USPAS Course
on
Recirculated and Energy Recovered Linear Accelerators

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Lecture 18: ERLs for High Energy and Nuclear Physics

Outline

- Introduction
- The role of ERLs in HENP
- Nuclear Physics Motivation for Electron-Ion Colliders
- Beam Requirements
- ERL-Based Electron Cooling
- ERL-Based Electron-Ion Colliders
  - e-RHIC
  - ELIC
- Key R&D Issues
- Conclusions

The Role of ERLs in High Energy and Nuclear Physics

- Electron cooling of hadron storage rings

The requirements:

1. Low-energy
2. High brightness
3. High-Charge
4. High-current

- Provide electron beams for high-luminosity colliders.

The requirements:

1. High-energy
2. Polarization
3. High-current

Nuclear Physics Motivation

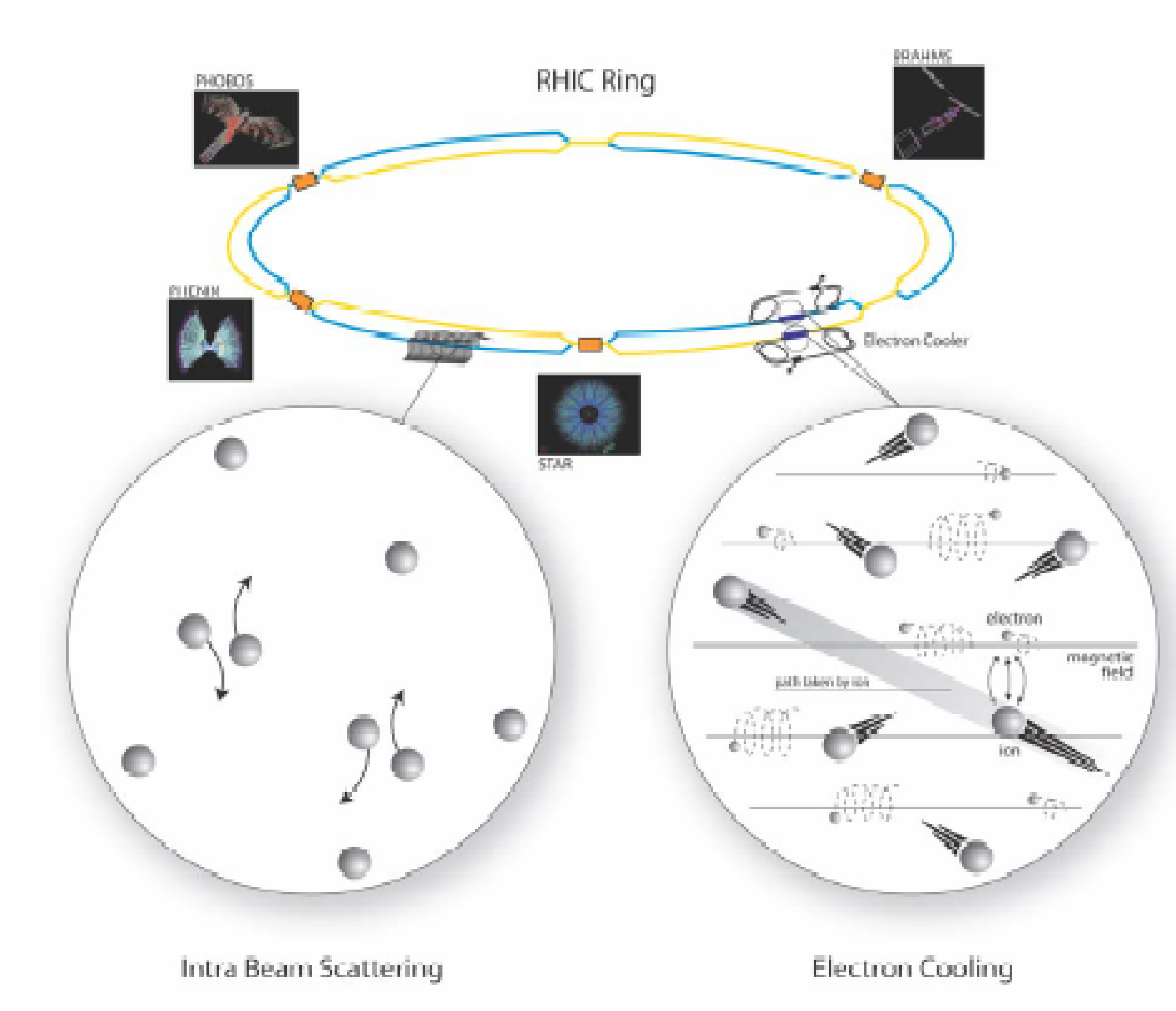
- A high luminosity polarized electron – light ion collider has been proposed as a powerful new microscope to probe the partonic (quarks and gluons) structure of matter
- Over the past two decades we have learned a great amount about the hadronic structure
- Some crucial questions remain open:
  - What 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

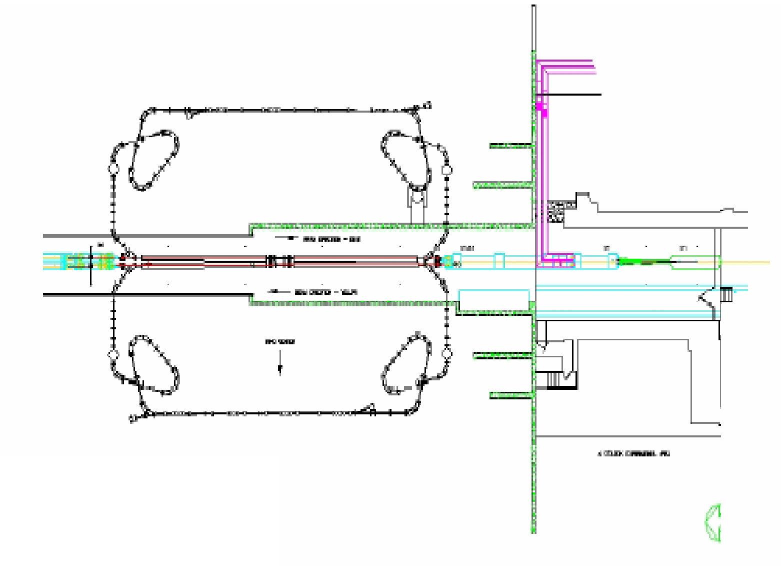
- The features of the facility necessary to address these issues:
  - Center-of-mass energy between 20 GeV and 150 GeV

    with energy asymmetry of ~10
  - CW Luminosity from 10^{33} to 10^{35} cm^{-2} sec^{-1}
  - Ion species of interest: protons, deuterons, ^{3}He, heavy ions
  - 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

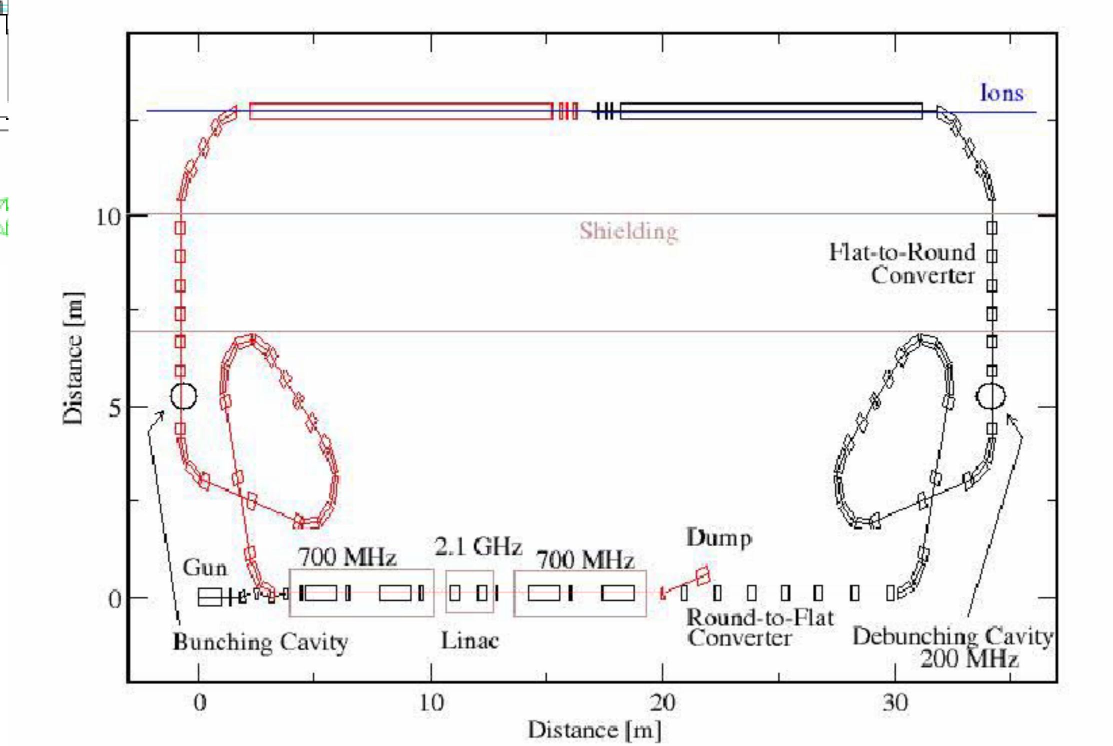
Electron Cooling



ERL-Based Electron Cooler



RHIC electron cooler is based on a 200 mA, 55 MeV ERL 20 nC per bunch, 9.4 MHz

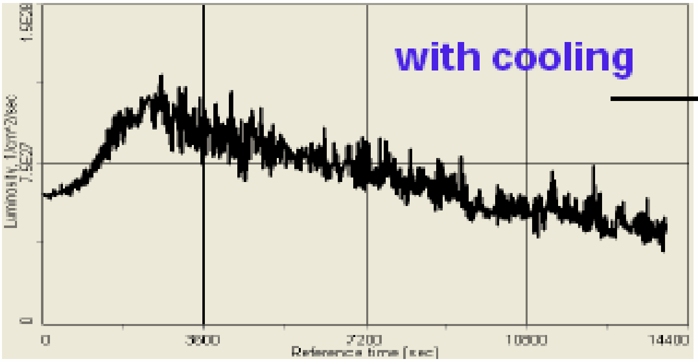


Luminosity of Electron Cooled RHIC (RHIC-II)

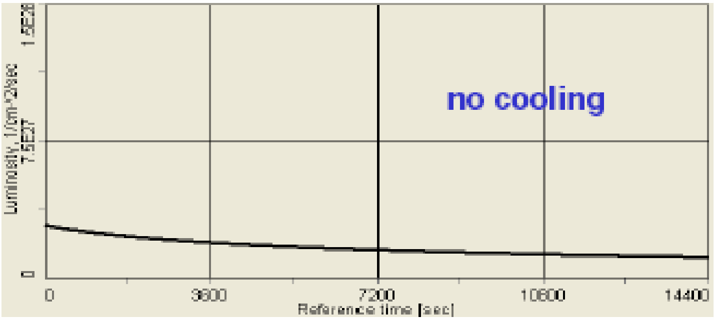
RHIC-II Luminosity (Au 100 GeV)

$N=10^9$ per bunch, 112 bunches

Alexei Fedotov

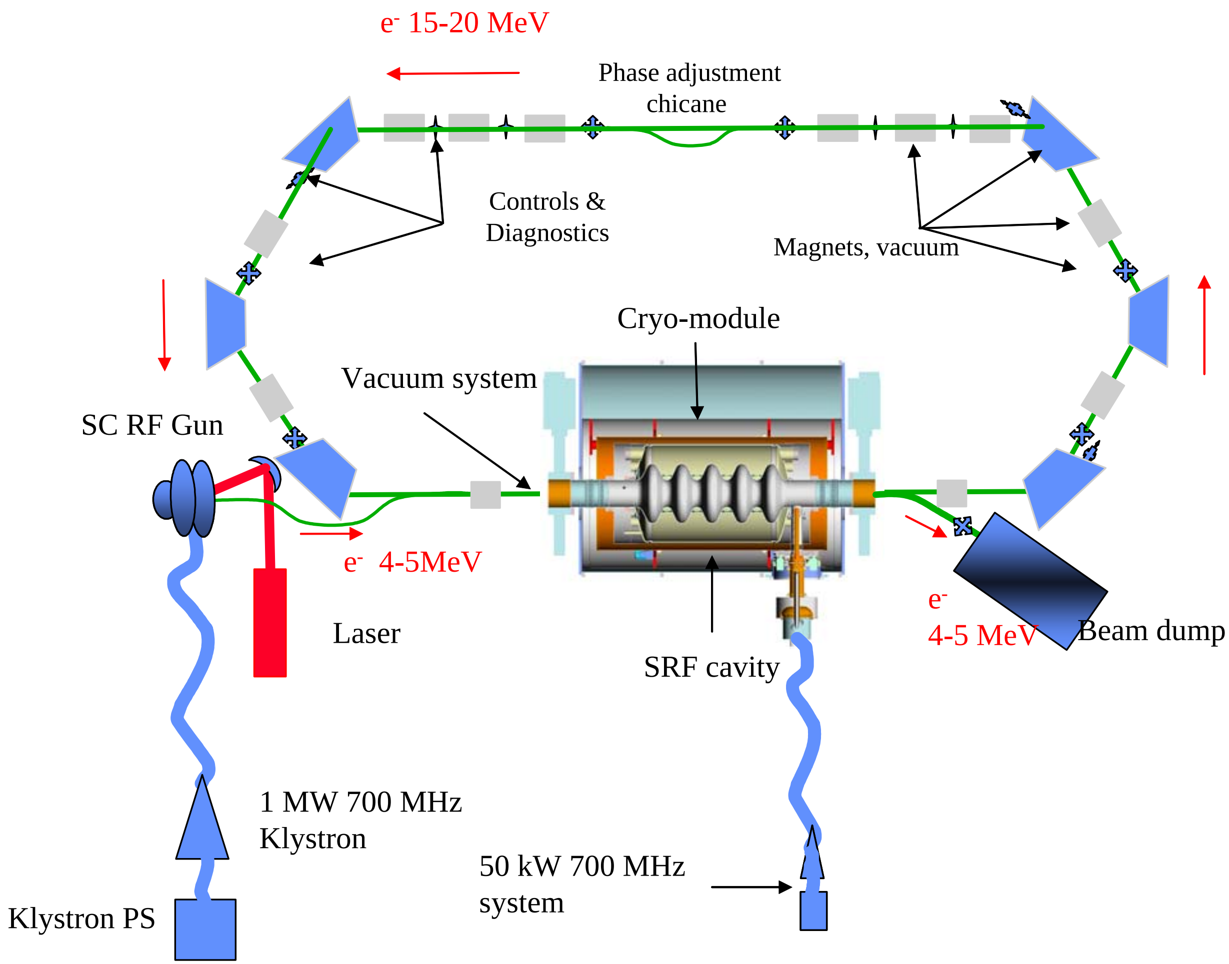


$\langle L \rangle = 7 * 10^{27}$



E-cooling: factor of 10 increase in average luminosity per store

BNL ERL R&D Facility



Two Proposed Electron-Ion Colliders

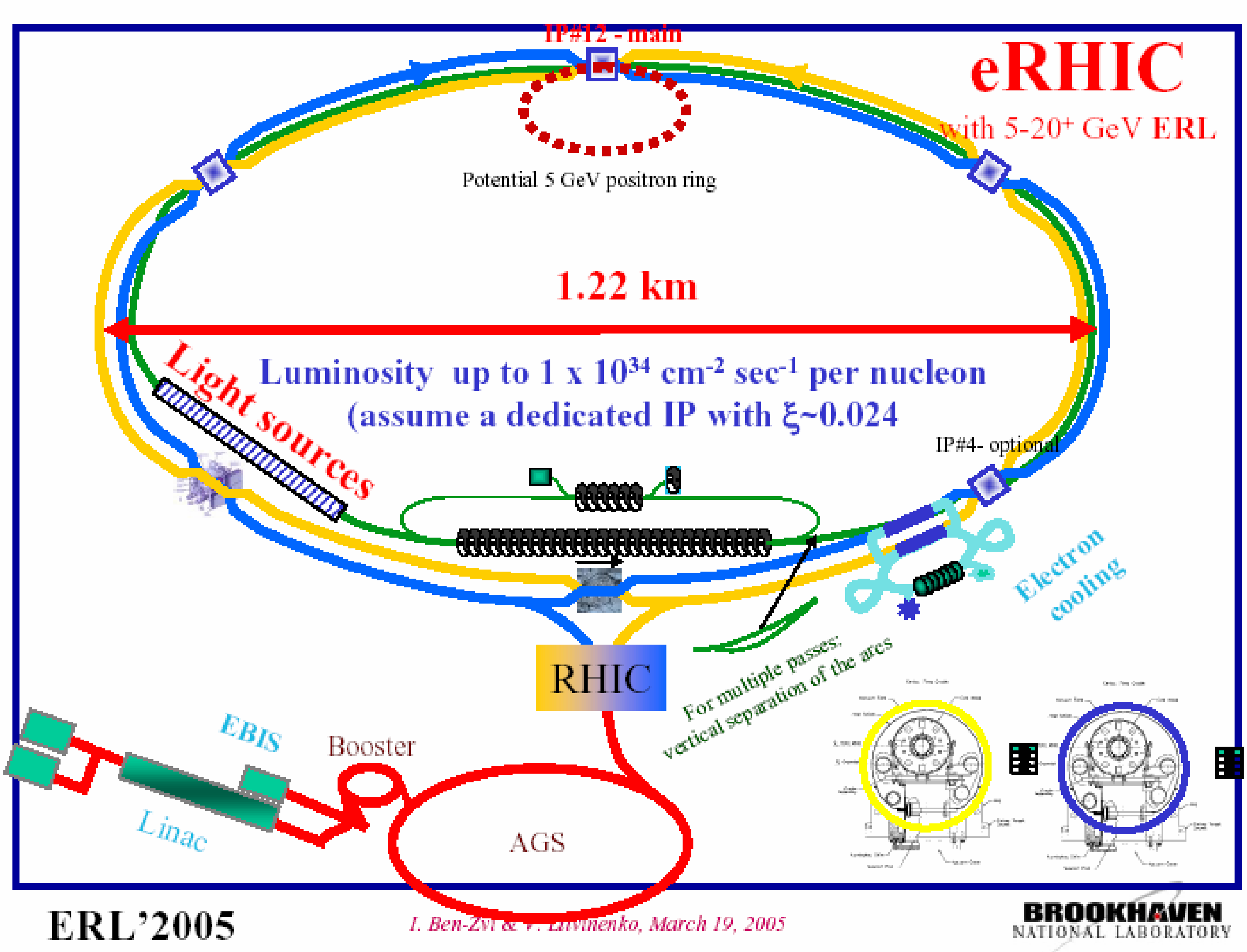
ELIC

- Multi-turn circulation ring for electrons
  - Lower injector current
  - Need injection / ejection
  - Partial benefit for electron beam-beam
- Very high bunch frequency
- Novel ion ring complex of "figure 8" rings
- Light ions only

eRHIC

- Single pass ERL
  - High e source current required
  - Simplified structure
  - Maximum benefit from beam-beam in electron machine
- Bunch frequency of RHIC
- Well known ion ring
- All ions

eRHIC



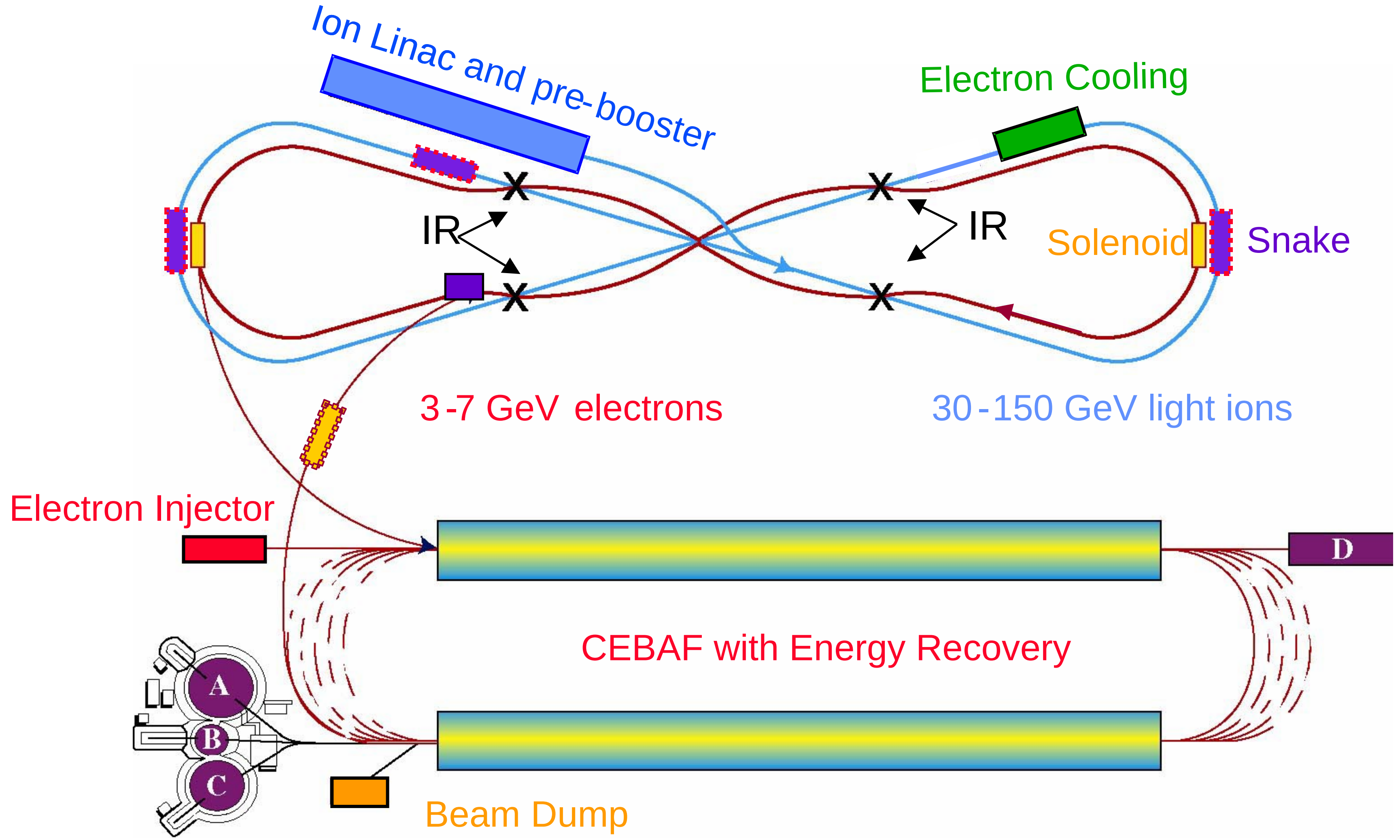
IP#12 - main
eRHIC
with 5-20+ GeV ERL
Potential 5 GeV positron ring
1.22 km
Light sources
Luminosity up to 1 x 10^34 cm^-2 sec^-1 per nucleon
(assume a dedicated IP with ξ~0.024
IP#4- optional
Electron cooling
RHIC
For multiple passes:
vertical separation of the arcs
EBIS
Booster
Linac
AGS
ERL'2005
BROOKHAVEN
NATIONAL LABORATORY

eRHIC Beam Parameters

	main case	option
RHIC	main case	*option*
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	*120*
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	$2.0 \cdot 10^{11}$	$6 \cdot 10^{11}$
Normalized 96% emittance [μm]	14.5	
β^* [m]	0.26	
RMS Bunch length [m]	0.2	
Beam-beam tune shift in eRHIC	0.005	
Synchrotron tune, Qs	0.0028 (see [2.4])	
Gold ions: number of bunches	360	*120*
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	$2.0 \cdot 10^{9}$	$6 \cdot 10^{9}$
Normalized 96% emittance [μm]	6	
β^* [m]	0.25	
RMS Bunch length [m]	0.2	
Beam-beam tune shift	0.005	
Synchrotron tune, Qs	0.0026	
Electrons:		
Beam rep-rate [MHz]	28.15	*9.38*
Beam energy [GeV]	2 - 10	
RMS normalized emittance [μm]	5- 50 *for $N_e = 10^{10} / 10^{11}$ e^- per bunch*	
β^*	~ 1m, *to fit beam-size of hadron beam*	
RMS Bunch length [m]	0.01	
Electrons per bunch	$0.1 - 1.0 \cdot 10^{11}$	
Charge per bunch [nC]	1.6 – 16	
Average e-beam current [A]	0.045 – 0.45	*0.015 – 0.15*

Beam parameters

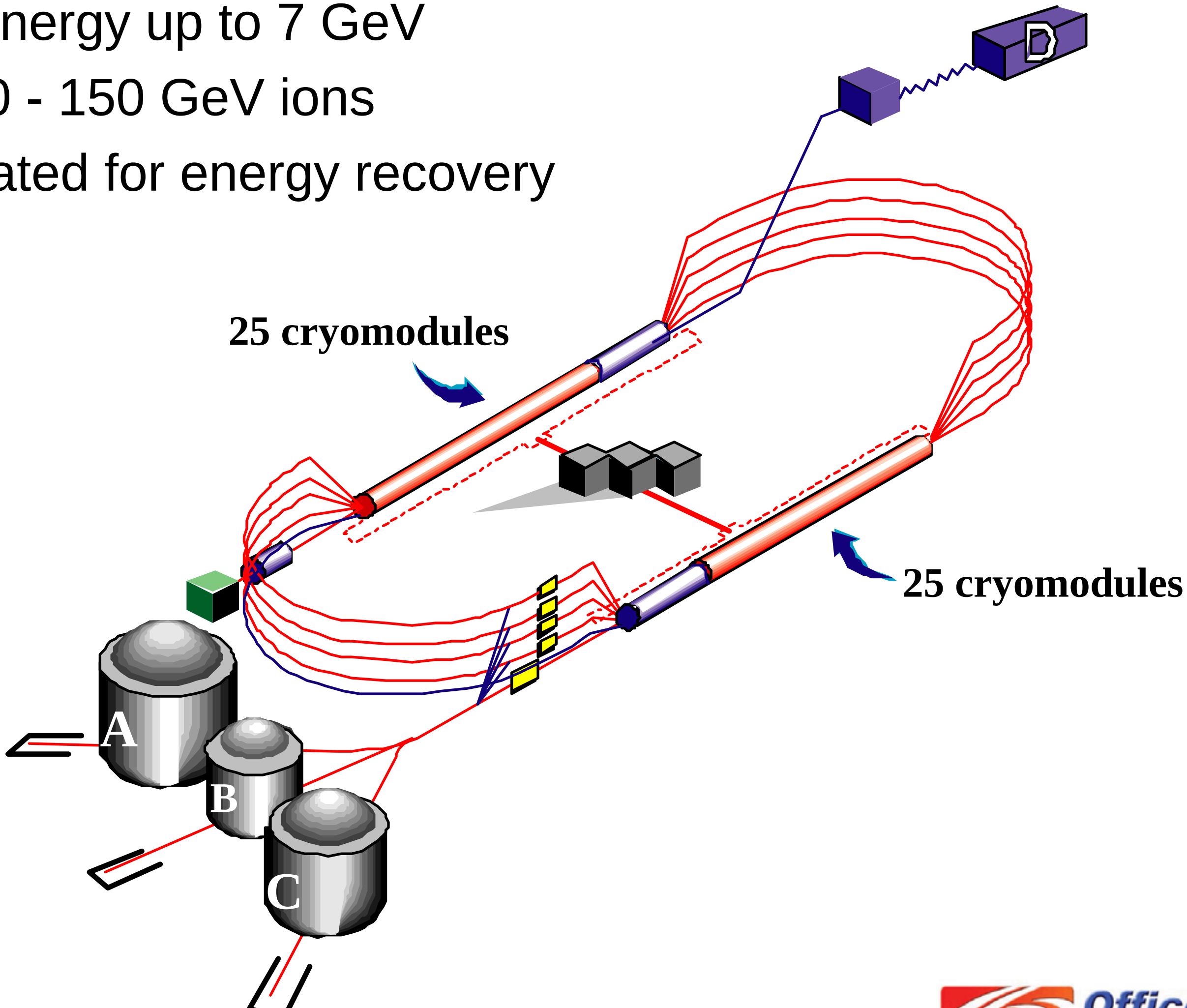
ELIC Design



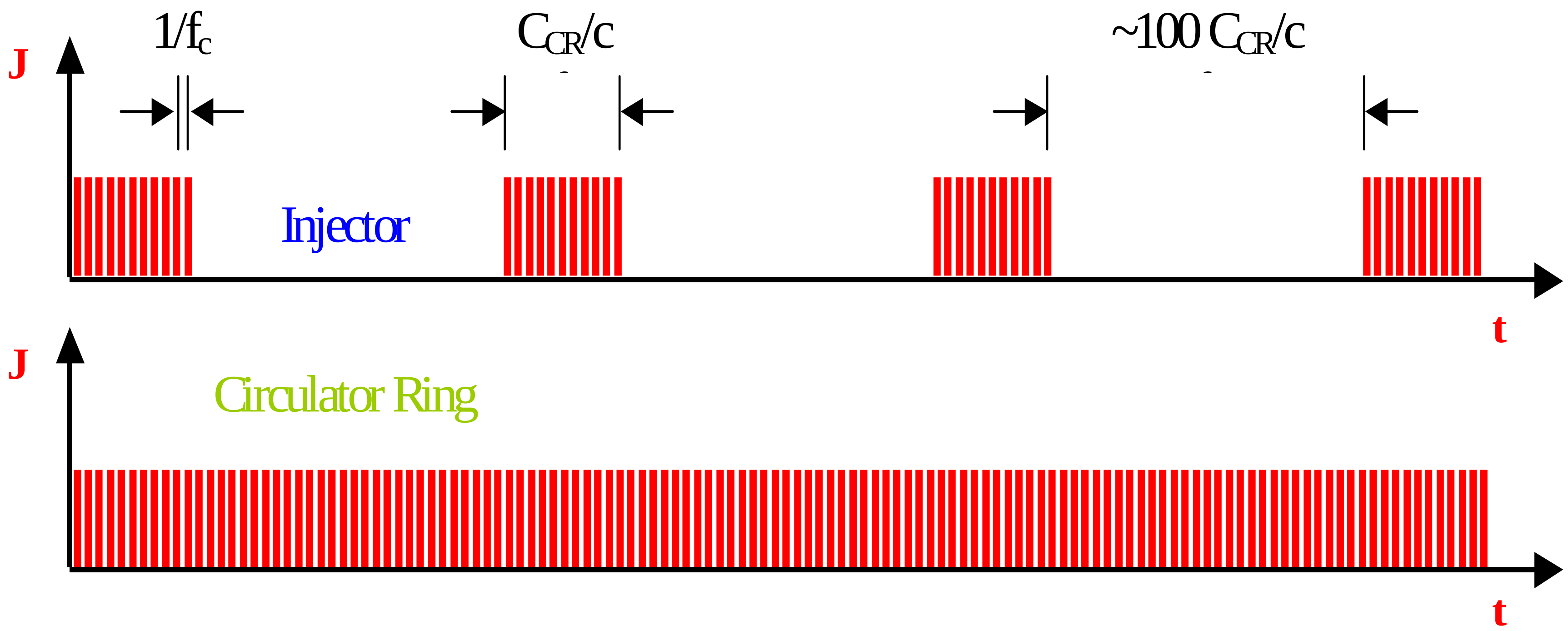
Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

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



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**

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**

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Accelerator Physics & Technology of the ERL

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

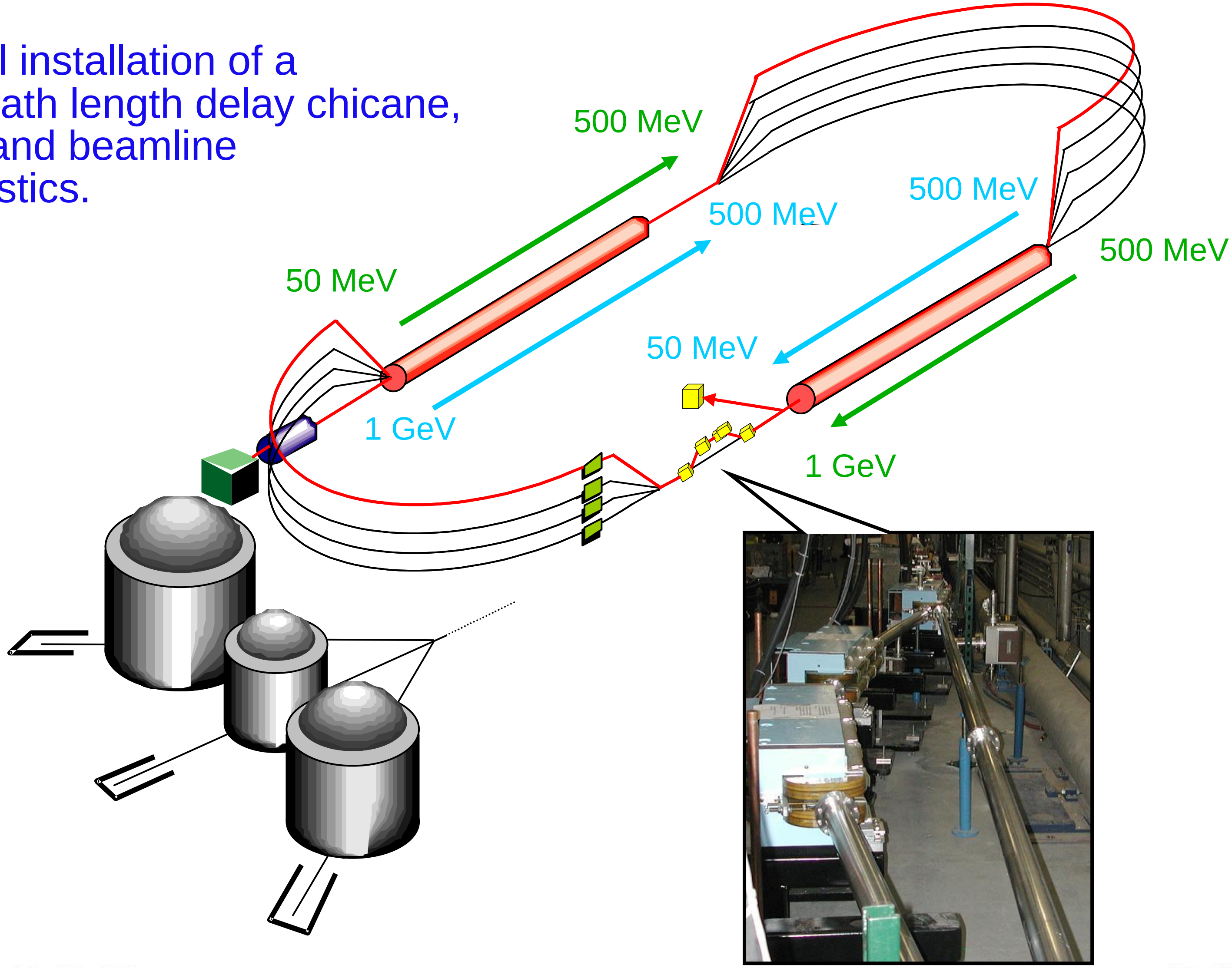
- IR design integrated with real detector geometry
- Beam-beam head-tail instability
  - The beam-beam force due to the relative offset between the head of the proton bunch and the electron beam will deflect the electrons. The deflected electrons subsequently interact with the tail of the proton bunch 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 during the beam-beam studies of linac-ring B-Factory. Linear theory 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.

High Energy Demonstration of Energy Recovery at CEBAF

- 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 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.

Key R&D Issues

Key R&D issues include:

- 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

Conclusions

- An excellent scientific case starts developing for a high luminosity, polarized electron-light ion collider, to address fundamental questions in Hadron Physics

- ERL-based 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

- ERL-based BNL design studies have led to luminosities of 10^{33} cm^{-2} sec^{-1} up to nearly 10^{34} cm^{-2} sec^{-1} for electrons with any ion up to 100 GeV CM.

- Planned R&D will address open readiness issues

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