Energy Recovery Linacs

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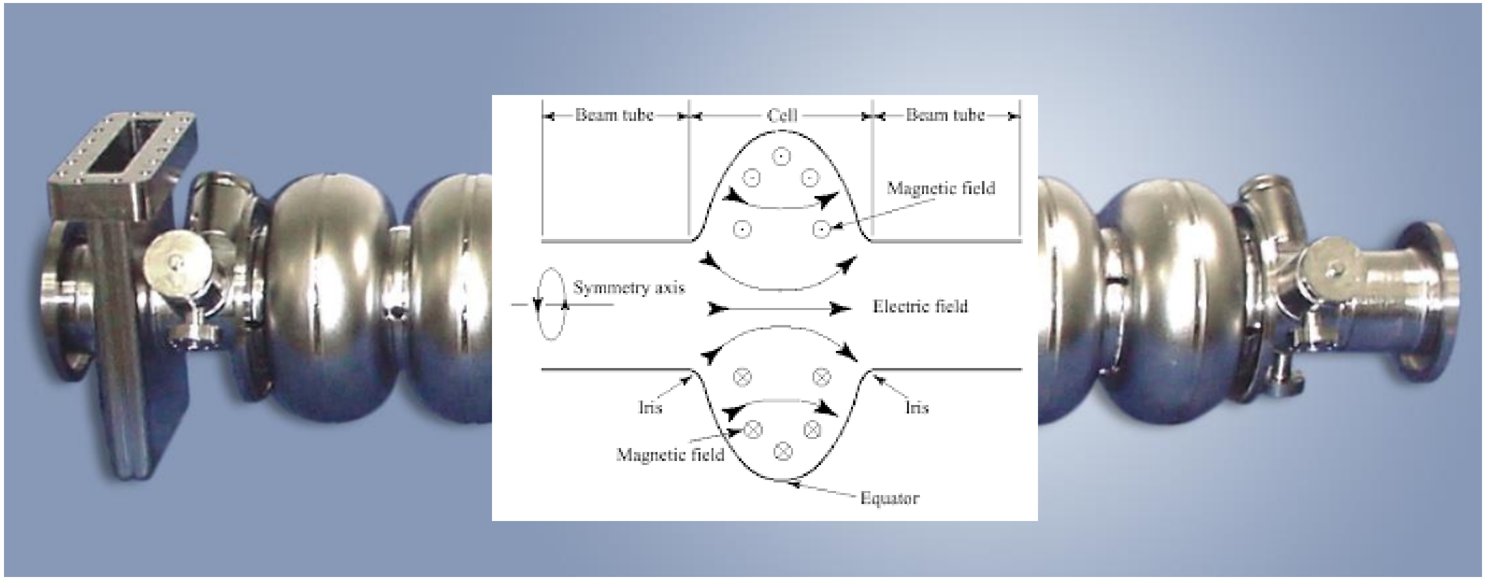
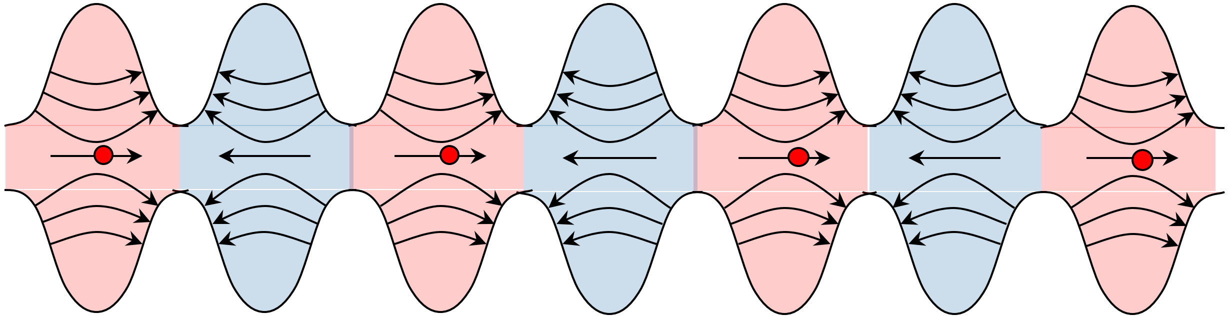
Introductions and Outline

- Principle of Energy Recovery Linacs
- Historical overview
  - First ideas and tests
  - Projects and facilities worldwide and progress on ERLs
- Applications on ERLs
  - Colliders
  - Light sources
  - Electron Cooling of Ions
- Challenges
  - ERL Demos & Roadmap
  - Transverse/Longitudinal Optics
  - Multi-pass ERL topologies
  - Beam Breakup Instability
- Summary and Outlook

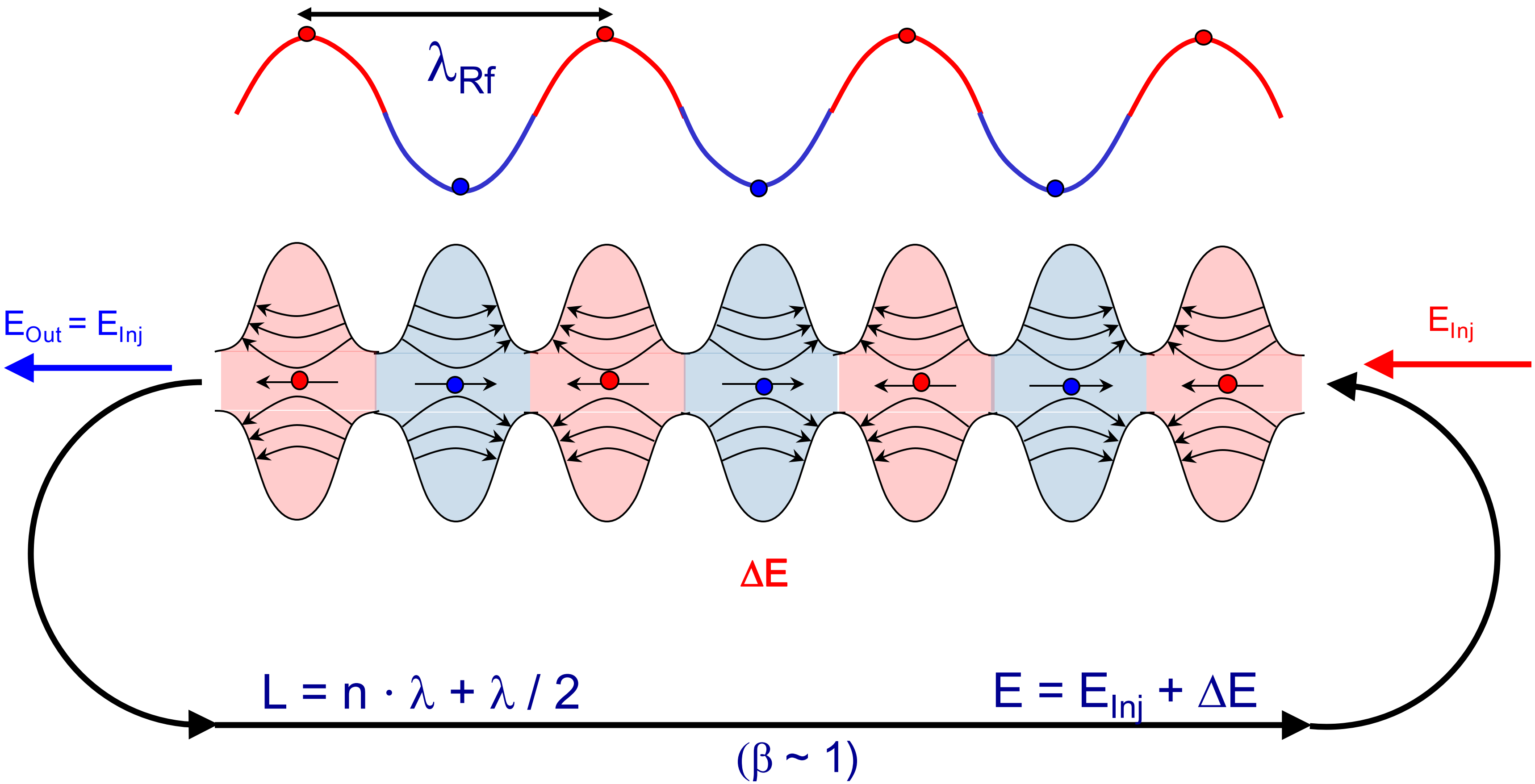
Principle of ERLs

- **Accelerating Cavity**





Principle of ERLs



Energy Flow = **Acceleration**

→ Energy Storage in the beam (loss free)

→ Energy Recovery = **Deceleration**

Principle of ERLs

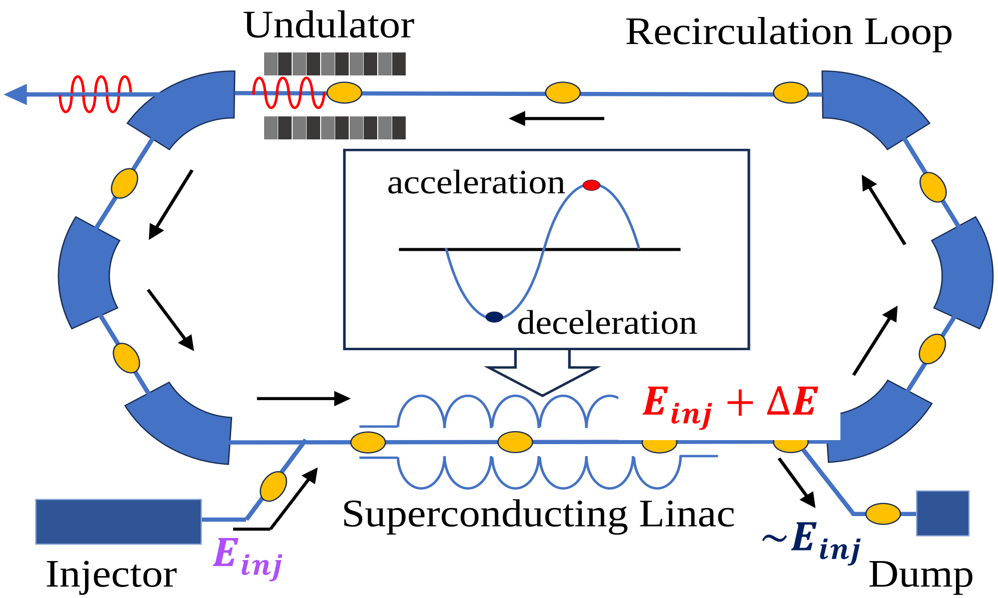
- **Mechanical Example:**

Principle of ERLs

- ERLs widen the applications of accelerators as:
- Provide (nearly) linac quality/brightness beam at (nearly) storage ring beam powers:
  - $P_{beam} >> P_{RF}$
  - beam quality *source* limited emittance: $e_{beam} < e_{ring\ equilibrium}$
- Radiation control as the beam dumps at low energy: (E_{max}/E_{inj})
  - can mitigate intractable (i.e. expensive) environmental/safety concerns
- High power beam with **reduced RF drive** $\Rightarrow$ allows us to consider higher power applications than would otherwise be unaffordable = **GW class beams**
- ERLs apply wherever one needs a beam with simultaneous **Superb Quality** (small emittance, short bunches) and **High Average Power**

Principle of ERLs

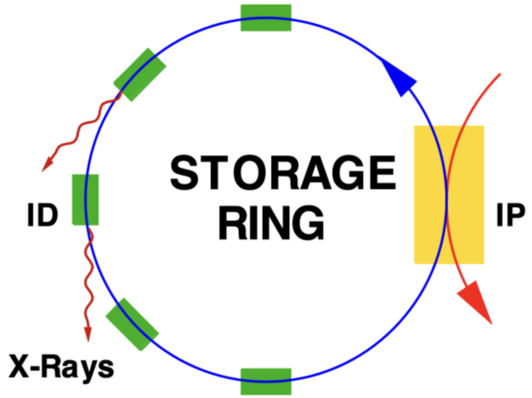
- Schematics of an ERL based light source:

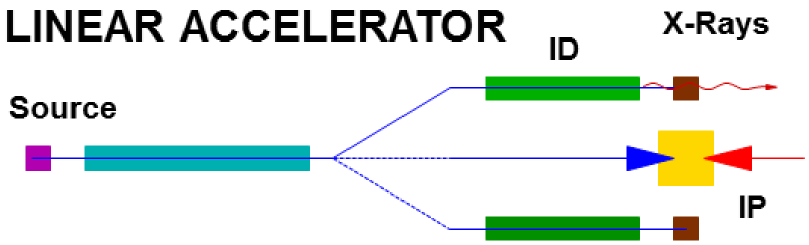


- For electrons to decelerate on second pass in the linac and deposit their energy back in to RF system:

$$\Delta L = \frac{1}{2}\lambda_{RF}$$

Storage Rings vs Linacs

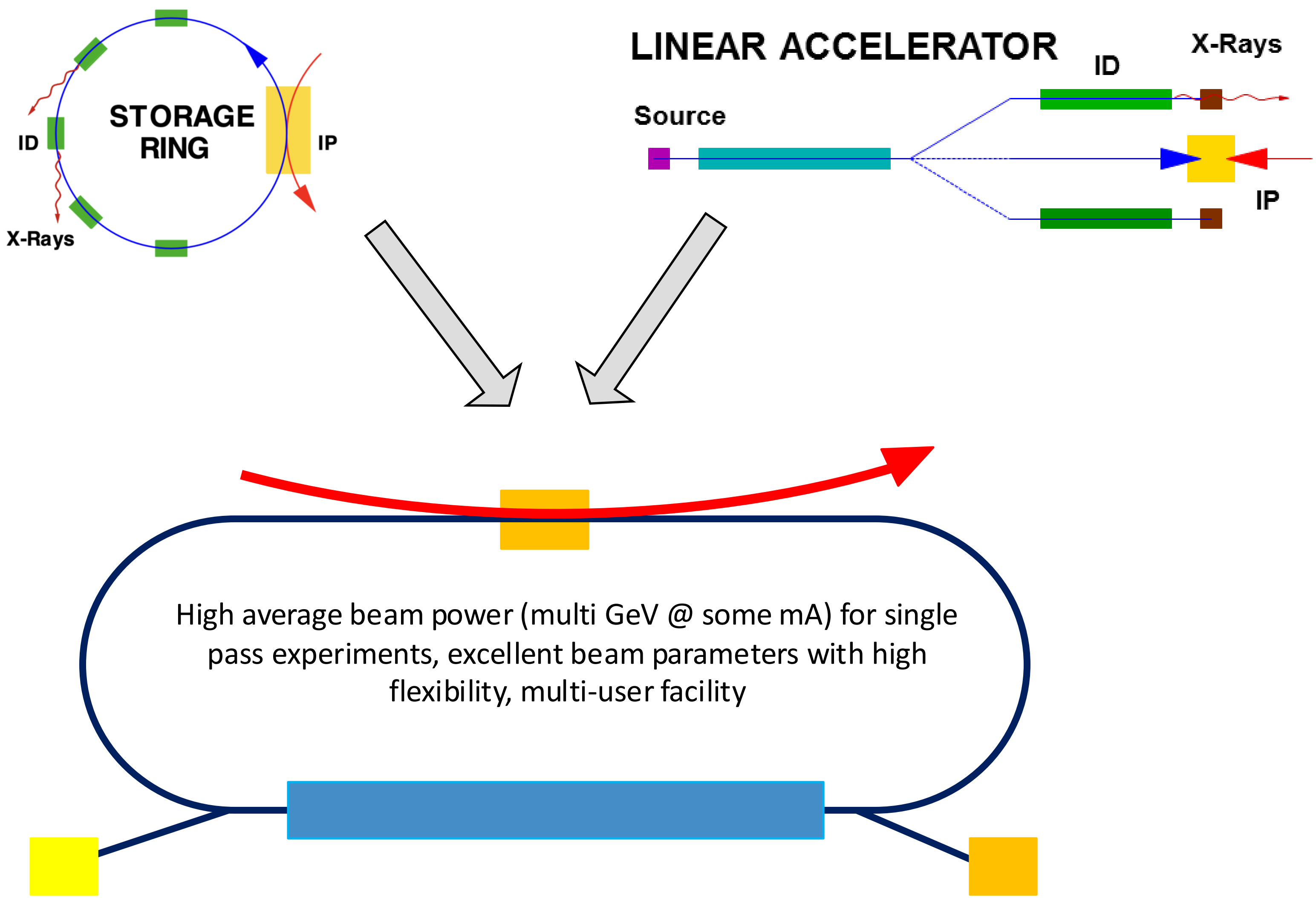




- Beam parameters determined by equilibrium
- Many user stations
- Limited flexibility due to recirculation
- High average beam current and power ('A', and multi GeV)
- Typically long bunches (20 ps – 200 ps)

- Beam parameters depends on the source
- Lower number of user stations
- Higher flexibility due to single pass
- Shorter bunches
- Limited average beam current and power (<<mA)

Storage Rings vs Linacs



Historical Overview of ERLs

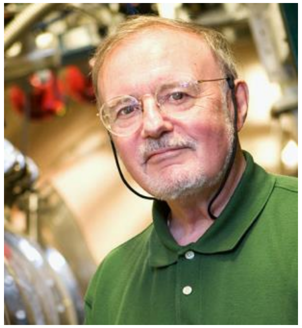
- Maury Tigner, proposed a possibility of energy recovery in 1965,as a result of developing e^+/e^- collider

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

M. TIGNER

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

(ricevuto il 2 Febbraio 1965)



Maury Tigner

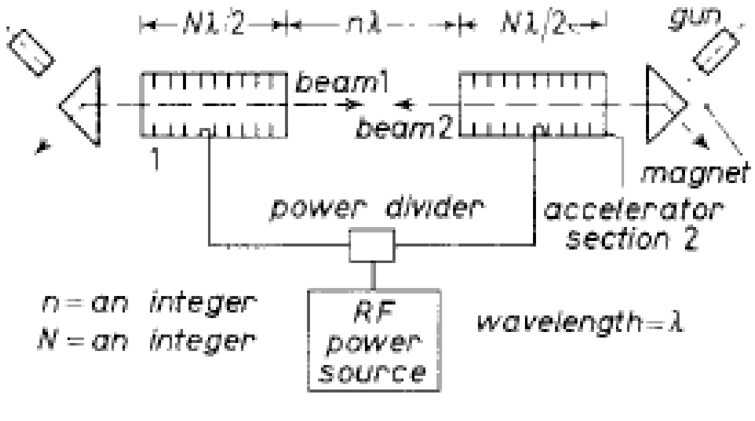


Fig. 2.

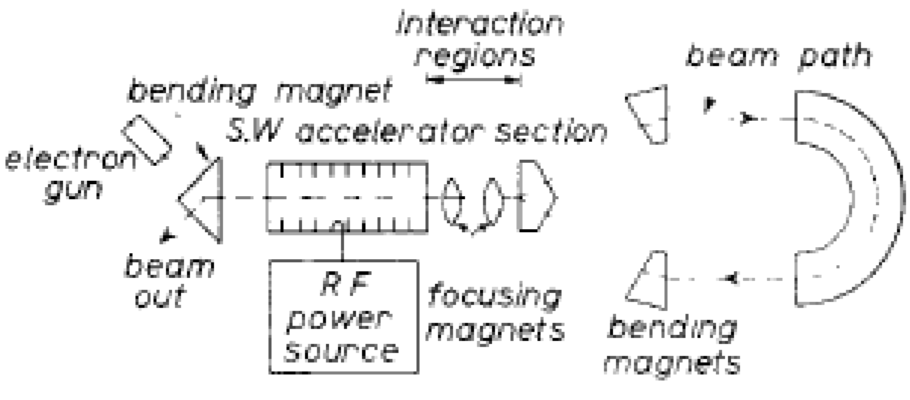


Fig. 3.

- First Test: The Chalk River Nuclear Laboratory: Two-pass reflexotron

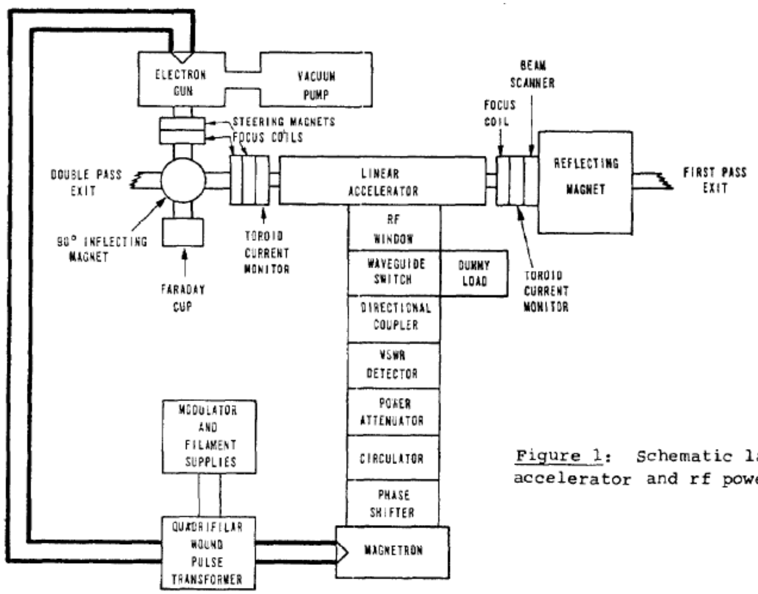


Figure 1: Schematic layout of accelerator and rf power syste

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

180° REFLECTING MAGNET

ACCELERATING STRUCTURE

NET 90° TARGET MAGNET

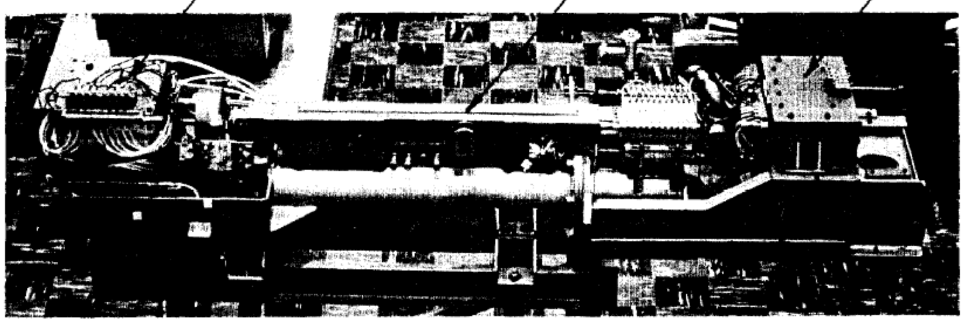
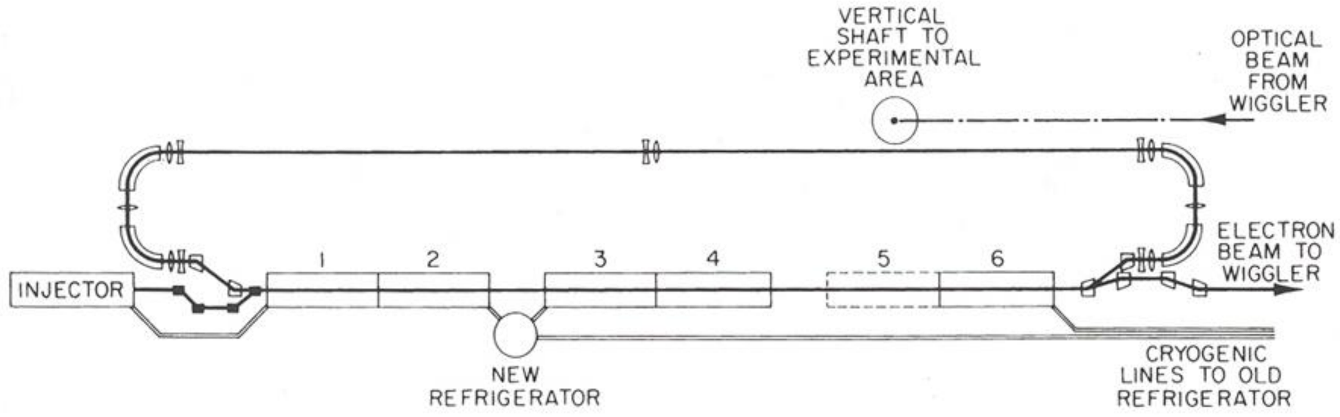


Figure 1. The 25 MeV electron accelerator attached to its strongback.

Historical Overview of ERLs

First Demonstration:

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

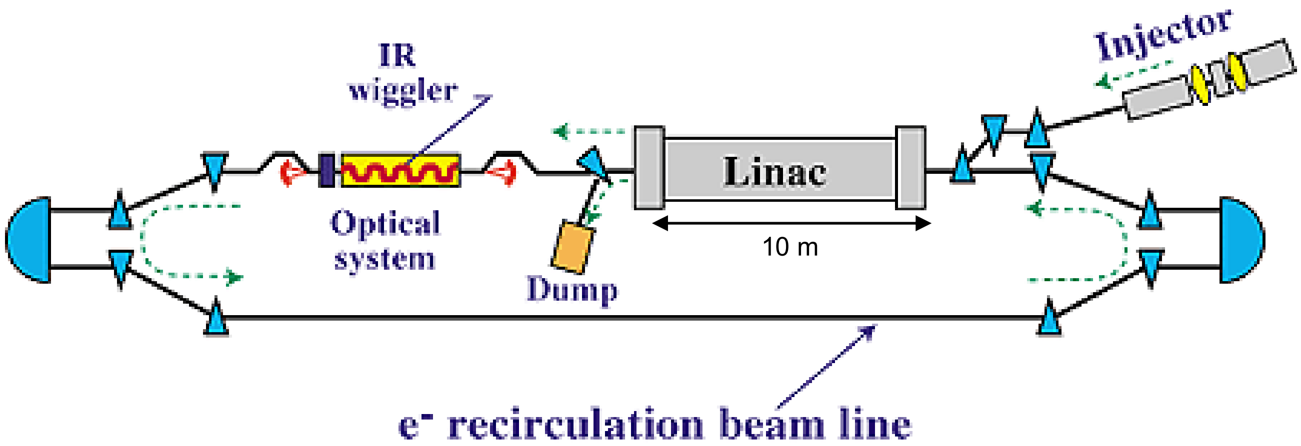


- first demonstrated at SCA/FEL in 1986, with 5 MeV injected beam into a ~50 MeV linac

- Recirculation loop with path-length varying capability to demonstrate acceleration/deceleration of e^- in the second pass

Same cell Energy Recovery

Jefferson Lab FEL:



Neil, G. R., et. al, Physical Review Letters, 84, 622 (2000)

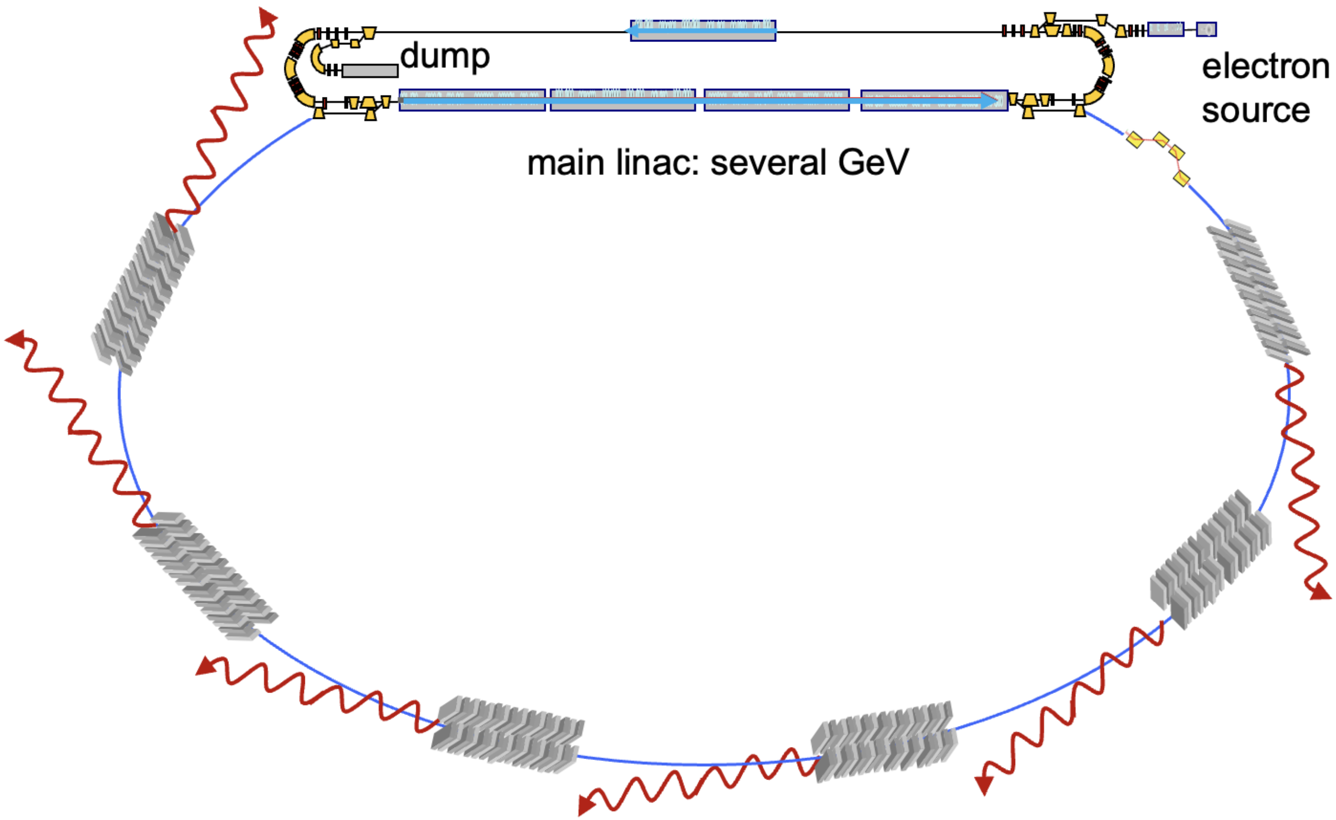
- IR demo: 5 mA, 41 MeV, exceeded the beam power x 10

- UV upgrade: 9 mA, 150 MeV, 10 kW: highest current that has been recirculated in an SRF ERL
  - kept same ERL efficiency
  - only about 300 kW of installed RF, thus demonstrating the most basic reason for building an ERL.

Applications of ERLs

ERL as a Next Generation Light Source:

- combines the features in linacs and storage rings



Applications of ERLs

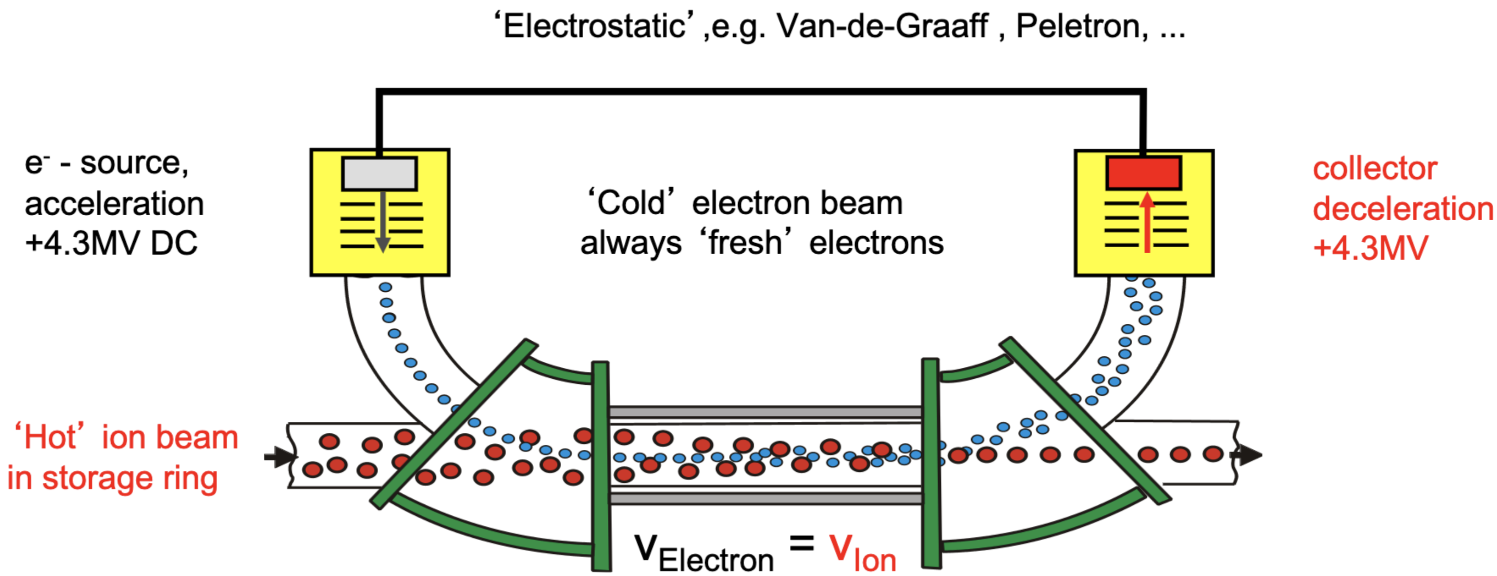
Advantages of **ERL based light sources**:

- Possibility of high operating beam power: 100mA @ many GeV possible
- Always "fresh" electrons (dumps energy recovered beam)
  - small emittance (~ 0.1 mm-rad norm. = 10 pm-rad at 6GeV)
  - high brilliance (x 100 – 1000 compared to storage rings)
  - short pulses (ps down to 10 – 100 fs)
- Not limited by Touschek intrateam scattering
- 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

Applications of ERLs

Electron Cooler for Ion Beams:

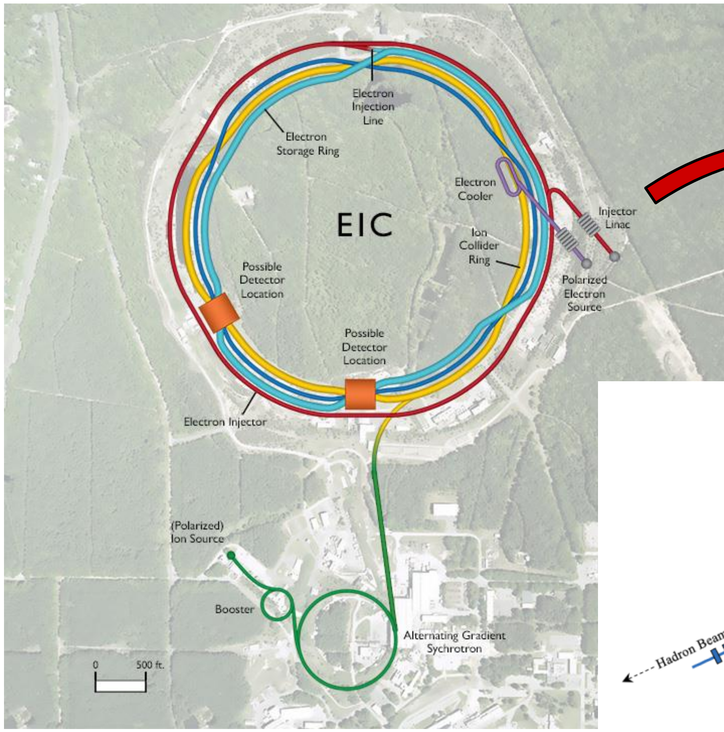


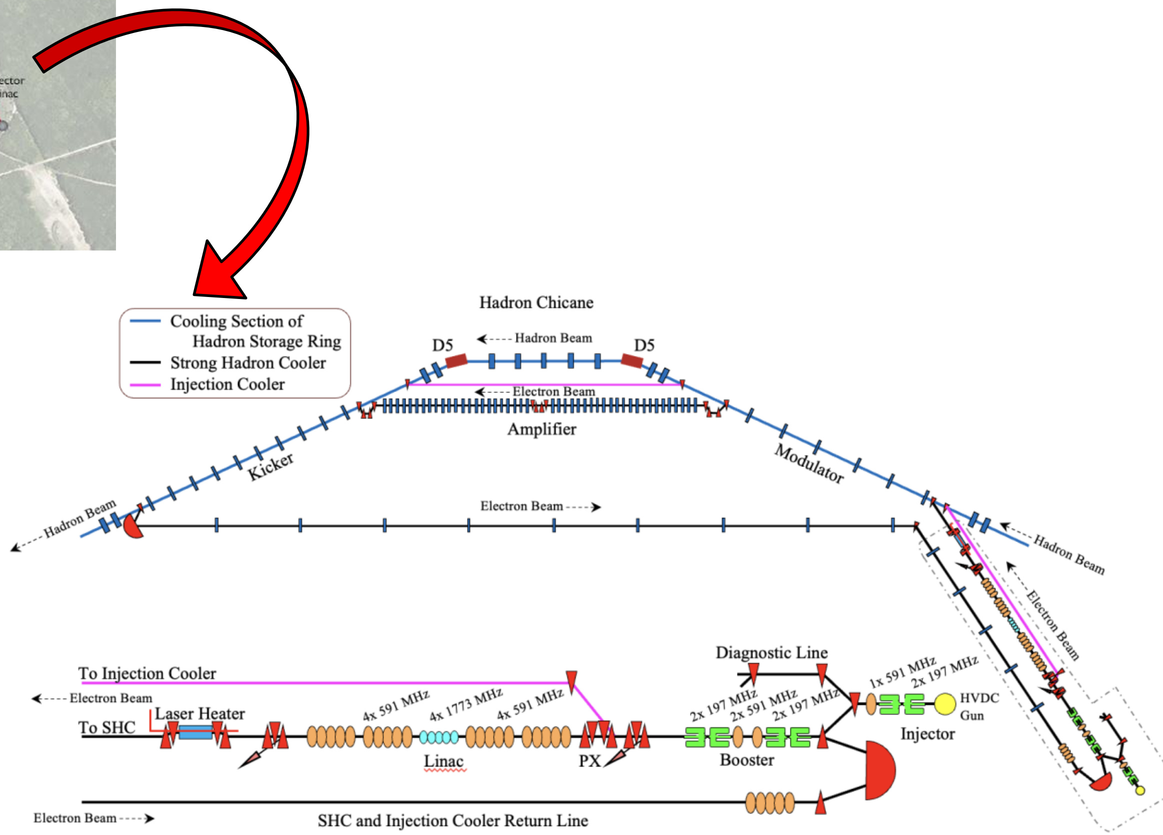
e.g. FermiLab recycler ring (Tevatron)

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

Applications of ERLs

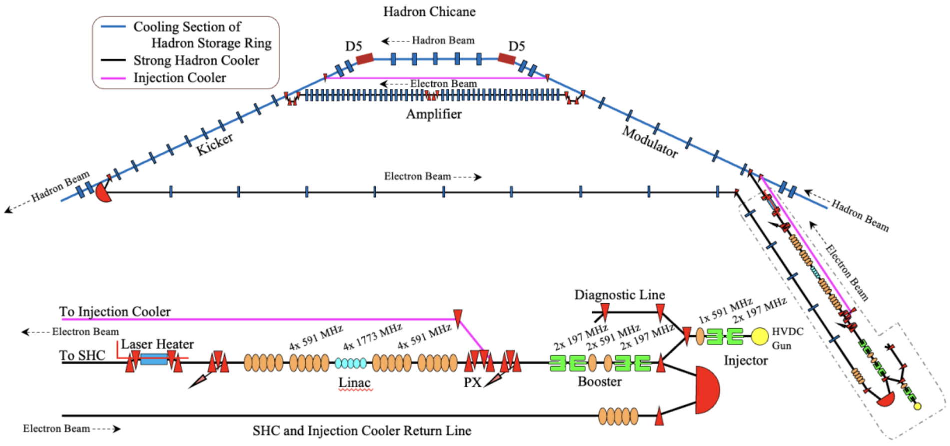
Electron Cooler for Ion Beams: Strong Hadron Cooler for EIC





Applications of ERLs

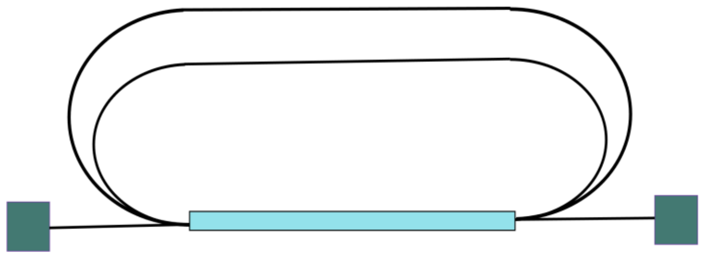
Electron Cooler for Ion Beams: Strong Hadron Cooler for EIC



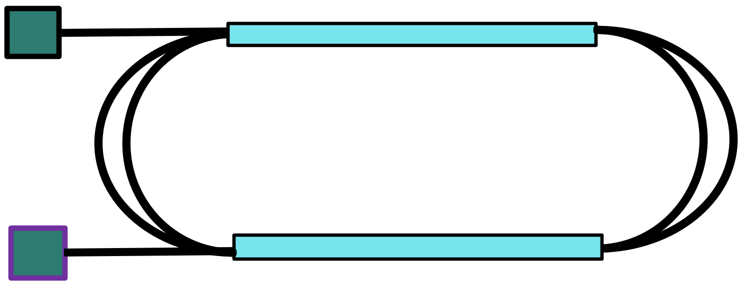
- 100 mA beam current with 1 nC bunch charge → High current
- Top energies:
  - **Mode A**: 150 MeV
    - To cool 275 GeV hadron beam
  - **Mode B**: 55 MeV
    - To cool 100 GeV hadron beam
- RMS bunch lengths 9 mm & 7 mm
- Normalized emittance 2.8 mm-mrad

ERL Configurations

Two main ERL Configurations:



Recirculating linac with a single linac



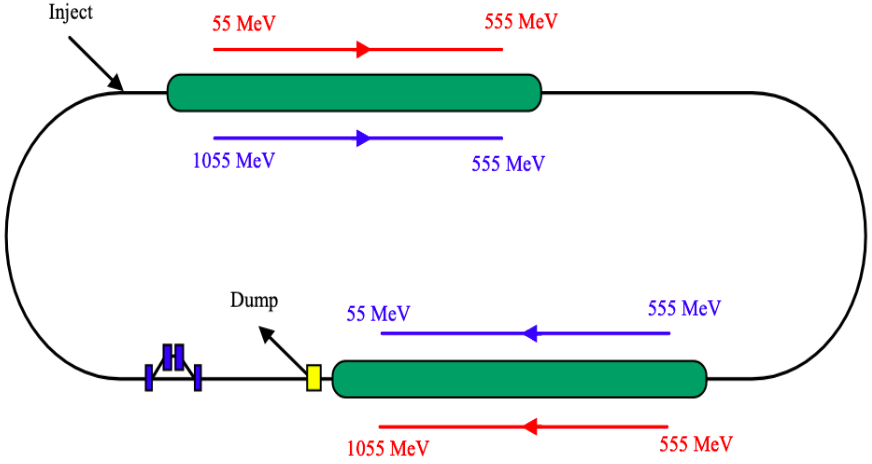
Recirculating linac with two linacs (Race track)

- Accelerate beams into higher energy with "N" recirculation, energy recovery is feasible in the "N" passes
- Multiple linac passes increase the maximum beam energy
- Return arc share accelerating and decelerating beams, with nearly the same energy
- Required phase-shift/path-length change is achieved by a chicane or adjusting arc path length

ERL Demonstrations

CEBAF-ER: 1up-1down ERL demo

- A successful energy recovery demonstration on CEBAF accelerator at Jefferson Lab in 2003
- 1-acceleration pass, 1-energy recovery pass, with maximum energy reach of 1055 MeV
- 55 MeV electron beam was injected into North and south Linacs, phase delay chicane provided 0.5 λ_{RF}, path length and decelerated in the next pass.
- Dumped energy recovered beam at ~ 55 MeV at the beam dump



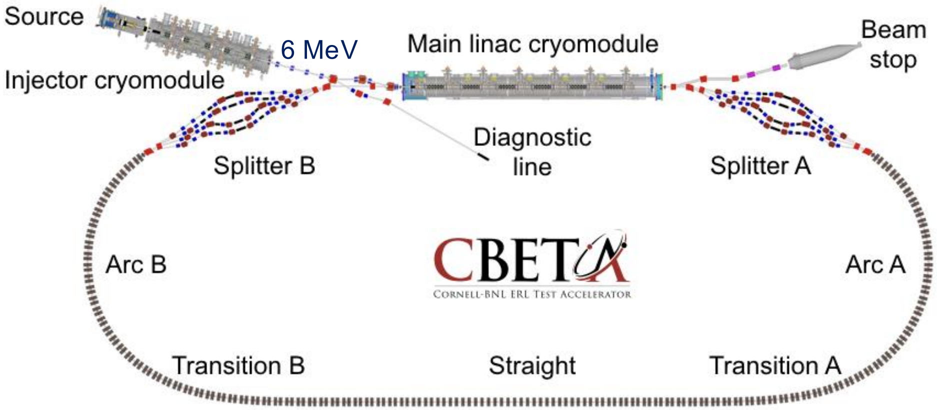
REF: C. Tennant et. al., CEBAF-ER: EXTENDING THE FRONTIER OF ENERGY RECOVERY AT JEFFERSON LAB, 2003

ERL Demonstrations

Cbeta: Cornell-BNL ERL Test Accelerator

Successfully demonstrated multi-turn energy recovery in SRF cavities.

- Multiple energy beam transportation in arcs relies on FFAG (Fixed Field Alternating Gradient) Magnets
- Used DC photoinjector@ 300 kV; 4-accelerating & 4- decelerating passes
- Highest beam energy is 150 MeV (42, 78, 114, 150 MeV)
- MLC is custom designed for ERL applications
- **Same cavity energy recovery**

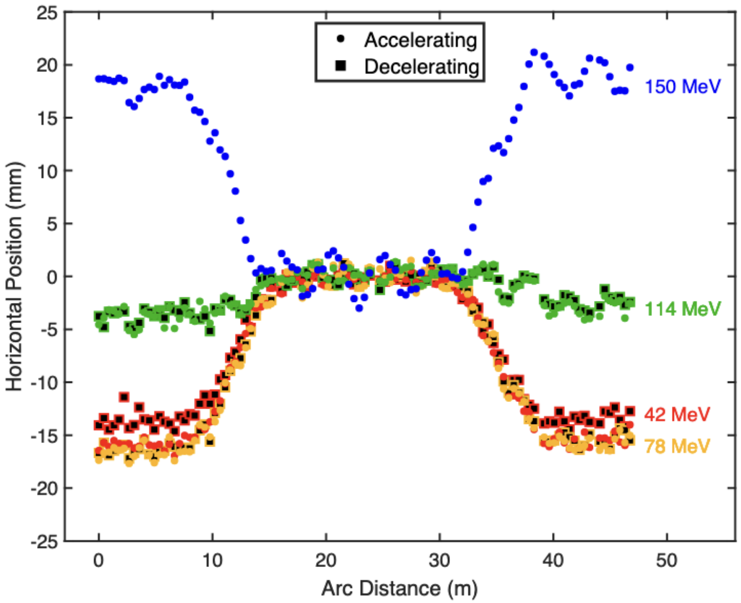


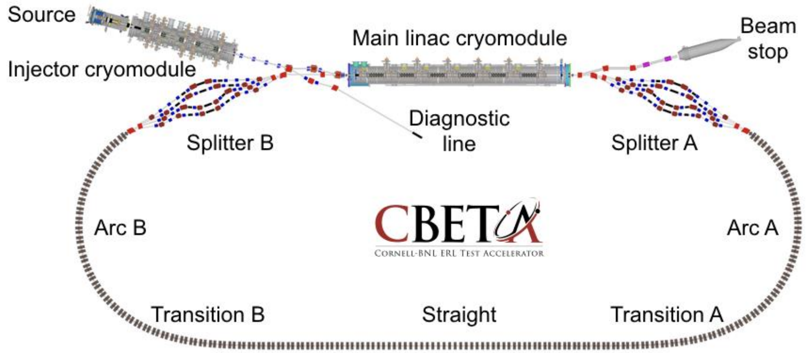
ERL Demonstrations

Cbeta: Cornell-BNL ERL Test Accelerator

- Measured orbits within FFAG arcs

- More details: Cebeta Article

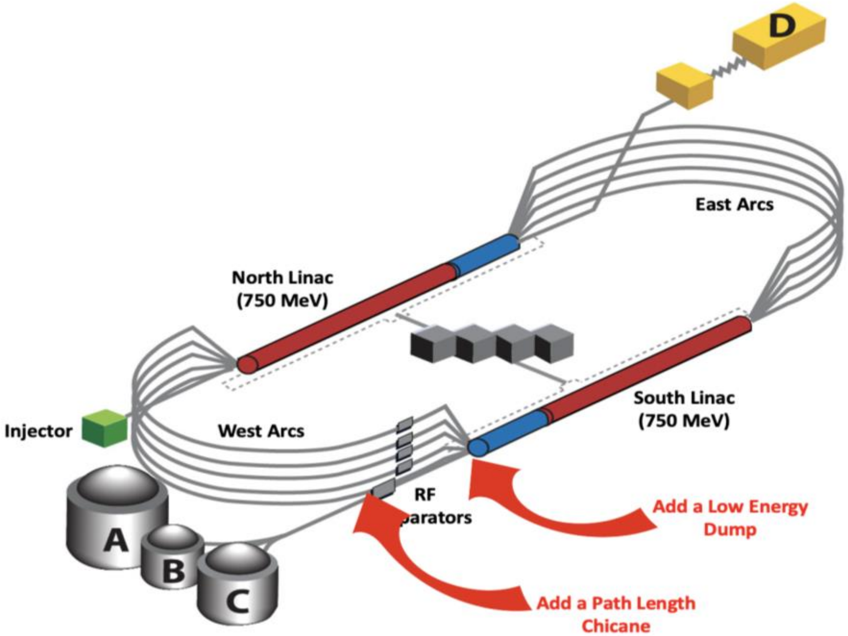




ERL Demonstrations

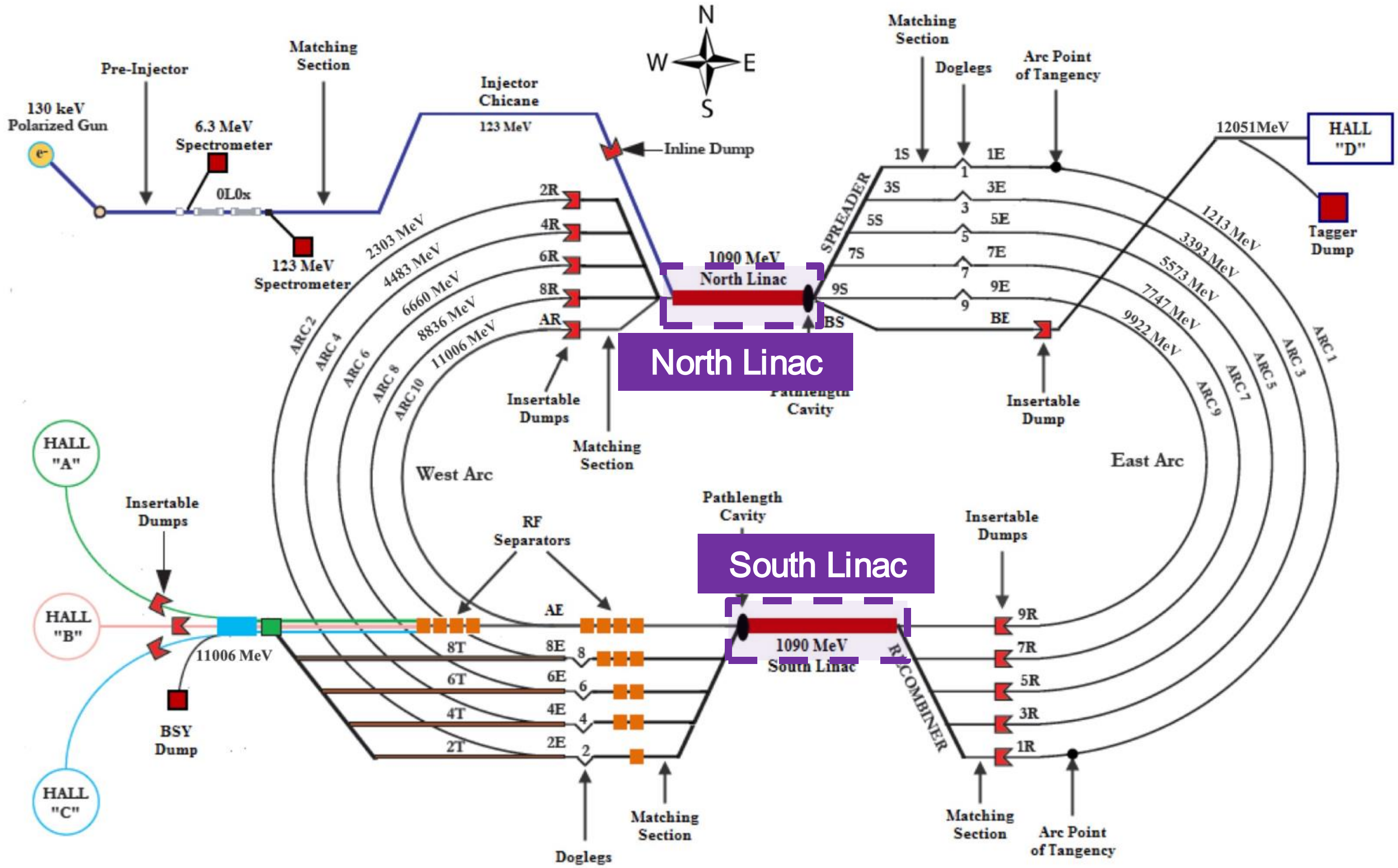
ER@CEBAF: 5-pass, multi GeV ERL demo at CEBAF

- ER@CEBAF was a proposal on demonstrating energy recovery at CEBAF with 5-accelerating and 5-decelerating passes
- 700-750 MeV energy gain per linac, to minimize Incoherent Synchrotron Radiation (ISR) losses & increase arc momentum acceptance
- Two new segments required:
  - Path length chicane
  - Low energy beam dump



REF: S. A. Bogacz et. al, ., ER@CEBAF: A test of 5-pass energy recovery at CEBAF, 2016

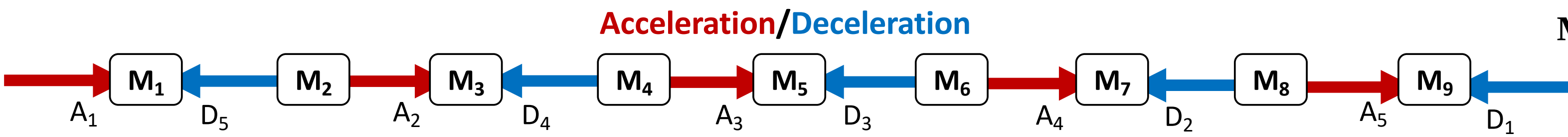
ER@CEBAF: Multipass, multi GeV range ERL



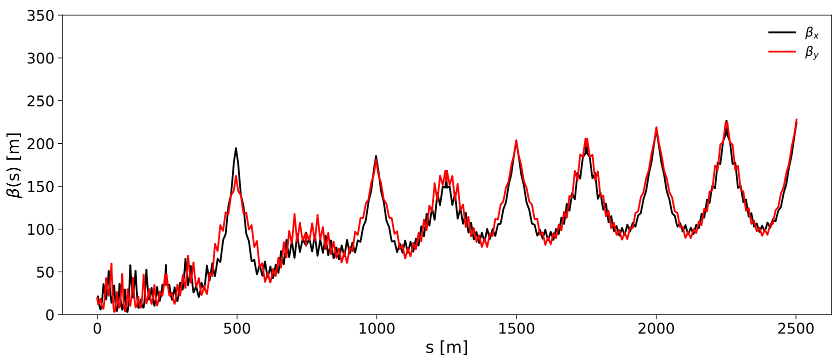
ER@CEBAF: Multipass, multi GeV range ERL

Beam recirculation within arcs require mirror-symmetric optics for two linacs

- Linac optics optimization used MOGA approach



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



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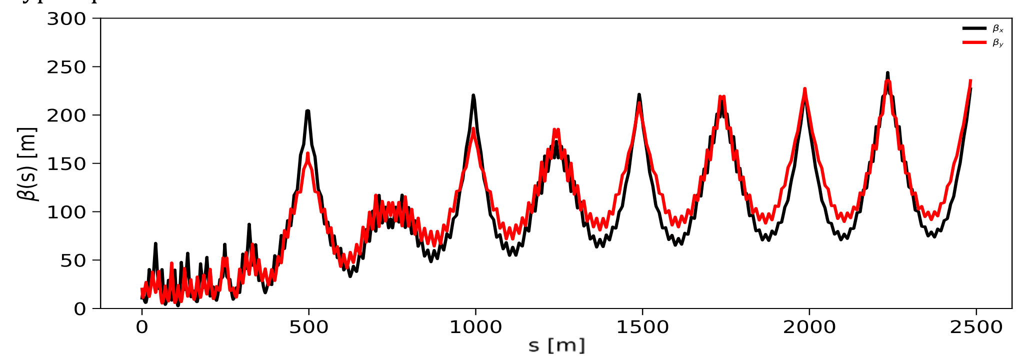
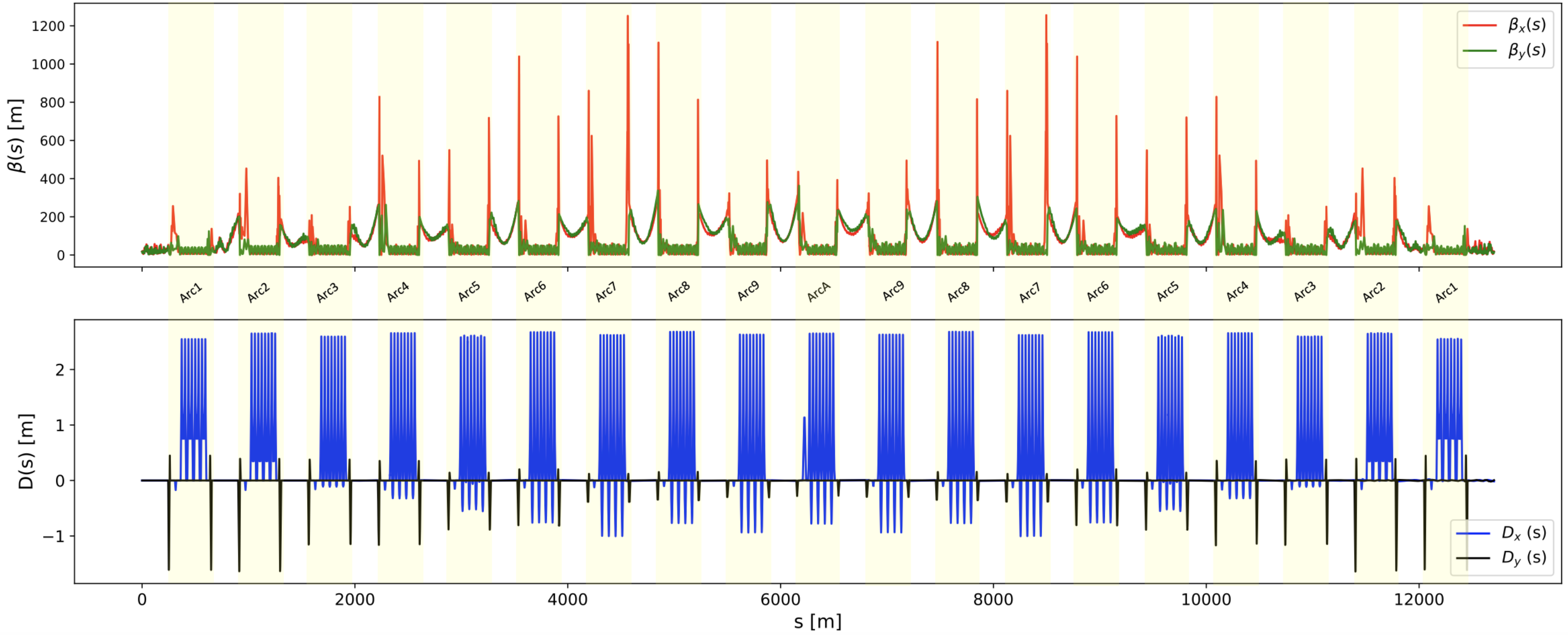


- **Quadrupole Gradient:**

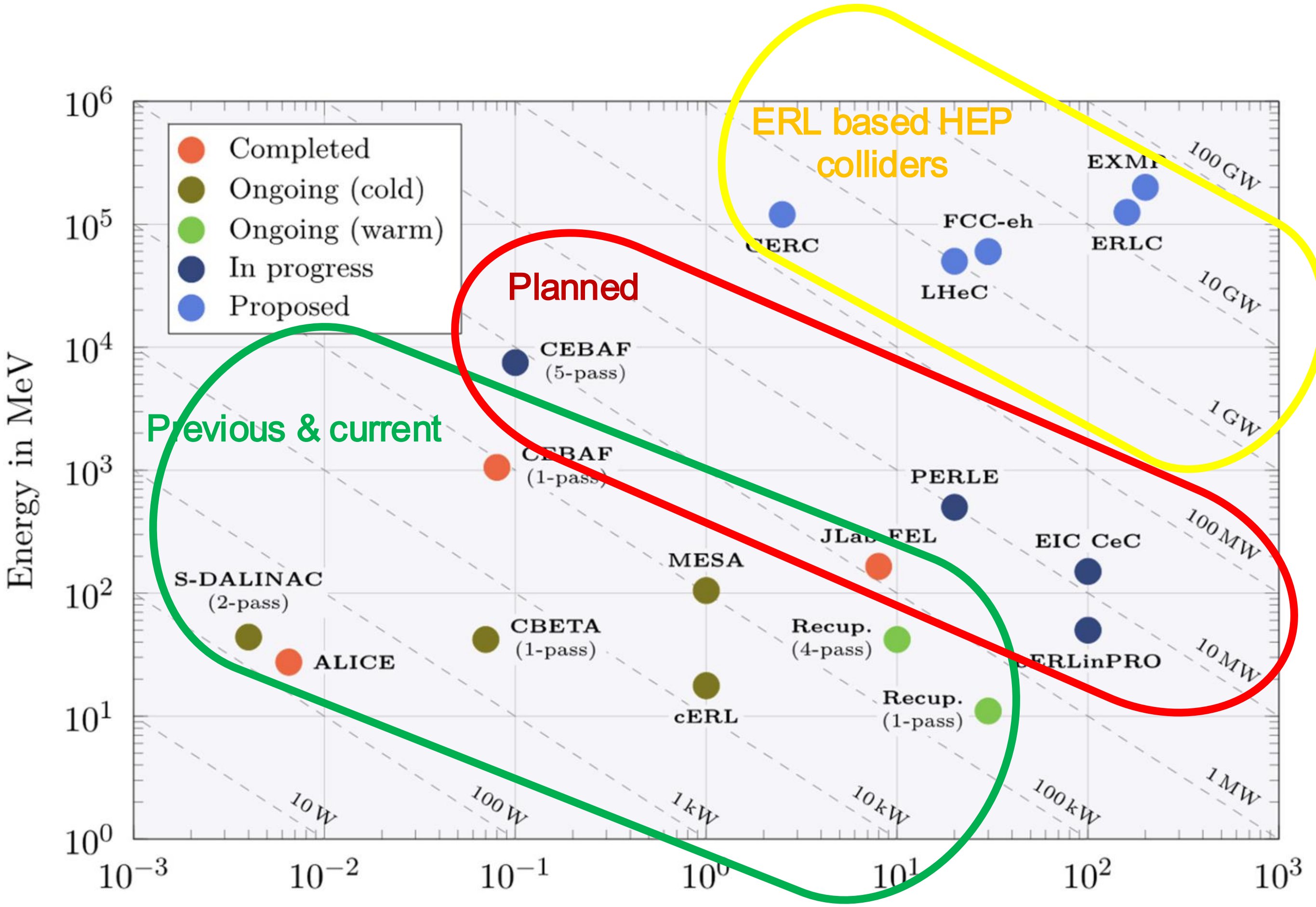
$$G = \frac{dB}{dL} = \frac{k_1 pc}{e} \propto p$$

ER@CEBAF: Multipass, multi GeV range ERL

- The 10 pass ER@CEBAF beamline was created combining all the linac and arc lattice segments. $\beta(s)$ and $D(s)$ are plotted



ERL Roadmap



ERL based HEP colliders
Planned
Previous & current
Completed
Ongoing (cold)
Ongoing (warm)
In progress
Proposed
Energy in MeV
Average current in mA
CEBAF (5-pass)
CEBAF (1-pass)
S-DALINAC (2-pass)
ALICE
CBETA (1-pass)
MESA
cERL
JLab FEL
Recup. (4-pass)
Recup. (1-pass)
PERLE
EIC CeC
ERLinPRO
LHeC
FCC-eh
ERLC
EXMP
CERC
10 W
100 W
1 kW
10 kW
100 kW
1 MW
10 MW
100 MW
1 GW
10 GW
100 GW

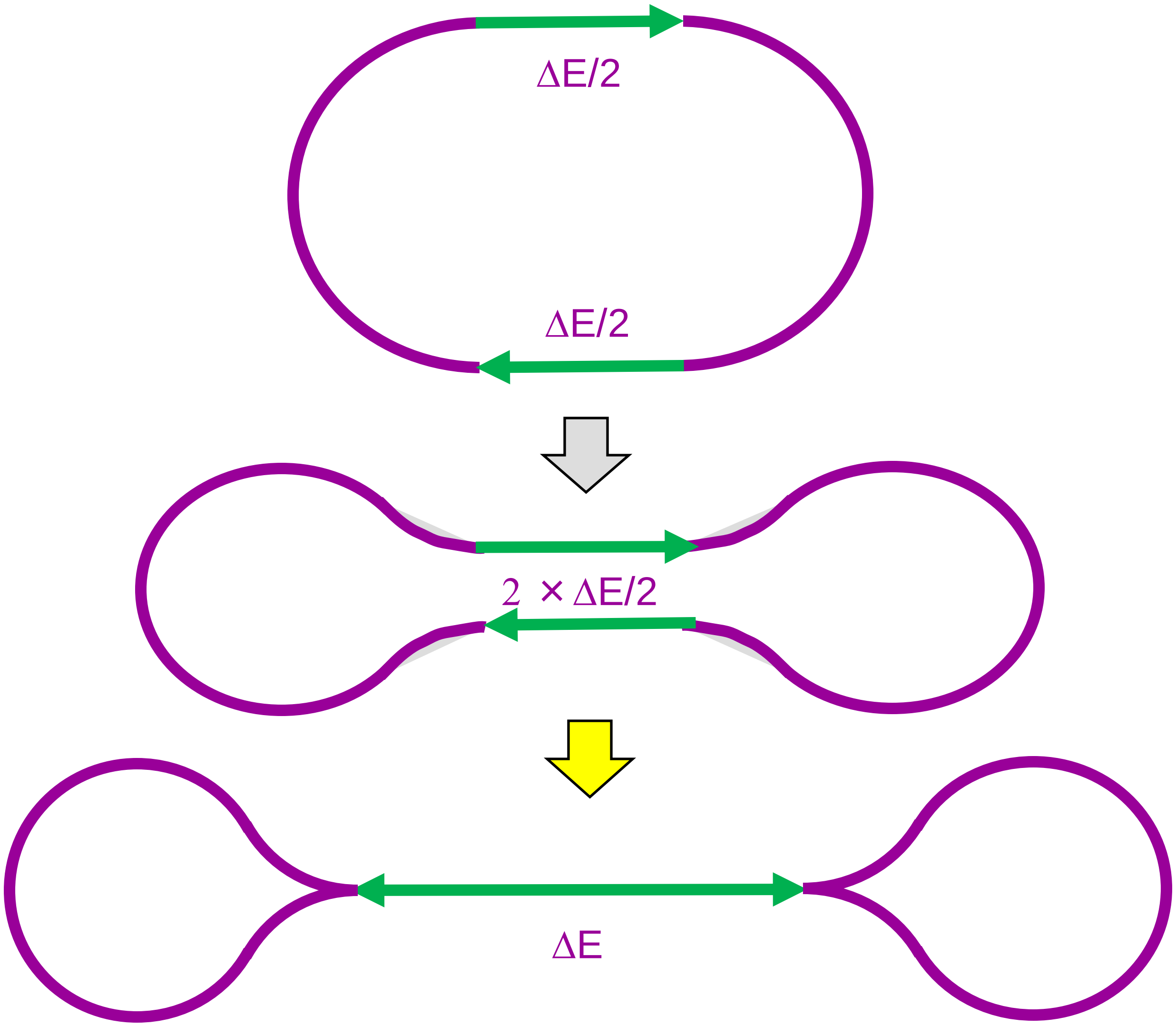
Key Challenges in ERLs

- High Brightness Electron injectors:
  - As in linacs, electron source determines the important beam parameters (bunch charge, emittances, temporal structure)
  - Uses DC thermionic guns to state-of-art SRF photocathode guns
  - Buncher and booster: Chop the continuous beam and to compress the bunch to the desired length
  - Merger: transports the high current bunch exiting the injector to the recirculation line
- SRF cryomodules:
  - Field emission, multipacting. HOM damping
- Beam control and diagnostics:
  - Several R&D work is going on as new challenges arise different ERL designs

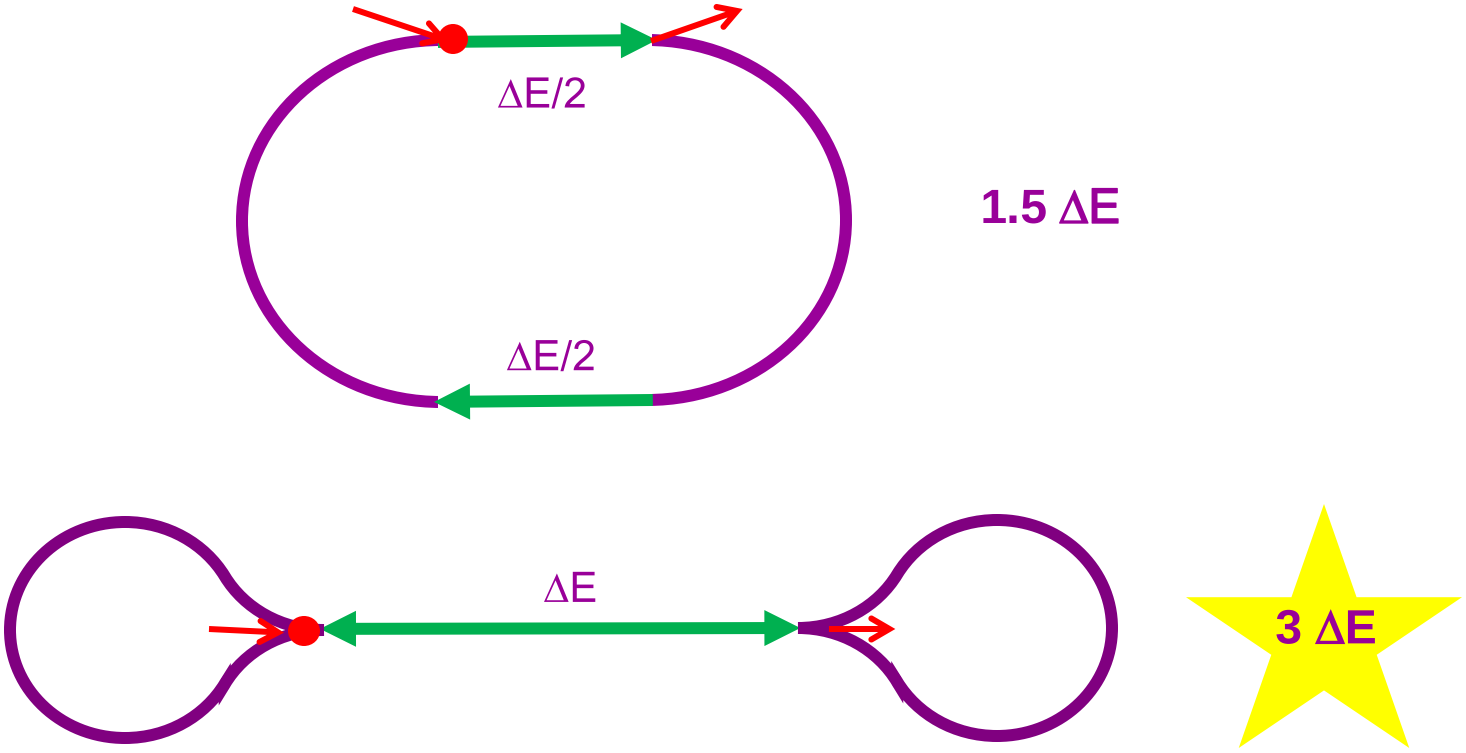
RLA Topologies

'Racetrack'

'Dogbone'

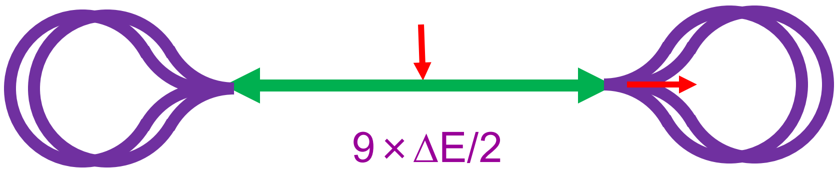


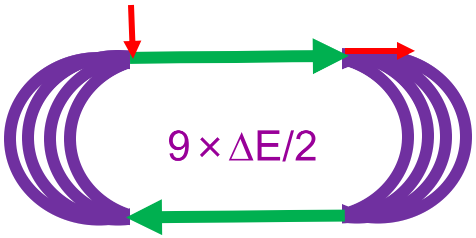
’Racetrack’ vs ‘Dogbone’ RLA Topologies

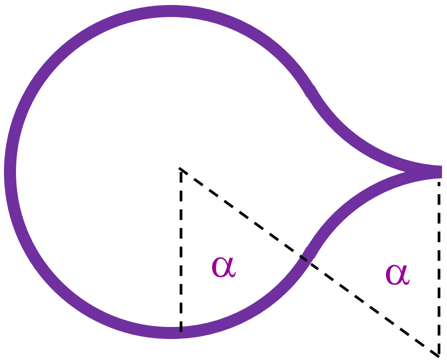


Twice the acceleration efficiency – traversing the linac in both directions while accelerating

‘Dogbone’ vs ‘Racetrack’ RLA- Arc length





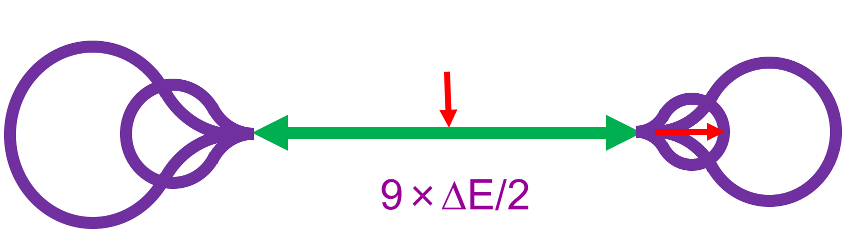


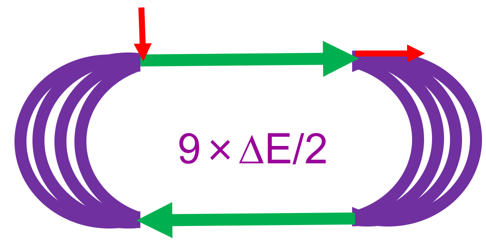
$= \quad n(\pi + 4\alpha)R$

$= \quad 2n\pi R$

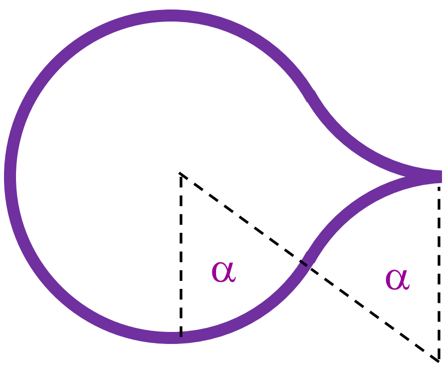
Net arc-length break even: if $\alpha = \pi/4$

‘Dogbone’ vs ‘Racetrack’ RLA- Arc length



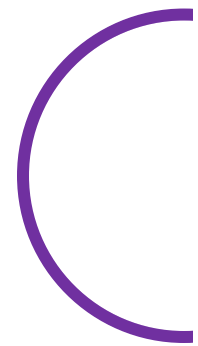


$n \times$



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

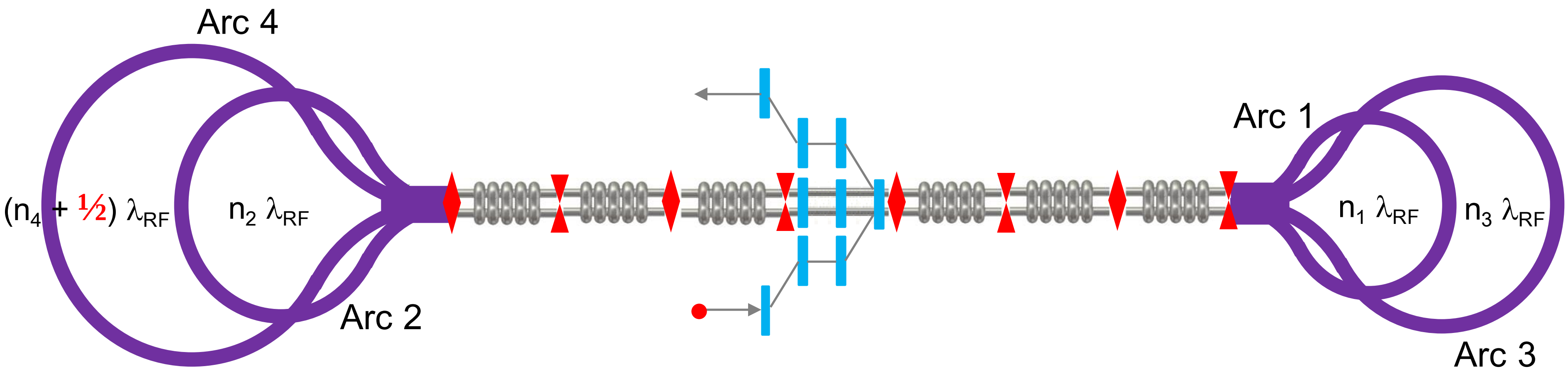
$2n \times$

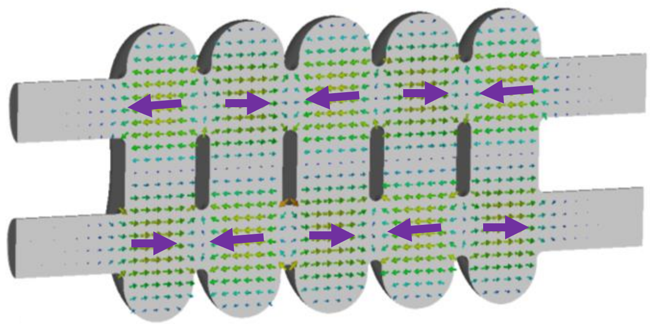


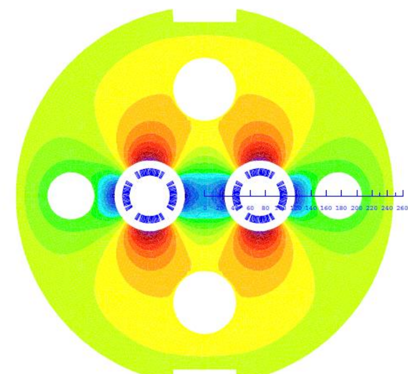
$= 2n\pi R$

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

‘Dogbone’ ERL with Twin-axis cavities



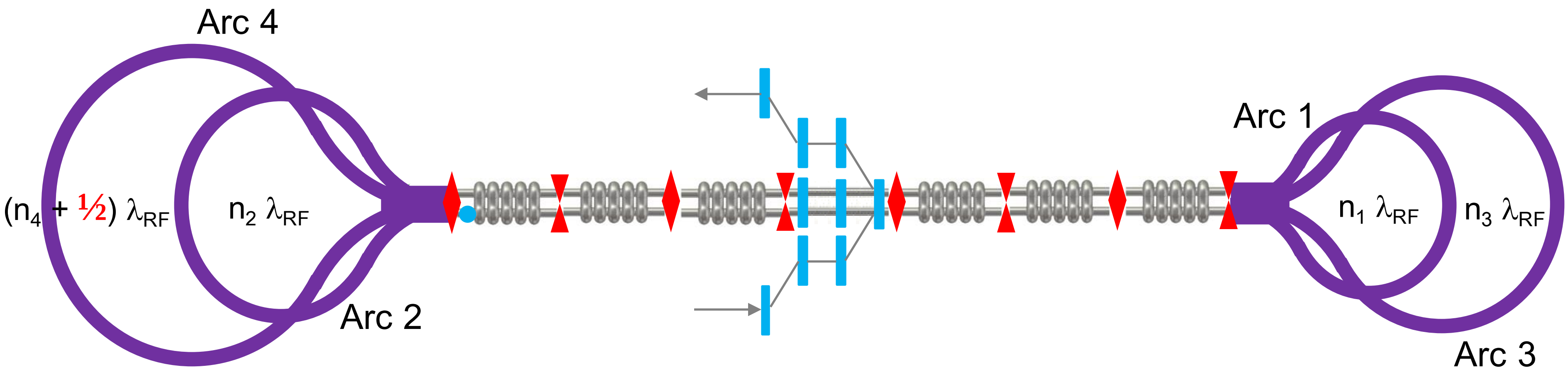


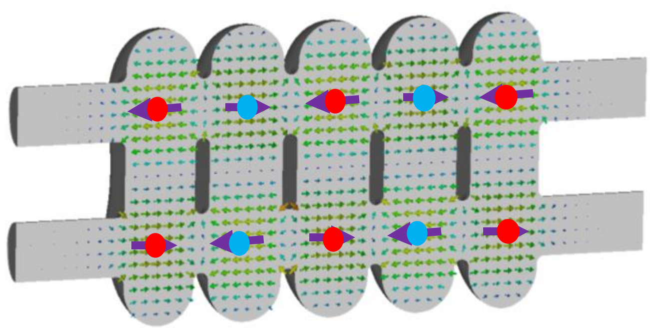


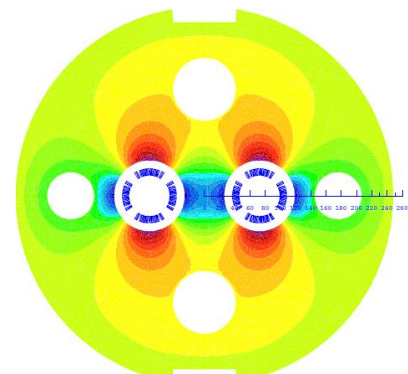
Elliptical Twin Axis Cavity capable of accelerating, or decelerating beams in **two separate beam pipes**

Double-aperture quad - single layer coil design (CERN)

‘Dogbone’ ERL with Twin-axis cavities





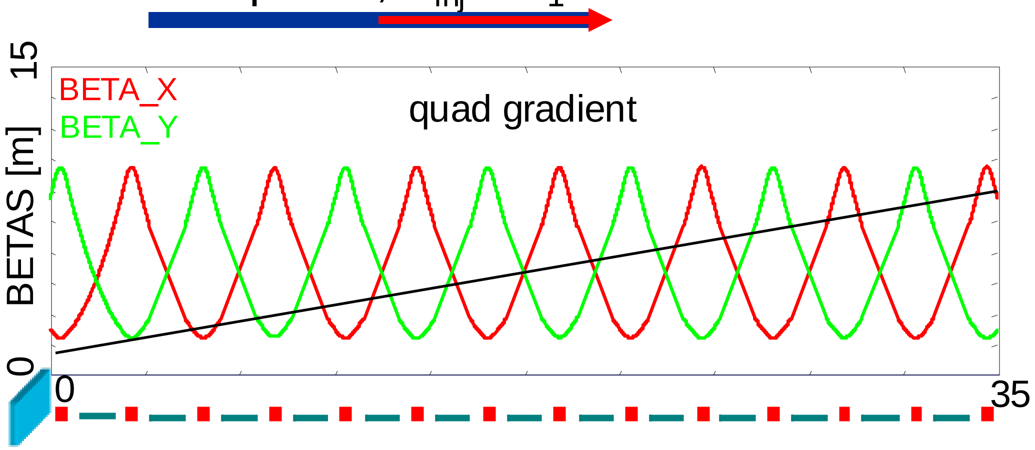


Elliptical Twin Axis Cavity capable of accelerating, or decelerating beams in **two separate beam pipes**

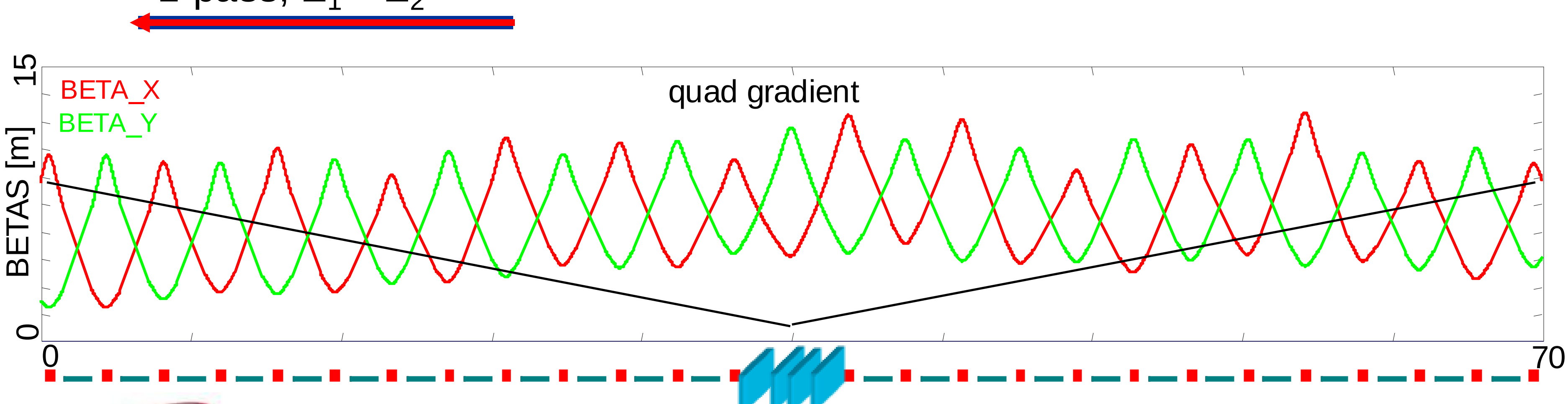
Double-aperture quad - single layer coil design (CERN)

Bi-sected Linac Optics

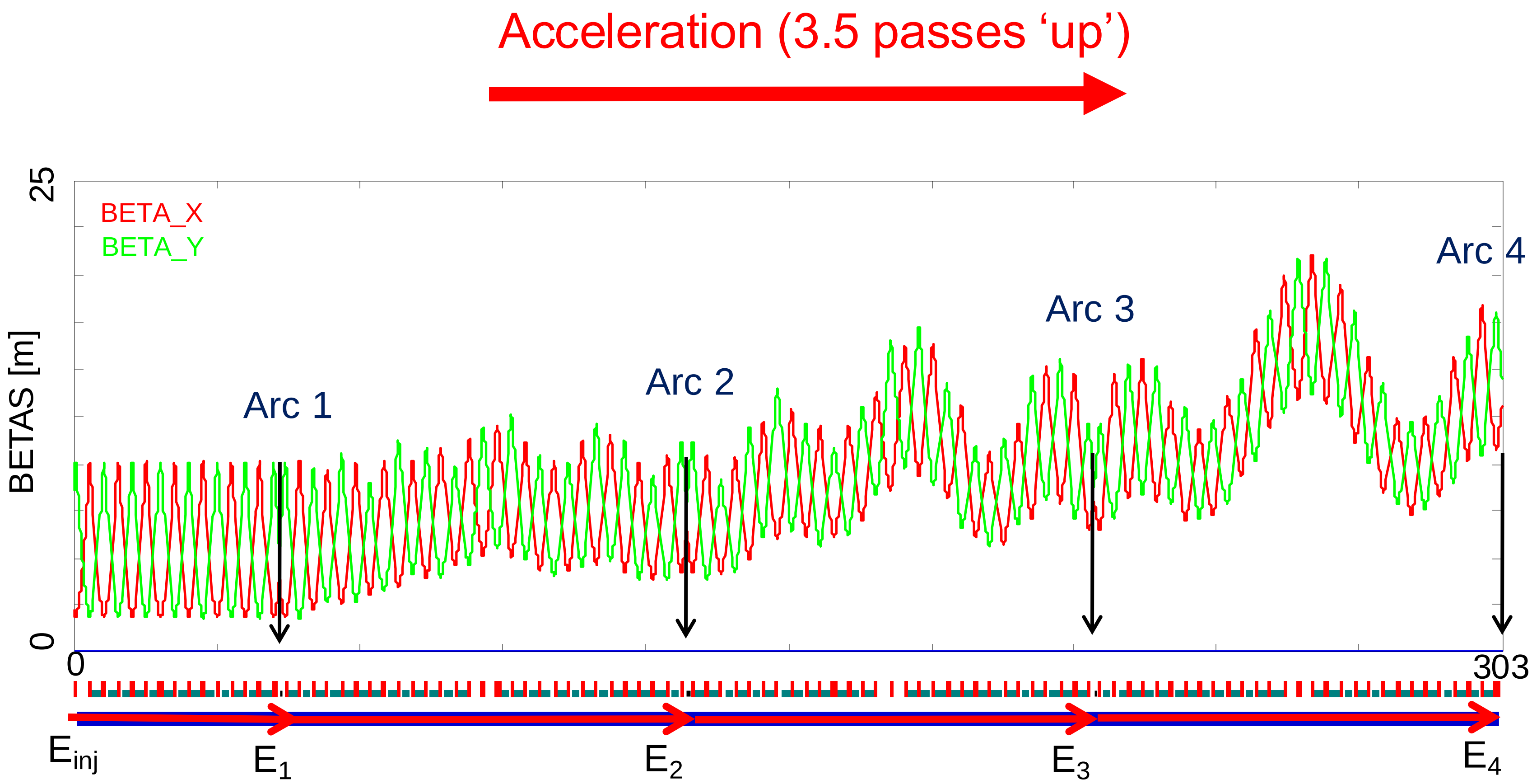
‘half pass’ , $E_{inj} – E_1$



1-pass, $E_1 – E_2$

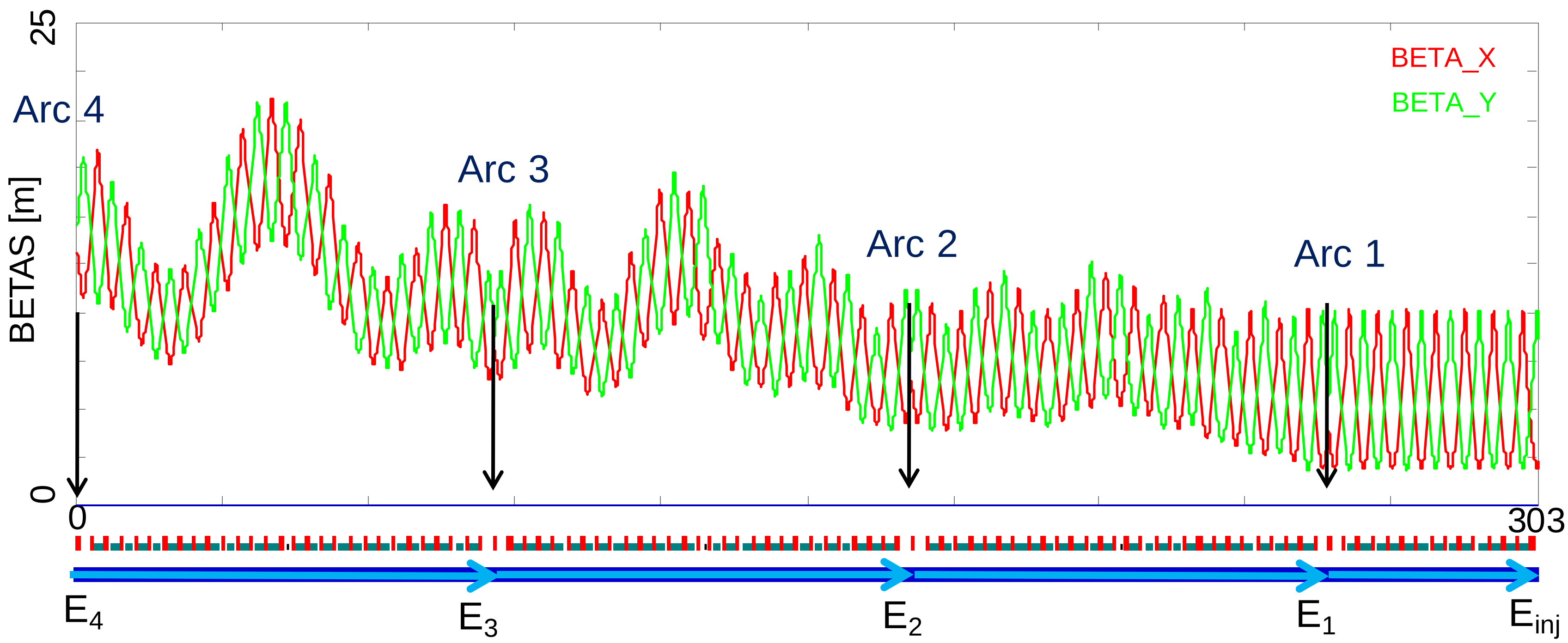


Multipass Linac Optics

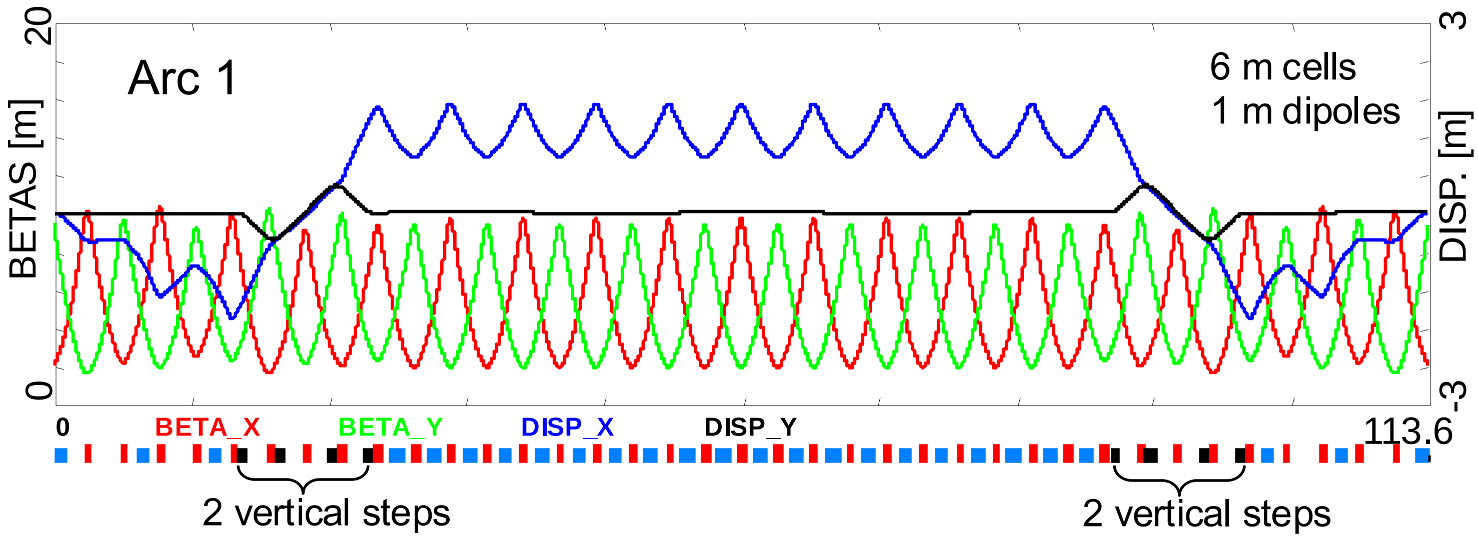


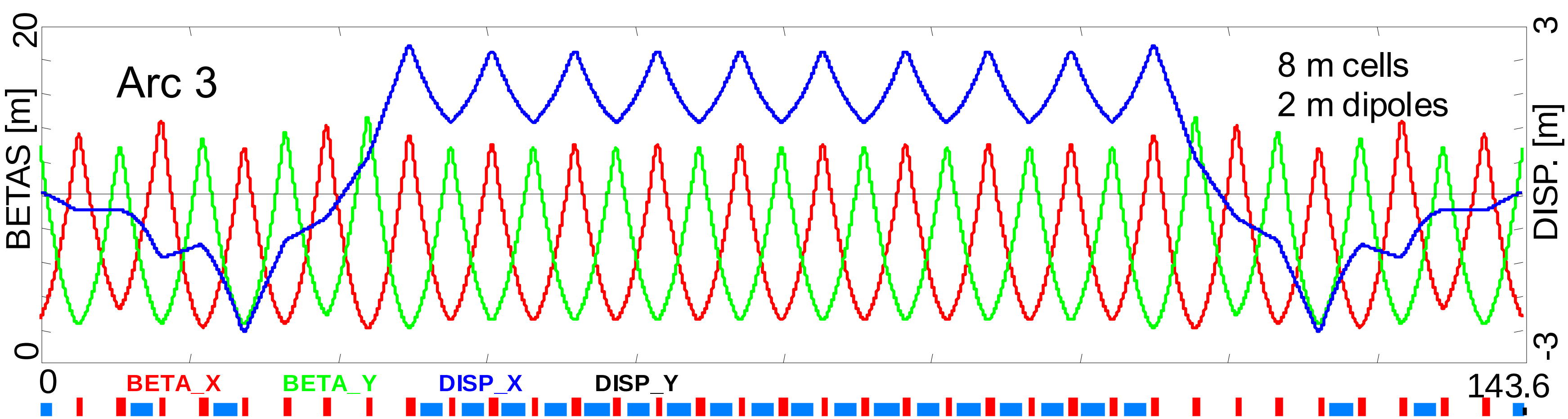
Multipass Linac Optics

Deceleration (3.5 passes 'down')

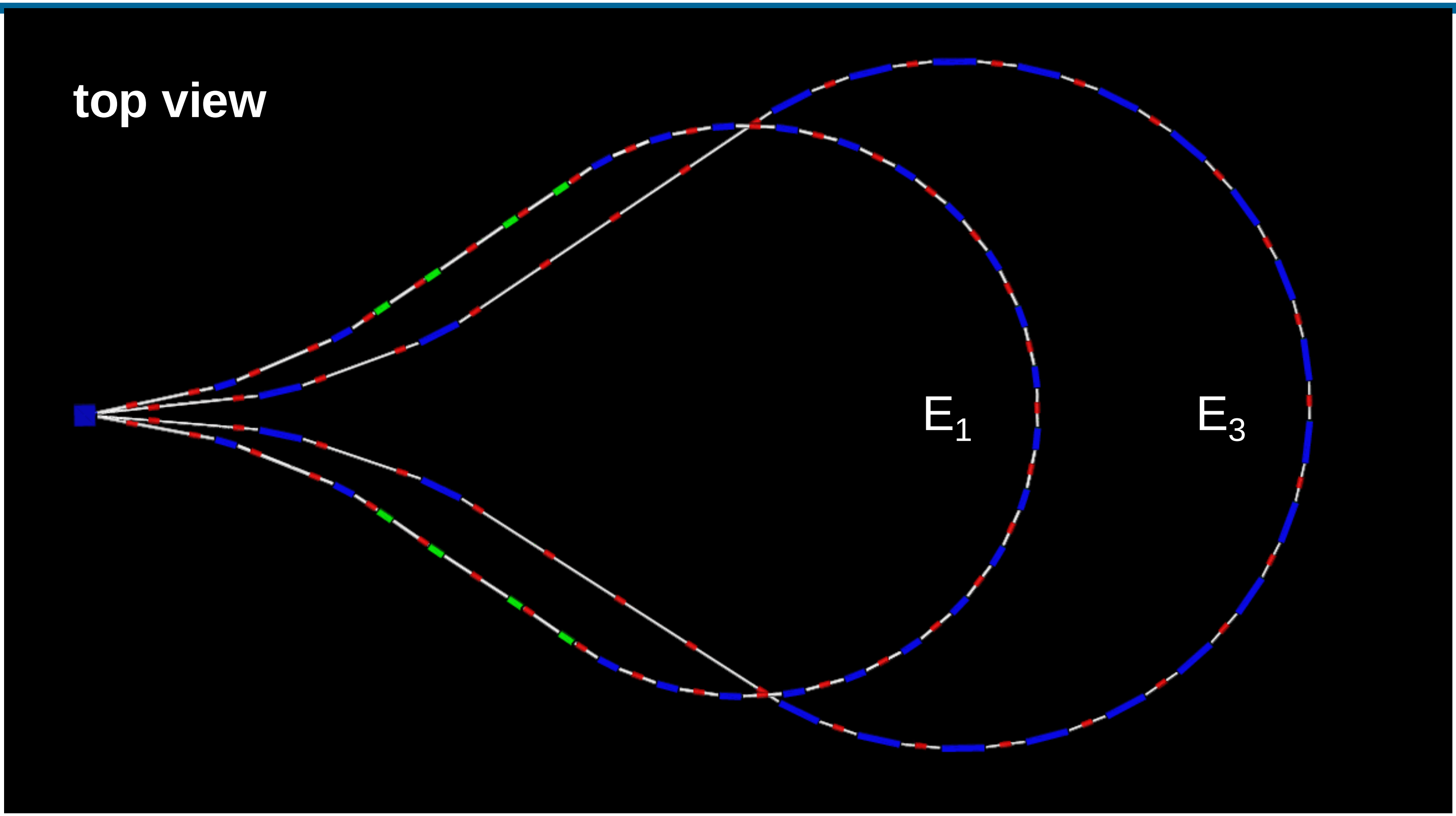


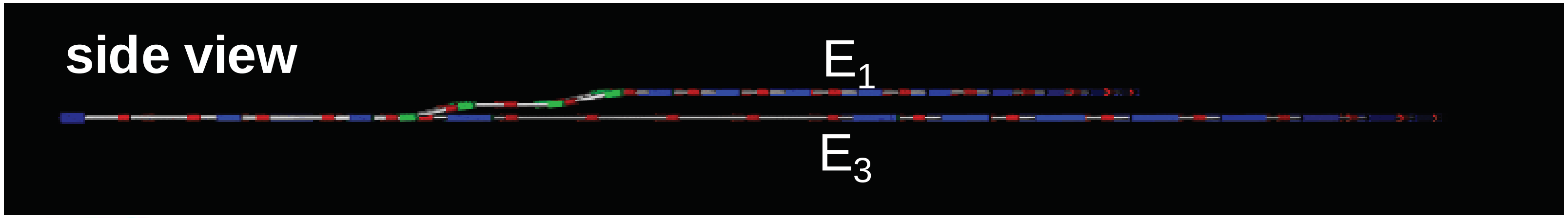
Arc 1 & 3 Optics



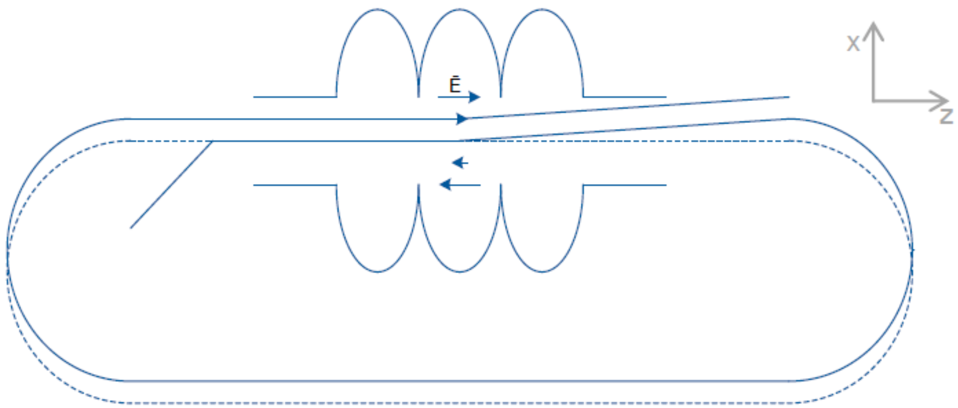


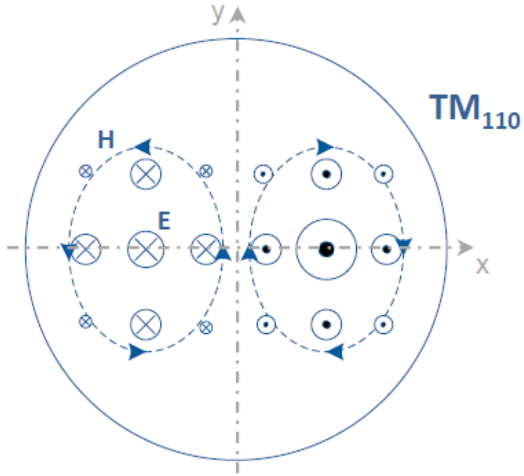
Arc 1 & 3 Configuration





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 varies 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 2^{nd} 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: $P_c = \dfrac{V_a^{\,2}}{(\omega_\lambda / c)^2 a^2 (R/Q)_\lambda \; Q_\lambda}$

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

→ **threshold current:**

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

valid for:

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

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

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

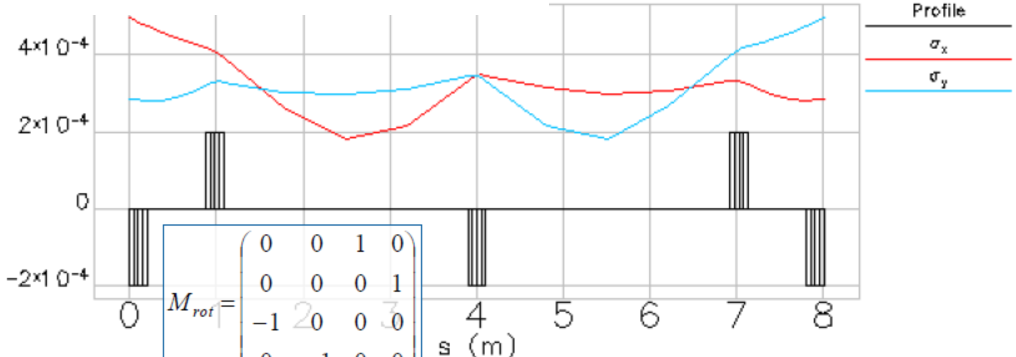
Beam Breakup Instability (BBU)

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):

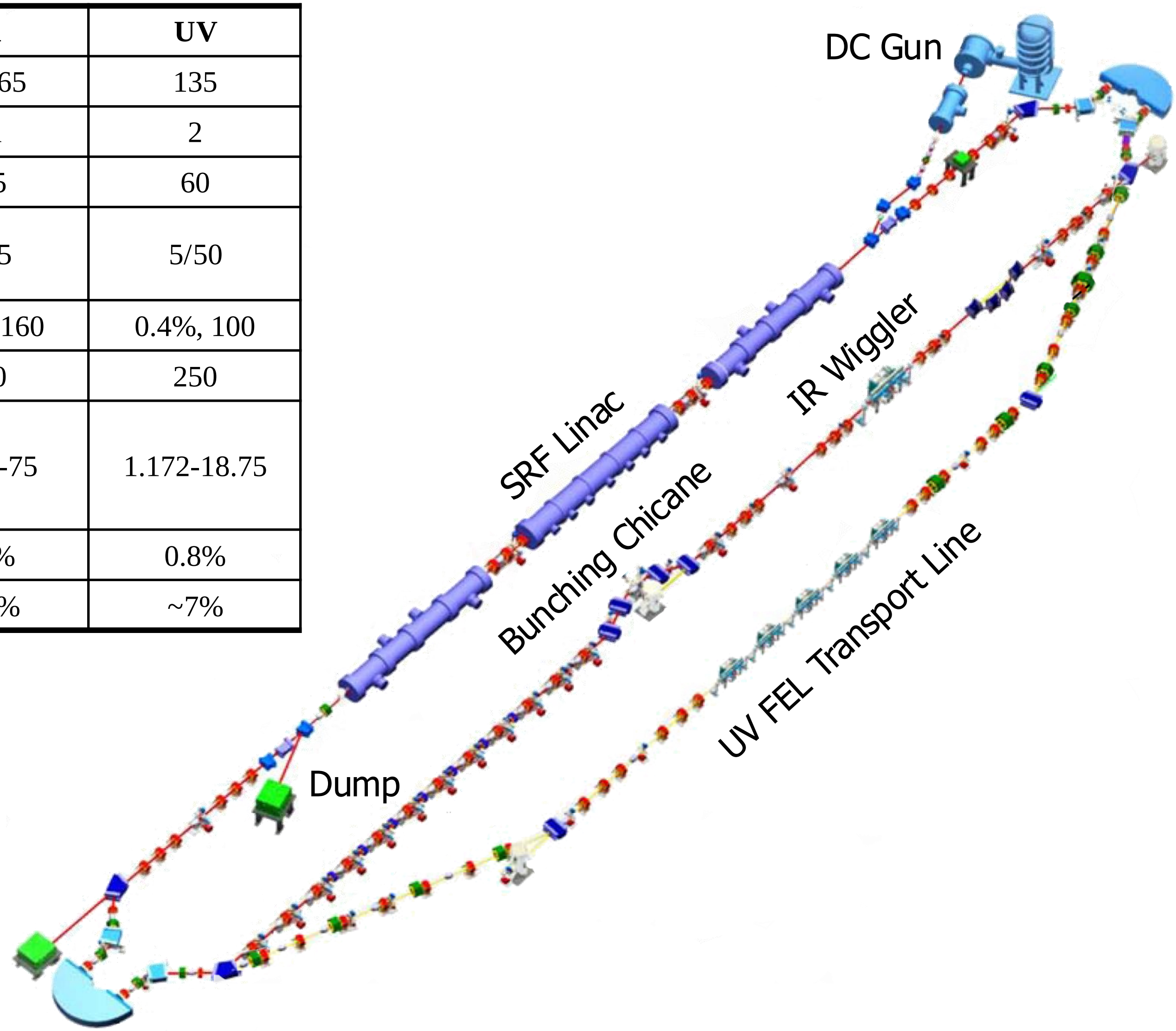
- coupled beam transport: switching of planes $M=((M_x,0),(0,M_y)) \rightarrow M=((0,M_{yx},0),(0,M_{xy}))$ $m_{12}=0 \rightarrow$ horizontal HOM kick transforms to vertical offset $\rightarrow$ HOM not further excited by the oscillatory part of x_2
- $\rightarrow$ two options: solenoid (low energy),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



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

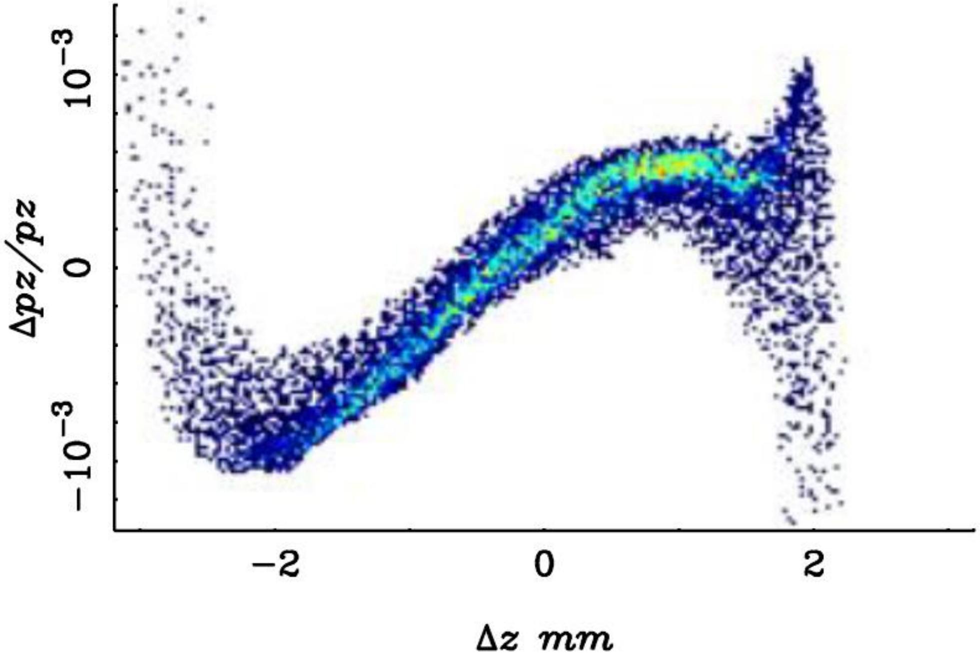
JLAB IR/UV FEL

Parameter	IR	UV
Energy (MeV)	88-165	135
I_{ave} (mA)	9.1	2
Q_{bunch} (pC)	135	60
ε_N transverse/longitudinal (mm-mrad/keV-psec)	8/75	5/50
$\sigma_{\delta p/p}$, σ_l (fsec)	0.4%, 160	0.4%, 100
I_{peak} (A)	400	250
FEL repetition rate (MHz) (cavity fundamental 4.6875)	0.586-75	1.172-18.75
η_{FEL}	2.5%	0.8%
ΔE_{full} after FEL	~15%	~7%



Nonlinear Beam Optics

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



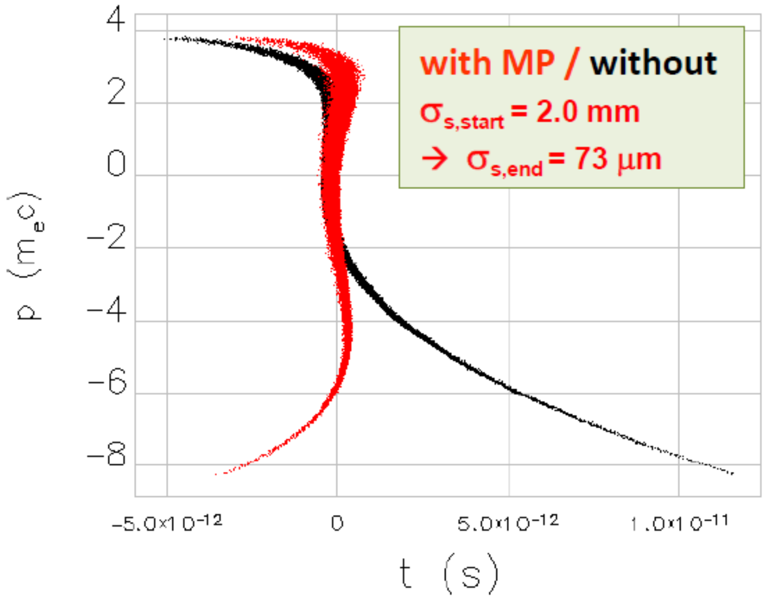
Nonlinear Beam Optics

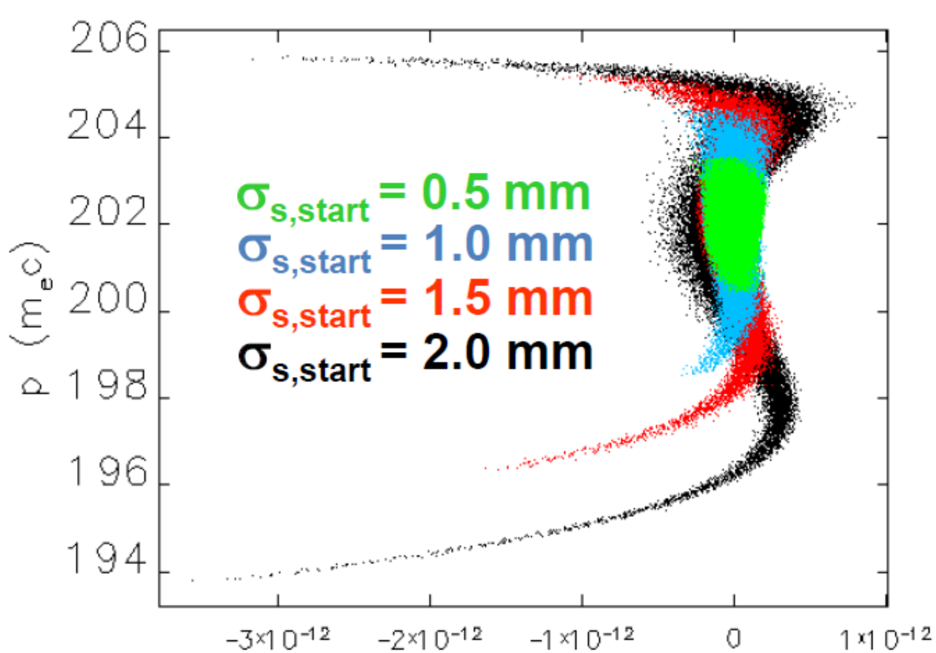
- RF curvature: $E(t)=E_0 \cos(\omega t + \varphi_0)$
- aberrations: geometric & chromatic

  caused and counteracted by nonlinear fields → multipole magnets

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

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

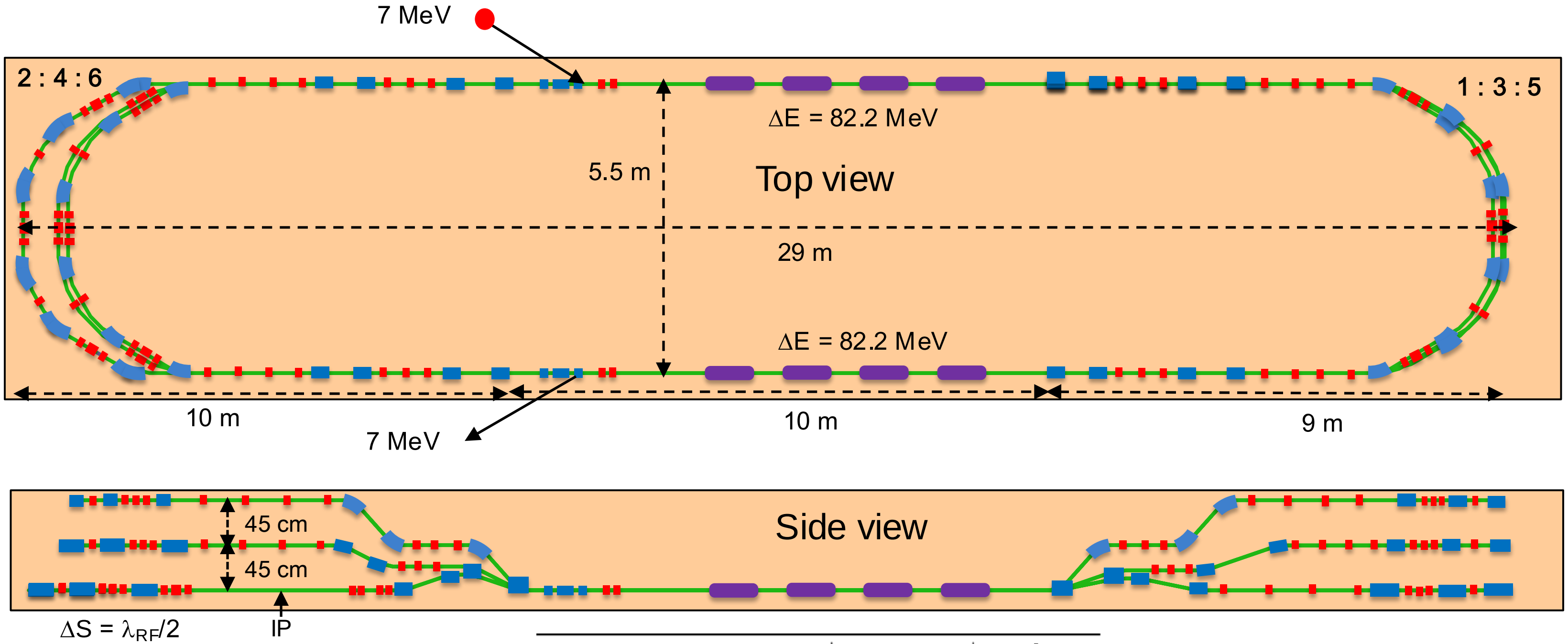




bERLinPro recirculator test: bunch compression with varying initial bunch length; linac phase, sextupole and octupole magnets optimized

PERLE (500 MeV) - Baseline Layout

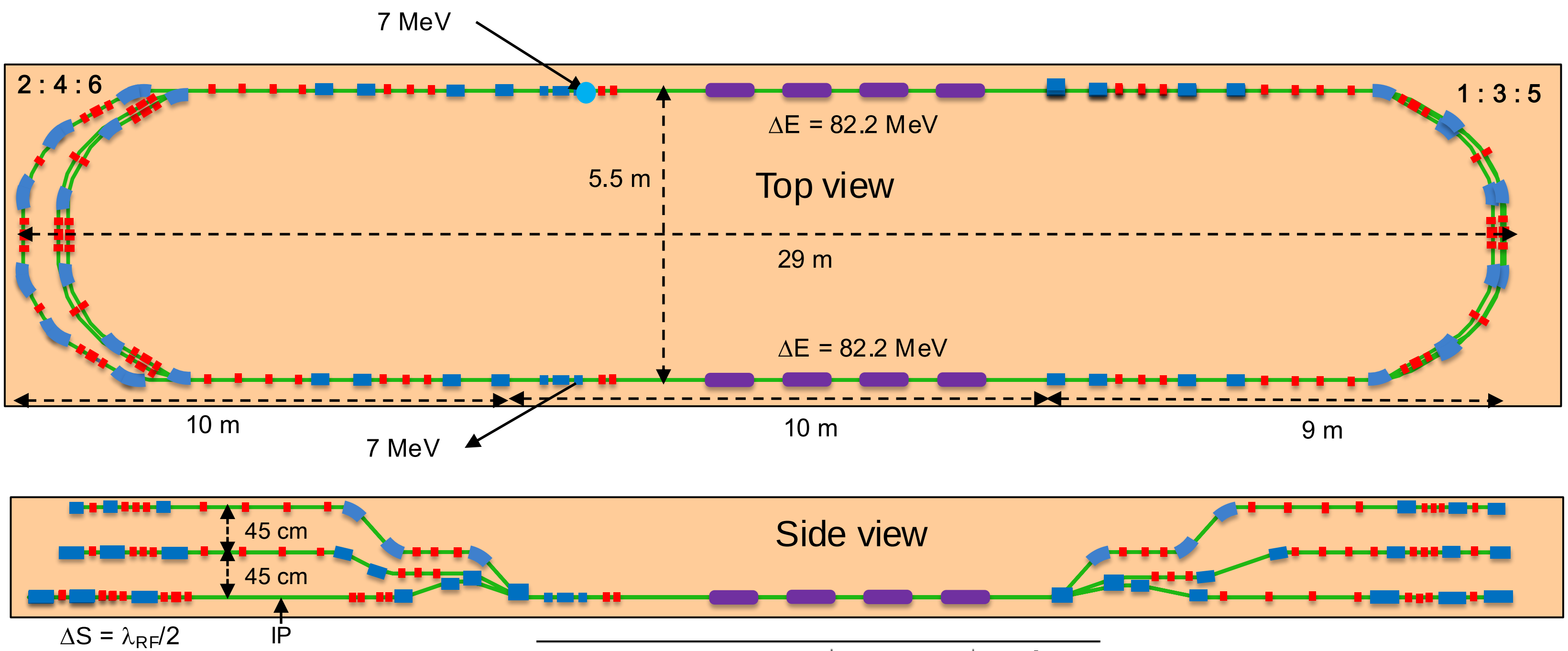
Footprint: 29 m × 5.5 m × 0.9 m



Parameter	Unit	Value
Injection energy	MeV	7.0
Top energy	MeV	500.0
Beam current	mA	20.0
Bunch population	$10^9 e^-$	3.1
Bunch charge	pC	500
Bunch spacing	ns	25
Normalised emittance	mm.mrad	6.0
RMS bunch length	mm	3.0
Longitudinal emittance	keV.mm	25.0
RF frequency	MHz	801.6

PERLE (500 MeV) - Baseline Layout

Footprint: 29 m × 5.5 m × 0.9 m



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RMS bunch length	mm	3.0
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RF frequency	MHz	801.6

Summary & Ouutlook

- 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 - h_{ERL}). Required RF power becomes nearly independent of beam current.

- ERLs 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.
- Maximizing number of passes is the key to a cost effective ERL scheme. However need to overcome multiple challenges in doing so
- Wide range of applications: Light Sources/FELs, Colliders, Ion 'Coolers', Isotope production…