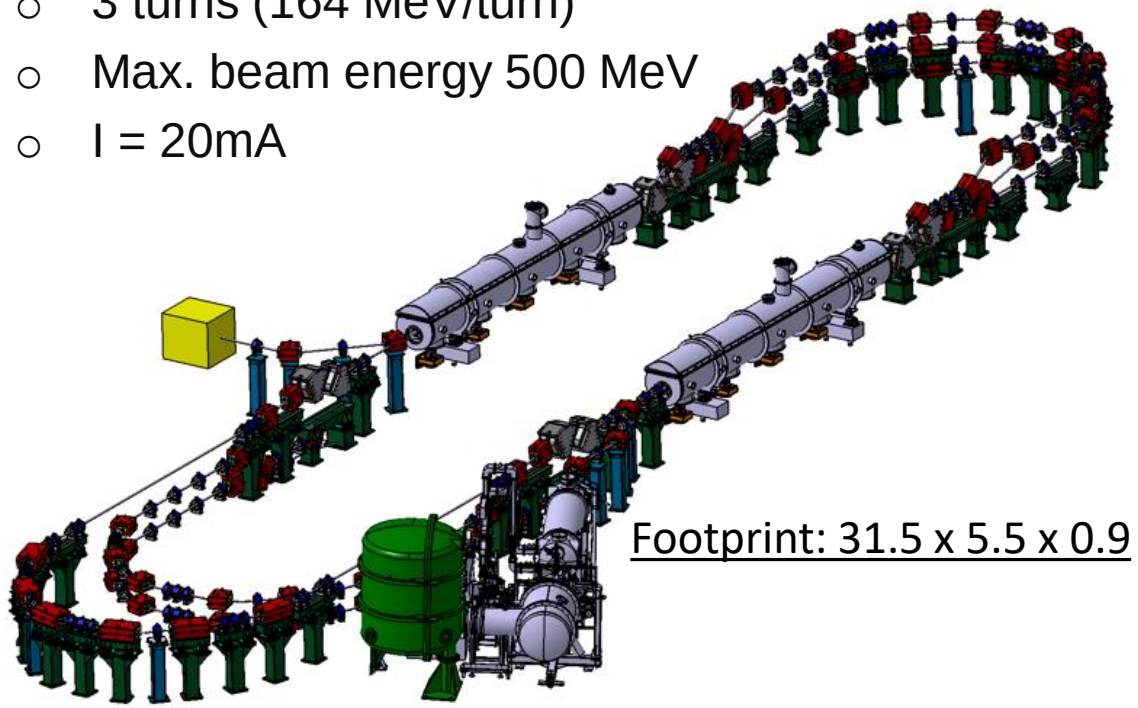


The short story of the PERLE Genesis

PERLE: A testbed to explore and validate a broad range of accelerator phenomena & technical choices on the pathway to the LHeC and other new frontier machines realisation.

Main challenges: Multi-turn, high bunch charge, high power energy recovery, …

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (164 MeV/turn)
- Max. beam energy 500 MeV
- I = 20mA



Footprint: 31.5 x 5.5 x 0.9

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

The future projects with ERL. The project PERLE@Orsay

- **The development of ERLs has been recognized as one of the five main pillars of accelerators R&D in support of the European Strategy for Particle Physics (ESPP).**

ERL Panel formed, see slides of Jorgen D'Hondt

ESPP R&D Accelerator RoadMap
https://arxiv.org/ftp/arxiv/papers/2201/2201.07895.pdf

Three main actions to succeed the ESPP Accelerator Roadmap as far as the ERL is concerned

- The Realisation of PERLE Multi-turn ERL (3+3 passes) 20 mA beam current
- Upgrade bERLinPRO toward the First ERL Facility to operate 100mA in single turn with FRT control
- Key Technology R&D Program – next generation ERLs

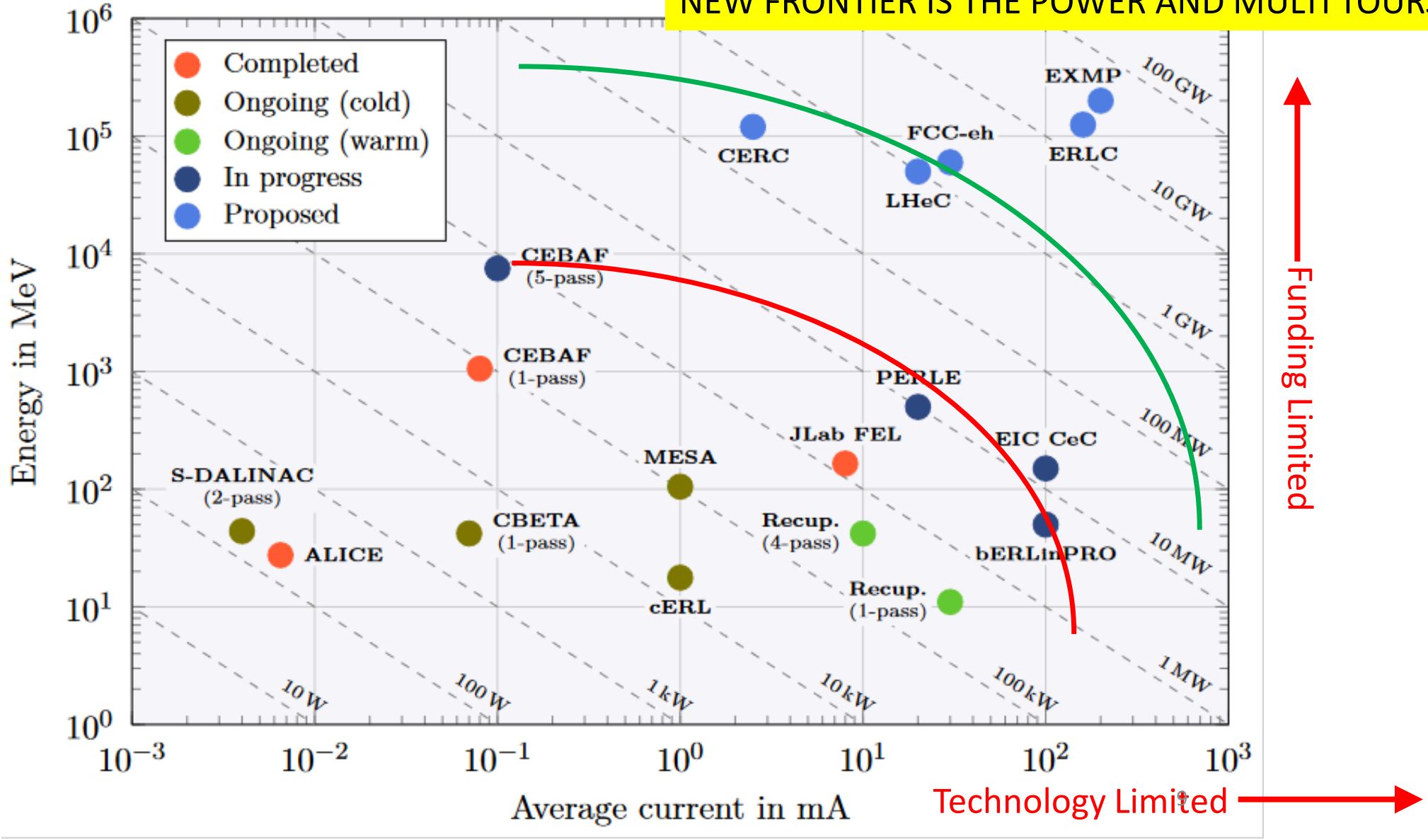
ERL machines « should allow » to reach

- high currents → high luminosity
- high energies and stay compact

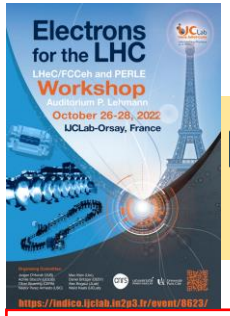
Provided we can implement multi-turn, high power = high current x energy ERL machine

Many projects in the world : demonstrators, small machines, future projects…

NEW FRONTIER IS THE POWER AND MULTI TOURS !

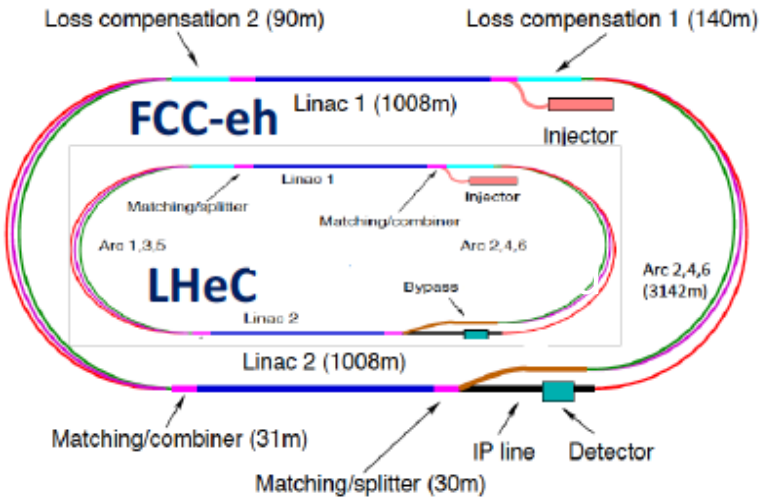


DIS (Deep Inelastic Scattering) ep Physics at High Energy in the next decades



Energy frontier DIS at HEP is necessary to explore SM and beyond

LHeC and **FCC-eh** are partners of LHC and FCC.



I(e) = 20mA

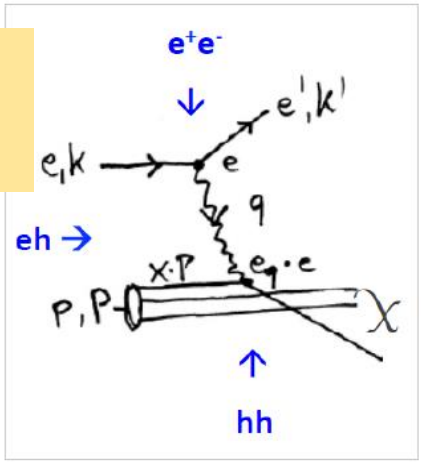
sqrt(s_{ep}) = 1-4 TeV

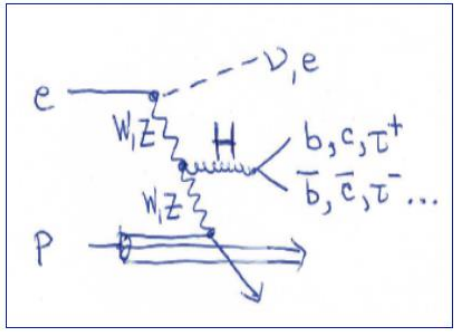
L(HERA) x 1000
(ERL and LHC)

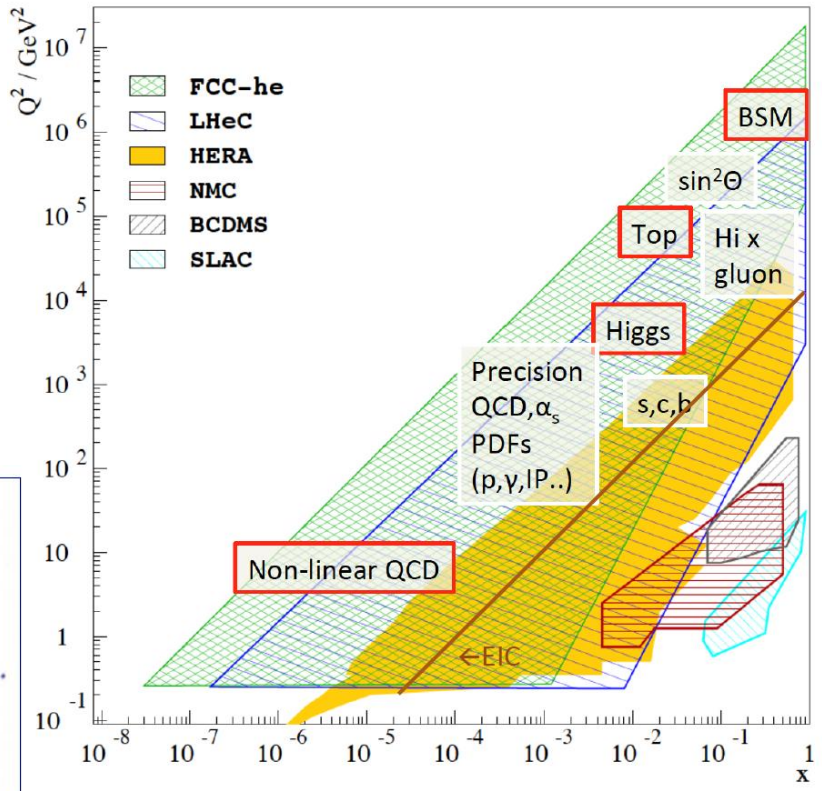
1206.2913, JPhysG
2007.14491, JPhysG

f=802Mz,
3+3 passes: 20mA x 6
20 MV/m, $Q_0 > 10^{10}$

Same parameters as the ones for PERLE@Orsay

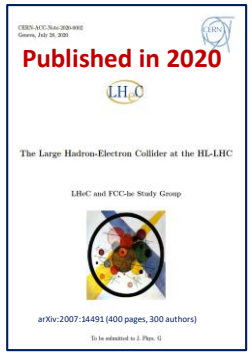






- Cleanest High Resolution Microscope: QCD Discovery
- Empowering the LHC/FCC Search Programme
- Transformation of LHC/FCChh into high precision Higgs facility
- Discovery (top, H, heavy ν's..) Beyond the Standard Model
- A Unique Nuclear Physics Facility

Collection : from Max Klein

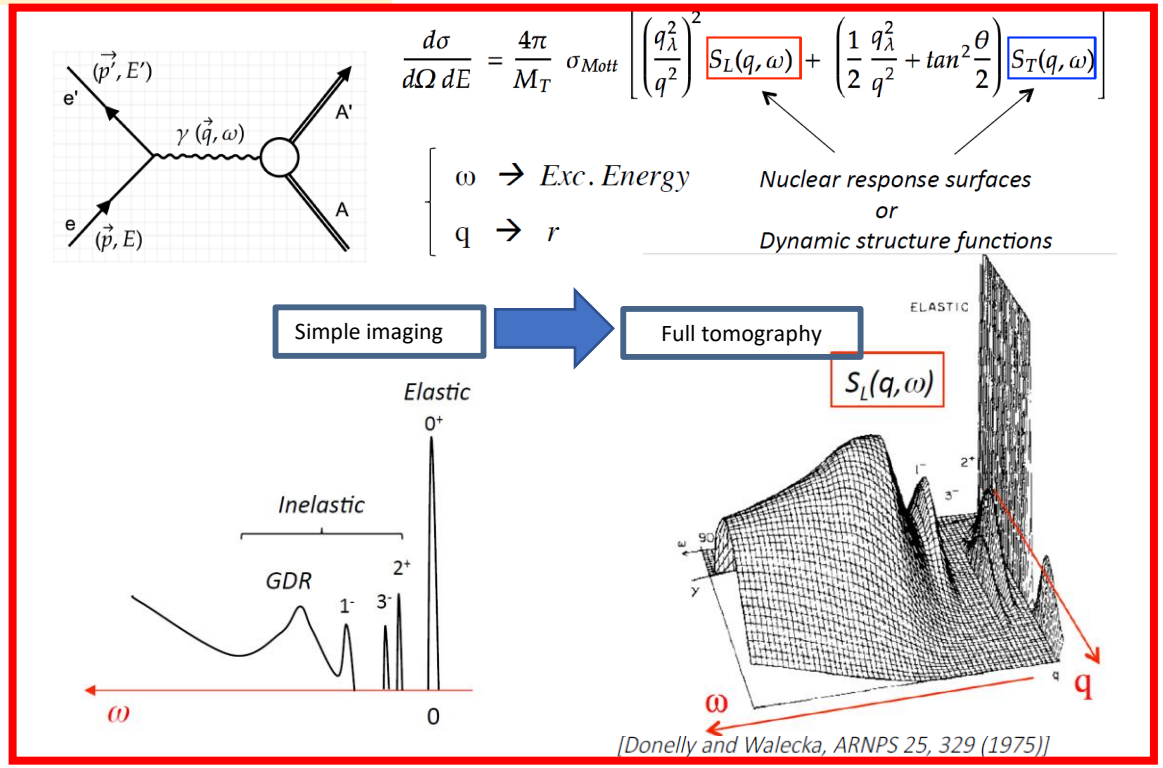


The New Frontier : e-RIB (Radioactive Nuclei Beam)scattering !

A completely new horizon, explore the interior of exotic nuclei :
charge radius, shape… New properties are emerging (halo, pairing..) !

- all interesting phenomena occur at $q \gtrsim 2\text{fm}^{-1}$; the higher the q transferred the lower the cross section; consider previous achievements in this domain
  → **compromise starting at $E_e = 250 \longrightarrow \simeq 500$ MeV (~0.5fm)**

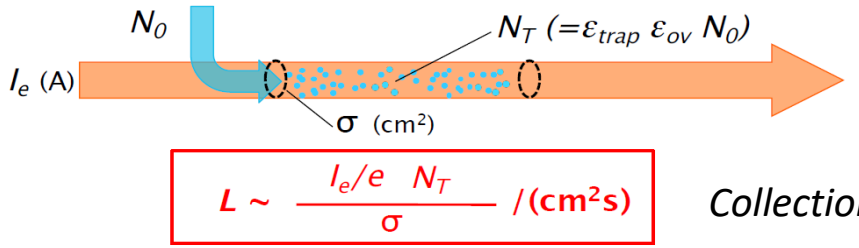
- aimed luminosity should be 10^{29} $\text{cm}^{-2}\text{s}^{-1}$ but much can be already done at
  → **$\mathcal{L} \simeq 10^{27} \; ^{-} \; 10^{28}$ (with unstable nuclei EVERYTHING is new !)**



A long road ahead before reaching the full tomography of an exotic nucleus
The starting point is :

DESTIN [**DE**ep **ST**ructure **I**nvestigation of (exotic) **N**uclei]

Very chanellenging
The beam will confine RIB in longitudinal plane e- with positive ions), and traps have to confined RIB in transversal plane (à la SCRIT at RIKEN)



Collection : from David Verney

PERLE a key ERL project : HEP and Nuclear Physics communities

ERL machines open a new Frontier for the physics of "the electromagnetic probe"

(1) At low energy	e Nuclei	(PERLE and Destin@Orsay)	250-500 MeV
(2) At Higher Energy	e p (e A)	(LHeC and/or FCC-eh)	60 GeV

You need high luminosity → High current (from 10mA up to 100mA)
You need to increase the energy (remaining compact) → Multi turns

The (1) machine (PERLE@Orsay)

- will be the **first ERL dedicated to Nuclear Physics** for studying the eN interaction with radioactive nuclei.
- It's a **necessary demonstrator for the (2) -HEP machine (LHeC / FCC-eh)-** (same technological choices & beam parameters)

The key points : high power (current x energy) and complex machine in terms of beam dynamics (multi-turns)

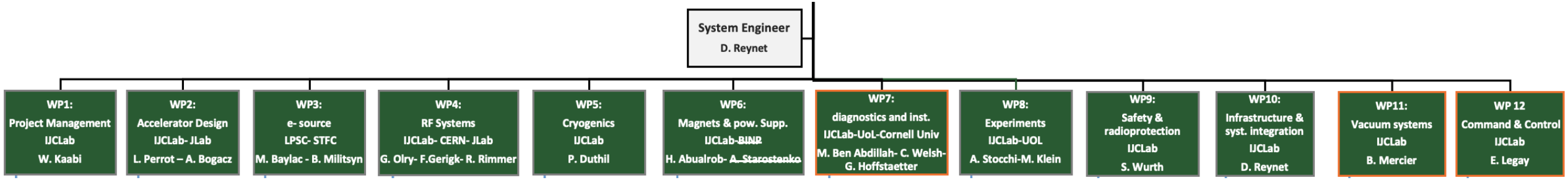
+ PERLE@Orsay (*not time today to discuss it)*

- is also a necessary demonstrator for other future machines and applications
- Elastic ep Scattering at PERLE (p Radius, Dark Photons, PV)
- Possibility of Nuclear Photonics (inverse Compton scattering y's)

PERLE@Orsay is an international collaboration

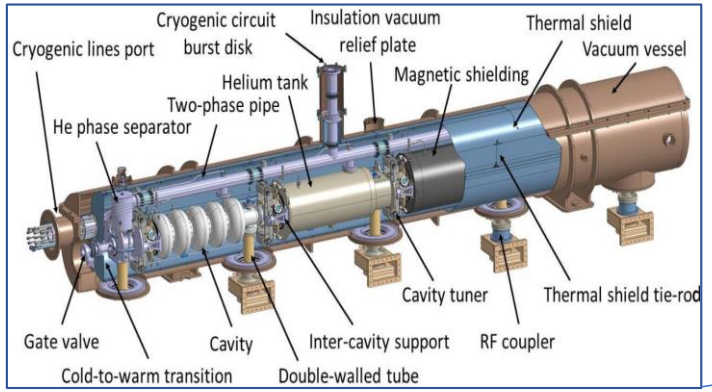
~60 people involved sofar (and 5 PHD running thesis).

Spokesperson : **Max Klein** (Liverpool)
Project leader : **Walid Kaabi** (IJCLab)
CB composed by the PI of the different laboratoires and chaired by **Oliver Bruning** (CERN)

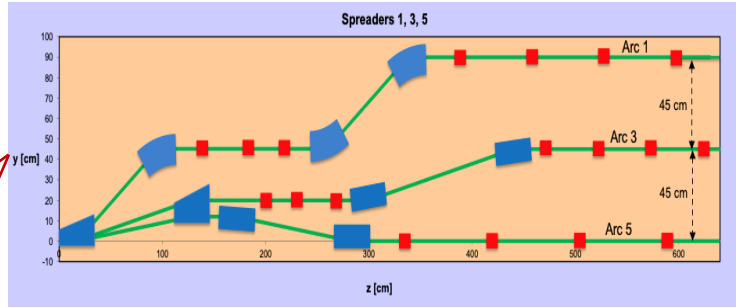


PERLE Configuration

PERLE: first multi-turn ERL, based in SRF technology, designed to operate at 10MW (20 mA, 500 MeV) power regime



- 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

3 staked recirculation arcs for beams at different energies (Arcs 1, 3, 5).

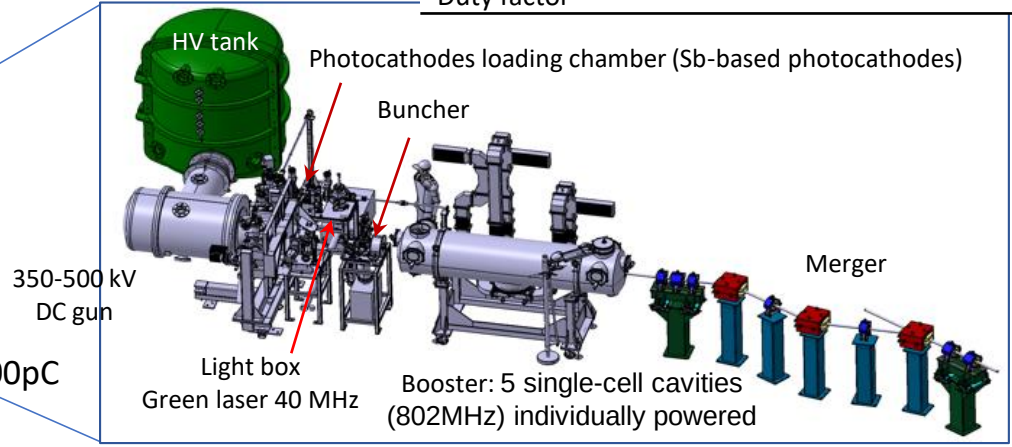
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

Beam dump

Interaction Points

3 staked (& inversed) recirculation arcs for beams at different energies (Arcs 2, 4, 6)

Injection line delivering 500pC bunches at 7 MeV.



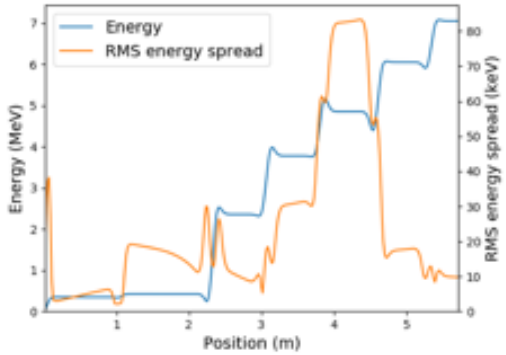
Injection line optimisation

Electron source to booster exist optimisation:

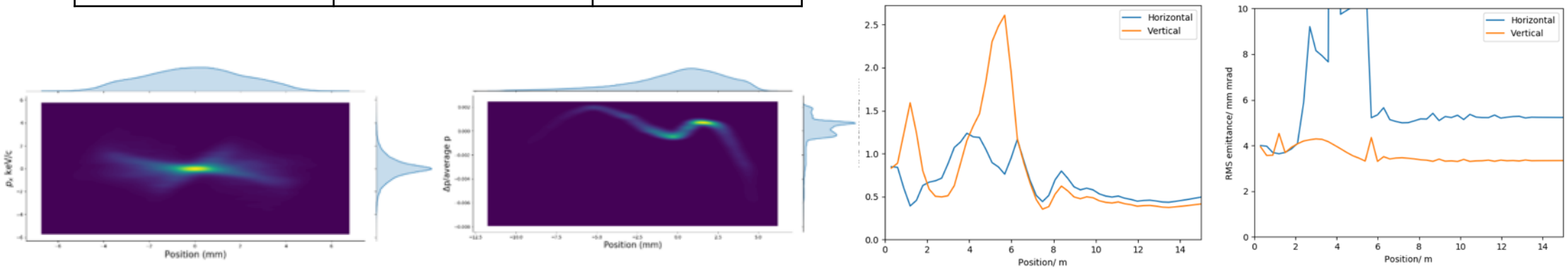
- The ALICE electron gun electrode geometry has been re-optimised for PERLE's new requirements.
- Optimisation with a 4 cavity booster, from the cathode to the booster exit, was performed and meets the specification:

	Achieved values	Specification
Horizontal emittance	5.23 mm mrad	< 6 mm mrad
Vertical emittance	3.34 mm mrad	< 6 mm mrad
Bunch length	3.22	3 mm
Kinetic energy	86.1 MeV	88.6 MeV
Horizontal beta function	7.89 (mismatch 8.3 %)	8.6
Horizontal alpha function	-0.74 (mismatch 11.6 %)	-0.66
Vertical beta function	8.76 (mismatch 1.8 %)	8.6
Vertical alpha function	-0.67 (mismatch 1.5 %)	-0.66

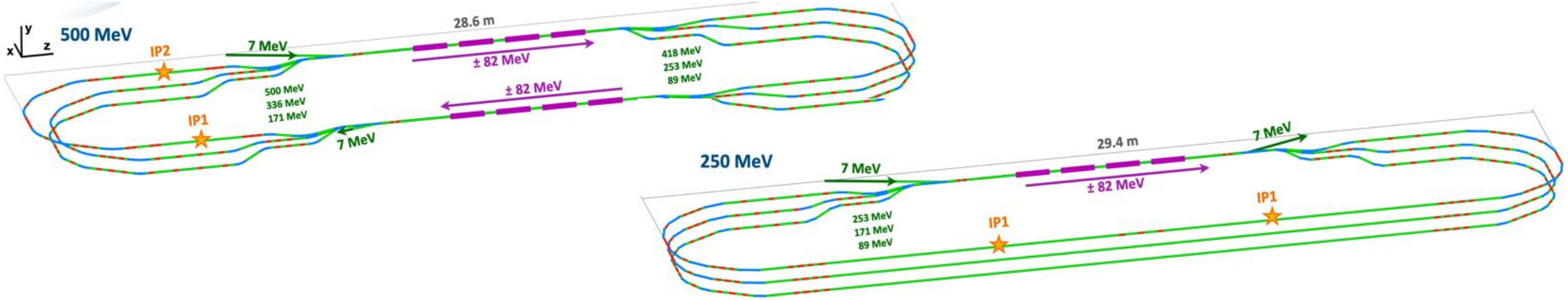
Energy spread



Transverse beam size and emittance



Lattice optimization of the 250 MeV version of PERLE



Lattice design of the 250 MeV version of PERLE

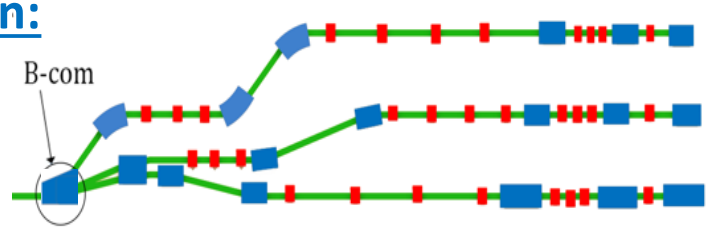
- **compatible with the upgrade to 500 MeV version** (the same elements used, only about 30 meters of extra beam pipes)
- **reduced immediate expenses** (second cryo-module and 18 dipoles can be purchased later)
- **demonstration of ERL with 6 paths at high current** (same as in 500 MeV version, but with half of the power)
- more space for experimental areas
- **additional expenses / manpower / shutdown time** (rebuilding / recommissioning for the full power machine)

Filling pattern (Arc optics architecture)

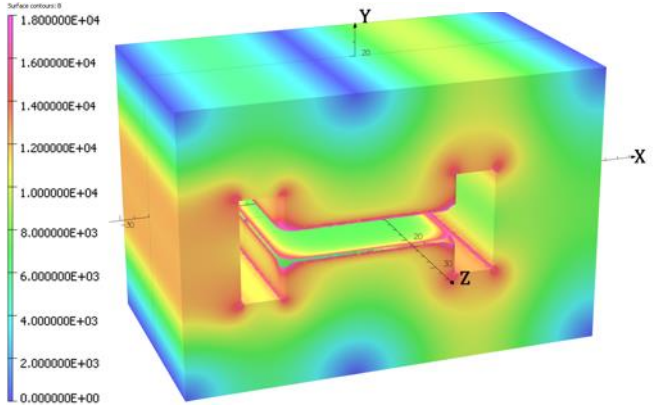
- the optimal filling pattern for 500 MeV version requires extra space (28.6 m → 30.6 m)
  but current configuration is fine (Alex Bogacz, Peter Williams, Robert Apsimon)
- for the 250 MeV version we consider the optimal filling (more essential at lower energies, inline with the optics)

Status of B-com Magnet design

B-COM magnet design:



Field calculations:



Harmonics content calculated along beam trajectory:

Energy (MeV)	b_1 (G)	b_2 (G)	b_3 (G)	b_4 (G)	b_5 (G)	$\sqrt{\sum_{n=1}^{5} b_n^2/b_1}$
171	-2.897 $\times 10^5$	-1.005 $\times 10^2$	25.48	-10.19	5.194×10^{-1}	-3.5949×10^{-4}
336	-2.807×10^5	19.62	9.217×10^{-1}	4.623	8.187×10^{-1}	-7.1943×10^{-5}
500	-2.791×10^5	34.82	3.534	-9.722	-6.311×10^{-1}	-1.3018×10^{-4}

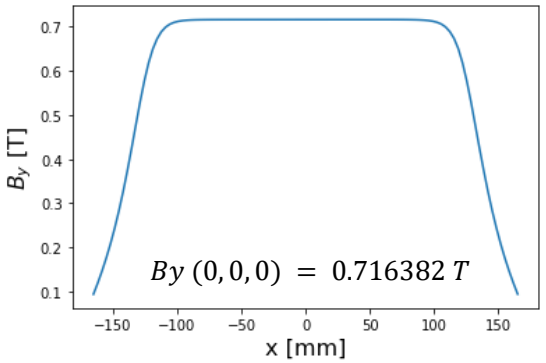
- Field homogeneity along the beam path: 0.036%

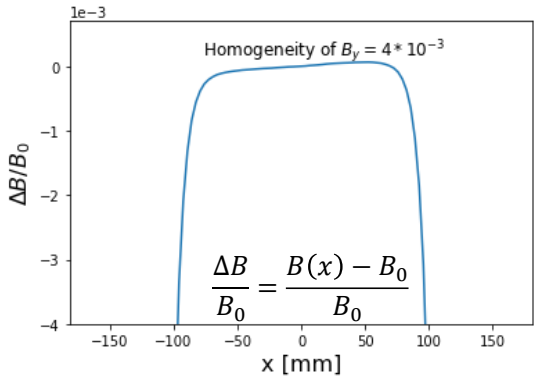
→ Quadrupole & sextupole components can be dealt within the lattice.

- Initial design: 0.1% field quality

→ Improvement by one order of magnitude

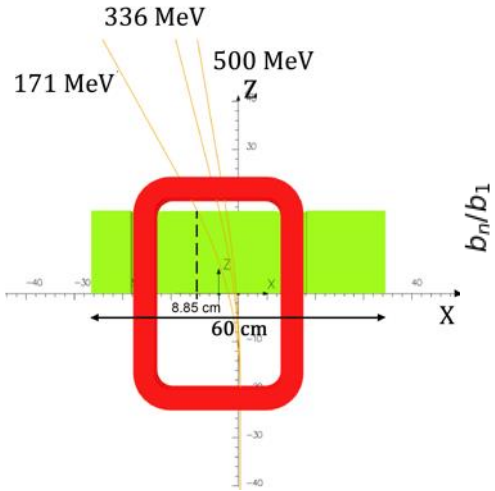
No chamfer or shims added, only a blend radius of 8 mm is used

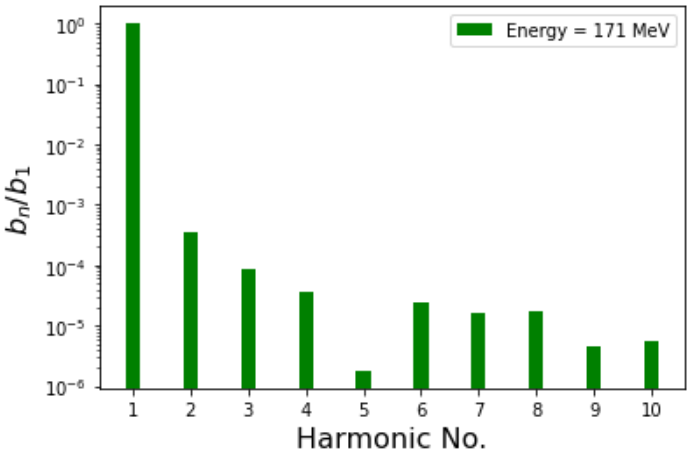




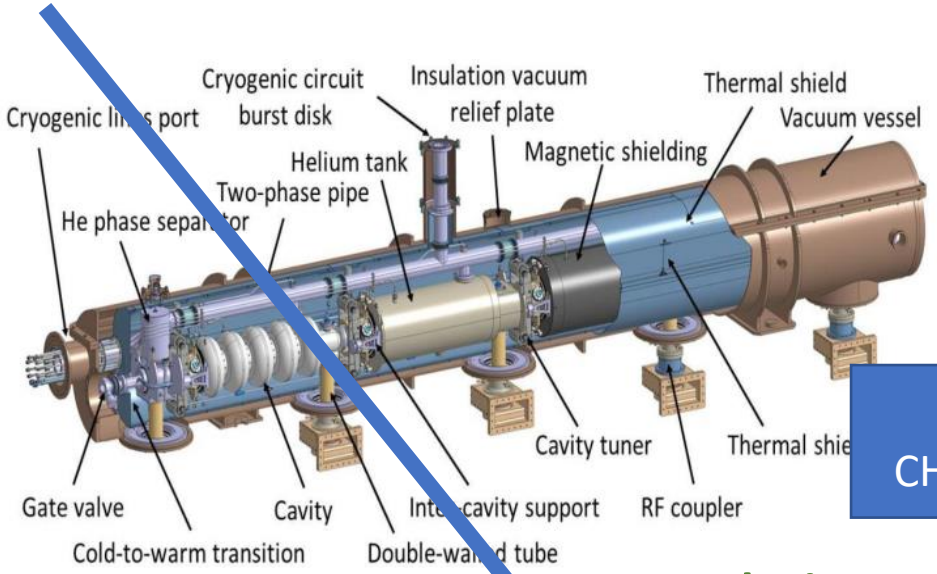
$\int B.dl = 0.3$ T. m along the magnet length for 0.34 m yoke length

→ B = 0.88 T

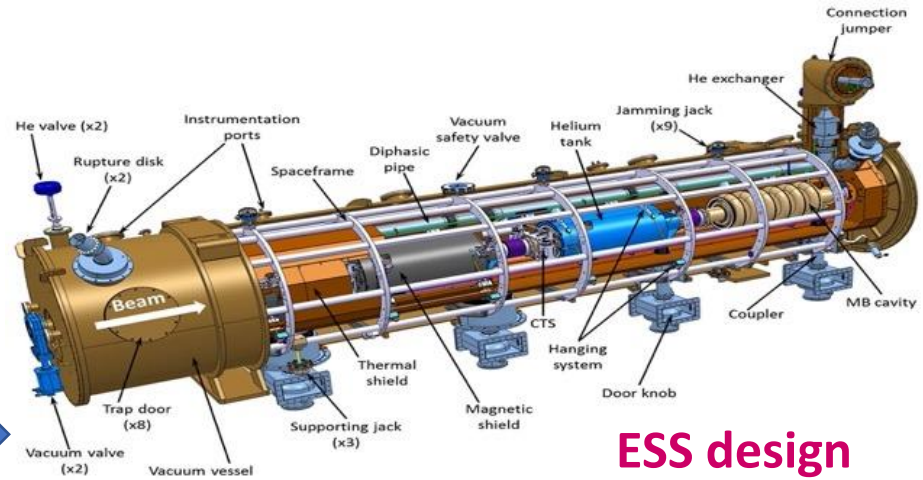




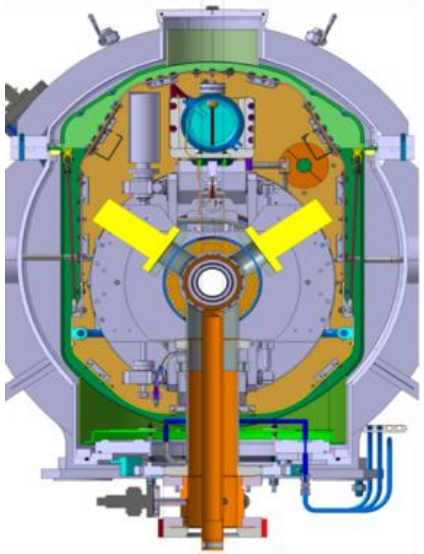
Cryomodule design



NOW CHOOSEN !



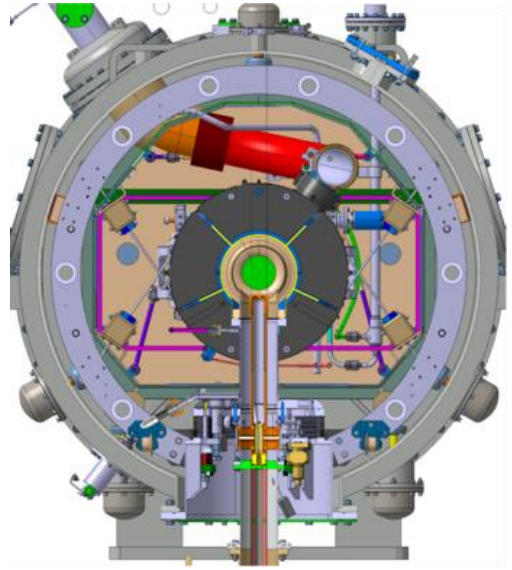
SPL design



- Vacuum vessel with top cover
- Insertion of the assembled cavity string by the top
- Cavity string supported by couplers
- Connexion to valve box at the extremity of the vacuum vessel
- Vacuum vessel fabricated (top cover to be modified)
- Compact design >> lack of space

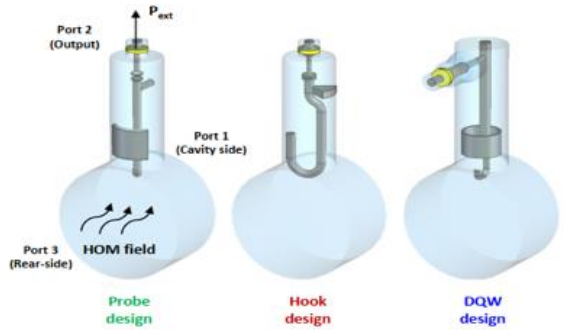
ESS design

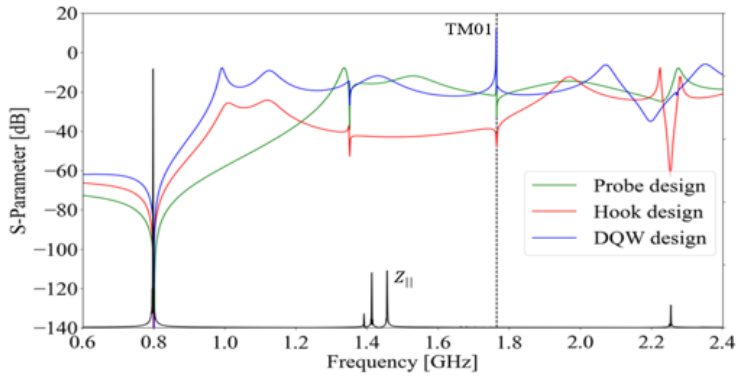
- Intermediate supporting structure (spaceframe)
- Cavity string hung by rods
- Insertion of the cavity string by the extremity (rollers)
- Trap doors for tuner access
- Connexion to the valve box on the top of the vacuum vessel
- More available space inside (+ 400mm in diameter and more transversal space between cavities)
- Design validated: series fab. & tests ongoing (Qty 30)

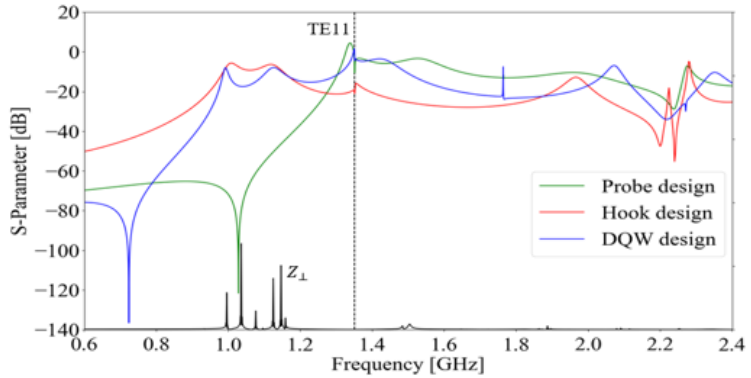


Status of HOM design Studies:

HOM coupler optimization of 3 different designs

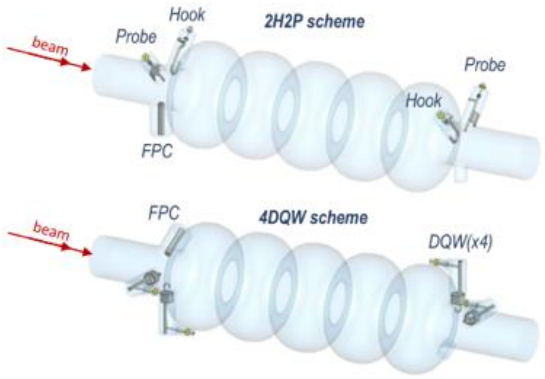


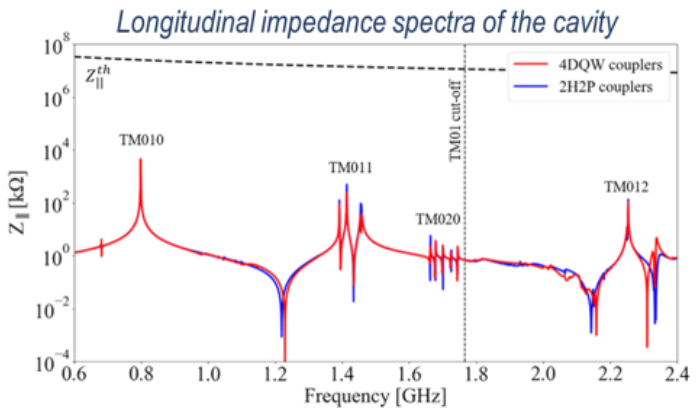


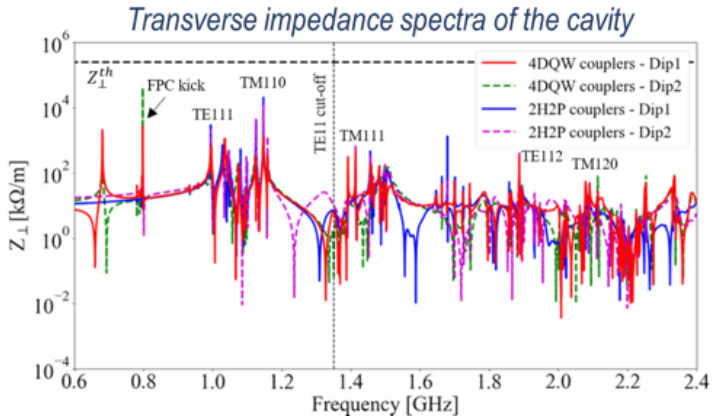


- Couplers geometrically optimized according to the HOM spectrum & S-parameters btw port 1 (beam pipe) & port 2 (coupler output) studied.
- The hook coupler provides higher damping of the first two dipole passbands (TE111 and TM110)
- The DQW coupler exhibits a better monopole coupling for TM010 mode than the probe design.

Study of 2 damping schemes with 4 HOM couplers (Especially for dipole HOM extraction)



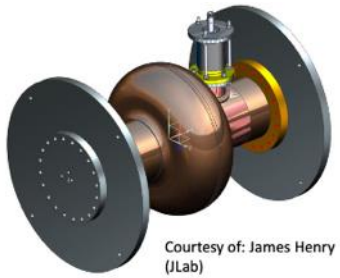




Promising results of DQW configuration: It allow damping both monopole and dipole HOMs below the analytically-computed beam-stability limits

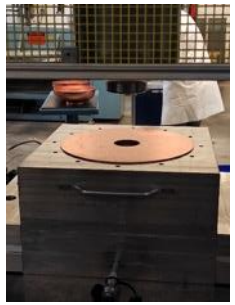
Plans on HOMs and cavity activities :

- Hook type HOM coupler was fabricated at CERN by 3D printing (polymer + Cu coating).
- 2 other HOM coupler types (probe and DQW) are fabricated at CERN (same technique). Copper coating will follow soon.



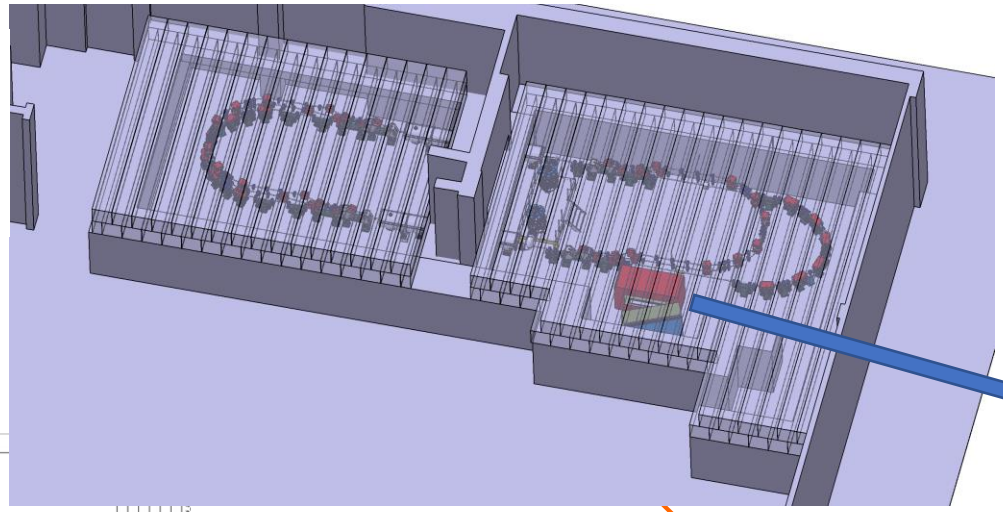
Next steps:

- HOM measurements on monocell then 5-Cell Cu cavity will be performed at Jlab (Feb/March 23). Cavities Fabrication/modifications done by JLAB.

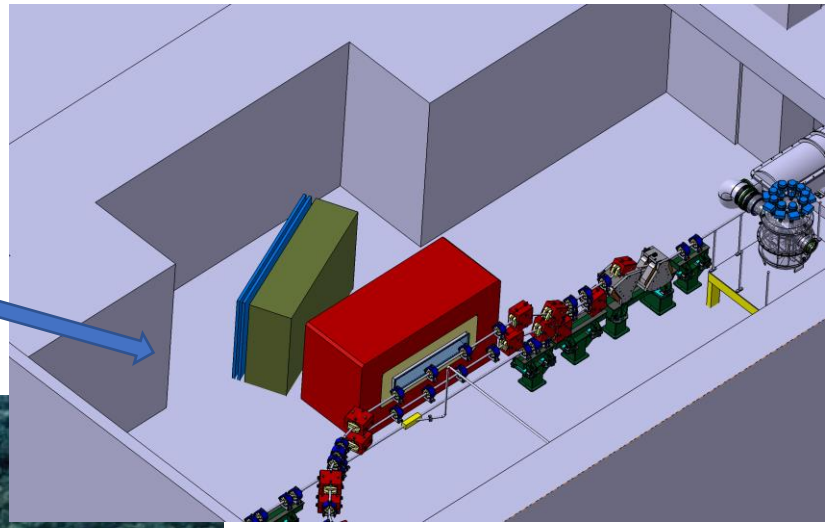


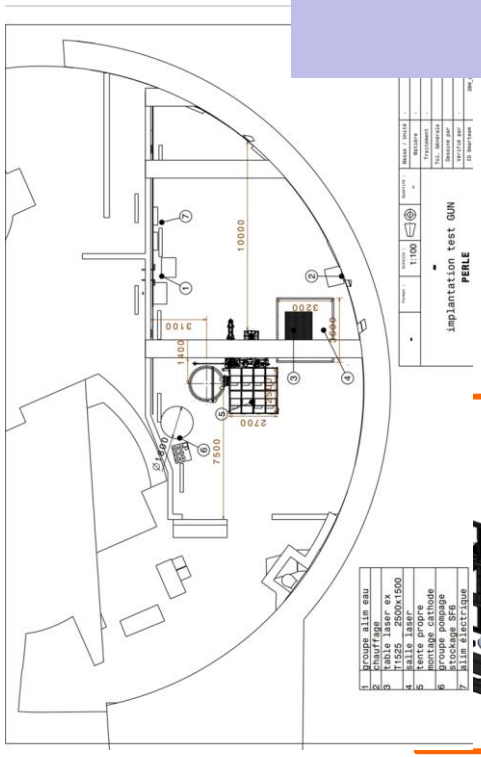
- 3D metal printing for the DQW coupler: under study with CERN. HOM couplers to be used with the 5-cell Cu cavity prototype in Feb/March 2023.

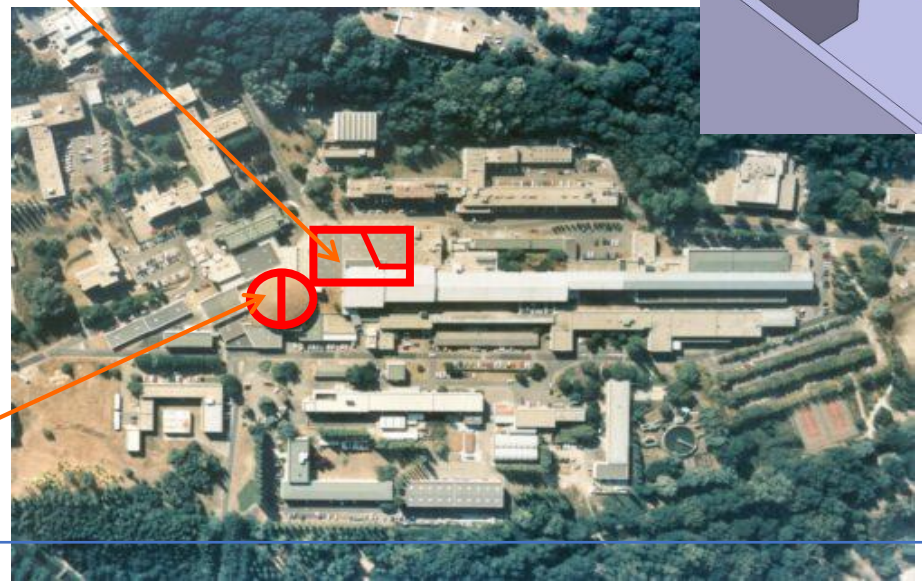
Proposed implantation @ IJCLab-Orsay. Infrastructure study work started

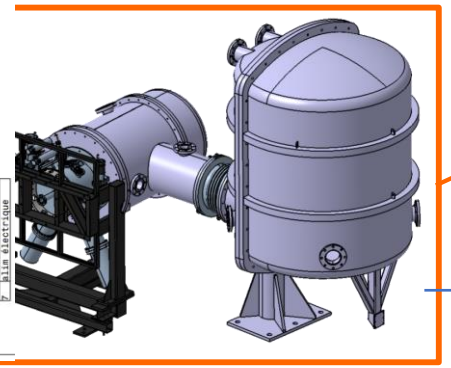


The possible footprint fo the nuclear eN experiment





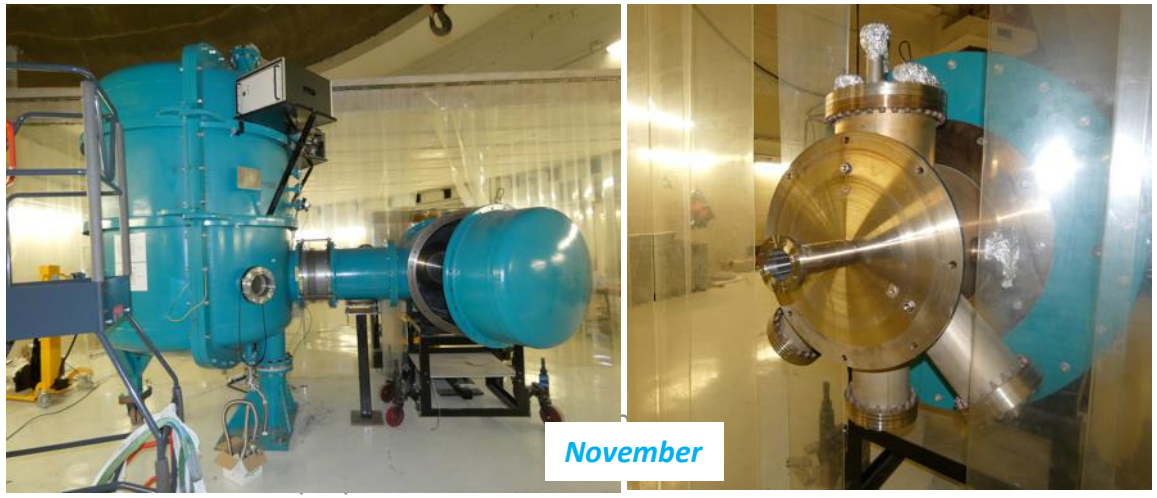


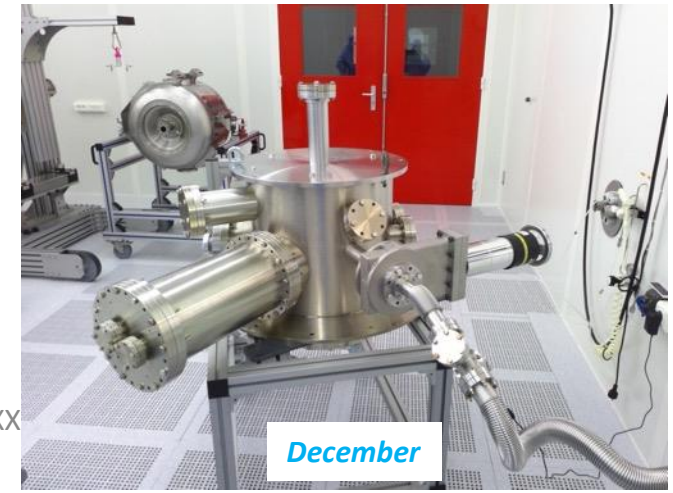


Start of the installation of the DC gun – see next slide

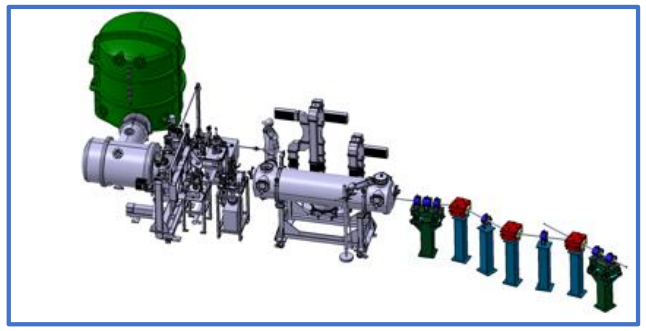
Photogun (ALICE)– Installation started in 2022 !

- Assembly and integration of the photogun started
  - Installation of the high voltage tank, leak test
  - Assembly of the HV columns, tests and modifications to the HV alim performed
  - Pre-positioning of the gun
  - Anode chamber cleaned, under test





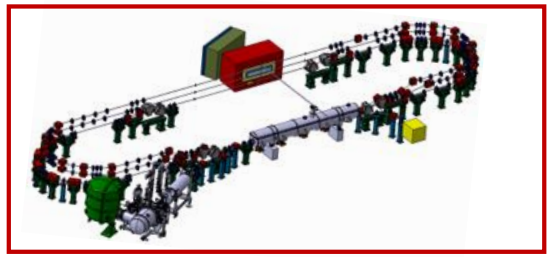
Planning



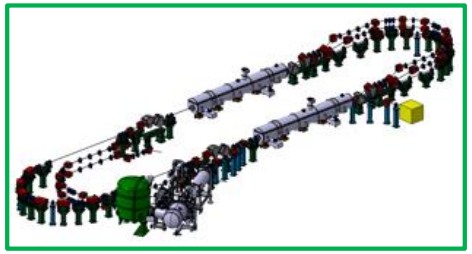
2023
PERLE TDR

2025
End Phase 0: Injection line

2028
End Phase 1: PERLE @ 250MeV



2030
End Phase 2: PERLE @ 500MeV



Conclusions

- ERL machines open a **new frontier** for the physics of "**the electromagnetic probe**" (ep, eA, eN). **PERLE@Orsay is a key ERL project for HEP and Nuclear Physics communities**

- **PERLE@Orsay** has been recognised (together with bERLinPro) as **essential pillars of the ERL ESPP** strategy. It combines high current and multi-passes (high luminosity / higher energy)

- **PERLE@Orsay is a very challenging machine** : RF CW operation, specific SFR systems, multi-bunches operation, high power machine, complex Lattice design, broad range diagnostics, beam dynamics...

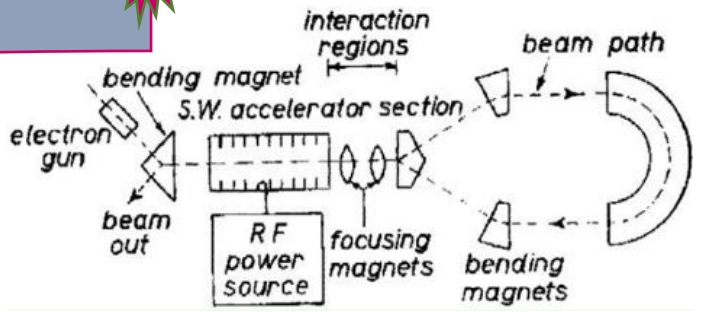
- **The International collaboration is formed** and still open (recently An-Najah and ESS-Bilbao) to new comers.

- **Important boost in the last 9 months** and we are actively entering in the **TDR** and the **Praparatory Building Phase !**

BACKUP

ERL History and achievements

1965 M. Tigner
"A possible apparatus for electron clashing-beam experiments"



1987 High Energy Physics Lab
Stanford University
SRF cavities, proof of principal experiment

1987 Los Alamos
FEL-operation, nc,
coupled acc/dec cavities

2000
Jefferson Lab
"Front End Test"
SRF, first CW
recovery

2002 JEARI, Japan
FEL, SRF, 700kW beam power

2005 Daresbury Lab, GB
"Alice", SRF, 26MeV, versatile
10-year user program

2002
Jefferson Lab
"IR-Demo"
SRF, 5mA, 48MeV,
2.1kW beam power IR
2003
CEBAF, 1 GeV, single turn
2007 Upgrade:
9mA, 150MeV
1.1MW beam power with
~300kW total power

2004 BINP, Russia
FEL-operation
normal conducting RF,
30 mA
2007: 4-passes

2013 KEK, Japan
"cERL", prototype
ERL light source
Industrial applications

2020, Cornell/BNL
cbeta, FFA-arc
4-pass ERL
(80mA injector, e = 0.3mm mrad)

under construction:
MESA, Germany
particle physics application

PERLE, France
Technology test facility
(LHeC/FCC-eh) + eRIB test facility

bERLinPro, Germany
SRF/ERL technology test facility

CeC, BNL, USA
Coherent electron cooling for EIC

Courtesy to Bettina Kuske