ELIC: A High Luminosity and Efficient Spin Manipulation Electron-Light Ion Collider at CEBAF

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Outline

- Nuclear Physics Motivation & Requirements
- Early Design Studies
- ELIC Layout
- Luminosity Potential
- Luminosity Lifetime Limits
- Accelerator Physics & Technology Issues
  - CEBAF-ER: A High Energy Demonstration of Energy Recovery
- Integration with 25 GeV Fixed Target Program
- R&D Strategy
- 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 45 GeV

    with energy asymmetry of ~10, which yields

    E_e ~ 3 GeV on E_i ~ 30 GeV up to E_e ~ 5 GeV on E_i ~ 100 GeV
  - CW Luminosity from 10^{33} to 10^{35} cm^{-2} sec^{-1}
  - Ion species of interest: protons, deuterons, ^3He
  - 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

Two Design Scenarios

- Two accelerator design scenarios have been proposed:
  - ring – ring*
  - linac – ring
- Linac – ring option presents advantages with respect to
  - spin manipulations
  - reduction of synchrotron radiation load on the detectors
  - wide range of continuous energy variability
- Feasibility studies were conducted at BNL† (based on RHIC) and Jefferson Lab‡ to determine whether the linac-ring option is viable

* Y. Shatunov et al., 2nd EPIC Workshop, 2000

† I. Ben-Zvi, J. Kewisch, J. Murphy, S. Peggs, NIM A Vol. 463 (2001)

‡ L. Merminga, G. Krafft, V. Lebedev, Proc. of HEACC 2001

Conclusions of Generic Linac-Ring Studies

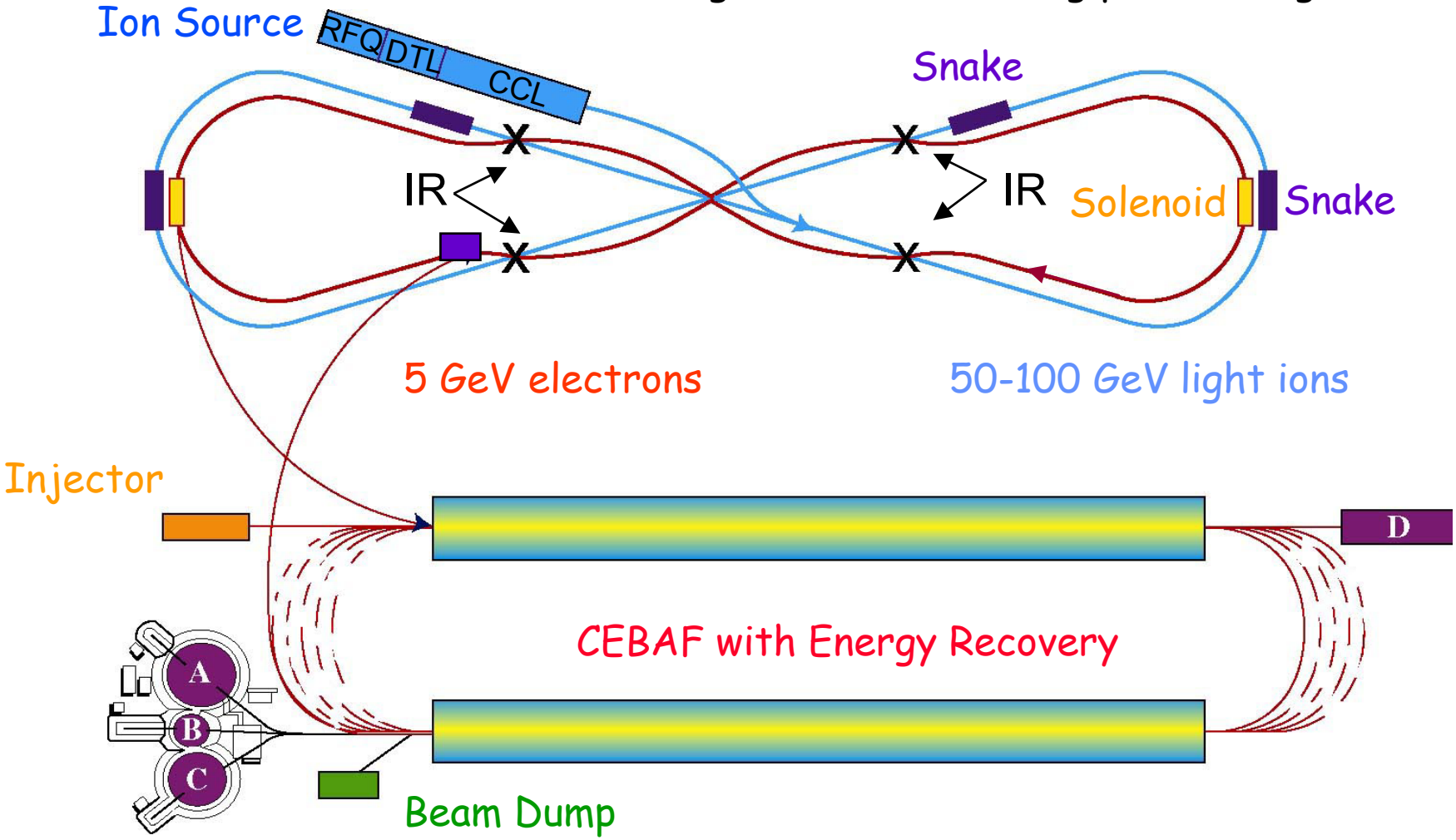
- Luminosities at or greater than 10^{33} cm^{-2} sec^{-1} appear attainable with an electron linac-on-proton ring design

- RF power and beam dump considerations require that the electron linac is an Energy Recovering Linac (ERL)

- Electron cooling of the protons is required for luminosity at or above 10^{33} cm^{-2} sec^{-1}

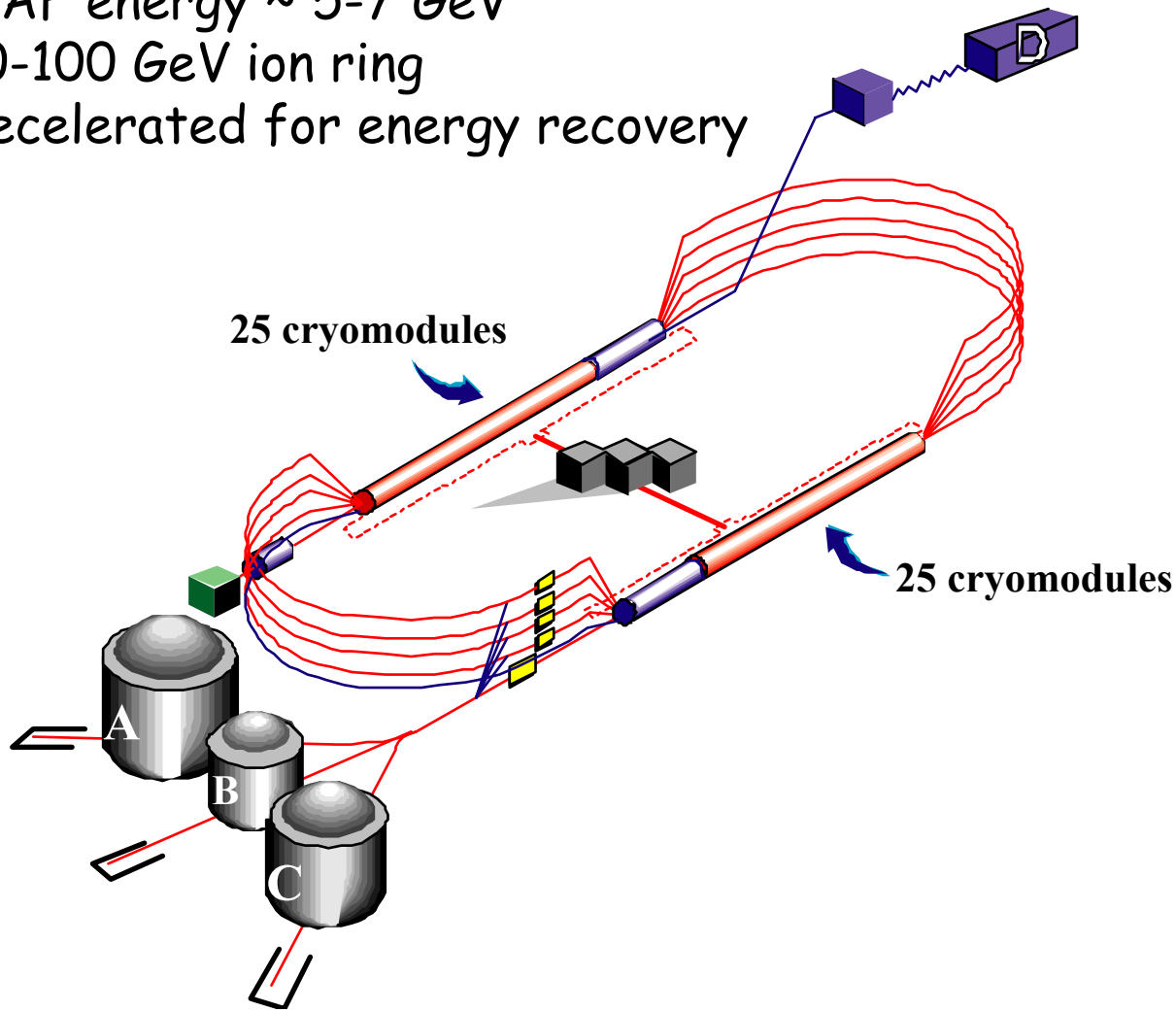
ELIC Layout

One accelerating & one decelerating pass through CEBAF



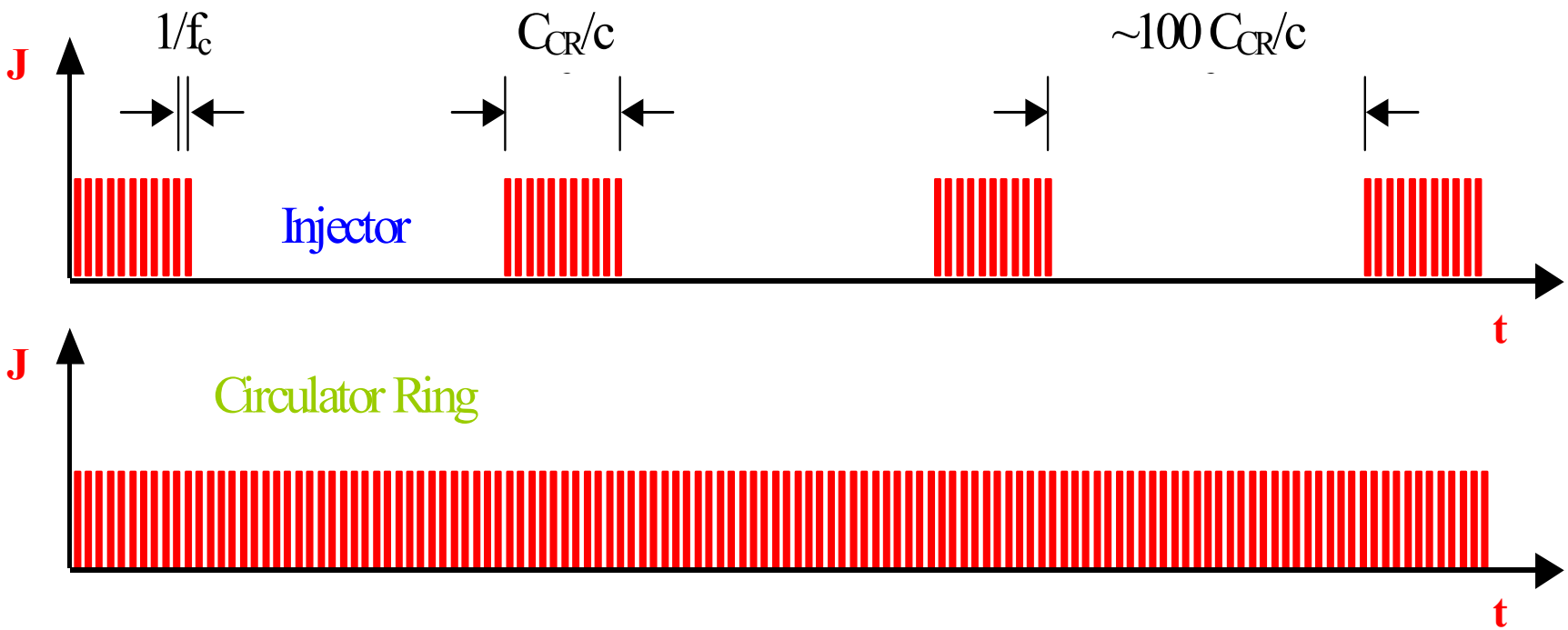
CEBAF with Energy Recovery

- Install 50 Upgrade CEBAF cryomodules at ~20 MV/m in both linacs
- Single-pass CEBAF energy ~ 5-7 GeV
- Collision with 50-100 GeV ion ring
- Electrons are decelerated for energy recovery



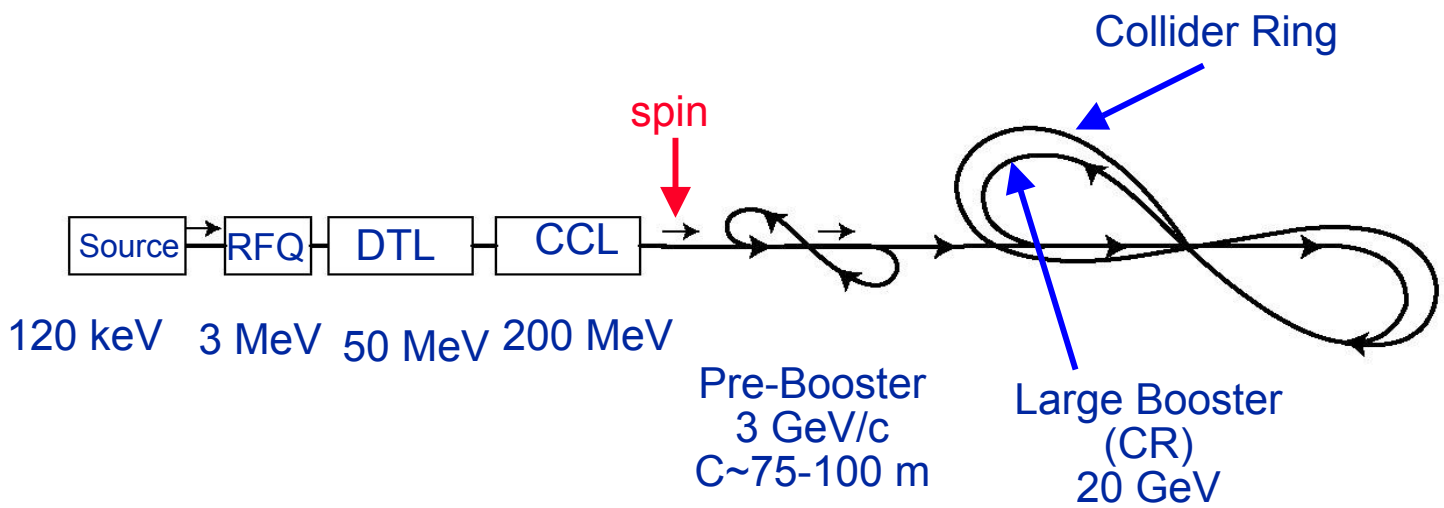
Circulator Ring

Y. Derbenev



Different filling patterns are being explored (Hutton, Litvinenko)

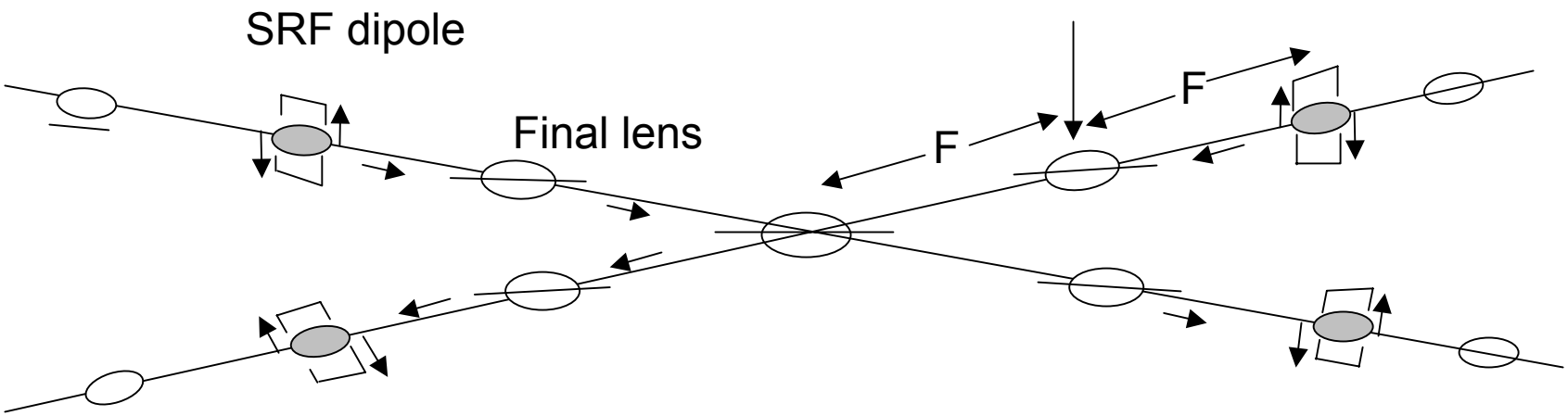
Ion Complex


Collider Ring
spin
Source
RFQ
DTL
CCL
120 keV
3 MeV
50 MeV
200 MeV
Pre-Booster
3 GeV/c
C~75-100 m
Large Booster
(CR)
20 GeV

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 Parameter Table

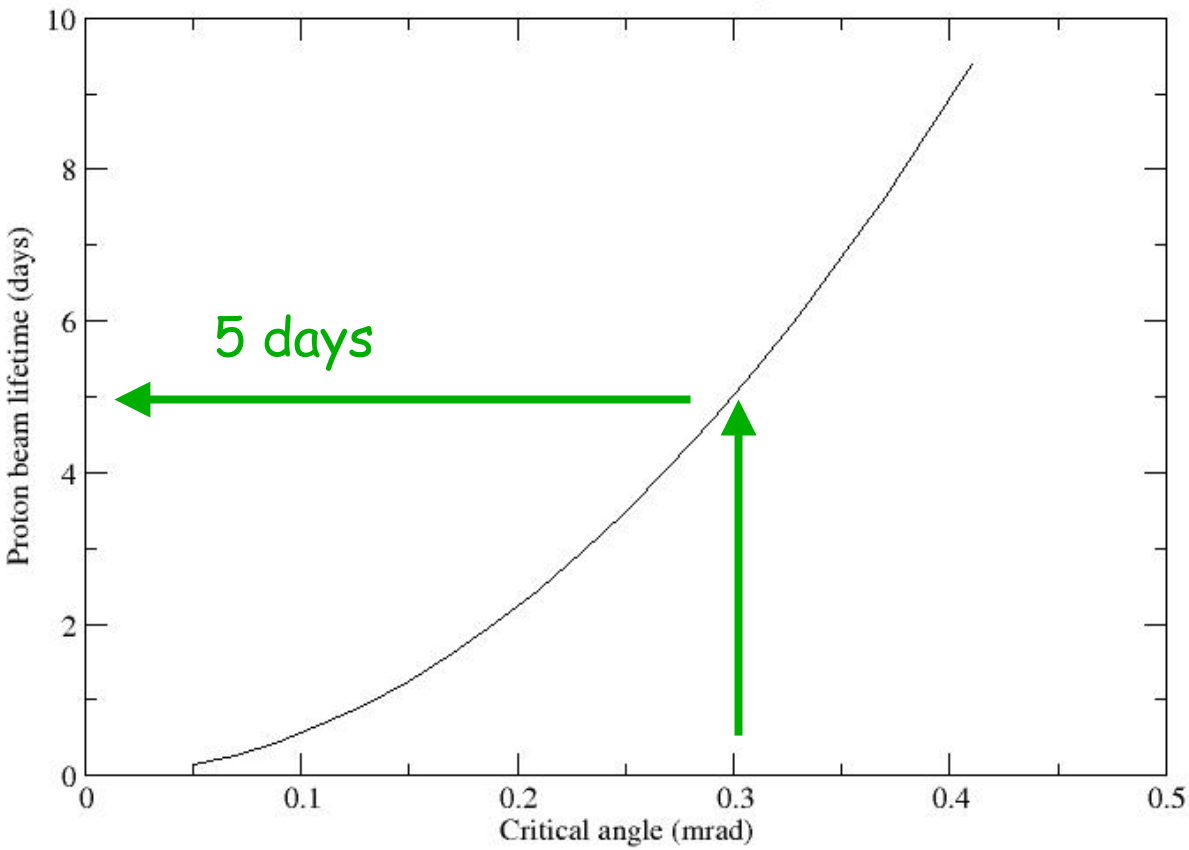
Parameter	Units	Point Design 1		Point Design 2		Point Design 3	
		e^-	Protons	e^-	Protons	e^-	Protons
Energy	GeV	5	50	5	50	5	50/100
Cooling	-	-	Yes	-	Yes	-	Yes
CR			No		Yes		Yes
Lumi	cm^{-2} sec^{-1}	1×10^{33}		1×10^{34}		6×10^{34} / 1×10^{35}	
N_{bunch}	ppb	1×10^{10}	2.5×10^{10}	2×10^{10}	5×10^{9}	1×10^{10}	1×10^{10}
f_c	MHz	150		500		1500	
I_{ave}	A	0.24	0.6	1.6	0.4	2.5	2.5
σ^*	μm	14	14	6	6	4.5/3.2	4.5/3.2
ε_n	μm	10	0.2	10	0.2	10	0.1
β^*	cm	20	5	4	1	2/1	1
σ_z	cm	0.1	5	0.1	1	0.1	1
ξ_e / ξ_i	-	0.5	0.006	0.1	0.01	0.2	0.01
$\Delta\nu_L$	-	-	0.05	-	0.05	-	0.09

Luminosity Lifetime Limits

- So far we have not taken into account processes that could limit the luminosity lifetime
- Two classes of processes may present limitations:
  - Interactions between colliding beams (Background processes)
  - Intrabeam scattering (Touschek effect)

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.

Lifetime due to Intrabeam Scattering

- IBS heating mechanism: Energy exchange at intra-beam collisions leads to x-emittance increase due to energy-orbit coupling, and y-emittance increase due to 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.
- Since $L \propto \sigma_x \sigma_y$, reduction of transverse coupling while conserving beam area, would result in decrease of impact of IBS on luminosity
- Electron cooling then leads to a flat equilibrium with aspect ratio of 100:1.
- Touschek effect: IBS at large momentum transfer (single scattering) drives particles out of the 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.

IBS and Flat Beams

Beam energy	GeV	150/7
Energy of cooling beam	MeV	75
Bunch collision rate	GHz	1.5
Number of particles/bunch	10^{10}	0.2/1
Beam current	A	0.5/2.5
Horizontal emittance, norm	μm	1/100
Vertical emittance, norm	μm	0.01/1
Number of interaction points		4
Total beam-beam tune shift		0.04/0.16
Space charge tune shift in proton beam		0.02
Luminosity over 4 interaction points	$10^{35}/cm^2.s$	2
Cooling/IBS time in proton beam core	min	5
Core and luminosity Touschek's lifetime	hours	20

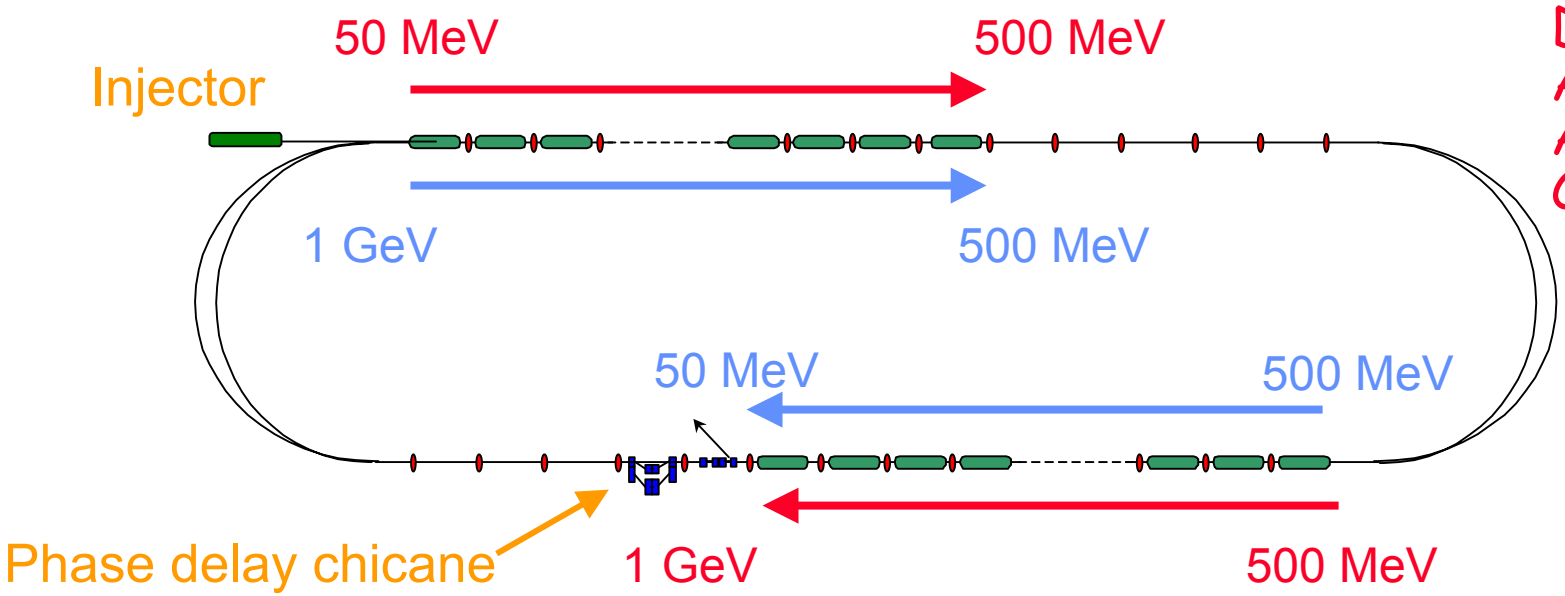
R&D Topics

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 100 GeV protons requires 50 MeV electrons. Practical only if based on SRF-ERL technology, demonstrated and routinely used at the JLab IRFEL
  - 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

CEBAF-ER: High Energy Demonstration of Energy Recovery at CEBAF

- Beam accelerated from ~50 MeV to 1 GeV and energy recovered to 50 MeV. Plan to inject at 10 to 20 MeV and test energy recovery with energy ratio up to ~100
- Beam properties, beam halo to be measured at several locations
- Experiment was approved and scheduled for March-April 2003



D. Douglas
A. Bogacz
A. Hutton
C. Tennant
et al.

CEBAF-ER Installation

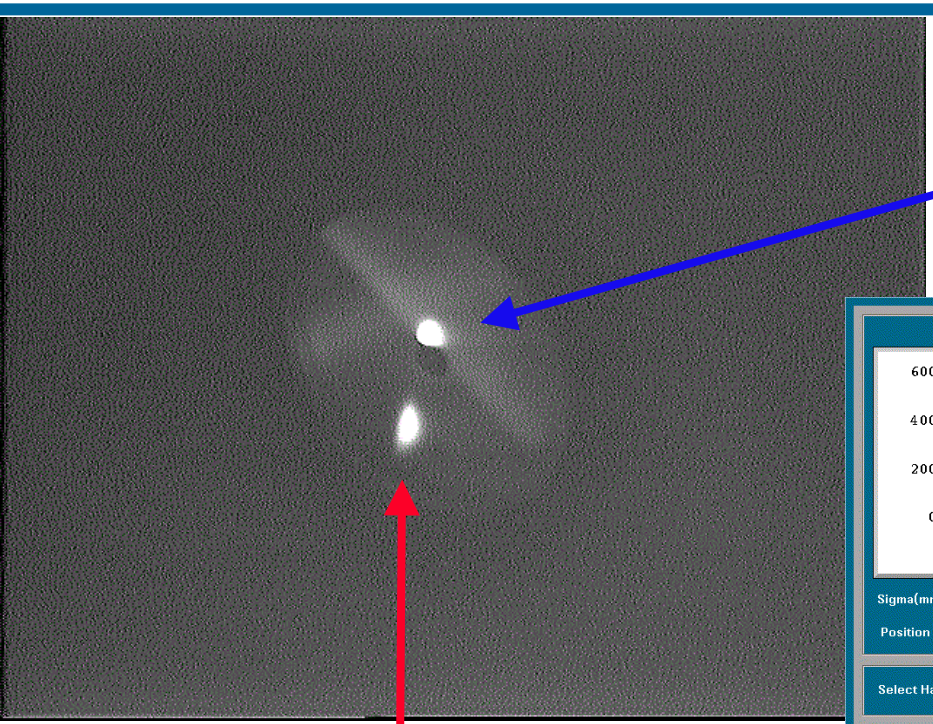
CEBAF-ER Preliminary Results

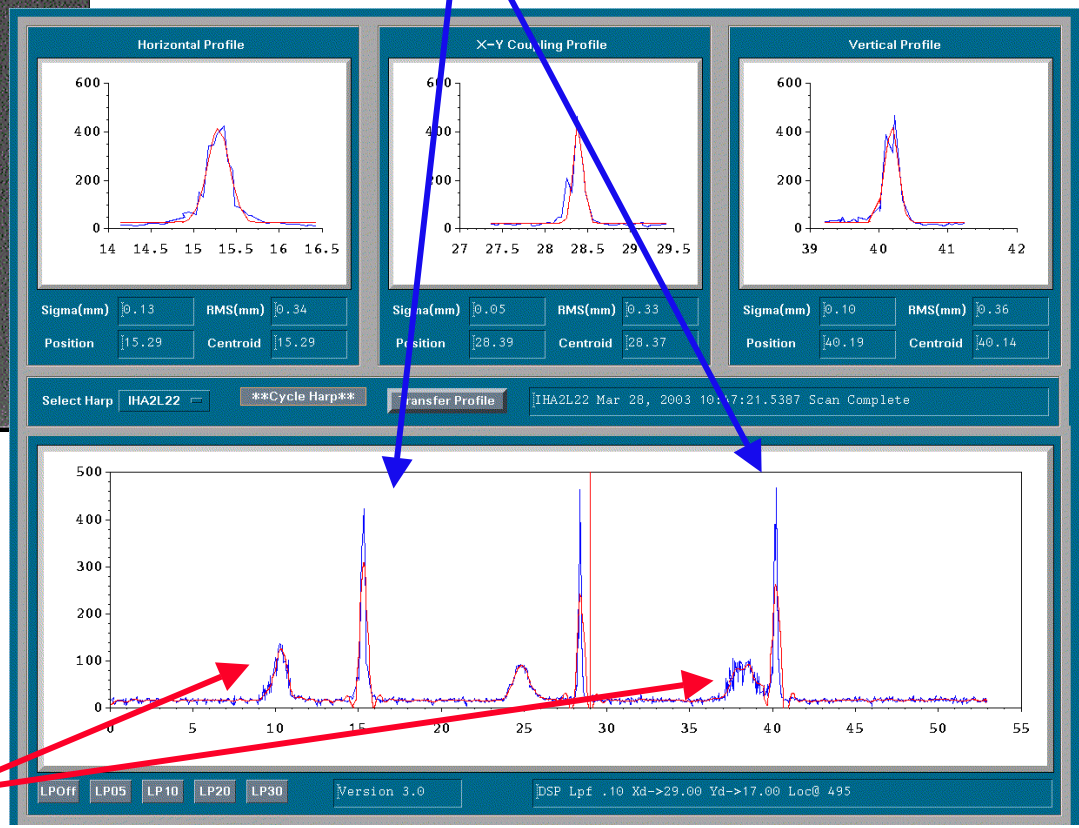
- Phase I of CEBAF-ER is complete: 1 GeV scale demonstration of energy recovery
- Demonstration of final-to-injection energy ratios - 20:1 and 50:1
- 80 μA cw beam current was injected at 56 MeV into CEBAF, accelerated to 1 GeV and energy recovered down to ~ 56 MeV
- 10 μA pulsed beam was injected at 20 MeV into CEBAF, accelerated to 1 GeV and energy recovered down to ~ 20 MeV
- Beam emittance, beam halo (6 decades of intensity covered) and rf measurements complete and data analysis in progress to characterize the transport

CEBAF-ER: Emittance Measurements

Beam profiles at end (SL16) of South Linac

~ 1 GeV Accelerating beam

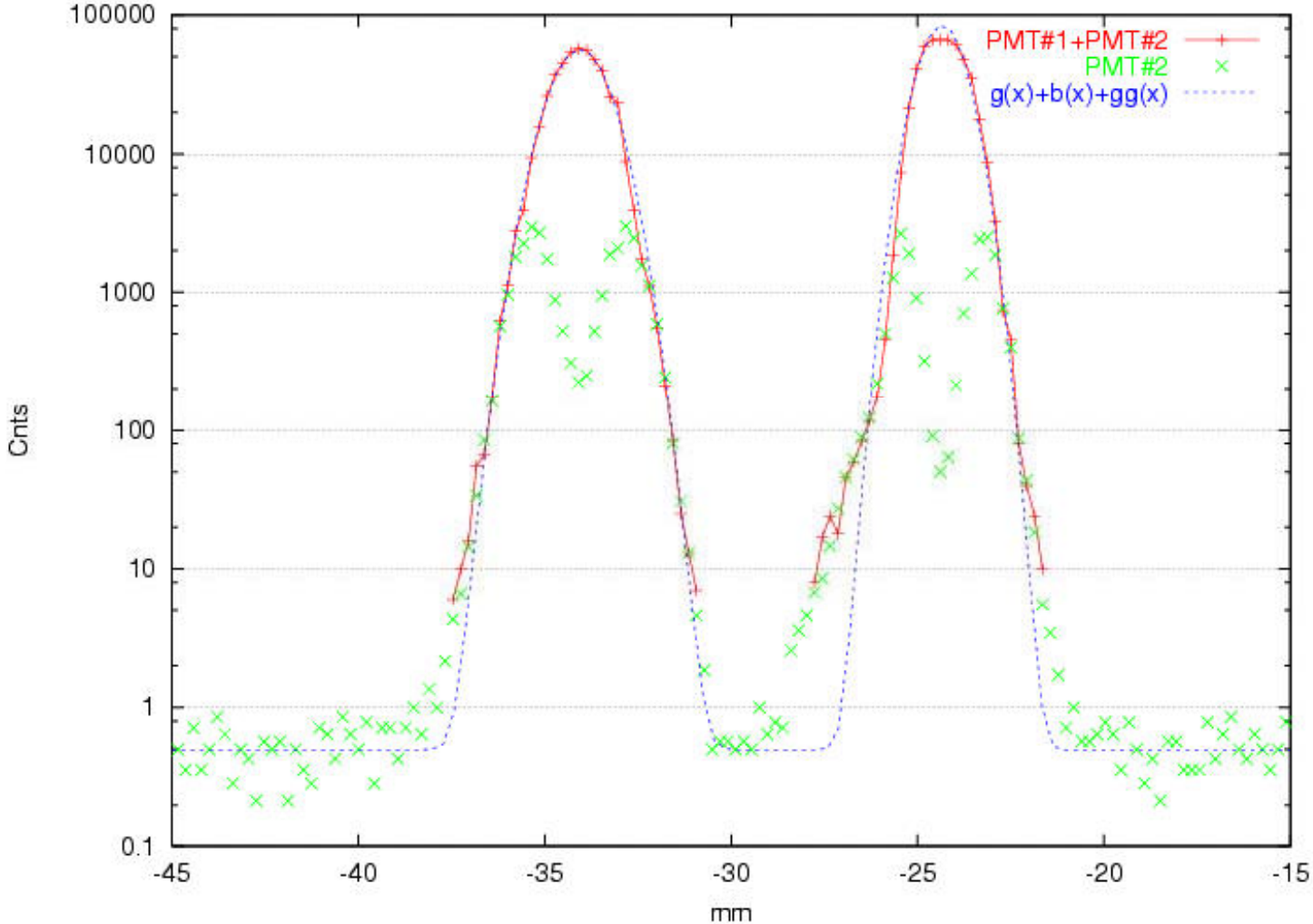




~ 100 MeV Decelerating beam

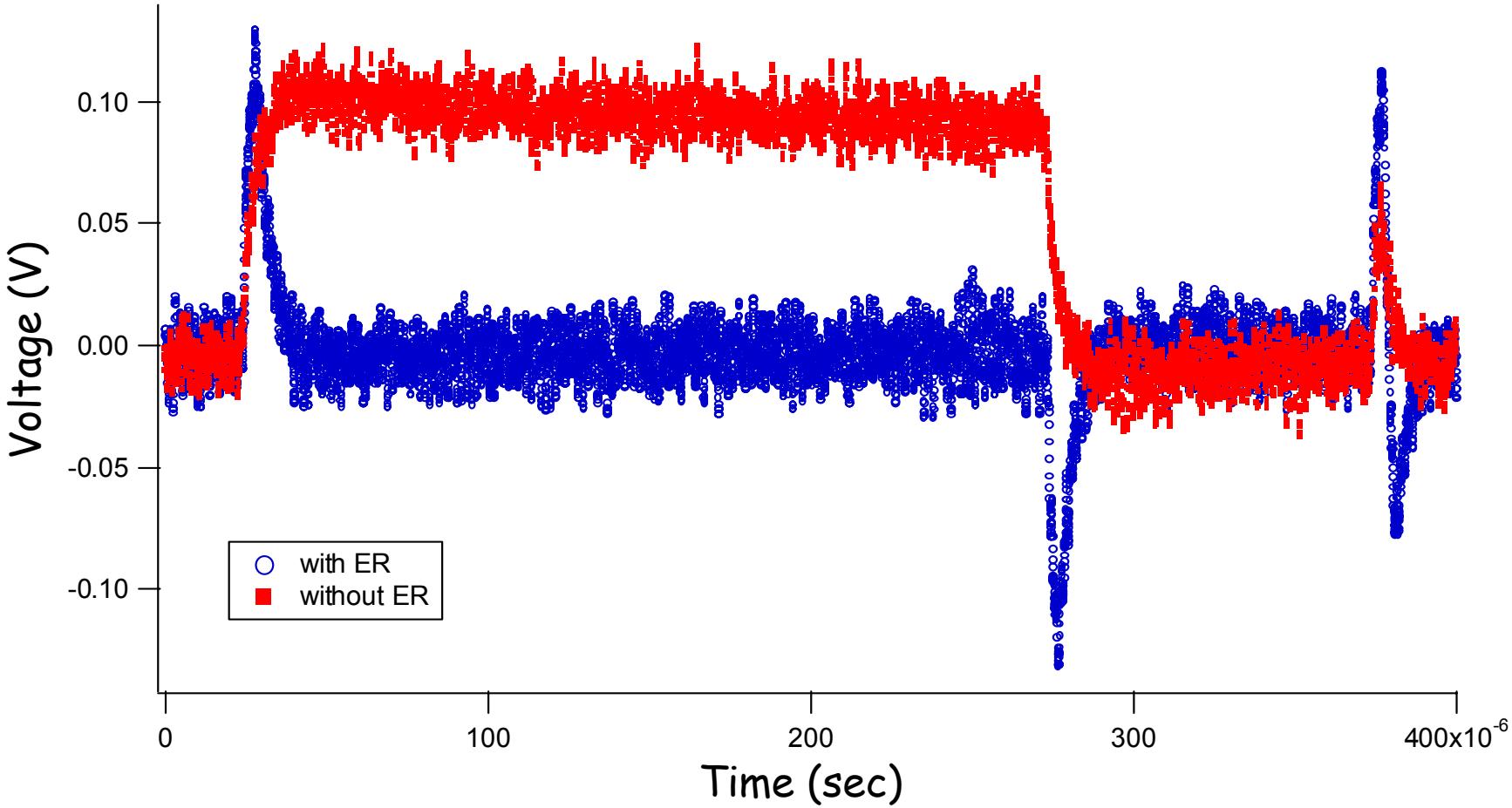
CEBAF-ER: Beam Halo Measurements

Beam halo (56 MeV, 1 mA beam) measured with a wire scanner and 3 PMTs



CEBAF-ER: RF Measurements

Gradient modulator drive signals with and without energy recovery in response to 250 μsec beam pulse entering the rf cavity

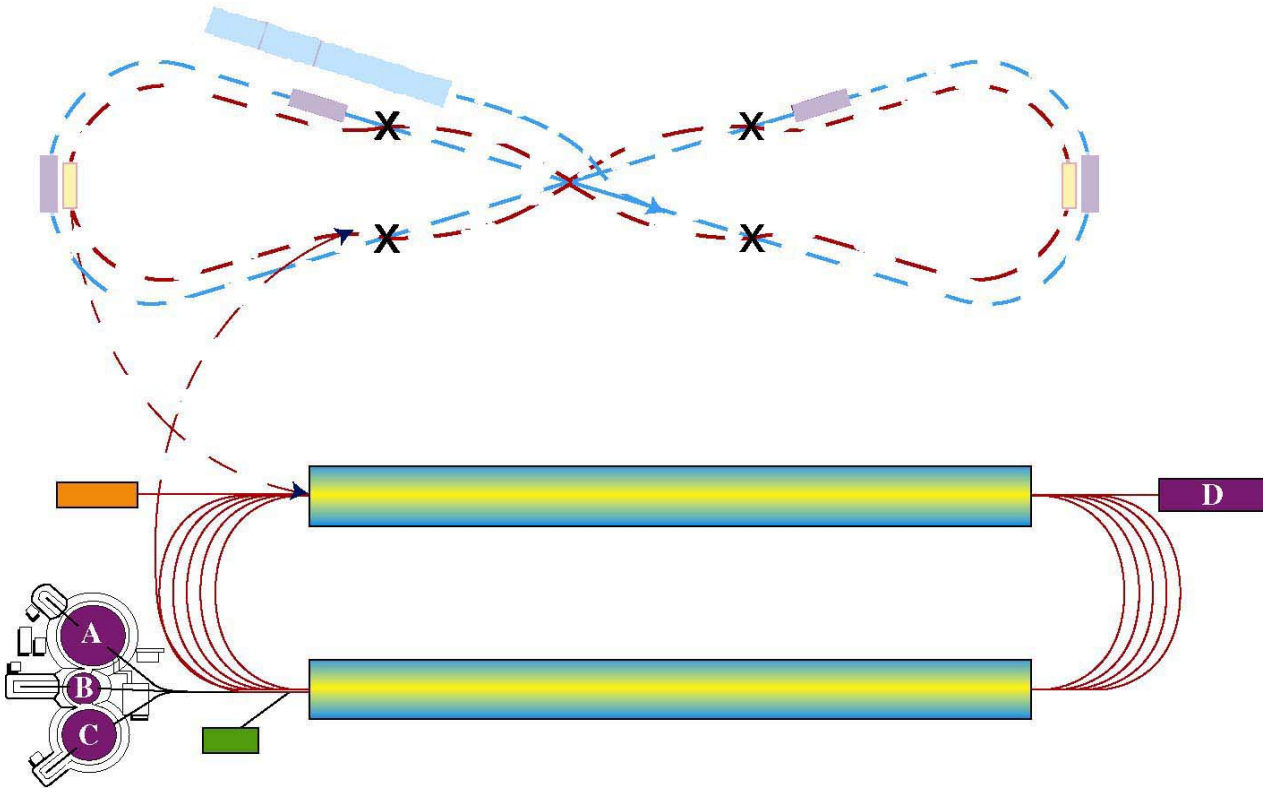


The same electron accelerator can also provide 25 GeV electrons for fixed target experiments for physics

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

(One accelerating & one decelerating pass through CEBAF ⇒ 20-45 GeV CM Collider Program)

- Exploring whether collider and fixed target modes can run simultaneously



R&D Strategy

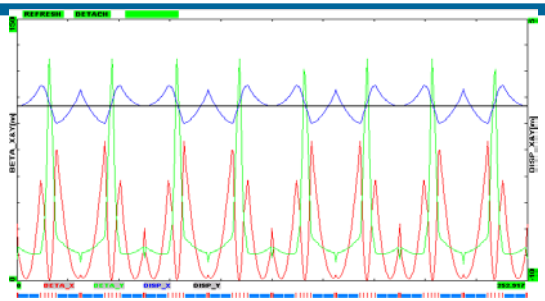
Our R&D strategy is multi-pronged:

- Conceptual development
  - "Circulator Ring" concept promises to ease high current polarized photoinjector and ERL requirements significantly
  - Additional concepts for luminosity improvements are being explored
- Analysis/Simulations
  - Electron cooling and short bunches
  - Beam-beam physics
  - Circulator ring dynamics
  - ERL physics
- Experiments
  - JLab FEL (10mA), Cornell/JLab ERL Prototype (100mA), BNL Cooling Prototype (100mA) to address high current ERL issues
  - CEBAF-ER: The Energy Recovery experiment at CEBAF to address ERL issues in large scale systems

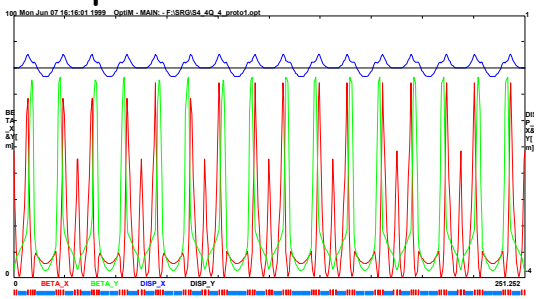
Conclusions

- 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 up to 10^{35} cm^{-2} sec^{-1}, for electron-light ion collisions at a center-of-mass energy between 20 and 45 GeV
- This design can be realized cost-effectively 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

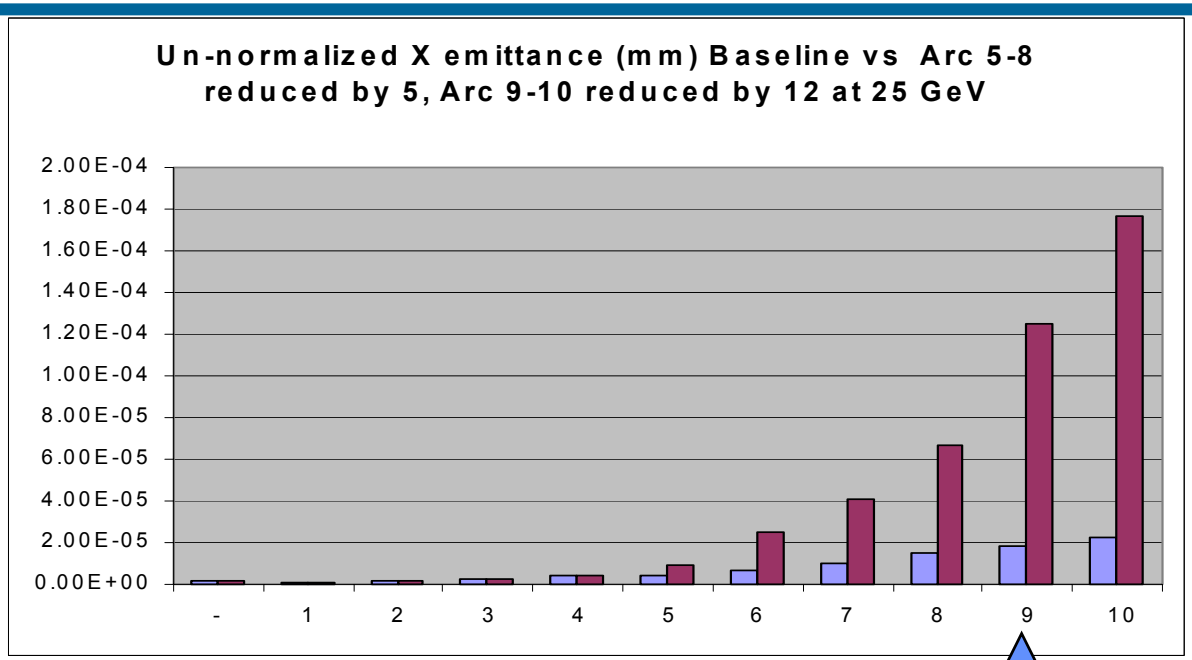
Feasibility of 25 GeV FT Program at CEBAF



Optics for arcs 5-8



Optics for arcs 9, 10



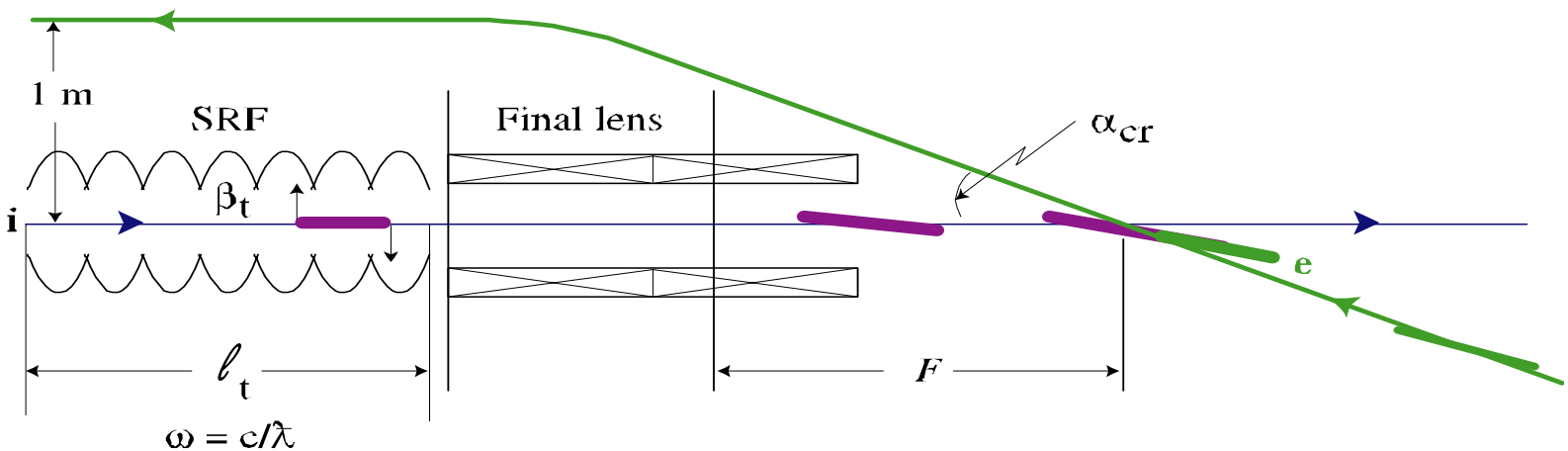
Arc 9 β-functions ~70 m

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



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

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

$$E = 100 \; GeV$$

$$F = 3 \; m$$

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

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

$$l_t = 4 \; m$$

$$\sigma_f = 1 \; mm$$

$$\alpha_{cr} = 0.1$$

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