The High Luminosity Polarized Electron-Ion Collider Project at Jefferson Laboratory

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Cool 2013

Mürren Switzerland
10 -14 June 2013

OUTLINE

- JLab in Nuclear Physics business
- Electron-Ion Collider* for Nuclear Science
- EIC@JLab Layout and Operation Scenario
- Concept for high luminosity
- Basic Design Choices
- Interaction Region with Integrated Detector
- Polarized Beams in MEIC
- ERL-based Electron Cooling
- Advanced studies

* EIC is the generic name for the Nuclear Science-driven Electron-Ion Collider, presently considered in the US

JLab Nuclear Science: 12 GeV CEBAF

CEBAF fixed target program

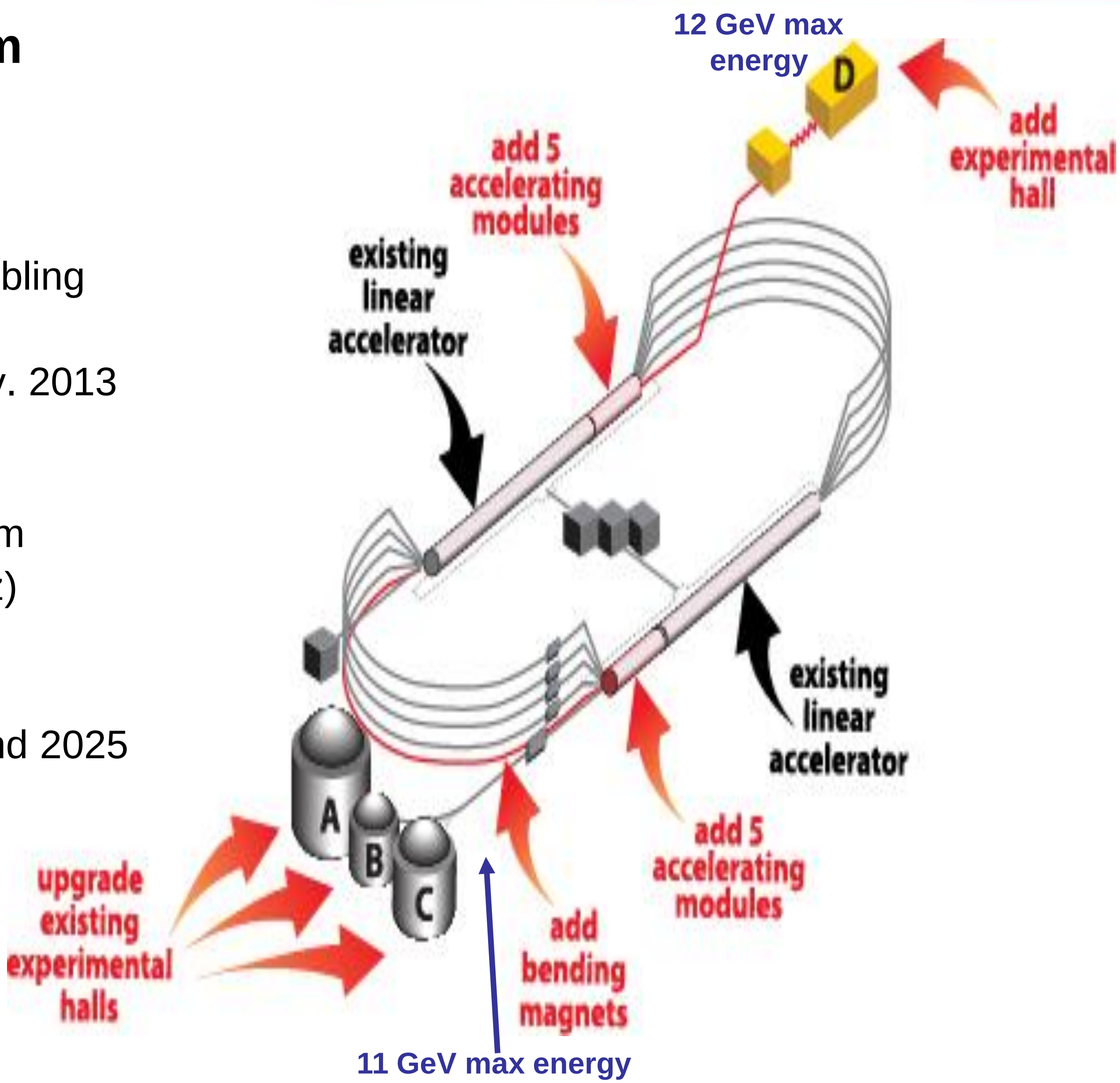
- 5-pass recirculating SRF linac

12 GeV CEBAF Upgrade

- A $340M project for energy doubling
- Construction near completion
- Commissioning will start on Nov. 2013

New CEBAF will provide

- Up to 12 GeV CW electron beam
- High repetition rate (3x499 MHz)
- High polarization (>80%)
- Very good beam quality
- Exciting science program beyond 2025



Into the "sea": the EIC

("Medium-Energy") MEIC@JLab energy choices driven by:

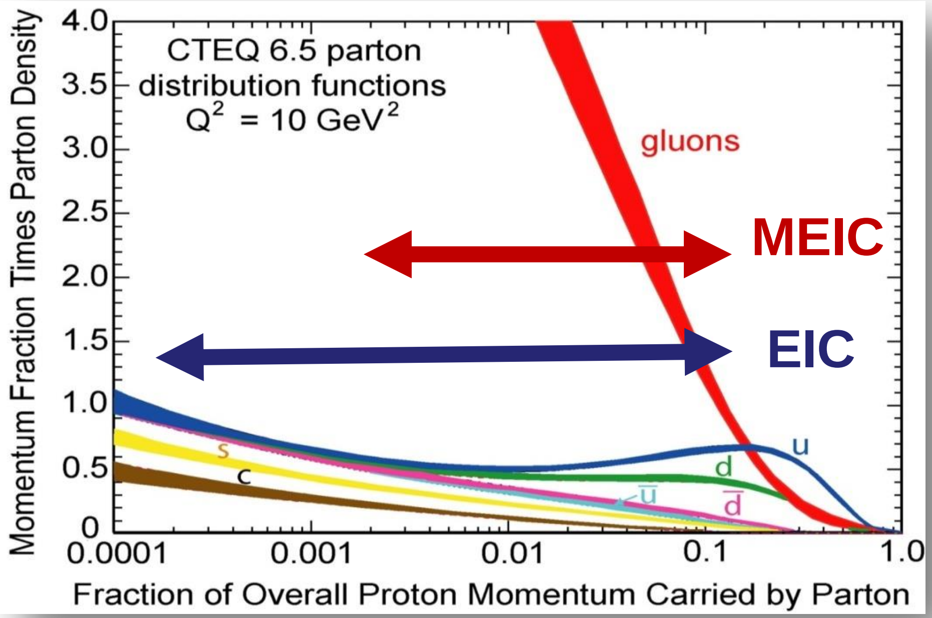
access to sea quarks and gluons

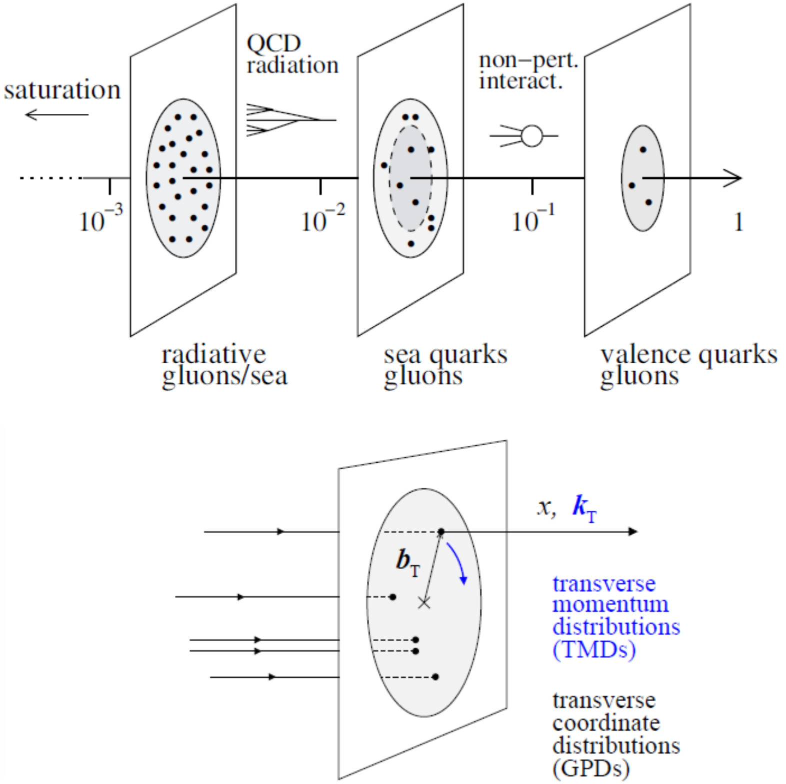
→ s = few 100 - 1000 seems right ballpark

→ s = few 1000 allows access to gluons, shadowing

Polarization + good acceptance to detect spectators & fragments

An EIC aims to study the sea quarks and gluon-dominated matter.





Long range Jlab NP enterprise plan

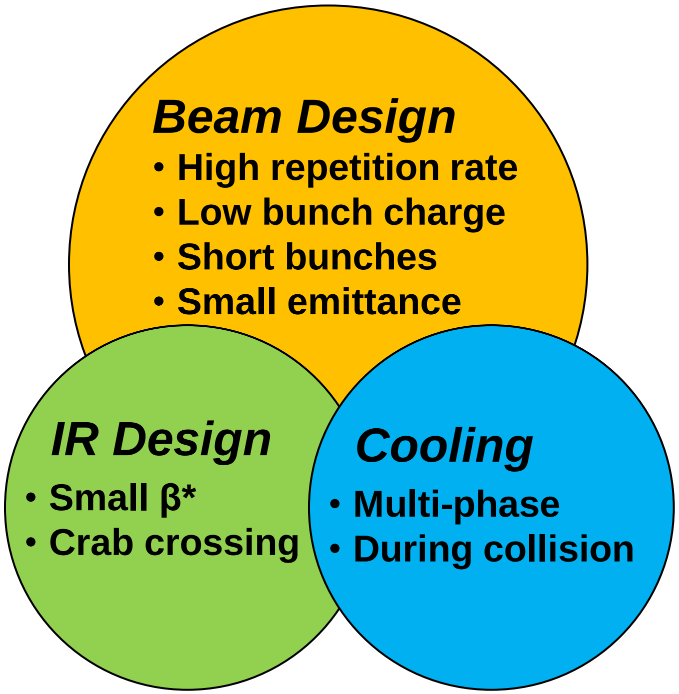
- JLab's fixed target program after the 12 GeV CEBAF upgrade will be world-leading for at least a decade.
- A *M*edium energy *E*lectron-*I*on *C*ollider (MEIC) at JLab will open new frontiers in nuclear science.
- The timing of MEIC construction can be tailored to match available DOE-ONP funding while the 12 GeV physics program continues.
- MEIC parameters are chosen to optimize science, technology development, and project cost.
- We maintain a well defined path for future upgrade to higher energies and luminosities.
- A conceptual machine design has been completed recently, providing a base for performance evaluation, cost estimation, and technical risk assessment.
- A design report was released on August, 2012.

MEIC project

MEIC design collaboration

[1] Jefferson Lab
[2] Argonne National Laboratory
[3] Brookhaven National Laboratory
[4] Catholic University of America
[5] College of William and Mary
[6] DESY
[7] Hampton University
[8] Idaho State University
[9] Joint Institute for Nuclear Research, Dubna
[10] Moscow Institute of Physics & Technology
[11] Muons Inc., USA
[12] Northern Illinois University
[13] Old Dominion University
[14] Paul Scherrer Institute
[15] SLAC National Accelerator Lab
[16] Science and Technique Lab Russia
[17] Universidad de Guanajuato
[18] University of Wisconsin-Madison
19 Fermi National Accelerator Lab
20 Oak Ridge National Accelerator Lab

MEIC Design Features: High Luminosity, Stable Spin, Full Acceptance Detection + Forward Tagging

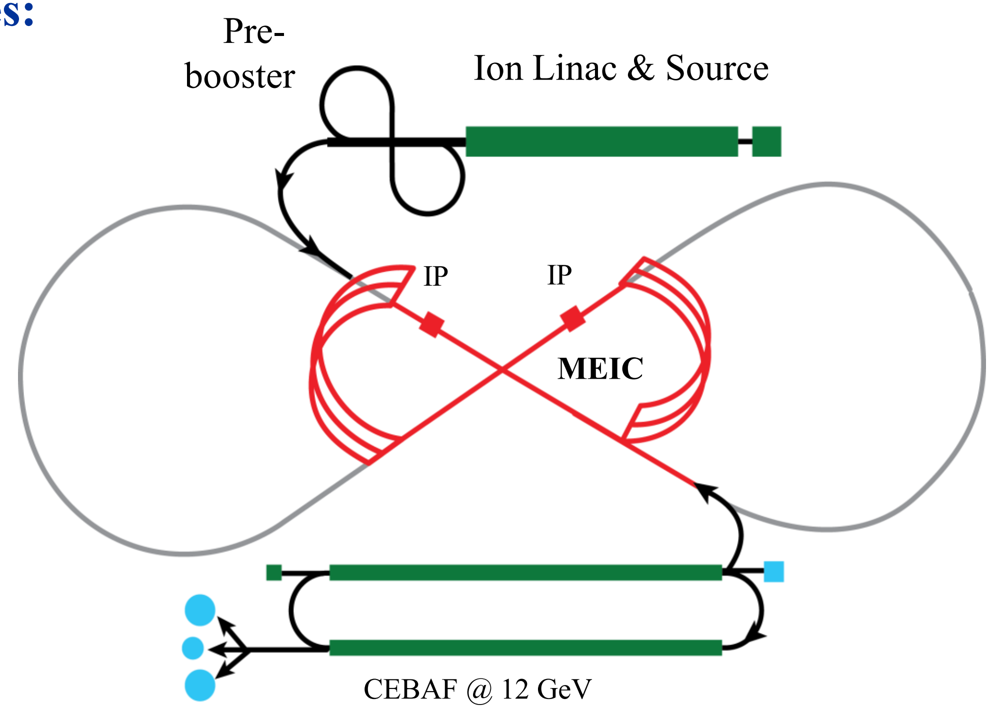


JLab is poised to build a ring-ring EIC taking the advantages of:

- **CEBAF** as a **full energy injector** for electron storage ring
- A high luminosity design based on ***short bunches*, *high repetition rate, crab-crossing*** colliding beams
- SRF-ERL-based ***Circulated Electron Cooling***
- ***Twisted Spin*** dynamics in ***figure 8*** booster and collider rings providing for spin stability and manipulation for all polarized species ***including deuterium***
- A novel **<u>full acceptance + forward tagging detector</u>** design suitable for ***crab-crossing*** beams and corresponding to the EIC aims to study the **<u>sea quarks and gluon-dominated matter</u>**

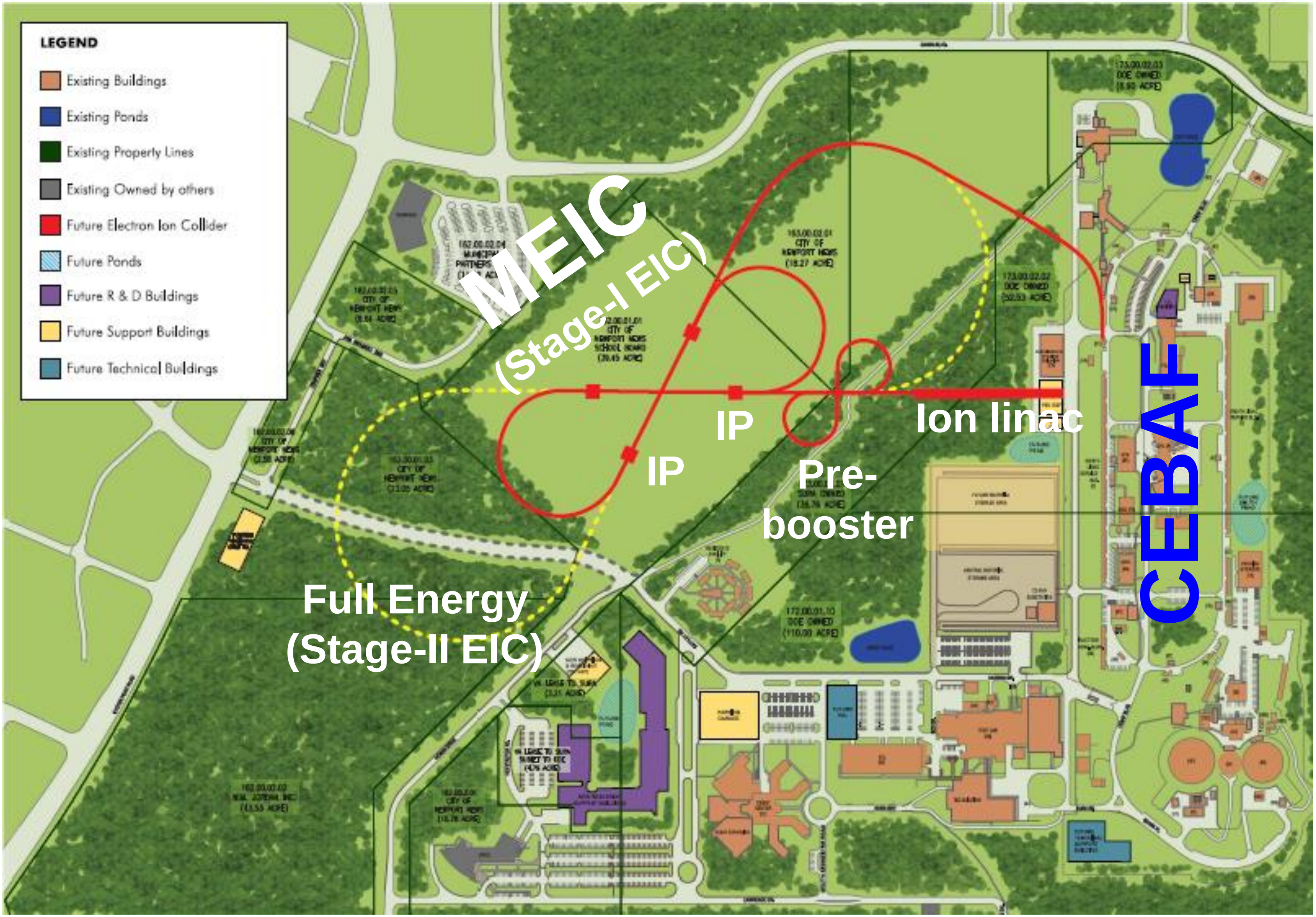
EIC layout scheme

MEIC figure 8 tunnel accommodates:
- large ion booster
- ion and electron storage rings



- **Running fixed-target experiments in parallel with collider**

MEIC/EIC Layout



MEIC Design Report

- **[Posted: arXiv:1209.0757]**
- Article on MEIC science case
  (arXiv:1110.1031; EPJ A48 (2012) 92)

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Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

S. Abeyratne[8], A. Accardi[1], S. Ahmed[1], D. Barber[5], J. Bisognano[15], A. Bogacz[1], P. Chevtsov[12], S. Corneliussen, J. Delayen[11], W. Deconinck[4], Ya. Derbenev[1], S. DeSilva[11], D. Douglas[1], V. Dudnikov[9], R. Ent[1], B. Erdelyi[10], Yu. Filatov[7,8], D. Gaskell[1], V. Guzey[1], T. Horn[3], A. Hutton[1], C. Hyde[11], R. Johnson[9], Y. Kim[6], F. Klein[3], A. Kondratenko[14], M. Kondratenko[14], G. Krafft[1,11], R. Li[1], F. Lin[1], S. Manikonda[2], F. Marhauser[9], R. McKeown[1], V. Morozov[1], P. Nadel-Turonski[1], E. Nissen[1], P. Ostroumov[2], F. Pilat[1], M. Poelker[1], A. Prokudin[1], R. Rimmer[1], T. Satogata[1], M. Spata[1], H. Sayed[12], M. Sullivan[13], C. Tennant[1], B. Terzić[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

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Editors: Y. Zhang and J. Bisognano

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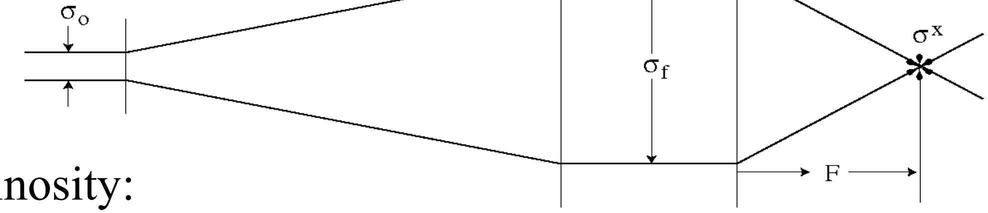
A collider as a microscope

$\sigma \cdot \theta = \varepsilon$ -emittance

$\sigma_0 \theta_0$ $\sigma_f \theta_f$ $\sigma^* \theta^*$



$$\sigma^* = F\theta_f = F\frac{\varepsilon}{\sigma_f}$$

Luminosity:

$$L = \frac{N_1 N_2}{4\pi\sigma^{*2}} f = e^{-3} JE \frac{\Delta\nu}{\beta^*}$$

$$\beta^* = \frac{F^2}{\beta_l} = \frac{F^2 \varepsilon_n}{\gamma \sigma_f^2} \propto \frac{m}{BA}\left(\frac{A}{\sigma_f}\right)^2 \varepsilon_n$$

A requirement to bunch length:

$$\sigma_z < \frac{\sigma^*}{\theta^*} \equiv \beta^* = F^2 \frac{\varepsilon}{\sigma_f^2}$$

Parameter	Units	Value
γ		100
F	m	3
σ_f	mm	2
ε_n	μm	.4

Small transverse and longitudinal beam emittance allows one to design and use a strong final focus:

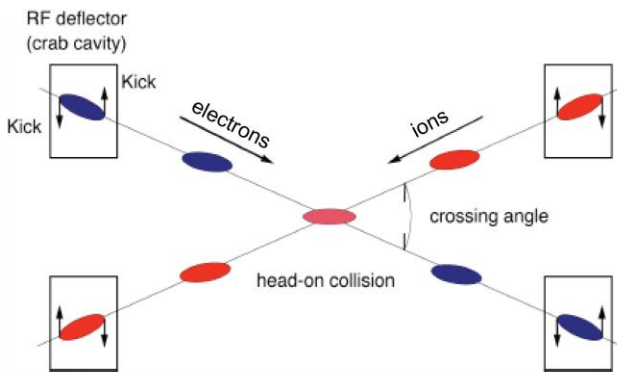
β* about 5 mm or even shorter can be designed

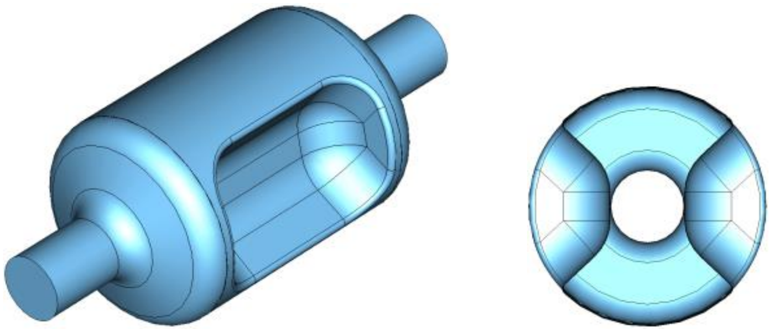
- **Chromaticity** $\Delta F = F\Delta p / p$ **is a constraint, but it can be compensated (an algorithm is established)**

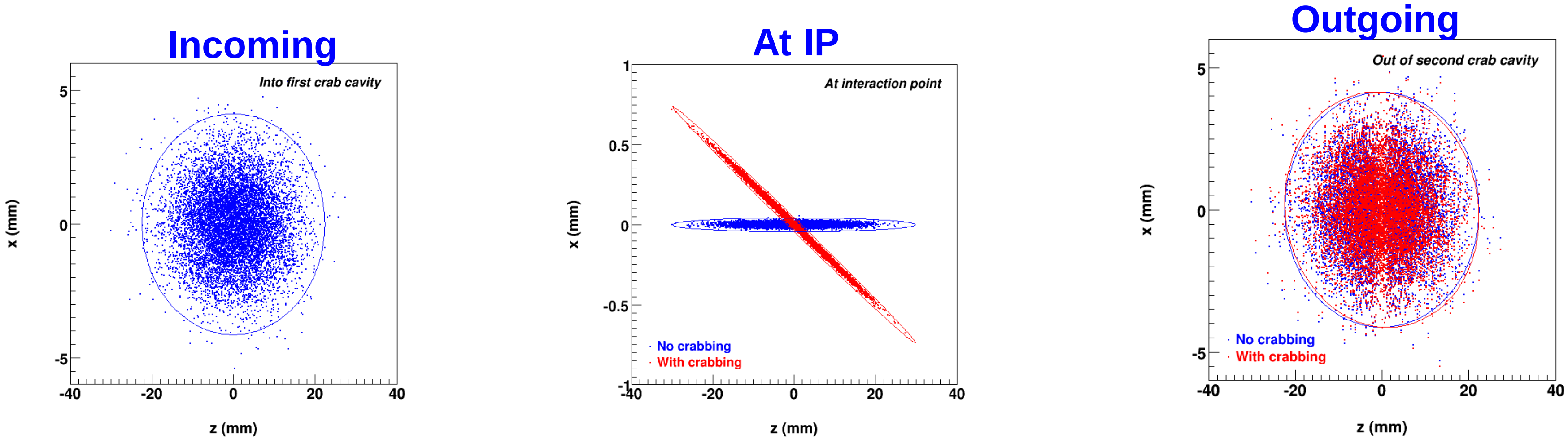
The (6D) emittance is a subject to change by cooling!

Crab Crossing

- Restore effective head-on bunch collisions with 50 mrad crossing angle ⇒ Preserve luminosity
- Dispersive crabbing (regular accelerating / bunching cavities in dispersive region) vs. Deflection crabbing (novel TEM-type SRF cavity at ODU/JLab, very promising!)
- **Feasible for short bunches with HF SC cavities!**





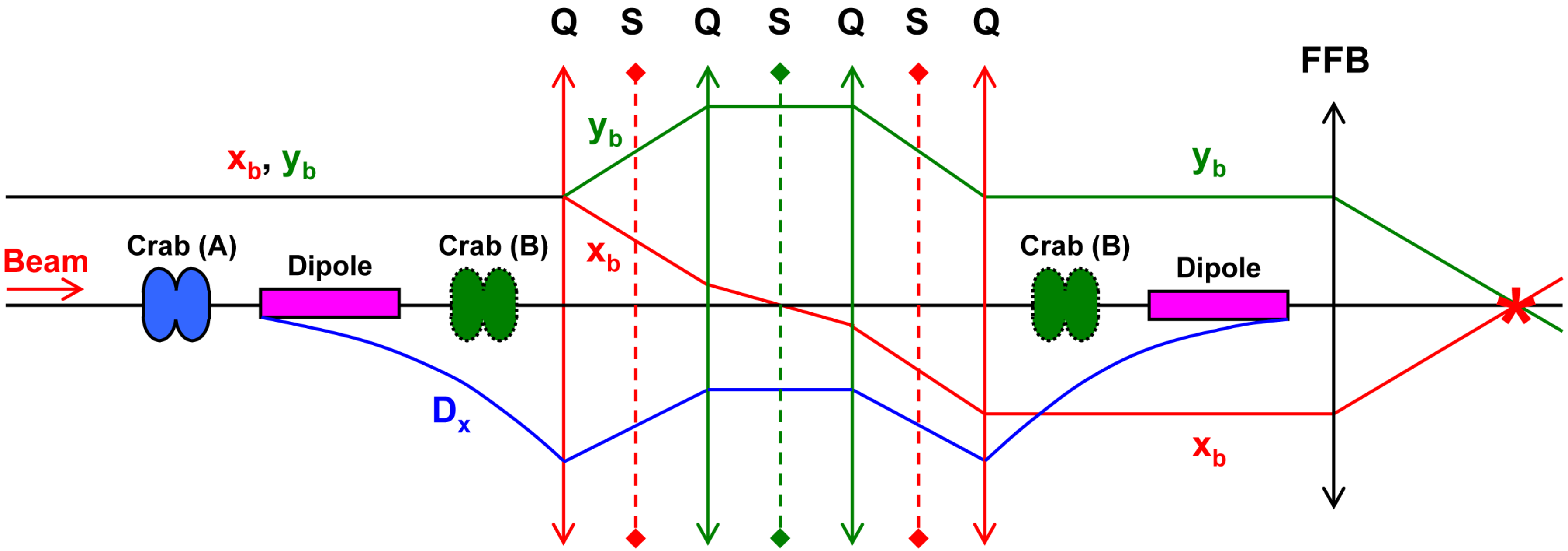


MEIC Point Design Parameters

Detector type		Full acceptance		high luminosity & Large Acceptance	
		Proton	Electron	Proton	Electron
Beam energy	GeV	60	5		
Collision frequency	MHz	750	750		
Particles per bunch	10^{10}	0.416	2.5		
Beam Current	A	0.5	3		
Polarization	%	> 70	~ 80		
Energy spread	10^{-4}	~ 3	7.1		
RMS bunch length	mm	10	7.5		
Horizontal emittance, normalized	µm rad	0.35	54		
Vertical emittance, normalized	µm rad	0.07	11		
Horizontal and vertical β*	cm	10 and 2	10 and 2	4 and 0.8	4 and 0.8
Vertical beam-beam tune shift		0.014	0.03		
Laslett tune shift		0.06	Very small		
Distance from IP to 1st FF quad	m	7	3.5	4.5	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6		14.2	

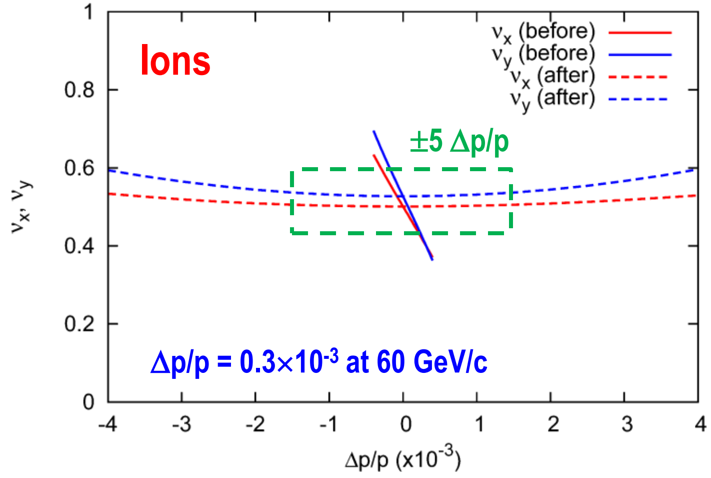
Chromaticity Compensation Concept

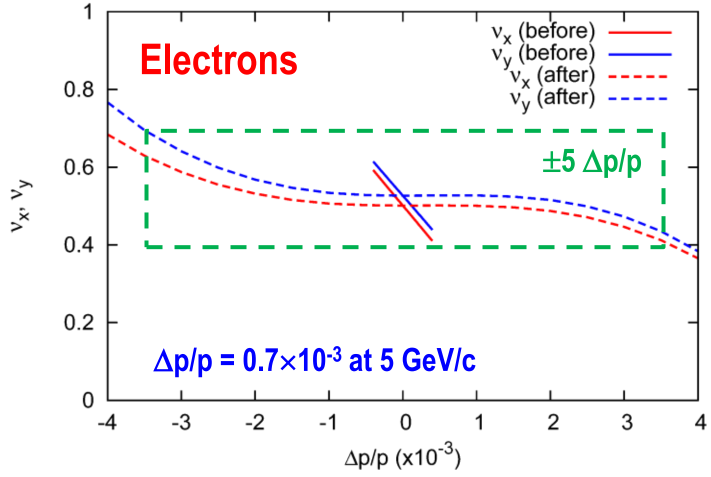
- Dedicated Chromaticity Compensation Blocks (CCB) with symmetric arrangement of orbital motion and magnetic fields
- Local compensation of Final Focusing Block's (FFB's) chromatic effect
- Simultaneous compensation of
  - chromatic and sextupole beam smear at the IP (restoration of luminosity)
  - associated non-linear betatron phase advance (restoration of dynamic aperture)



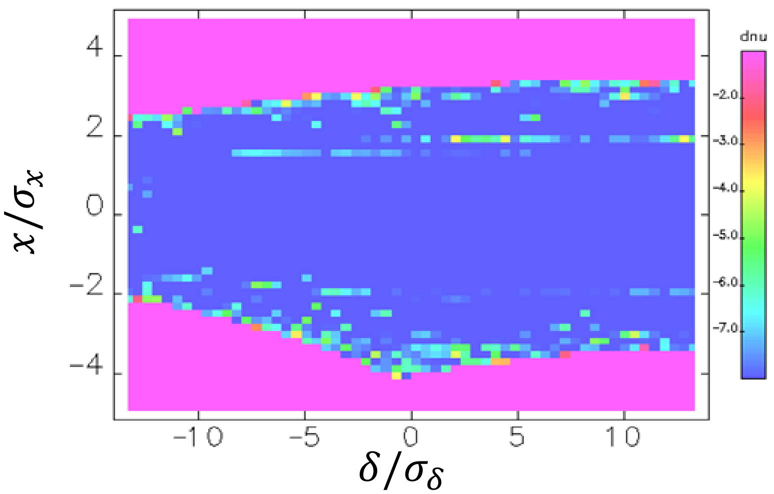
Chromaticity Compensation and Dynamic Aperture

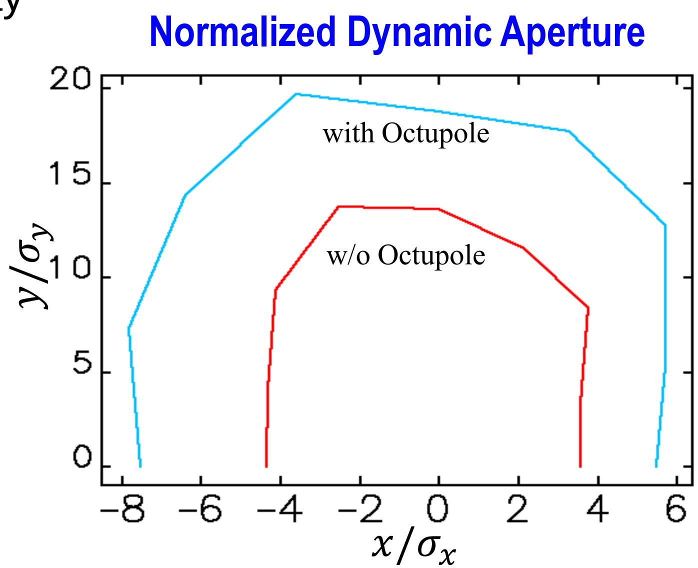
- Compensation of chromaticity with 2 sextupole families only using symmetry





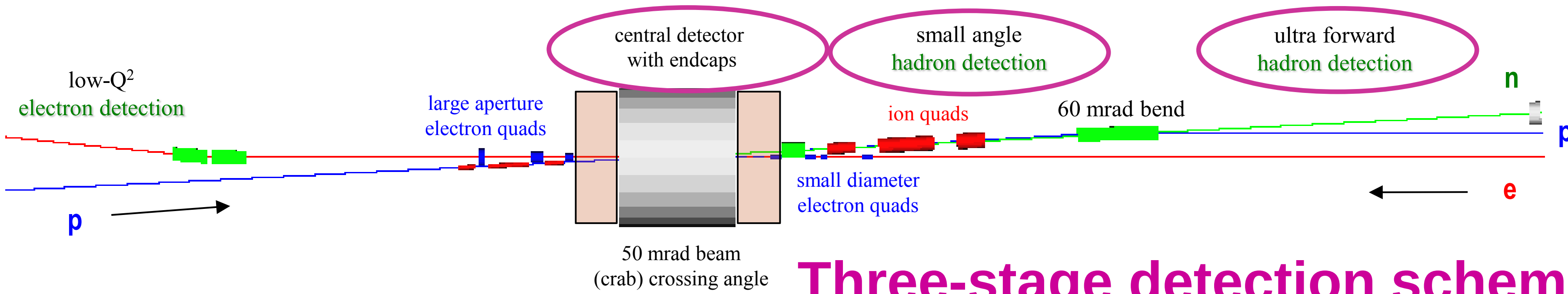
- Non-linear dynamic aperture optimization under way





Design Feature: Full-Acceptance Detector

In general, e-p and even more e-A colliders have a large fraction of their science related to the detection of what happens to the ion beams… spectator quark or struck nucleus remnants will go in the forward (ion) direction → this drives the **integrated** detector/interaction region design



Three-stage detection scheme

Full acceptance detector

- Demonstrated excellent acceptance & resolution
- Completed the detector-optimized IR optics
- Fully integrated detector and interaction region
- Working on hardware engineering design

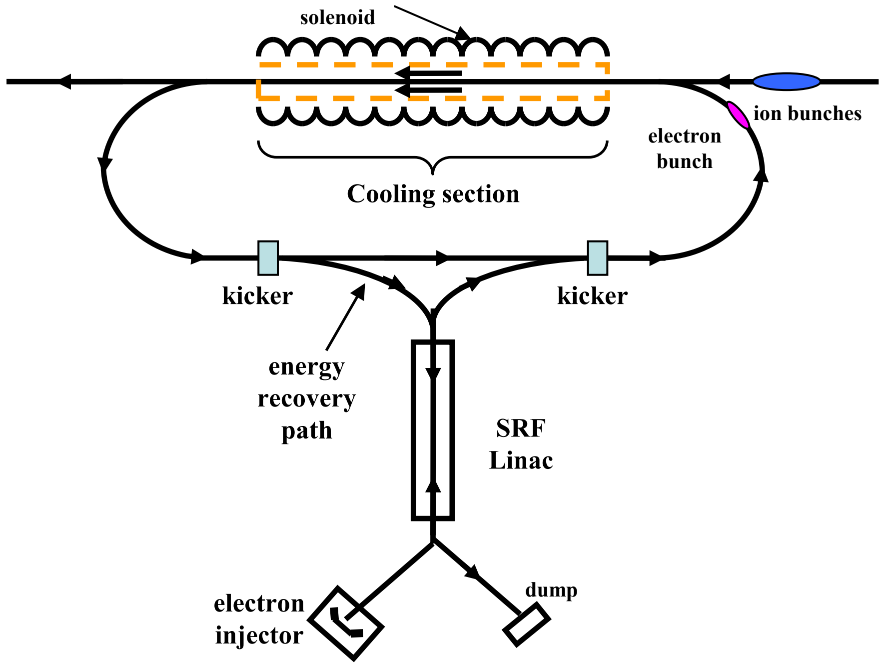
Addressing accelerator challenges

- Demonstrated chromaticity compensation

- *Neutron* detection in a 25 mrad cone *down to zero degrees*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to 2-3 mrad for *all momenta*
- Momentum *resolution < $3x10^{-4}$*
  - limited by intrinsic beam momentum spread

ERL based Circulated HEEC*

*(See invited talk by Yuhong Zhang, Tuesday, June 11)



- **Circulator-cooler ring makes 100 time reduction of beam current from injector/ERL**
- **Fast kickers operated at 15 MHz repetition rate and 2 GHz frequency bend width are required**

Initial cooling after injection in collider ring
Final cooling after boost & re-bunching, reaching design values
Continuous cooling during collision for suppressing IBS

Ion Polarization in Twisted Rings

All ion rings (two boosters, collider) have a figure-8 shape

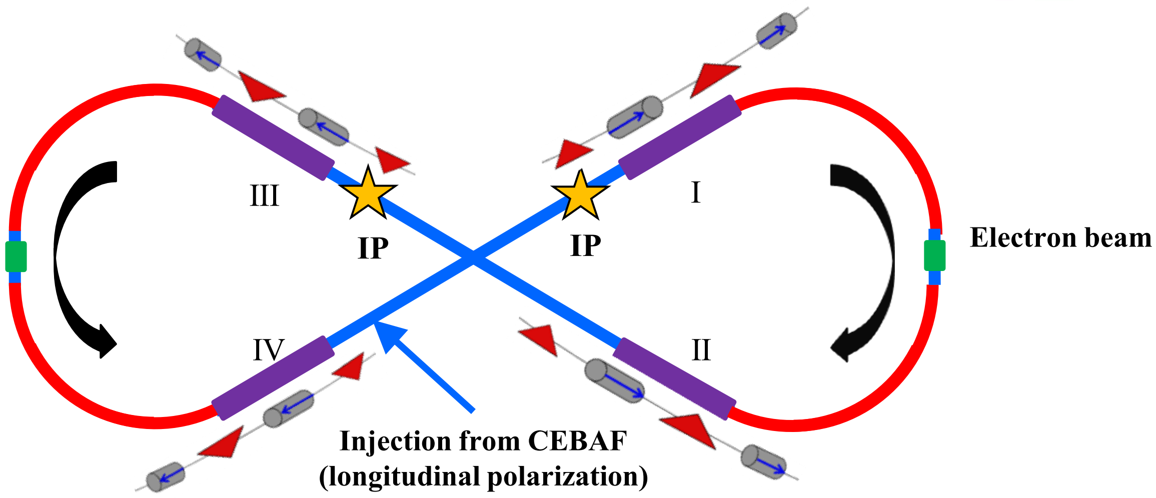
- Spin precession in the left & right parts of the ring are exactly cancelled
- Special insertions invented to provide energy independent spin tune off 0 at constant orbit
- Ensures spin preservation and manipulation by ***easy means***
- Avoids energy-dependent spin sensitivity for ion all species
- ***The only practical way to accommodate medium energy polarized deuterons***

which allows for "clean" neutron measurements

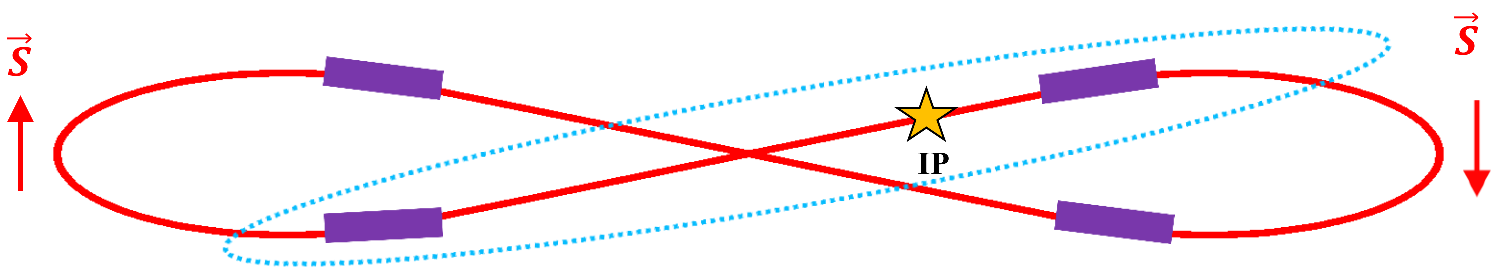
This design feature offers *a* ***firm no-pain long term operation runs*** for all polarized beams at low and high energies, since:

- Intrinsic spin resonances stay away
- High order intrinsic effects are diminished with <u>*cooled emittance*</u>

e-Ring with Universal Spin Rotator



Sokolov-Ternov effect can be used to polarize an accumulated **positron beam**



Polarization Time

- Calculated depolarization time at 5, 9 and 11 GeV using the code SLICK[1]

Energy (GeV)	Equi. Pol.[2] (%)	Spin-Orbit Depolarization Time (s)				Sokolov-Ternov Depolarization Effect		Spin Tune[4]
		Mode I[3]	Mode II[3]	Mode III[3]	Total	Pol. (%)	Time (s)	
5	0	48798	4E6	24758	21017	0	9063	0.01427105
9	0	2734	46924	1821	1696	0	476	0.00217532
11	0	605	3331	726	715	0	174	0.00064646

1. Thick-lens code SLICK was created and developed by Prof. A. W. Chao and Prof. D. P. Barber for studying the electron spin dynamics under the linear orbit and spin approximation,
2. Equilibrium polarization due to the spin-orbit coupling effect and Sokolov-Ternov effect,
3. Mode I, II, III are the horizontal, vertical and longitudinal motion, respectively, if there is no orbit coupling in the ring,
4. Non-zero spin tunes are generated by the weak solenoid fields in the region with a longitudinal polarization.

Advance Studies

- *IR design : Expanding limits of strong star-focusing (improving compensation for high order effects of sextupoles in IR)*
- *Electron Cooling:*
  - *- Magnetized cooling*
  - *- Sweep-cooling*
  - *- Dispersive cooling*
  - *- Flat beams cooling*
  - *- Matched cooling*
- *Coherent Electron Cooling (in cooperation with BNL group and other interested groups and individuals)*
- *Diminishing Space Charge impact in ion rings*
  - *- Strip-stacking into the circular focusing modes*
  - *- Round to flat ion beams in collider ring*
- *Electron polarization*
  - *- Improving Spin Rotator design*
  - *- Optimizing Spin Matching*

Summary

- EIC is the ultimate tool to study sea quarks and gluons
- EIC allows a **unique opportunity** to make a breakthrough in nucleon structure and QCD dynamics
- Collider environment provides tremendous advantages
  - Kinematic coverage (low to high center-of-mass energy)
  - Polarization measurements with excellent Figure-of-Merit
  - Detection of spectators, recoil baryons, and target fragments
- High efficiency of EIC@Jlab project is provided with several critical innovations and advances in beam cooling, polarized beams and detector techniques.
  - MEIC design report completed and available on the arXiv
  - Our immediate goal is full validation of the MEIC design with R&D. Some accelerator and detectors R&D funds have been allocated.
- JLab is establishing and expanding more R&D and design collaborations with the interested laboratories and experts
- We promote possible design upgrades and study of the advanced concepts

Backup slides

Further ongoing MEIC Accelerator R&D

- **Space Charge Dominated Ion Beam in the Pre-booster**
  - Simulation study is in progress by Argonne-NIU collaborators
- **Beam Synchronization**
  - A scheme has been developed; SRF cavity frequency tunability study is in progress
- **Beam-Beam Interaction**
  - Phase 1 simulation study was completed
- **Interaction Region, Chromaticity Compensation and Dynamic Aperture**
  - Detector integration with IR design has been completed, offering excellent acceptance
  - Correction scheme has been developed, and incorporated into the IR design ✓
  - Tracking simulations show excellent momentum acceptance; dynamic aperture is increased
  - Further optimization in progress (*e.g.*, all magnet spaces/sizes defined for IR +/- 100 m)
- **Beam Polarization**
  - Electron spin matching and tracking simulations are in progress, achieving acceptable equilibrium polarization and lifetime (collaboration with DESY) ✓
  - New ion polarization scheme and spin rotators have been developed (collaboration with Russian group) – numerical demonstration of figure-8 concept with misalignments ongoing ✓
- **Electron Cloud in Ion Ring**
- **Universal Polarized Ion Source**

Study for Polarized Positrons in MEIC

- Use CEBAF beam to generate unpolarized positrons (working out an optimum scheme in process)
- Accelerate, inject and stack in the storage ring
- Arrange and wait for possibly fastest ST polarization (at 10-12 GeV, perhaps , and (or) by use special wigglers)
- Ramp energy down to a reasonable minimum for experiment
- Use spin-resonance SC cavities for *spin flip* (***frequent*** flip for the ***whole*** beam or ***one-time*** flip for ***half*** beam***)***

/ techniques by A. Krisch – V. Morozov – A. Kondratenko and collaborators/

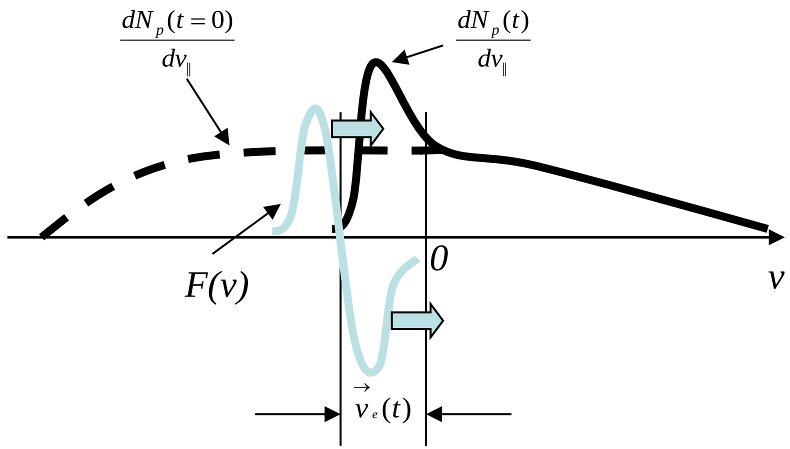
Optimized Electron Cooling

- ***Magnetized cooling***

  In a strong solenoid, cooling rate has low sensibility to electron Larmor oscillations

- ***Sweep cooling***

  The ion beam has a small transverse temperature but large the longitudinal one. Use *sweep cooling to* gain *a large reduction* of longitudinal cooling time



- ***Dispersive cooling***

  Use dispersion and e-beam gradients in order to equalize cooling decrements

- ***Flat beams cooling***
  - **based on flattening ion beam by reduction of coupling around the ring**
  - **IBS rate at equilibrium becomes reduced**

Matched Electron Cooling and Ion AMDB

Application of an old idea (NIM, 2000)

Cooling of nucleon beams at energies below 30 GeV of protons may present an issue of ion *space charge*. This problem can be alleviated with help of *round-to-flat ion beam* and *matched electron cooling* techniques

What is *matched electron cooling*:

– Rotation of one of two circular modes of ion beam is stopped in solenoid of cooling section
– Other mode then is transformed to cyclotron rotation in solenoid
– Only the cyclotron mode has the intrinsic cooling effect in the accompanying e-beam
– Cooling of this mode cannot be stopped by the ion space charge, so its equilibrium emittance can reach a very small value
– Cooling of the stopped mode (limited by the ion space charge) can be provided by *cooling redistribution* mechanism