Challenges and Opportunities of Energy Recovering Linacs

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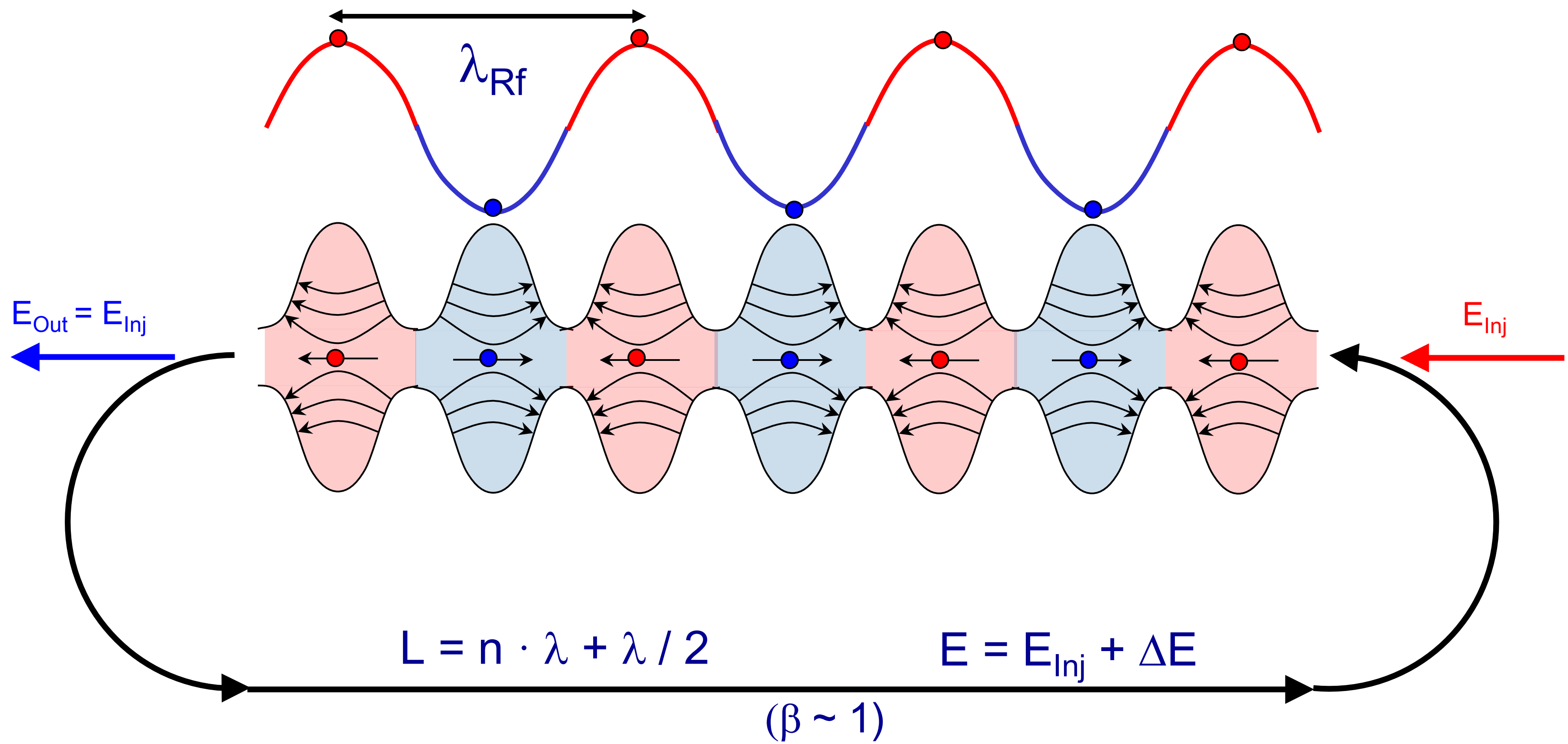
Outline

- Principle of Energy Recovering Linacs
- Historical overview
  - First ideas
  - First tests and demonstrations
- Applications of ERLs
  - Colliders
  - Light sources
  - Electron Cooling of Ions
- Challenges
  - Transverse/Longitudinal Optics
  - Multi-pass ERL topologies
  - Beam Breakup Instability
  - Nonlinear Effects
- Projects and facilities worldwide
- Summary and Outlook

Energy Recovery – Fundamental Idea



Energy Flow = **Acceleration**

$\rightarrow$ Energy **Storage** in the beam (loss free)

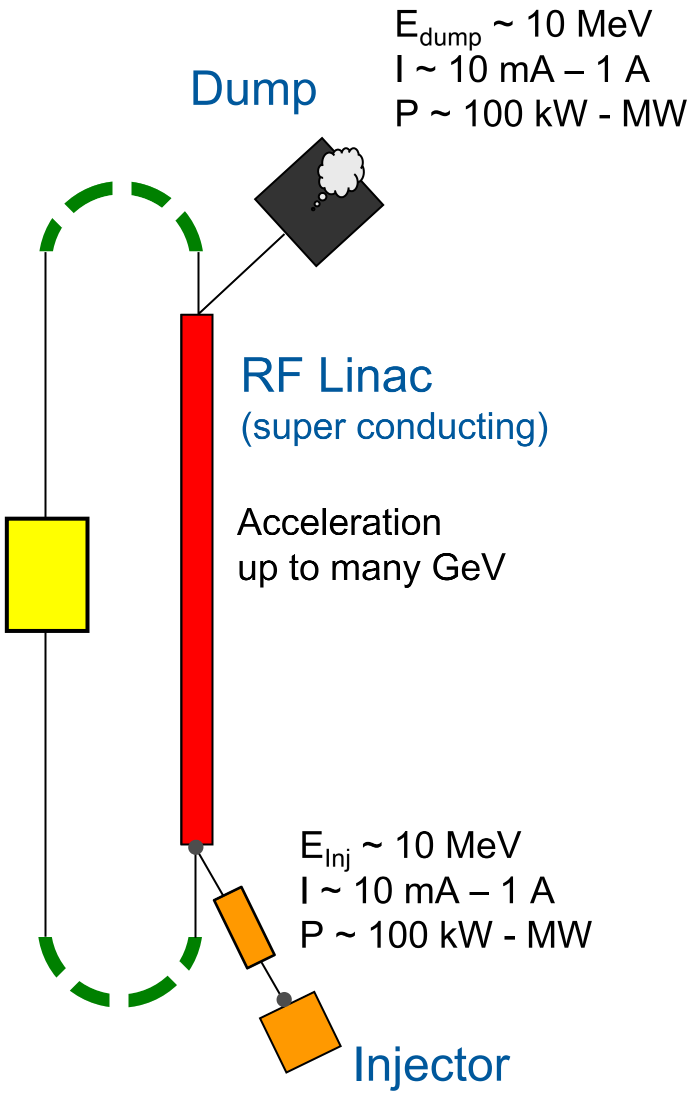
$\rightarrow$ Energy Recovery = **Deceleration**

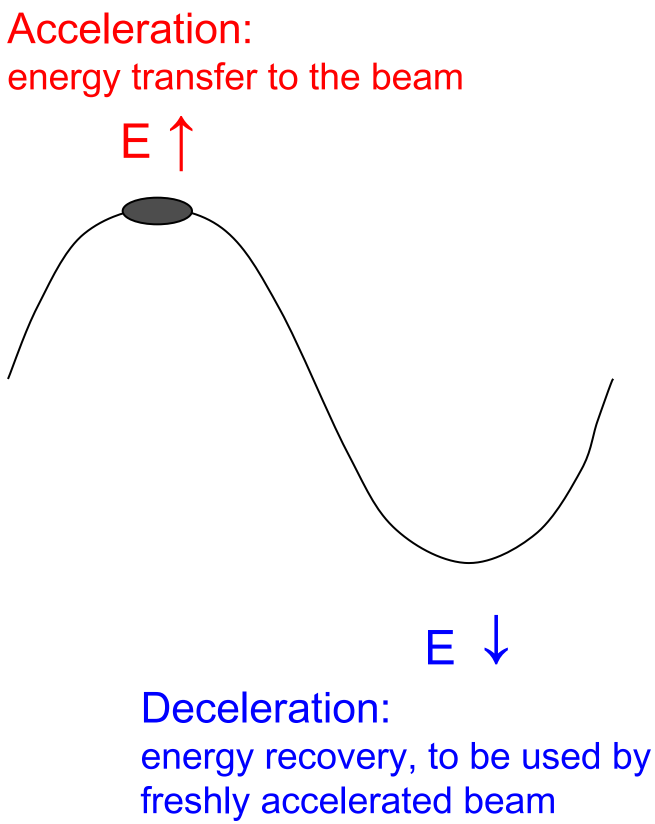
Principle of Energy Recovering Linac

Experiments need high beam power (MW to GW)

and

Supply of ever 'fresh' beam





History – First Idea

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

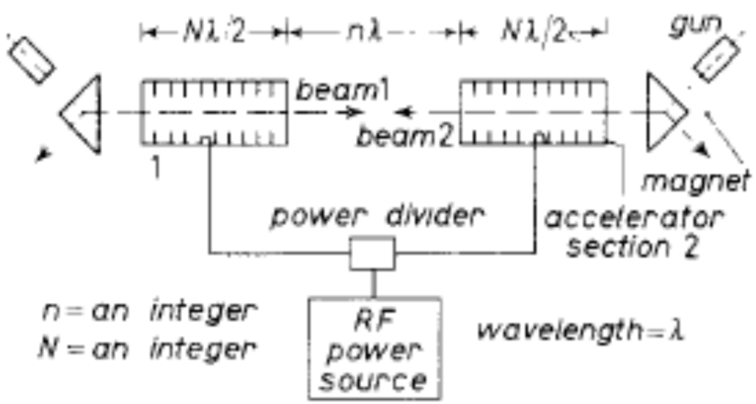


Fig. 2.

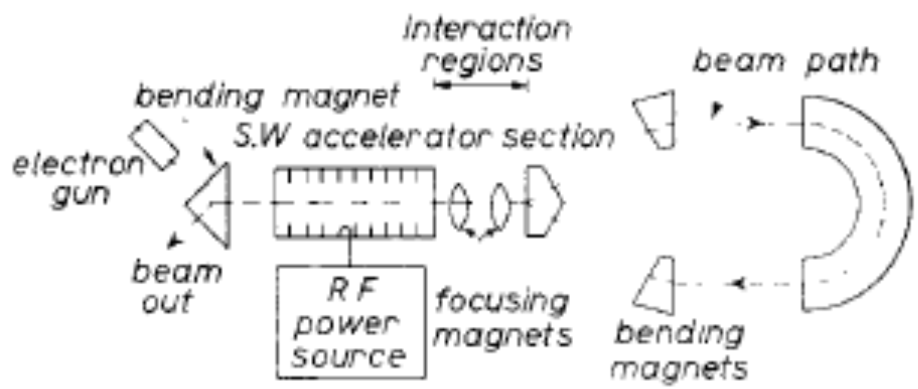
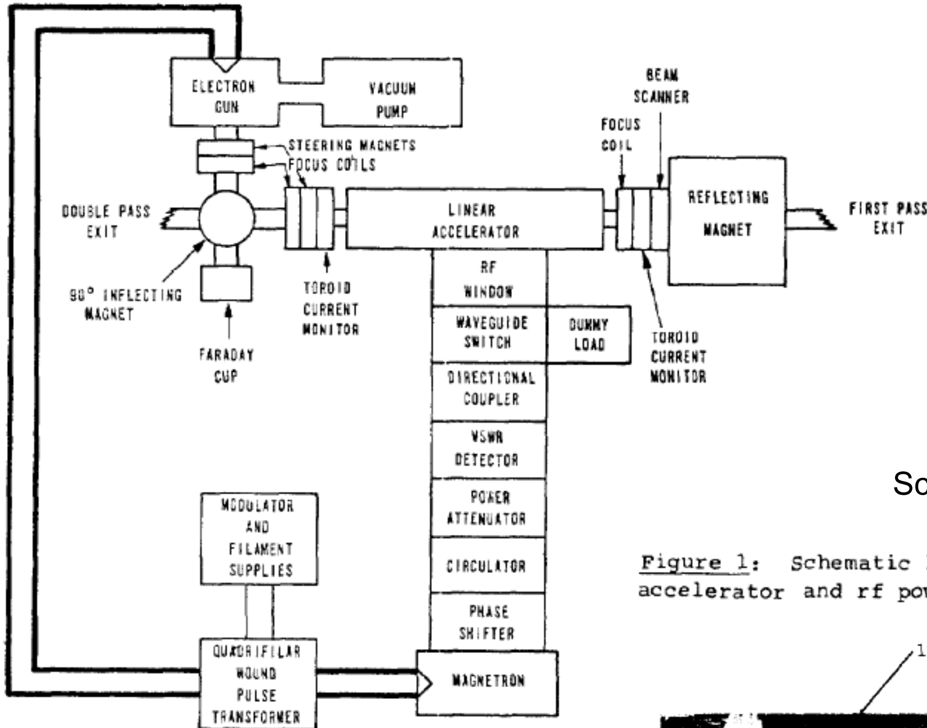


Fig. 3.

Nuovo Cimento, **37**, 1228 (1965)

History – First Test



The Chalk River Reflexotron

Schriber, Funk, Hodge, Hucheon, PAC1977, 1061-1063

Figure 1: Schematic layout of accelerator and rf power system.

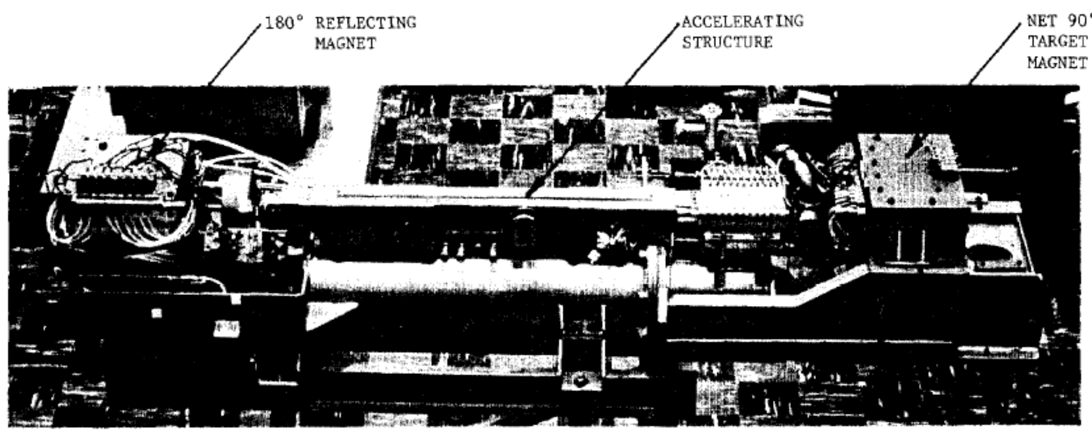


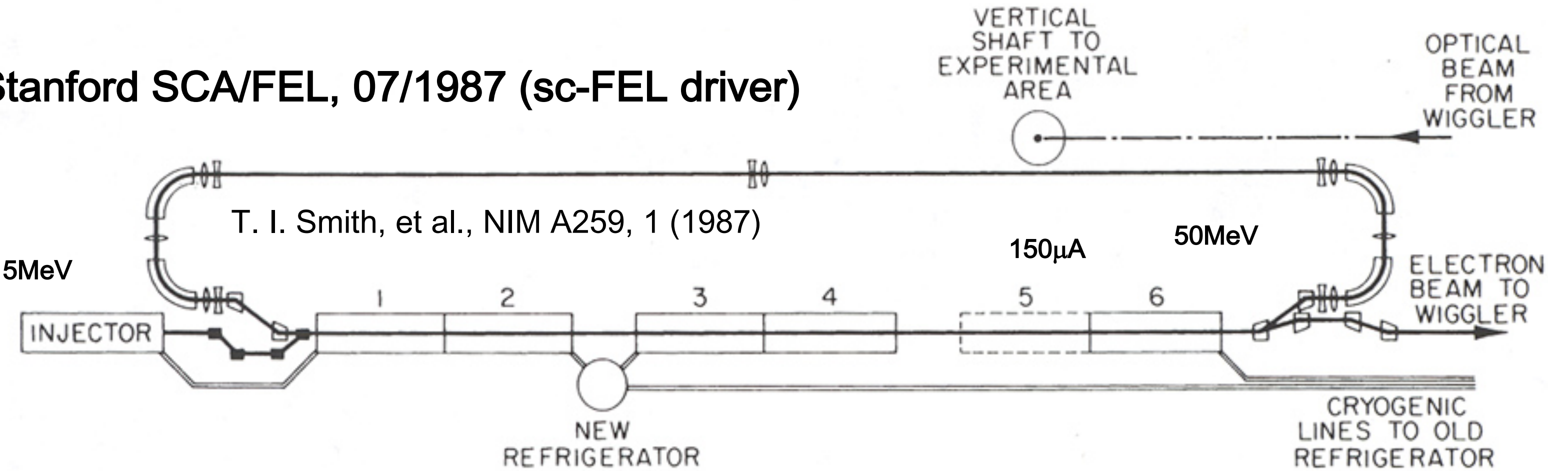
Figure 1. The 25 MeV electron accelerator attached to its strongback.

History – First Demonstration

MIT Bates Recirculated Linac (2.857GHz, nc, pulsed), 1985

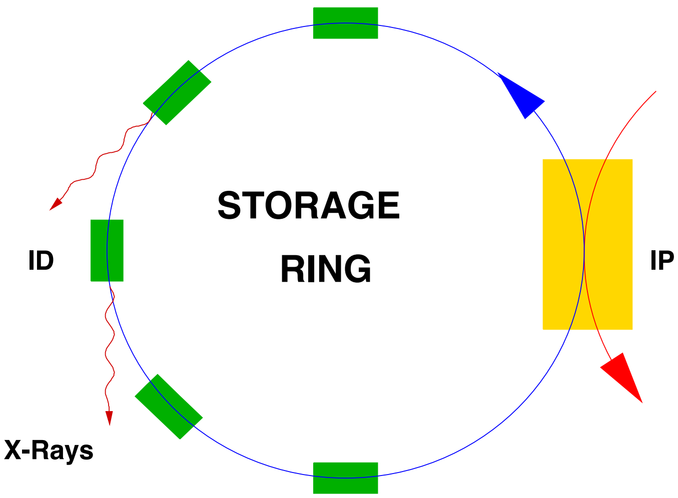
J.B. Flanz et al., IEEE Trans. Nucl. Sci., NS-32, No.5, p.3213 (1985)

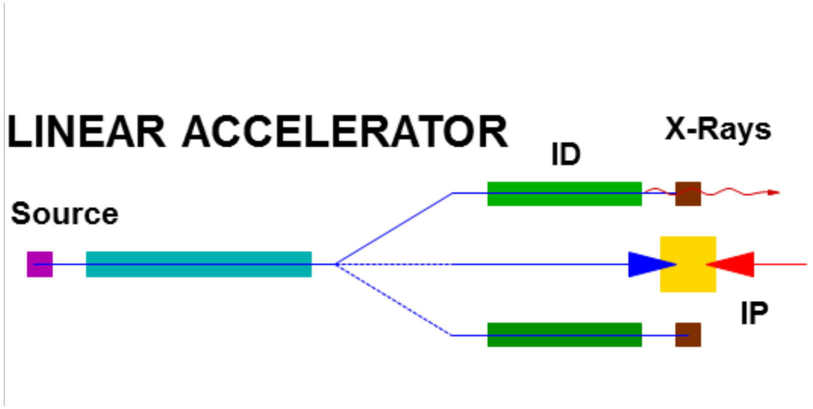
Stanford SCA/FEL, 07/1987 (sc-FEL driver)



T. I. Smith, et al., NIM A259, 1 (1987)

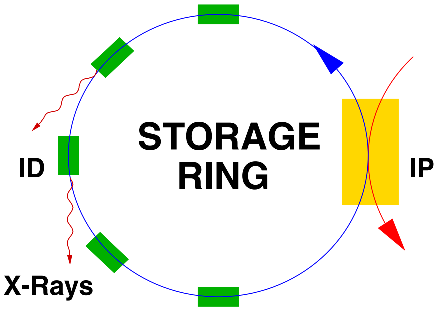
Storage Rings vs Linacs

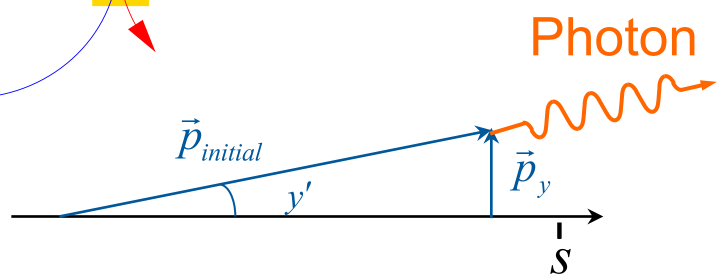




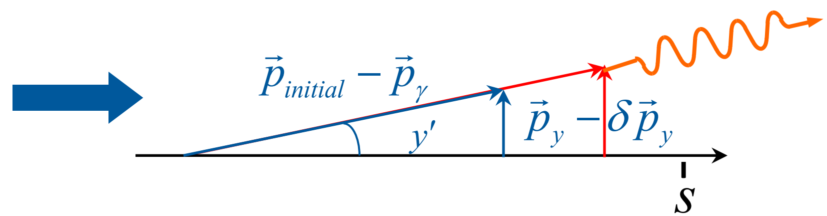
Driven by different mechanism of emittance evolution

Radiation Damping

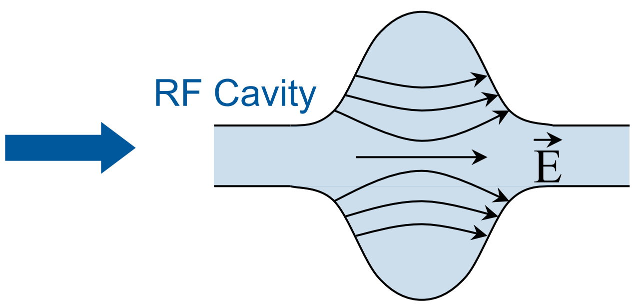




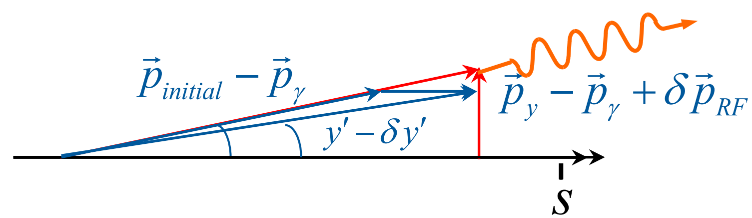
electron emits a photon



it looses momentum (also transverse)

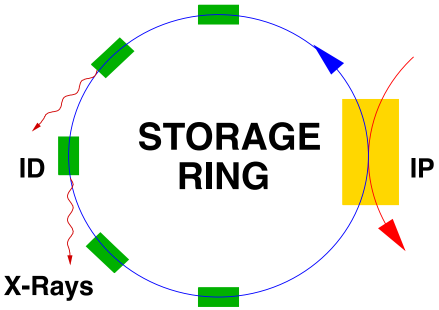


longitudinal momentum restored by accelerating cavity

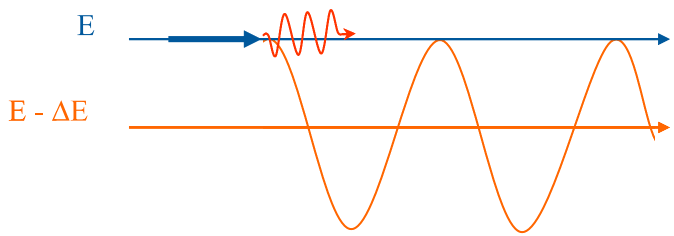


angle and displacement reduced
→ transverse emittance reduced

Radiation Heating

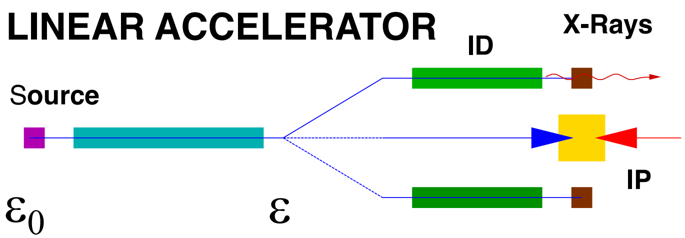


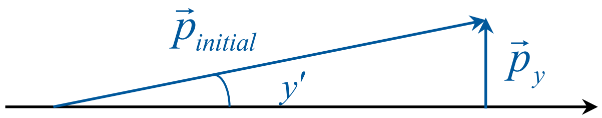
emission of a photon at position with dispersion (e.g. in a dipole, where the transverse position is energy dependent)
electron oscillates around reference orbit
$\rightarrow$ emittance increase



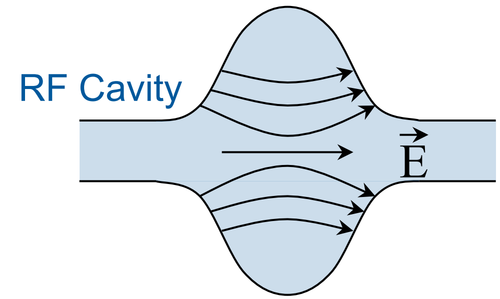
Transverse emittance is defined by an equilibrium between these two processes (damping and heating)

Adiabatic Damping

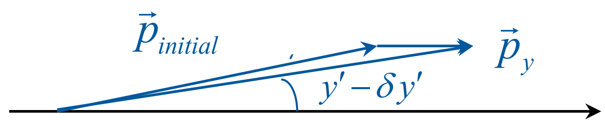




electron has initial transverse momentum



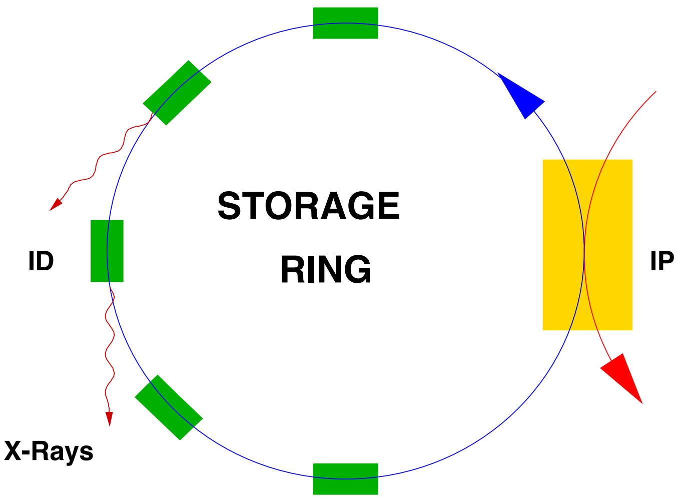
longitudinal component increases during acceleration

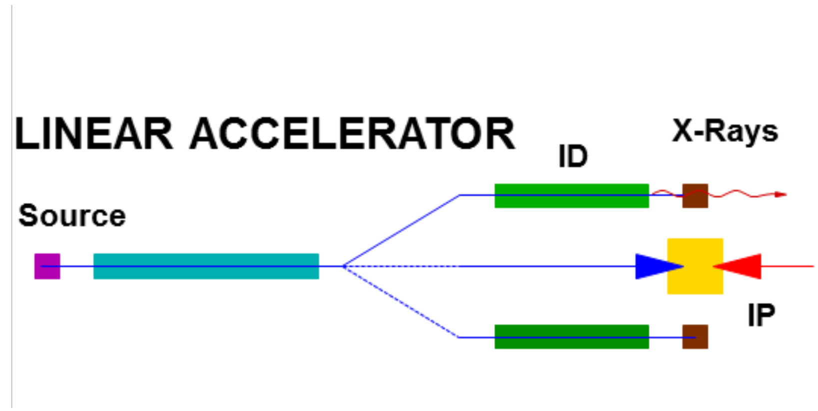


angle reduces with acceleration, emittance shrinks: $\varepsilon = \frac{\varepsilon_0}{\gamma}$

Beam quality is defined by the source, the rest is a proper acceleration and phase-space control.

Storage Rings vs Linacs

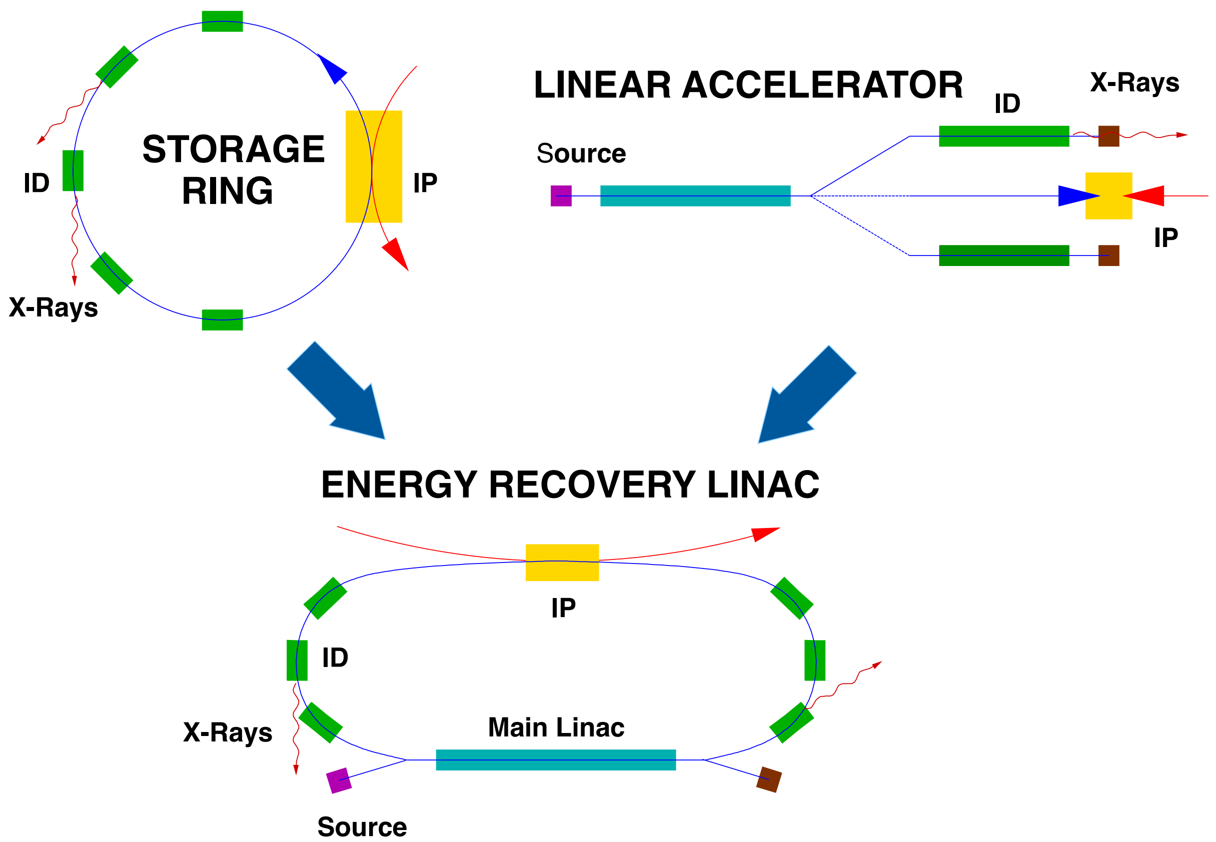




- beam parameters defined by equilibrium
- many user stations
- limited flexibility – multi-pass
- high average beam power (A, multi GeV)
- typically long bunches (20 ps – 200 ps)

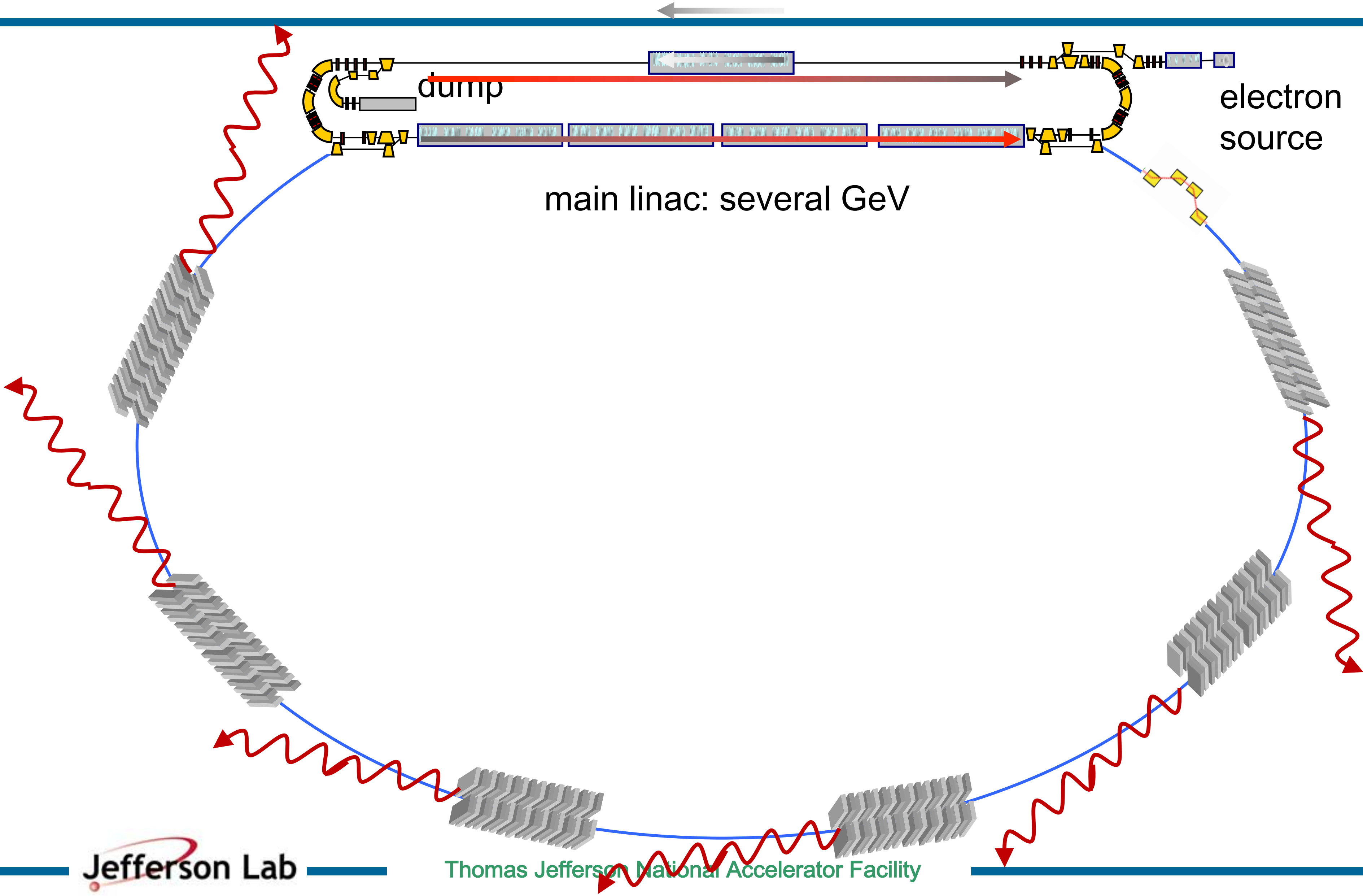
- beam parameters defined by the source
- low number of user stations
- high flexibility – single pass
- limited average beam power (<< mA)
- possible short bunches (sub psec)

ERLs – The best of both worlds



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

ERL as a Next Generation Light source



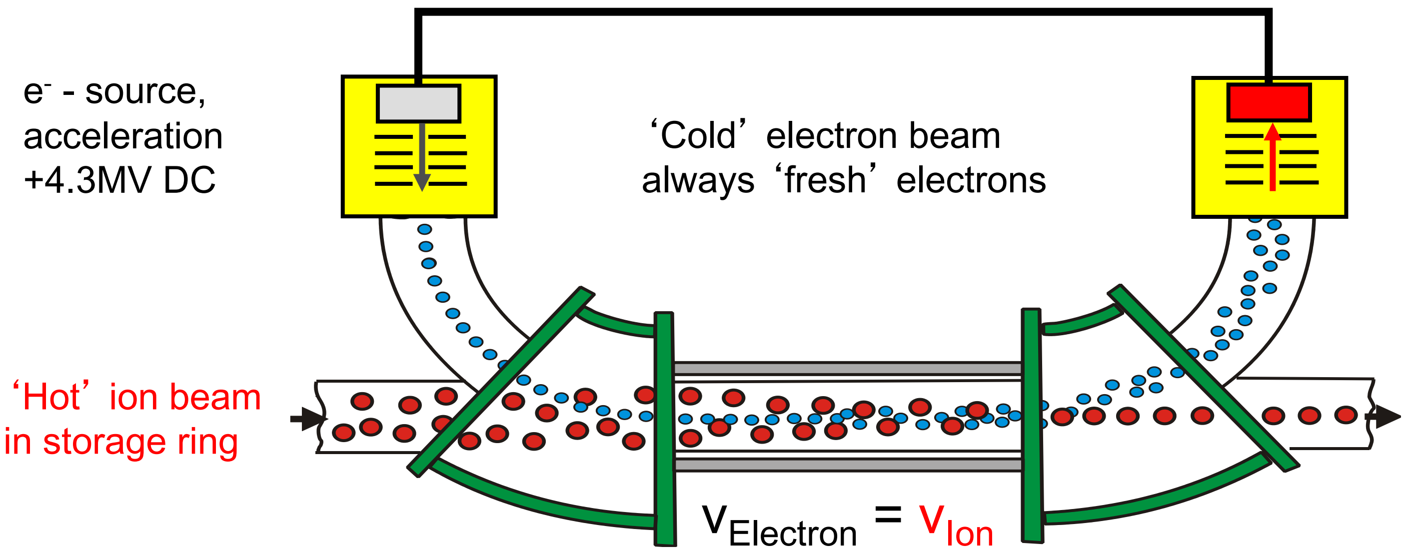
Light source ERLs – 'The best of both worlds'

- Combines the 'amenities' of storage rings and linacs
  - with energy recovery: some 100mA @ many GeV possible
  - always "fresh" electrons (no equilibrium)
    - small emittance (~ 0.1 μm rad norm. = 10 pm rad@6GeV)
    - high brilliance (x 100 – 1000 compared to storage rings)
    - short pulses (ps down to 10 – 100 fs)
  - flexible choice of polarization
  - 100% coherence up to hard X-rays
  - real multi-user operation at many beam lines
  - tailored optics at each insertion device
- Flexible modes of operation (high brilliance, short pulse, different pulse patterns) adaptable to user requirements!

‘Electron Cooler’ for Ion Beams

first devices in the 70ies

‘Electrostatic’, e.g. Van-de-Graaff , Peletron, ...



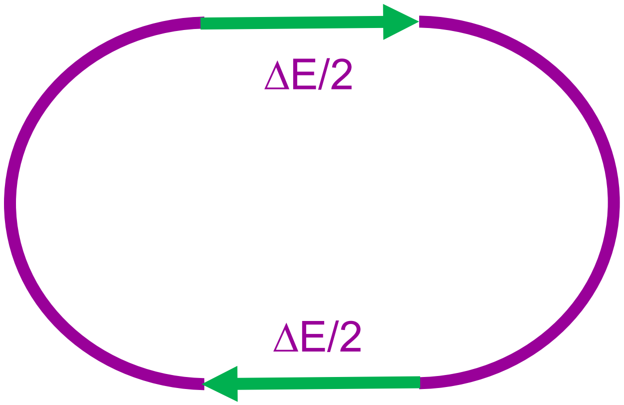
e.g. FermiLab recycler ring (Tevatron)

anti protons:	E = 9 GeV	$\rightarrow \beta = 0.994$
electrons:	E = 4.9 MeV	$\rightarrow U_{Cooler} = 4.39$ MV
	I = 0.5A (DC)	$\rightarrow$ P = 2.2 MW

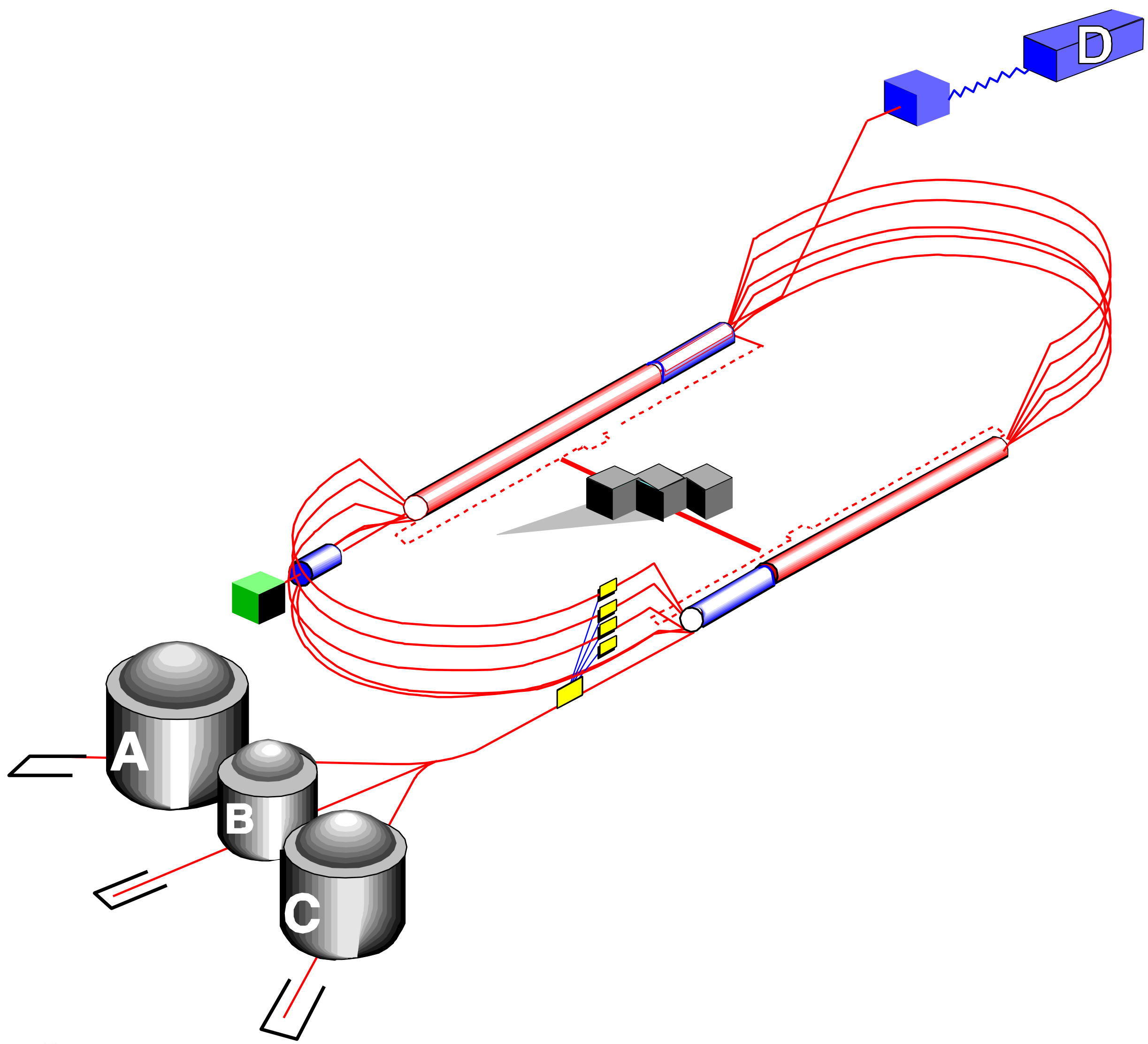
ERL Configurations

Single Linac

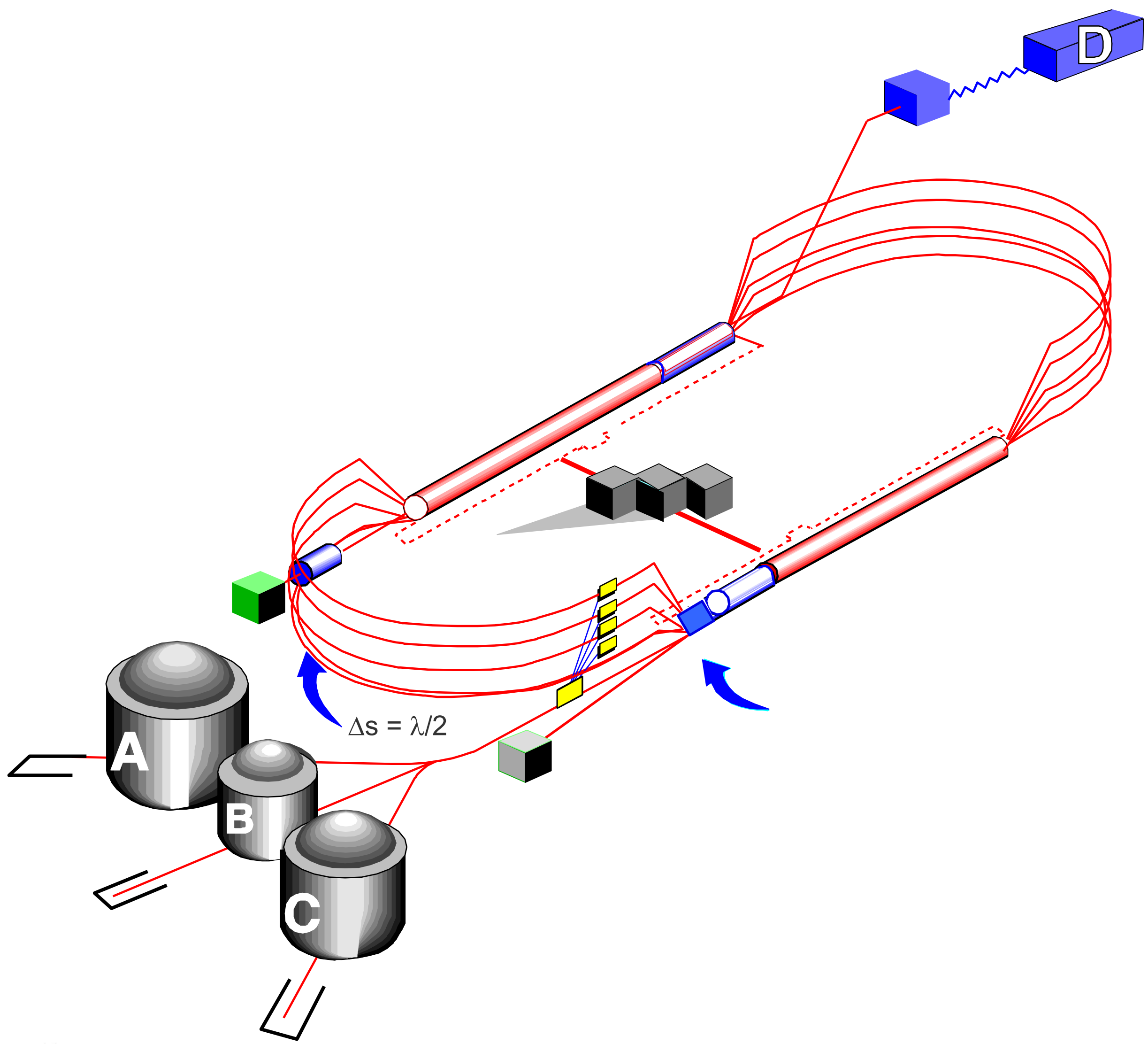
'Racetrack'



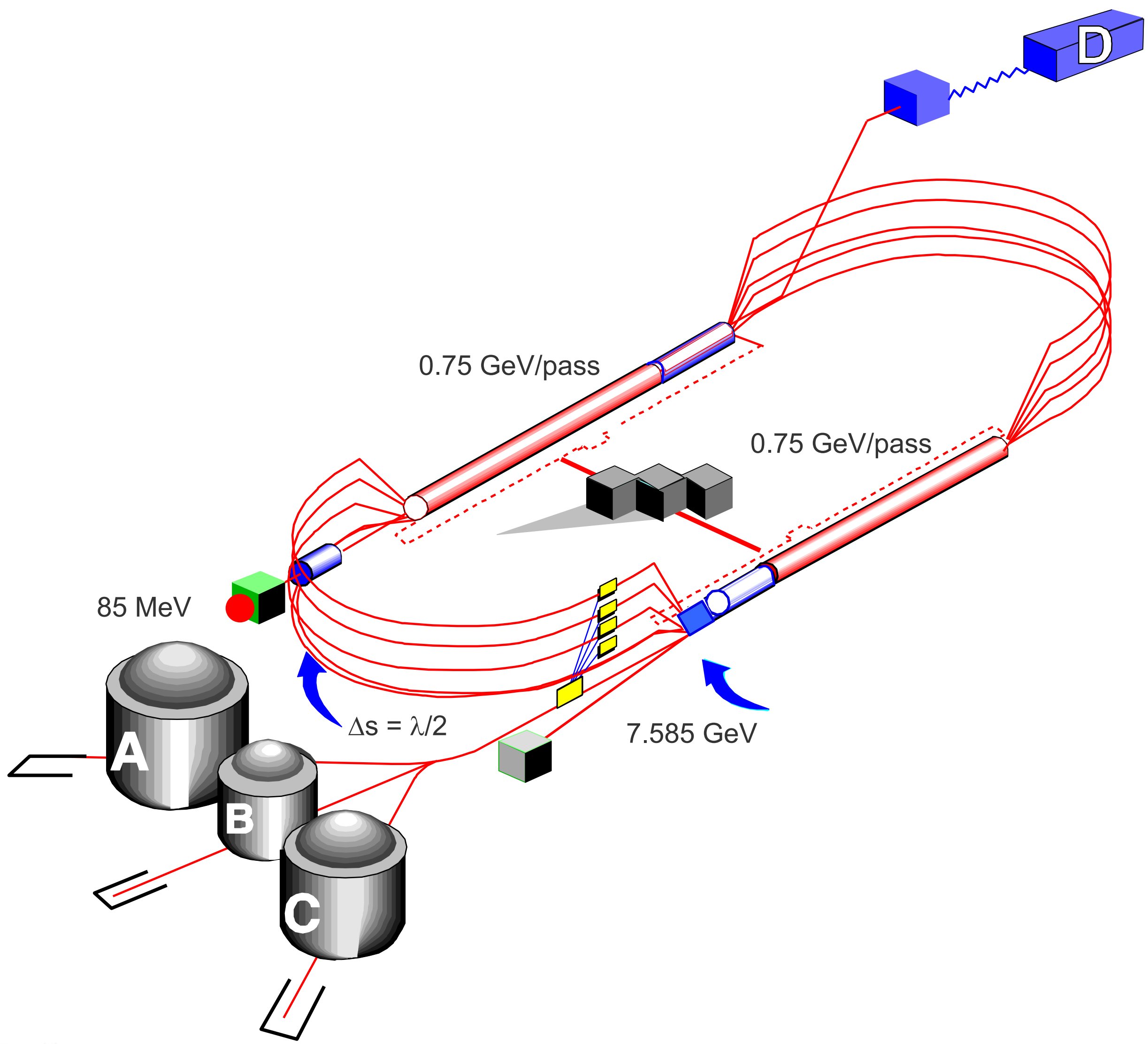
CEBAF ERL



CEBAF ERL



CEBAF ERL



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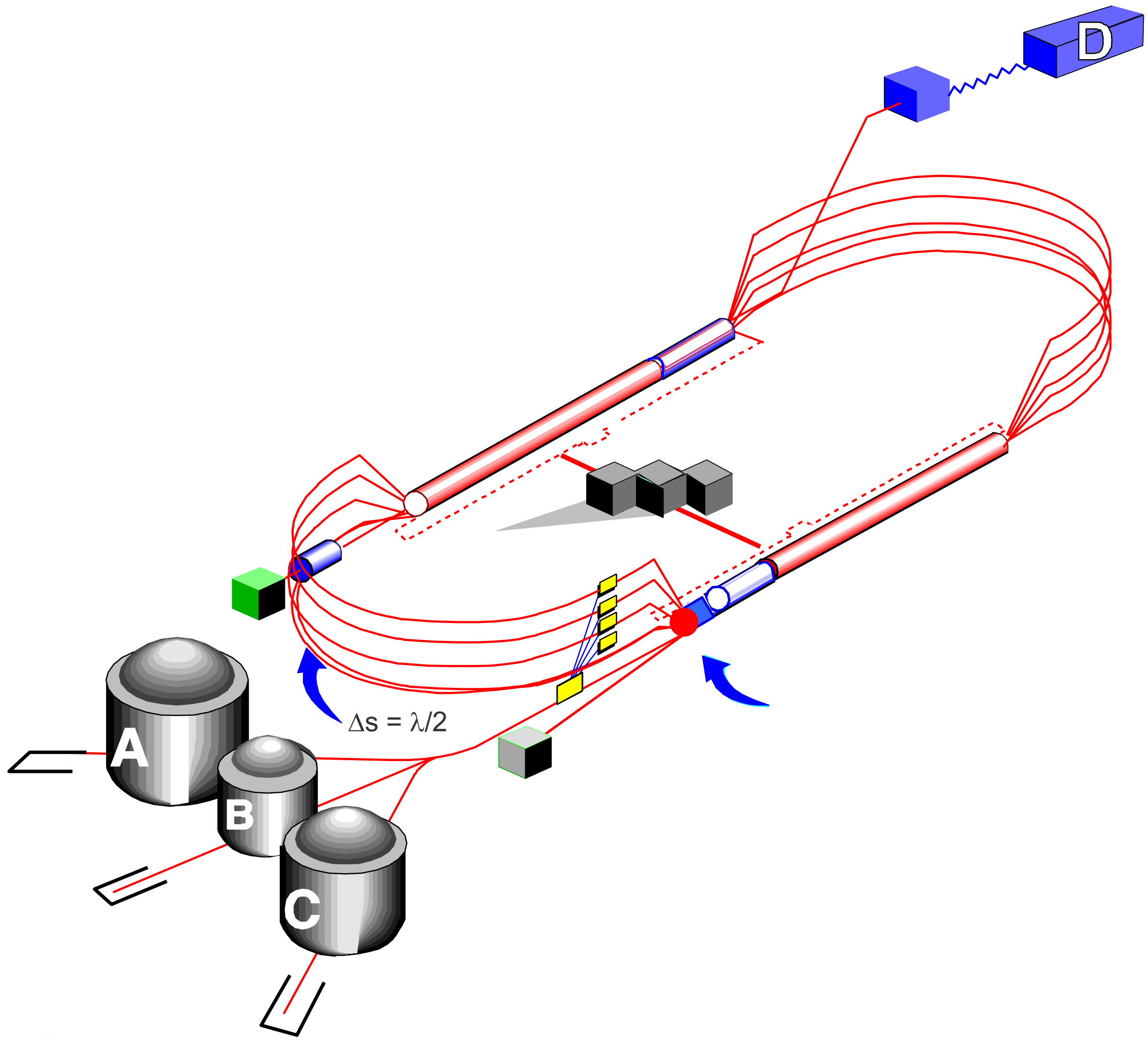

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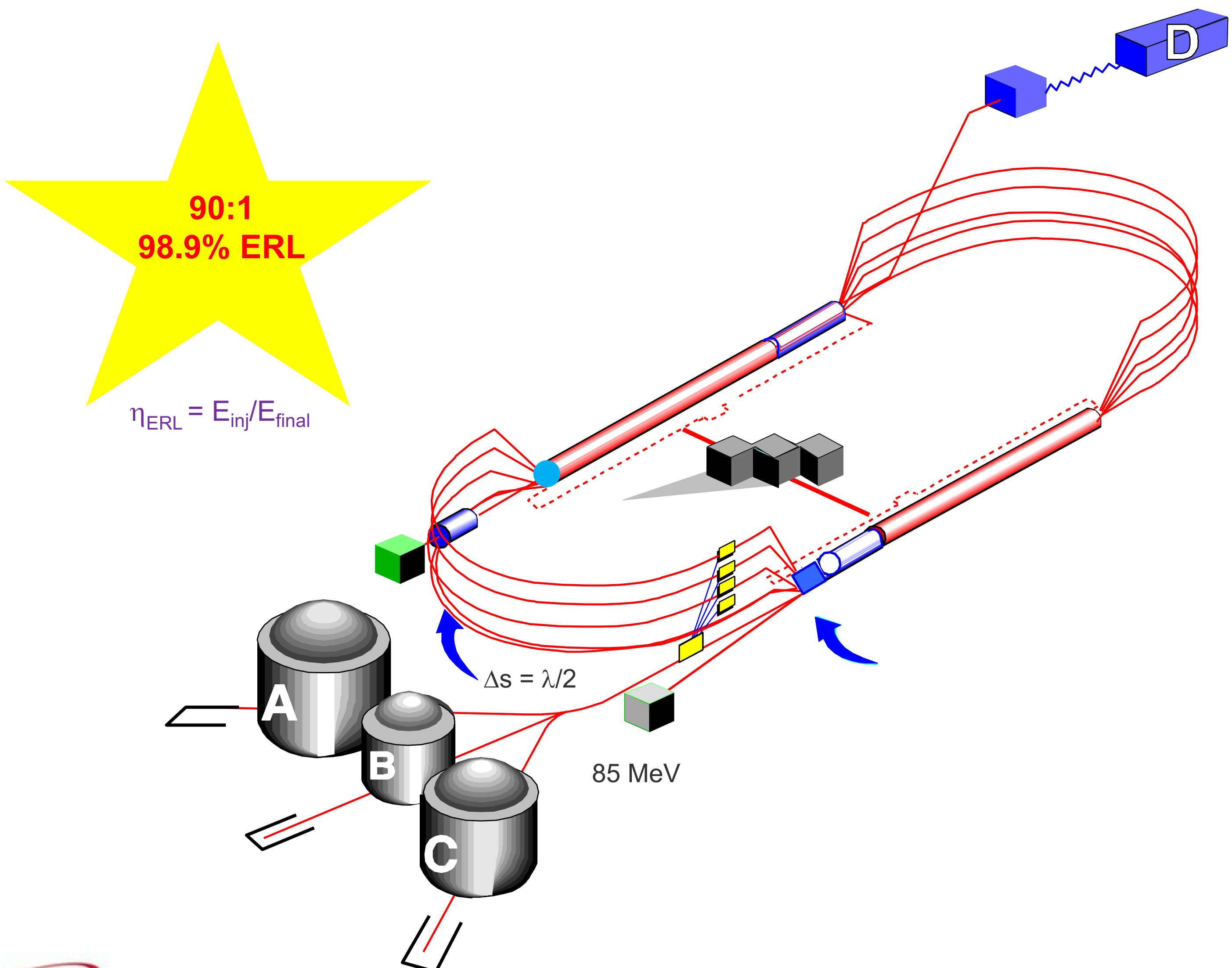
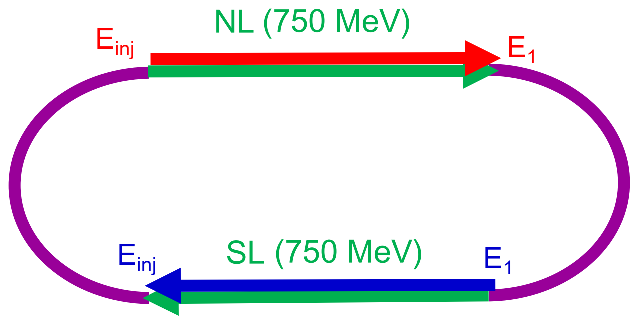
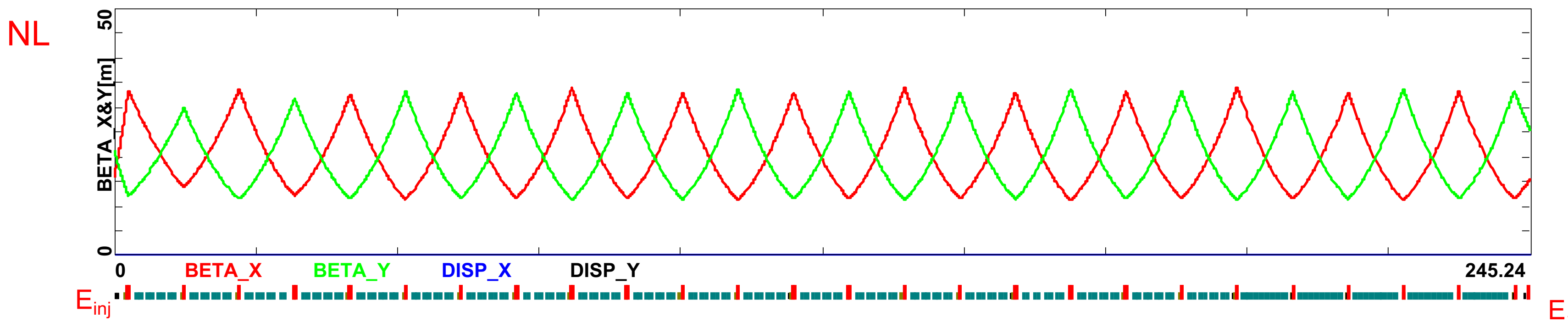
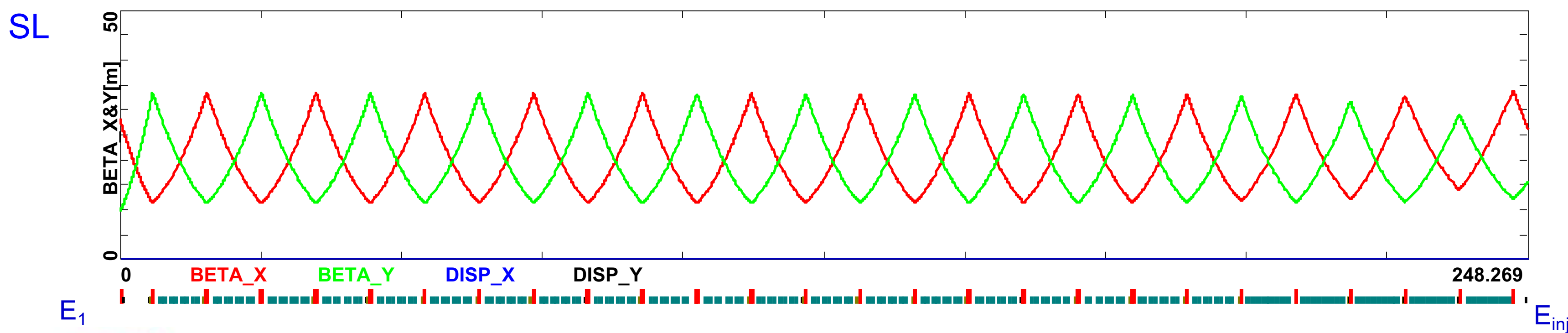


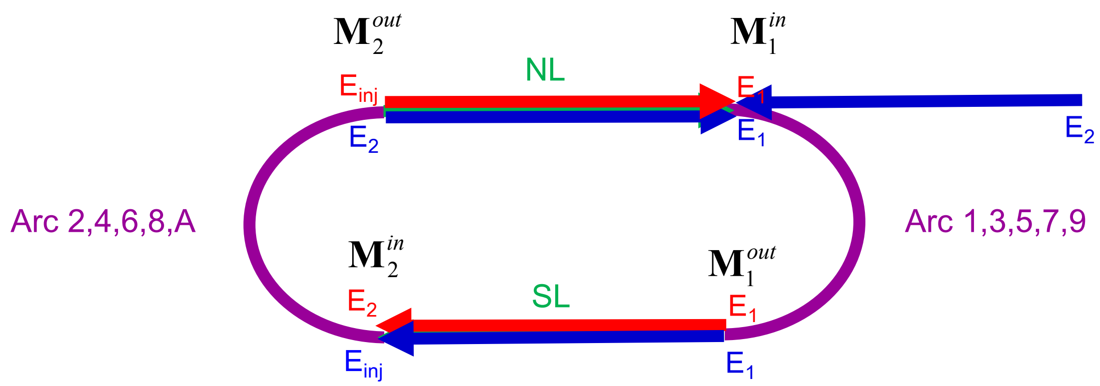
Linacs Optics – Lowest pass



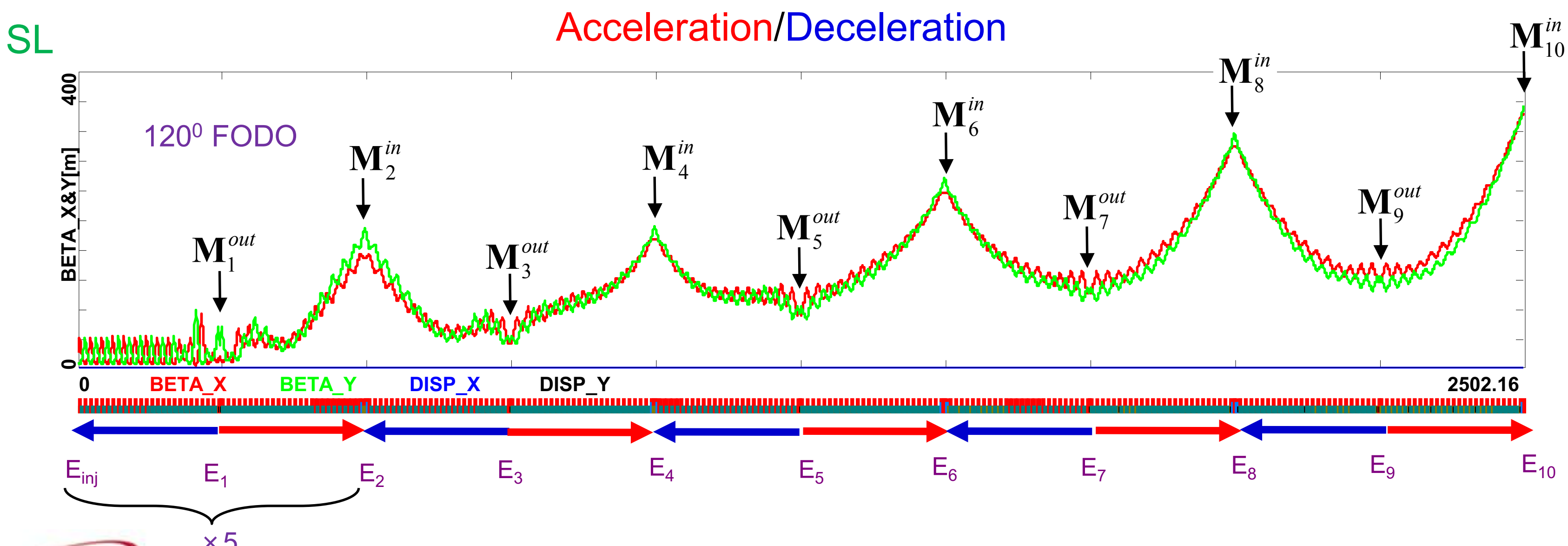




Multi-pass ER Optics



$$\mathbf{M} = \begin{bmatrix} \beta_x \\ -\alpha_x \\ \beta_y \\ -\alpha_y \end{bmatrix}$$



Linacs Optics – Optimization Criteria

❖ **The optimization of the linac optics aims at mitigating the impact of imperfections and collective effects such as wake-fields driven by:**

$$\left\langle \frac{\beta}{E} \right\rangle = \int_{\text{Acceleration}} \frac{\beta}{E} ds,$$

minimize →

Free parameters:
Input optics functions
(β function and its derivative)
Quads Strength profile

❖ **One should also consider the interaction of bunches at different passes, resulting in the integrals:**

$$I_{ij} = \int_{\text{Linac1,2}} \frac{\sqrt{\beta_i \beta_j}}{\sqrt{E_i E_j}} ds,$$

where the energy and the β functions need to be evaluated for the different pass numbers: i, j

$$F = \sqrt{\left(I_{11} + I_{22} + I_{33}\right)^2 + 2\left(I_{12} + I_{23}\right)^2 + 2\left(I_{13}\right)^2}.$$

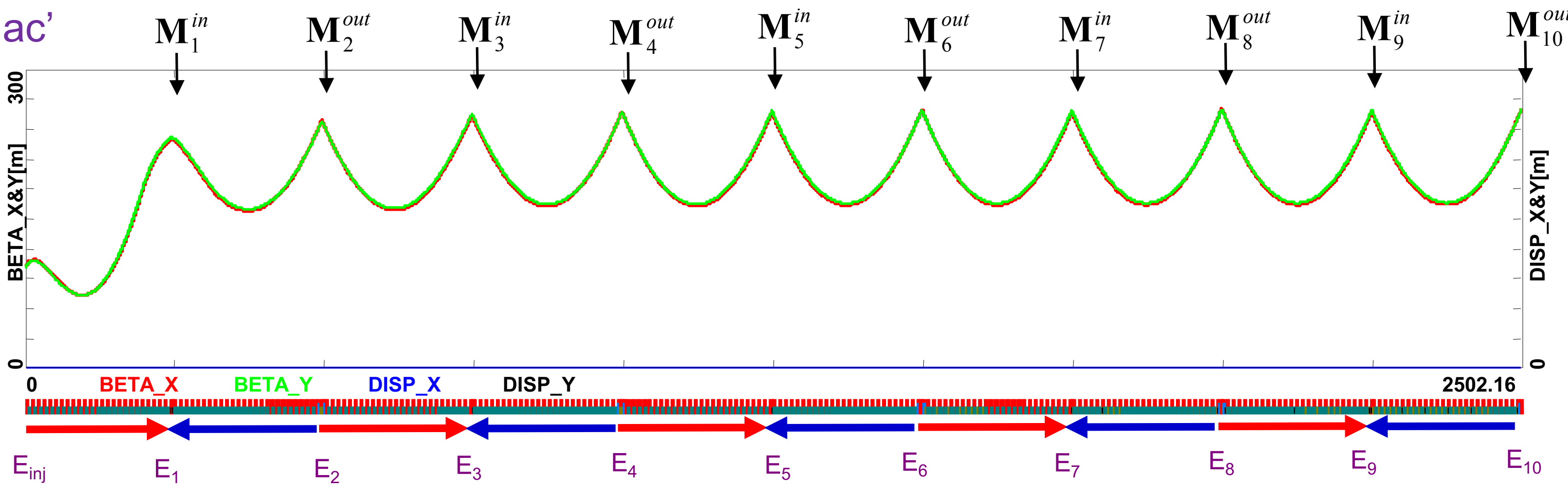
minimize →

Merit function (3-pass)

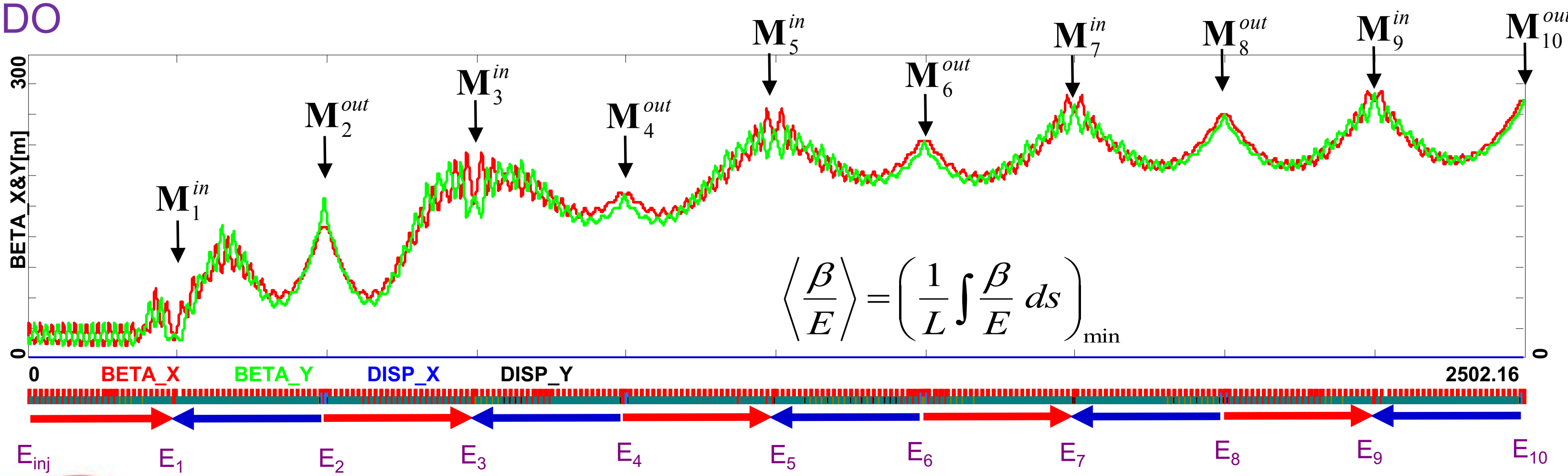
Optimized Multi-pass ER Optics

Acceleration/Deceleration

'Drift Linac'

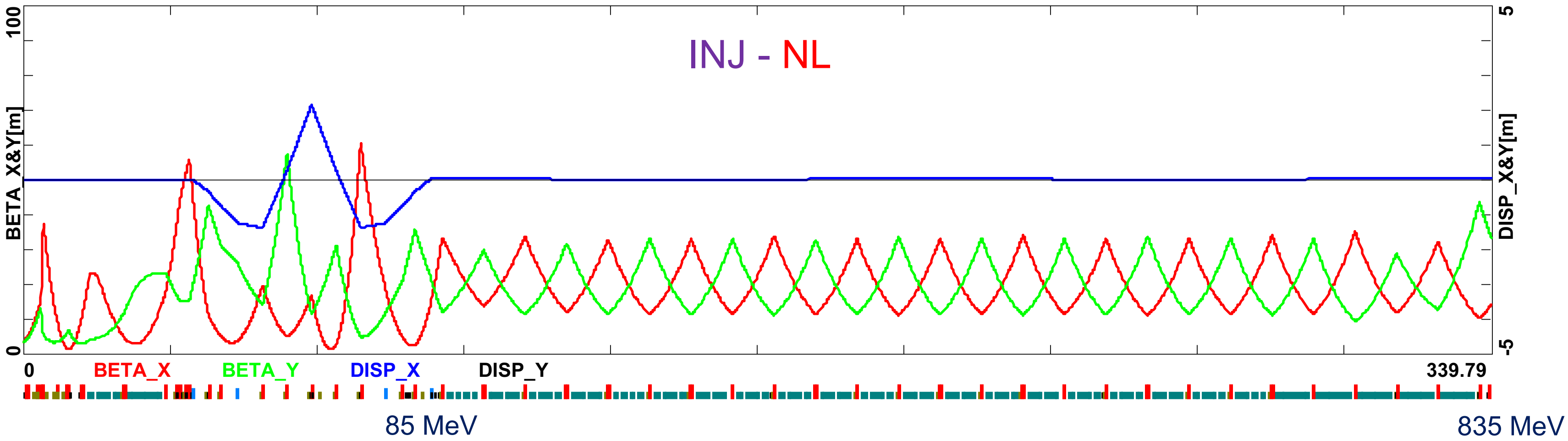


60^0 FODO

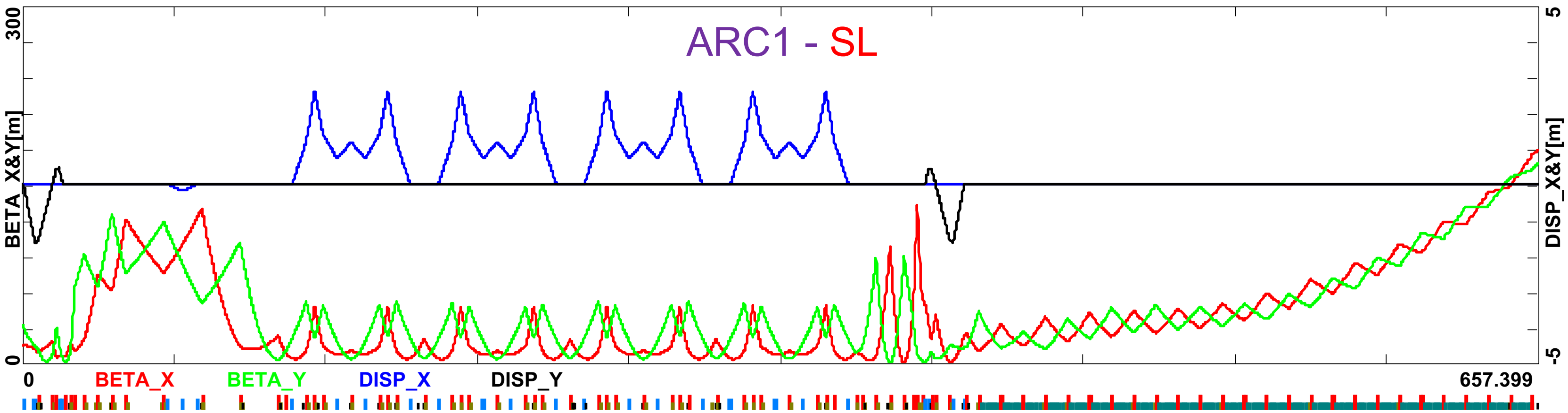


$$\left\langle \frac{\beta}{E} \right\rangle = \left(\frac{1}{L} \int \frac{\beta}{E}\, ds \right)_{\min}$$

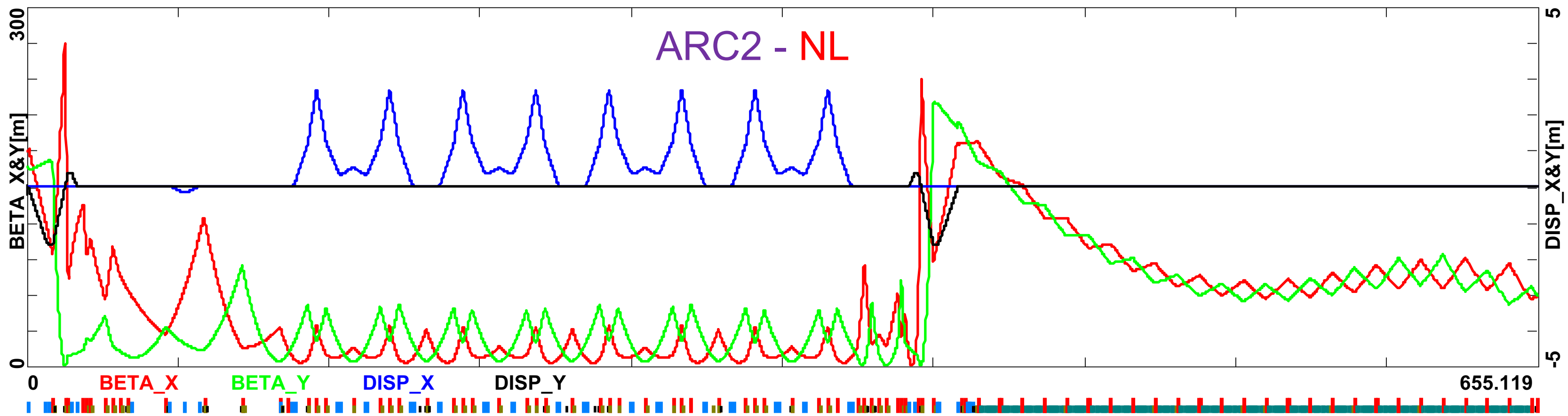
1-pass 'up' - Optics



1-pass 'up' - Optics

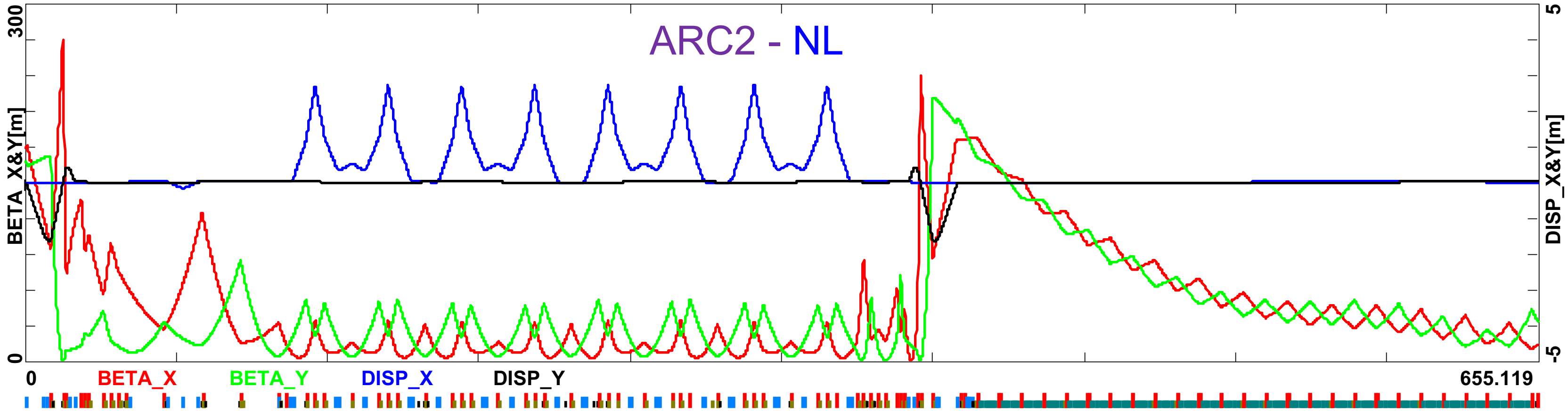


835 MeV 1585 MeV

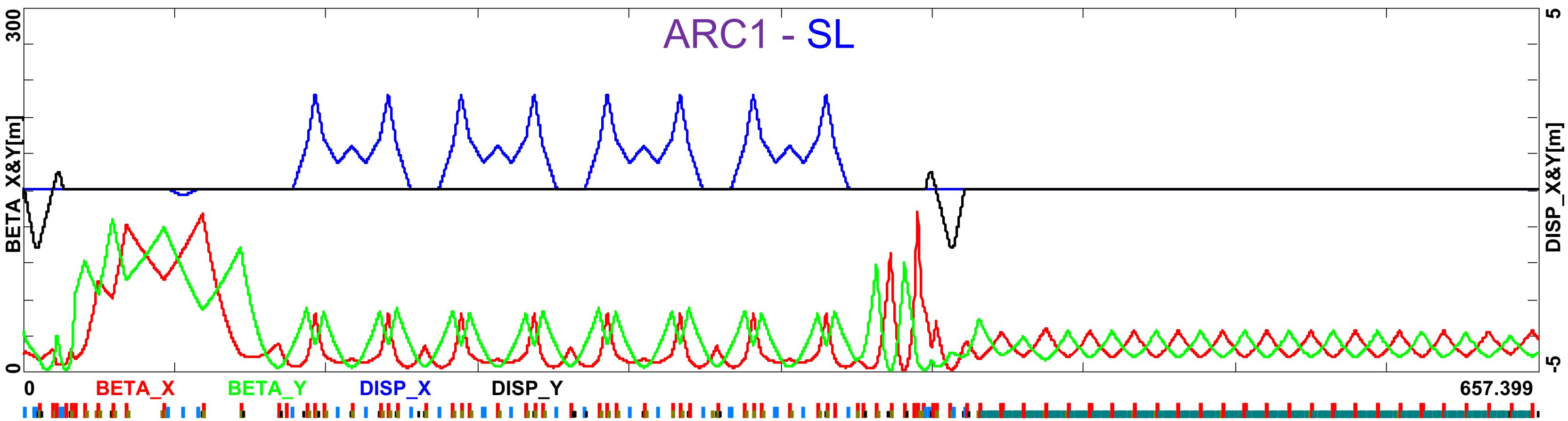


1585 MeV 2335 MeV

1-pass 'down' - Optics



1585 MeV 835 MeV

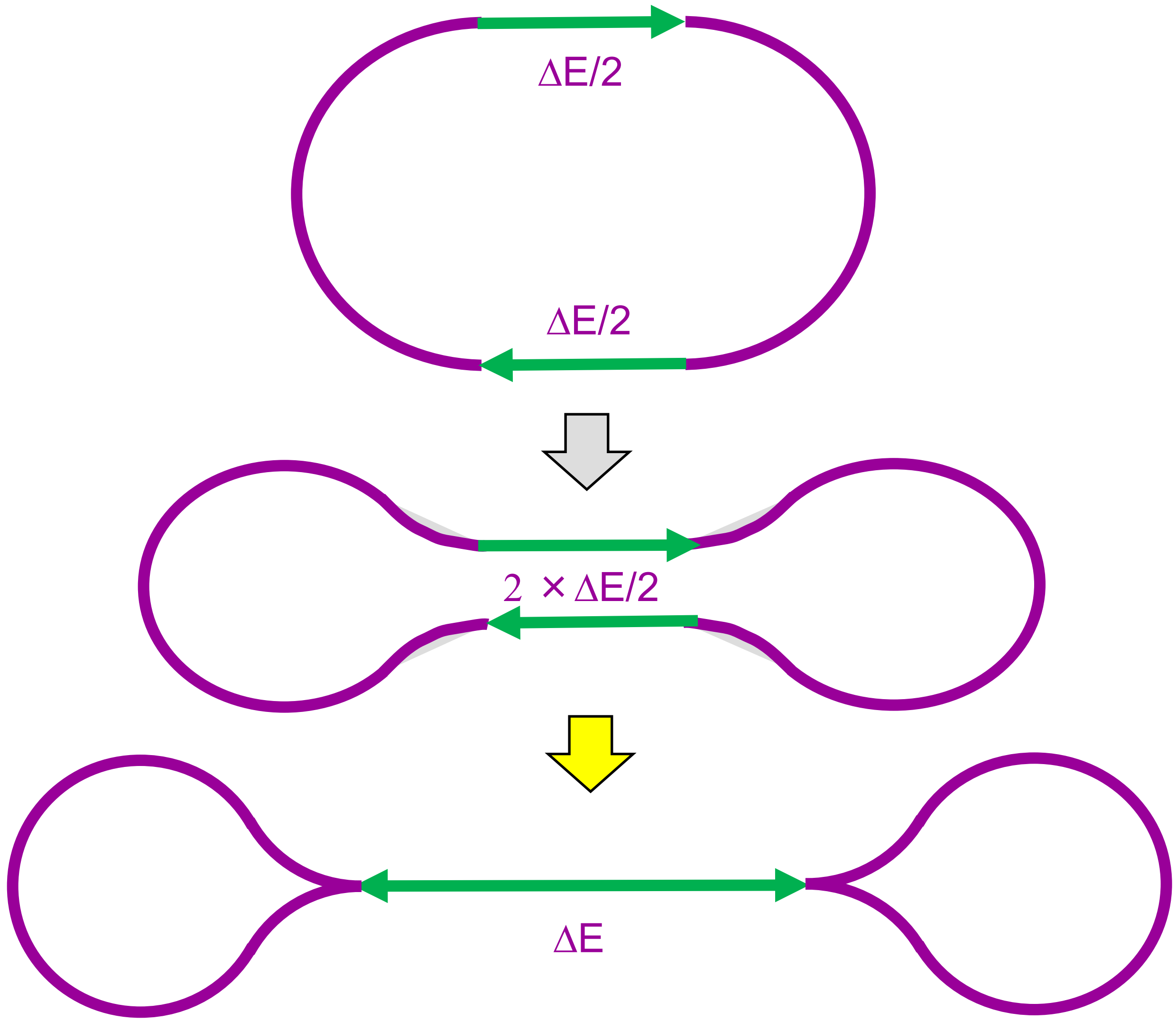


835 MeV 85 MeV

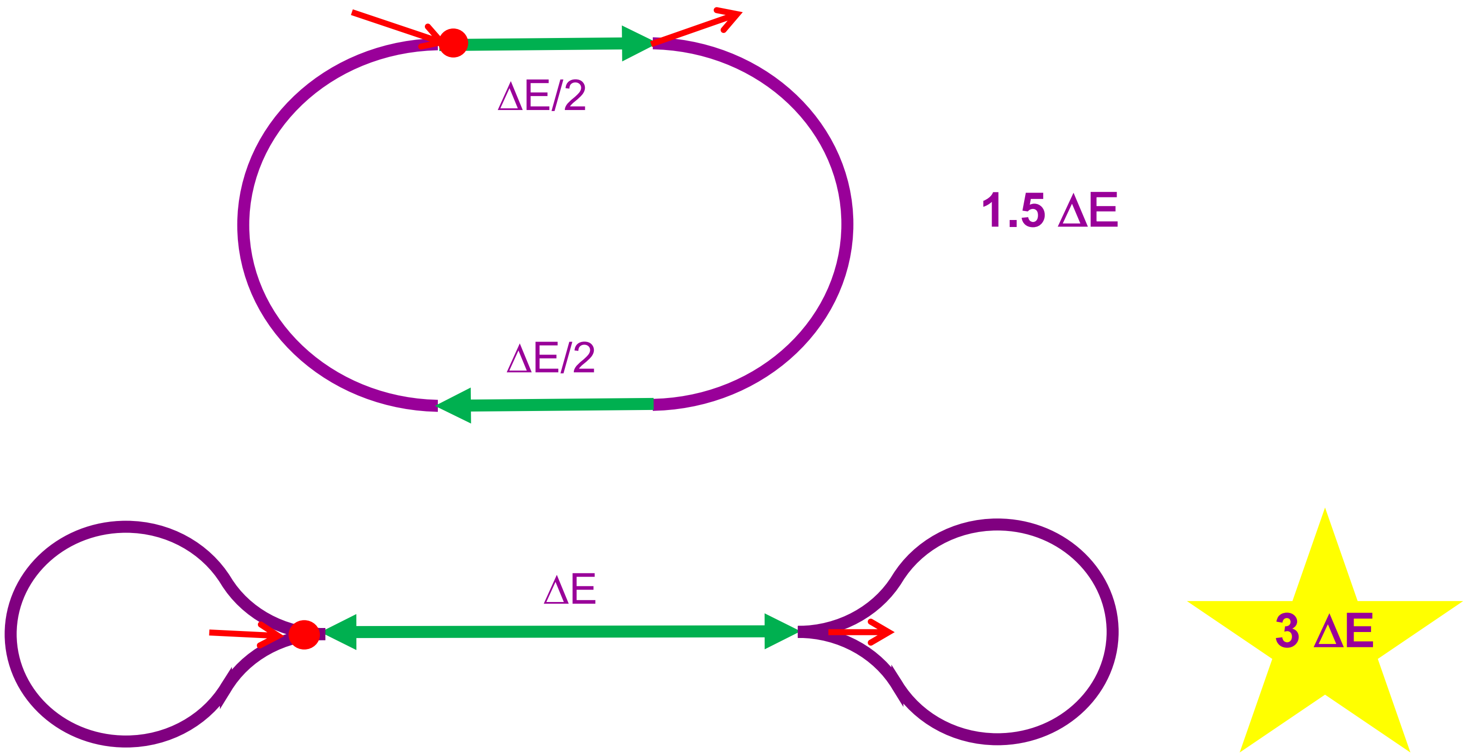
RLA Topologies

'Racetrack'

'Dogbone'

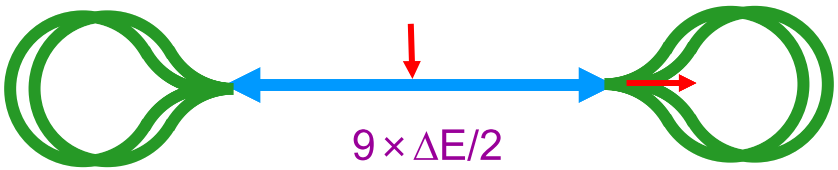


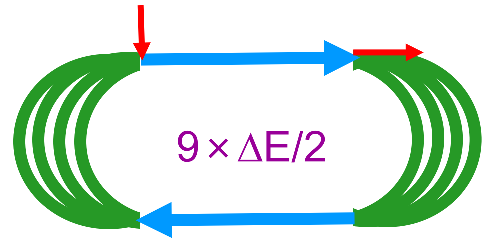
‘Racetrack’ vs ‘Dogbone’ RLA



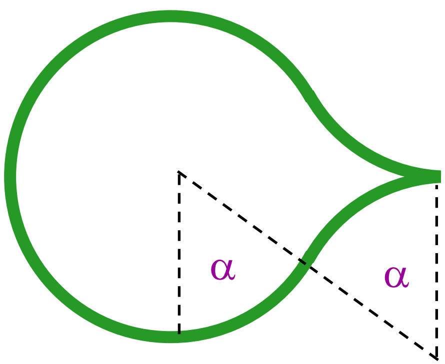
Twice the acceleration efficiency – traversing the linac in both directions while accelerating

‘Dogbone’ vs ‘Racetrack’ – Arc-length



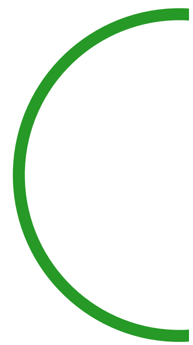


n ×



$= n(\pi + 4\alpha)R$

2n ×

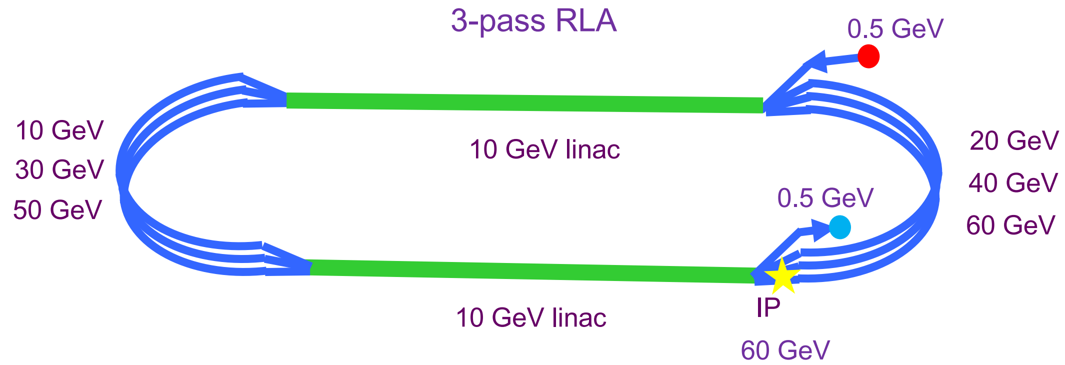


$= 2n\pi R$

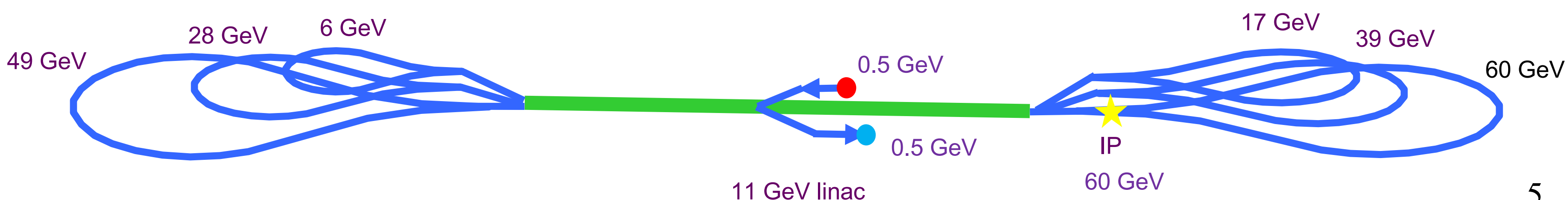
Net arc-length break even: if $\alpha = \pi/4$

‘Racetrack’ vs ‘Dogbone’ ERL

‘Racetrack’

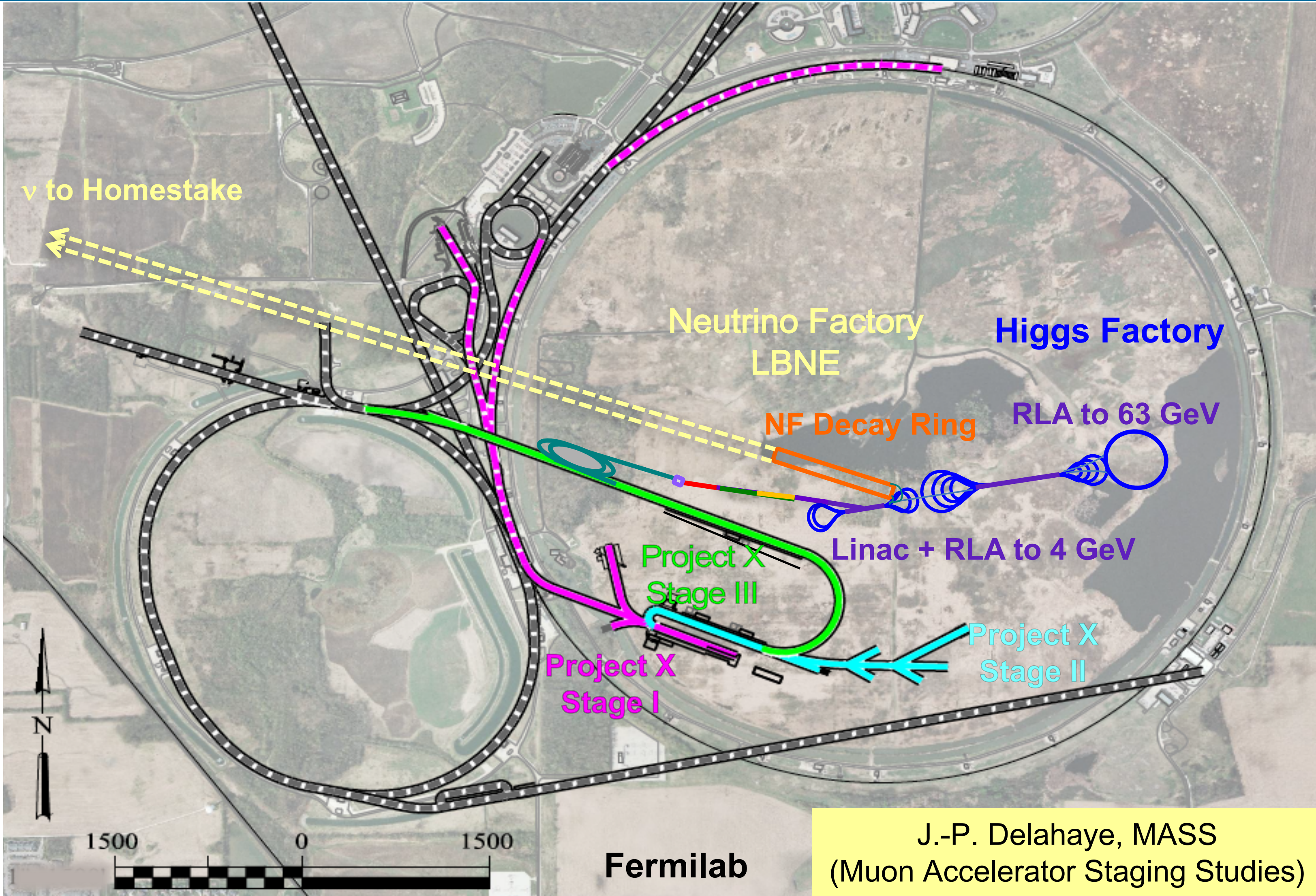


‘Dogbone’



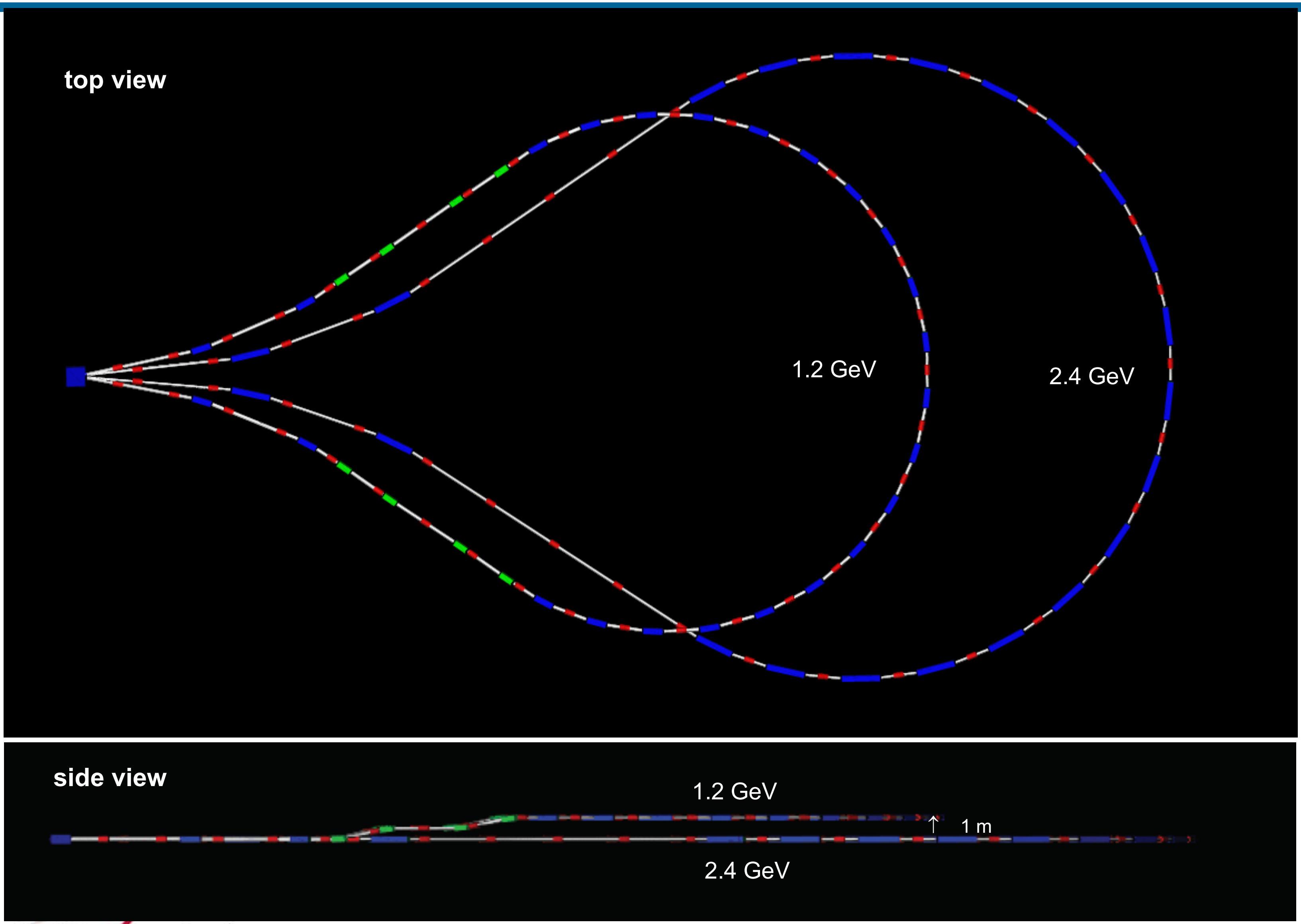
$\alpha = \pi / 6$ $\qquad \frac{5}{3} = \frac{300}{180}$

Future Muon Facilities – Muon Acceleration



J.-P. Delahaye, MASS
(Muon Accelerator Staging Studies)

Droplet Arcs – Layout

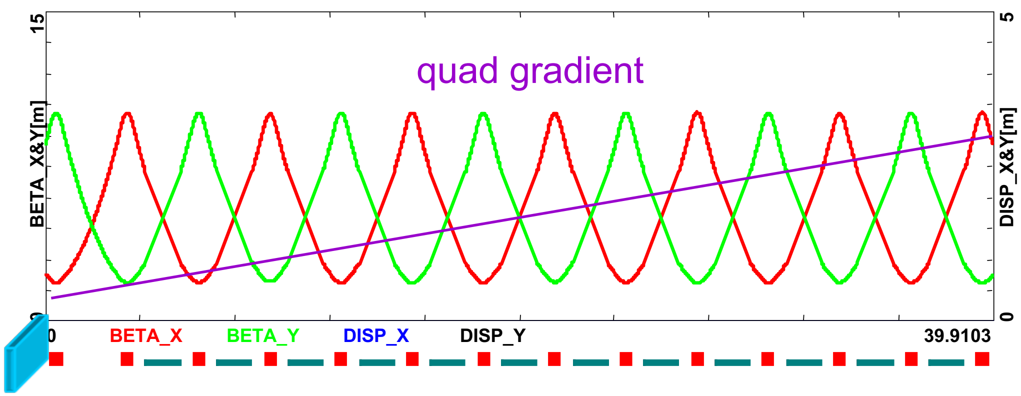


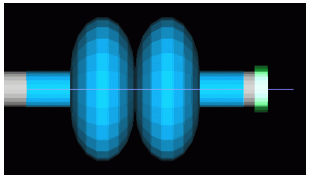
Multi-pass Linac Optics – Bisected Linac

'half pass', 900-1200 MeV

initial phase adv/cell 90 deg. scaling quads with energy

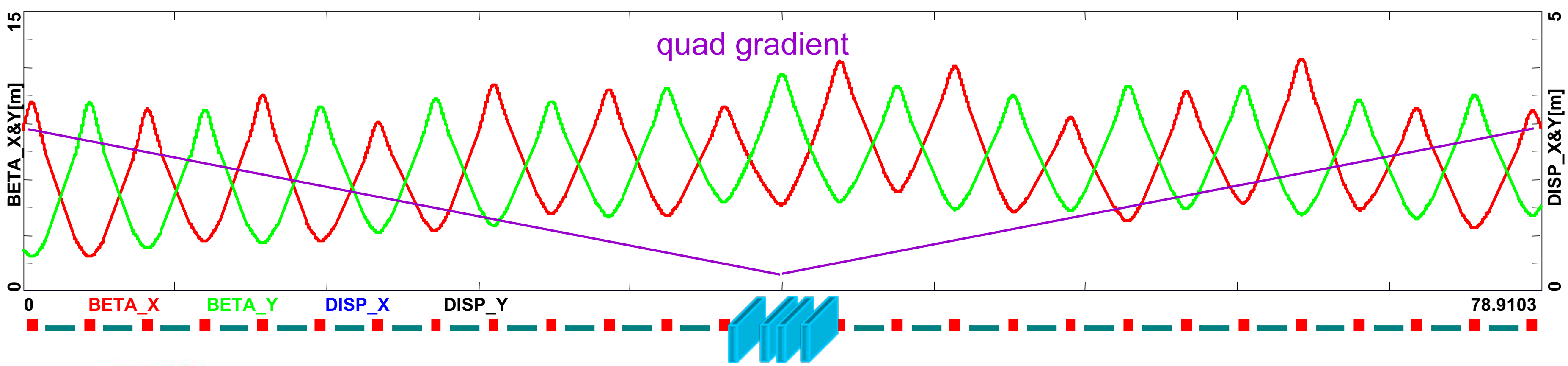
6 meter 90 deg. FODO cells
17 MV/m RF, 2 cell cavities



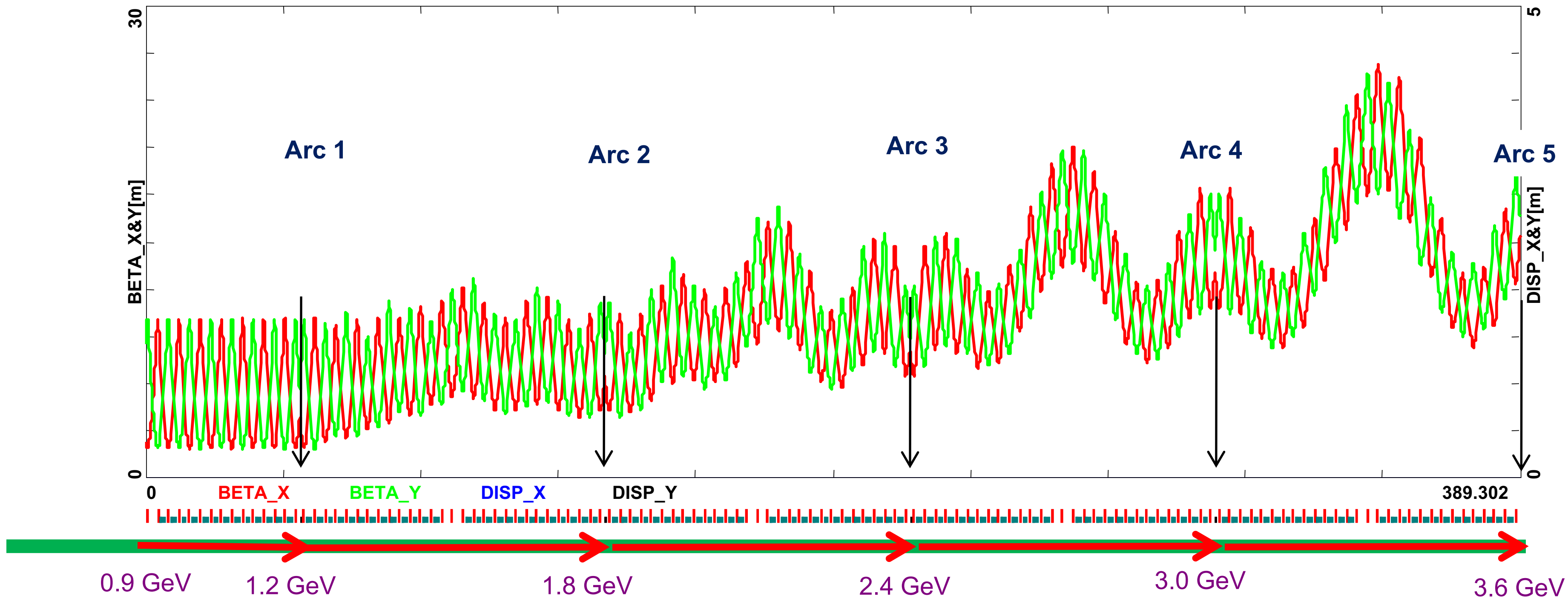


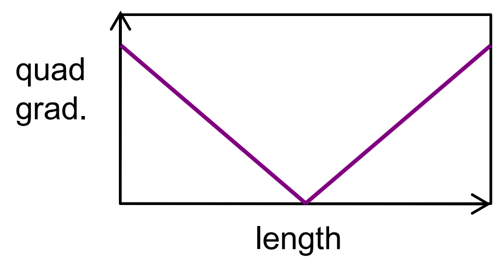
1-pass, 1200-1800 MeV

mirror symmetric quads in the linac

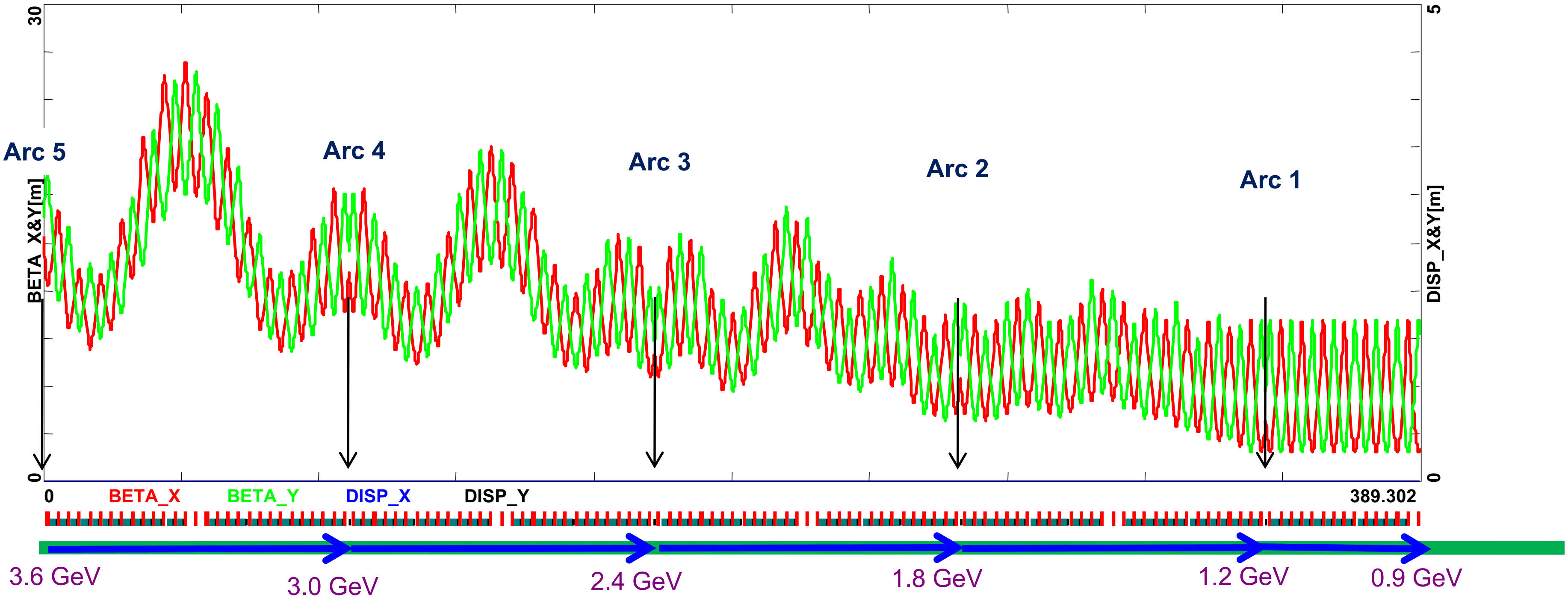


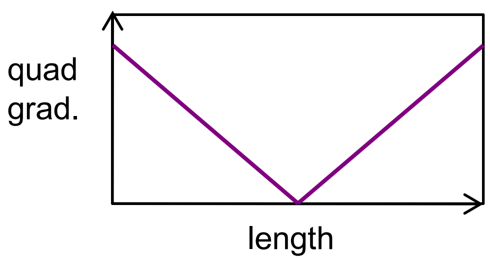
Multi-pass Linac Optics – Acceleration



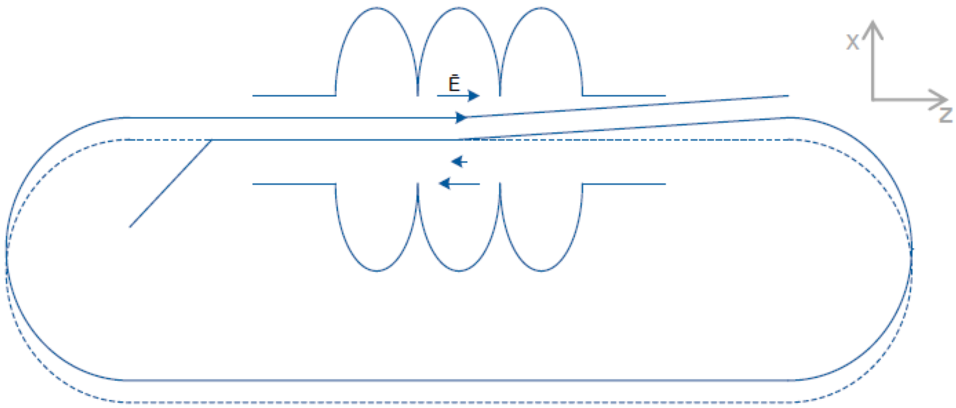


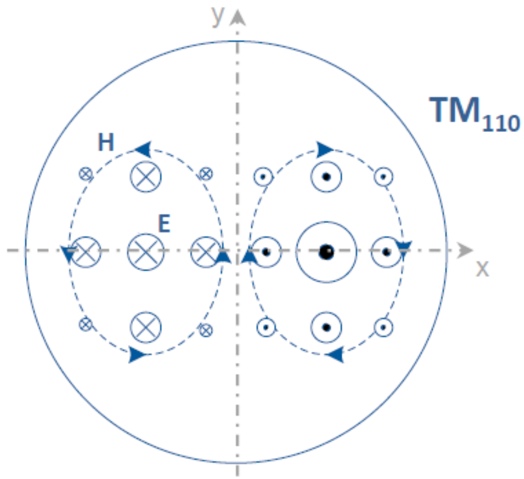
Multi-pass Linac Optics – Deceleration





Beam Breakup Instability (BBU)





Regenerative transverse BBU (single cavity, single turn, one mode):

- Bunch passes through cavity “off axis” during accelerating passage → induce HOM voltage & transverse kick due to Higher Order Modes (HOM)
- After recirculation kick transforms to an offset & HOM damp according to its Q
- Bunch passes through cavity with varied offset on decelerating passage → induce HOM voltage & transverse kick due to HOM
- **BBU Threshold: HOM excitation exceeds HOM damping → kick strength growth → beam loss**

Beam Breakup Instability (BBU)

beam induced change of cavity energy:

$$\Delta U_1 = -q_b \frac{V_a}{a} \cos(\varphi)\left(x_1 \cos(\alpha) + y_1 \sin(\alpha)\right)$$

$$\Delta U_2 = -q_b \frac{V_a}{a} \cos(\varphi + \omega_\lambda T_{rec})\left(x_2 \cos(\alpha) + y_2 \sin(\alpha)\right)$$

bunch offset at 2nd passage: $x_2 = m_{11}x_1 + m_{12}x_1' + m_{13}y_1 + m_{14}y_1' - \frac{qV_a}{\omega_\lambda a\, p} \sin(\varphi)\left(m_{12}\cos(\alpha) + m_{34}\sin(\alpha)\right)$

ohmic losses → damping of HOM: $P_c = \frac{V_a^{\,2}}{(\omega_\lambda / c)^2 a^2 (R/Q)_\lambda\, Q_\lambda}$

balanced HOM: $\langle \Delta U_1 + \Delta U_2 \rangle_\varphi \cdot f_b = P_c$

→ **threshold current:**

$$I_{th} = -\frac{2\,pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

valid for:

- $m^* \sin(\omega_\lambda T_{rec}) < 0$
- $\omega_\lambda \neq n^* \omega_{rf}$

$$m^* = m_{12}\cos^2(\alpha) + (m_{14} + m_{32})\sin(\alpha)\cos(\alpha) + m_{34}\sin^2(\alpha)$$

Krafft, Bisognano, and Laubach, unpublished (1988)

Beam Breakup Instability (BBU)

Countermeasures:

$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

1. **cavity design:**
   - HOMs: small R/Q, varying ω_λ at fixed ω_0 → multi cavity BBU thresholds increase
   - no HOM on a fundamental's harmonics: $\omega_\lambda \neq n^*\omega_{rf}$
   - low Q for HOM → HOM dampers (ferrites, waveguides, …)

2. **recirculator beam optics:**
   - for α=0 & uncoupled beam transport → $m^* = m_{12} = (\beta_1\beta_2)^{1/2} \sin(\Delta\varphi_x)$

     → stable for $\Delta\varphi = n\pi$
   - adjust $\sin(\omega_\lambda T_{rec}) = 0$ for the worst HOM

     large path length change → inpractical

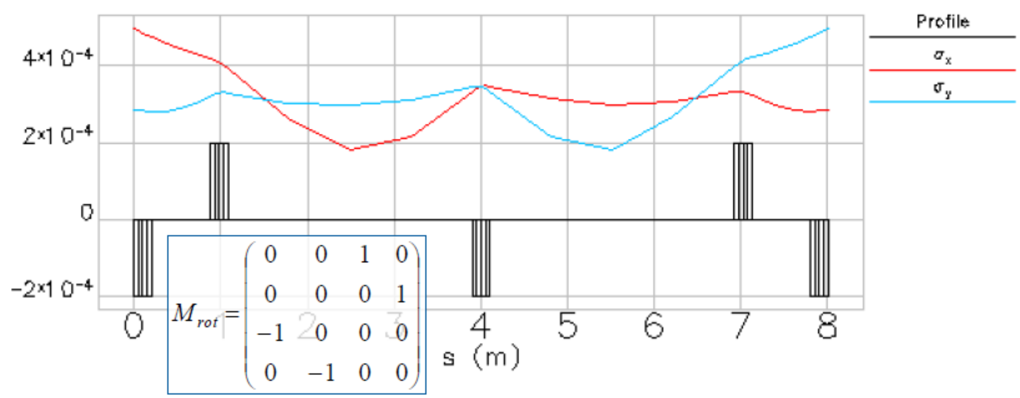
Beam Breakup Instability (BBU)

Countermeasures:

$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

2. recirculator beam optics (continued):

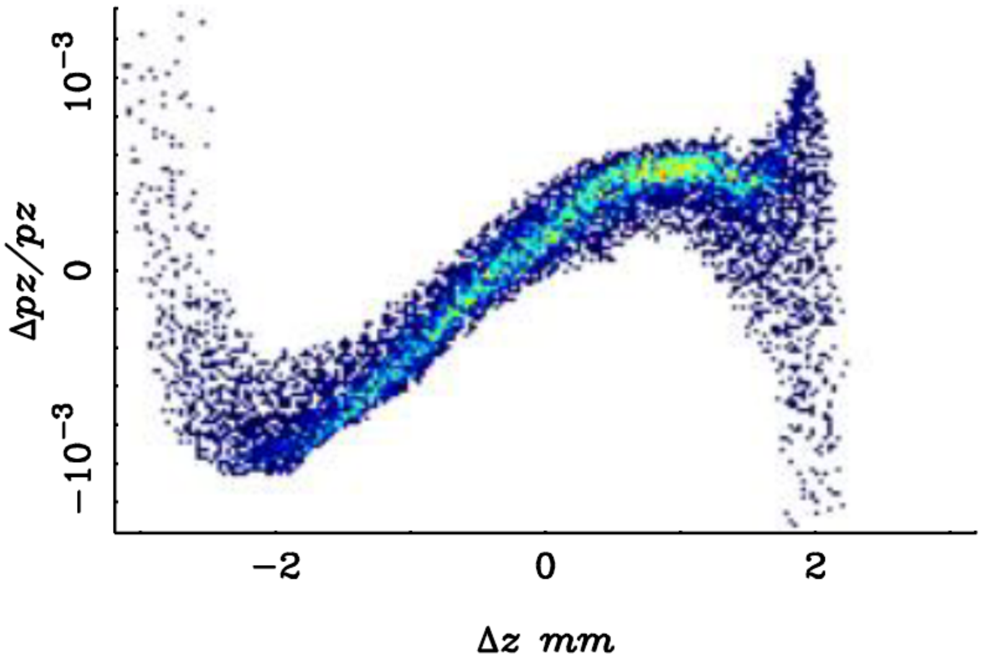
- coupled beam transport: switching of planes $M=((M_x,0),(0,M_y)) \rightarrow M=((0,M_{yx},0),(0,M_{xy}))$
  $m_{12}=0 \rightarrow$ horizontal HOM kick transforms to vertical offset $\rightarrow$ HOM not further excited by the oscillatory part of x_2
- $\rightarrow$ two options: solenoid (low energy), rotator



$$M_{rot} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

Nonlinear Beam Optics

- RF curvature: $E(t)=E_0 \cos(\omega t + \varphi_0)$



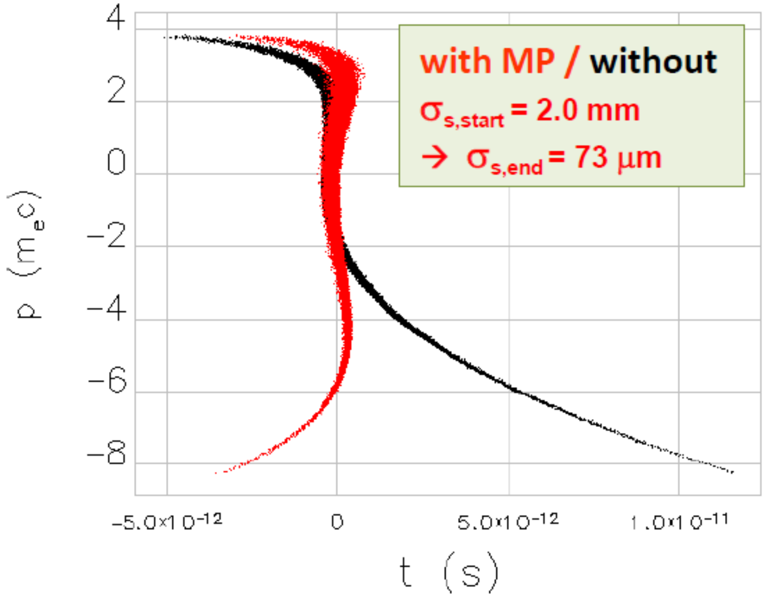
Nonlinear Beam Optics

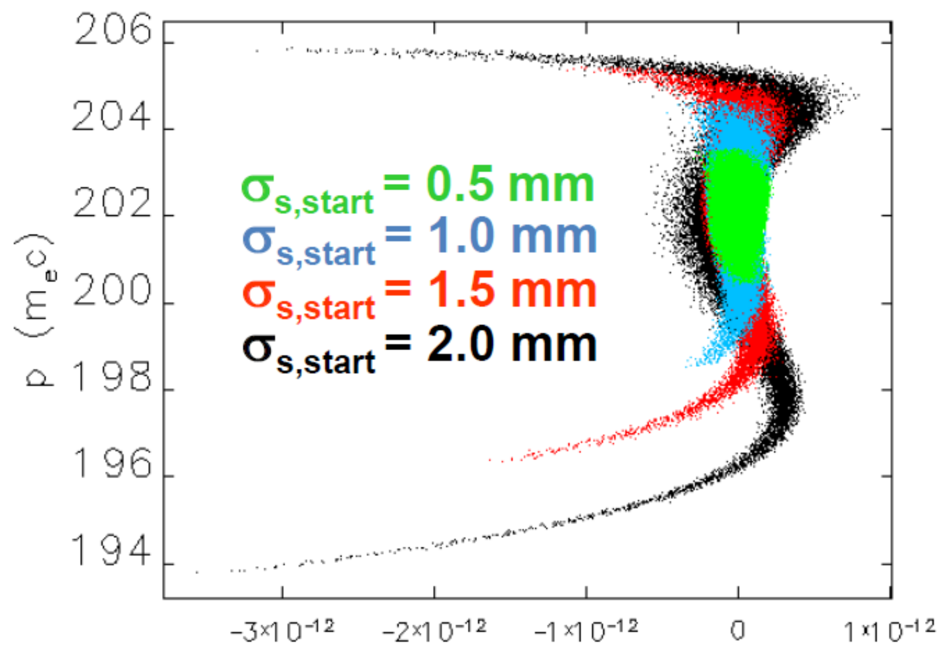
- RF curvature: $E(t)=E_0 \cos(\omega t + \varphi_0)$
- aberrations: geometric & chromatic

  caused and counteracted by nonlinear fields → multipole magnets

  Example: bunch compression $E(s_i) = E_0 \cos(s\, 2\pi/\lambda - \varphi_0) \rightarrow \delta_i = E(s_i)/E_0\cos(-\varphi_0)$

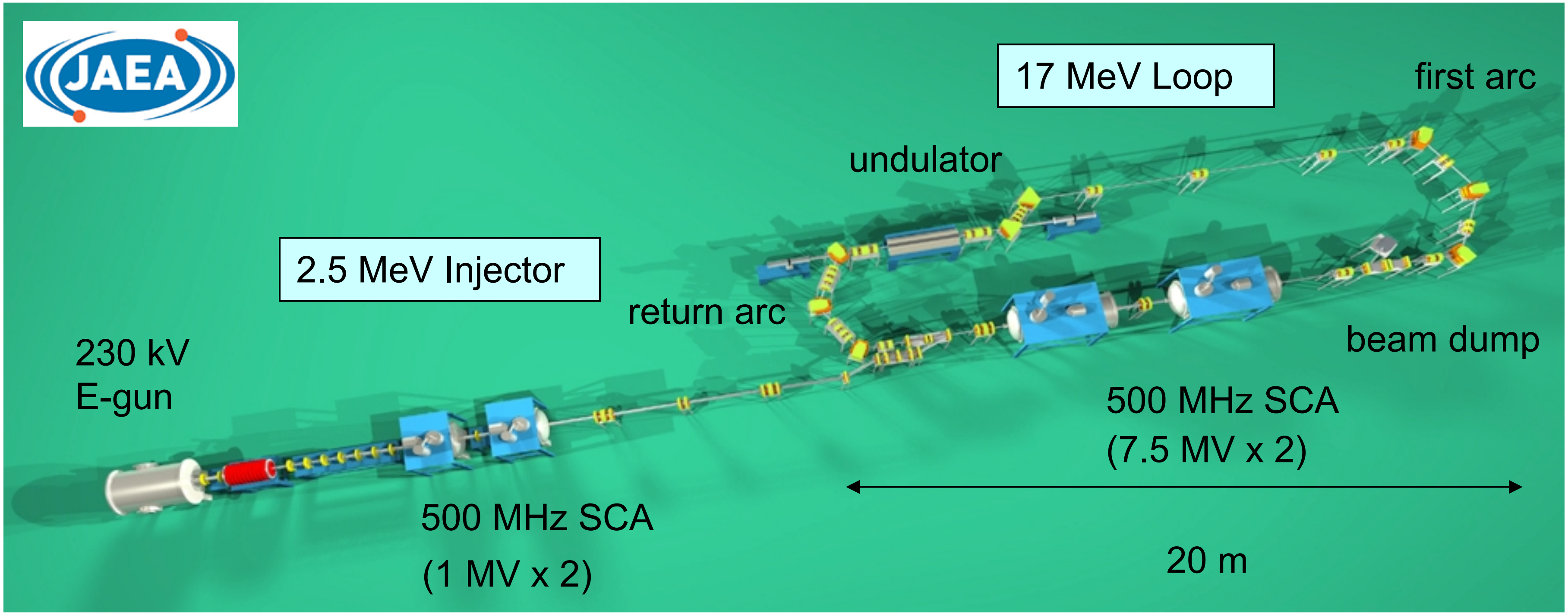
  $\Delta L_i = R_{56}\,\delta_i + T_{566}\,\delta_i^2 + U_{5666}\,\delta_i^3 + \ \ldots$





bERLinPro recirculator test: bunch compression with varying initial bunch length; linac phase, sextupole and octupole magnets optimized

17 MeV-ERL at JAEA

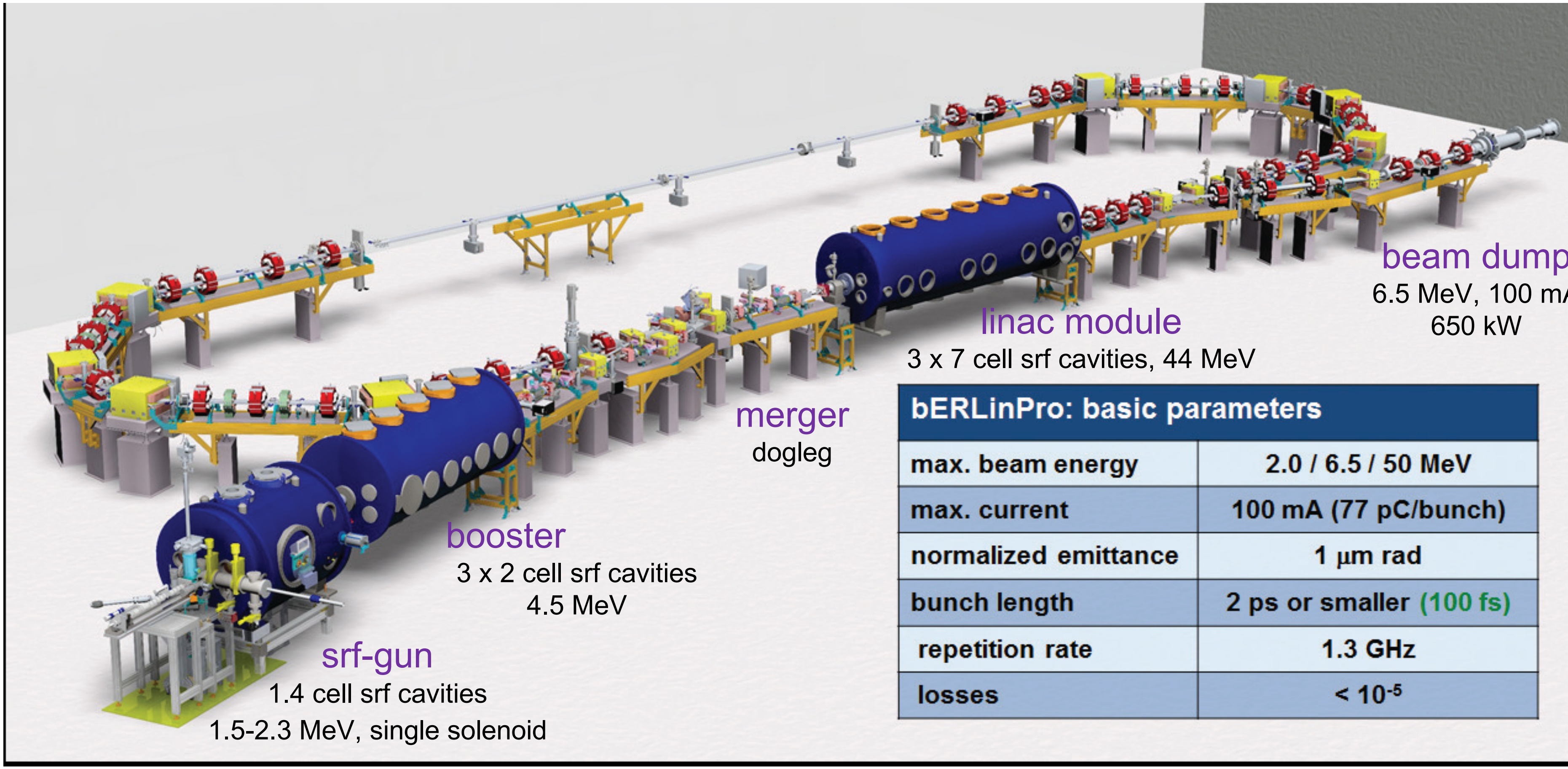


2.5 MeV injector consists of 230 keV thermionic cathode gun, 83 MHz sub harmonic buncher, and two single-cell 500 MHz SCAs.

17 MeV loop consists of a merger chicane, two five-cell 500 MHz SCAs, a triple-bend achromat arc, half-chicane, undulator, return-arc, and beam dump.

bERLinPro – Berlin ERL Project

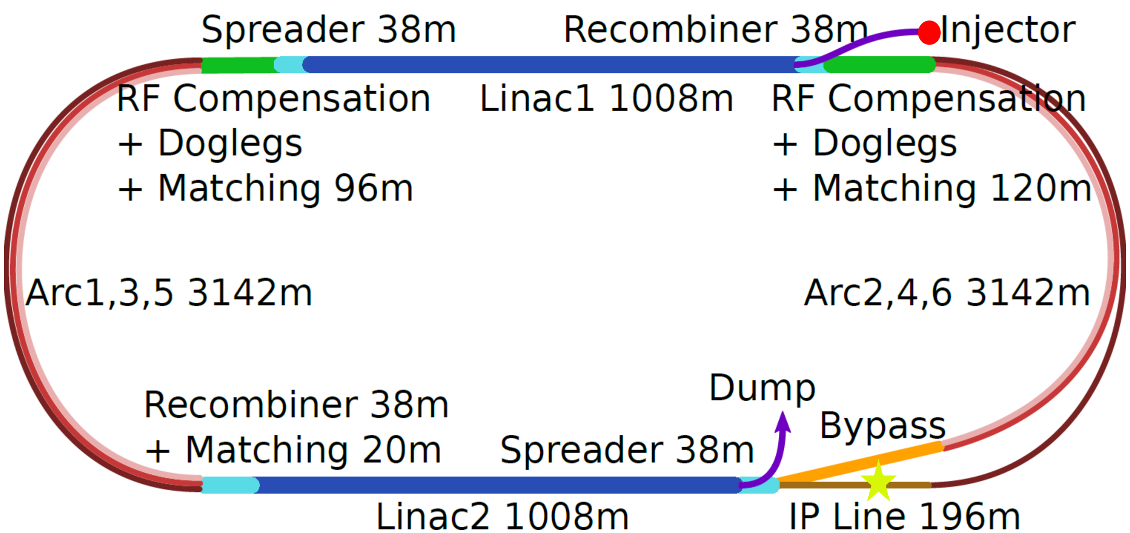
100 mA / low emittance technology demonstrator (covering key aspects of a large scale ERL)



bERLinPro: basic parameters	
max. beam energy	2.0 / 6.5 / 50 MeV
max. current	100 mA (77 pC/bunch)
normalized emittance	1 µm rad
bunch length	2 ps or smaller (100 fs)
repetition rate	1.3 GHz
losses	< 10^{-5}

bERLinPro
Helmholtz-Zentrum Berlin

ERL for of Electron Ion Collider



60 GeV (e) x 7 TeV (p)

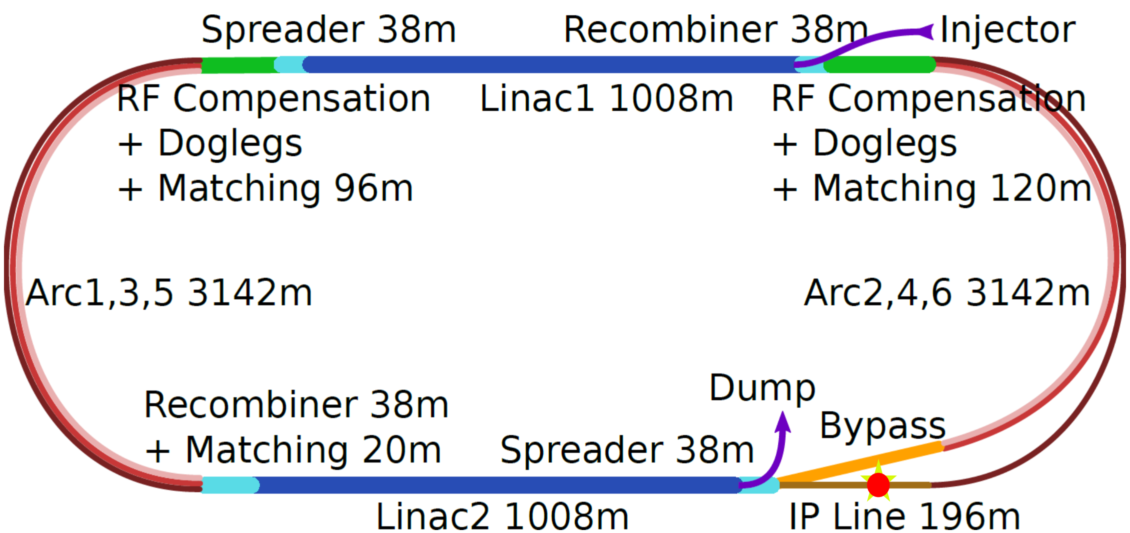
RECIRCULATOR COMPLEX

- 0.5 Gev injector
- Two SCRF linacs (20 GeV per pass)
- Six 180° arcs, each arc 1 km radius
- Re-accelerating stations
- Switching stations
- Matching optics
- Extraction dump at 0.5 GeV

TOTAL CIRCUMFERENCE ~ 8.9 km

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
Average Beam Current [mA]	1112	25 delivered 150 in linacs
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

ERL for of Electron Ion Collider



Arc6: $\Delta s = \lambda/2$

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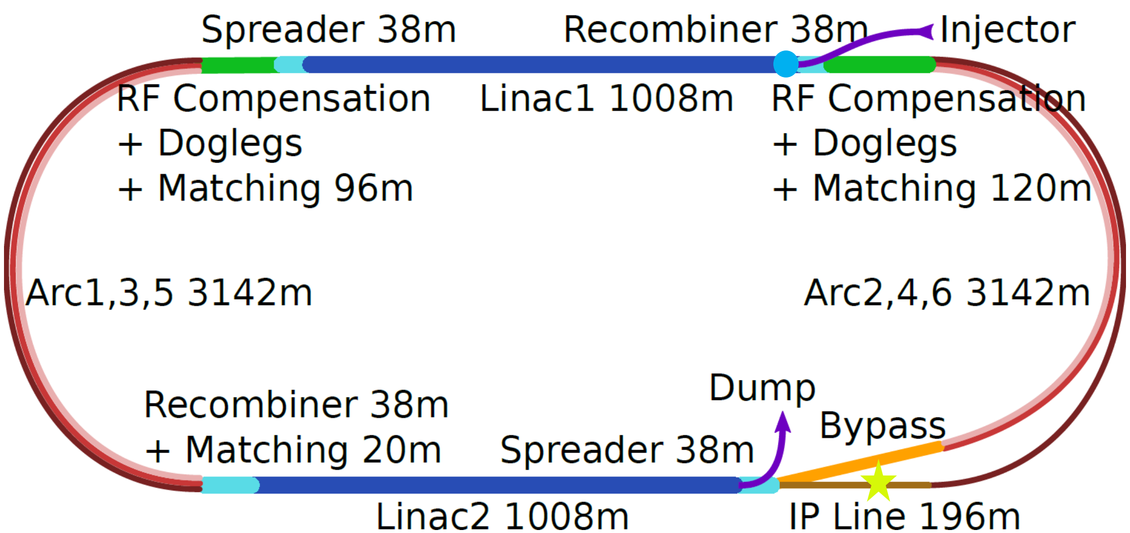
ERL for of Electron Ion Collider



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'Green' High Luminosity Colliders Need ERLs

Max Klein

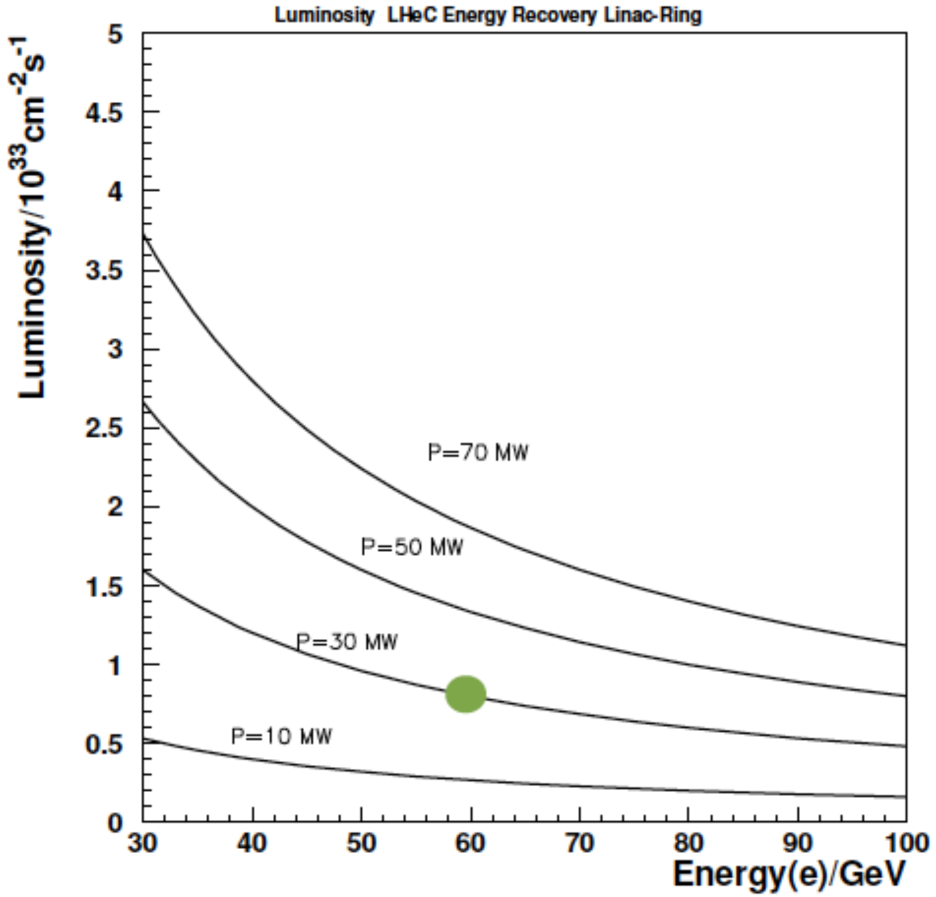
$$L = \frac{N_e N_p f \gamma_p}{4\pi \epsilon_p \beta^*}$$

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

High luminosity needs nearly GW of power P, for 60 GeV energy E

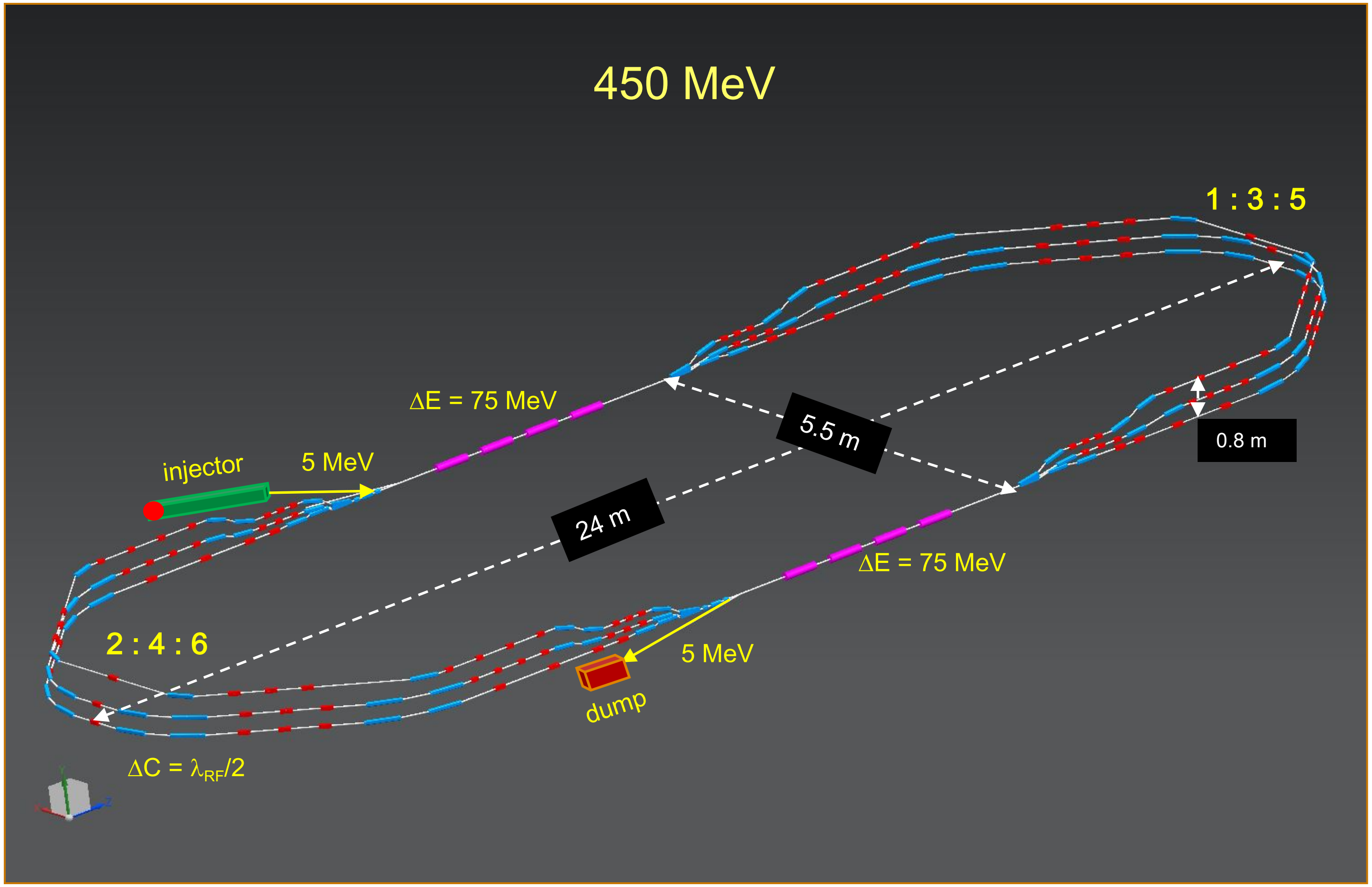
This can only be achieved with efficient energy recovery technique

P = P_0 /(1-ε)   ERL efficiency

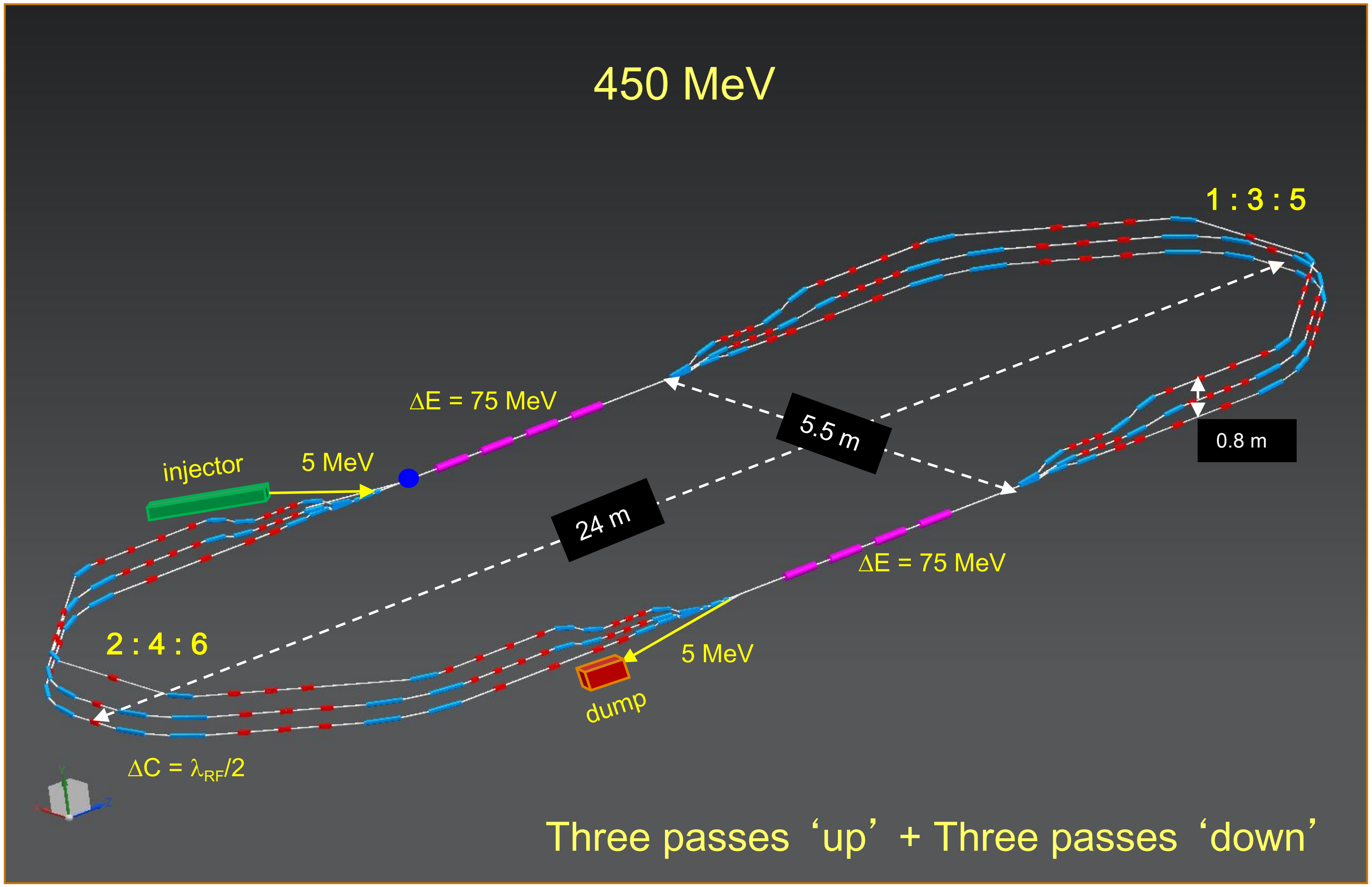


CDR of LHeC: Goal now is 10^{34} could NOT pay for power and not realise high lumi w/o ERL

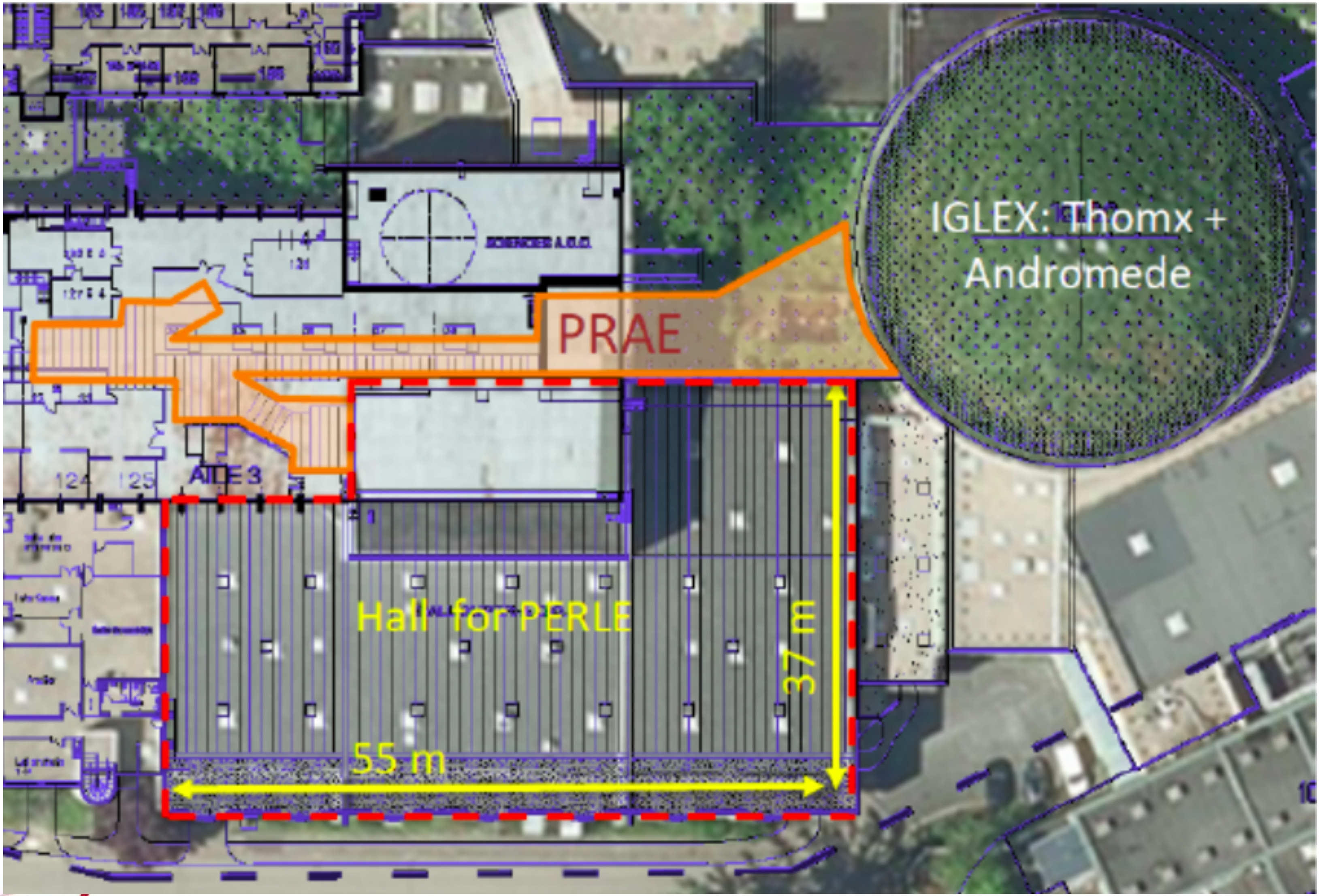
PERLE@Orsay – Layout



PERLE@Orsay – Layout



PERLE@Orsay – Site



PERLE Magnets

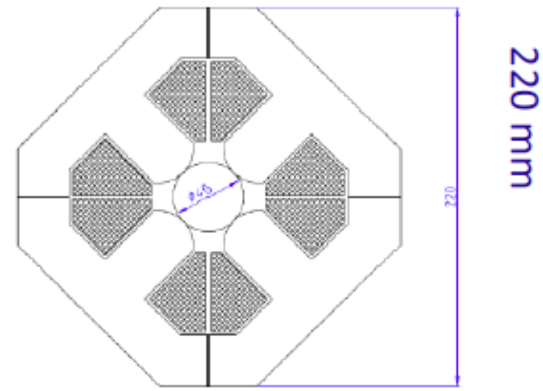
70 dipoles 0.45-1.29 T

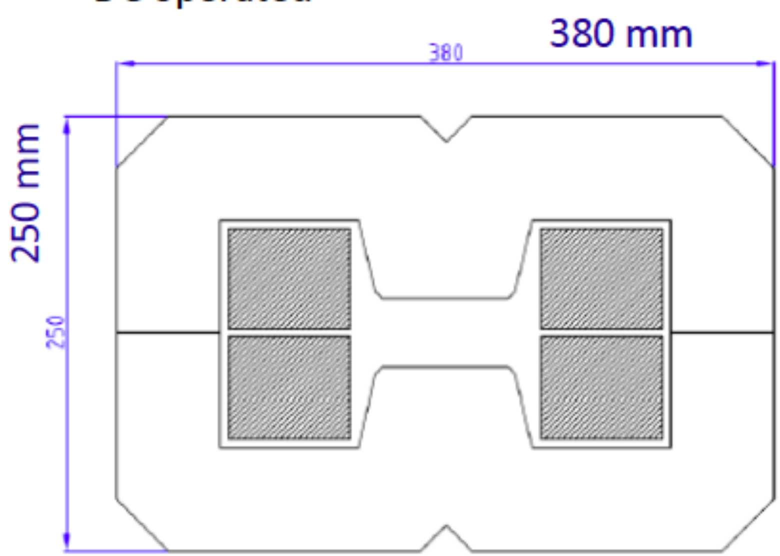
+- 20 mm aperture, l=200,300,400 mm

May be identical for hor+vert bend

7A/mm2 (in grey area) water cooled

DC operated





114 quadrupoles   max 28T/m

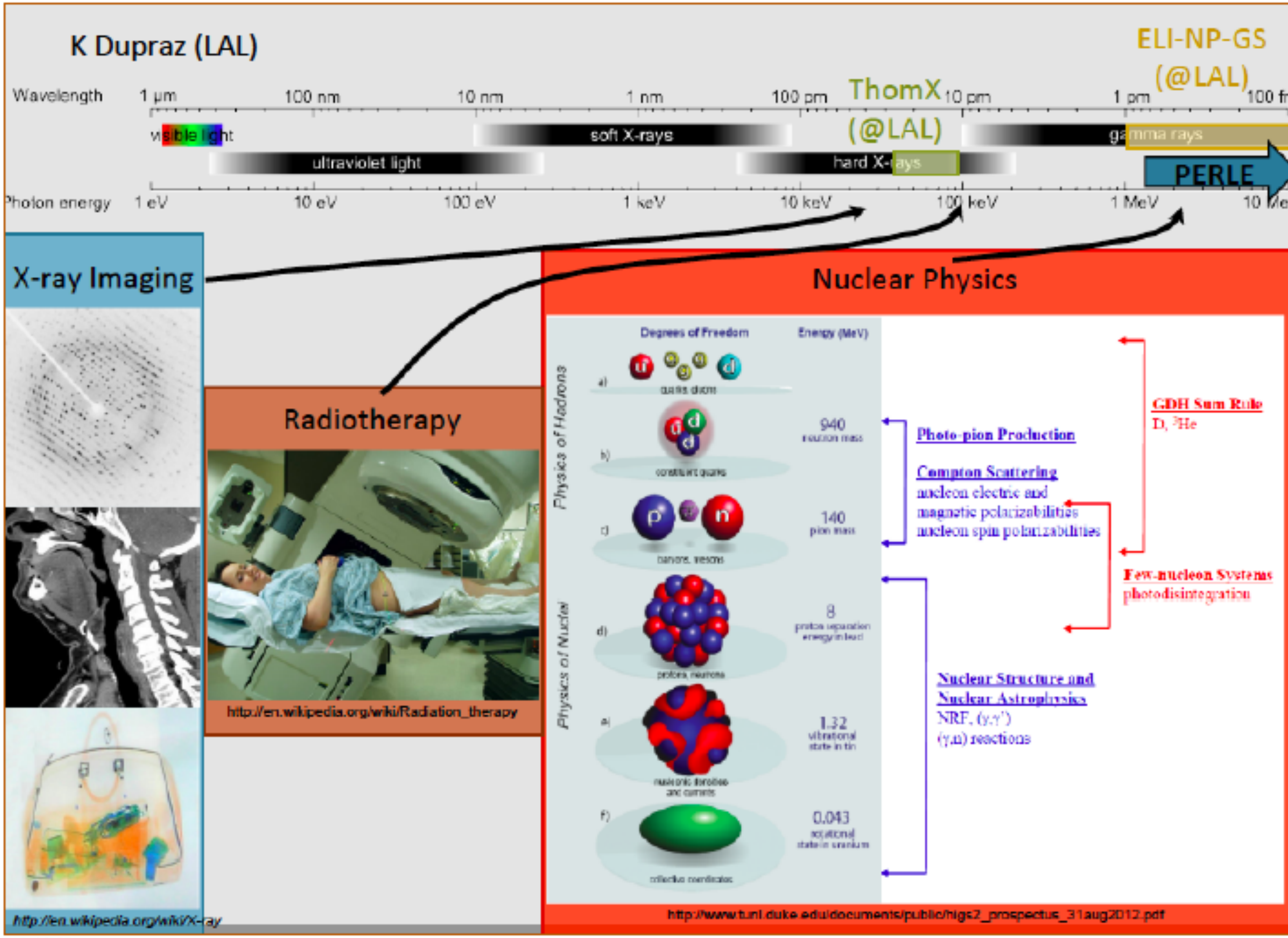
Common aperture of 40mm all arcs

Two lengths: 100 and 150mm

DC operated

P Thonet, A Milanese (CERN), C Vallerand (LAL), Y Pupkov (BINP)

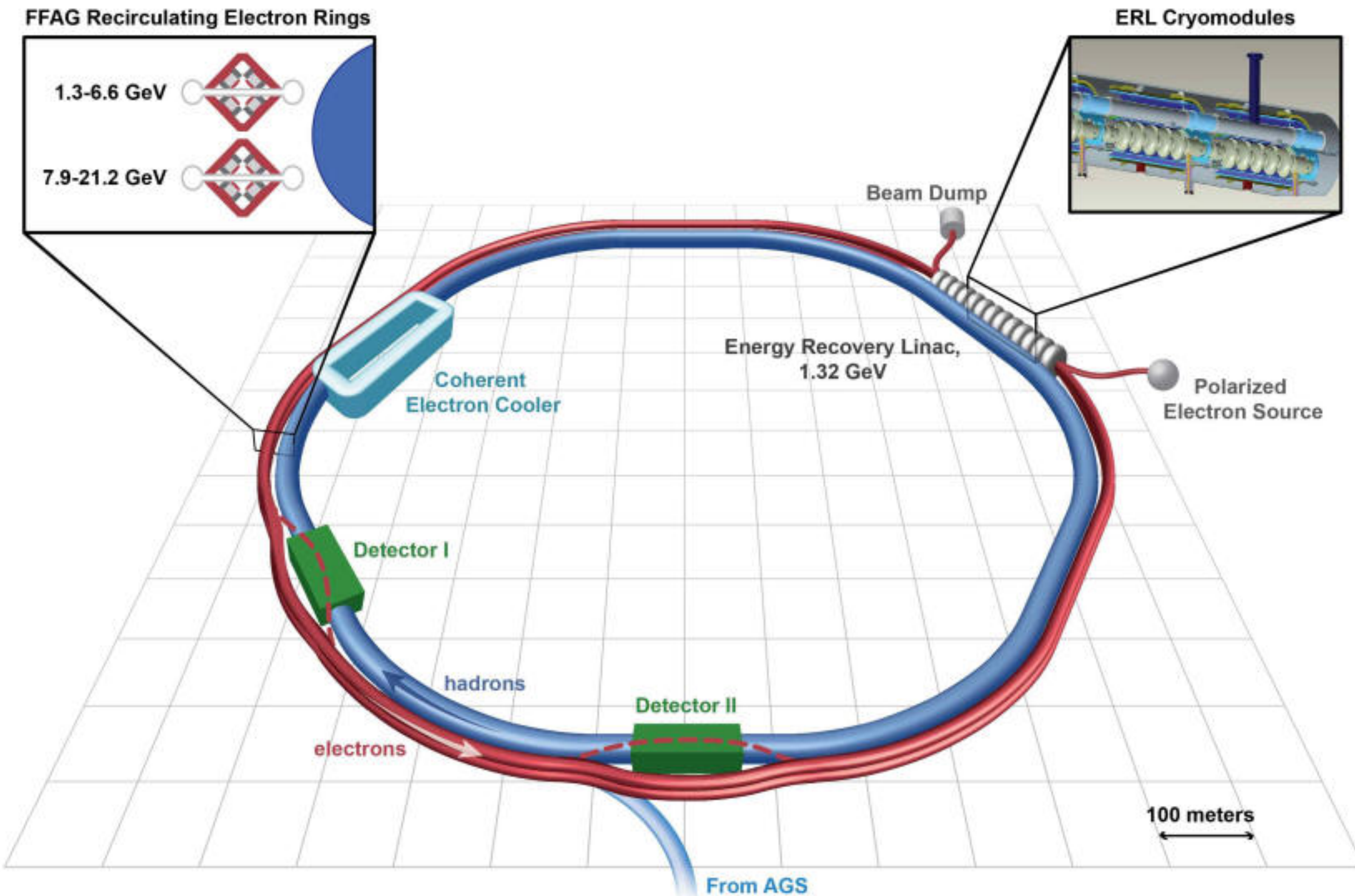
PERLE – Photon Physics (Compton scattering)



CDR: Photonuclear reactions, Nuclear Structure, Neutrino Physics, Nuclear Astrophysics

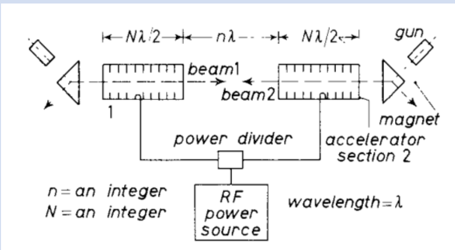
→ High energy, high intensity (100-1000 x ELI) – next generation photon physics facility

Electron Ion Collider eRHIC

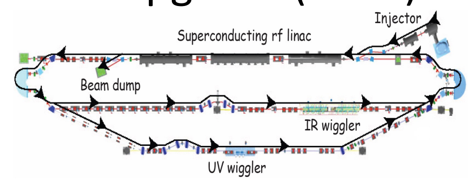


Overview of Projects and Facilities

First idea:
M. Tigner (1965)

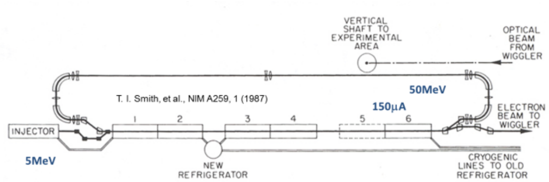


JLAB-FEL: Demo-FEL (1999)
& FEL Upgrade (2004)

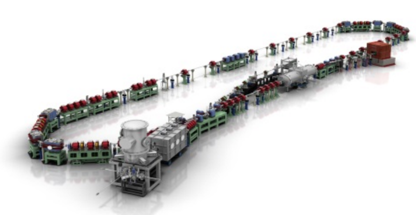


1960 1980 2000 2020

First energy recovery:
Stanford SCA/FEL (1987)

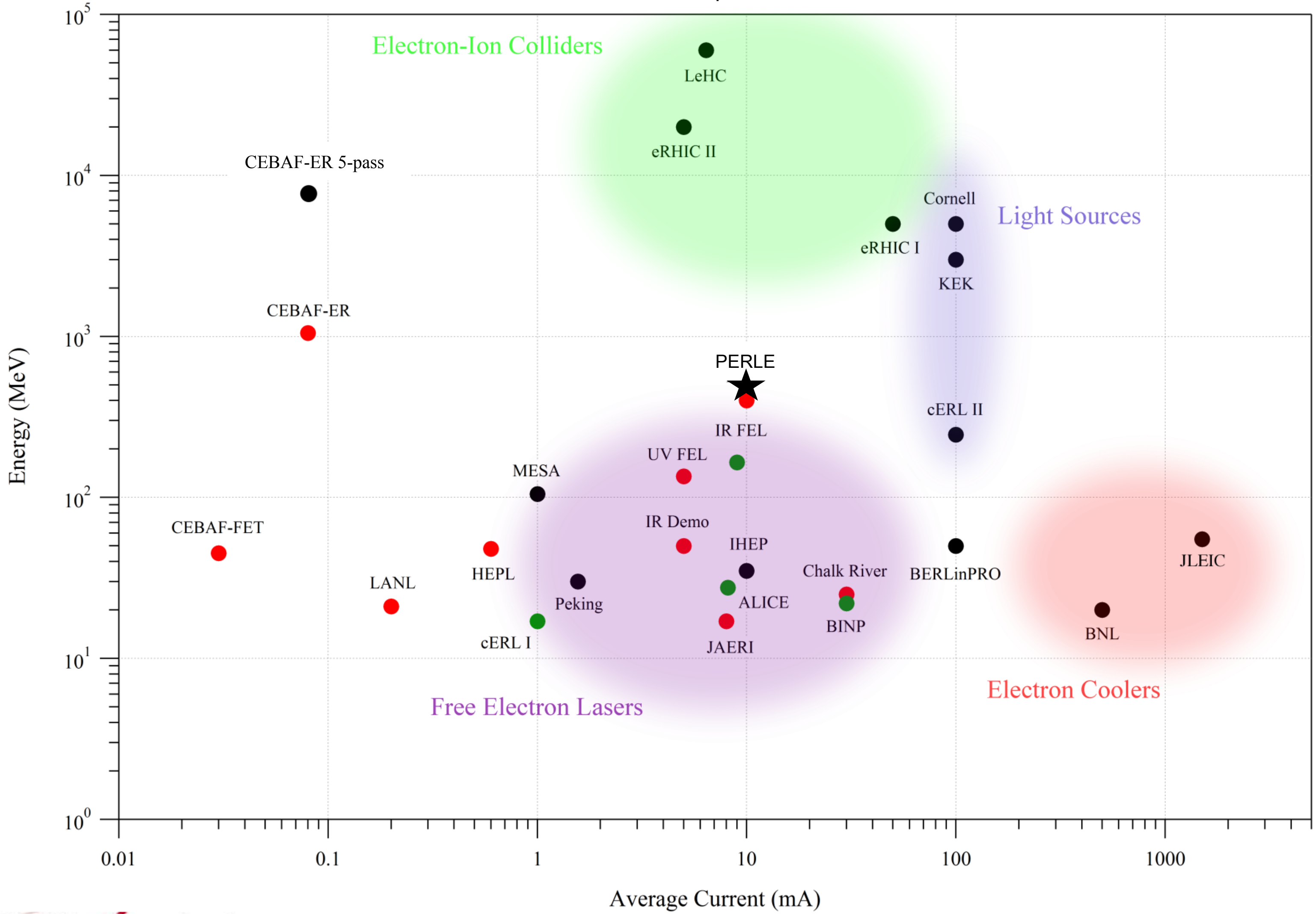


KEK cERL (2014):
recirc. & energy recovery



ERL Worldwide Landscape

red markers denote previous ERL demonstrations, green markers indicate current ERLs, and **black** markers represent future ERLs.



Summary and Outlook

- High energy (tens of GeV), high current (tens of mA) beams: (sub GW beam power) would require GW-class RF systems (klystrons) in conventional linacs.

- Invoking Energy Recovery alleviates extreme RF power demand (reduced by factor of: $1 - \eta_{ERL}$). Required RF power becomes nearly independent of beam current.

- Energy Recovering Linacs promise efficiencies of storage rings, while maintaining beam quality of linacs: superior emittance and energy spread and short bunches (sub-pico sec.)

- The next generation of high energy, high current, recirculating linear accelerators (RLAs) will rely on the energy recovery (ER) process to mitigate their extreme power demand.

- Wide range of applications: Light Sources/FELs, Colliders, Ion ‘Coolers’, Isotope production…

- Maximizing number of passes is the key to a cost effective ERL scheme.

Thank you!

Special Thanks to:

Oliver Brüning

David Douglas

Andreas Jankowiak

and

Max Klein