EIC@JLab

Yuhong Zhang

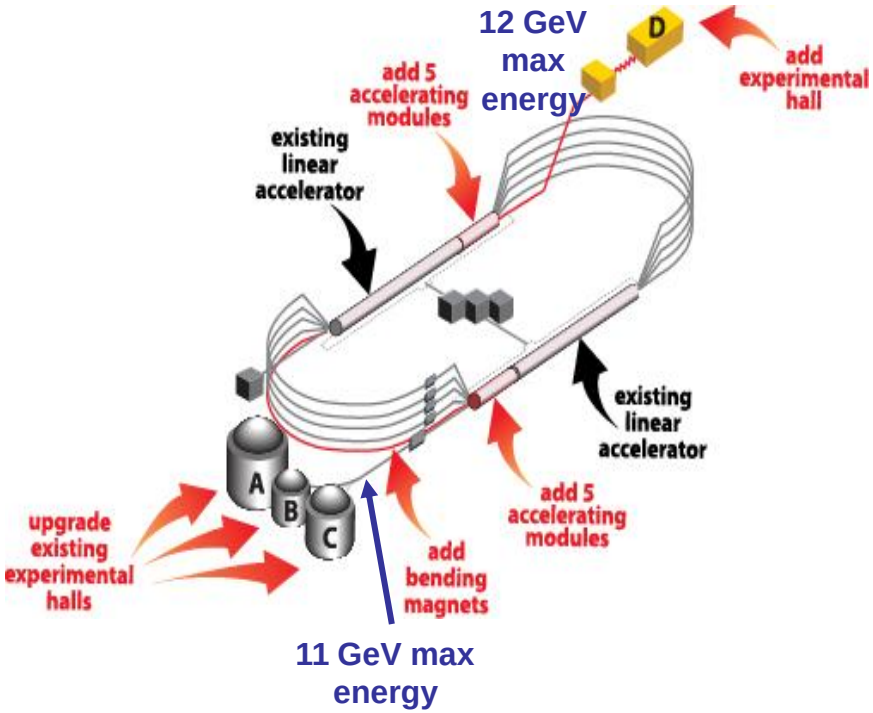
For ELIC Study Group

Common ENC/EIC Workshop at GSI, May 28 -30, 2009

Outline

- Introduction
- An EIC@JLab: *100<s<2600 with high luminosity*
- An EIC@JLab at High Energy: Design Update & Staging
- More details on EIC@JLab Design
- EIC@JLab R&D
- Summary

Great Opportunities Ahead of Us



- **12 GeV CEBAF Upgrade**
  - CD3 for upgrade approved,
  - Construction already started
  - Exciting fixed target program beyond 2020
- **What CEBAF will provide**
  - Up to 12 GeV CW electron beam
  - High repetition rate (3x499 MHz)
  - High polarization (>80%)
  - Very good beam quality
  - World first multi-pass recirculated SRF linac above GeV energy

Opportunity: ***Electron-Ion Collider*** on CEBAF

- Add a *modern* ion complex with a *Green Field* design
- Expand science program beyond 12 GeV CEBAF fixed target physics
- Open up new science domain with higher CM energy

Science Motivation and Detector Requirements

- Key issues in nucleon structure & nuclear physics
  - Sea quark and gluon imaging of nucleon with GPDs (x >~ 0.01)
  - Orbital angular momentum, transverse spin, and TMDs
  - QCD vacuum in hadron structure and fragmentation
  - Nuclei in QCD: Binding from EMC effect, quark/gluon radii from coherent processes, transparency

- Machine/detector requirements
  - High luminosity > 10^{34}: Low rates, differential measurements
  - CM energy: s ~ 1000 GeV^2: Reach in Q2, x
  - Detactability: Angular coverage, particle ID, energy resolution

➔ favors lower, more symmetric energies!

ELIC Design Goals

- **Energy**

  Wide CM energy range between 10 GeV and 100 GeV
  - Low energy: 3 to 10 GeV e on 3 to 12 GeV/c p (and ion)
  - Medium energy: up to 11 GeV e on 60 GeV p or 30 GeV/n ion
    and
  - High energy: up to 10 GeV *e* on 250 GeV *p* or 100 GeV/n *ion*

- **Luminosity**
  - 10^{33} up to 10^{35} cm^{-2} s^{-1} *per* interaction point
  - Multiple interaction points

- **Ion Species**
  - Polarized H, D, ^{3}He, possibly Li
  - Up to heavy ion A = 208, all striped

- **Polarization**
  - Longitudinal at the IP for both beams, transverse of ions
  - Spin-flip of both beams
  - All polarizations >70% desirable

- **Positron Beam** *desirable*

Design Challenges & Opportunities

Design an Electron-Ion Collider that

- Covers a wide CM energy range (10 to 100 GeV) in a ***unified & coherent*** way for highest science productivity
  - *Medium energy EIC is our immediate goal so it should be given first priority for maximum design optimization*
  - *High energy EIC is a future goal so it should be leaved with greatest flexibility and upgrade potential*
- Deliver best collider quality in terms of high luminosity, high polarization, multiple interaction points, maximum flexibility and reliability
- Takes maximum advantages of existing CEBAF
- Offers a good path for staging and future upgrade
- Requires minimum R&D and realizes in a most cost effective way

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- Ion complex is a ***green field*** design so we have freedom to be innovative
- We can take benefit of knowledge learnt in the last several decades and incorporate many proofed great ideas/schemes in the design
- We have an opportunity to design a brand new class of hadron collider just we had done in CEBAF near twenty years ago.

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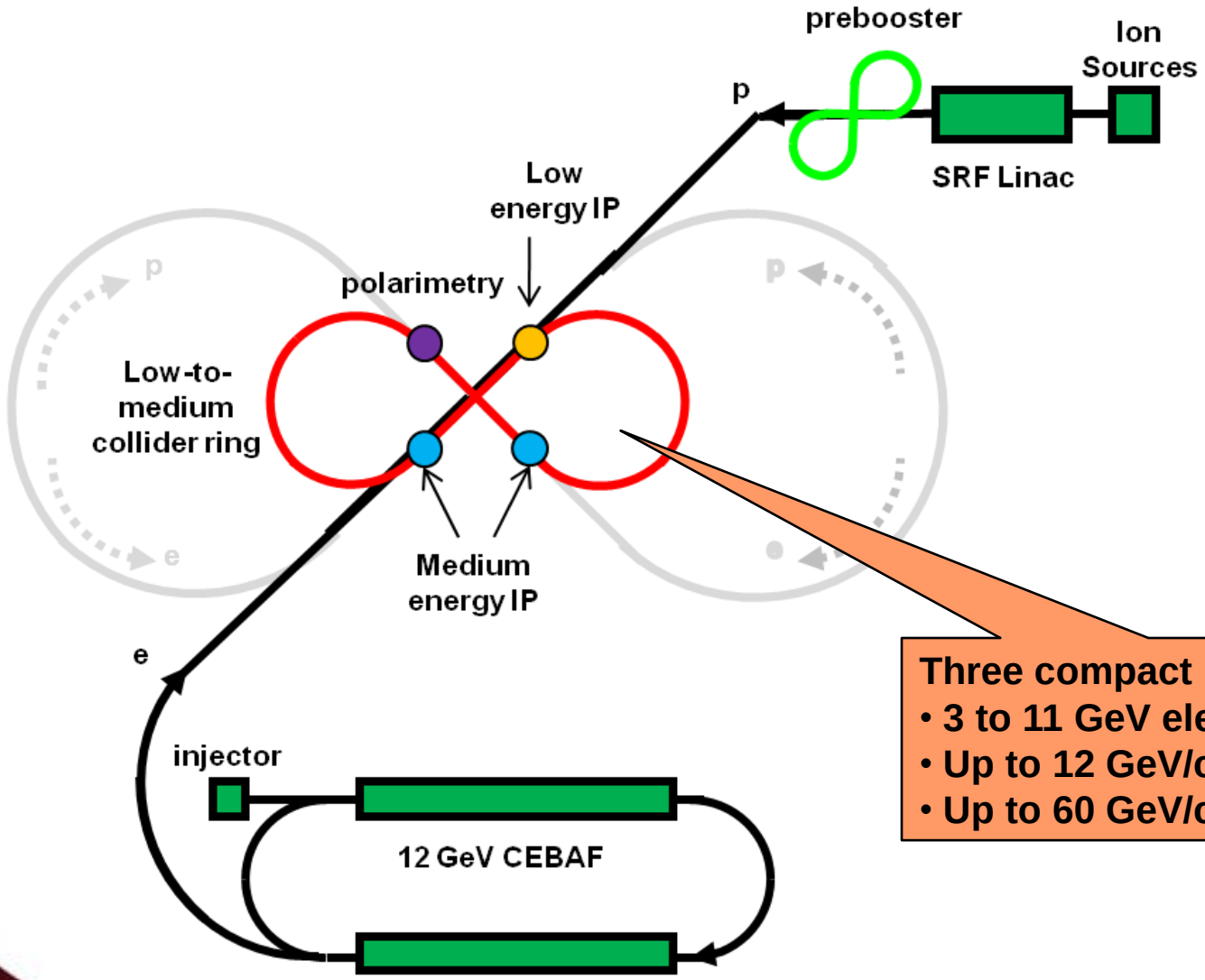
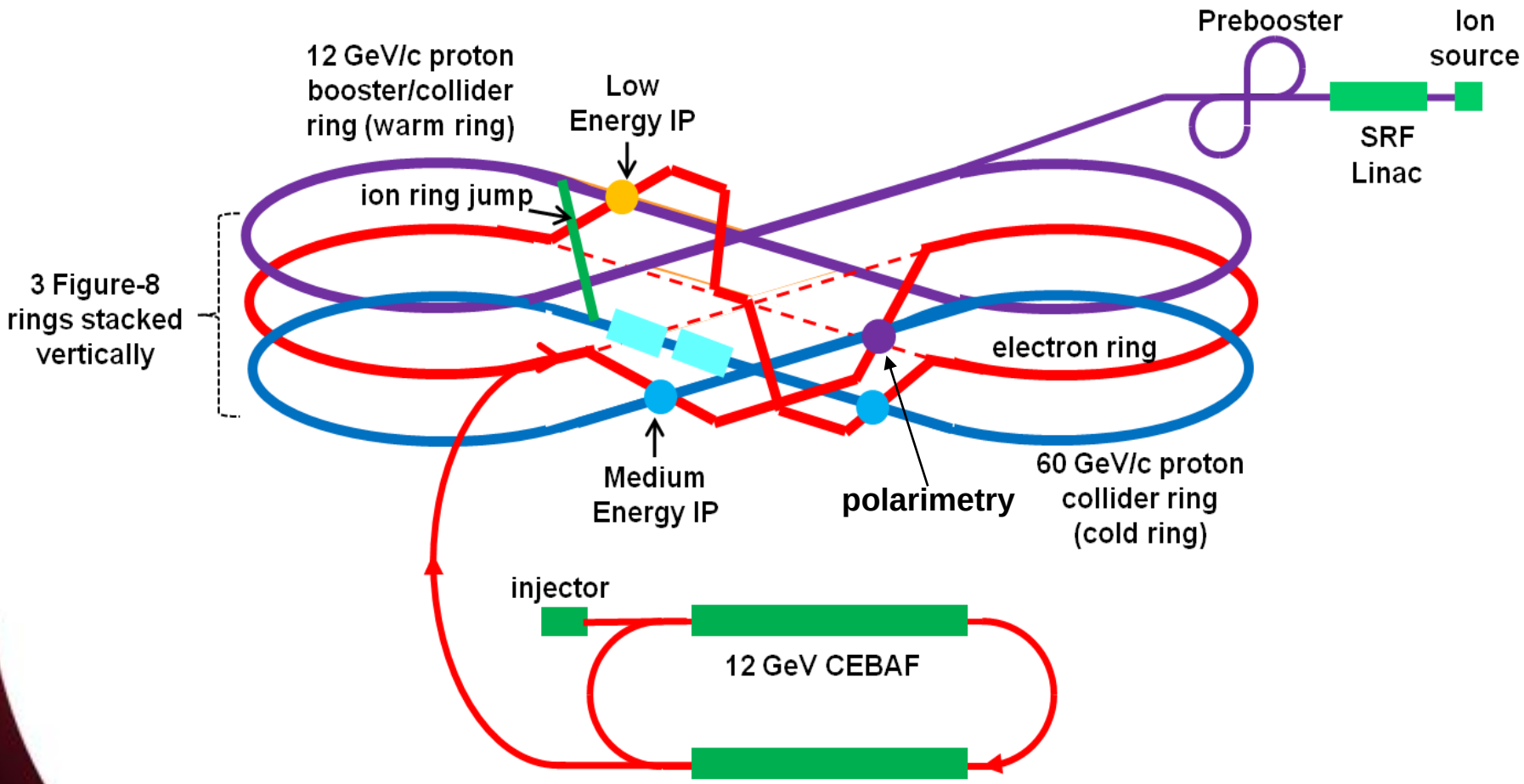
EIC@JLab at Low to Medium Energy

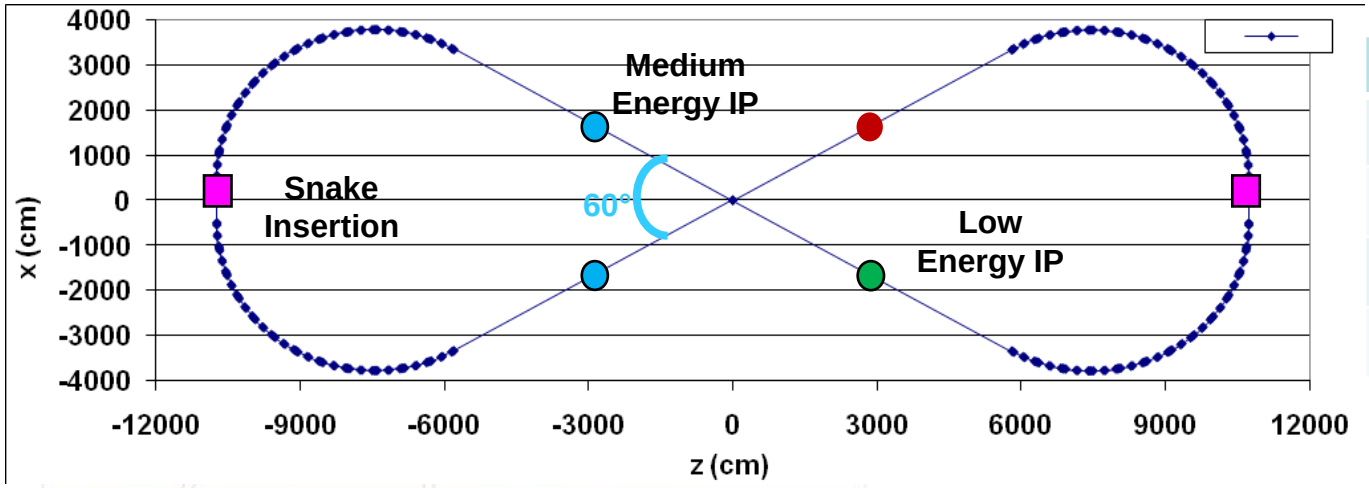


Three compact rings:
- **3 to 11 GeV electron**
- **Up to 12 GeV/c proton (worm)**
- **Up to 60 GeV/c proton (cold)**

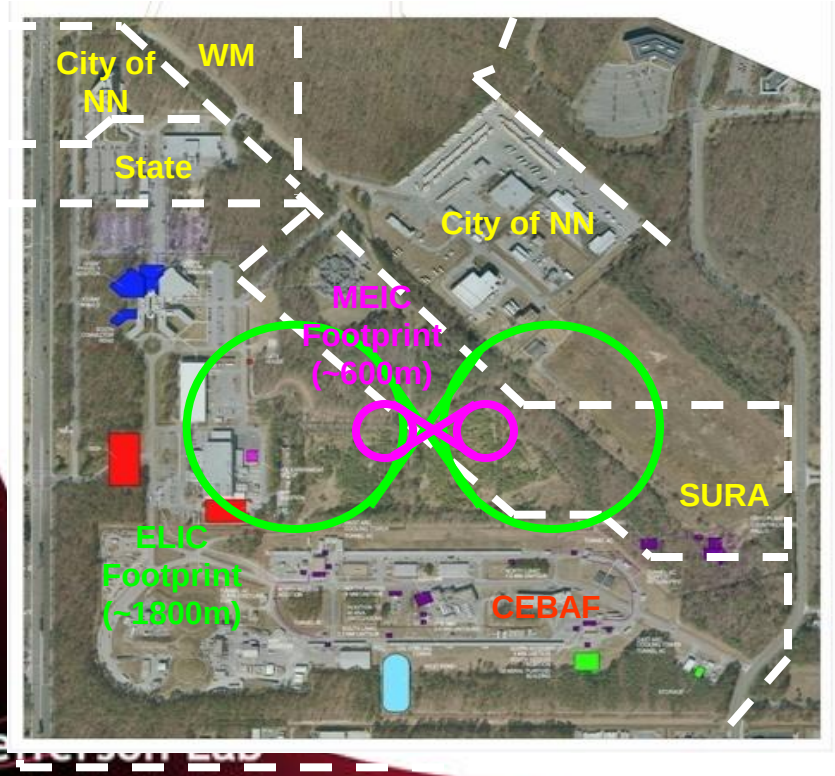
EIC@JLAB at Low to Medium Energy



ELIC Figure-8 Collider Ring Footprint



Arc	157 m
Figure-8 straight	150 m
Insertion	10 m
Circumference	634 m



- Ring design is optimized with
  - Synchrotron radiation power of e-beam
    ➔ prefers large ring (arc) length
  - Space charge effect of i-beam
    ➔ prefers small ring circumference
- Multi IPs require long straight sections
- Straight sections also hold required components (e-cooling, injection and ejections, etc.)

EIC@JLab Parameters at Low-to-Medium Energy

Beam Energy	GeV	60/5	60/3	12/3
Collision freq.	MHz	499		
Particles/bunch	10^{10}	0.74/2.9	1.1/6	0.47/2.3
Beam current	A	0.59/2.3	0.86/4.8	0.37/2.7
Energy spread	10^{-4}	~ 3		
RMS bunch length	mm	5	5	50
Horz. emit., norm.	μm	0.56/85	0.8/75	0.18/80
Vert. emit. Norm.	μm	0.11/17	0.8/75	0.18/80
Horizontal beta-star	mm	25	25	5
Vertical beta-star	mm	5		
Vert. beam-beam tune shift / IP		0.01/0.03	0.015/0.08	0.015/0.013
Laslett tune shift (p-beam)		0.1	0.054	0.1
Peak Luminosity/IP, **10^{34}**	$cm^{-2}s^{-1}$	1.9	4.0	0.59

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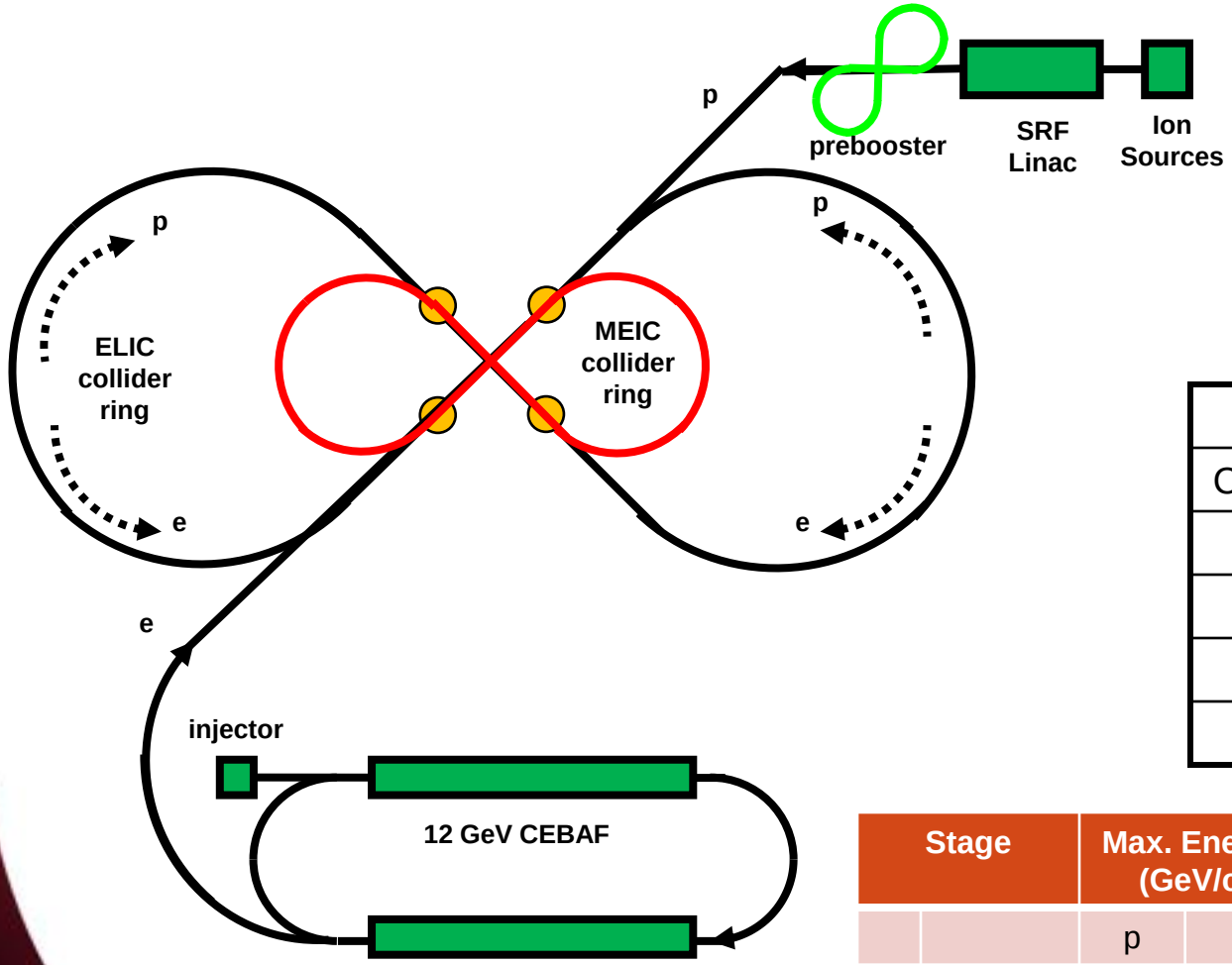
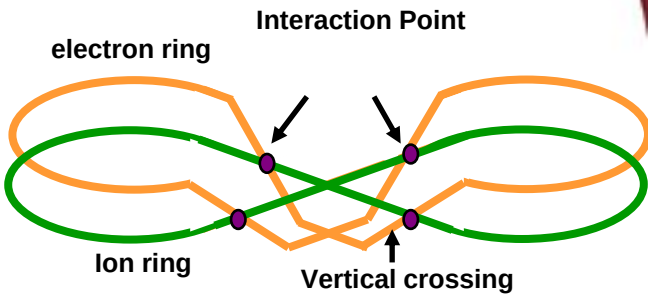
ELIC at High Energy & Staging





		Small	Large
Circumference	m	1800	2500
Radius	m	140	180
Width	m	280	360
Length	m	695	920
Straight	m	306	430

Stage		Max. Energy (GeV/c)		Ring Size (M)		Ring Type		IP #
		p	e	p	e	p	e	
1	Low	12	5 (11)	630	630	Warm	Warm	1
	Medium	60	5 (11)	630	630	Cold	Warm	2
2	Medium	60	10	600	1800	Cold	Warm	4
3	High	250	10	1800	1800	Cold	Warm	4

EIC@JLab Parameters: High Energy

Beam Energy	GeV	250/10	150/7
Collision freq.	MHz	499	
Particles/bunch	10^{10}	1.1/3.1	0.5/3.25
Beam current	A	0.91/2.5	0.4/2.6
Energy spread	10^{-4}	3	
RMS bunch length	mm	5	
Horz. beta-star	mm	125	75
Vert. beta-star	mm	5	
Horz. emit., norm.	μm	0.7/51	0.5/43
Vert. emit. Norm.	μm	0.03/2	0.03/2.87
B-B tune shift per IP		0.01/0.1	0.015/0.05
Laslett tune shift (p-beam)		0.1	0.1
Lumi. per IP, 10^{34}	$cm^{-2}s^{-1}$	11	4.1

Major design change: symmetric IR ➔ asymmetric IR

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ELIC Baseline Design Choice

- Energy Recovery Linac-Storage-Ring (ERL-R)
- ERL with Circulator Ring – Storage Ring (CR-R)
- Back to Ring-Ring (R-R)

  by taking CEBAF advantage as full energy polarized injector

- Reason of design change:

  High current polarized electron/positron source R&D too challenging

  - ERL-Ring: 2.5 A
  - Circulator ring: 20 mA
  - State-of-art: 0.1 mA

  ➔ Note we don't have to have ERL in order to delivering high luminosity

  ➔ Key for high luminosity is *high repetition, small beta* & short bunch*

- 12 GeV CEBAF Upgrade polarized source/injector already meets beam requirement of ring-ring design

- CEBAF-based R-R design still preserves high luminosity, high polarization (+polarized positrons…)

Achieving High Luminosity

ELIC design luminosity

$L \sim 4 \times 10^{34}\ cm^{-2}\ s^{-1}$ for medium energy (60 GeV x 3 GeV)

$L \sim 1 \times 10^{35}\ cm^{-2}\ s^{-1}$ for high energy (250 GeV x 10 GeV)

ELIC luminosity Concepts

- High bunch collision frequency (0.5 GHz, can be up to 1.5 GHz)
- Short ion bunches ($\sigma_z \sim 5$ mm) ***(also much smaller bunch charge)***
- Relative long bunch (comparing to beta*) for very low ion energy
- Strong final focusing ($\beta^*_y \sim 5$ mm)
- Large beam-beam parameters (~0.01/0.1 per IP,
  0.025/0.1 largest achieved)

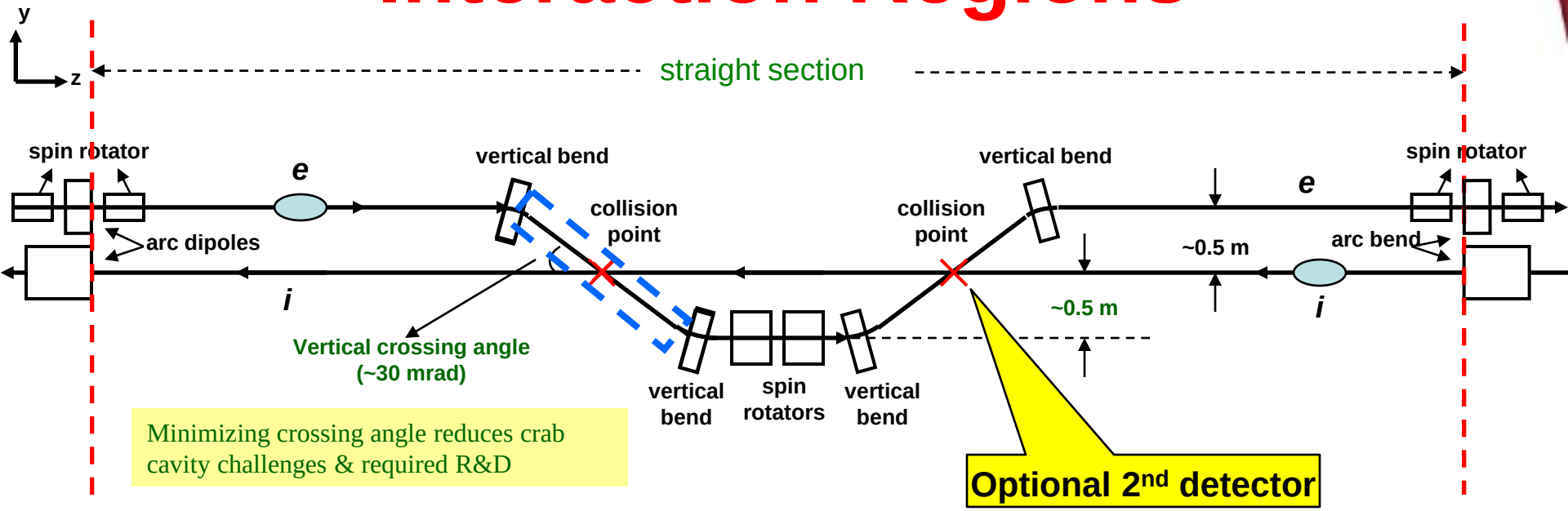
- Need electron cooling of ion beams
- Need crab crossing colliding beams

- Large synchrotron tunes to suppress synchrotron-betatron resonances
- Equal (fractional) betatron phase advance between IPs

ELIC Ring-Ring Design Features

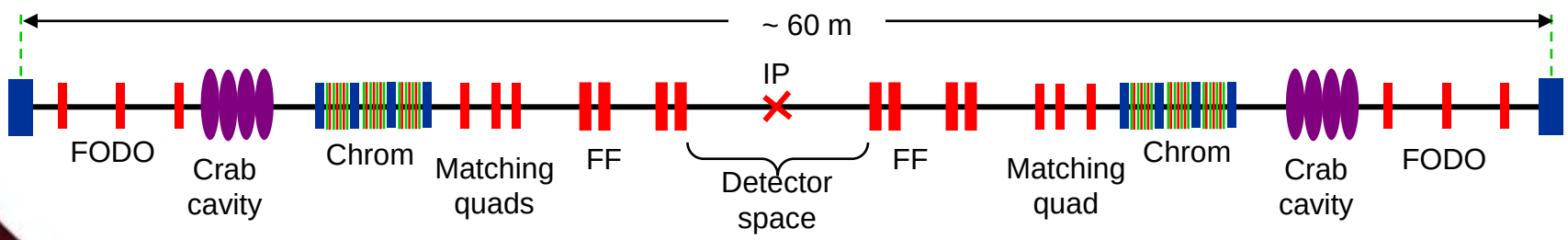
- Unprecedented high luminosity
- Electron cooling is an essential part of ELIC
- Up to four IPs (detectors) for high science productivity
- "*Figure-8*" ion and lepton storage rings
  - Ensure spin preservation and ease of spin manipulation
  - No spin sensitivity to energy for all species.
- Present CEBAF injector meets storage-ring requirements
- 12 GeV CEBAF can serve as a full energy injector to electron ring
- *Simultaneous* operation of collider & CEBAF fixed target program.
- Experiments with polarized positron beam are possible.

Figure-8 Straight Sections & Interaction Regions

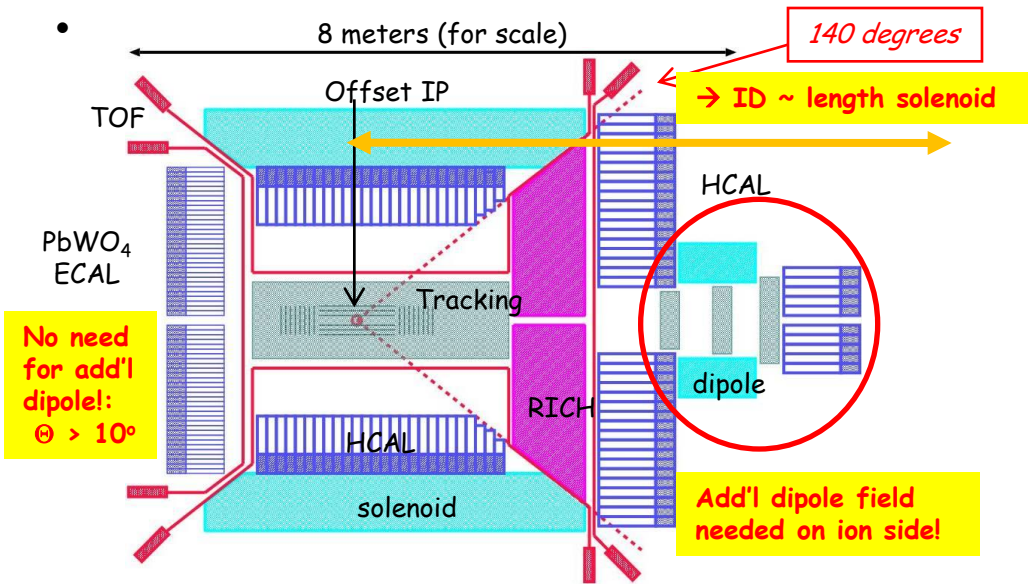


Minimizing crossing angle reduces crab cavity challenges & required R&D

Interaction Region

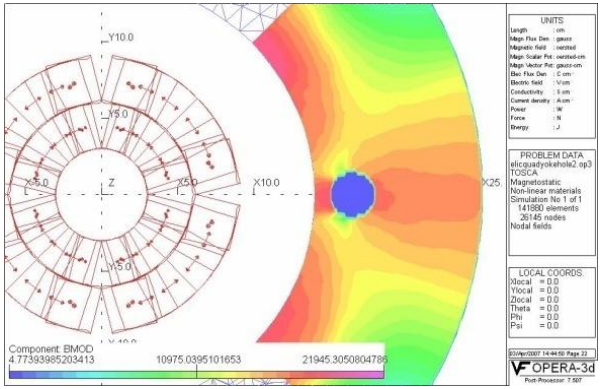


Interaction Regions and Detectors

- 

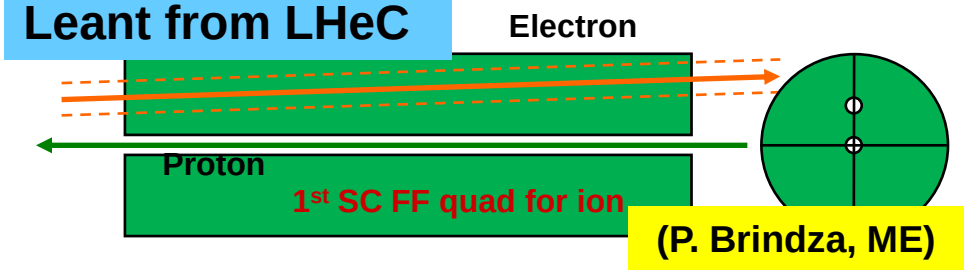
Ent's talk on ELIC detector design in this Workshop

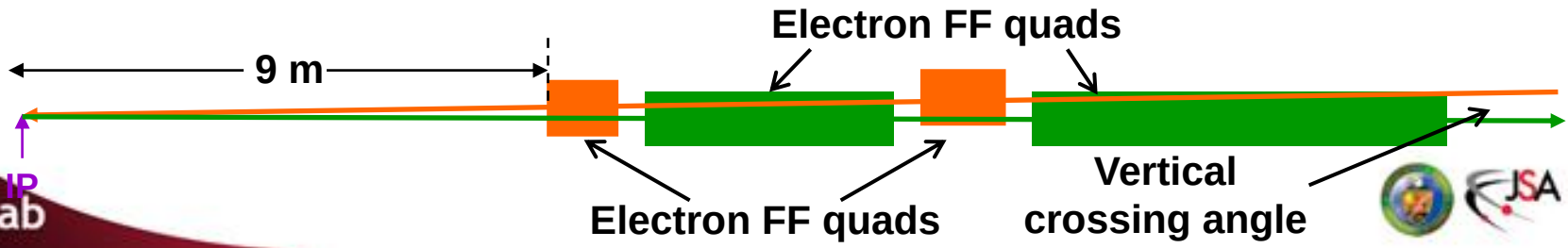
Magnetic Field in cold yoke around electron pass.



IP	Energy	Type	Space
1	Medium	General purpose	9+9 m
2	Medium	Diffraction/low_Q^2	
3	Low	DVCS-type	
4		(polarimetry)	

Leant from LHeC





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EIC@JLab Accelerator R&D

We have identified the following critical R&D for ELIC

- Electron cooling
- Crab crossing and crab cavity
- Forming high intensity low energy ion beam
- Beam-beam effect
- Traveling focusing for very low energy ion beam

Will discuss issues/requirements/state-of-art/challenges/activities

Level of R&D	Low-to-Medium Energy (12x3 GeV/c) & (60x5 GeV/c)	High Energy (up to 250x10 GeV)
Challenging		Electron cooling
Semi Challenging	Electron cooling Traveling focusing (for very low i energy)	Crab crossing/crab cavity
Likely	Crab crossing/crab cavity High intensity low energy i beam Beam-beam	High intensity low energy i beam Beam-beam
Know-how	Spin tracking IP design/chromaticity	Spin tracking IP design/chromaticity

Electron Cooling: ERL Circulator Cooler

Issues

- Essential for delivering ion bunches with small emittances and short length.
- Cooling electron energy
  - up to 6.5 MeV for low energy ELIC
  - up to 33 MeV for medium energy ELIC
  - up to 136 MeV for high energy
- Up to 3 A CW un-polarized beam (~nC bunch charge)

State-of-Art

Fermilab electron cooling demo. (4.34 MeV, 0.5 A DC)

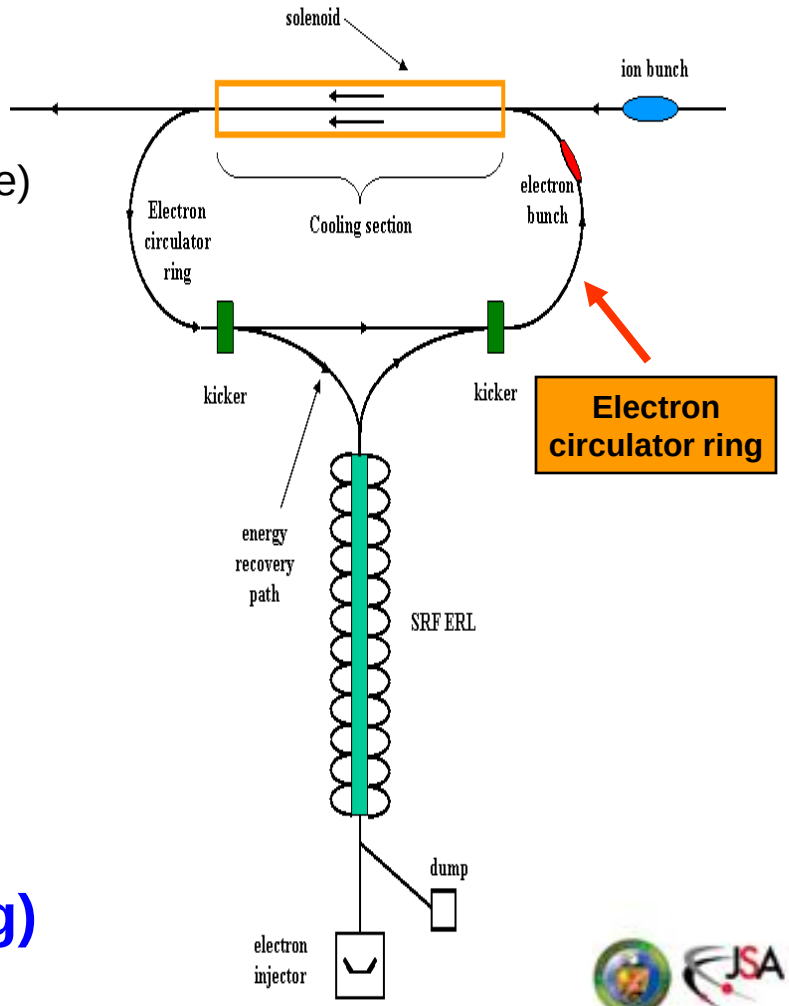
ERL Based Circulator Cooler

- SRF ERL able to provide high average current CW beam with minimum RF power
- Circulator ring for reducing average current from source/ERL

ERL Key technologies

- High intensity un-polarized electron source/injector
- Energy Recovery Linac (ERL)
- Fast kicker

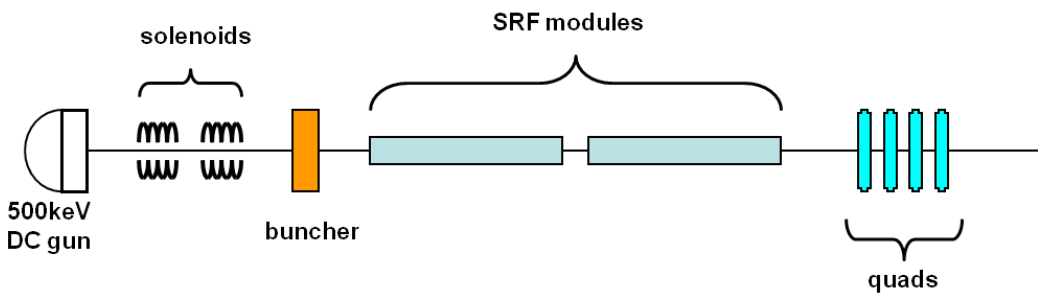
Beam Dynamics R&D (staged cooling)



EC Enabling Technologies

High intensity *e* source/injector

- 30 mA, up to 136 MeV, 1 nC bunch charge
- Cathode lifetime is ok with circulator ring
- Conceptual design adopts light source (FEL) photo-injector
- Beam qualities should be OK

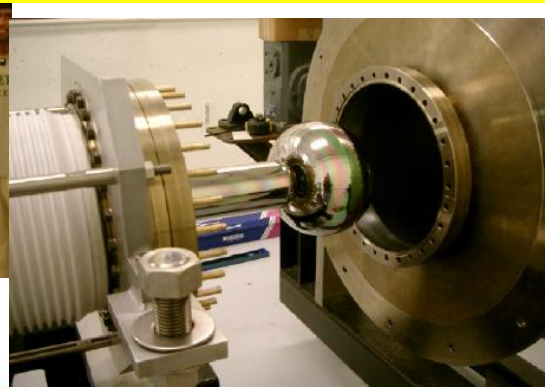


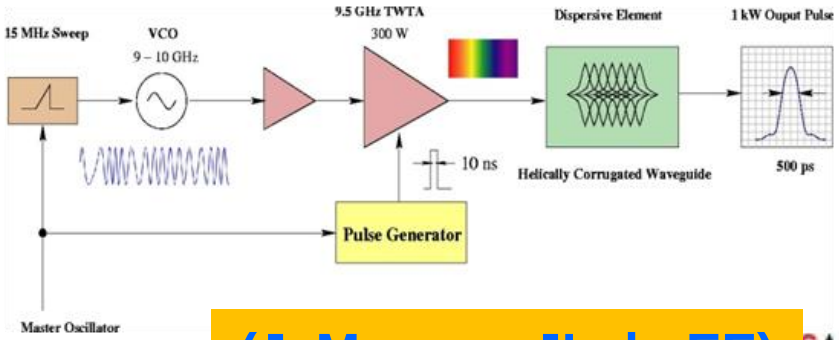
Fast kicker

- RF deflecting cavity
- High power ultra-short pulse (sub-ns, 20kW)

Beam energy	MeV	125
Kick angle	10^{-4}	3
Integrated BdL	GM	1.25
Frequency BW	GHz	2
Kicker Aperture	Cm	2
Peak kicker field	G	3
Kicker Repetition Rate	MHz	15
Peak power/cell	KW	10
Average power/cell	W	15
Number of cells	20	20

JLab FEL Gun R&D

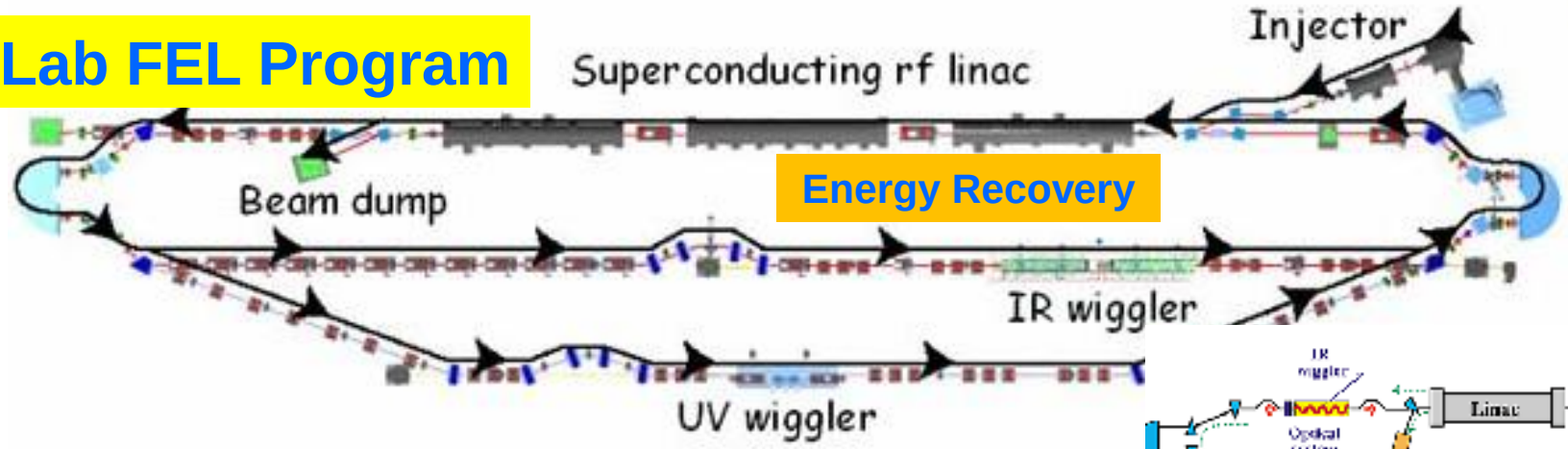


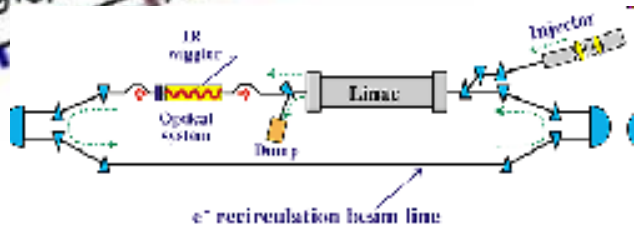


(J. Musson JLab, EE)

EC Enabling Technology: ERL

JLab FEL Program





Energy	**MeV**	**80-200**
Charge/bunch	**pC**	**135**
Average current	**mA**	**10**
Peak current	**A**	**270**
Beam power	**MW**	**2**
Energy spread	**%**	**0.5**
Normalized emittance	**µm-rad**	**<30**

- ERL based FEL
- High average power up to14 kW (***world record***)
- mid-infrared region, extension to UV is planned
- Photocathode DC injector, 10 mA class CW beam, sub-nC bunch charge
- Beam energy up to 200 MeV, energy recovery
- Next step/proposal: 100kW average power, 100 mA CW beam with ERL, nC-class bunch charge

JLab is world leader in ERL technology !

We are considering using this facility to test ERL based circulator cooler ring and for beam dynamics studies

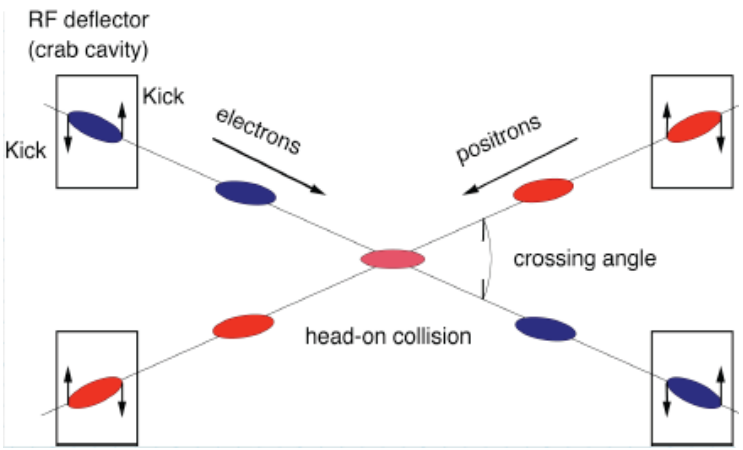
Crab Crossing & Crab Cavity

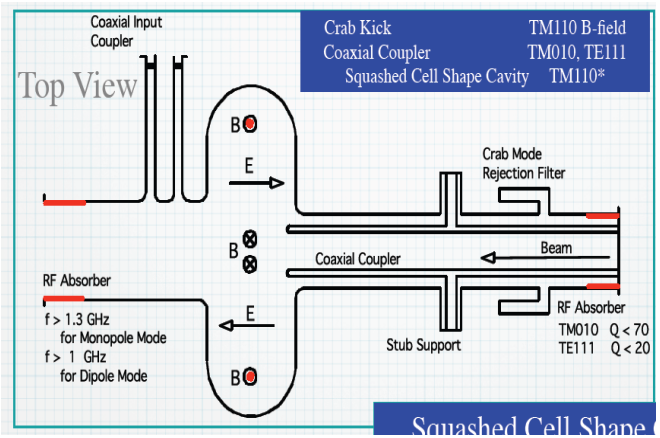
Issues

- High bunch repetition requires crab crossing colliding beams to avoid parasitic beam-beam
- Crab cavities are needed to restore head-on collision and avoid luminosity reduction
- ELIC crossing angle: ~ 2x12 mrad (9+9 m IR)

Stage	Beam Energy (GeV/c)	Integrated Kicking Voltage (MV)	R&D
electron	10	~ 1	State-of-art
Proton	12	~ 1	State-of-art
Proton	60	5	Not too far away
Proton	250	21	

- Crab cavity development & gradient limits
- Phase & amplitude stability requirements
- Beam dynamics/luminosity dependence of crab crossing



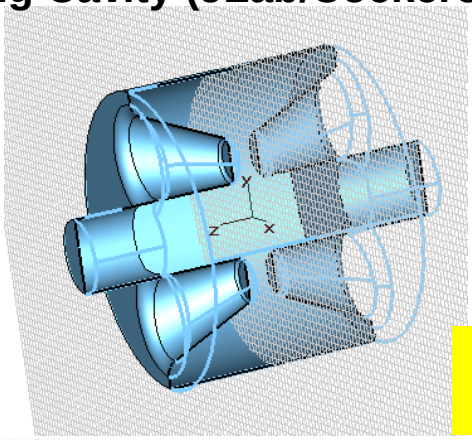


State-of-art:

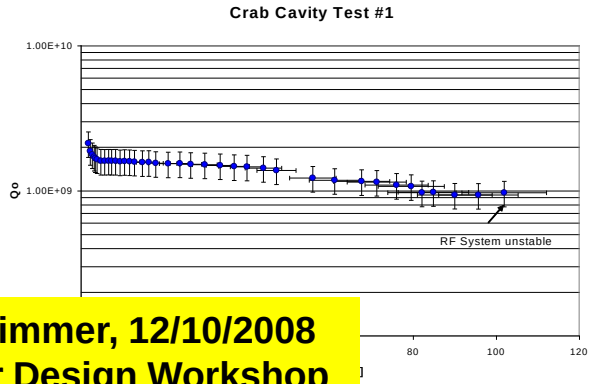
KEKB Squashed cell@TM110 Mode
Crossing angle = 2 x 11 mrad
V_{kick}=1.4 MV, E_{sp}= 21 MV/m

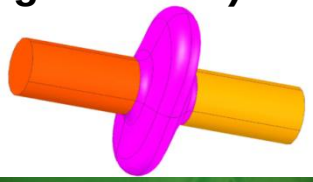
JLab Crab Cavity Development

Multi-cell TM110 and Loaded Structure of Crabbing Cavity (JLab/Cockcroft/Lancaster)

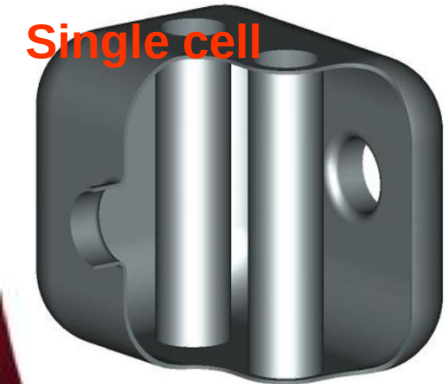


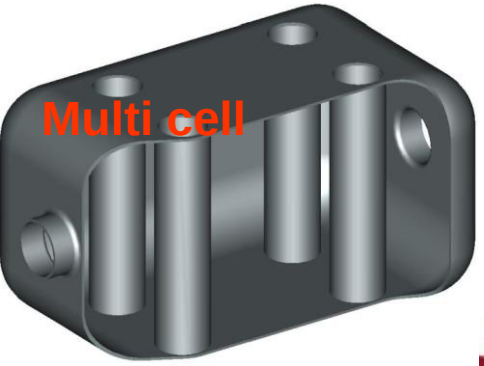
Elliptical squashed SRF cavity R&D for APS (JLab/LBNL/AL/Tsinghua Univ.)





H. Wang, R. Rimmer, 12/10/2008
Moun Collider Design Workshop





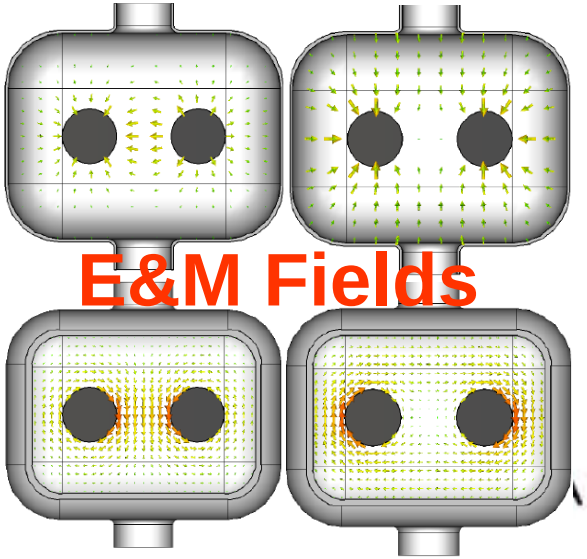
New (Innovative) Program

- Compact TEM-type, parallel-bar
- Deflecting ➔ 12 GeV CEBAF
- Crabbing ➔ ELIC
- Providing high transverse kinking

Single cell: 37x50cm, 4 MV@500MHz

Multi-cell: ~ n x (37 cm), n x (4 MV)

J. Delayen, H. Wang, PRST 2009
J. Delayen, JLab seminar, 02/19/09



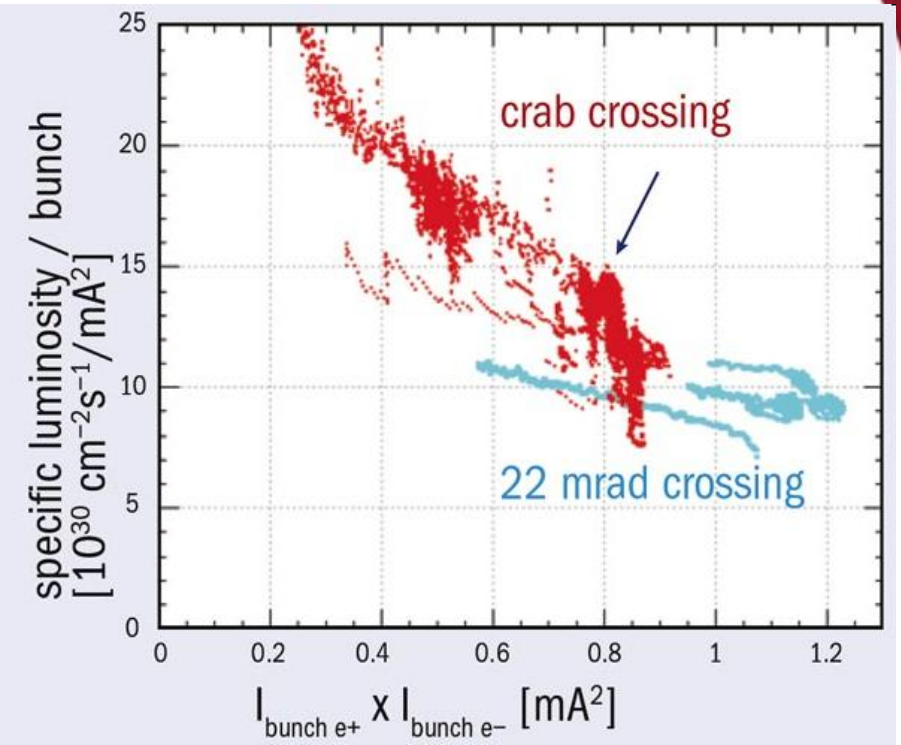
Great News From KEK

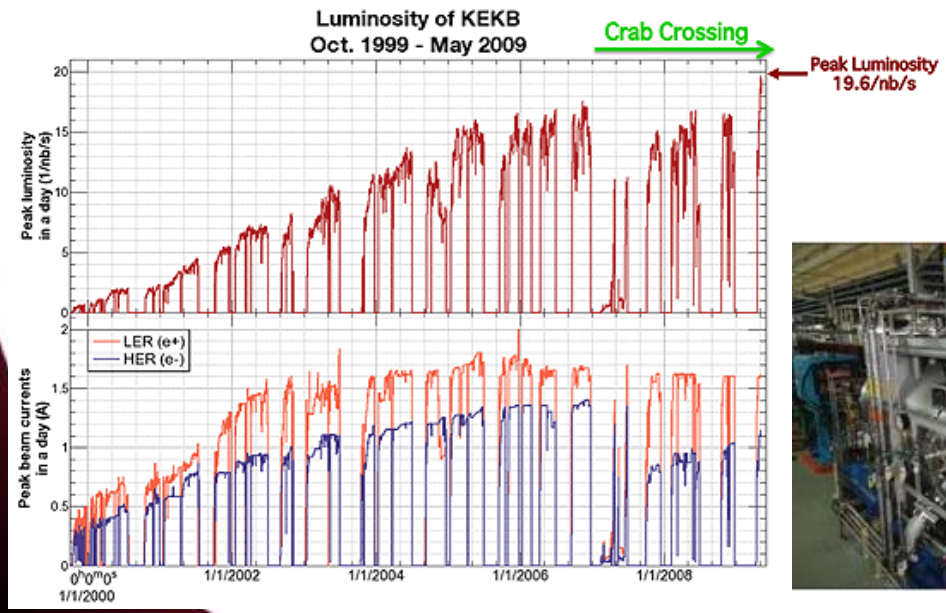
KEK Press Release (05/11/09)

"Using Crab Cavities, KEKB Breaks Luminosity World Record"

Symmetry*Breaking* (05/11/09)

"Record luminosity collisions due to "crab" crossing,





Trick: 28 skew sextupoles

Forming High Intensity Ion Beam

	Length (m)	Energy (GeV/c)	Cooling Scheme	Process
Source/SRF linac		0.2		Full stripping
Accumulator-cooler Ring /prebooster	100	3	DC electron	Stacking/accumulating Energy booster
Low energy ring (booster)	630	12	Electron	Fill ring/Energy boosting RF bunching (for collision)
Medium energy ring (large booster)	630	60	Electron	Energy boosting RF bunching (for collision)
High energy ring	1800	250	Electron	Fill ring/energy boosting RF bunching

Stacking/accumulation process

- Multi-turn (~20) pulse injection from SRF linac into an accumulator-cooler ring
- Damping/cooling of injected beam
- Accumulation of 1 A coasted beam at space charge limited emittence
- Fill prebooster/large booster, then acceleration
- Switch to collider ring for energy booster, RF bunching and initial/continuous cooing

Stacking proton beam in ACR

Circumference	M	100
Arc radius	M	3
Crossing straights length	M	2 x 15
Energy/u	GeV	0.2 -0.4
Electron current	A	1
Electron energy	KeV	100-200
Cooling time for protons	Ms	10
Stacked ion current	A	1
Norm. emit. After stacking	µm	16

In addition to simulation study, we are considering team up with ORNL to study space charge effect at SNS

Beam-Beam Interactions

Simulation Model

- Single/multiple IP, head-on collisions
- Ideal rings for e & p, a linear one-turn map
- Radiation damping & quantum excitations

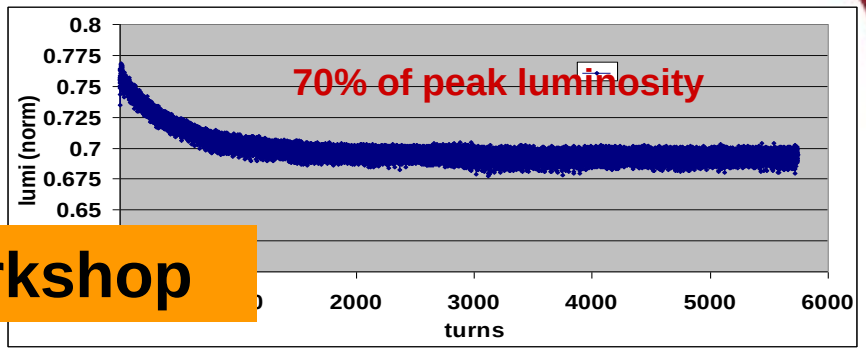
Simulation Co

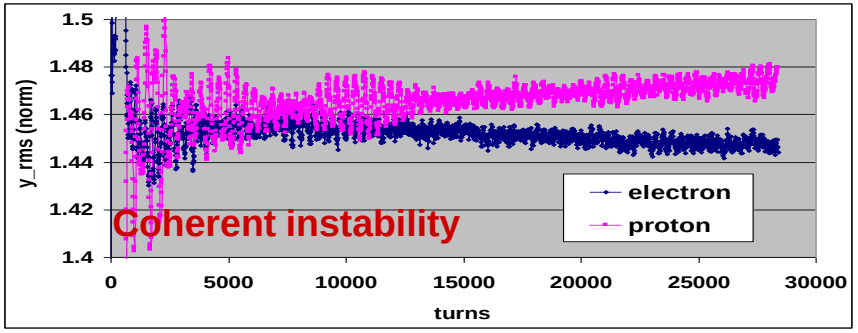
My talk in this Workshop

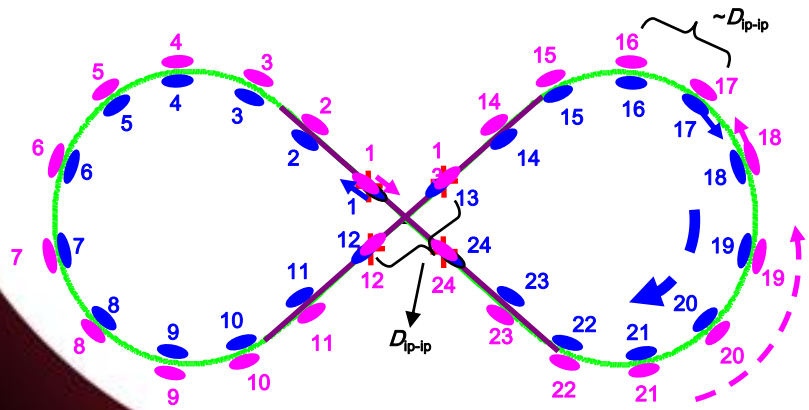
- BeamBeam3D by LBNL

Simulation Scope & Limitations

- 10k ~ 30k turns for a typical simulation run (multi-days of NERSC supercomputer)
- 0.15 s of storing time (12 damping times)
- reveals short-time dynamics with accuracy
- can't predict long term (>min) dynamics







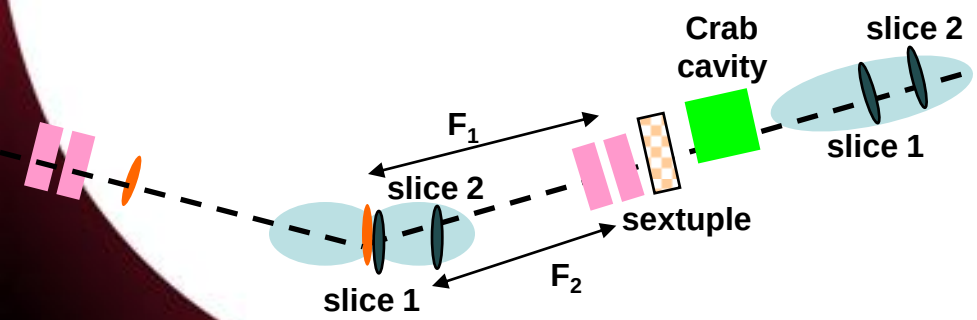
Low-to-medium energy b-b problem

- Non-relativistic, space charge dominated
- Ring transport can't be treated as a one-turn map, coupling everywhere
- Long ion bunch (up to 20 x β*), longitudinal dynamics important
- Traveling focusing scheme introduces non-linear optics

Boosting luminosity at low ion energy: Traveling Final Focusing/Crab Waist

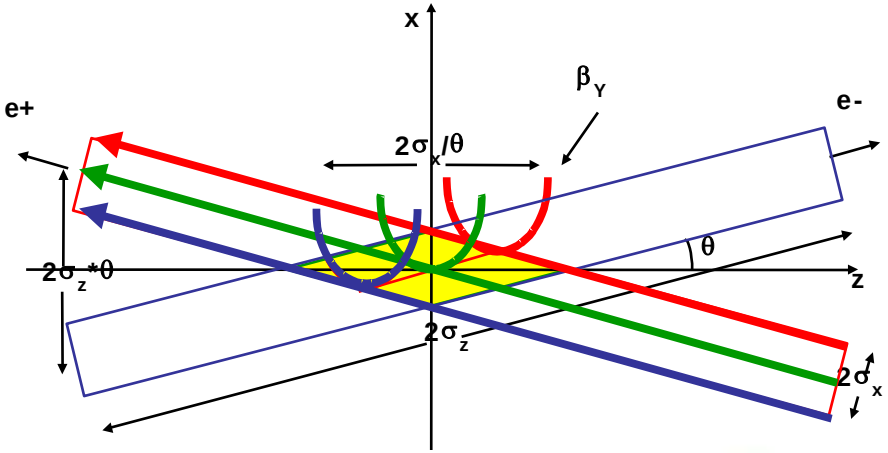
Traveling Final Focusing

- Laslett tune-shift limits bunch charge for very low energy ions (space charge dominated)
- Long bunch length enables more bunch charges, therefore high luminosity
- Hour glass effect could kill luminosity if bunch length is much large than beta-star
- “Traveling Focusing” (Brinkmann/Dohlus), can mitigate hour-glass effect
- New realization: crab crossing beam with sextuples



Crab Waist

- Proposed by P. Raimondi for Super-B factory for luminosity enhancement
- It deals with large Piwinski angle and low vertical beat-star
- Current Super-B design calls 0.2 mm beta-star while bunch length is 6 mm
- Recent proof-of-principle experiment done at DAΦNE very positive



Crabbed waist can be realized with a sextupole in with IP in x and at π/2 in y

Summary

- EIC@JLab promises to accelerate and store a wide variety of polarized light ions and un-polarized heavy ions to collider with polarized electron or positron beam enabling a unique physics program.
- The ELIC covers a wide CM energy range (10 to 100 GeV) in a coherent way. However, the low-to-medium energy one (CM energy 10 to 50 GeV) is our **immediate goal & R&D focus.**
- EIC@JLab luminosity for *e-p* collisions should exceed $1x10^{35}$ $cm^{-2}s^{-1}$ at high energy end (250x10 GeV^2), reach **$4x10^{34}$ $cm^{-2}s^{-1}$ at medium energy (60x3~5 GeV^2),** and $6x10^{33}$ $cm^{-2}s^{-1}$ at low energy end (12x3 GeV^2)
- Positron beam can also be used for additional positron-ion and electron-positron collision programs. Both electron & positron beam possess high (>80%) polarization.
- We have identified the critical R&D topics for EIC@JLab. In general, R&D for the medium energy EIC is much easy than for high energy one, which also provides a nice staging approach for accelerator R&D. We are aggressively pushing R&D programs to validity and optimize ELIC design

ELIC is the primary future of JLab!

ELIC Study Group

A. Afanasev, A. Bogacz, J. Benesch, P. Brindza, A. Bruell, L. Cardman, Y. Chao, S. Chattopadhyay, E. Chudakov, P. Degtiarenko, J. Delayen, Ya. Derbenev, R. Ent, P. Evtushenko, A. Freyberger, D. Gaskell, J. Grames, L. Harwood, T. Horn, A. Hutton, C. Hyde, R. Kazimi, F. Klein, G. A. Krafft, R. Li, L. Merminga, J. Musson, A. Nadel-Turonski, M. Poelker, R. Rimmer, C. Tengsirivattana, A. Thomas, M. Tiefenback, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory staffs and users

W. Fischer, C. Montag - Brookhaven National Laboratory

D. Barber - DESY

V. Danilov - Oak Ridge National Laboratory

V. Dudnikov - Brookhaven Technology Group

P. Ostroumov - Argonne National Laboratory

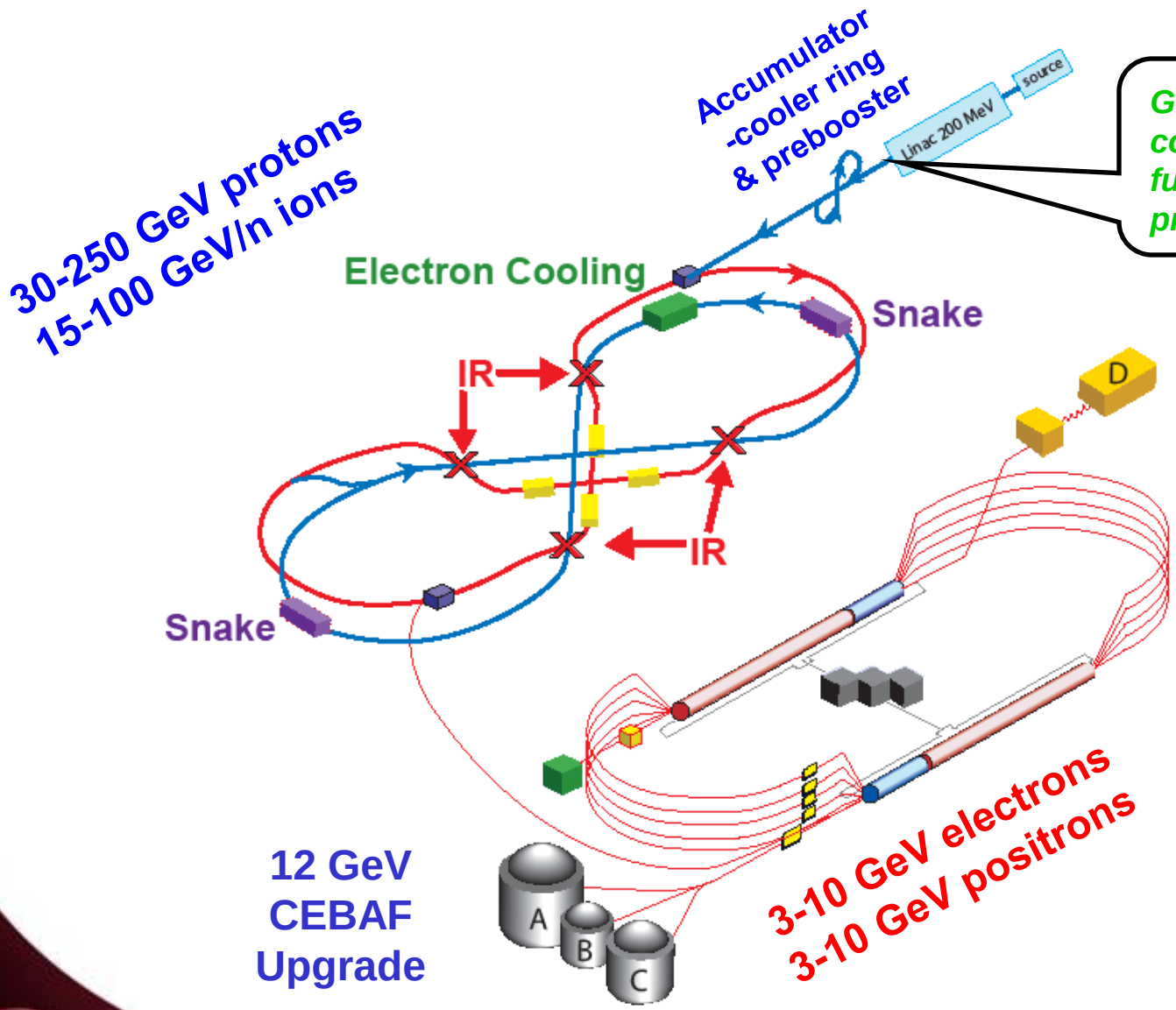
V. Derenchuk - Indiana University Cyclotron Facility

A. Belov - Institute of Nuclear Research, Moscow, Rssia

V. Shemelin - Cornell University

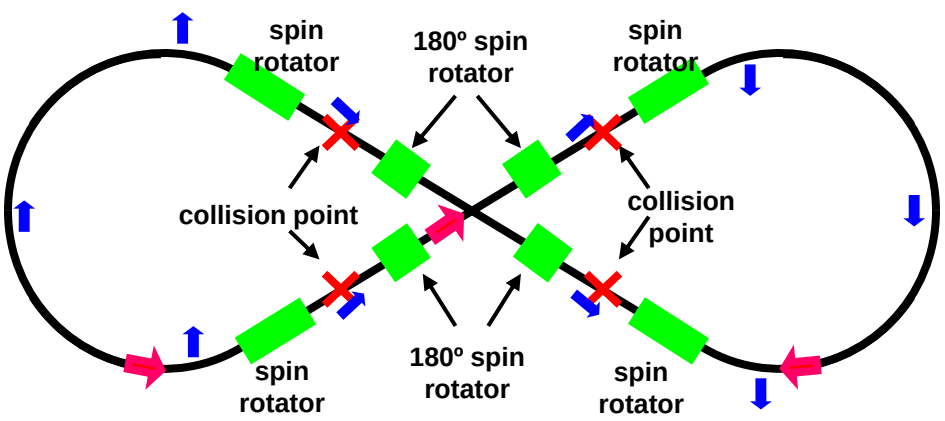
Backup Slides

ELIC Conceptual Design



Green-field design of ion complex directly aimed at full exploitation of science program.

Electron Polarization

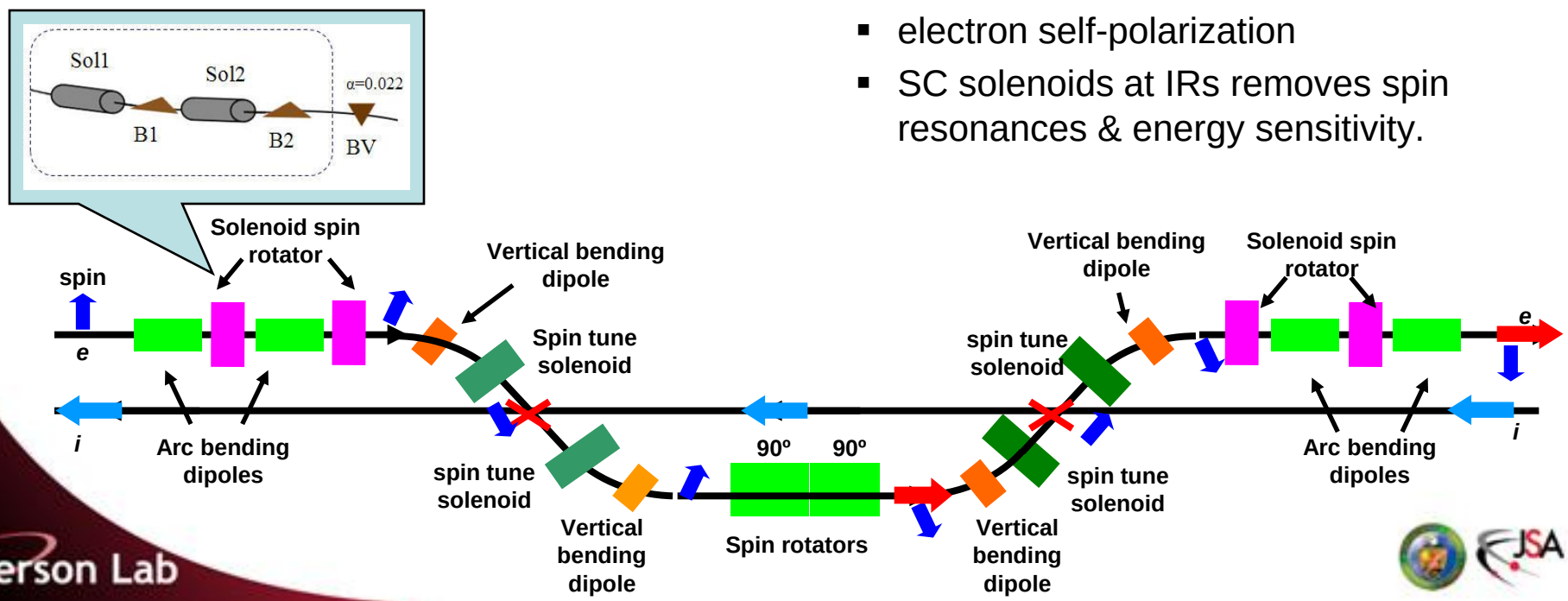


Producing/matching

- Polarized electron source of CEBAF
- Preserved in recirculated CEBAF
- Injected into Figure-8 ring with vertical polarization
- Turn to longitudinal polarization at IP using vertical crossing bends and solenoid spin rotators

Maintaining in the ring

- electron self-polarization
- SC solenoids at IRs removes spin resonances & energy sensitivity.

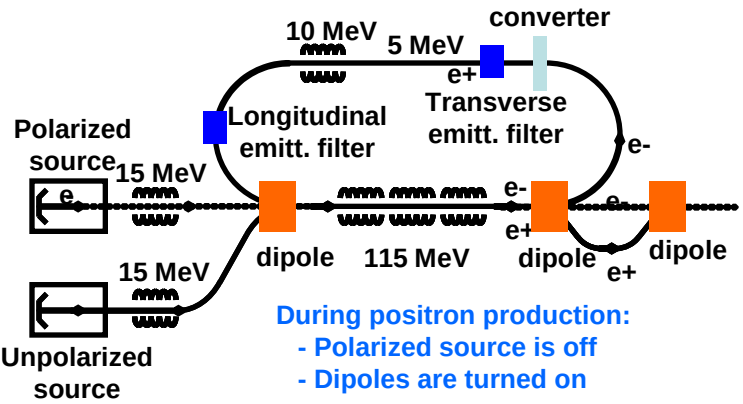


Positrons in CEBAF/ELIC

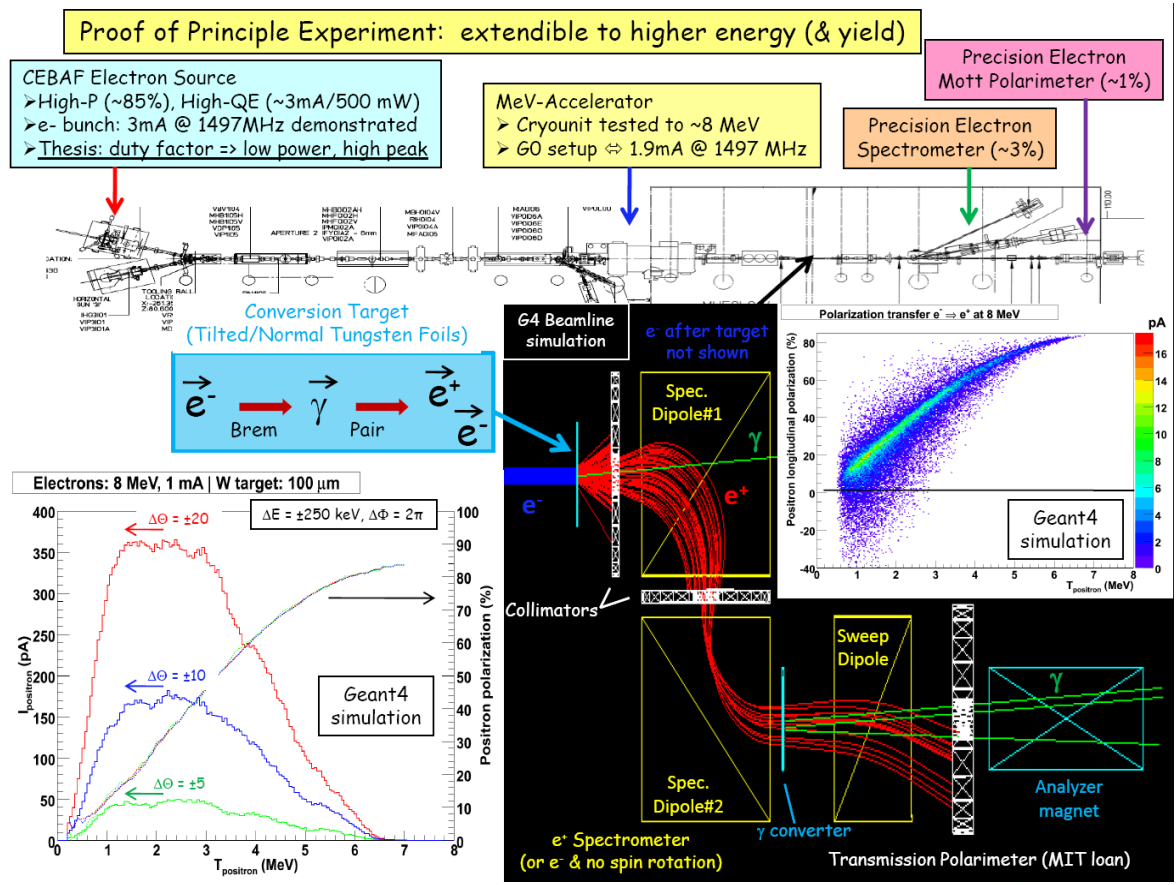
International Workshop on Positrons at Jefferson Lab

March 25-27, 2009

- **"CEPBAF", S. Golge (Ph. D thesis) / A. Freyberger**
- **Polarized Positron Source, J. Dumas (Ph.D thesis) /J. Grames**
- **Joint JLab/Idaho Univ. Position Program**



- Non-polarized positron bunches generated from modified electron injector through a converter
- Polarization realized through self-polarization at ring arcs



(M. Polker)

Other R&D