CEBAF-ER: Extending the Frontier of Energy Recovery at Jefferson Lab

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(On behalf of the E02-102 Collaboration)

Center for Advanced Studies of Accelerators
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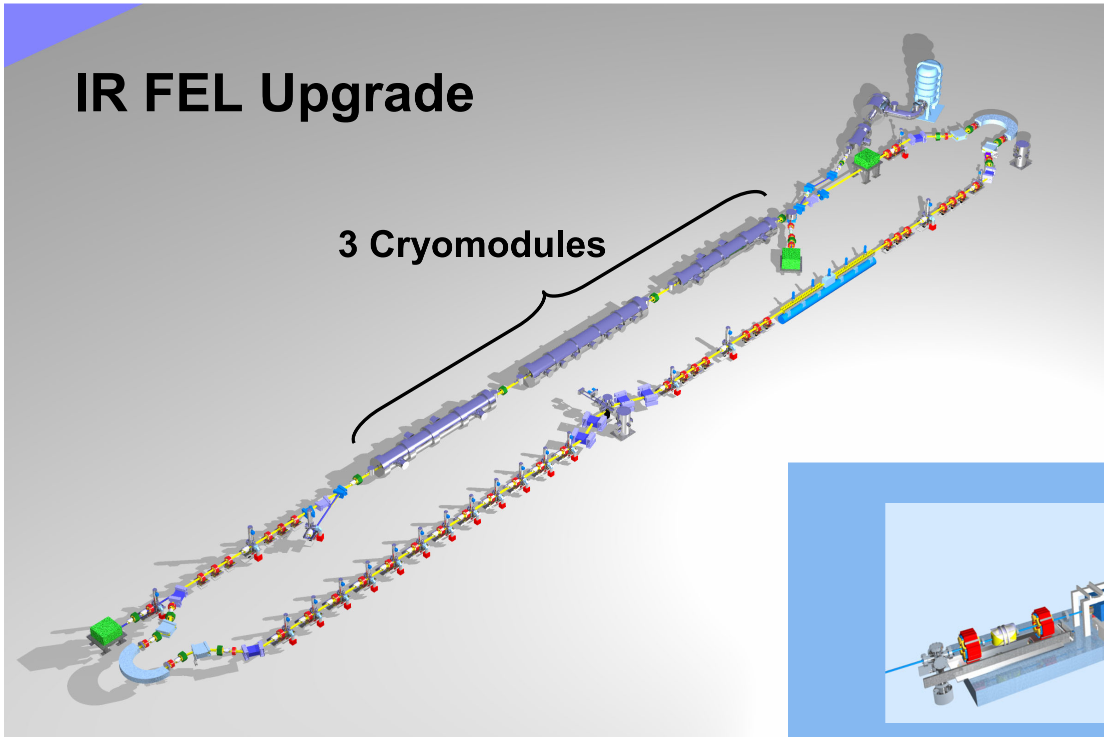
Introduction to Energy Recovery

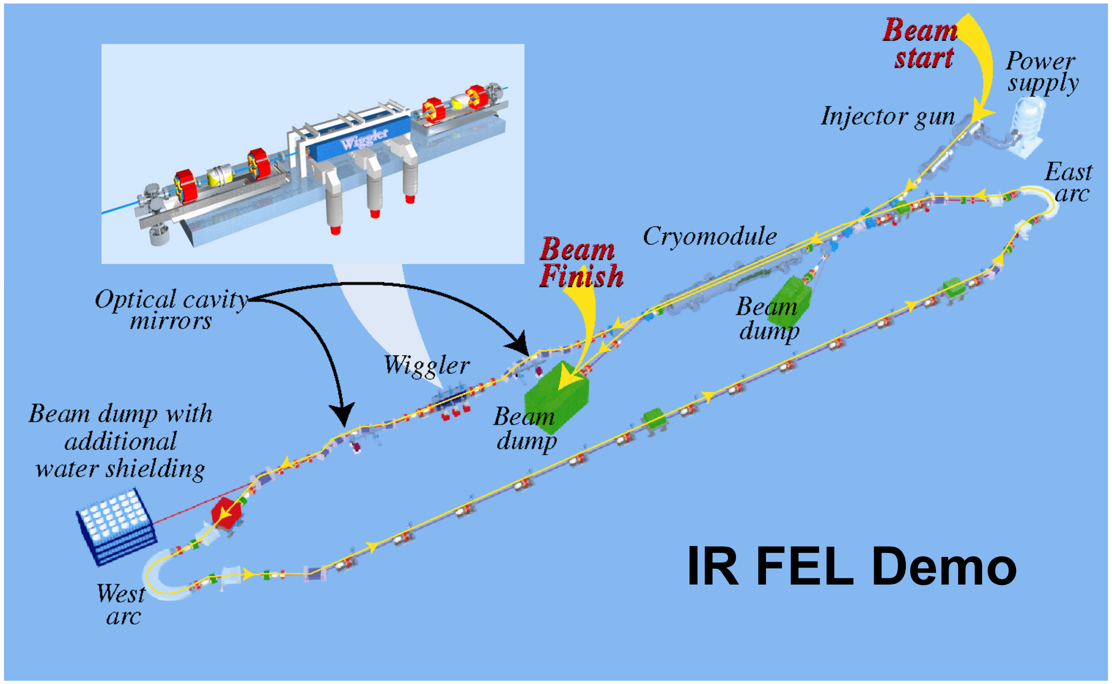
- What is Energy Recovery?
  - It is the process by which the energy invested in accelerating a beam is returned to the RF cavities by decelerating the same beam (via proper path length of recirculation pass)
- Why use Energy Recovery?
  - Required RF power becomes nearly independent of beam current
  - Increases overall system efficiency
  - Reduces electron beam power to be disposed of at beam dumps by ratio of E_{final}/E_{inject}
  - If beam energy is dumped below the neutron production threshold (13 MeV), requirements related to high average current beam dump designs are relaxed
- Why use SRF Technology?
  - Since RF power no longer depends on beam current, to establish cavity fields must overcome wall losses: for SRF cavities high Q's mean small wall losses

JLab FEL (Past and Present)



- IR FEL upgrade is currently being commissioned.
- At design, it will energy recover 145 MeV of 10 mA beam through 3 cryomodules.

- IR FEL Demo consistently and reliably energy recovered 50 MeV of 5 mA beam through a single cryomodule.



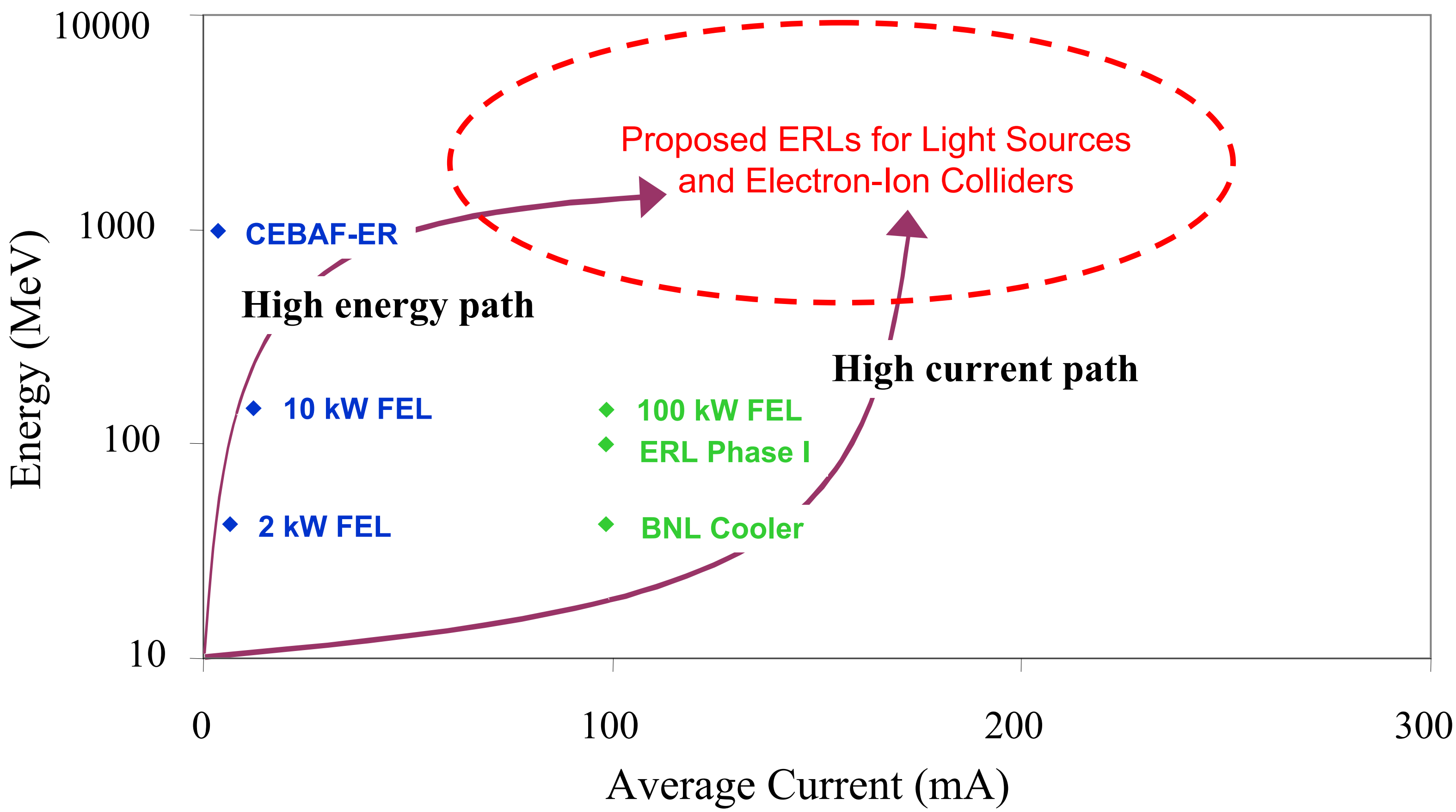
Introduction to Energy Recovery (cont'd)

Ultimately, Energy Recovering Linacs (ERLs) promise efficiencies approaching those of storage rings, while maintaining beam quality characteristics of linacs: superior emittance and energy spread, and sub-picosecond bunches.

Because of the advantages offered by ERLs, there are proposals world-wide for their application as

i. Light sources
ii. FELs
iii. Electron cooling devices
iv. Electron-Ion colliders

ERL Landscape

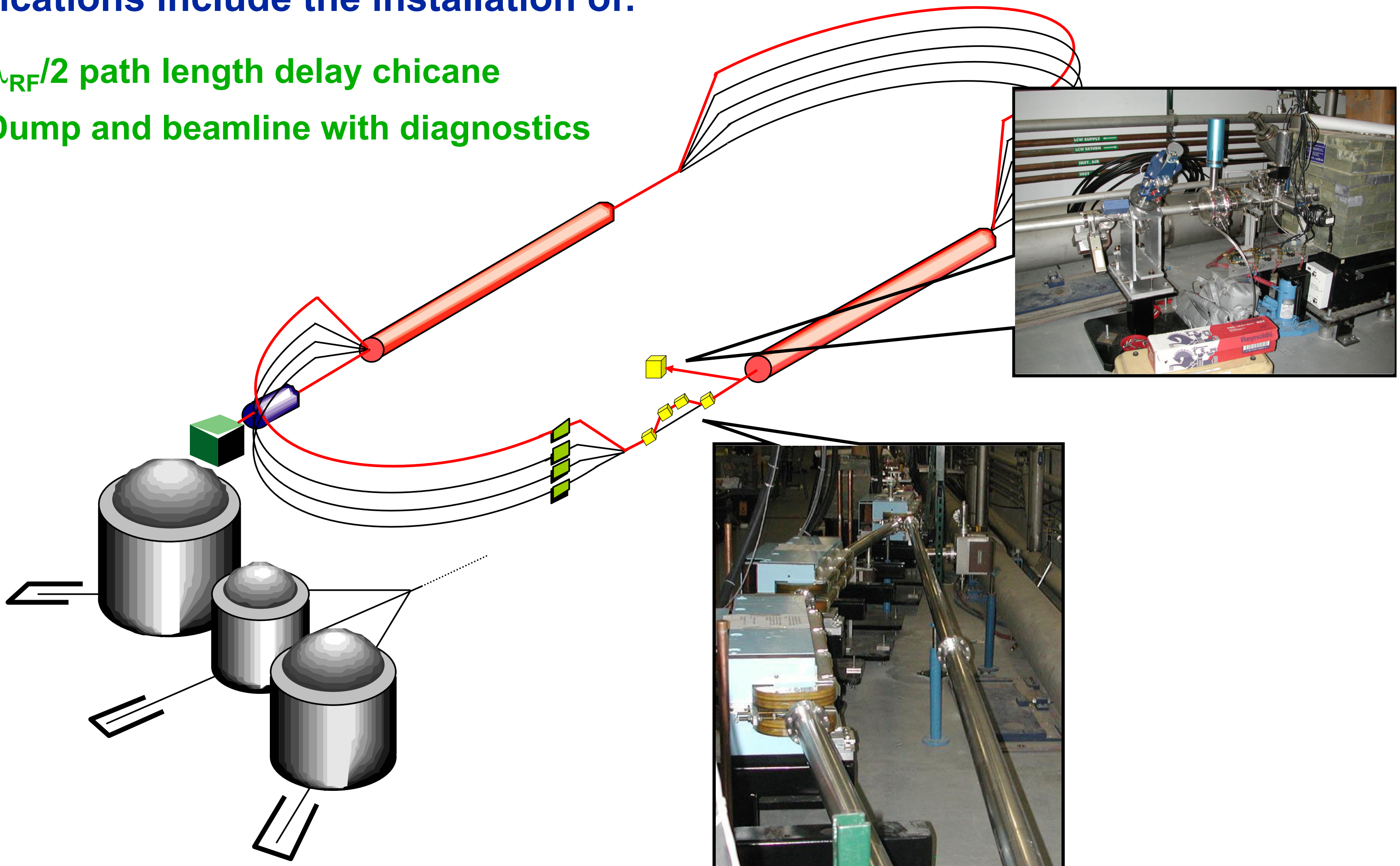


In an effort to address the issues of energy recovering high energy beams, Jefferson Lab proposed a minimally invasive energy recovery experiment utilizing the CEBAF superconducting, recirculating, linear accelerator

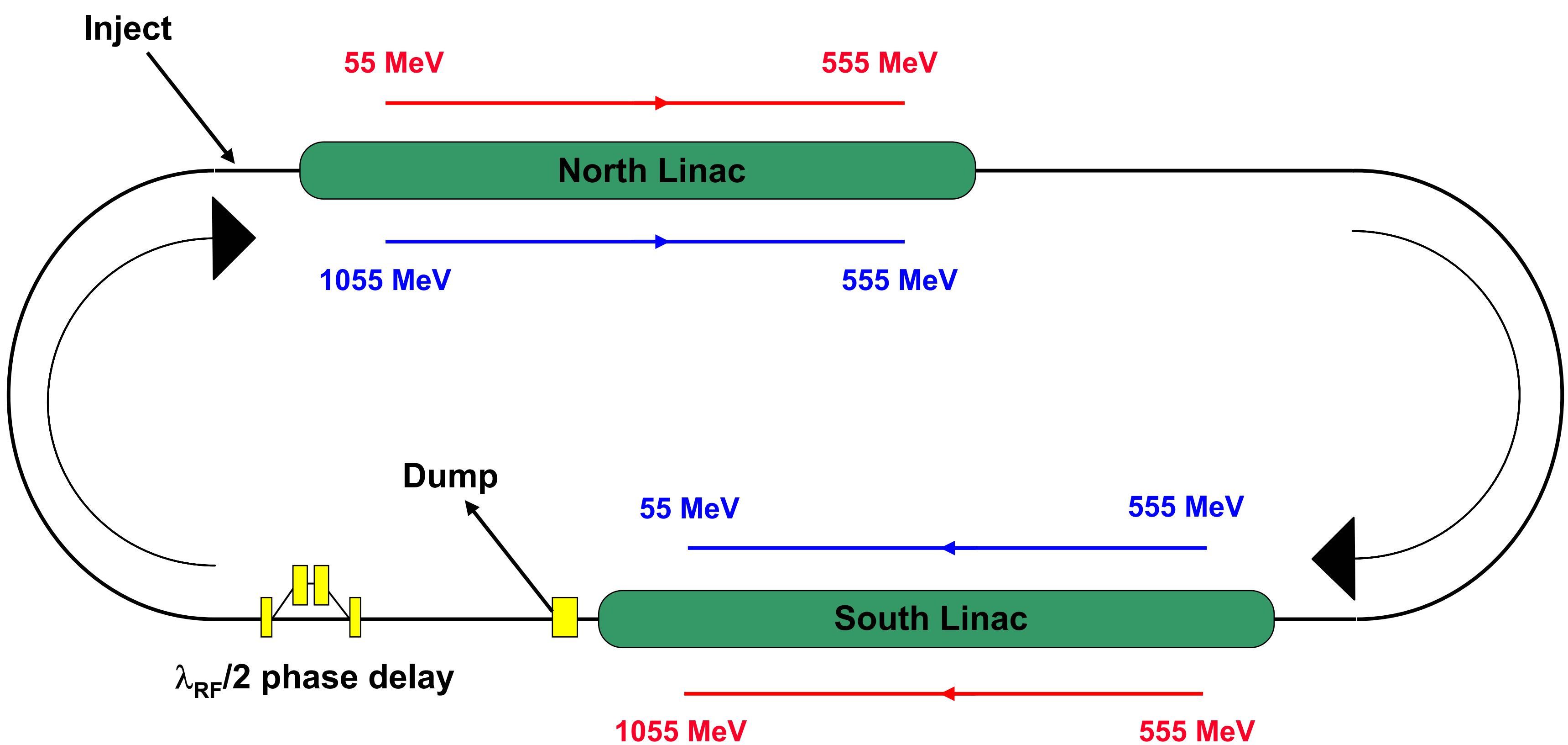
CEBAF Modifications

Modifications include the installation of:

- $\lambda_{RF}/2$ path length delay chicane
- Dump and beamline with diagnostics

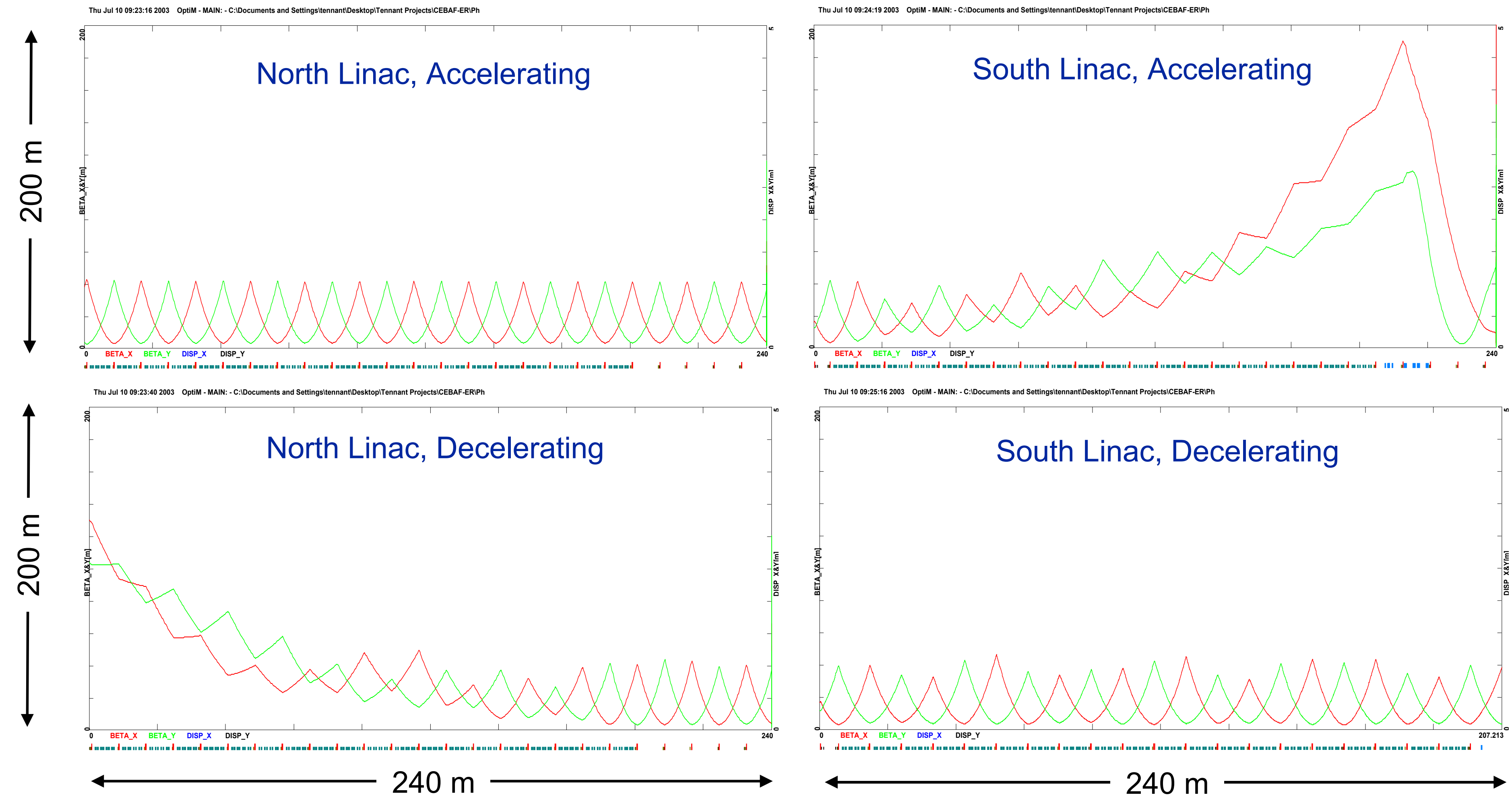


"1 Pass-Up / 1 Pass-Down" Operation



Machine Optics

Linacs - standard 120° lattice for the lowest energy beam in each linac and mismatched optics on the other pass.



Measurements Performed

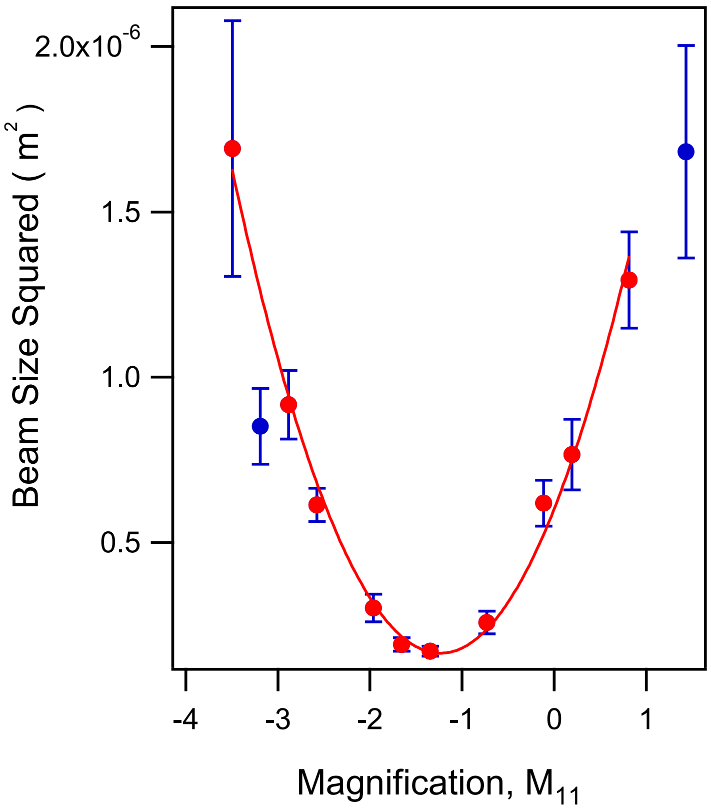
- In an effort to gain a quantitative understanding of the 6D phase space, the following measurements were taken:
  - Measuring the transverse emittance of the beam in the injector, in each Arc and immediately before being sent to the dump
  - To characterize the longitudinal phase space, the momentum spread was measured in each Arc
- Measure energy recovered beam profiles with a large dynamic range as a way to characterize halo
- Measured the RF's response to energy recovery

These measurements were performed with E_{inj} = 55 MeV and 20 MeV

(i.e. exercise final-to-injector energy ratios (E_{final} / E_{inj}) of 20:1 and 50:1)

Emittance Measurements

- Transverse emittance in the injector and Arcs were performed using the standard method of using multiple optics and multiple wire scanners.
- Measuring the emittance of the energy recovered beam proved to be tricky since we had to make the measurements in the presence of two, co-propagating beams.

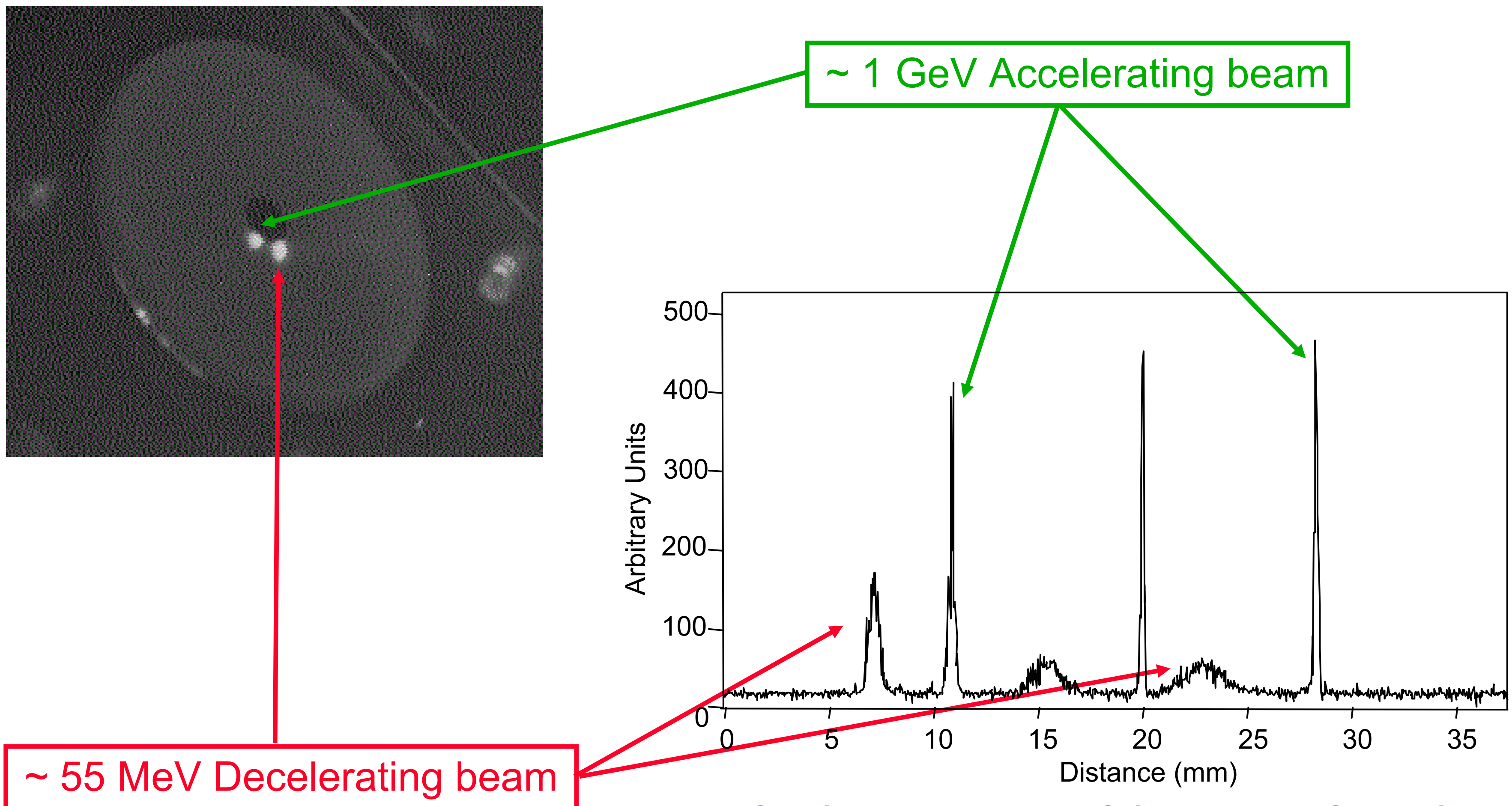


- A single scanning quadrupole and downstream wire scanner scheme was used.
- The beam size squared at the wire scanner depends quadratically upon the quadrupole strength and from that the emittance can be extracted. That is,

$$\sigma^2_{measured} = \beta_{wire}\varepsilon = (1+kL)^2 \underbrace{(\beta_{quad}\varepsilon)}_{\mathbf{A}} - (1+kL)\underbrace{(\alpha_{quad}\varepsilon)}_{\mathbf{B}} 2L + L^2 \underbrace{(\gamma_{quad}\varepsilon)}_{\mathbf{C}}$$

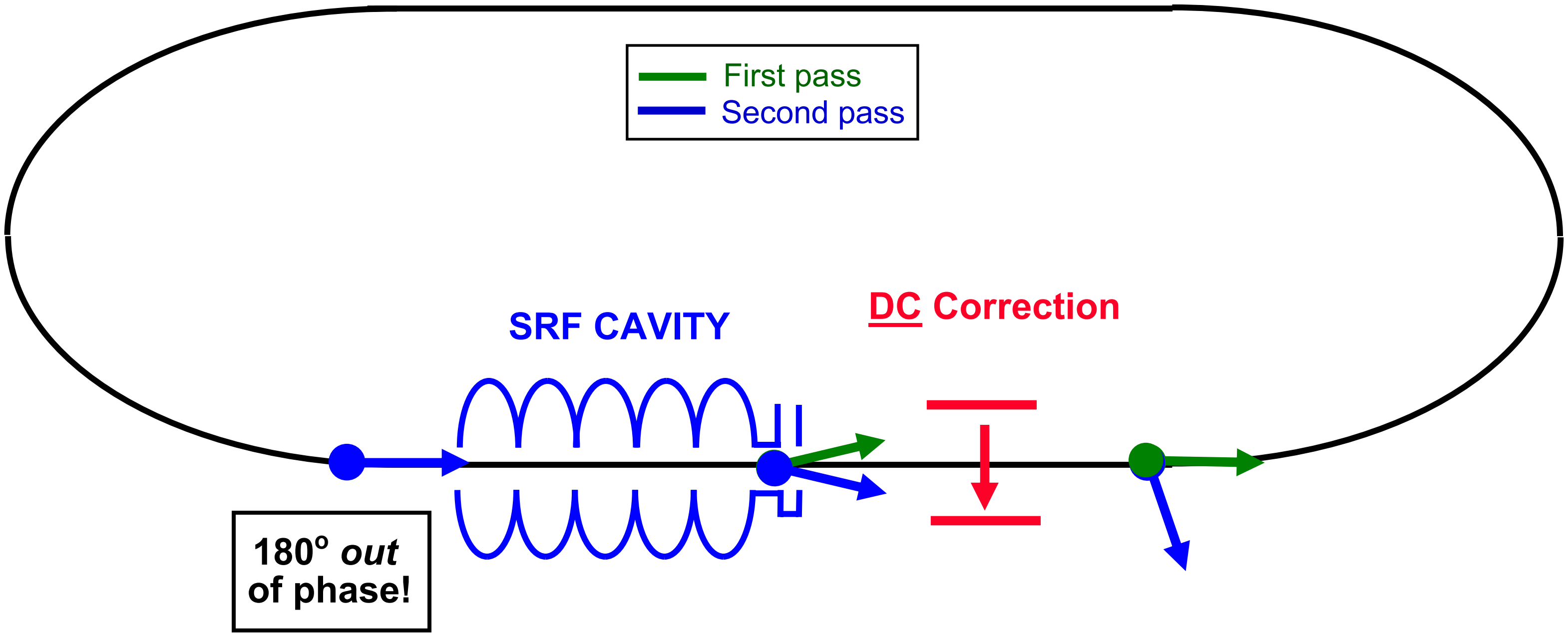
CEBAF-ER Experimental Run

Beam viewer near the exit of the South Linac



3-wire scanner x 2 beams = 6 peaks

FPC Dipole Mode Driven Steering

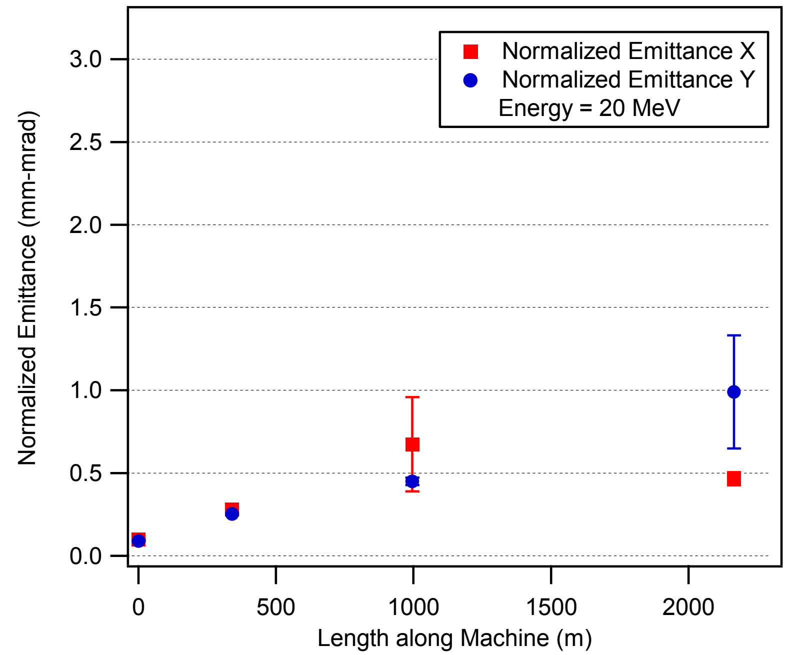


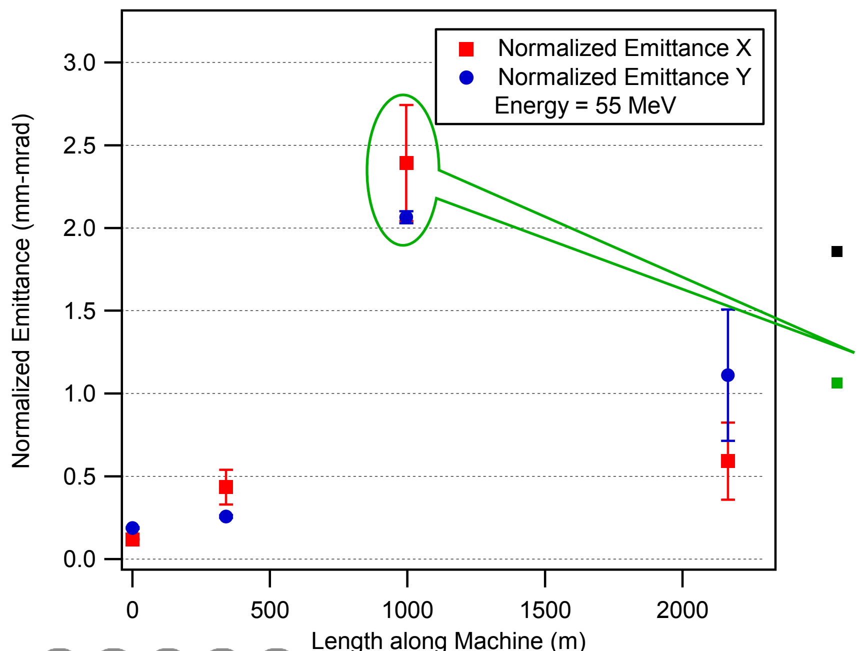
- The same general concept applies to cavity HOM coupler induced transverse coupling – you can use DC magnetic skew quad to locally correct one pass with the consequence of *doubling* the coupling in the other pass.
- Operated with a “Up – Down” correction scheme (correct lowest energy beam in each linac).
- *Future cavity designs should accommodate the influence of these and similar effects.*

Results of Emittance Measurements

Preliminary Conclusions

- Emittance is degraded by passage through linacs
  - FPC dipole head-tail steering (order $\Delta\varepsilon$~1mm-mrad/pass)
  - HOM coupler induced coupling
- The process of energy recovery does not contribute to the emittance degradation since the emittance of the recirculating pass is consistent with the accelerating pass.





- Data for E_{inj} = 55 MeV is consistent with E_{inj} = 20 MeV results *except* for Arc 2 emittance…
- This data point is under investigation and plans are being made to redo measurement

Beam Profiles of ER Beam

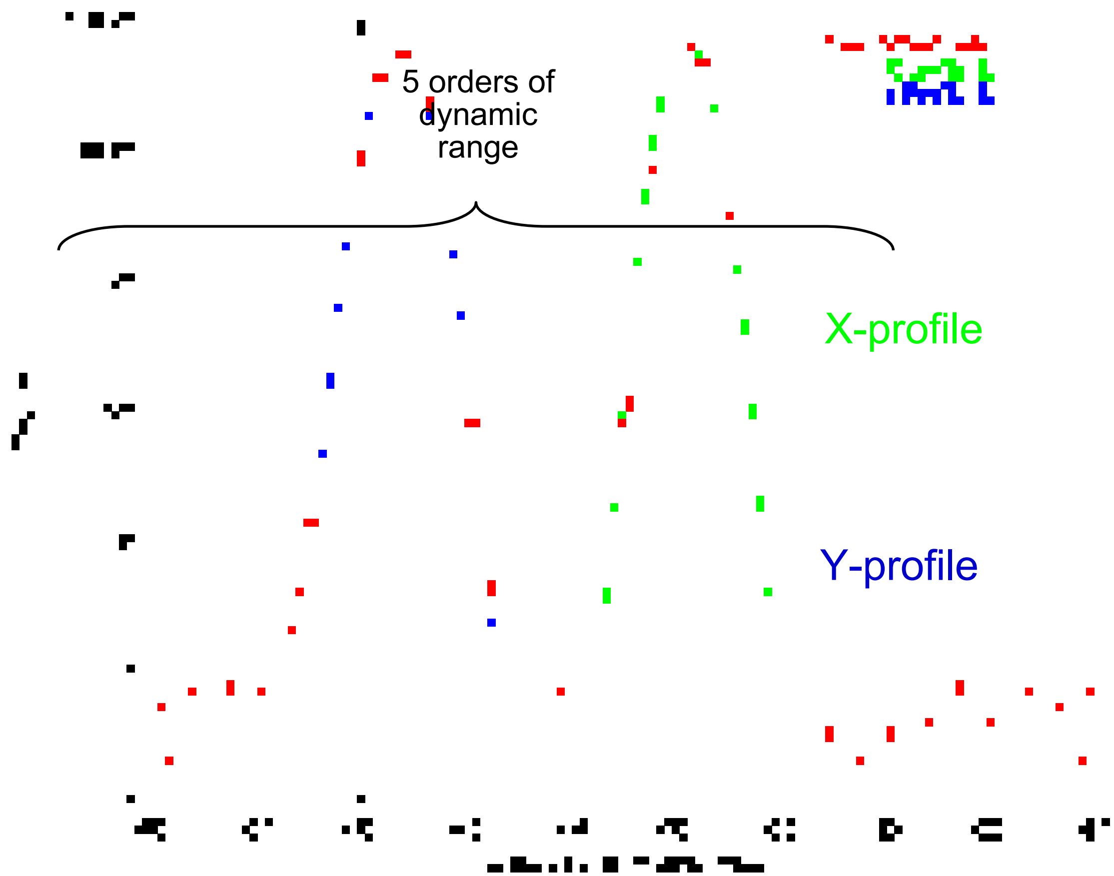
- Increase dynamic range of beam profile measurements to detect particles outside the Gaussian core – ultimately this will aid in the measurement of beam loss
- Beam profiles (55 MeV, 1μA beam) measured with a wire scanner and 3 downstream photomultiplier tubes (PMTs)
- Each profile (X and Y) is fit with a function of the form:

$$F = Gaussian + Background$$

- An upper limit of halo is calculated from the ratio

$$\frac{A_{Background}}{A_{Core}}$$

- For the transverse profiles the ratio is 1×10^{-4}

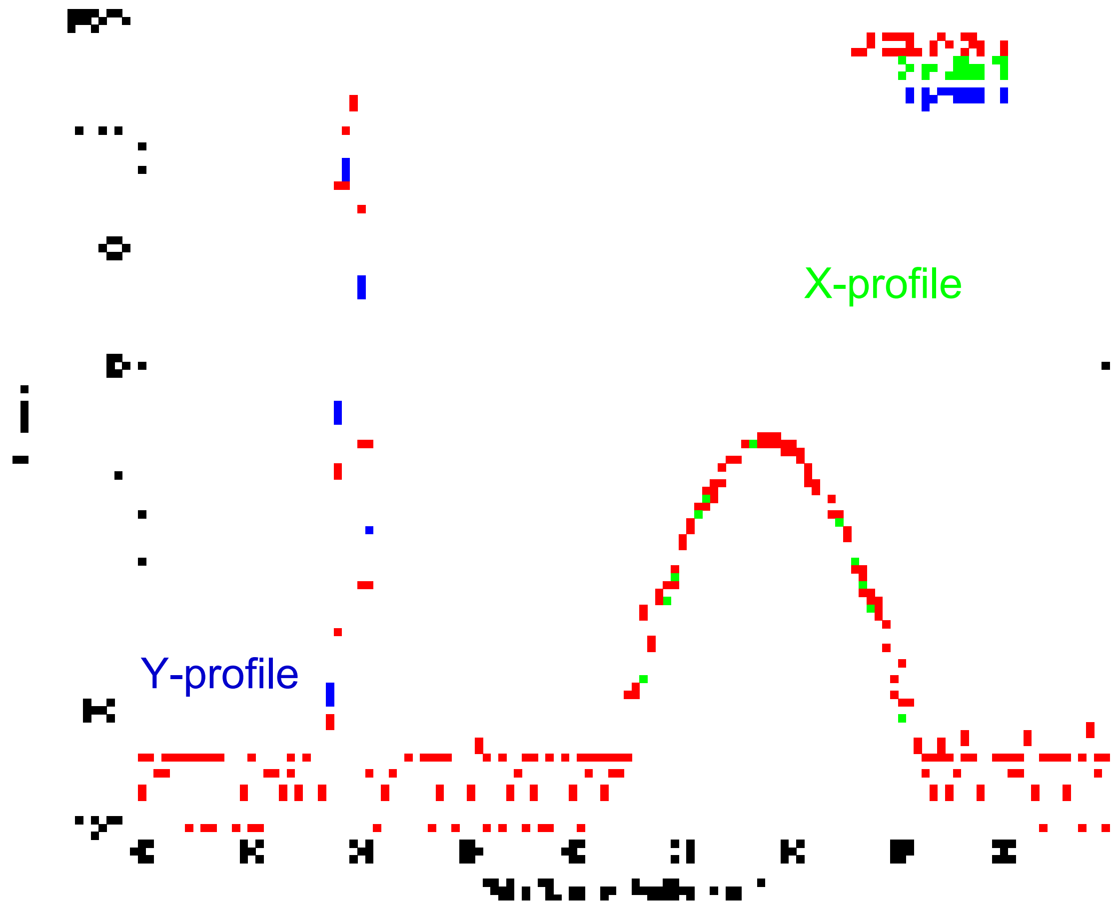


(courtesy A. Freyberger)

Beam Profiles of ER Beam (cont'd)

- Beam profiles (20 MeV, 1μA beam) measured with a wire scanner and 3 downstream PMTs

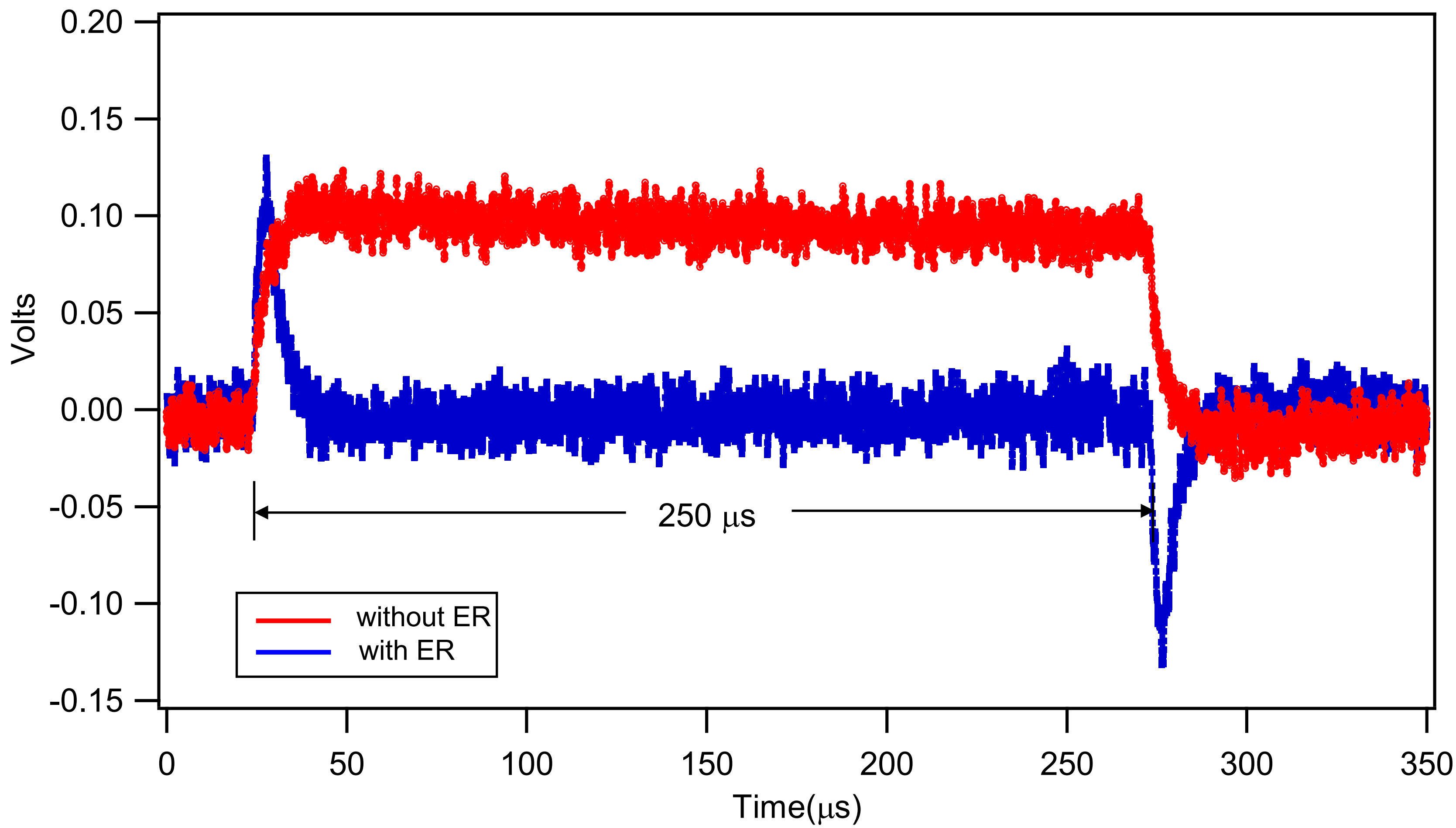
- The Y-profile shows a good Gaussian fit over 6 orders of dynamic range.
- The width of the X-profile is scaled by (ΔE/E) from the E_{inj} = 55 MeV case.
- Width of X-profile could potentially explain the increased scraping observed at E_{inj} = 20 MeV.



(courtesy A. Freyberger)

RF Response to Energy Recovery

- Gradient modulator drive signals **with** and **without** energy recovery in response to 250 μsec beam pulse entering the RF cavity *(SL20 Cavity 8)*



Conclusions

- **Achievements**
  - Demonstrated the feasibility of energy recovering a high energy (1 GeV) beam through a large (~1 km circumference), superconducting (39 cryomodules) machine.
  - 80 μA of CW beam accelerated to 1055 MeV and energy recovered at 55 MeV.
  - 1 μA of CW beam, accelerated to 1020 MeV and energy recovered at 20 MeV, was steered to the ER dump.
  - Tested the dynamic range on system performance by demonstrating high final-to-injector energy ratios (E_{final}/E_{inj}) of 20:1 and 50:1.
- **Future Activities**
  - Important accelerator physics and technology challenges are topics of vigorous research at JLab. They will also be addressed experimentally by a number of prototypes, such as the 10 mA JLab FEL, 100 mA FEL upgrade and continued activities with CEBAF-ER.

E02-102 Collaboration

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Lia Merminga
Mike Tiefenback
Hiro Toyokawa

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