Status of Collective Instabilities in JLEIC

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Outline

- Introduction
  - Luminosity concepts in JLEIC design and impact of collective instabilities
  - Generals discussion of collective instabilities
- Machine impedances
- JLEIC beam processes and parameters
- Estimation of instabilities in JLEIC
  - Longitudinal single and multibunch instabilities
  - Transverse single and multibunch instabilities
- Summary and future plans

Introduction

- Luminosity concept for JLEIC

IR: crab crossing

High rep rate

$$L = \frac{\gamma_p N_p f_{rep} \xi_{yp}}{2 r_p \beta^*_{yp}} \left(1 + \frac{\sigma^*_y}{\sigma^*_x}\right)$$

features of colliding beam

Small beta-star
Short bunch length

$$\xi_{yp} = \frac{r_p N_e}{\gamma_p} \frac{\beta^*_{yp}}{2\pi\sigma^*_y(\sigma^*_x+\sigma^*_y)}$$

6D electron cooling

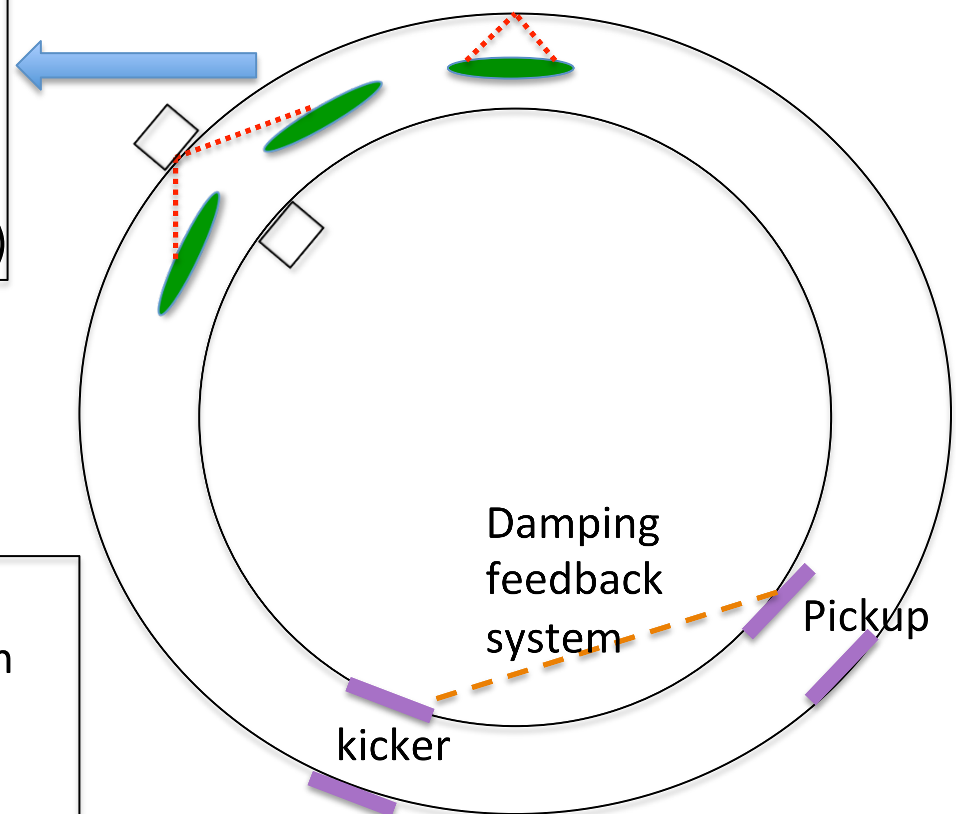
Small transverse emittances

Beam Features and Collective Effects

- Colliding beam in JLEIC design
  - High collision frequency
  - Short bunches (~cm)
  - High intensity/ high brightness e and p or ion bucnches
- Wide range of ion species and collision energies
  - Ee: 3-10GeV
  - E_p: 20-100 GeV
  - Up to 40 GeV/u for ions (light and heavy ion up to lead)
- Collective effects could cause 6D phase space growth coherent motion of bunches, and set limit to the luminosity performance
  - Need to preserve luminosity and control instabilities

Collective Instabilities, Feedback System and Landau Damping

Beam instability: positive feedback system among
- Charged bunches
- Wall impedance
- Optics (slip factor in MWI)



Landau Damping:
- Revolution or synchrotron tune spread
  - Energy spread
  - Nonlinearity in RF
- Betatron tune spread
  - Nonlinearity in optics
  - Chromaticity (optics)

Impedances

- Impedance: describes the response of the beam-surrounding geometry to the bunch perturbation in frequency domain

$$Z_{\|}(\omega)=\frac{V(\omega)}{I(\omega)}, \qquad Z_{\perp}(\omega)=\frac{c}{b^2}\frac{Z_0^{\|}}{\omega} \text{ (for cylindrical pipe)}$$

(boundary property)

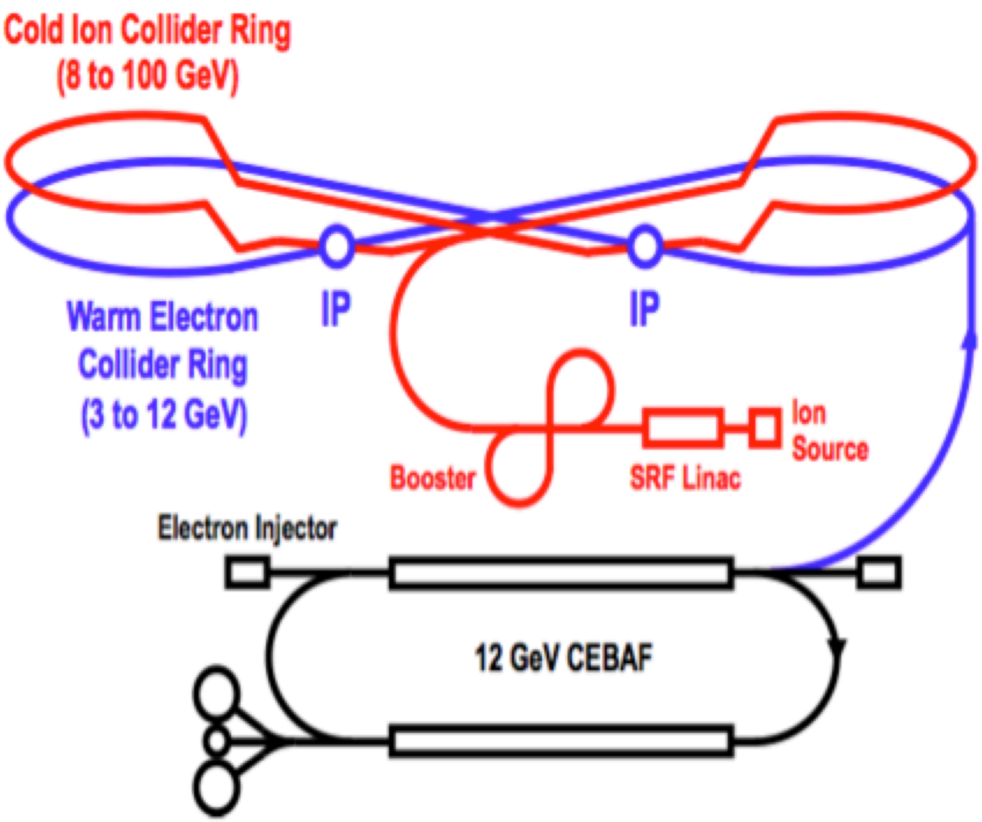
$$\left|\frac{Z_{\|}}{n}\right| \rightarrow \left|\frac{Z_{\|}}{n}\right|_{\mathrm{eff}} = \frac{\int |Z(n)/n| \rho^2(n)\, dn}{\int \rho^2(n)\, dn}$$

(include bunch frequency)

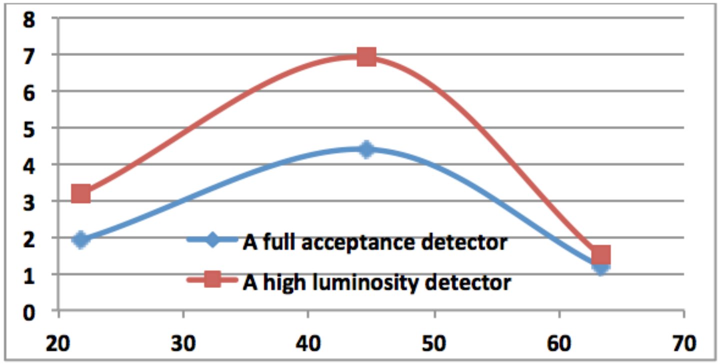
- Broad-band impedance
  - Excite short-lived wakefield
  - Cause single-bunch instability
  - Space charge impedance
  - Resistive wall, BPM, bellows, injection and abort kickers, collimators, vacuum port and gate volves

- Narrow-band impedance
  - Excite long-lived wakefield
  - Cause coupled-bunch instability
  - Resistive wall impedance
  - RF cavity resonances, HOM

JLEIC Beam Processes and Parameters



Luminosity Plot



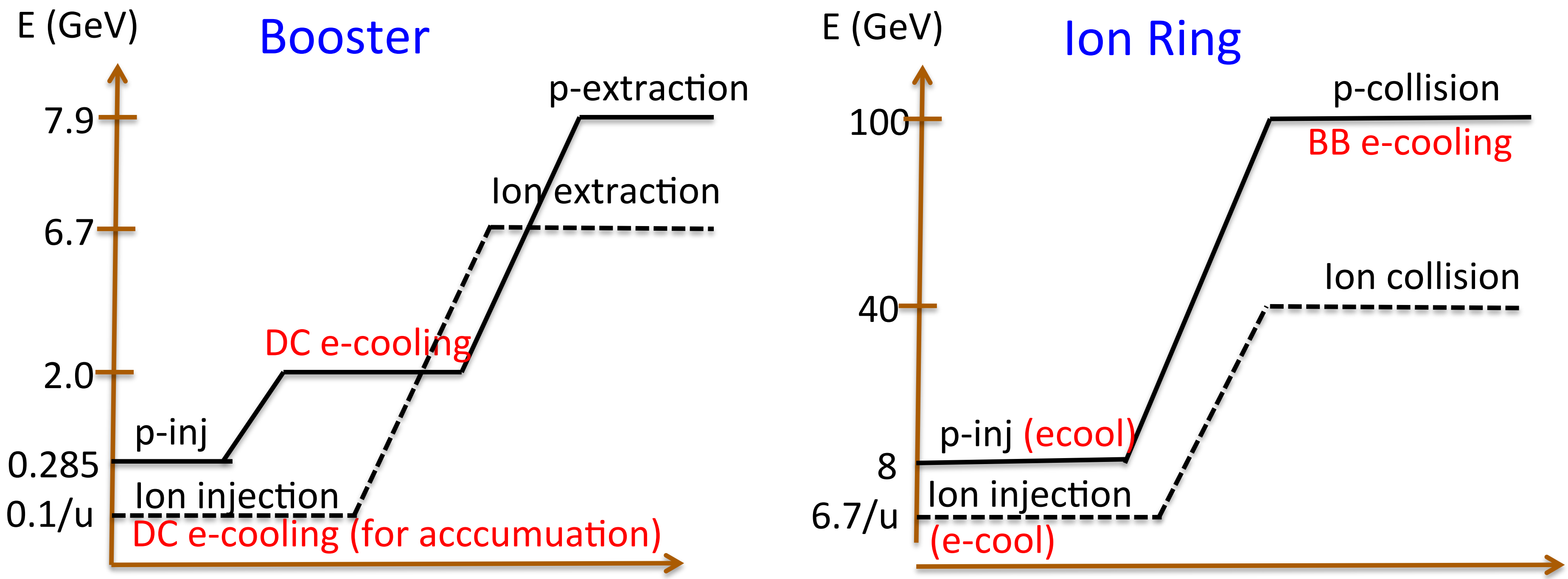
JLEIC Design Parameters

Table 3.1: MEIC main design parameters for a full-acceptance detector.

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	*e*	*p*	*E*	*p*	*e*
Beam energy	GeV	30	4	100	5	100	10
Collision frequency	MHz	476		476		159	
Particles per bunch	10^{10}	0.66	3.9	0.66	3.9	2.0	2.8
Beam current	A	0.5	3	0.5	3	0.5	0.72
Polarization	%	>70	~80	>70	~80	>70	~80
Bunch length, RMS	cm	2.5	1.2	1.5	1.2	2.5	1.2
Norm. emittance, vert./horz.	μm	0.5/0.5	74/74	1/0.5	144/72	1.2/0.6	1152/576
Horizontal and vertical β^*	cm	3 (1.2)	5 (2)	2/4 (1.6/0.8)	2.6/1.3 (1.6/0.8)	5/2.5 (2/1)	2.4/1.2 (1.6/0.8)
Vert. beam-beam parameter		0.01	0.02	0.006 (0.004)	0.014 (0.021)	0.002 (0.001)	0.013 (0.021)
Laslett tune-shift		0.055	small	0.007	small	0.01	small
Detector space	m	±7(4.5)	±3.5	±7 (4.5)	±3.5	±7 (4.5)	±3.5
Hour-glass (HG) reduction factor		0.89 (0.67)		0.85 (0.69)		0.73 (0.58)	
Lumi./IP, w/HG correction, 10^{33}	$cm^{-2}s^{1}$	1.9 (3.5)		4.4 (6.9)		1.0 (1.4)	

(Values for a high-luminosity detector with a 4.5 m ion detector space are given in parentheses.)

Ion Beam Processes



booster → Ion ring (Bunch transfer, 8 batches(?))

Bunch formation process, RF configurations, bunch phase space evolution…

Estimation of Instabilities in JLEIC

- Longitudinal instabilities
  - Longitudinal microwave instability
  - Longitudinal coupled bunch instability
- Transverse instabilities
  - Head-tail instability
  - Transverse coupled bunch instability

(Estimations for both the ion ring and e-ring)

Longitudinal Single-bunch Instability

- Caused by longitudinal broad-band impedance
- Instability mechanism

  longitudinal perturbation->excite wakefield->energy modulation

  ->slip factor enhances perturbation
- Phenomena
  - potential well distortion
  - Turbulent bunch lengthening, increase of energy spread
  - Sawtooth instability
- Mitigation methods
  - Hard to develop feedback system to damp the many modes
  - Reduce $Z_{//}^{BB}$
  - Reduce I_{peak}

Stability Criterion

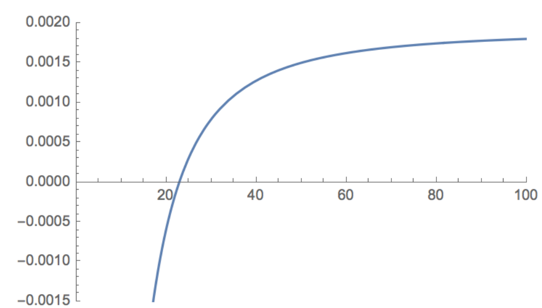
Optics, beam energy

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

Bunch property

Boundary property

Bunch length
Z^{SC} varies with beam energy



- Acceleration: $\eta(\gamma) = \gamma_t^{-2} - \gamma^{-2}$ varies

  $E\sigma_\delta^2 = \sigma_{\Delta E}^2 / E$ decreases with $E \uparrow$

  Imaginary gamma-t: no transition crossing (Booster optics by A. Bogacz)

- RF rebucketing, bunch splitting, , IBS, cooling: $I_{peak} = N_b / (\sqrt{2\pi}\sigma_z)$ and σ_δ change

LMWI for e-Ring: JLEIC Electron Ring

	PEP-II (LER)	JLEIC Electron Ring		
E (GeV)	3.1	4	5	10
I_p(A)	113	44.6 $\xrightarrow{N_b \uparrow}$	62.35	62.35
η (10^{-3})	1.31	2.2	2.2	2.2
σ_δ (10^{-4})	8.0	3.64	4.55	9.1
$\left\|Z_\parallel/n\right\|_{\mathrm{eff,th}}$ [Ω]	0.14	0.12	0.23	2.56

PEPII machine impedance is lower than this threshold

Impedance threshold estimation:

- JLEIC e-ring is safe from LMBI at nominal energy
- At low energy the impedance threshold is comparable to that for PEP-II LER

Machine impedances:

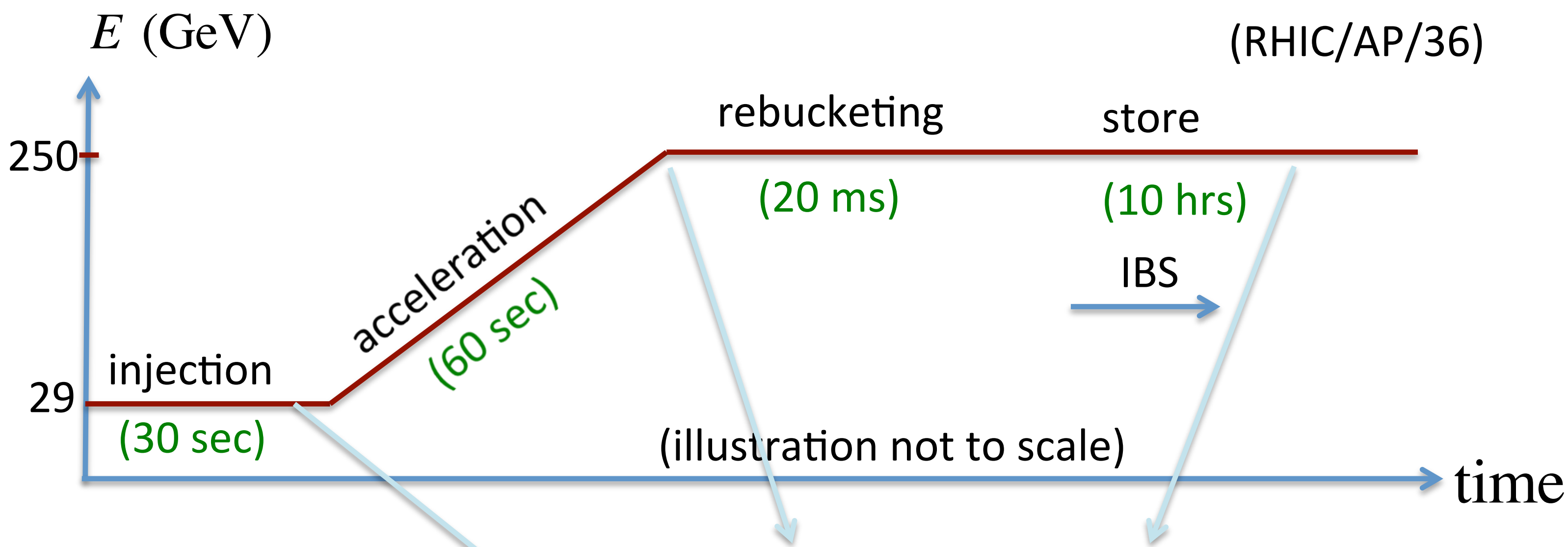
- JLEIC e-ring reuses the RF cavities, vacuum pipe, etc in PEP-II
- Further detailed impedance studies need to be done for e-ring in JLEIC

LMWI for Ion ring: RHIC Proton Beam

Proton beam

$N_b = 10^{11}$

$(\gamma_t = 22.89)$



- Estimated impedance threshold

	injection	acceleration	store
E (GeV)	29	250	250
I_p(A)	5.4	5.4	26.6
$\eta\ (10^{-3})$	0.72	1.9	1.9
$\sigma_\delta\ (10^{-4})$	4.66	0.54	2.65
$\left\|Z_\parallel/n\right\|_{\text{eff,th}}\,[\Omega]$	5.2	2.1 (1.6)	7.9

safe

- Machine impedance:

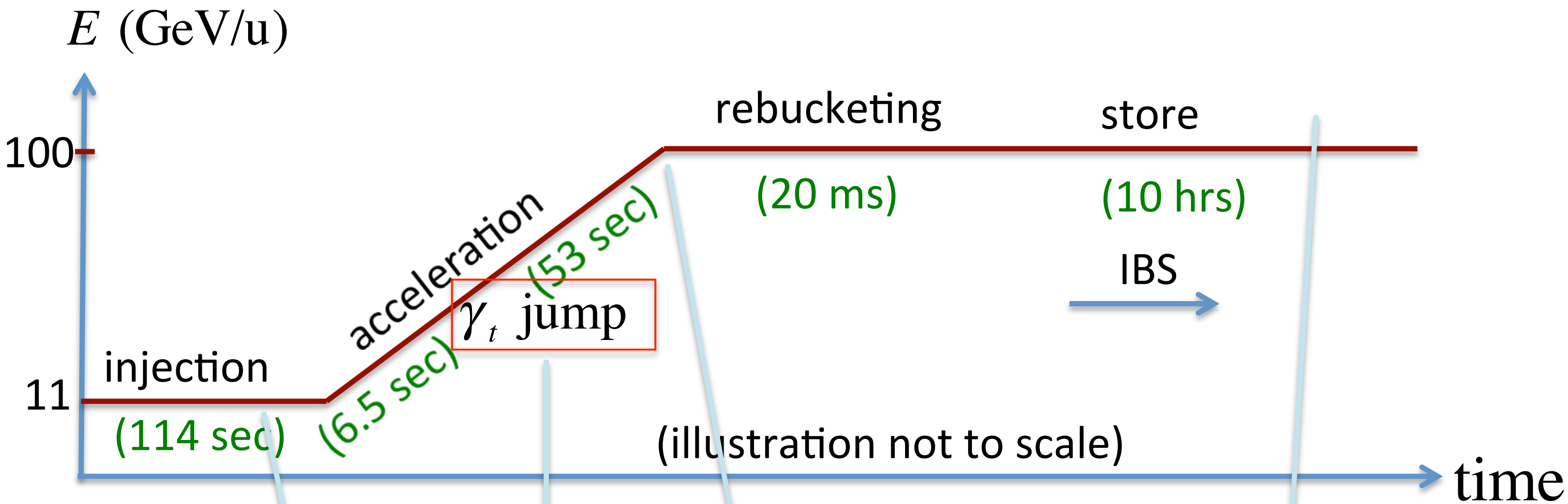
Bunch spectrum around 400 MHz, $\left|Z_\parallel/n\right|_{\text{eff}} = 0.5\ \Omega$ (for $f > 250$ MHz)

LMWI Threshold for RHIC Gold Beam

Gold beam

$N_b = 10^{11}$

$(\gamma_t = 22.89)$



- Estimated impedance threshold

$\left|Z_{\parallel}/n\right|_{\text{eff}} < 47\ \Omega$ safe

$\left|Z_{\parallel}/n\right|_{\text{eff}} < 16\ \Omega$ safe

$\left|Z_{\parallel}/n\right|_{\text{eff}} < 190\ \Omega$ safe

$\left|Z_{\parallel}/n\right|_{\text{eff}} < 2.4\ \Omega$

safe

- Machine impedance

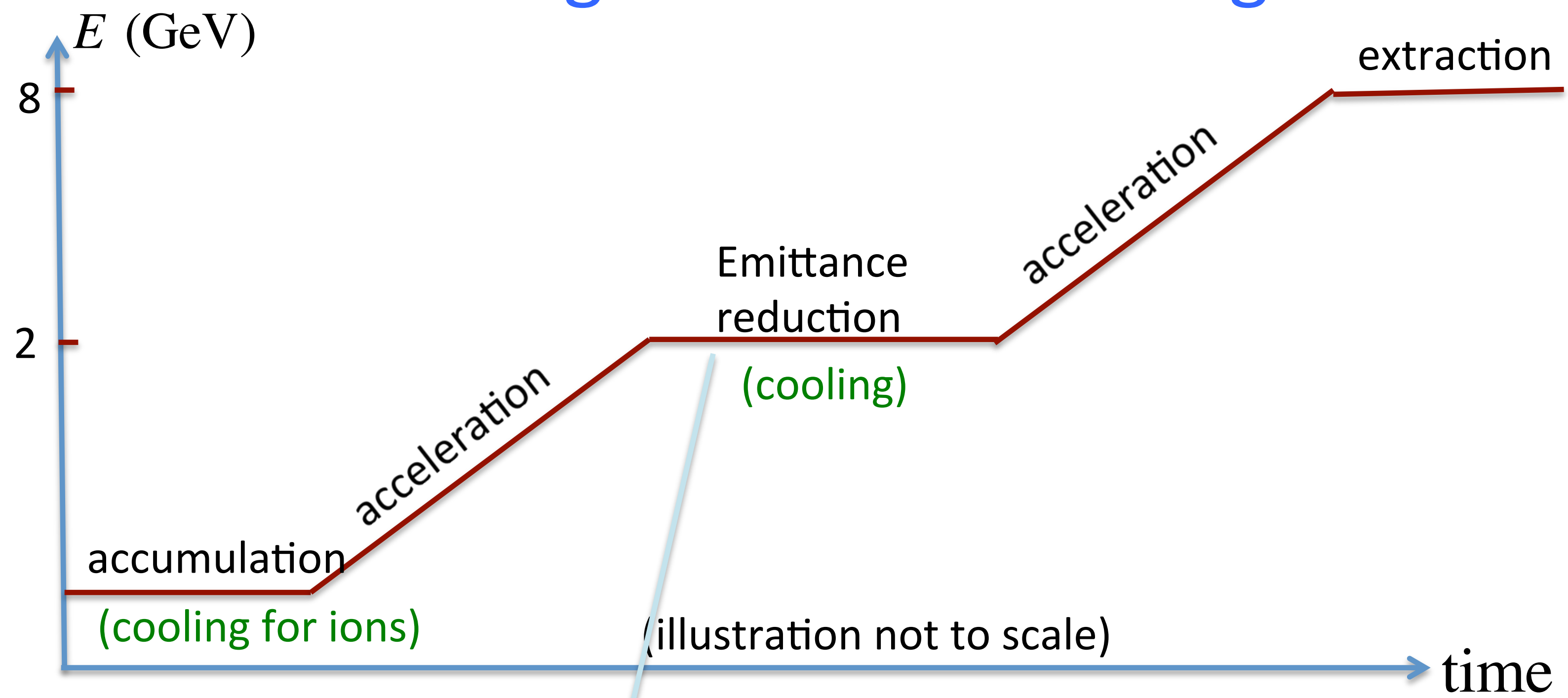
At γ_t jump $\quad \left|Z_{\parallel}/n\right|_{\text{eff}}^{\text{Space charge}} = 1.3\ \Omega$

(RHIC/AP/36)

LMWI for Ion Ring: JLEIC Booster Ring

Proton beam

$N_b = 2.8\times10^{12}$
$(\gamma_t = 10)$



- Estimated impedance threshold

	injection
E (GeV)	2
I_p(A)	0.49
η (10^{-3})	10
σ_δ (10^{-4})	2
$\left\|Z_{\|\|}/n\right\|_{\mathrm{eff,th}}$ $[\Omega]$	10.2

Below transition,
safe from negative mass instability

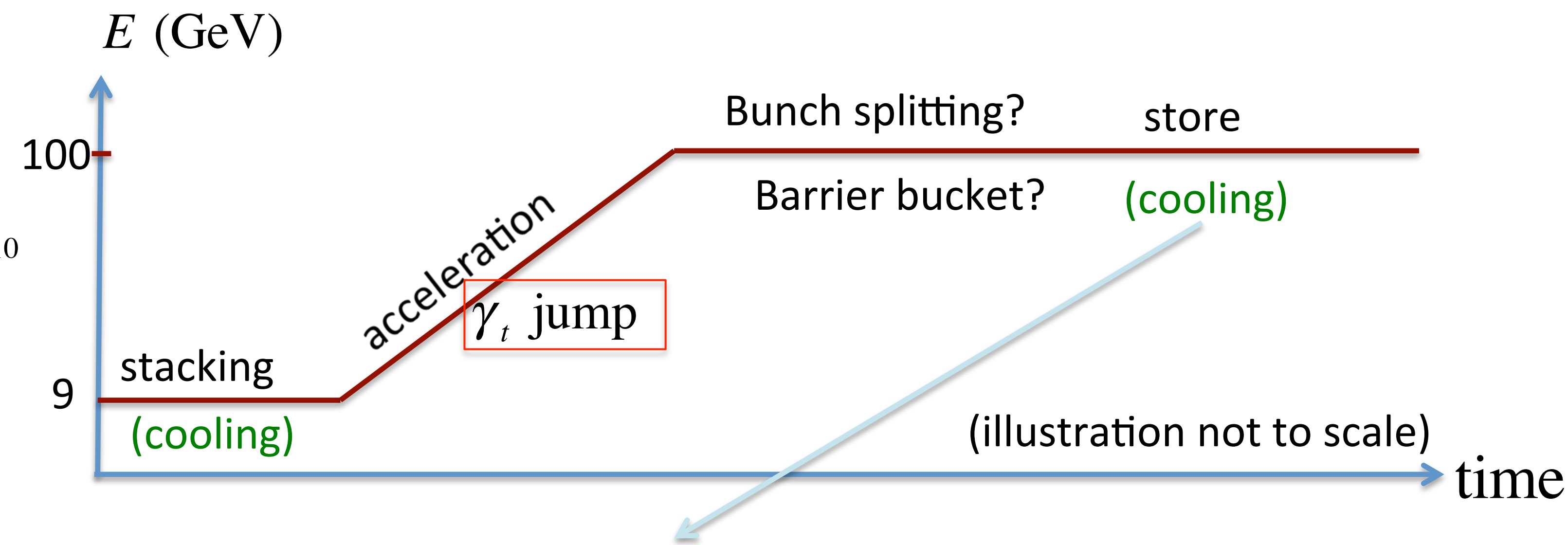
- Estimating impedance threshold
  Need bunch longitudinal phase space evolution for the whole cycle
- Machine impedance
  Need impedance studies for the booster

LMWI Threshold for JLEIC Ion Collider Ring

Proton beam

$N_b = 2\times10^{10}$

$(\gamma_t = 12.46)$



- Estimated impedance threshold

	store
E (GeV)	100
I_p(A)	15.3
$\eta\ (10^{-3})$	6.45
$\sigma_\delta\ (10^{-4})$	3
$\lvert Z_\parallel/n\rvert_{\text{eff,th}}\ [\Omega]$	23.8

Safe here

- Estimating impedance threshold
  Need (1) bunch formation scheme (2) know bunch longitudinal phase space evolution for the whole cycle

- Machine impedance
  Need impedance studies for ion ring

Longitudinal Coupled Bunch Instability

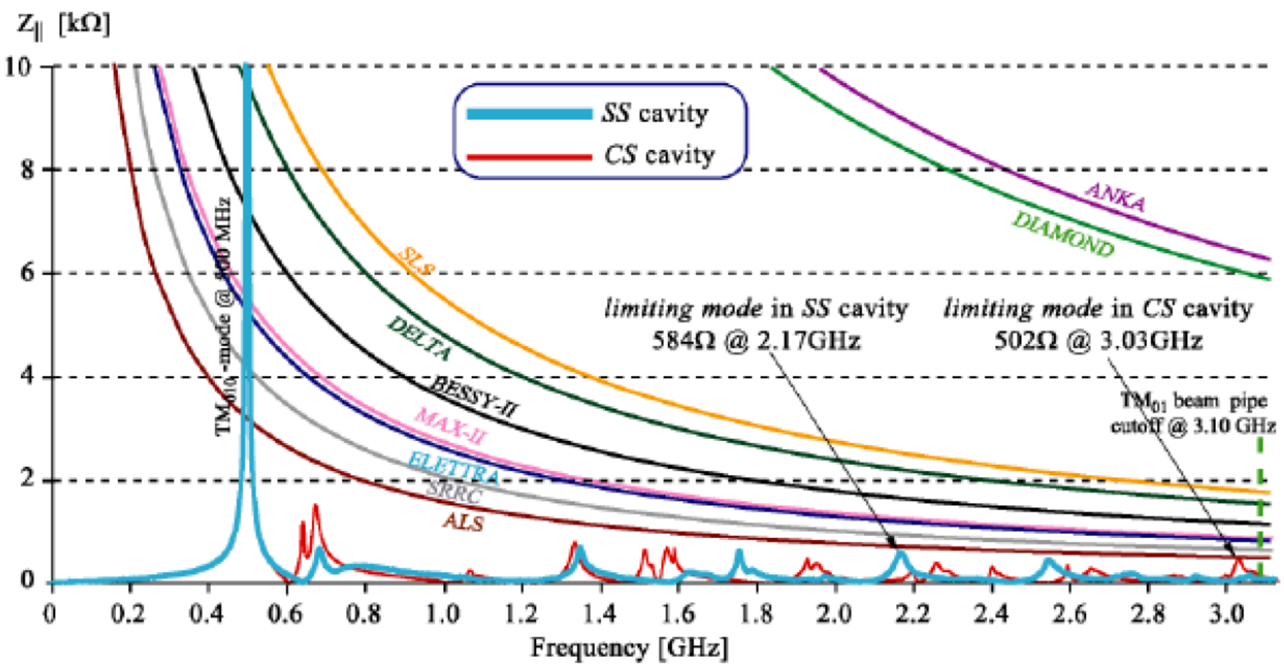
- Caused by narrow-band impedance (RF HOM)
- Mechanism
  - HOM excited by earlier bunches can act on later bunches
- Phenomena
  - Above threshold, amplitude of synchrotron sideband grow rapidly vs. current
- It is the most severe problem in storage rings that limit achievable average current
- Mitigation methods
  - Landau cavity to increase synchrotron tune spread
  - Use uneven fill
  - Radiation damping
  - Damping HOM impedance
  - Use LFB

Examples:

Longitudinal impedance spectra and impedance threshold of various SR sources using 500 MHz RF-systems

(F. Marhauser et al, PAC2001)

SR Source	N_C	E_0[GeV]	I_b [mA]
DIAMOND	6	3.0	300
BESSY-II	4	1.7	250
ELETTRA	4	2.0	300
ALS	2	1.5	400
SLS	4	2.4	500
ANKA	4	2.5	400
DELTA	1	1.5	220
MAX-II	2	1.5	250
SRRC	2	1.5	200



$$\frac{1}{\tau_g} = \frac{\eta\, I}{2\,\nu_s \left(\frac{E}{e}\right)} f Z_{\parallel}(f)$$

Let $\tau_E = \tau_g$

$$Z_{\parallel}(f) = \left(\frac{2\,\nu_s E/e}{\eta\, I\, \tau_E}\right) \frac{1}{f}$$

Given a E, I, and τ_E, one can get maximum Impedance for each freq allowable for the LCBI to be damped by syn. rad.

A single HOM mode can be responsible for LCBI

Conservative assumptions:

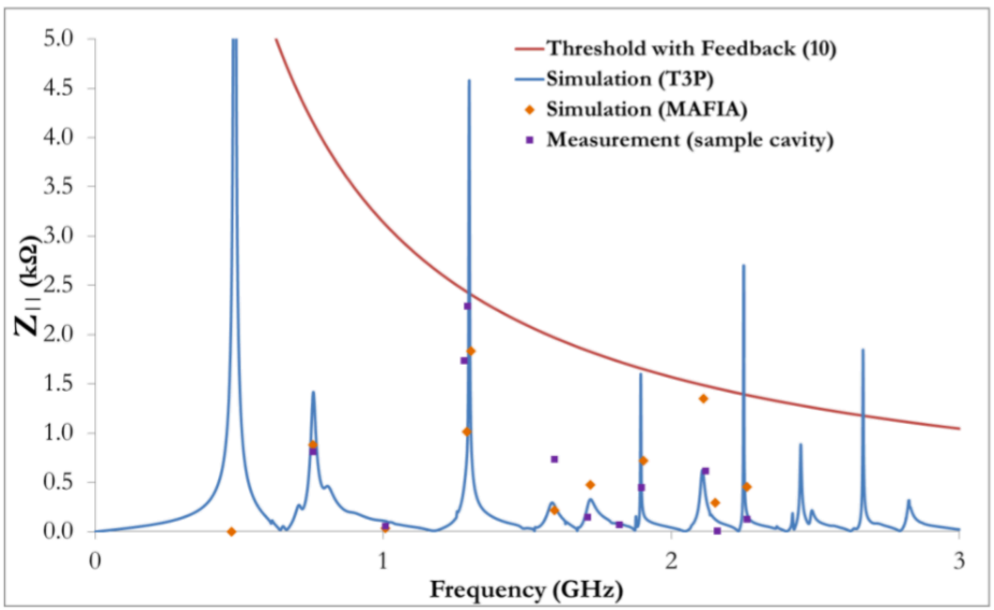
- Every HOM coincides with an instability driving beam frequency
- Impedances for Nc cavities are the same

CBI and Cavity Impedance

High beam current induced another constraint in e ring, the Coupled-Multi-Bunch-Instability, CMBI:

we have short bunch spacing and high bunch charge, under some unfavored condition, the beam induced wake fields in RF cavities are not fully damped before next bunch comes, and the coupled motion of bunches could lead to instability. It is termed with impedance. In e ring, the threshold of impedance is the balance between SR damping and CMBI:

PEP II Cavity



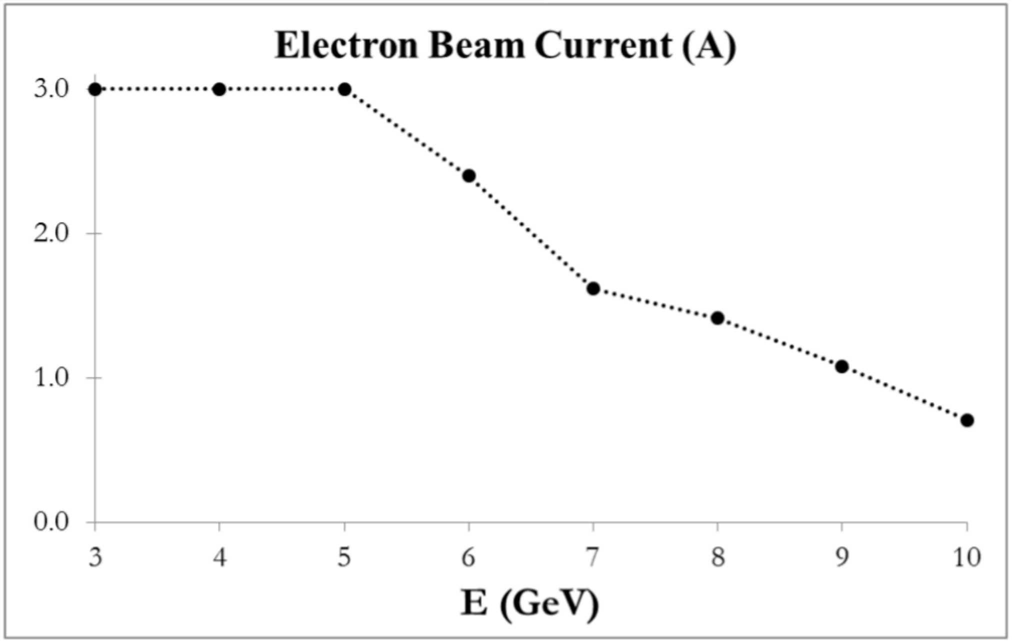
$$Z_{||}^{thresh} = \frac{2E\upsilon_s}{N_{cav} f_{\mathrm{HOM}} I_b \alpha \tau_s}$$

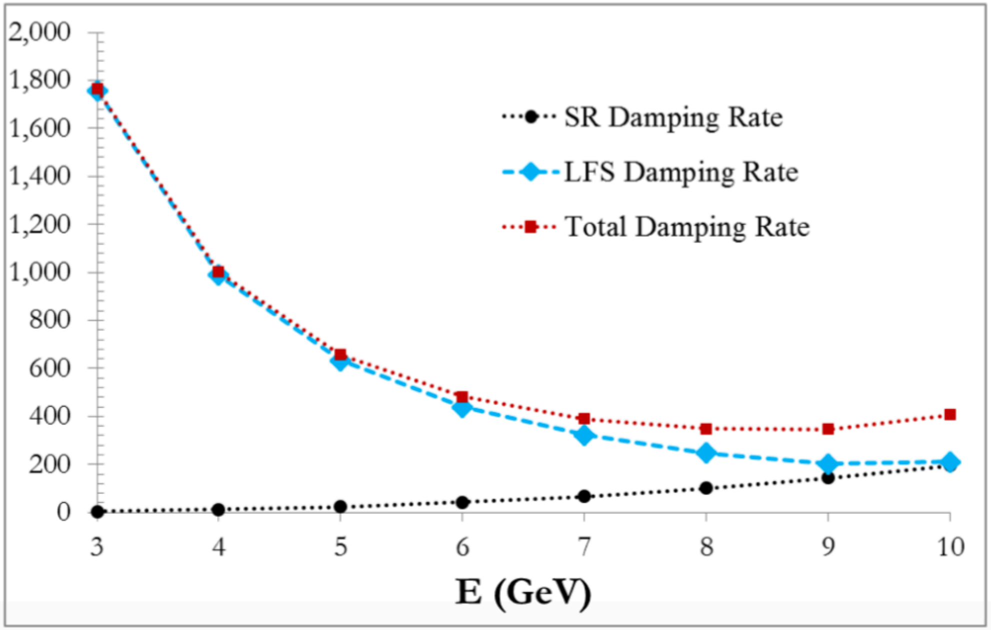
$$\tau_s \approx \frac{E}{E_{loss\ per\ turn} f_{\mathrm{rev}}}$$

$$E_{SR\ energy\ loss\ per\ turn} = \frac{F_{\varphi} C_{SR} E^4}{R_{dipole}}$$

(S. Wang)

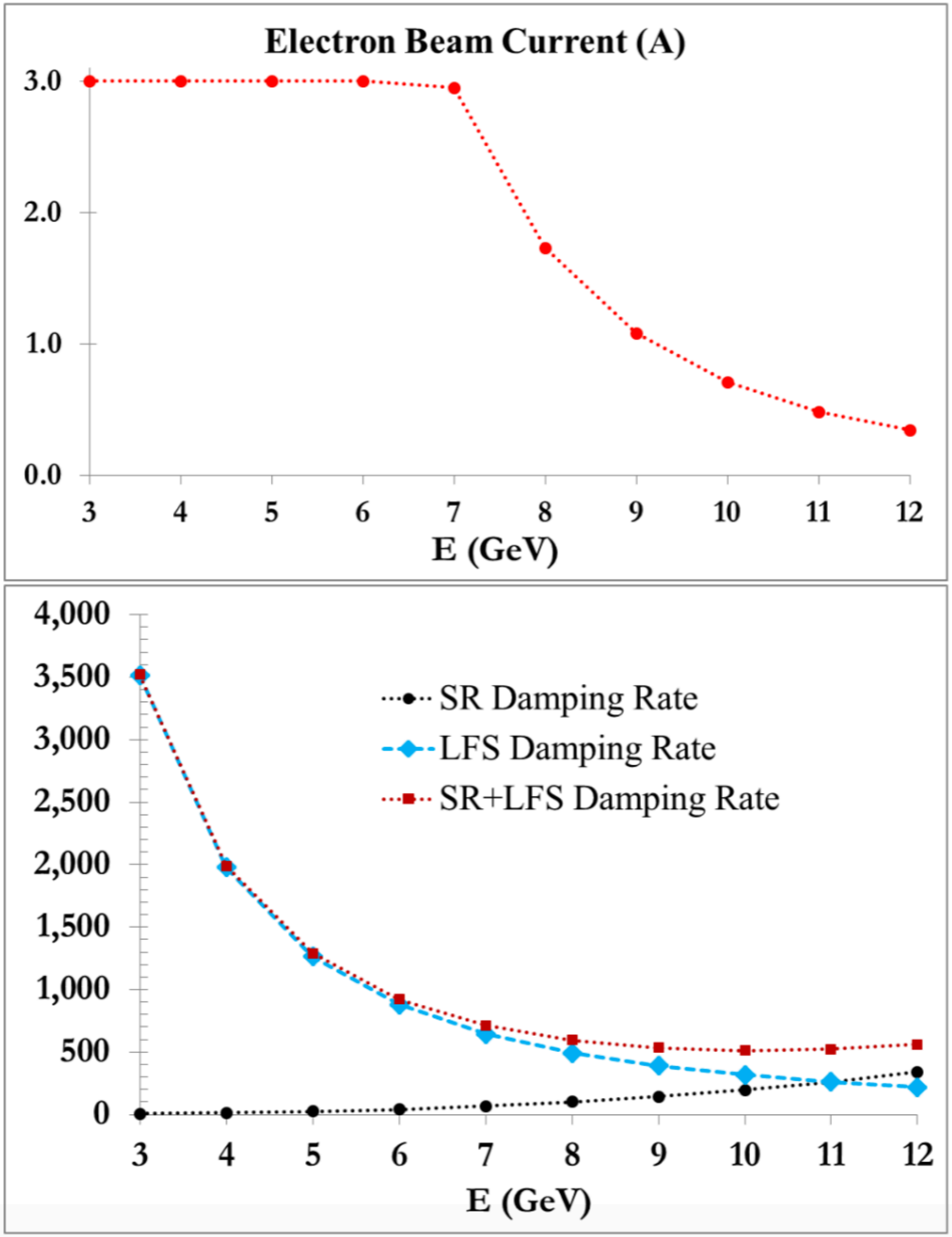
JLEIC with PEP II cavity (1.5kV/0.5 deg)





(S. Wang)

JLEIC with SRF Cavity (1.5kV/0.5 deg



(S. Wang)

Questions and Comments

- Can the PEPII-like feedback system applied to the JLEIC ion ring?
- For ion bunch formation process, bunching structure changes, what kind of LFB is needed?
- LHC has I_{ave}=0.5 A, same as in JLEIC, but their bunch rep rate is f_{rep}~34MHz, the consideration of LFB is quite different.

Transverse Single Bunch Instability

- Caused by Resistive wall impedance, RF cavity, space charge
- Mechanism
  - Synchrobetatron coupling resonance
  - Mode coupling for strong head-tail instability
- Phenomena
  - Transverse oscillations depending on chromaticity
  - Cause rapid beam loss in one synchrotron period
  - Cause slow emittance growth
- Mitigation methods
  - Use feedback system for m=0 mode
  - Lattice nonlinearity to damp m>0 mode
  - Damping by space charge tune spread

TMCI Impedance Threshold and Parametric Dependences

- TMCI threshold

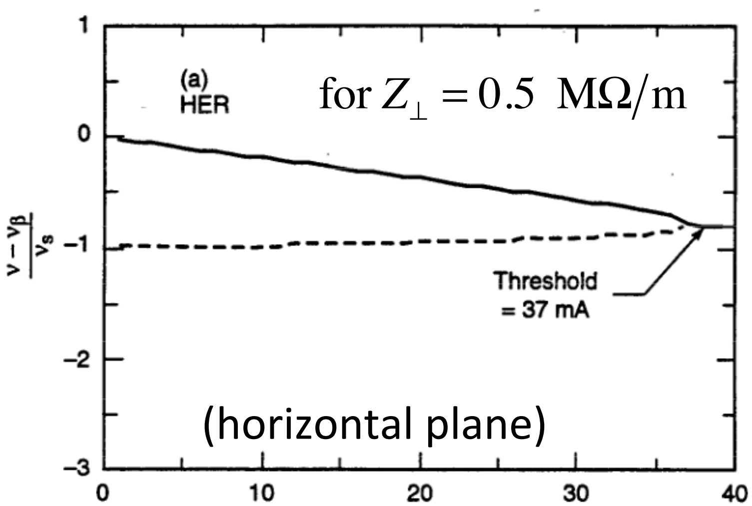
$$\boxed{I_b = \frac{4(E/e)\nu_s}{<\mathrm{Im}(Z_\perp)\beta_\perp> R}\frac{4\sqrt{\pi}}{3}\sigma_l}$$

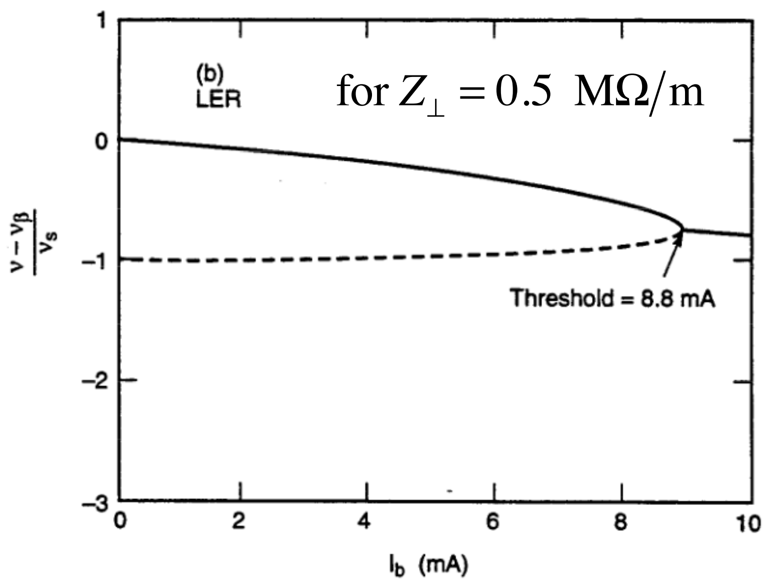
  - RF cavities: Can be hidden at small beta region
  - Lower threshold for low energy beam in a large ring

    Could be a problem at injection
  - Transition crossing: syn. tune =0

    TMCI can be suppressed by chromaticity

In PEPII Design Report





The instability sets in when m=0 and m=-1 Frequencies merge.

Threshold calculated by MOSES [Chin]

$Z_\perp = 1.3\ \mathrm{M\Omega/m}$

$I_b == 6.5$ mA (HER)

$I_b = 2.2$ mA (LER)

Required single bunch current:

$I_b == 0.6$ mA (HER)

$I_b = 1.3$ mA (LER)

$\Rightarrow$ stable!

TMCI for e-Ring: JLEIC Electron Ring

	PEP-II (LER)	JLEIC Electron Ring		
E (GeV)	3.1	4	5	10
I_b(mA)	1.3	0.87	0.87	0.21
$Z_\perp$(MΩ/m)	0.5	0.5	0.5	0.5
ν_s (10^{-2})	3.7	1.7	2.8	4.8
I_b^{th}(mA)	2.2	1.3	2.6	9.2

TMCI threshold estimation:

- JLEIC e-ring is safe from TMCI
- Here we assume $\langle \beta_y \rangle = 20\mathrm{m}$ as in PEPII ring optics

Machine impedances:

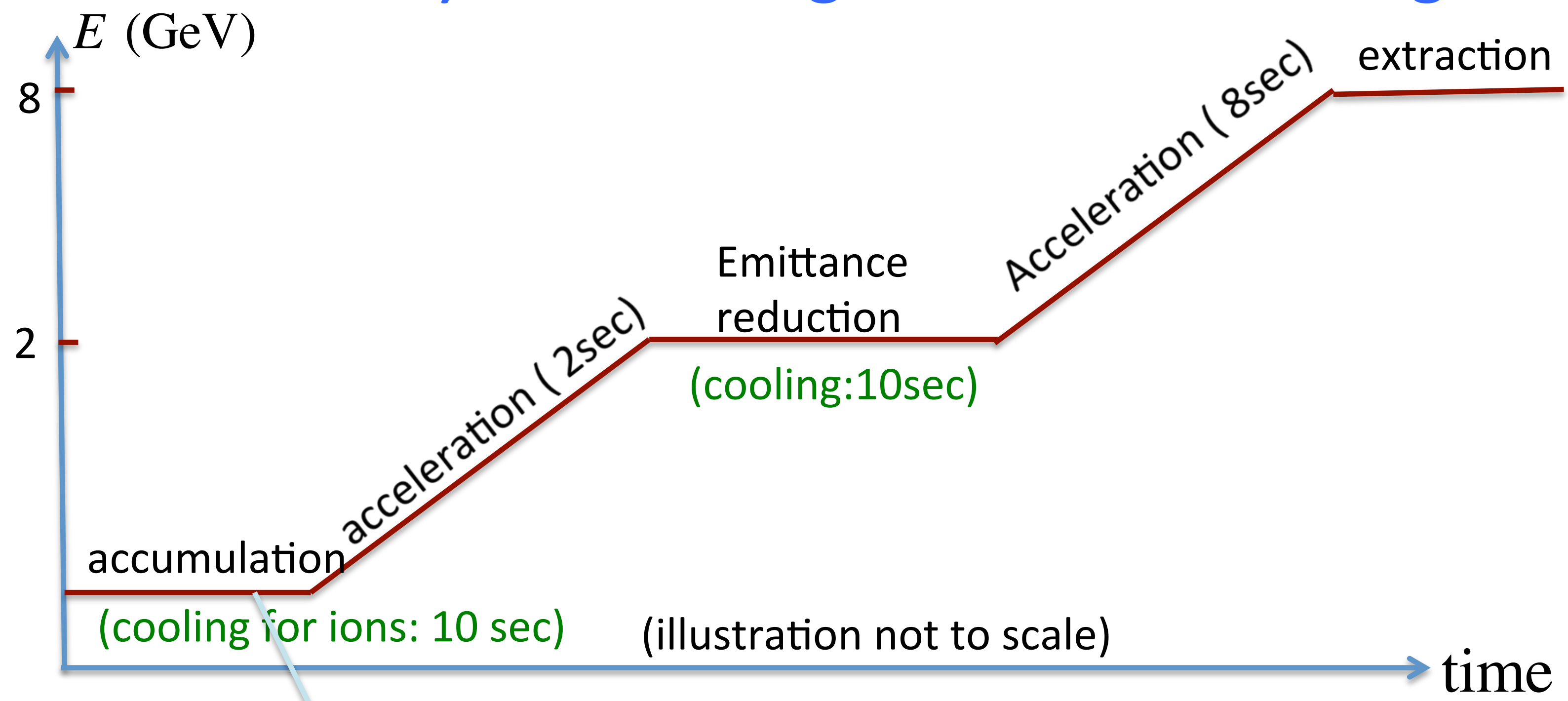
- In PEPII estimation, $Z_\perp \sim 1.3\ \mathrm{M\Omega/m}$ is mainly from hardware of arc vacuum chamber
- Here we assume the same impedance for JLEIC.
- More detailed studies are needed.

Transverse Instability for Ion Ring: JLEIC Booster Ring

Proton beam

$N_b = 2.8 \times 10^{12}$

$(\gamma_t = 10)$



- Estimated impedance threshold

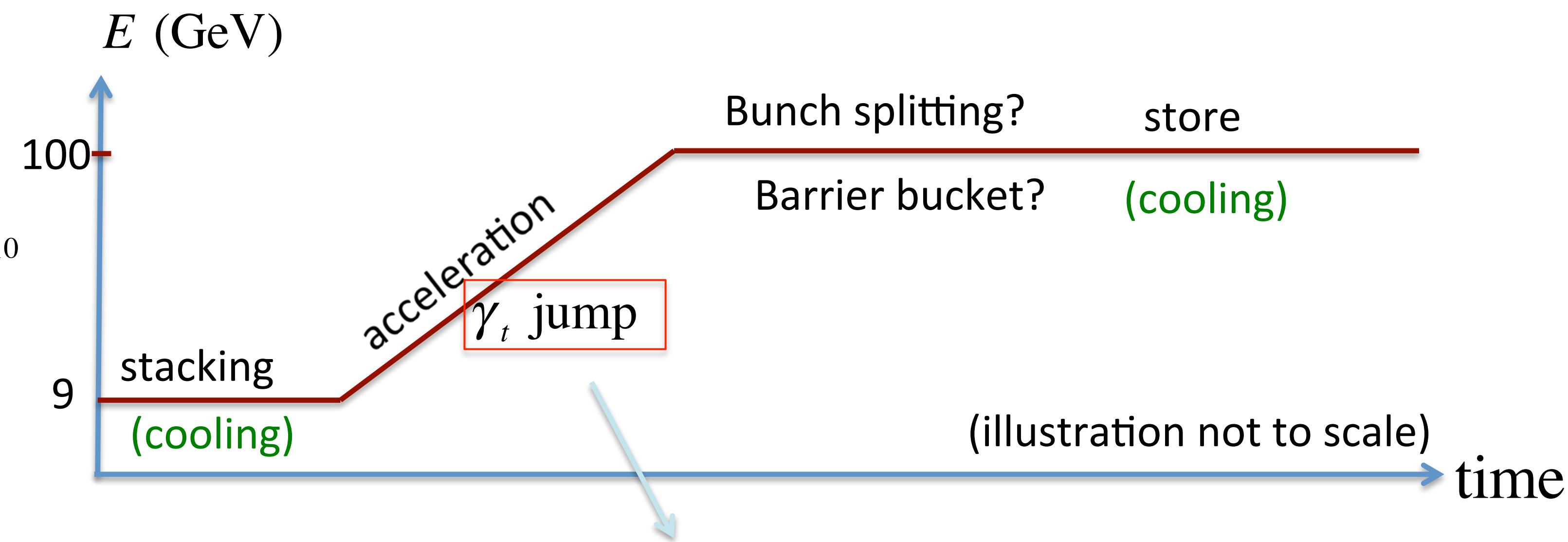
- With chromaticity and active feedback system, we should be mostly safe from head-tail instability
- Space charge could play an important role for transverse single bunch instability
- Need to do some careful studies on impedance and mode coupling calculations

Head-tail Instability for JLEIC Ion Collider Ring

Proton beam

$N_b = 2\times 10^{10}$

$(\gamma_t = 12.46)$



- May need chromaticity jump at transition crossing
- Machine impedance
  Need impedance studies for ion ring
- Active feedback system

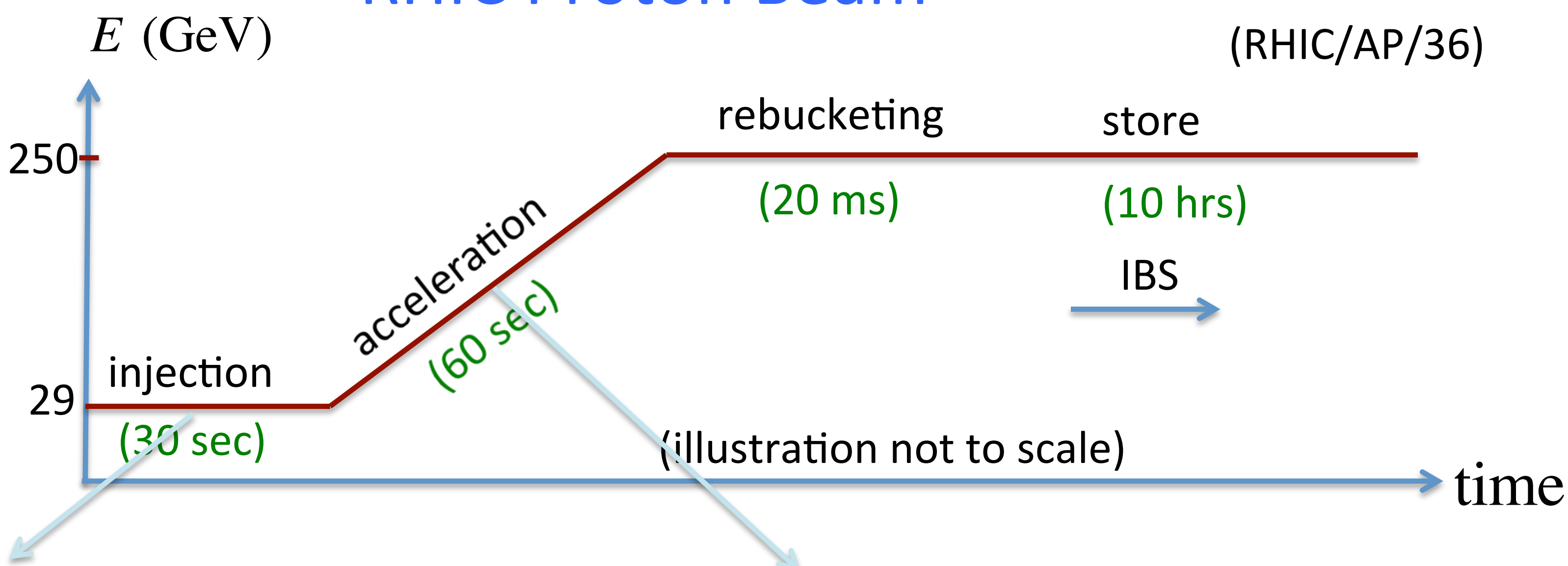
Transverse Coupled-Bunch Instability for Ion ring: RHIC Proton Beam

(RHIC/AP/36)

Proton beam

$N_b = 10^{11}$

$(\gamma_t = 22.89)$



χ	α_d [s^{-1}]	$\alpha_{\max}$ [s^{-1}]	l	s
0.0	0	26.6	0	28
1.4	0	.06	5	28
2.8	0	.00	19	28
0.0	30	.002	5	2
1.4	30	.002	8	28
2.8	30	.000	—	—

χ	α_d [s^{-1}]	$\alpha_{\max}$ [s^{-1}]	l	s
0.0	0	5.60	0	28
1.4	0	.30	1	28
2.8	0	.08	2	28
0.0	6	.004	3	2
1.4	6	.003	5	28
2.8	6	.005	5	28
4.2	6	.002	6	28

α_d : damping rate

$\alpha_{\max}$: growth rate

l : synchrotron mode

s : coupled bunch mode

- Weak-coupling limit
- Calculated by ZAP
- With or without active damping

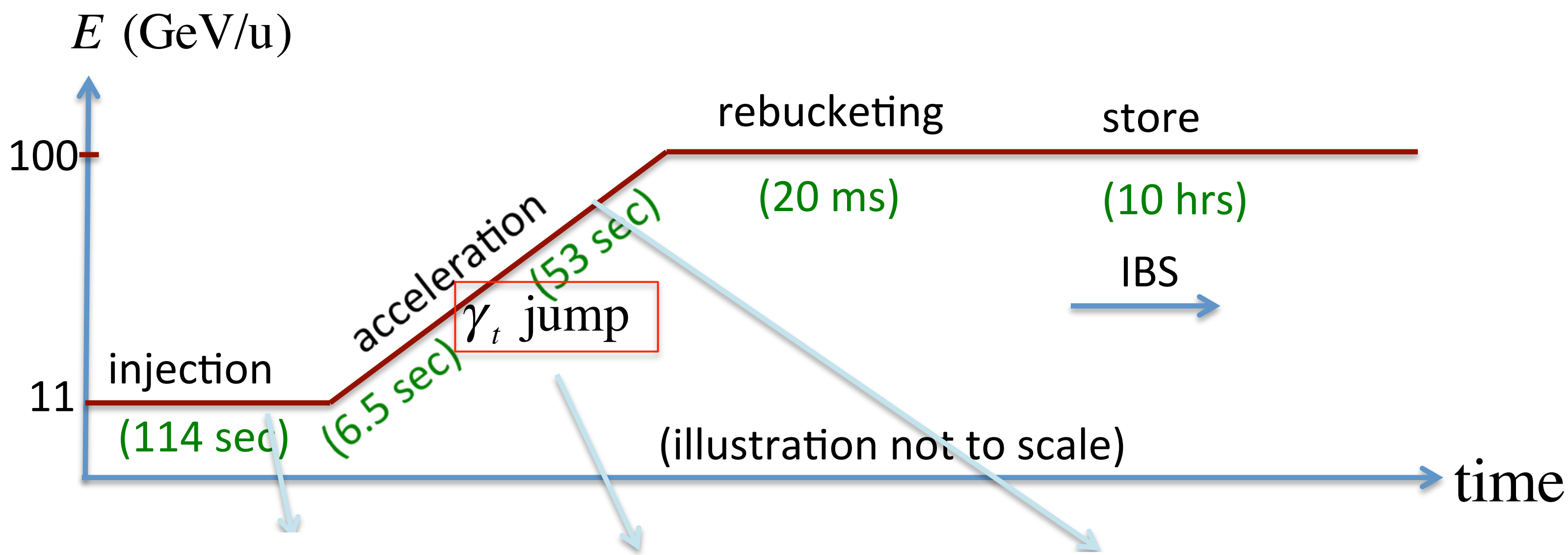
(Peggs and MacKay)

Transverse coupled-bunch Instability for Ion ring: RHIC Gold Beam

Gold beam

$N_b = 10^{11}$

$(\gamma_t = 22.89)$



χ	α_d $[\mathrm{s}^{-1}]$	$\alpha_{\max}$ $[\mathrm{s}^{-1}]$	l	s
0.0	0	20.8	0	28
-1.4	0	7.73	0	28
-2.8	0	1.86	1	28
-4.2	0	.38	2	28
-5.6	0	.07	4	28
0.0	30	.00	6	2
-1.4	30	.00	—	—
-2.8	30	.00	—	—

γ_t jump:

$\gamma < \gamma_t$, ξ=-2

$\gamma > \gamma_t$, ξ=3

Chromaticity jump

within $\tau_s = 28$ ms

χ	α_d $[\mathrm{s}^{-1}]$	$\alpha_{\max}$ $[\mathrm{s}^{-1}]$	l	s
0.0	0	4.40	0	28
1.4	0	.03	3	28
2.8	0	.00	9	28
0.0	6	.00	14	2
1.4	6	.00	17	24
2.8	6	.00	17	28

Summary and Future Plans

- Some estimations of instabilities in JLEIC are done using reference of impedance in other colliders, mostly safe, some are marginal
- Need more development
  - updated baseline design
  - Impedance budget for each ring
  - Bunch formation/splitting scheme and RF configurations
- Further studies
  - Transverse coupled-bunch instability
  - Electron cloud effect for ions

    Safe from head-tail instability (Ohmi, Zimmermann)

    Need to evaluate other instabilities
  - Ion effects for electrons

    For the colliding e-beam and the high-energy e-cooling beam