# ERL Prospects for High Energy Colliders

- Introduction: Luminosity limitations in ‘conventional’ Colliders

- The Energy Recovery concept

- LHeC; FCCeh, FCC-ee und ERLC (ILC) as show case applications of the ERL concept in HEP:

  Push-Pull; Racetrack and Circular ERL configurations

- Key aspects that need to be validated and demonstrated

# Circular Collider: Peak Luminosity

- Luminosity recipe (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

Assumptions for a HEP collider:
Equal number of bunches and matched beam sizes

1) maximize bunch intensities ➔ Limited by beam-beam interaction
2) minimize the beam emittance ➔ Injector complex / Synchrotron radiation
3) minimize beam size @ IP (constant beam power); ➔ Optics & magnet aperture
4) maximize number of bunches; ➔ Beam Power & Synchrotron Radiation
5) Optimize and potentially compensate for geometric form factor ‘F’; Hourglass, X-ing etc
6) Improve machine ‘Efficiency’

# Performance limitation of circular colliders

- Beam-Beam Interaction:

  Imposes a limit to the maximum acceptable bunch intensity

  ➔ Limits the luminosity reach of a circular collider

$$\xi_y = \frac{N r_e \beta_y^*}{2\pi\gamma\sigma_x^*\sigma_y^*} \leq 0.1$$

- Circular machine ➔ Synchrotron Radiation in arcs:

  Beam size increases in horizontal and shrinks in vertical plane

  ➔ flat beams! ➔ minimize $\sigma_y^*$

$$\xi_y^* \propto \frac{\beta_y^*}{\sqrt{\beta_x^*\beta_y^*}} = \sqrt{\frac{\beta_y^*}{\beta_x^*}} \ll 1$$

# Performance limitation of circular colliders

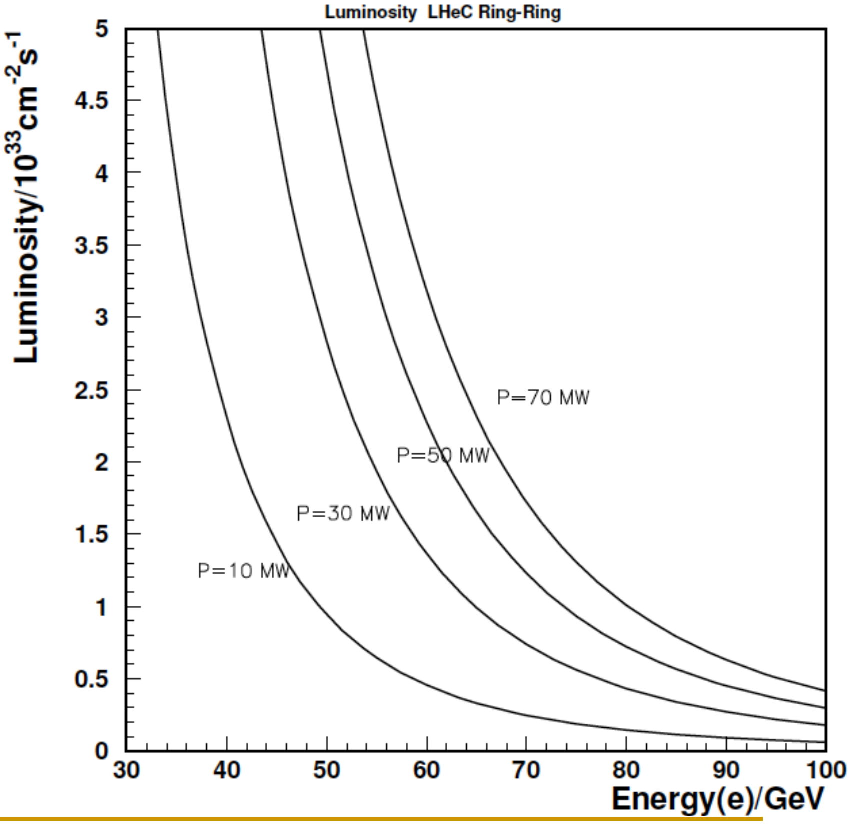
- Synchrotron Radiation in arcs:

  Beam size increases in hor and shrinks in vert

**Circular lepton collide performance is limited by:**
Beam-beam ➔ bunch intensity
Synchrotron Radiation power ➔ total beam current

➔ Reduced performance reach for higher beam energies
@ fixed power footprint ➔ limits total beam current!
If bunch intensity is limited by beam-beam, then
SR limits the number of bunches

LHeC CDR; arXiv:1206.2913



# Linac Luminosity

D.

A linear Collider overcomes the beam-beam limit of a circular collider
[as the beam does not need to remain to be stable over many passages]
and even utilizes it for performance enhancement [pinch factor]
and minimizes the power losses through Synchrotron Radiation [no bends]

But it does so at the price of power requirements for luminosity production
and that the particles have only once the chance to collide!!!

➔ Luminosity proportional to beam power [Beam Current x Energy]

**And $e^+$ production might be challenging!**

Markus Roth TU Darmstadt; Accelerators for Medical Applications 2015; Vösendorf, Austria

# Energy Recovery

- Recuperate the energy [and $e^+$] from the spend beam after the interaction point before the beam is dumped

➔ non-linearity of the beam-beam interaction can not lead to instabilities and beam losses if the circulation of the particles in the machine is short after the interaction

# The Best of both Worlds

- Energy Recovery Linac concept: First proposal 50 years ago

  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

Truly Revolutionary Accelerator design Concept!!!!

With the potential of changing the collider landscape!!!


- First Tests: Done at SCA @ Stanford in 1986

  Interesting concept for FELs and Compton photon light sources, and high current electron cooler concepts and **colliders!!!**

# Energy Recovery Linac Configurations

- Push-Pull Configuration:

  2 SC linacs facing each other

  → Allows only pulsed linac operation

  → But allows Energy Recovery

- Coupled Linac Configuration:

  4 SC linacs facing each other

  → Allows CW linac operation

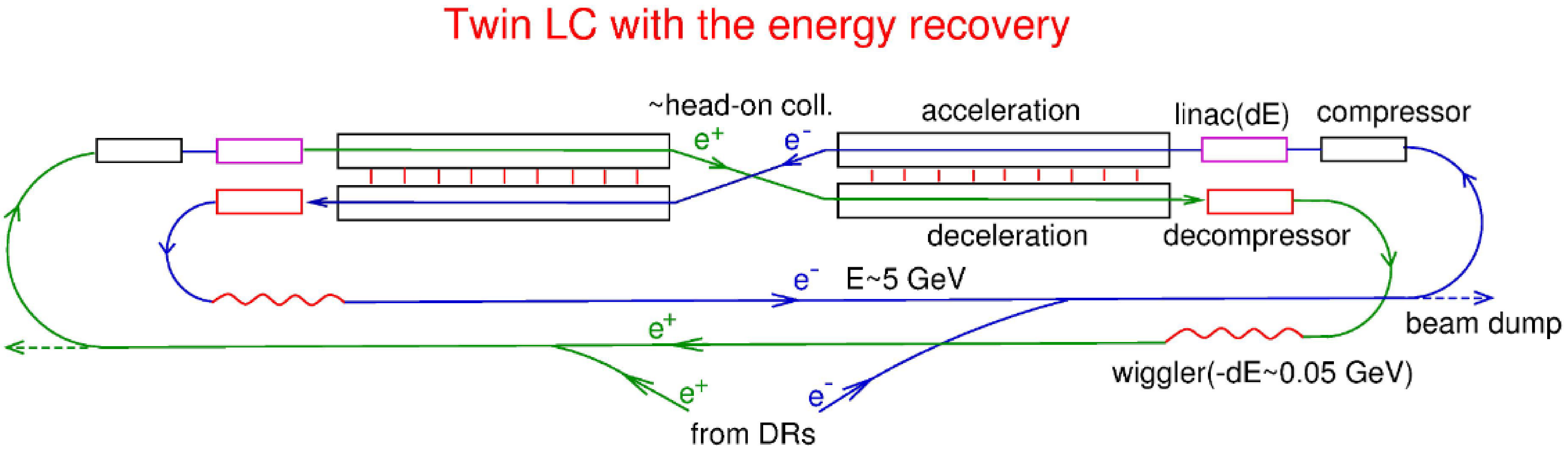
  → Allows Energy Recovery

  → Allows Positron recovery!

  → Costly implementation as 2 x SRF and SRF is the main cost driver for the ERL

# 4 Linac ERL Collider Concept:

Valery Telnov BINP




- In his proposal the machine is still pulsed and the cycle duration [seconds] is determined by the refrigeration system
- Projects peak luminosity of ca $10^{36}$ $cm^{-2}s^{-1}$ @ 200MW wall plug power [wiggler 5MW; HOMs 45MW; cryo 110MW]
- Luminosity independent of beam energy due to Energy Recovery! But Cryo sclaes with Linac length and HOM with I!
- 250GeV machine with 0.16A @ 1/3rd duty cycle ➔ > 10GW beam power!!!

➔ https://indico.cern.ch/event/995633/contributions/4275159/attachments/2208757/3755756/telnov-lcws21.pdf

# 4 Linac ERL Collider Concept:

Valery Telnov BINP

- SRF taken from LCLS-II:

  $Q_0 = 3\ 10^{10}$ @ 1.8K with E = 20MeV/m ➔ heat of about 1kW/GeV

  ➔ 1/3rd duty factor with 3m bunch spacing ➔ L = 0.5 $10^{36}$ $cm^{-2}s^{-1}$ @ 160MW

  and N= $10^{10}$, d = 3m, I = 0.16A and 250GeV CME

# Energy Recovery Linac Configurations

- Recirculating Linac Configuration:

SC linac(s) that are connected through return arcs

- ➔ Still implies gn ca. ½ of ring)
- ➔ More cost e re than once
- ➔ Allows true ents during ramp-up]
- ➔ Still avoids
- ➔ Implies som s lattice design!
- ➔ Multiple pa me SC linac implies high beam c

Effective ERL applications require

SRF technology with $Q_0 > 10^{10}$ and

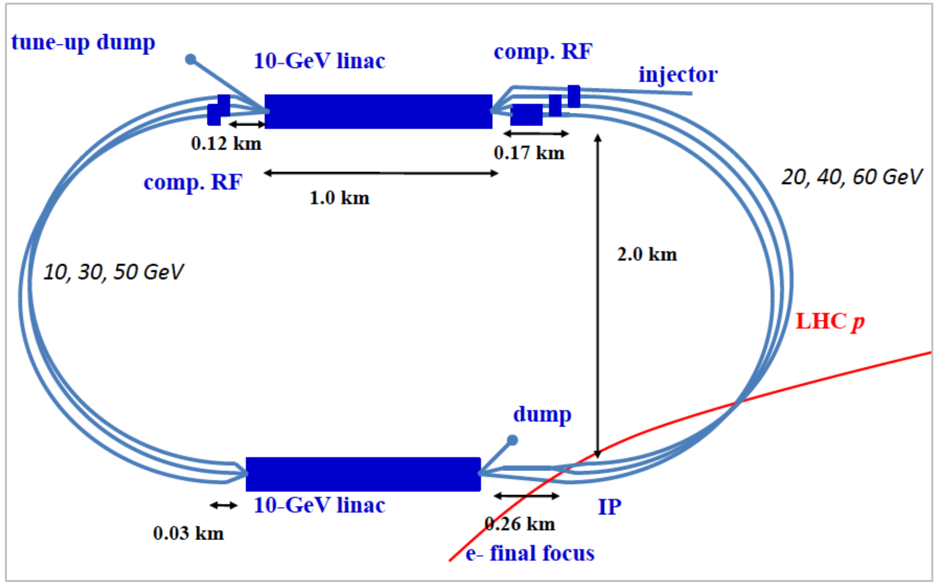
Cost effectiveness requires peak fields of

V > 15MV/m

# LHeC / FCC-eh Racetrack ERL Collider configuration:

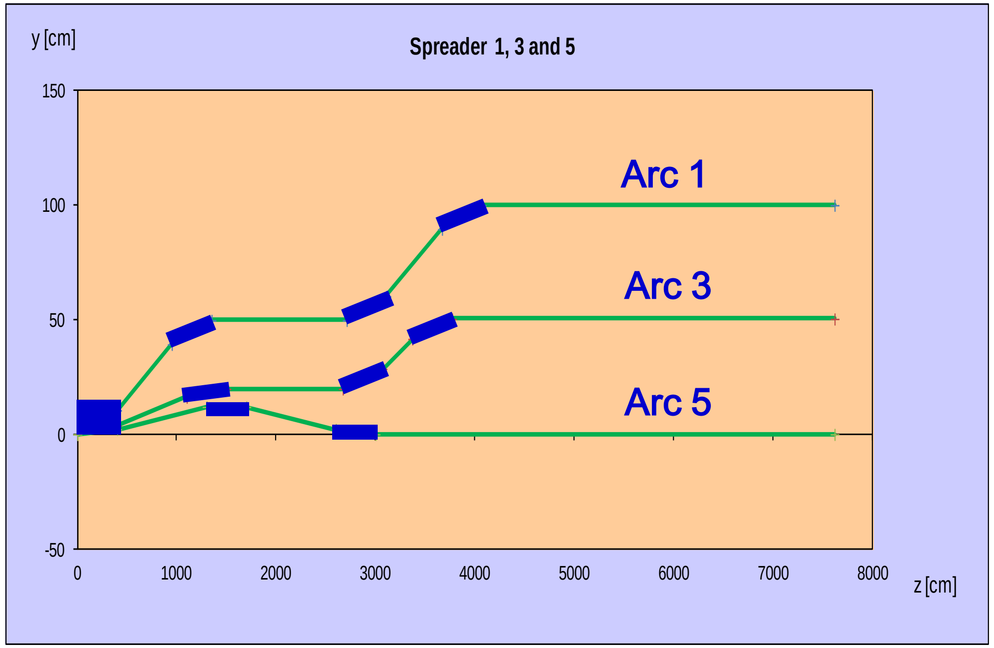
* LHeC CDR, arXiv:2007.14491

## Example LHeC: 3-turn Recirculating SRF Linac and ERL operation




**Operation in parallel with LHC/HE-LHC/FCC-hh**

- TeV scale collisions ➔ 50-60 GeV e-beam energy
- power consumption < 100 MW




➔ 2 1km long SRF linacs

➔ 3 separate return arcs at each end of the linac, matched for the beam energies

➔ Each beam passes 6 times through the SRF: 3 passes with acceleration and 3 with passes deceleration ➔ 6 times $I_e$ in SRF!

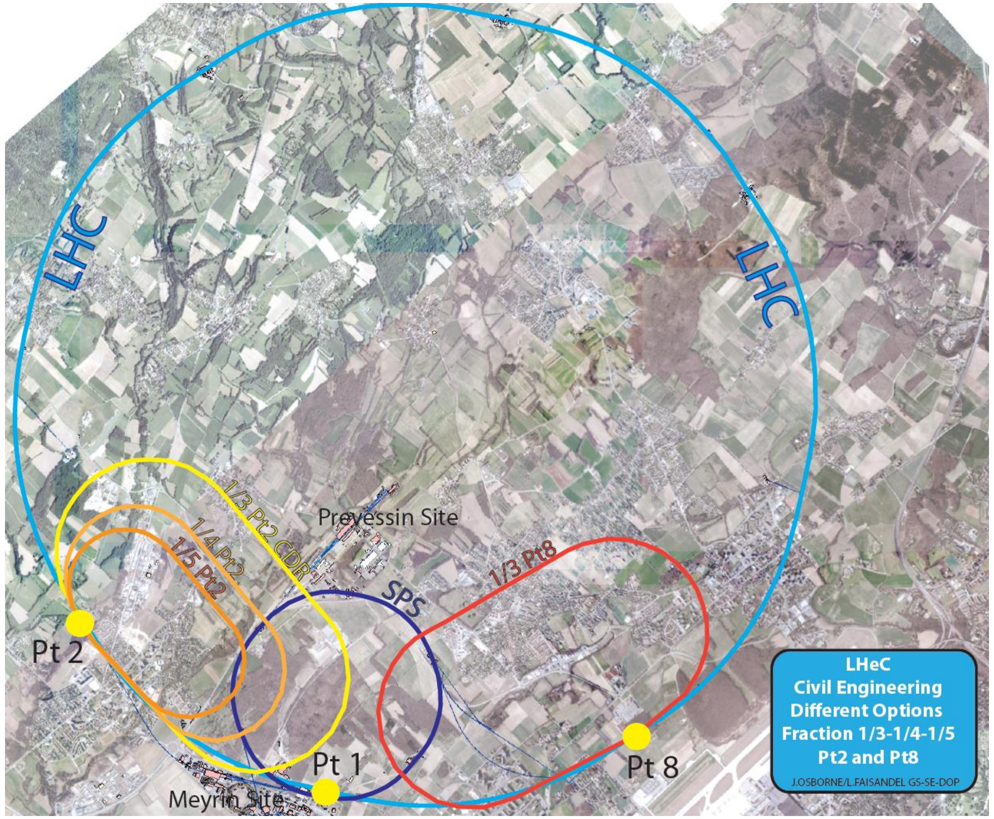
# LHeC / FCC-eh ERL Configuration: Layout Options & Scaling

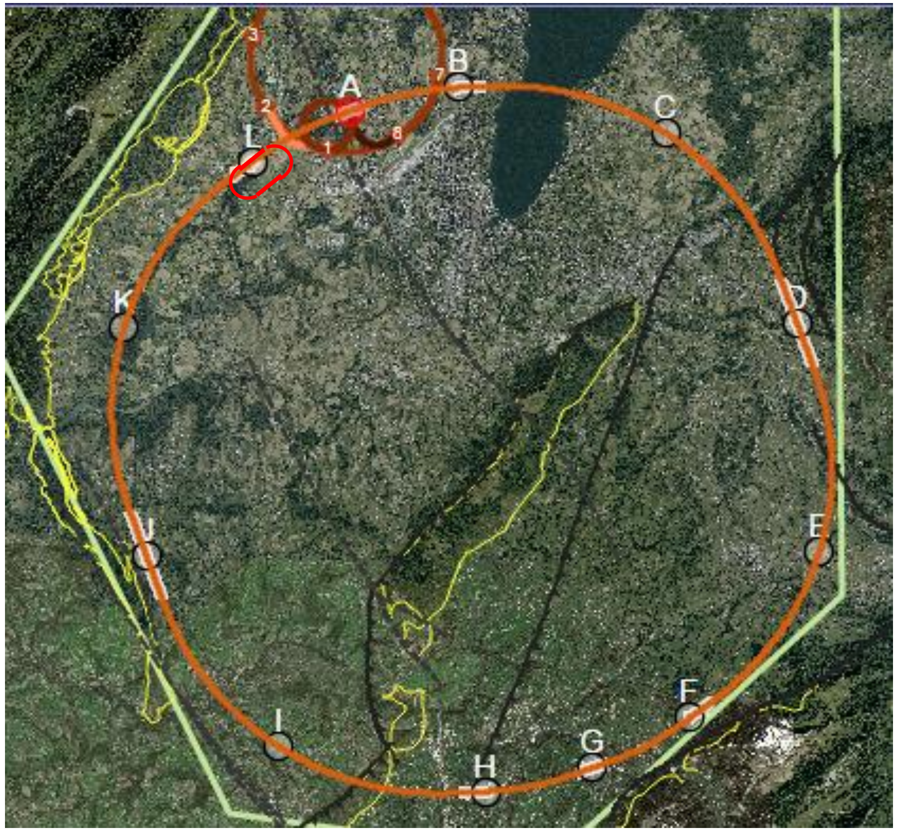
## Configurations:

LHeC

FCC-he considers Point 'L' since FCC Week in Berlin

arXIV:2007.14491



# LHeC: Recirculating Linac with ERL Operation as Baseline

- Performance with 100MW Wall Plug Power limit:

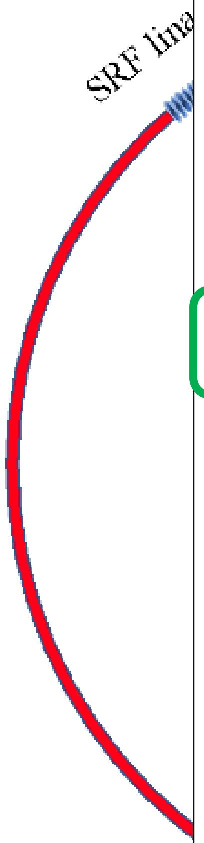
arXIV:2007.14491

| $10^{34}$ $cm^{-2}$ $s^{-1}$ 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 σ□$^*_{x,y}$ [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 |

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

Vladimir Litvinenko; BNL and Stony Brook University

# Circular ERL Collider Concept:




| Mode of operation | $Z$ | $W$ | $HZ$ | $t\bar{t}$ | $HHZ$ | $Ht\bar{t}$ |
|---|---|---|---|---|---|---|
| Beam energy, GeV | 45.6 | 80.0 | 120.0 | 182.5 | 250.0 | 300 |
| Normalized emittance $\varepsilon_x/\varepsilon_y$, $\mu$m rad | 4/0.008 | 4/0.008 | 6/0.008 | 8/0.008 | 8/0.008 | 8/0.008 |
| RMS bunch length, mm | 0.8 | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 |
| Bunch charge, nC | 12.5 | 12.5 | 25.0 | 22.5 | 19.0 | 19.0 |
| Bunch frequency, kHz | 297 | 270 | 99 | 45 | 18 | 9 |
| Beam current, mA | 3.71 | 3.37 | 2.47 | 1.01 | 0.35 | 0.16 |
| Luminosity, $10^{34}$ cm$^{-2}$ s$^{-1}$ | 67.4 | 86.6 | 77.8 | 31.4 | 13.8 | 8.6 |
| IP beta function $\beta_x/\beta_y$, cm | 15/0.08 | 20/0.10 | 100/0.1 | 100/0.2 | 100/0.2 | 100/0.2 |
| Disruption parameter, $D_x/D_y$ | 0.6/183 | 0.6/177 | 0.1/129 | 0.2/143 | 0.2/121 | 0.2/121 |
| Energy loss during collision, GeV | 0.05 | 0.16 | 0.28 | 0.30 | 0.55 | 0.95 |
| Damping ring energy, GeV | 2 | 2 | 2 | 2 | 2 | 2 |
| Damping time, ms | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Damping ring current, mA | 1603 | 1457 | 1069 | 437 | 152 | 70 |
| Particle energy loss, GeV | 4.0 | 4.4 | 6.0 | 14.8 | 42.7 | 92.7 |
| Total radiated power, MW | 30.0 | 29.8 | 29.8 | 30.0 | 30.0 | 30.0 |
| Total ERL linacs voltage, GV | 10.9 | 19.6 | 29.8 | 46.5 | 67.4 | 89.1 |
| Efficiency of energy recovery, % | 91.1 | 94.5 | 95.0 | 91.9 | 82.9 | 69.1 |

SRF linacs in 4 pass

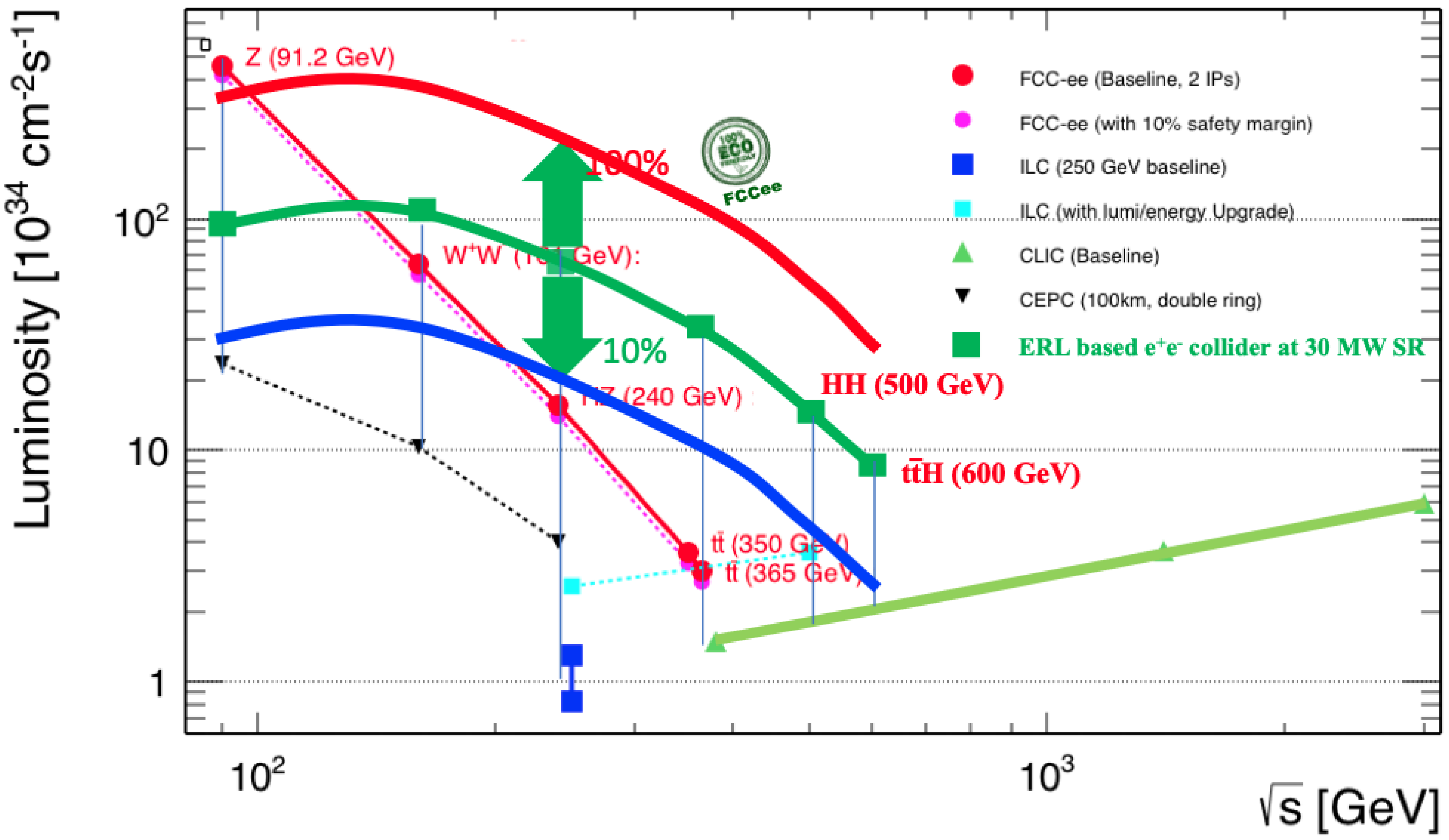
sumption as
ar collider
of 500GeV in 100km
el

.909.04437

f 300MW per beam
47mA

# Circular ERL Collider Concept:

Vladimir Litvinenko; BNL and Stony Brook University

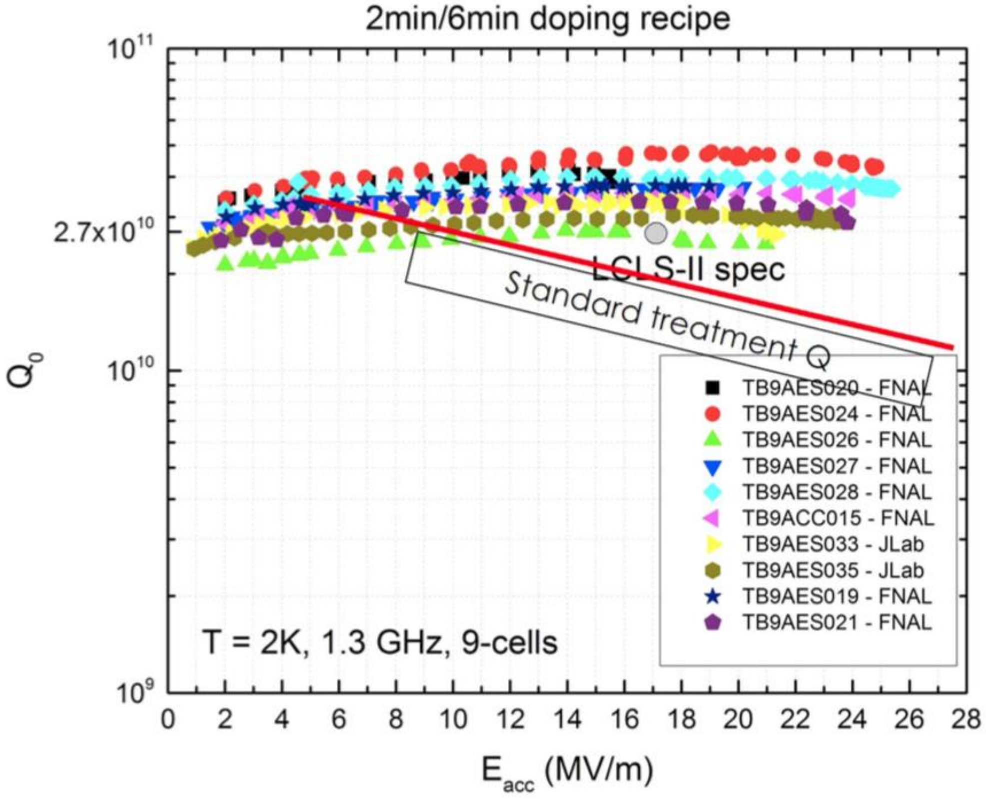


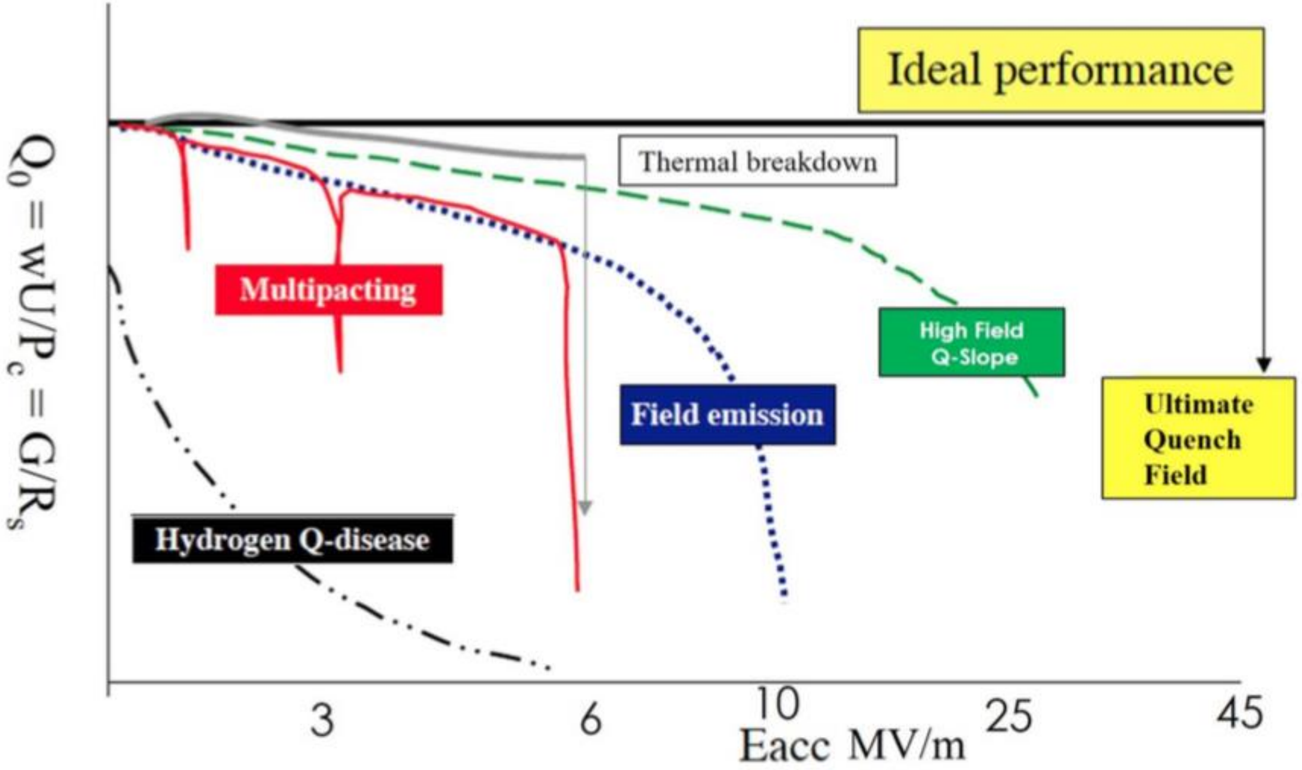

- 10MW RF power
- 30MW RF power
- 100MW RF power

# ERL: SRF Challenge

- $Q_0$ versus accelerating voltage:

$$A(t) = A_0 * e^{-t/\tau}; \quad Q_0 = \omega\tau / 2$$




➔ impressive progress over the last 10 years!!!

➔ $Q_0$ directly linked to required cryogenics power!!

Hasan Padamse: '50 years of success for SRF accelerators' Superconducting Sci. Technol. 30 (2017) 053003

See talk by Bob Rimmer at this Symposium for more details!

# Performance Optimization for ERL Configurations

- Synchrotron Radiation Power:
  - ➔ Can not be avoided for the racetrack configuration ➔ requires scaling of the return arcs with beam energy! But can reduce SRP by about 50% wrt ring
- Beam-Beam interaction:

Need to demonstrate total beam intensity limit for stability in SRF

➔ how many re-circulations and beam currents are possible?!

and need to demonstrate

Limits for beam perturbation with beam-beam interaction and SR in ERL configuration

➔ What level of non-linearity and beam size are acceptable!!!

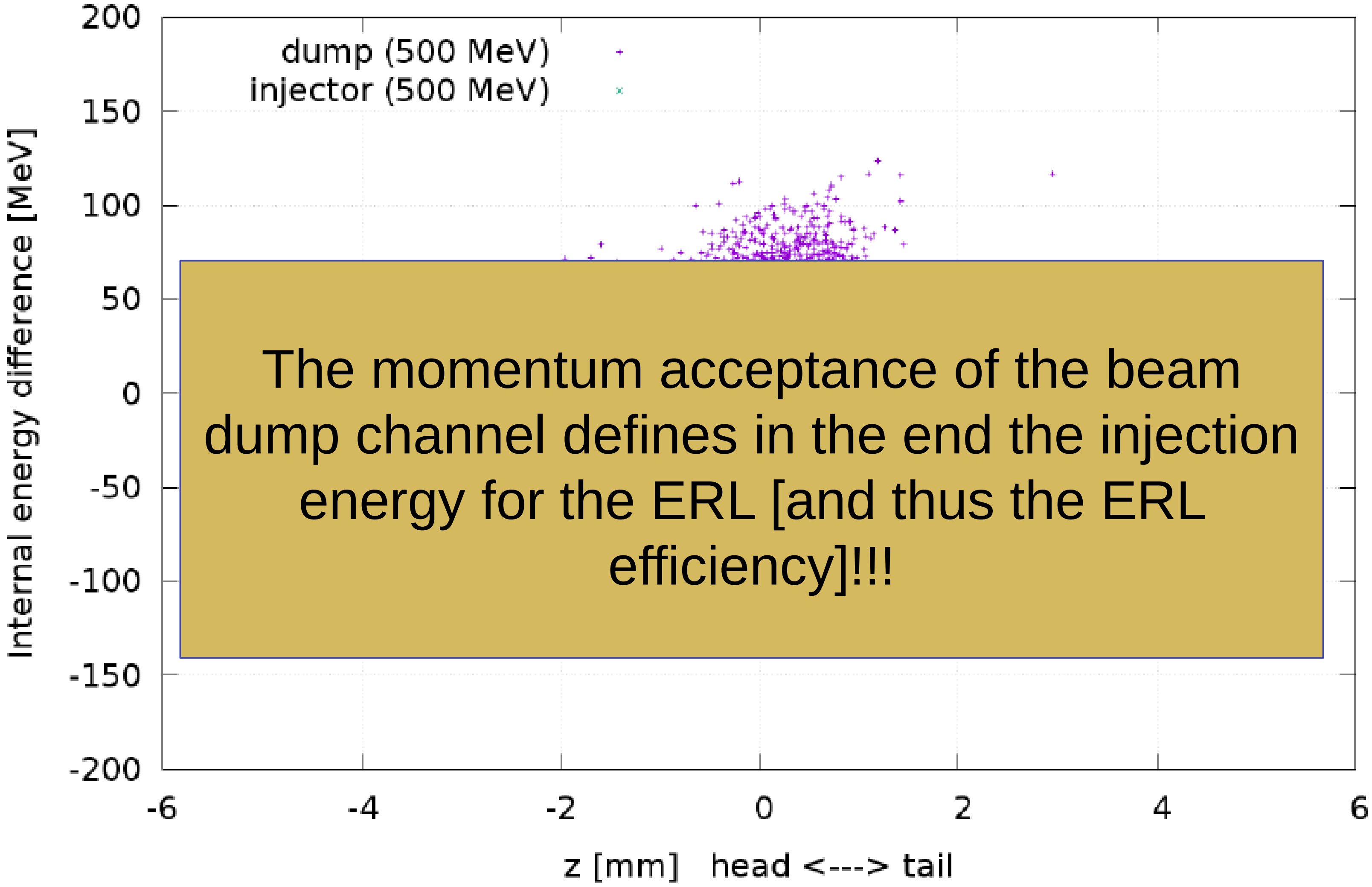
➔ Acceptance of deceleration path!

- Lattice and Optics design of return arcs:
  - ➔ Novel lattice design requirements for return-arcs!!! Optics and FFAGs.

# Synchrotron Radiation

## Evolution of the Longitudinal Phase Space

D. Pellegrini (EPFL/CERN) @ ERL'15

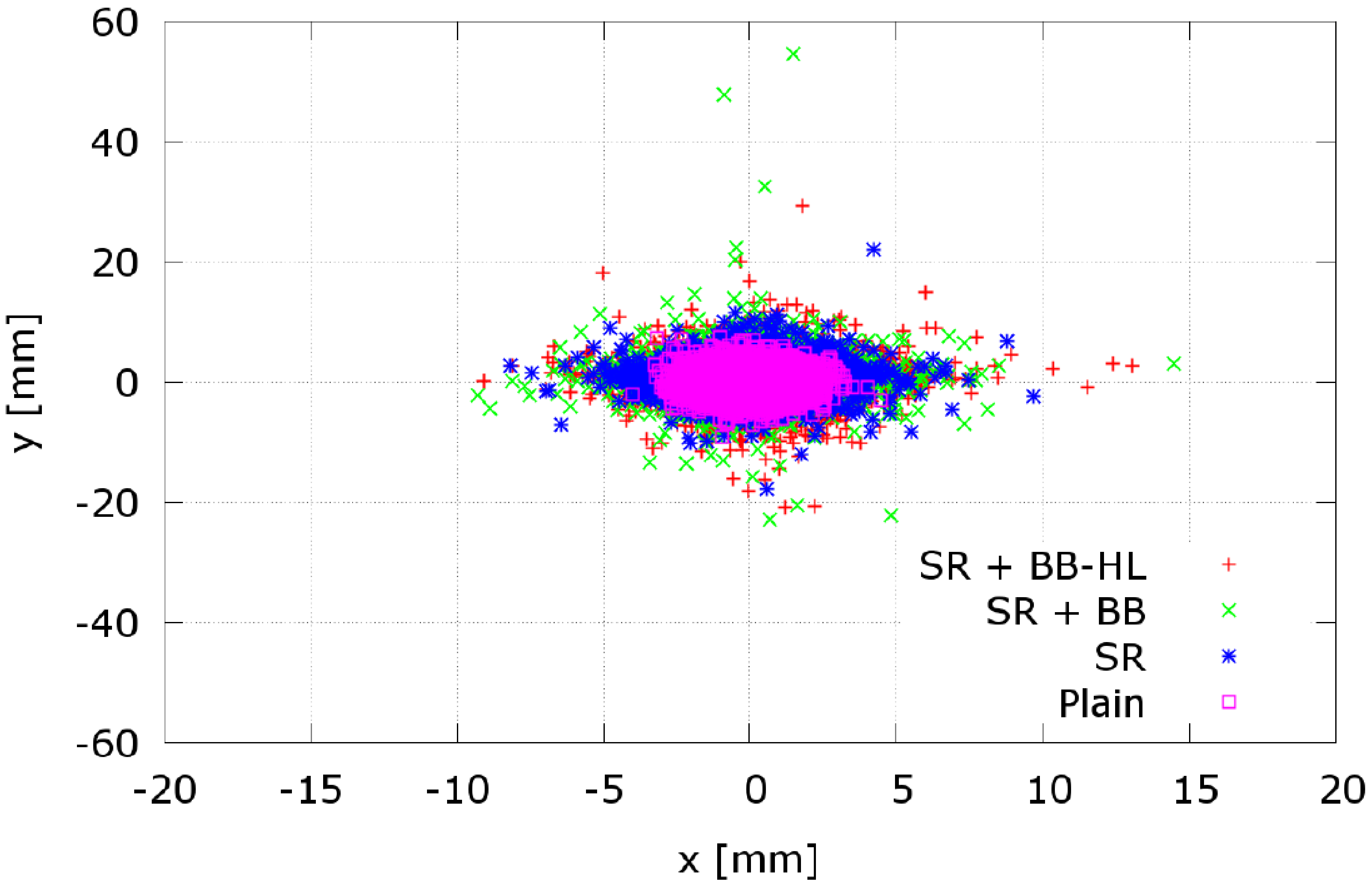



The momentum acceptance of the beam dump channel defines in the end the injection energy for the ERL [and thus the ERL efficiency]!!!

# Synchrotron Radiation and Beam-Beam

## Transverse Plane at Dump

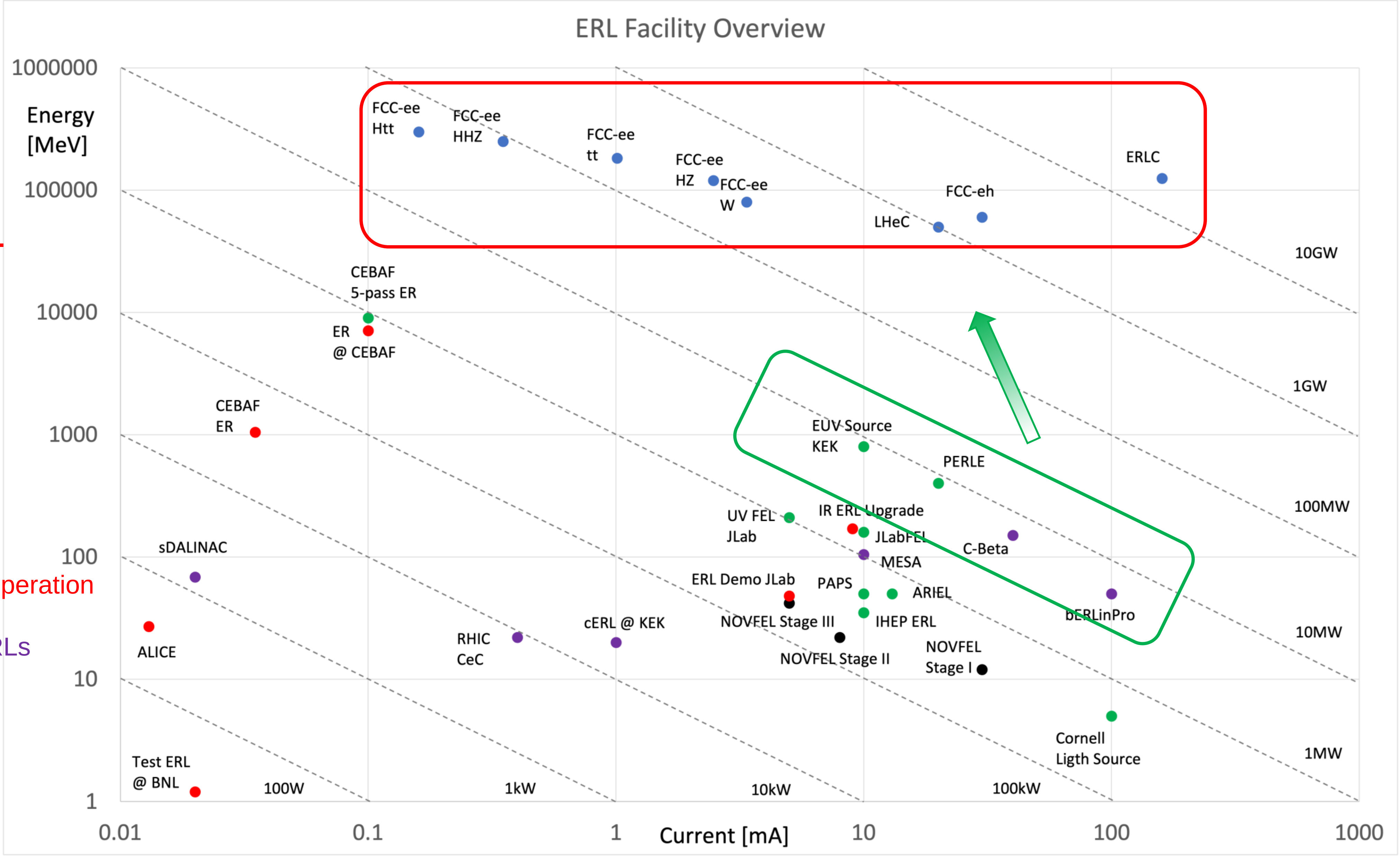
D. Pellegrini (EPFL/CERN) @ ERL'15




Aperture radius of the SPL cavity is 40 mm.

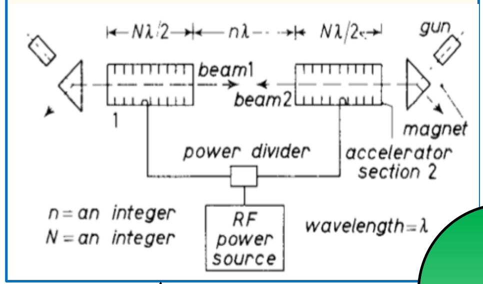
# ERL Facilities Overview:

e.g.
ERL2017 workshop @ CERN and Updated 2019 & 2021

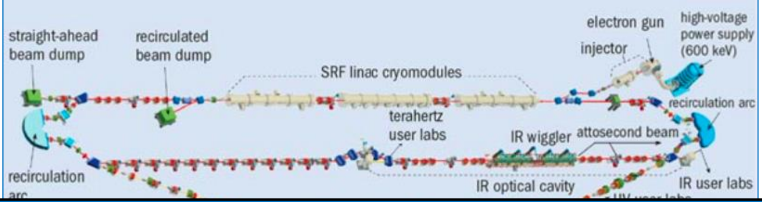



- Legacy ERLs no longer in operation
- Operational & upcoming ERLs
- Planned ERL facilities
- Normal Conducting ERLs
- HEP ERL based studies

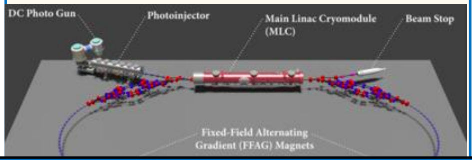
First Idea:
M. Tigner 1965



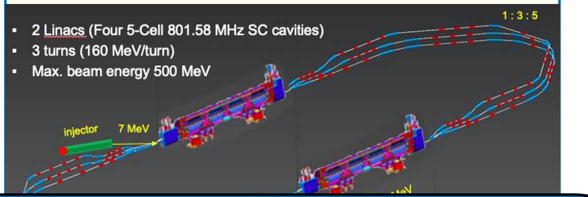

JLab First MW beam power operation
FEL Demo [1999] & Upgrade [2000]




Multi-turn SRF
C-Beta 2019-2020




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

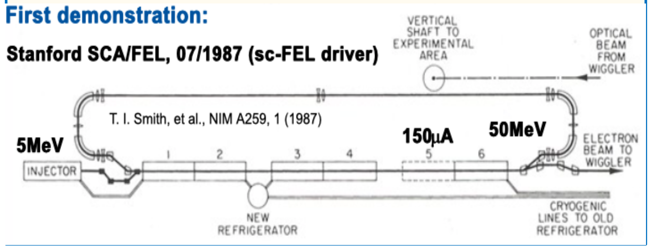



1960
1970

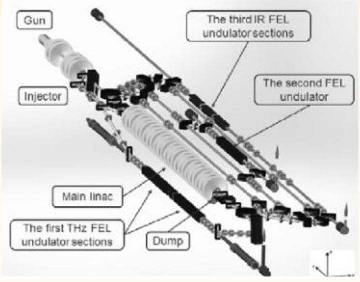
**PERLE can validate the next 10-fold step in beam power**

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

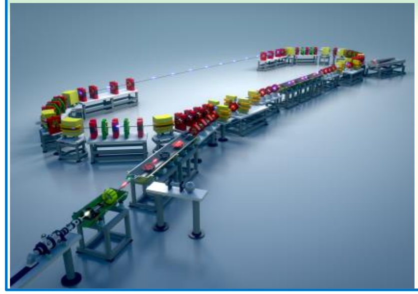
First Demonstration
SLAC SCA / FEL 1987



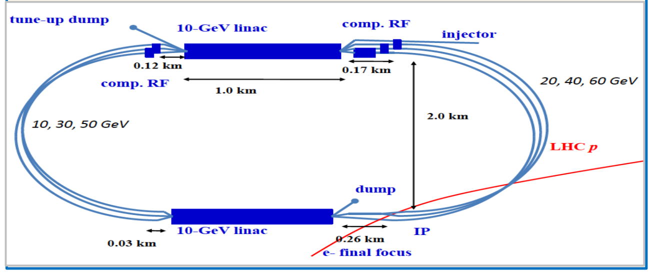

Multi-turn Operation
BINP FEL 2004 [NC]




Multi-MW Operation
bERLin-Pro 2020



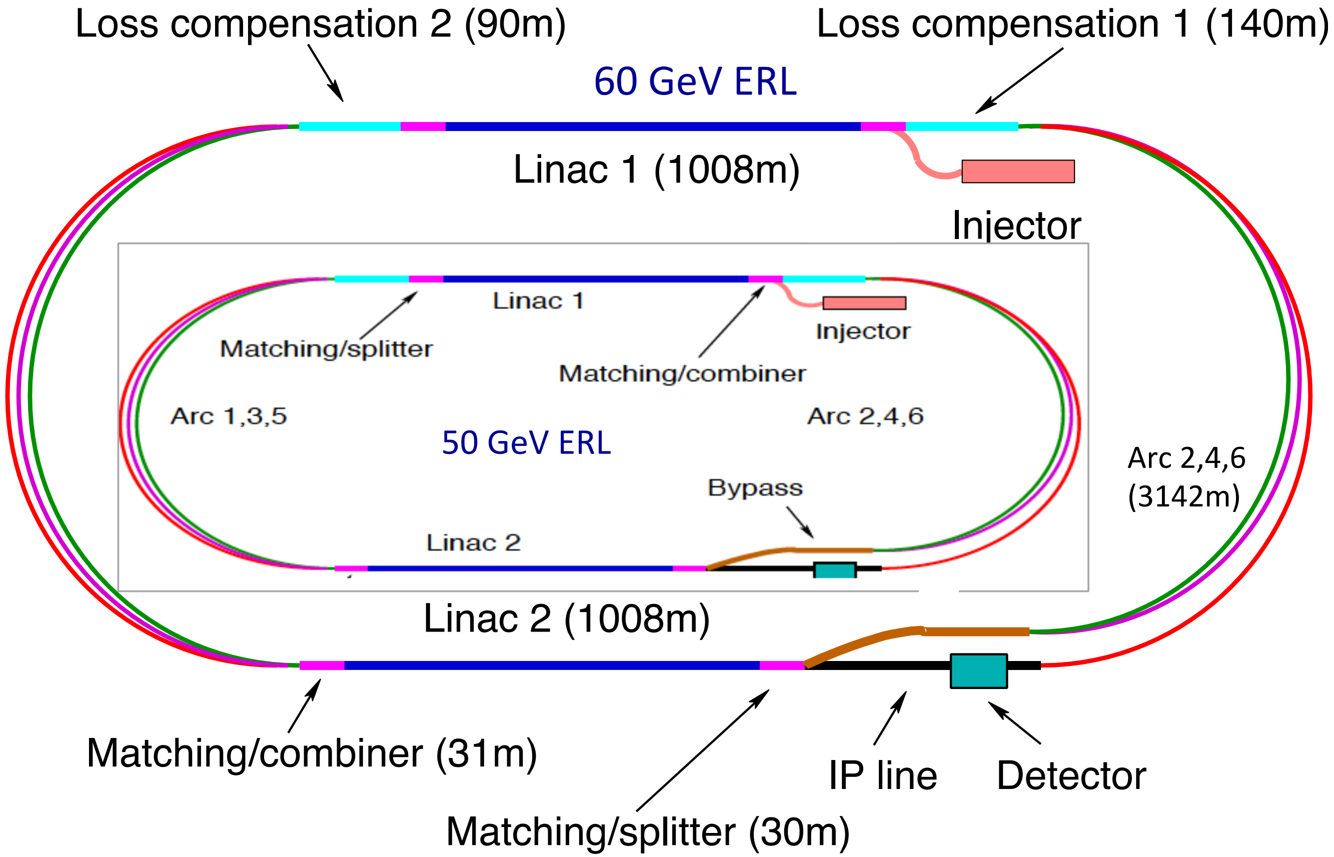
HEP / NP ERL application
LHeC/FCC-eh; FCC-ee; ILC;



# End

# Variations in the ERL Configuration:

Super Conducting 3-turn Recirculating Linac with Energy Recovery operation




O. Brüning, M. Klein and LHeC and PERLE Collaboration
Topical Review Exploring the energy frontier with deep inelastic scattering at the LHC
Journal of Physics G: Nuclear and Particle Physics, Volume 46 #2; November 2019

**Operation in parallel with LHC/HE-LHC/FCC-hh**

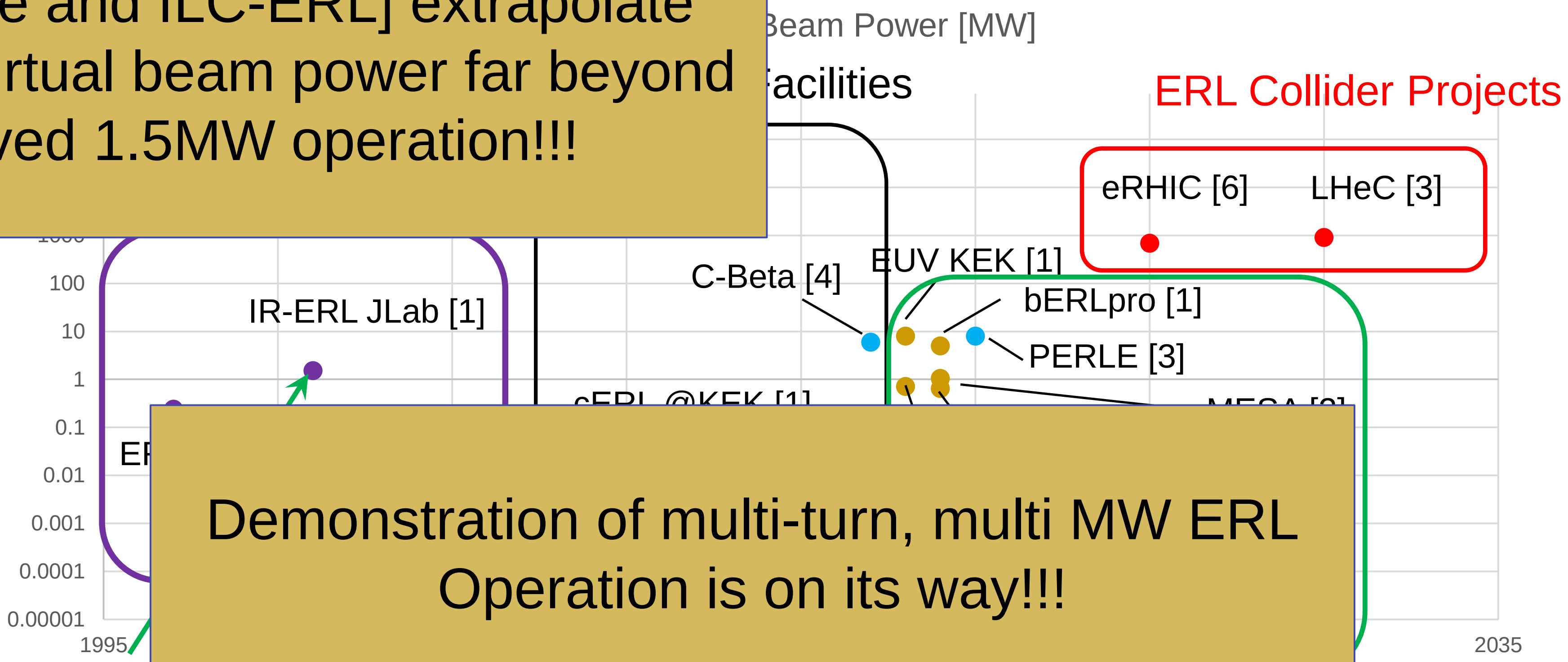
- TeV scale collision energy
  - ➔ 50-60 GeV electron beam energy
- power consumption < 100 MW

➔ CDR option with 9.3km [1/3rd of LHC]; 60 GeV

➔ Smaller version with 5km [1/5th of LHC]; 50 GeV

# ERL Validation Needs and Experience

1MW virtual beam power:




Proposed Collider Projects [e.g. LHeC / FCC-eh and FCC-ee and ILC-ERL] extrapolate demonstrated virtual beam power far beyond the achieved 1.5MW operation!!!

Demonstration of multi-turn, multi MW ERL Operation is on its way!!!

C-Beta and PERLE

1.5MW Hig
demonstrat
Virtual bear
power

pplications

# Arc Optics: Emittance preserving FMC cells

[Flexible Momentum Compaction]

Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015 and LHeC at HL-LHC", to be published

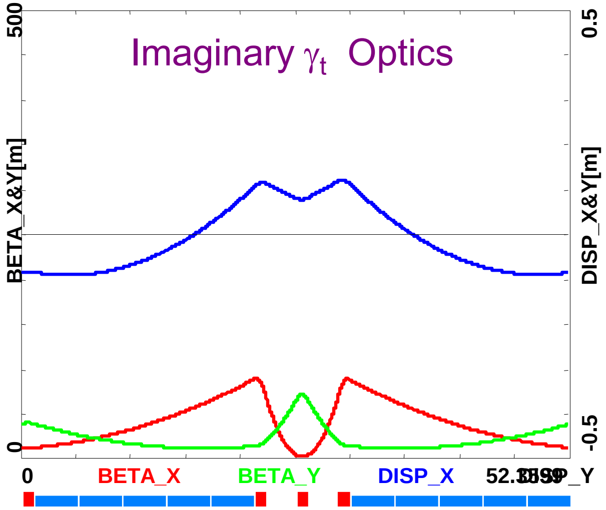
- Scaling with beam energy and radius of curvature!

$$\Delta\varepsilon^N = \frac{55\, r_0}{48\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^6 I_5$$

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\theta \langle H \rangle}{\rho^2}$$

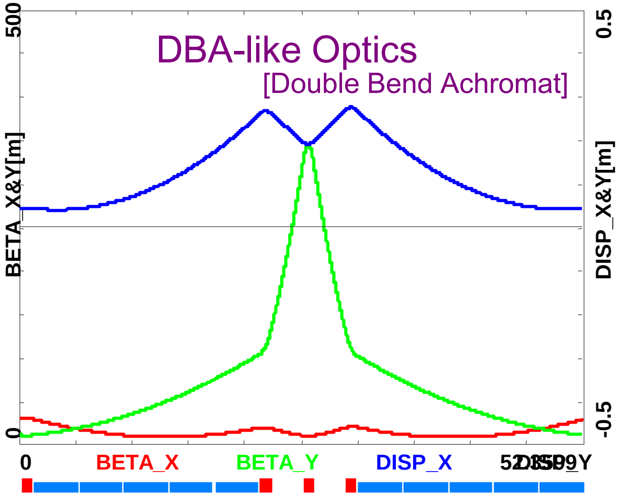
$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 , Arc 2



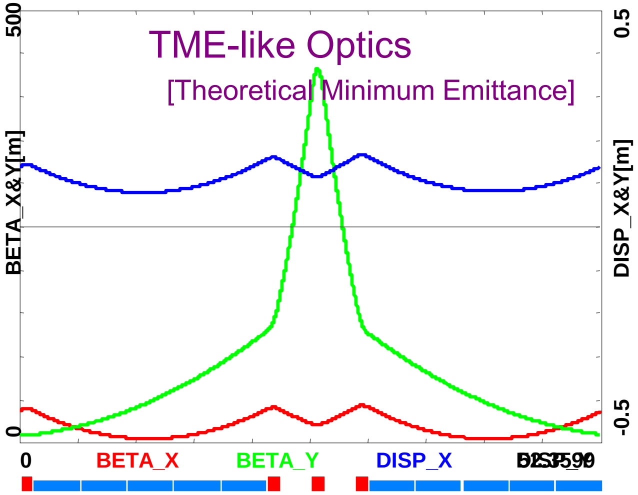

$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4




$$\langle H \rangle = 2.2 \times 10^{-3}\ m$$

Arc 5, Arc 6




$$\langle H \rangle = 1.2 \times 10^{-3}\ m$$

total emittance increase in Arc 1- 5: $\Delta\varepsilon_x^N = 4.9\ \mu\text{m rad}$ factor of 20 smaller than FODO

# ERL Facilities Overview:

Andrew Hutton @ this Symposium