# MEIC Status

Andrew Hutton

For the MEIC Collaboration

# MEIC Collaborators

- I am presenting the work of a large group of passionate scientists and engineers who have been working together for several years
- National Laboratories:
  - Alberto Accardi, Shahid Ahmed, Alex Bogacz, Pavel Chevtsov, Slava Derbenev, Rolf Ent, Vadim Guzey, Tania Horn, Andrew Hutton, Charles Hyde, Geoff Krafft, Rui Li, Frank Marhauser, Bob McKeown ,Vasili Morozov, Pavel Nadel-Turonski, Fulvia Pilat, Alexei Prokudin, Bob Rimmer, Todd Satogata, Mike Spata, Balša Terzić, Haipeng Wang, Christian Weiss, Byung Yunn, Yuhong Zhang from Jefferson Lab
  - Shashikant Manikonda, Peter Ostroumov from Argonne National Lab
  - Mike Sullivan from SLAC
- Universities
  - J. Delayen, Suba DeSilva, Hisham Sayed from Old Dominion University
  - Samanawathie Abeyratne, Bela Erdelyi from Northern Illinois University
  - Yujong Kim from Idaho State University
- Industry
  - V. Dudnikov, R. Johnson from Muons Inc.

# Overview of talk

1. Overview of project
    1. Vision – energy range, luminosity range, detector needs
    2. Parameter list
    3. Layout – CEBAF, ion complex, booster, collider, cooling
2. Interaction Region Layout
    1. Free space, longitudinal and transverse
3. Date for Cost Estimate
4. Status of Report

# Machine Requirements from INT Report

- Highly polarized (> 70%) electron and nucleon beams
- Ion beams from deuterium to the heaviest nuclei - uranium or lead
- Center of mass energies: from about 20 GeV to about 150 GeV
- Maximum collision luminosity $\sim 10^{34}\ cm^{-2}\ s^{-1}$
- Non-zero crossing angle of colliding beams without loss of luminosity (so-called crab crossing)
- Cooling of the proton and ion beams to obtain high luminosity
- Staged designs where the first stage would reach CM energies of about 70 GeV
- Possibility to have multiple interaction regions

# Design Requirements translated by Rolf Ent

- Highly polarized (>70%) electron and nucleon beams
  - Longitudinally polarized electron and nucleon beams
  - Transversely polarized nucleon beams
- Ion species from deuterium to A = 200 or so
- Center of mass energies from $\sqrt{s}$ ~ 20 to 70 GeV & variable
  - Electron energies above 3 GeV to allow efficient electron trigger
  - Proton energy adjustable to optimize particle identification
- Upgradeable to center of mass energy of $\sqrt{s}$ ~150 GeV
- Multiple interaction regions

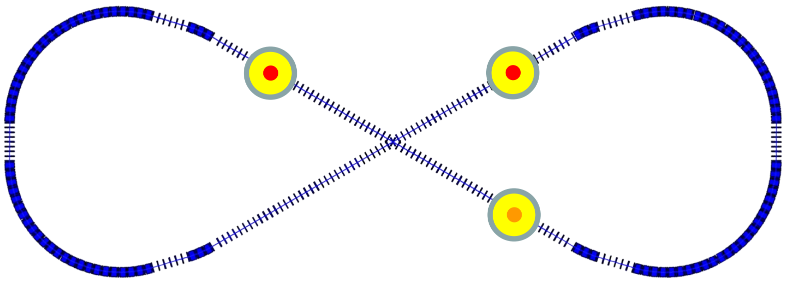
# Design Requirements translated by Rolf Ent

- High luminosity ~$10^{34}$ e-nucleons $cm^{-2}$ $s^{-1}$
  - Optimal luminosity in √s ~ 30-50 region
  - Luminosity ≥$10^{33}$ e-nucleons $cm^{-2}$ $s^{-1}$ in √s ~ 20-70 region
- Integrated detector/interaction region
  - Non-zero crossing angle of colliding beams
    - Crossing in ion beam to prevent synchrotron background
    - Ion beam final focus quads at ~7 m to allow for detector space
  - Bore of ion beam final focus quads sufficient to let particles pass through up to t ~ 2 $GeV^2$ (t ~ $Ep^2Q^2$)
- Positron beam desirable

# Project Overview

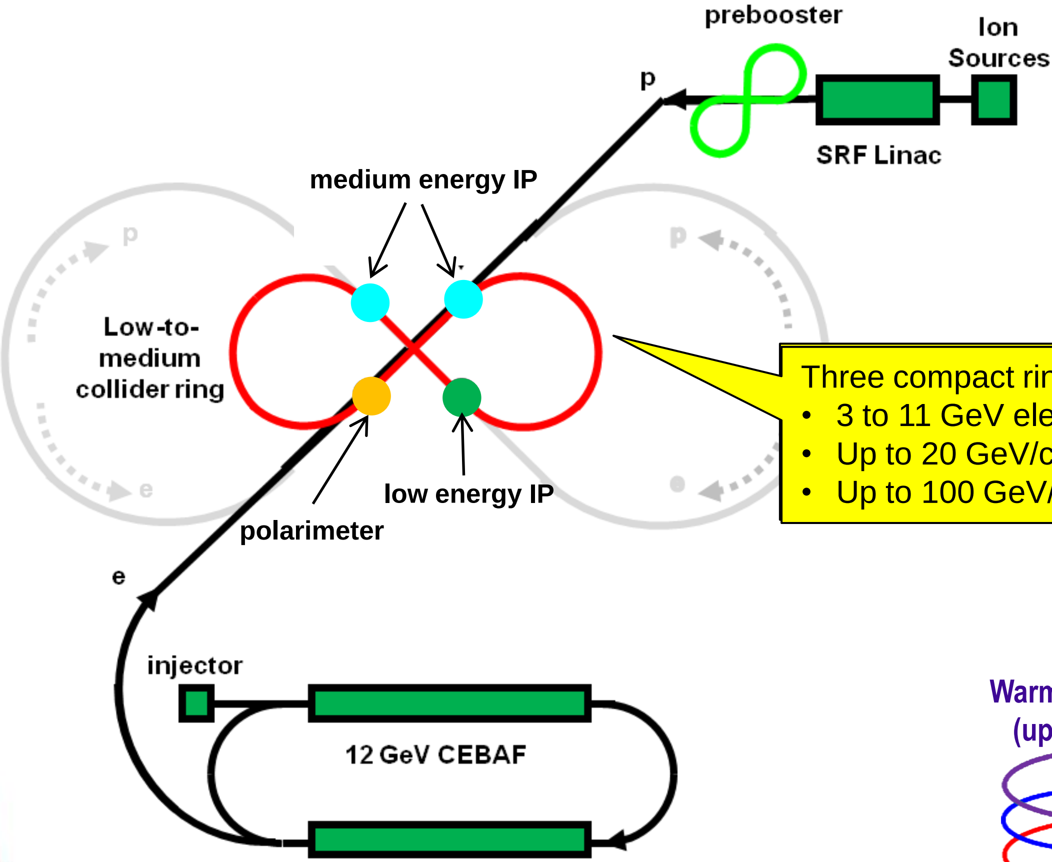
# Overview

- Collider is based on a figure eight concept
  - Avoids crossing polarization resonances
    - Improves polarization for all species
    - Makes polarized deuterons possible
  - Advantage of having a new ion ring

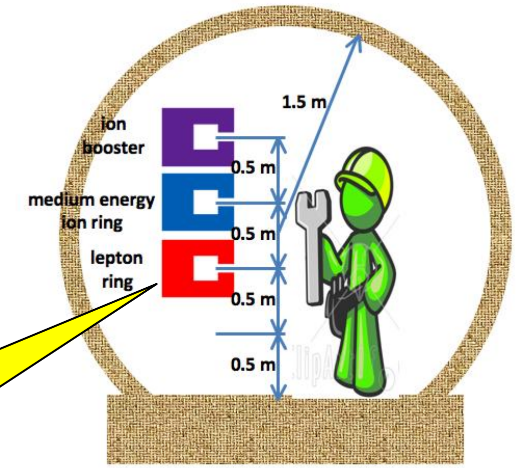


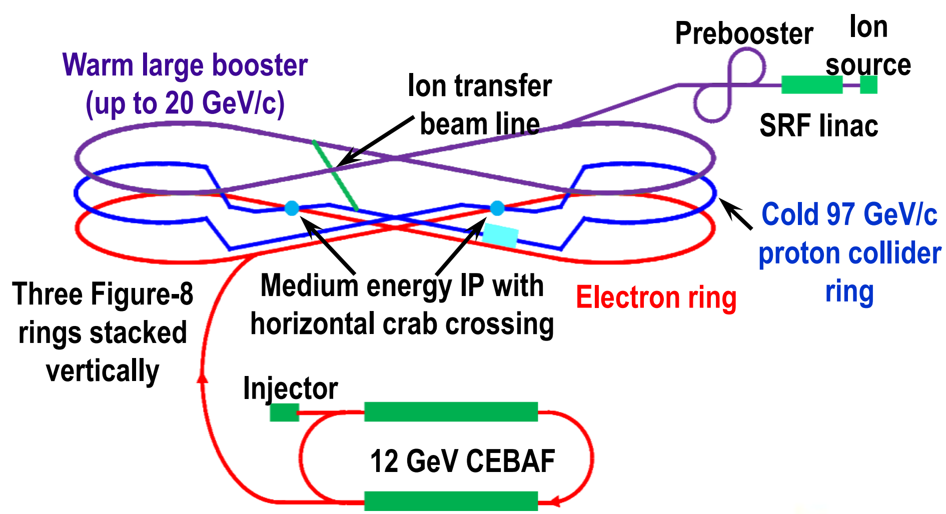
- Highest luminosity comes with final focus quadrupoles close together
  - Interferes with detection of particles at small angles
  - MEIC is designed around a high-acceptance detector with **±7 meters** free space around the interaction point and a high-luminosity detector with **±3.5 meters** free space

# MEIC Layout

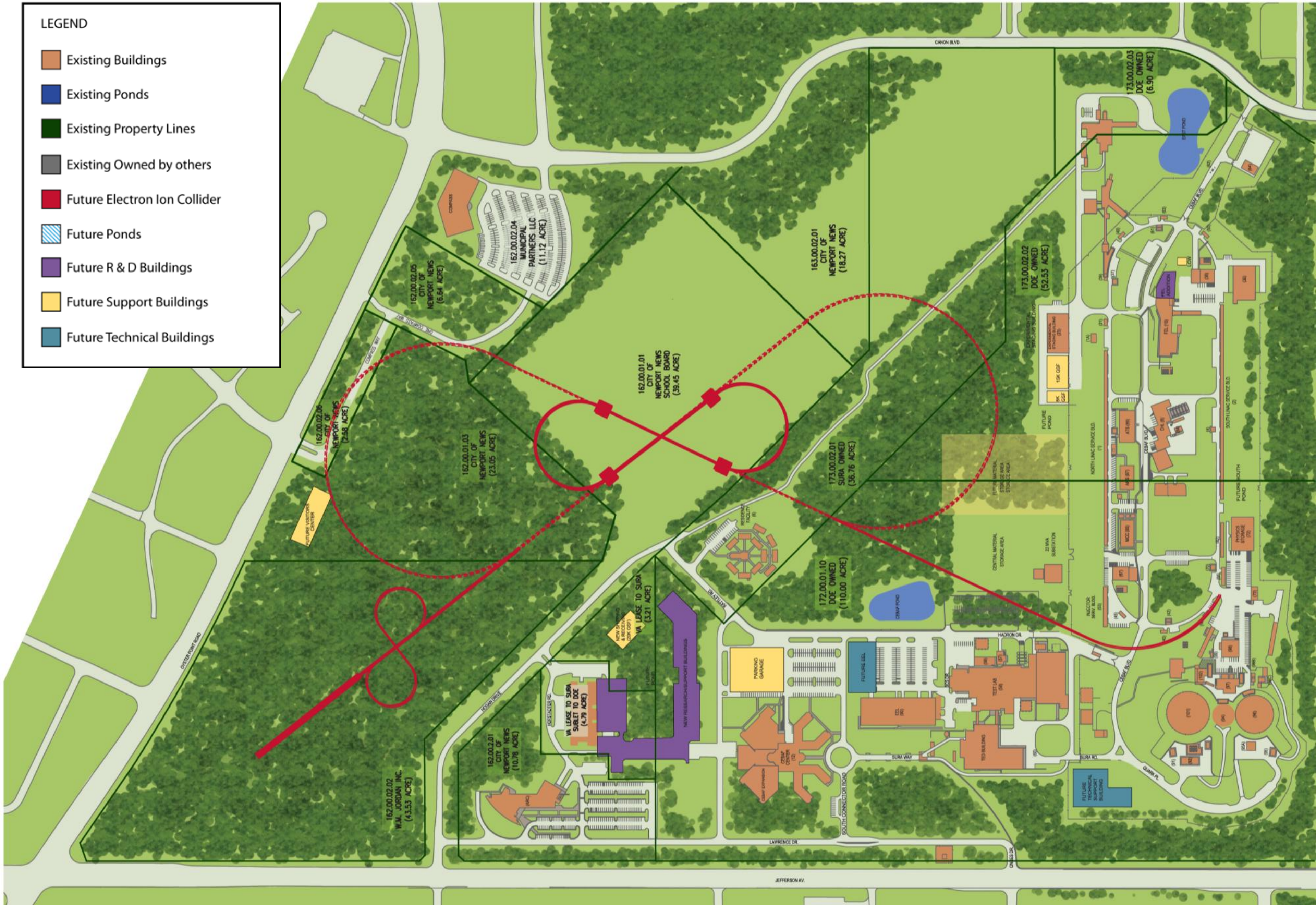



Three compact rings:
- 3 to 11 GeV electron
- Up to 20 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)



# MEIC and Upgrade on JLab Site Map



# Parameters for Full Acceptance Detector

| | | 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 | cm | 10 | 7.5 |
| Horizontal emittance, normalized | µm rad | 0.35 | 54 |
| Vertical emittance, normalized | µm rad | 0.07 | 11 |
| Horizontal β* | cm | 10 | 10 |
| Vertical β* | cm | 2 | 2 |
| 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 |
| Luminosity per IP | $cm^{-2}s^{-1}$ | $5.6 \times 10^{33}$ | |

# Parameters for High Luminosity Detector

| | | 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 | cm | 10 | 7.5 |
| Horizontal emittance, normalized | µm rad | 0.35 | 54 |
| Vertical emittance, normalized | µm rad | 0.07 | 11 |
| Horizontal β* | cm | 4 | 4 |
| Vertical β* | cm | 0.8 | 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 | 4.5 | 3.5 |
| Luminosity per IP | $cm^{-2}s^{-1}$ | $14.2 \times 10^{33}$ | |

# Layout of Accelerator Complex

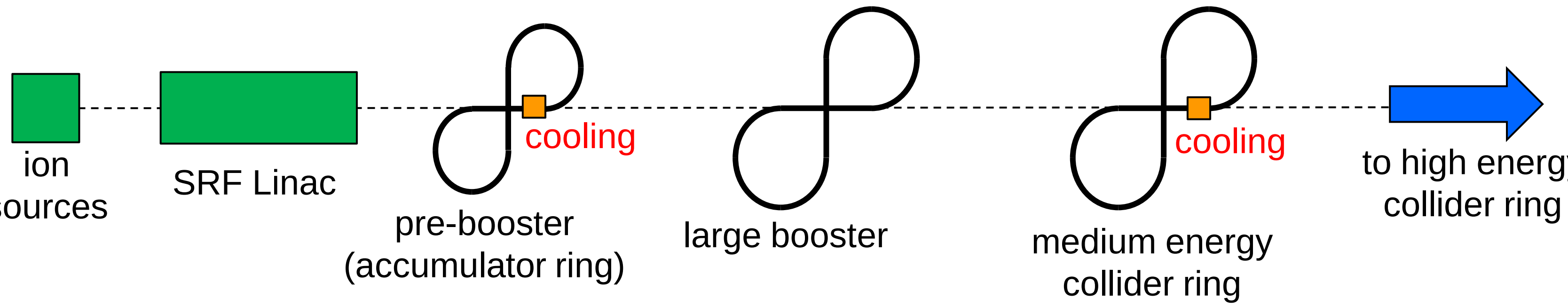
Jefferson Lab

# Schematic of the Ion Complex

## MEIC ion complex design goal

- Generate, accumulate and accelerate ion beams for collisions
  - All required varieties of ion species
- Match the temporal, spatial and phase space structure of the electron beam (bunch length, transverse emittance and spacing)

## Schematic layout




| | Length (m) | Max. energy (GeV/c) | Electron Cooling | Process |
|---|---|---|---|---|
| SRF linac | | 0.2 (0.08) | | |
| Pre-booster | ~300 | 3 (1.2) | DC | accumulating |
| booster | ~1300 | 20 (8 to 15) | | |
| collider ring | ~1300 | 96 (40) | Staged/ERL | |

* Numbers in parentheses represent energies per nucleon for heavy ions

# Ion Pre-booster

## Purpose of pre-booster

- Accumulating ions injected from linac
- Accelerating ions
- Extracting/transferring ions to large booster

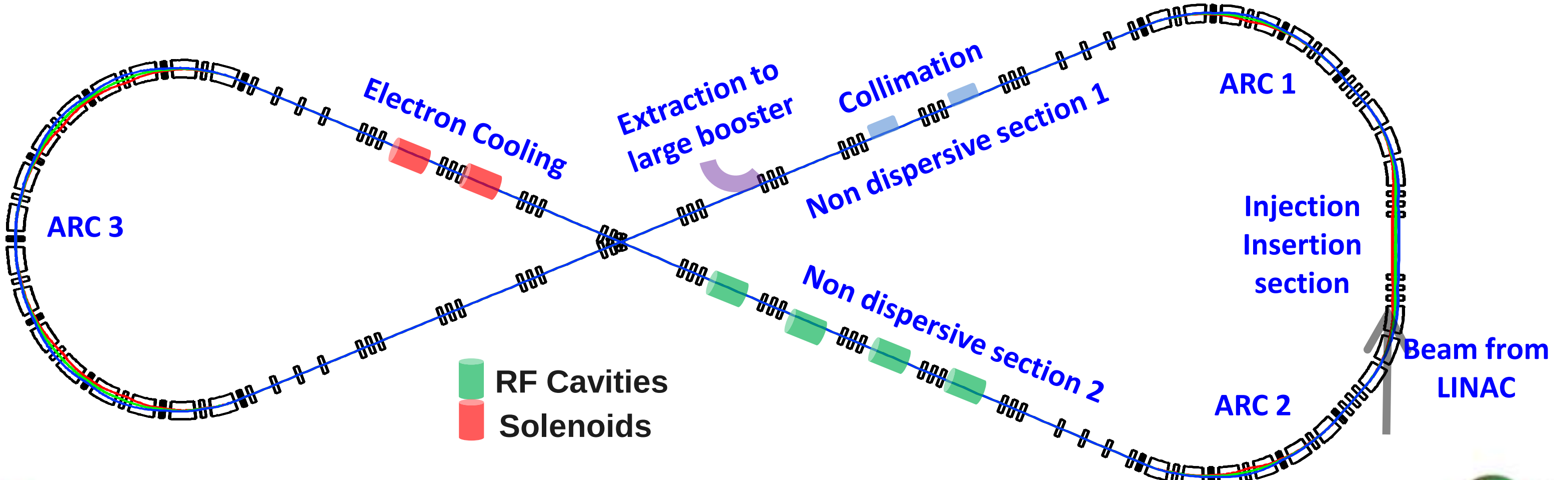
## Design Concepts

- Figure eight shape
- (Quasi-independent) modular design
- FODO arcs for simplicity and ease of optics corrections

## Design constraints

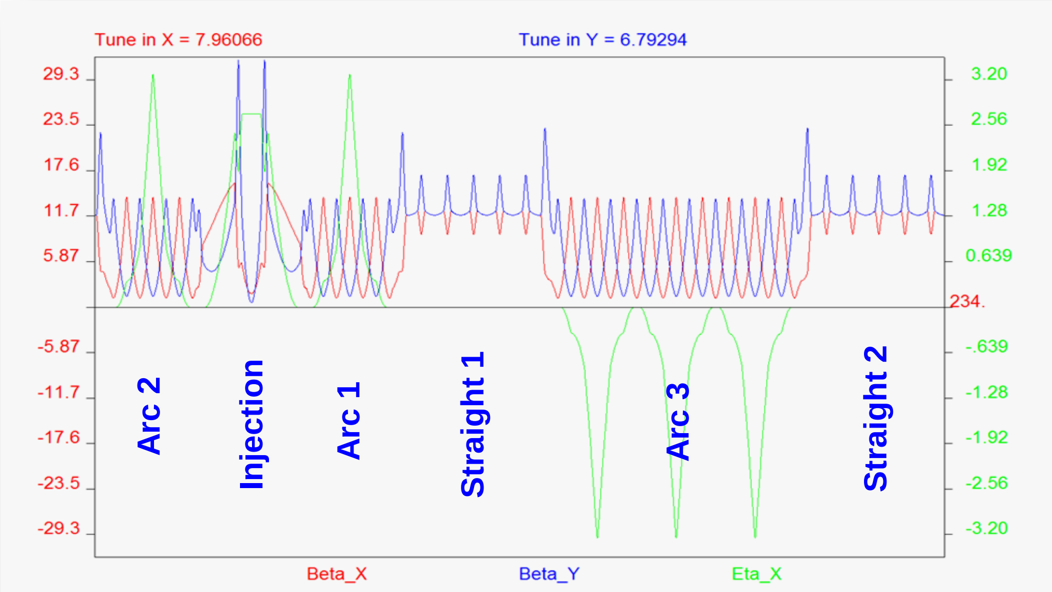
- Maximum bending field: 1.5 T
- Maximum quad field gradient: 20 T/m
- Momentum compaction smaller than 1/25
- Maximum beta functions less than 35 m
- Maximum full beam size less than 2.5 cm
- 5m dispersion-free sections for RF, cooling, collimation and extraction

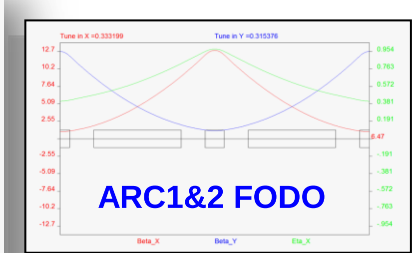
## Layout

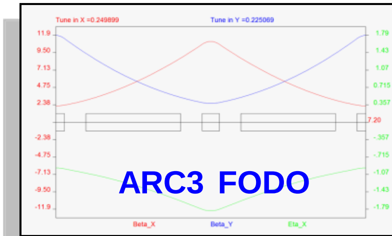


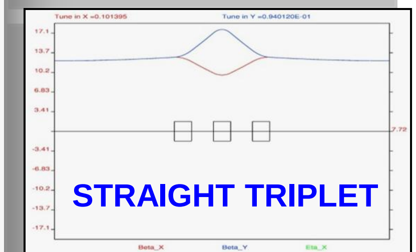

Bela Erdelyi

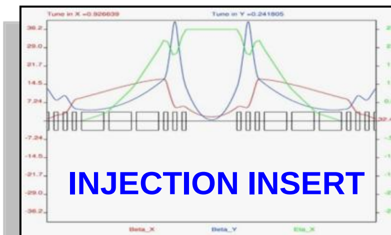
# Pre-booster Lattice



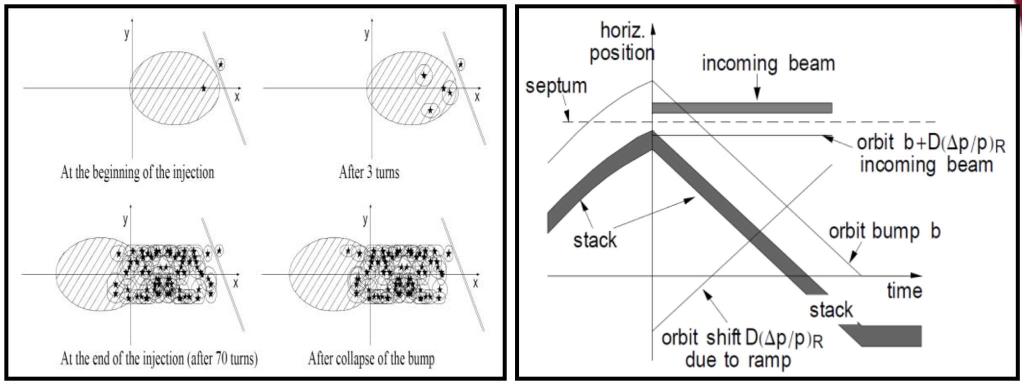




| | | |
|---|---|---|
| Circumference | m | 234 |
| Angle at crossing | deg | 75 |
| # of dispersive FODO cells (Type I & 2) | | 6 & 9 |
| # of triplet cells & # of matching cells (2 types) | | 10 & 4 |
| Minimum drift length between magnets | cm | 50 |
| Drift in the injection insertion & between triplets | m | 5 |
| Beta maximum in X and Y | m | 16 & 32 |
| Maximum beam size | cm | 2.3 |
| Maximum vertical beam size in dipole magnets | cm | 0.5 |
| Maximum dispersion (x\|delta_KE) | m | 3.36 |
| Normalized dispersion value at injection insert | $m^{1/2}$ | 2.53 |
| Tune in X and Y | | 7.96 & 6.79 |
| Gamma of particle and transition gamma | | 4.22 & 5 |
| Momentum compaction | | 0.04 |

| | quantity | Parameter | Unit | Value |
|---|---|---|---|---|
| Quad | 95 | Length | cm | 40 |
| | | Half Aperture | cm | 5 |
| | | Max. pole tip field | T | 1.53 |
| | | Min. pole tip field | T | 0.15 |
| Dipole | 36 | Length | cm | 219 |
| | | Radius | cm | 9 |
| | | Vertical aperture | cm | 3 |
| | | Strength | T | 1.41 |
| | | Bending angle | deg | 14 |

# Injection, Accumulating, Electron Cooling, Accelerating and Ejection in Pre-booster

- Injection
  - Proton & light ions
    - stripping injection
  - Heavy ions
    - Repeated multi-turn injection
    - Transverse and longitudinal painting
    - Conventional (50 keV DC) electron cooling for stacking/accumulation
- Booster
  - RF swing necessary is [0.4,2] MHz
  - 15 kV/cavity, 50kV/turn => 3-4 cavities
  - 56,000 turns for 200 MeV➔ 3 GeV
  - Less than 80 ms acceleration time

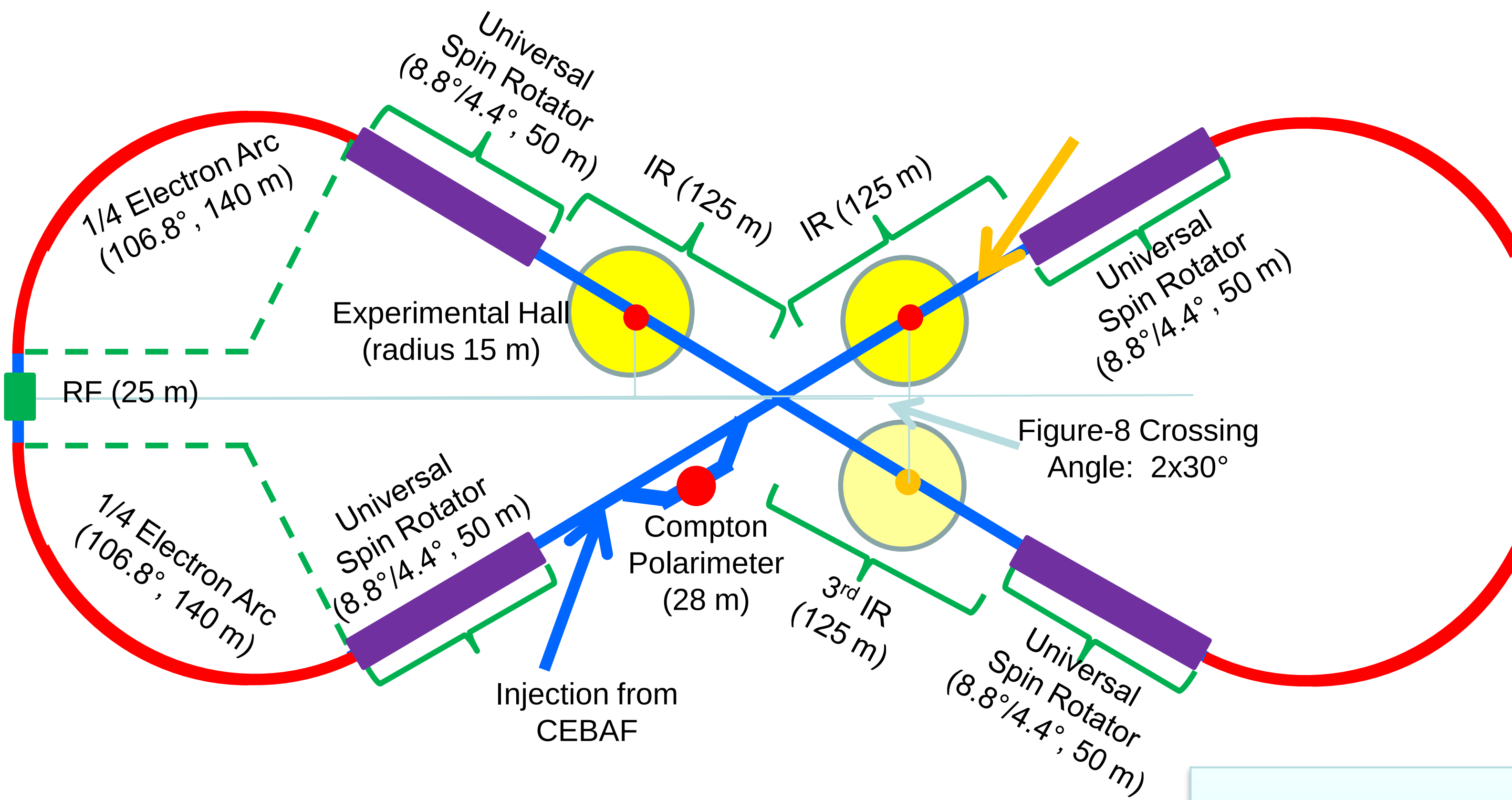



**Injection & painting**

**Conventional DC Electron Cooling**

**LEIR-Type Cavity**

# MEIC Collider Ring Footprint




**Ring design is a balance between**

- Synchrotron radiation ➔ prefers a large ring (arc) length
- Ion space charge ➔ prefers a small ring circumference

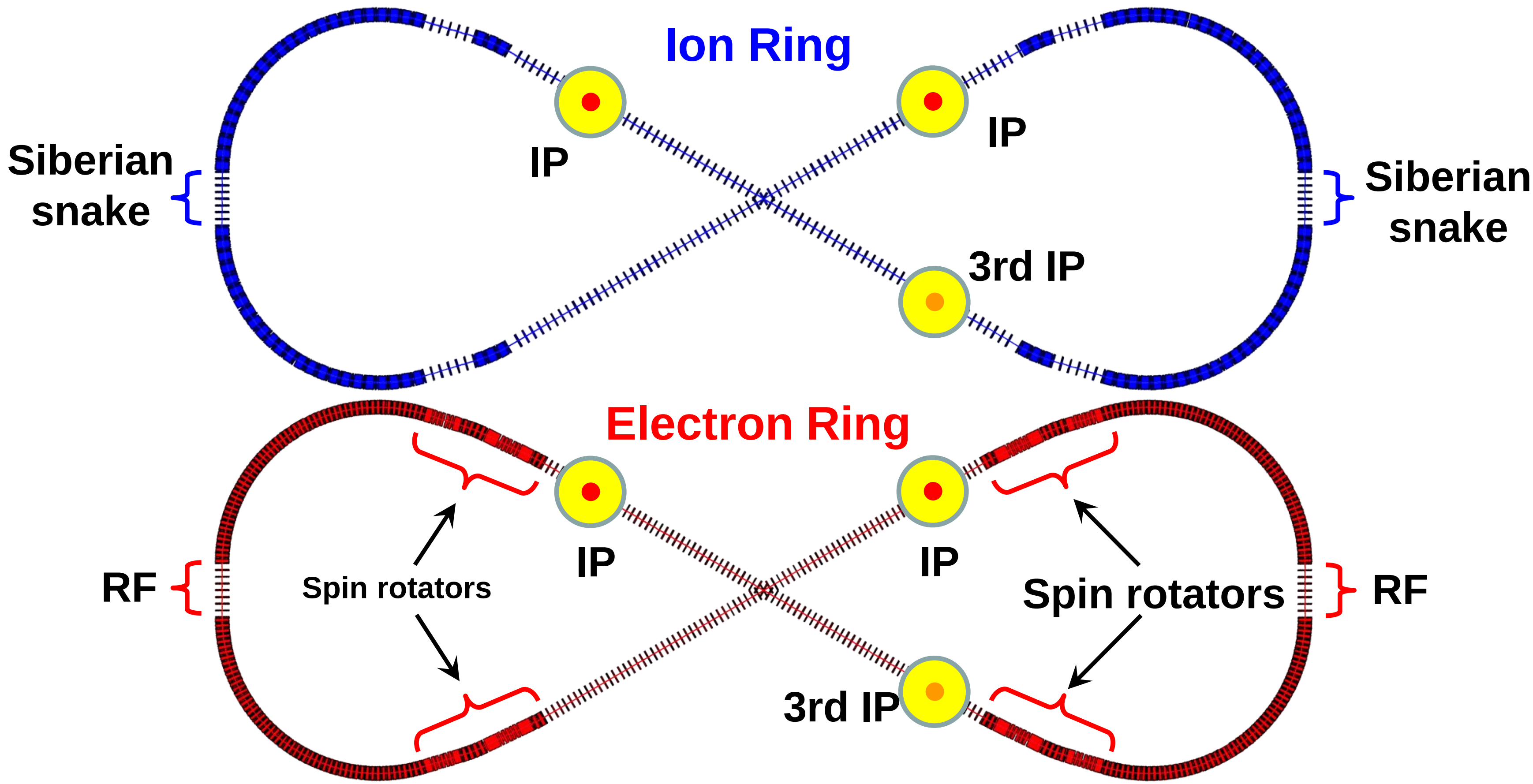
**Multiple IPs require long straight sections**

**Straights also hold required service components**

(cooling, injection and ejection, etc.)

| | m |
|---|---|
| Quarter arc | 140 |
| Universal spin rotator | 50 |
| IR insertion | 125 |
| Figure-8 straight | 140 x 2 |
| RF short straight | 25 |
| Circumference | ~ 1300 |

# Vertically Stacked, Horizontal Crossing

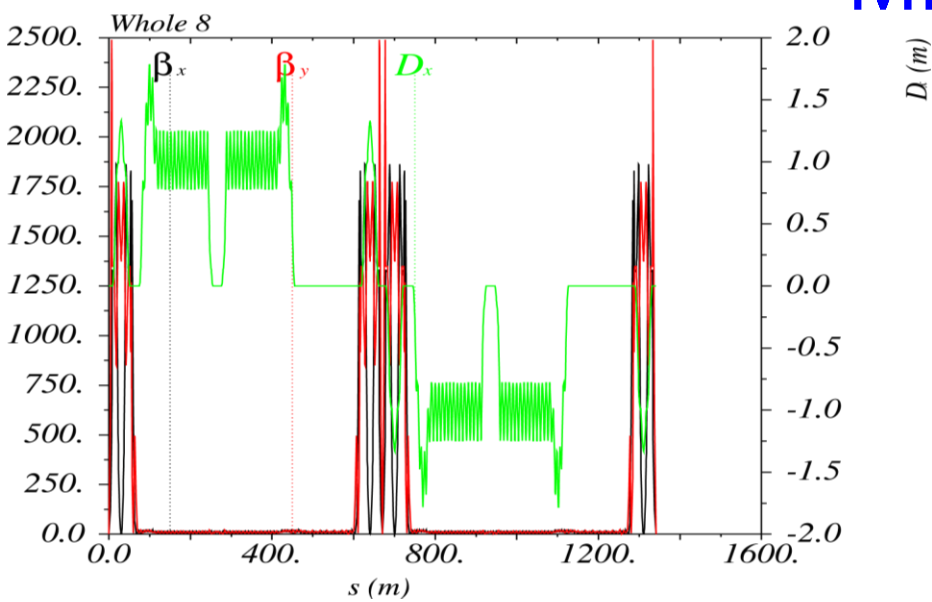



- Vertical stacking provides identical ring circumferences
- Horizontal crab crossing at IPs due to flat colliding beams
- Ion beams are brought into the plane of the electron orbit to enable horizontal crossing

- **Ring circumference: 1340 m**
- **Maximum ring separation: 4 m**
- **Figure-8 crossing angle: 60 degree**

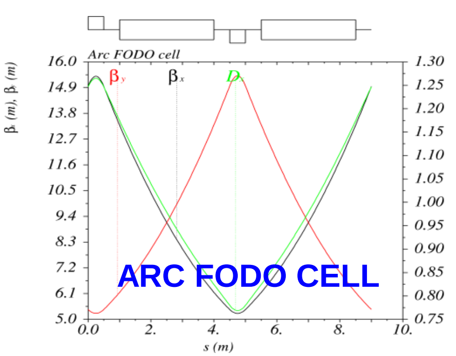
# MEIC Ion Collider Ring

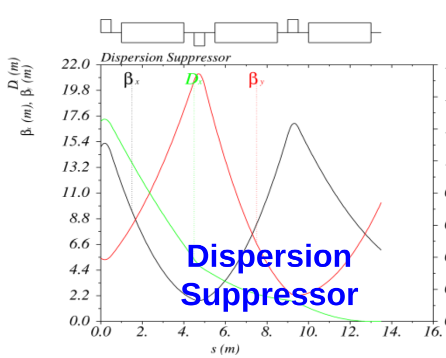
**Alex Bogacz & Vasiliy Morozov**

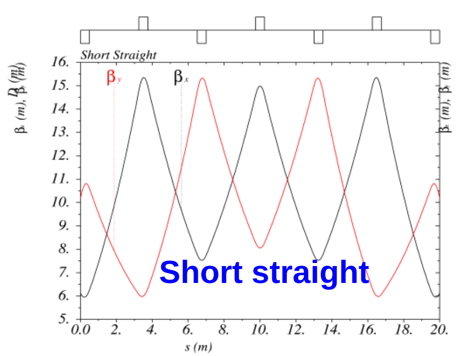


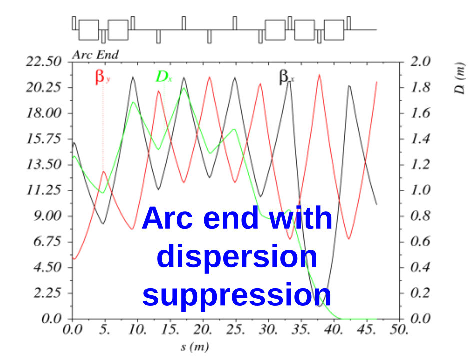

| Circumference | m | 1340.92 |
|---|---|---|
| Total bend angle/arc | deg | 240 |
| Figure-8 crossing angle | deg | 60 |
| Averaged arc radius | m | 93.34 |
| Arc length | m | 391 |
| Long and short straight | m | 279.5 / 20 |
| Lattice base cell | | FODO |
| Cells in arc / straight | | 52 / 20 |
| Arc/Straight cell length | m | 9 / 9.3 |
| Phase advance per cell | m | 60 / 60 |
| Betatron tunes ($\nu_x$, $\nu_y$) | | 25.501 /25.527 |
| Momentum compaction | $10^{-3}$ | 5.12 |
| Transition gamma | | 13.97 |
| Dispersion suppression | | Adjusting quad strength |

| | | |
|---|---|---|
| **Dipole** | | 144 |
| Length | m | 3 |
| Bending radius | M | 53.1 |
| Bending Angle | deg | 3.236 |
| Field @ 60 GeV | T | 3.768 |
| **Quad** | | 298 |
| Length | M | 0.5 |
| Strength @ 60 GeV | T/m | 92 / 89 |

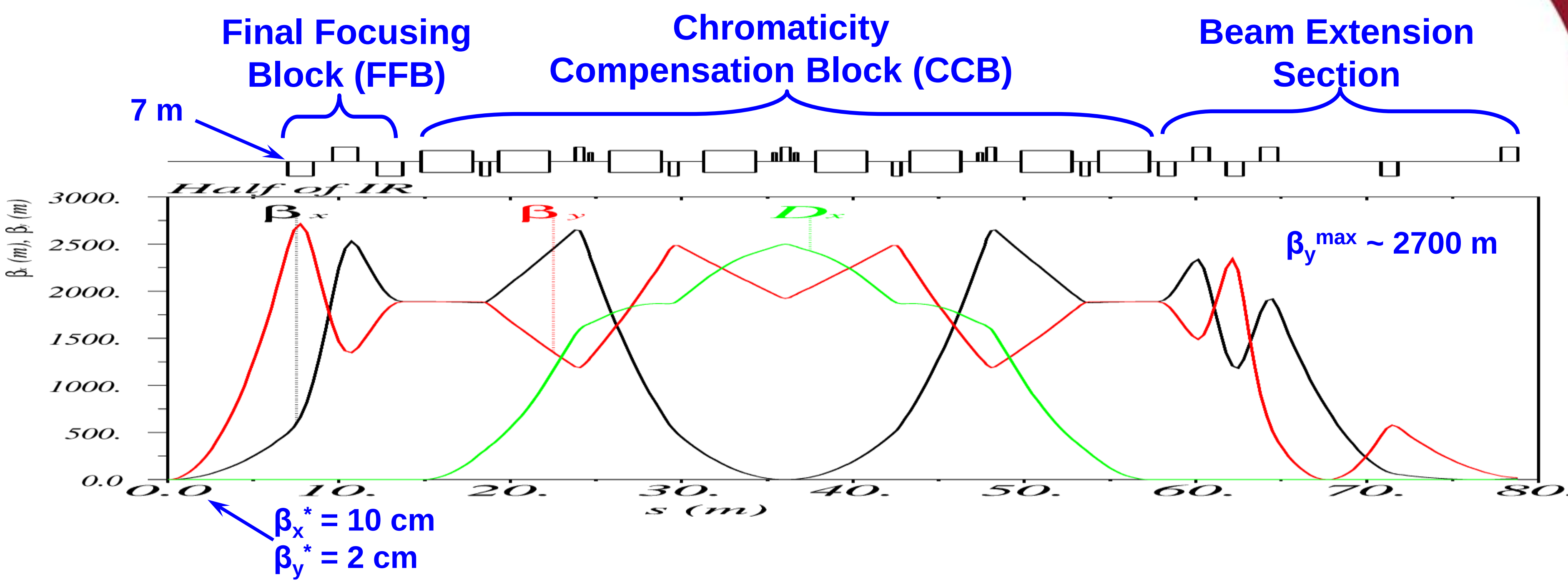


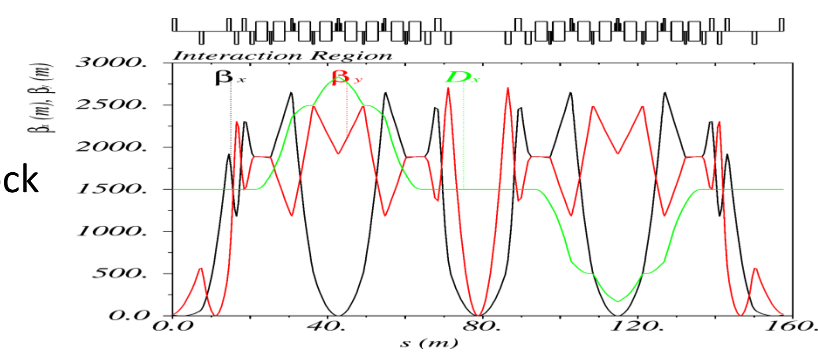



# Interaction region: Ions




- Distance from the IP to the first Final Focus quad = 7 m
- Maximum quad strength at 100 GeV/c
  - 64.5 T/m at Final Focusing Block
  - 88.3 T/m at Chromaticity Compensation Block
  - 153.8 T/m at Beam Extension Section
- Symmetric CCB design (both orbital motion & dispersion) required for efficient chromatic correction

**Whole Interaction Region: 158 m**

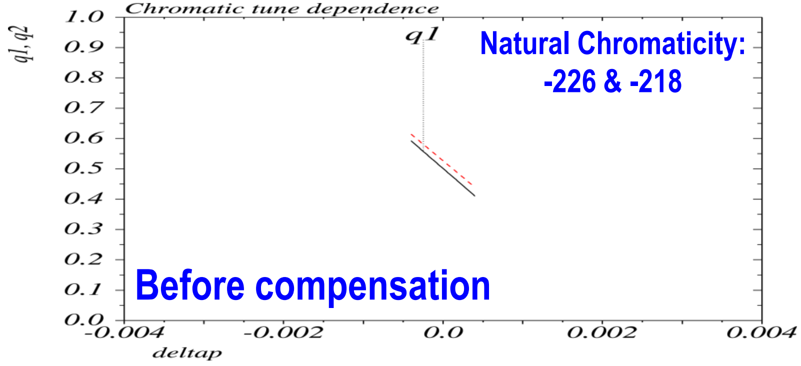


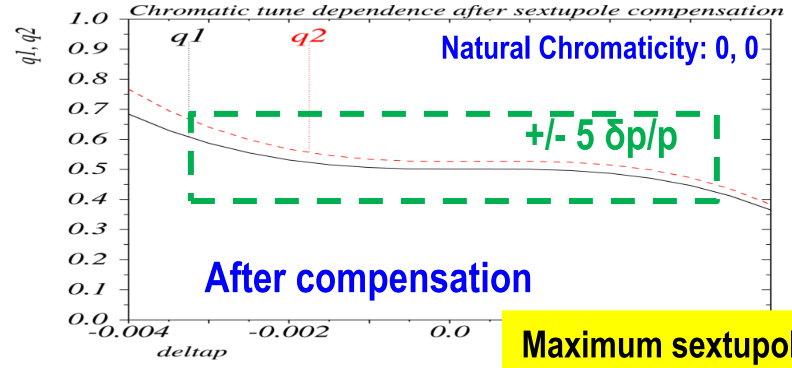
Vasiliy Morozov

# Chromatic Corrections

**Scheme:** sets of sextupoles placed in the symmetric chromatic compensation block

## Electron

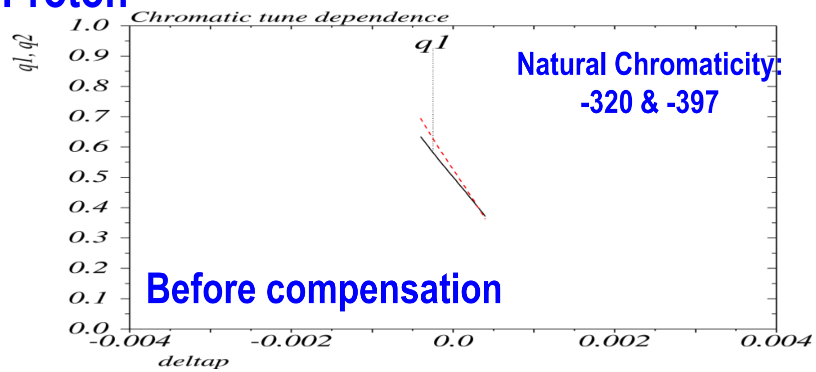


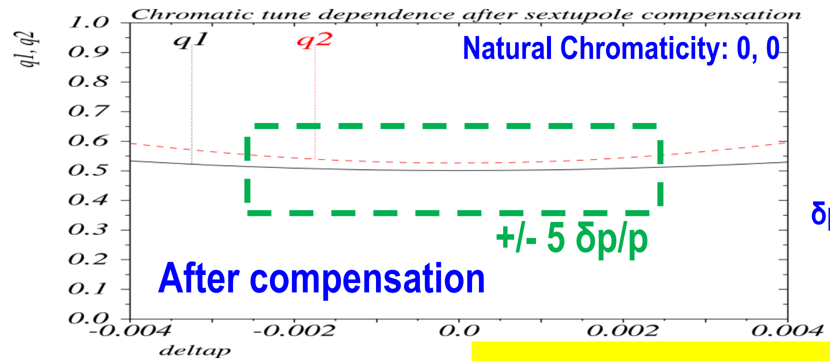




$\delta p/p = 0.66 \times 10^{-3}$ for 5 GeV

**Maximum sextupole strength at 5 GeV/c = 281.4 T/m$^2$**

## Proton



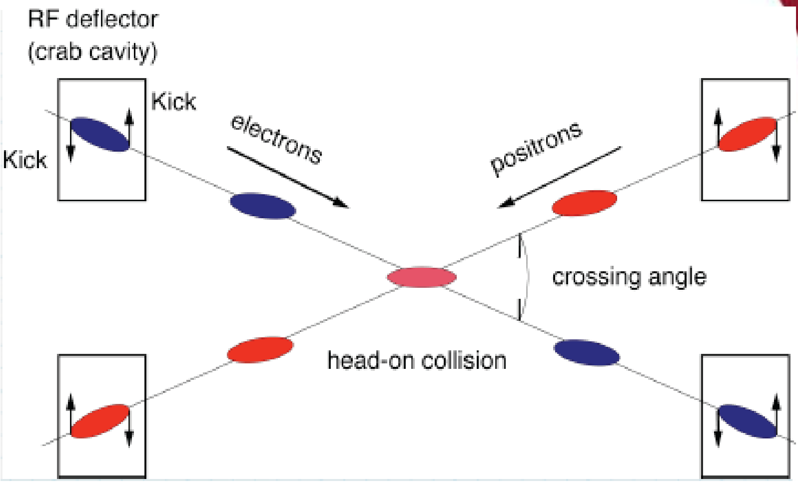

$\delta p/p = 5 \times 10^{-4}$ for 60 GeV

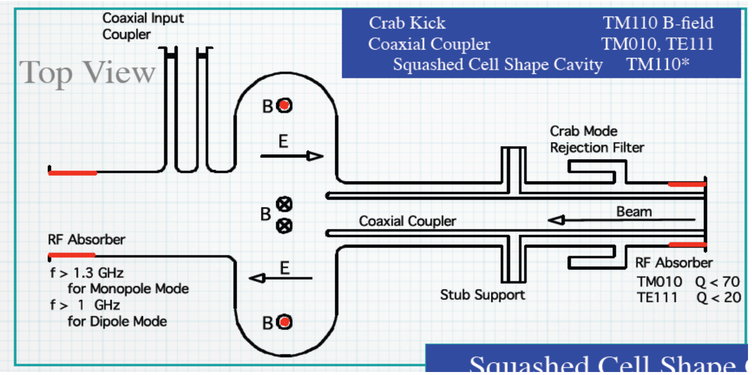
**Maximum sextupole strength at 60 GeV/c = 391.8 T/m$^2$**

- (Natural) chromaticity correction looks good,
- Momentum acceptance for electron is not satisfactory, needs further optimization
- Particle tracking simulations & dynamical aperture studies in progress

# Crab Crossing

- High bunch repetition rate requires crab crossing of colliding beams to avoid parasitic beam-beam collisions
- Present baseline: 50 mrad crab crossing angle
- Studying two schemes to restore head-on collisions
  - Crab cavities
  - Dispersive crabbing




| Crab Cavity | Energy (GeV/c) | Kicking Voltage (MV) | R&D |
|---|---|---|---|
| electron | 5 | 1.35 | State-of-art |
| Proton | 60 | 8 | Not too far away |

| Dispersive crab | Energy (GeV/c) | RF Voltage (MV) |
|---|---|---|
| electron | 5 | 34 |
| Proton | 60 | 51 |

**Crab cavity State-of-the-art**:
KEKB Squashed cell@TM110 Mode
$V_{kick}$=1.4 MV, $E_{sp}$= 21 MV/m

New type SRF crab cavity currently under development at ODU/JLab

Pavel Chevtsov, Anatoliy Kondratenko

# Ion Polarization

## Design Requirements

- High (>70%) polarization of stored electron beam
- Preservation of polarization during acceleration (in boosters and collider ring)
- ***Longitudinal and transverse*** polarization at interaction points
- ***Polarized deuteron***

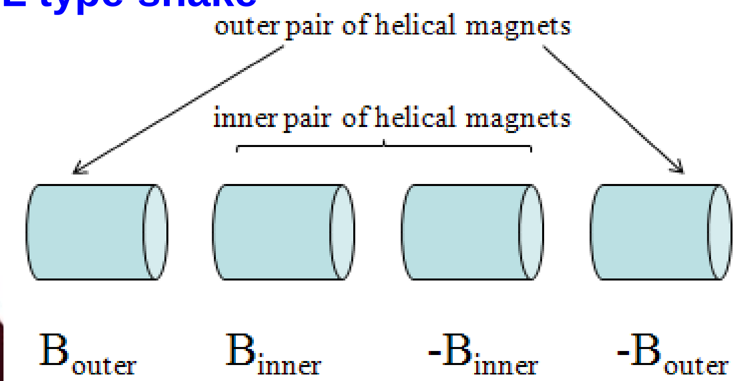
## Design Choices

* Polarized ion sources     * Figure eight ring     * Siberian snakes

## Polarization schemes we have worked out

- Proton: longitudinal, transverse and combined polarizations at IPs
- Deuteron: longitudinal and transverse polarization at IPs

### BNL type snake




### Snake parameters for longitudinal scheme

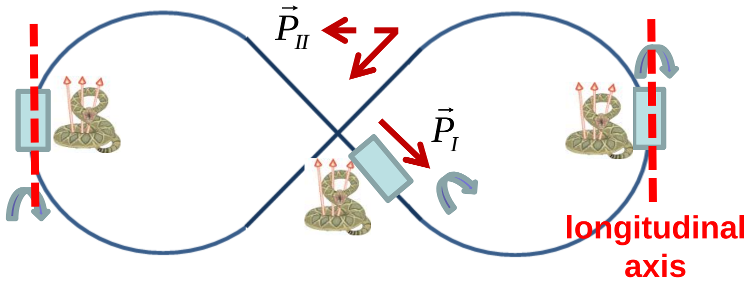
| E (GeV) | 20 | 40 | 60 | 100 | 150 |
|---|---|---|---|---|---|
| $B_{outer}$ (T) | -2.13 | -2.16 | -2.173 | -2.177 | -2.184 |
| $B_{inner}$ (T) | 2.83 | 2.86 | 2.88 | 2.89 | 2.894 |

### Snake parameters for transverse scheme

| E (GeV) | 20 | 40 | 60 | 100 | 150 |
|---|---|---|---|---|---|
| $B_{outer}$ (T) | -1.225 | -1.241 | -1.247 | -1.251 | -1.253 |
| $B_{inner}$ (T) | 3.943 | 3.994 | 4.012 | 4.026 | 4.033 |

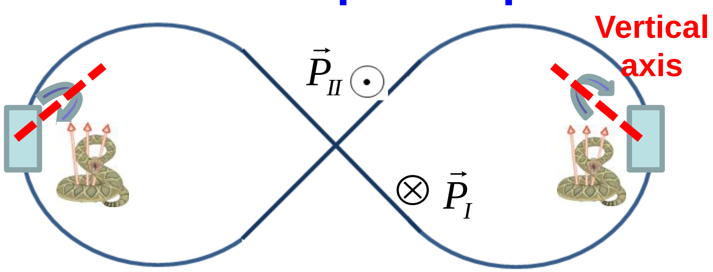
# Proton Polarization at Interaction Points

## Case 1: Longitudinal Proton Polarization at IP's



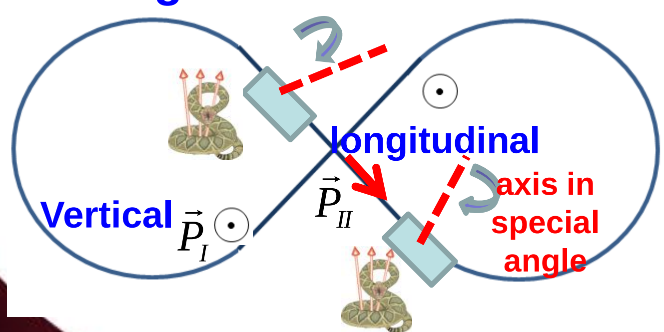

- Three Siberian snakes, all longitudinal-axis
- Third snake in straight is for spin tune
- Spin tune: 1/2

## Case 2: Transverse proton polarization at IP's




- Three Siberian snakes, both in horizontal-axis
- Vertical polarization direction periodic
- Spin tune: 1/2

## Case 3: Longitudinal & transverse proton polarization on two straights




- Two Siberian snakes, with parameters satisfying certain requirements
- Spin tune: 1/2

# Staged Electron Cooling In Collider Ring

**Present design is based on an extrapolation of standard electron cooling**

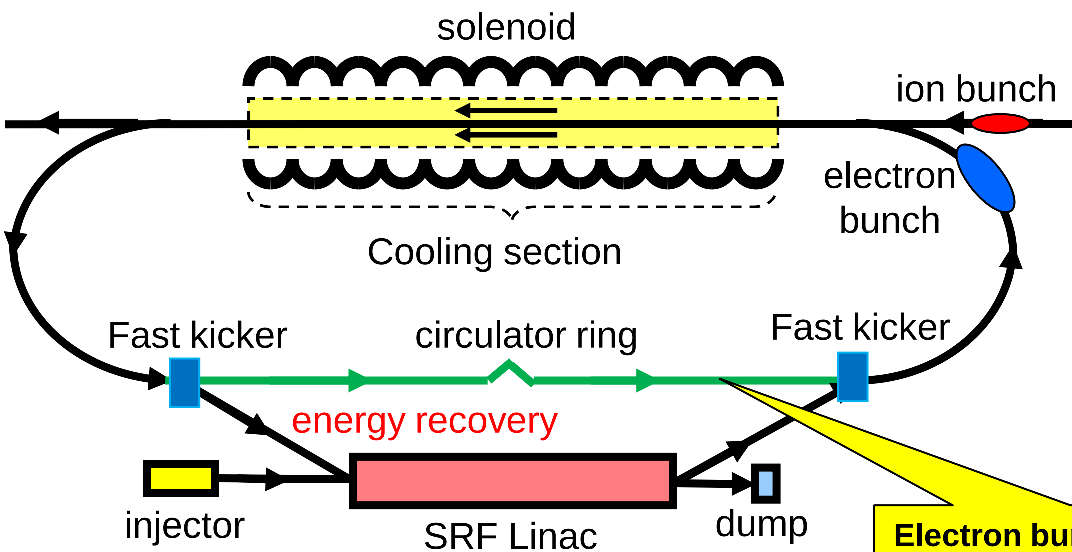
- **Initial cooling:** after injection for reduction of longitudinal emittance before acceleration
- **Final cooling:** after boost & rebunching, for reaching design values of beam parameters
- **Continuous cooling:** during collision for suppressing IBS & preserving luminosity lifetime

| | | Initial Cooling | after boost & bunching | Colliding Mode |
|---|---|---|---|---|
| Energy | GeV/MeV | 20 / 8.15 | 60 / 32.67 | 60 / 32.67 |
| Beam current | A | 0.5 / 3 | 0.5 / 3 | 0.5 / 3 |
| Particles/Bunch | $10^{10}$ | 0.42 / 3.75 | 0.42 / 3.75 | 0.42 / 3.75 |
| Ion and electron bunch length | Cm | (coasted) | 1 / 2~3 | 1 / 2~3 |
| Momentum spread | $10^{-4}$ | 10 / 2 | 5 / 2 | 3 / 2 |
| Horizontal and vertical normalized emittance | µm | 4 / 4 | | 0.35 / 0.07 |
| Laslett tune shift | (proton) | 0.002 | 0.006 | 0.07 |
| Cooling length /circumference | m/m | 15 / 1000 | 15 / 1000 | 15 / 1000 |

| | formula | | Longitudinal | Horizontal | Vertical |
|---|---|---|---|---|---|
| IBS | Piwinski | s | 66 | 86 | |
| IBS | Martini (BetaCool) | s | 50 | 100 | 1923 |
| Cooling | Derbenev | s | ~7.9 | | |

* Assuming I.e.=3 A, 60 GeV/32.67 MeV

# ERL Based Circulator Electron Cooler




**Electron bunches circulate 100+ times, leads to a factor of 100+ reduction of current from a photo-injector/ERL**

## Design Choice

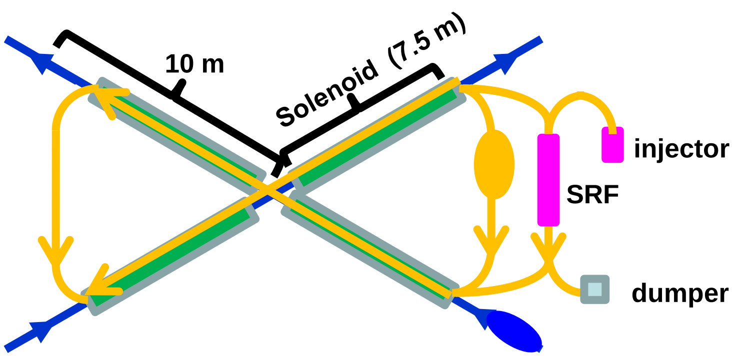
to meet design challenges

- RF power (up to 50 MW)
- Cathode lifetime (130 kC/day)

## Required technology

- High bunch charge gun
  ERL (50 MeV, 15 mA)
  Ultra fast kicker

## Cooling at the center of Figure-8

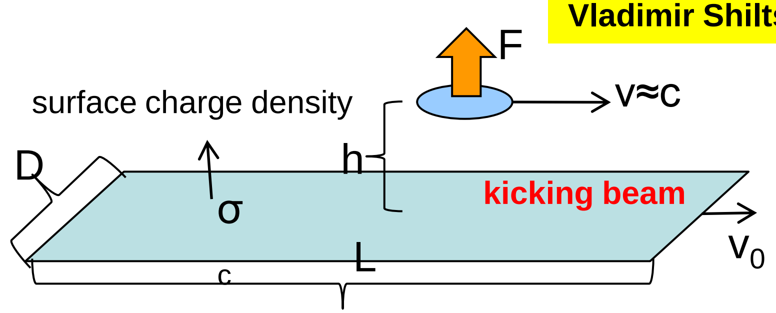



**Eliminating a long return path could**

- **cut cooling time by half, or**
- **reduce the cooling electron current by half, or**
- **reduce the number of circulations by half**

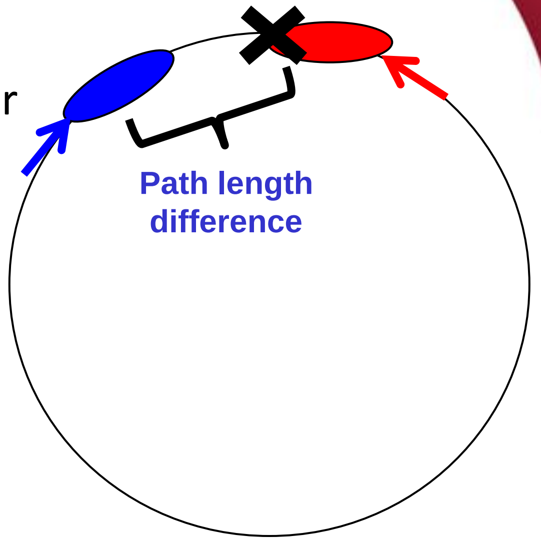
## Beam-beam fast kicker

**Vladimir Shiltsev**



Slava Derbenev, Andrew Hutton

# Beam Synchronization




- Problem
  - Electrons travel at the speed of light, protons/ions are slower
  - Slower ion bunches will not meet the same electron bunch at the collision point after one revolution
  - Synchronization condition must be achieved at every collision point in the collider ring simultaneously
- Path length difference in collider rings

Assuming: (*nominal*) collider ring circumference ~1000 m

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| proton: | 60 GeV | design point | | | | | |
| | 20 GeV | → | -97.9 cm | → | 2.44 bunch spacing | → | 2 unit of HN |
| Lead: | 23.8 GeV/u | → | -65.7 cm | → | 1.64 bunch spacing | → | 2 unit of HN |
| | 7.9 GeV/u | → | -692 cm | → | 17.3 bunch spacing | → | 17 unit of HN |

- Present conceptual solutions
  - Low energy (up to 30 GeV proton & all energies for ions): change bunch number in ion ring
  - Medium energy (proton only, 30 GeV & up): change orbit or orbit and RF frequency together
    - Option 1: change Ion orbit → mounting SC magnets on movers, unpleasant but affordable
    - Option 2: change electron orbit and RF frequency (less than 0.01%) → large magnet bore

# MEIC Design Report

- Completed five chapters of an intermediate MEIC design report
  - Chapters in final editing by Joe Bisognano
    - Currently, Director, Synchrotron Radiation Center, Wisconsin
    - Previously, Head of Accelerator Physics at JLab
  - Goal is to ensure that the report is internally consistent
    - Joe will also verify that claims are not exaggerated
- Expect report to be completed by January 2012

# An Intermediate Design Report for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

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

[1] Thomas Jefferson National Accelerator, Facility, Newport News, VA 23606, USA

[2] Old Dominion University, Norfolk, VA 23529, USA

[3] Paul Scherrer Institute, Switzerland

[4] Catholic University of America, Washington, DC 20064, USA

[5] SLAC National Accelerator Laboratory, Menlo Park, CA 94305, USA

[6] Argonne National Laboratory, Argonne, IL 60439, USA

[7] Northern Illinos University, De Kalb, IL 50115, USA

[8] Muons Inc., Batavia, IL 60510, USA

[9] Idaho State University, Pocatello, ID 83209, USA

[10] STL "Zaryad", Novosibirsk, Russian Federation

[11] College of William and Mary, Williamsburg, VA 23187, USA

# Plan for Developing a Cost Estimate

- Bill Schneider, a retired senior engineer, will do a rough scaling to calculate the approximate cost and identify the cost drivers
- JLab engineers will then do a more detailed estimate of the top three or four cost drivers
  - If the two estimates are close, we will continue with detailed estimates of the next few cost drivers
- This will allow us to present a cost estimate where the cost drivers are accurately known and the error bar on the rest can be estimated
  - Expected completion date January 2012

# Summary

- The MEIC design meets all of the requirements laid out in the INT Report
- The design utilizes the advantages of the JLab site (electron injector) but profits from the flexibility of having new ion ring to design a high-polarization facility
  - Figure 8 layout (or is it infinity?)
- We have an enthusiastic group of collaborators helping design the machine
- We are wrapping up the design report and the cost estimate to be ready for the next NSAC Long Range Plan