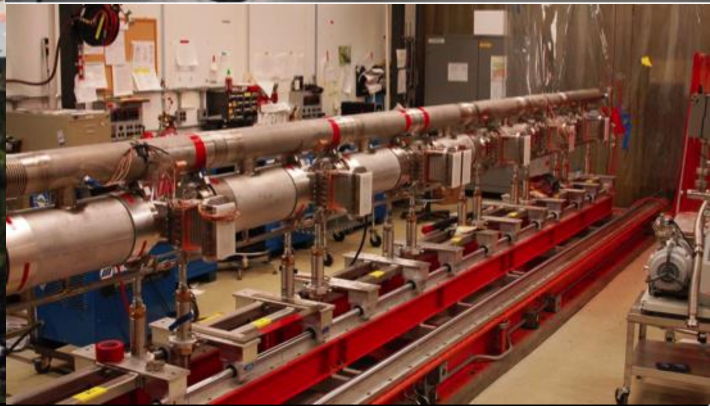
ER@CEBAF: A Test of 5-Pass Energy Recovery at CEBAF

Todd Satogata



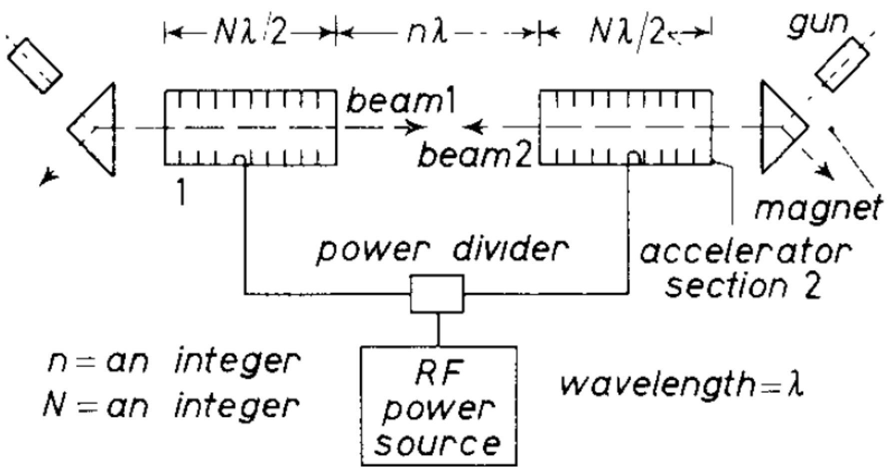
Accelerator Physics Seminar Jan 12 2017

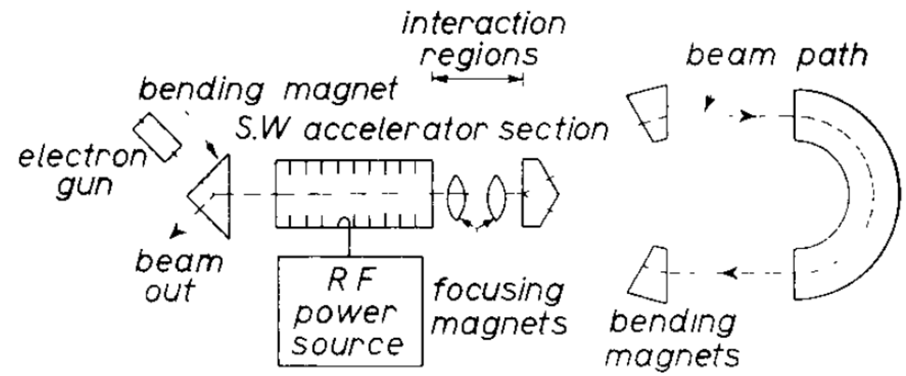
Seminar Outline

- Background
  - History and current state of energy recovery (ER)
  - Jefferson Lab's role and leadership
  - Motivations, advantages, challenges
- ER@CEBAF
  - Collaboration with BNL and proposal
  - **Layout**: new chicane and new beam dump
  - **Optics**: longitudinal match, transverse match
  - **Diagnostics**: multi-pass BPMs, decelerating emittance
  - **BBU**: beam breakup instability studies, scaling
- Summary and path forward

Energy Recovery: History

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



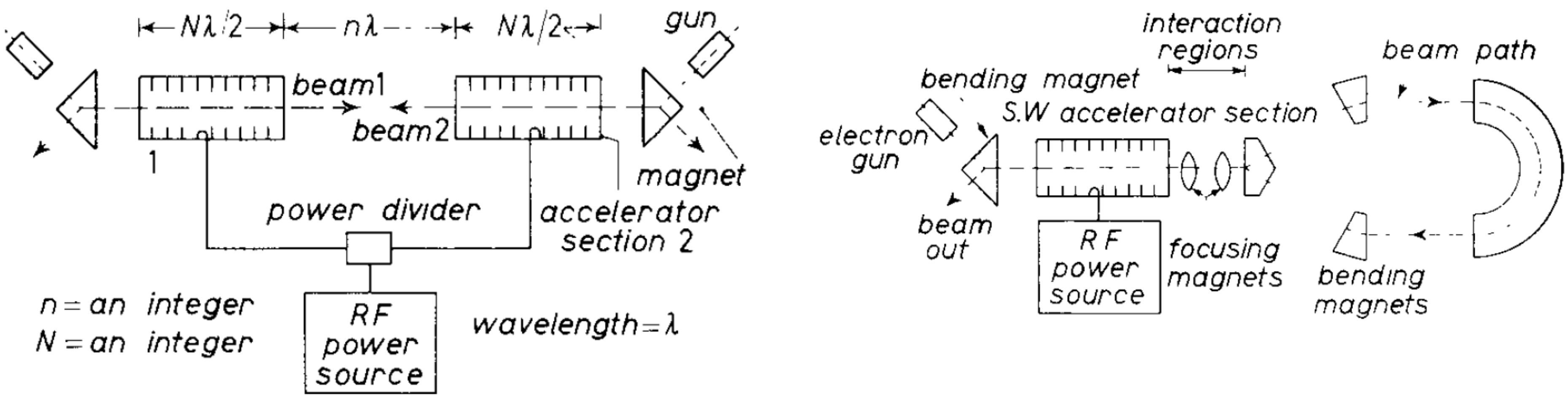


- How to make high power electron colliders?
  - 100+ MW accelerating power anticipated
  - **Option 1**: Throw lots of power into the RF system
    - Maury: “Although in principle it may be possible to produce and handle this large power, the sheer brutishness of the scheme robs it of all appeal.”

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

Energy Recovery: History

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

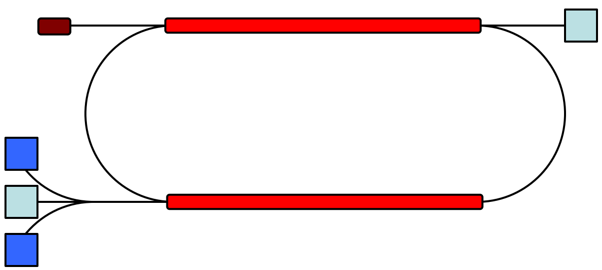


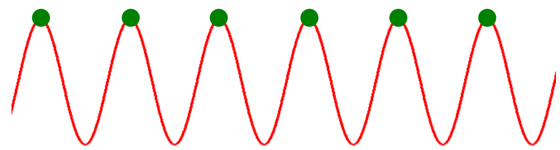
- **Option 2**: Decelerate beam through same RF system
  - Decelerating beam power goes back into cavity fields
  - "Constant" CW beam requires very little net RF drive
    - Ultimately want beam power >> drive power
- Paper: L=3x10^{30} cm^{-2} s^{-1} for 3 GeV 120 mA collider
  - Maury: "A low-density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





Linac RF voltage (1 pass)
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: CEBAF

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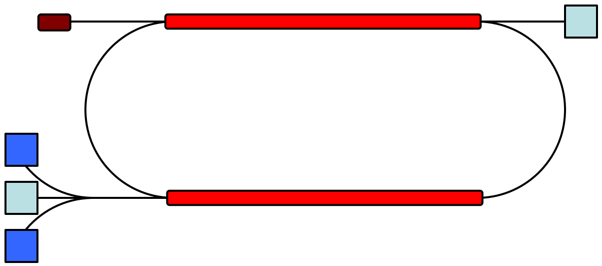

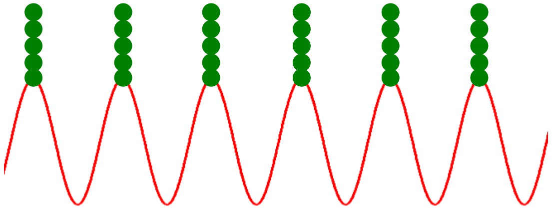

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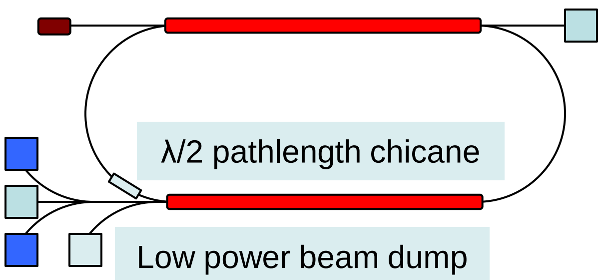
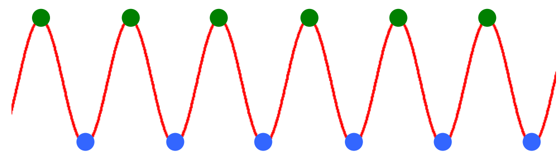
Energy Recovery Linacs: ER@CEBAF

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



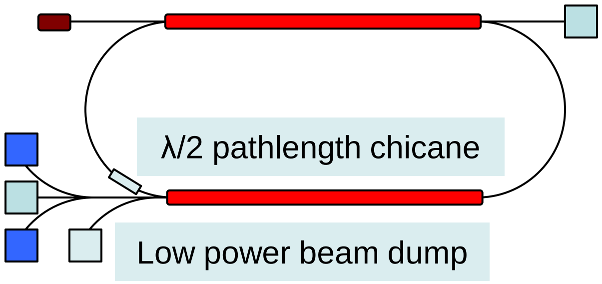


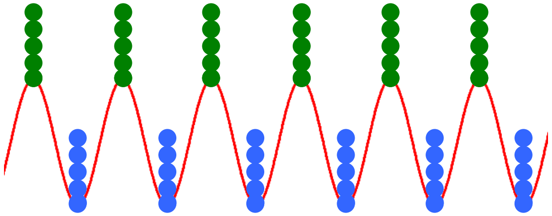
Linac RF voltage (1 pass)
Beams exchange power with RF

- 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





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 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

  – 2015, 2013, 2011, 2009, 2007
  – ERL'17 to be held at CERN, 18-23 June
    - Alex Bogacz on program committee

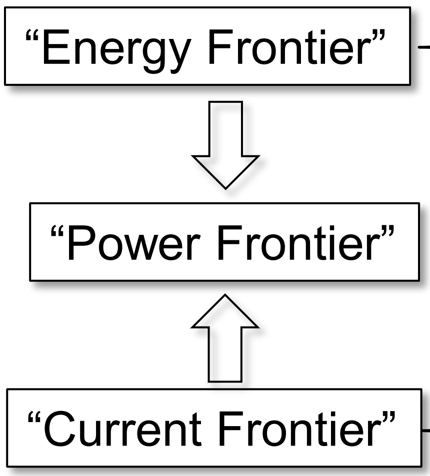
http://www.jacow.org/Main/Proceedings?sel=ABDW

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

Shameless ~~Promotion~~ Admission

HIGH-CURRENT ENERGY-RECOVERING ELECTRON LINACS

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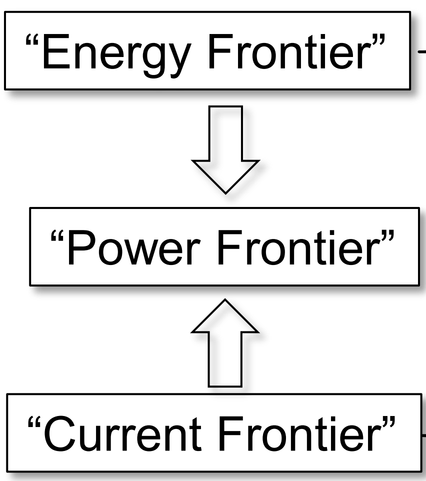
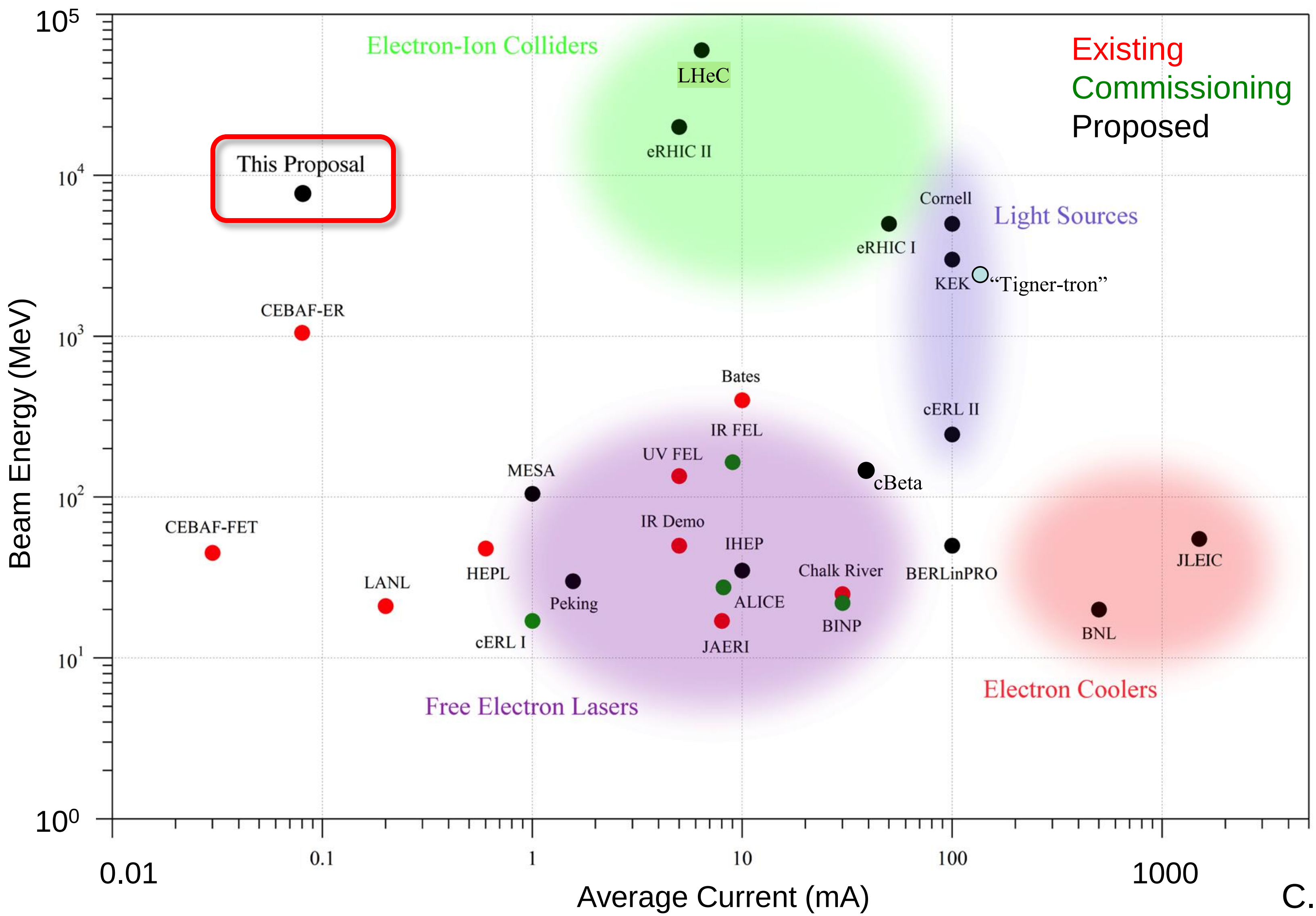


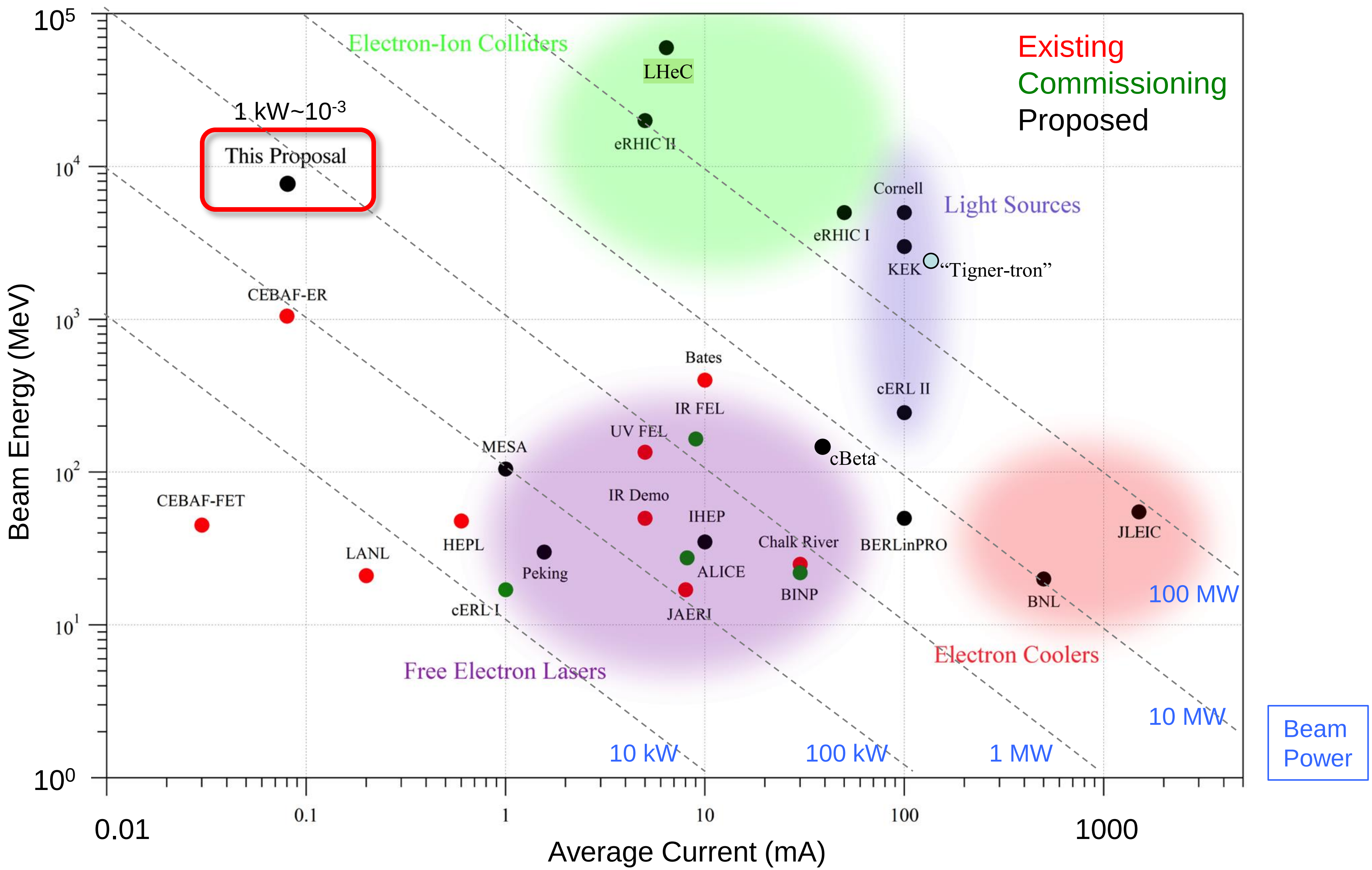
http://uspas.fnal.gov/materials/05UCB/Merminga-Douglas-Krafft.pdf

World ERL Landscape

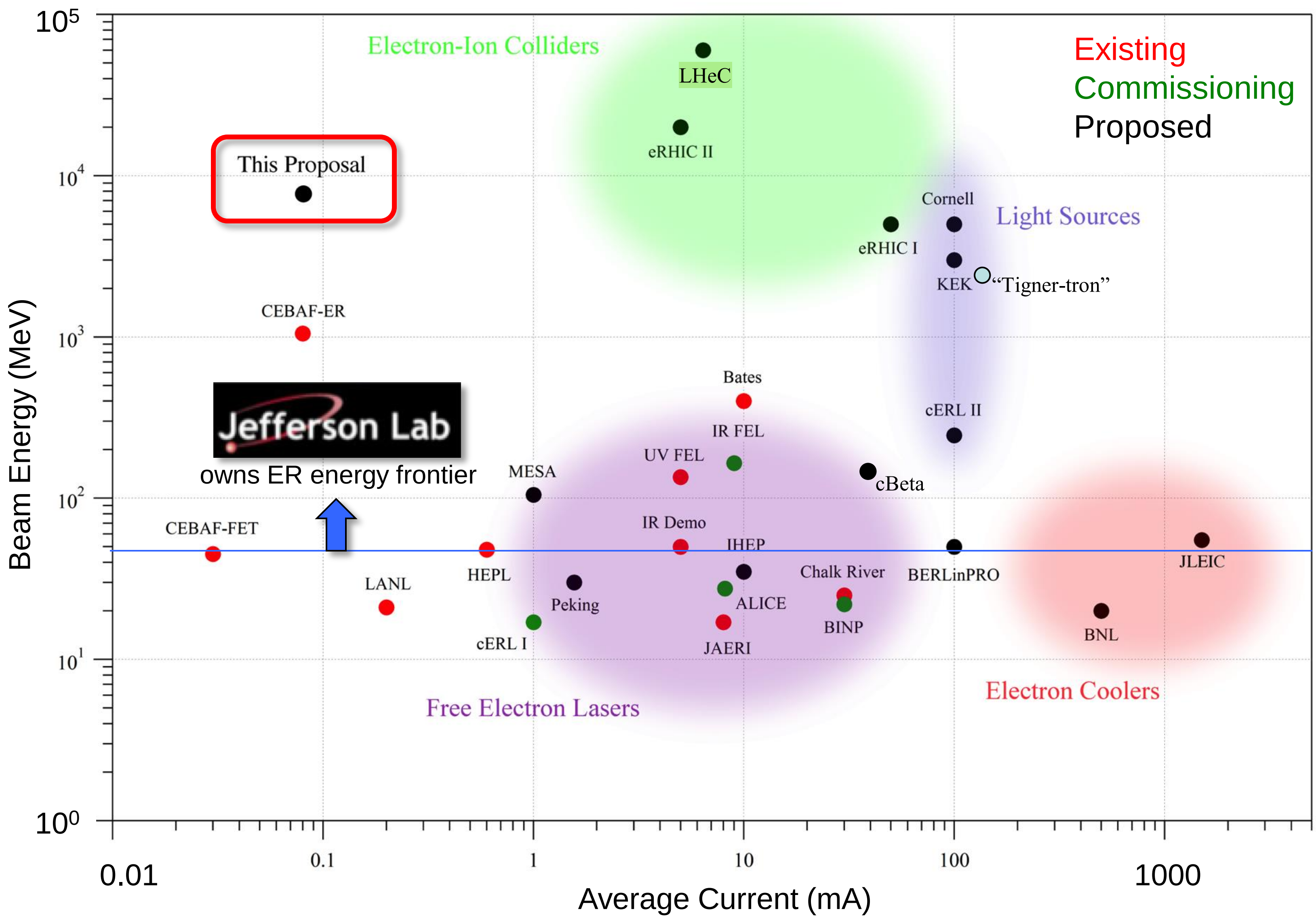


C. Tennant

World ERL Landscape: Power



World ERL Landscape: Energy Frontier

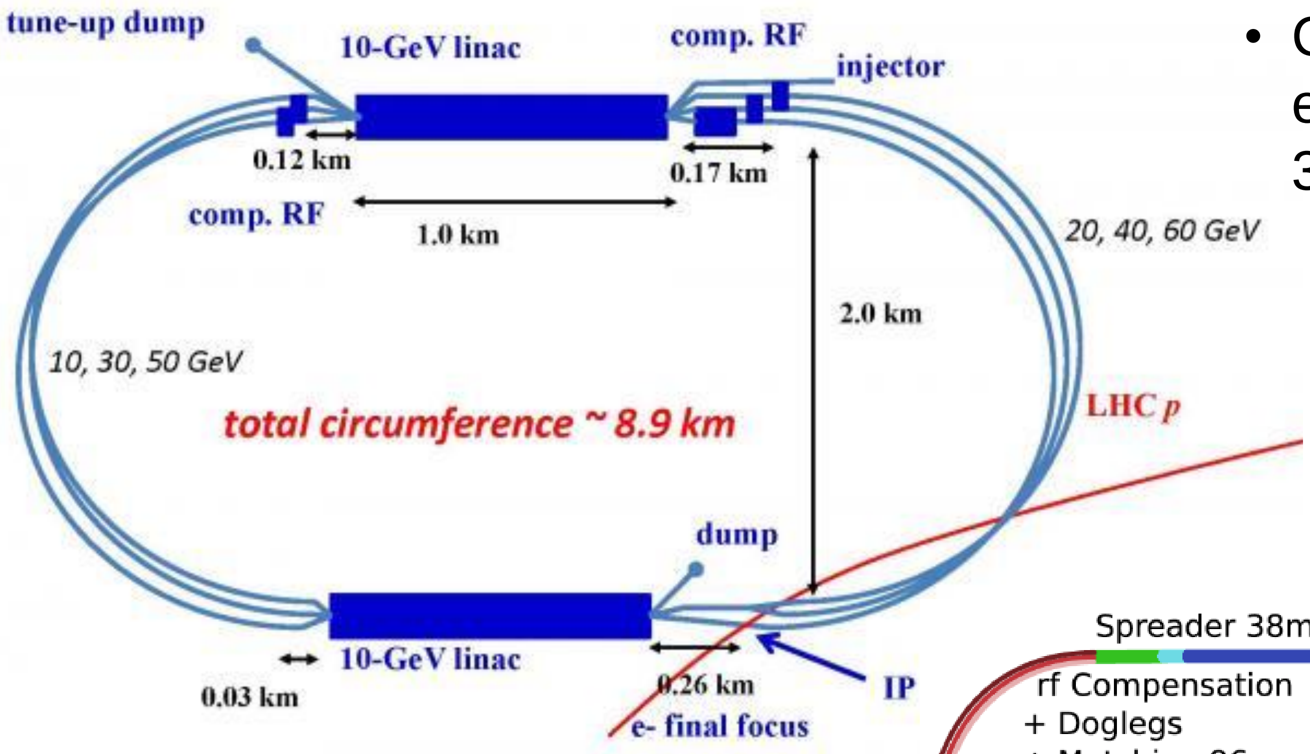


ERLs at Jefferson Lab

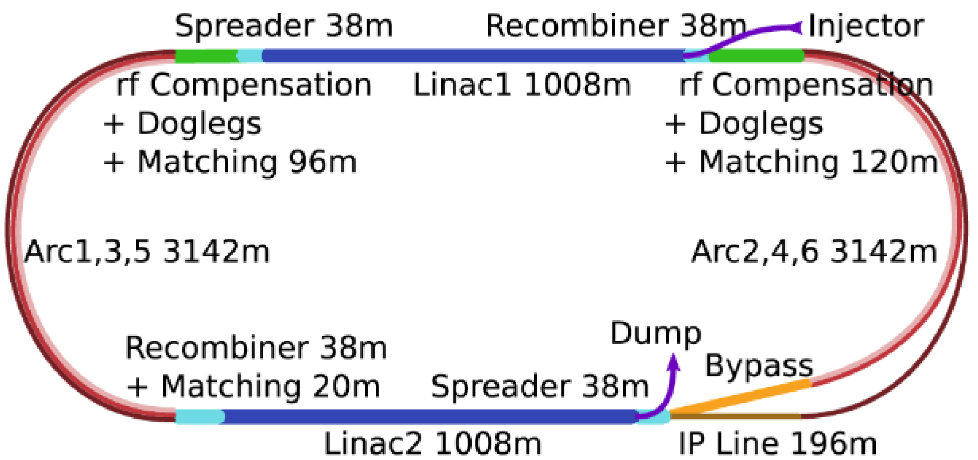
- Jefferson Lab has a history of world leadership in ERLs
  - 1993: CEBAF front end ERL test
  - 1998-2001: IR FEL demo
    - First demonstration of ERL-based light source
  - 2002-3: CEBAF one-pass energy recovery expt
    - Remains world leader in ERL beam energy
  - 2002-10: UV FEL
    - Remains world 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



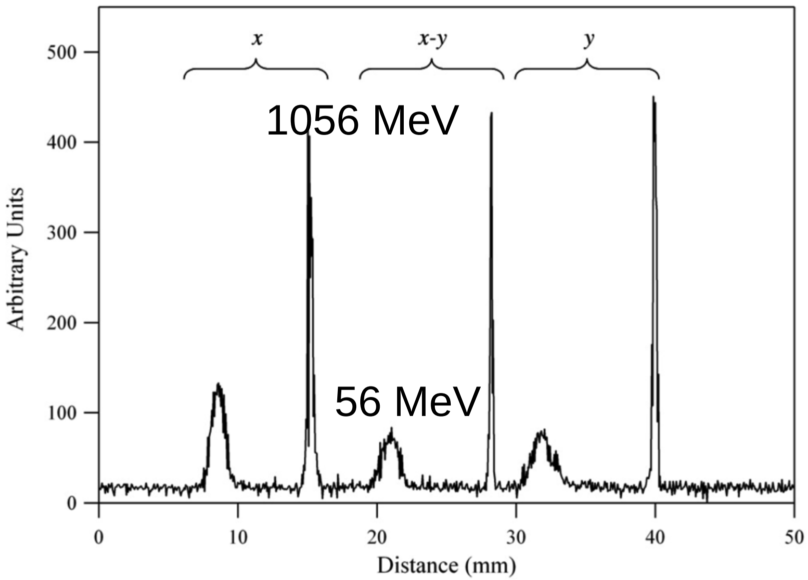
- Collides 6.4 mA 60 GeV e- with LHC protons ➔ 384 MW!



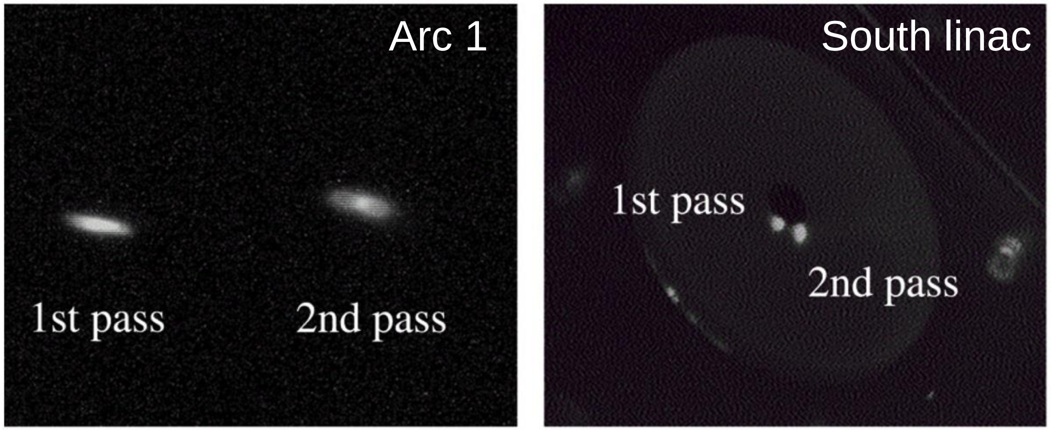
- Meeting on PERLE test ERL demonstrator Orsay Feb 2017

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

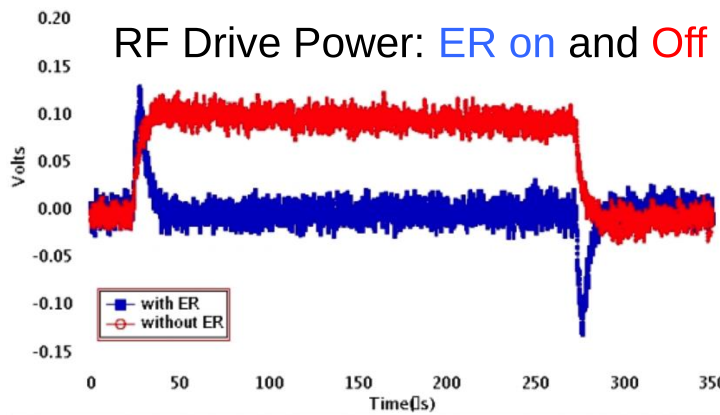


2003 2-pass harp scan (2L24)



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

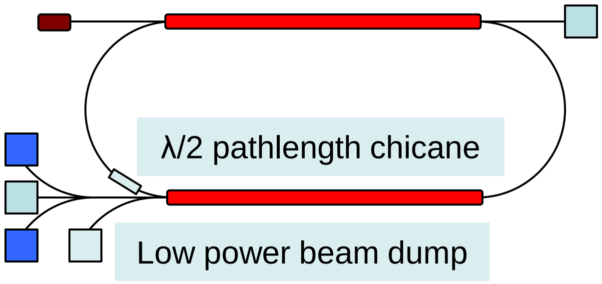
⋆ Co-spokesperson

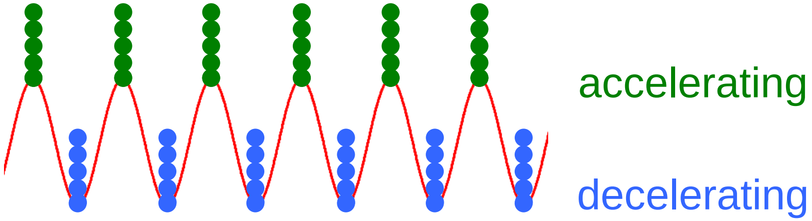
A collaboration between Jefferson Lab and BNL
(Also an amusing football game)

Meetings (on and off) since July 2015

ER@CEBAF Again

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





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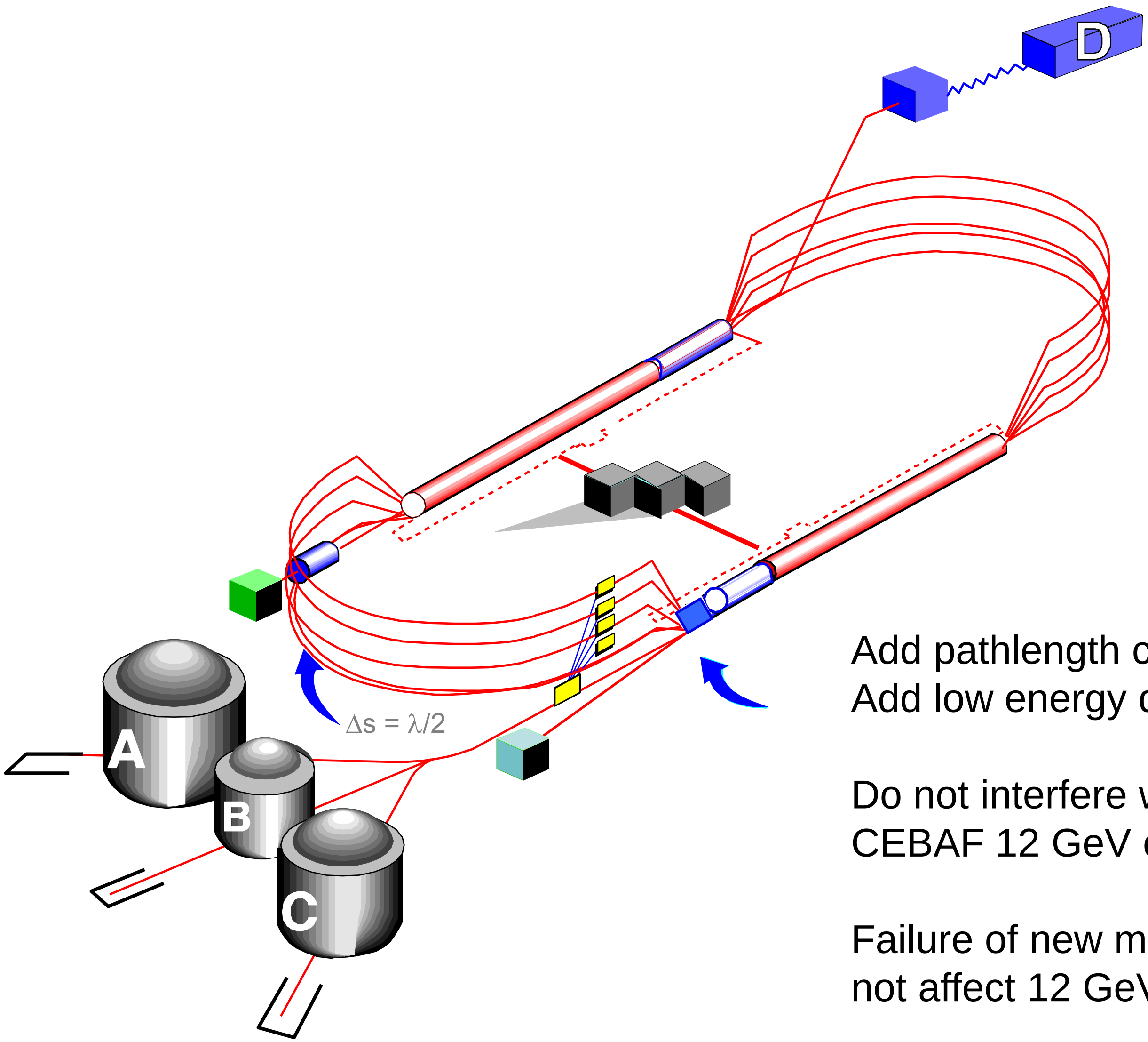
ER@CEBAF



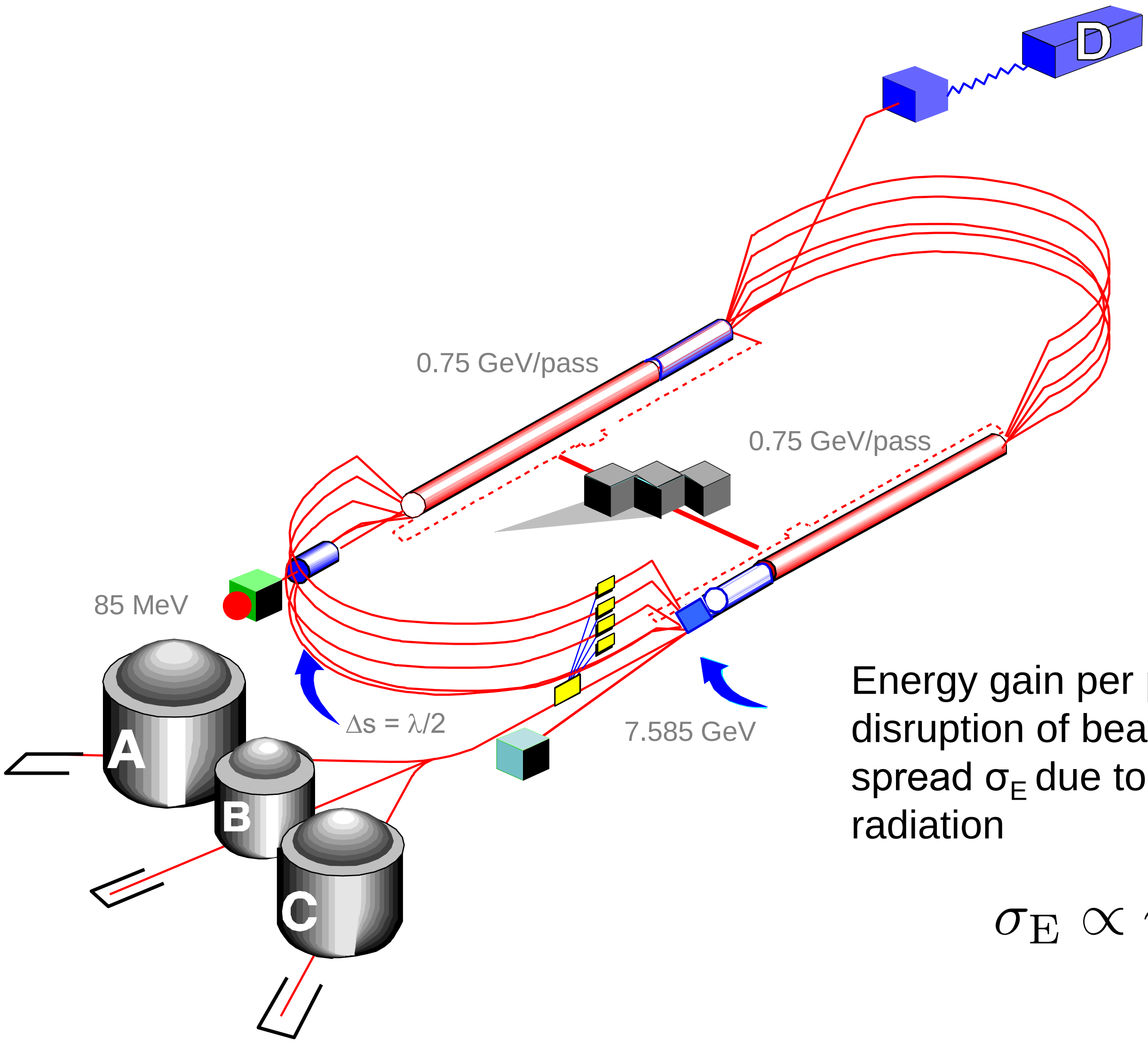
Add pathlength chicane
Add low energy dump line

Do not interfere with existing CEBAF 12 GeV capabilities

Failure of new magnets does not affect 12 GeV capability

A. Bogacz

ER@CEBAF: Accelerating

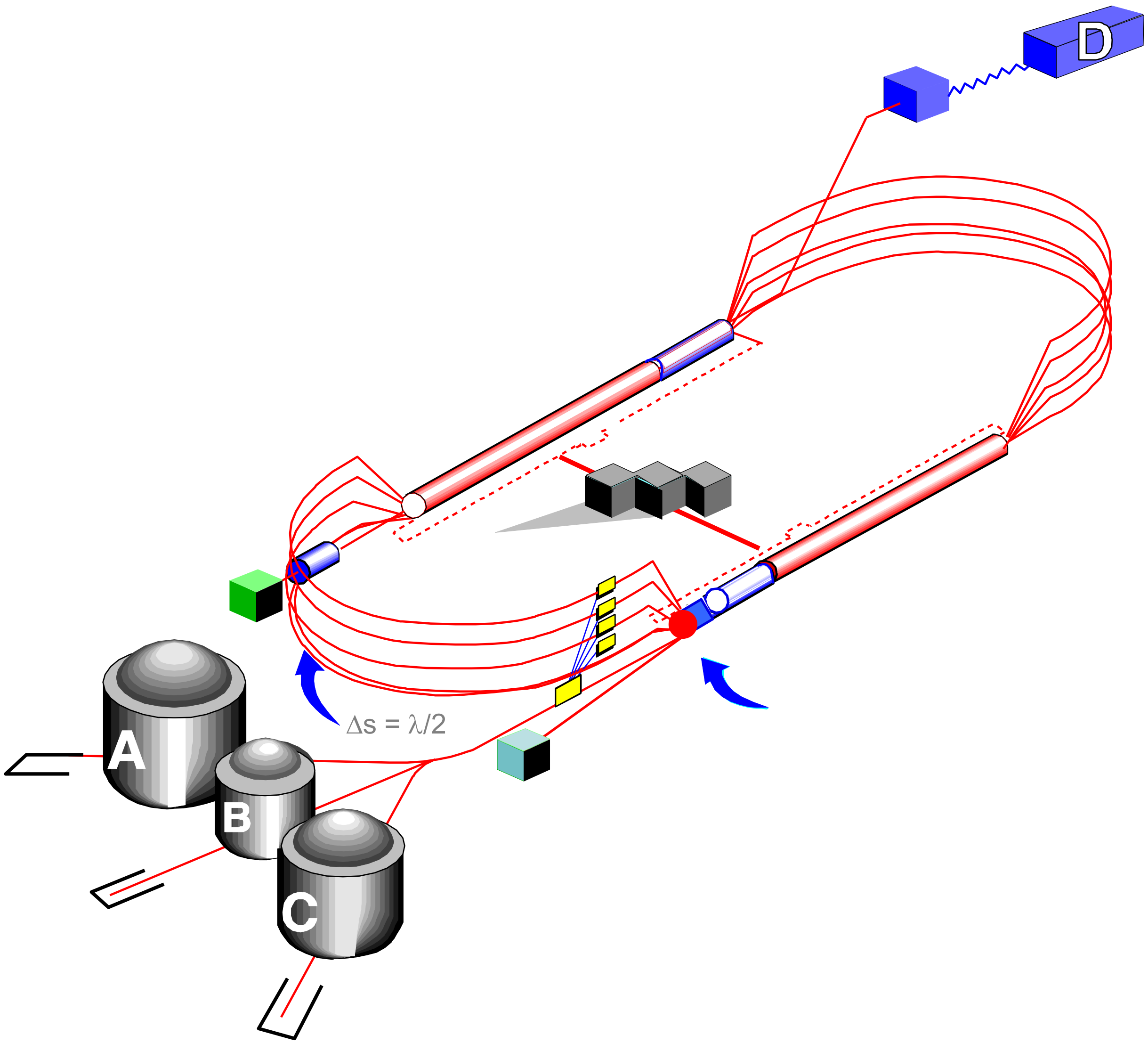


Energy gain per pass limited by disruption of beam energy spread σ_E due to synchrotron radiation

$$\sigma_{\mathrm{E}} \propto \gamma^{7/2}$$

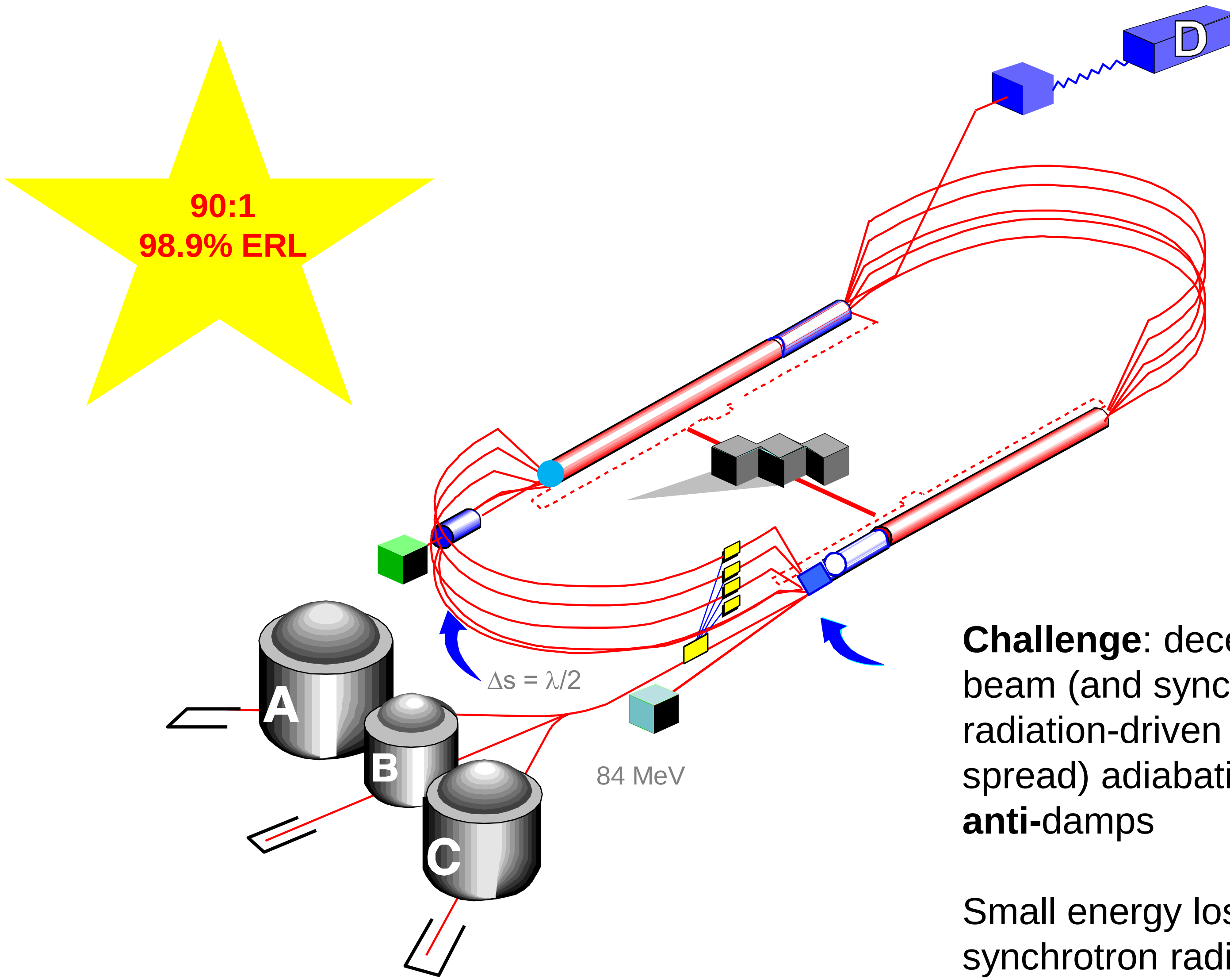
A. Bogacz

ER@CEBAF: Slip Half RF Wavelength



A. Bogacz

ER@CEBAF: Decelerating

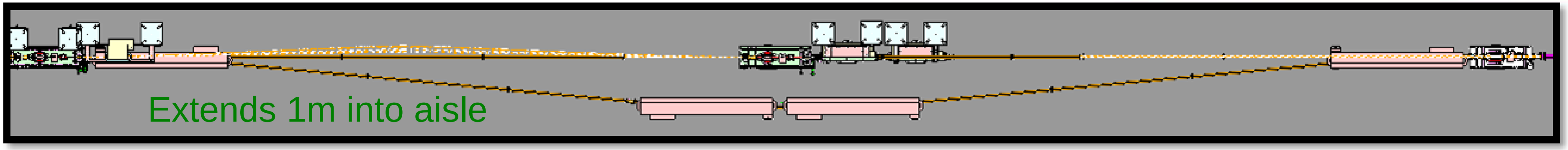


Challenge: decelerating beam (and synchrotron radiation-driven energy spread) adiabatically **anti-**damps

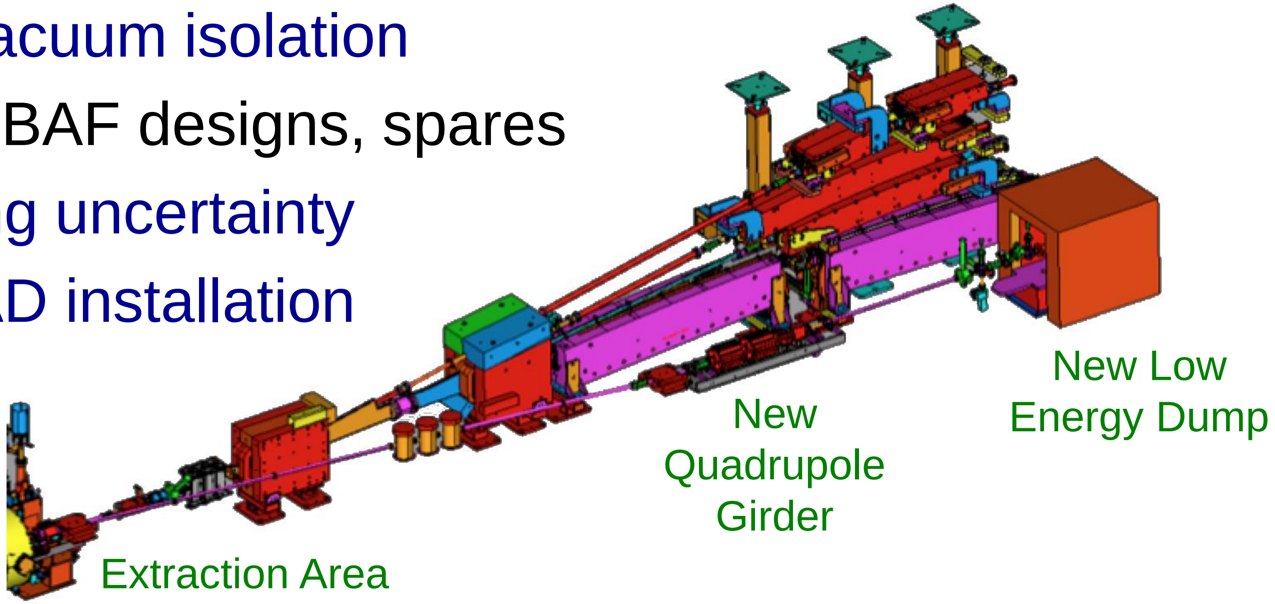
Small energy losses to synchrotron radiation

A. Bogacz

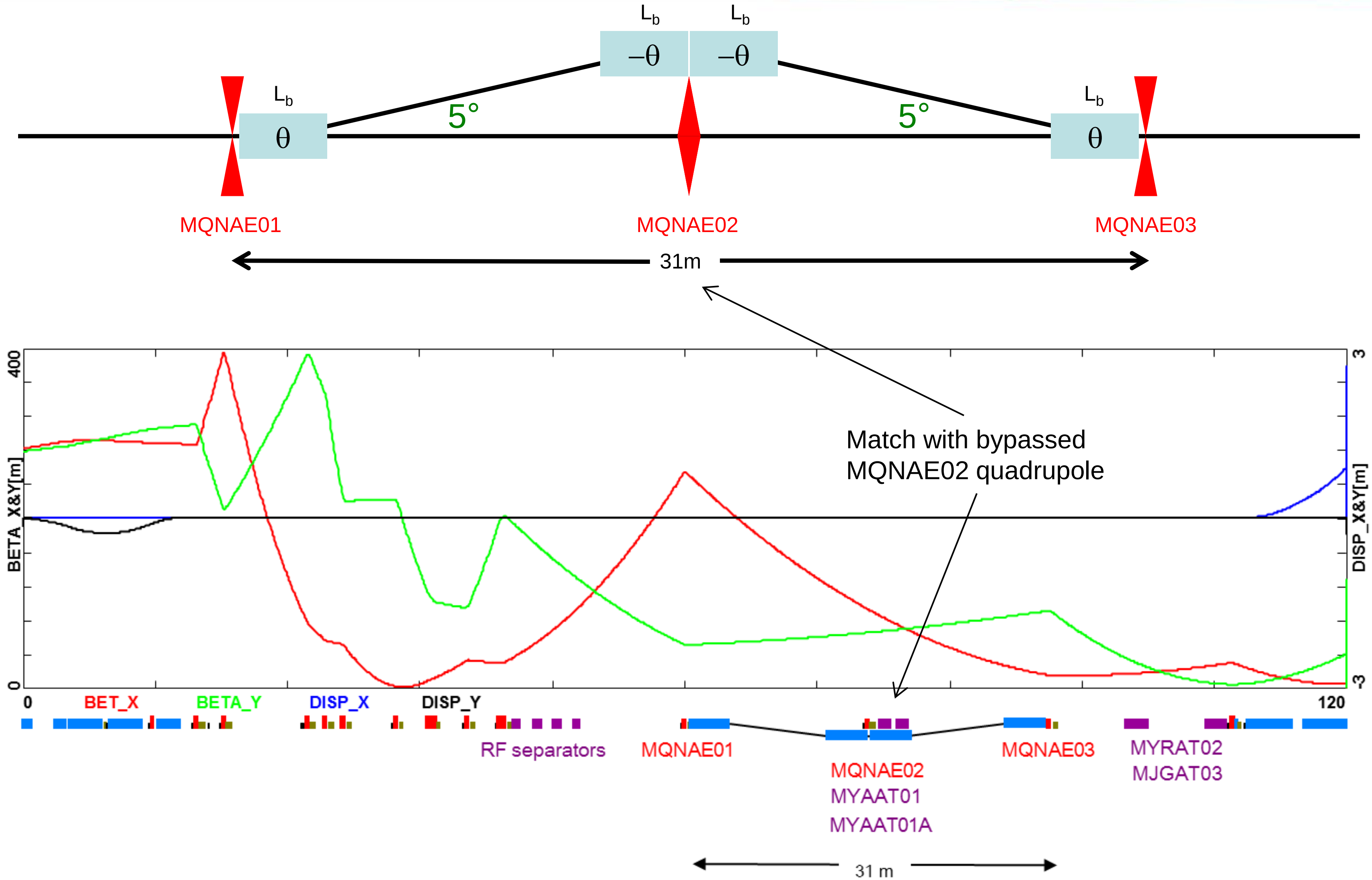
CEBAF Hardware Modifications



- **λ/2 pathlength chicane**: Add four 3m dipoles in AE region
  - Optics solution designed, only magnet strength changes
- **Low energy dump**: Add quadrupole girder, low energy dump
  - Located at end of south linac next to SL spreader
  - Maintains vacuum isolation
- Use existing CEBAF designs, spares
  - Small costing uncertainty
  - Summer SAD installation

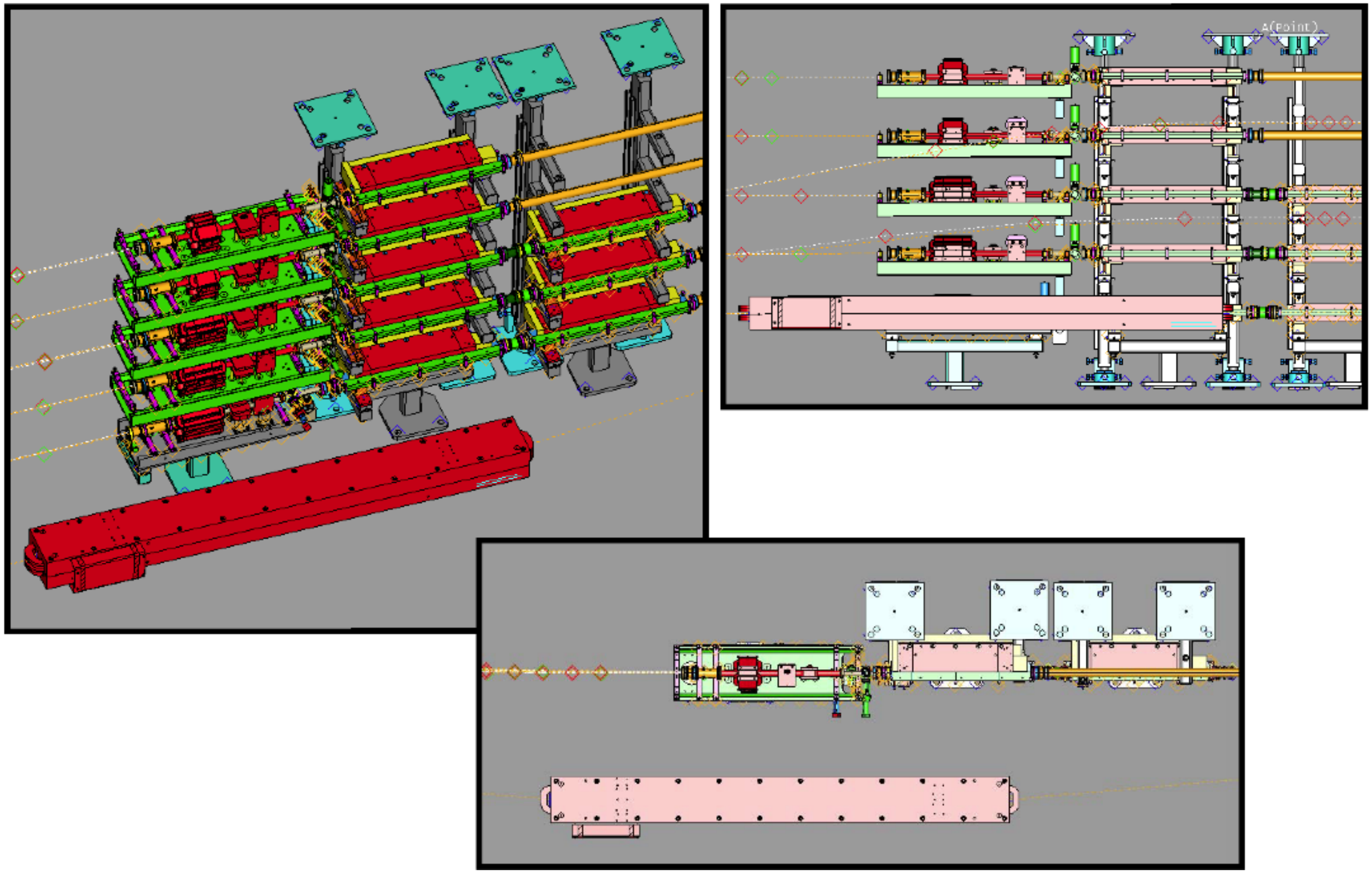


Pathlength Chicane



A. Bogacz

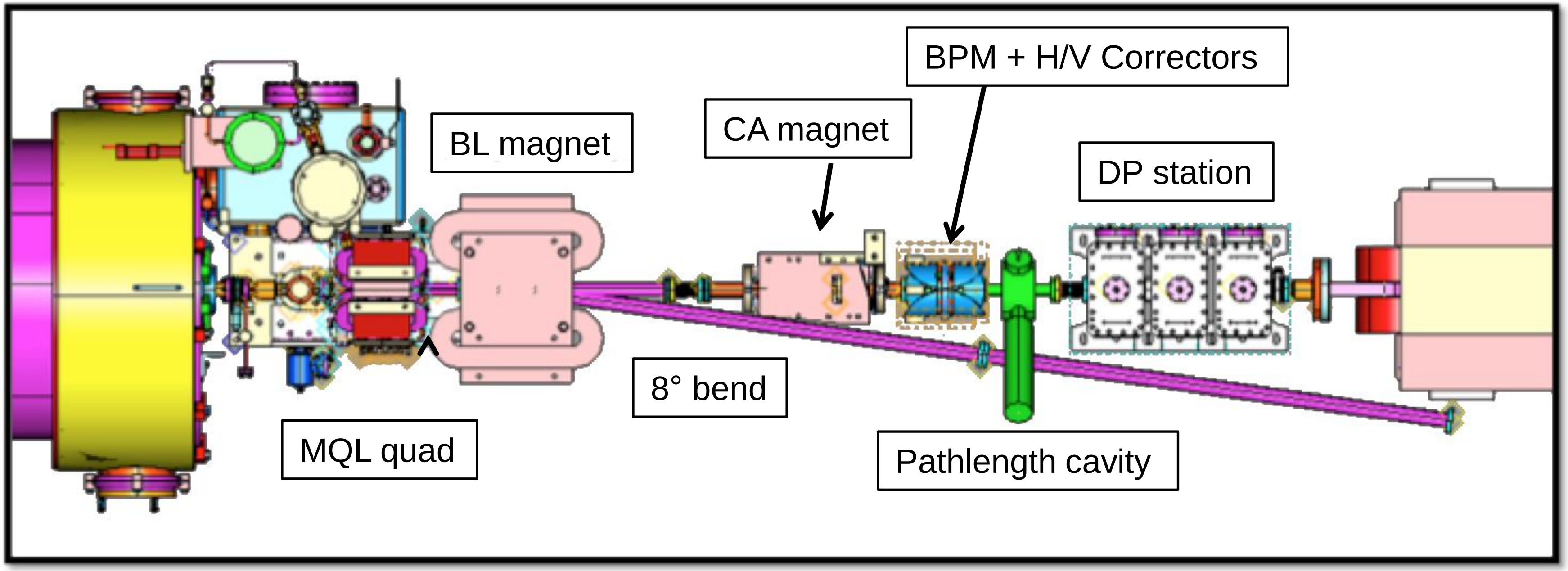
Pathlength Chicane: AE02 region



- Use established BA dipole magnets
- No cryomodule passthrough clearance necessary

C. Dubbe

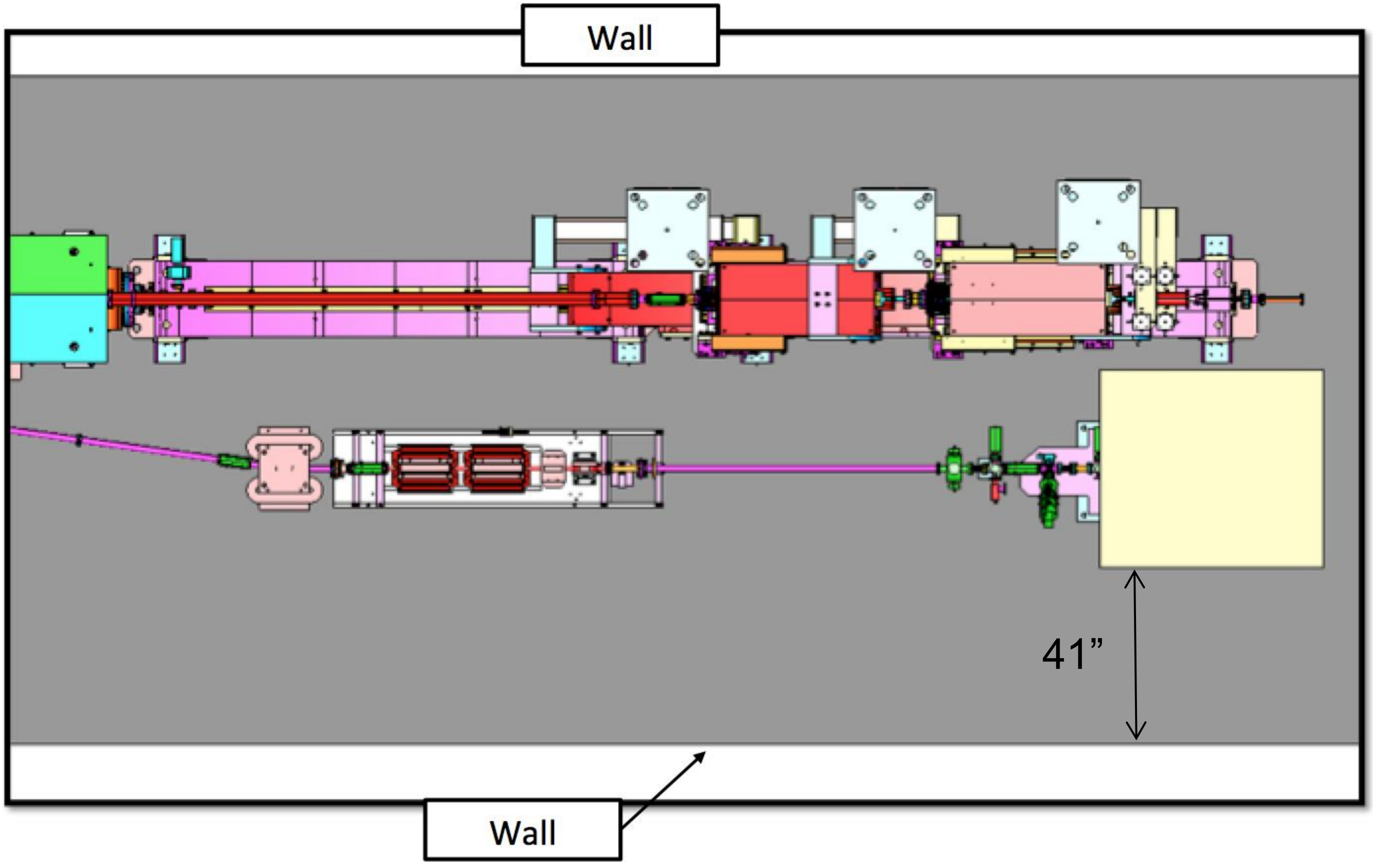
Dump Extraction Detail



- Existing area has corrector / BPM / quad downstream of 2L27 C100 cryomodule
  - No additional apertures or points of failure created
  - Dump line diagnostics angled away from C100 cone
  - BL magnet failure only affects ER@CEBAF capability

M. Spata

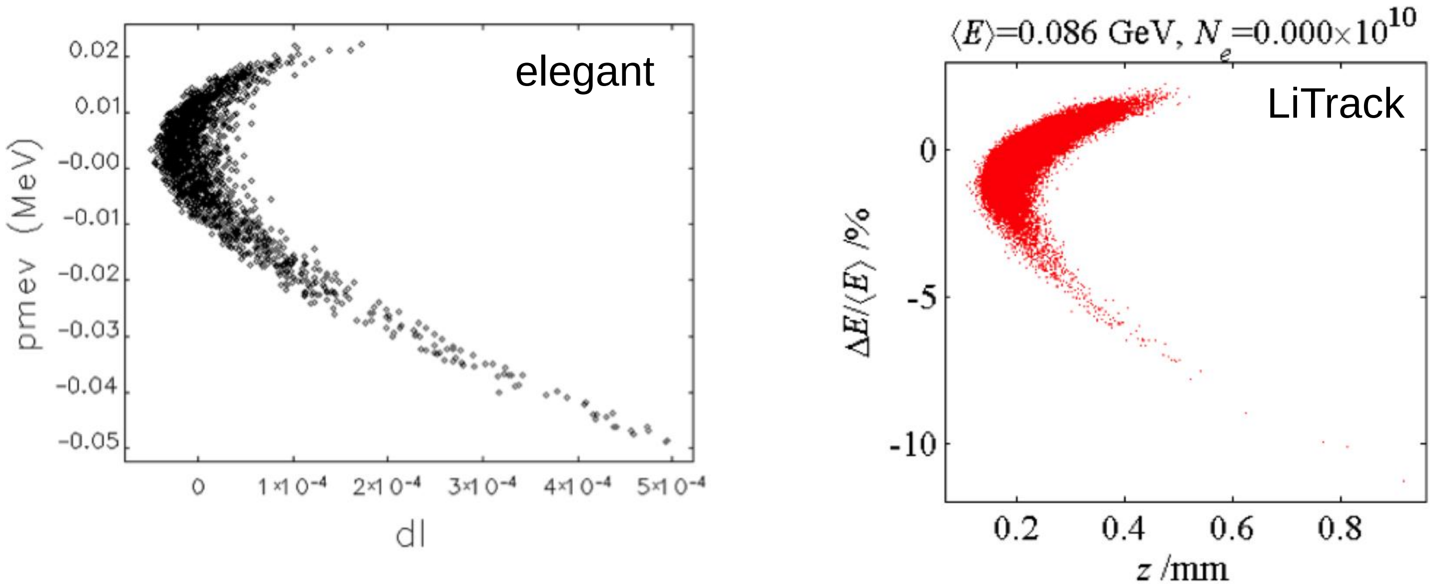
Dump Traffic Clearance



- Dump line maintains clearance for magnet carriage clearance
  - Cryomodule carriage clearance not required in this area
  - ER@CEBAF would not interfere with expected tunnel traffic

Longitudinal Simulations and Match

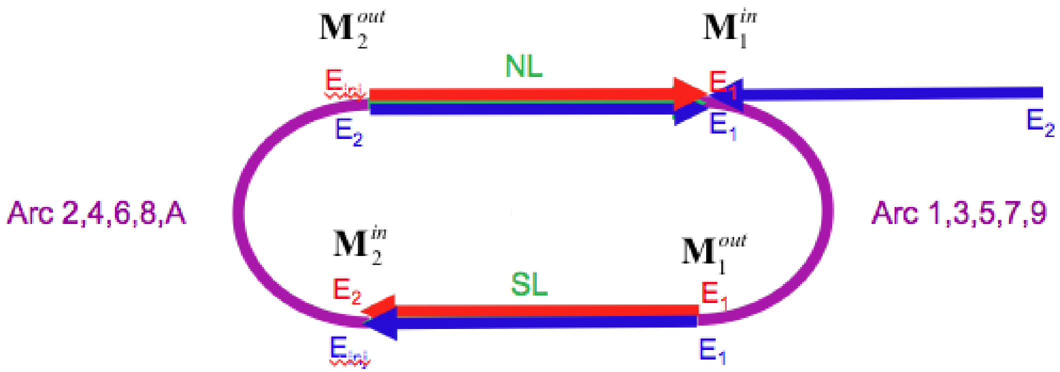
- Collaboration with BNL using four accelerator simulation codes to verify optics design
  - Manipulate bunch length and compression
  - Collaborative benefits to CEBAF parity quality program, CEBAF energy spread control



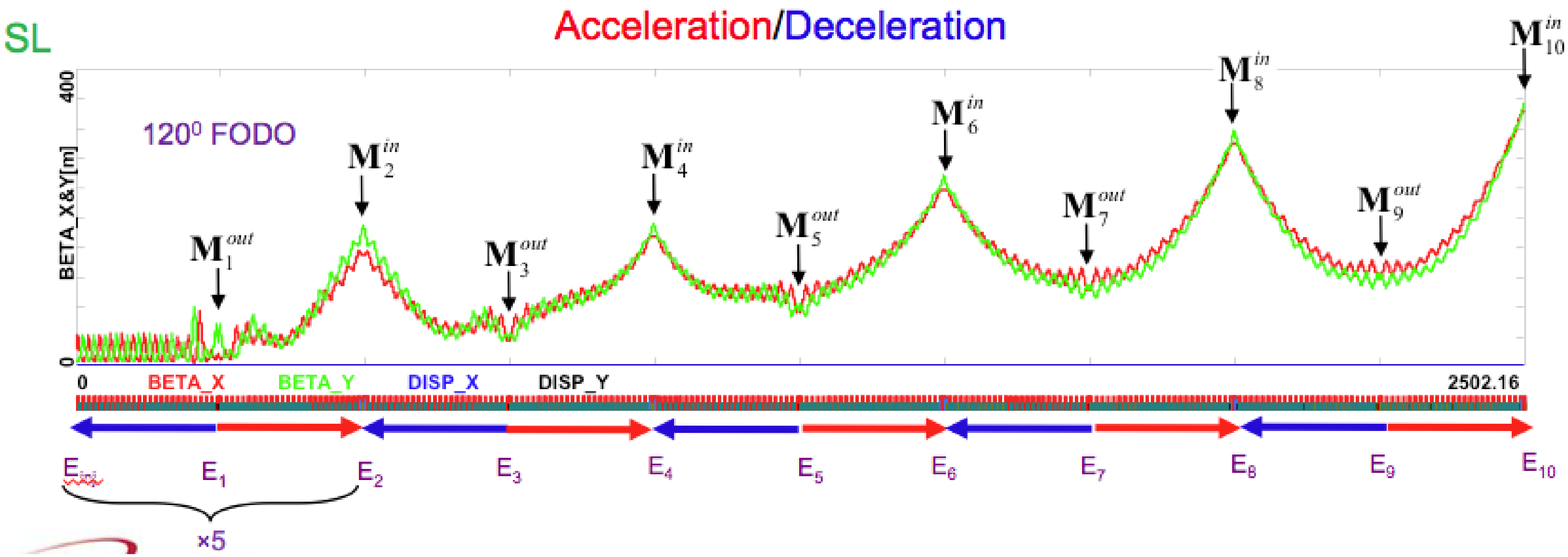
Beam energy/longitudinal position distributions after energy recovery

Y. Roblin

Optimized Linac Optics



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

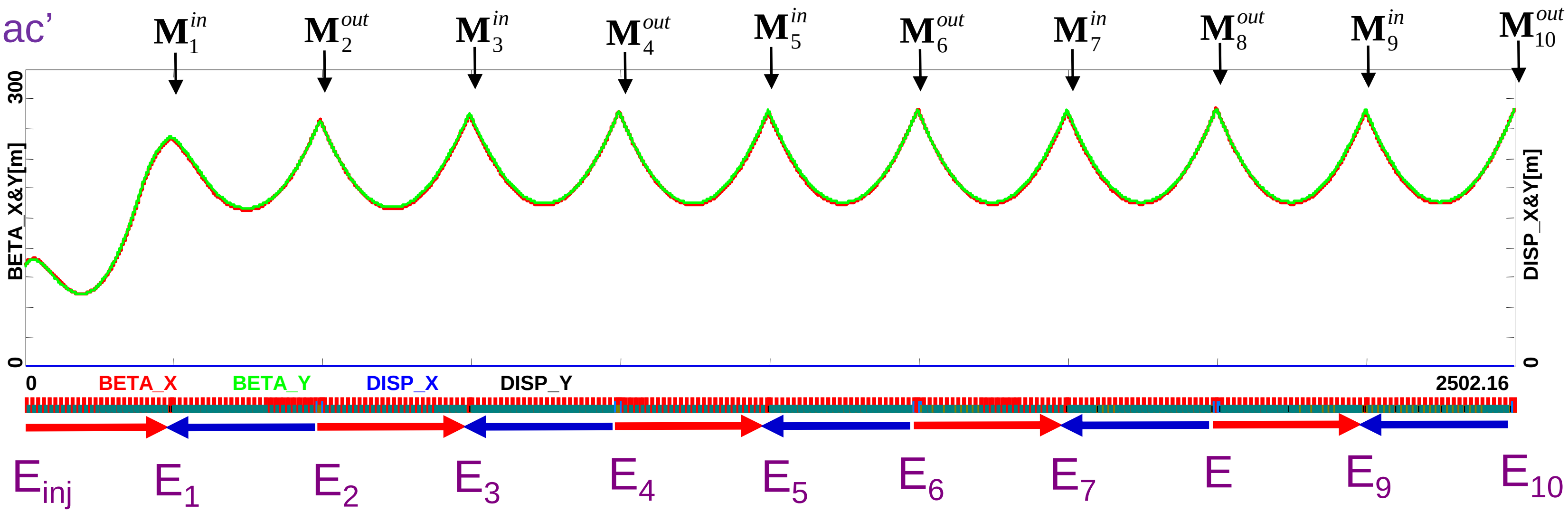


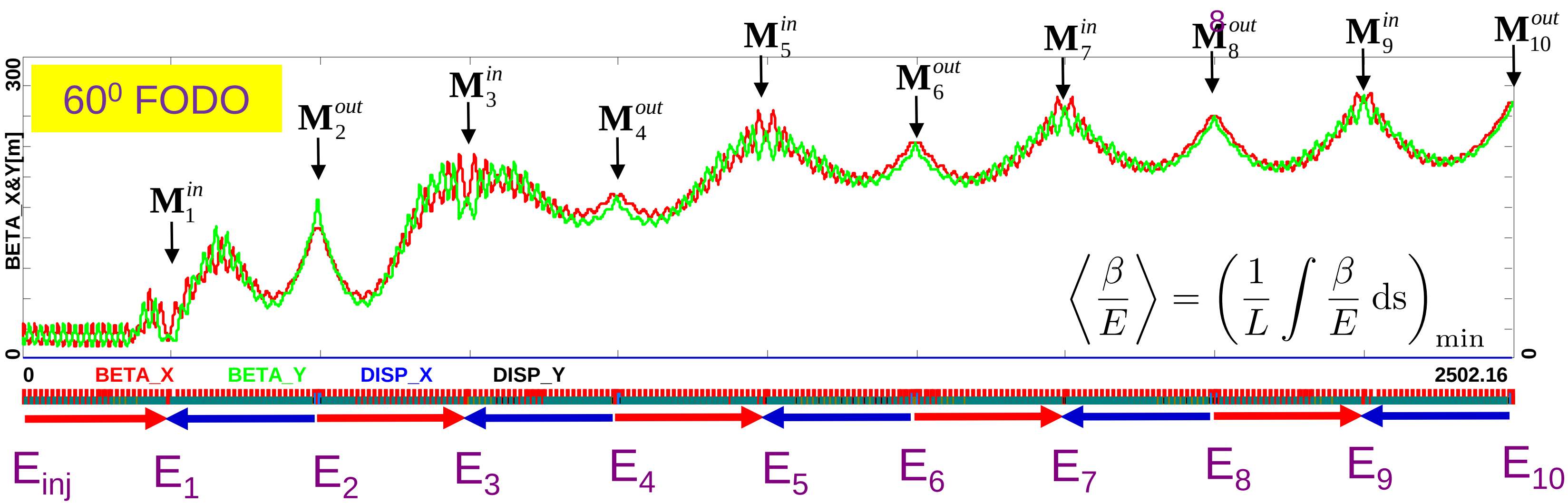
A. Bogacz: APS SLC 2016 Talk

Optimized Linac Optics

Acceleration/Deceleration

'Drift Linac'





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

A. Bogacz

Diagnostics and Measurements: BPMs

- Linac SEE BPM extension
  - Current linac SEE BPMs temporally multiplex 5-6 passes of beam
  - Feasible to extend to 10 passes with software and beam pulse structure modification

- 3 GHz BPMs
  - Six modified SEE BPMs (3 each Arcs 1 and 9)
  - Establishes accelerating/decelerating energy ratios
  - Wire scanners resolve both accelerating and decelerating beams
  - No other decelerating arc BPMs
    - no steering degrees of freedom

Diagnostics and Measurements: Dump

- Extraction beam measurements
  – Leverage well-calibrated Hall A dipole system
  – IHA1C12 and viewer provide energy spread
  – Emittance measurements in zero-dispersion 2C line
  – All measurements feasible each even pass up/down

- Dump line includes full diagnostics suite
  – Three BPMs for steering
  – Two quadrupoles for focus/emittance measurements
  – MPS BCM for total beam transmission
  – Viewer for dump beam images

Phased Hardware Commissioning

- ½ pass: NL accelerating, SL decelerating
  - Commission dump line extraction, diagnostics
  - Compare injection / dump line beam characterization
  - 1-2 days

- 1 pass: reproduce 2003 ER experiment results
  - Requires first pass beam passing through Arc A
  - Commission pathlength chicane, Arc 1 3 GHz BPMs
  - Demonstrate intermediary beam diagnostics
  - Evaluate MOMOD pathlength control tolerances
  - 3-4 days (took 1.5 days in 2003 experiment)
  - Preferably E_{inj} = 56 MeV (same as 2003), E_{linac}=500 MeV
  - Does not require changes to arc optics

Phased Hardware Commissioning

- 5 pass (E_{linac} up to 750 MeV, E_{inj} up to 85 MeV)
  - Commission new arc optics, longitudinal beam manipulations
  - Commission Arc 9 3 GHz BPMs, 10-beam BPM software
  - Further demonstrate intermediary beam diagnostics
    - Use 500 MHz separators at start of west arcs
  - Perform tuning tolerance studies
  - Demonstrate full decelerating beam transport
  - Perform RF tuning studies
  - Demonstrate CW energy recovery
  - ~14 days of tuning and characterization

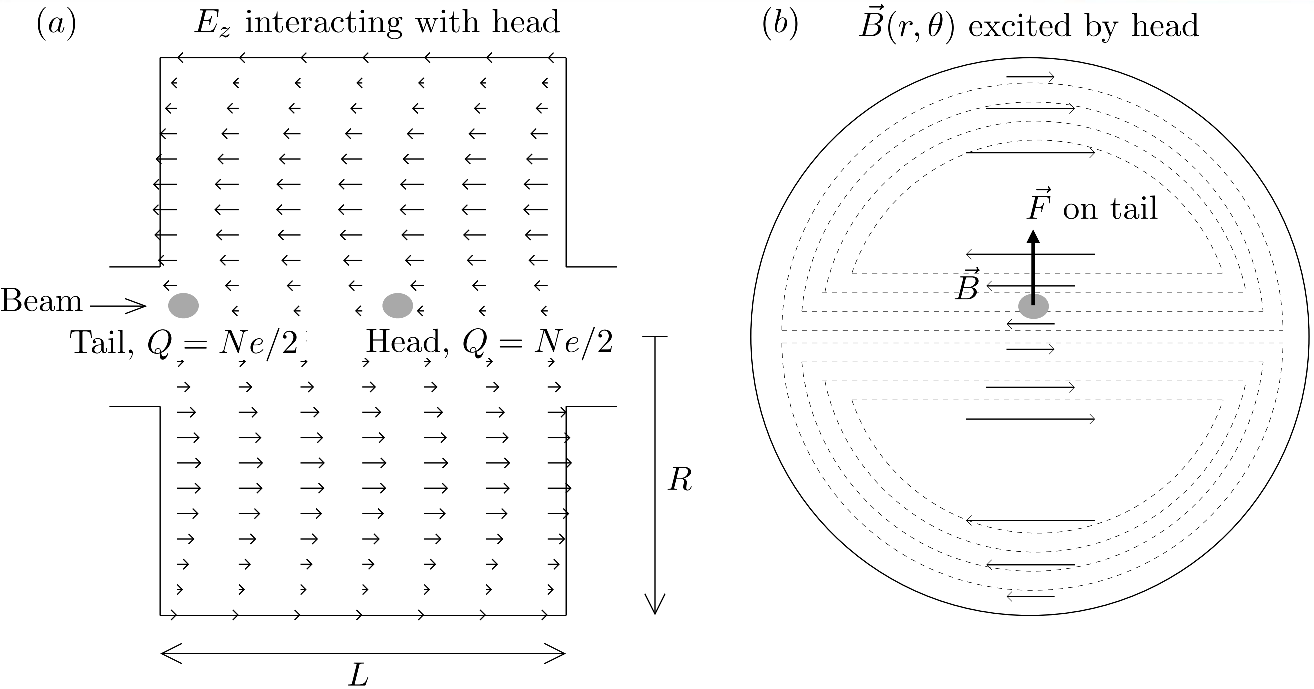
Recirculating Beam Breakup (BBU)

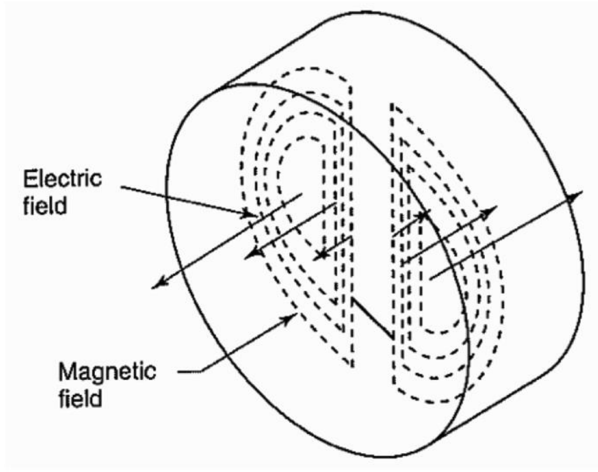
- Recirculating beam breakup
  - Positive feedback loop between beam power and higher order mode RF power
  - Couples through beam transport
  - Many RF higher order modes communicate with beam, each other in near-exponential complexity
  - Limits total beam current

- 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

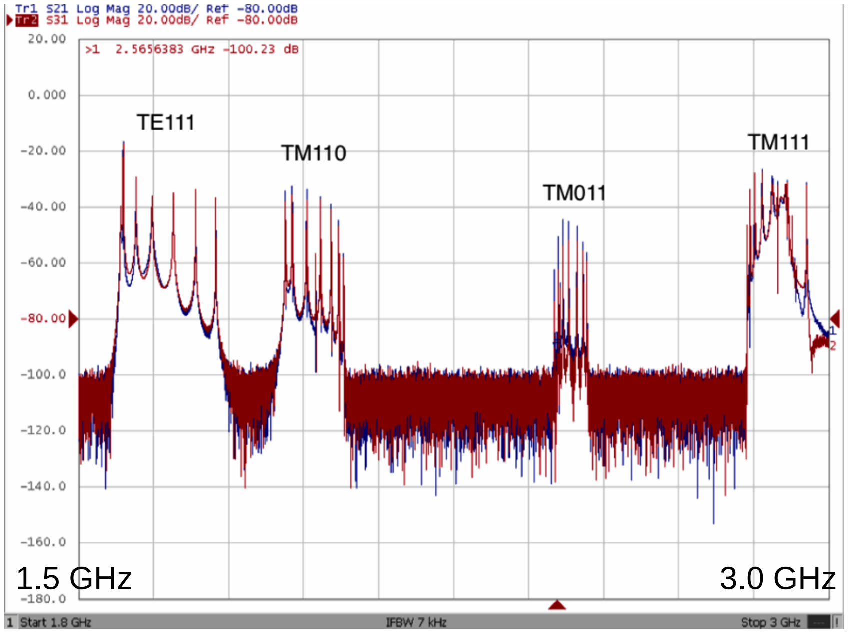
BBU Mechanism: TM110 mode





- 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?

Summary

- High energy ERLs are a required technology for affordable, high-quality, high power electron beams
  - Required for future high-energy EIC designs
  - Energy frontier exploration requires large facility
- CEBAF is a unique facility to study energy recovery of high energy, disrupted beams in a large installation
  - Synchrotron radiation: graceful energy scaling
  - Design in hand to add capability to CEBAF 12 GeV facility without affecting base program
  - Optics optimization, BBU studies accessible
- ER@CEBAF will make Jefferson Lab a world leader in **high energy** ERL beam and RF studies