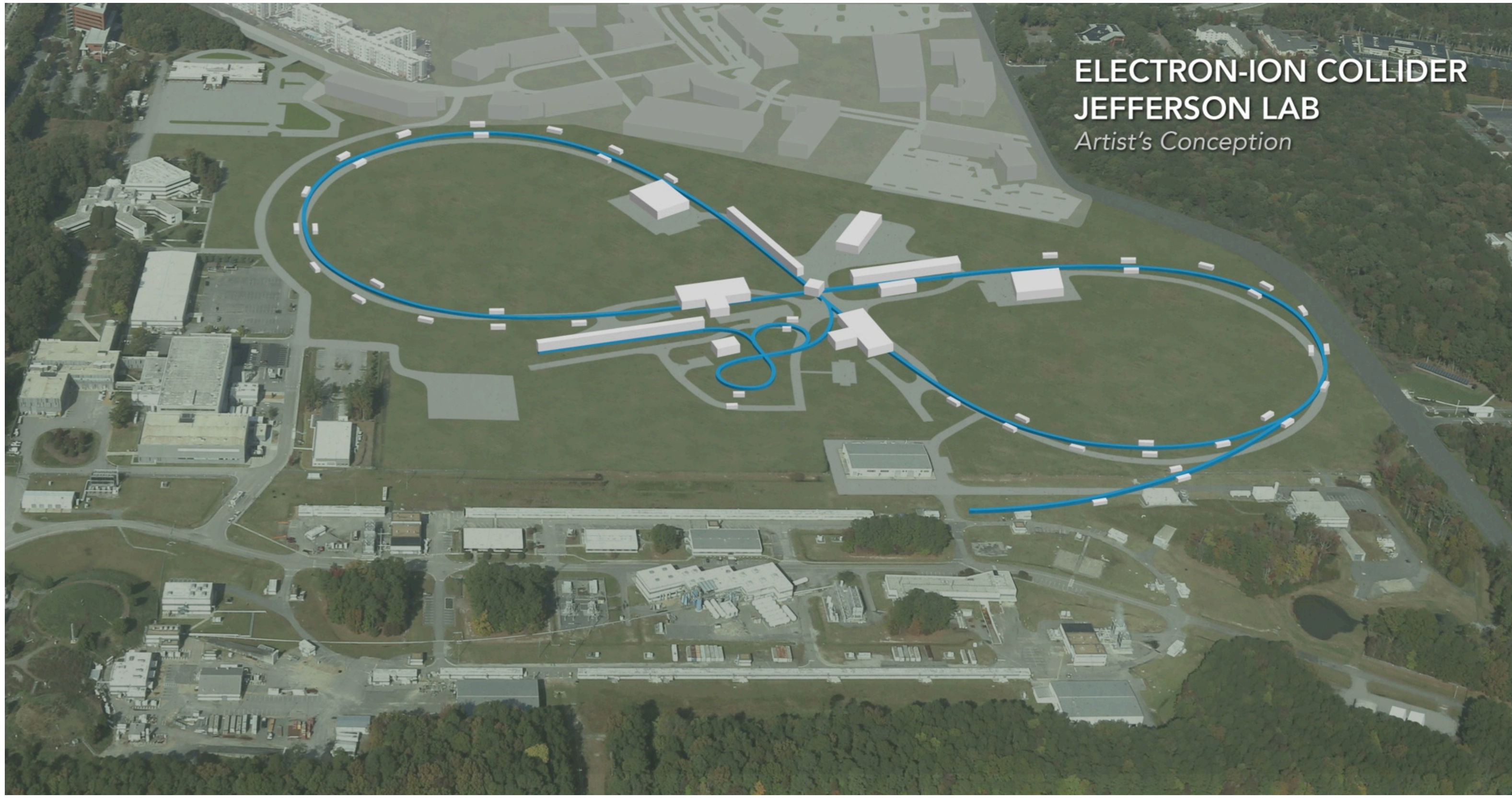
Collective Effects in JLEIC

Rui Li



EIC Accelerator Collaboration Meeting

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Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science
JSA

Acknowledgement

JLEIC Impedance Study Collaboration

CASA: K. Deitrick, R. Li, T. Satogata,

RF Group: J. Guo, F. Marhauser, R. Rimmer, H. Wang, S. Wang

Engineering Group: C. Hutton, T. Michalski, M. Wiseman, R. Lassiter

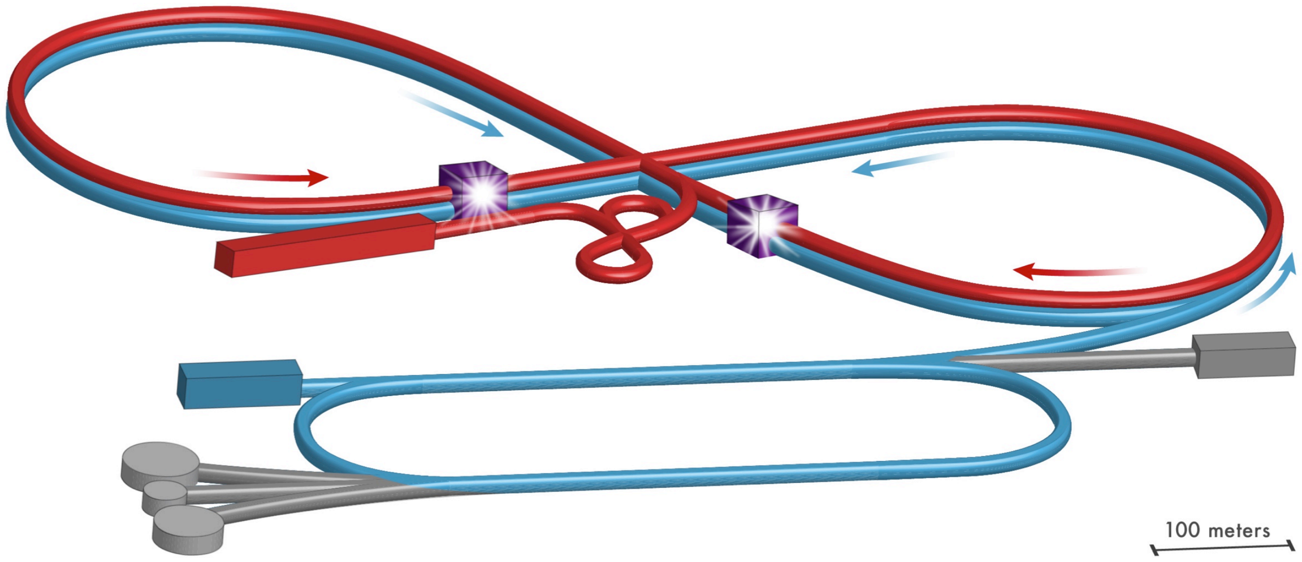
ODU: J. Delayen, H. Park, S. Sosa, S. De Silva

Outline

1. Introduction
2. Impedance Studies for JLEIC
3. Collective Instability Estimations
   - Wakefield-induced instabilities
   - Two-stream instabilities
4. Summary

1. Introduction

- Design goals of JLEIC
  - Luminosity: 10^{33}~10^{34} [$cm^{-2}s^{-1}$]
  - Wide range of $E_{CM:}$ 30~100 [GeV]
  - Wide range of ion species
  - High polarization (~70% for e^- and light ions)



- Special Features of JLEIC
  - Figure-8 rings
  - High-energy bunched beam electron cooling

- Goal of Collective Effect Studies for JLEIC

  Ensure beam stability and phase space quality for
  - a wide range of energies for the electron and ion beams during collision
  - wide range of ion species
  - the whole ion bunch formation process

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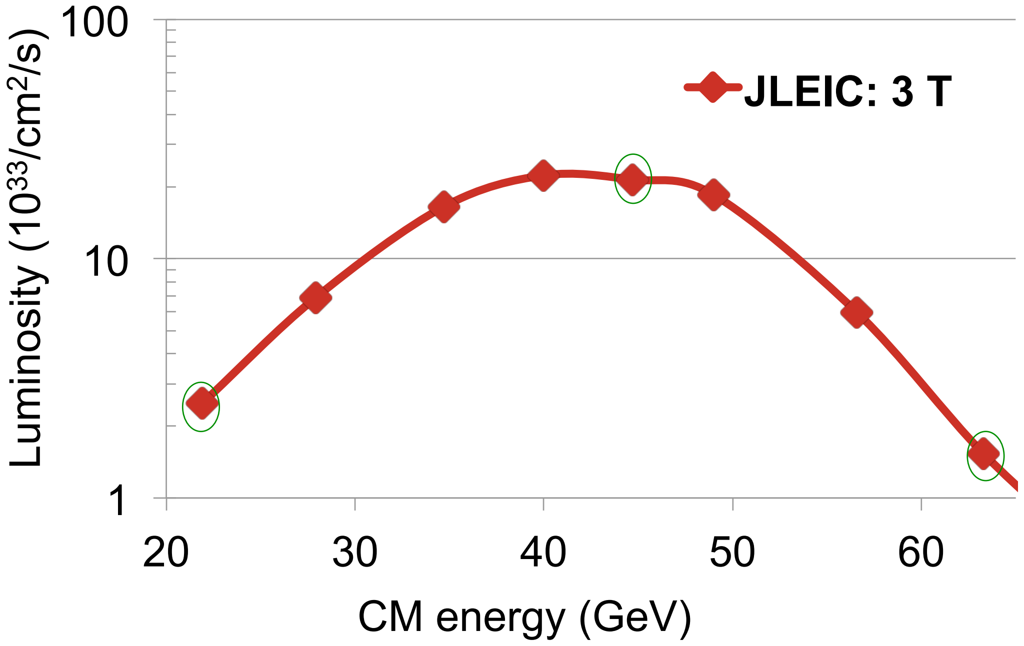
Luminosity Concepts and Features of Collective Effects

- Luminosity concepts of JLEIC
  - Moderate single bunch charge, with low emittances and short bunch length (1.2~1.4 cm)
  - High bunch rep rate (n_b=3420)
  - small beta at IP (1 cm)



- Implication for behaviors of collective effects
  - Moderate single-bunch effects (except at low energies)
  - Strong coupled-bunch effects

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JLEIC Baseline e-p Parameters

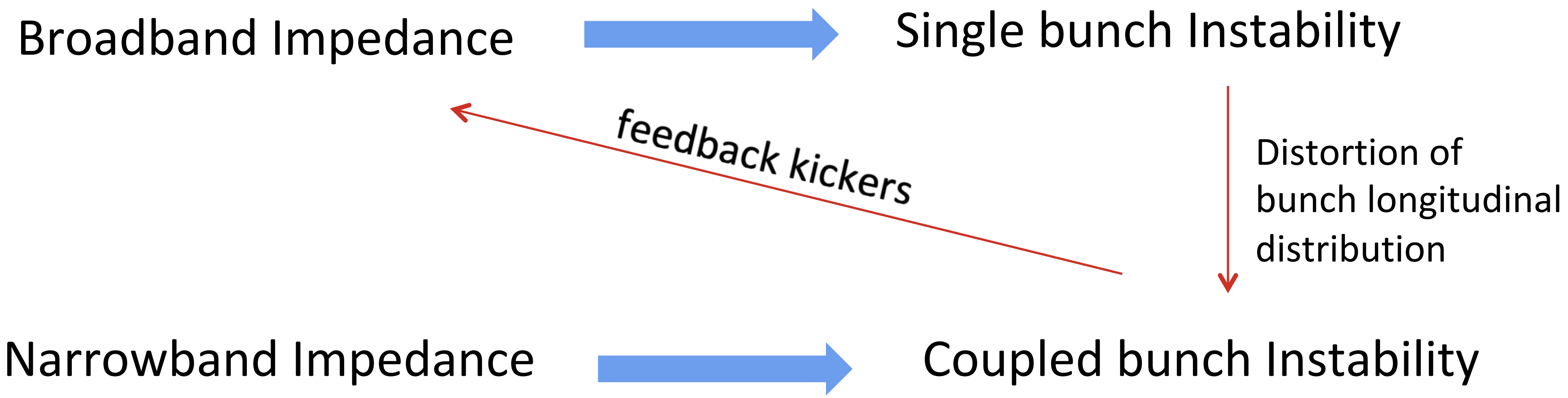
CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	**3**	**100**	**5**	100	**10**
Collision frequency	MHz	**476**		**476**		**476**	
Particles per bunch	10^{10}	**0.98**	**3.7**	**0.98**	**3.7**	**0.98**	**0.93**
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	**3**	**1**	**1**	**1**	**1**	**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	0.002	0.009
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		0.86	
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)

Collective Effects in the JLEIC Complex

Electron Ring Ion Rings	Electron Cooler
• Incoherent: Laslett tune shift, emittance growth, halo • Coherent: Single-bunch Instability, Coupled-bunch Instability (induced by wakefield or impedances) • 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	

2. Impedance Studies for JLEIC



Status of JLEIC Broadband Impedance

- Impedance budget studies requirement
  - Complete inventory of impedance-generating components
  - Engineering design and drawing of each components
  - EM field modeling for wakefield or impedance spectrum

- Current status of impedance studies in JLEIC
  - Engineering design is still in the initial phase
  - Component counts are done (subject to modification)
  - Impedance are estimated using impedance budget of existing machines for reference

Broadband Impedance Estimation: JLEIC e-Ring

- Component Counts (T. Michalski)

Elements	e-Ring
Flanges (pairs)	1215
BPMs	405
Vacuum ports	480
Bellows	480
Vacuum Valves	23
Tapers	6
Collimators	16
DIP screen slots	470
Crab cavities	2
RF cavities	32
RF valves	68
Feedback kickers	2
IR chamber	1

- Impedance Estimation (K. Deitrick)

Broadband Impedance	Reference: PEP-II	Reference: SUPERKEKB	
L [nH]	99.2	28.6	
$\left\|Z_{\parallel}/n\right\|$ [Ω]	0.09	0.02	$\leq$ 0.1 Ω
$k_{\parallel}$ [V/pC]	7.7	19	
$\left\|Z_{\perp}\right\|$ [kΩ/m]	60	13	$\leq$ 0.1 MΩ

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

Broadband Impedance Estimation: JLEIC ion-Ring

- Component Counts (T. Michalski)

Elements	p-Ring
Flanges (pairs)	234
BPMs	214
Vacuum ports	92
Bellows	559
Vacuum Valves	14
Tapers	6
Collimators	16
DIP screen slots	-
Crab cavities	8
RF cavities	40
RF cavity bellows	40
RF valves	24
Feedback kickers	2
IR chamber	1

- Impedance Estimation (K. Deitrick)

Broadband Impedance	Reference: PEP-II	
L [nH]	97.6	
$\left\|Z_{\parallel}/n\right\|$ [Ω]	0.08	$\leq 0.1\ \Omega$
$k_{\parallel}$ [V/pC]	8.6	
$\left\|Z_{\perp}\right\|$ [kΩ/m]	80	$\leq 0.1\ \mathrm{M\Omega}$

- The short bunch length (1.0cm) at collision is unprecedented for the ion beams in existing ion rings
- Bunch length varies through the whole bunch formation process

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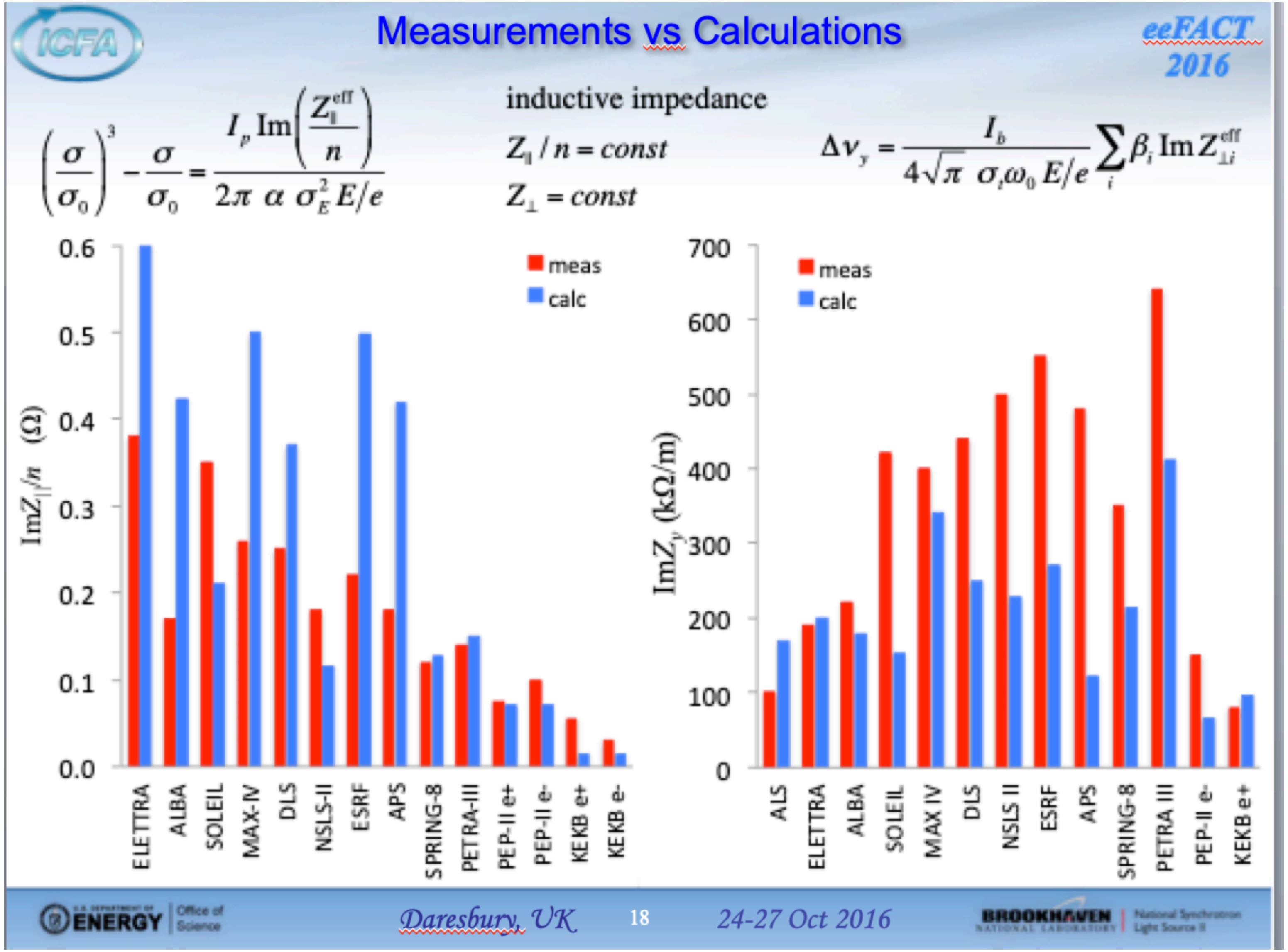
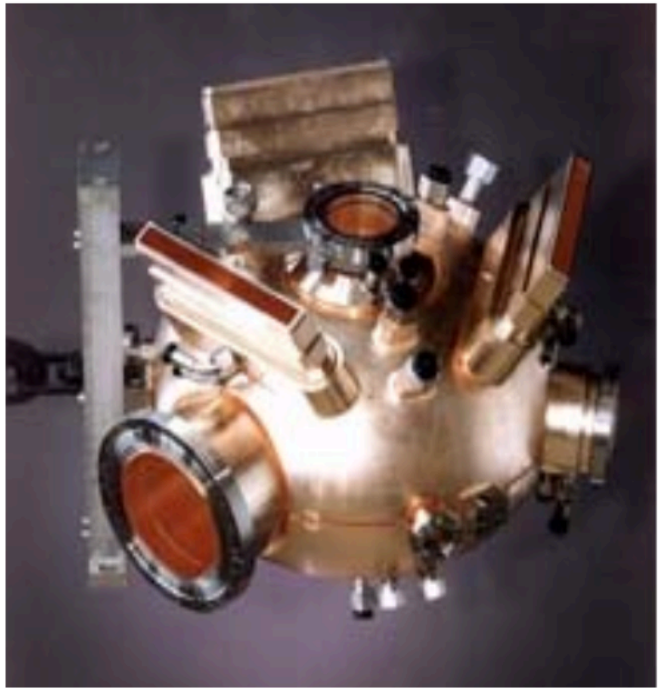
Impedance Measurement vs. Calculation



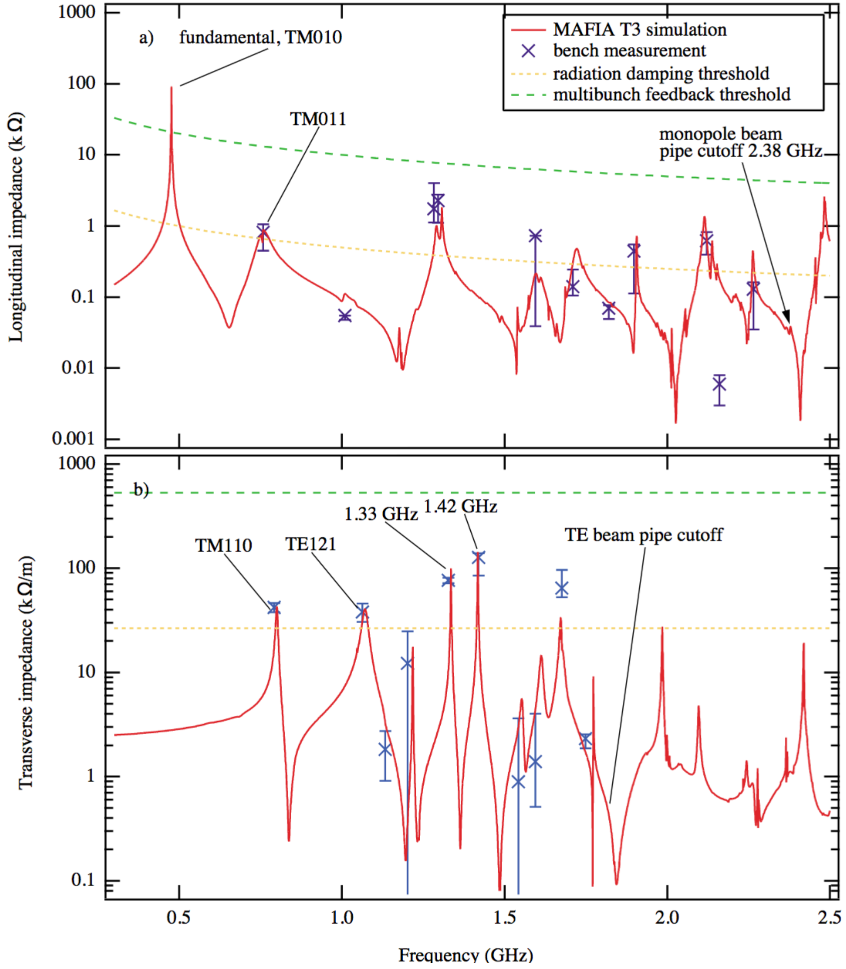
(V. Smaluk, eeFACT2016)

Narrowband Impedance Estimation: JLEIC e-Ring

- RF cavity in e-Ring (PEP-II cavities)



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

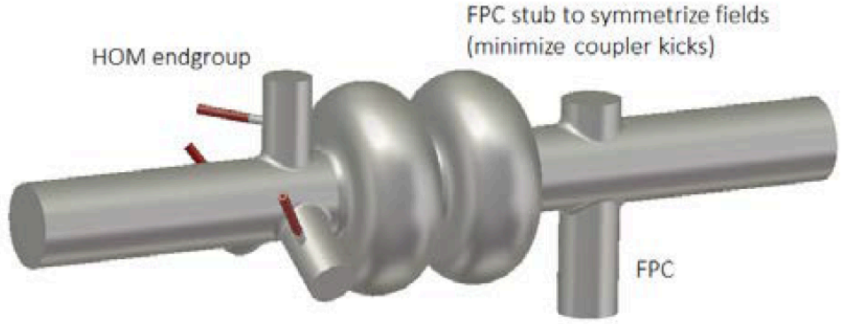


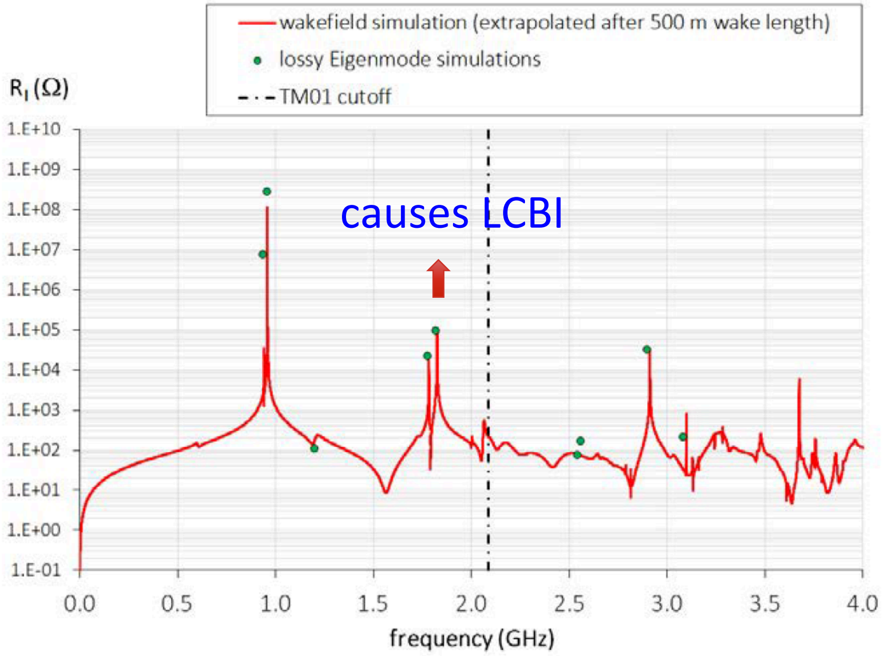
Narrowband Impedance : JLEIC ion-Ring

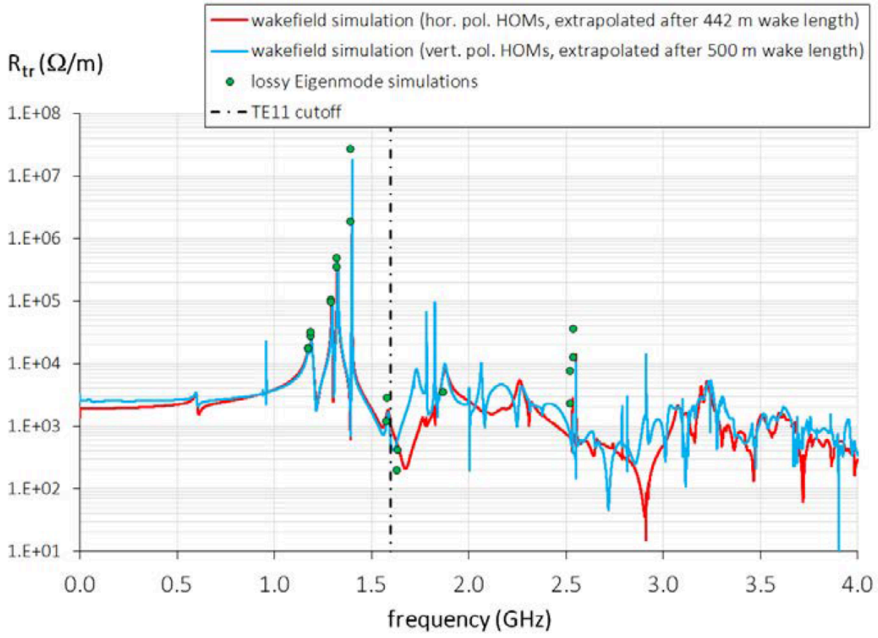
with coaxial couplers

- 956 MHz 2-cell Cavity (F. Marhauser)

as tradeoff between accelerating and HOM-damping efficiency







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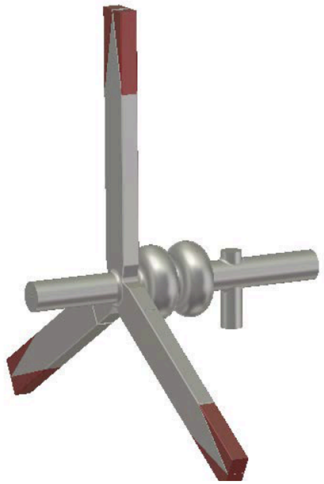
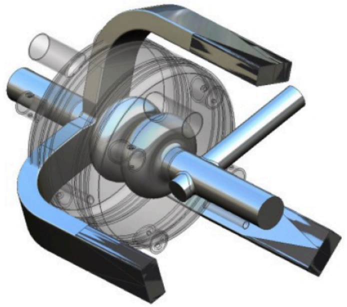
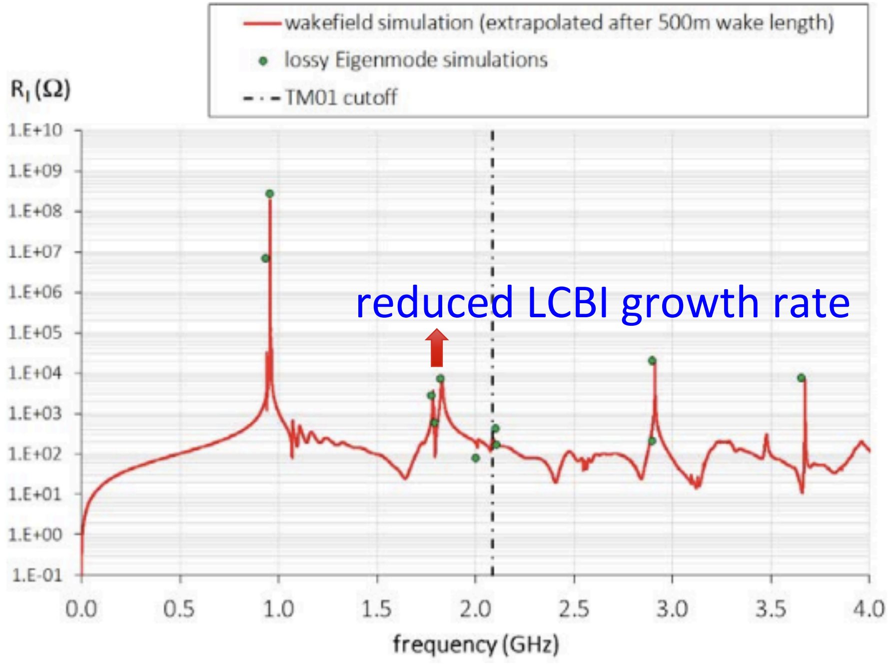
Narrowband Impedance : JLEIC ion-Ring

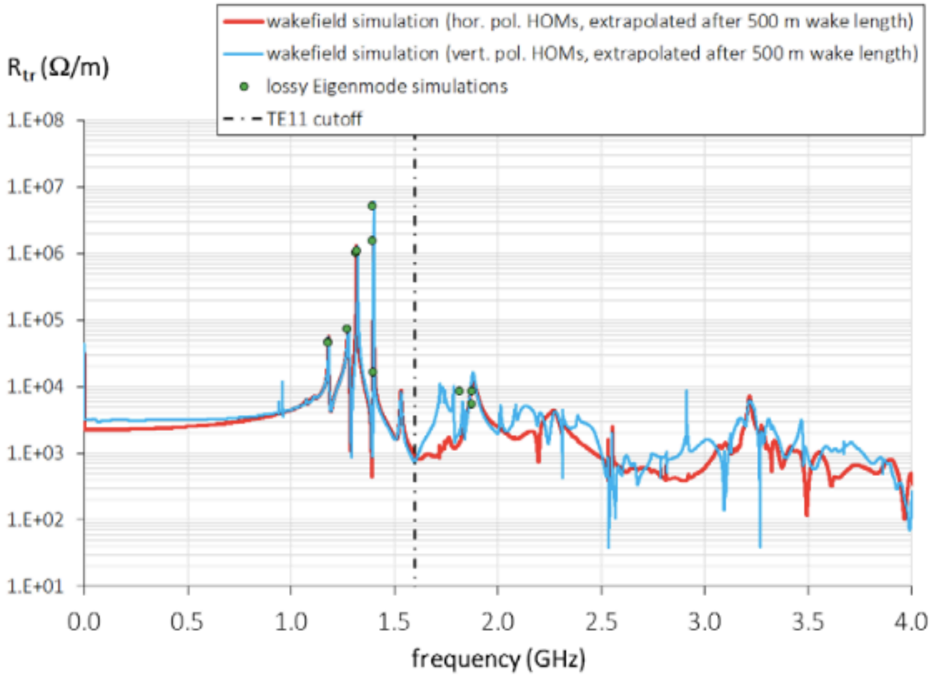
- 956 MHz 2-cell Cavity (F. Marhauser)



waveguide couplers

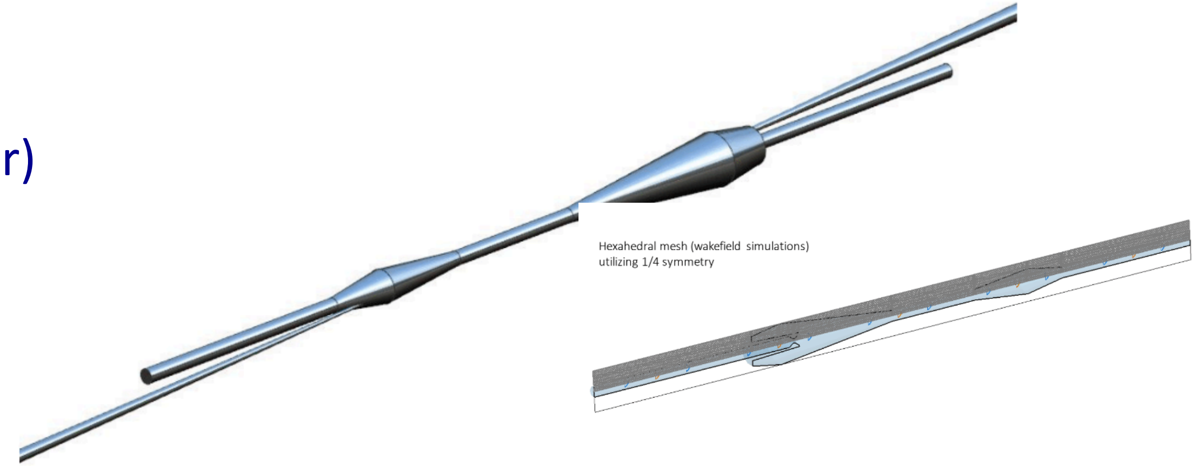




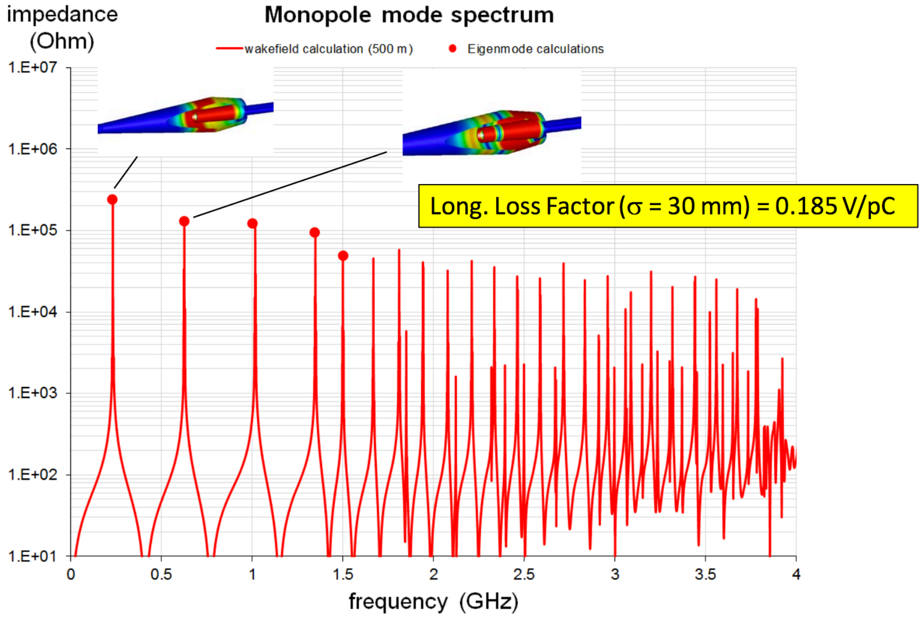


Narrowband Impedance: IR Chamber

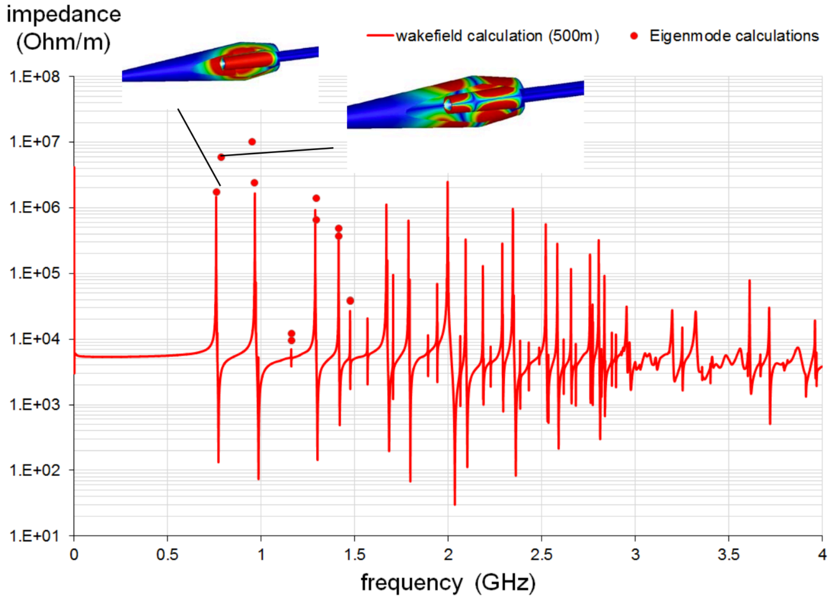
JLEIC IR Chamber CAD Model (Marhauser)



Monopole Modes



Dipole Modes



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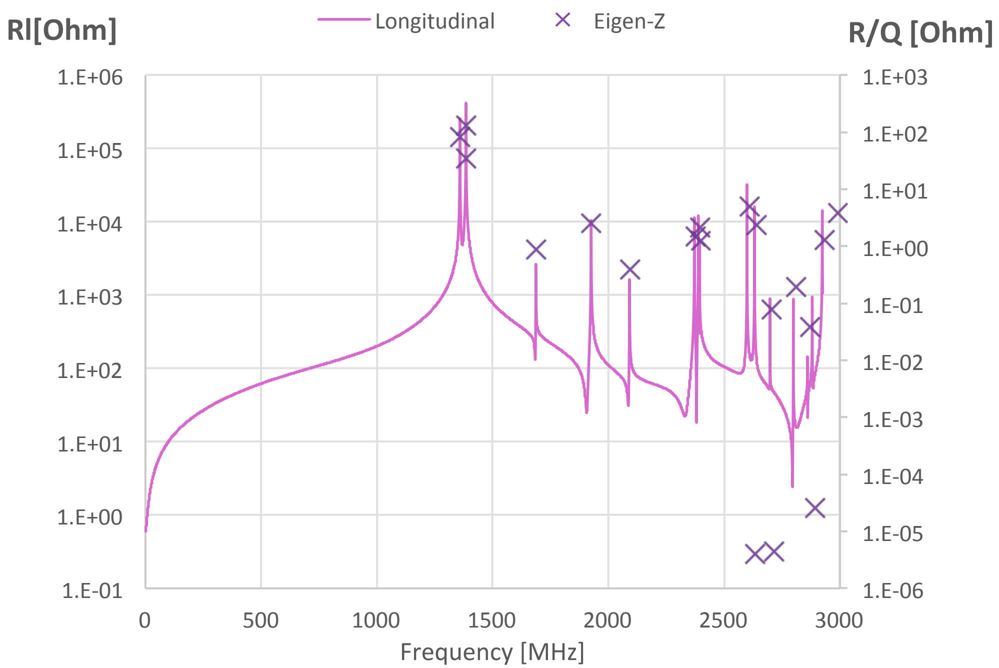
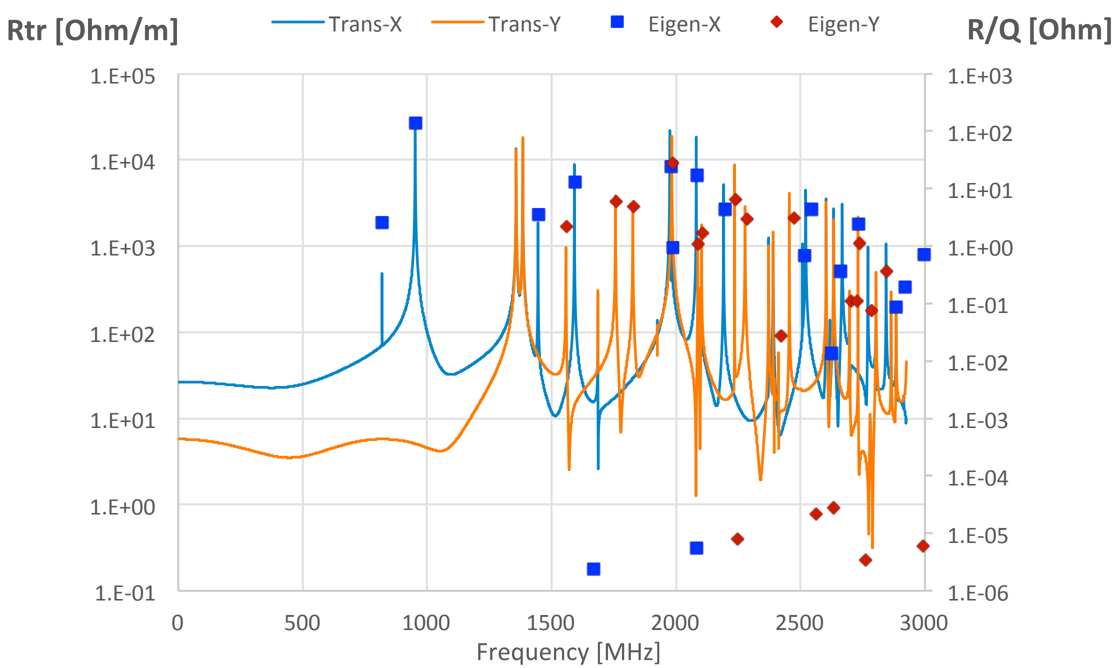
Narrow Impedance : Crab Cavity (e-Ring: 2 crab cavities, Ion Ring: 8 crab cavities)

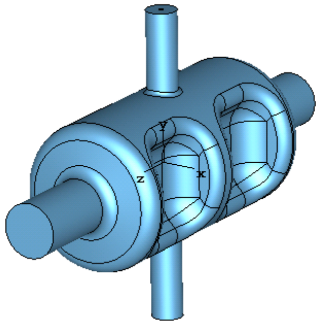
- Prototype converging to a 952.6 MHz 2-cell RFD cavity. (HK Park)
- Bare cavity impedance



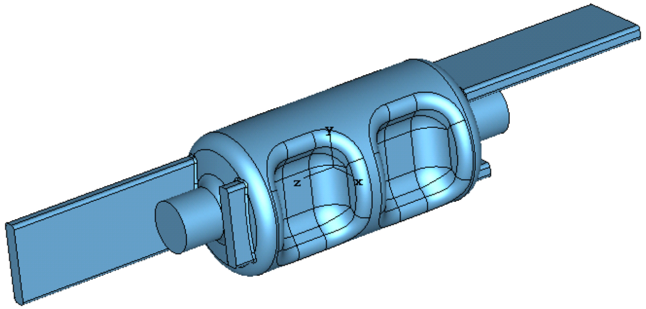


- Damping under study

2 hook couplers



2 wave guides



JLEIC Impedance Status

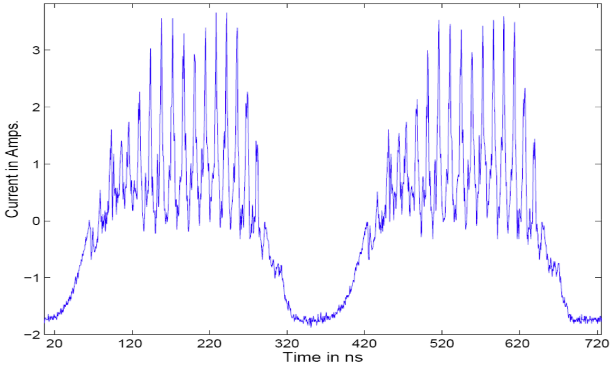
- We are at the beginning phase of impedance studies
- Preliminary estimations are done
- Engineering design and EM modeling are underway

3. Collective Instabilities in JLEIC

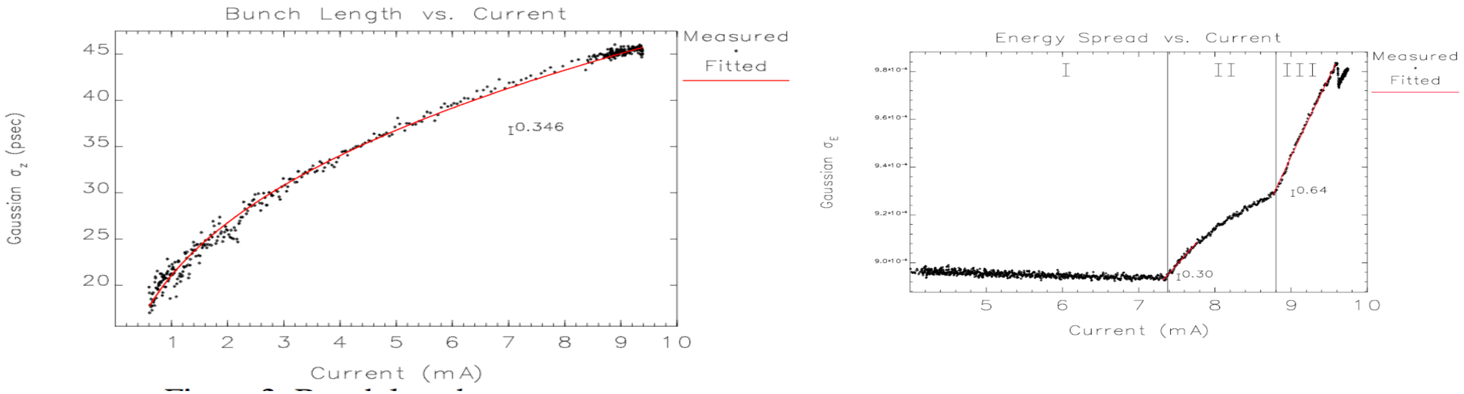
- Wakefield induced instabilities
  - Single bunch instability
  - Coupled bunch instability
- Two-stream instabilities
  - Electron cloud in the ion ring
  - Ion effect in the e-ring

Single Bunch Instability: Longitudinal Microwave Instability

Longitudinal wakefield and momentum compaction can form a positive feedback loop to amplify density modulation

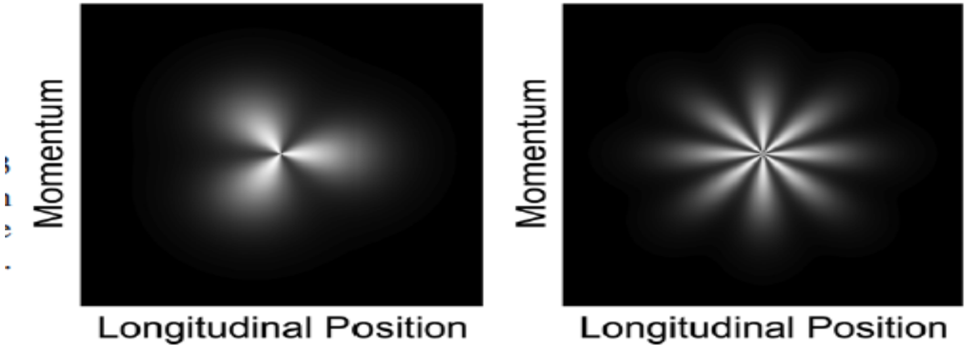


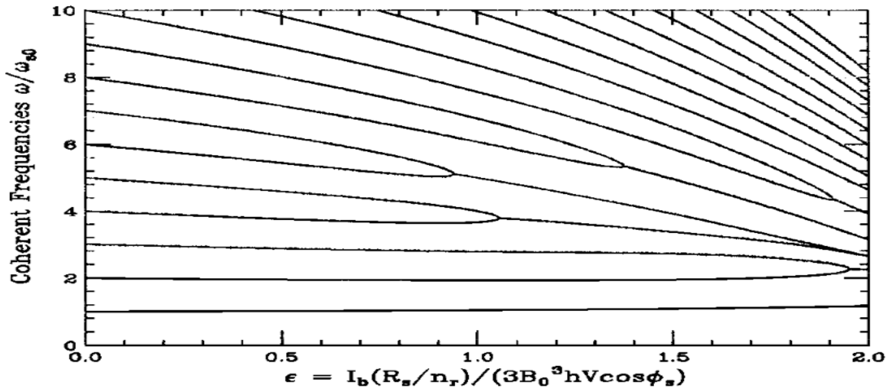
(Observation at PSR)



Observation at APS (2001)

- Longitudinal Mode Coupling Instability





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Single Bunch Instability: Longitudinal Microwave Instability

- Longitudinal Single-Bunch Instability Threshold

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

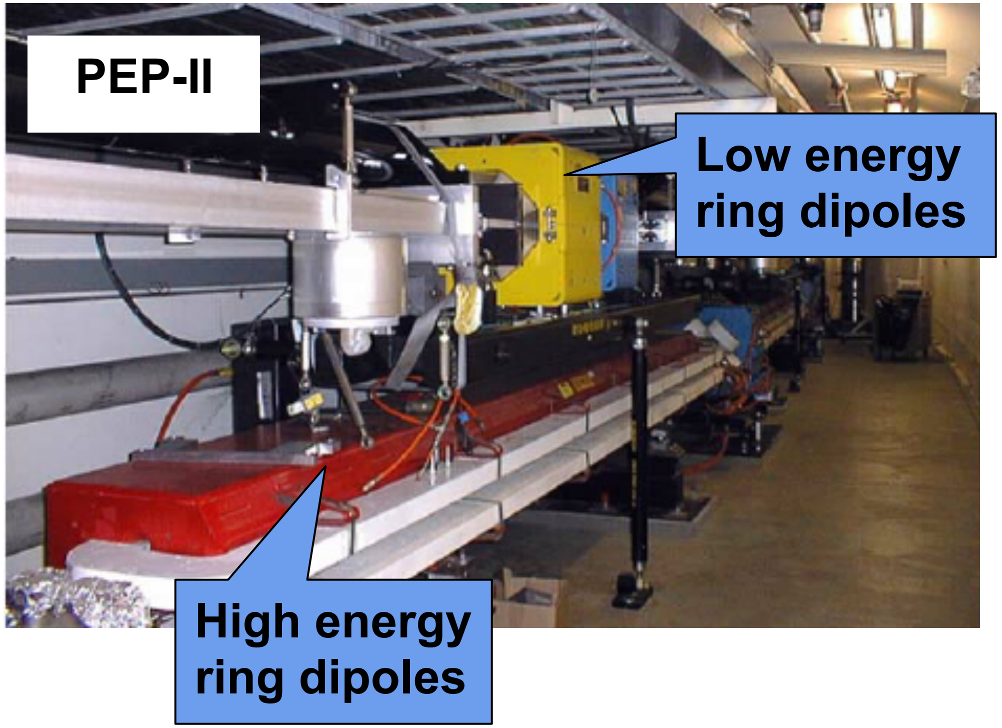
	PEP-II (LER)	JLEIC Electron Ring			JLEIC p-Ring
E (GeV)	3.1	3	5	10	100
I_p(A)	113	59.0	62.35	50.6	15.6
η (10^{-3})	1.31	1.09	1.09	1.09	6.22
σ_δ (10^{-4})	8.0	2.78	4.55	9.28	3.0
$\left\|Z_{\parallel}/n\right\|^{\text{th}}$ [Ω]	0.145	0.027	0.125	1.16	22.5
	Stable	Unstable!	Marginally Stable	Stable	Stable

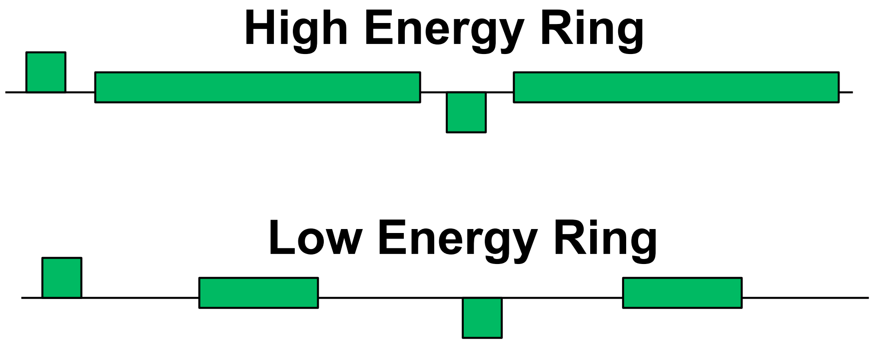
Estimated e-Ring impedance $\left|Z_{\parallel}/n\right|^{\text{Ring}} \approx 0.1\ \Omega$

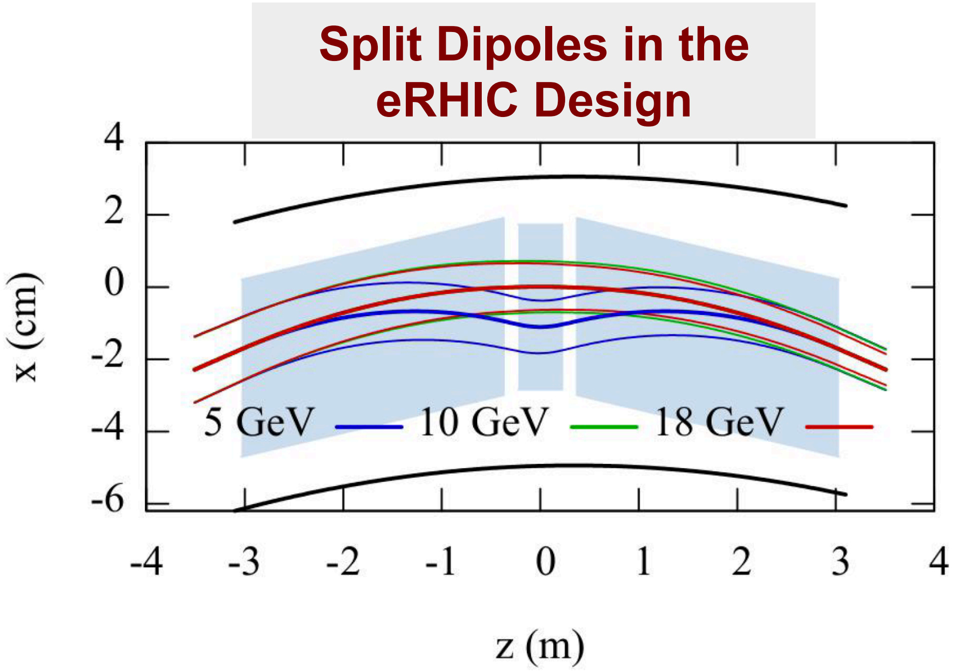
Estimated p-Ring impedance $\left|Z_{\parallel}/n\right|^{\text{Ring}} \approx 0.1\ \Omega$

Mitigation Methods

- Alternative beamline configurations at low energies



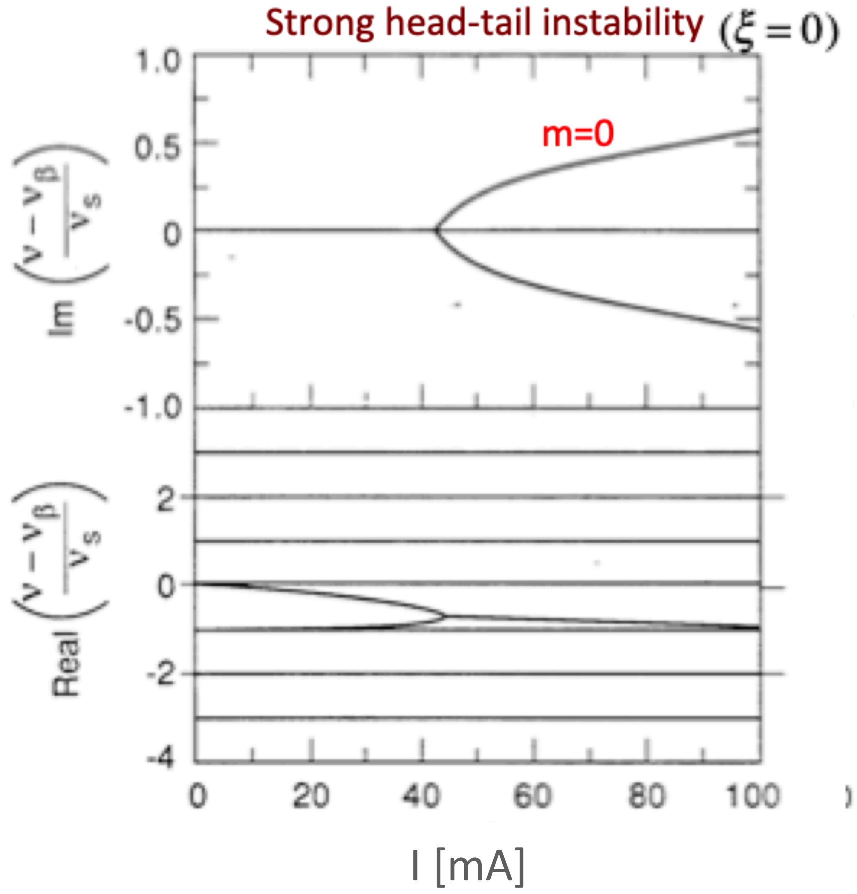




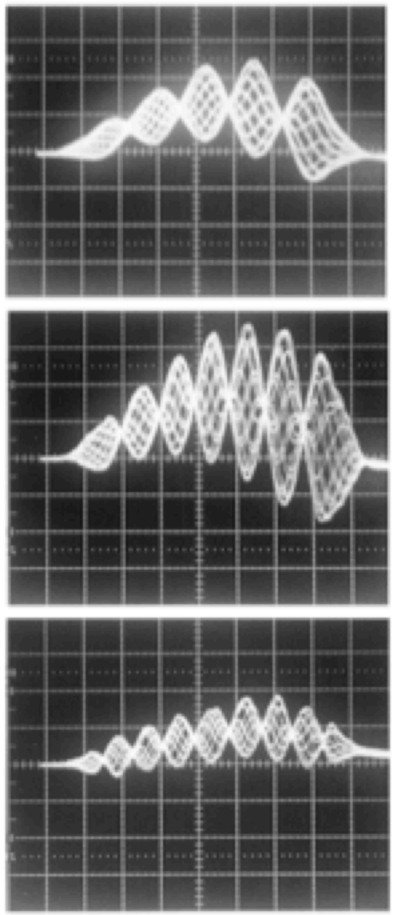
- Split dipole as proposed in the eRHIC design
- Damping wigglers
- Landau cavity

Single Bunch Instability: Transverse Mode Coupling Instability

- Synchrobetatron coupling via transverse wakefield causes frequency shifts for coherent modes

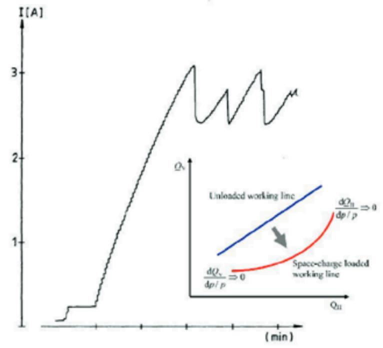


- Observation



m=8,10

- Feature: fatal beam loss



(brick-wall instability)

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Single Bunch Instability: Transverse Mode Coupling Instability

- Transverse Single-Bunch Instability Threshold

$$\left|Z_{\perp}(n)\right|_{\mathrm{eff,th}} \approx \frac{16\sqrt{2}\pi}{3} \frac{(E/e)\upsilon_s}{\langle \beta_{\perp} \rangle I_{peak}}$$

(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
$\left\|Z_{\perp}\right\|^{\mathrm{th}}$ [MΩ/m]	1.2	0.81	2.25	9.0	63

Stable — All Stable — Stable

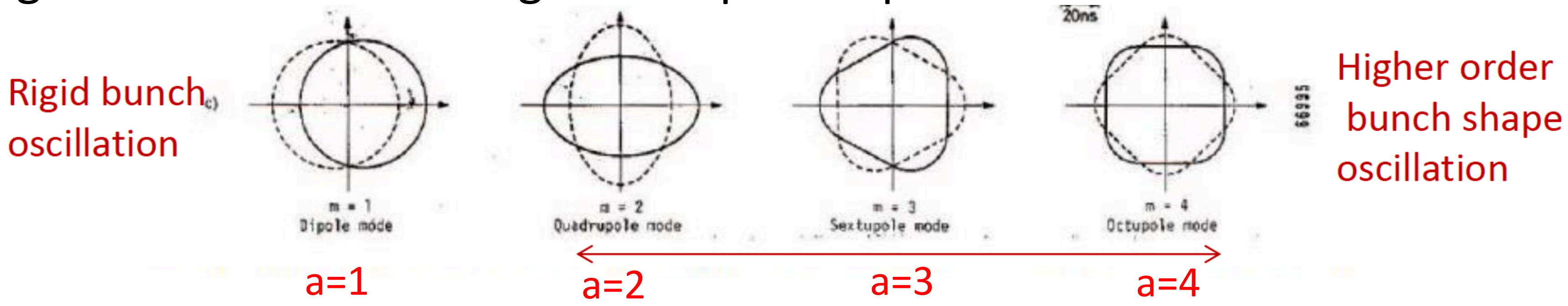
More serious effects could take place during the bunch formation process

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

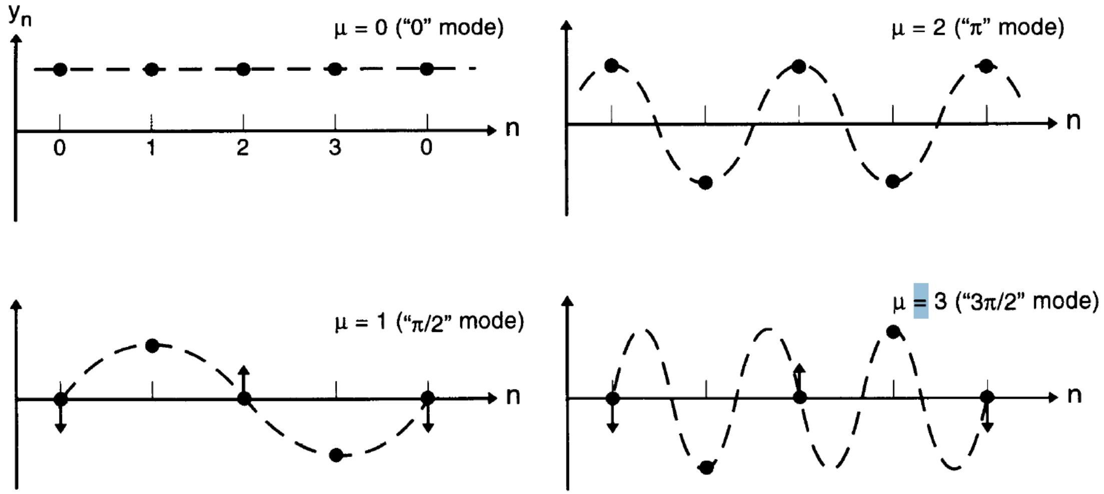
Coupled Bunch Instability

This instability happens when single bunch coherent motion gets coupled among bunches when there is long range wakefield.

- Single bunch modes in longitudinal phase space



- Coupled Bunch Modes



Growth Rate Estimation

- Zotter's formula

Growth Rate: $\tau_{\mu,a}^{-1} = \mathrm{Im}(\Delta\omega_{\mu,a})$

(assumes even bunch fill pattern)

Longitudinal Coupled Bunch Instability (LCBI)

Frequency shift:
$$\Delta\omega_{\mu,a}^{\parallel} = i\frac{a}{a+1}\frac{q_i I_b \omega_0^2 \eta}{3(L/2\pi R)^3 2\pi\beta^2 (E_T/e)\omega_s}\left[\frac{Z_{\parallel}}{n}\right]_{\mathrm{eff}}^{\mu,a}$$

Effective impedance:
$$\left[\frac{Z_{\parallel}}{n}\right]_{\mathrm{eff}}^{\mu,a} = \sum_{p=-\infty}^{\infty}\frac{Z_{\parallel}(\omega_p'')}{\left(\omega_p''/\omega_0\right)}\frac{h_a(\omega_p'')}{S_a(\omega_p'')}, \quad \text{for} \quad \omega_p'' = pk_b + \mu + a\nu_s$$

Transverse Coupled Bunch Instability (TCBI)

Frequency shift:
$$\Delta\omega_{\mu,a}^{\perp} = -i\frac{1}{a+1}\frac{q_i I_b \beta c^2}{2\omega_\beta (E_T/e)L}\left[Z_{\perp}\right]_{\mathrm{eff}}^{\mu,a}$$

Effective impedance:
$$\left[Z_{\perp}\right]_{\mathrm{eff}}^{\mu,a} = \sum_{p=-\infty}^{\infty} Z_{\perp}(\omega_p^{\perp})\frac{h_a(\omega_p^{\perp}-\omega_\xi)}{S_a\left(\omega_p^{\perp}-\omega_\xi\right)}, \quad \text{for} \quad \omega_p^{\perp} = pk_b + \mu + \nu_{\perp} + a\nu_s$$

Effective Impedance

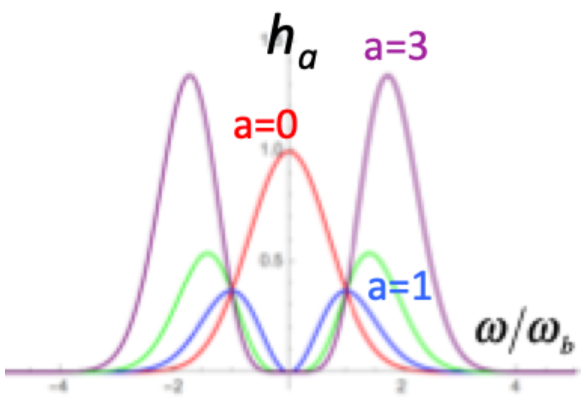
$$\left[\frac{Z_\parallel}{n}\right]^{\mu,a}_{\text{eff}} = \int d\omega \left(\frac{Z_\parallel(\omega)}{\omega/\omega_0}\right) f_b(\omega),$$

machine impedance; bunch spectra

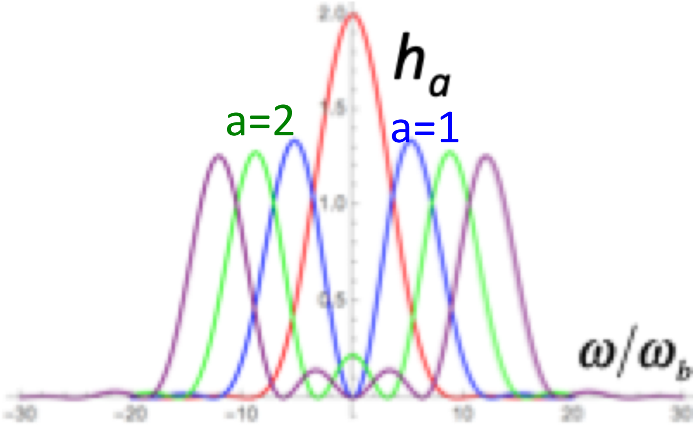
$$f_b(\omega)=\frac{h_a(\omega)}{\sum_p h_a(\omega)}\sum_{p=-\infty}^{\infty}\delta\left(\omega-\omega''_p\right)$$

single-bunch mode spectra; Multi-bunch spectra

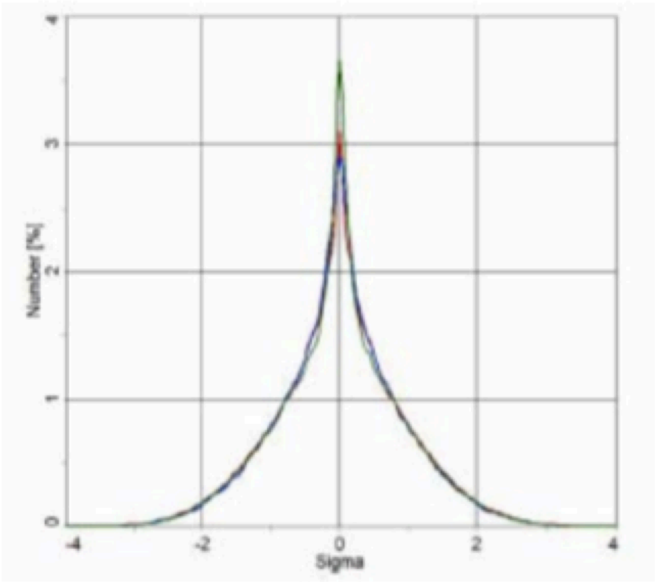
Gaussian Bunch



Parabolic Bunch



Bunch distribution under strong electron cooling



Longitudinal Coupled Bunch Instability

JLEIC Electron-ring

E [GeV]	3	5	10
$\tau_{a=1}$ [ms]	2.9	4.0	72.8
$\tau_{a=2}$ [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

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

Caused By Z^{RW}!

- Need feedback to damp longitudinal quadrupole mode CBI
- Need to consider growth rate for a non-parabolic bunch

- Here the growth times are calculated using ZAP for Z^{RF} +Z^{RW} (assuming even bunch filling).
- Stability is assessed by comparing the growth time with the damping time (1ms) of state-of-art fast feedback system.
- 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

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

due to resistive wall impedance (Cu)

Cannot be improved by HOM damping

JLEIC p-ring

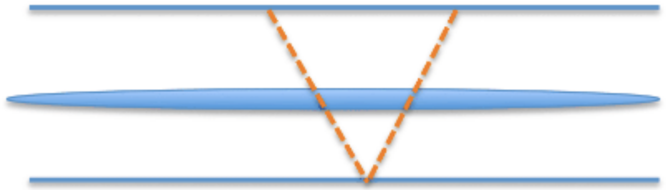
E [GeV]	100
$\tau_{a=0}$ [ms]	24.4
$\tau_{a=1}$ [ms]	805
τ_y [min]	>30
V_{RF} [MV]	42.6
Cavity Number	34

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

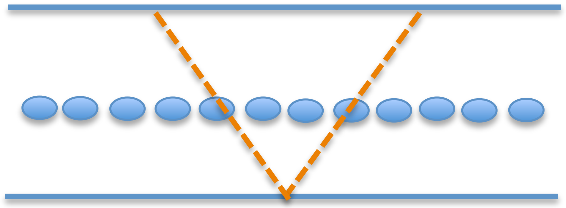
Two-Stream Instability: Electron Cloud in the JLEIC Ion Ring

- Electron Cloud Build-up Behaviors

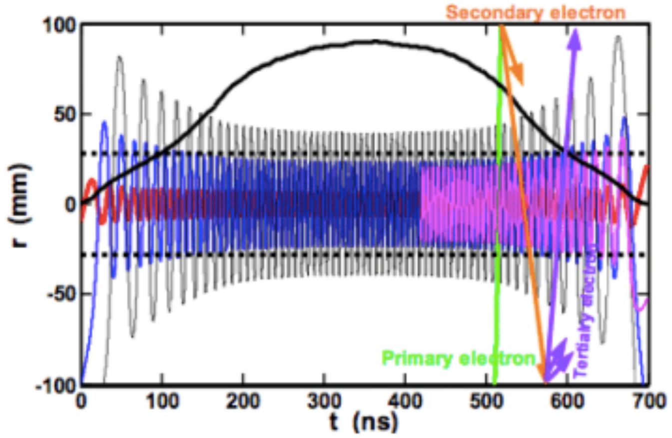
  - Long ion bunch with low rep rate (in conventional ion ring)



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



Trailing-Edge Effect



Short-bunches:

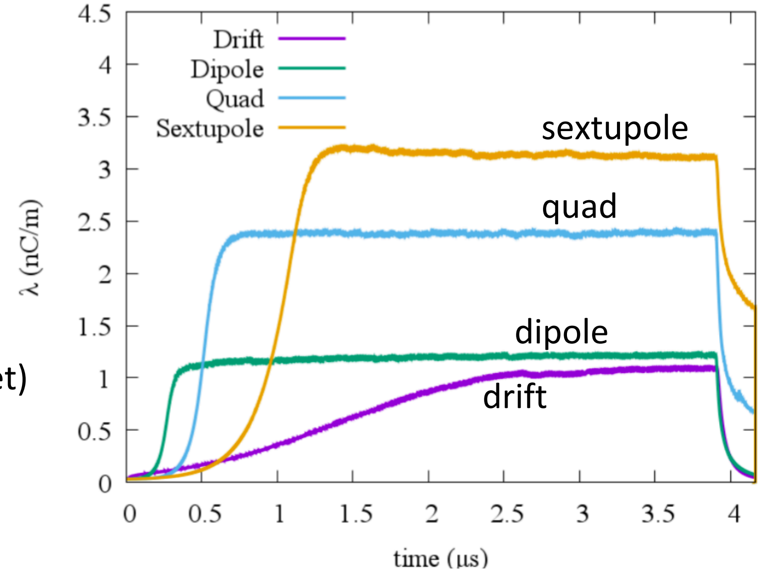
e-cloud build up rapidly and saturate at an equilibrium density

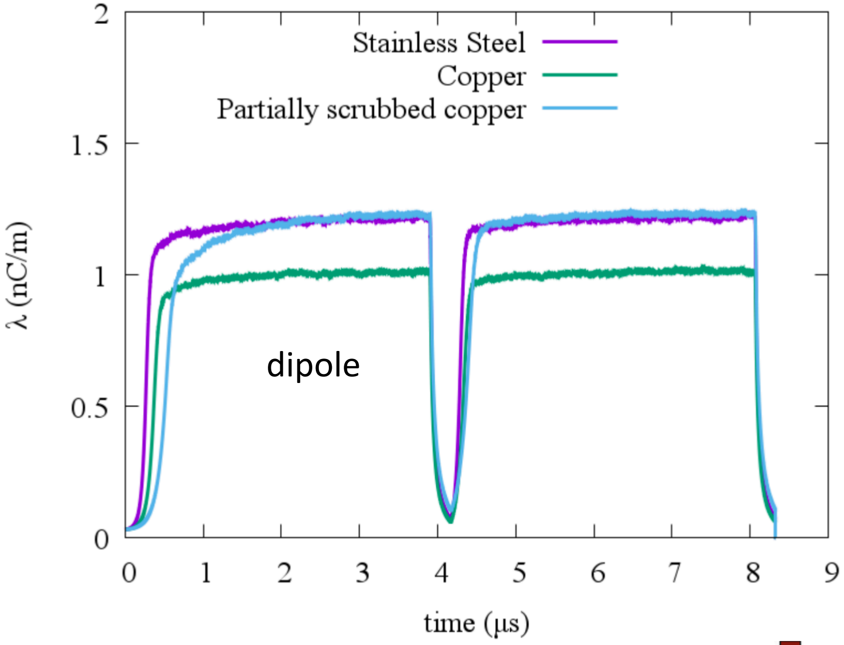
Electron Cloud Build-up in the JLEIC Ion Ring

- Electron Cloud Build up (K. Deitrick, et al., LINAC2018)

PyECLOUD Results

(1856 bunches followed by 126 empty bucket)

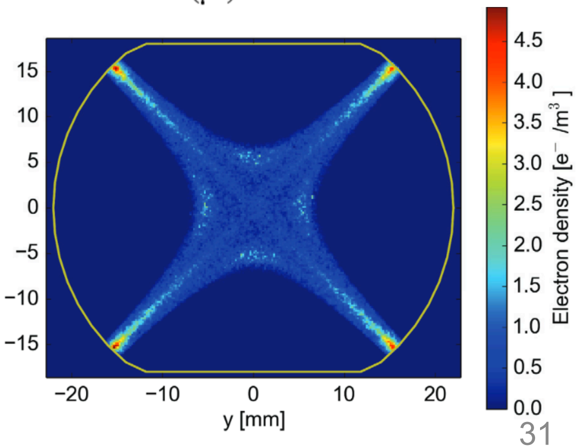




2 bunch trains with a gap

Table 3: Simulation results for different magnetic elements.

Element	λ_e (nC/m)	ρ_e (m^{-3})	$\Delta\nu_x$ (10^{-3})	$\Delta\nu_y$ (10^{-3})
Drift	1.09	1.36×10^{12}	1.06	1.43
Dipole	1.23	1.53×10^{12}	1.20	1.62
Quadrupole	2.40	2.99×10^{12}	2.34	3.16
Sextupole	3.11	3.87×10^{12}	3.03	4.10



Electron cloud distribution in a quadruple

(I. Iadarola, CERN)

Electron Cloud Effects in the JLEIC Ion Ring

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

  From two-particle model, the instability threshold for the e-cloud density is

$$\rho_{th} = \frac{2\gamma Q_s A}{\pi r_p Z C \beta_y} = 1.7\times10^{13}\ \mathrm{m}^{-3} \quad > \quad \text{saturated density } \rho_e = 3.87\times10^{12}\ \mathrm{m}^{-3}$$

Stable!

- Other e-cloud effects
  - e-cloud induced coupled-bunch instability is a concern (as observed in PEPII-LER)
  - The behavior of e-cloud build-up varies during the ion bunch formation process
  - Even without coherent instability from e-cloud effect, e-cloud could cause incoherent effect of emittance and bunch halo formation, causing heat load and beam lifetime problem, and background at IR

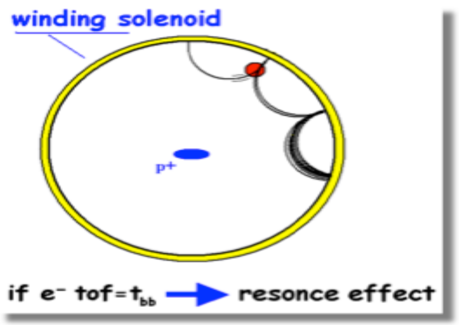
→ Require comprehensive numerical modeling

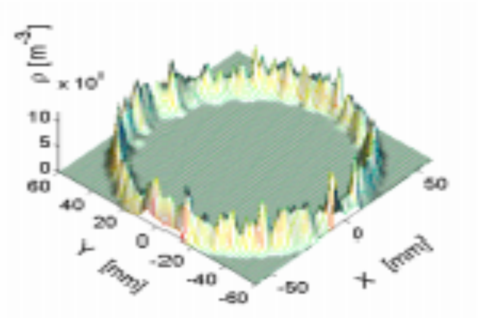
Mitigation Schemes for the Electron Cloud Effects

- Surface treatment
  - Scrubbing (constant bombardment by electrons reduces SEY)
    LHC 25ns bunch spacing for scrubbing run
  - Inner surface of entire SNS ring is coated with TiN (SEY reduce by 0.5)
- Solenoid confinement of ecloud (~30 Guass)

  -ecloud confined near wall surface

  -Applied to field-free region





- Clearing electrodes
  - Alter ecloud pattern
- Better bunch pattern
- Better vacuum
- Modify chamber geometry (grooves)
- Chromaticity
  - Helps to reduce head-tail instability
- Fast feedback system
  - In CESRTA, even after feedback to remove coherent motion, fast emittance growth exists due to incoherent effects.

Two-Stream Instability: Fast Beam-Ion Instability in the JLEIC e-Ring

- Scattering of the electron beam with the residual gas (H_2, H_2O, CO) in vacuum chamber could cause ionization of the gas molecules

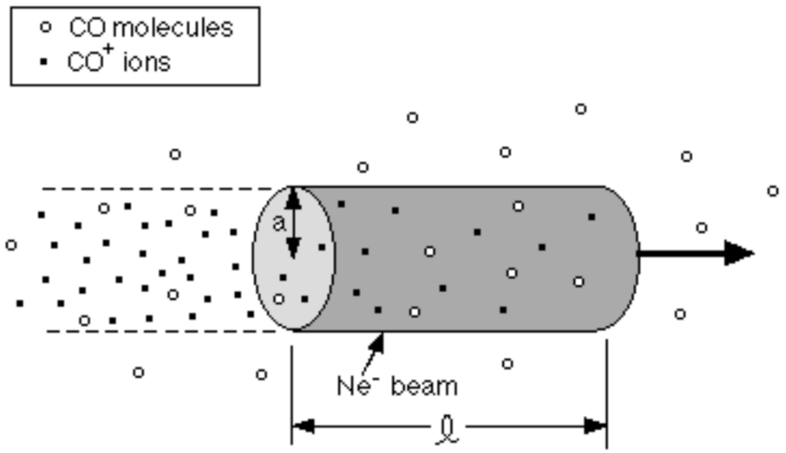
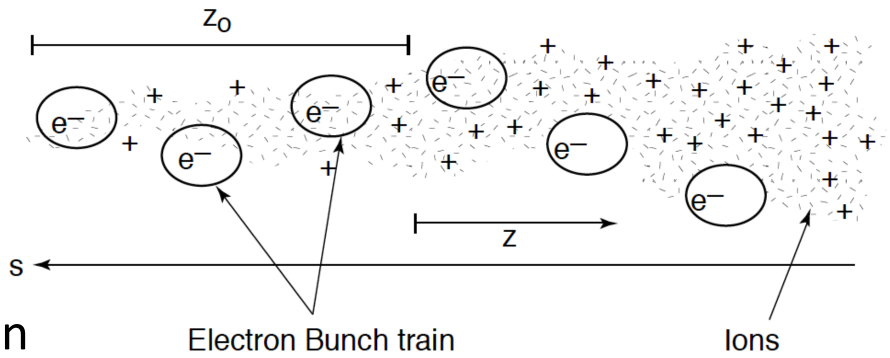


Figure 4.2: Ionization process.

- Fast ion instability

Ions are generated by the head of the bunch and keep accumulating until they are cleared by the bunch train gap

The ions slices will be dipole kicked by the previous electron slices and act back on the dipole motion of the trailing electron slices, serving as a transverse wakefield similar to the RF HOM wakes



Two-Stream Instability: Fast Beam-Ion Instability in the JLEIC e-Ring

- Fast-ion Instability could cause coupled transverse motion of the electron bunches

$$y_b(t) \propto \left(t/\tau_g\right)^{-1/4} e^{\sqrt{t/\tau_g}}, \quad \text{with} \quad \tau_g^{-1}[s^{-1}] = 5p[\text{Torr}] \frac{N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma\, \sigma_y^{3/2} \left(\sigma_x + \sigma_y\right)^{3/2} A^{1/2} \omega_\beta}$$

Assumption:

- Force between ion and electron beam is linear to their dipole offsets
- Constant ion frequency for all ion oscillations

- For realistic beam, Landau damping is considered as a result of ion oscillation frequency spread due to bunch size variation

$$y_b(t) \propto e^{t/\tau_e}, \quad \text{with} \quad \tau_e^{-1} \approx \tau_g^{-1} \frac{c}{4\sqrt{2\pi} L_{sep} n_b a_{bt} f_i}$$

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 HER case

- Possible mitigation methods:
  - Use clearing electrodes---(contribute to the broadband impedance)
  - Use chromaticity to damp FBII
  - Use multiple bunch trains to reduce the growth amplitude
- Comprehensive numerical modeling of FBII and its mitigation will be performed

PEPII Observation

- Originally envisioned gap: 10% (about 120 buckets)
- In real operation, abort-kicker gap: 18 buckets (about 100ns)
- With 16 bucket gap, instability takes place---unstable when colliding, and stable otherwise

The previously concerned effect could be shifted due to the combined action of the transverse bunch-by-bunch feedback and the Landau damping from the beam-beam interaction

Possible fast ion instability

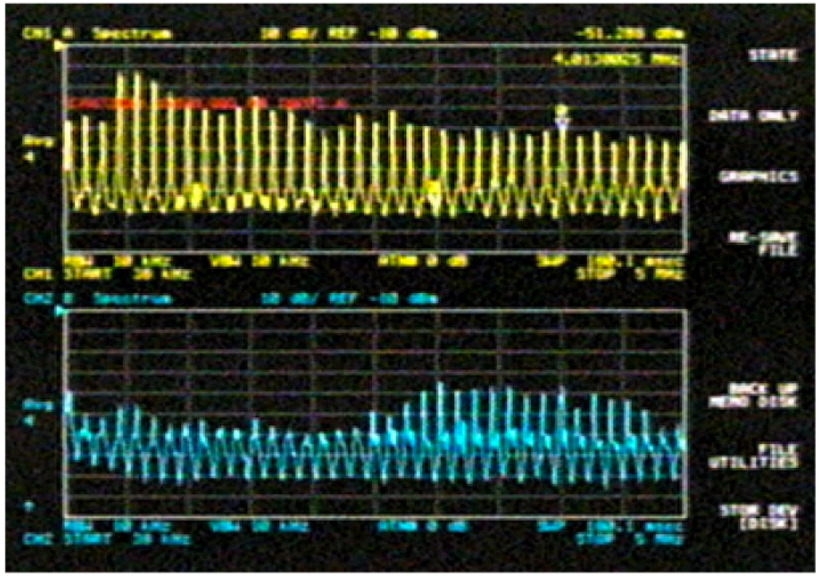


Figure 7: Transverse spectra of the HER with 16-bucket gap (34 ns). Top trace (yellow) is horizontal; bottom trace (blue), vertical motion. The frequency range is from 20 kHz to 5 MHz and the vertical scale is 10 dB/div in both spectra.

(Wienands, EPAC08)

Challenges on Modeling and Feedback System Needs

- Topics related to bunch train gap and bunch spacing
  - Coupled Beam-beam dipole instability in gear change scheme
  - Multiple bunch train for mitigation of fast ion instability
  - Bunch train pattern for mitigation of electron cloud
  - Injection and abortion gap

  How the instability would look like, and what kind of feedback system is needed?

- Multi-physics effects and modeling challenges
  - Beam-beam tune spread induced Landau damping
  - Coupled bunch instability from both RF and crab cavities
  - Ion effect for the e-beam and electron cloud for ion beam
  - Feedback

Summary and Future Plan

	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	🔴	🔴	🟢	

Future Plan

- Continue with impedance studies
- Comprehensive modeling of various effects
  - Longitudinal microwave instability, bunch lengthening, etc
  - Instability studies for bunch formation process
  - Coupled bunch instability from combined effects of RF, crab cavity, electron cloud, ion effect, and interplay with single bunch distribution
  - FBII and beam-beam tune spread
- Mitigation schemes
  - longitudinal single bunch instability at low e-beam energies
  - FBII
- Stability assessment for the whole bunch formation process
- Collective Effects in the Electron-Cooler

Thank you!

Jefferson Lab