USPAS Accelerator Physics 2019
Northern Illinois University and UT-Batelle

14+: Electron Linacs, FELs, and ERLs

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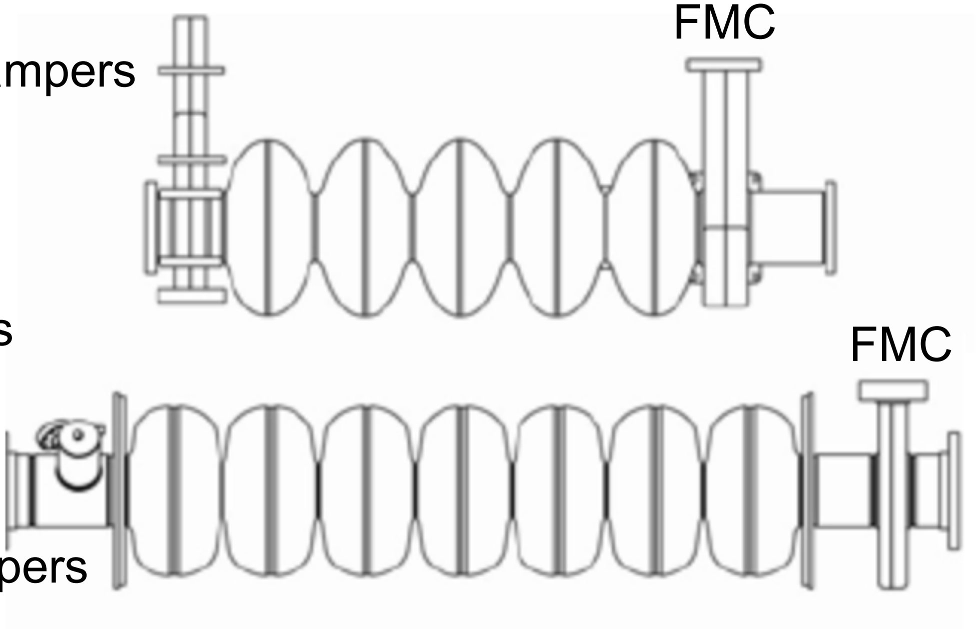
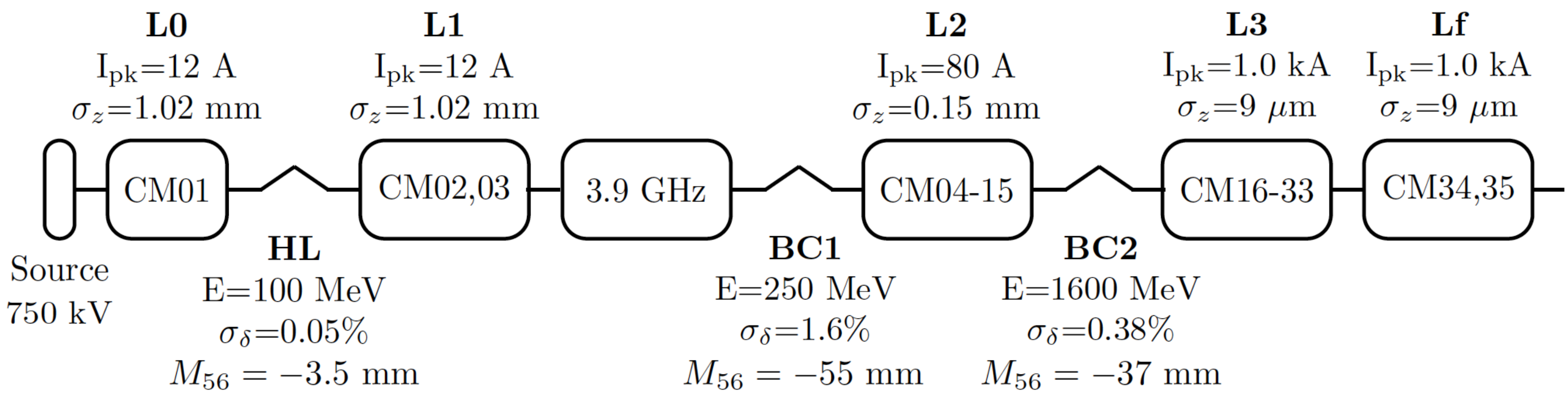
Happy birthday to Thomas Merton, Norman Mailer, and Philip Glass!
Happy Hug and Economist Day, Scotch Tape Day, and Eat Brussel Sprouts Day!

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: LCLS-II Layout



- Completely dominated by accelerating structures
  - Only one main frequency, and a few cavities of its harmonic!
- Bunch length shrinks drastically: mm to um
  - Short bunches **required** for FEL lasing
  - Fractional momentum spread shrinks due to adiabatic damping

Electron Linacs: Negligible RF Focusing

- Longitudinal effective drift: M_{56} without additional magnets

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

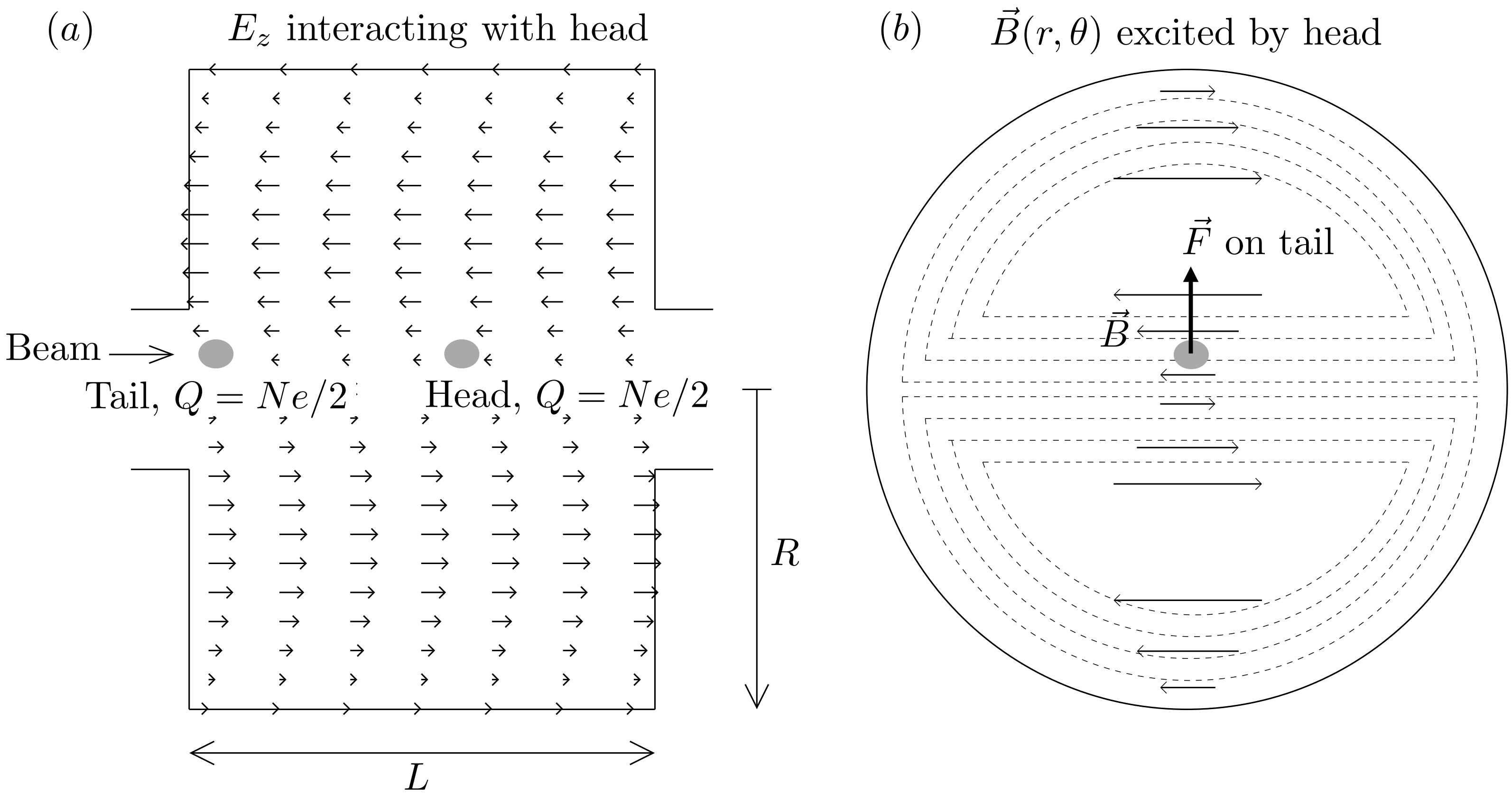
$$L_e = -\frac{1}{mc^2} \boxed{\frac{1}{\beta^2\gamma^3}} \frac{2\pi(s_{n+1} - s_n)}{\lambda_{RF}}$$

$$\beta \approx 1$$
$$\gamma \sim o(10^2 - 10^4)$$

  - No longitudinal focusing: bunch distribution is very nearly **frozen** in electron linac (though not in chicanes/other magnets!)
  - Maximize energy gain per meter: run **on crest** in principle
- Radial defocusing is also negligible (cf ion linacs)

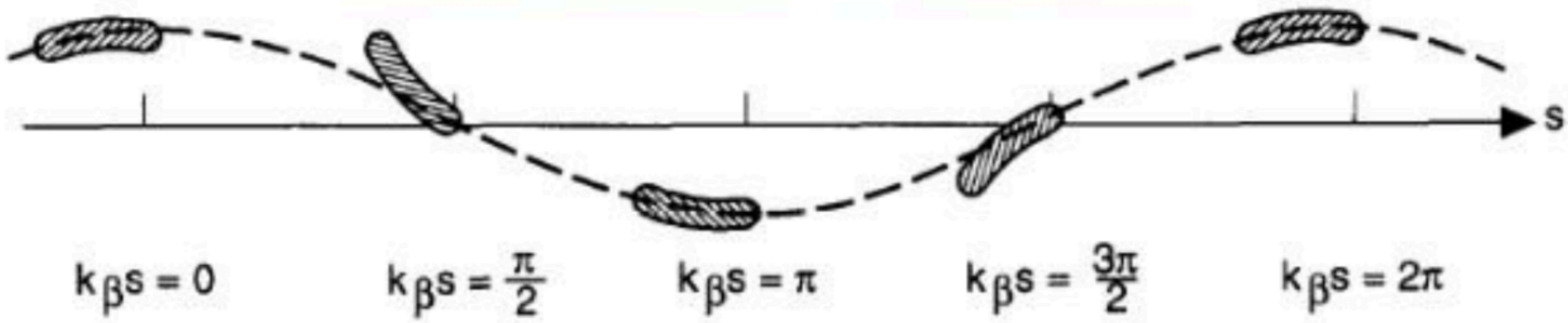
$$\Delta r' = -\frac{\pi q E_0 T_1 L}{mc^2 \boxed{\beta^3\gamma^3} \lambda} \cdot \sin(\phi_r) \cdot r$$

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



Tail amplitude grows over traversal of many cavities

14.5: BBU Formalism and Rescue via BNS

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

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

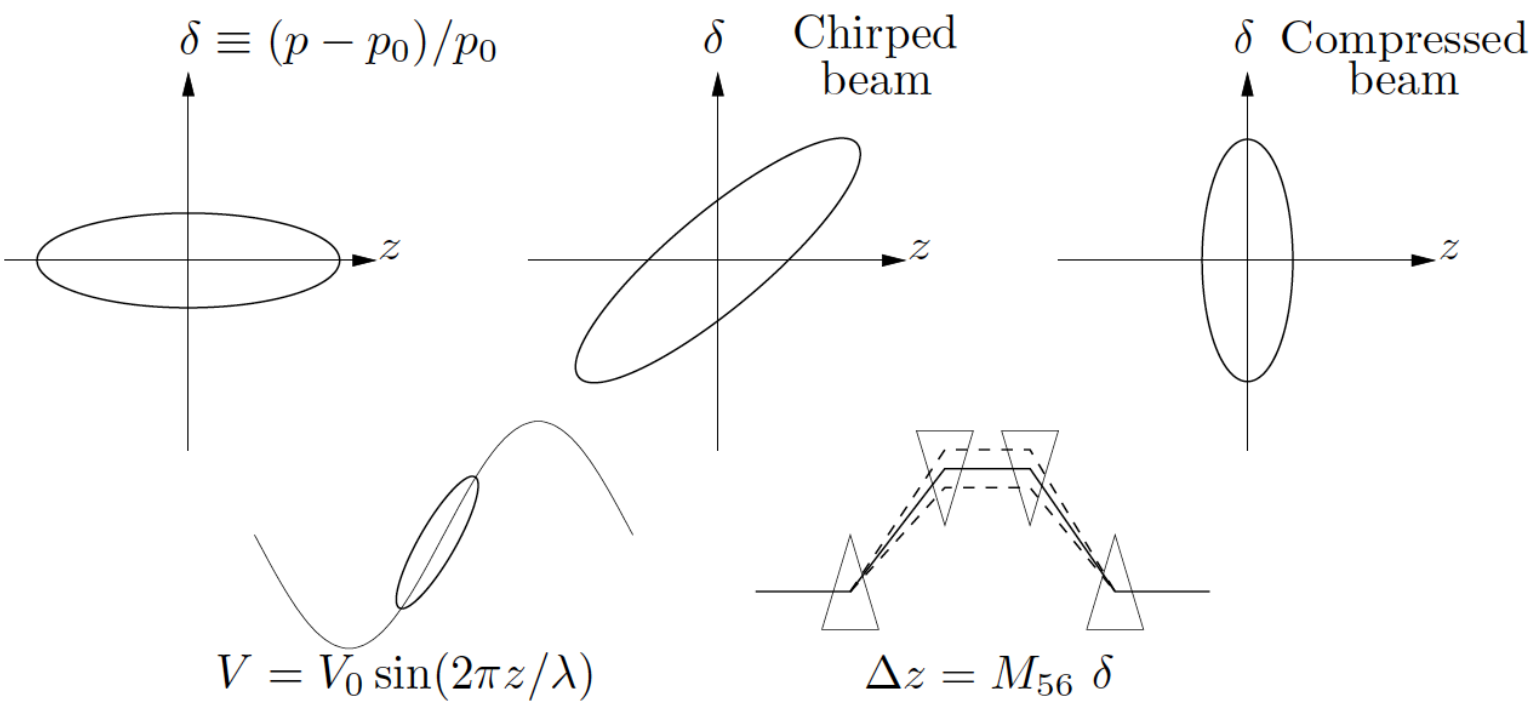
$$x_{\mathrm{tail}}(s) \;=\; \hat{x}\cos(k_\beta s) - \left(\frac{Ne^2W_1(z)}{4k_\beta EL}\right) s\,\hat{x}\,\sin(k_\beta s) \qquad (14.24)$$

- 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

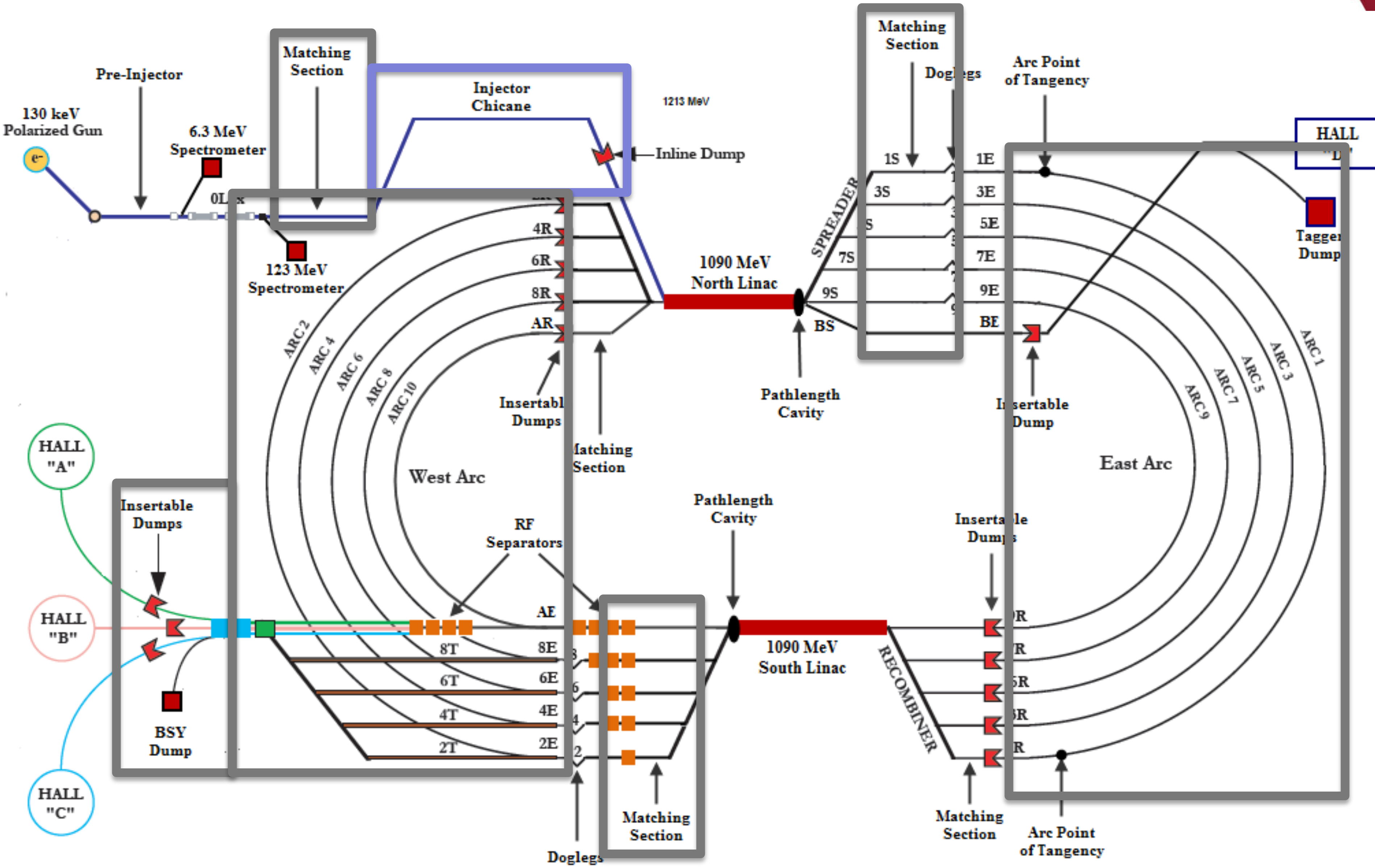
$$\delta k_\beta \;=\; -\frac{Ne^2W_1(z)}{4\,k_\beta\,EL}$$

14.3: Bunch Compressors/Decompressors

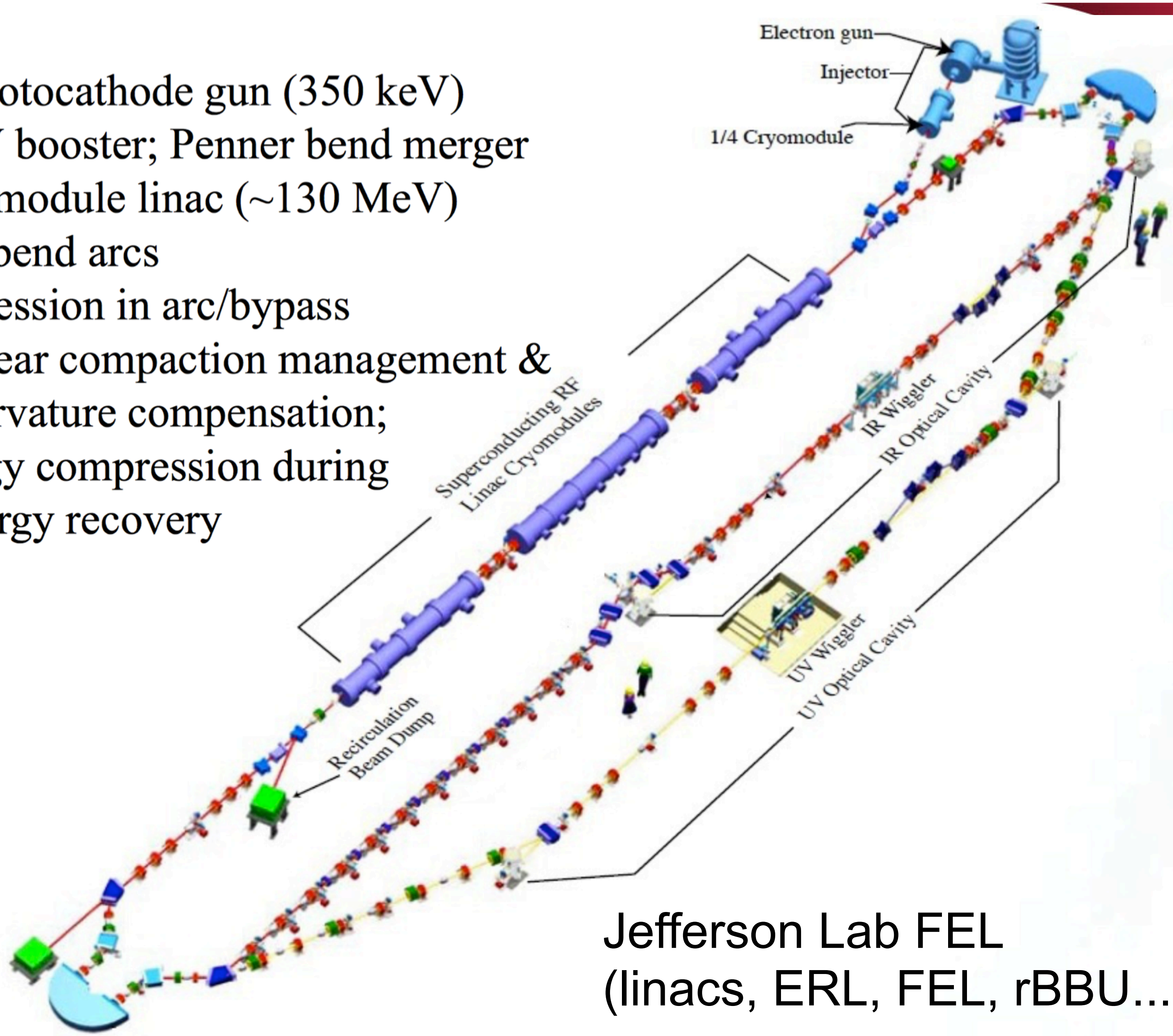
- How does one manipulate electron bunch lengths?
  - Important for FELs (short bunches)
  - Important for handling instabilities (CSR/uBI for short bunches) by lengthening bunches



CEBAF Detail Schematic



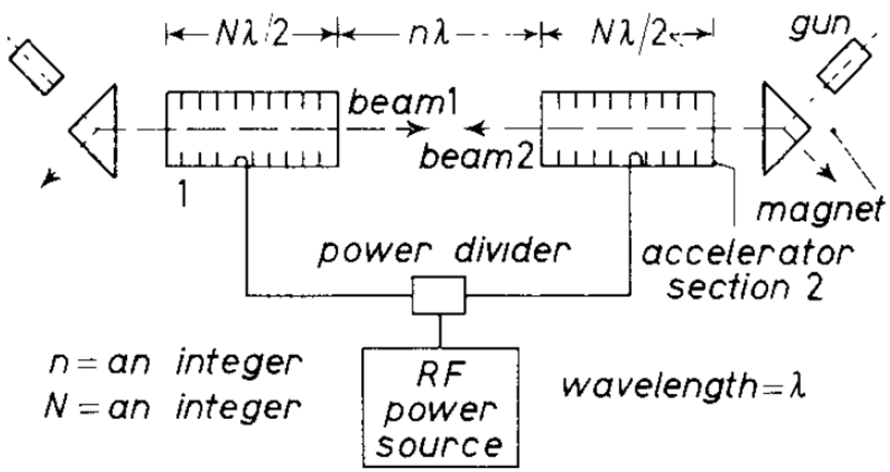
- DC photocathode gun (350 keV)
- 9 MeV booster; Penner bend merger
- 3 cryomodule linac (~130 MeV)
- Bates bend arcs
- compression in arc/bypass
- nonlinear compaction management & RF curvature compensation; energy compression during energy recovery

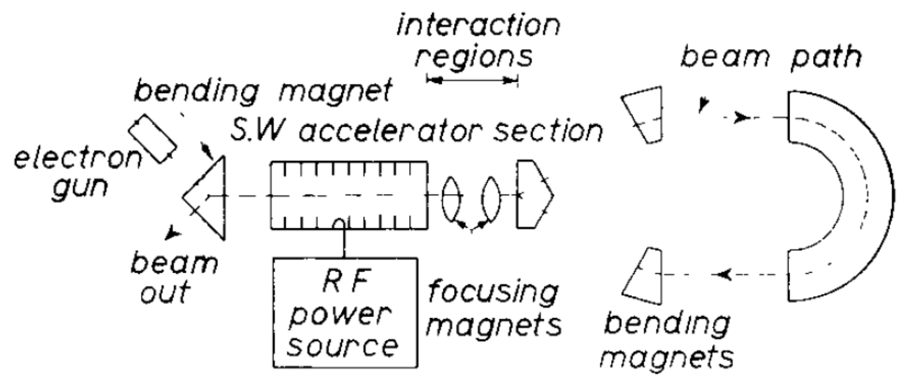


Jefferson Lab FEL
(linacs, ERL, FEL, rBBU...)

Energy Recovery: History

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



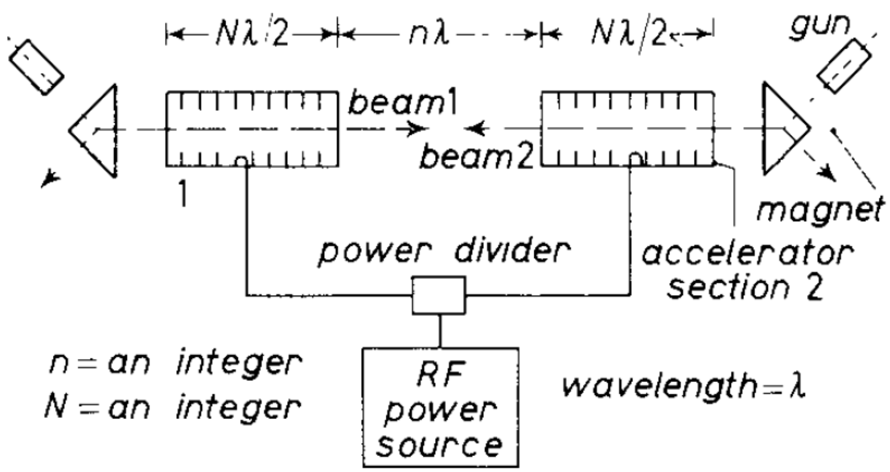


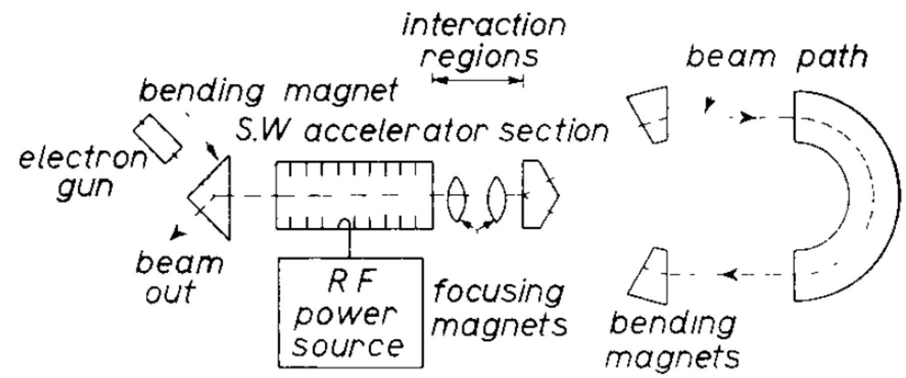
- How to make high power electron colliders?
  - 100+ MW accelerating power anticipated
  - **Option 1**: Throw lots of power into the RF system
    - Maury: "Although in principle it may be possible to produce and handle this large power, the sheer brutishness of the scheme robs it of all appeal."

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

Energy Recovery: History

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



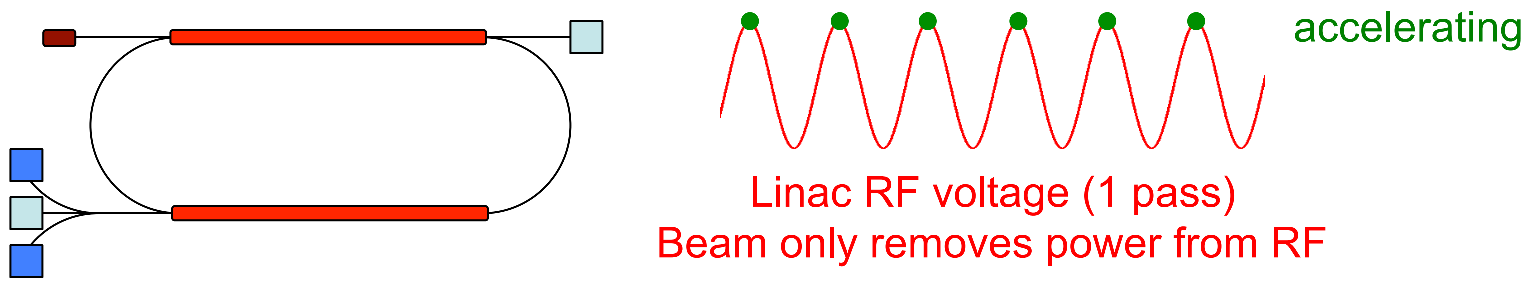


- **Option 2**: Decelerate beam through same RF system
  - Decelerating beam power goes back into cavity fields
  - "Constant" CW beam requires very little net RF drive
    - Ultimately want beam power >> drive power
- Paper: L=3x10^{30} cm^{-2} s^{-1} for 3 GeV 120 mA collider
  - Maury: "A low-density 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

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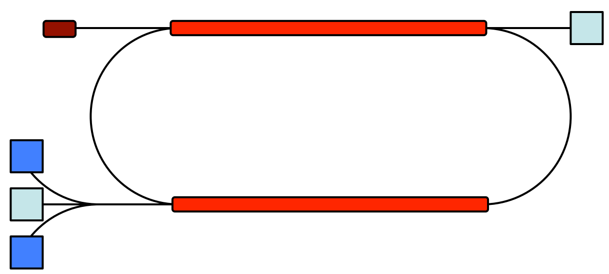

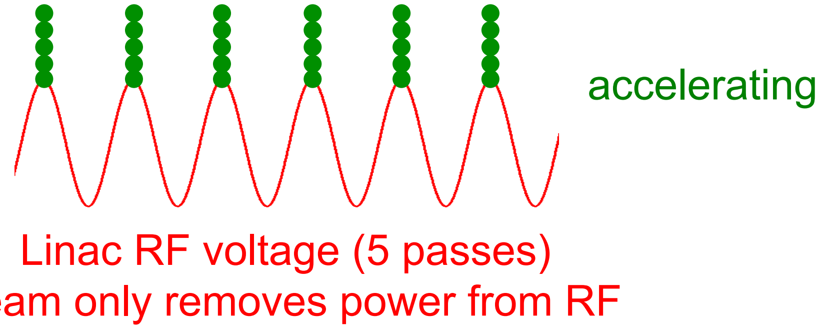

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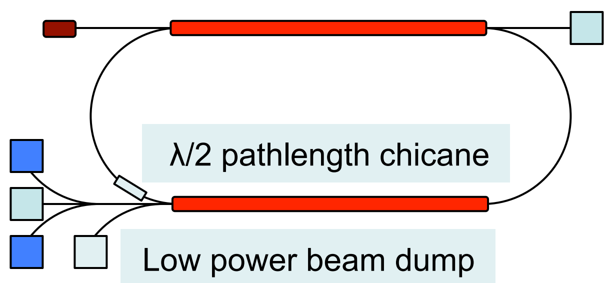
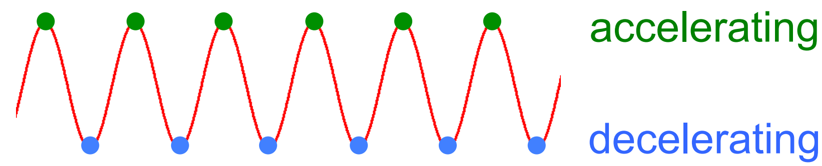
Energy Recovery Linacs: ER@CEBAF

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



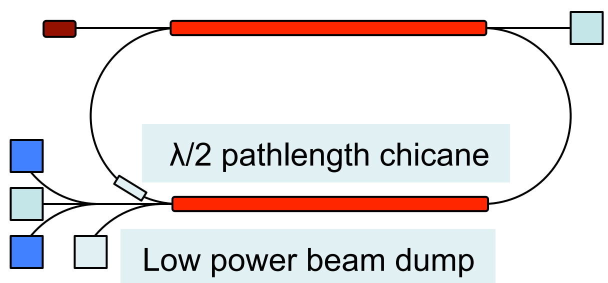


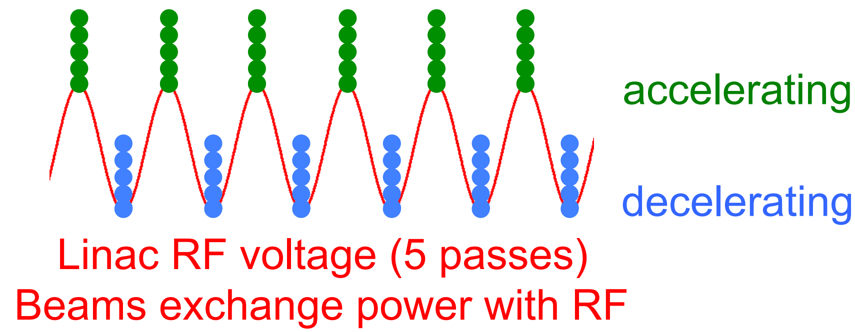
Linac RF voltage (1 pass)
Beams exchange power with RF

- 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

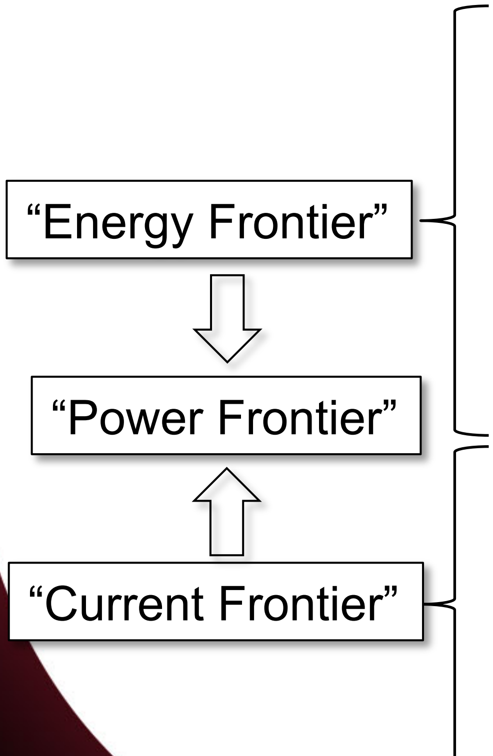
http://www.jacow.org/Main/Proceedings?sel=ABDW

Shameless Promotion

HIGH-CURRENT ENERGY-RECOVERING ELECTRON LINACS

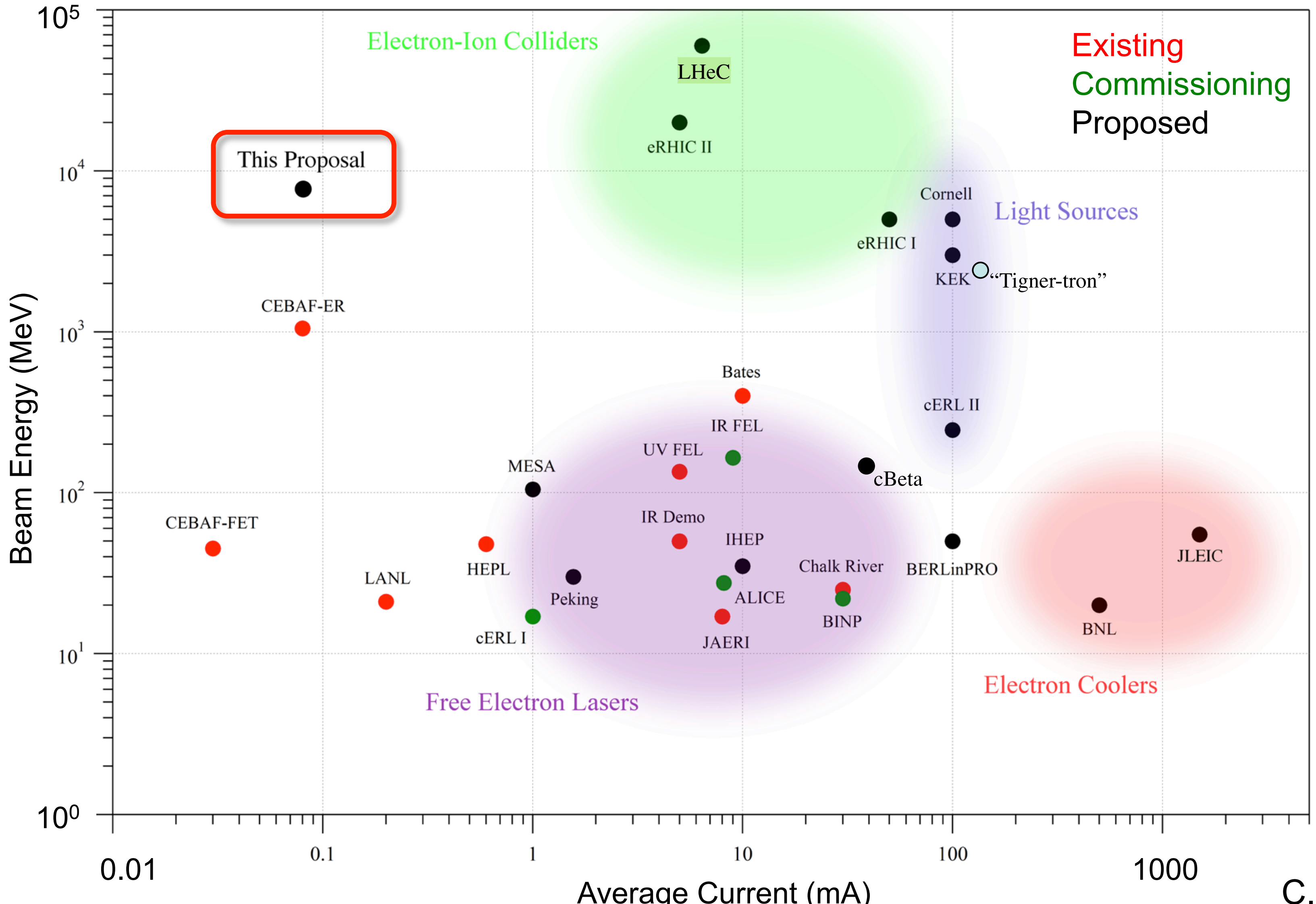
Annu. Rev. Nucl. Part. Sci. 2003. 53:387–429
doi: 10.1146/annurev.nucl.53.041002.110456

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



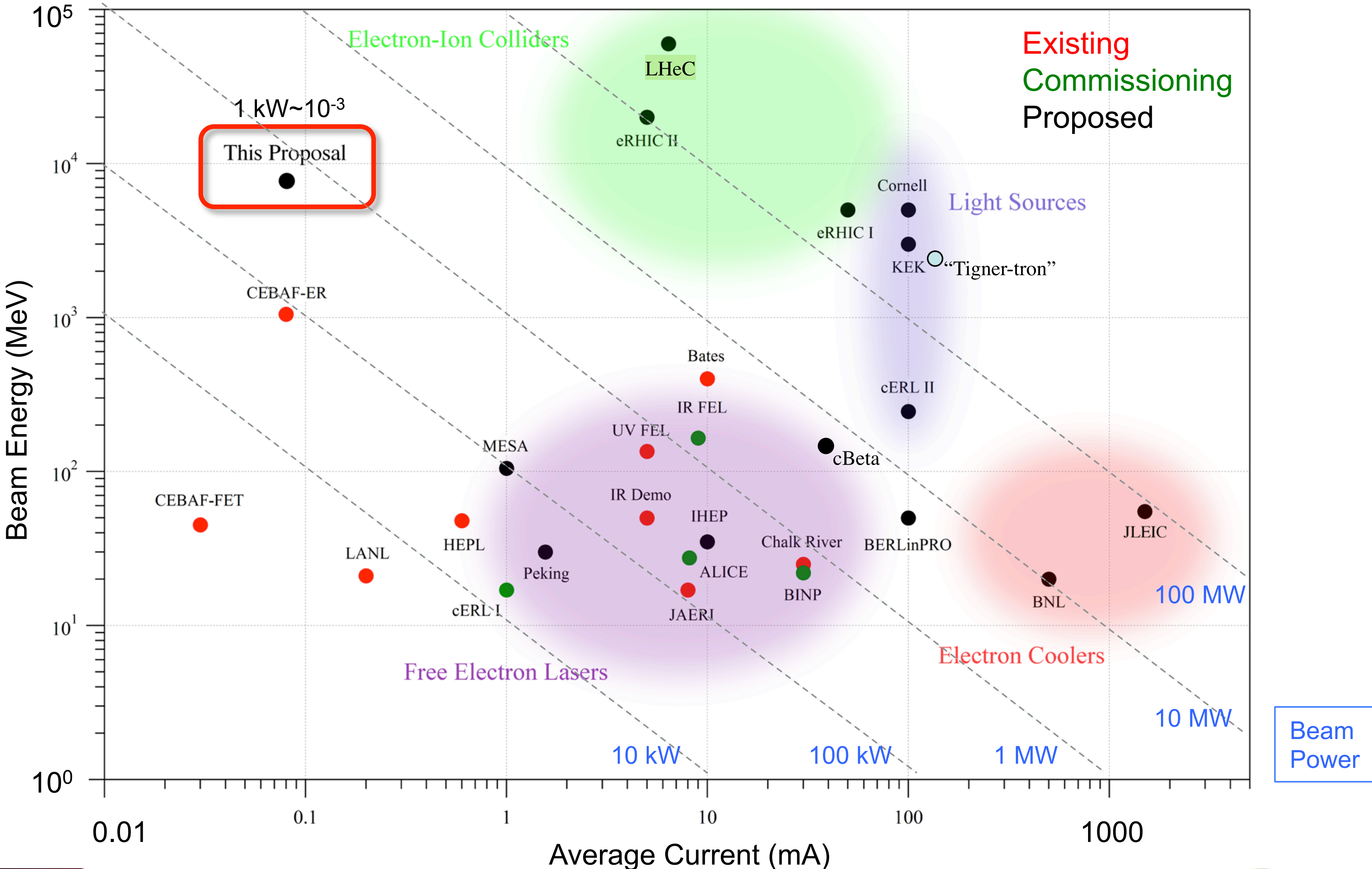
http://uspas.fnal.gov/materials/05UCB/Merminga-Douglas-Krafft.pdf

World ERL Landscape



C. Tennant

World ERL Landscape: Power

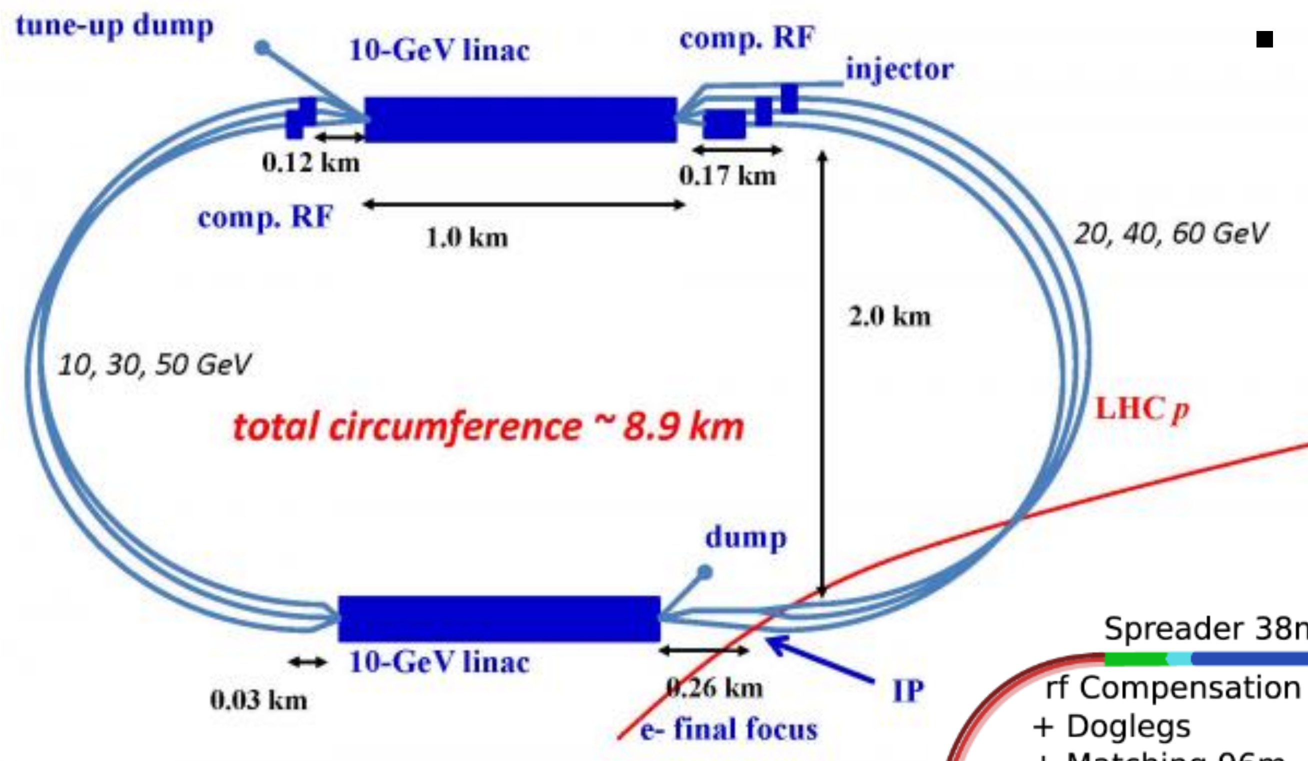


ERLs at Jefferson Lab

- Jefferson Lab has a history of world leadership in ERLs
  - 1993: CEBAF front end ERL test
  - 1998-2001: IR FEL demo
    - First demonstration of ERL-based light source
  - 2002-3: CEBAF one-pass energy recovery expt
    - Remains world leader in ERL beam energy
  - 2002-10: UV FEL
    - Remains world leader in beam power (2 MW)
  - Present: Electron-ion collider ERL collaborations
    - LHeC, BNL

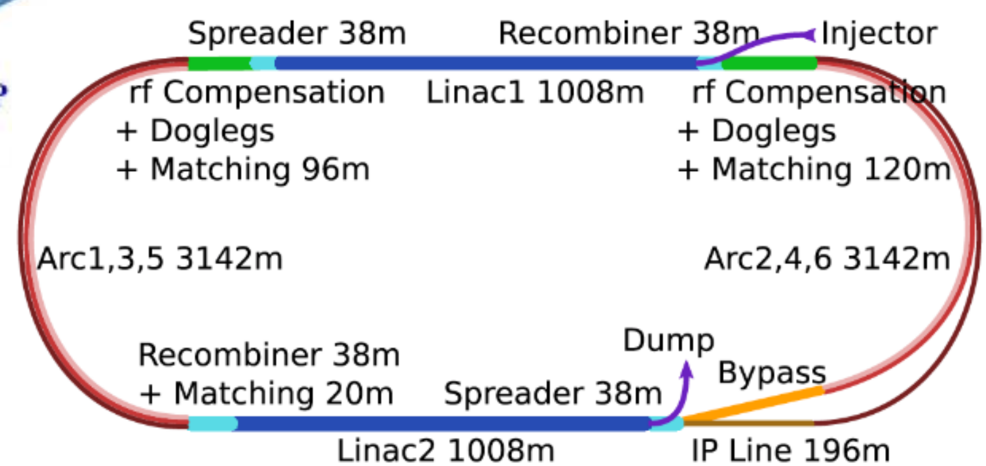
- ER@CEBAF will make Jefferson Lab a world leader in high energy ERL beam and RF studies

LHeC Electron-Ion Collider ERL



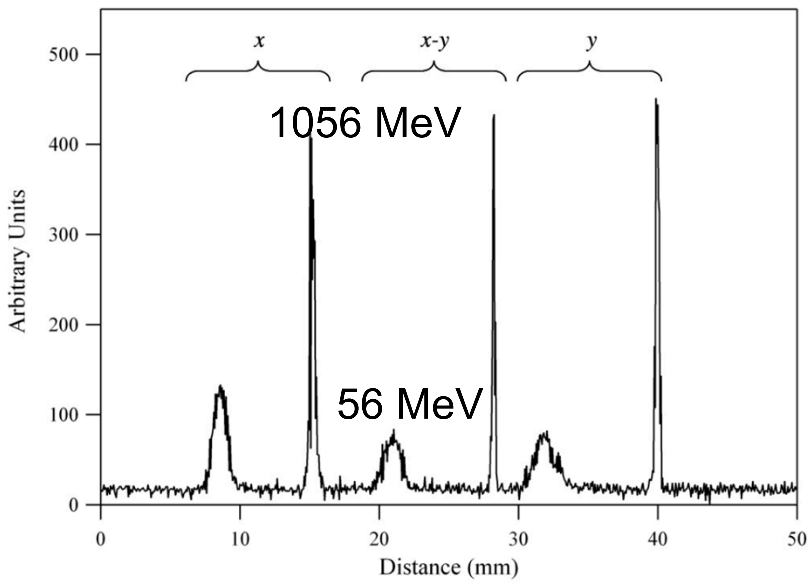
- Collides 6.4 mA 60 GeV e- with LHC protons ➔ 384 MW!

- Meeting on PERLE test ERL demonstrator Orsay Feb 2017

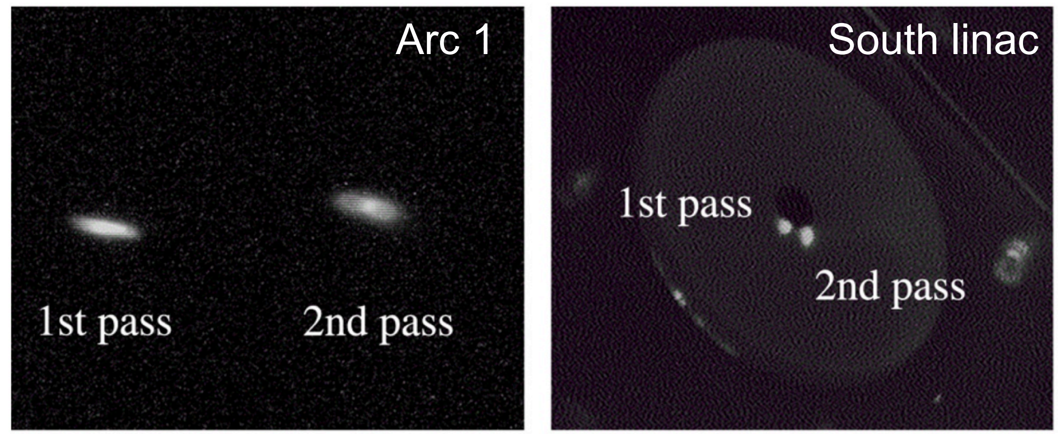


S.A. Bogacz (JLab), D. Pellegrini, A. Latina, D. Schulte (CERN) Dec 2015
http://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.121004

2003 CEBAF-ER Measurements

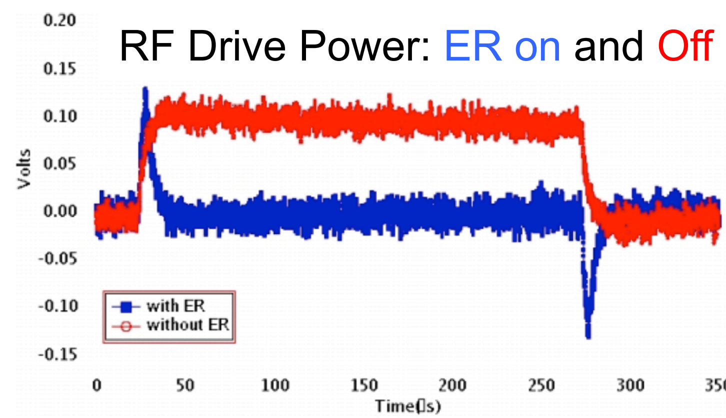


2003 2-pass harp scan (2L24)



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



Note RF transients even with ER on!

Collaboration

ER@CEBAF: A Test of 5-Pass Energy Recovery at CEBAF

S.A. Bogacz, D. Douglas, C. Dubbe, A. Hutton, T. Michalski,
F. Pilat, Y. Roblin, T. Satogata*, M. Spata, C. Tennant, M. Tiefenback
Jefferson Lab, Newport News, VA 23606, USA

I. Ben-Zvi, Y. Hao, P. Korysko, C. Liu, F. Méot*, M. Minty,
V. Ptitsyn, G. Robert-Demolaize, T. Roser, P. Thieberger, N. Tsoupas
Brookhaven National Laboratory, Upton, NY 11973, USA

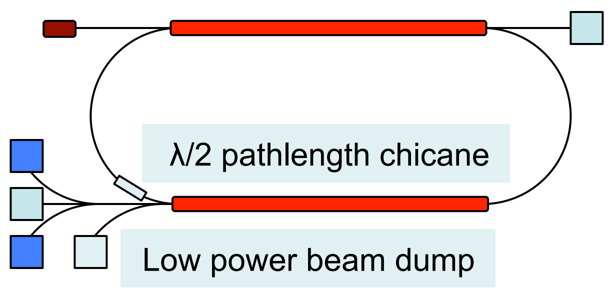
* Co-spokesperson

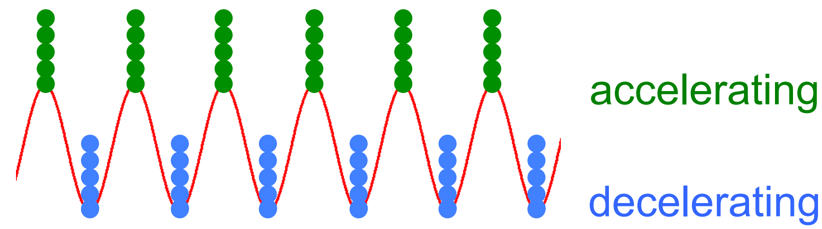
A collaboration between Jefferson Lab and BNL
(Also an amusing football game)

Meetings (on and off) since July 2015

ER@CEBAF Again

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

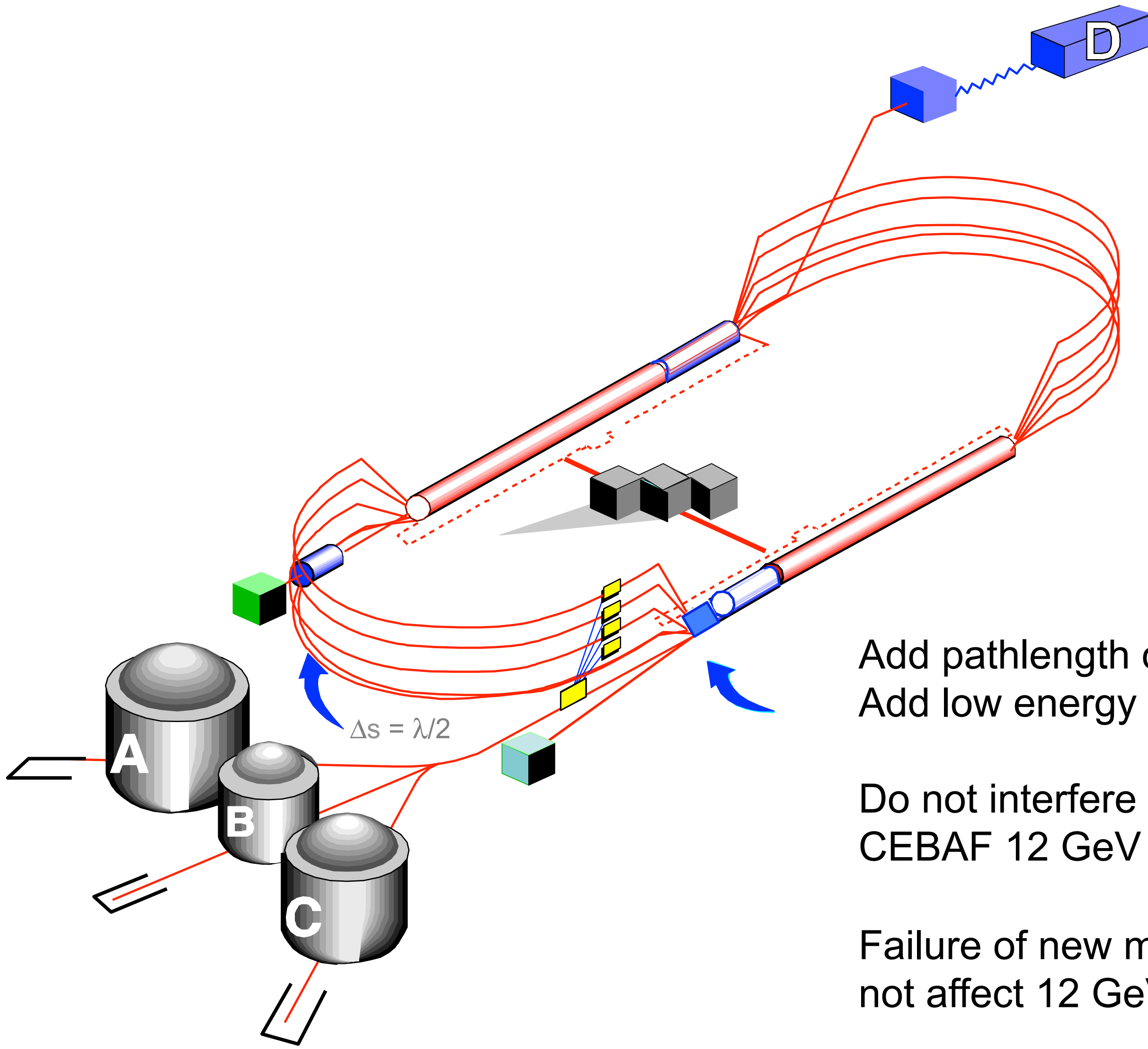




Linac RF voltage (5 passes)
Beams exchange power with RF

- 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

ER@CEBAF



Add pathlength chicane
Add low energy dump line

Do not interfere with existing CEBAF 12 GeV capabilities

Failure of new magnets does not affect 12 GeV capability

A. Bogacz

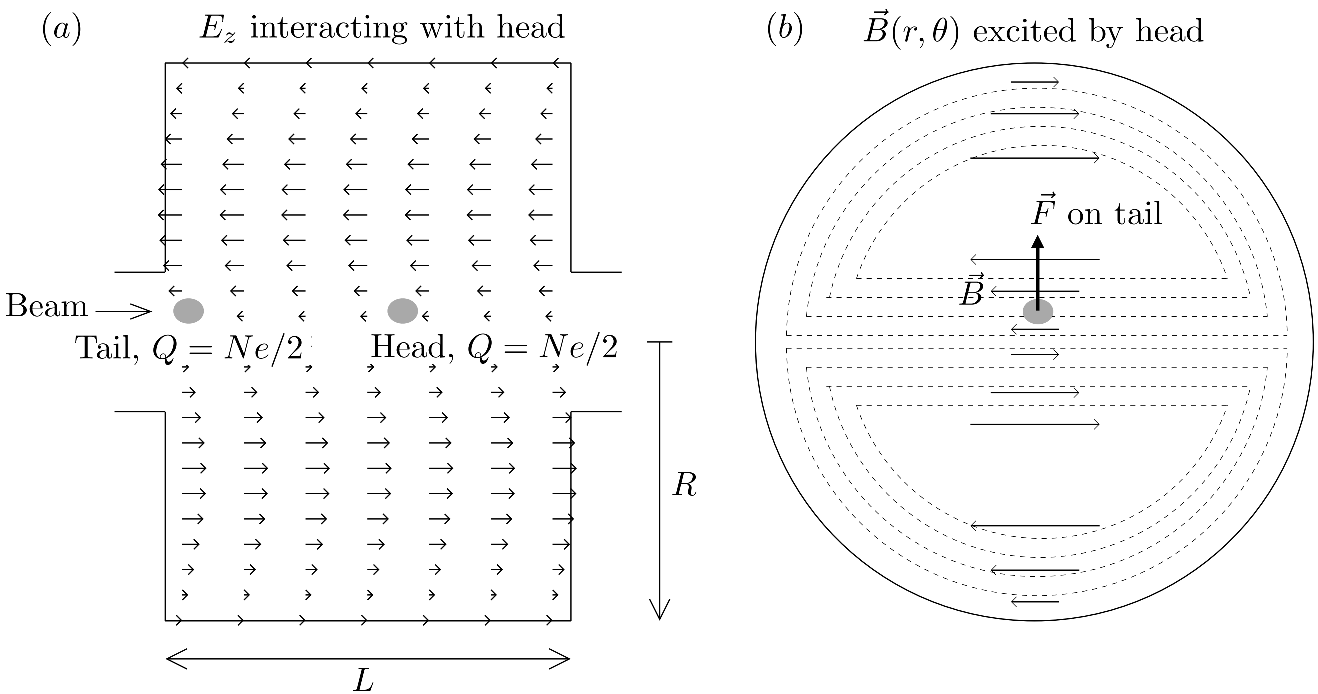
Recirculating Beam Breakup (BBU)

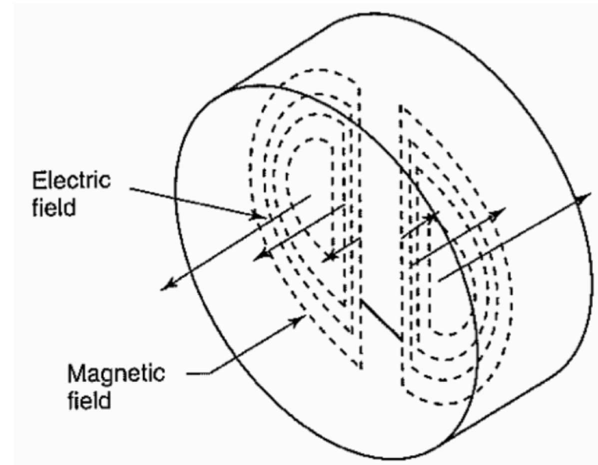
- Recirculating beam breakup
  - Positive feedback loop between beam power and higher order mode RF power
  - Couples through beam transport
  - Many RF higher order modes communicate with beam, each other in near-exponential complexity
  - Limits total beam current

- 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

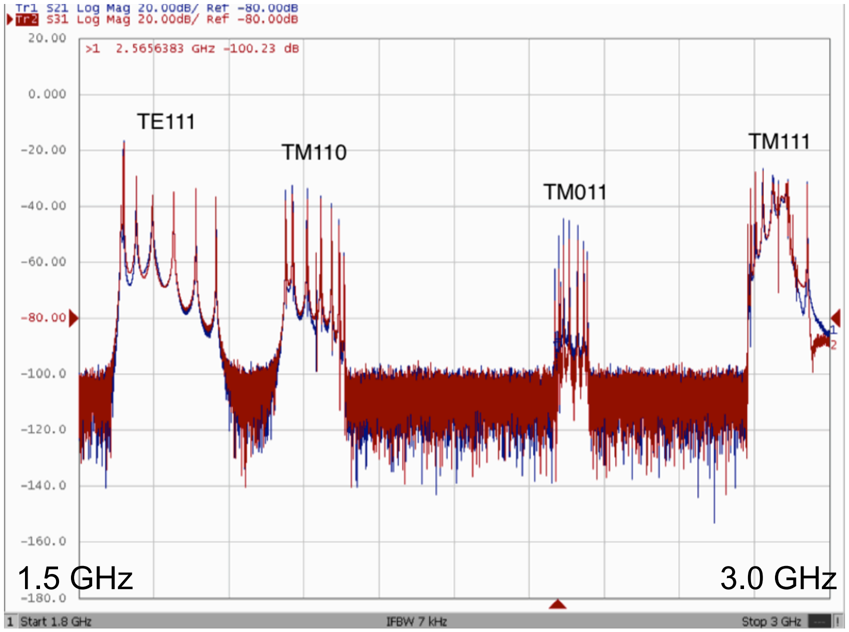
BBU Mechanism: TM110 mode

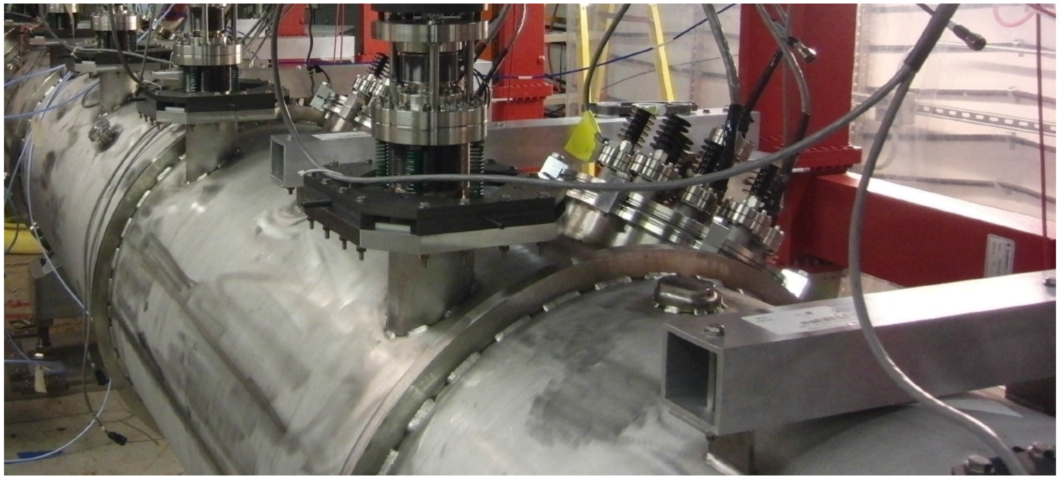




- Recirculating beam breakup RF cavity HOM
  - TM110 mode shown here: illustrates mechanism
- High Q HOM modes are most dangerous
  - Deposited power rings for longer time
  - More chance for positive feedback with later bunches

BBU Measurements: C100 Warm HOM Loads





- C100 HOM, BBU experiment: Ilkyoung Shin's PhD thesis
- Surveyed HOMs using warm coupler ports in CMTF, tunnel
  - With and without beam loading, varying recirculation optics
- Based on techniques described in Chris Tennant's thesis
- HOM power and BBU measurements are accessible
- Can we drive BBU instability in ER@CEBAF with existing beam?