Exploring QCD with light nuclei at EIC

Center for Frontiers in Nuclear Science

Stony Brook University
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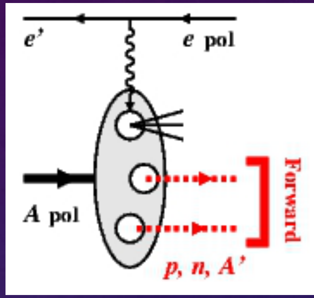

BEAM OPTICS AND MOMENTUM RESOLUTION IN FORWARD ION DETECTION WITH EIC

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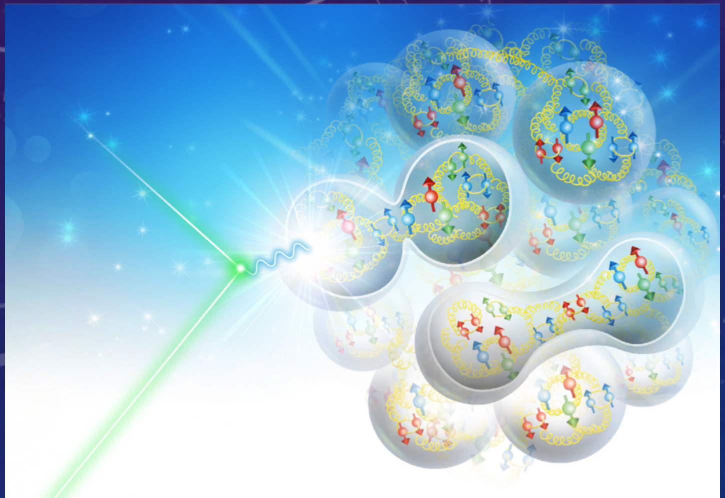
OLD DOMINION UNIVERSITY



PHYSICS CONCEPTS I.
DEEP VIRTUAL EXCLUSIVE SCATTERING

- $ep \to eVN, \qquad V = \rho, \phi, J/\psi$:
  - Resolve kinematics ($\Delta_\perp$) via charged particle decays of Vector meson
  - Detect final proton, or veto N^* *via* detection of final state
    - $N^* \to p\pi^0$: $1 - P(p)/P_0 > m_\pi/M_N = 14\%$
    - $N^* \to n\pi^+$: Requires large phase space (p,θ) for pion veto or High Resolution ZDC: $40\%/\sqrt{E} \leq 4\%$ for $E_n \geq 100$ GeV
- $ep \to e\gamma p$: Need to detect exclusive proton for high resolution determination of kinematics

PHYSICS CONCEPTS II. SPECTATOR TAGGING

- $eD \rightarrow epX$: Inclusive, Semi-Inclusive, Exclusive, Double-tag…
  - $P_p = \frac{\alpha}{2} P_D \approx \frac{1}{2} P_D$ $(\alpha \approx 1 \pm k_F/M_N)$: Rigidity $K_p = \frac{P_p}{Q_p} \approx \frac{1 \pm k/M}{2} K_D$
- $eHe^3 \rightarrow eppX$:
  - $P_p = \frac{\alpha}{3} P_D \approx \frac{1 \pm 0.2}{3} P_3$ Rigidity $K_p = \frac{P_p}{Q_p} \approx \left[\frac{P_3}{3}\right] / \left[\frac{P_3}{2}\right] \approx \frac{2}{3} K_3$
- $eHe^3 \rightarrow edX$:
  - $P_d \approx \frac{2}{3} P_3$ Rigidity $K_d \approx \frac{4}{3} K_3$ "Super-Exclusive"
- $eHe^4 \rightarrow e' \, He^3$ X Rigidity $K_3 \approx \frac{3}{4} K_4$
- $eHe^4 \rightarrow e' \, H^3$ X Rigidity $K_t \approx \frac{3}{2} K_4$ "Super-Exclusive"

PHYSICS CONCEPTS III. NUCLEAR FINAL STATES

$e^{-} + {}^{A}Z \rightarrow e' + {}^{A'}Z' + \ldots.$

- Knockout N ($P \approx q$), Fragmentation N,d,… ($P \approx P_F$)
- Evaporation N, d,… ($P^2 \approx MkT$), $kT \approx 10$ MeV
- Evaporation Residue ${}^{A'}Z'$
  - Relative Rigidity $K'/K \approx \frac{A'}{Z'} / \frac{A}{Z} = \frac{A'}{A} \cdot \frac{Z}{Z'}$
  - Extreme cases (see BEAGLE Simulations)
    - $A' = A-1$, $Z'=Z$ → $K'/K = (A-1)/A = 0.995$ for ${}^{A}Z = {}^{208}Pb$
    - $A' = A$, $Z' = Z-1$ → $K'/K = Z/(Z-1) = 1.012$ for ${}^{A}Z = {}^{208}Pb$
- Nuclear Fragmentation is as demanding as proton DVCS on small $\delta P_L/P_L$ acceptance and resolution
  → Detect Ions with rigidity within 1% of beam rigidity

BEAM EMITTANCE LIMIT ON DETECTION RESOLUTION FOR FORWARD IONS

- eRHIC
  (275 GeV *p*) x (10 GeV e^{-})
  - https://www.bnl.gov/cad/eRhic/
  - 2019/napac19/program-agenda
    MOOHC2

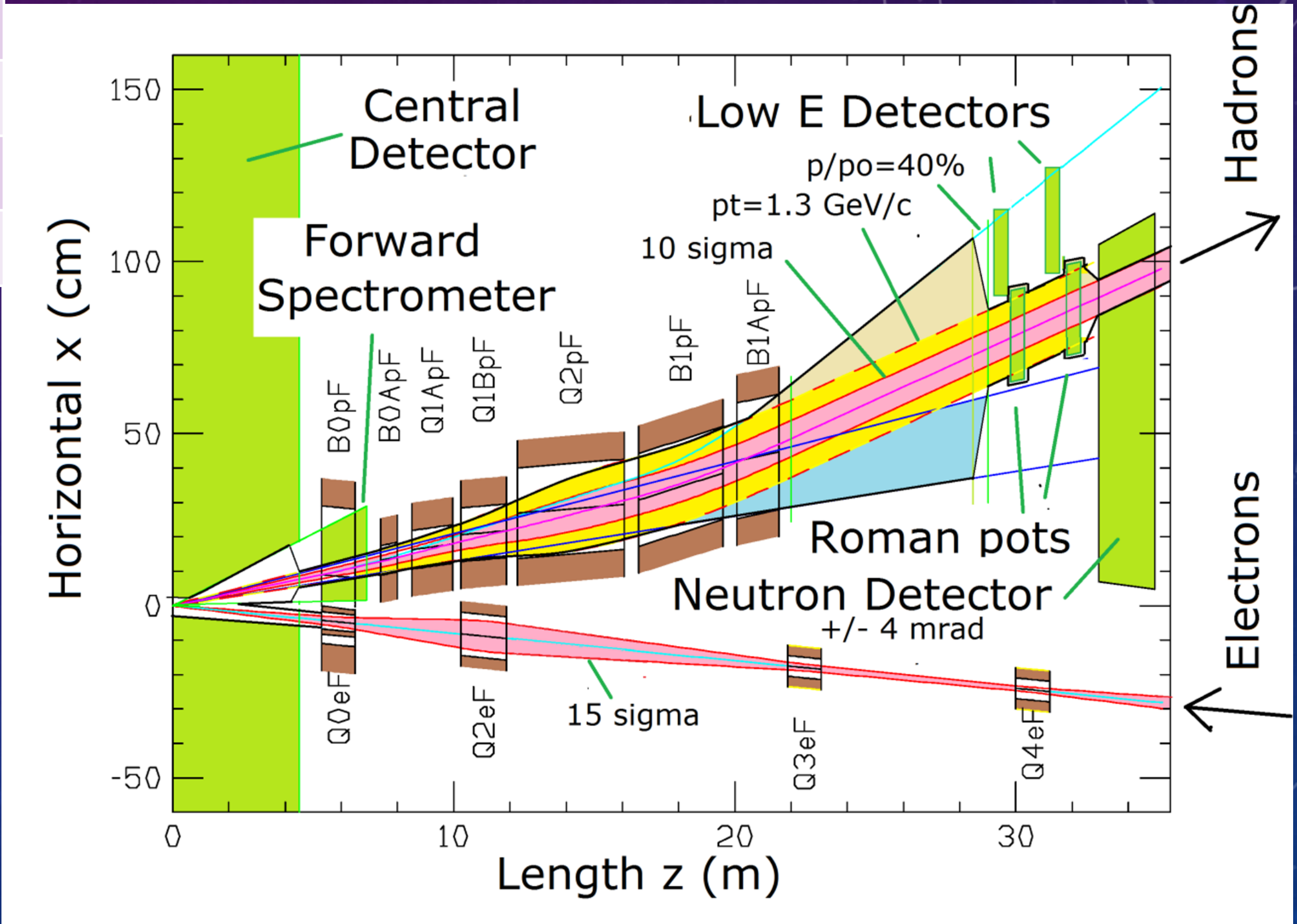
	Nominal Design (with cooling)		Risk Mitigation (no cooling)	
Species	**p**	**e**	**p**	**E**
Bunch frequency [MHz]	112.6		56.3	
Bunch intensity [10^11]	0.6	1.5	1.05	3.0
Number of bunches	1320		660	
Beam current [A]	1	2.5	0.87	2.5
Rms norm. emit. h/v [um]	2.7/0.38	391/20	4.1/2.5	391/95
Rms emittance h/v [nm]	9.2/1.3	20/1	13.9/8.5	20/4.9
β* h/v [cm]	90/4	42/5	90/5.9	63/10.4
IP rms beam size h/v [um]	91/7.2		112/22.5	
IR rms angular spread h/v [urad]	101/179	219/143	124/380	179/216
b-b parameter (/IP) h/v	0.013/0.007	0.064/0.099	0.015/0.005	0.1/0.083
Rms bunch length [cm]	5	1.9	7	1.9
Rms energy spread, 10^-4	4.6	5.5	6.6	5.5
Max space charge parameter	0.004	neglig.	0.001	neglig.
IBS growth time tr/long, h	2.1/2.0		9.2/10.1	
Polarization, %	80	70	80	70
Hourglass and crab crossing factor	0.87		0.85	
Peak luminosity [10^33 cm-2s-1]	**10.1**		**4.4**	
Integrated luminosity/week, fb^{-1}	**4.51**		**1.12**	

eRHIC IR OPTICS

SEPT 2019

Species	p	e^-
RMS emittance ϵ(H/V) (nm)	9.2/1.3	20/1
β^* H/V (cm)	90/4	42/5
IP RMS beam size H/V (μm)	91/7.2	112/22
IP RMS Angular Spread H/V (mrad)	0.10/0.2	0.22/0.15
RMS Bunch Length (cm)	5	2
RMS Energy Spread (σ_P/P) (10^{-4})	4.6	5.5

- P_A = (275 GeV/c) Z
- Downstream Optics non-focusing
- Angular acceptance ± 4mrad
  $|p_T| \leq$ 1.3 GeV @ 275 GeV
  $|p_T| \leq$ 0.5 GeV @ 100 GeV



MOMENTUM RESOLUTION AT ROMAN POTS?

MY ANALYSIS FROM GRAPH: NOT EXACT

- $10\sigma_x(RP) \approx 5$ cm ➔ $\sigma_x(RP) = 1$cm
- $\sigma_x(RP) = [(\beta)^{RP} (\epsilon_H) + (D \bullet \sigma(\delta)^{IP})^2]^{1/2}$
- $D \approx 40\text{cm}/60\% = 67\text{ cm}/100\%$
- $\epsilon_H = 10^{-8}$ m, $\sigma(\delta)^{IP} = 4.6 \bullet 10^{-4}$ ➔ $(\beta)^{RP} \approx 10^4$ m !!
- If $[(\beta)^{RP} (\epsilon_H)]^{1/2} = 1$ cm and $D = 67$ cm ➔
  Resolution on δ = 1cm/(67cm) = 1.5% regardless of RP spatial resolution

GAPS IN ACCEPTANCE WITHOUT FOCUSSING

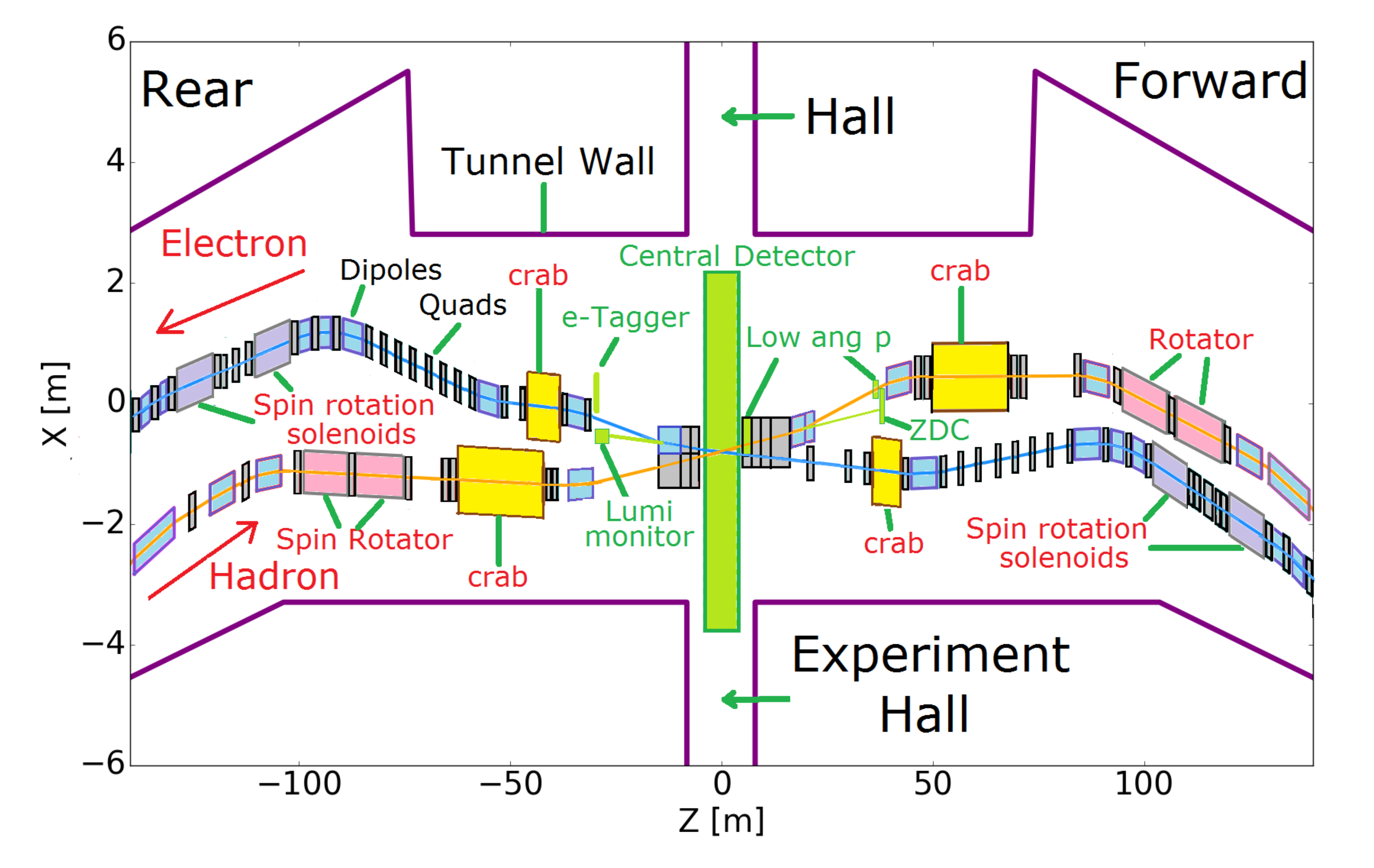
- Without a secondary high-dispersion focus, there are significant gaps in the acceptance as a function of δ, P_T
  - These gaps can be filled by running at different beam energies, BUT:
- DVCS physics requires **full** acceptance over a broad range in *s*.
  - M. Defurne, *et al,* Nature Physics **8** (2017) 1408:
    Measurements at fixed (Q^2, x_B, Δ^2) & multiple *s*-values enable separation of $Re[DVCS^\dagger BH]$, $Im[DVCS^\dagger BH]$, and $|DVCS|^2$ terms
  - Only technique without positrons!

FOCUSING CONCEPT IN JLEIC IR DESIGN

- Downstream iFFQ triplet + Dipoles captures the beam from the IP focus, and forms a downstream focus ($z \approx 40$ m)
  - $D^{RP} \approx 1$ m, $(\beta^*)^{RP} \approx 1$m, Magnification = $\langle \theta_H^{RP} | \theta_H^{IP} \rangle \approx -0.5$
  - Intrinsic beam size = $[(\beta)^{RP} (\epsilon_H) + (D \bullet \sigma(\delta)^{IP})^2]^{1/2} = [1+(4.6)^2]^{1/2}(10^{-4}$ m) $\sigma_H^{IP} \approx 0.5$ mm, dominated by beam energy spread
  - Achievable momentum resolution = $\sigma_H^{IP} / D = 5 \bullet 10^{-4}$
    - Precision DVCS kinematics
    - $\Delta Z = 1$, $\Delta A = 1$ resolution on beam residue across periodic chart (and exotic nuclei)

eRHIC BEAMLINE

- Is a focusing forward beam line possible at eRHIC?
  - Adjust IR in range 20 to 80 m
- Crab cavities must be at $(2n+1)\pi/2$ phase relative to IP
- JLEIC Crab Cavities at ±300 m



CONCLUSION

- It is urgent to complete a full review of practical options for the IR design(s).
- The IR design will likely be frozen within this year , and will not be changed for 20 years.
  - Changes to IR magnets after detector design require major changes to central detector and parts of accelerator
  - HERA demonstrated that retrofitting forward optics/detection cannot deliver the full physics program

CONCLUSIONS

- A large variety of Physics topics require large acceptance/high – resolution far-forward detection.
  - dK/K from -0.5 to +0.33 to infinity (neutrons, gammas)
  - Current design has –0.4≤ dK/K ≤ ∞ (neutron)
    - Lengthen quads, reduce acceptance to –0.5 ≤ dK/K to create focus at Roman Pot location
- Secondary Focus enhances resolution/acceptance
- Detection inside dipoles needed for vertex resolution on KS->pipi, Lambda -> p pi

BACKUP

Ion Collider Ring Optics

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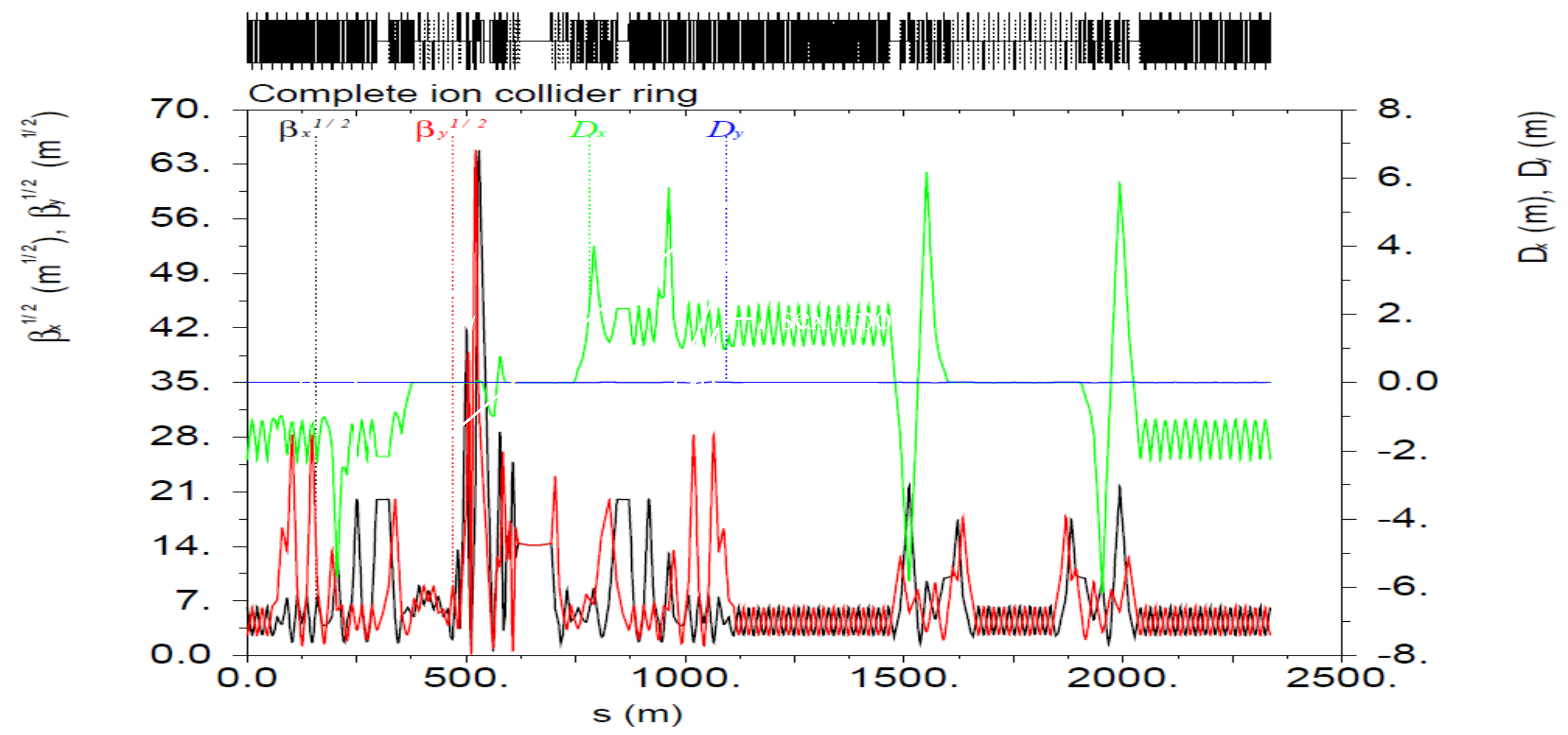

Jefferson Lab

JLEIC Ion Collider Ring

- Circumference of 2335.975 m optimized for synchronization
- 200 GeV/c protons
- 6 T $\cos\theta$ dipoles and $\cos 2\theta$ quadrupoles