Short introduction to Energy Recovery Linac (ERL).

- Introduction. The Idea. Rings vs Linac vs ERL
- How an ERL works (by me, an non expert)
- Future projects with ERL
- **The project PERLE@Orsay**

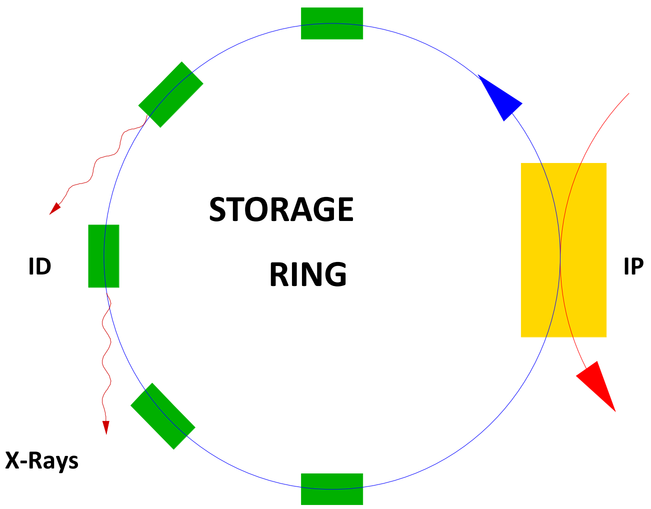
Material from
Walid Kaabi, Erk Jensen, Oliver Bruning, Max Klein, David Verney…

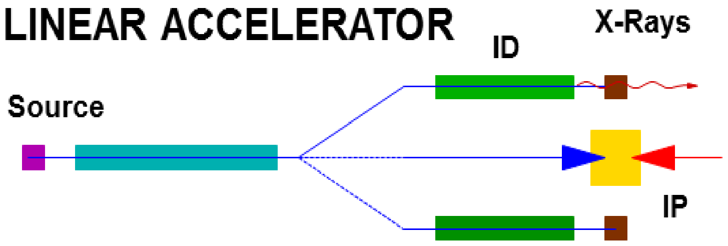
Many thanks !

- Introduction. The Idea. Rings vs Linac vs ERL
- How an ERL works (by me, an non expert)

Few pages to introduce the subject !

Introduction. The Idea. Rings vs Linac vs ERL - I

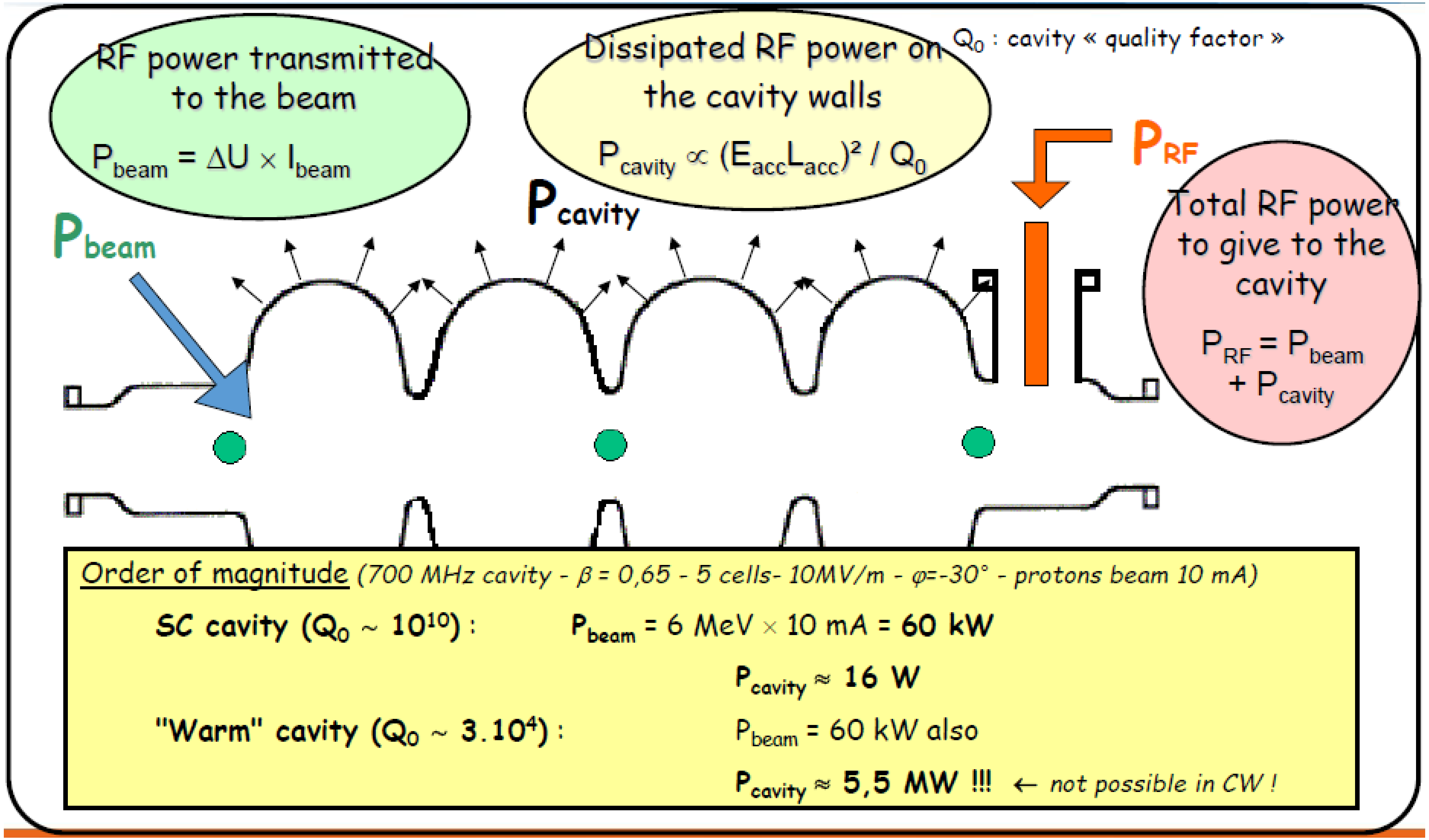




- beam parameters defined by equilibrium
- many user stations
- limited flexibility – multi-pass
- high average beam power (A, multi GeV)
- typically long bunches (20 ps – 200 ps)

- beam parameters defined by the source
- low number of user stations
- high flexibility – single pass
- limited average beam power (<< mA)
- possible short bunches (sub psec)

consideration on **Power consomption**



RF power transmitted to the beam

$P_{beam} = \Delta U \times I_{beam}$

Dissipated RF power on the cavity walls

$P_{cavity} \propto (E_{acc}L_{acc})^2 / Q_0$

Q_0 : cavity « quality factor »

Total RF power to give to the cavity

$P_{RF} = P_{beam} + P_{cavity}$

Order of magnitude *(700 MHz cavity - β = 0,65 - 5 cells- 10MV/m - φ=-30° - protons beam 10 mA)*

SC cavity ($Q_0 \sim 10^{10}$) : P_{beam} = 6 MeV × 10 mA = **60 kW**

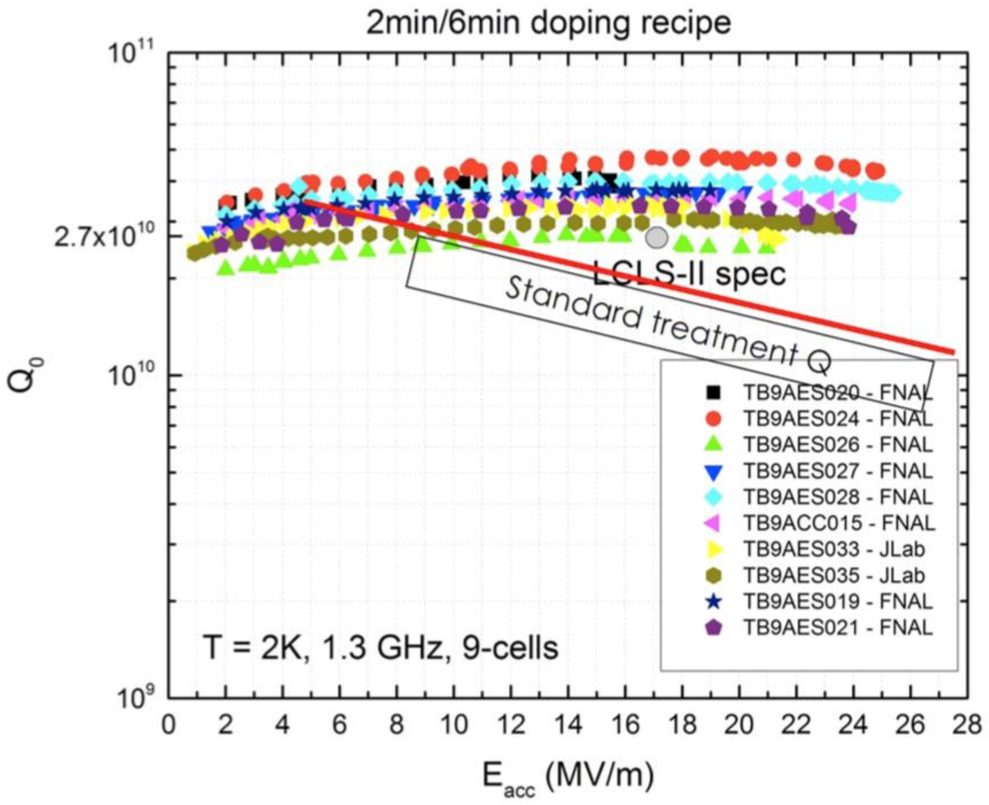
$P_{cavity} \approx$ **16 W**

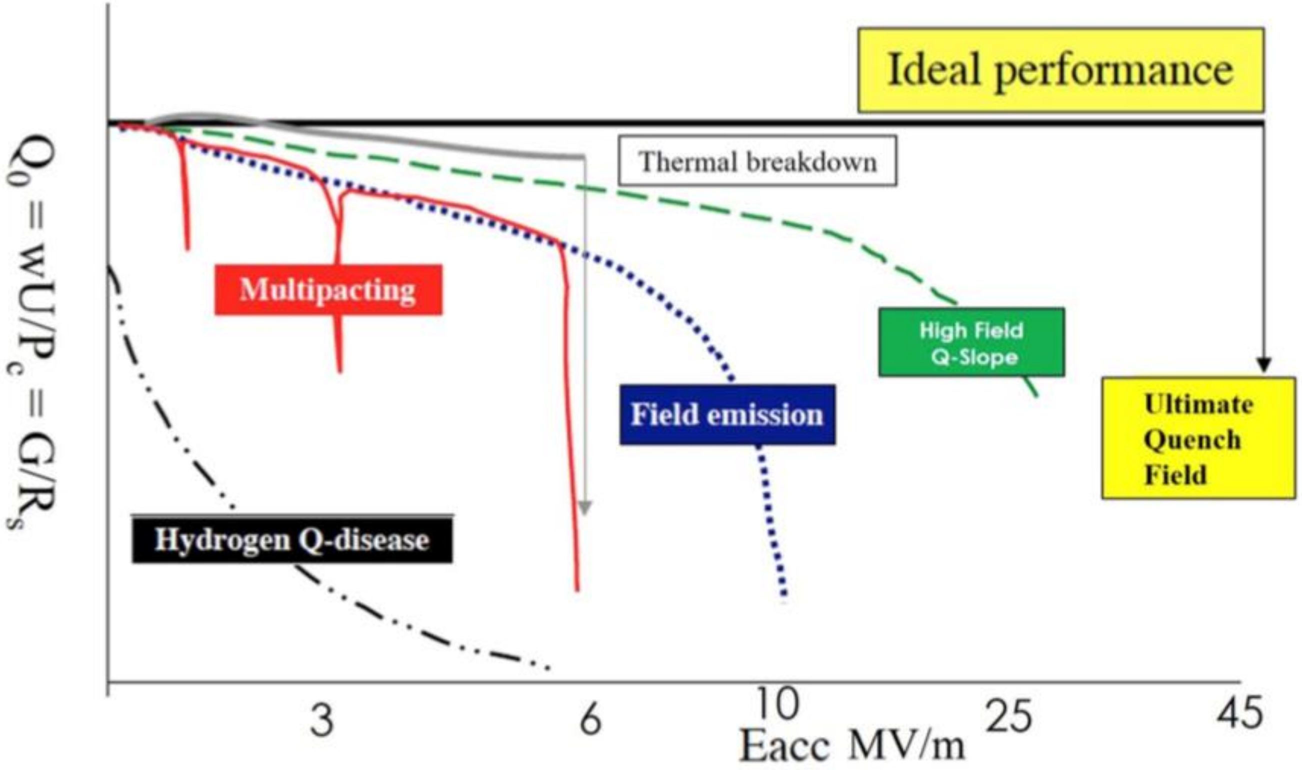
"Warm" cavity ($Q_0 \sim 3.10^4$) : P_{beam} = 60 kW also

$P_{cavity} \approx$ **5,5 MW !!!** ← *not possible in CW !*

SRF Challenge

Q_0 versus accelerating voltage:





➔ impressive progress over the last 10 years!!!

➔ Q_0 directly linked to required cryogenics power!!

Just to tell you that you need superconductive cavities !

But even with SFR…Power consomption is a big issue

More. Consider a circular collider.

$$L = \frac{N_e N_p f \gamma_p}{4\pi \epsilon_p \beta *} \quad *$$

Performance limitation of circular colliders

Synchrotron Radiation in arcs

$$I_e = e N_e f = \frac{P}{E_e}$$

Power Scales with E^4 and r^{-1}

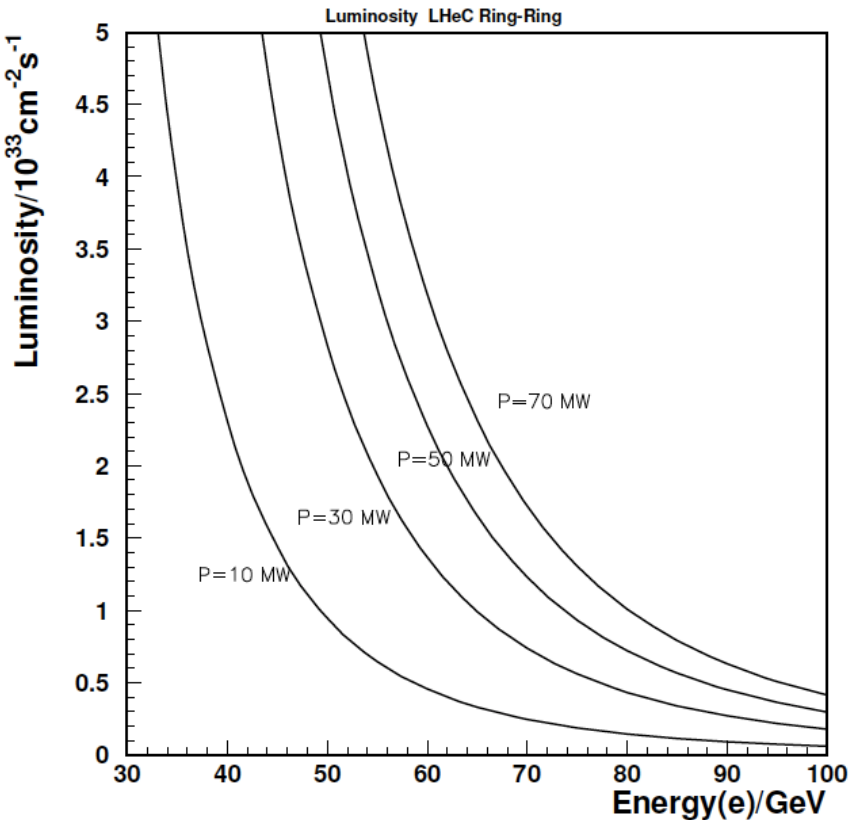
$$P_{arc} = \frac{N_b}{n_b} \frac{e^2 \gamma^4}{6 \epsilon_0 \rho}$$

➔ Reduced performance reach for higher beam energies

@ fixed power footprint ➔ limits total beam current!

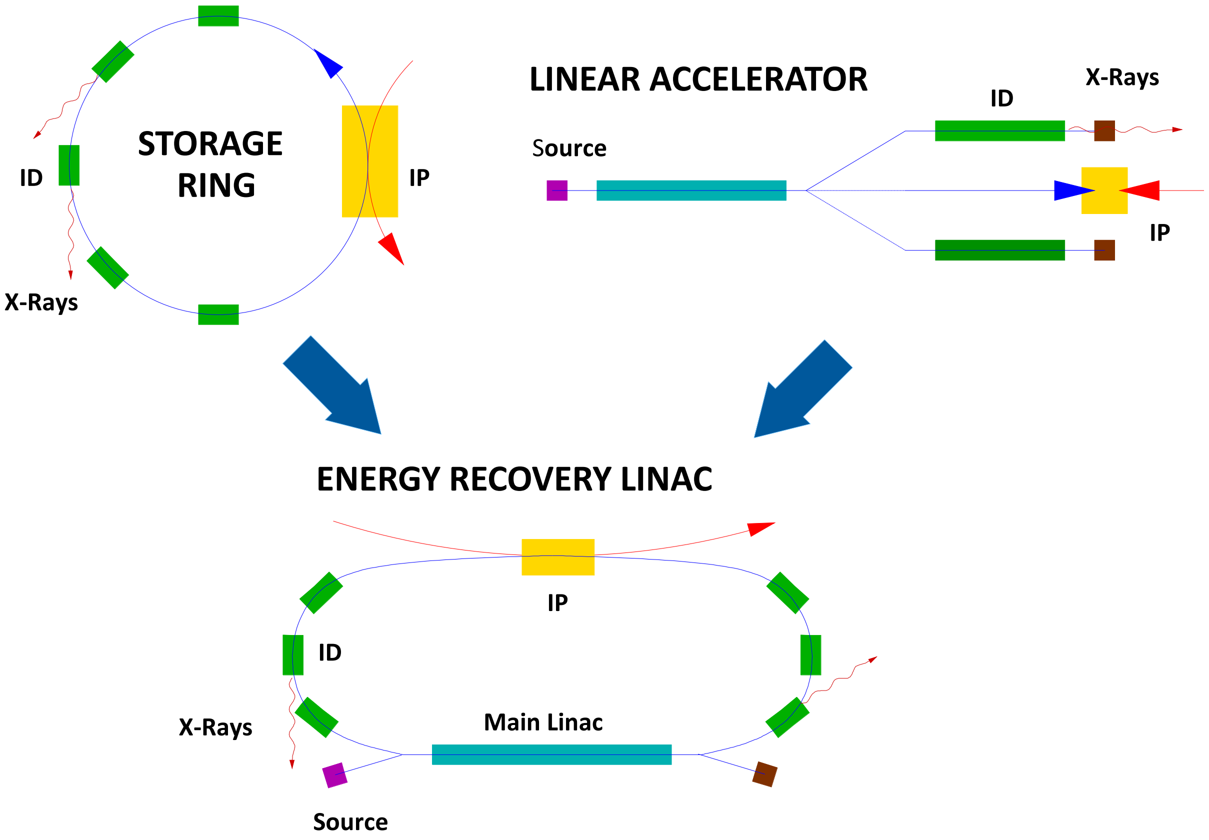
*Luminosity is an Essential parameter N(events)= σ x L

Exemple of ep collider LHeC CDR; arXiv:1206.2913



LHeC: Goal now is 10^{34} could NOT pay for power and not realise high lumi

Introduction. The Idea. Rings vs Linac vs ERL - II

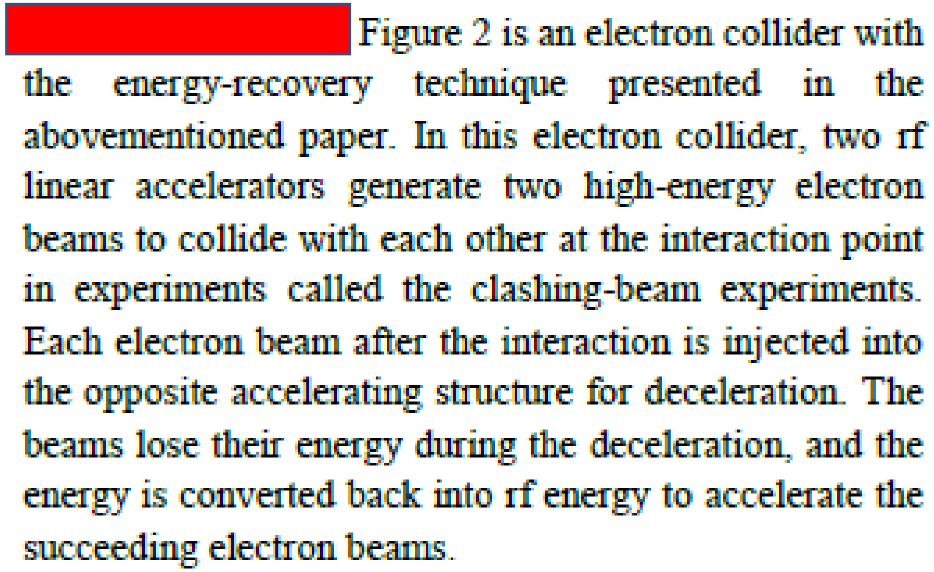


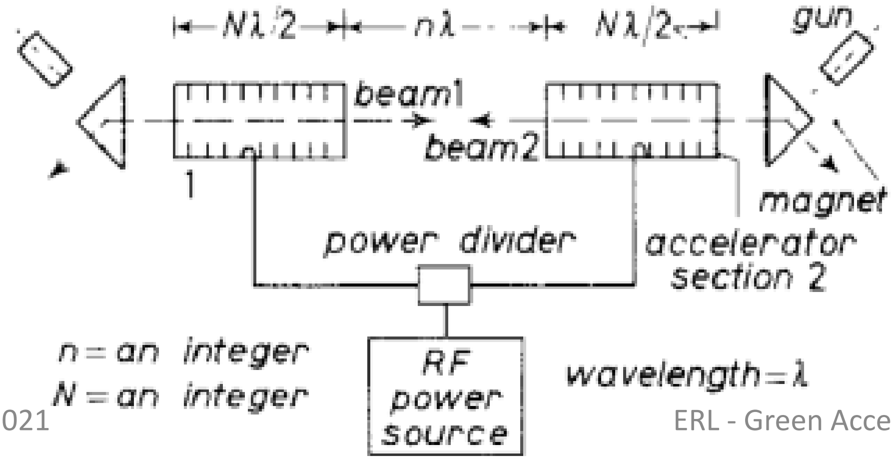
High average beam power (multi GeV @ some 100 mA) for single pass experiments, excellent beam parameters, high flexibility, multi user facility

Introduction. The Idea. Rings vs Linac vs ERL - III

- ERL concept was proposed first in 1965 by Maury Tigner

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


[redacted] Figure 2 is an electron collider with the energy-recovery technique presented in the abovementioned paper. In this electron collider, two rf linear accelerators generate two high-energy electron beams to collide with each other at the interaction point in experiments called the clashing-beam experiments. Each electron beam after the interaction is injected into the opposite accelerating structure for deceleration. The beams lose their energy during the deceleration, and the energy is converted back into rf energy to accelerate the succeeding electron beams.



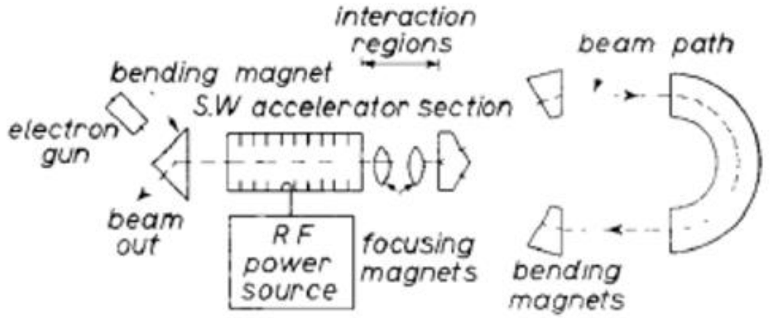
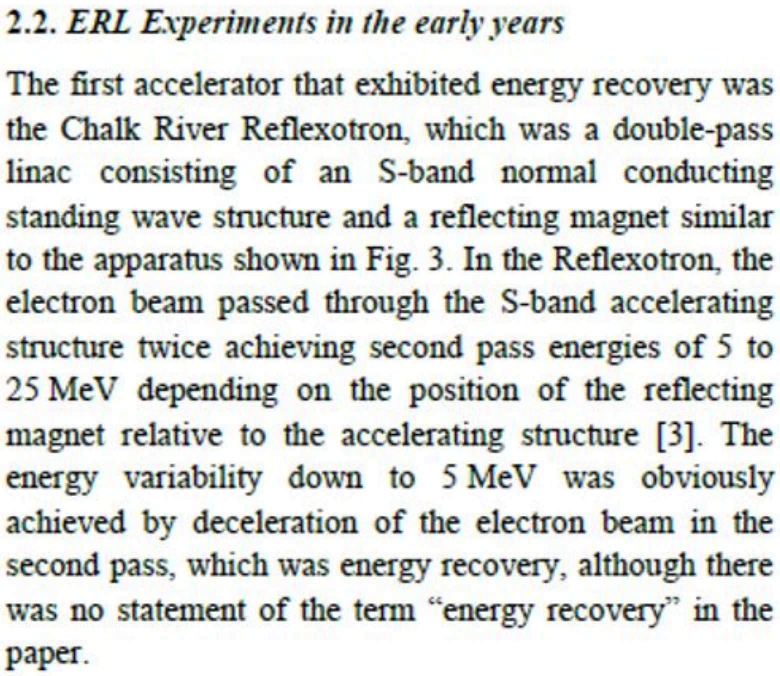


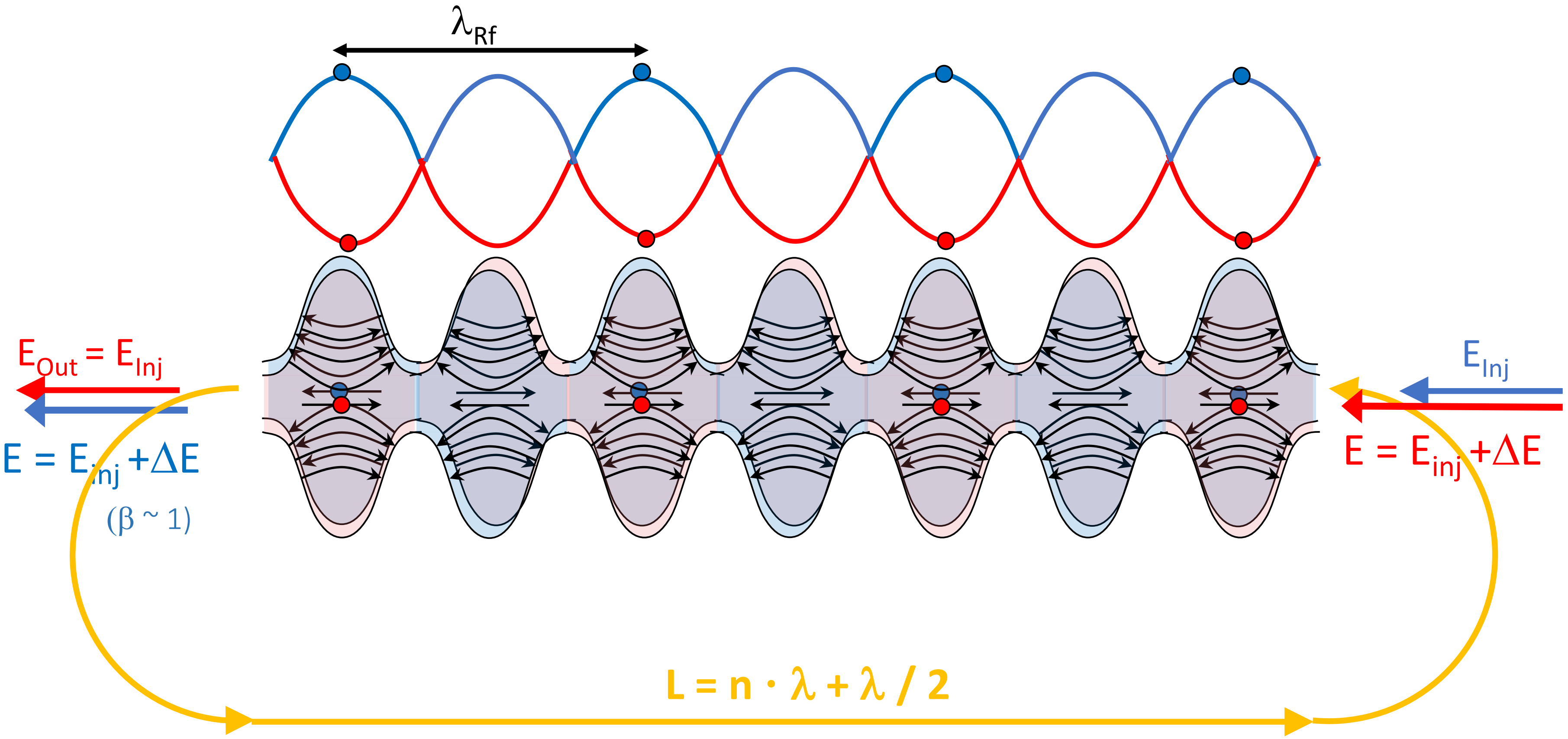
Figure 3. Single-beam electron collider with energy-recovery technique [2].


2.2. *ERL Experiments in the early years*

The first accelerator that exhibited energy recovery was the Chalk River Reflexotron, which was a double-pass linac consisting of an S-band normal conducting standing wave structure and a reflecting magnet similar to the apparatus shown in Fig. 3. In the Reflexotron, the electron beam passed through the S-band accelerating structure twice achieving second pass energies of 5 to 25 MeV depending on the position of the reflecting magnet relative to the accelerating structure [3]. The energy variability down to 5 MeV was obviously achieved by deceleration of the electron beam in the second pass, which was energy recovery, although there was no statement of the term "energy recovery" in the paper.

ERL how it works - I

Energy recovery in RF fields:



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

SINGLE TOUR

MULTI TOUR

More complex, but allows to go up in energy !

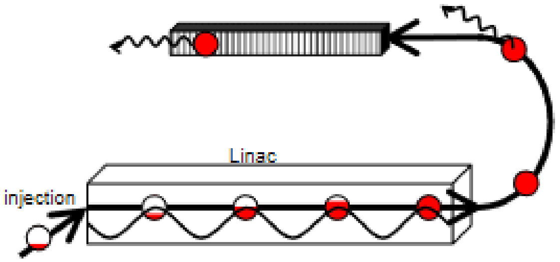


Fig. 1: Step one of an ERL – acceleration

In the first step of an ERL, electrons from the injector are accelerated (Fig. 1). The electron beam is then conducted to the experimental area where the synchrotron radiation is extracted.

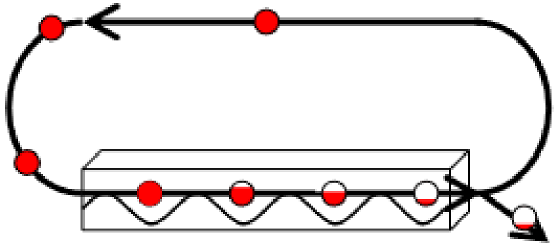


Fig. 2: Step two of an ERL – deceleration

In the second stage of the ERL, the electron beam is directed back to the accelerating structure but with a phase change of 180 degrees. Thus the electrons are decelerated instead of accelerated, and after the deceleration they are extracted at low energy and dumped (Fig. 2).

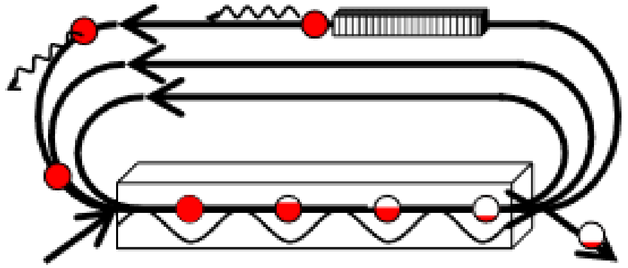
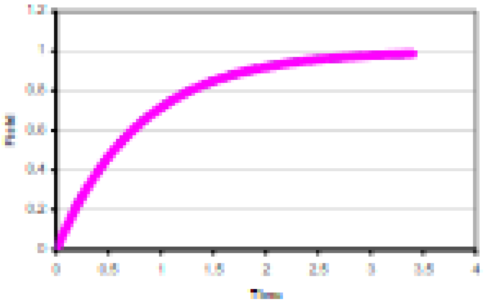


Fig. 3: Alternative layout of an ERL – acceleration and deceleration over several turns

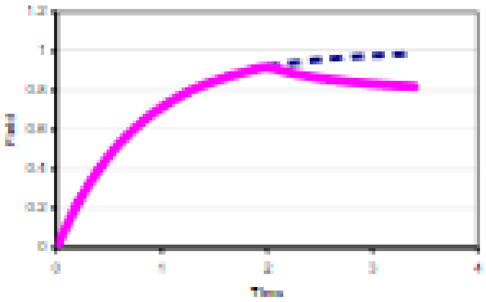
An alternative way of operating the ERL is to run acceleration over several turns, using the same accelerating structure more than once (Fig. 3). In the final (outermost) turn the generation of synchrotron radiation takes place and the electrons arrive in the subsequent turns in the decelerating phase. Thus passing the same orbits in reverse order until they are slowed down to the injection energy and can be dumped.

The energy recovery in this process takes place in the accelerrating structure. The energy taken from the electron beam in the decelerating phase is stored in the accelerating structure and can be used to accelerate electron bunch

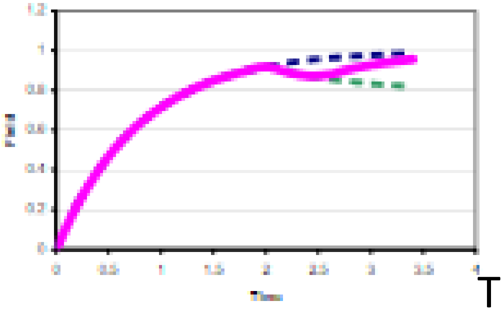
Filling empty cavity



An accelerated beam loads the cavity



Decelerated beam fill the cavity



The fields in a cavity in an ERL is shown in the Figure.

The loading of the cavity goes exponentially toward the maximum value.

When the beam is accelerated in the cavity, the fields are decreased toward a new equilibrium.

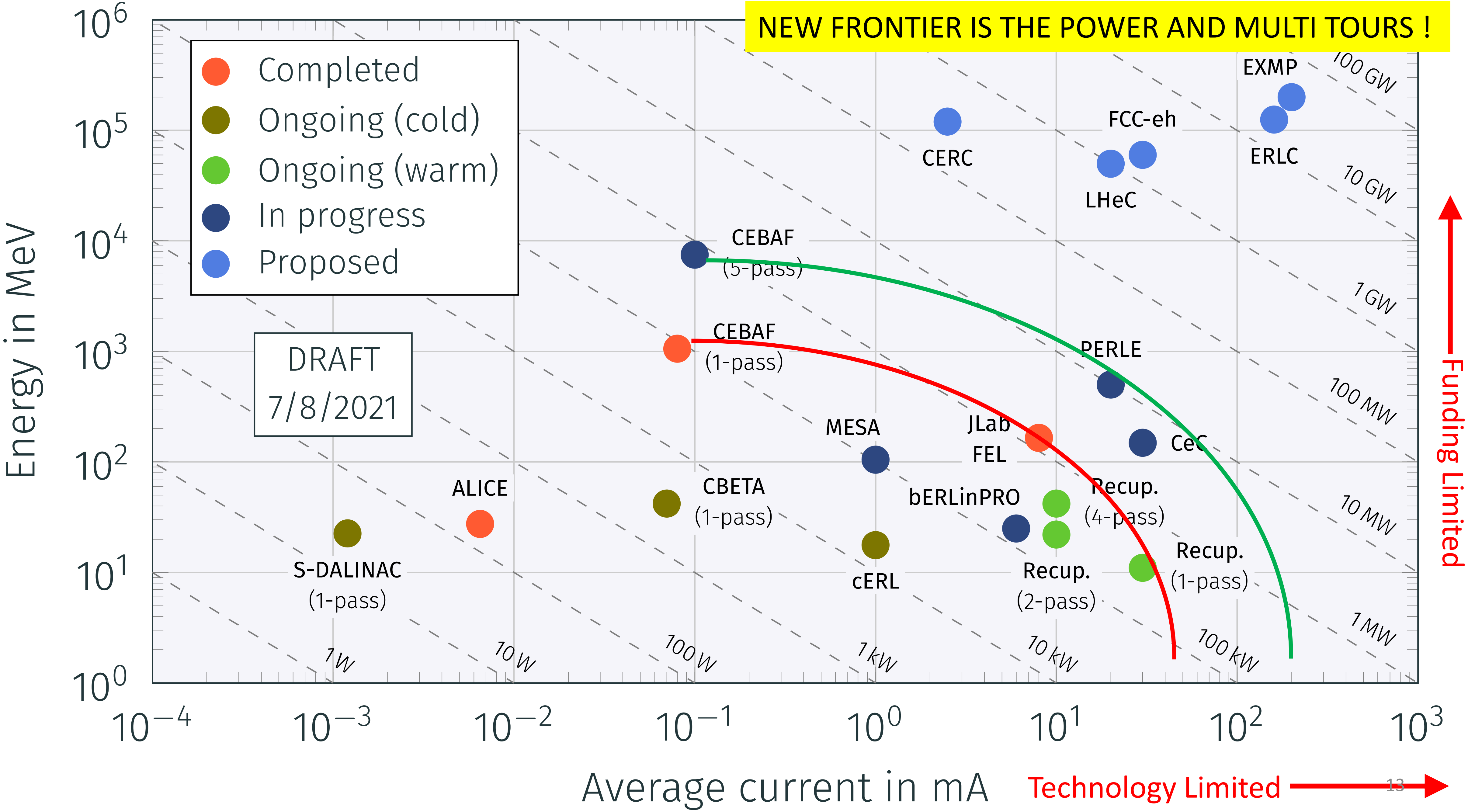
Finally the accelerated beam returns to further load the cavity and the field inscrease toward an higher equilibrium.

If we increase Q-value we acheive much smaller losses for a given stored energy. The decay and change over time will also be slower and less senitive. On the other hand, the « memory of the cavity will be much longer

- **Future projects with ERL**
- **The project PERLE@Orsay**

A lot of slides, more seminar oriented !

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



NEW FRONTIER IS THE POWER AND MULTI TOURS !

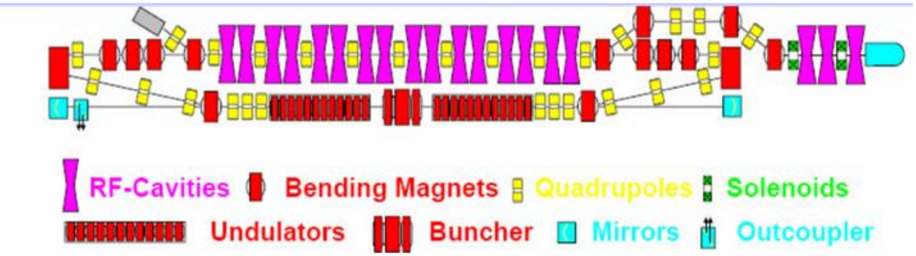
Funding Limited

Technology Limited

ERLs around the world:

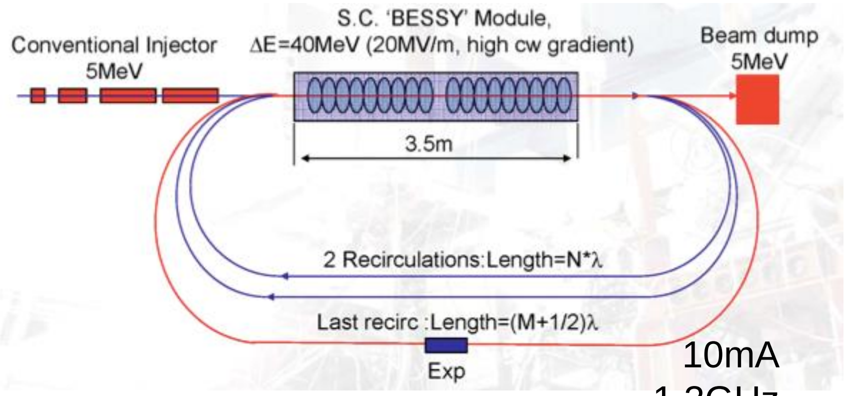
Normal Conducting 180 MHz + DC Gun

30 mA, 11 MeV, 70-100 ps



BINP, Novosibirsk

- 3-4 turn ERL
- Normal conducting RF

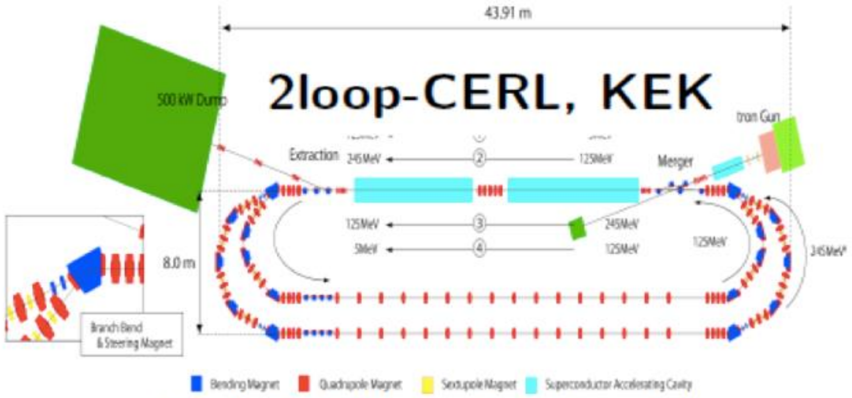


10mA

1.3GHz

5-125 MeV

MESA

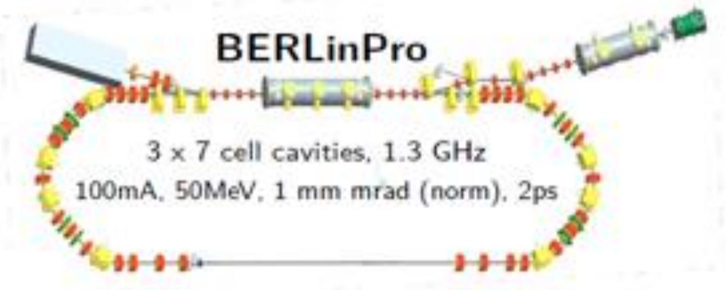


2loop-CERL, KEK

9 cell, 1.3 GHz cavities, 4 modules

77 pC, 245 MeV, 1-3 ps

- At the moment only single loop operation
- Severe limitations in beam current due to injector



BERLinPro

3 x 7 cell cavities, 1.3 GHz

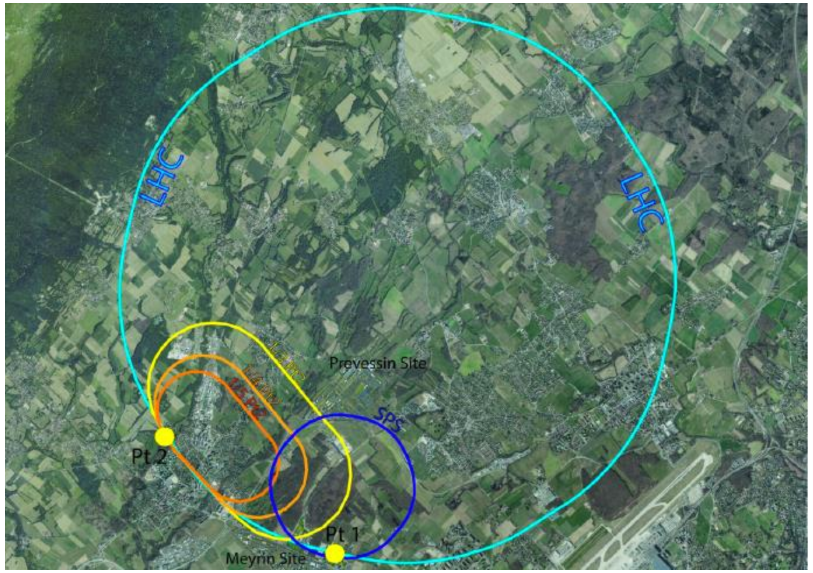
100mA, 50MeV, 1 mm mrad (norm), 2ps

WHY THIS FOISONNEMENT of ERL ?

ERL allows to conceive new machine and opened a very wide field of possible applications !

- Physique electron-proton : LHeC et FCC-ep, and also eA !
- Low energy electrophysics
- e-Nuclei physics
- Industrial applications
- New ideas of ERL-linear collider
- New idea of ERL-based e+e- factory

LHeC and FCC-eh



50 x 7000 GeV^2: 1.2 TeV ep collider

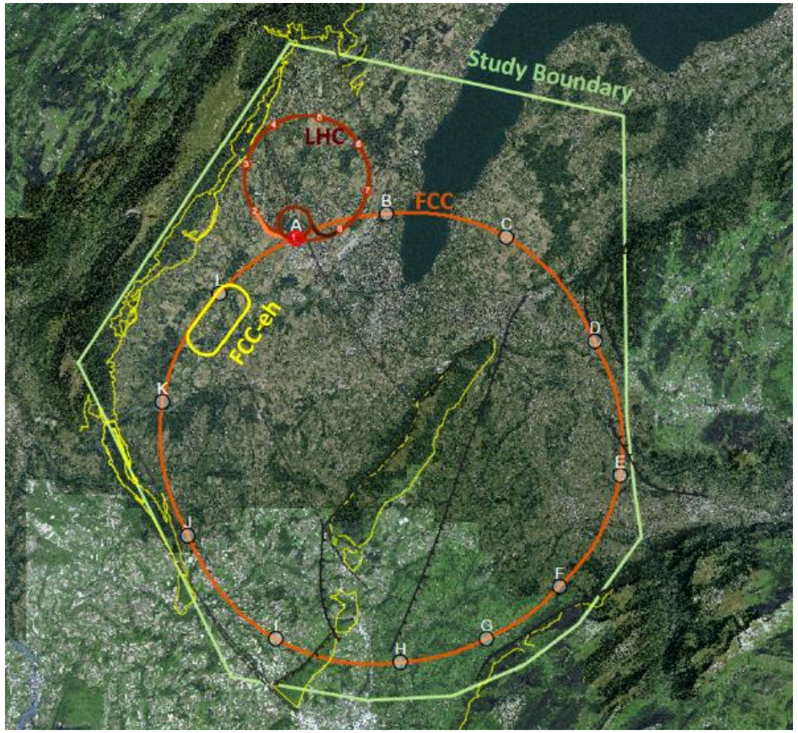
Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

arXiv:2007.14491, J.Phys.G to appear



60 x 50000 GeV^2: 3.5 TeV ep collider

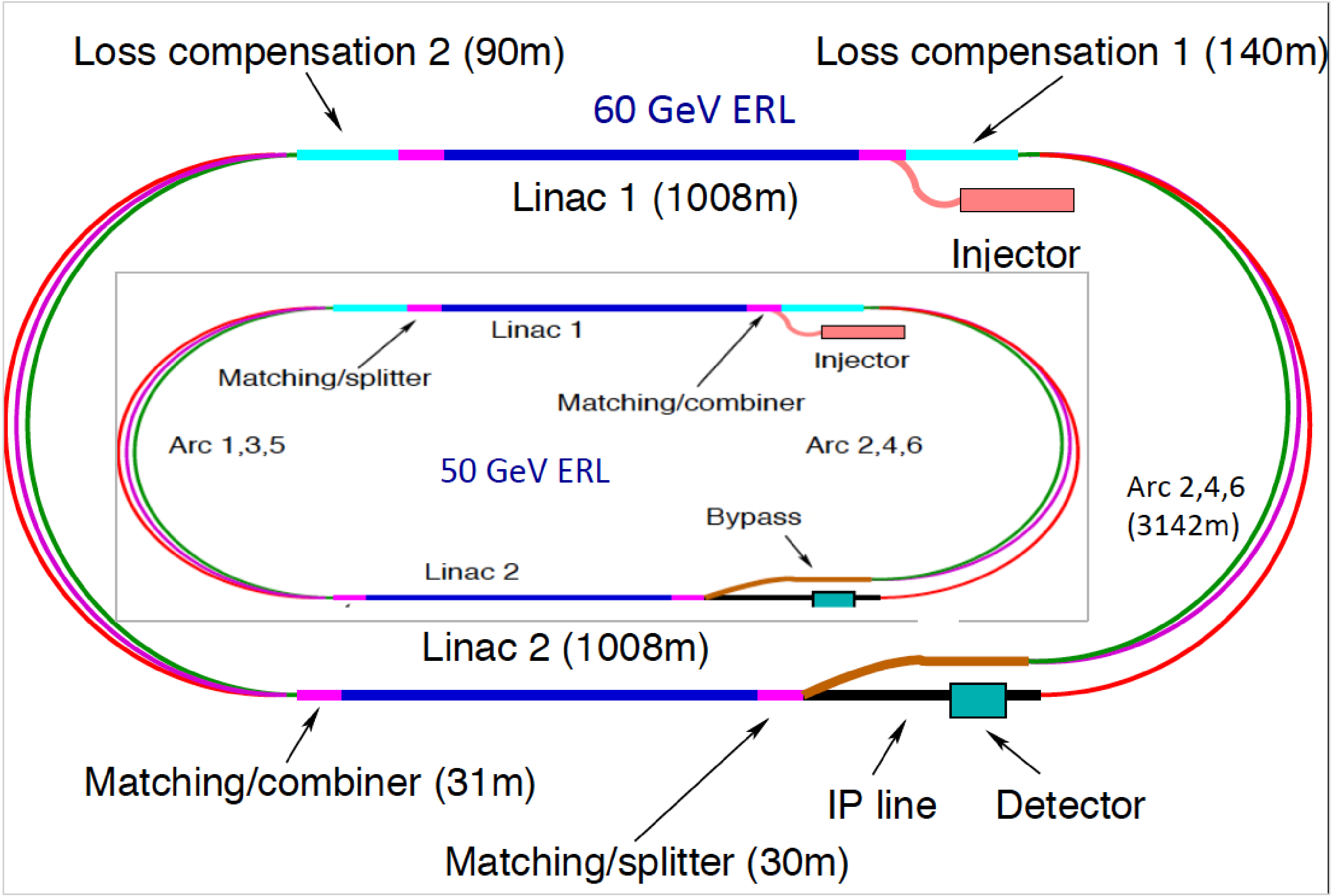
Operation: 2050+, Cost (of ep) O(1-2) BCHF

Concurrent Operation with FCC-hh

FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

LHeC Configuration (for two electron beam energies) [CERN, BNL, Jlab for CDR]



3-turn energy recovery racetrack configuration. Modular for LHeC/FCC-eh

Energy recovery linac(s)

20mA I_e

Concurrent ep + pp operation with LHC

Integrated luminosity in e^-p up to O(1) ab^{-1}

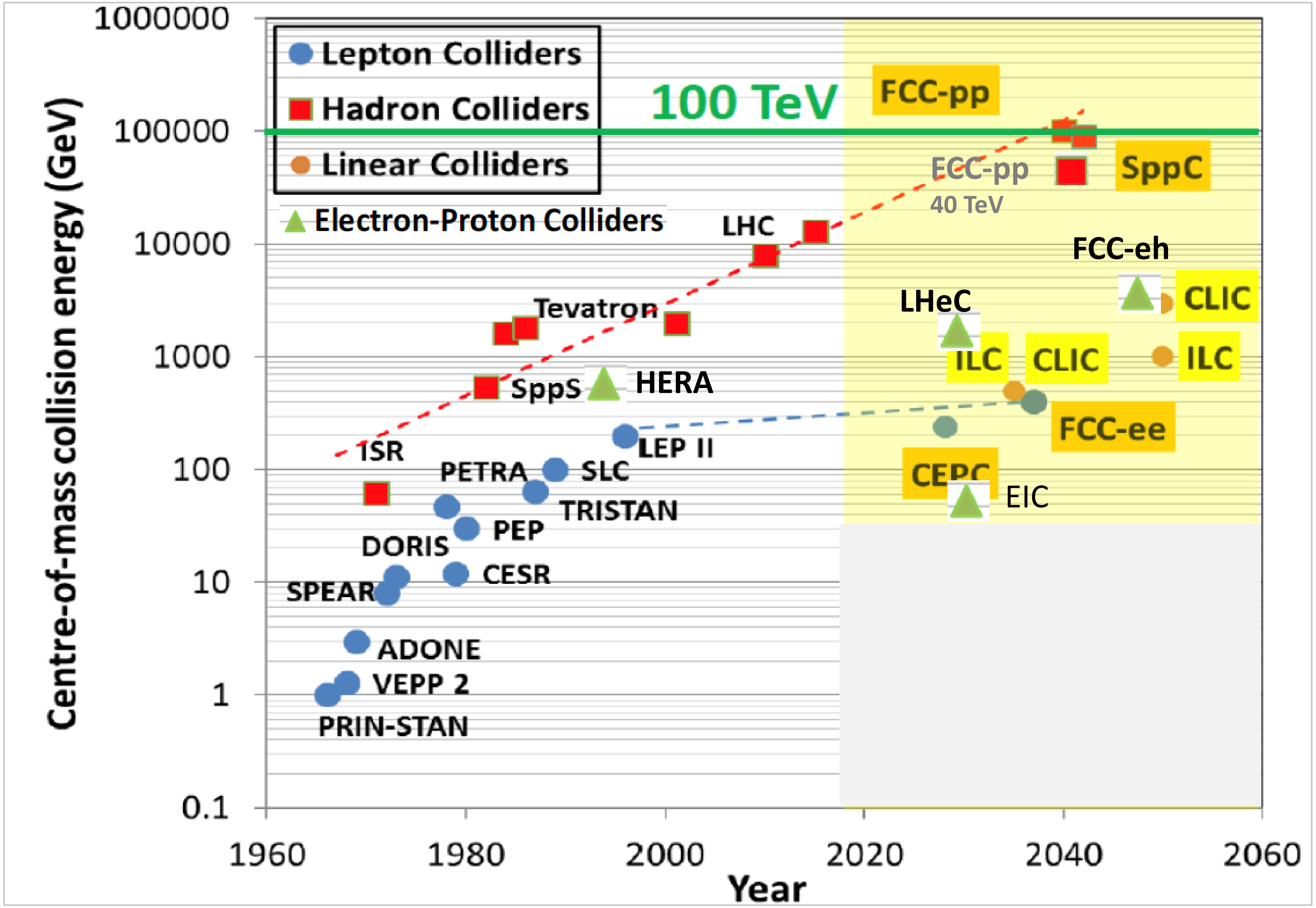
U(ep) = 1/n U(LHC)

Likely n=3 (CDR) → n=4 gains 20-30% cost. E< 60

H, BSM, top, low x.. require E > 50 GeV

Frequency set to 802 MHz, commensurate with LHC and 401/802 at CERN+FCC. also beam-beam stability

Hundred Years of HEP Colliders



ep/A Parameters:

MK EPS 7/19. adapted from M Benedikt (3/19)

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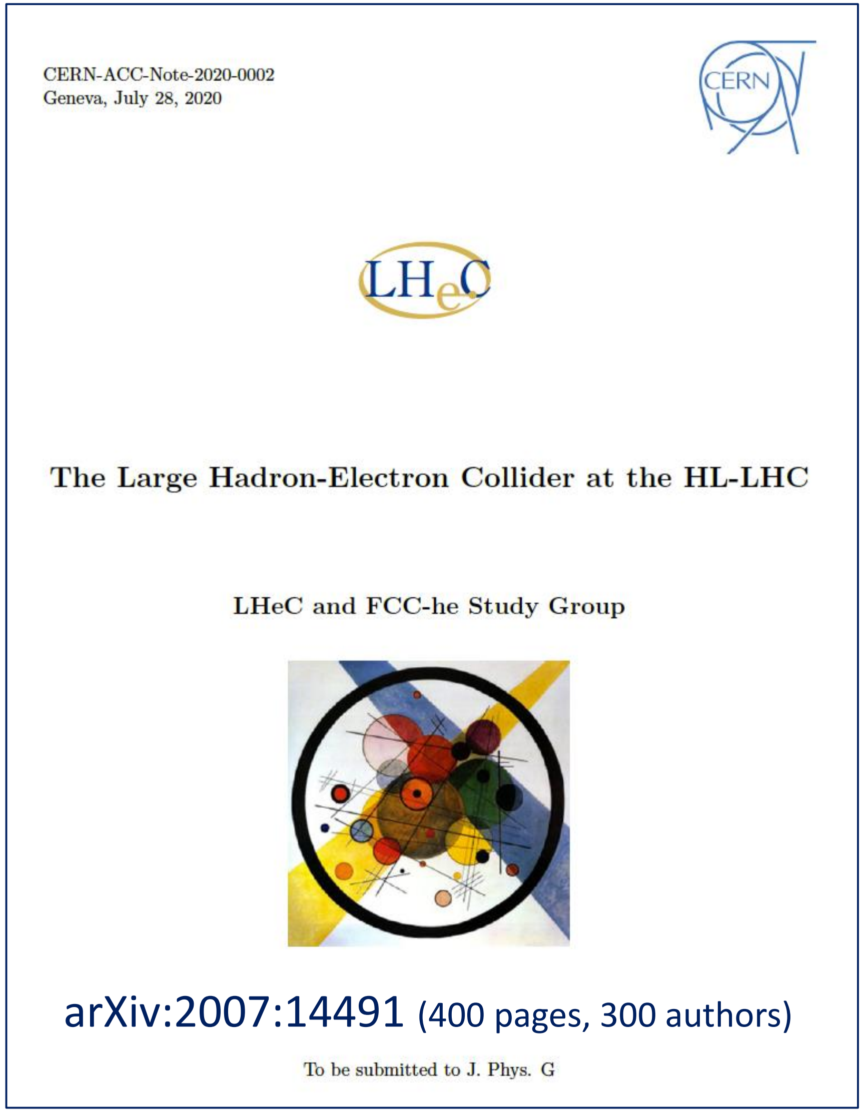

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

arXiv:2007:14491 (400 pages, 300 authors)

To be submitted to J. Phys. G

P. Agostini[1], H. Aksakal[2], H. Alan[3], S. Alekhin[4,5], P. P. Allport[6], N. Andari[7], K. D. J. Andre[8,9], D. Angal-Kalinin[10,11], S. Antusch[12], L. Aperio Bella[13], L. Apolinario[14], R. Apsimon[15,11], A. Apyan[16], G. Arduini[9], V. Ari[17], A. Armbruster[9], N. Armesto[1], B. Auchmann[9], K. Aulenbacher[18,19], G. Azuelos[20], S. Backovic[21], I. Bailey[15,11], S. Bailey[22], F. Balli[7], S. Behera[23], O. Behnke[24], I. Ben-Zvi[25], M. Benedikt[9], J. Bernauer[26,27], S. Bertolucci[9,28], S. S. Biswal[29], J. Blümlein[24], A. Bogacz[30], M. Bonvini[31], M. Boonekamp[32], F. Bordry[9], G. R. Boroun[33], L. Bottura[9], S. Bousson[7], A. O. Bouzas[34], C. Bracco[9], J. Bracinik[6], D. Britzger[37], S. J. Brodsky[36], C. Bruni[7], O. Brüning[9], H. Burkhardt[9], O. Cakir[17], R. Calaga[9], A. Caldwell[37], A. Calıskan[38], S. Camarda[9], N. C. Catalan-Lasheras[9], K. Cassou[39], J. Cepila[40], V. Cetinkaya[41], V. Chetvertkova[9], B. Cole[42], B. Coleppa[43], A. 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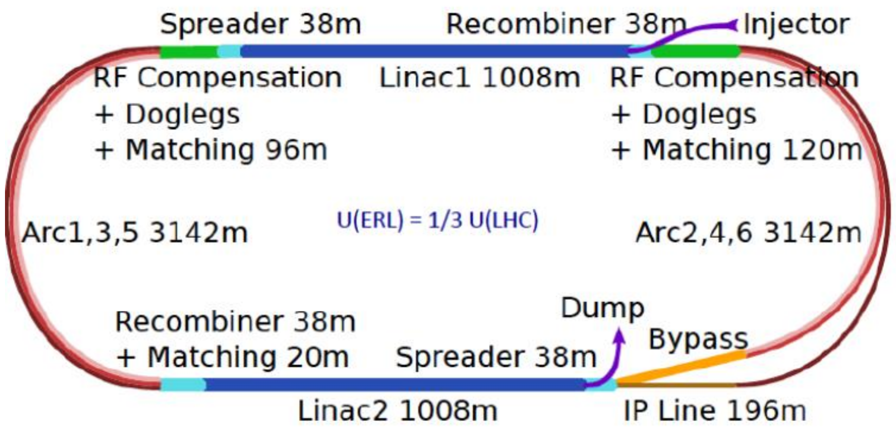
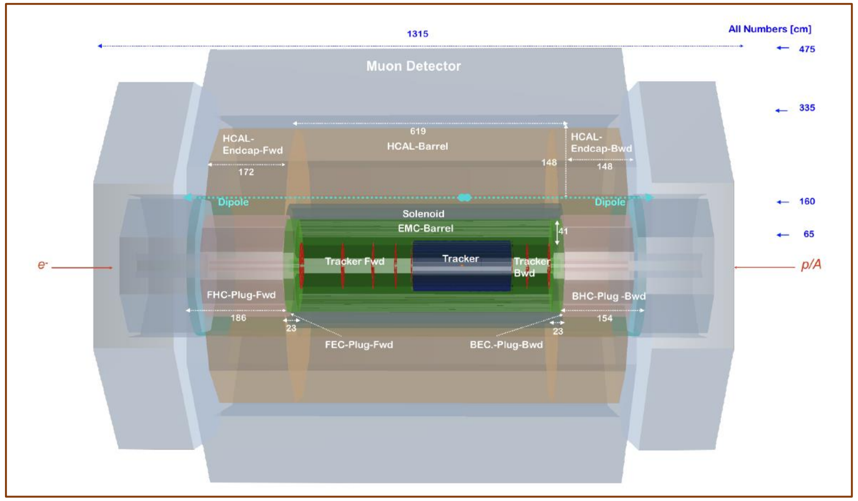
5 page summary: ECFA Newsletter Nr 5., August 20

https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

156 Institutions involved

Concluding Remarks





This is indeed affordable - O(1) billion CHF for another TeV collider

It sustains the HL-LHC and exploits this massive O(5) BCHF investment

Physics: Unique: Microscope of substructure (not resolved!), empowers LHC searches and Higgs measurements challenging e^+e^-, Discovery in electroweak and strong i.a. sector, Revolution of HI physics

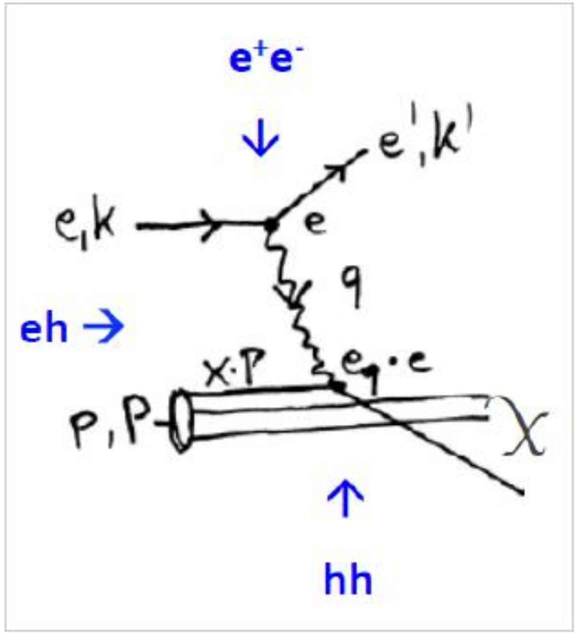
Technology: Accelerator: highest energy ERL application - green. Detector: exciting place for new technology (CMOS, timing, thin calo.. etc) in classic DIS, low radiation environment, no pileup. Exciting place also for known technology to reappear and work.

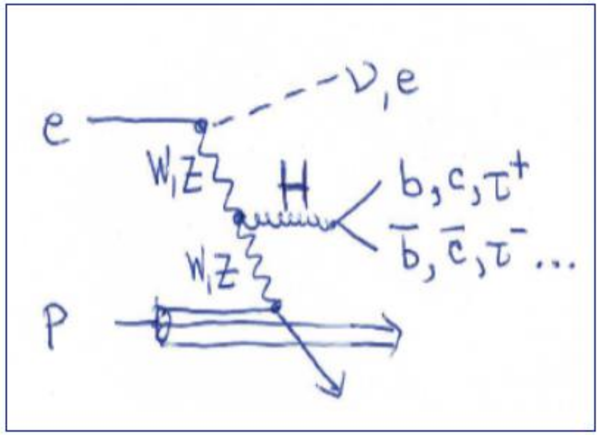
Merging LHeC with A3 resolves conceptual conflict on IP2 and promises to lead to new chapter of HI and accelerator physics (tentative)

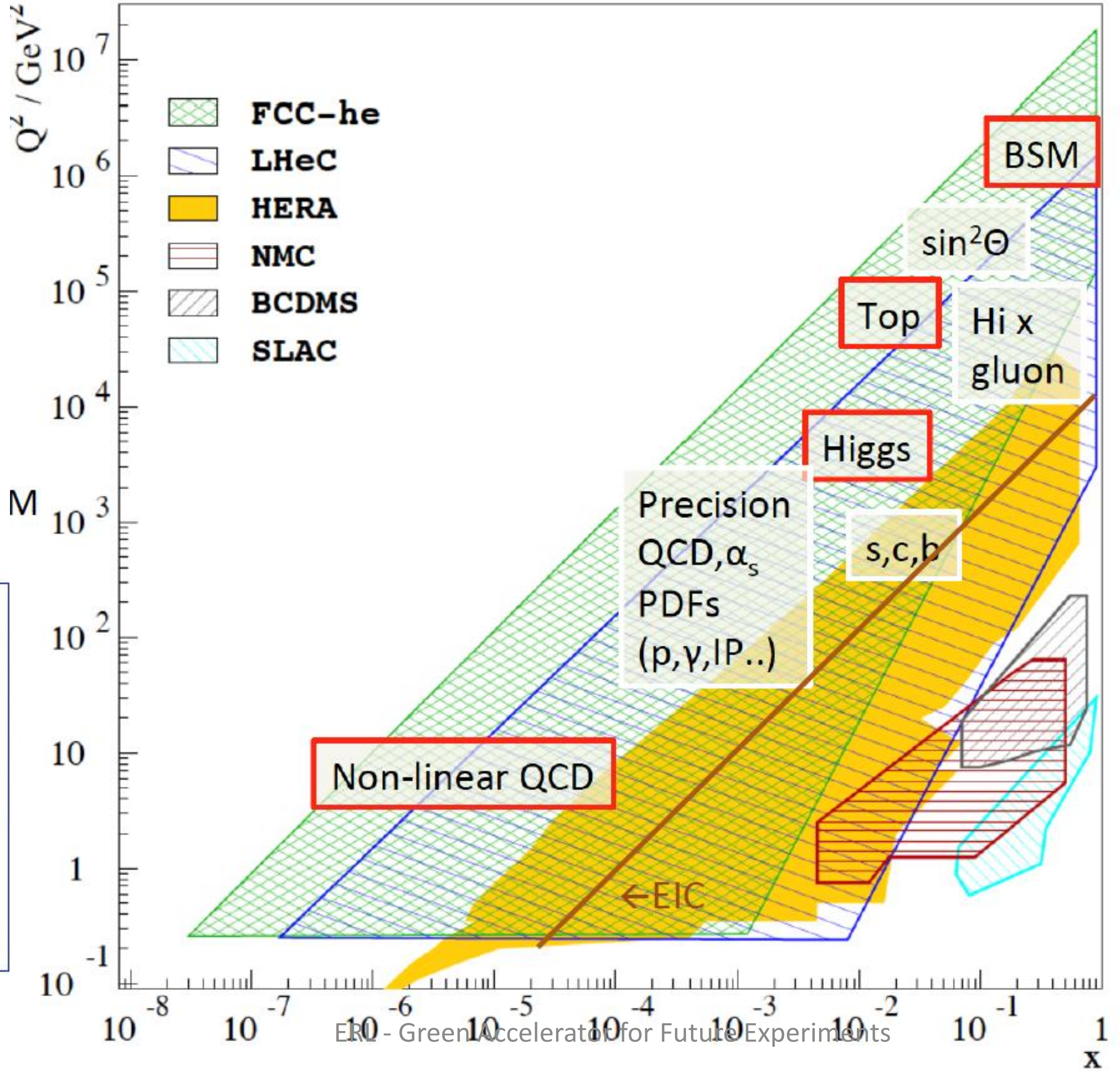
Next steps: PERLE facility at Orsay, considerations for a detector proposal to LHCC, embedded and subject to CERN's future, which is also related to that of the CEPC.

The LHeC group believes that diversity (at the energy frontier too) is key to help particle physics theory to restore its predictive power..

Physics with Energy Frontier DIS







Raison(s) d'etre of ep/eA at the energy frontier

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

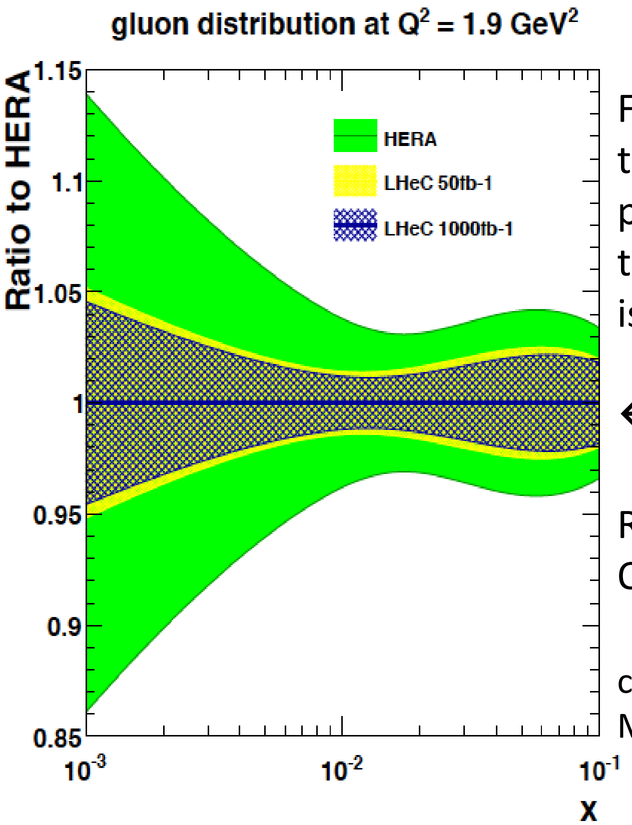
Parton Distributions

Complete unfolding of parton contents in unprecedented kinematic range: u,d,s,c,b,t, xg
Strong coupling to permille accuracy (incl + jets):

Crucial for LHC:

- high precision eweak, Higgs measurements
- Extension of high mass search range
- Non-linear low x parton evolution; saturation?

DIS: clean theory, light cone, redundant e/h FS reconstruction, ..



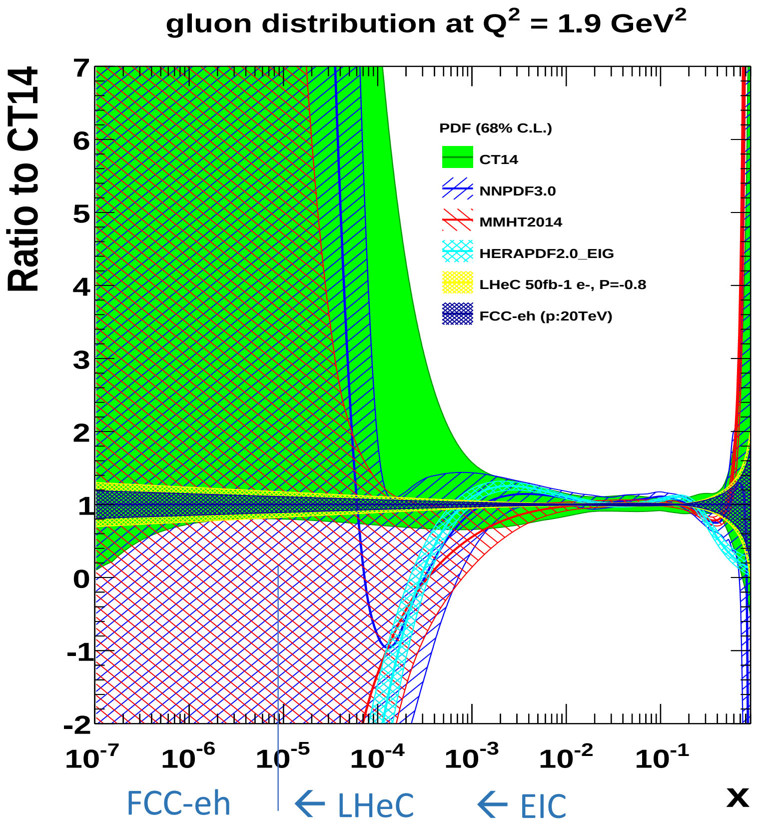
For LHC to have an impact on the search and precision physics program at HL-LHC it is crucial that PDF and QCD information is available early.

← PDF study with 50 vs 1000 fb^{-1}

Remove essential party of QCD uncertainties of gg→ H

cf C. Gwenlan, talk at DIS19 and M Cooper Sarkar yesterday at EPS

Figure 6: Uncertainty on the determination of the gluon distribution in the x range relevant for Higgs measurements at the LHC, based on the combined HERA data (outer band, green) and for the LHeC with the full data set (inner band, blue) and from the first running period (yellow, around the inner band. The LHeC uncertainties comprise full correlated systematic error estimates besides the statistics.



← HERA

Note that 50fb^{-1} is 100 times H1's total luminosity: Low x needs 1fb^{-1}.

Higgs in ep and pp [LHC and FCC]

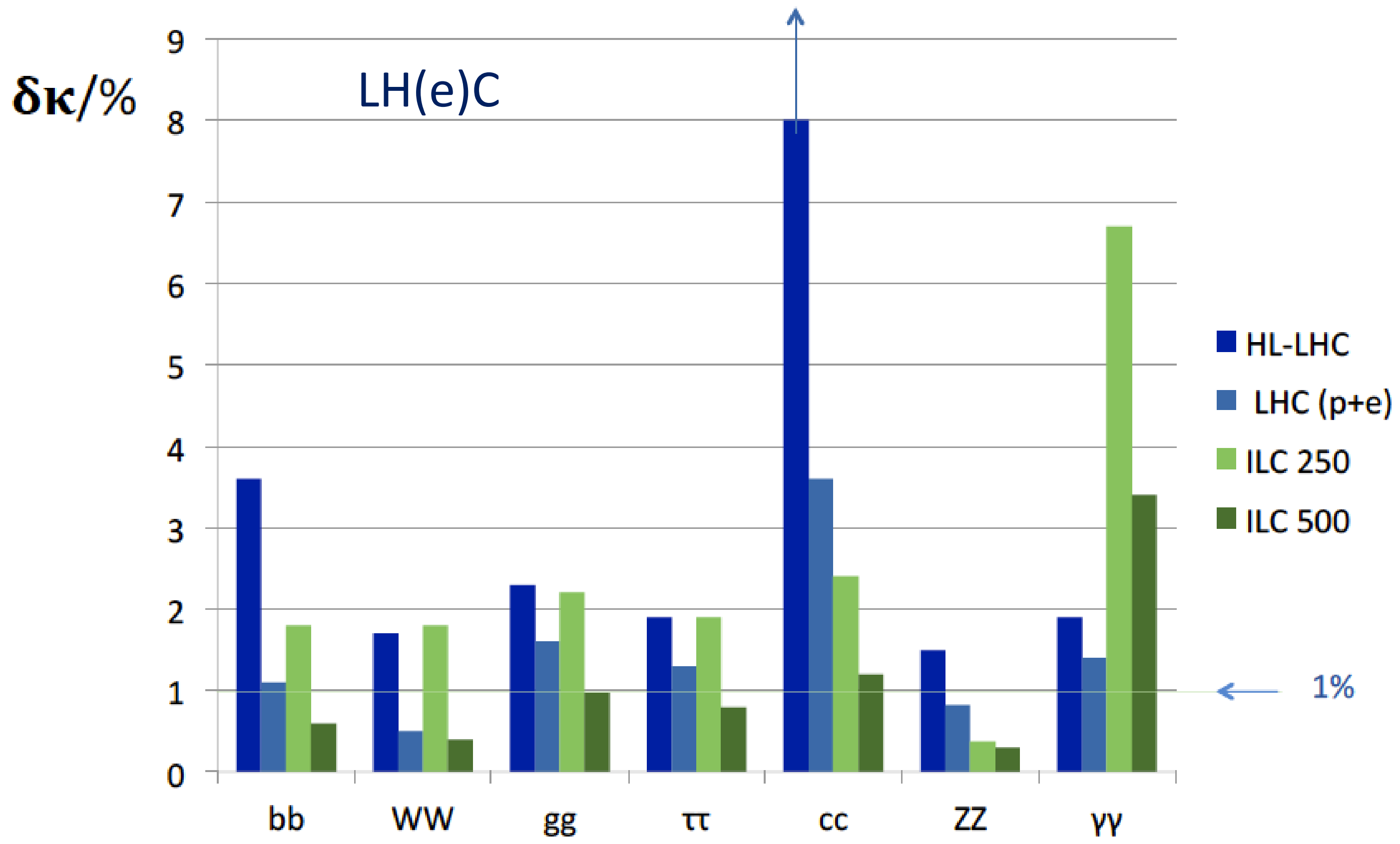


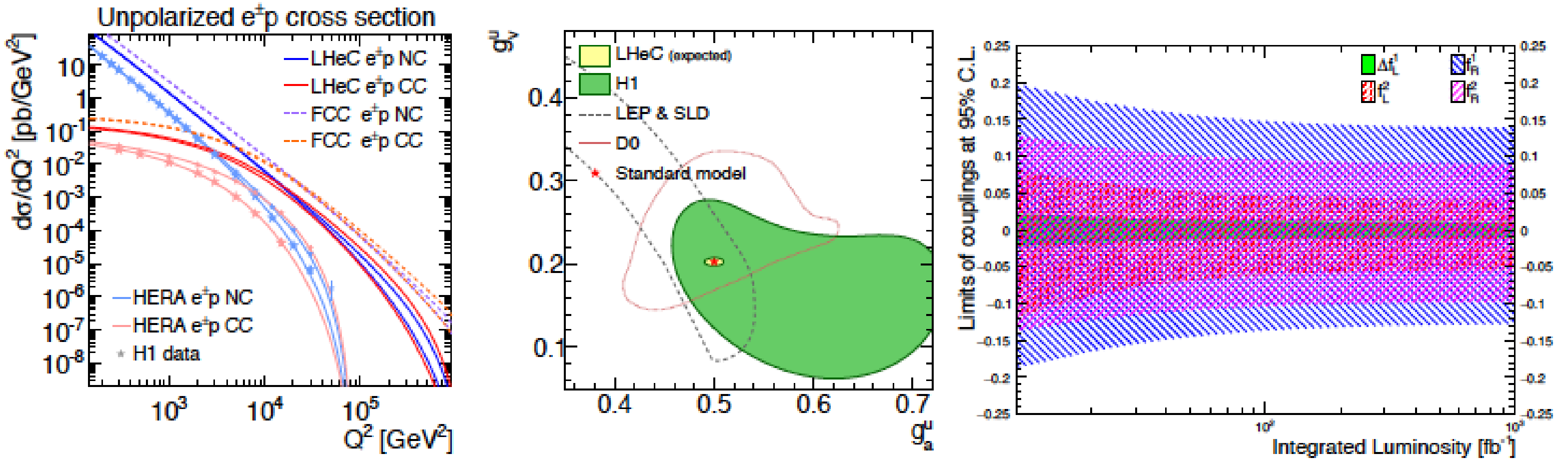
Fig.1*: Results of prospect evaluations of the determination of Higgs couplings in the SM kappa framework for HL-LHC (dark blue), LHC with LHeC combined (p+e, light blue), ILC 250 (light green) and ILC-500 (dark green).*

Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	**1.3**	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	**0.17**	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	**0.43**	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	**0.61**	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	**1.21**	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	**1.01**	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	**0.74**	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	**9.0**	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	**3.9**	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	–	1.7
BR_{EXO} (%)	< 1.0	n.a.

Prospects for high precision measurements of **Higgs couplings at FCC ee and ep**. Note ee gets the width with Z recoil. ee is mainly ZHZ, while ep is mainly WWH: complementary also to pp

Precision Electroweak Physics

Anomalous Wtb couplings

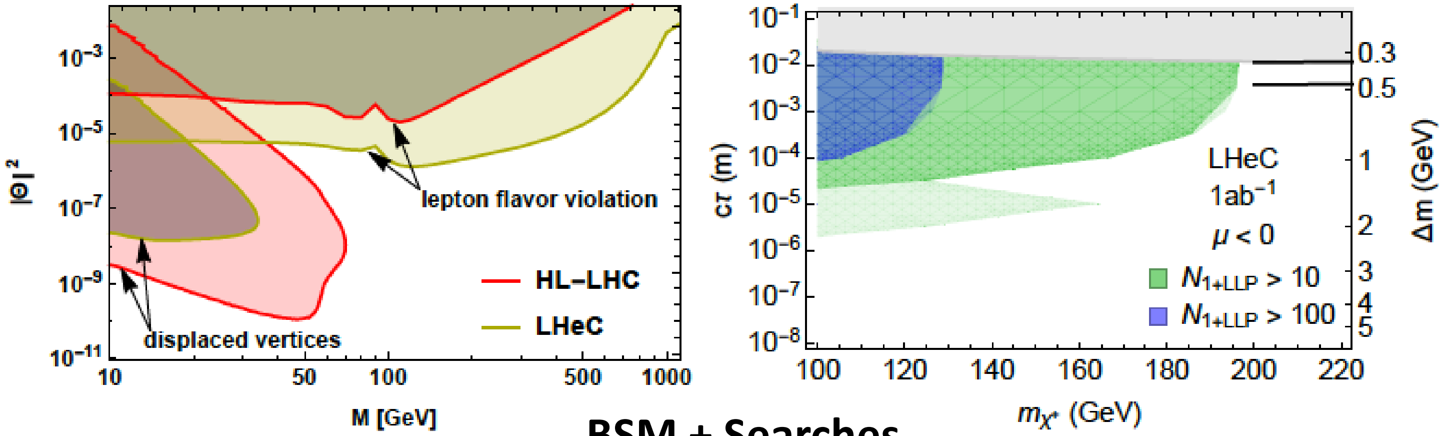


Electroweak+Top Physics

Figure 1: Left: Unpolarised inclusive NC and CC DIS cross sections as a function of Q^2 at the LHeC, in comparison to HERA (H1 [17]) and FCC-eh expectations; Middle: Determination of the up-quark weak neutral current vector and axial-vector couplings with LHeC (yellow) compared with current determinations; Right: Expected sensitivities as a function of the integrated luminosity on the SM and anomalous W_{tb} couplings [18].

Heavy Neutrinos

Higgsinos



BSM + Searches

Figure 4: Left: Prospects for direct right-handed neutrino searches at the LHeC, first estimates for HL-LHC prospects for comparison, based on [34]. Right: Reach for long-lived Higgsinos in the mass (m_χ) - lifetime ($c\tau$) plane, compared to disappearing tracks at the HL-LHC [35], shown by the black lines. Light shading indicates the uncertainty in the predicted number of events due to different hadronization and LLP reconstruction assumptions. For details, see [36].

From LHeC strategy paper CERN-ACC-NOTE-2018-0084

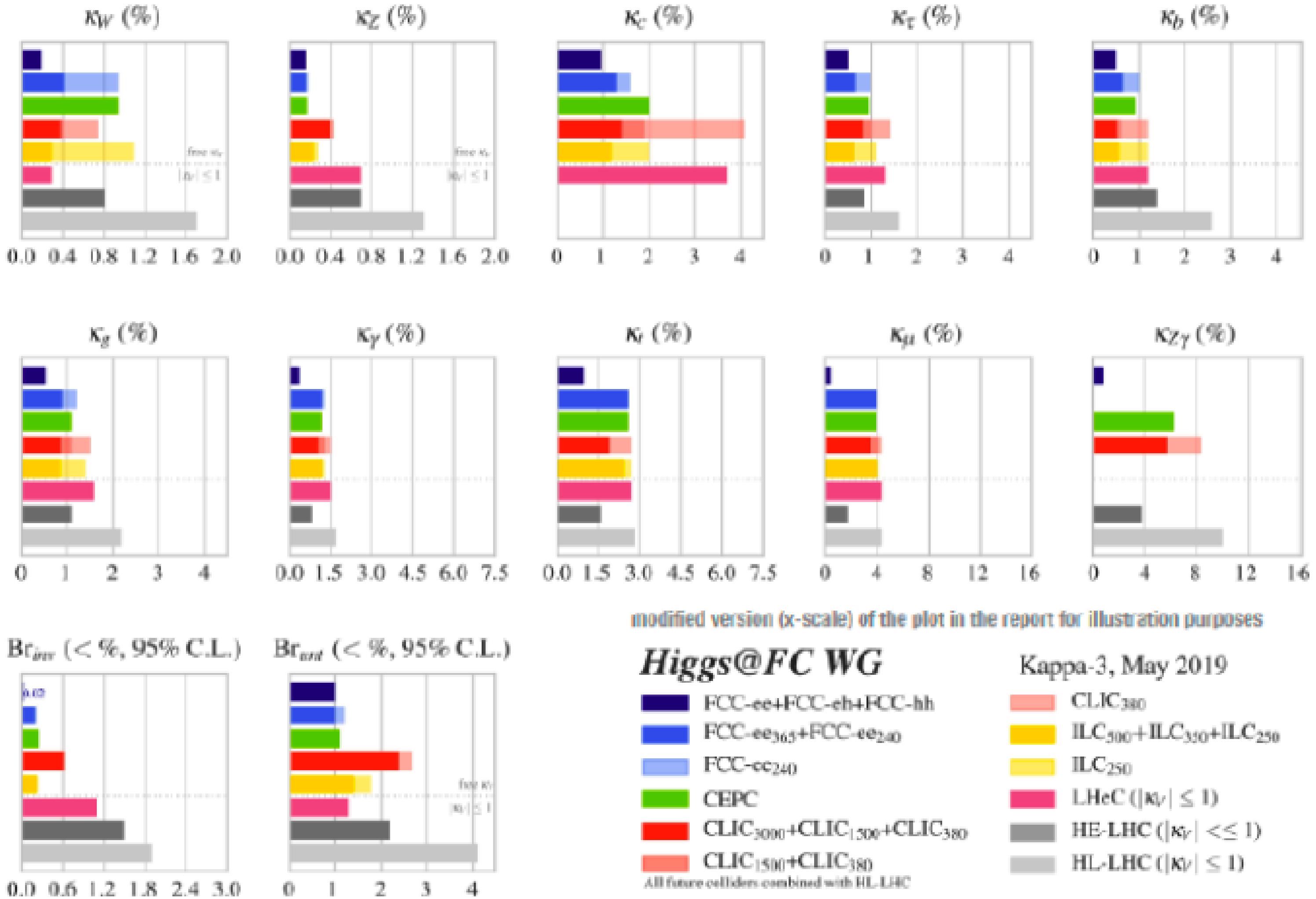
MK at EPS 2019

Comparison of Colliders: kappa-framework

Some observations:

- **HL-LHC** achieves precision of ~1-3% in most cases
  - In some cases model-dependent
- Proposed e^+e^- and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10
- Initial stages of e^+e^- colliders have comparable sensitivities (within factors of 2)
- ee colliders constrain $BR \rightarrow \mathit{untagged}$ w/o assumptions
- Access to κ_c at ee and eh

arXiv:1905.03764



modified version (x-scale) of the plot in the report for illustration purposes

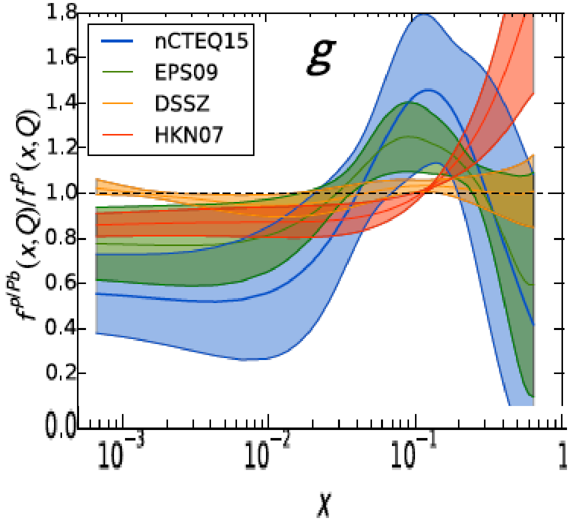
Nuclear PDFs at LHeC/FCCeh

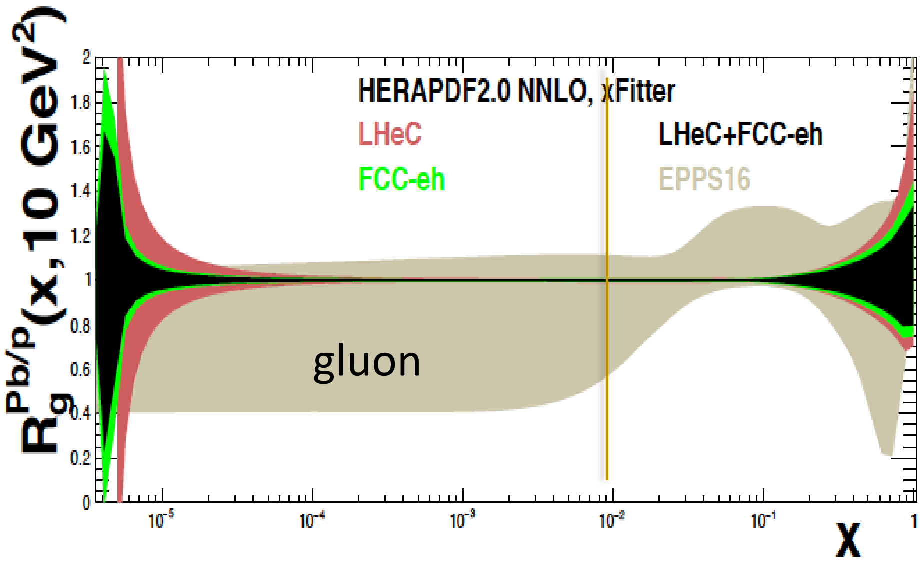
Unique nuclear/HI physics programme
Extension of fixed target range by 10^{3-4}
QCD of QGP, de-confinement, saturation..
nPDFs independent of p PDFs

High luminosity ~ 10^{33} enables high statistics in short eA runs
cf J Jowett et al

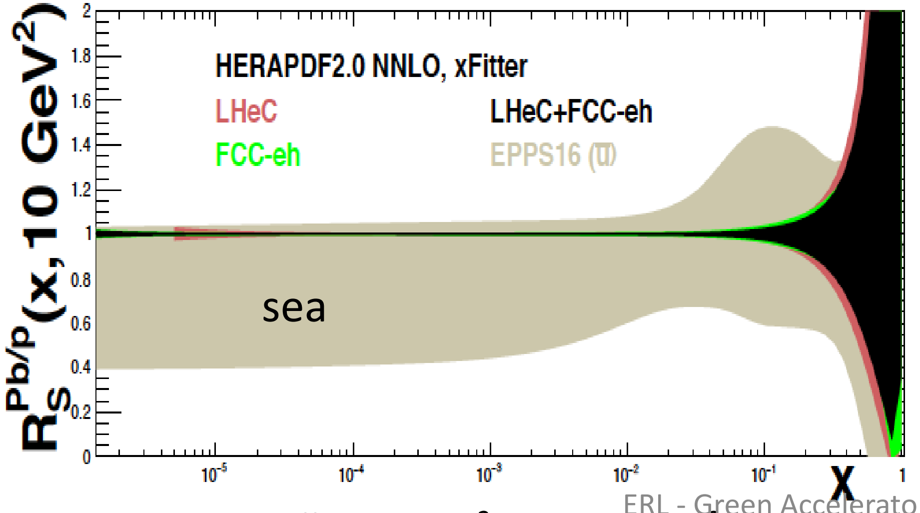
present status → on xg Pb/p

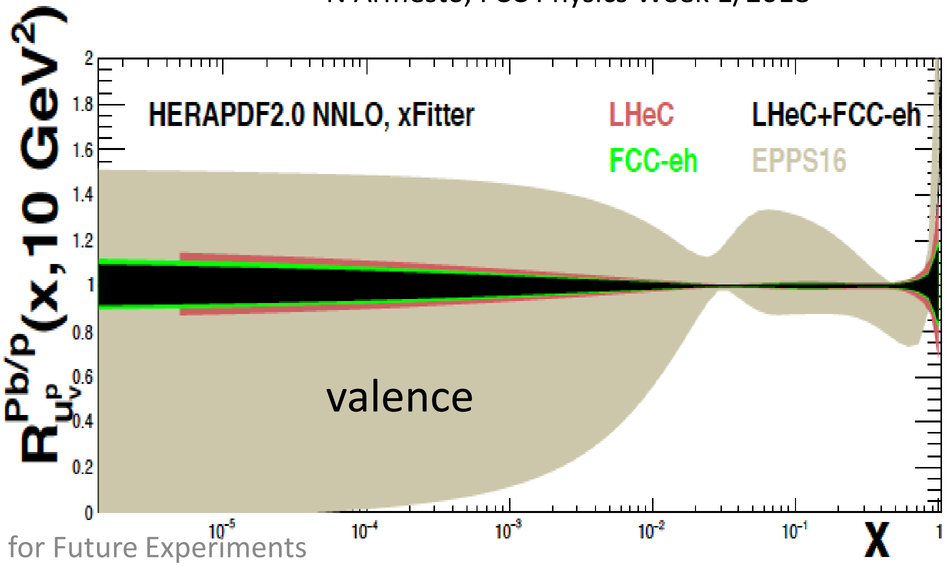
1509.00792





N Armesto, FCC Physics Week 1/2018



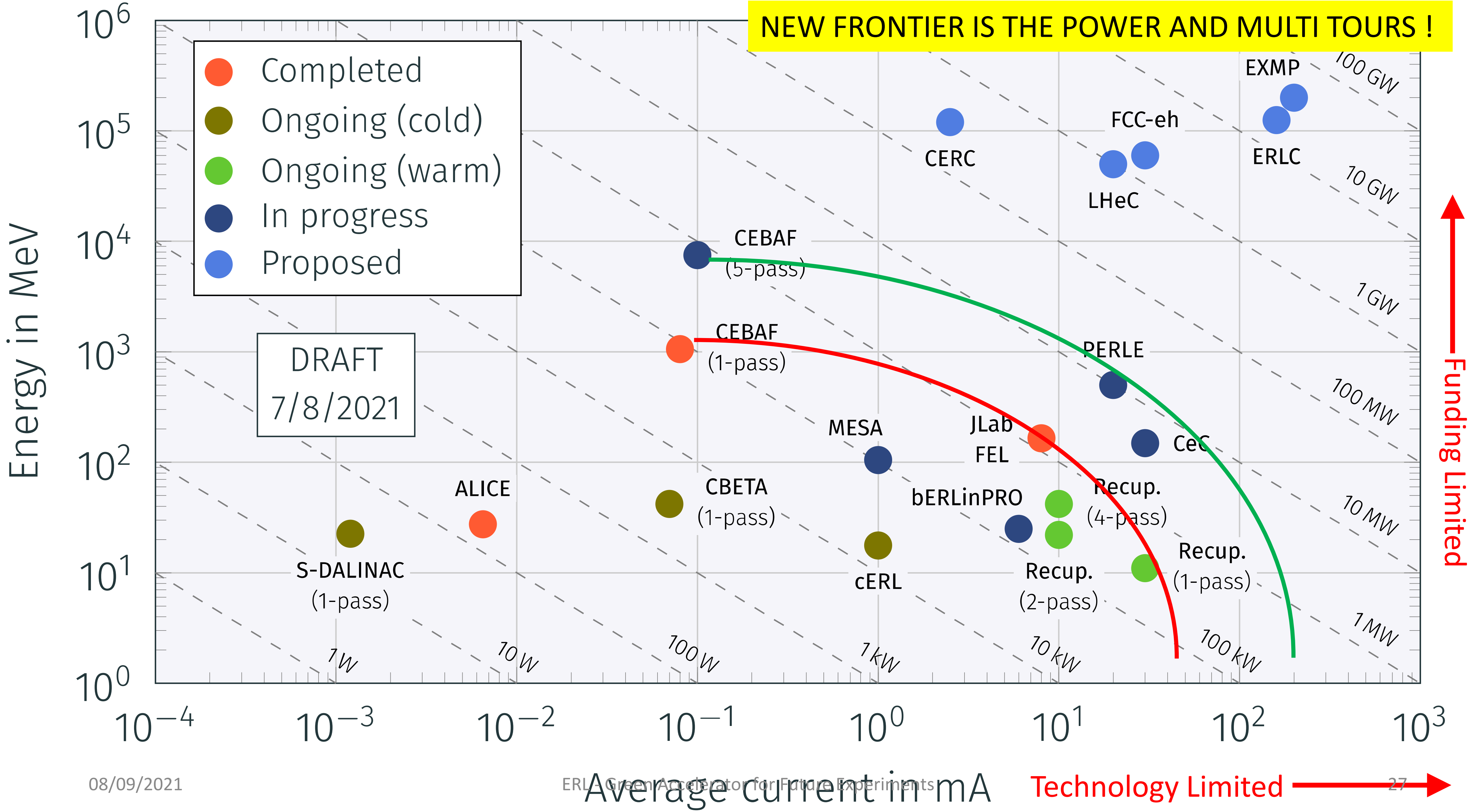


cf talk by
A Stasto today

LHeC: Full error, $\Delta\chi^2 = 1$. EPPS $\Delta\chi^2 = 52$

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

NEW FRONTIER IS THE POWER AND MULTI TOURS !

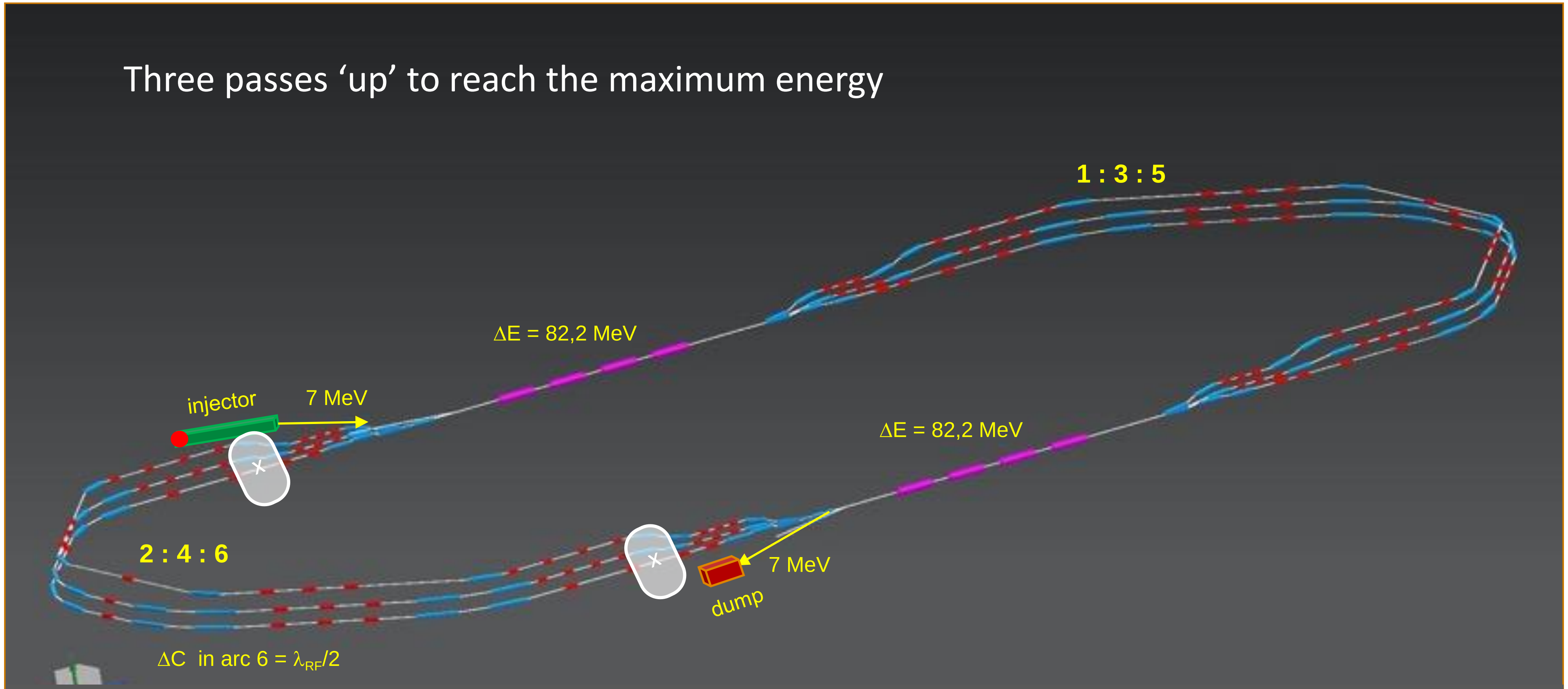


Funding Limited

Technology Limited

To prouve that we can go at high energy we need a demonstrator : PERLE

PERLE Configuration



Three passes ‘up’ to reach the maximum energy

Electron beam at maximum energy could be used for:

- Elastic electron-proton scattering with polarised beam (Particle physics)
- Exploration of proton densities in exotic nuclei by electron scattering (Nuclear physics)
- Gamma ray production between 0.2 and 5 MeV (wide applications in Photo-nuclear physics),

PERLE parameters

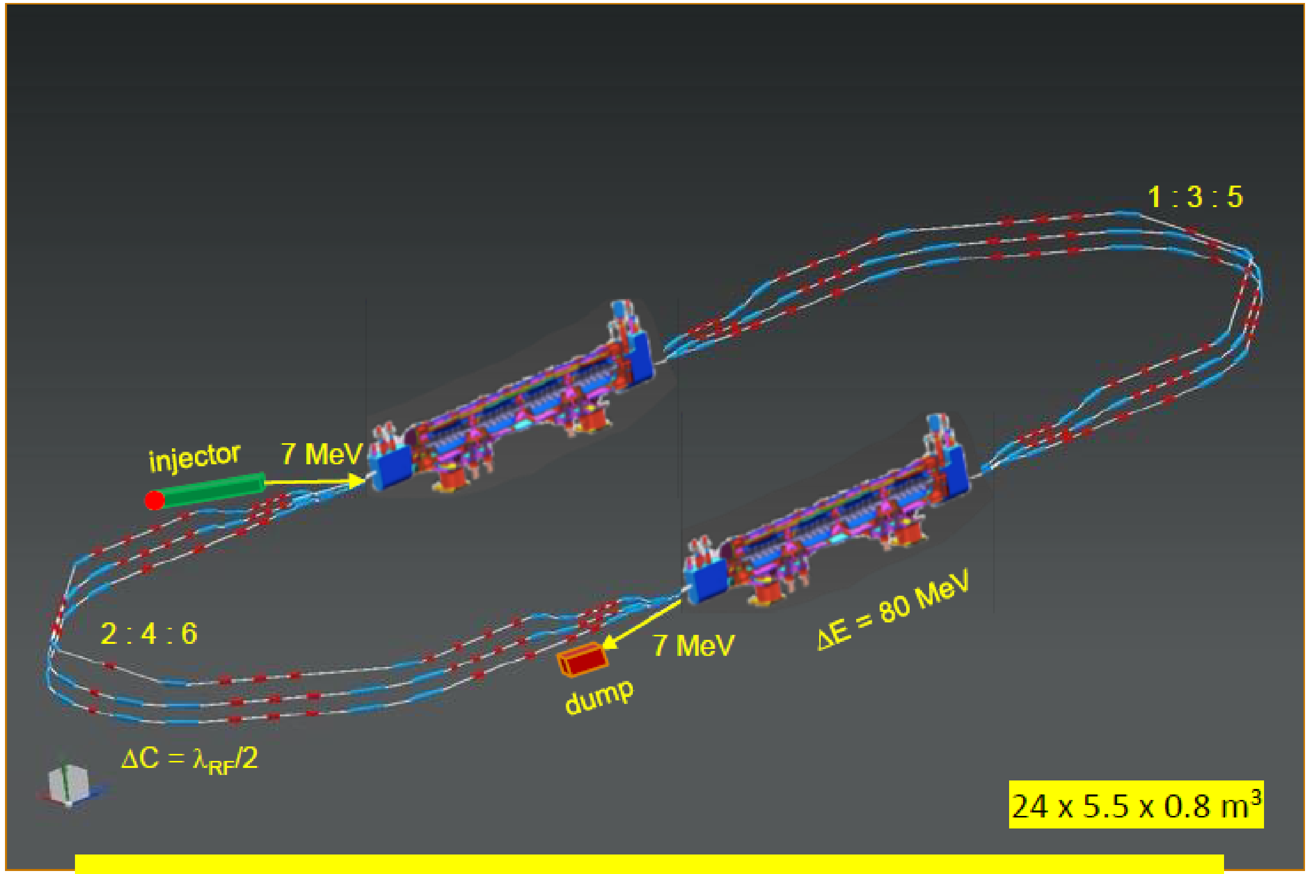
PERLE: A proposed multiple pass ERL based on SRF technology, to serve as testbed for validating and testing a broad range of accelerator phenomena & technical choices for future projects.

Particularly, design challenges and beam parameters are chosen to enable PERLE as the hub for technology development (especially on SRF) for the Large Hadron Electron Collider (LHeC)

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

PERLE * (ERL R&D → Physics [NP, PP])

ALICE DC Photocathode, JLEIC Booster and SPL Cryomodule – in kind



Collaboration is formed but still opened to new comers !

CERN, Cornell, Daresbury, Jefferson Lab, Liverpool, Novosibirsk, IJCLab Orsay (Host) Collaboration, growing: Grenoble, GANIL +

Paramater	Unit	Value
Frequency	MHz	801.58
Number of cells		5
active length l_{act}	mm	917.9
loss factor	V pC^{-1}	2.742
R/Q (linac convention)	Ω	523.9
$R/Q \cdot G$ per cell	Ω^2	28788
Cavity equator diameter	mm	327.95
Cavity iris diameter	mm	130
Beam tube inner diameter	mm	130
diameter ratio equator/iris		2.52
E_{peak}/E_{acc}		2.26
B_{peak}/E_{acc}	mT/(MV/m)	4.2
cell-to-cell coupling factor k_{cc}	%	3.21
TE$_{11}$ cutoff frequency	GHz	1.35
TM$_{01}$ cutoff frequency	GHz	1.77

Table 10.15: Parameter table of the 802 MHz prototype five-cell cavity.

LHeC Design Update
2007.14491
J.PhysG, 21

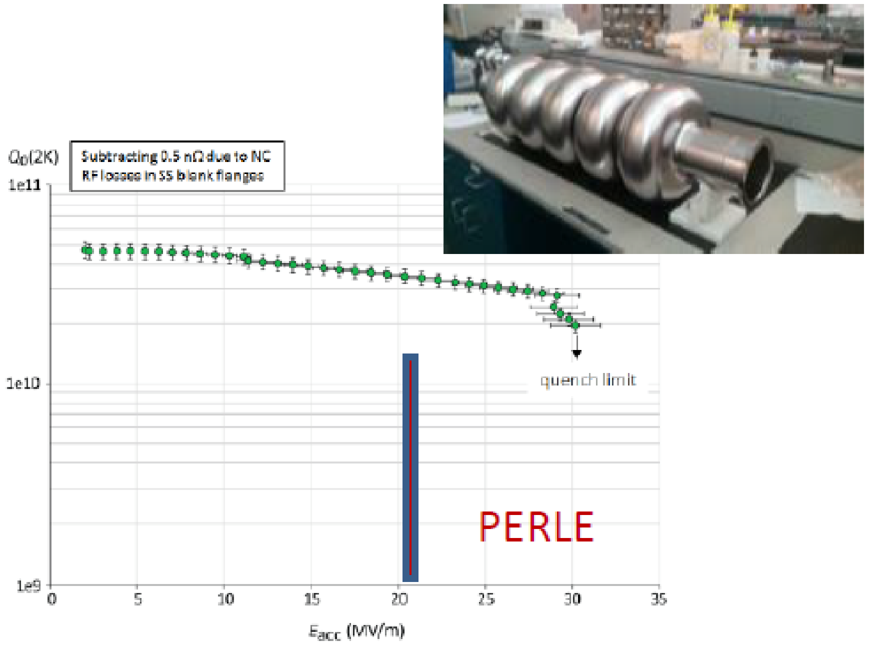


Figure 10.20: Vertical test result of the five-cell 802 MHz niobium cavity prototype.

[* PERLE. Powerful energy recovery linac for experiments. Conceptual design report](#)
Published in: *J.Phys.G* 45 (2018) 6, 065003 e-Print: 1705.08783 [physics.acc-ph]

2025
End Phase 0: Injection line

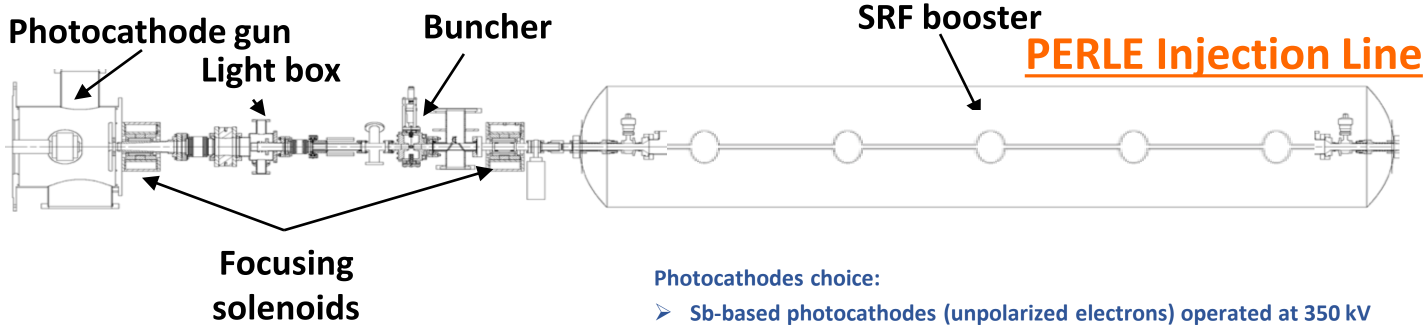
2030
End Phase 2: PERLE @ 500MeV

2022
PERLE TDR

2028
End Phase 1: PERLE @ 250MeV

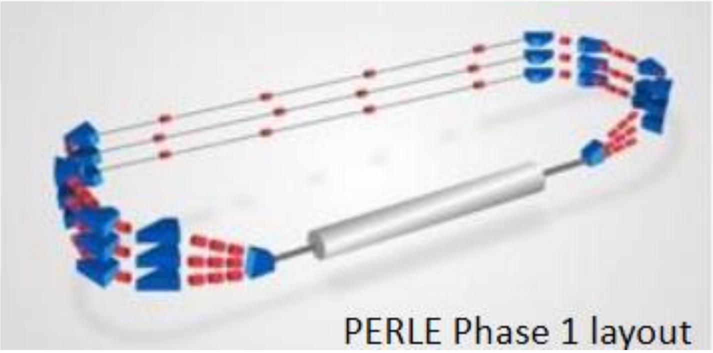
Already some nice acheivement on machine design, injection lines, SFR cavity…

PERLE Injection Line



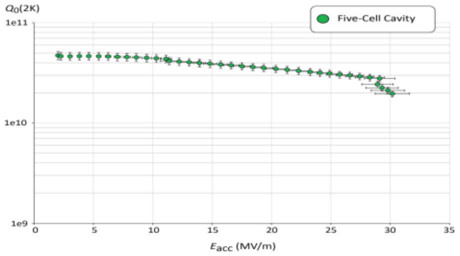
Photocathodes choice:

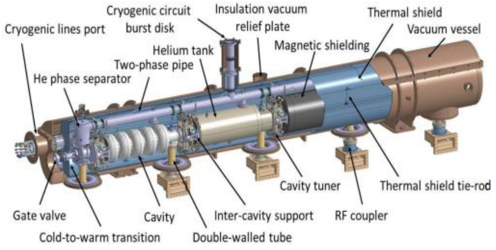
- Sb-based photocathodes (unpolarized electrons) operated at 350 kV
- GaAs photocathodes (polarized electrons) operated at 220 kV


PERLE Phase 1 layout

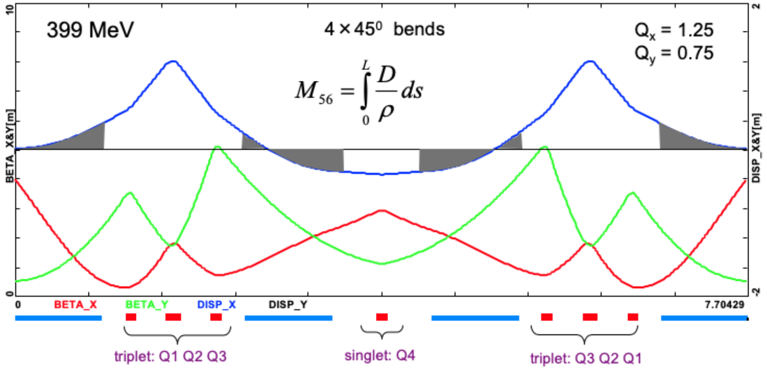

PERLE Phase 2 layout

PERLE SRF System

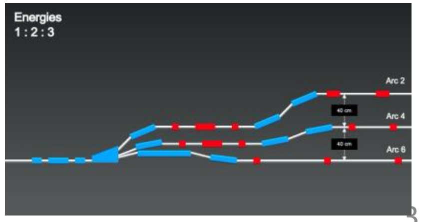




Lattice design optimisation of switchyards and circulating arcs



$$M_{56} = \int_0^L \frac{D}{\rho} ds$$



+ some important new material coming to Orsay….

Transportation of the ALICE gun to Orsay


Image created using Canva.com

+ and identification of the zone where we want to install the machine…

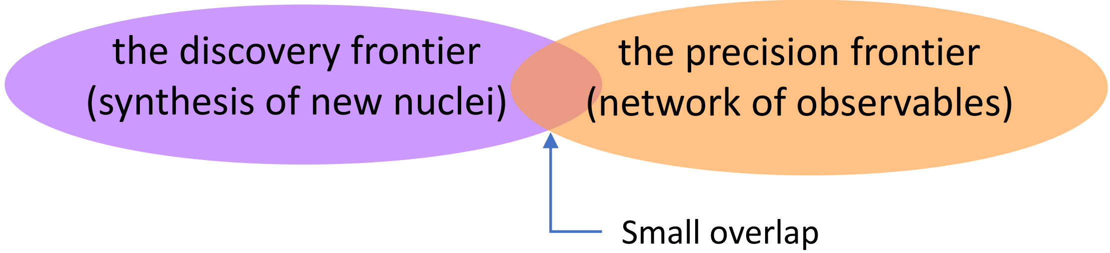
Could you do already physics with PERLE… Namely a low energy ERL .. ?

Some nuclear physics opportunities with PERLE@Orsay and the perspectives it would open

DESTIN initiative – **DE**ep **ST**ructure **I**nvestigation of (exotic) **N**uclei

DIS at lower energy !

XXIst century's challenge for nuclear physics:


the discovery frontier (synthesis of new nuclei)

the precision frontier (network of observables)

Small overlap

The electromagnetic probes for low-energy nuclear physics

- ion manipulation with em fields: mass measurements
- interaction with the hyperfine field : laser spectroscopy, nuclear orientation→ $I^{(\pi)}$,μ, Q_s, $\delta<r^2_c>$

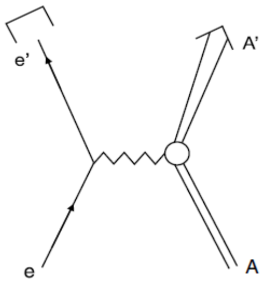
e.g. ISOL (DESIR/SPIRAL2, ALTO …) low-energy physics

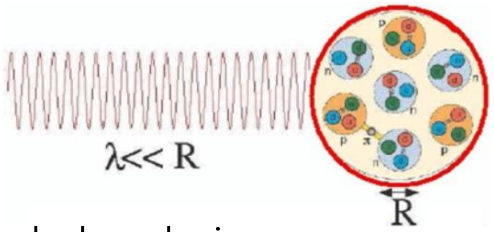
- γ-spectroscopy : lifetimes, B(Eλ), B(Mλ)

e.g. AGATA physics

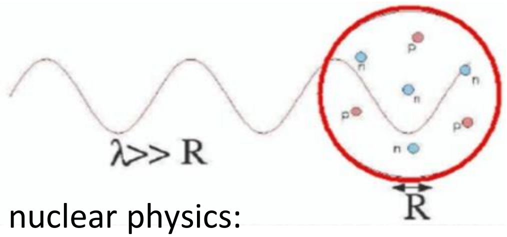
- e- scattering

e momentum transfer q $\approx 1/\lambda$





hadron physics:
structure of the nucleon



nuclear physics:
internal structure of the nucleus

E_e= 500 MeV → ≈0.5 fm scale

contrary to hadron probe, the only unknown in the reaction is the nuclear part

The main challenge : luminosity

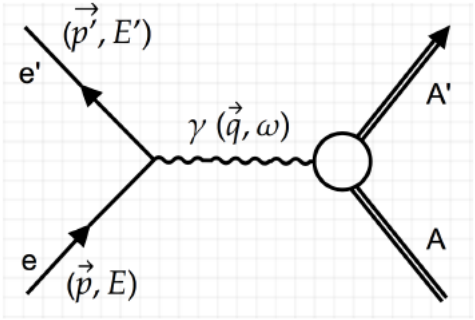
DIS at lower energy !

RIB = Radioactive Nuclei Beam

We know/have studied the stable Nuclei,
BUT not the Radioactive ones !
How they look like : charge radius, shape… ?
New properties are emerging (halo, pairing..)

What we need to measure :

$$\frac{d\sigma}{d\Omega\, dE} = \frac{4\pi}{M_T}\,\sigma_{Mott}\left[\left(\frac{q_\lambda^2}{q^2}\right)^2 \boxed{S_L(q,\omega)} + \left(\frac{1}{2}\frac{q_\lambda^2}{q^2} + \tan^2\frac{\theta}{2}\right)\boxed{S_T(q,\omega)}\right]$$



$$\begin{cases} \omega \rightarrow Exc.\,Energy \\ q \rightarrow r \end{cases}$$

Nuclear response surfaces
or
Dynamic structure functions

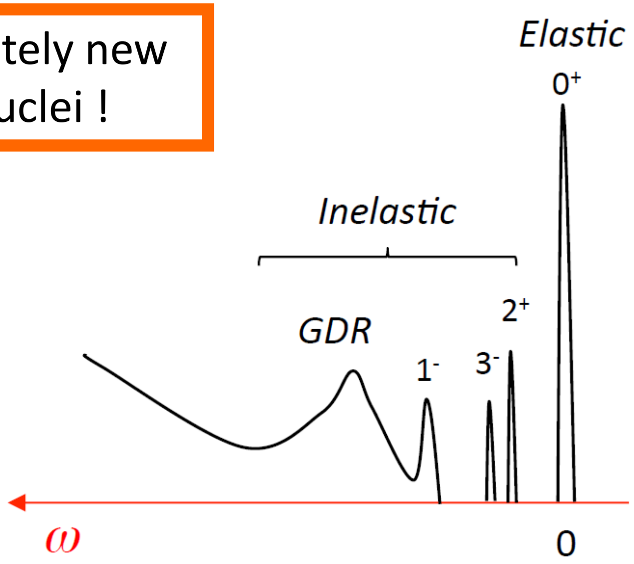
Simple imaging → Full tomography

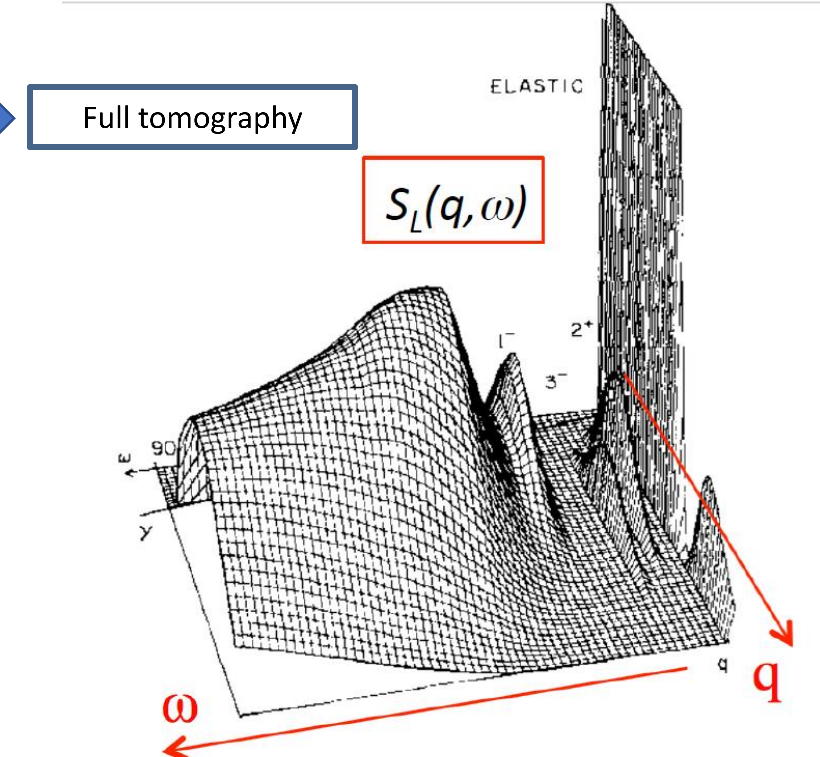
Combined with RIB : would open a completely new horizon, explore the interior of exotic nuclei !

…and walk in the footsteps of R. Hofstadter

(1953 : e scattering off gold, Stanford)

Nobel price 1961





[Donelly and Walecka, ARNPS 25, 329 (1975)]

The main challenge : luminosity

	Ee	N_{beam}	target thickness	Luminosity
Hofstadter's era (1950s)	150 MeV	~ 1nA ($\sim 10^9$ /s)	$\sim 10^{19}$ /cm^2	$\sim 10^{28}$ /cm^2/s
JLAB	6 GeV	~100µA ($\sim 10^{14}$ /s)	$\sim 10^{22}$ /cm2	$\sim 10^{36}$ /cm^2/s

- **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**

  $\Rightarrow$ compromise $E_e \simeq 500$ MeV

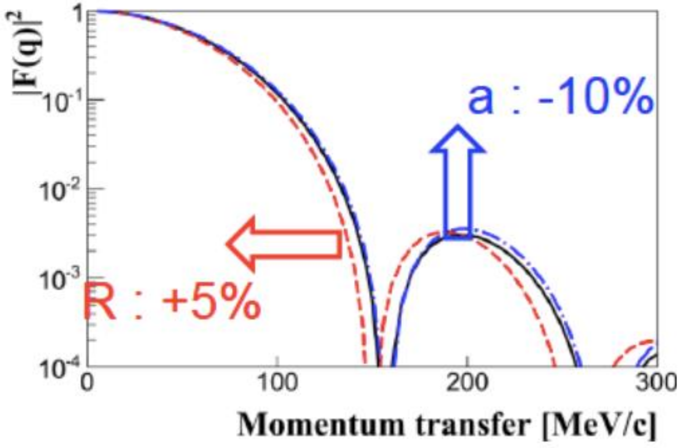
- Luminosity : $L = F_e n_e \dfrac{N_e N_A}{4\pi\sigma_x\sigma_y} = \dfrac{I_e\ N_A}{4\ \pi\ \sigma_x\ \sigma_y\ q_e}$

Observables deduced quantities	**Reactions** *(q: momentum transfer)*	**Type of nucleus**	**Required luminosity L**
r.m.s. charge radii	**(e,e)** *elastic at small q*	Light ($Z^2 \leq 100$)	L: 10^{24} cm^{-2}s^{-1}
Charge density distribution with 2 parameters ρ_{ch}	**(e,e)** *First min. in elastic form factor*	Light Medium Heavy	**L: 10^{28} 10^{26} cm^{-2}s^{-1} 10^{24}**
Charge density distribution with 3 parameters ρ_{ch}	**(e,e)** *2^{nd} min. in elastic form factor*	Medium Heavy	**L: 10^{29} cm^{-2}s^{-1} 10^{26}**
F_L, F_T Magnetic form factors→ Proton, neutron transition densities *Direct access to neutron-skin*	**(e,e)** *2^{nd} min. in elastic form factor*	Odd-even Medium Heavy	**L: 10^{30}cm^{-2}s^{-1} 10^{29}**
Energy spectra, width, strength, decays, collective excitations	**(e,e')**	Medium-Heavy	L: $10^{28\text{-}29}$ cm^{-2}s^{-1}
Extraction of the density distribution *using functionals (series of Fourier-Bessel functions …)*	**(e,e) (e,e')**	Light Medium-Heavy	**(e,e) (e,e') L : $10^{30\text{-}31}$ (e,e) (e,e') L ~$10^{29\text{-}30}$**
Spectral functions, correlations	**(e,e'p)**		$10^{30\text{-}31}$ **(e,e'p) L ~$10^{30\text{-}31}$** cm^{-2}s^{-1}

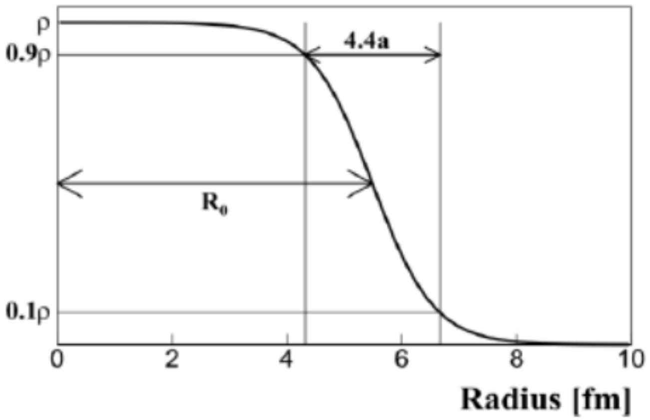
Extracted from "Electron scattering on radioactive ions at GANIL^2" (2020)
Authors: A. Chancé, P. Delahaye,¤, F. Flavigny, V. Lapoux,
A. Matta, V. Somà

$\Rightarrow$ the aimed luminosity should be 10^{29} cm^{-2}s^{-1}

but much can be already done at $\mathcal{L} \simeq 10^{28}$ (with unstable nuclei EVERYTHING is new !)



$$\rho_C = \rho/(1 + e^{(r-R)/a})$$



The main challenge : luminosity

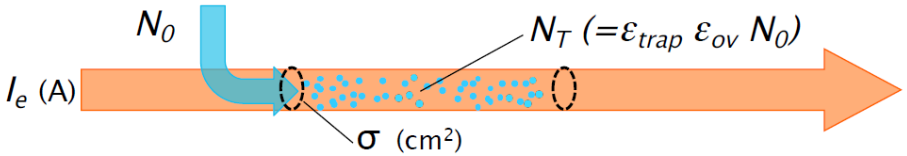
Two different strategies to address e-RIB scattering

→ double-ring collider : e.g. ELISE project at FAIR, DERICA project at JINR

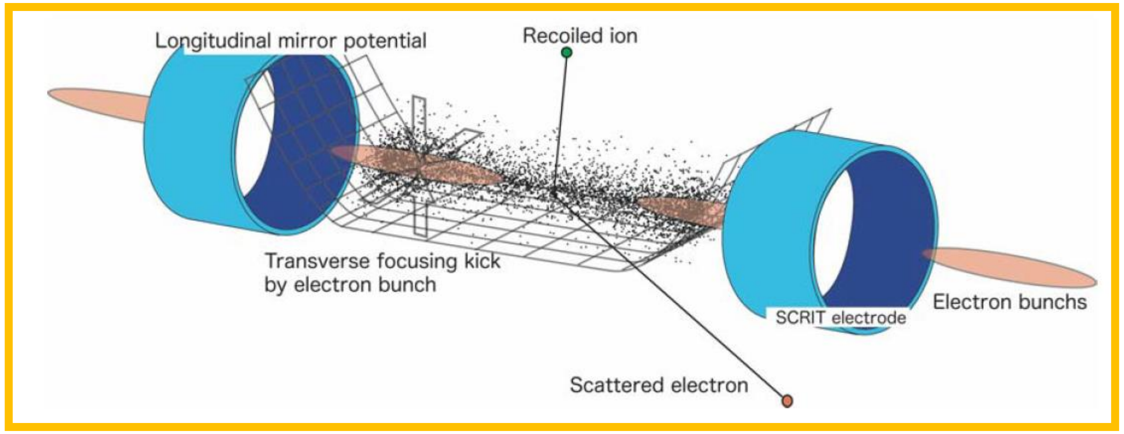
→ Self-confining fixed target : e.g. SCRIT at RIKEN

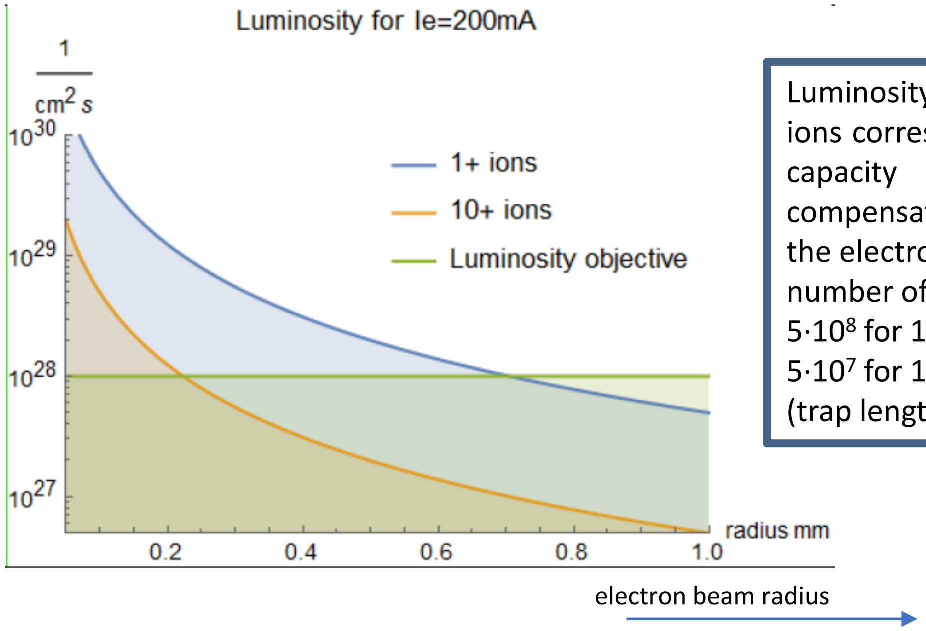
Perle@Orsay approach. Very chanllenging The beam will confine RIB in longitudinal plane e- with positive ions), and traps have to confined RIB in transversal plane

Achievable luminosity



$$L \sim \frac{I_e/e \quad N_T}{\sigma} \ /(\mathrm{cm^2 s})$$





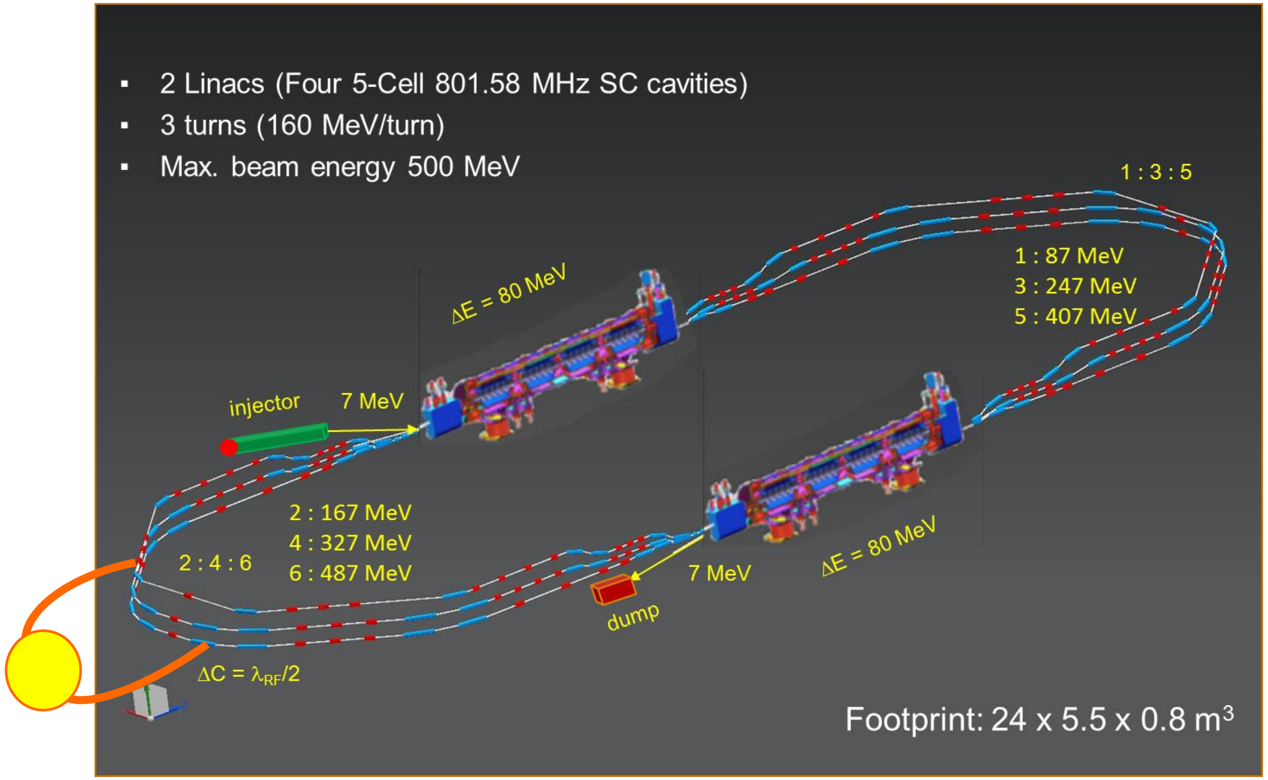
Luminosity for a number of trapped ions corresponding to the maximum capacity of the trap (i.e. fully compensating the space charge of the electron beam).
number of trapped ions:
$5 \cdot 10^8$ for 1^+
$5 \cdot 10^7$ for 10^+
(trap length 120 mm)

Pre-study extracted from “Electron scattering on radioactive ions at GANIL²” (2020)
Authors: A. Chancé, P. Delahaye, F. Flavigny, V. Lapoux, A. Matta, V. Somà

One of the conclusions : r_e<200 µm leads to considerable loss of trapping efficiency (ion heating)

A long road ahead before reaching
the full tomography of an exotic nucleus !

DESTIN [DEep STructure Investigation of (exotic) Nuclei]
would be a first step in that direction



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV

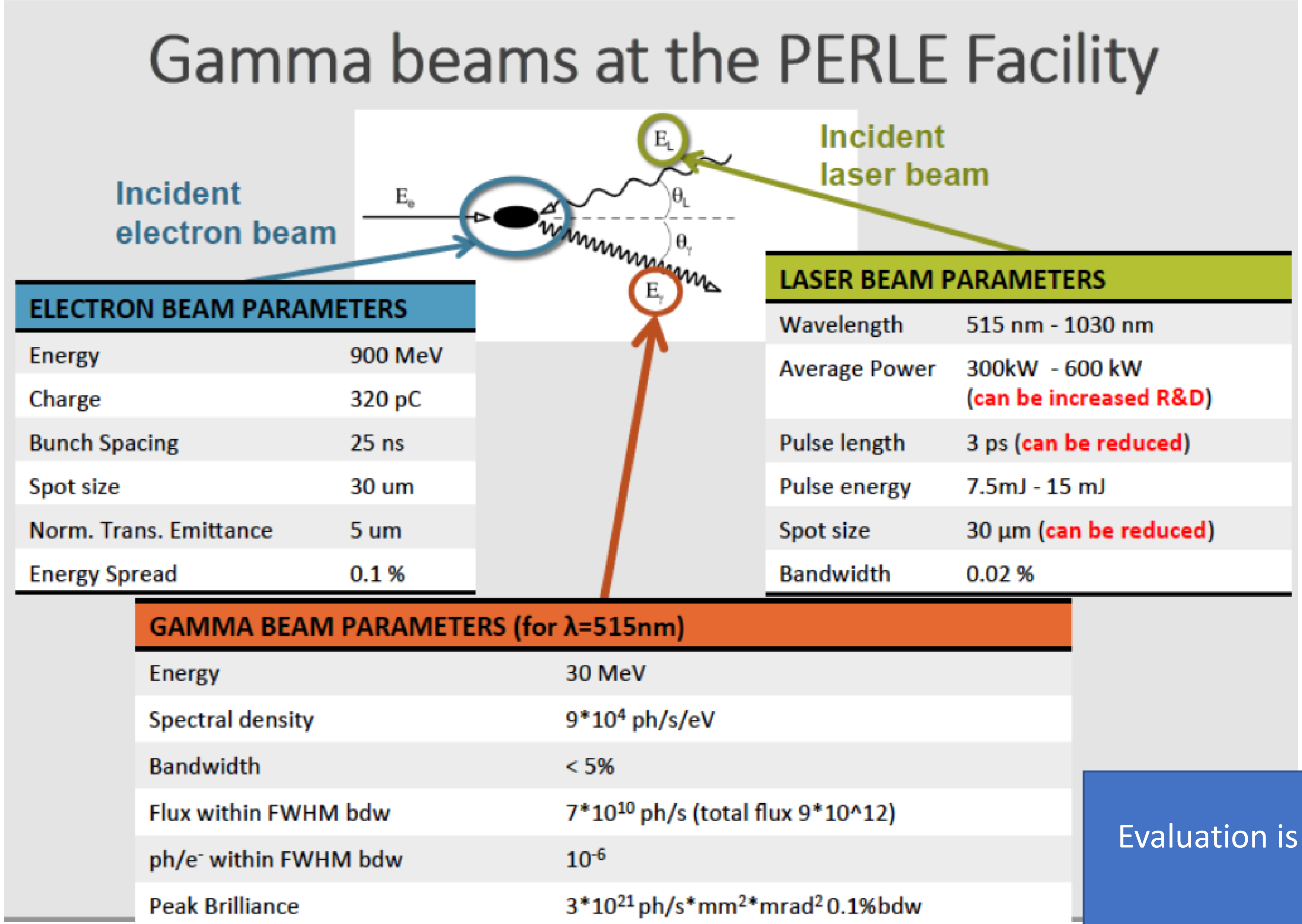
Footprint: 24 x 5.5 x 0.8 m^3

IP on arc #6

Goals:

- to seize the opportunity of the construction of an ERL prototype at PERLE @Orsay to build an RI-e-scattering experimental setup (inspired by SCRIT)
- a necessary demonstration step : e scattering off fixed very short lived target for the first time

→ Prepare all necessary R&D towards a fully optimized setup ($\rightarrow \mathcal{L} \simeq 10^{29}$) at GANIL (behind DESIR ?)
→ Explore a low-luminosity ($\mathcal{L} \simeq 10^{27}$) elastics scattering program with fission fragments RIB at Orsay



Gamma beams at the PERLE Facility

ELECTRON BEAM PARAMETERS	
Energy	900 MeV
Charge	320 pC
Bunch Spacing	25 ns
Spot size	30 um
Norm. Trans. Emittance	5 um
Energy Spread	0.1 %

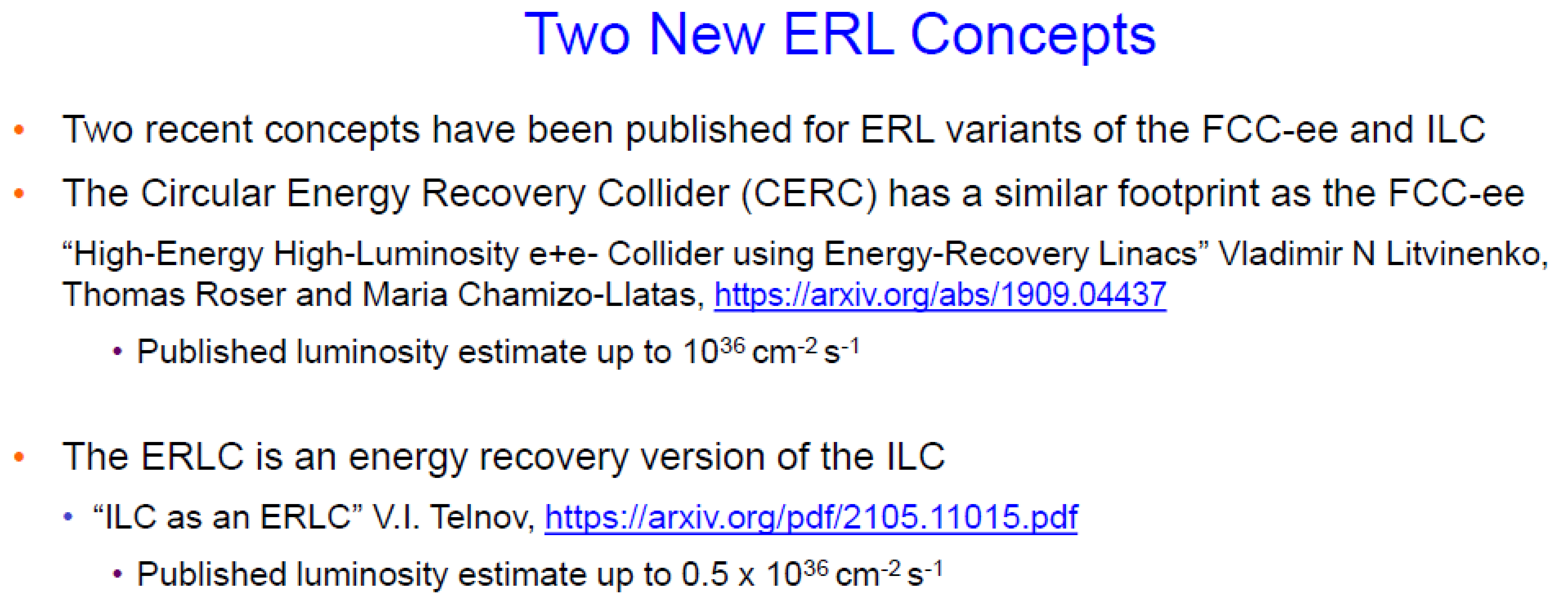
LASER BEAM PARAMETERS	
Wavelength	515 nm - 1030 nm
Average Power	300kW - 600 kW (can be increased R&D)
Pulse length	3 ps (can be reduced)
Pulse energy	7.5mJ - 15 mJ
Spot size	30 µm (can be reduced)
Bandwidth	0.02 %

GAMMA BEAM PARAMETERS (for λ=515nm)	
Energy	30 MeV
Spectral density	$9*10^4$ ph/s/eV
Bandwidth	< 5%
Flux within FWHM bdw	$7*10^{10}$ ph/s (total flux 9*10^12)
ph/e⁻ within FWHM bdw	10^{-6}
Peak Brilliance	$3*10^{21}$ ph/s*mm^2*mrad^2 0.1%bdw

Also photonics !

Evaluation is going on with 250 and 500 MeV beam

At the end I want just to showing you , two new ideas !



Two New ERL Concepts

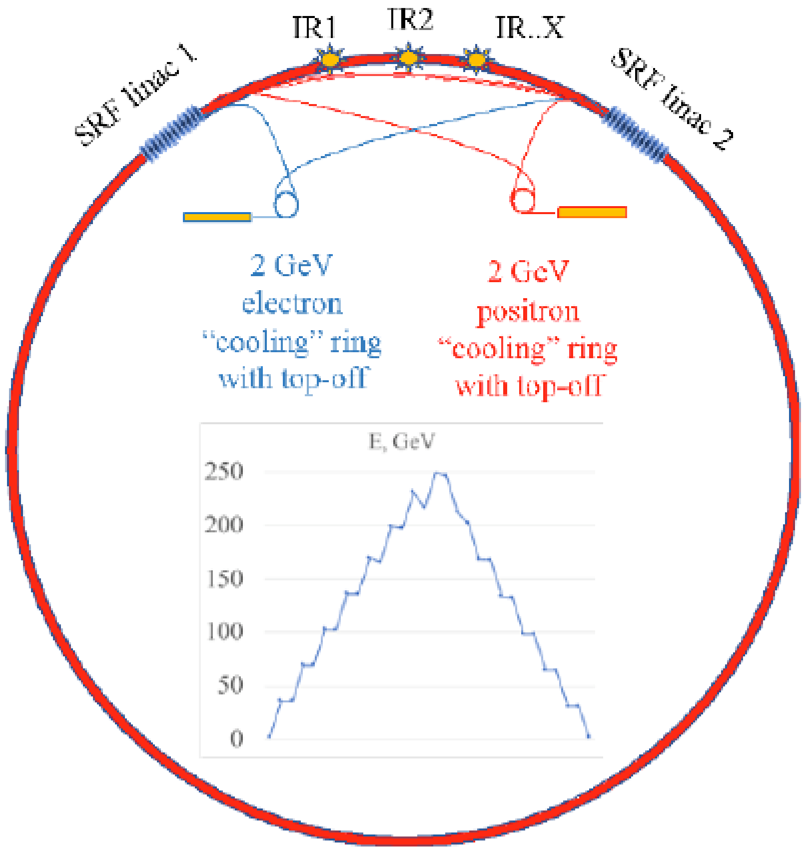
- Two recent concepts have been published for ERL variants of the FCC-ee and ILC
- The Circular Energy Recovery Collider (CERC) has a similar footprint as the FCC-ee

  “High-Energy High-Luminosity e+e- Collider using Energy-Recovery Linacs” Vladimir N Litvinenko, Thomas Roser and Maria Chamizo-Llatas, https://arxiv.org/abs/1909.04437

    - Published luminosity estimate up to 10^{36} cm^{-2} s^{-1}

- The ERLC is an energy recovery version of the ILC
  - “ILC as an ERLC” V.I. Telnov, https://arxiv.org/pdf/2105.11015.pdf
    - Published luminosity estimate up to 0.5 x 10^{36} cm^{-2} s^{-1}

Circular Energy Recovery Collider Concept: CERC proposal



- Two 11 to 90 GeV SRF linacs in 4 pass configuration
- 1/3rd of power consumption as compared to circular collider
- CM Energy reach of 600 GeV in 100 km circumference tunnel
- Damping rings for emittance reduction and recycling of beams

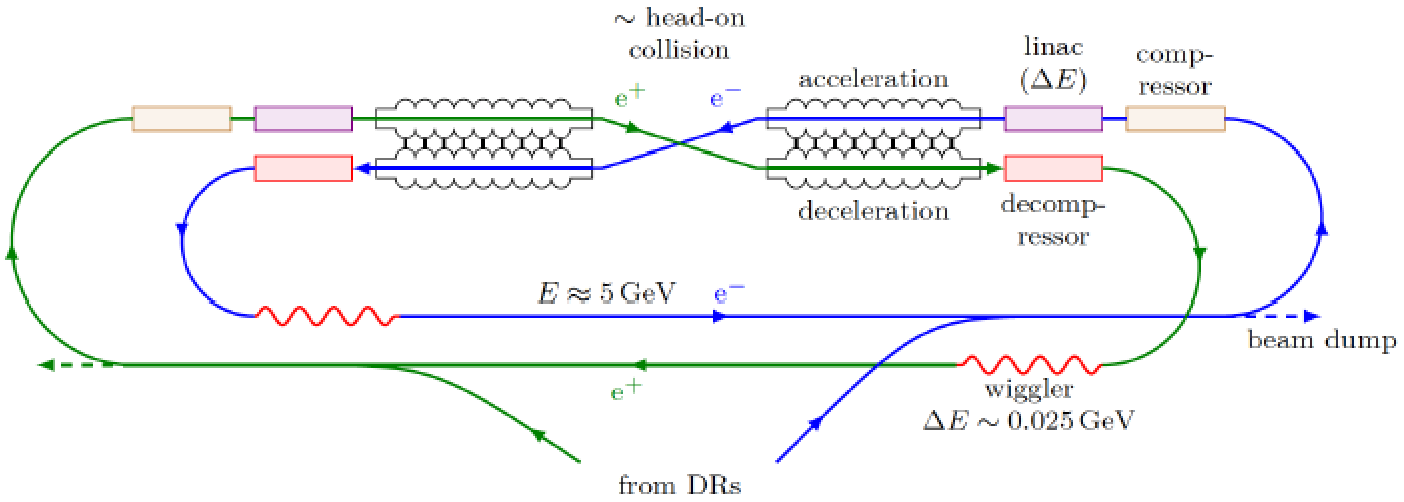
https://arxiv.org/abs/1909.04437

Physics Letters B, 804 (2020) 135394

- Maximum Power of 300 MW per beam @ 120 GeV and 2.47 mA

V. Litvinenko BNL and Stony Brook University; T. Roser BNL; C. Llatas BNL

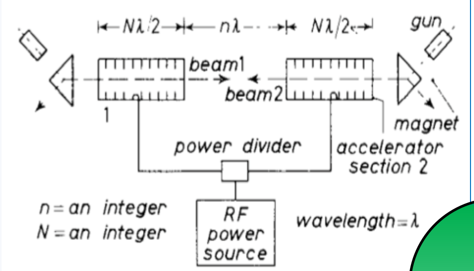
Energy Recovery Linear Collider Concept: ERLC proposal



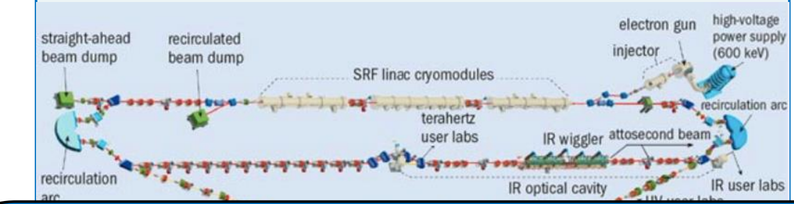
- ERLC consists of two parallel superconducting linacs connected to each other with RF-couplers, so that the fields are equal at any time
  - One line is for acceleration, the other for deceleration.
- Damping is provided by wigglers (no damping rings) at the “return” energy about E~5 GeV
- The energy loss per turn $\delta E/E \sim 1/100$
- Damping is needed to reduce the energy spread arising from collision of beams

PERLE parameters and prouve of principle which PERLE will do are also crucial to push forward these ideas !!

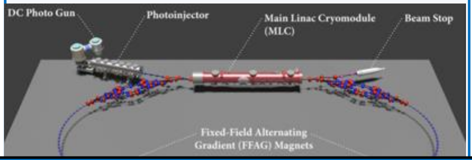
First Idea:
M. Tigner 1965



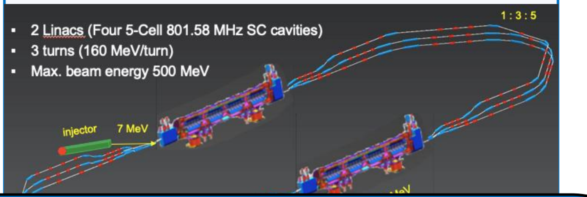
JLab First MW beam power operation
FEL Demo [1999] & Upgrade [2000]



Multi-turn SRF
C-Beta 2019-2020



Multi-turn SRF, multi-MW
PERLE@Orsay 2025



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV

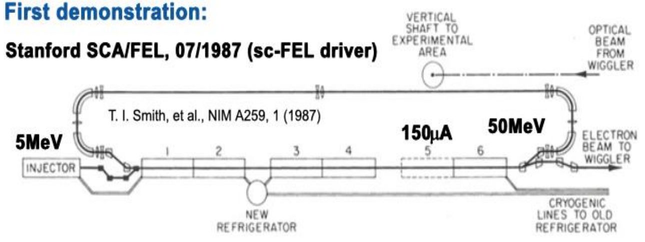
PERLE can validate the next 10-fold step in beam power

and provide the remaining demonstrations
[multi-turn ERL efficiency at high beam power]
➔
HEP is ready for implementing a truly green accelerator concept!

1960

1970

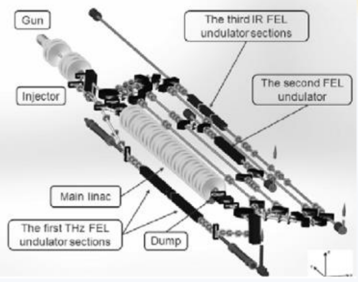
First Demonstration
SLAC SCA / FEL 1987



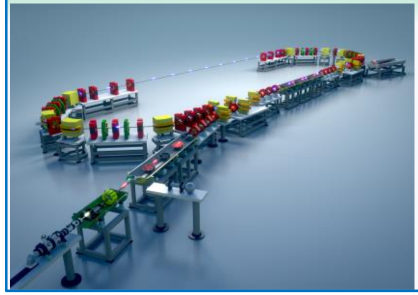
First demonstration:

Stanford SCA/FEL, 07/1987 (sc-FEL driver)

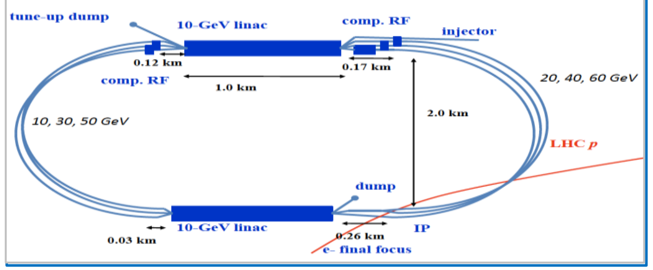
Multi-turn Operation
BINP FEL 2004 [NC]



Multi-MW Operation
bERLin-Pro 2020



HEP / NP ERL application
LHeC/FCC-eh; FCC-ee; ILC;



Animation from last workshop / conference ...

I hope I shown you how beautiful and fruitful is the ERL concept !

and of course

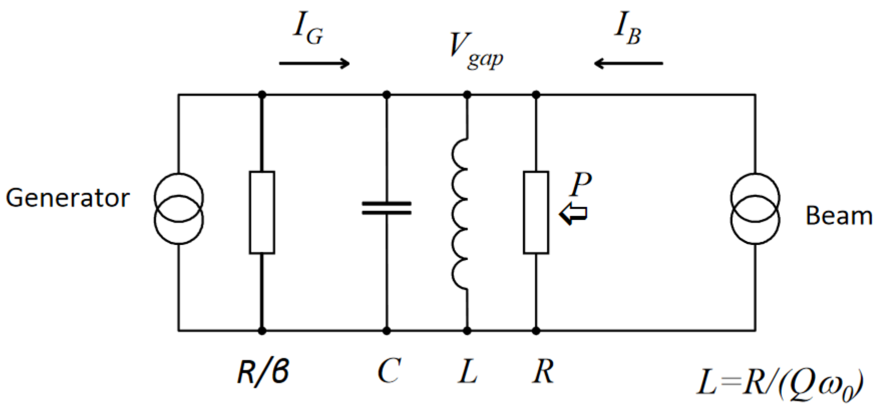
I hope I convinced you that is just the right time to work on ERL !

Looking forward to discuss with you and meeting you

BACKUP

Cavity resonator – equivalent circuit

Simplification: single mode



$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

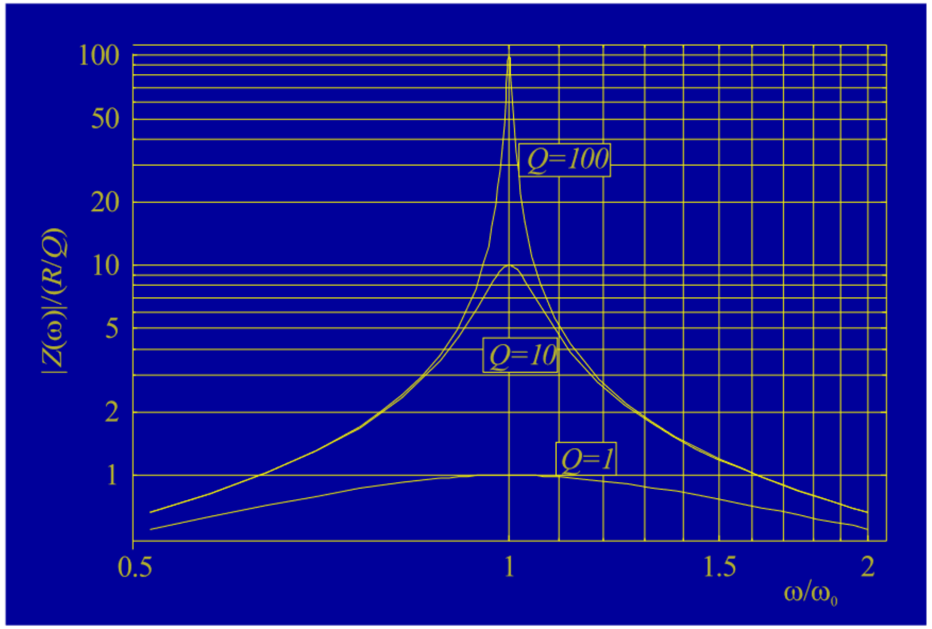
β: coupling factor

Cavity

R: Shunt impedance

$\sqrt{L/C}$: R-upon-Q

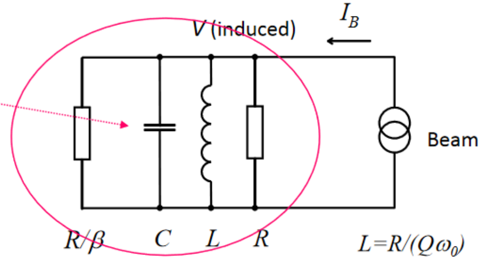
Resonance



Loss factor

Impedance seen by the beam

$$k_{loss}=\frac{\omega_0}{2}\frac{R}{Q}=\frac{|V_{gap}|^2}{4\,W}=\frac{1}{2\,C}$$



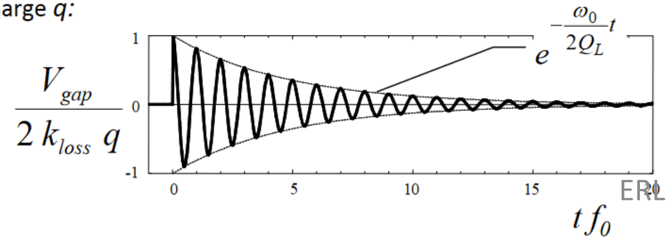
$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

Cavity

Energy deposited by a single charge *q*: $k_{loss}\,q^2$

Voltage induced by a single charge *q*:



Summary: relations V_{gap}, W, P_{loss}

gap voltage
V_{gap}

$$\frac{R}{Q}=\frac{|V_{gap}|^2}{2\,\omega_0 W}$$

$$k_{loss}=\frac{\omega_0}{2}\frac{R}{Q}=\frac{|V_{gap}|^2}{4\,W}$$

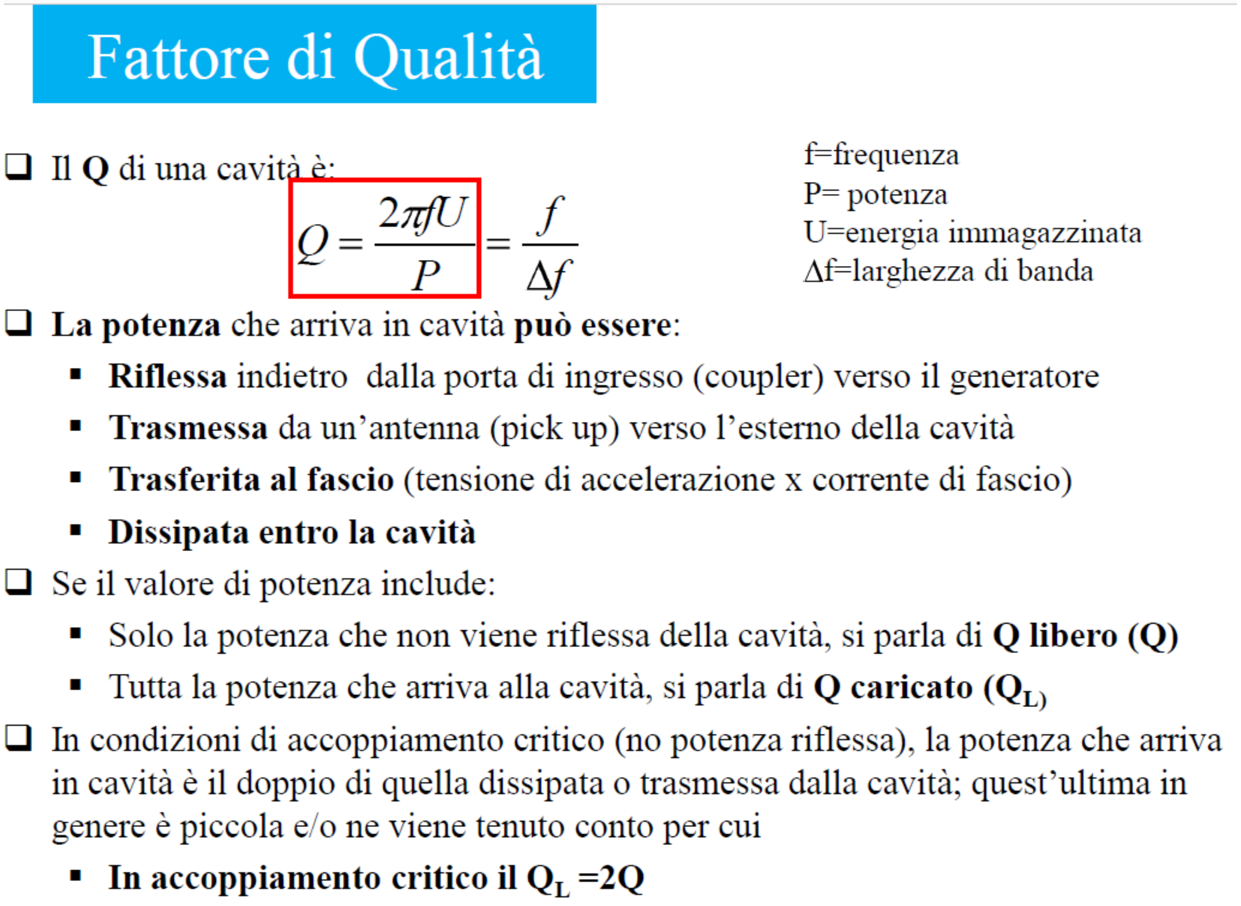
$$R_{shunt}=\frac{|V_{gap}|^2}{2\,P_{loss}}$$

Energy stored inside the cavity
W

Power lost in the cavity walls
P_{loss}

$$Q=\frac{\omega_0 W}{P_{loss}}$$

The Q Factor.



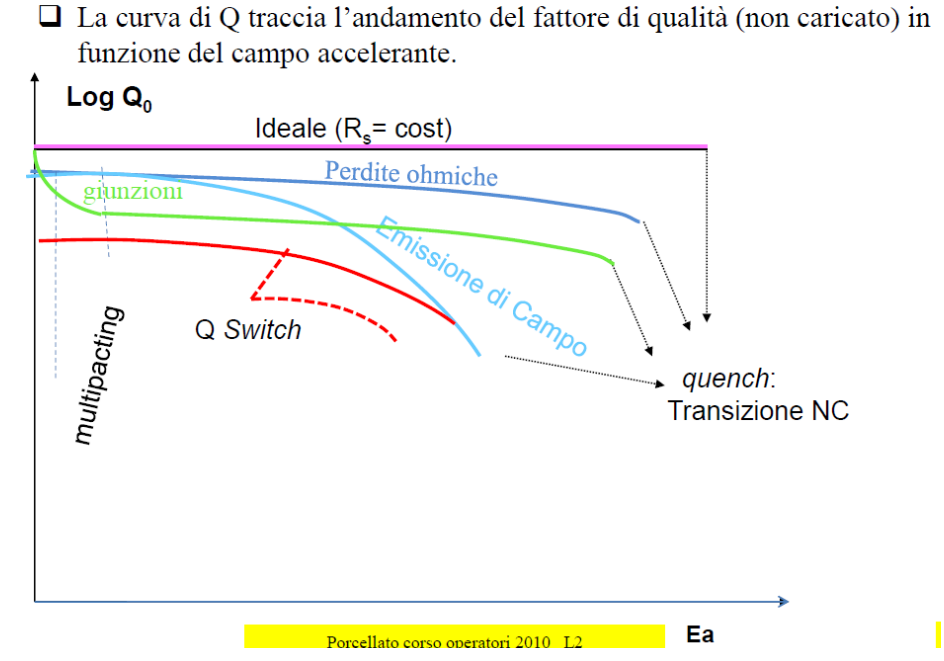
Fattore di Qualità

- ❑ Il **Q** di una cavità è:

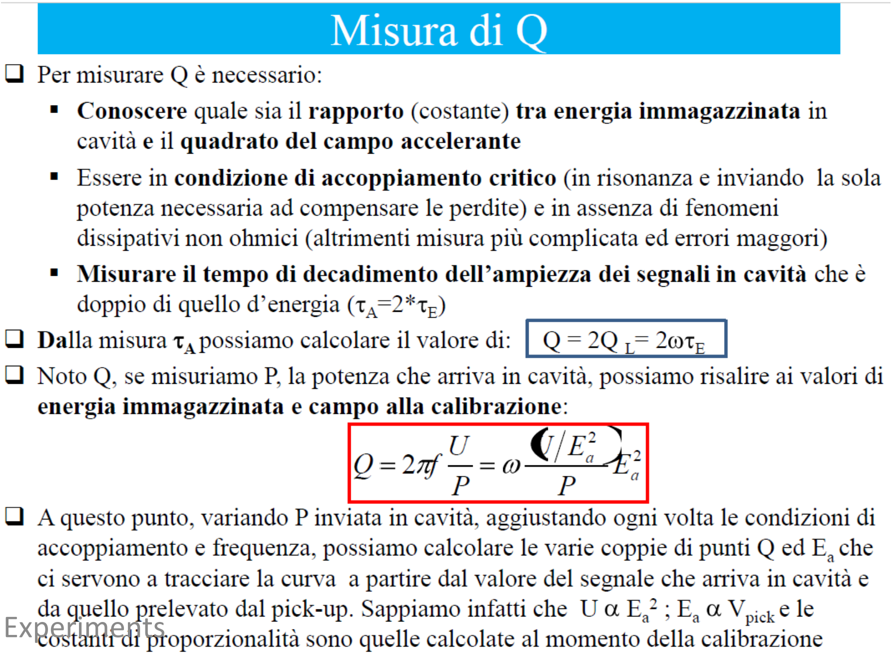
$$\boxed{Q = \frac{2\pi f U}{P}} = \frac{f}{\Delta f}$$

f=frequenza
P= potenza
U=energia immagazzinata
Δf=larghezza di banda

- ❑ **La potenza** che arriva in cavità **può essere**:
  - **Riflessa** indietro dalla porta di ingresso (coupler) verso il generatore
  - **Trasmessa** da un'antenna (pick up) verso l'esterno della cavità
  - **Trasferita al fascio** (tensione di accelerazione x corrente di fascio)
  - **Dissipata entro la cavità**
- ❑ Se il valore di potenza include:
  - Solo la potenza che non viene riflessa della cavità, si parla di **Q libero (Q)**
  - Tutta la potenza che arriva alla cavità, si parla di **Q caricato (Q_L)**
- ❑ In condizioni di accoppiamento critico (no potenza riflessa), la potenza che arriva in cavità è il doppio di quella dissipata o trasmessa dalla cavità; quest'ultima in genere è piccola e/o ne viene tenuto conto per cui
  - **In accoppiamento critico il Q_L =2Q**



- ❑ La curva di Q traccia l'andamento del fattore di qualità (non caricato) in funzione del campo accelerante.

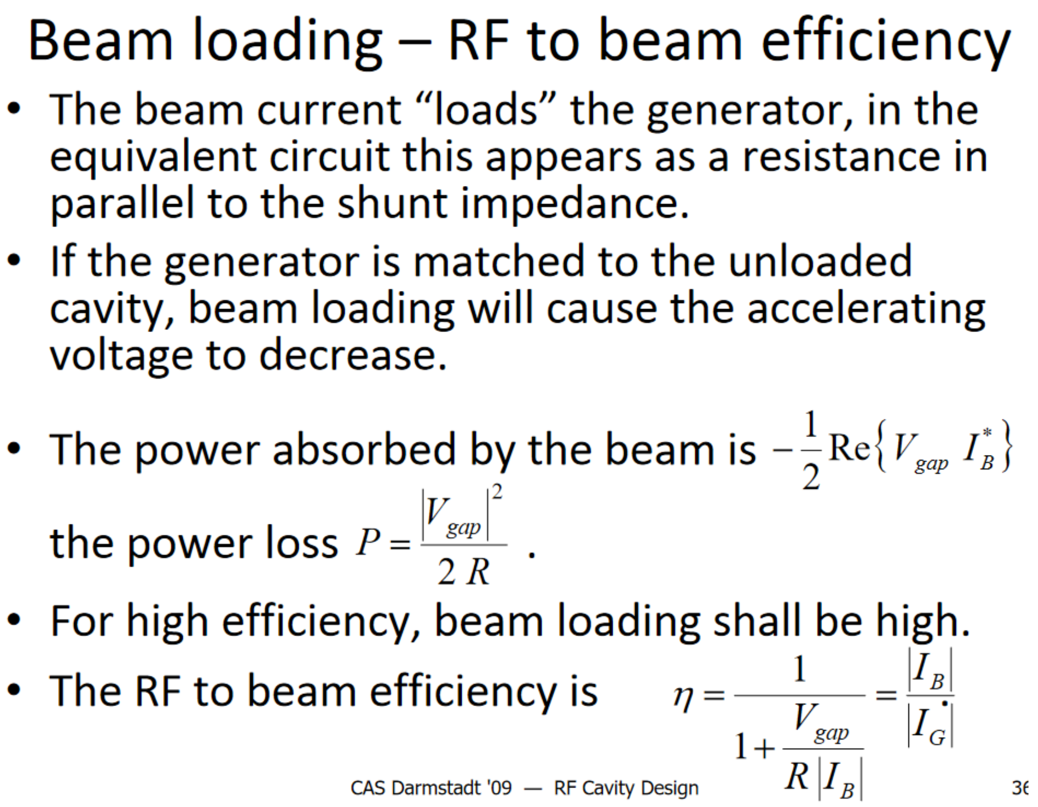


Misura di Q

- ❑ Per misurare Q è necessario:
  - **Conoscere** quale sia il **rapporto** (costante) **tra energia immagazzinata** in cavità **e** il **quadrato del campo accelerante**
  - Essere in **condizione di accoppiamento critico** (in risonanza e inviando la sola potenza necessaria ad compensare le perdite) e in assenza di fenomeni dissipativi non ohmici (altrimenti misura più complicata ed errori maggiori)
  - **Misurare il tempo di decadimento dell'ampiezza dei segnali in cavità** che è doppio di quello d'energia (τ_A=2*τ_E)
- ❑ **Dalla misura τ_A** possiamo calcolare il valore di: $\boxed{Q = 2Q_L = 2\omega\tau_E}$
- ❑ Noto Q, se misuriamo P, la potenza che arriva in cavità, possiamo risalire ai valori di **energia immagazzinata e campo alla calibrazione**:

$$\boxed{Q = 2\pi f \frac{U}{P} = \omega \frac{(U/E_a^2) E_a^2}{P}}$$

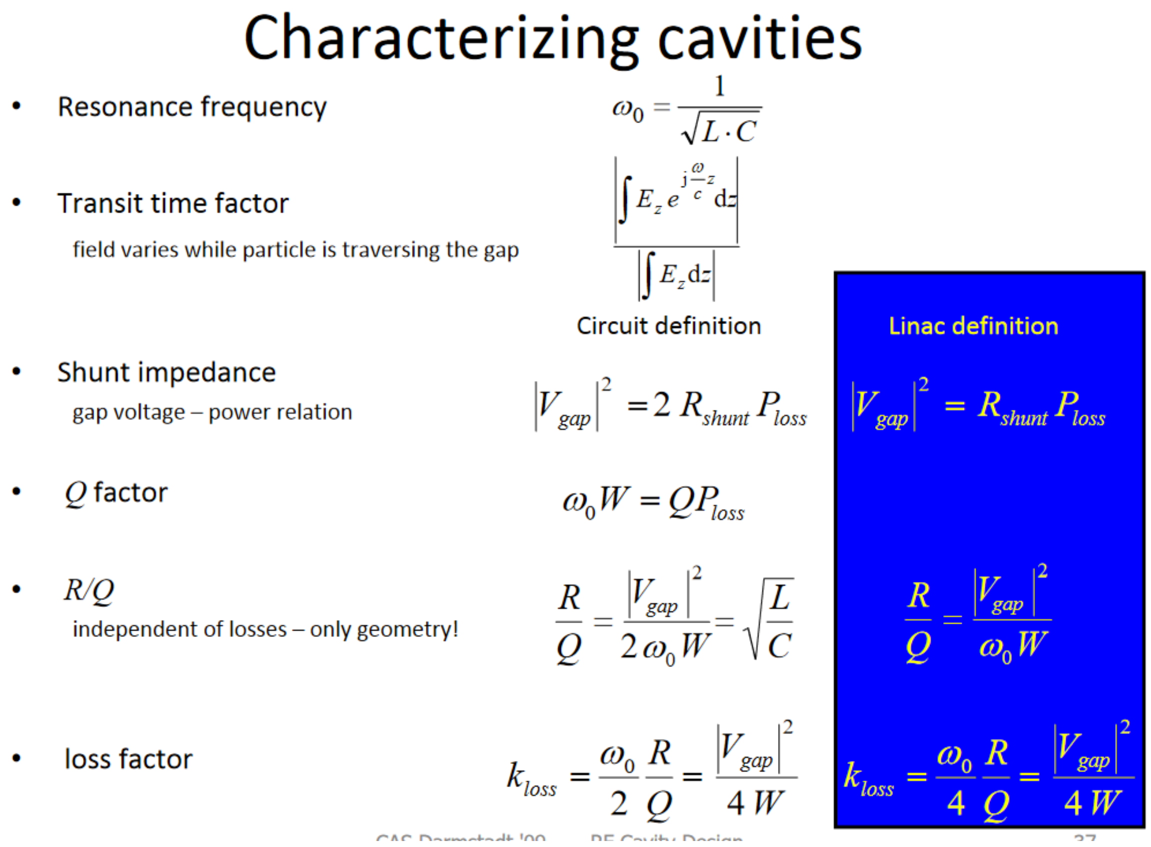
- ❑ A questo punto, variando P inviata in cavità, aggiustando ogni volta le condizioni di accoppiamento e frequenza, possiamo calcolare le varie coppie di punti Q ed E_a che ci servono a tracciare la curva a partire dal valore del segnale che arriva in cavità e da quello prelevato dal pick-up. Sappiamo infatti che U α E_a^2 ; E_a α V_{pick} e le costanti di proporzionalità sono quelle calcolate al momento della calibrazione



Beam loading – RF to beam efficiency

- The beam current “loads” the generator, in the equivalent circuit this appears as a resistance in parallel to the shunt impedance.
- If the generator is matched to the unloaded cavity, beam loading will cause the accelerating voltage to decrease.
- The power absorbed by the beam is $-\frac{1}{2}\mathrm{Re}\left\{V_{gap}\, I_B^*\right\}$
  the power loss $P = \frac{\left|V_{gap}\right|^2}{2\,R}$.
- For high efficiency, beam loading shall be high.
- The RF to beam efficiency is $\eta = \frac{1}{1+\frac{V_{gap}}{R\left|I_B\right|}} = \frac{\left|I_B\right|}{\left|I_G\right|}$

CAS Darmstadt '09 — RF Cavity Design 3



Characterizing cavities

- Resonance frequency $\omega_0 = \frac{1}{\sqrt{L \cdot C}}$
- Transit time factor $\frac{\left|\int E_z e^{j\frac{\omega}{c}z}\,\mathrm{d}z\right|}{\left|\int E_z\,\mathrm{d}z\right|}$
  field varies while particle is traversing the gap

Circuit definition

- Shunt impedance $\left|V_{gap}\right|^2 = 2\,R_{shunt}\,P_{loss}$
  gap voltage – power relation
- Q factor $\omega_0 W = Q P_{loss}$
- R/Q $\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{2\,\omega_0 W} = \sqrt{\frac{L}{C}}$
  independent of losses – only geometry!
- loss factor $k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4\,W}$

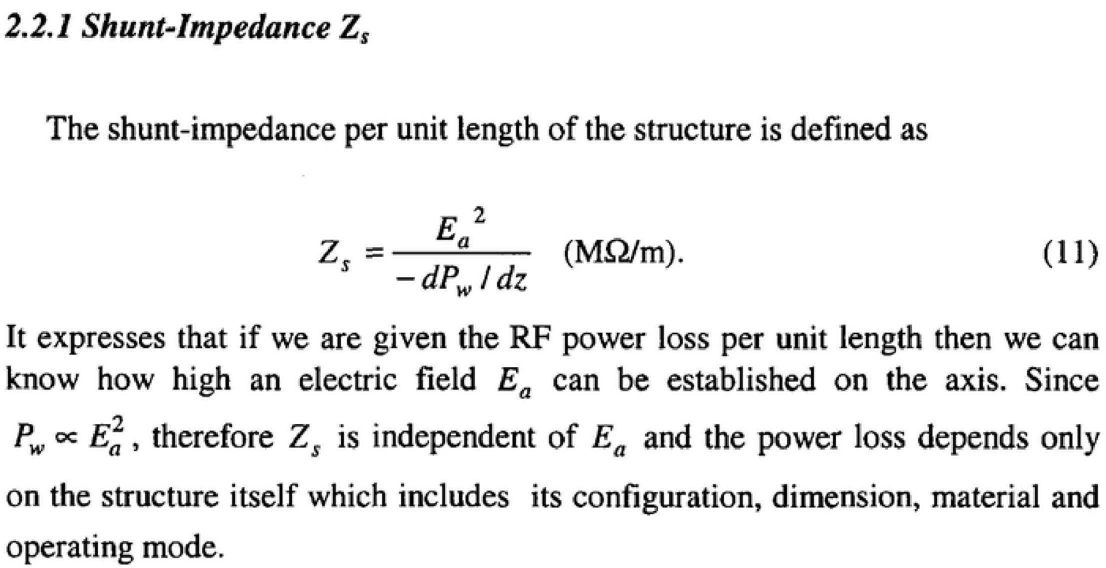
Linac definition

$$\left|V_{gap}\right|^2 = R_{shunt}\,P_{loss}$$

$$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{\omega_0 W}$$

$$k_{loss} = \frac{\omega_0}{4}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4\,W}$$

CAS Darmstadt '09 — RF Cavity Design 37

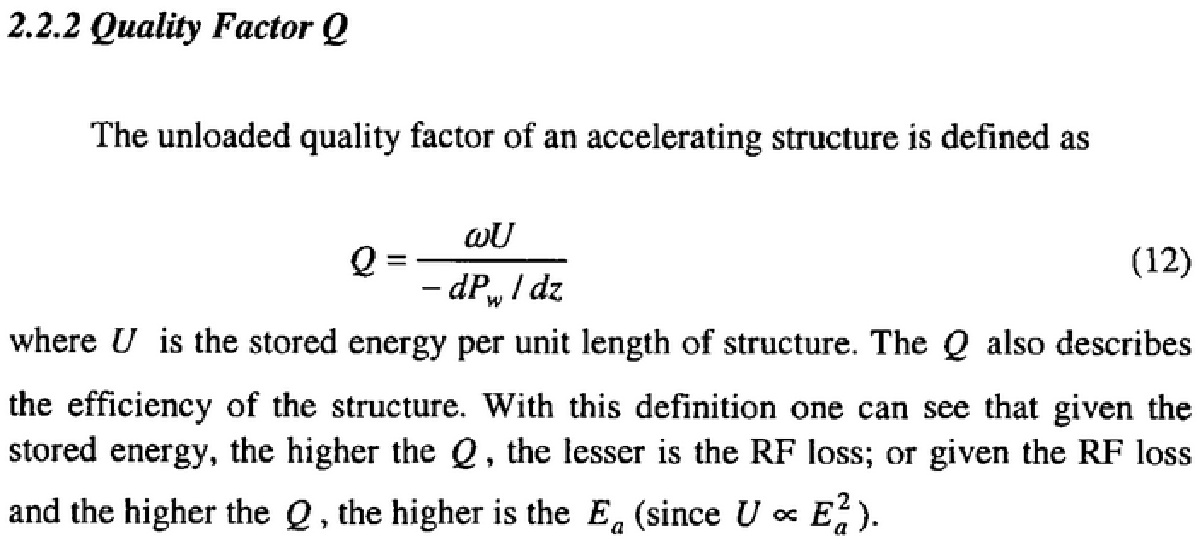


2.2.1 *Shunt-Impedance Z_s*

The shunt-impedance per unit length of the structure is defined as

$$Z_s = \frac{{E_a}^2}{-dP_w / dz} \quad (\mathrm{M\Omega/m}). \tag{11}$$

It expresses that if we are given the RF power loss per unit length then we can know how high an electric field E_a can be established on the axis. Since $P_w \propto E_a^2$, therefore Z_s is independent of E_a and the power loss depends only on the structure itself which includes its configuration, dimension, material and operating mode.

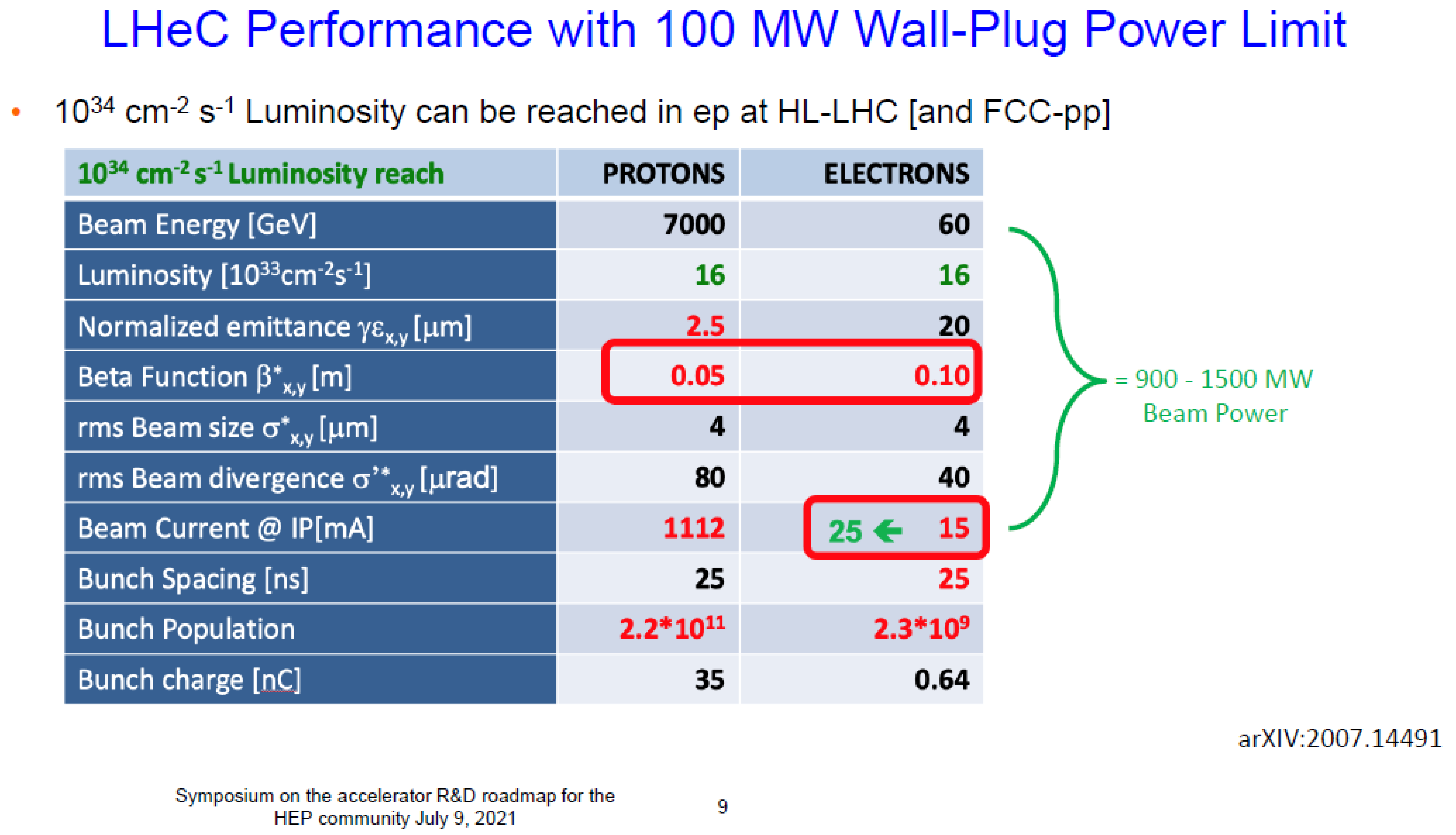


2.2.2 *Quality Factor Q*

The unloaded quality factor of an accelerating structure is defined as

$$Q = \frac{\omega U}{-dP_w / dz} \tag{12}$$

where U is the stored energy per unit length of structure. The Q also describes the efficiency of the structure. With this definition one can see that given the stored energy, the higher the Q, the lesser is the RF loss; or given the RF loss and the higher the Q, the higher is the E_a (since $U \propto E_a^2$).



LHeC Performance with 100 MW Wall-Plug Power Limit

- 10^{34} cm^{-2} s^{-1} Luminosity can be reached in ep at HL-LHC [and FCC-pp]

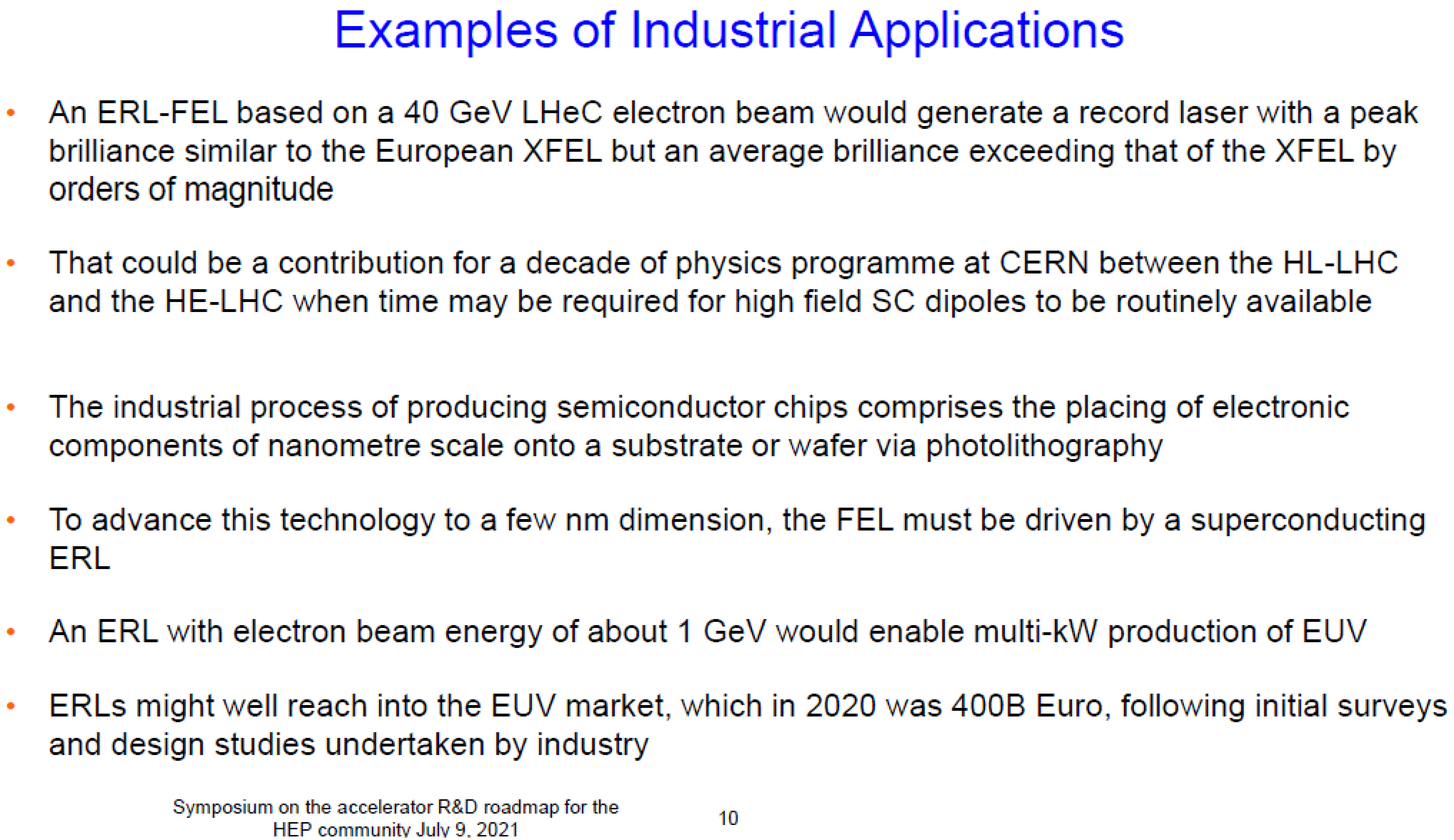
10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40
Beam Current @ IP[mA]	1112	25 ← 15
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$2.3*10^{9}$
Bunch charge [nC]	35	0.64

= 900 - 1500 MW
Beam Power

arXIV:2007.14491

Symposium on the accelerator R&D roadmap for the HEP community July 9, 2021

9



Examples of Industrial Applications

- An ERL-FEL based on a 40 GeV LHeC electron beam would generate a record laser with a peak brilliance similar to the European XFEL but an average brilliance exceeding that of the XFEL by orders of magnitude
- That could be a contribution for a decade of physics programme at CERN between the HL-LHC and the HE-LHC when time may be required for high field SC dipoles to be routinely available
- The industrial process of producing semiconductor chips comprises the placing of electronic components of nanometre scale onto a substrate or wafer via photolithography
- To advance this technology to a few nm dimension, the FEL must be driven by a superconducting ERL
- An ERL with electron beam energy of about 1 GeV would enable multi-kW production of EUV
- ERLs might well reach into the EUV market, which in 2020 was 400B Euro, following initial surveys and design studies undertaken by industry

Nuclear Physics Applications

Intense, inverse Compton scattering

- A ~1 GeV energy superconducting ERL operating at high average electron current in the 10 to 100 mA range would enable a high-flux, narrowband gamma source based on ICS of the electron beam with an external laser within a high-finesse recirculating laser cavity
- The production of 10 to 100 MeV gammas via ICS results in properties of the gamma beam fundamentally improved with respect to standard bremsstrahlung generation
- This ICS process would be a step change in the production of high-flux, narrowband, energy-tunable, artificial gamma-ray beams
- They will enable quantum-state selective excitation of atomic nuclei along with a yet-unexploited field of corresponding applications

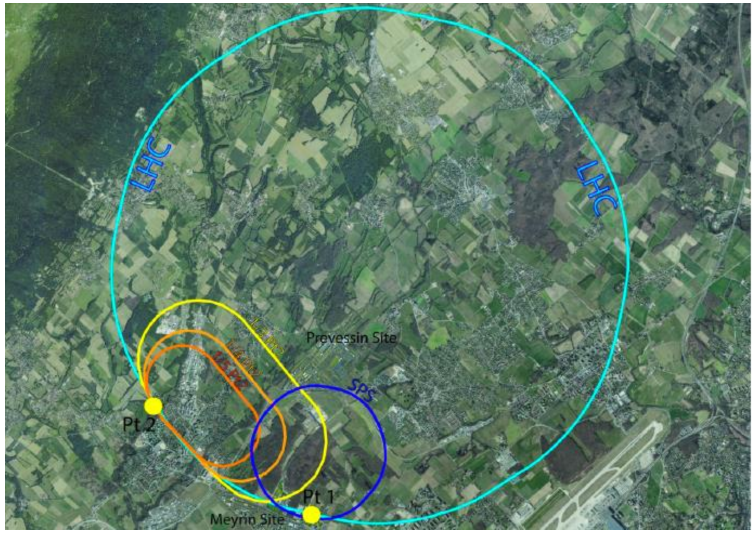
Nuclear Physics:

- Example of IGS, also strong programme for e-A scattering

ERL: Accelerator Energy Frontier

CERN-ACC-Note-2020-0002
Version v1.0
Geneva, June 2, 2020

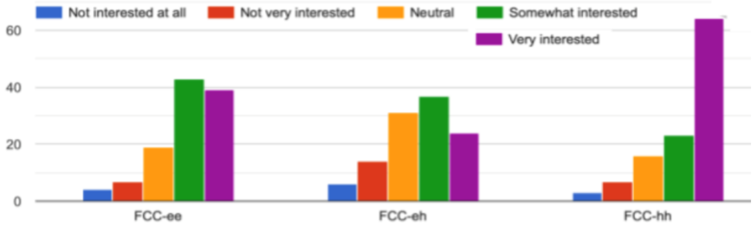
400 pages update of 2012 CDR - to appear



50 GeV to limit cost [1/4 or 1/5 of U(LHC)]
Three pass ERL, two ~800m long linacs
I_e=20mA for 10^{34} luminosity, f=801.58 MHz
(Erk at Daresbury 16, Frank M at Orsay 18)
Operation concurrent to LHC (+dedicated)

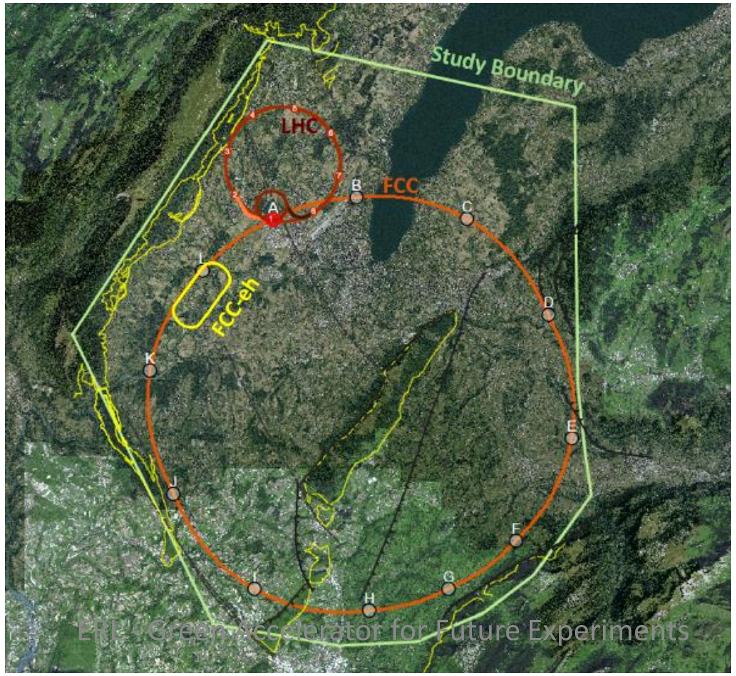
(when) will that happen.? We don't know
I met Abhay Deshpande in Snowmass 2001,
when he presented the EIC, not for the 1st time

HL-LHC dominates all of PP,
Its programme will extend to 2040

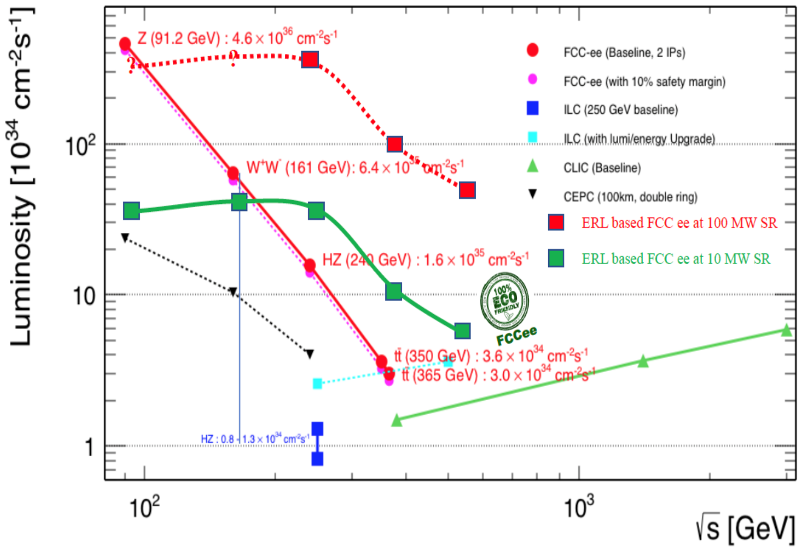


ECFA: Interest of young scientists 2002.02837

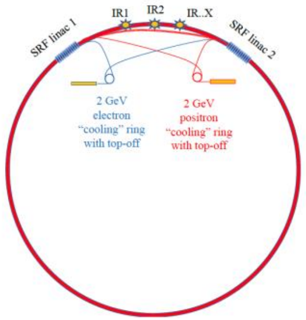
60 GeV ERL design applied to FCC-he



FCC-ee



Vladimir Litvinenko et al, 1909.04437



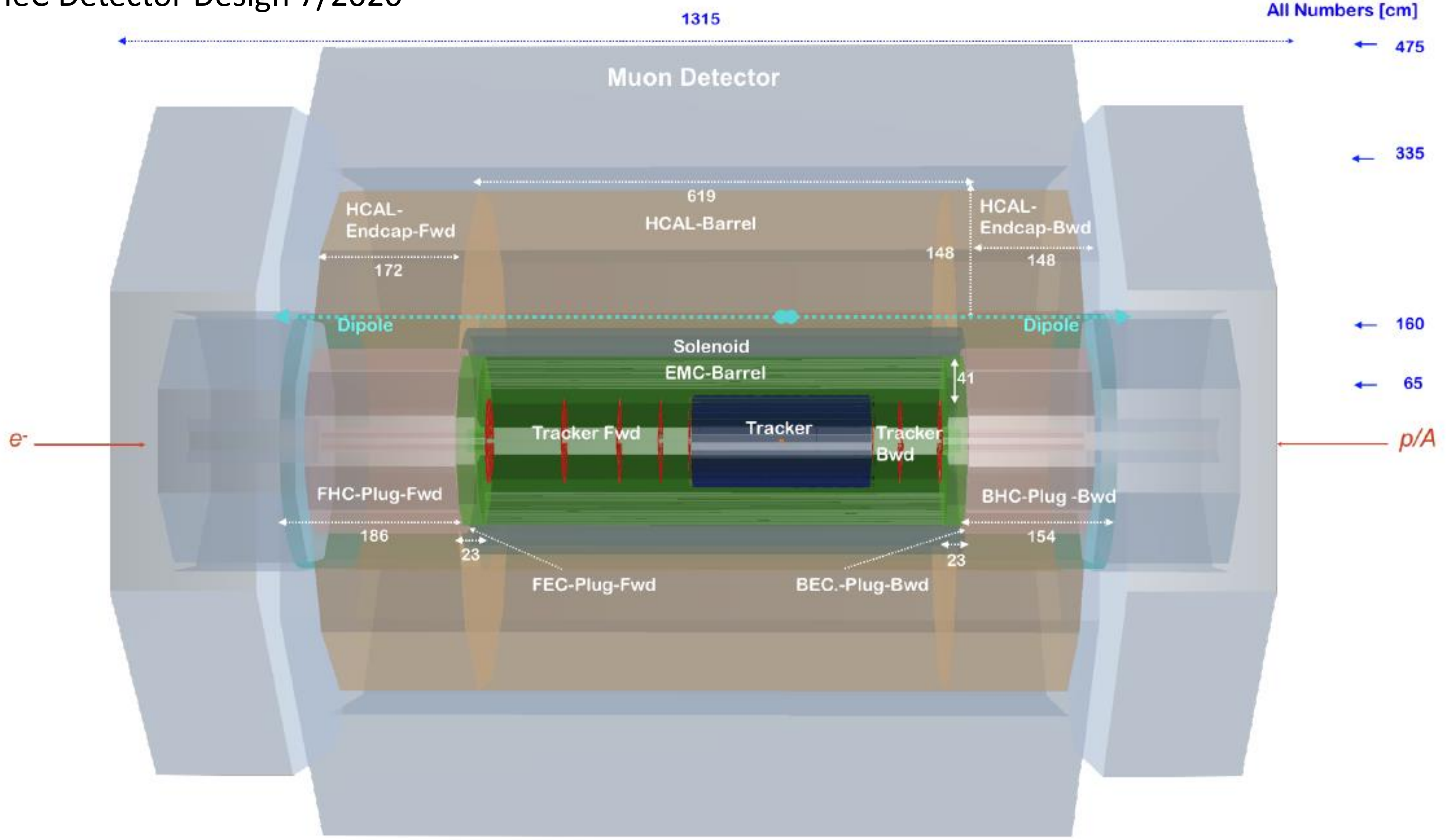
4-6 turns

E/linac = $M_{Z,..HH}/(2 * N_{turn})$

EIC: Polarised eh Collider at BNL
IBS: emittance growth: needs ERL 100mA (!)
CW e beam cooling of p/A beam (for CBETA)
cf e.g. F Willeke APS talk, April 2018

Coherent Electron Cooling
V.N. Litvinenko, Y.S. Derbenev, *PRL* **102**, 114801, 2009

LHeC Detector Design 7/2020

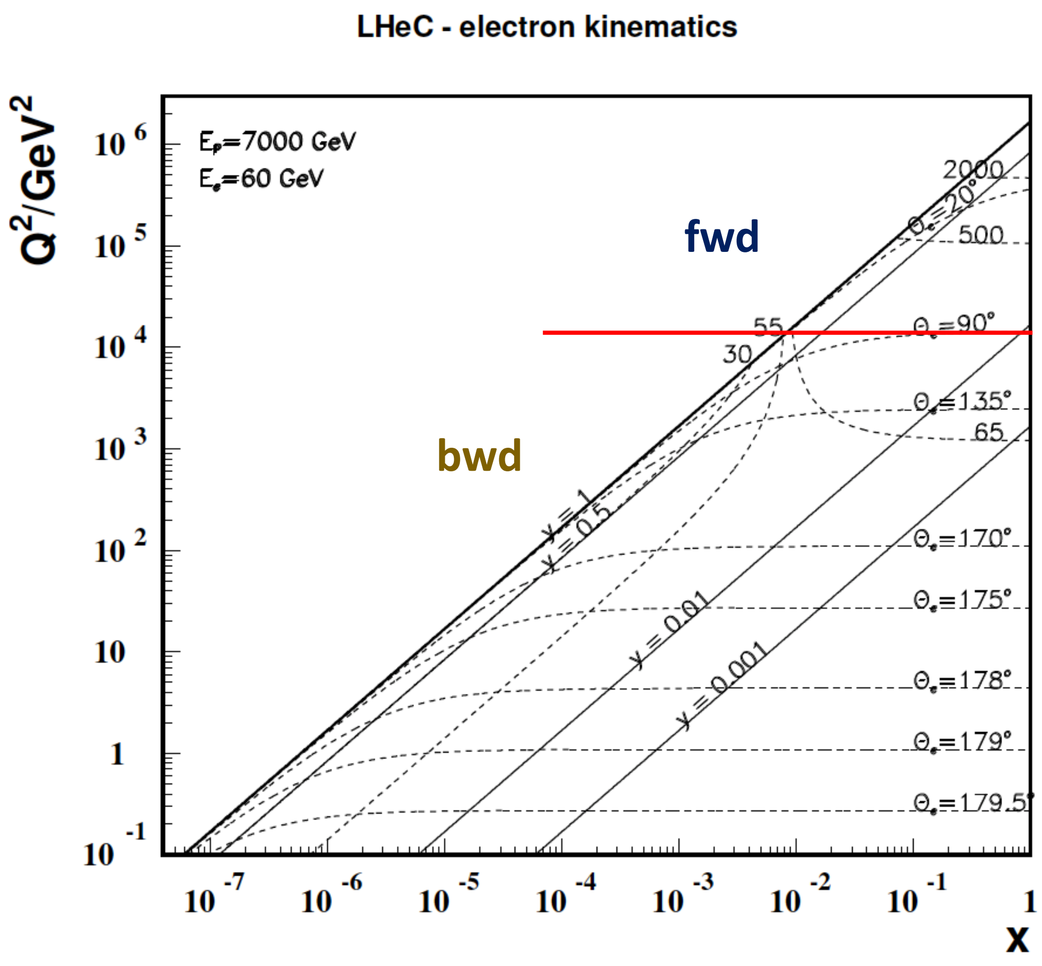


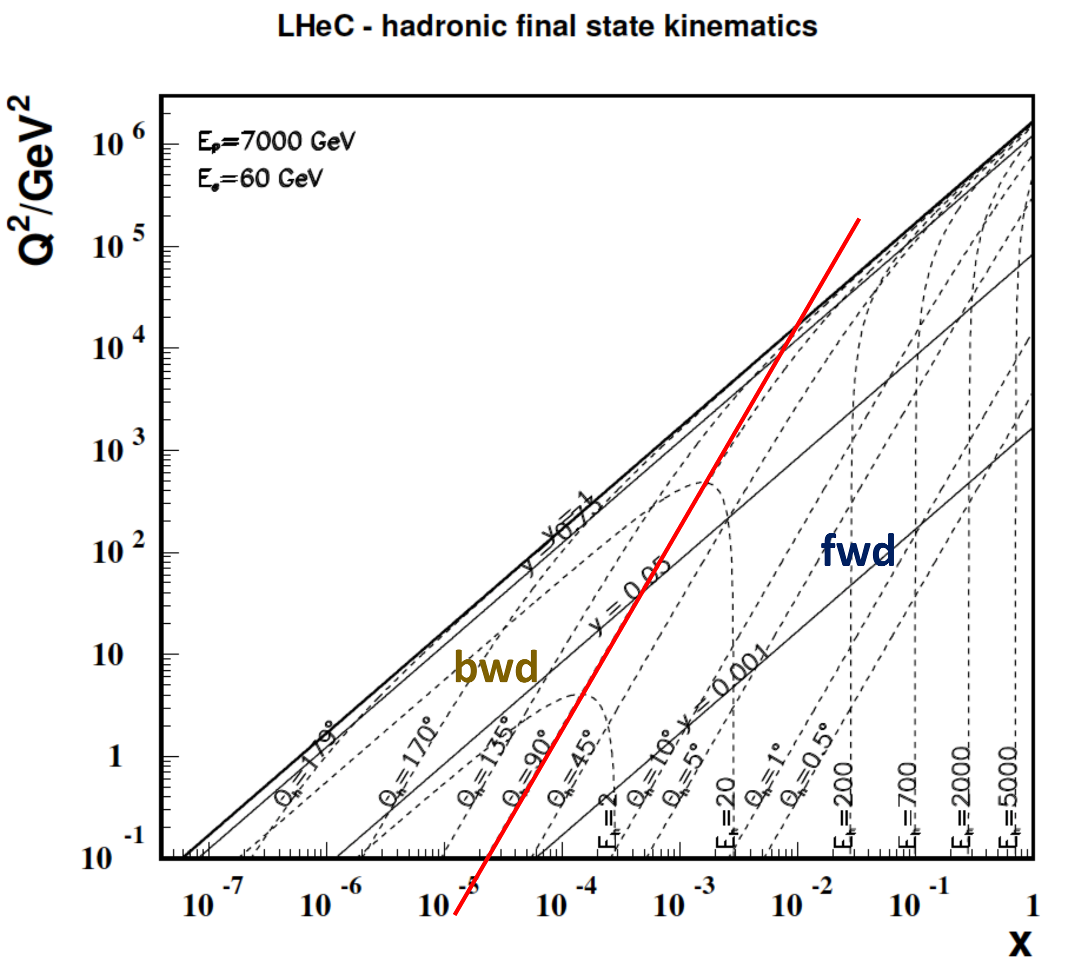
No pile up, low radiation wrt pp; high precision through overconstrained kinematics: e-h; modular for rapid installation

Tracker radius 40 → 60cm, B 3.5T; LxD =13 x 9m^2 [CMS 21 x 15m^2 , ATLAS 45 x 25 m^2]..

arXiv:1206.2913+2007.14491

Kinematics: fwd: in p beam direction, bwd: e direction


LHeC - electron kinematics

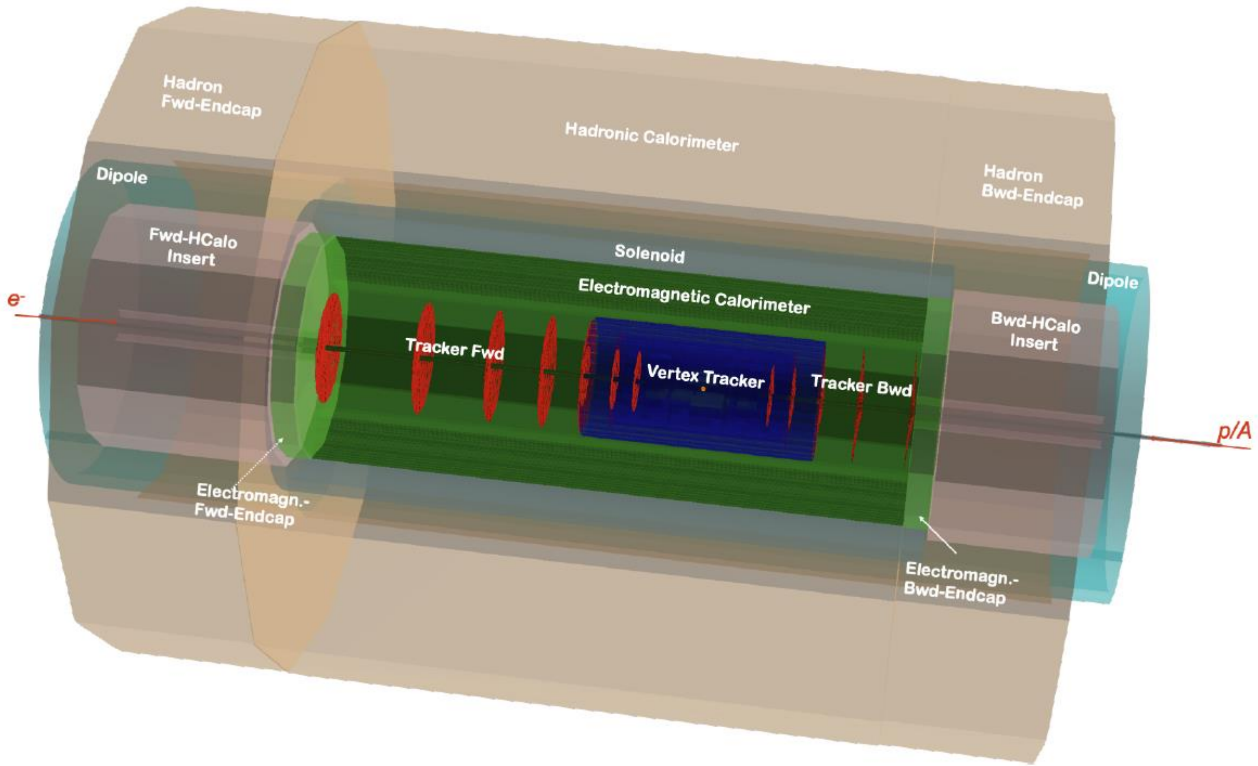

LHeC - hadronic final state kinematics

Electrons in bwd direction have low energy ($E'_e < E_e$ beam)
in fwd direction high energy up to Ep, Rutherford backscattering
Q^2=1 GeV^2 is 179°, or eta =4.74 = ln tan theta/2, ~ E_e^2 !

Hadrons in bwd direction have low energy $E_h < E_e$ beam
in fwd direction hadrons carry energy up to E_p beam

→ Asymmetric energy coverage of LHeC detector. Fwd region: resembles hh conditions

LHeC Calorimeters



Complete coverage to +- 5 in (pseudo)rapidity

Central Region: 2012: LAr, 2020 Sci/Fe option.

Forward Region: dense, high energy jets of few TeV

H → bb and other reactions demand resolution of HFS

Backward Region: in DIS only deposits of $E < E_e$

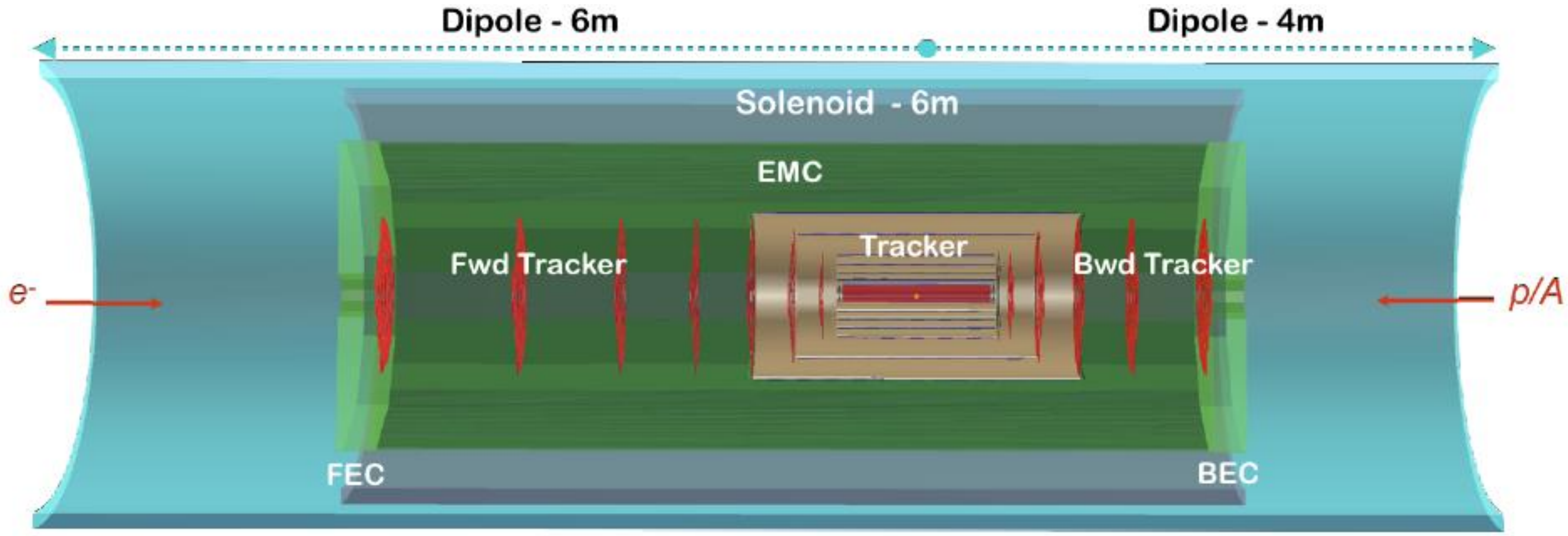
Barrel Calorimeters

Calo (LHeC)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	38	58	45	50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
$\eta_{\max}, \eta_{\min}$	2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0	$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci [m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	300	49	49	165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
$\eta_{\max}, \eta_{\min}$	5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si [m^2]	1354	187	187	745

arXiv:2007.14491



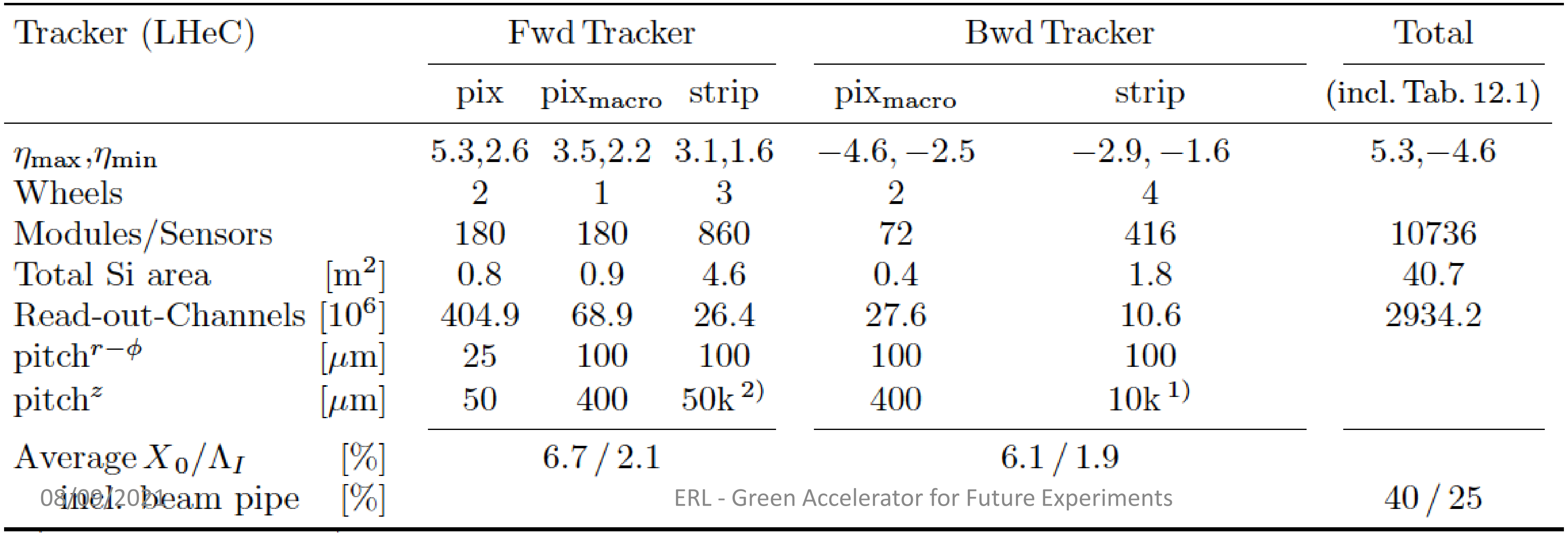
Inner Tracker

Rapidity to ~5

r_O = 60 cm

impact resolution 5-10 µm

40.7 m^2 Si



Tracker (LHeC)		Fwd Tracker			Bwd Tracker		Total
		pix	$\text{pix}_{\text{macro}}$	strip	$\text{pix}_{\text{macro}}$	strip	(incl. Tab. 12.1)
$\eta_{\max}, \eta_{\min}$		5.3,2.6	3.5,2.2	3.1,1.6	$-4.6, -2.5$	$-2.9, -1.6$	5.3,-4.6
Wheels		2	1	3	2	4	
Modules/Sensors		180	180	860	72	416	10736
Total Si area	[m^2]	0.8	0.9	4.6	0.4	1.8	40.7
Read-out-Channels	[10^6]	404.9	68.9	26.4	27.6	10.6	2934.2
$\text{pitch}^{r-\phi}$	[μm]	25	100	100	100	100	
pitch^{z}	[μm]	50	400	50k [2)]	400	10k [1)]	
Average X_0/Λ_I	[%]	6.7 / 2.1			6.1 / 1.9		
incl. beam pipe	[%]						40 / 25