MCBI in an Electron Ion Collider

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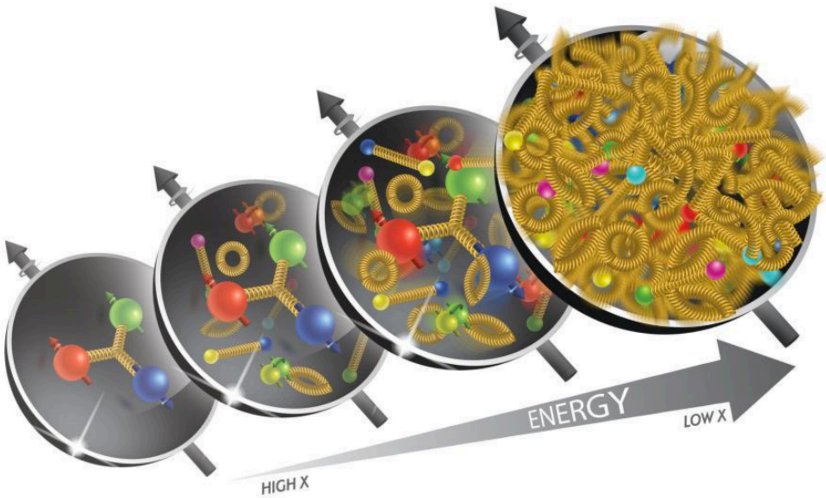
Outline

1. Introduction
2. Collective Instabilities in JLEIC and eRHIC
3. MCBI in an EIC
4. Summary

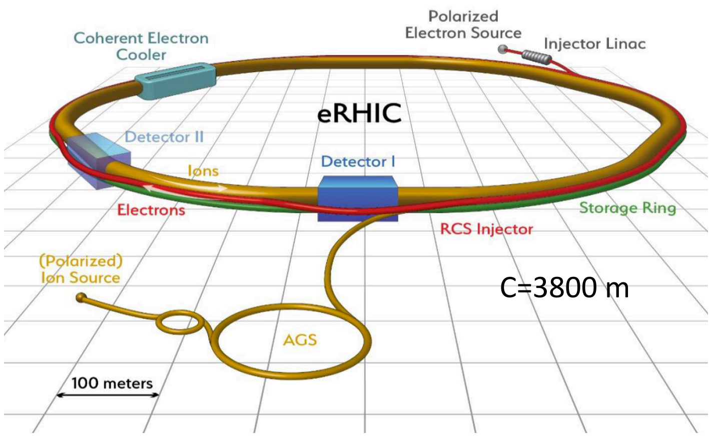
1. Introduction

An electron-ion collider (EIC) is identified as the next exploring machine for probing the QCD structure and the dynamics of nuclear matter

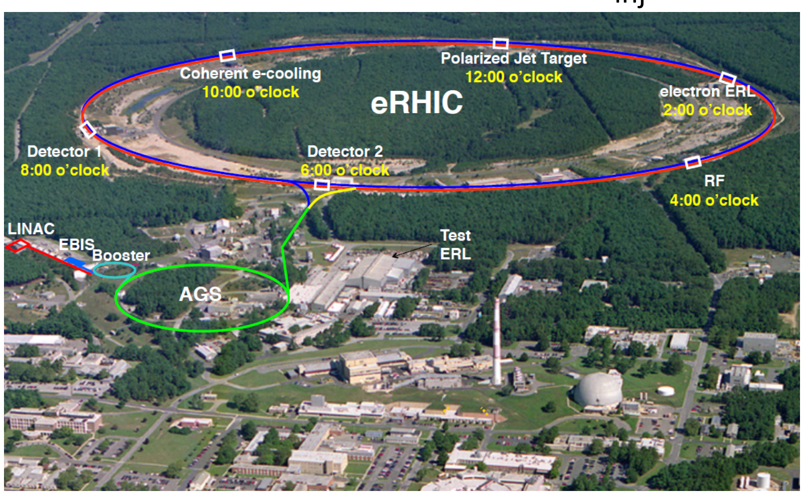
- high center-of-mass energy (30~140 GeV),
- high luminosity (10^{33}~10^{34} $cm^{-2}s^{-1}$)
- wide range of ion species
- high polarization (~70% for the electron and light ion beams)

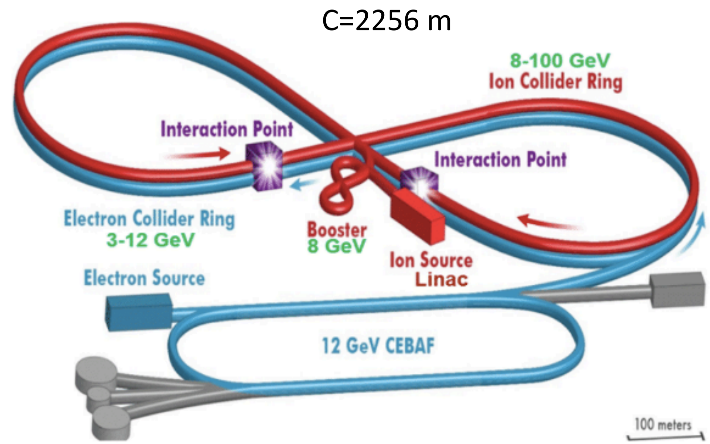


# eRHIC	# JLEIC

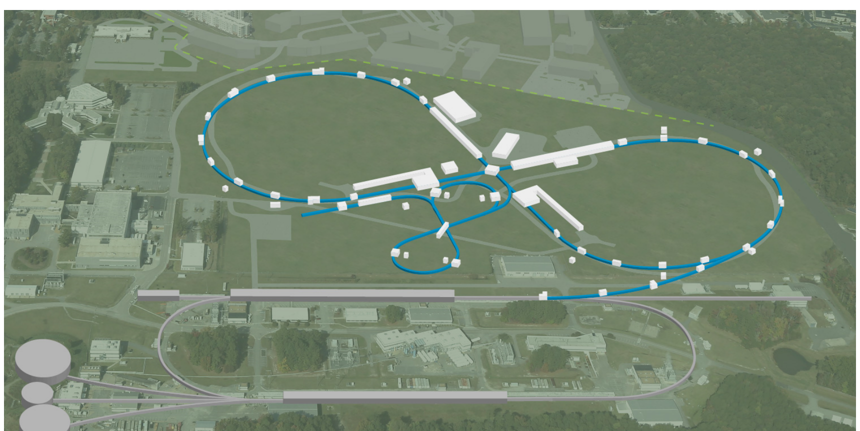


- ion ring: modified RHIC (E_p=41-275 GeV)
- e-ring (E_e= 5-18 GeV)
- Rapid recycling synchrotron (E_{inj}=400MeV)





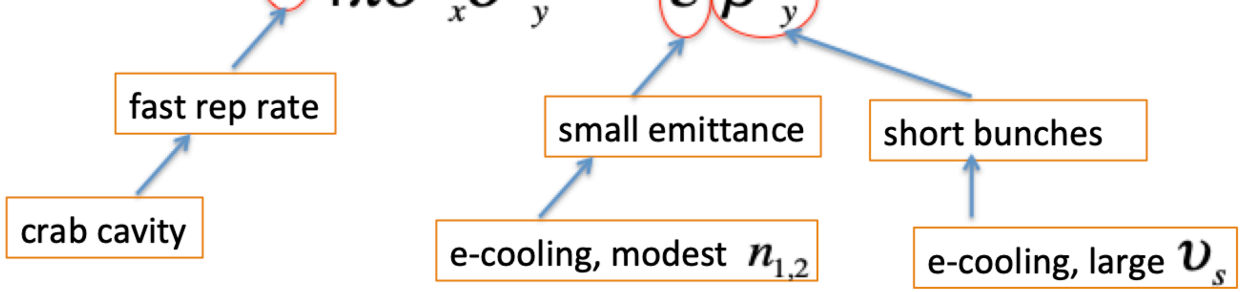
- figure-8 ion ring (E_p=30-200 GeV)
- figure-8 e-ring (E_e= 3-12 GeV)
- 12 GeV CEBAF as full-energy e-ring injector



Behaviors of Collective Effects in JLEIC

Luminosity concepts: adopt concepts in lepton colliders

$$L = f \frac{n_1 n_2}{4\pi \sigma^*_x \sigma^*_y} \sim f \frac{n_1 n_2}{\varepsilon \beta^*_y}$$



- High rep rate
- Moderate bunch charge
- Small beta*
- Short bunch length
- Low emittance

(new regime for ion beams)

JLEIC p-beam:

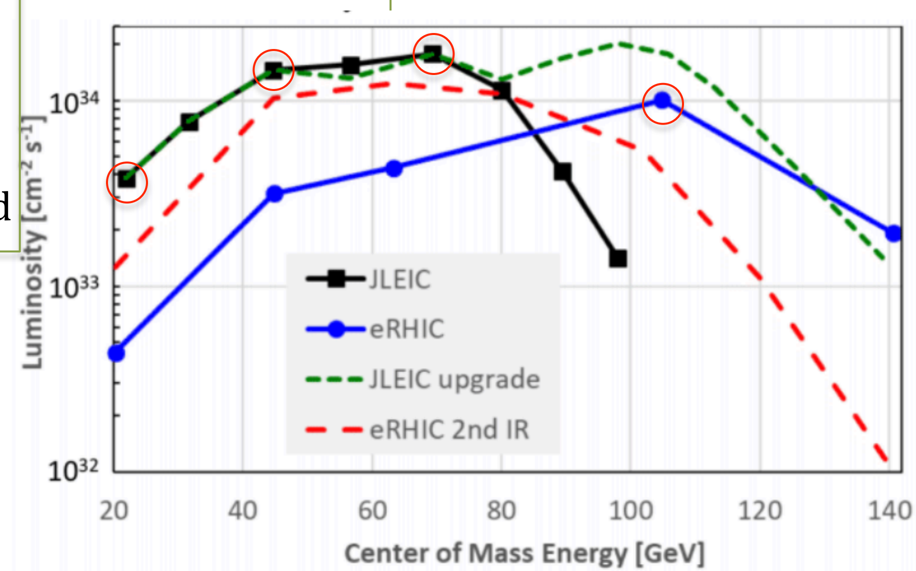
$n_b = 3360,\ s_b = 2$ ns, $\sigma_z = 1$ cm, $\beta_y = 1$ cm, θ=50 mrad

eRHIC p-beam:

$n_b = 1320,\ s_b = 9$ ns, $\sigma_z = 5$ cm, $\beta_y = 5$ cm, $\theta = 22$ mrad

Features of collective effects

- Weak or moderate single-bunch coherent effect (E_e dependent)
- Strong coupled-bunch coherent effect
- Possibly harmful ion effects



Special Regime of JLEIC Parameters

JLEIC: $n_b = 3360,\ s_b = 2\ \text{ns},\ \sigma_z = 1\ \text{cm},\ \beta_y^* = 1\ \text{cm},\ \theta = 50\ \text{mrad}$

- e-Ring

Beam parameters are similar to those in a lepton collider

Optics should be feasible for $E_e = 3 \sim 12\ \text{GeV}$

Moderate bunch charge: $N_e = 3.7 \times 10^{10}/\text{b},\ I_{ave} = 1 \sim 3\ \text{A}$

How to choose optics so it gives the energy spread that is sufficient for Landau damping of LSBI?

- Ion Ring

Beam parameters are similar to those in a lepton collider

collision while under strong electron cooling $\left(\varepsilon_{nx}/\varepsilon_{ny} = 0.5/0.1\ \mu\text{m}\right)$

High rep rate (476MHz), short bunch length (1 cm), $Q_s = 0.05$

Moderate bunch charge: $N_p = (1 \sim 4) \times 10^{10}/\text{b},\ I_{ave} = 0.75\ \text{A}$

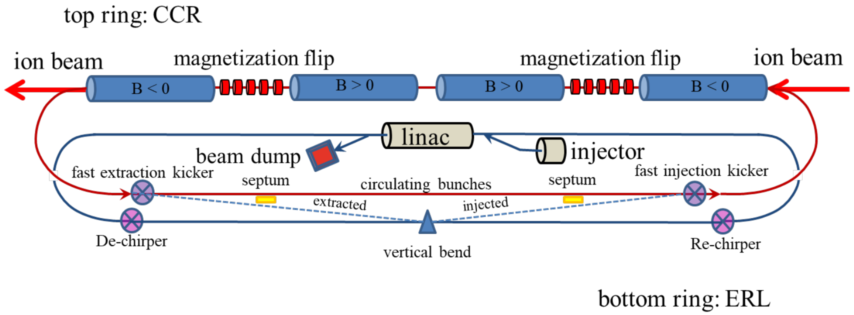
With strong coupled-bunch effect , does large Q_s affect the longitudinal damper?

Could noise of damper in the collider ring cause emittance growth?

What's the role of synchro-betatron coupling in hour-glass effect in damper design?

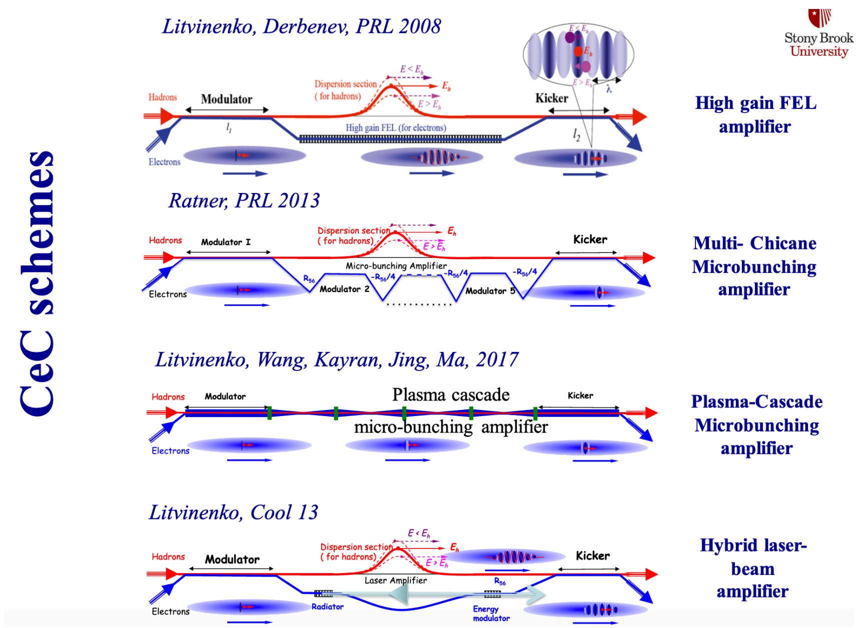
Strong Bunched Electron Cooling at High Energy

JLEIC



- Magnetized electron beam (E=20-55 MeV)
- ERL for minimizing power consumption (I_{ave}=138 mA, 476.3 MHz)
- Circulator cooler ring (11 turns, 3.2nC/b)

eRHIC



- Coherent electron cooling
- Options for amplifier

2. Collective Effects in an EIC

Electron Ring	Ion Rings	Electron Cooler
• Incoherent: Laslett tune shift, emittance growth • Coherent: Single-bunch Instability, Coupled-bunch Instability • Scattering: IBS, Touschek scattering, Residual gas scattering • Heat load • Feedback		• Space charge • CSR • BBU • Scattering • Two stream effects
• Two-stream effects: Beam-Beam Ion effects	E-cloud effects		

JLEIC Baseline *e-p* Parameters

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	**3**	**100**	**5**	100	**10**
Collision frequency	MHz	**476**		**476**		**476/4=119**	
Particles per bunch	10^{10}	**0.98**	**3.7**	**0.98**	**3.7**	**3.9**	**3.7**
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	**3**	**1**	**1**	**1**	**2.2**	**1**
Norm. emitt., horiz./vert.	μm	**0.3/0.3**	24/24	**0.5/0.1**	54/10.8	**0.9/0.18**	432/86.4
Horizontal & vertical β*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam param.		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**2.5**		**21.4**		**5.9**	

For the electron ring, we consider Ee=3, 5, 10 GeV

For the ion ring, we consider Ep=100 GeV (middle column)

eRHIC Baseline *e-p* Parameters

Parameter	hadron	electron
Center-of-Mass Energy [GeV]	104.9	
Energy [GeV]	275	10
Number of Bunches	1320	
Particles per Bunch [10^{10}]	6.0	15.1
Beam Current [A]	1.0	2.5
Horizontal Emittance [nm]	9.2	20.0
Vertical Emittance [nm]	1.3	1.0
Hor. β-function at IP β_x^* [cm]	90	42
Vert. β-function at IPβ_y^* [cm]	4.0	5.0
Hor./Vert. Fractional Betatron Tunes	0.3/0.31	0.08/0.06
Horizontal Divergence at IP [mrad]	0.101	0.219
Vertical Divergence at IP [mrad]	0.179	0.143
Horizontal Beam-Beam Parameter ξ_x	0.013	0.064
Vertical Beam-Beam Parameter ξ_y	0.007	0.1
IBS Growth Time longitudinal/horizontal [hours]	2.2/2.1	-
Synchrotron Radiation Power [MW]	-	9.18
Bunch Length [cm]	5	1.9
Hourglass and Crab Reduction Factor	0.87	
Luminosity [10^{34}cm-2sec-1]	1.05	

(for collision at highest luminosity)

First a Brief Summary for JLEIC …

- **Machine broadband impedance**

  use impedance budget in existing machines as reference
- **Single-bunch Instability**

  Comparing threshold impedance with machine impedance

- **Machine narrowband impedance**

  Cavity design with HOM couplers
- **Coupled-bunch Instability**

  using Zotter's formula for

  even bunch fill

	Electron			Proton
E [GeV]	3	5	10	100
Single bunch longitudinal instability	🔴	🟡	🟢	🟢
Single bunch transverse instability	🟢	🟢	🟢	🟢
Coupled bunch longitudinal instability		Require state-of-art fast bunch-by-bunch feedback system		🟡
Coupled bunch transverse instability				
Electron cloud				Ok for TMCI Question for CBI
Ion effects	🔴	🔴	🟢	

Broadband Impedance Estimation

JLEIC e-Ring

Broadband Impedance	Reference: PEP-II	Reference: SUPERKEKB
L [nH]	99.2	28.6
$\lvert Z_{\parallel}/n \rvert$ [Ω]	0.09	0.02
$k_{\parallel}$ [V/pC]	7.7	19
$\lvert Z_{\perp} \rvert$ [kΩ/m]	30	6.5

- JLEIC plans to use PEP-II vacuum systems
- Effective impedance is bunch length dependent

JLEIC ion-Ring

Broadband Impedance	Reference: PEP-II
L [nH]	97.6
$\lvert Z_{\parallel}/n \rvert$ [Ω]	0.08
$k_{\parallel}$ [V/pC]	8.6
$\lvert Z_{\perp} \rvert$ [kΩ/m]	40

- The short bunch length (1.2cm) at collision is unprecedented for the ion beams in existing ion rings
- Bunch length varies through the whole bunch formation process

Longitudinal Single Bunch Instability

- Longitudinal Single-Bunch Instability Threshold

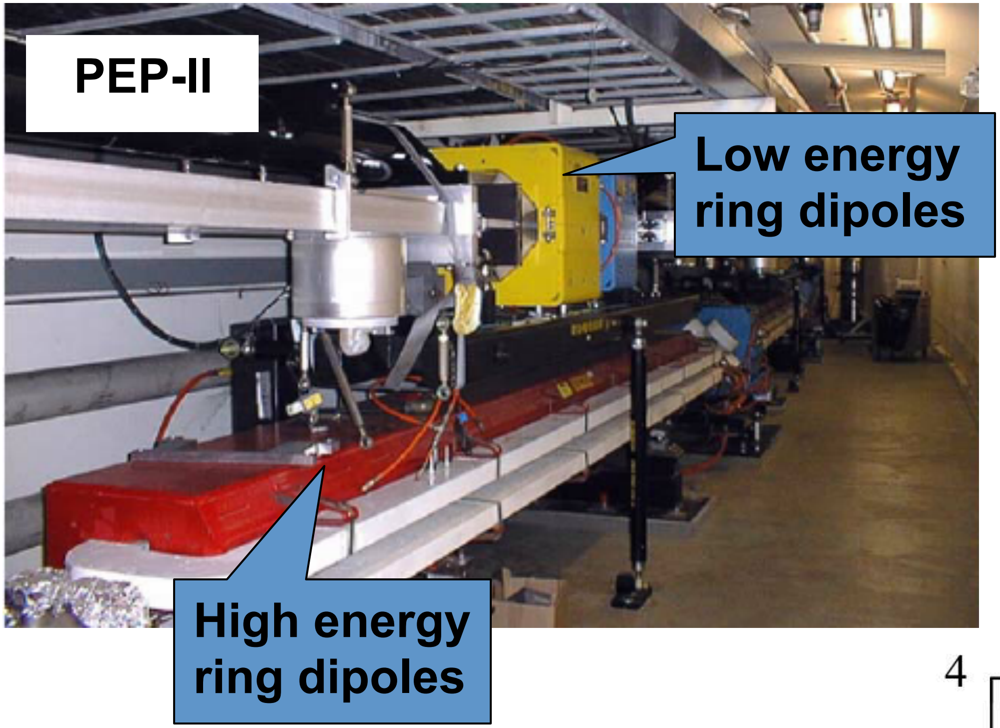
$$\left|\frac{Z_{\parallel}(n)}{n}\right|_{\text{eff,th}} = \frac{2\pi|\eta|(E/e)\sigma_\delta^2}{I_{peak}}$$

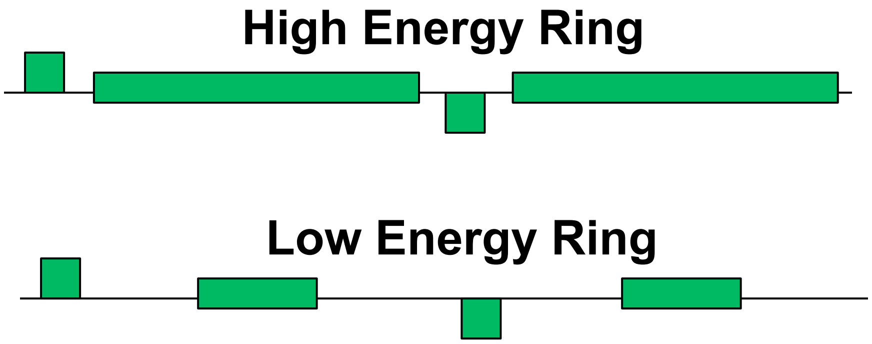
	PEP-II (LER)	JLEIC Electron Ring			JLEIC p-Ring
E (GeV)	3.1	3	5	10	100
I_p(A)	113	59.0	62.35	50.6	15.6
η (10^{-3})	1.31	1.09	1.09	1.09	6.22
σ_δ (10^{-4})	8.0	2.78	4.55	9.28	3.0
$\lvert Z_{\parallel}/n\rvert_{\text{eff,th}}$ [Ω]	0.145	0.027	0.125	1.16	22.5
	Stable	Unstable!	Marginally Stable	Stable	Stable

Estimated e-Ring impedance $|Z_{\parallel}/n|_{\text{eff}} \approx 0.1\ \Omega$

Estimated p-Ring impedance $|Z_{\parallel}/n|_{\text{eff}} \approx 0.1\ \Omega$

Alternative Beamline Configurations at Low Energies

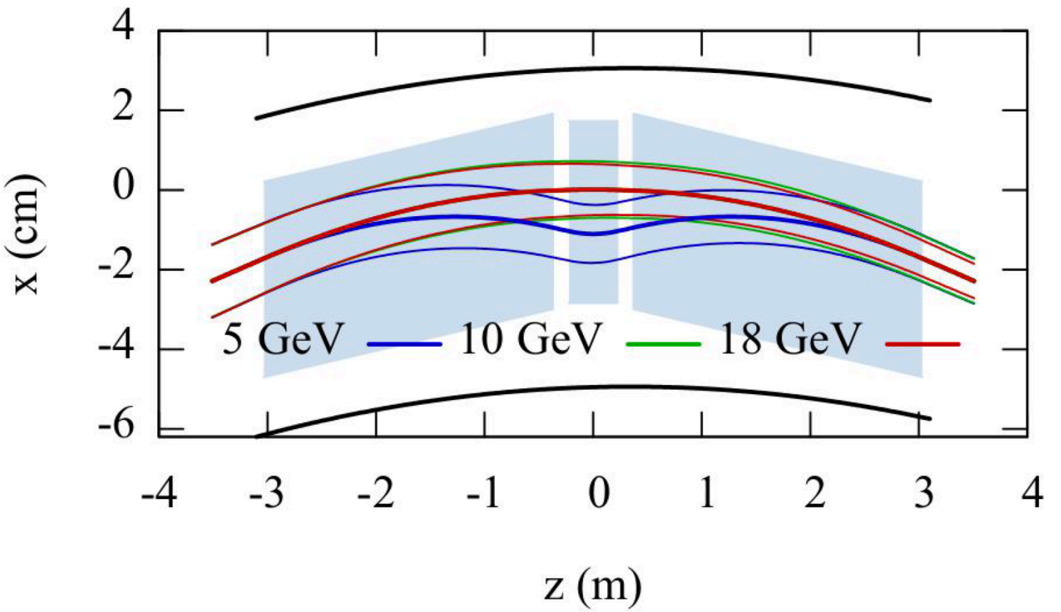




Damping Wiggler

-Energy spread: will increase if wiggler field is stronger than arc dipole
-Require higher RF Voltage
-Emittance: depending on dispersion at the damping wiggler

Split Dipoles in the eRHIC Design



Transverse Single Bunch Instability

- Transverse Mode Coupling Instability Threshold

$$\left|Z_{\perp}(n)\right|_{\text{eff,th}} \propto \frac{(E/e)\upsilon_s}{\left\langle \beta_{\perp} \right\rangle I_{peak}}$$

(should include bunch lengthening effects)

	PEP-II (LER)	JLEIC Electron Ring			JLEIC p-Ring
E (GeV)	3.1	3	5	10	100
I_p(A)	113	59.0	62.35	50.6	15.6
ν_s (10^{-2})	3.7	0.88	1.46	2.51	5.3
$\langle \beta_{\perp} \rangle$	20	13	13	13	64
$\left\|Z_{\perp}\right\|_{\text{eff,th}}$ [MΩ/m]	1.2	0.81	2.25	9.0	63

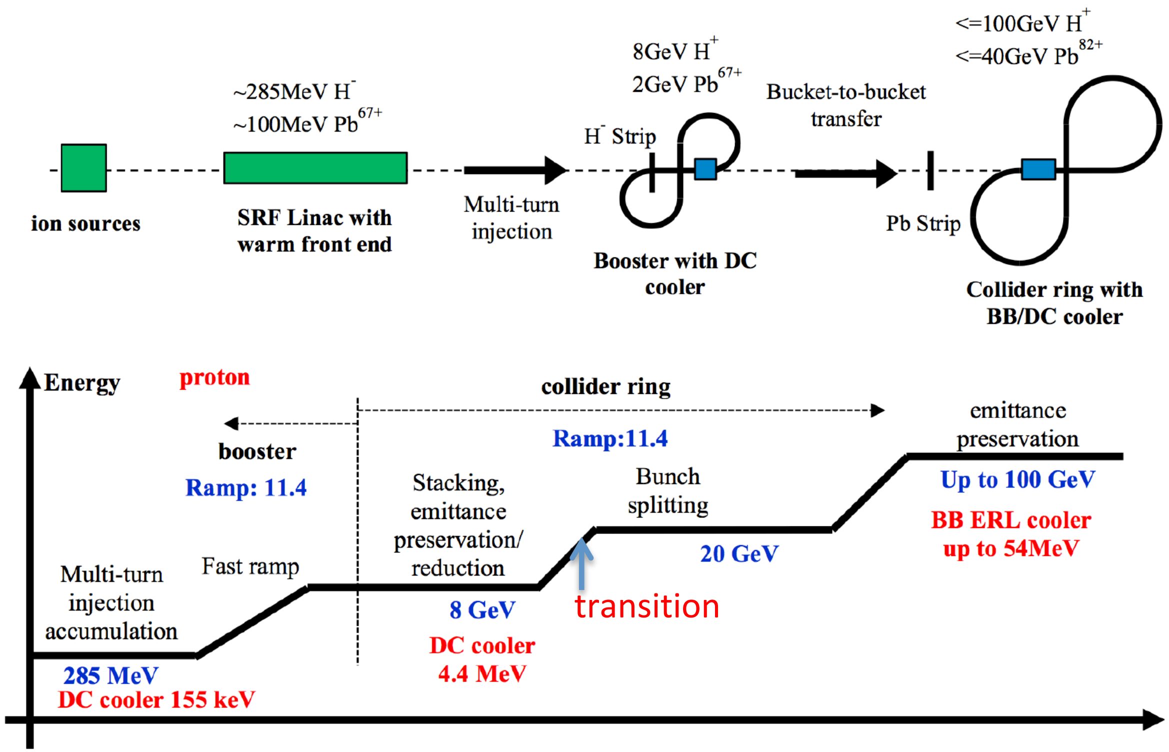
Machine:
$\left|Z_{\perp}\right| \leq 0.1\text{M}\Omega/\text{m}$

Stable

All Stable

Bunch Formation Process (JLEIC)

The ion bunch goes through a complicated formation process

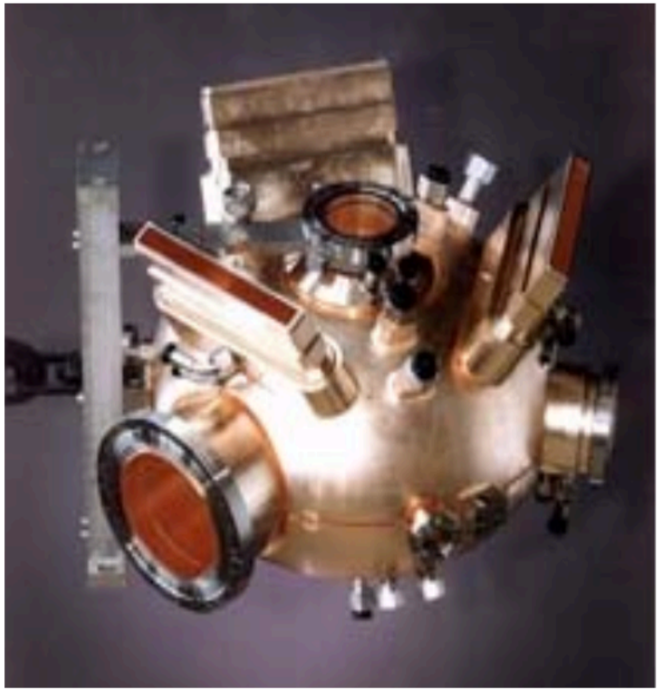


Bunch parameters keep varying during the bunch formation process, so instability threshold keeps changing

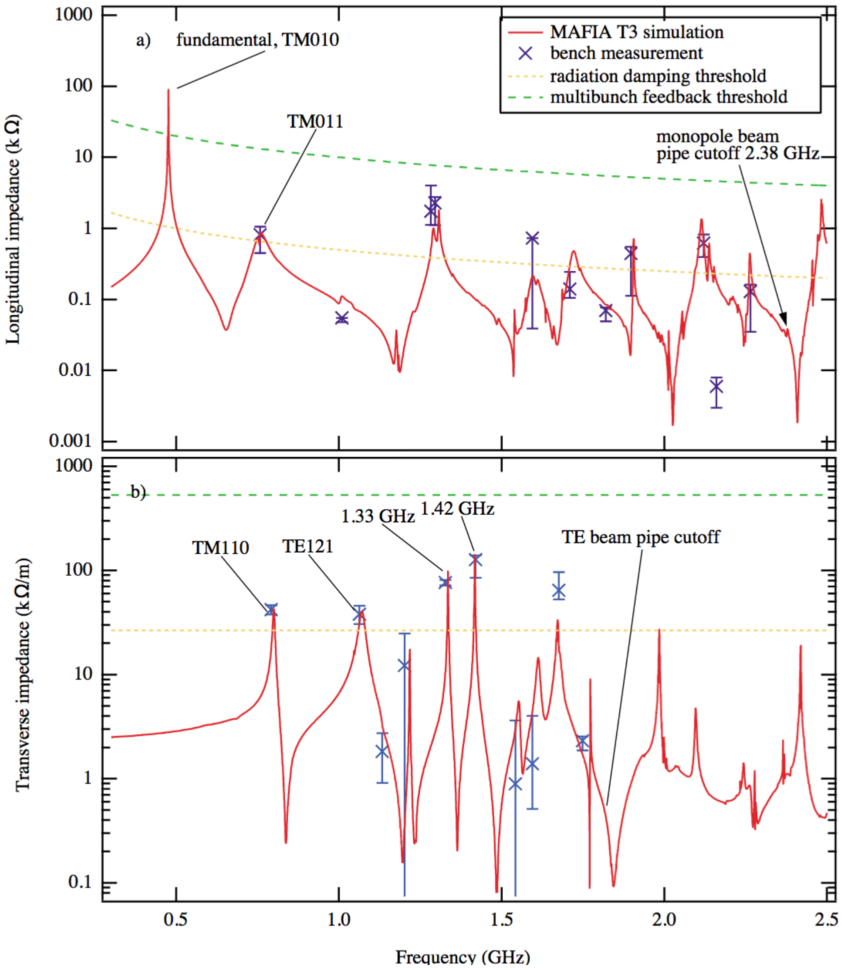
TMCI with space charge, and LLD, could takes place at injection, etc.

Narrowband Impedance Estimation: JLEIC e-Ring

- RF cavity in e-Ring



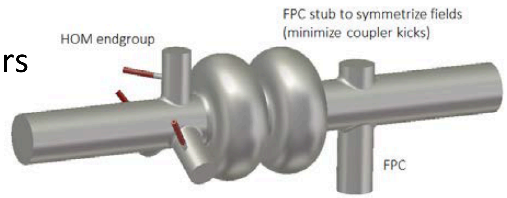
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

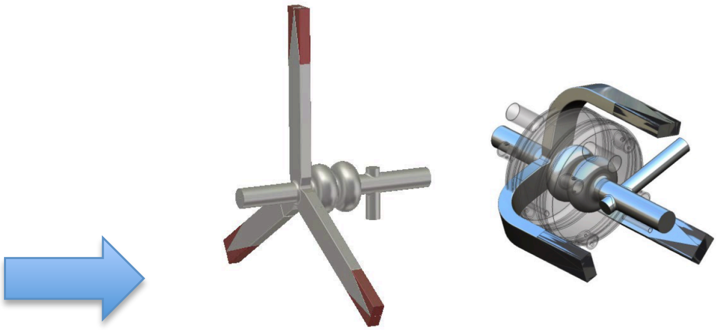


Narrowband Impedance : JLEIC ion-Ring

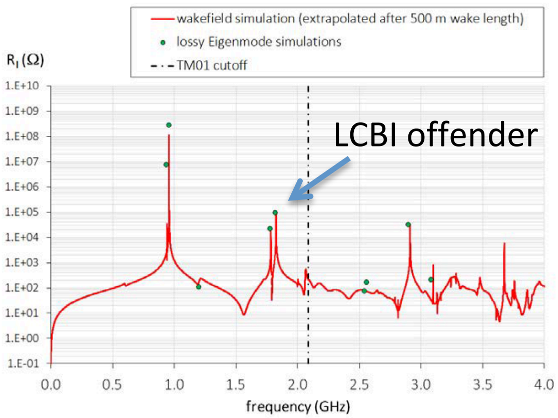
- 956 MHz 2-cell Cavity

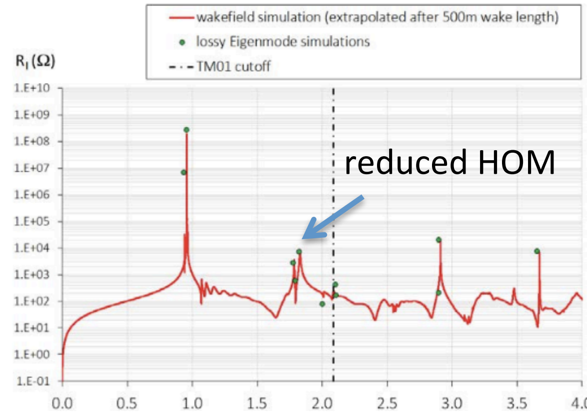
Coaxial couplers

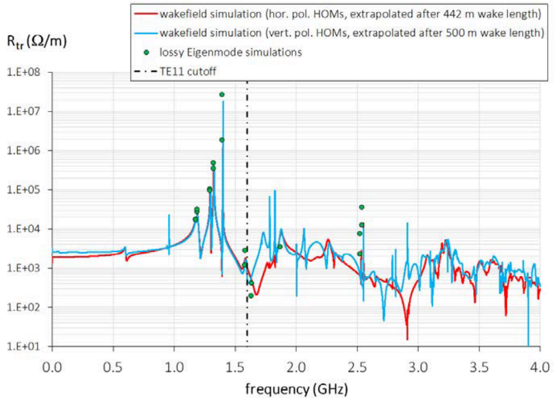


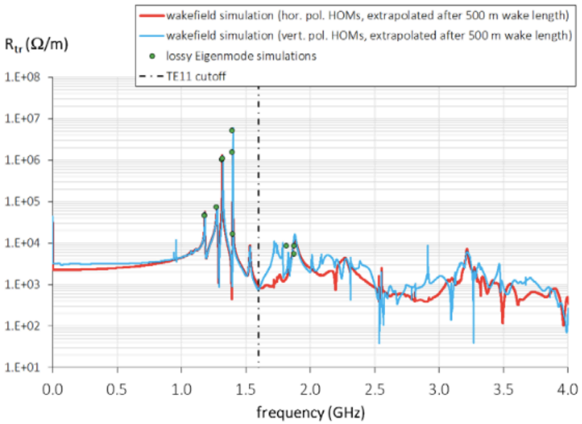


Waveguide couplers









Longitudinal Coupled-Bunch Instability

- **Growth Rate**

(Zotter's formula)

$$g_{\mu,a} = \left(\frac{a}{a+1}\right)\frac{I_b\omega_0^2\eta}{3(L/2\pi R)^3 2\pi\beta^2(E_T/e)\omega_s}\left[\frac{Z_{\parallel}}{n}\right]_{\text{eff}}^{\mu,a}$$

for

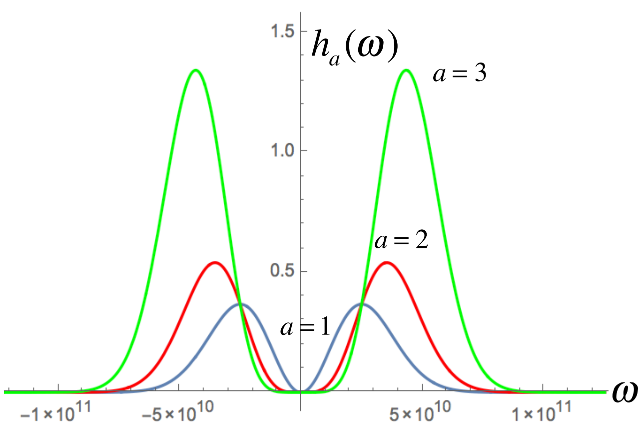
$$\left[\frac{Z_{\parallel}}{n}\right]_{\text{eff}}^{\mu,a} = \frac{\sum_{p=-\infty}^{\infty}\frac{Z_{\parallel}(\omega_p'')}{(\omega_p''/\omega_0)}h_a(\omega_p'')}{\sum_{p=-\infty}^{\infty}h_a(\omega_p'')}$$

$$\omega'' = (pM+\mu+\nu_s)\omega_0$$

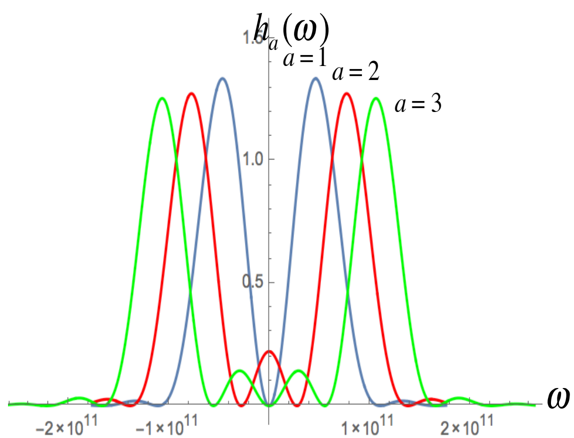
Single-bunch mode spectra

bunch profile under strong electron cooling

Gaussian Bunch



Parabolic Bunch



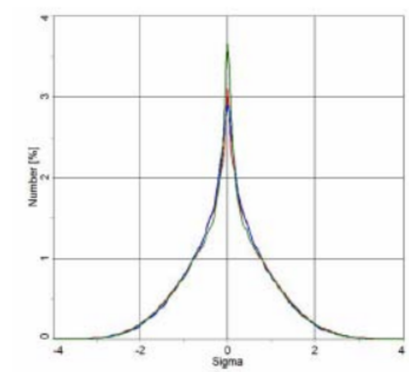


Figure 2: Horizontal (red), vertical (blue) and longitudinal (green) ion beam profiles based on assumption of Gaussian velocity distribution in all three planes.

Impact on the *l=2* mode growth rate ?

Longitudinal Coupled-Bunch Instability

JLEIC Electron-ring (Gaussian bunch)

E [GeV]	3	5	10
$\tau_{l=1}$ [ms]	2.9	4.0	72.8
$\tau_{l=2}$ [ms]	31.3	43.5	466
τ_E [ms]	187.4	40.5	5.1
V_{RF} [MV]	0.40	2.02	17.87
Cavity Number	1	2	15

JLEIC p-ring (Parabolic bunch)

E [GeV]	100
$\tau_{l=1}$ [ms]	30.7
$\tau_{l=2}$ [ms]	6.2
V_{RF} [MV]	42.6
Cavity Number	34

Caused By Z^{RW}!

- Is the *l=2* mode real?
- Can it be damped? $T_0 = 75\ \mu s$, $T_s = 20\ T_0$, $\tau_g = 6$ ms=40 T_s what about damper noise?
- The combined effects of HOM from both RF and crab will be studied later

Transverse Coupled-Bunch Instability

JLEIC Electron-ring

E [GeV]	3	5	10
$\tau_{a=0}$ [ms]	1.6	2.7	64
$\tau_{a=1}$ [ms]	12.8	19.6	39.8
τ_{y} [ms]	375	81	10.1
V_{RF} [MV]	0.40	2.02	17.87
Cavity Number	1	2	15

(for deQ factor=1)

(assume ξ=1, $\Delta\upsilon_{\beta}$=3e-04)

JLEIC p-ring

E [GeV]	100
$\tau_{a=0}$ [ms]	24.4
$\tau_{a=1}$ [ms]	805
τ_{y} [min]	>30
V_{RF} [MV]	42.6
Cavity Number	34

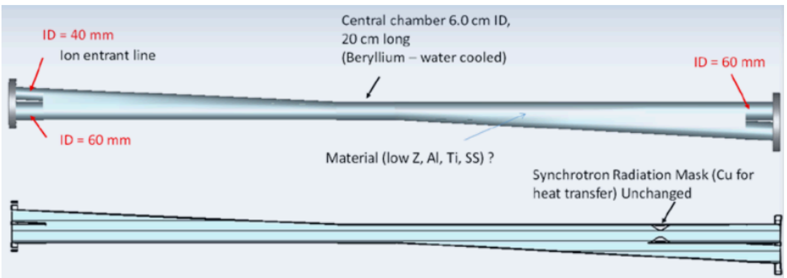
(for deQ factor=1)

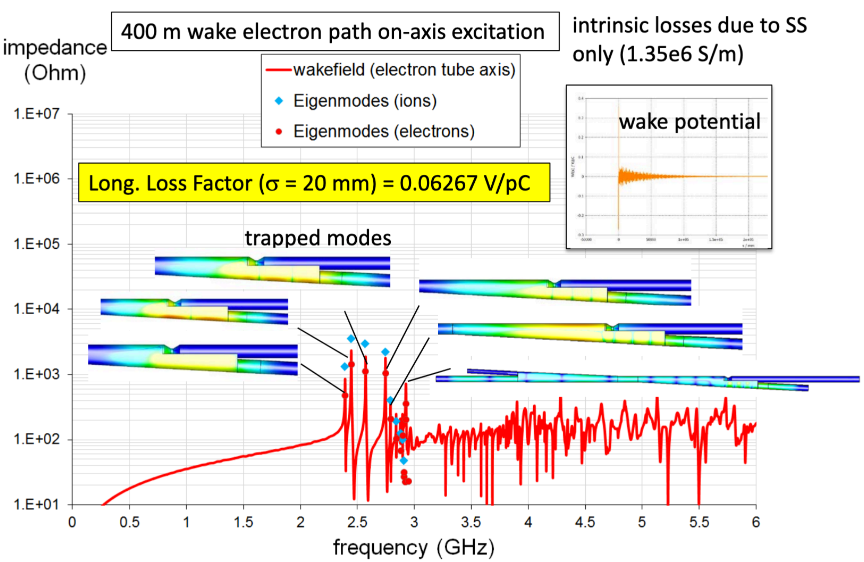
(assume ξ=1, $\Delta\upsilon_{\beta}$=3e-04)

Other Narrowband Impedances

JLEIC IR Chamber

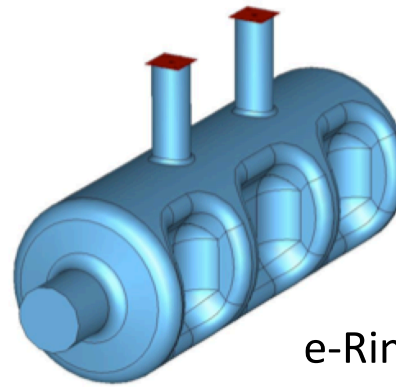
(design is still on-going)





Crab Cavity

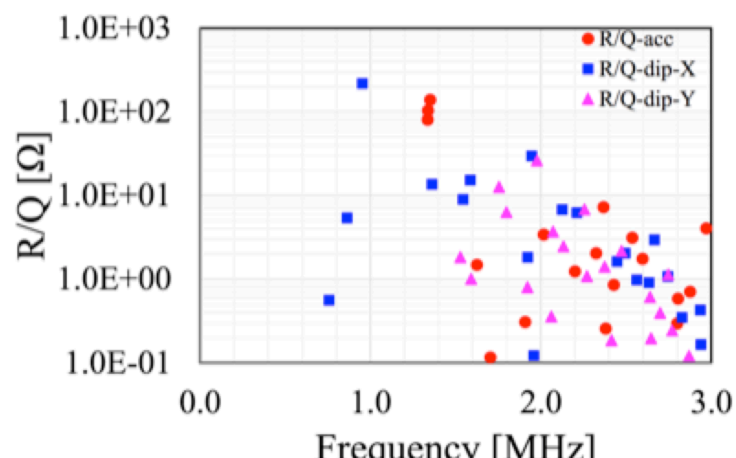
(design is still on-going)



3-cell 952.6 MHz rf dipole with coaxial couplers

e-Ring: 2 crab cavities

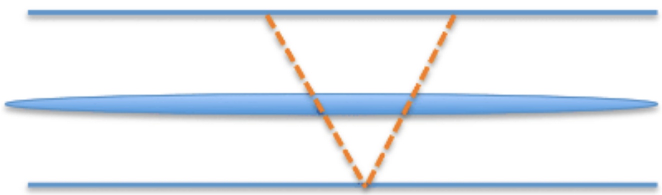
ion-Ring: 8 crab cavities



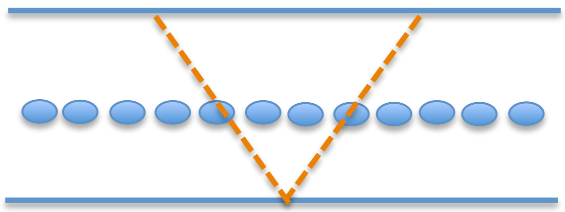
Electron Cloud in the JLEIC Ion Ring

- Electron Cloud Build up

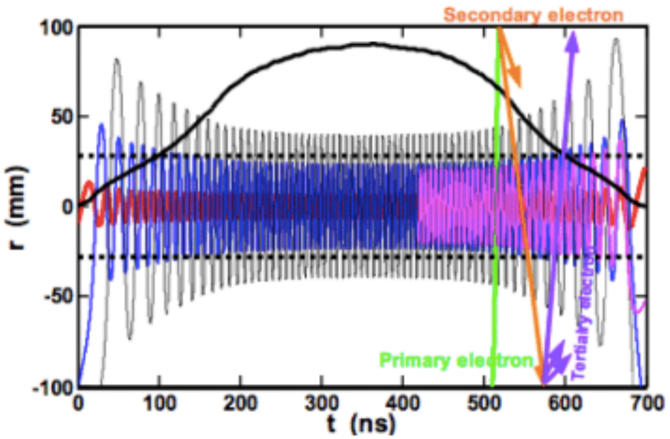
  - Long ion bunch with low rep rate (in conventional ion ring)



  - Short ion bunch with fast rep rate (in JLEIC)



Trailing-Edge Effect



Short-bunches:

e-cloud build up rapidly and saturate around the neutralization density

$$\rho_{neu} = \frac{N_b}{\pi b^2 s_b}$$

Electron Cloud in the JLEIC Ion Ring

- Electron Cloud Build-up

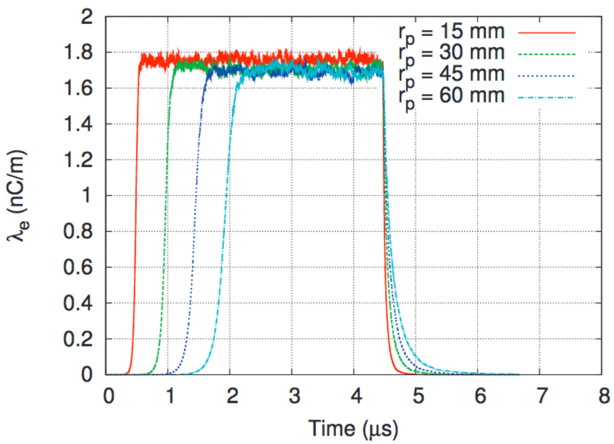


Figure 4: Time evolution of electron cloud for beam pipe with different radii. Simulations are run for 3350 consecutive bunches.

- Single-bunch head-tail instability from e-cloud

The instability threshold for the e-cloud density (two-particle model)

$$\rho_{th} = \frac{2\gamma Q_s A}{\pi r_p Z C \beta_y} = 1.7\times 10^{13}\ \ \mathrm{m}^{-3}$$

$$\rho_{th} \gg \rho_{sat} = \frac{N_b}{\pi b^2 s_b} = 2\times 10^{12}\ \ \mathrm{m}^{-3} \quad \text{(stable)}$$

- E-cloud caused coupled-bunch instability for PEPII-LER
- E-cloud effects in JLEIC require careful numerical studies, especially for the process of bunch formation in the ion ring

Fast Beam-Ion Instability in the JLEIC e-Ring

Growth time of FBII for the JLEIC e-Ring

E_e [GeV]	3	5	10
$\tau_g [\mu s]$	0.01	0.11	13.9
$\tau_e [ms]$	0.02	0.1	3.2

10s or 100 times faster

Comparable to PEP-II case

- Possible mitigation method
  - Use chromaticity to damp FBII
  - Use multiple bunch trains to reduce the growth amplitude
  - Natural Landau damping from beam-beam tune-shift spread
- Comprehensive numerical modeling of FBII and its mitigation will be performed

Collective Instabilities in eRHIC (Mike Blaskiewicz)

e-Ring

- Longitudinal and transverse single bunch instabilities are Landau damped
- Longitudinal coupled-bunch instability is mitigated by damper
- Transverse coupled-bunch instability set the threshold current (Landau damping from beam-beam tune spread included)

  I_e^{th}=2.7 A at E_e=10 GeV I_e^{th}=1.7 A at E_e=5 GeV

  3rd harmonic cavity is used to increase Q_e^{th}= 48nC (by coupling synchrotron tune spread to transverse via chromaticity)
- Ion effect
  - a significant fraction of ions survive the abort gap and can allow the tail of the bunch train to drive the head of the bunch train
  - Landau damping by Beam-beam tune spread

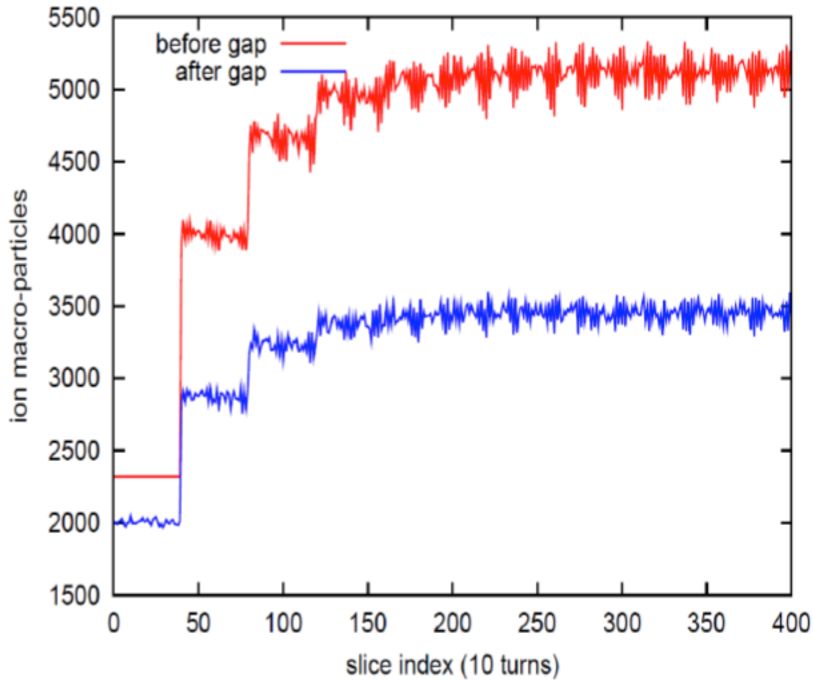
Ion-Ring

- coating the vacuum chamber with copper to reduce the heat load on the cryo-system
- plan to add amorphous carbon to reduce secondary yield
- working on a backup plan involving copper coated inserts.

Ion Effects in eRHIC

(M. Blaskiewicz, NAPAC19)

- Simulation
  - Ion creation, drift, and interaction with e-bunch, at distributed ion slices around the ring
  - Gaussian electron bunch transported in between ion slices, and interact with ions via EM interaction
  - Beam-beam kick (thin lens model)



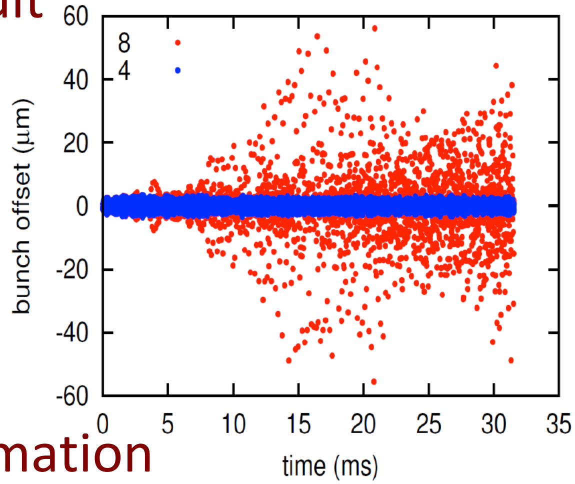
- Results
  - H_2 unstrapped within the bunch train
  - CO is trapped within the bunch train but unstable when gap is included
  - Considerable CO survive a 10% gap

Beam-beam Damping of Ion Instability in eRHIC

- Tracking Result

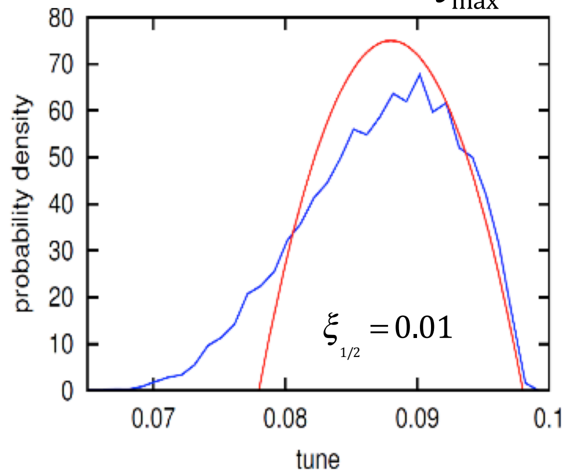
1160 e-bunches,
100 bunch gap
10^4 macroparticles/bunch
Beam-beam: $\xi_{max} = 0.05$

$n_{CO} = 4 \times 10^{12}\ m^{-3}$



- Dispersion Relation

Beam-beam tune spread: $\xi_{max} = 0.05$



Use parabolic distribution
Function for dispersion
function

- Analytical estimation

$$\left(\frac{\partial}{\partial t} + \omega_0 \frac{\partial}{\partial \theta}\right)^2 y_e + \omega_y^2 y_e = \omega_e^2 y_I$$

$$\left(\frac{\partial^2}{\partial t^2} + \frac{\omega_I}{Q_I}\frac{\partial}{\partial t} + \omega_I^2\right) y_I = \omega_I^2 y_e$$

Take $y_{e,I}(\theta,t) = \hat{y}_{e,I} \exp(in\theta - i\Omega t)$ with $\Omega \approx \omega_I$.
The unstable mode has

$$\mathrm{Im}(Q_y) = \frac{r_e \lambda_I Q_I c^2}{2\omega_0 \omega_y \gamma \sigma_x \sigma_y}$$

Growth rate
$\mathrm{Im}(Q_y) = 0.0051$

~ agree

Beam-beam tune shift=0.05
Δ=0.01 can suppress:
$\mathrm{Im}(Q_y) = 0.0042$

3. MCBI in an EIC

	Electron			Proton
E [GeV]	3	5	10	100
Single bunch longitudinal instability	🔴	🟡	🟢	🟢
Single bunch transverse instability	🟢	🟢	🟢	🟢
Coupled bunch longitudinal instability		Require state-of-art fast bunch-by-bunch feedback system		🟡
Coupled bunch transverse instability				
Electron cloud				Ok for TMCI Question for CBI
Ion effects	🔴	🔴	🟢	

damping wiggler
split dipole
(η, σ_δ)

octupole
Chromaticity
damper

Landau cavity
damper

octupole
chromaticity
Damper
beam-beam

chromaticity
beam-beam
gap in bunch train
damper, clearing electrode

4. Summary

- We've done some preliminary assessment of instabilities in JLEIC and eRHIC, and see areas vulnerable for instability
- More detailed analysis and simulations will be performed, especially when multiple mechanisms are involved
- We'll seek more active methods to mitigate the instabilities
- Community support is important for EIC designs. We welcome collaborations.

Thank you for your attention!