USPAS Accelerator Physics 2021
(Virtually) Texas A&M University

14+: Electron Linacs, FELs, and ERLs

Todd Satogata (Jefferson Lab and ODU) / satogata@jlab.org

Steve Peggs (BNL) / peggs@bnl.gov

Daniel Marx (BNL) / dmarx@bnl.gov and Nilanjan Banerjee / nb522@cornell.edu

http://www.toddsatogata.net/2021-USPAS

Username test / Password test

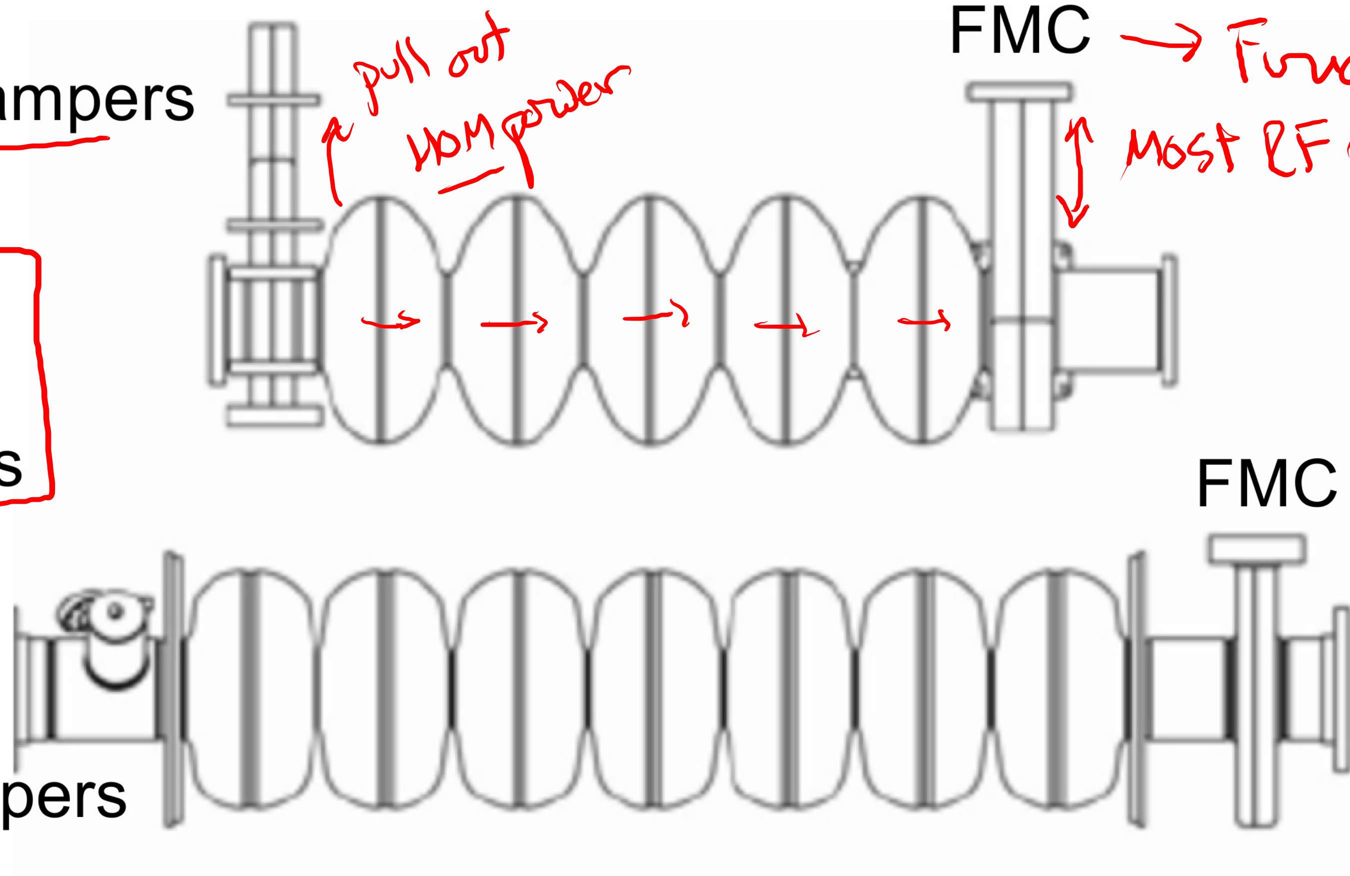
Chapter 14: Linacs - electrons

- Introduction and principles ⇐ vs protons
- 14.2: RF capture
- 14.1: Longitudinal and transverse focusing
- 14.3: Bunch compression
- 14.4: Recirculating linacs and ERLs
- 14.5: BBU

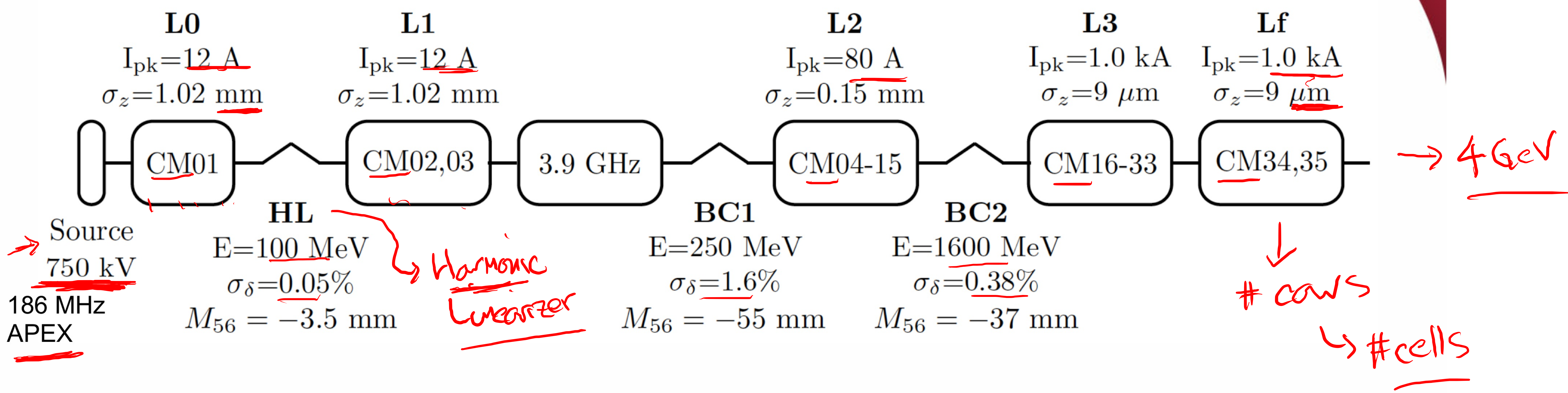
ERLs & ER @CEBAF (& 1 slide on cβ)

Electron Linacs

- Electron linacs are the most ubiquitous accelerators
  - Most industrial accelerators: X-ray sources, sterilization...
  - Excellent at creating X- and gamma-rays
  - Cavities main dimensions defined by frequency: $\lambda = c/f$
- (Mostly) multi-cell cavities: 5/7/9 are common
  - Limited by HOMs, RF drive control, and transit time



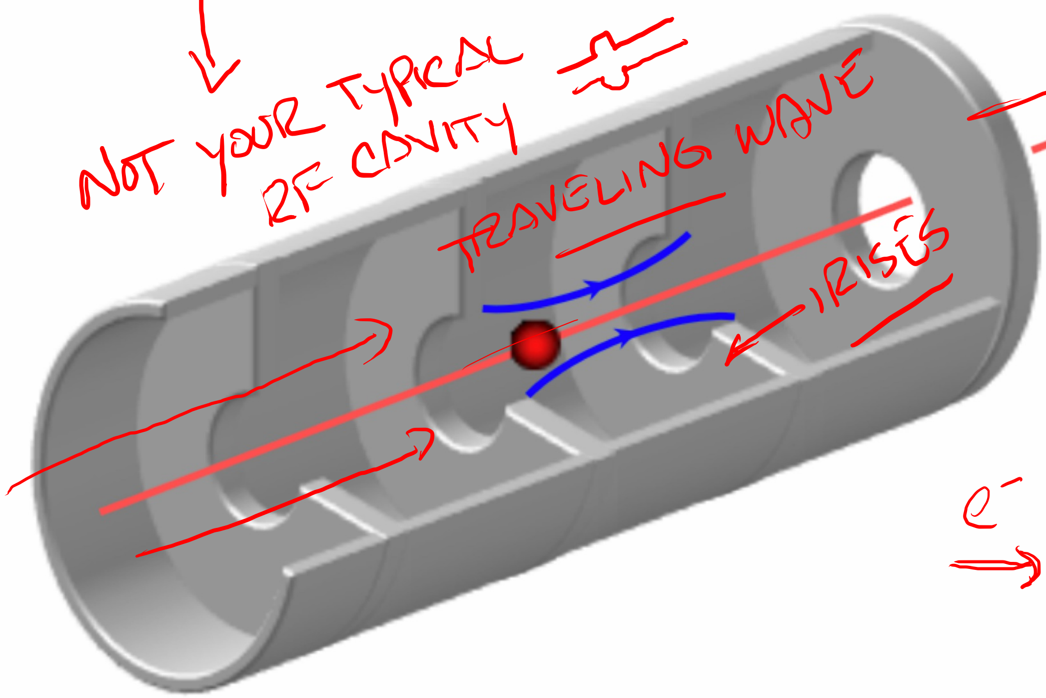
Modern Linac: 4 GeV LCLS-II Layout

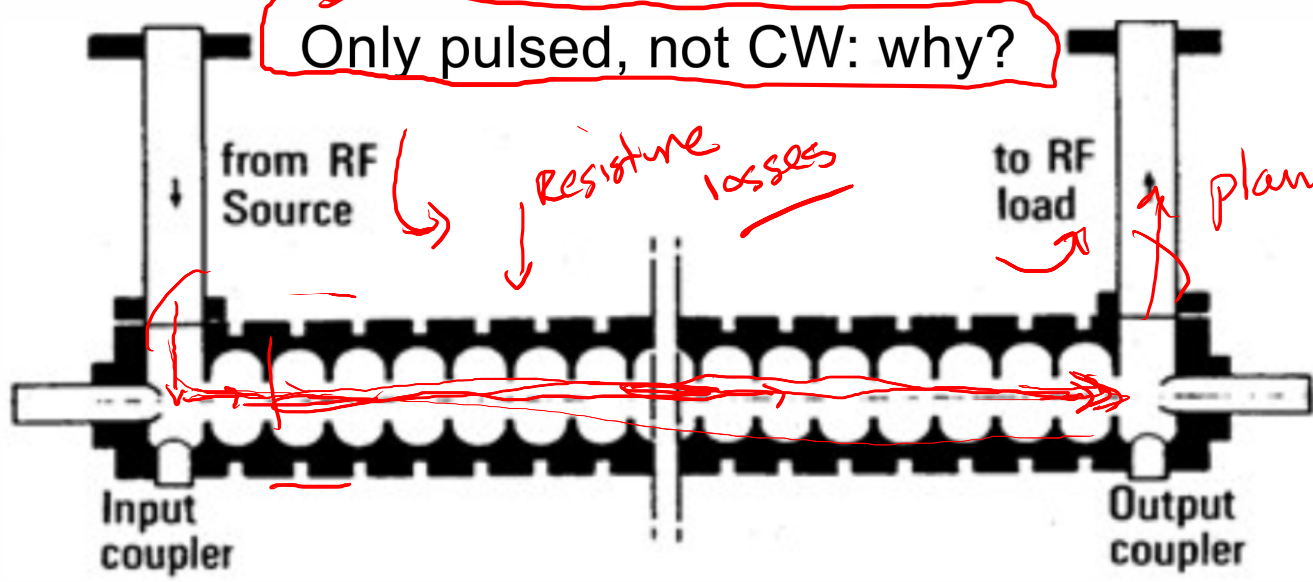


- Completely dominated by accelerating structures
  - Only one main frequency (1.3 GHz)
  - A few 3rd harmonic cavities (3.9 GHz) for linearization
- Bunch length shrinks drastically: mm to um
  - Short bunches **required** for FEL lasing
  - Fractional momentum spread σ_p/p or σ_δ shrinks due to adiabatic damping

Electron Linacs Do Not Have To Be SRF

- Electron bunches are short (mm-um or ps-fs)
  - RF frequencies can be high (X-band, 10s of GHz)
  - Cu RF still practical; wavelengths o(cm)
- Electron linac RF includes efficient traveling wave structures
  - Retard RF phase velocity to match particle velocity
  - Resistive losses tolerable for short linacs (e.g. medical linacs)





14.1: Longitudinal and Transverse Focusing

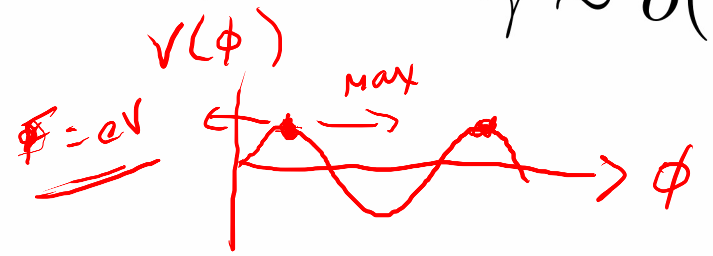
- Ballistic drift: M_{56} without additional magnets

$$\begin{pmatrix} \delta\phi \\ \delta W \end{pmatrix}_{n+1} = \begin{pmatrix} 1 & L_e \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \delta\phi \\ \delta W \end{pmatrix}_n$$

$$L_e = -\frac{1}{mc^2}\frac{1}{\beta_r^3\gamma_r^3}\frac{2\pi(s_{n+1}-s_n)}{\lambda_{RF}}$$

$$\beta \approx 1$$

$$\gamma \sim o(10^2 - 10^4)$$



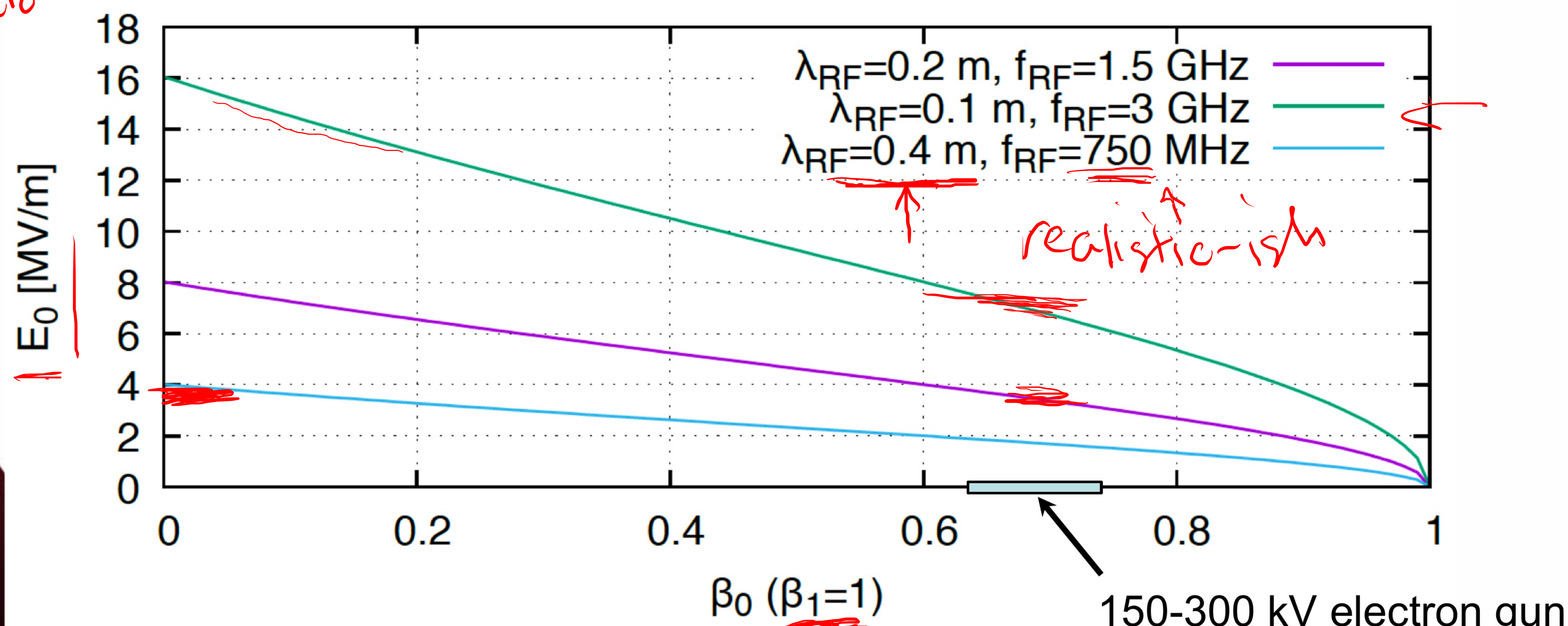
  - No longitudinal focusing
  - **Maximize** energy gain per meter: run **on crest** in principle
  - Some nonlinearity: Bunch length vs RF wavelength
- Radial defocusing is also negligible (vs. ion linacs)

$$\Delta r' = -\frac{\pi q E_0 T_1 L}{mc^2 \beta^3\gamma^3 \lambda} \cdot \sin(\phi_r) \cdot r$$

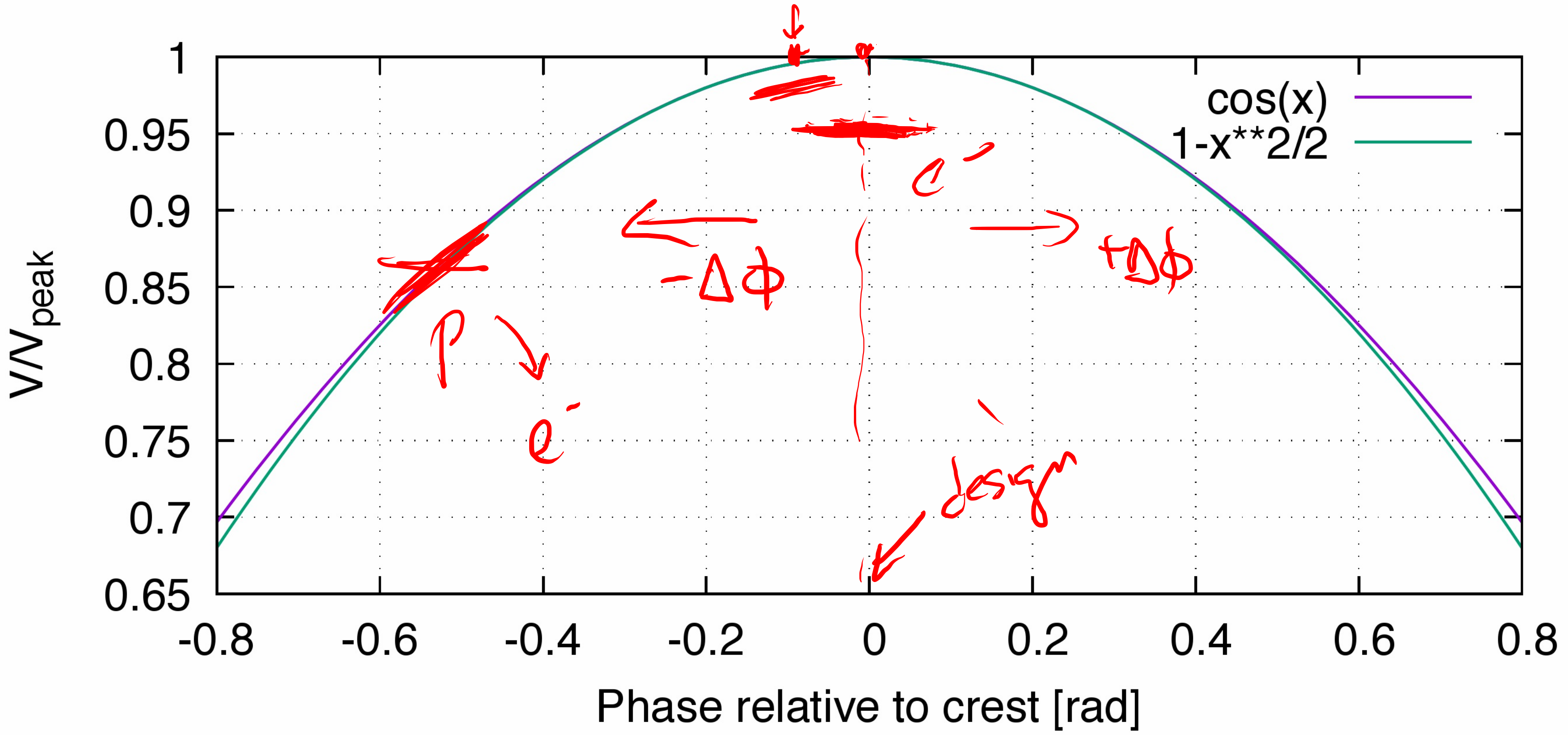
14.2: RF Capture

- We cannot lower EM wave phase velocity arbitrarily
  - Easy to guess that even $\beta_r \approx 0.8$ creates challenges
  - Slower accelerating electrons can fall out of phase with RF
- RF capture conditions

$$E_0 \geq \frac{\pi\, mc^2}{\lambda_{\rm rf} e}\left[\sqrt{\frac{1-\beta_0}{1+\beta_0}} - \sqrt{\frac{1-\beta_1}{1+\beta_1}}\right] \quad (14.14)$$

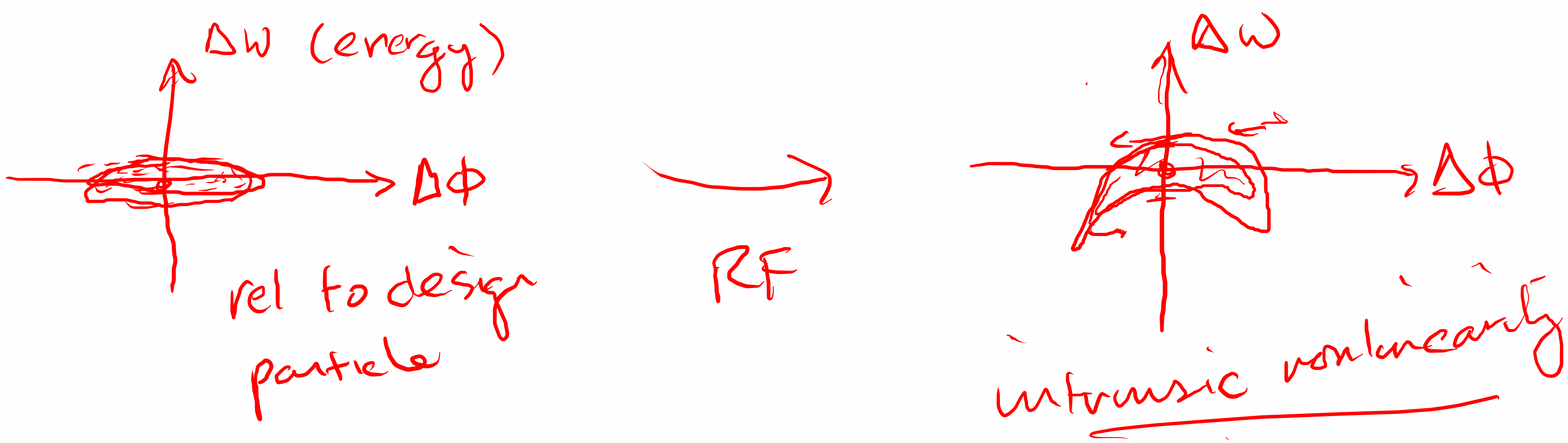


Longitudinal Nonlinearity

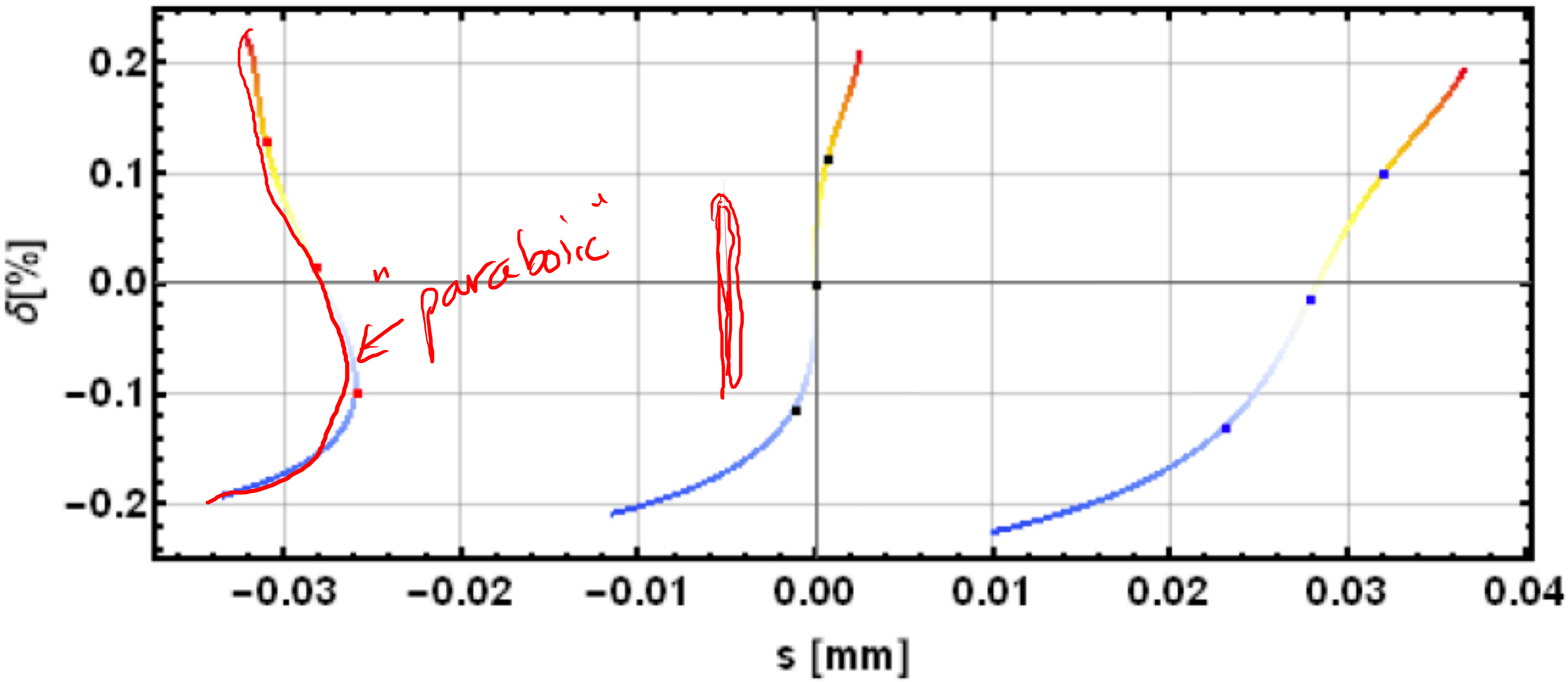


Even short bunch lengths develop nonlinear energy spread

→ Run "off crest" to have some long focusing



ER@CEBAF Longitudinal Phase Space Example



Decompress with arc 9 – flat bunch in arc 1

Arc 9 $R_{56} = 0.25$ m

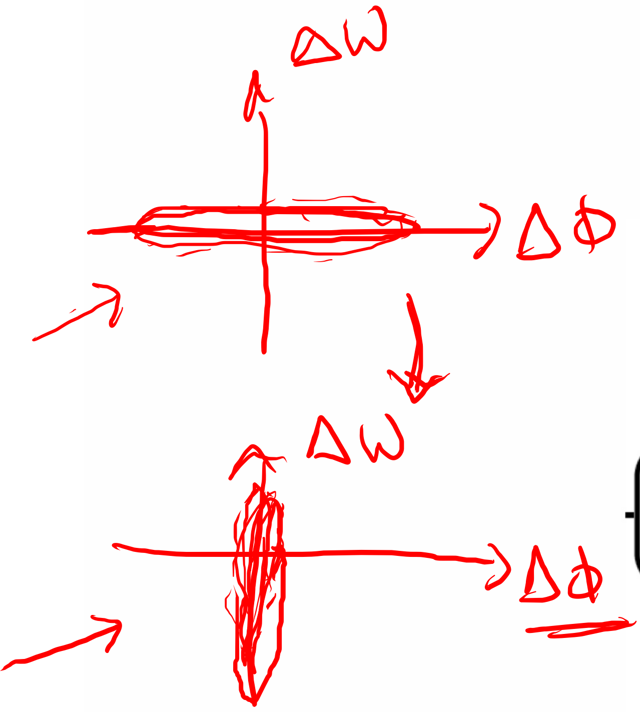
Arc 9 $T_{566} = 7.4$ m

Arc 10 $R_{56} = -0.44$ m

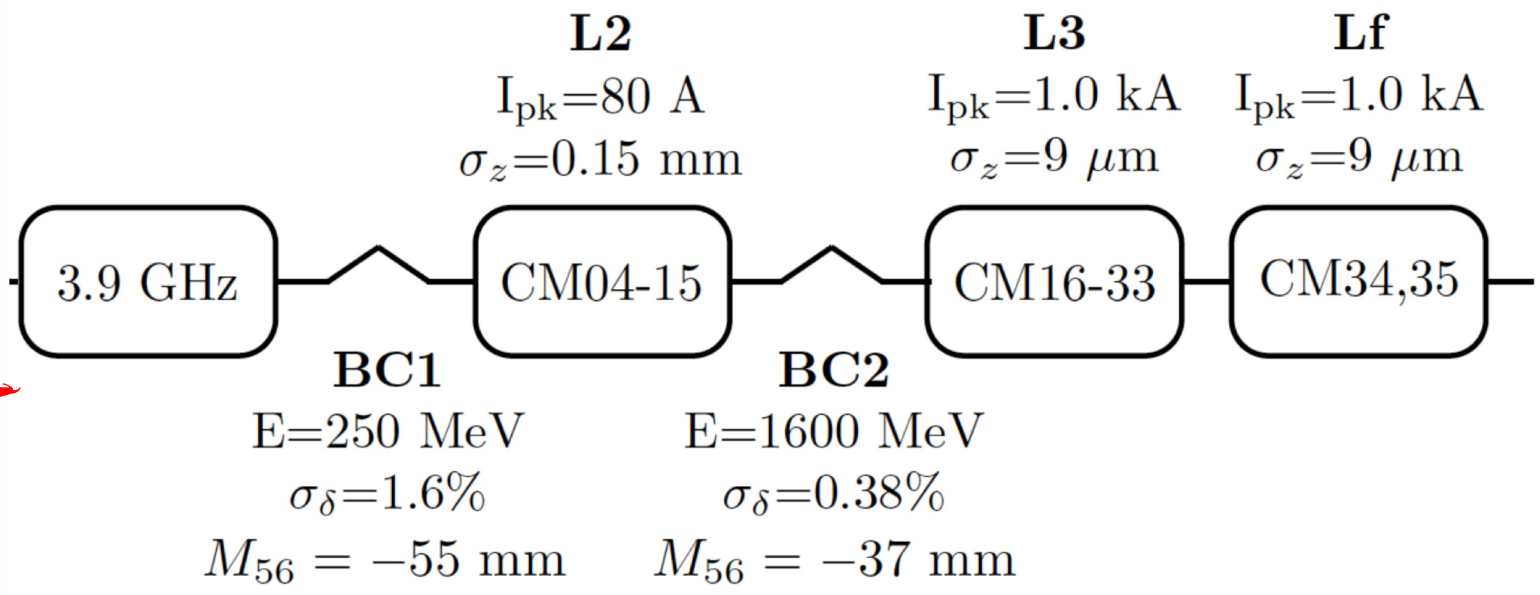
Arc 10 $T_{566} = -13.1$ m

→ HW

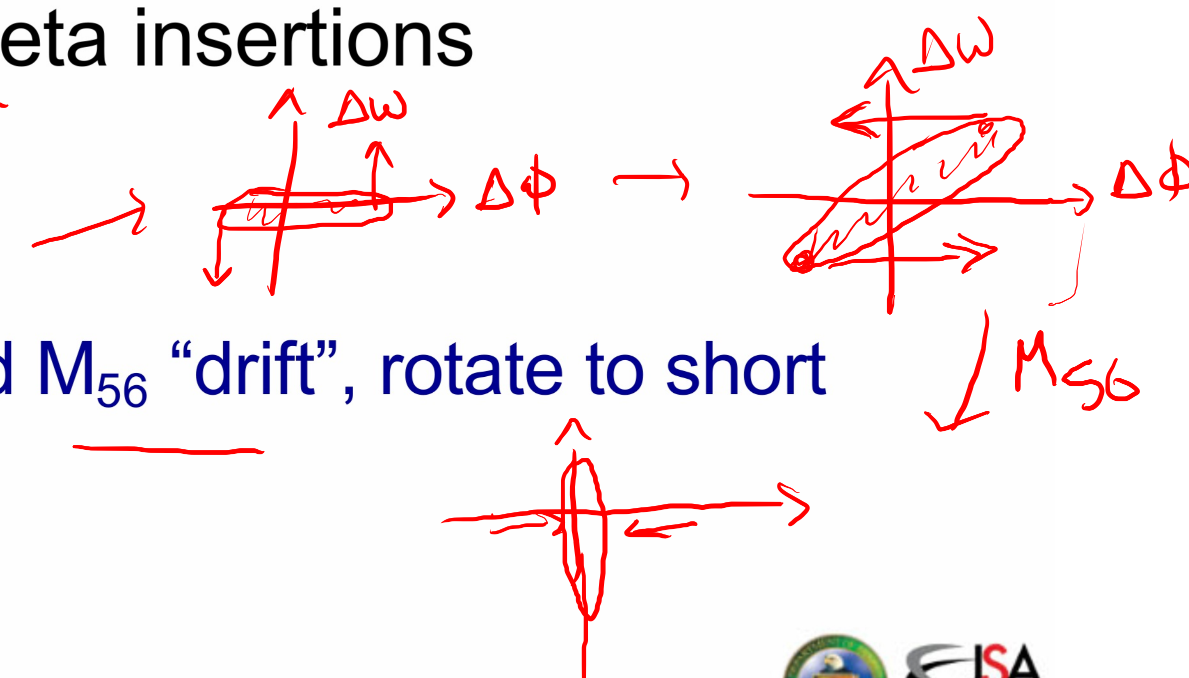
Gustavo Pérez Segurana / Peter Williams
Lancaster University & The Cockcroft Institute



14.3: Bunch Compression

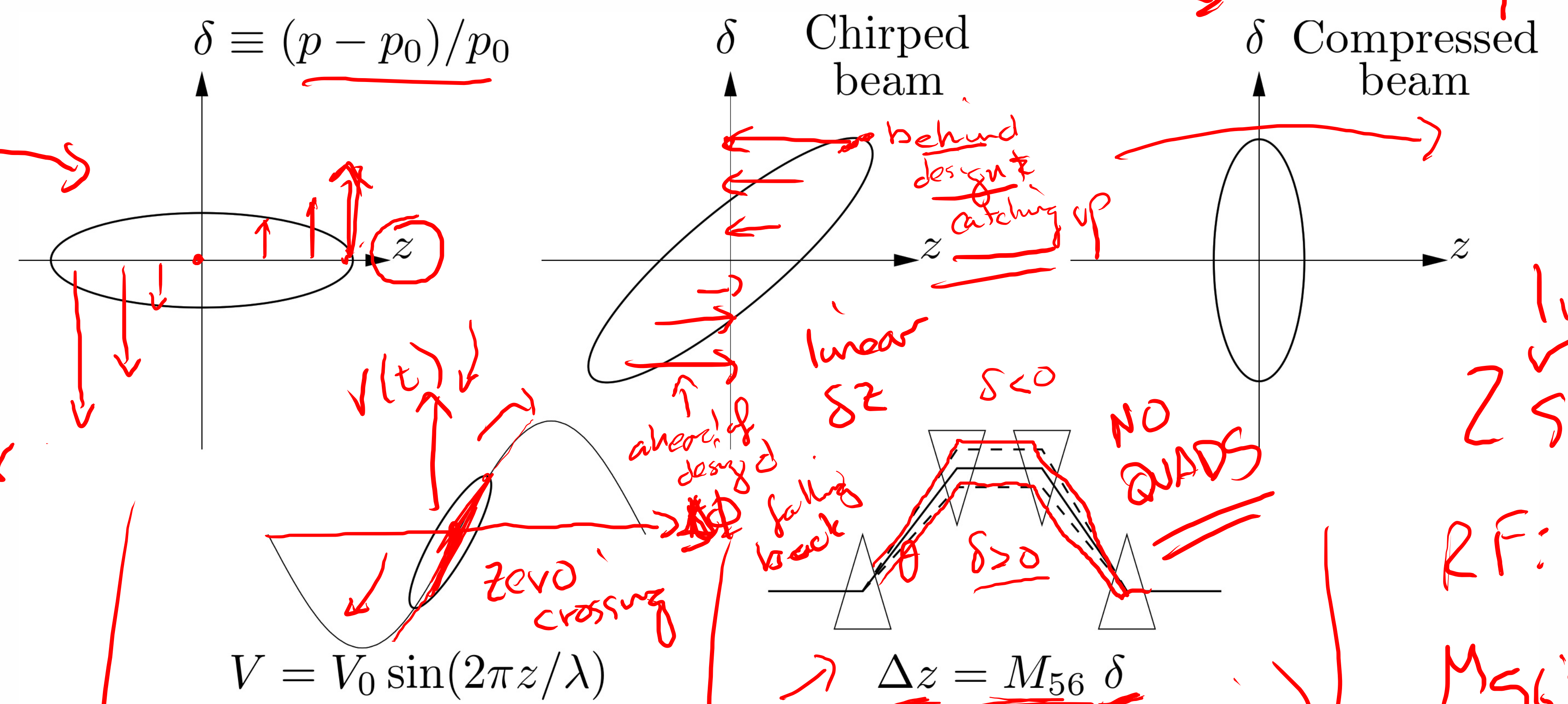


- Manipulate electron beam longitudinal phase space/length
  - Short bunches: FELs, electron colliders, high freq RF...
  - Long bunches: reduce peak current, space charge, avoid CSR...
- Some similarity to transverse low-beta insertions
- Principles:
  - Tilt longitudinal ellipse (modulator)
  - Use chicane for localized controlled M_{56} "drift", rotate to short



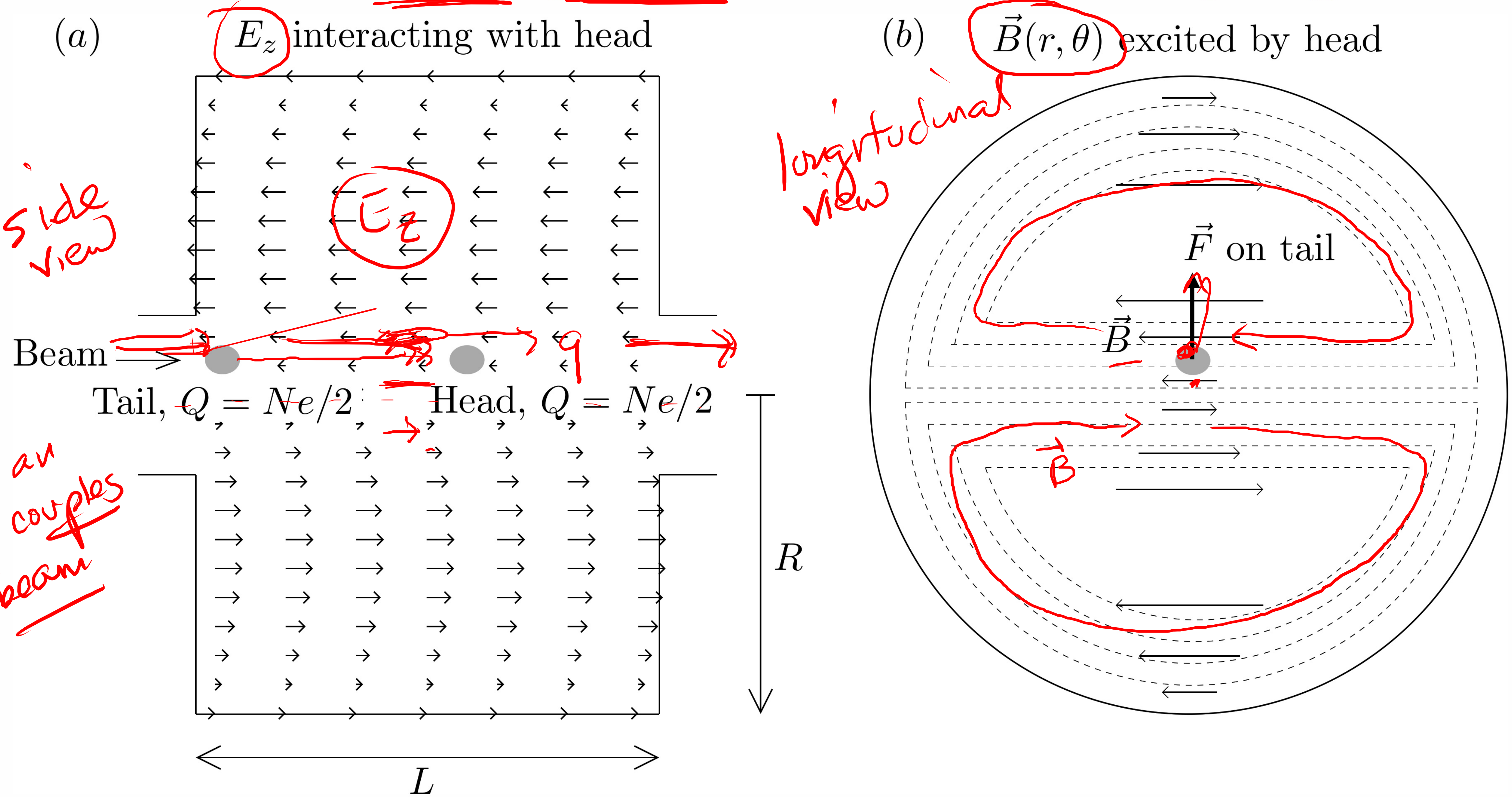
Chicane-Based Bunch Compressor

▪



→ RF affects transverse e⁻ dynamics (higher orders)

14.5: HOMs, BBU and BNS Damping

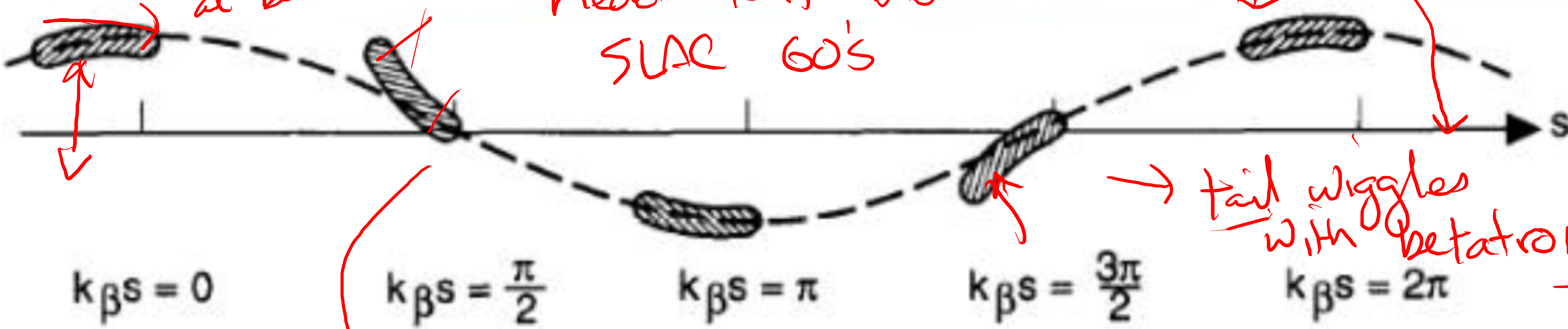


- Passing electron bunches can have transverse displacement
  - Interact with HOMs and deposit energy in cavity
  - Later beam at right phases can add energy constructively
  - Eventually field gets large enough to trip beam or trip RF control

Beam Breakup (BBU)

Head-tail BBU
SLAC 60's

offsets in RF cavs at betatron frequency



→ tail wiggles with betatron frequency

head exciting HOM in cavity

→ B field kicks on tail

HOM freq > f_{RF}

Tail amplitude grows over traversal of many cavities

→ long linac

→ a_β → wall

14.5: BBU Formalism and Rescue via BNS

$$x_{\text{head}}(s) \;=\; \hat{x}\cos(k_\beta s)$$

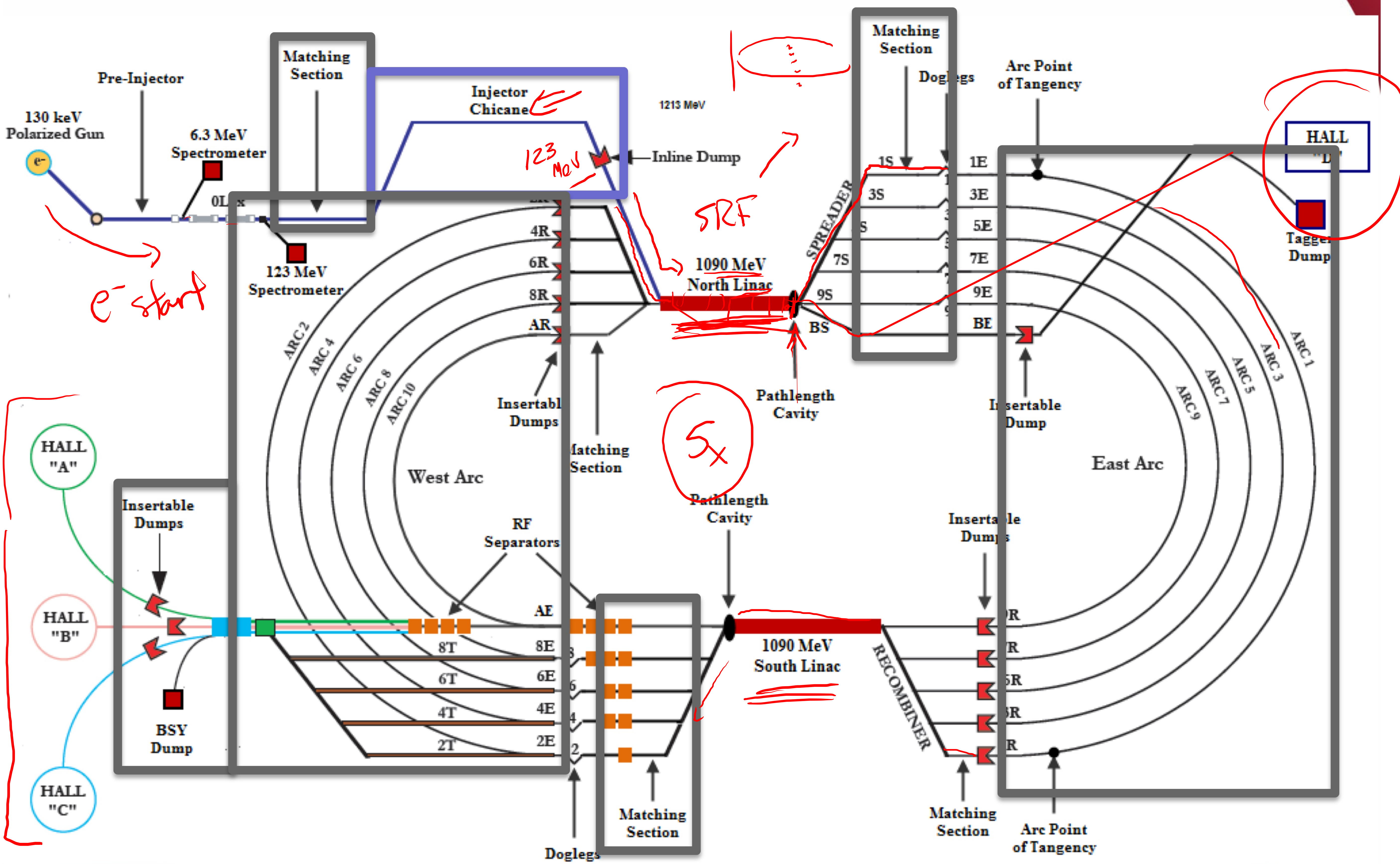
$$x''_{\text{tail}}(s) + k_\beta^2\, x_{\text{tail}}(s) \;=\; -\left(\frac{Ne^2 W_1(z)}{2EL}\right)\hat{x}\cos(k_\beta s) \qquad (14.23)$$

$$x_{\text{tail}}(s) \;=\; \hat{x}\cos(k_\beta s) - \left(\frac{Ne^2 W_1(z)}{4k_\beta EL}\right) s\,\hat{x}\sin(k_\beta s) \qquad (14.24)$$

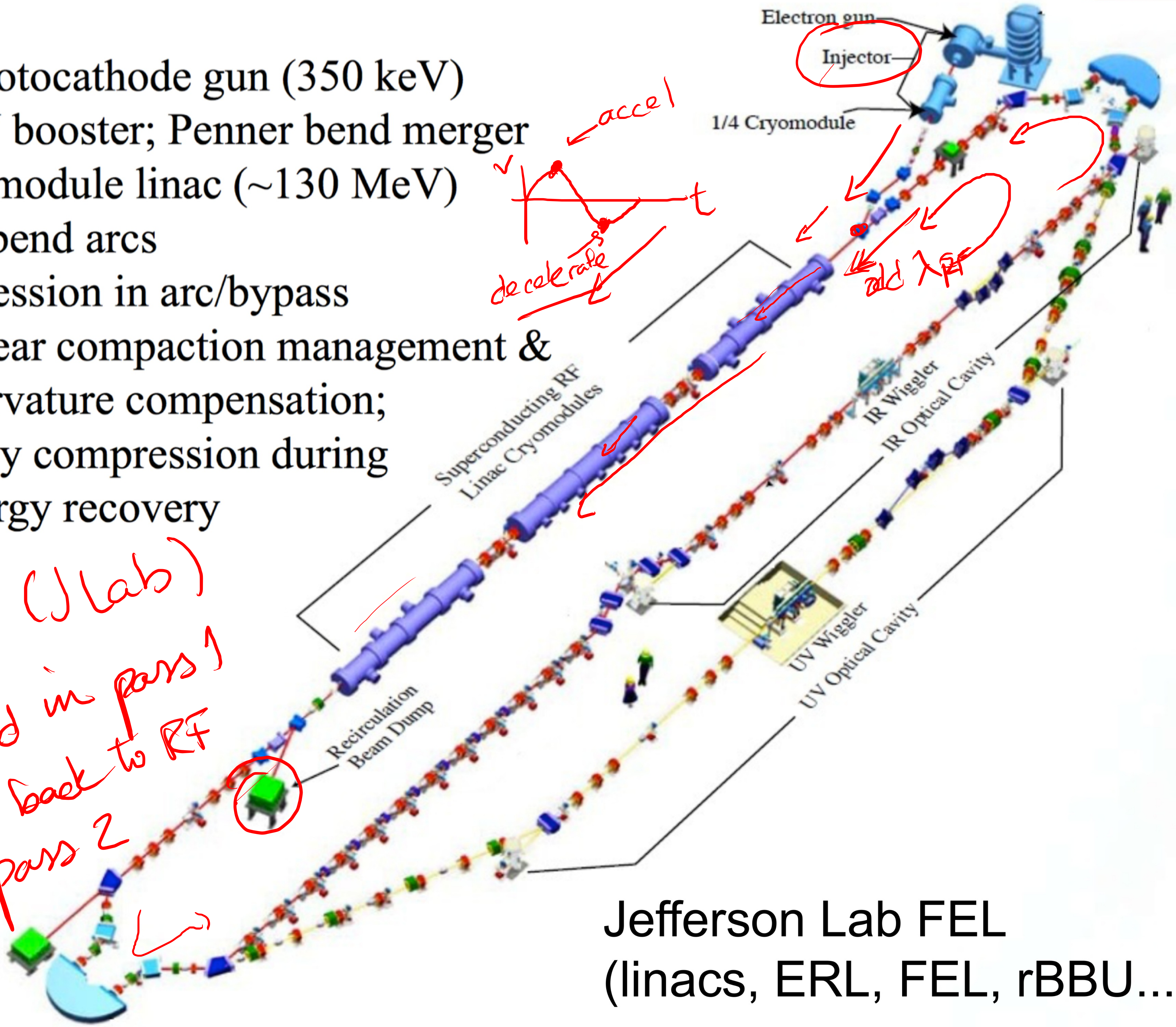
- Additional betatron focusing for the tail of the beam helps
- (Making accurate magnetic RF quadrupoles is really hard)
- Run off-crest, tail of beam has lower energy and is focused a little more due to chromatic focusing

$$\delta k_\beta \;=\; -\frac{Ne^2 W_1(z)}{4\,k_\beta\,EL}$$

CEBAF Detail Schematic



- DC photocathode gun (350 keV)
- 9 MeV booster; Penner bend merger
- 3 cryomodule linac (~130 MeV)
- Bates bend arcs
- compression in arc/bypass
- nonlinear compaction management & RF curvature compensation; energy compression during energy recovery



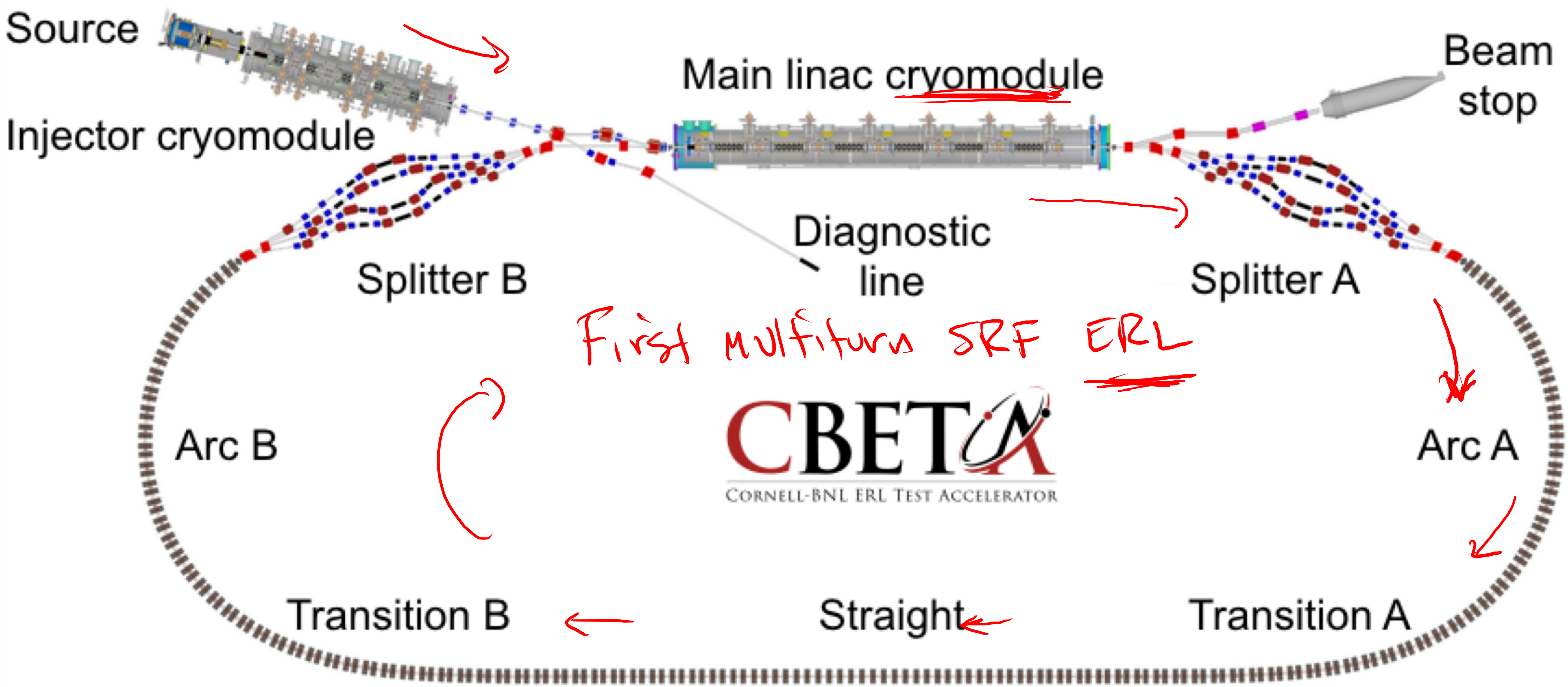
ERL (JLab)

E gained in pass 1 given back to RF in pass 2

Jefferson Lab FEL
(linacs, ERL, FEL, rBBU...)

CBETA

ERL



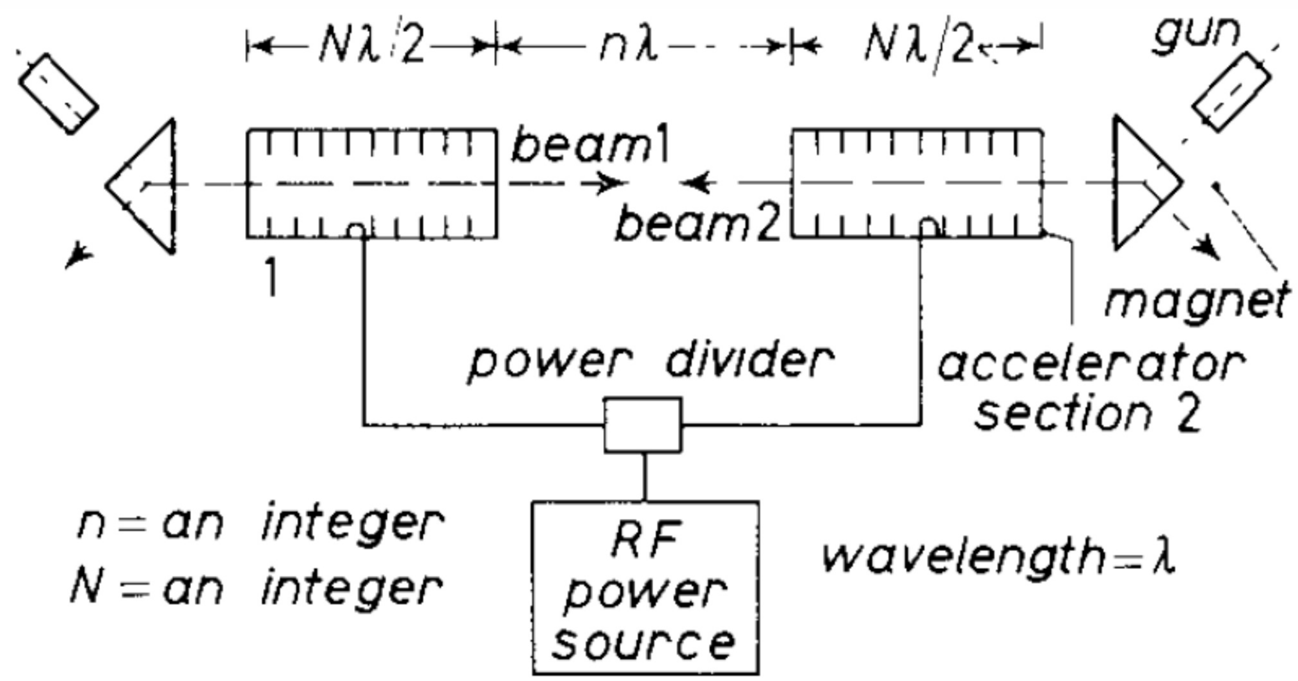
- Up to 4 up/4 down energy recovery
  - Energies [MeV]: 42 / 78 / 114 / 150 / 114 / 78 / 42
- Permanent magnet FFA arcs (very large momentum acceptance)

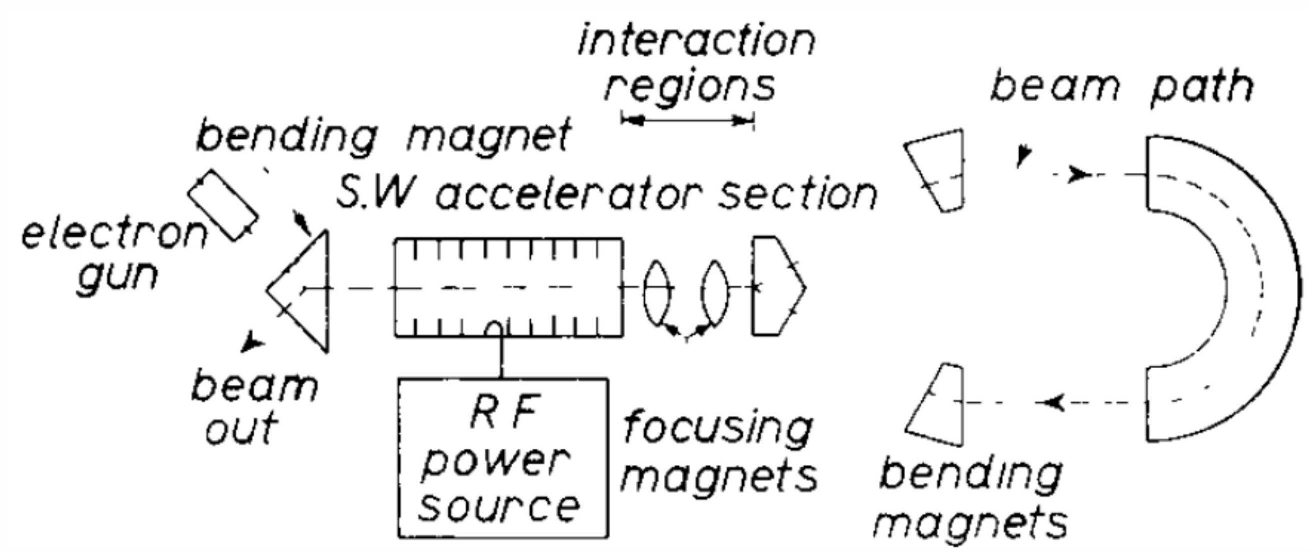
Nilanjan/Steve

https://www.classe.cornell.edu/CBETA_PM/

Energy Recovery: History

- **February 1965***: Maury Tigner, Nuovo Cimento



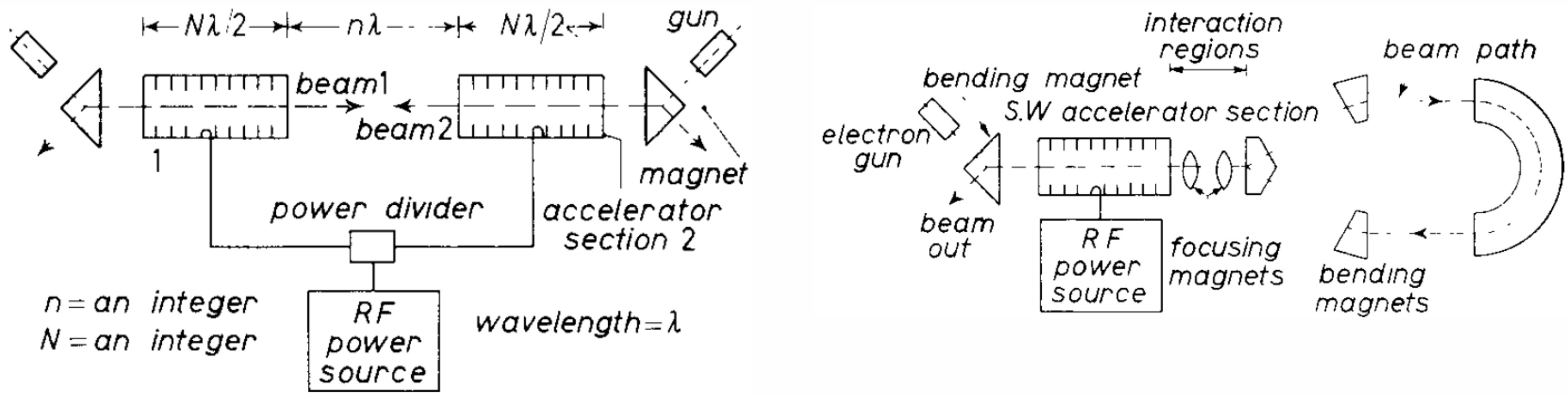


- How to make high power electron colliders?
  - 100+ MW accelerating power anticipated
  - **Option 1**: Throw lots of power into the RF system
    - Maury: "Although in principle it may be possible to produce and handle this large power, the sheer brutishness of the scheme robs it of all appeal."

* So energy recovery is almost exactly one year older than your presenter

Energy Recovery: History

- **February 1965**: Maury Tigner, Nuovo Cimento

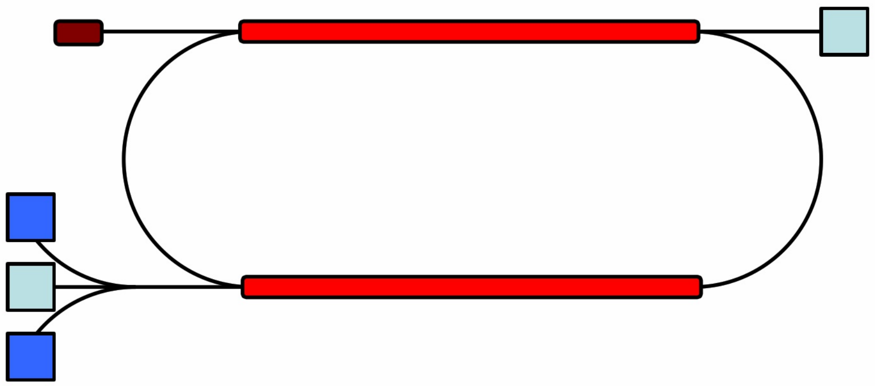


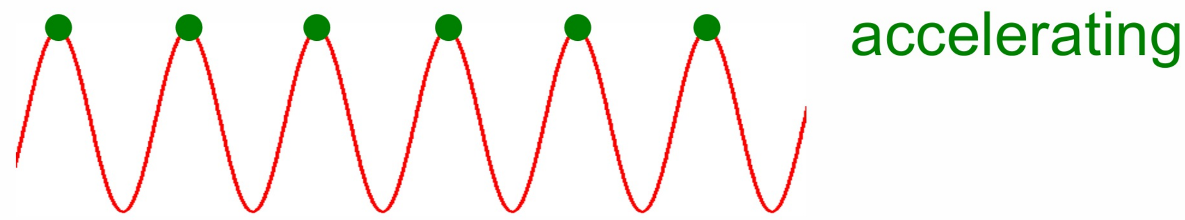
- **Option 2**: Decelerate beam through same RF system
  - Decelerating beam power goes back into cavity fields
  - "Constant" CW beam requires very little net RF drive
    - Ultimately want beam power >> drive power
- Paper: L=3x10^{30} cm^{-2} s^{-1} for 3 GeV 120 mA collider
  - Maury: "A low-density target such as liquid hydrogen might be placed in the return leg of the magnet system"!

360 MW!
1 kW=3e-6!

Energy Recovery Linacs: CEBAF

- CEBAF (a traditional recirculating linear accelerator)



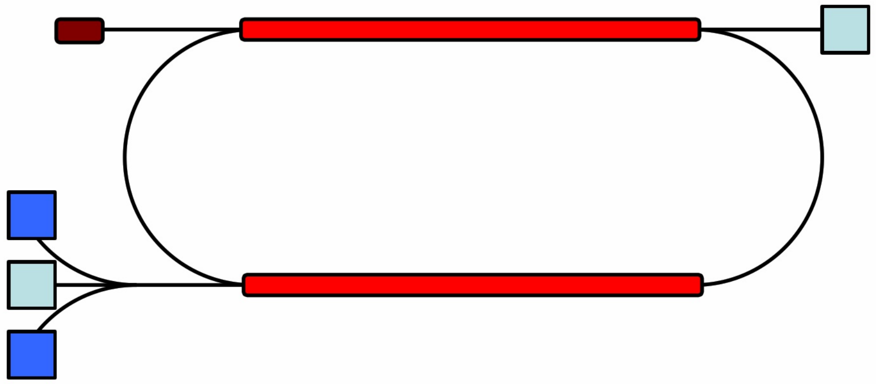


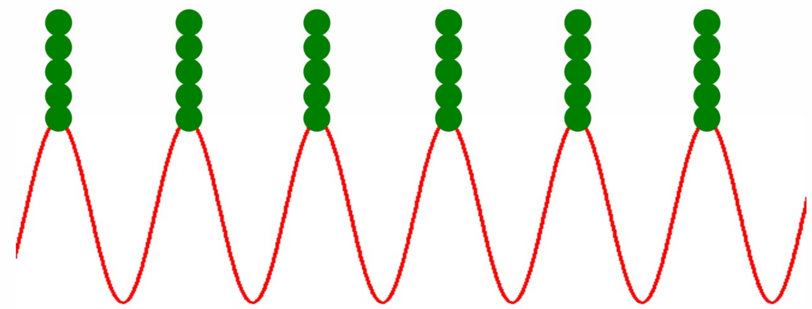
- Applied RF power in linacs drives beam power
  - Up to MW of beam power at A/C beam dumps

- Disadvantages:
  - Cost / contamination of MW class beam dumps
  - MW of power: RF ➔ beam ➔ dump full power
  - Very high power beam operation cost prohibitive

Energy Recovery Linacs: CEBAF

- CEBAF (a traditional recirculating linear accelerator)



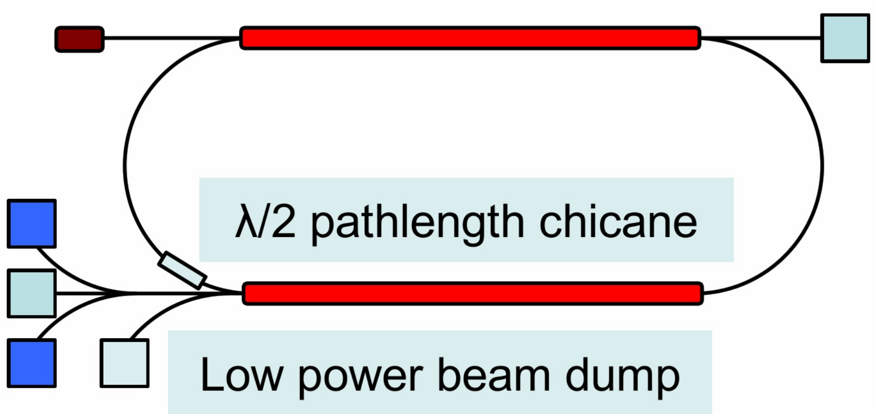


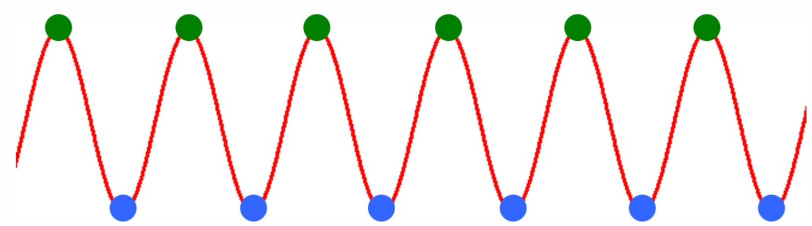
Linac RF voltage (5 passes)
Beam only removes power from RF

- Applied RF power in linacs drives beam power
  - Up to MW of beam power at A/C beam dumps
- Disadvantages:
  - Cost / contamination of MW class beam dumps
  - MW of power: RF ➔ beam ➔ dump full power
  - Very high power beam operation cost prohibitive

Energy Recovery Linacs: ER@CEBAF

- ER@CEBAF: 1-Pass Energy Recovery at CEBAF



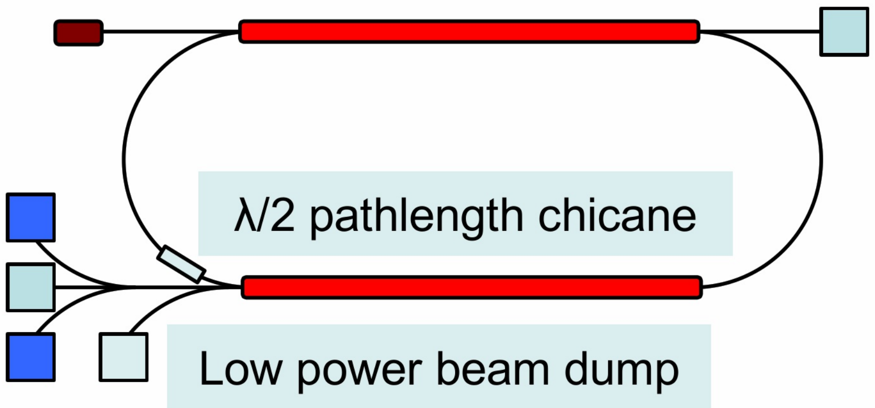


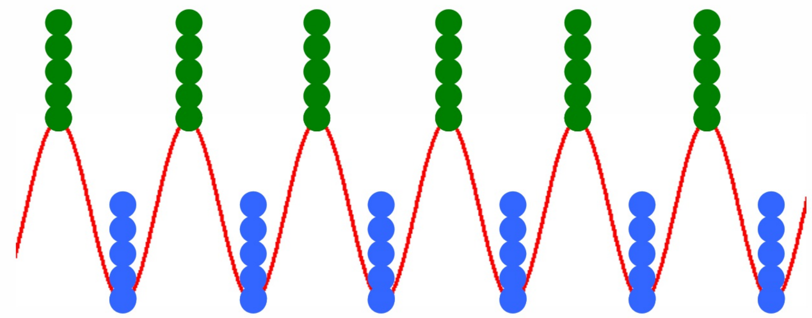
Linac RF voltage (1 pass)
Beams exchange power with RF

- Decelerating beam provides part of RF drive power
  - Can be very efficient with superconducting RF
- Advantages
  - MW of power: RF ➔ beam ➔ dump injector power
  - RF drive power nearly independent of beam current
- A prerequisite for multi-MW electron coolers

Energy Recovery Linacs: ER@CEBAF

- ER@CEBAF: 5-Pass Energy Recovery at CEBAF





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- A “prerequisite” for multi-MW electron coolers

ER is Timely

- ICFA Beam Dynamics Newsletter (Dec 2015)

Year	April	August	December
2016			No. 69 (Collective Effects)
2015	No. 66 (Radiation Damage of Accelerator Components)	No. 67 (Future e+e- Colliders)	No. 68 (ERL and Beam Dynamics Challenges)
2014	No. 63 (Microbunching Instability)	No. 64 (Beam Cooling I)	No. 65 (Beam Cooling II)

http://icfa-usa.jlab.org/archive/newsletter.shtml

- ERL ICFA Advanced Beam Dynamics Workshops

ERL2015: Proceedings of the 56th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

  - 2017, 2015, 2013, 2011, 2009, 2007
  - ERL'17 was held at CERN, 18-23 June

http://www.jacow.org/Main/Proceedings?sel=ABDW

Shameless Promotion

HIGH-CURRENT ENERGY-RECOVERING ELECTRON LINACS

Annu. Rev. Nucl. Part. Sci. 2003. 53:387–429
doi: 10.1146/annurev.nucl.53.041002.110456

Lia Merminga, David R. Douglas, and Geoffrey A. Krafft

"Energy Frontier"

⇩

"Power Frontier"

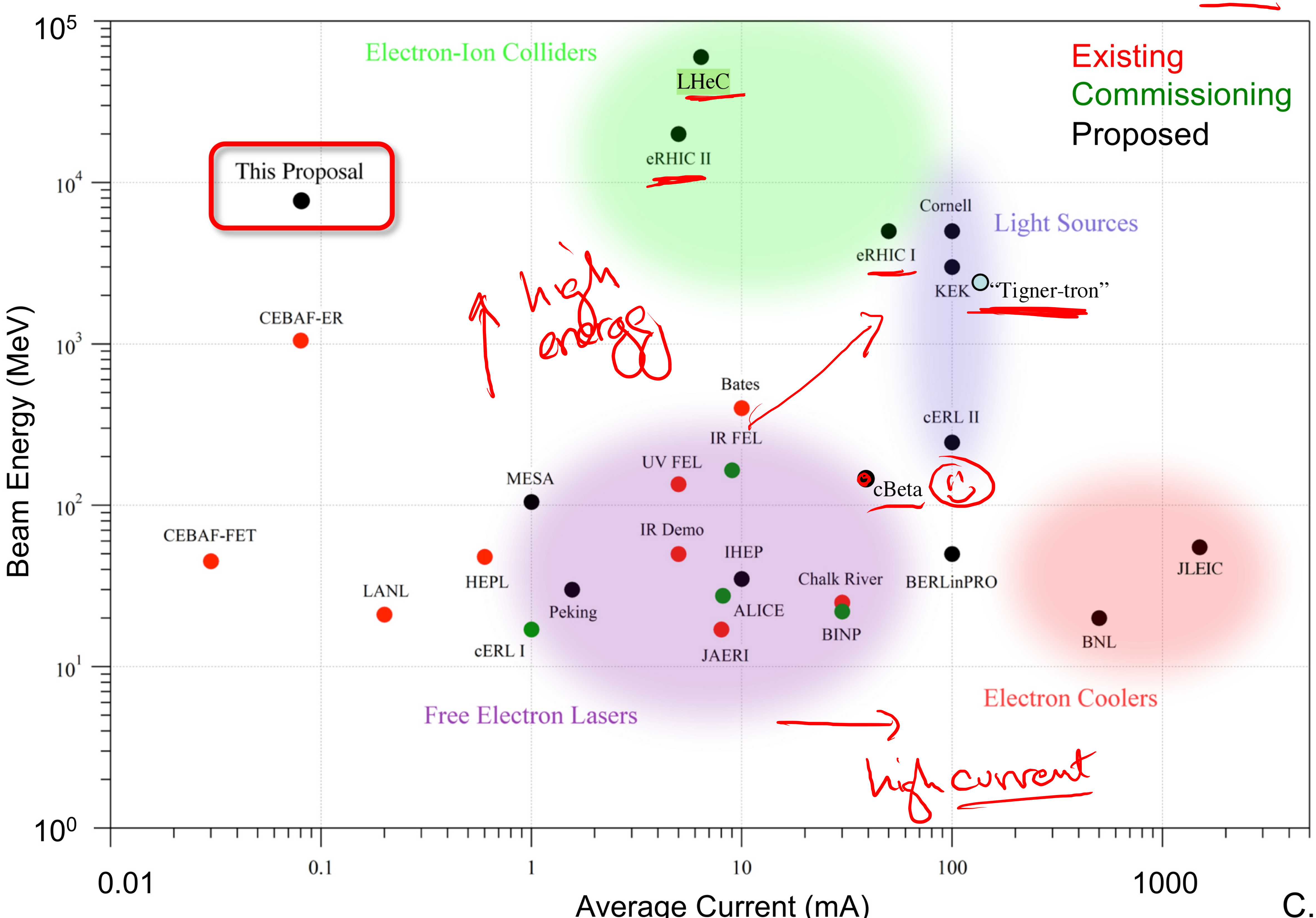
⇧

"Current Frontier"

http://uspas.fnal.gov/materials/05UCB/Merminga-Douglas-Krafft.pdf

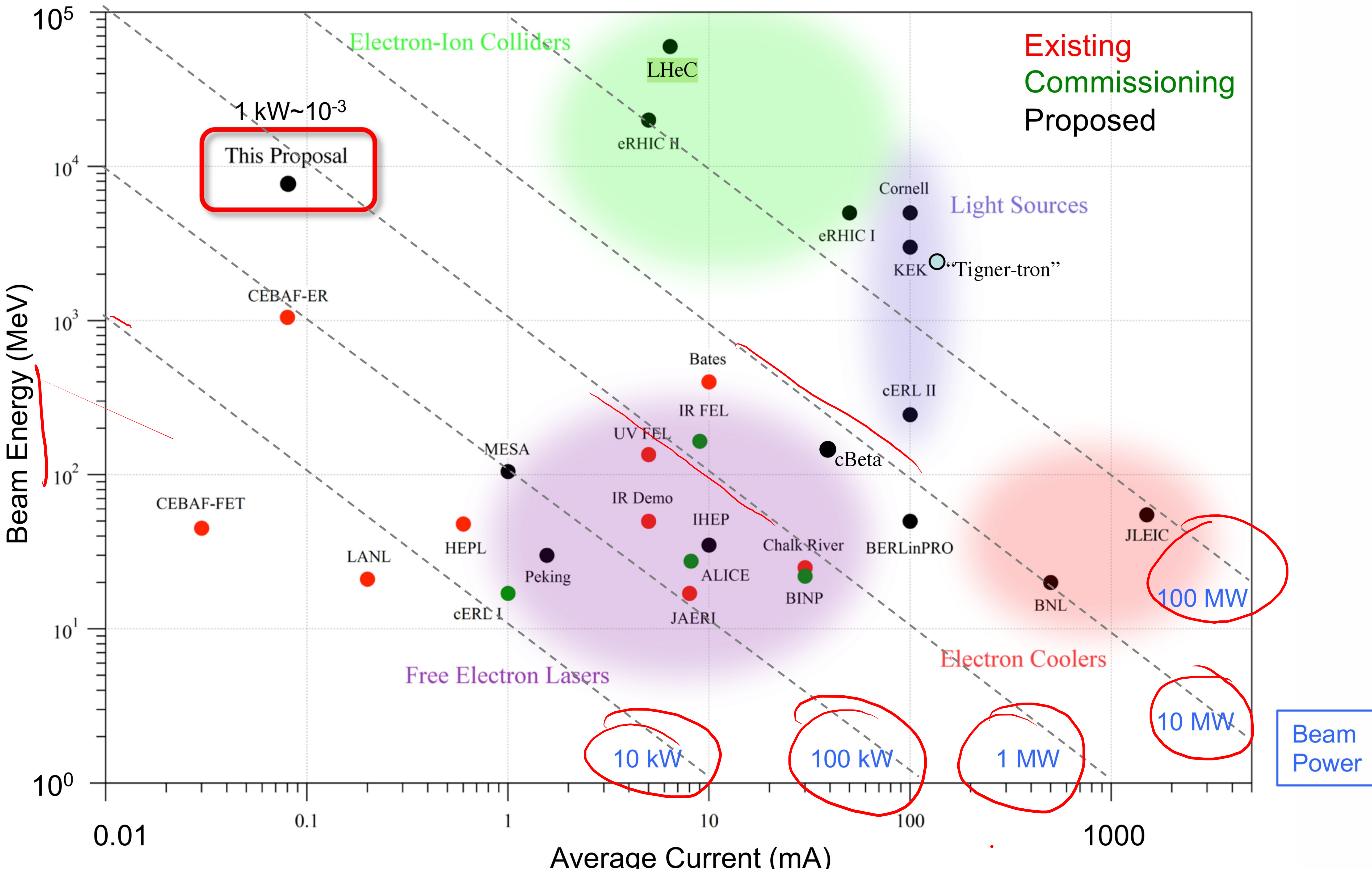
World ERL Landscape

Chris Tennant
JLab

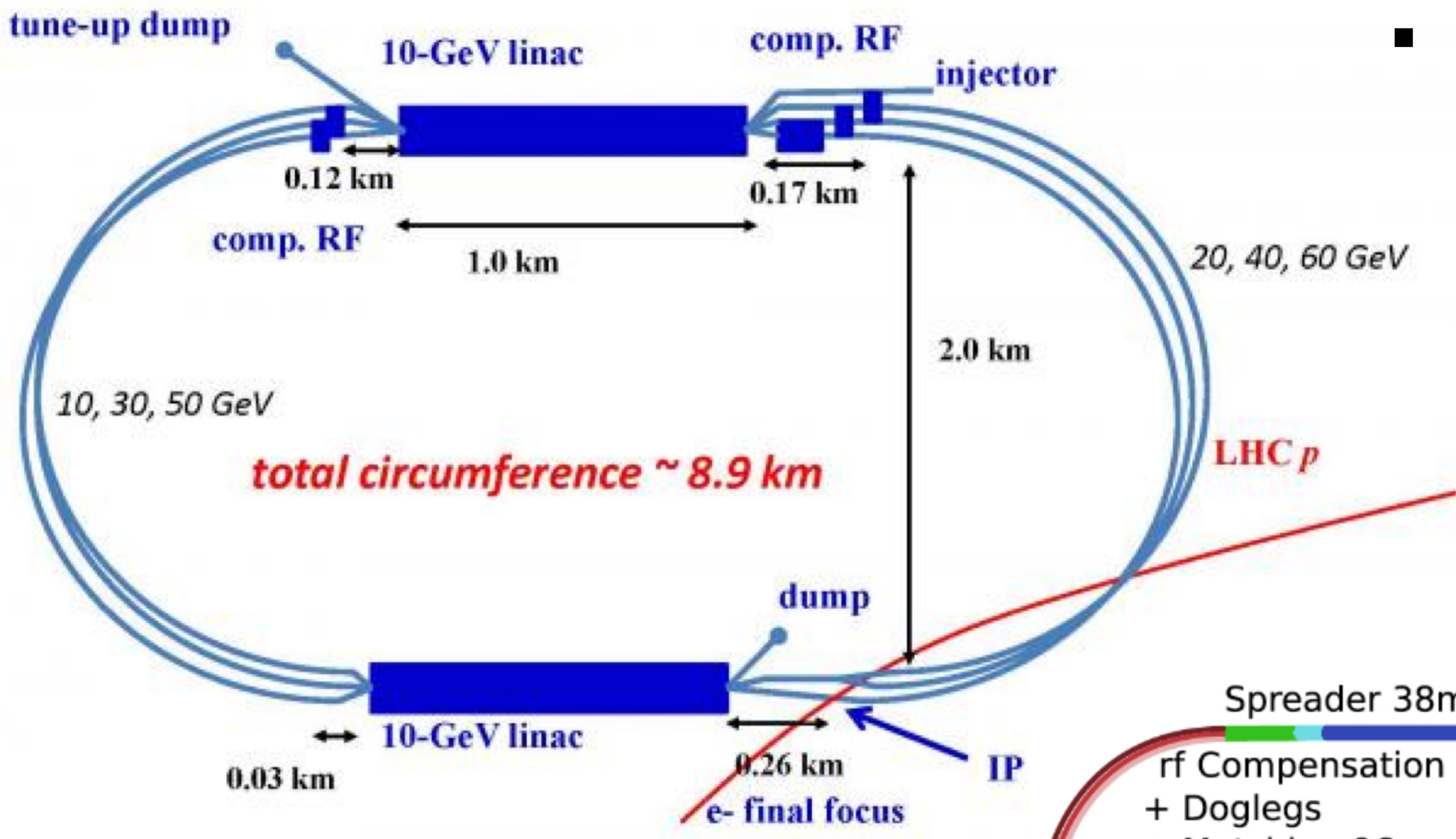


C. Tennant

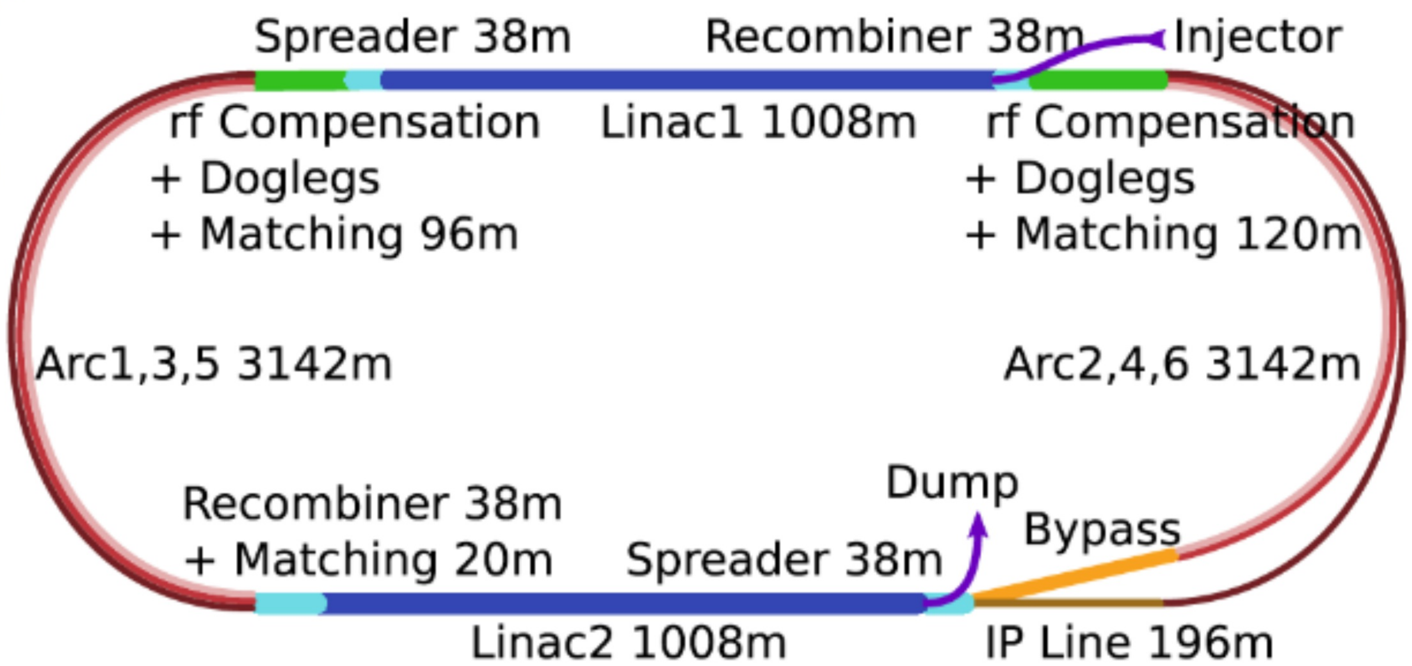
World ERL Landscape: Power



LHeC Electron-Ion Collider ERL



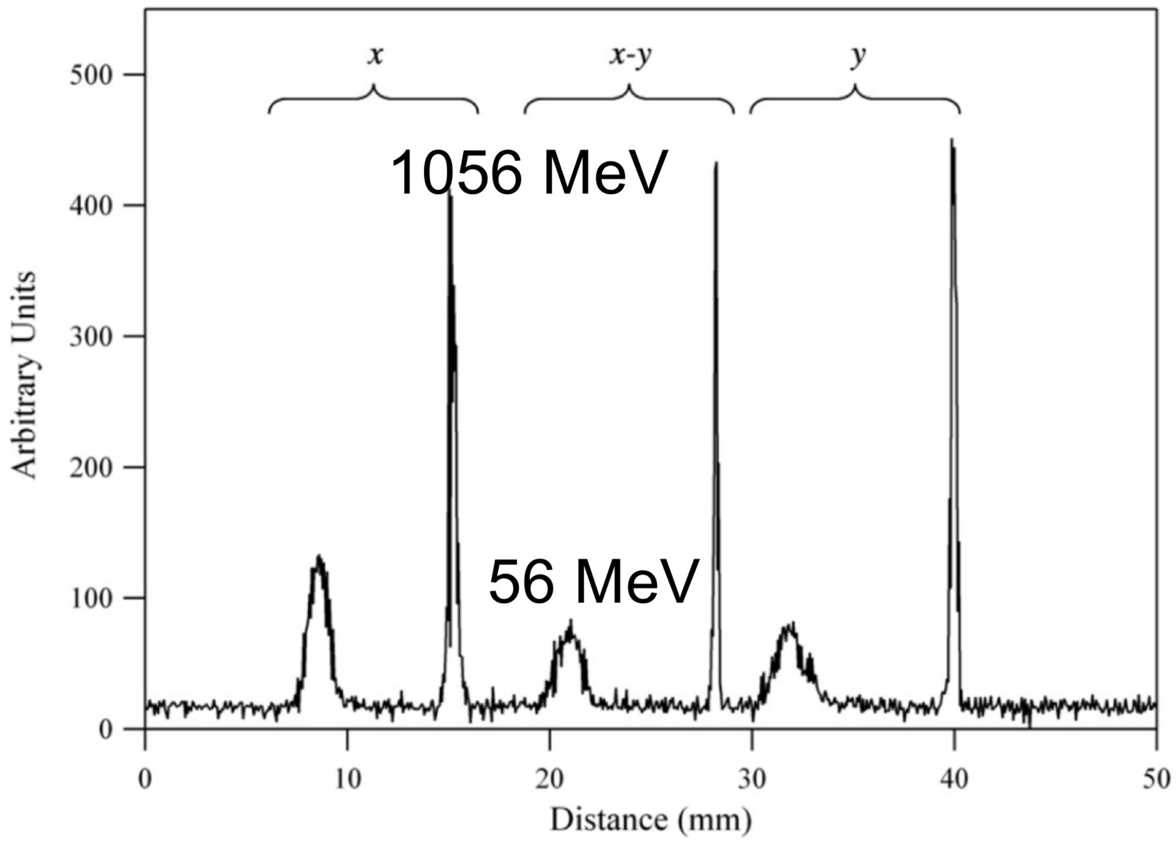
- Collides 6.4 mA 60 GeV e- with LHC protons ➔ 384 MW!



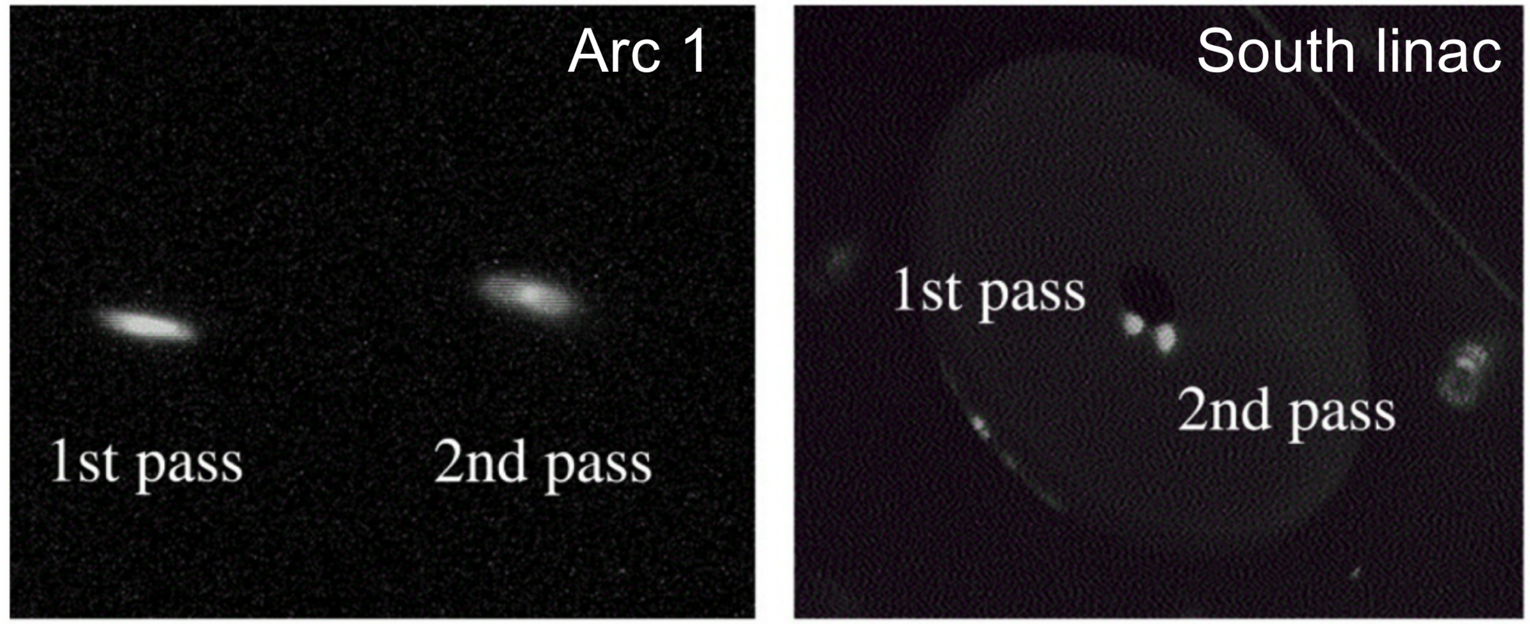
- Meeting on PERLE test ERL demonstrator Orsay Feb 2017

S.A. Bogacz (JLab), D. Pellegrini, A. Latina, D. Schulte (CERN) Dec 2015
http://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.121004

2003 CEBAF-ER Measurements



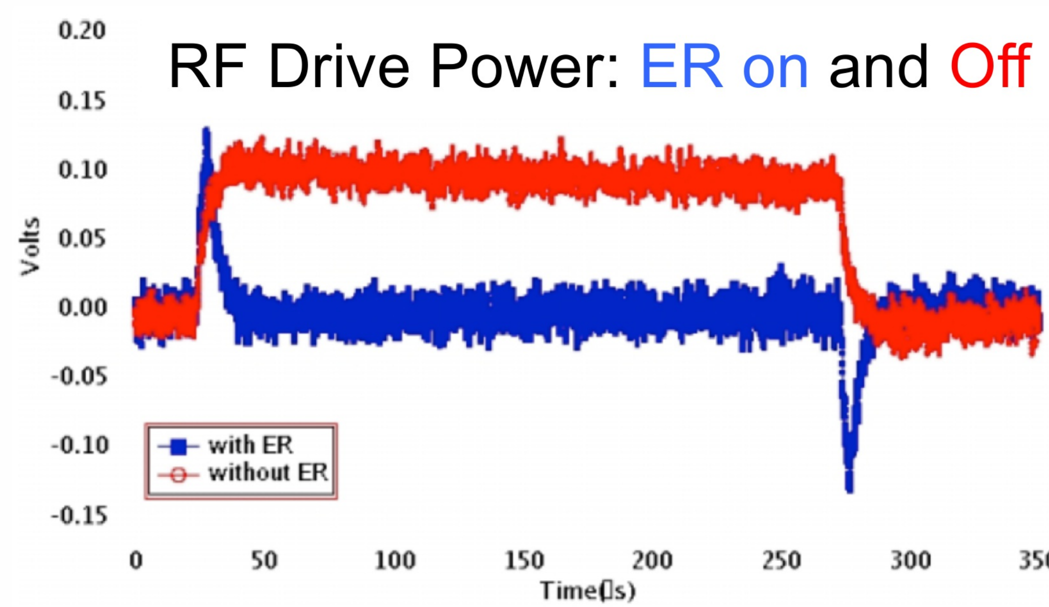
2003 2-pass harp scan (2L24)



2003 2-pass viewer images

- Injector energies: E_{inj}=20 MeV and 56 MeV
- Viewers and harps discriminated multiple pass beams
- 12 GeV era emittance measurements much improved
  - Dispersion control and matching also much improved

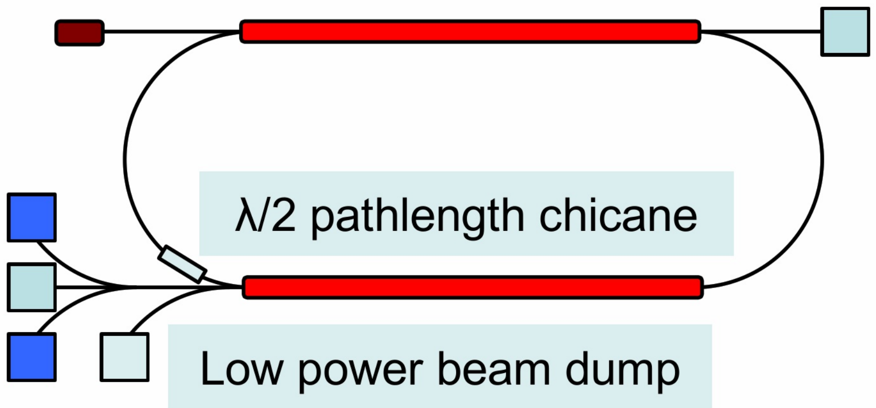
RF Drive Power: ER on and Off

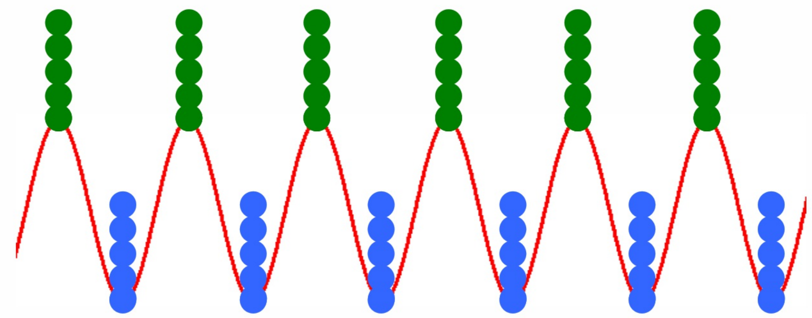


Note RF transients even with ER on!

ER@CEBAF Again

- ER@CEBAF: 5-Pass Energy Recovery at CEBAF





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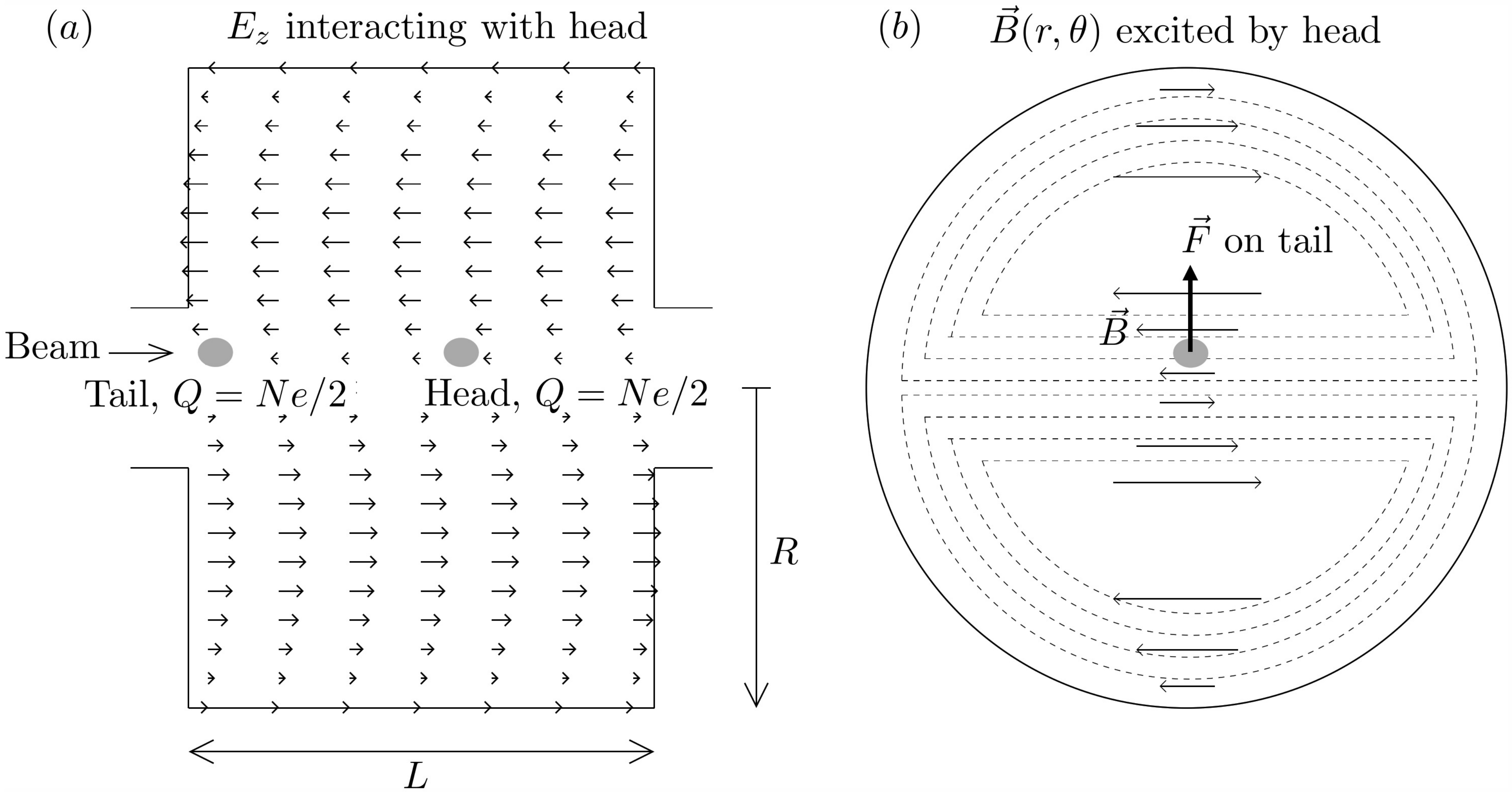
Recirculating Beam Breakup (BBU)

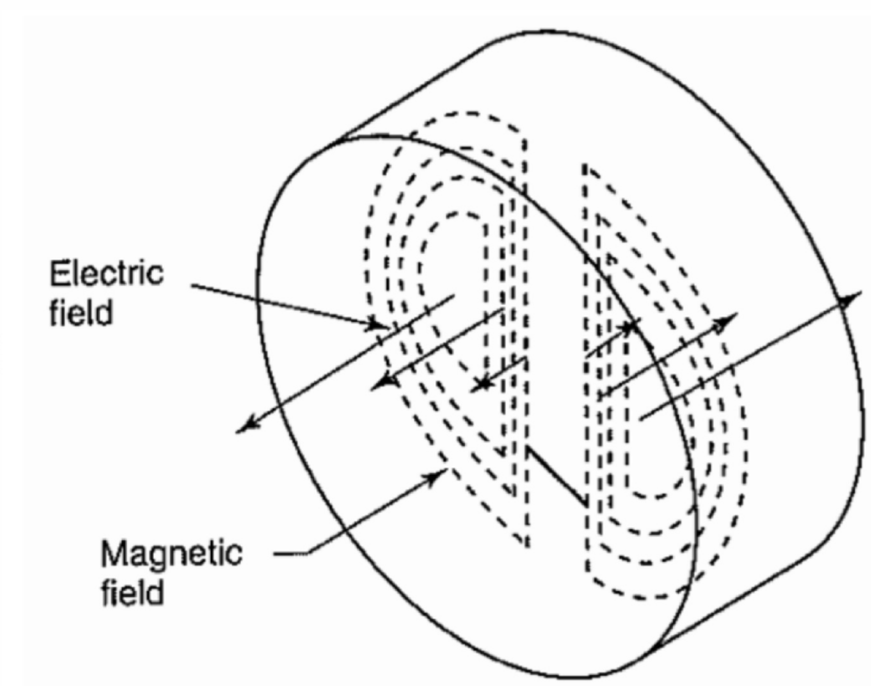
- Recirculating beam breakup
  - Positive feedback loop between beam power and higher order mode RF power
  - Couples through beam transport
  - Many RF higher order modes communicate with beam, each other in near-exponential complexity
  - Limits total beam current

- Open questions in current literature
  - Hofstaetter/Bazarov PRST:AB: Scale as N_{pass} or N_{pass}^2 ?
  - May only be answerable experimentally
  - ER@CEBAF SRF scale is ideal test bed
    - E.g. C100 warm HOM damper loads accessible

http://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.7.054401

BBU Mechanism: TM110 mode





- Recirculating beam breakup RF cavity HOM
  - TM110 mode shown here: illustrates mechanism
- High Q HOM modes are most dangerous
  - Deposited power rings for longer time
  - More chance for positive feedback with later bunches