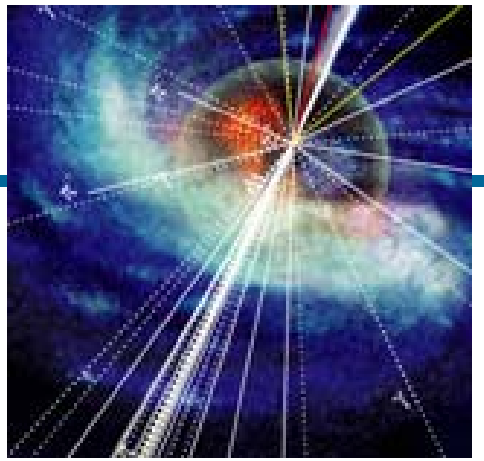


ELIC Design

Ya. Derbenev, K. Beard, S. Chattopadhyay, J. Delayen, J. Grames, A. Hutton, G. Krafft, R. Li, L. Merminga, M. Poelker, E. Pozdeyev, B. Yunn, Y. Zhang

Center for Advanced Studies of Accelerators

Jefferson Lab

Second Electron-Ion Collider Workshop
Jefferson Lab
March 15 - 17, 2004

Outline

- Nuclear Physics Motivation & Requirements
- ELIC Concept
- ELIC Layout / Integration with 25 GeV Fixed Target Program
- Electron Cooling and Luminosity Lifetime
- Parameter Choices / Table of Parameters
- Accelerator Physics & Technology Issues
  - Ion Ring
  - Electron Linac
  - Electron-Ion Collisions
- R&D Topics / Activities
  - CEBAF-ER: A High Energy Demonstration of Energy Recovery
- Conclusions

Nuclear Physics Motivation

- A high luminosity polarized electron – light ion collider has been proposed as a powerful new microscope to probe the partonic (quarks and gluons) structure of matter
- Over the past two decades we have learned a great amount about the hadronic structure
- Some crucial questions remain open:
  - What is the structure of the proton and neutron in terms of their quark and gluon constituents?
  - How do quarks and gluons evolve into hadrons?
  - What is the quark-gluon origin of nuclear binding?

Nuclear Physics Requirements

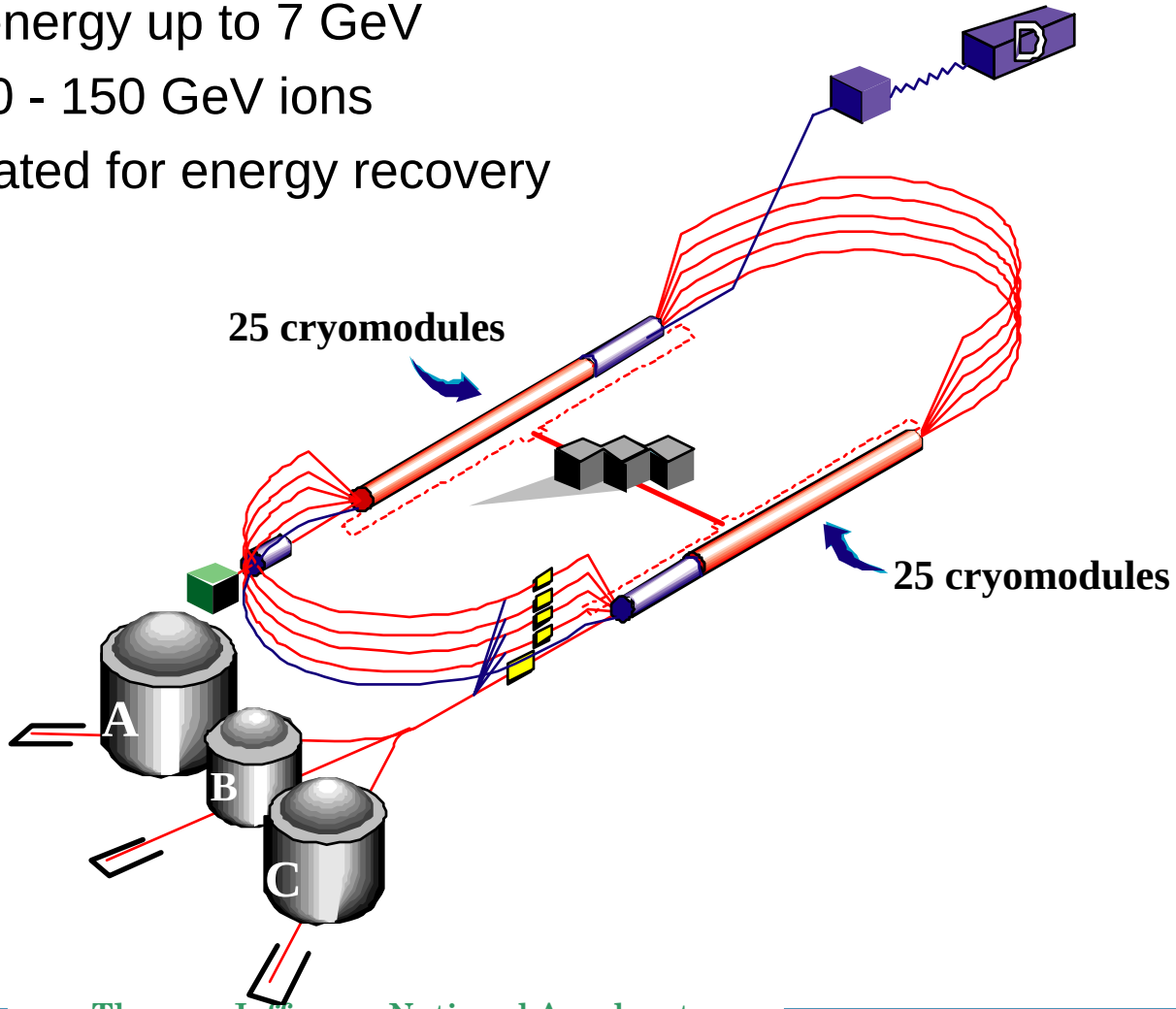
- The features of the facility necessary to address these issues:
  - Center-of-mass energy between 20 GeV and 65 GeV

    with energy asymmetry of ~10, which yields

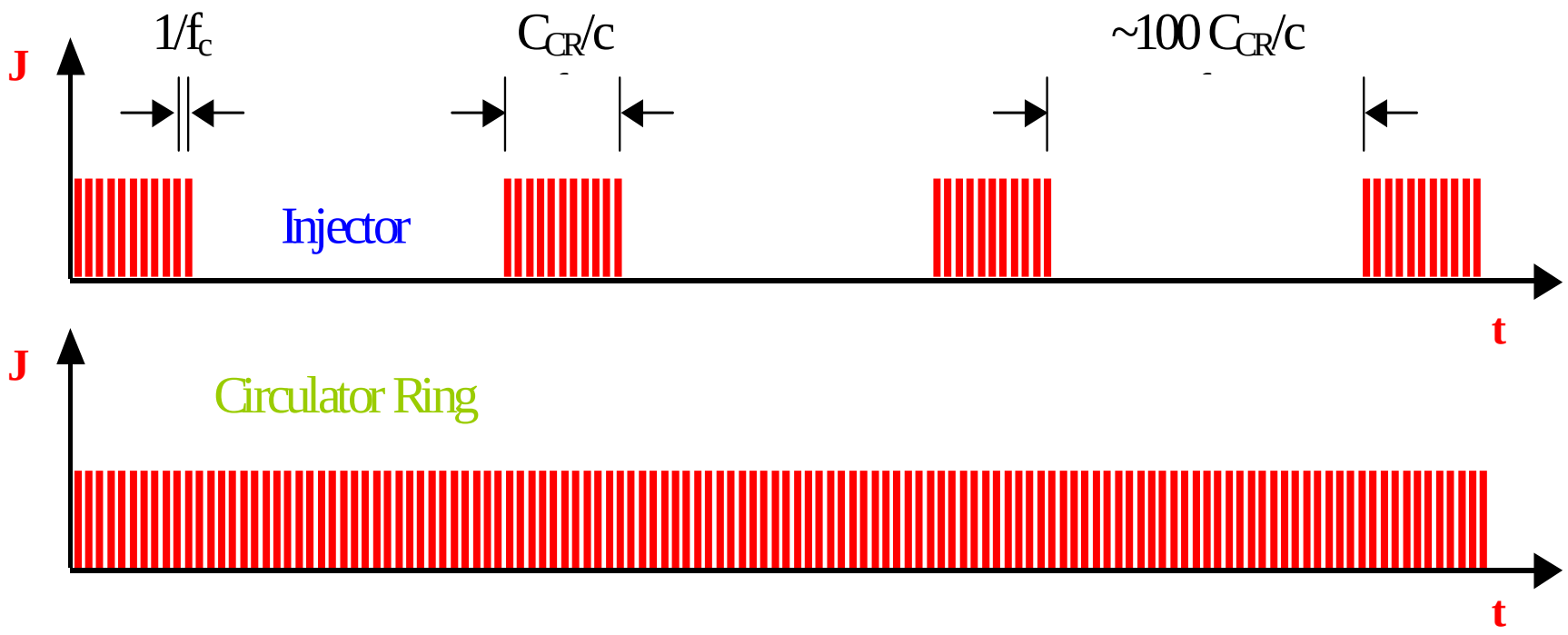
    E_e ~ 3 GeV on E_i ~ 30 GeV up to E_e ~ 7 GeV on E_i ~ 150 GeV
  - CW Luminosity from 10^{33} to 10^{35} cm^{-2} sec^{-1}
  - Ion species of interest: protons, deuterons, ^{3}He
  - Longitudinal polarization of both beams in the interaction region $\geq$ 50% –80% required for the study of generalized parton distributions and transversity
  - Transverse polarization of ions extremely desirable
  - Spin-flip of both beams extremely desirable

CEBAF with Energy Recovery

- Install 50 CEBAF Upgrade (7-cell) cryomodules at gradient up to 23 MV/m
- Single-pass CEBAF energy up to 7 GeV
- After collisions with 30 - 150 GeV ions
- Electrons are decelerated for energy recovery



Circulator Ring

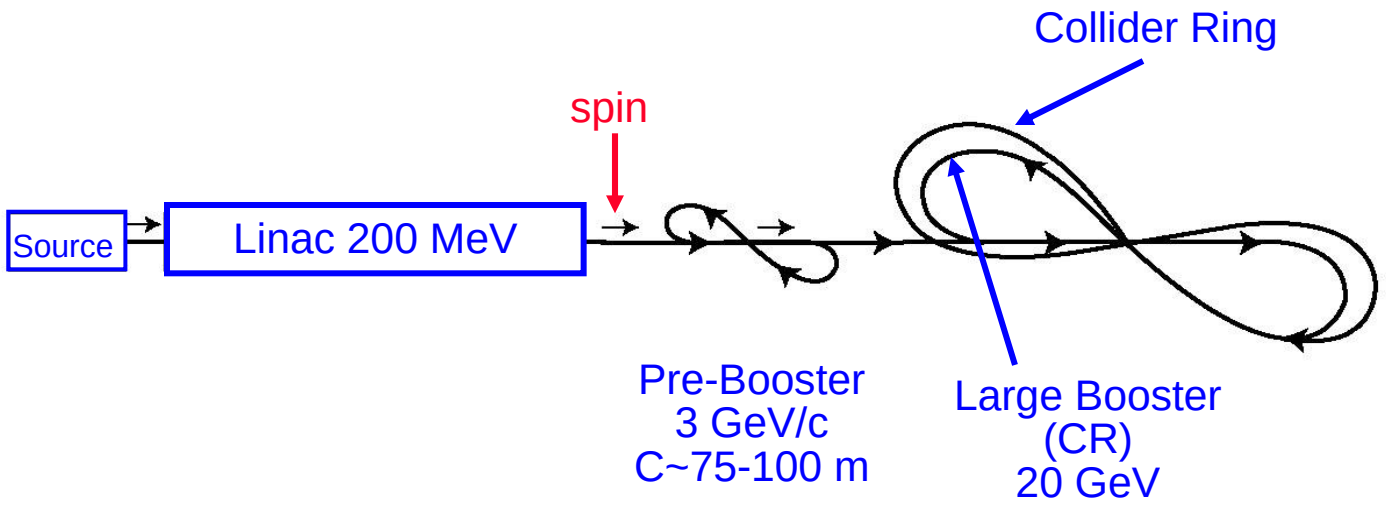


Different filling patterns are being explored (Derbenev, Hutton, Litvinenko)

Ion Complex

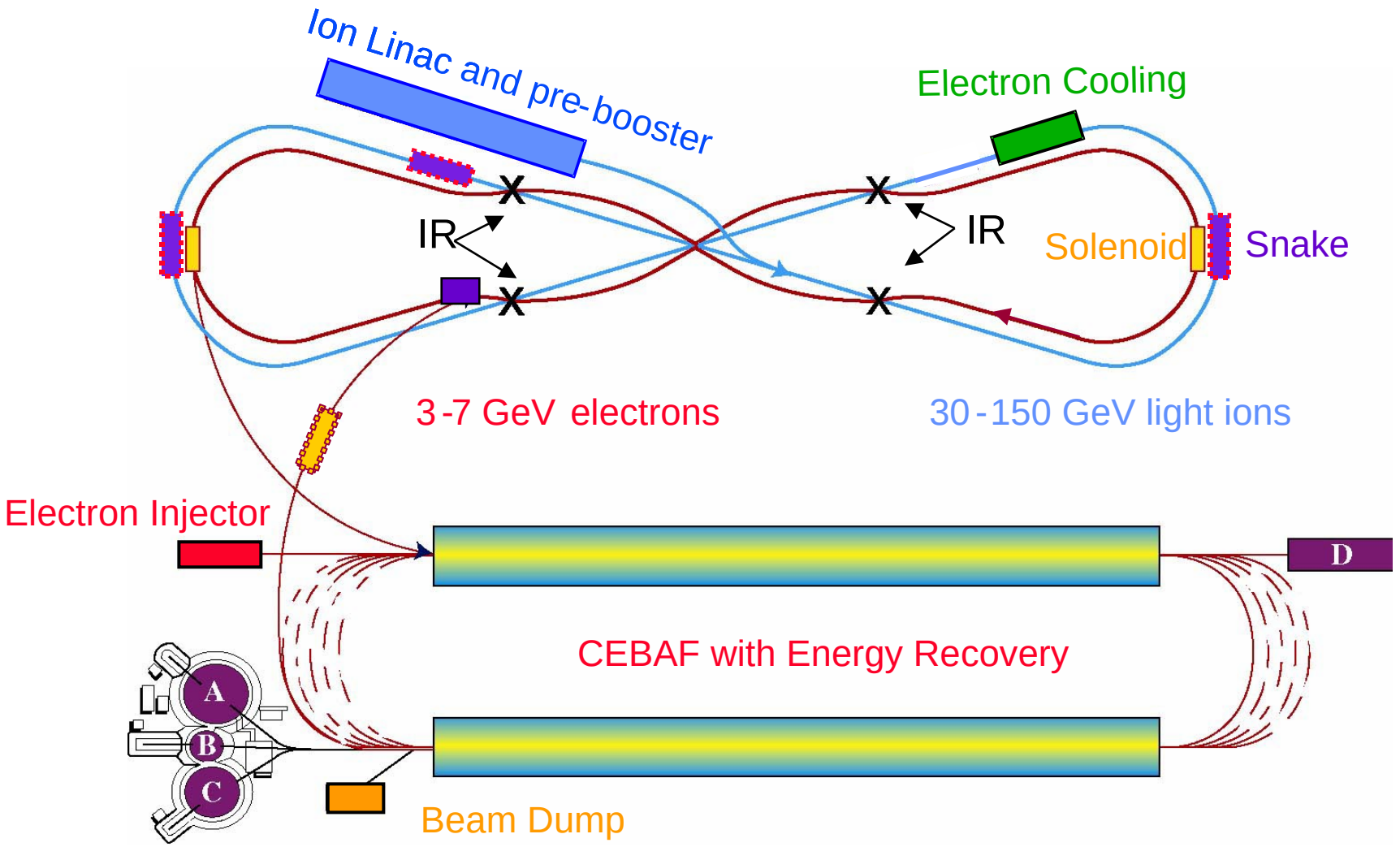
"Figure-8" storage rings:

- Zero spin tune avoids intrinsic spin resonances
- No spin rotators required



Talk by **Derbenev** on **Ion Polarization in ELIC**

ELIC Layout

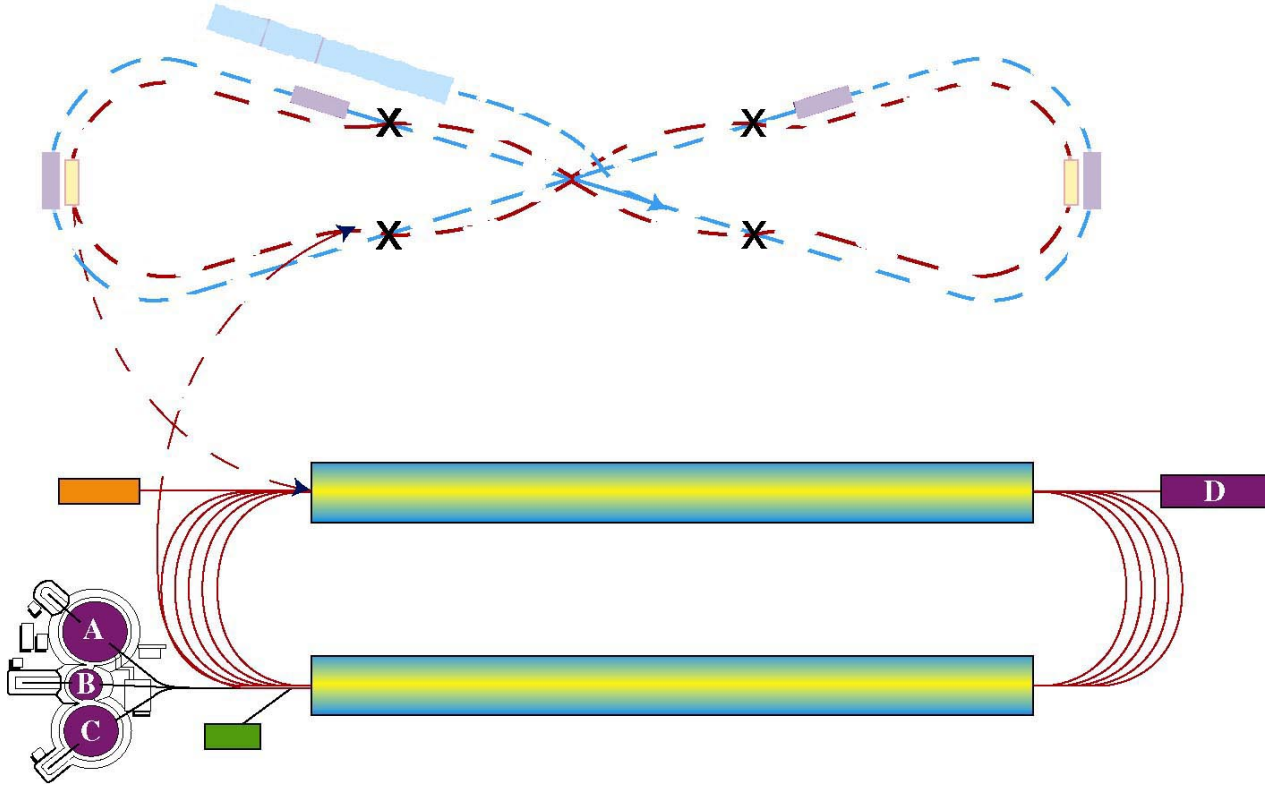

Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

The same electron accelerator can also provide 25 GeV electrons for fixed target experiments for physics

- Implement 5-pass recirculator, at 5 GeV/pass, as in present CEBAF

(One accelerating & one decelerating pass through CEBAF $\Rightarrow$ 20-65 GeV CM Collider Program)

- Exploring whether collider and fixed target modes can run simultaneously



Electron Cooling, Intrabeam Scattering and Luminosity Lifetime

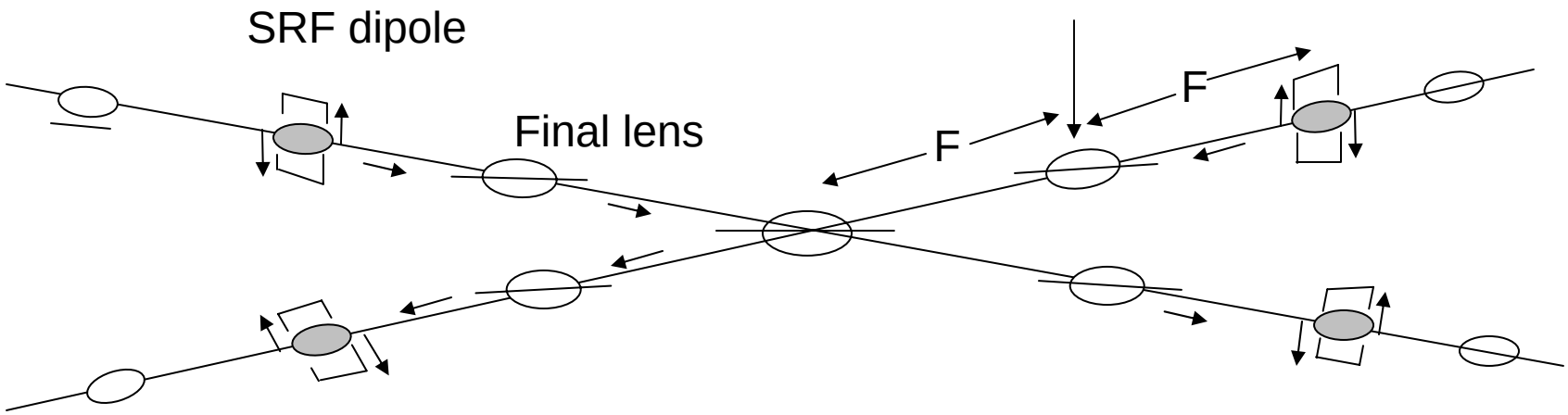
Talk by **Derbenev** on **Electron Cooling and Luminosity of EIC**

- IBS heating mechanism: Energy exchange at intra-beam collisions increases the energy spread and excites horizontal oscillations via dispersion, and vertical oscillations via x-y coupling.
- Electron cooling is introduced to suppress beam blow up due to IBS, and maintain emittances near limits determined by beam-beam interaction.
- For low transverse coupling, electron cooling leads to flat beams (with emittance aspect ratio of 25:1 for ELIC).
- Therefore, reducing the transverse coupling while conserving beam area (which determines the luminosity), decreases the impact of IBS on luminosity
- Touschek effect: IBS at large momentum transfer (single scattering) drives particles out of the beam core, limiting luminosity lifetime.
- A phenomenological model which includes single scattering and cooling time of the scattered particles has been used to estimate an optimum set of parameters for maximum luminosity, at a given luminosity lifetime.

Crab Crossing

Short bunches make feasible the Crab Crossing

SRF deflectors 1.5 GHz can be used to create a proper bunch tilt



Parasitic collisions are avoided without loss of luminosity

ELIC Parameters at different CM energies

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**	**100/5**	**30/3**
Cooling beam energy	**MeV**	**75**	**50**	**15**
Bunch collision rate	**GHz**	**1.5**		
Number of particles/bunch	**10^{10}**	**.4/1.0**	**.4/1.1**	**.12/1.7**
Beam current	**A**	**1/2.4**	**1/2.7**	**.3/4.1**
Cooling beam current	**A**	**2**	**2**	**.6**
Energy spread, rms	**10^{-4}**	**3**		
Bunch length, rms	**mm**	**5**		
Beta-star	**mm**	**5**		
Horizontal emittance, norm	**μm**	**1/100**	**.7/70**	**.2/43**
Vertical emittance, norm	**μm**	**.04/4**	**.06/6**	**.2/43**
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.073**	**.01/.007**
Space charge tune shift in p-beam		**.015**	**.03**	**.06**
Luminosity per IP*, 10^{34}	**cm^{-2} s^{-1}**	**7.7**	**5.6**	**.8**
Core & luminosity IBS lifetime	**h**	**24**	**24**	**> 24**
Lifetime due to background scattering	**h**	**200**	**> 200**	**> 200**

ELIC Parameter choices

- We envision an evolutionary upgrade path to the luminosity of ELIC, which starts at ~ 10^{33} cm^{-2} sec^{-1} at bunch rep rate of 150 MHz, progresses to ~ 10^{34} cm^{-2} sec^{-1} at higher bunch rep rate while ~ 1 Ampere of electron beam current will require the use of circulator ring, and reaches the ultimate potential of nearly $8x10^{34}$ cm^{-2} sec^{-1} at maximum rep rate of 1.5 GHz. In addition to the circulator ring, this scenario assumes that strong SRF fields in the SR together with electron cooling allow very short ion bunches, which in turn allow very low beta-star and make crab crossing feasible.

- All parameter sets assume electron cooling and the resulting flat beams at equilibrium and parameters have been calculated at the beam-beam tuneshift limit for the ion beam of 0.01. Equal beam sizes for electrons and ions are assumed at the IP.

Luminosity Evolution of ELIC

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**		
Cooling beam energy	**MeV**	**75**		
Bunch collision rate	**GHz**	**.15**	**.5**	**1.5**
Number of particles/bunch	**10^{10}**	**.4/1.0**		
Beam current	**A**	**.1/.24**	**.3/.8**	**1/2.4**
Cooling beam current	**A**	**.2**	**.6**	**2**
Energy spread, rms	**10^{-4}**	**3**		
Bunch length, rms	**mm**	**25/5**	**10/5**	**5/5**
Beta-star	**mm**	**25**	**10**	**5**
Horizontal emittance, norm	**μm**	**1/100**		
Vertical emittance, norm	**μm**	**.04/4**		
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.086**	**.01/.086**
Space charge tune shift in p-beam		**.003**	**.007**	**.015**
Luminosity per IP*, 10^{34}	**cm^{-2} s^{-1}**	**.15**	**1.2**	**7.7**

Short Ion Bunches and Low β^*

Cooled p-bunches in a ring with SRF cavities

Parameter	Unit	Value
Beam energy	GeV	150
RF frequency	GHz	1.5
Voltage amplitude	MV	100
Ring circumference	km	1.2
Compaction factor	10^{-3}	4
Synchrotron tune		.06
Energy acceptance	%	.3
Energy spread, rms	10^{-4}	3
Bunch length, rms	mm	5

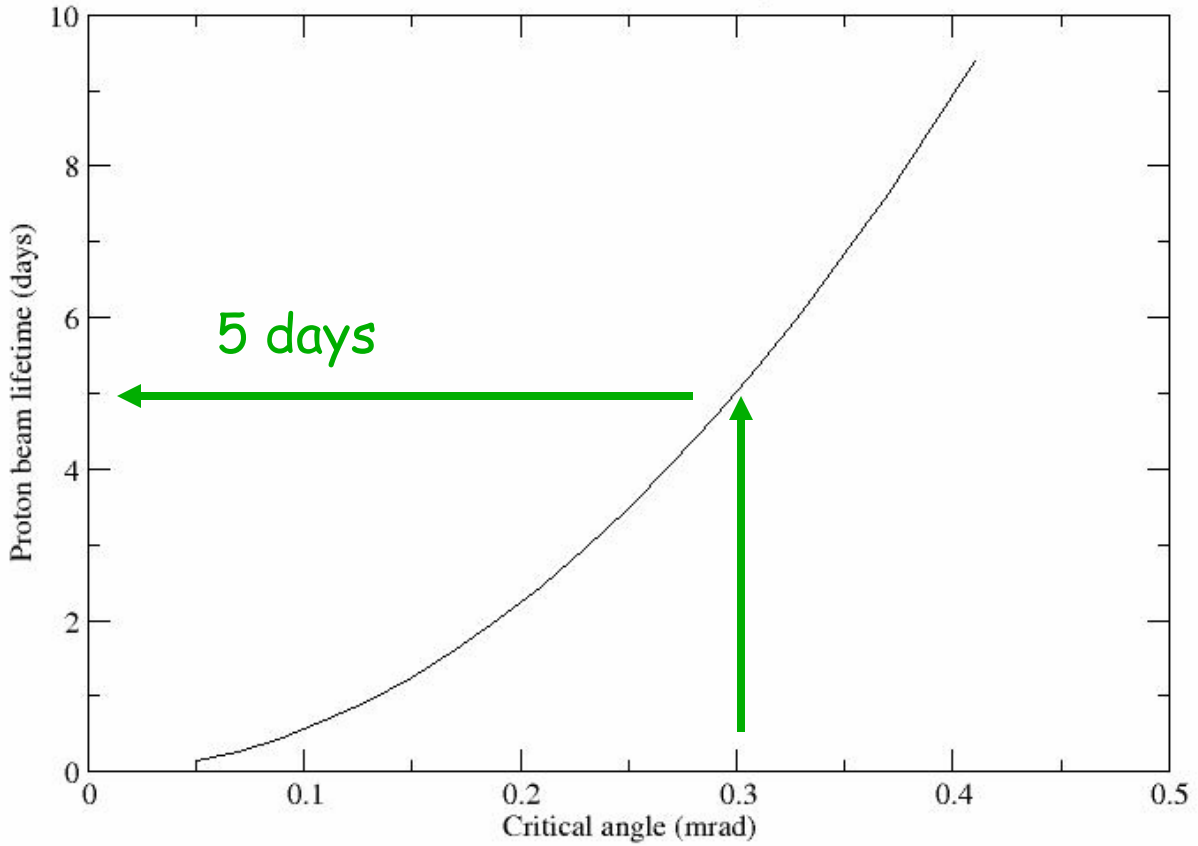
Final focus of ELIC with short bunches (p/e)

Beam energy	GeV	150/7
Bunch length, rms	mm	5/5
Focal length	m	4/4
Large beta	km	3.2/3.2
Beta-star	mm	5/5
Transverse emittance, norm, rms	μm	1/100
Beam size at large beta, rms	mm	5/5
Beam size at star point, rms	μm	6/6

Strong SRF -> high synchrotron tune (0.06) which helps stabilize short ion bunches against microwave instabilities and beam-beam interaction.

Lifetime due to Background Processes

Proton beam lifetime from small-angle elastic ep-scattering



Contributions from inelastic processes have smaller effect by factor of ~10

Courtesy: A. Afanasev, et al.

Accelerator Physics of the Ion Ring

Instability mechanisms have been examined for the top luminosity parameters:

- Longitudinal Microwave Instability ok
- Transverse Microwave Instability ok
- Longitudinal Coupled Bunch Instability → Would require feedback
- Transverse Mode Coupling Instability
- Electron Cloud Instability ok

Accelerator Physics & Technology of the Electron Linac

- Electron Source
  - State of the art in high average current, polarized sources: ~1 mA at 80% polarization [M. Poelker, JLab]
  - State of the art in high average current, unpolarized sources: JLab FEL Upgrade achieved 7 mA, design 10 mA
  - Circulator ring concept greatly reduces source requirements

Talk by **Poelker** on **High Current Prospects for Polarized Electron Sources**

- Accelerator Transport in the ERL
  - Demonstrate energy recovery with large energy ratio ➡ more later
  - High current stability in the ERL ➡ adequate damping of long. and transverse HOMs
- SRF/RF/Cryogenics issues

Accelerator Physics Issues of the Electron-Ion Collisions

- IR design integrated with real detector geometry
- Beam-beam head-tail instability
  - The beam-beam force due to the relative offset between the head of the proton bunch and the electron beam will deflect the electrons. The deflected electrons subsequently interact with the tail of the proton bunch through beam-beam kick
  - The electron beam acts as a transverse impedance to the proton bunch, and can lead to an instability
  - The instability has been observed in numerical simulations [R. Li, J. Bisognano, (1993)] during the beam-beam studies of linac-ring B-Factory. Linear theory developed by Lebedev, Li and Yunn (2001) predicts threshold current.
  - Landau damping introduced by tunespread caused by electron beam and perhaps chromaticity expected to increase the threshold current of the instability.
  - Simulation methods have been developed to study the general nonlinear problem.

Talk by **Krafft** on **Beam-beam effects in Linac-Ring scenario**

R&D Topics

Several important R&D topics have been identified:

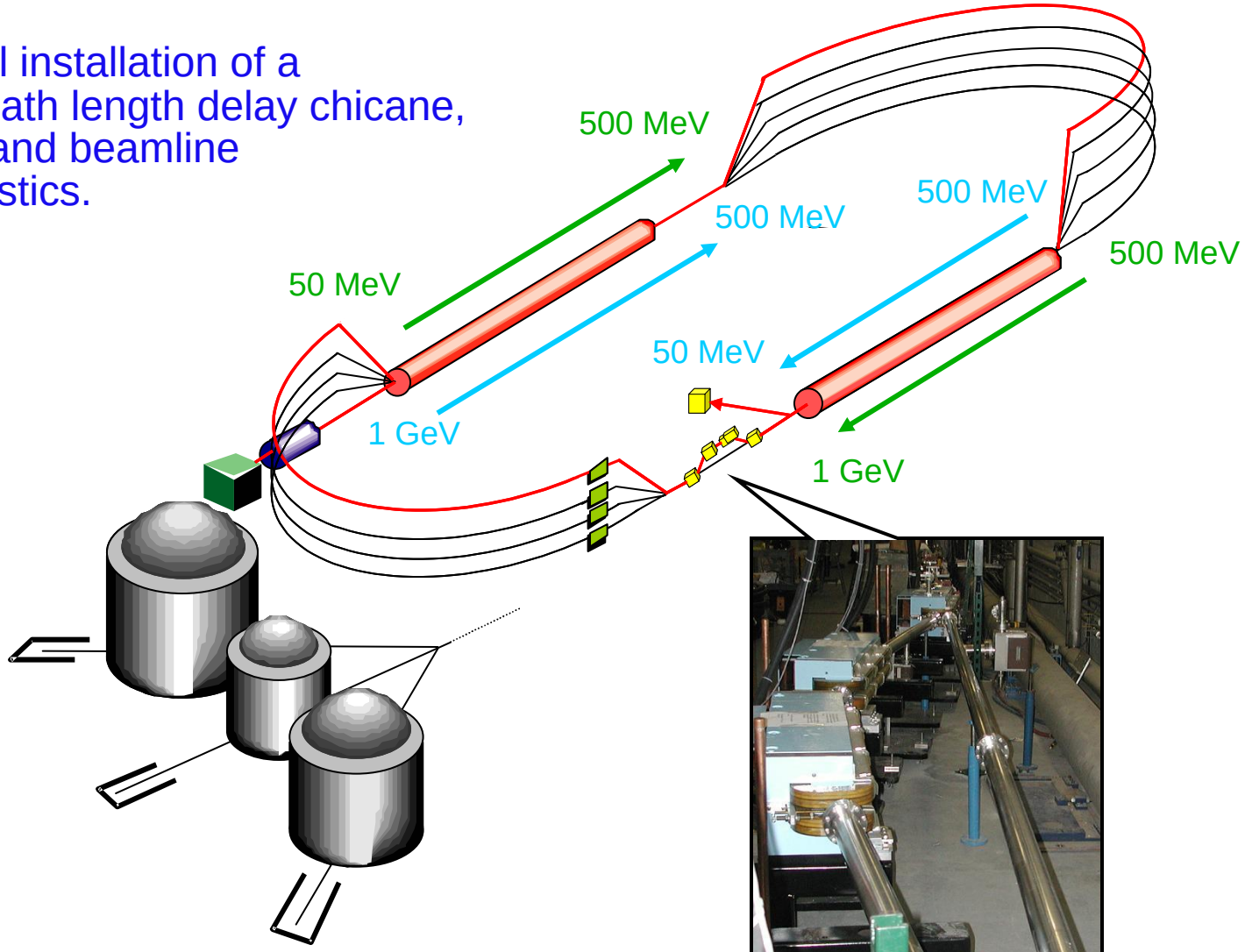
- High charge per bunch and high average current polarized electron source
- High energy electron cooling of protons/ions
  - Electron cooling of 150 GeV protons requires 75 MeV electrons. Practical only if based on SRF-ERL technology, demonstrated and routinely used at the JLab FEL
  - BNL/BINP, in collaboration with JLab, pursuing an ERL-based electron cooling device for heavy ions at RHIC
- Integration of interaction region design with detector geometry
- High current and high energy demonstration of energy recovery

High Energy Demonstration of Energy Recovery

- Energy recovery had been demonstrated at the FEL for a single cryomodule, and has been extended in the FEL Upgrade to two (later three) cryomodules.
- CEBAF-ER is a high energy (GeV scale) demonstration of energy recovery – 40 cryomodules.
  - Demonstrate sufficient operational control of two coupled beams of substantially different energies in a common transport channel, in the presence of steering, focusing errors.
  - Quantify evolution of transverse phase space during acceleration and energy recovery.
  - Test the dynamic range of system: large ratio of final to injected beam energies.

CEBAF-ER Experiment

Special installation of a $\lambda_{RF}/2$ path length delay chicane, dump and beamline diagnostics.



CEBAF-ER Installation

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

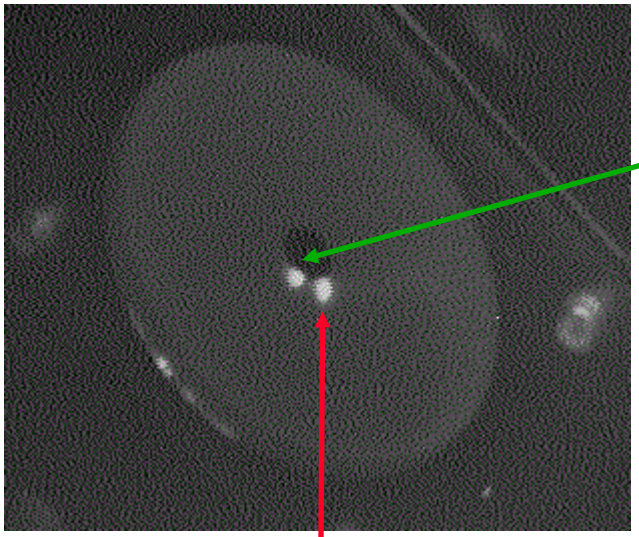
These measurements were performed with E_{inj} = 55 MeV and 20 MeV

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

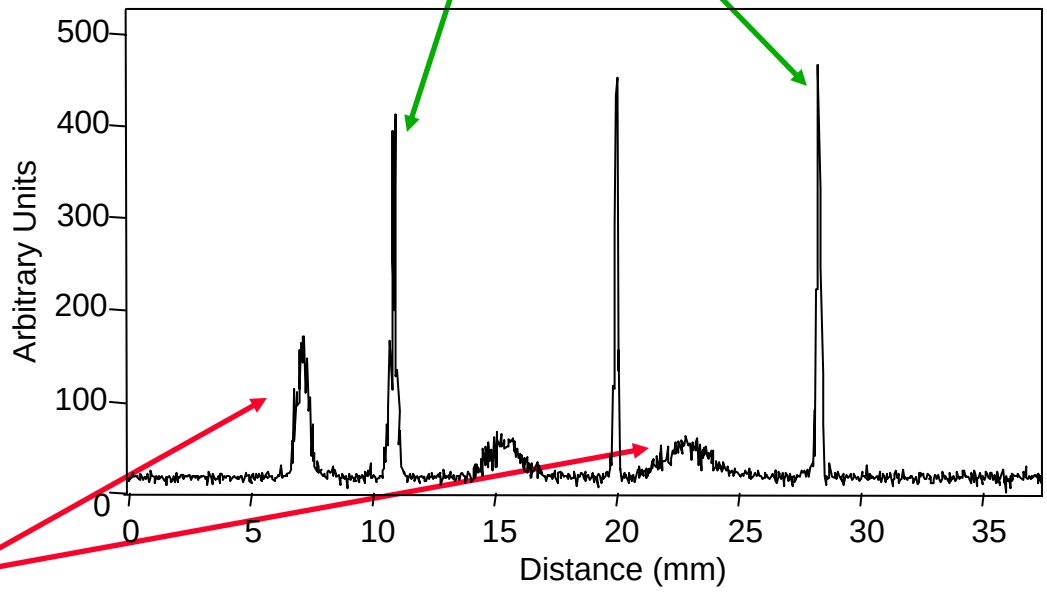
A. Bogacz, et al., "CEBAF Energy Recovery Experiment," Proc. PAC 2003

CEBAF-ER Emittance Measurements

Beam profiles at end of South Linac



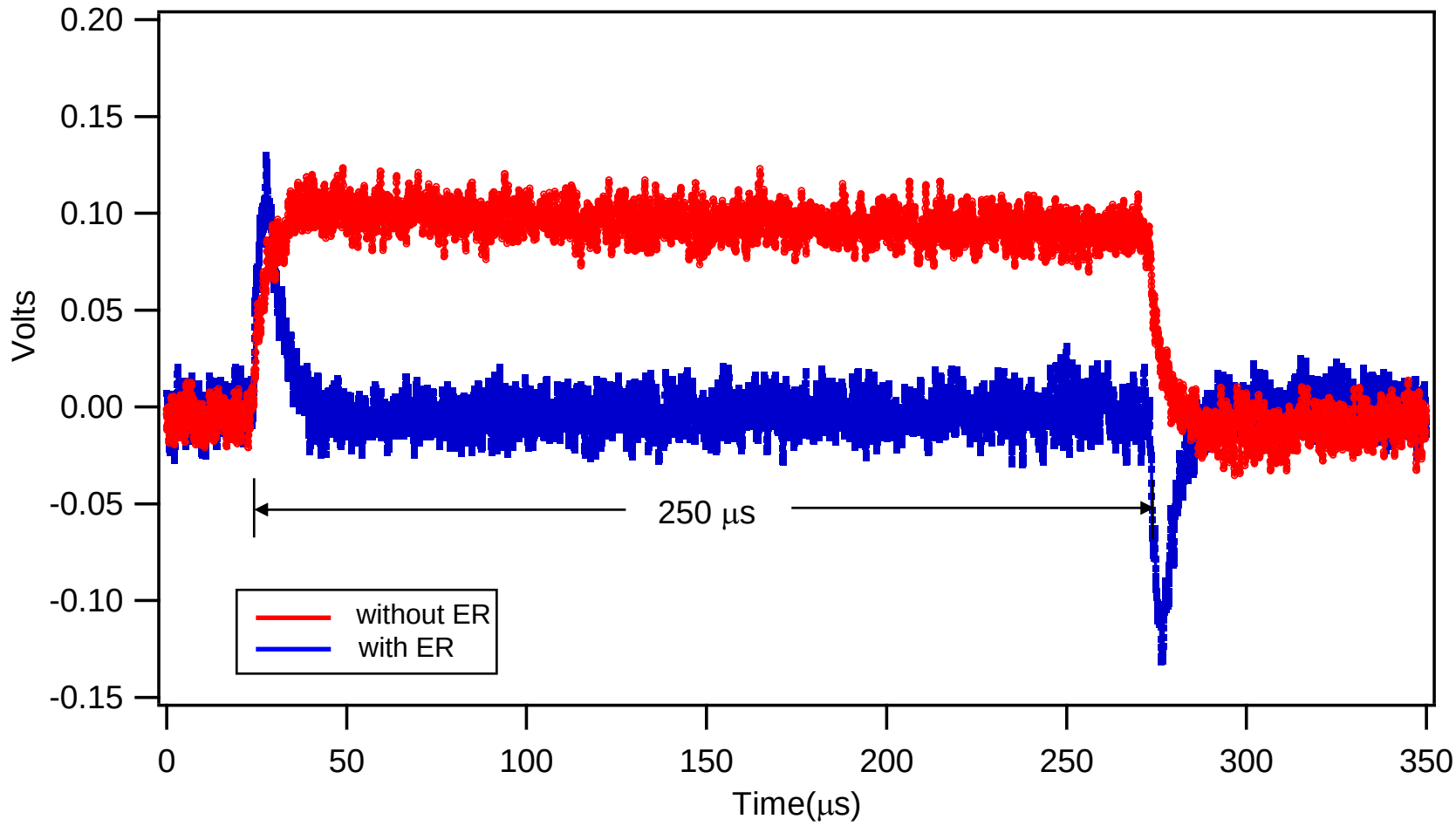
~ 1 GeV Accelerating beam



~ 55 MeV Decelerating beam

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)*



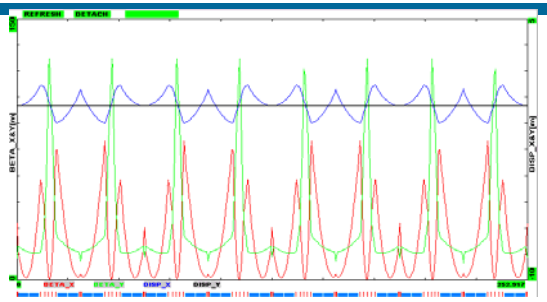
CEBAF-ER Preliminary Results

- 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 -> Performance limit at low injection energy.
- 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.

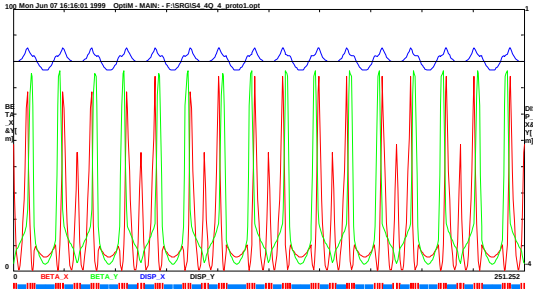
Conclusions

- An excellent scientific case starts developing for a high luminosity, polarized electron-light ion collider, to address fundamental questions in Hadron Physics
- JLab design studies have led to an approach that promises luminosities from 10^{33} cm^{-2} sec^{-1} up to nearly 10^{35} cm^{-2} sec^{-1}, for electron-light ion collisions at a center-of-mass energy between 20 and 65 GeV
- This design can be realized using energy recovery on the JLab site and can be integrated with a 25 GeV fixed target program for physics
- Planned R&D will address open readiness issues

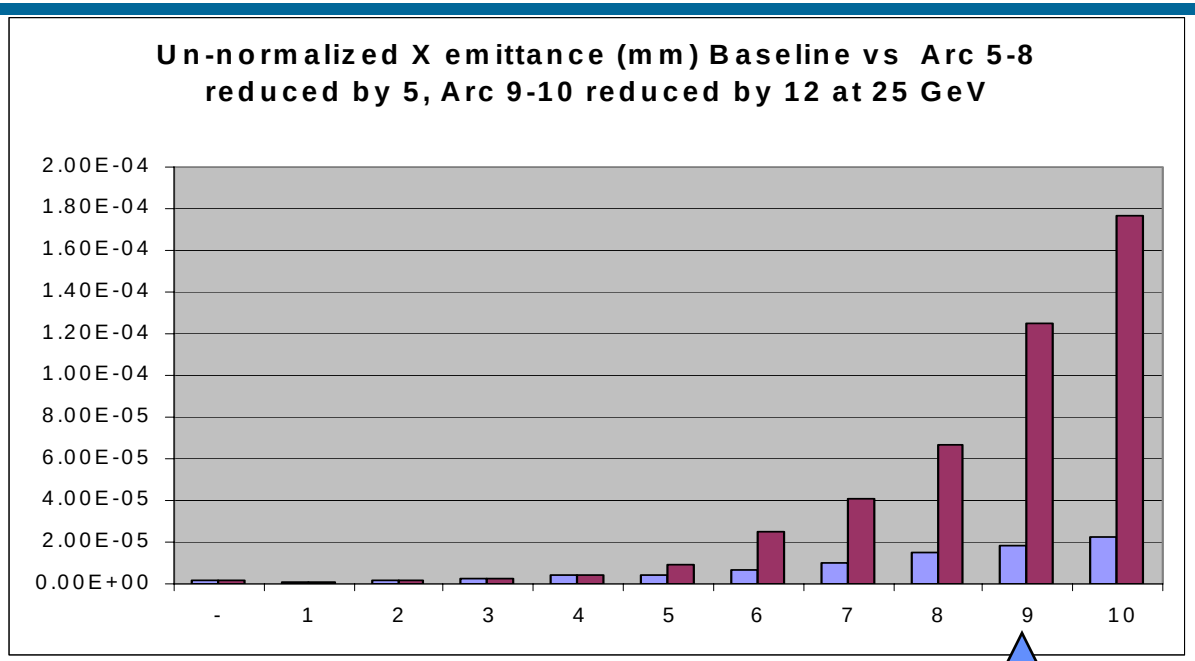
Feasibility of 25 GeV FT Program at CEBAF



Optics for arcs 5-8



Optics for arcs 9, 10



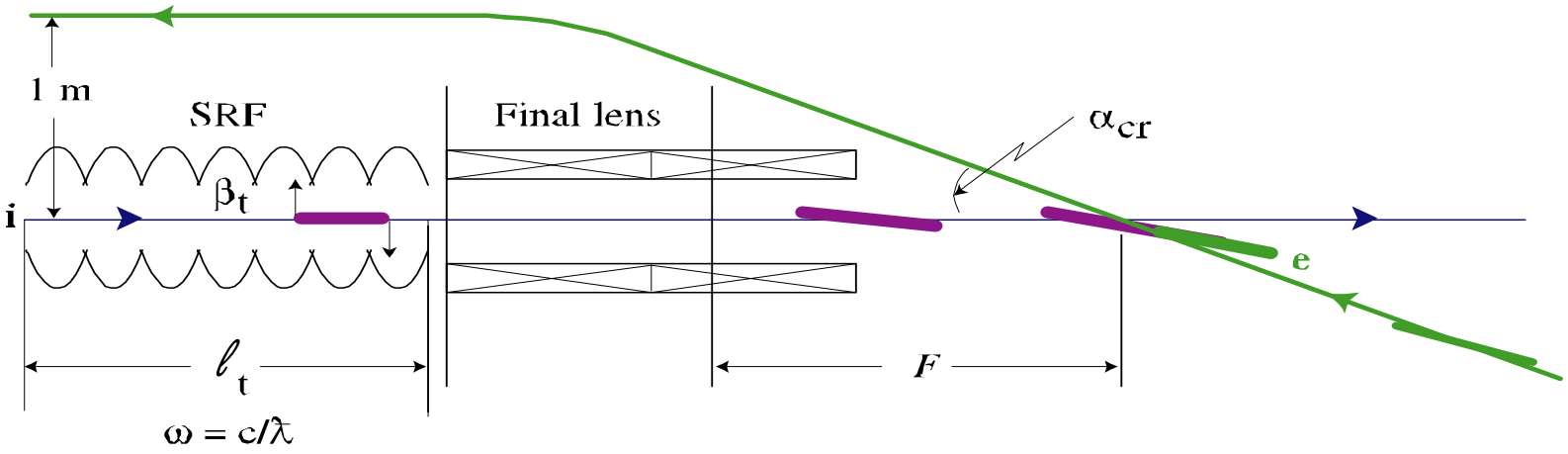
Arc 9 β-functions ~70 m

Emittance incl. SR at arc 9: 2×10^{-8} m rad

SR leads to spot sizes at the IP of 0.3-0.5 mm at 25 GeV

See Y. Chao, Jlab TN 99-037

Crab Crossing



$$\alpha_{cr} = 2\alpha_f = 2\theta_t \frac{F}{\lambda} \; 2\pi$$

$$\theta_t = \frac{eB_t l_t}{E}$$

$E = 100\ GeV$

$F = 3\ m$

$\lambda = 20\ cm \quad (1.5\ GHz)$

$B_t = 600\ G \quad (= 20\ MV/m)$

$l_t = 4\ m$

$\sigma_f = 1\ mm$

$$\alpha_{cr} = 0.1$$

$$\theta_t = 5 \cdot 10^{-4}$$