CFB: Fast Feedback System and Kicker Design for e-Ring Coupled-Bunch Instability Control with 2 ns Spacing
• Description
  — Conceptual design and specification of a fast feedback kicker system for the JLEIC e-ring for up to 3A current, 476.3 MHz bunch rate (2.1 ns), at 3 GeV. This work will be performed in collaboration with Industry.

• Status
  — In progress

• Main goal
  — Demonstrate capability for stable beam operation at maximum current over JLEIC operating energy range of 3-12 GeV. This is up to 3A at low energy reducing at higher energy limited by 10 MW synchrotron radiation power

• Supported by JLab’s Additional DoE NP Accelerator R&D funding

• The project’s funding is not continued by the FY’18 NP Accelerator R&D FOA. However, one collaboration funded FY’18 project with ANL(PI Zack Conway) will benefit from this project’s results.
Fast Feedback System & Kicker Design

- **Budget**

<table>
<thead>
<tr>
<th>Task</th>
<th>FY’17 Q1</th>
<th>FY’17 Q2</th>
<th>FY’17 Q3</th>
<th>FY’17 Q4</th>
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<tbody>
<tr>
<td>System specifications and electromagnetic design of fast feedback kickers for this application</td>
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<table>
<thead>
<tr>
<th></th>
<th>FY’17-FY’18</th>
<th>Totals</th>
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<tbody>
<tr>
<td>a) Funds allocated</td>
<td>$135,000</td>
<td>$135,000</td>
</tr>
<tr>
<td>b) Actual costs to date</td>
<td>$64,935</td>
<td>$64,935</td>
</tr>
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</table>

- **Deliverables and schedule**

- The project corresponds to Line 19, “High-power fast kickers for high bandwidth (2 ns bunch spacing) feedback”, Priority High-B of the Jones’ Panel report
Statement of the problem to be solved

• The JLEIC electron and ion storage rings are high-current with many bunches
• The individual bunch charge is chosen to avoid single bunch instability limits
• Collective effects and multi-bunch instabilities are challenging
  — Dominated by narrow-band impedances from RF cavities, vacuum chamber, collimators, etc.
  — Compared to PEP-II we will have more cavities and reach to lower energy
• Broad-band bunch-by-bunch feedback systems are necessary
• Such systems are routinely used in B-Factories and light sources

• What are the requirements of the feedback systems?
• What technical solutions are appropriate?
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

Rigid bunch oscillation

Higher order bunch shape oscillation

- Coupled Bunch Modes

PEP-II actual bunch rate $\leq 476/2 = 238$ MHz, 119 MHz BW needed (kickers built)
Transverse FB electronics DC-238 MHz
W. Barry, PAC95
LFB cavity 952-1190 MHz
(1071 MHz center frequency, 238 MHz BW)
P. McIntosh PAC03
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,
e-ring cavities

- e-ring baseline uses PEP-II RF at 476.3 MHz
- Need to adjust input beta for better match at 3A
- Large contribution to impedance budget
- Reconstructing RF model
- Starting station layouts

PEP-II raft assembly

RF model

PEP-II station layout
Contributions to damping from Feedback and synchrotron radiation in e-ring

LFB: Longitudinal Feedback
LFB Kicker Total Voltage: 7kV
LFB phase resolution: 0.02 rad
Max LFB “Gain”: 3.5e5

FFB system is mandatory!
Narrowband Impedance: JLEIC ion-Ring initial design

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

as tradeoff between accelerating and HOM-damping efficiency

Unstable!

causes LCBI
Narrowband Impedance: JLEIC ion-Ring new baseline

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

Stable!

Reduced LCBI growth rate
Narrowband Impedance: IR Chamber first look

JLEIC IR Chamber CAD Model (Marhauser)

Many trapped modes!
Needs optimization

Monopole Modes

Dipole Modes

Long. Loss Factor ($\sigma = 30 \text{ mm}$) = 0.185 V/pC
Narrow Impedance: Crab Cavity

- Prototype converging to a 952.6 MHz 2-cell RFD cavity.
- HOM damping under development

(HK Park, ODU

2 hook couplers

Damping under study

2 wave guides

RFD type cavity
JLEIC Impedance Status

• We are at the beginning phase of impedance studies
• Engineering analysis and EM modeling are underway
• Best estimates from known impedances and scaling from other rings
  ─ PEP-II cavities - well characterized
  ─ Vacuum chamber – scaled from B-Factories
  ─ IR – studies just starting
  ─ Crab cavities – under development
• Use best available data for modeling, understanding it may change
### JLEIC Electron-ring

<table>
<thead>
<tr>
<th>(E [\text{GeV}])</th>
<th>3</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a=1 \ [\text{ms}])</td>
<td>2.9</td>
<td>4.0</td>
<td>72.8</td>
</tr>
<tr>
<td>(a=2 \ [\text{ms}])</td>
<td>31.3</td>
<td>43.5</td>
<td>466</td>
</tr>
<tr>
<td>(E \ [\text{ms}])</td>
<td>187.4</td>
<td>40.5</td>
<td>5.1</td>
</tr>
<tr>
<td>(V_{RF} \ [\text{MV}])</td>
<td>0.40</td>
<td>2.02</td>
<td>17.87</td>
</tr>
<tr>
<td>Cavity Number</td>
<td>1</td>
<td>2</td>
<td>15</td>
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</table>

### JLEIC p-ring

<table>
<thead>
<tr>
<th>(E [\text{GeV}])</th>
<th>100</th>
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<tbody>
<tr>
<td>(a=1 \ [\text{ms}])</td>
<td>30.7</td>
</tr>
<tr>
<td>(a=2 \ [\text{ms}])</td>
<td>6.2</td>
</tr>
<tr>
<td>(V_{RF} \ [\text{MV}])</td>
<td>42.6</td>
</tr>
<tr>
<td>Cavity Number</td>
<td>34</td>
</tr>
</tbody>
</table>

- 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.
- Need feedback to damp longitudinal quadrupole mode CBI.
- Need to consider growth rate for a non-parabolic bunch.
## Transverse Coupled-Bunch Instability

### JLEIC Electron-ring

<table>
<thead>
<tr>
<th>$E$ [GeV]</th>
<th>3</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a=0$ [ms]</td>
<td>1.6</td>
<td>2.7</td>
<td>64</td>
</tr>
<tr>
<td>$a=1$ [ms]</td>
<td>12.8</td>
<td>19.6</td>
<td>39.8</td>
</tr>
<tr>
<td>$y$ [ms]</td>
<td>375</td>
<td>81</td>
<td>10.1</td>
</tr>
<tr>
<td>$V_{RF}$ [MV]</td>
<td>0.40</td>
<td>2.02</td>
<td>17.87</td>
</tr>
<tr>
<td>Cavity Number</td>
<td>1</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

(assume $x=1$, $\Delta b = 3e-04$)

### JLEIC p-ring

<table>
<thead>
<tr>
<th>$E$ [GeV]</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a=0$ [ms]</td>
<td>24.4</td>
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<tr>
<td>$a=1$ [ms]</td>
<td>805</td>
</tr>
<tr>
<td>$y$ [min]</td>
<td>$&gt;30$</td>
</tr>
<tr>
<td>$V_{RF}$ [MV]</td>
<td>42.6</td>
</tr>
<tr>
<td>Cavity Number</td>
<td>34</td>
</tr>
</tbody>
</table>

(assume $x=1$, $\Delta b = 3e-04$)

Due to resistive wall impedance (Cu), cannot be improved by HOM damping.
Feedback system specifications

Key questions:
• What feedback kick voltage is needed in each ring, each plane?
  — ~2x PEP-II looks reasonable
• What is the best operating band to choose for each system?
  — Need full 238 MHz bandwidth
• What is the best kicker technology?
  — Damped cavity longitudinal, high-power striplines transverse
• How many total kickers are needed?
  — TBD

Pathways to answers:
• Compare with existing machines like B-Factories, LHC, RHIC, JPARC
• Contract with industry (Dimitel Inc.) for high-level system architecture
• Take advantage of new kicker designs like APS and DAPHNE
Longitudinal feedback

- PEP-II feedback systems allowed running above threshold. Similar systems are now commercially available.
- System will be coupled to main RF for low modes.
- Reliable high-power **kickers** are needed.

![DAPHNE type kicker](image)

![PEP-II Longitudinal Feedback system concept](image)
Transverse feedback

- PEP-II feedback systems allowed running above threshold. Similar systems are now commercially available.
- Initial kickers had problems with feedthroughs and overheating.
- Reliable high-power kickers are needed (e.g. APS type) – FY18 FOA award to ANL.
Conclusions and future work

- Preliminary estimates of ring impedances have been made
- Growth rates confirm the necessity of feedback systems
- Predicted parameters are similar to existing machines
- New kicker technologies in light sources and colliders can be adapted to JLEIC

Path forward
- Industry will be used to provide high level electronic design (subcontract to Dimitel Inc.)
- ANL will develop kicker designs based on APS (Z. Conway)
- Impedance model will be continuously updated
- Final specifications and system design will be ready for CDR.
Thank you!
Growth Rate Estimation

• Zotter’s formula

\[
\text{Growth Rate: } \imath_{m,a} = \text{Im}(\imath_{m,a})
\]

(assumes even bunch fill pattern)

Longitudinal Coupled Bunch Instability (LCBI)

Frequency shift:

\[
\Delta \omega_{\mu,a} = i \frac{a}{a + 1} \frac{q_i I_b \omega_0^2 \eta}{3(L / 2\pi R)^3 2\pi B^2 (E_T / e) \omega_s} \left[ \frac{Z}{n} \right]_{\text{eff}}^{\mu,a}
\]

Effective impedance:

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

for \( \omega_p'' = pk_b + \mu + av_s \)

Transverse Coupled Bunch Instability (TCBI)

Frequency shift:

\[
\text{Frequency shift: } \imath_{m,a} = i \frac{1}{a + 1} \frac{q_i I_b c^2}{2 (E_T / e) L} \left[ Z \right]_{\text{eff}}^{m,a}
\]

Effective impedance:

\[
\left[ Z \right]_{\text{eff}}^{m,a} = \sum_{p=-\infty}^{\infty} Z \left( \frac{h_a(p)}{S_a(p)} \right), \text{ for } p = pk_b + \mu + av_s
\]
Impedance Measurement vs. Calculation

\[
\left( \frac{\sigma}{\sigma_0} \right)^3 \frac{I_p \Im \left( \frac{Z_{\text{eff}}}{n} \right)}{2 \pi \alpha \sigma_0^2 E/e} = \frac{Z_{\text{eff}}}{n} = \text{const}
\]

\[
\Delta V = \frac{I_b}{4 \pi \sigma_0 \omega_0 E/e} \sum_i \beta_i \Im Z_{\text{eff}}^{i}
\]

(V. Smaluk, eeFACT2016)
Broadband Impedance Estimation: JLEIC e-Ring

- **Component Counts** (T. Michalski)

<table>
<thead>
<tr>
<th>Elements</th>
<th>e-Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flanges (pairs)</td>
<td>1215</td>
</tr>
<tr>
<td>BPMs</td>
<td>405</td>
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<tr>
<td>Vacuum ports</td>
<td>480</td>
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<tr>
<td>Bellows</td>
<td>480</td>
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<tr>
<td>Vacuum Valves</td>
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<tr>
<td>Tapers</td>
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<tr>
<td><strong>Collimators</strong></td>
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<tr>
<td>DIP screen slots</td>
<td>470</td>
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<tr>
<td>Crab cavities</td>
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<tr>
<td>RF cavities</td>
<td>32</td>
</tr>
<tr>
<td>RF valves</td>
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<tr>
<td>Feedback kickers</td>
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<tr>
<td>IR chamber</td>
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</table>

- **Impedance Estimation** (K. Deitrick)

<table>
<thead>
<tr>
<th>Broadband Impedance</th>
<th>Reference: PEP-II</th>
<th>Reference: SUPERKEKB</th>
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<tbody>
<tr>
<td>$L$ [nH]</td>
<td>99.2</td>
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<tr>
<td>$</td>
<td>Z_\parallel/n</td>
<td>$ [Ω]</td>
</tr>
<tr>
<td>$k_\parallel$ [V/pC]</td>
<td>7.7</td>
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<tr>
<td>$Z$ [kW/m]</td>
<td>60</td>
<td>13</td>
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</tbody>
</table>

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

$\leq 0.1$ $\leq 0.1 \text{ M}$
• Component Counts

<table>
<thead>
<tr>
<th>Elements</th>
<th>p-Ring</th>
</tr>
</thead>
<tbody>
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<td>Vacuum ports</td>
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<td>Vacuum Valves</td>
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<td>Collimators</td>
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<td>RF cavities</td>
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<tr>
<td>RF cavity bellows</td>
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(T. Michalski)

• Impedance Estimation

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<tbody>
<tr>
<td>$L$ [nH]</td>
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</tr>
<tr>
<td>$</td>
<td>Z_{</td>
</tr>
<tr>
<td>$k_{</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>Z</td>
</tr>
</tbody>
</table>

(K. Deitrick)

- 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

$\leq 0.1$ $\leq 0.1 \text{ M}$