The potential of Energy Recovery Linacs for sustainable HEP accelerator concepts

Acknowledgments:

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F. Gerigk – CERN; E. Jensen - CERN;

M. Seidel – PSI; P. Williams - STFC; A. Mosnier - CEA;

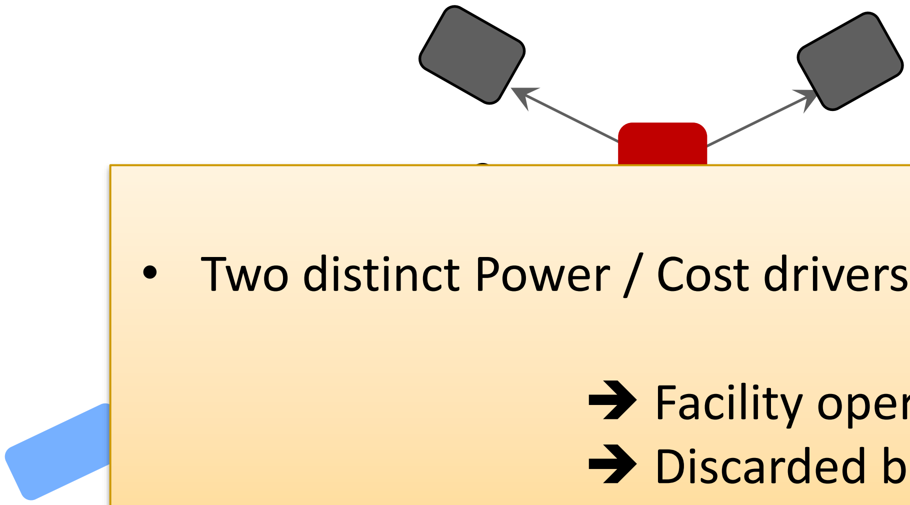
Overview

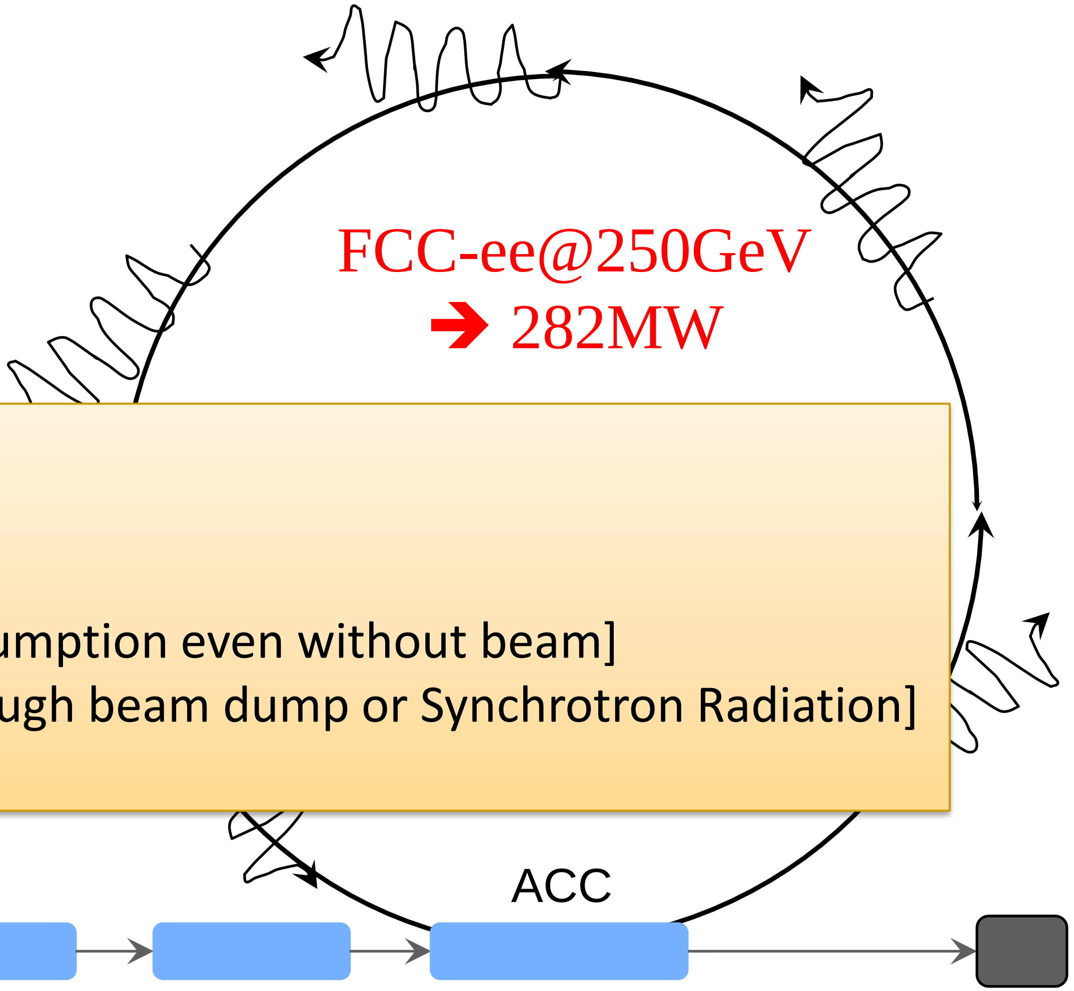
- Energy and power needs for HEP colliders
- Energy Recovery Linac concept & benefits
- LHeC / FCC-eh Studies
- Energy Recovery Linac challenges
- Potential ERL HEP applications
- Timeline

Power Needs for HEP e^+/e^- Colliders

Circular Collider

Linear Collider





- Two distinct Power / Cost drivers:

  ➔ Facility operation cost [Power consumption even without beam]
  ➔ Discarded beam power [either through beam dump or Synchrotron Radiation]

Bea

> 99.99999% of the beam energy is thrown away

➔ >500MW power consumption for CLIC @ 3TeV

How much power is 500MW and how much energy is that for 1d [12GWh]?

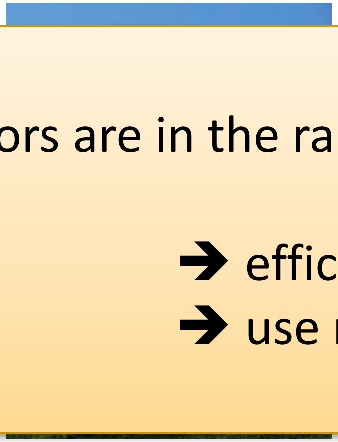
Electric Power: Orders of Magnitude – 12GWh

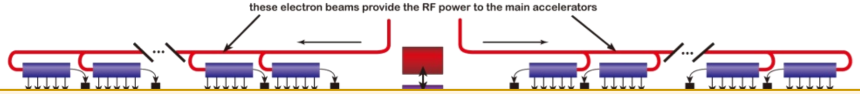
*) Battery Electric Vehicle

	generation	consumption	storage
kW	1d cyclist „Tour de France“ (4h x 300W): **1.2 kWh**	1 run of cloth washing machine: **0.9 kWh**	Car battery (60 Ah): **0.72 kWh** BEV*) Battery (Lithium-ion): **100 kWh**
MW	1d Wind Power Station (avg): **12 MWh**	1 … **8** …	All LHC magnets @ 8.33 T: **3 MWh** ITER superconducting coil: **12.5 MWh**
GW	1d nucl. Pow. Plant (e.g. Leibstadt, CH): **30 GWh**	1 … **12** …	All German storage hydropower: **40 GWh**

LHC: ca. 3GWh / day
Zürich: ca. 8GWh / day


cyclist,





car battery

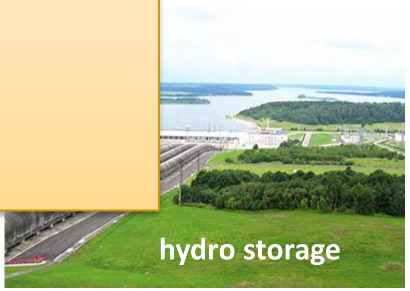

BEV battery


- Accelerators are in the range were they become relevant for society and public discussion.

➔ efficiency needs to become a key design feature!
➔ use renewable energy as much as possible


nucl. plant 1.3 GW


Poloidal Field (PF) coil (NbTi, 6 coils, 45 kA, 4 ~ 6 T)



M. Seidel/PSI

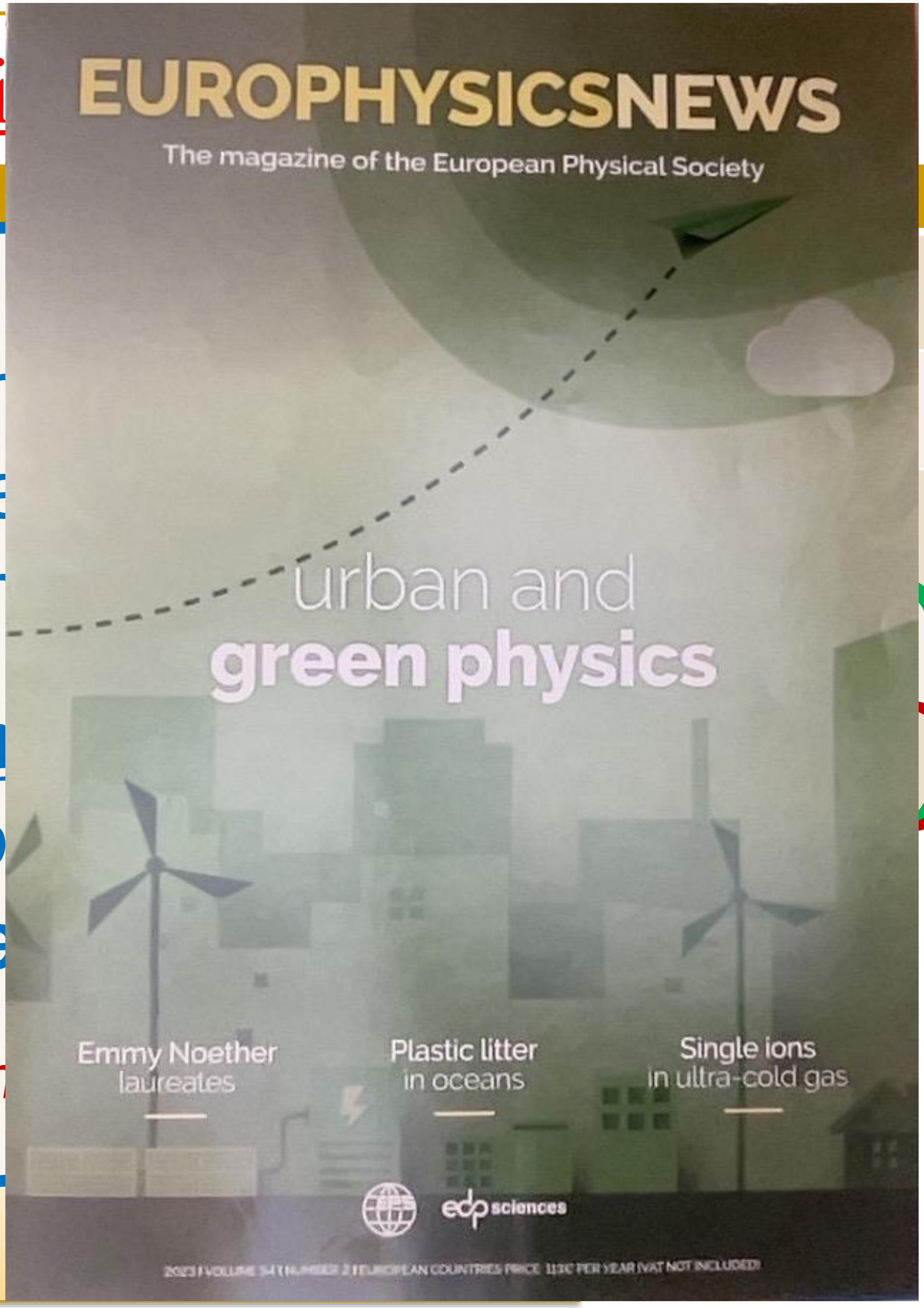
Power Production: Orders of Magni

generation	consumption
1d cyclist „Tour de France“	

The energy efficiency of presen
accelerators [...] is and should re
requiring constant atten

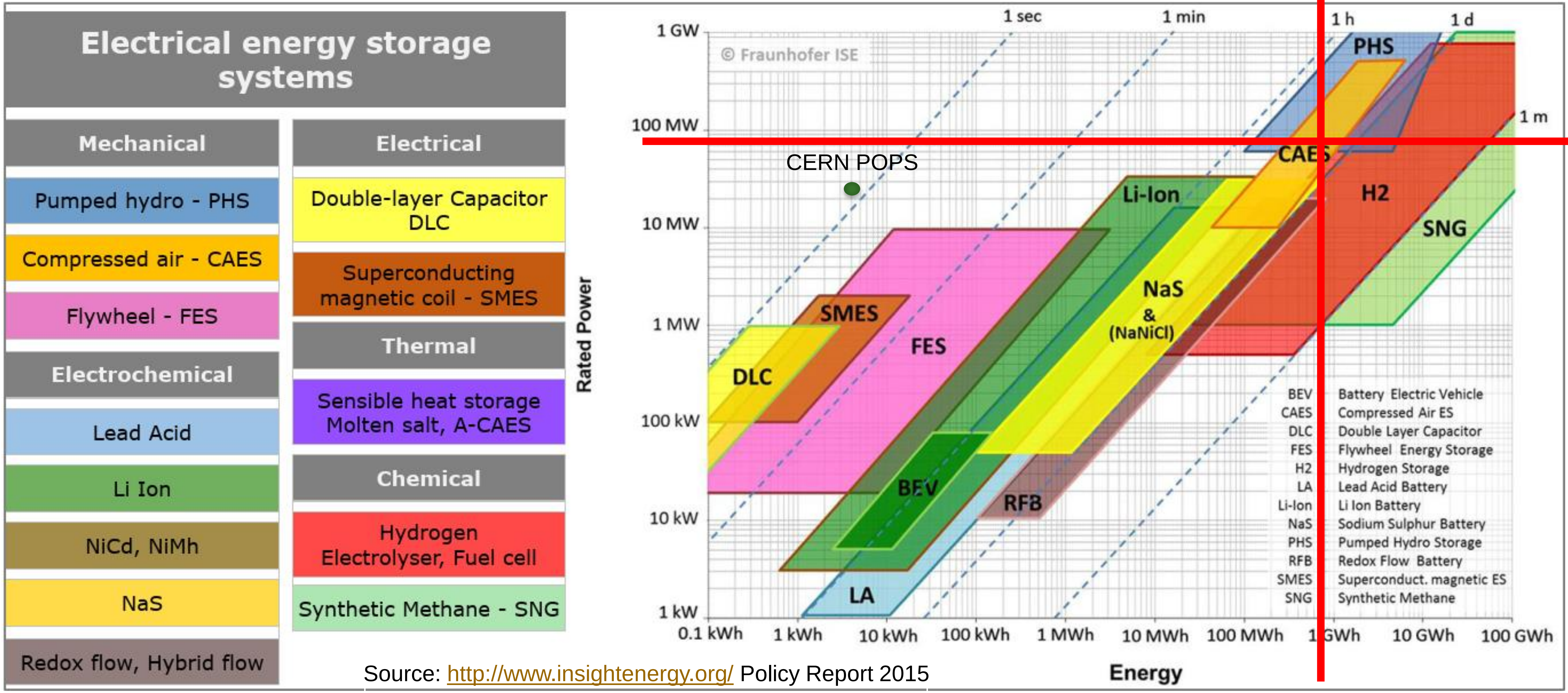
A detailed plan for the [...] savin
energy should be part of the ap
for any major proje

European Strategy for Particle Ph



Number of physics events, secondary particles, X-rays on sample

Energy Storage - Technologies



Source: http://www.insightenergy.org/ Policy Report 2015

Energy Recovery

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

Machine operation still requires the infrastructure overhead; but one can try to recuperate the beam power of the accelerated beams

➔ Initially proposed for linear colliders!

Beam Energy Recovery Linac Concept

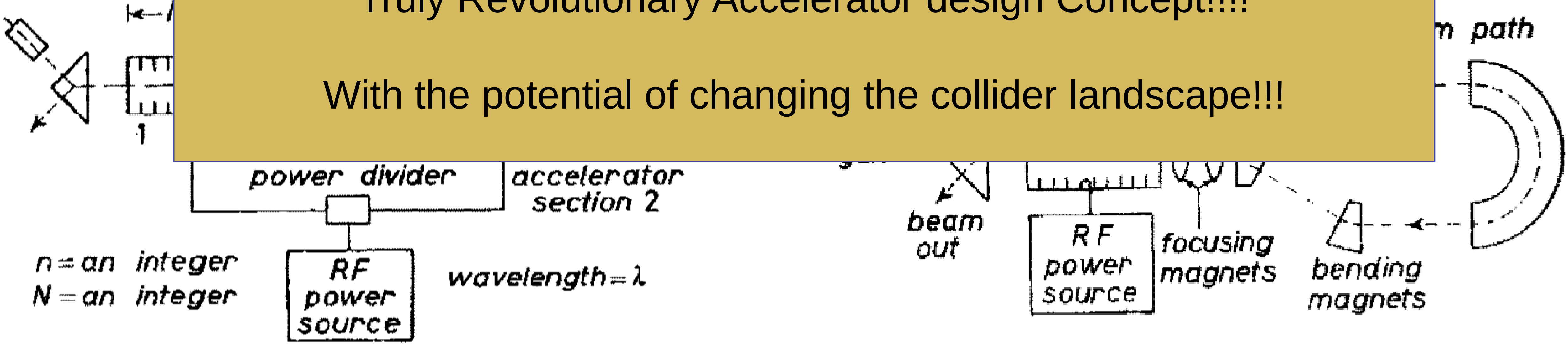
- First proposal 60 years ago:

  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!!!



Potential Applications

- Free Electron Lasers as photon sources → 4^{th} generation light sources offer diffraction limited photons and are more suitable for incoherent light sources. ERLs still pursued for high power XFELs

- Colliders: both linear and circular

- High current electron coolers and electron lenses

- High flux Xray sources using Compton Back Scattering

Circular Collider Peak Luminosity: added bonus for ERLs

Luminosity recipe (round beams):

Assumptions:
Equal number of bunches and matched beam sizes

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

1) maximize bunch intensities ➔ Limited by beam-beam interaction

2) minimize the beam emittance ➔ Synchrotron radiation & coupling

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

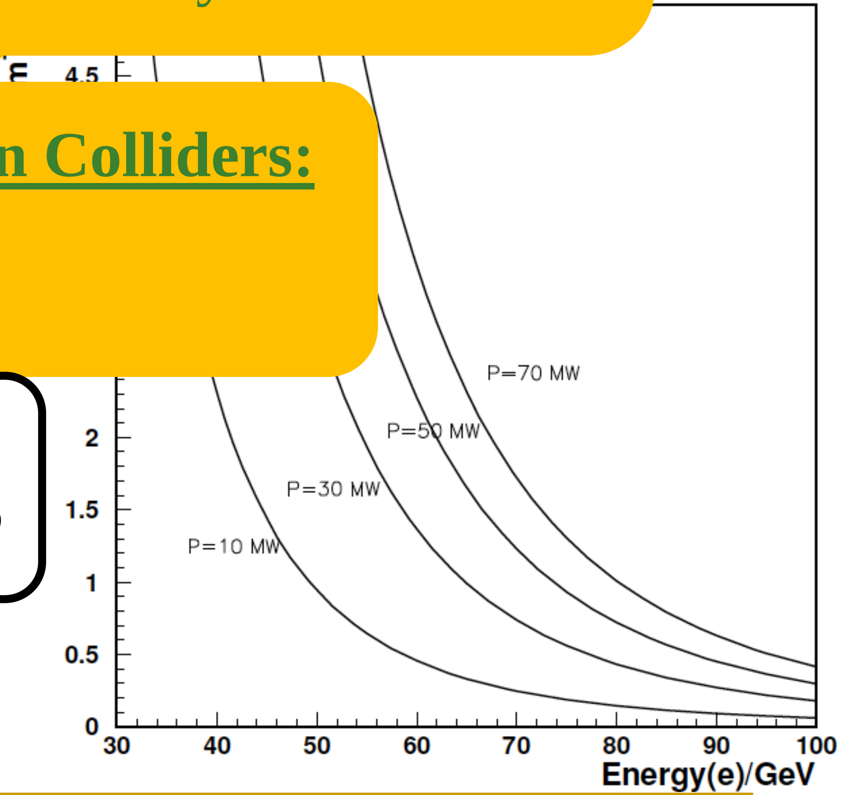
Linear Lepton Colliders:
Strongly suppressed synchrotron radiation
Not Beam-Beam limited ➔ even uses beam-beam for performance enhancement
But beams pass the infrastructure only once and can collide only once!

➔ Proposal of Linear accelerators for Future Lepton Colliders:
TESLA & ILC: 500GeV to 1.5TeV CME
CLIC: 1TeV up to 3TeV CME

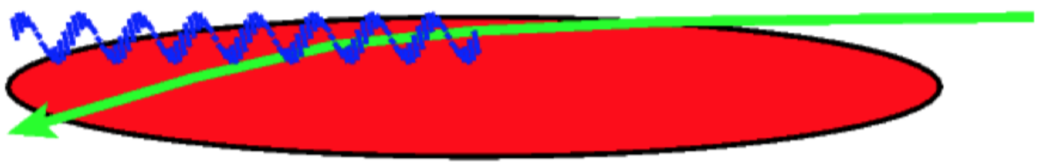
Power Scales with E^4 and ρ^{-2}

$$P \propto \frac{\gamma^4}{\rho^2} \cdot n_b \cdot N_b$$

➔ Reduced performance reach for higher beam energies ➔ limits number of bunches!



Linear Collider Luminosity



D. Schulte @ 9th International School for Linear Colliders

Bunches are squeezed for Maximum Luminosity

↓

Strong E-M Fields @ IP

↓

Particles follow curved trajectory through IP

↓

They emit photons [Synchrotron Radiation] @ the IP [beamstrahlung] → CM Energy spread

$$L \propto H_d \cdot \frac{N_p}{\sigma_x} \cdot N e n_b f_r \cdot \frac{1}{\sigma_y}$$

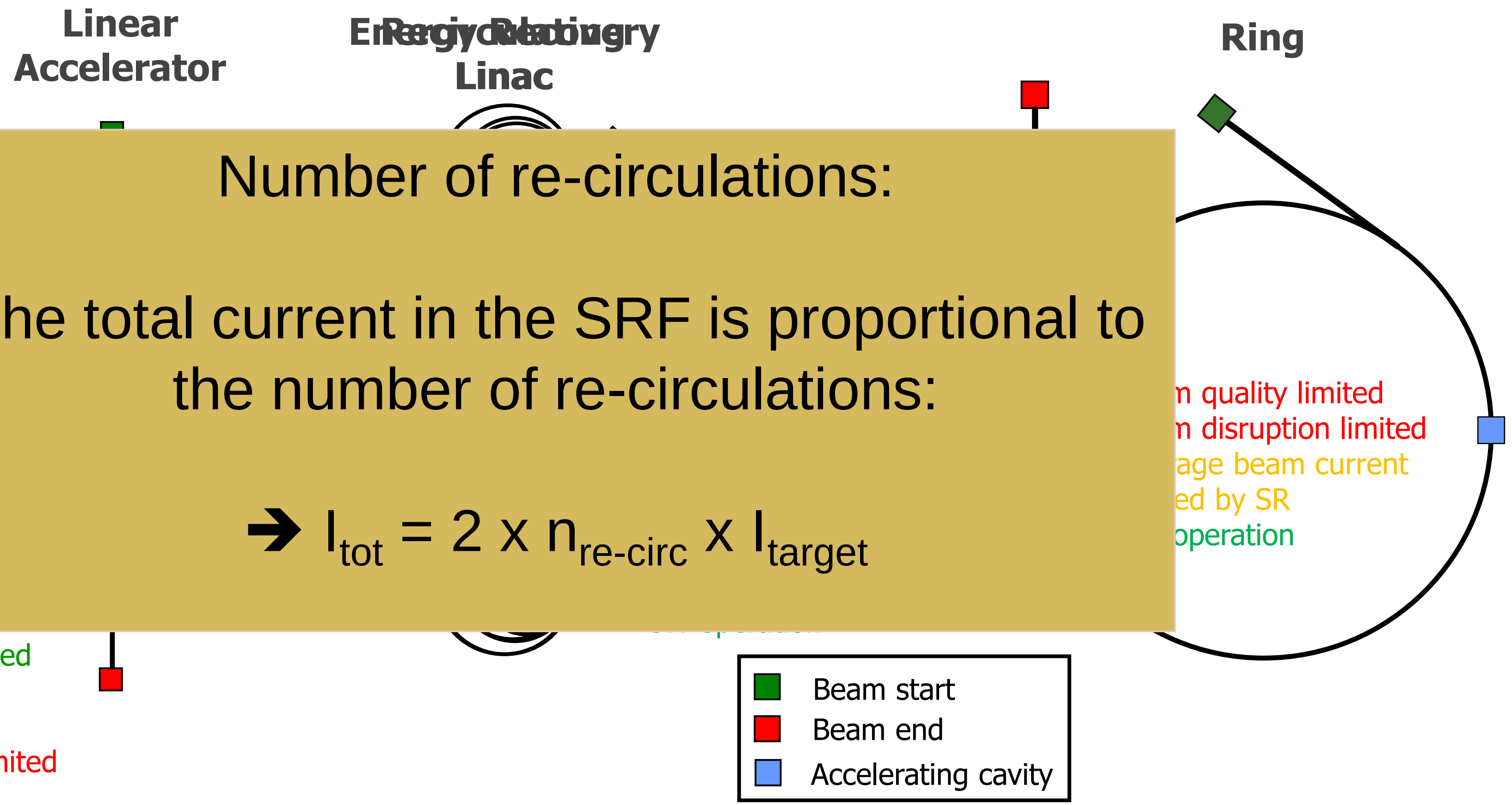
L Spectrum

Linac Beam Power

Beam Quality

→ Luminosity reach is directly proportional to beam power, and hence power consumption! Independent of the underlying linac technology!!!!! What matters is Wall plug Efficiency!! and power lost on the beam dump!!!

Re-circulating Linac Configuration with Energy Recovery: The best of Two Worlds!



Number of re-circulations:

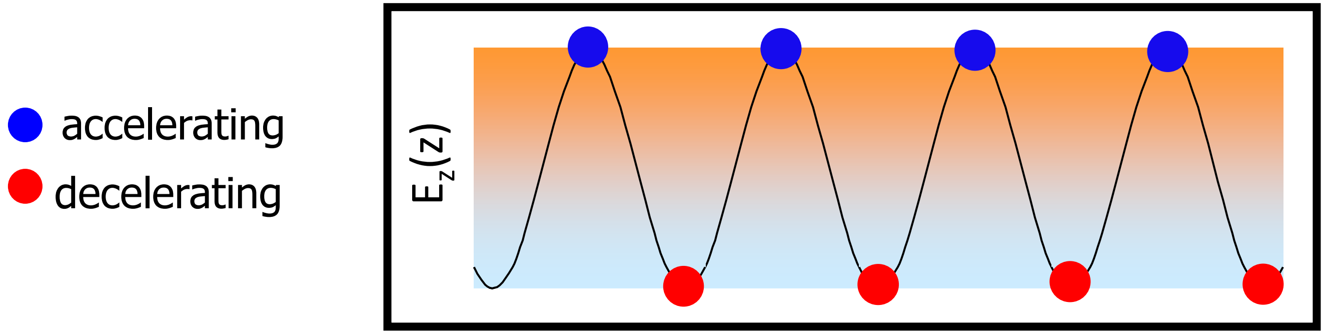
The total current in the SRF is proportional to the number of re-circulations:

➔ $I_{tot} = 2 \times n_{re\text{-}circ} \times I_{target}$

- Excellent beam quality
- Beam disruption not limited
- Strongly suppressed SR power loss
- Average beam current limited in pulsed operation
- Inefficient as hardware is passed by beam only once

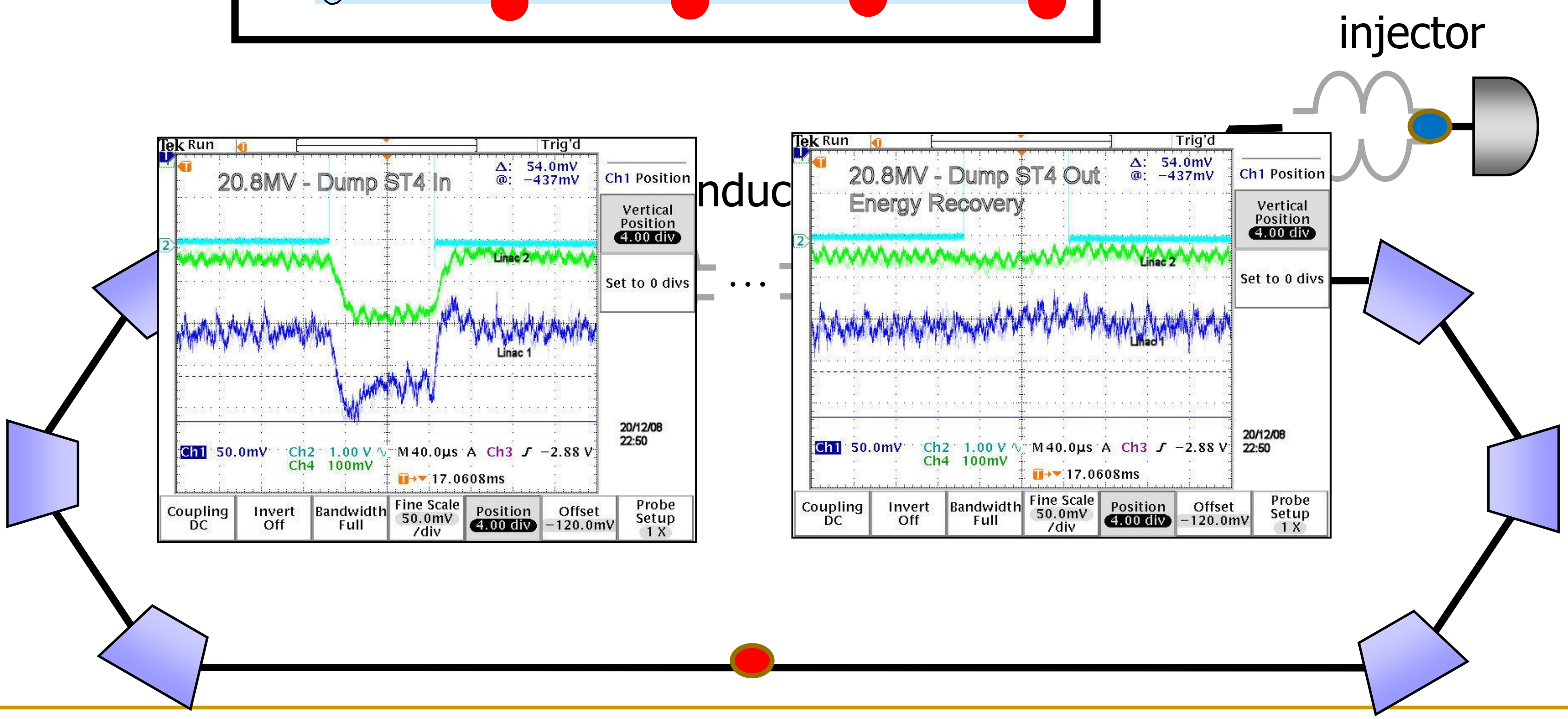
Re-circulating Linac Configuration

Accelerate → Use → Decelerate: pendulum concept



➔ Allows CW operation

➔ Increases the beam current in the SRF



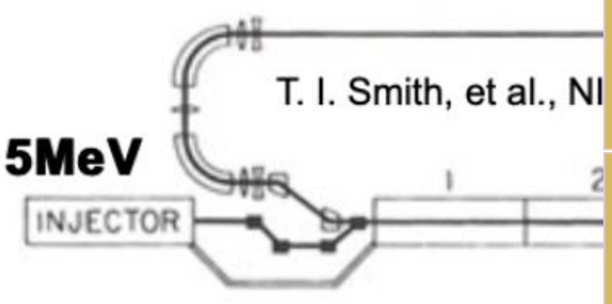
RF power demand reduces to zero when operated in ERL mode!

From first ER on ALICE @ Daresbury in **2008**!

First Demonstrators: 80ies

First demonstration:

Stanford SCA/FEL, 07/19



So why are they not routinely used

in accelerator projects?

➔ Effective ERL applications require

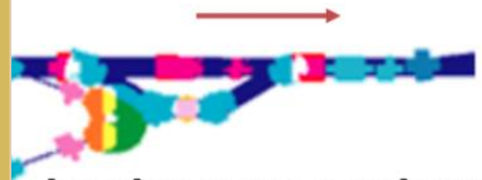
SRF technology with $Q_0 > 10^{10}$ and

Cost effectiveness requires peak fields of

$V > 15MV/m$

➔ Technology only ready since 2000

1985



isochronous + achromati
recirculation system
(energy bandpass: 6%)

Study for an ep / eA collider using the LHC / FCC

CDR Study assumptions:

-Assume parallel operation to HL-LHC / FCC-hh

-TeV Scale collision energy

➔ 50-150 GeV Beam Energy

-Limit power consumption to 100 MW ➔ 150MW

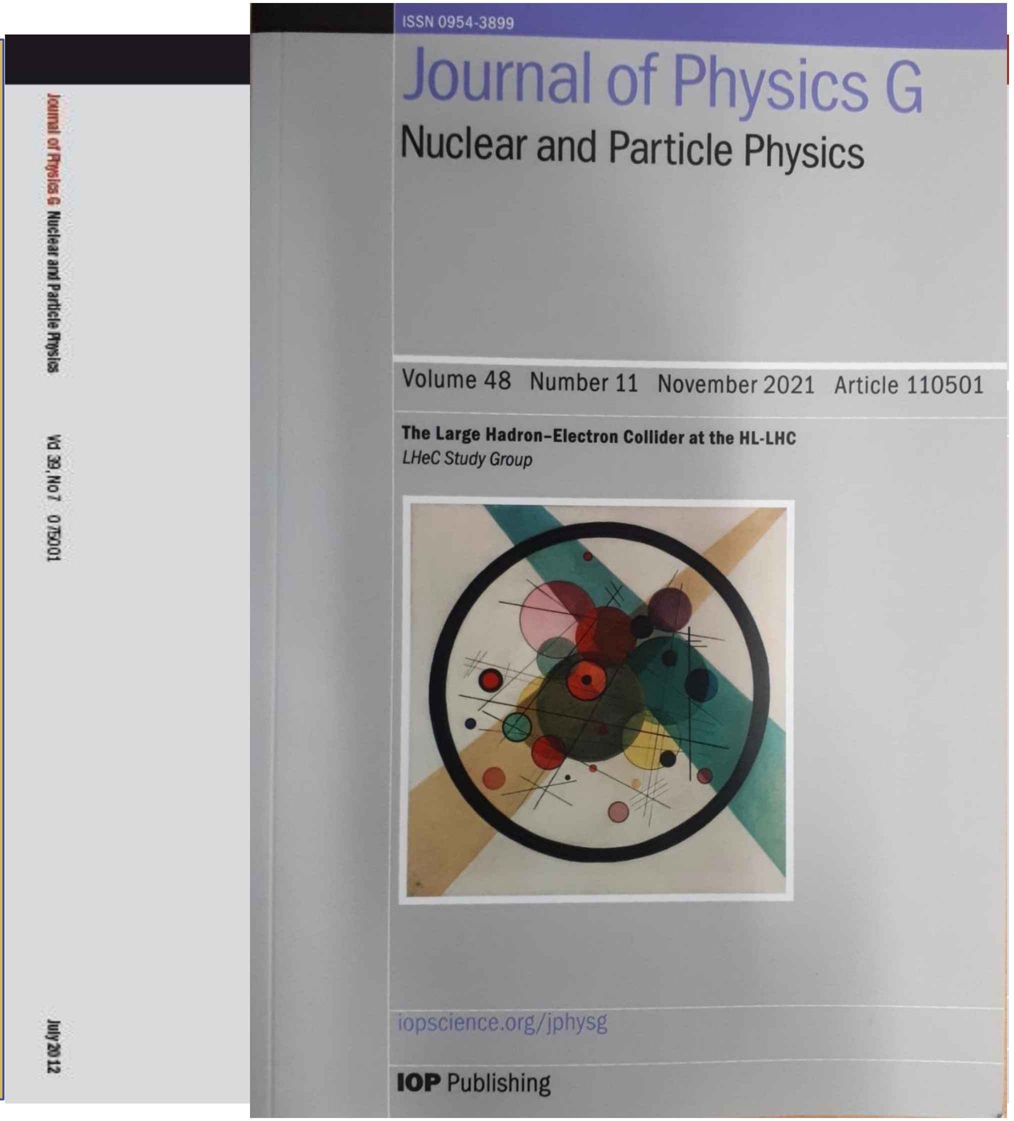
➔ (beam & SR power < 70 MW)

➔ 60 GeV beam energy ➔ 50GeV

-Int. Luminosity > 1000 * HERA

-Peak Luminosity > 10^{33} cm^{-2}s^{-1}

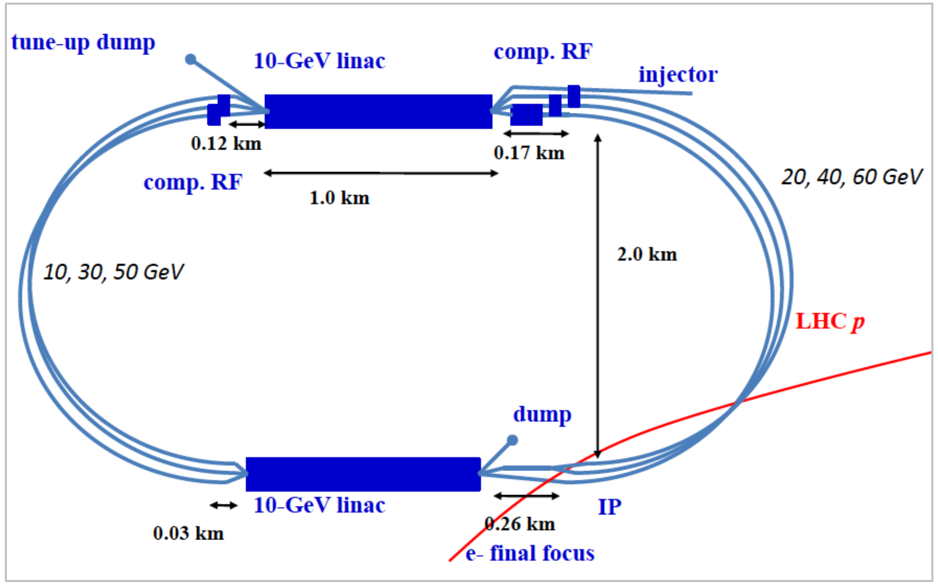
Higgs @ 125GeV ➔ > 10^{34} cm^{-2}s^{-1} & Cost Study



Application: LHeC / FCC ERL Configuration

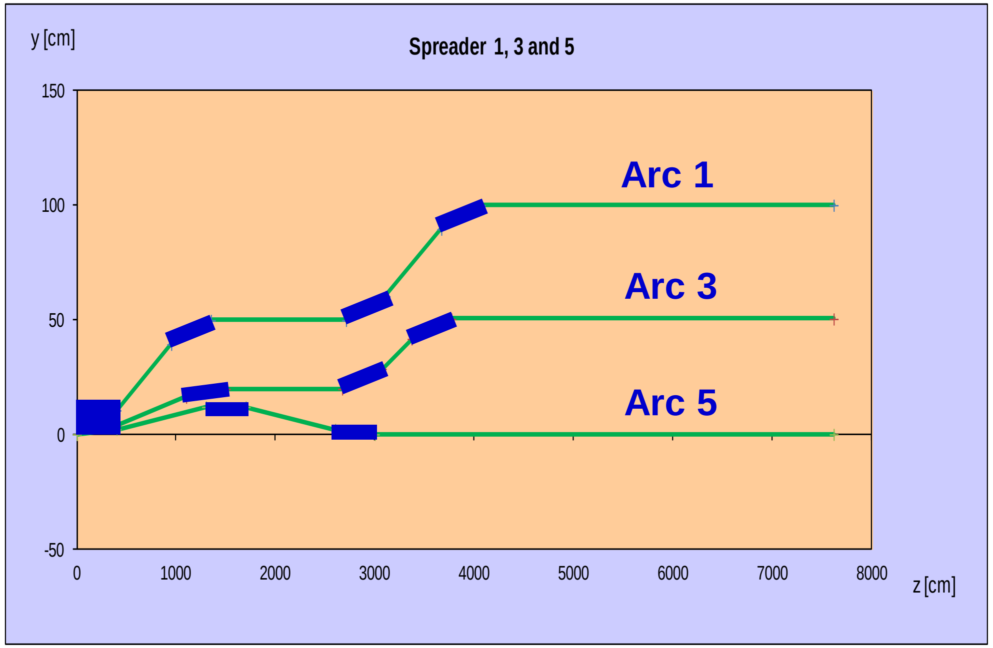
* LHeC CDR, arXiv:1206.2913

Racetrack design: 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 O(100 MW) ➔ ca. 50/50 SR and TI



➔ 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!

courtesy H.Burkhardt, BE-ABP CERN (layout scaled !)

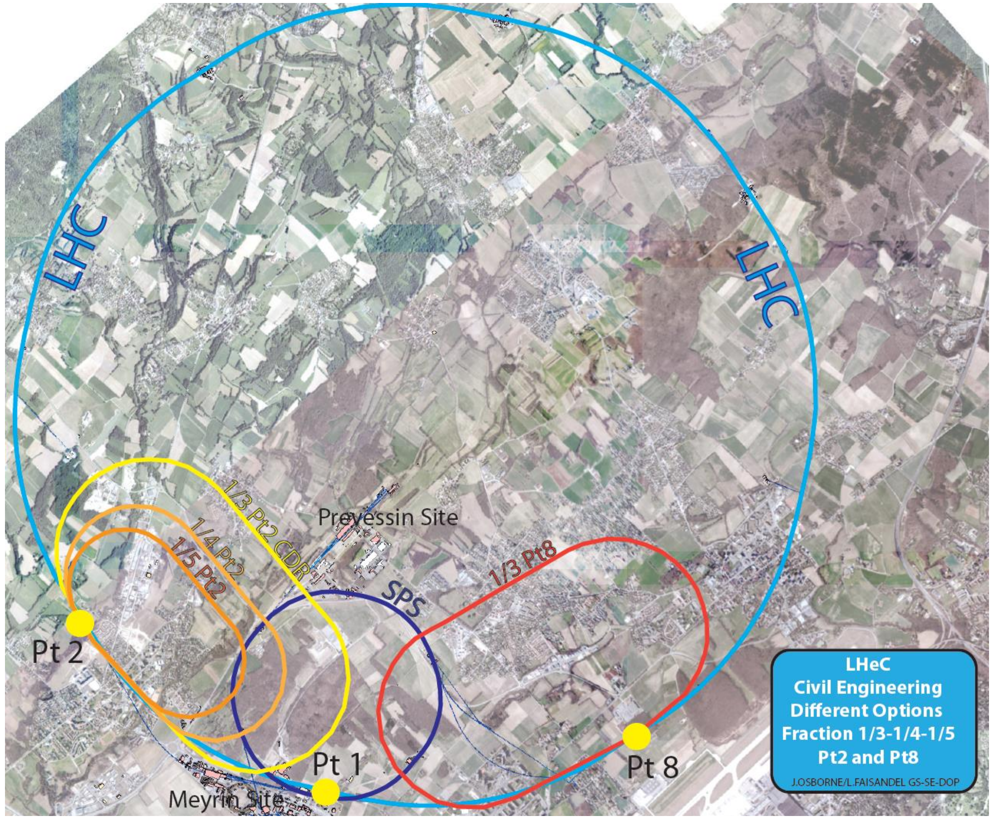
LHeC / FCC-eh ERL Configuration: Layout Options & Scaling

CERN-ACC-2018-0061

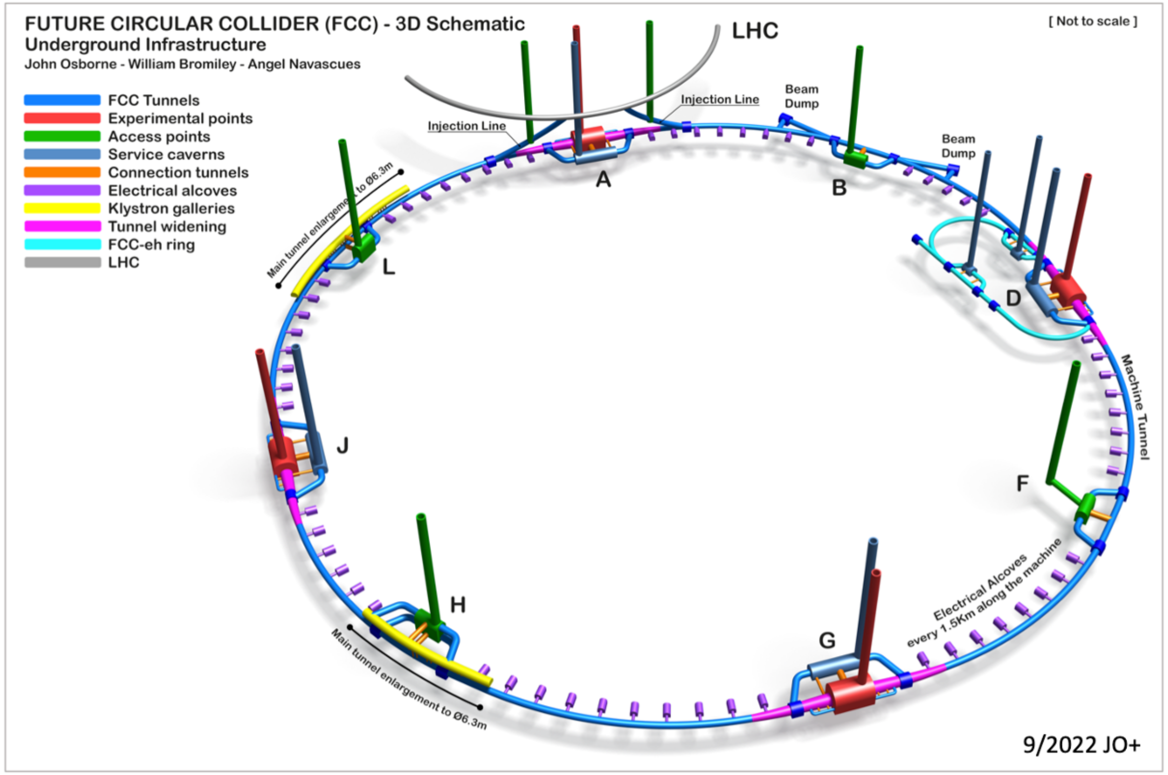
Configurations:

LHeC

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



CDR: 8 point FCC: point D



LHeC & FCC-eh Machine Configuration

➔ All technologies have been demonstrated [e.g. source, SRF, triplet magnets etc.]

➔ Infrastructure can also be used as FCC-ee injector with W top-up injection energy!

➔ Synergies with the FCC-ee SRF for top physics operation ➔ allows build-up of industrial partners for FCC-ee SRF production

➔ What is missing is high current multi-turn ERL operation ➔ PERLE @ IJC-Lab!

FCC-eh ERL Configuration:

Consistent Performance Projections for ep:

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV				
bunch sp				
protons				
$\gamma\epsilon_p$ [μm]				
electrons				
electron				
IP beta				
hourglas				
pinch fac				
proton fi				
luminosi				

1 GW beam Power!!!

But at ca. 100MW Facility power

Baseline Electron Beam Energy in 2012 CDR reduced from 60GeV to 50GeV in 2021 CDR update

➔ Compatible with circumference of 1/5th of LHC while assuring overall Power Consumption of ca. 100MW Keeping the accelerator cost @ 1BCHF
[CERN-ACC-2018-0061]

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

The Large Hadron-Electron Collider at the HL-LHC Journal of Physics G Vol 48, Number 11, November 2021

Consistent HL-LHC Performance Projections for ep:

LHeC

Three Operation scenarios for LHeC:

		1) Parasitic 30GeV	2) Pushed 50GeV	3) Dedicated 50GeV
Parameter	**Unit**	**Initial: Run 5**	**Design: Run 6**	**Dedicated**
Brightness $N_p/(\gamma\epsilon_p)$	10^{17} m^{-1}	2.2/2.5	2.2/2.5	2.2/2.5
electron beam current I_e	mA	15	25	50?
proton β^*	m	0.1	0.07	0.07
peak luminosity	10^{34} cm^{-2}s^{-1}	0.5	1.2	2.4
p beam lifetime	h	16.7	16.7	100
fill duration	h	11.7	11.7	21
turnaround time	h	4	4	3
overall efficiency	%	54	54	60
Physics time / year	days	160	180	185
Annual integrated lumin.	fb^{-1}	20	50	180

Limitations / Challenges for the ERL

- Low Emittance, High-Current Sources with large lifetime
- Synchrotron Radiation → beam size dilution and energy losses
- Final Beam energy of the decelerated particles → ERL efficiency
- Beam stability and beam losses along the accelerator
- Field decay in the RF structures between deceleration and next acceleration
- Cryogenic power needs for the SRF operation → operating temperature!
- Facility infrastructure energy requirements → Overall ERL facility efficiency

E.g. cooling and ventilation, cryogenics source, magnet powering

Arc Optics: Emittance preserving cells:

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

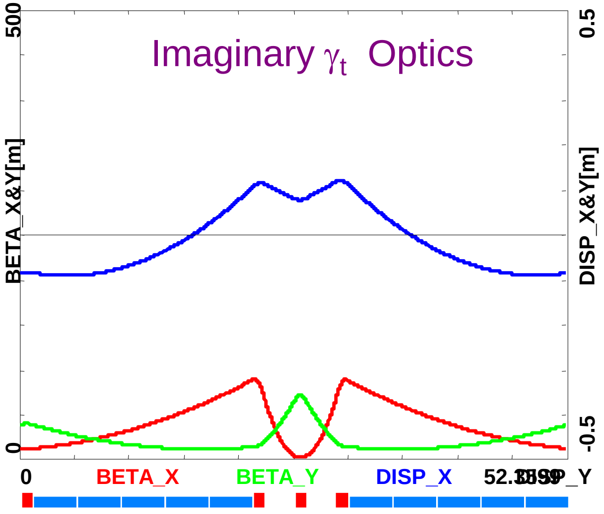
- Emittance dilution due to quantum excitations:

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

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

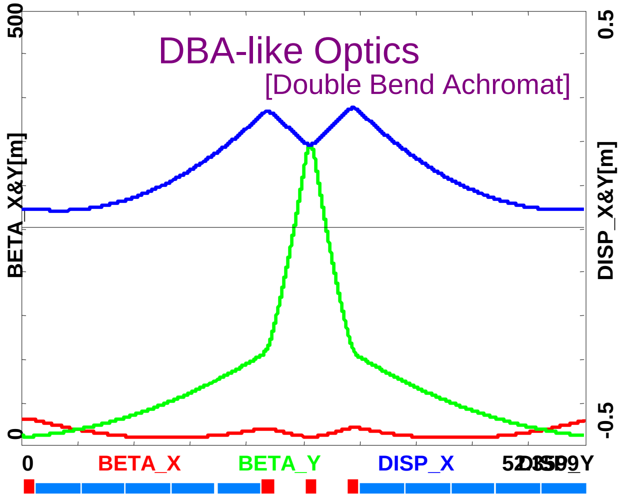
$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 , Arc2



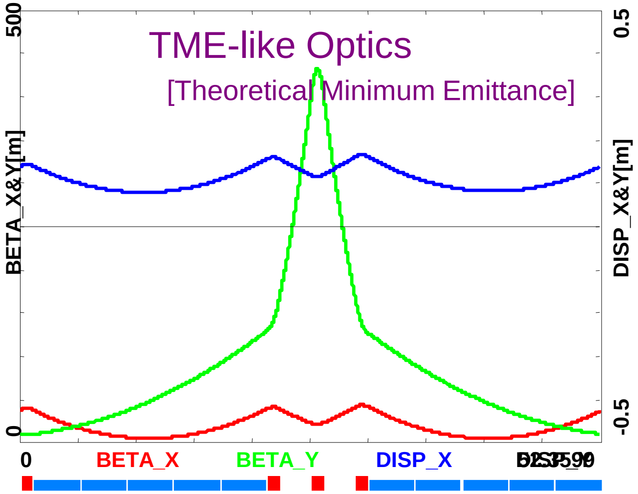
$$\langle H\rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4



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

Arc5, Arc 6



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

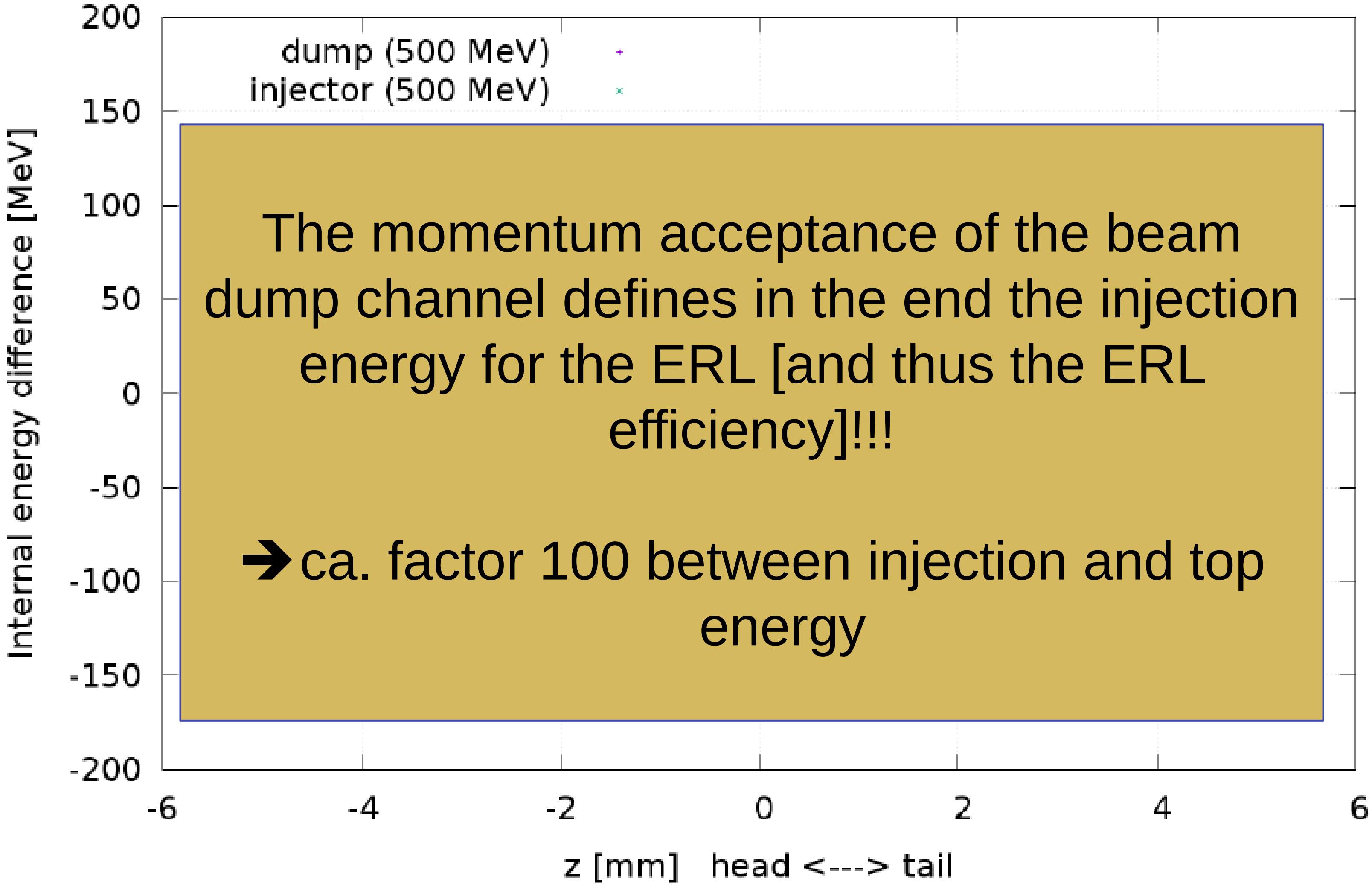
factor of 20 smaller than FODO

total emittance increase in Arc 1- 5: $\Delta\varepsilon_x^N = 4.9\ \mu$m rad

Synchrotron Radiation

Evolution of the Longitudinal Phase Space

Example LHeC: e-beam @ 60GeV
D. Pellegrini (EPFL/CERN) @ ERL’15



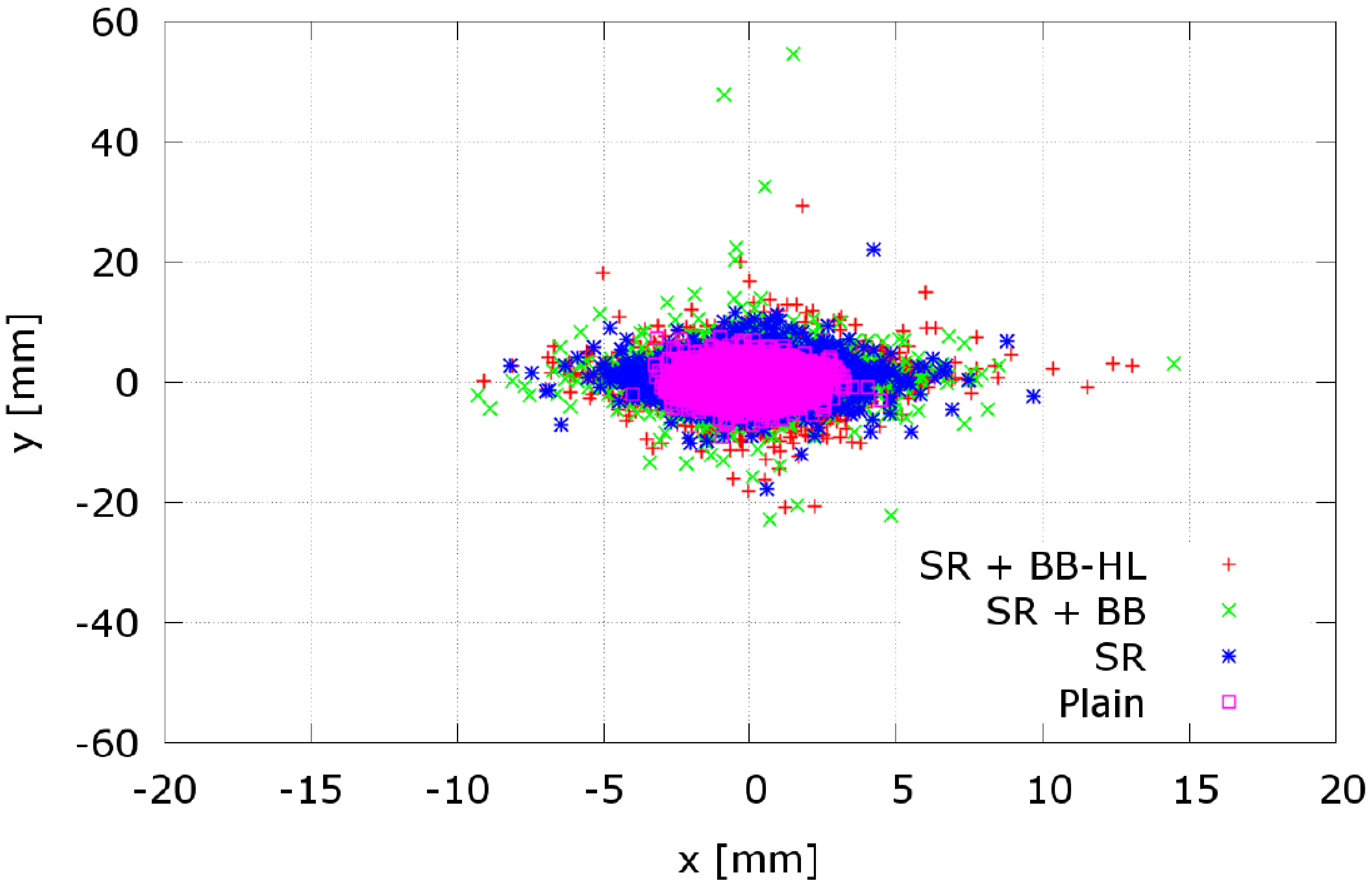
The momentum acceptance of the beam dump channel defines in the end the injection energy for the ERL [and thus the ERL efficiency]!!!

➔ ca. factor 100 between injection and top energy

Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump

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



Aperture radius of the SPL cavity is 40 mm.

Coherent Synchrotron Radiation

Beam Distribution in ERL:

Only small number of passage through RF system ➔ no equilibrium distribution

Distributions are source defined / limited: noise and spatial distribution features

Space charge and RF noise can introduce longitudinal structures within bunch

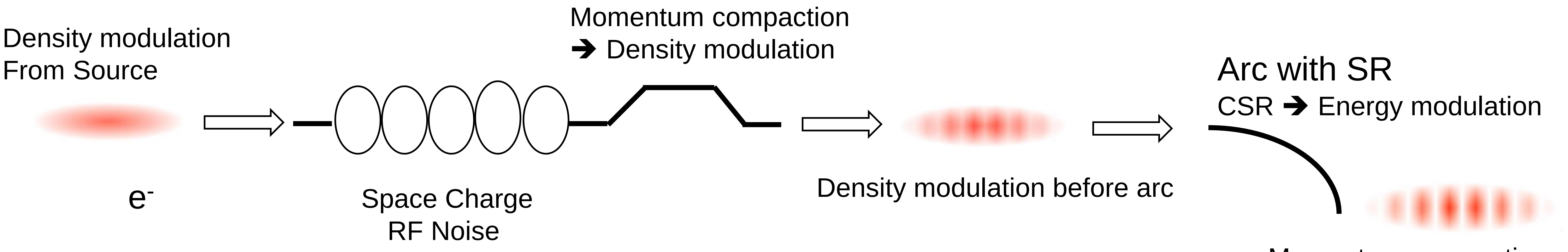
➔ bunches can feature density structures shorter than the typical wavelength of the SR

➔ Particles emit SR coherently ➔

$$P \propto \frac{\gamma^4}{\rho^2} \cdot [q \cdot N]^2$$

Coherent Synchrotron Radiation

Micro Bunching:



Energy loss, Emittance growth and instability:

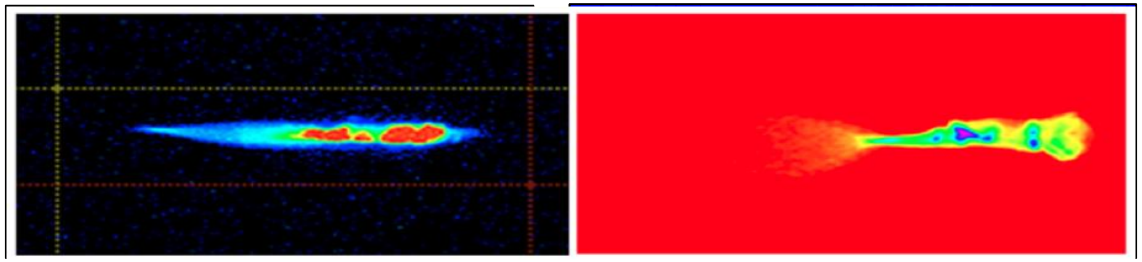
CSR translates small density perturbation into an energy modulation

➔ Finite momentum compaction yields density perturbation ➔ more CSR

➔ Stronger energy modulation

➔ High peak power CSR and instability

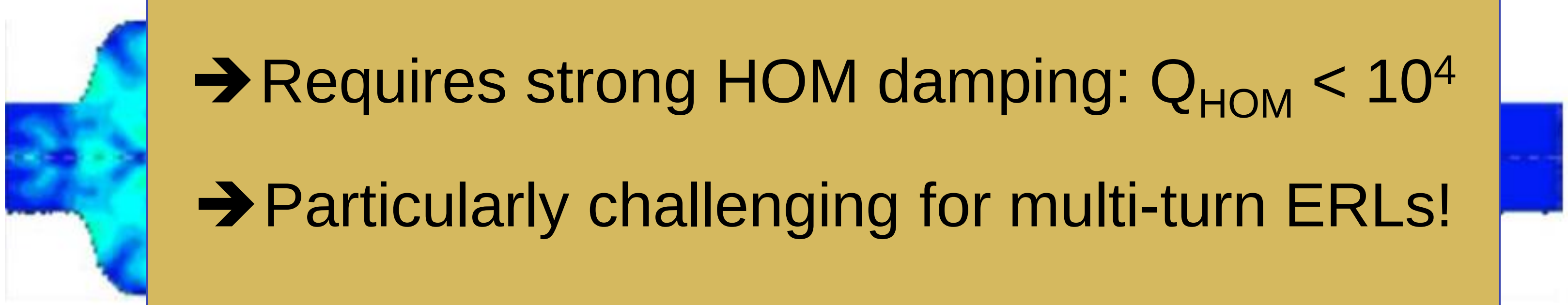
C-BETA @ PERLE Workshop May 2022



JLab Tennant et al ERL workshop 2017

HOM losses:

- As a bunch passes through an RF structure it leaves behind wake-fields



➔Requires strong HOM damping: $Q_{HOM} < 10^4$

➔Particularly challenging for multi-turn ERLs!

➔HOM power needs to be extracted and not deposited in the cryo system!

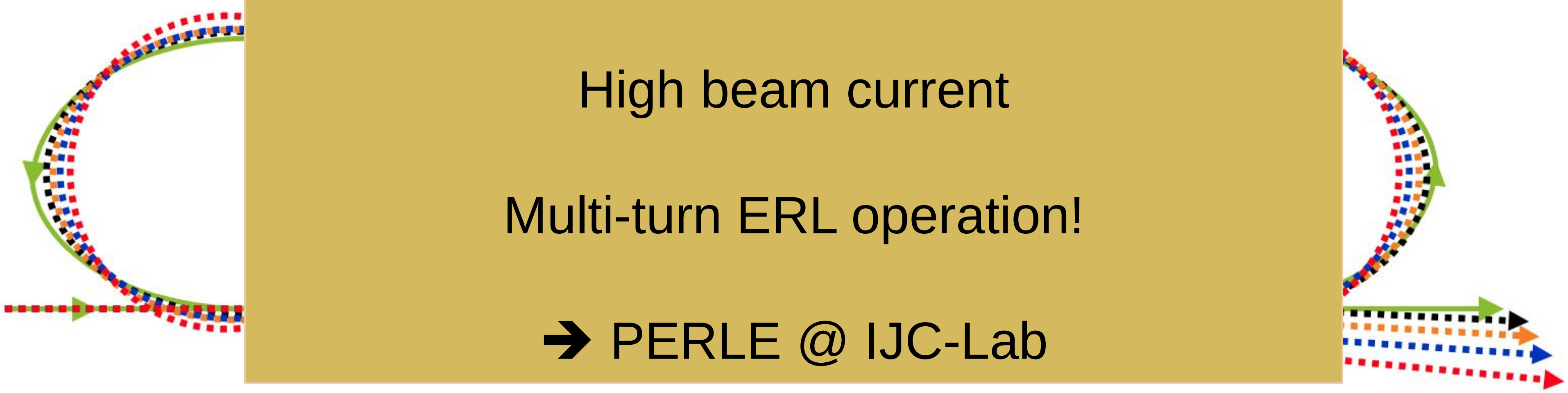
➔O(kW) for 100mA and Q_{HOM} 10^4

The wake fields e
In CW operation

- Non-resonant
- Resonant excitation: $P = (R/Q)_{HOM} \, Q_{HOM} \, I_0^2$

Beam Break Up [BBU] Instability:

- HOM start orbit … e HOMs



Need a demonstrator for

High beam current

Multi-turn ERL operation!

➔ PERLE @ IJC-Lab

➔ Instability sets a threshold limit for the total beam current in the SRF cavities

➔ ERLs have twice the beam current. Re-circulation designs increase I_{beam} further!

Field Decay in RF Structures

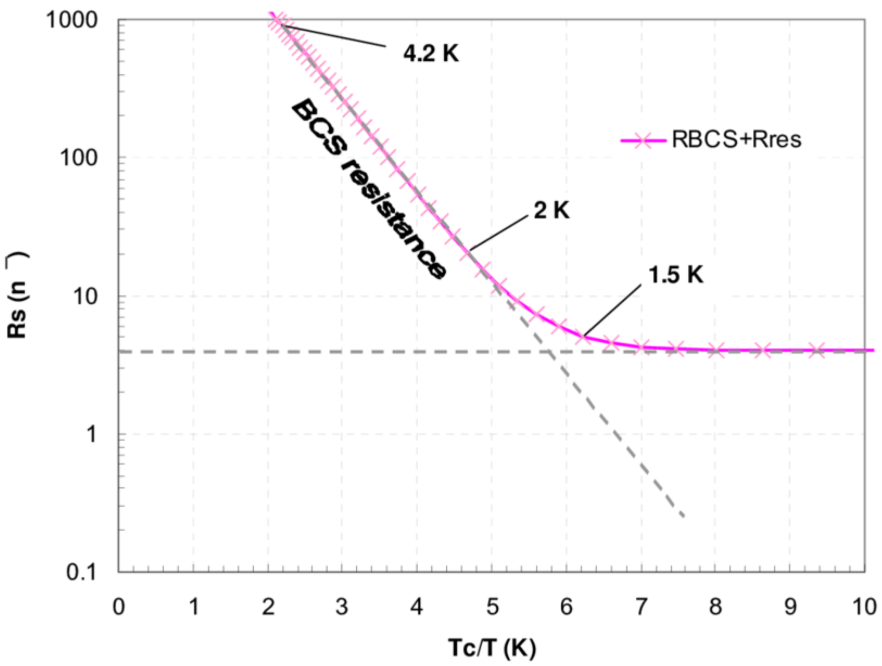
$Q_0 = G / R_s$ G is a geometric factor [cavity shape] and R_s the surface resistance

$$R_{s-normal} = \sqrt{\frac{\omega \mu_0}{2\sigma}}$$

Cupper conductivity @ 300K: $\sigma = 5.8\ 10^7\ /\Omega m$

For Type-II superconductors: $R_s = R_{BCS} + R_{res}$

BCS theory:
Bardeen-Cooper-Schrieffer
➔ energy loss of finite mass cooper-pairs within AC currents of RF fields



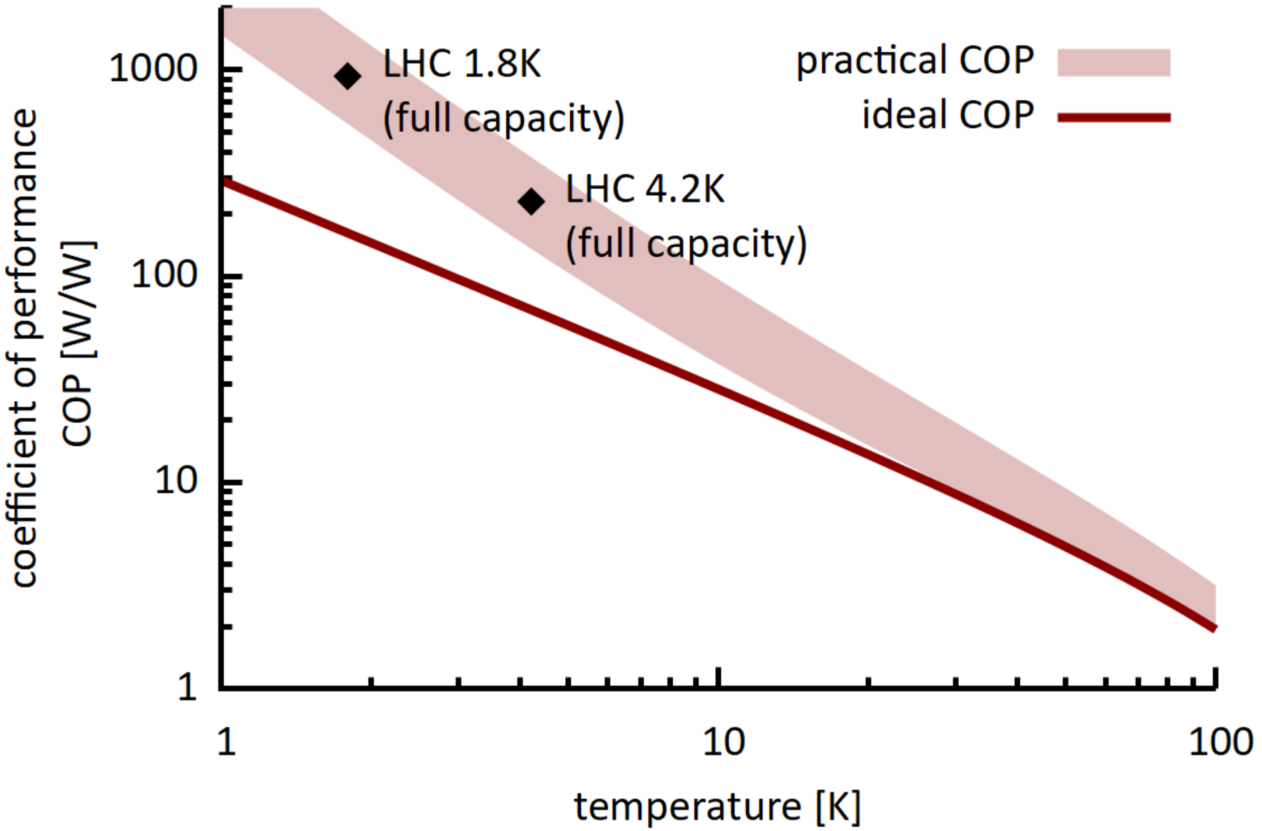
➔ You want the cavities at T << Tc!!!!

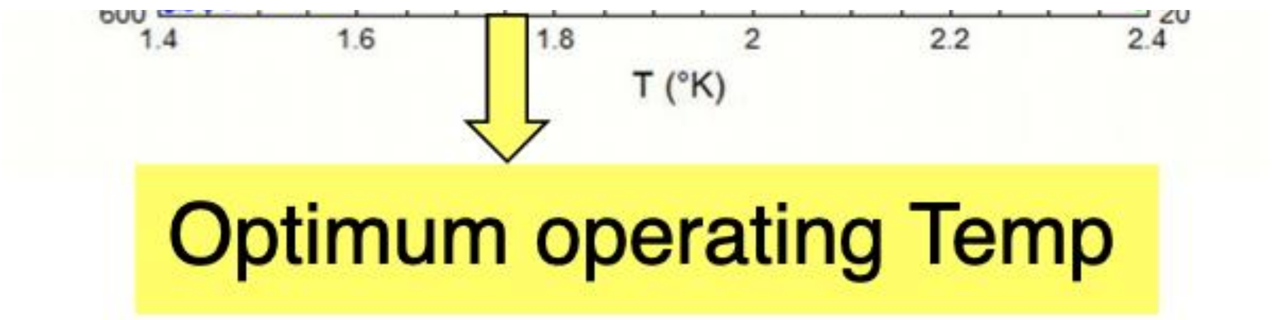
Implied Cooling Power

Carnot Process: Work done per Heat Transfe

$$W = \frac{T_0 - T_C}{T_C} Q_C$$

COP = Coefficient of Performance fo
a cryogenic plant = W / Q_C





Increased Efficiency for
High Temperature Superconductor!

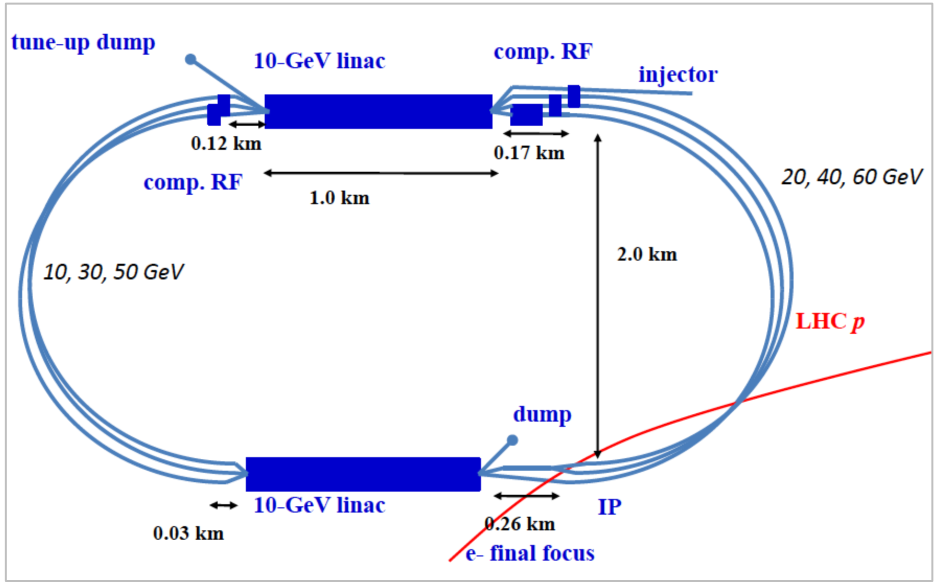
Potential ERL applications: Examples

- XFEL Light Source ➔ high power, high brightness coherent light source
- Collider
  - LHeC and FCC-eh
  - FCC-ee energy booster: CERC
  - ERLC: linear collider in ERL configuration
- Photon Source: Compton back scattering
- Hadron beam Cooler

LHeC / FCC ERL Configuration

* LHeC CDR, arXiv:1206.2913

Racetrack design: 3-turn Recirculating SRF Linac and ERL operation



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

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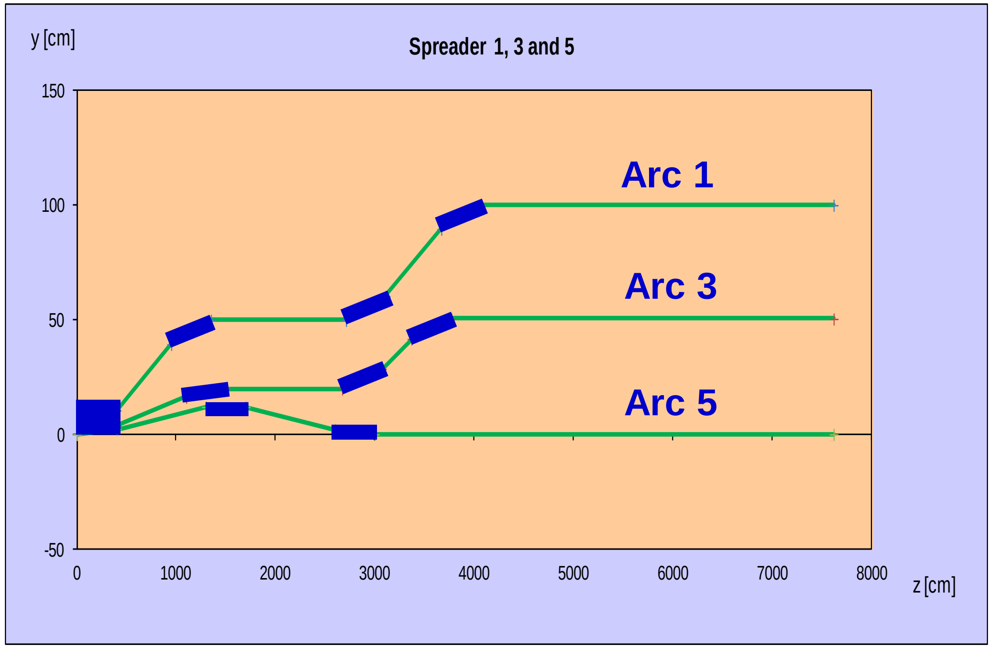
- power consumption O(100 MW) ➔ ca. 50/50 SR and TI



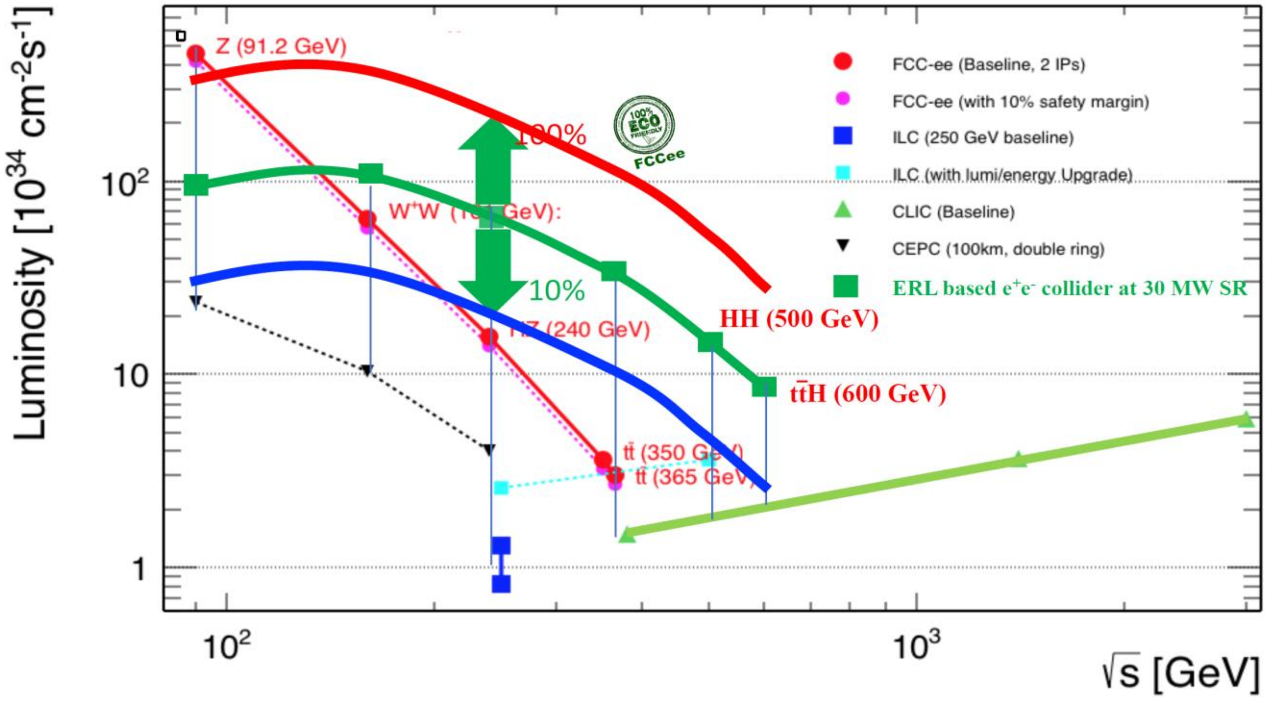
➔ 2 1km long SRF linacs

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

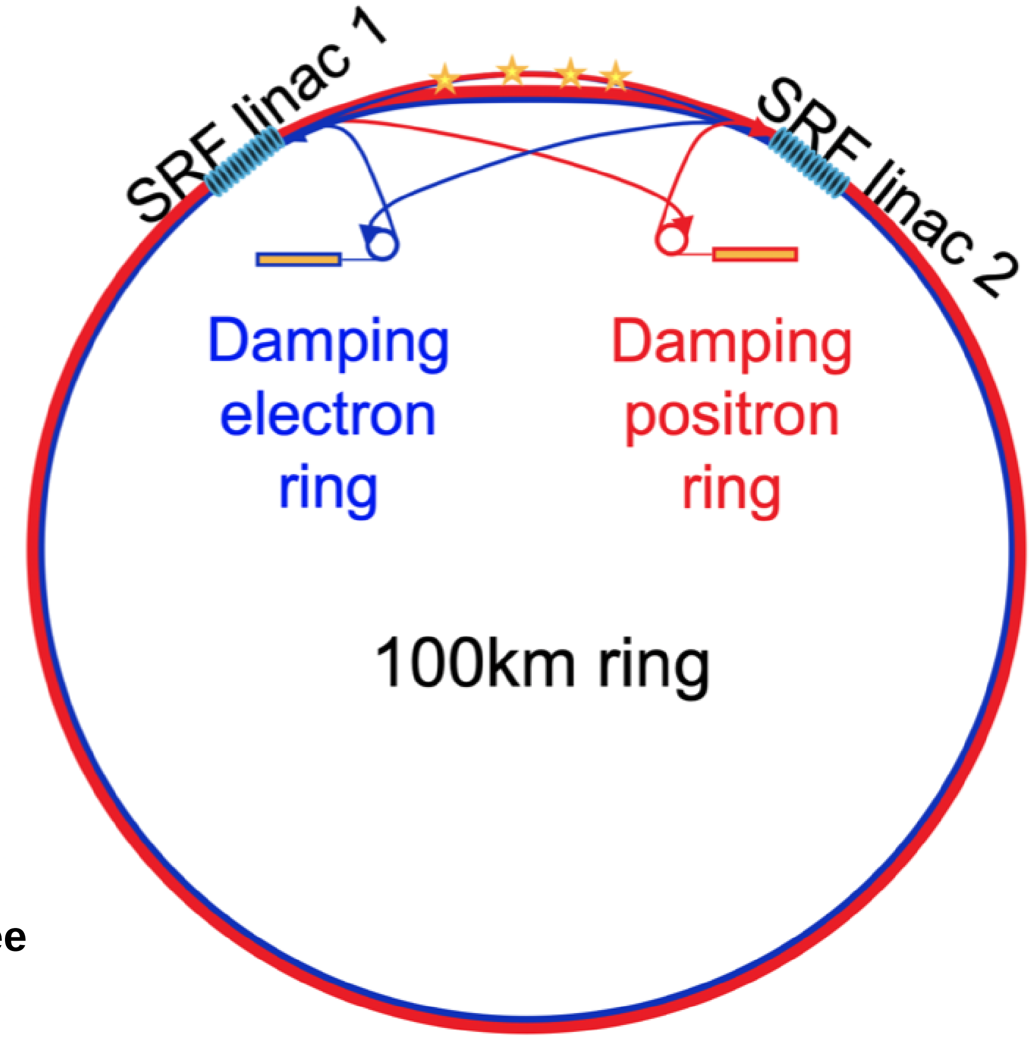
➔ Each beam passes 6 times through the SRF: 3 passes with acceleration and 3 with passes deceleration ➔ 6 times I_e in SRF!

courtesy H.Burkhardt, BE-ABP CERN (layout scaled !)

Example of CERC concept from ERL group of the ESPP

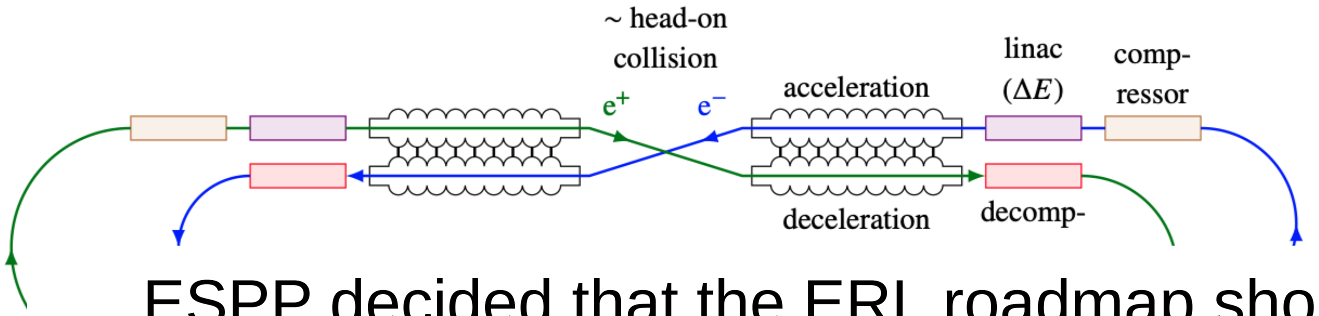


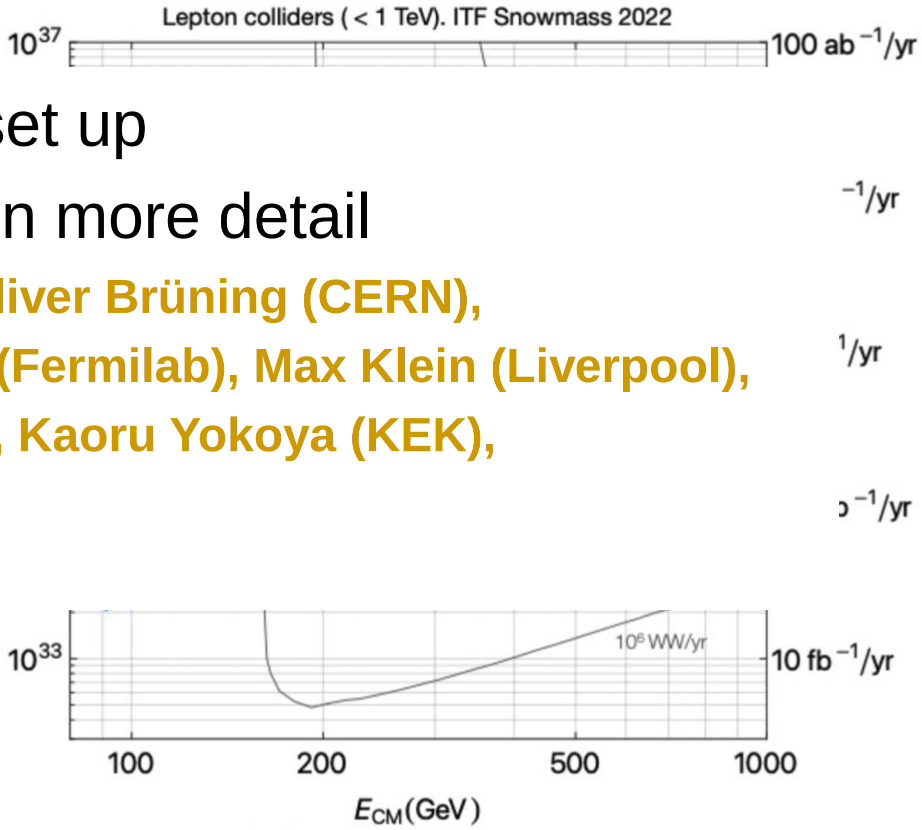
CERC Proposal by Litvinenko, Llatas & Roser, BNL
– re-imagining FCC-ee as an ERL



➔ can be used to either reduce power requirement for FCC-ee or to boost performance at given power foot-print

Example of ERLC concept from ERL group

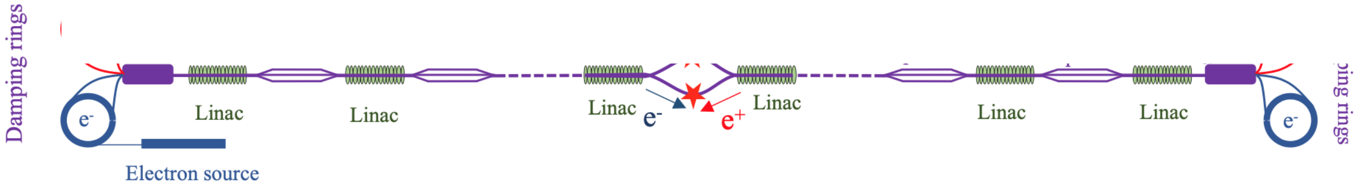




ESPP decided that the ERL roadmap should set up

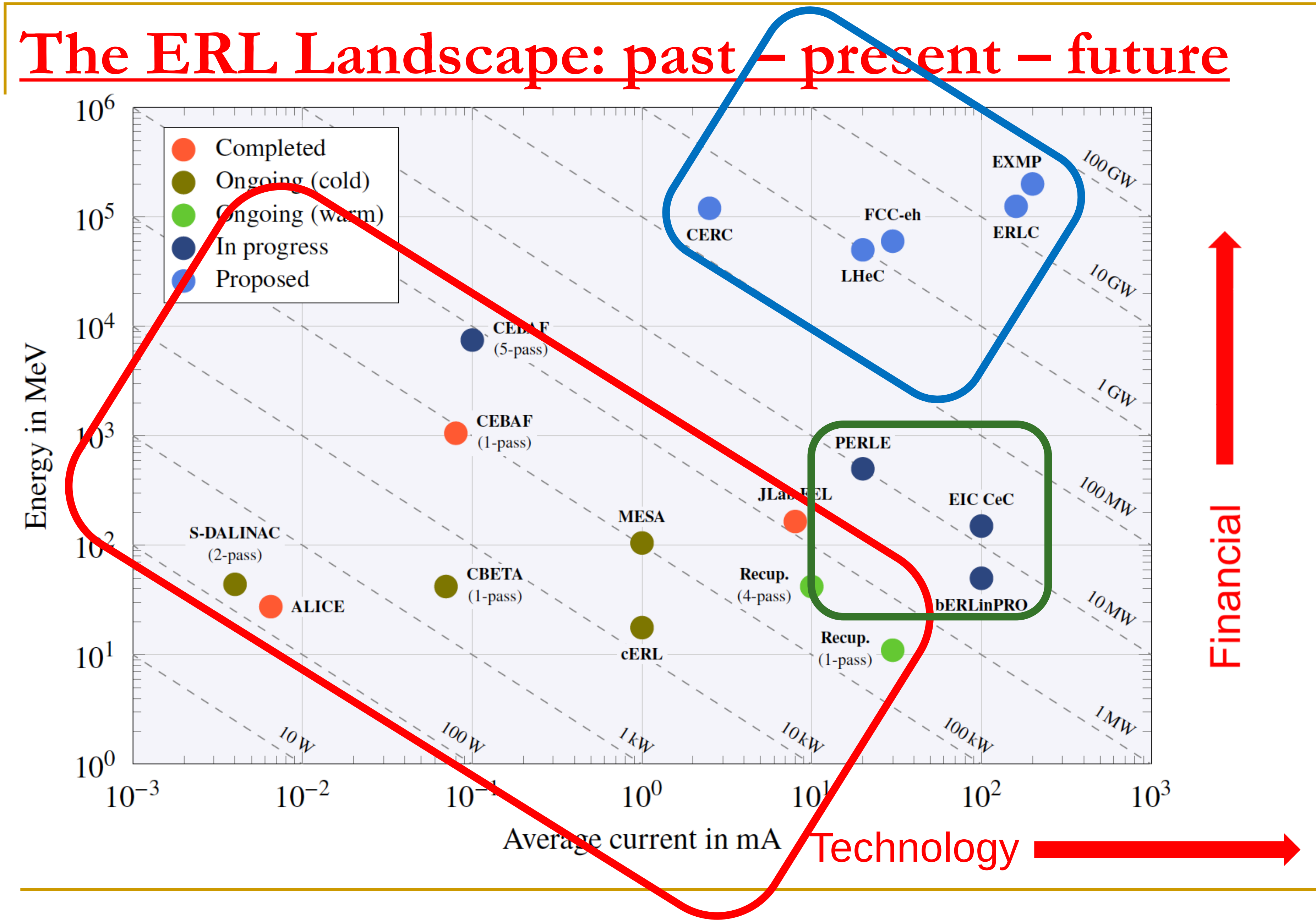
a **sub-panel** to evaluate these two proposals in more detail

Chris Adolphsen (SLAC), Reinhard Brinkmann (DESY), Oliver Brüning (CERN), Andrew Hutton (Jefferson Lab)—Chair, Sergei Nagaitsev (Fermilab), Max Klein (Liverpool), Peter Williams (STFC Daresbury), Akira Yamamoto (KEK), Kaoru Yokoya (KEK), Frank Zimmermann (CERN)



ReLiC Proposal by Litvinenko, Llatas & Roser, BNL – energy recycling LC

The ERL Landscape: past – present – future



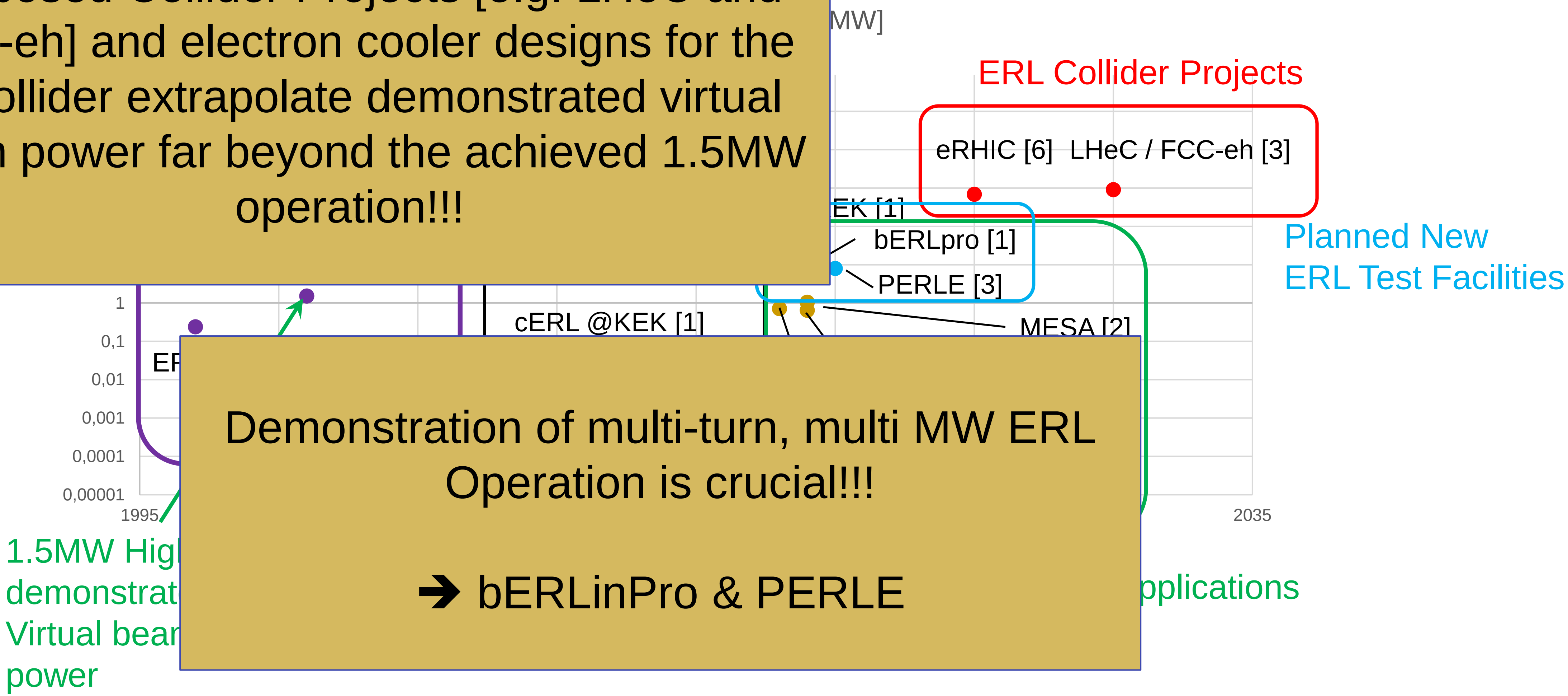
Beam powers in proposed **future facilities** for the 2040ies are in the GW regime!

Past ERL facilities reached about **1MW beam power** ➔ push performance by **3 orders of magnitude!**

Goals of **new facilities in the 2020s** designed to bridge the gap! ➔ **>> 10MW**

ERL Validation Needs and Experience

virtual beam power:

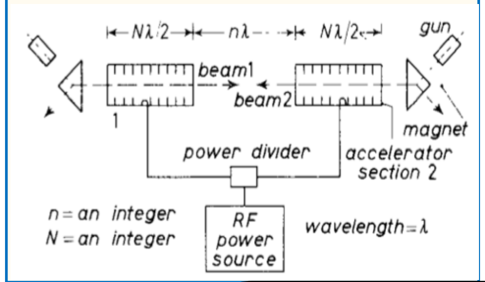


Proposed Collider Projects [e.g. LHeC and FCC-eh] and electron cooler designs for the eI collider extrapolate demonstrated virtual beam power far beyond the achieved 1.5MW operation!!!

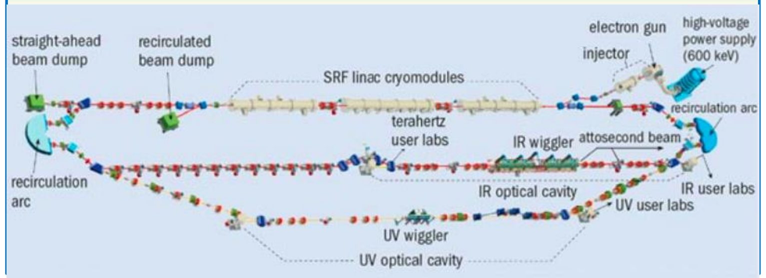
Demonstration of multi-turn, multi MW ERL Operation is crucial!!!

➔ bERLinPro & PERLE

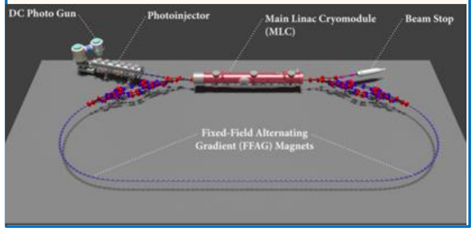
First Idea:
M. Tigner 1965



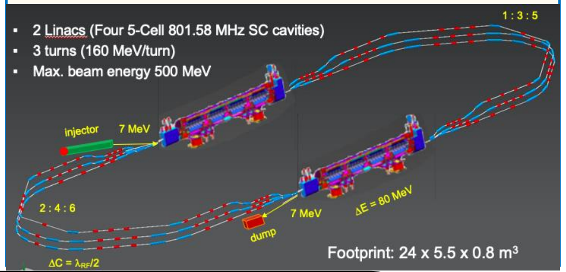
JLab First MW beam power operation
FEL Demo [1999] & Upgrade [2000]



Multi-turn SRF
C-Beta 2019-2020
S-DALINAC 2021



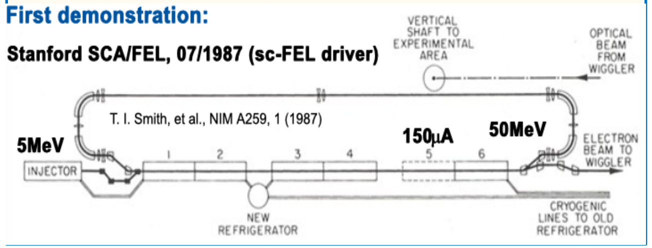
Multi-turn SRF, multi-MW
PERLE@Orsay 2025



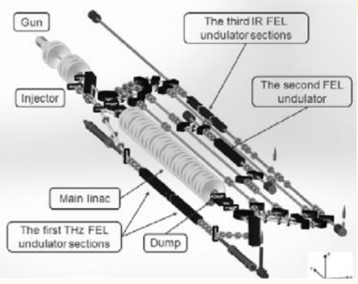
Developing an energy efficient accelerator concept!

1960

First Demonstration
SLAC SCA / FEL 1987

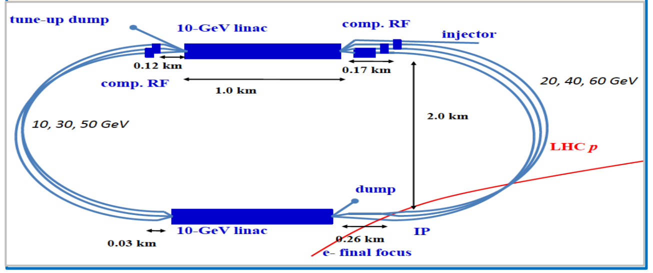


Multi-turn Operation
BINP FEL 2004 [NC]



Multi-MW Operation
bERLin-Pro 2024

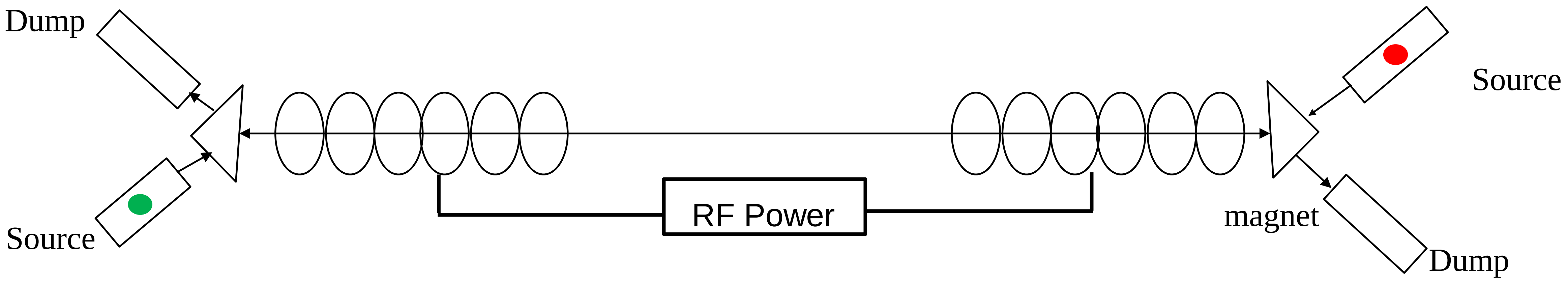
HEP / NP ERL application
LHeC; FCC-hh; ep and eI;



End

Energy Recovery Linac Configurations

- Push-Pull Configuration: allows best suppression of Synchrotron Radiation
  a) 2 SC linacs facing each other ➔ Allows only pulsed linac operation



Energy Recovery Linac Configurations

- Push-Pull Configuration with coupled RF systems:

… any particle accelerator where the accelerated beams are NOT consumed at the end of the acceleration cycle

& where the beam power is higher or comparable to the facility operation power needs!

… circular machines where the SR power loss becomes unattainable

Power Flow in Accelerators

Electricity grid

Accelerator
- Radio Frequency
- Magnets
- Vacuum etc.

Auxiliary systems
- Cryogenics
- Conv. cooling, AC etc.

Instruments
- E.g. particle detectors
- Computing

beam

conversion to secondary radiation (beam collisions, targets, undulators …)

direct beam application:
- p-therapy
- Isotope production

secondary radiation
- Exotic particles, e.g. Higgs, B-mesons
- Photons (synchrotron radiation)
- Neutrons
- Muons

Beam disposal at end of operation cycle

Eventually converted to waste heat!
E.g. cooling towers

➔ Re-use waste heat! & Minimize the facility power footprint!!!

Linear Accelerator:
Can we recuperate the beam energy at the end of the operation cycle?

➔ ca. 0.3 to 1.2 MW site power / GeV beam energy for the Facility Infrastructure!

Options / Technologies that are being explored for improving this base energy cost:

- Higher Q_0 and smaller HOMs ➔ less cooling needs
- Fast reactive tuners ➔ lower RF power requirements
- High Temperature SRF ➔ better cooling efficiency

Linear Collider ➔ ca. 11MW / 1 MW beam power ➔ beam power << Facility power

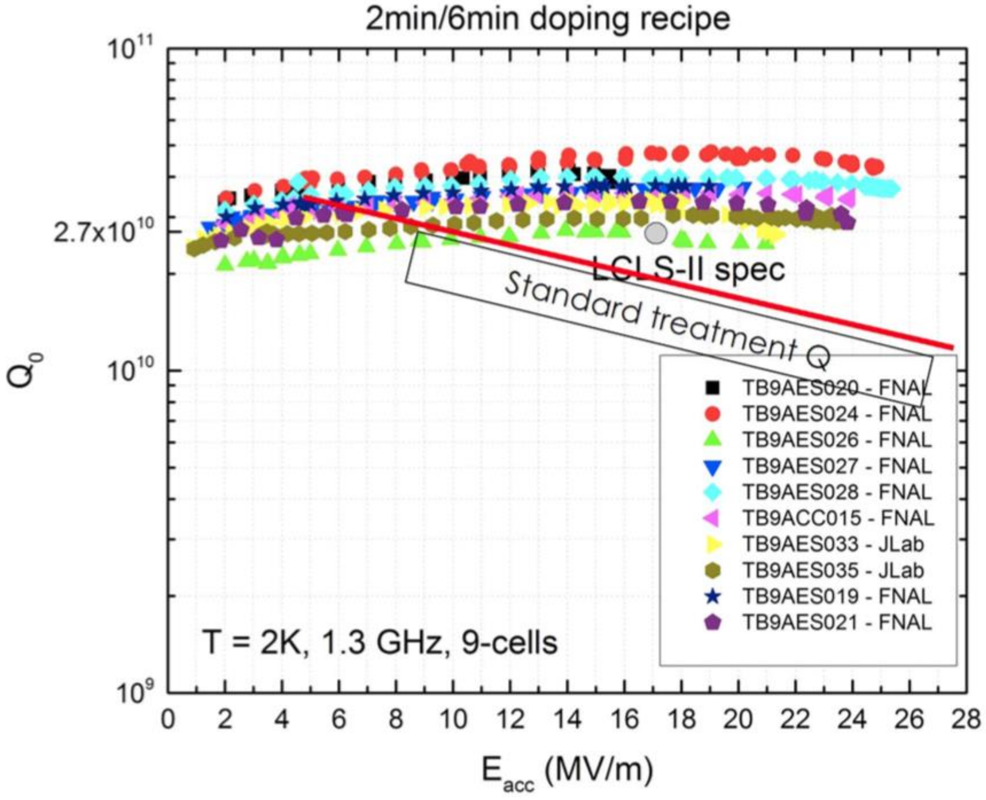
ERL ➔ comparable base Facility infrastructure cost, but beam power independent

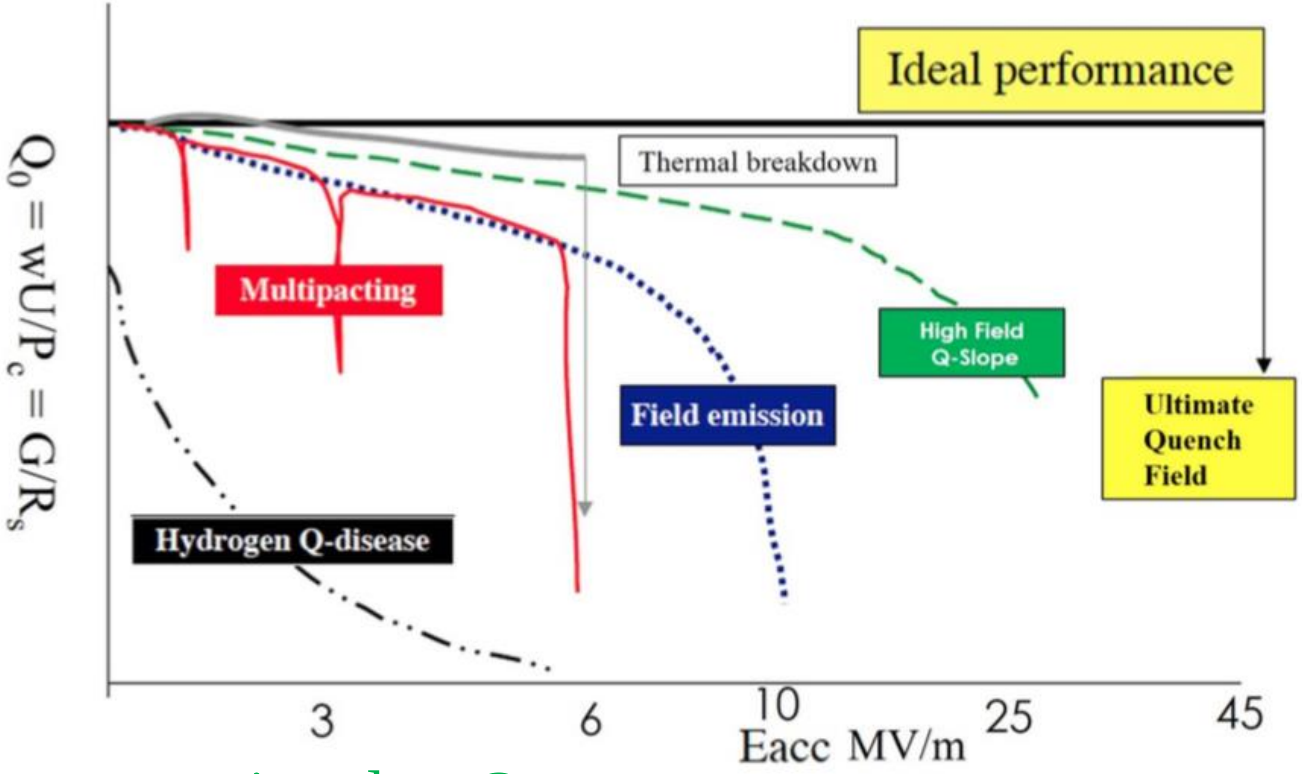
➔ beam power >> Facility power

ERL: SRF Challenge Q_0

- Q_0 versus accelerating voltage:

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





➔ τ is proportional to Q_0

➔ impressive progress over the last 10 years!!!

➔ Q_0 directly linked to required cryogenics power!!

RF accelerators' 3003

$$P_{\mathrm{dissip}} = \frac{U_a^2}{\left(\frac{R}{Q}\right) Q_0}$$

Synchrotron Radiation Losses

- Synchrotron Radiation Power per return arc:

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

Scales with E^4 and ρ^{-1} ➔ Power loss can be controlled by adapting ρ

➔ Installation cost for return arcs

Multi-turn re-circulations: most of the SR losses come from the high energy arc

- Emittance dilution per arc:

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

Depends on γ, ρ and on dispersion

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

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

Lattice needs to be optimized for a given energy and ρ

FCC-eh ERL Configuration:

[Daniel Schulte]

Performance Simulations for FCC-ep:

Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \rightarrow 1.1$	10
IP betafunction	mm	150	$42 \rightarrow 52$
Nominal RMS beam size	μm	$2.5 \rightarrow 1.8$	$1.9 \rightarrow 2.1$
Waist shift	mm	0	$65 \rightarrow 70$
Bunch population	10^{10}	$10 \rightarrow 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	$18.3 \rightarrow 14.3$	
Int. luminosity per 10 years	[ab^{-1}]	1.2	

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
"A Baseline for the FCC-he"

Daniel Schulte

Technical Challenges of the LHeC / FCC-eh design

LHeC

Technology:

-Source: maximum current, cathode lifetime, halo production, polarization
-SRF: Microphonics and beam stability at high gradient SRF operation
-SRF: Cryostat design and HOM integration, HOM power losses

-Interaction Region design with detector, proton and electron beams and SR
-IR Magnet design

Operation:

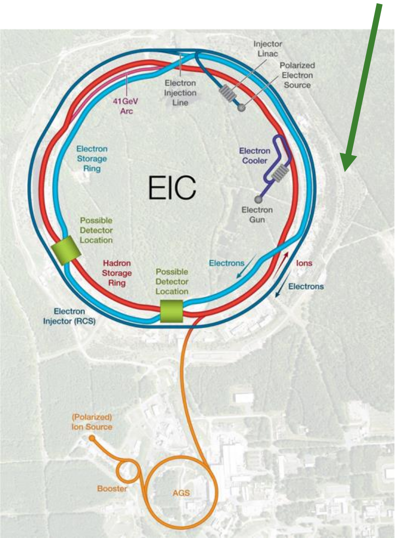
-Halo generation and beam losses along the ERL – beam diagnostics
-Emittance dilution along the ERL and beam dump acceptance - diagnostics

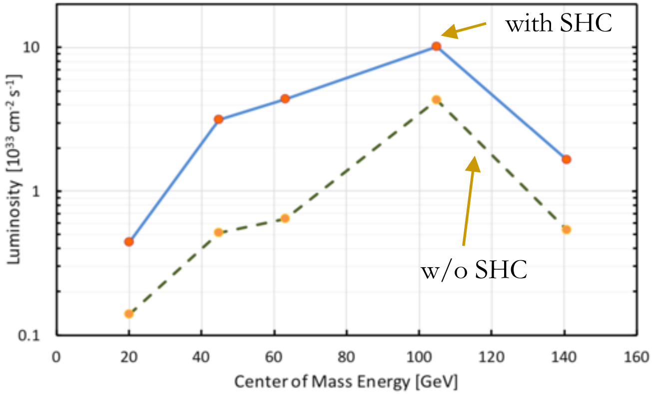
-Overall ERL efficiency with multi-turn high beam power operation

-Timeline of the HL-LHC Schedule

New Facility – EIC Cooler @ BNL

- The Electron Ion Collider will use the existing RHIC collider and a new electron storage ring to produce collisions of **electrons and ions with E_{cm} = 20 GeV - 141 GeV**
- **Strong Hadron cooling (SHC)** will be used to increase the luminosity to 10^{34} $cm^{-2}s^{-1}$

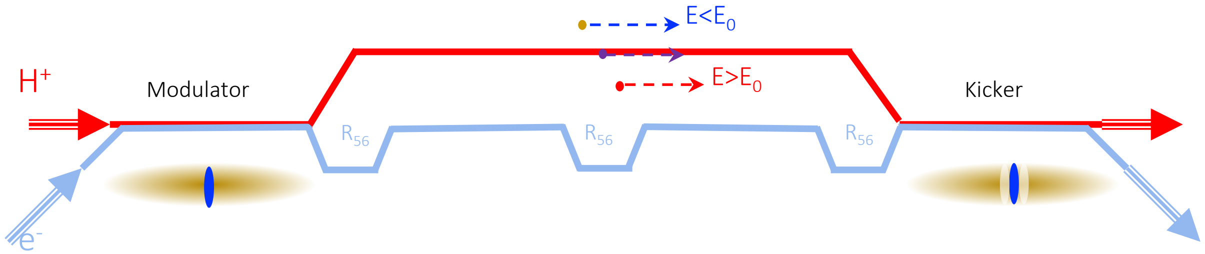




- EIC electron cooler is now in detailed design stage

- EIC SHC **cooling requirements**:
  1. **Intrabeam scattering longitudinal and transverse growth time is 2-3 hours**. Cooling time should be equal or less.
  2. Proton beam to be cooled at 275 and 100 GeV
  3. SHC must fit in the available space at IR 2

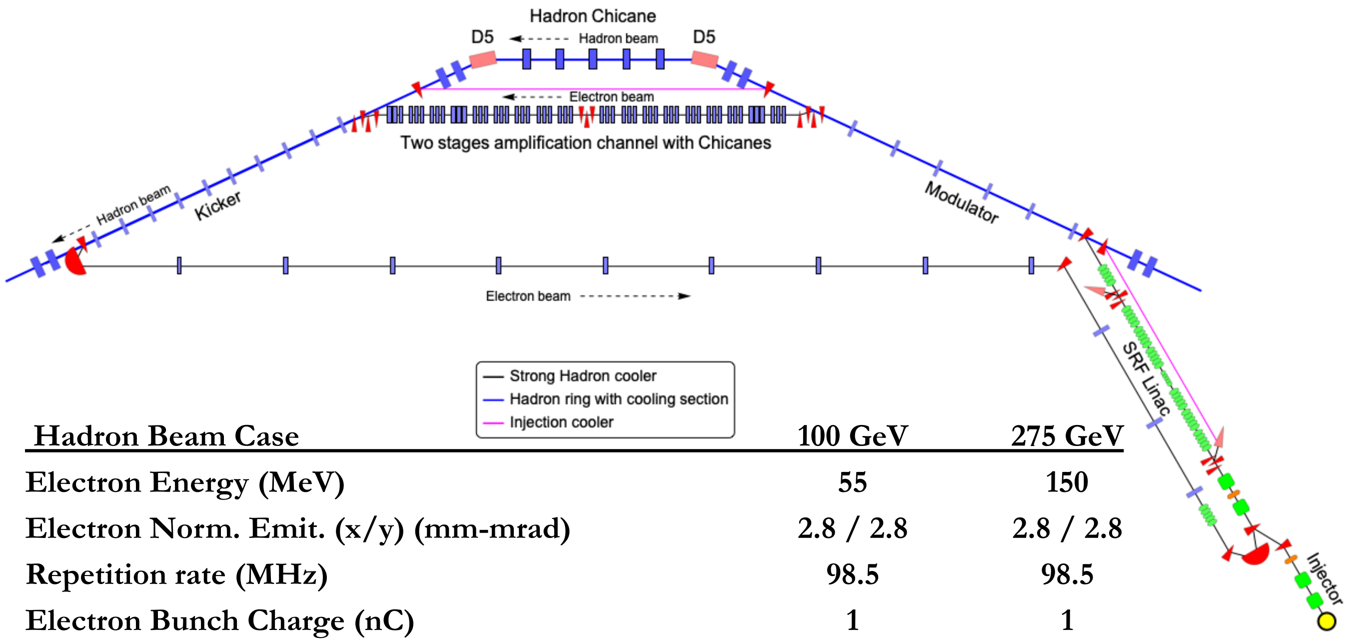
- SHC will operate on the principle of **Coherent Electron Cooling**. Similar to stochastic cooling, fluctuations in the hadron beam distribution (which are associated with larger emittance) are **detected, amplified and fed back** to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam
- High bandwidth (small slice size) = 10's THz → **use an electron beam to detect, amplify and kick**



- Pickup and kicker take the form of Coulomb interaction of co-propagating hadrons and electrons of equal γ
- Baseline amplification stage is through **inducing microbunching instability gain** with successive chicanes – implies very low noise beam!

New Facility – EIC Cooler @ BNL

- SHC needs a high-quality electron beam with 100 mA current, small energy spread, and small noise in the beam.
- It **requires development of an ERL with parameters beyond the state of the art.**
  - 400 - 500kV DC gun with 5.6 MV SRF injector
  - 13 MeV, 197 MHz injector for pre-cooling at hadron injection energy
  - 149 MeV, 591 MHz Superconducting Energy Recovery Linac
  - Low energy electron bypass the main linac and the amplifier section to **enable conventional non-magnetized thermal cooling at hadron injection energy**
  - Amplification section with quarter plasma wavelength per stage
  - Hadron chicane path length matching & R_{56} adjust
  - Requirement for long (30° main RF phase) electron bunches necessitates third harmonic RF (1773 MHz) within main linac
- Utilizing microbunching instability to amplify requires that noise within the beam close to shot noise – simulations to verify

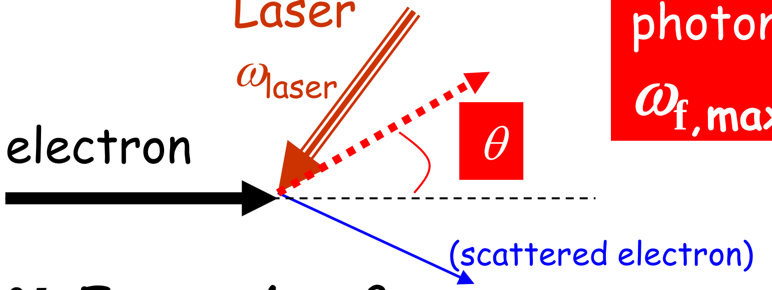


Hadron Beam Case	100 GeV	275 GeV
Electron Energy (MeV)	55	150
Electron Norm. Emit. (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Repetition rate (MHz)	98.5	98.5
Electron Bunch Charge (nC)	1	1
Electron Peak Current (A)	10	17
Electron Bunch Length (mm, rms)*	9	7
Electron Fractional Energy Spread	10^{-4}	10^{-4}
Hor./Vert. Elec. Betas in Modulator (m)	112 / 23	76 / 10
Hor./Vert. Electron Betas in Kicker (m)	55.3 / 6.3	26.8 / 2.5
Modulator Length (m)	35	35
Kicker Length (m)	35	35
H/V/L Cooling time(hr)	2/3.8/22.9	1.6/3.6/2.1

* *SuperGaussian of order 4 bunch assumed*

Gamma Source: Photo-Compton Scattering

F. Zomer @ 2018 LHeC workshop



photon : ω_f

$\omega_{f,max} = 4\gamma^2 \omega_{laser}$

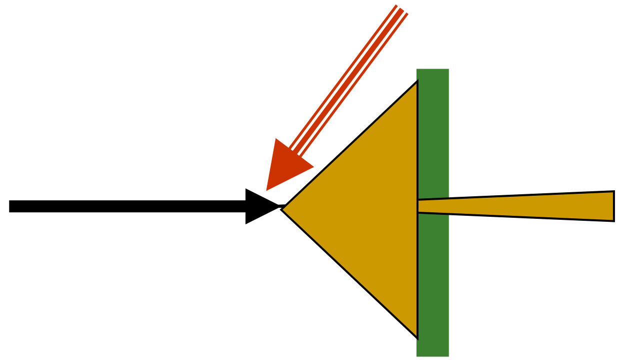
$\gamma = E_{electron}/m_e c^2$

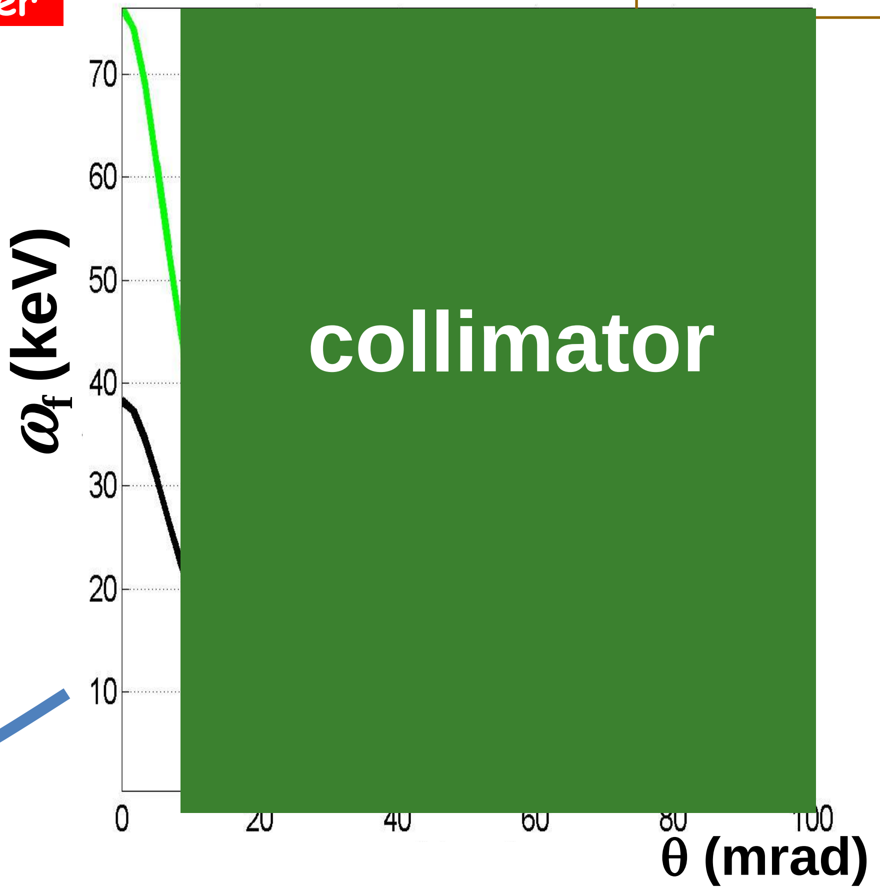
PRL138(1965)B1546

Compton scattering

Photon_laser+e→photon+e'

is a 2 body process ➔ $\omega_f = f(\theta)$



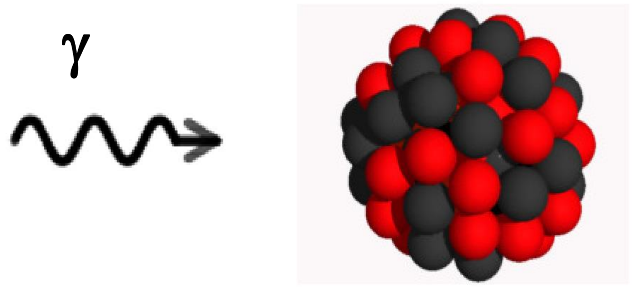


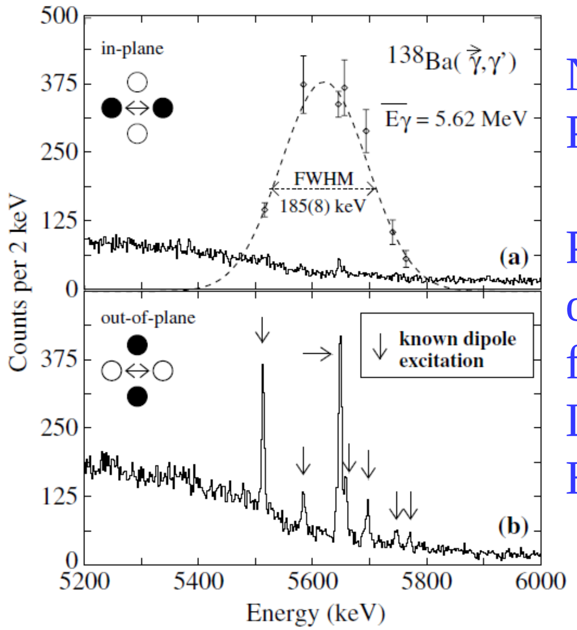
Quasi monochromatic X/gamma ray beam

Gamma Source: Applications

N. Pietralla @ LHeC Workshop 2015

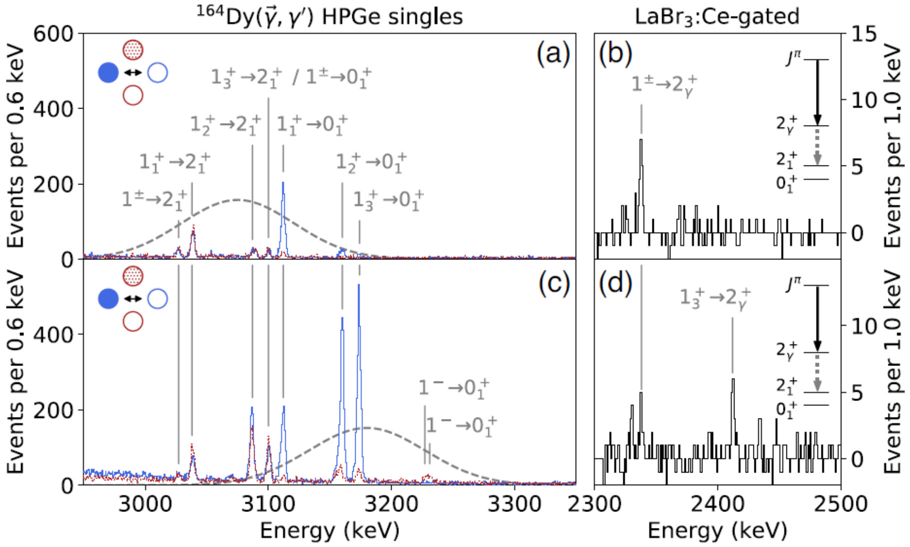
- Photonuclear Physics:
  - Absorption and excited states in nucleus
  - Electromagnetic dipole response, e.g.





N.Pietralla et al., PRL 88, 012502 (2001)

Parity quantum numbers of nuclear dipole excitations from scattering of polarized Laser-Compton photons at HIγS (Duke Univ.)



T.Beck et al.,PRL 125, 092501 (2020)
Structure of M1 modes of deformed nuclei at HIγS

- Industrial lithography [chip manufacturing] and Xray [import scanning] applications

Facility Energy Footprint

- SwissLightSource:

400mA @ 2.4GeV ➔ ca. 0.96kJ beam energy @ ca. 1MHz ➔ 960MW

Radiation loss per turn: 512keV ➔ 205kW

➔ only a few 10^{-4} power loss due to Synchrotron Radiation

➔ Facility energy footprint: 82MWh!

Facility Energy Footprint

- LHC:

2 x 0.7A @ 6.5TeV ➔ ca. 450MJ energy per beam @ 11kHz ➔ ca. 5TW @ IP / beam

2 fills per day ➔ 1.8GJ / 24 h ➔ ca. 20kW

Facility has ca. 120MW power consumption for the LHC ➔ Factor 6000

➔ ca. ½ of the beam power gets deposited into the detector, the rest on absorbers

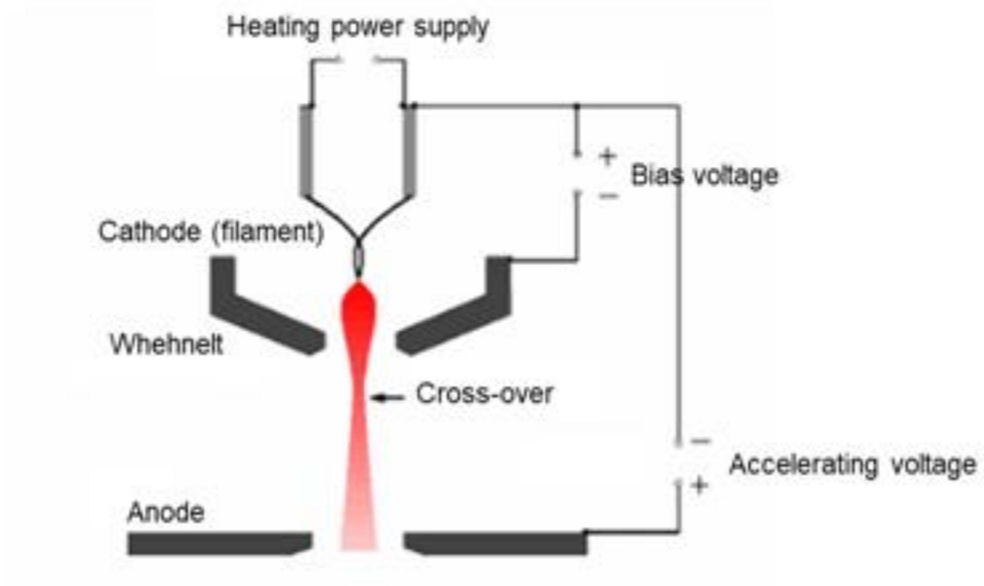
➔ Facility energy footprint?

➔ 120MW for 6.5TeV ➔ 0.02MW / GeV

Sources:

Thermionic guns - DC Anode voltage:

- Used for FELs
- Well established technology
- Low cathode fields ➔ large emittance
- No polarization
- Potentially able to generate high current



Thermionic guns - AC / RF modulated Anode voltage:

- Developed for BINP ERL
- Large emittance
- No polarization
- Potentially able to generate high current

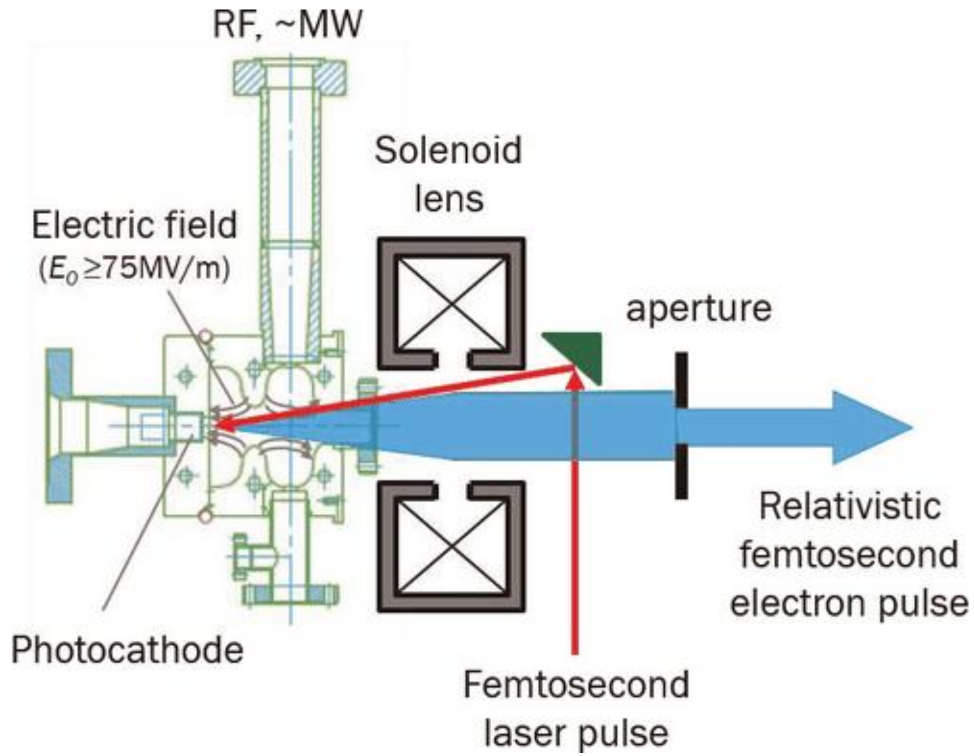
Sources:

Photocathode guns – NC RF & SRF: used for FELs

- High brightness
- High Cathode field
- Pulsed operation
- Polarization
- High average current
- Lifetime and quantum yield of cathode
- Exchange mechanism for cathode target

Photocathode guns – DC:

- Well established technology
- Arbitrary time structure for bunches
- polarization
- Potentially able to generate high current
- Low cathode field & low beam energy ➔ emittance



Energy Recovery Linac Configurations

- Recirculating Linac Configuration:
  - ➔ Allows CW linac operation
  - ➔ Cost efficien … once
  - ➔ Higher bean
  - ➔ Synchrotron

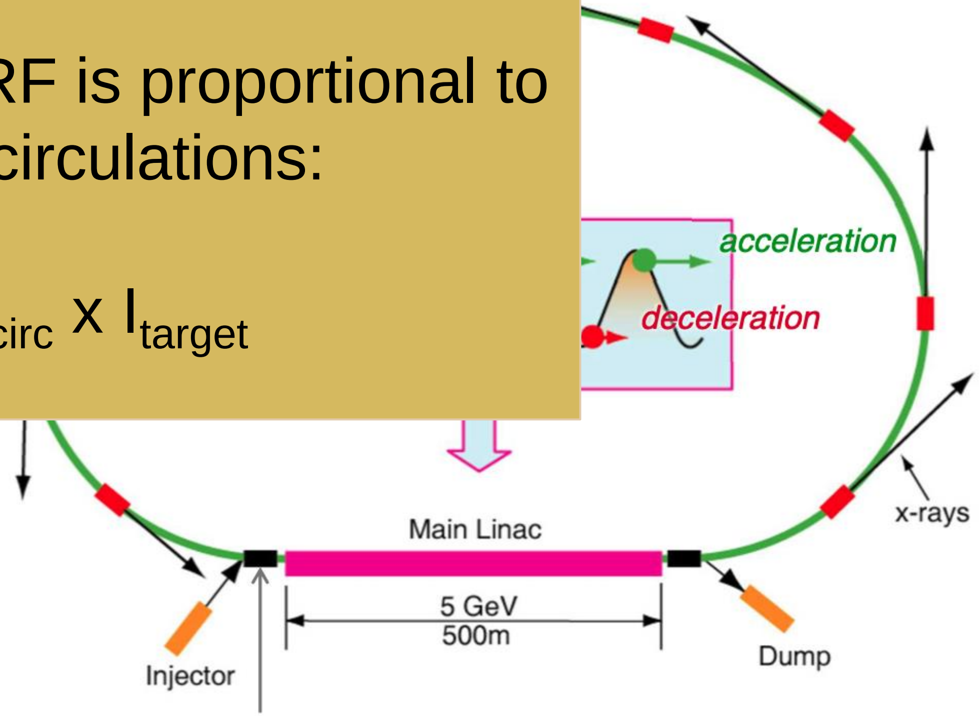
Number of re-circulations:

The total current in the SRF is proportional to the number of re-circulations:

➔ $I_{tot} = 2 \times n_{re\text{-}circ} \times I_{target}$

Example: Cornel E
for a light source
defined by source and SR

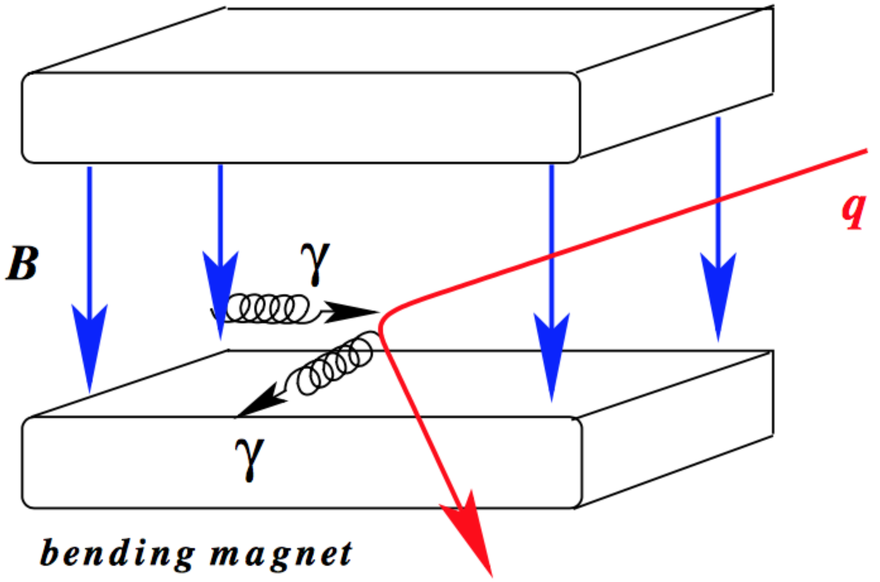
4^{th} generation circular light sources surpassed this proposal in the 2010s



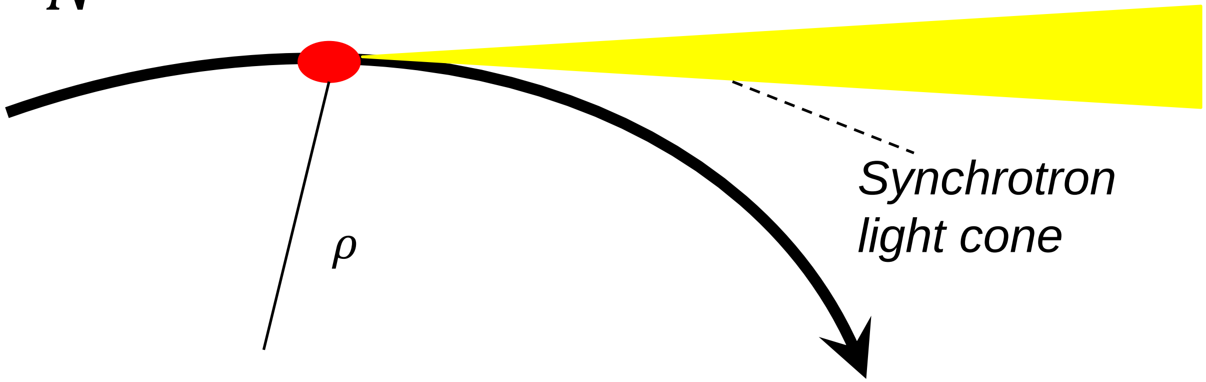
Circular Collider: Synchrotron Radiation

- Quantum Picture:

  → -radiation fan in the bending plane
  -opening angle $\propto \frac{1}{\gamma}$



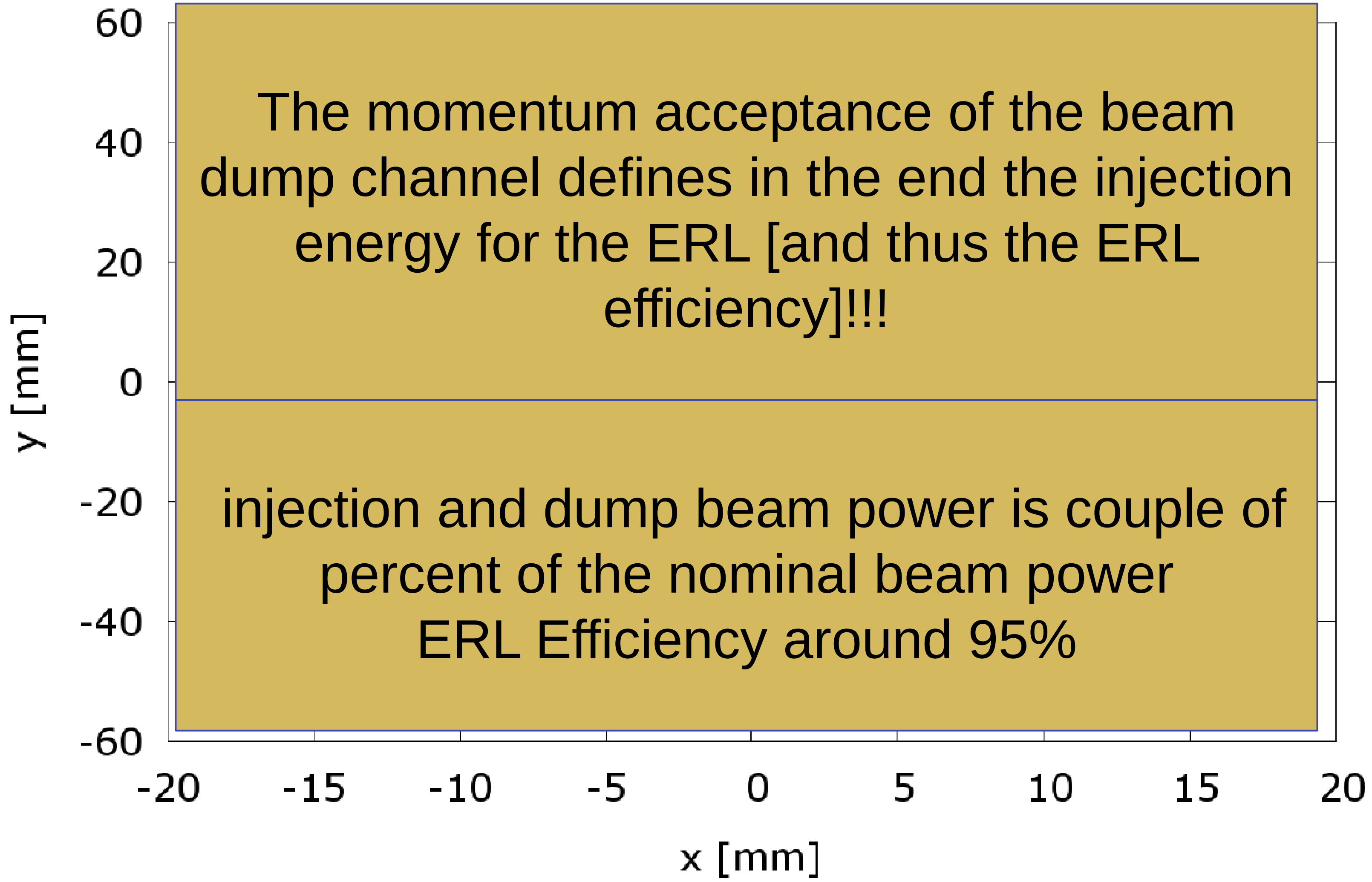
- $P \propto \frac{\gamma^4}{\rho^2} \cdot q^2 \cdot N$
- $\langle E_\gamma \rangle \propto \frac{\gamma^3}{\rho}$
- polarized



Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump

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]!!!

injection and dump beam power is couple of percent of the nominal beam power
ERL Efficiency around 95%

Aperture radius of the SPL cavity is 40 mm.

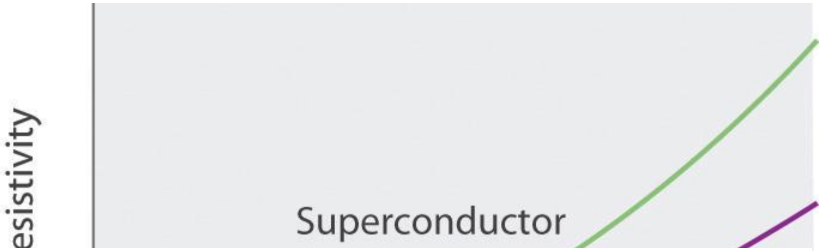
Field Decay in RF Structures

$Q_0 = G / R_s$ G is a geometric factor [cavity shape] and R_s the surface resistance

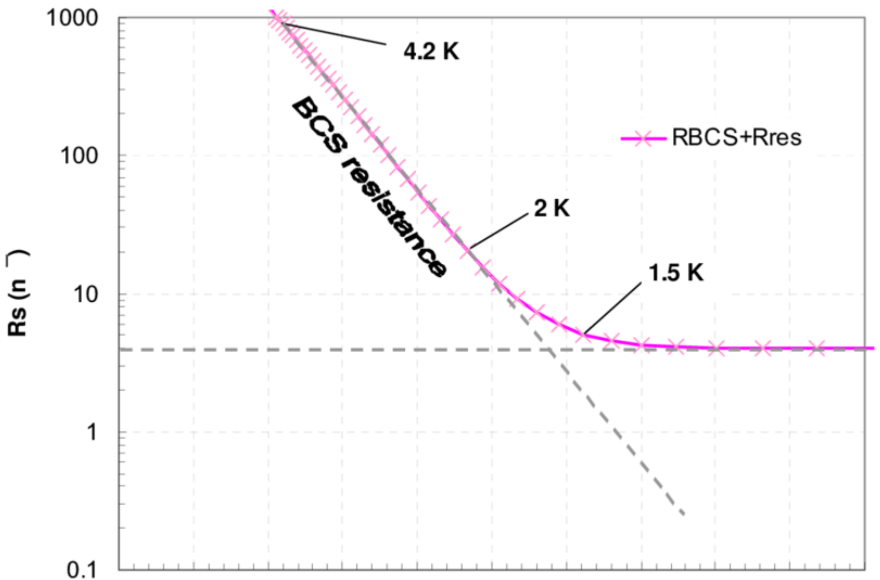
$$R_{s-normal} = \sqrt{\frac{\omega\mu_0}{2\sigma}}$$

Cupper conductivity @ 300K: $\sigma = 5.8\ 10^7\ /\Omega m$

For Type-II superconductors: $R_s = R_{BCS} + R_{res}$



BCS theory:
Bardeen-Cooper-Schrieffer
➔ energy loss of finite mass cooper-pairs within AC currents of RF fields



A linear Collider overcomes the beam-beam limit of a circular collider
[as the beam does not need to remain 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 pass accelerator only once and
have only once the chance to collide!!!

➔ Luminosity proportional to beam power [Beam Current x Energy]
➔ large overhead for facility operation cost [power]

And e^+ production might be challenging!

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

➔ca. 0.3 to 1.5 MW site power / GeV beam energy for the Facility Infrastructure!

Options / Technologies that are being explored for improving this base energy cost:

- Permanent magnet return arcs: no cooling
- Higher Q_0 and smaller HOMs ➔ less cooling needs
- High Temperature SRF ➔ better cooling efficiency

Linear Collider ➔ ca. 11MW / 1 MW beam power ➔ beam power << Facility power

ERL ➔ same base Facility infrastructure cost, but beam power independent

LHeC 50 GeV beam energy ➔ 50MW base facility ➔ beam power >> Facility power