Coherent Synchrotron Radiation in Energy Recovery Linacs

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Collaborators:

1 Colorado State University
2 Thomas Jefferson National Accelerator Facility
3 Los Alamos National Laboratory
Outline

- Introduction
  - Energy Recovery Linacs
  - Coherent Synchrotron Radiation
- Upcoming ERLs
- The JLab FEL Driver
- Summary of the Experiment\(^1\)
- Results/Comparison to Simulation
- Conclusion

Assuming perfect energy recovery:

\[
\frac{P_{\text{beam}}}{P_{\text{RF}}} \approx \frac{I_{\text{avg}}E_f}{I_{\text{avg}}E_{\text{inj}} + P_{\text{RF,linac}}}
\]
Coherent Synchrotron Radiation

Overview

Incoherent Emission

\[ \lambda_{rad} > l_b \]\[ P \propto N_e^2 \]

Coherent Emission

Very high CSR power possible in ERLs!

CSR leads to slice energy spread increase

Projected emittance growth after a dipole will increase
The Microbunching Instability

A small modulation in density leads to a modulation in energy via impedances.

Traversing a region with time/energy correlation can increase the density modulation, under the right conditions.
MEIC

Medium Energy Ion-Electron Collider at Jefferson Lab

Courtesy of D. Douglas
MEIC

- 0.5 nC with 3 cm long bunch (rms) tracked for 100 turns with CSR

Simulations suggest CSR induced microbunching will need to be accounted for

Courtesy of D. Douglas

Medium Energy Ion-Electron Collider at Jefferson Lab

Simulations suggest CSR induced microbunching will need to be accounted for

Courtesy of D. Douglas
Motivation

- ERL are very different from other accelerators:
  - Not at equilibrium like a ring.
  - Recirculation loops very different compared to standard linac.

- Bates bend structures allow for novel experiment. Using quads to adjust total $R_{56}$.

- Can study CSR over wide range of compression dynamics.

- Verify against 1-D CSR model*

*E. Saldin, et. al, NIM A 398, 373 (1997)
The Jefferson Lab ERL FEL

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Repetition Rate [MHz]</td>
<td>75</td>
</tr>
<tr>
<td>Bunch Charge [pC]</td>
<td>135</td>
</tr>
<tr>
<td>Beam Energy [MeV]</td>
<td>up to 160</td>
</tr>
<tr>
<td>Max Beam Current [mA]</td>
<td>10</td>
</tr>
<tr>
<td>Beam Power [MW]</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Observe 200 W/mA of CSR power
Controlling Momentum Compaction in the Arc

Transverse kicks given to the beam:

Quadrupole Kick \[ \delta x' = -Ax \]

Sextupole Kick \[ \delta x' = -Bx^2 \]

In the dipole:

\[ R_{52} = -\rho(1 - \cos \theta) \quad \text{and} \quad \theta = 180^\circ \]

Path Length Difference: \[ \delta z = -2\rho \delta x' \]
Varying the Compression Point

Quadrupoles in the 1st arc can be adjusted to change $R_{56}$ while maintaining achromatic transport.

$R_{56} \rightarrow$ variable

$R_{56}$ between -0.5 to +1.0 m possible

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$R_{56} = -52$ cm

$R_{56}$ for Critical Compression: +20 cm
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Quadrupoles in the 1st arc can be adjusted to change $R_{56}$ while maintaining achromatic transport.
### Experiment Machine Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>Injection energy [MeV]</td>
<td>9</td>
</tr>
<tr>
<td>$E_f$</td>
<td>Final energy [MeV]</td>
<td>135</td>
</tr>
<tr>
<td>-</td>
<td>Charge per bunch [pC]</td>
<td>135</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>Bunch length after injector [ps]</td>
<td>3</td>
</tr>
<tr>
<td>$\sigma_f$</td>
<td>Bunch length at max compression [fs]</td>
<td>150</td>
</tr>
<tr>
<td>$h$</td>
<td>Energy-position correlation (chirp) [$m^{-1}$]</td>
<td>±5</td>
</tr>
<tr>
<td>-</td>
<td>RF phase [degrees]</td>
<td>±10</td>
</tr>
<tr>
<td>-</td>
<td>RF frequency [GHz]</td>
<td>1.497</td>
</tr>
<tr>
<td>$R_{56}^{bc}$</td>
<td>Optical cavity chicane $R_{56}$ [cm]</td>
<td>-52</td>
</tr>
<tr>
<td>$R_{56}^{bb}$</td>
<td>THz suppression chicane $R_{56}$ [cm]</td>
<td>-4.6</td>
</tr>
<tr>
<td>$R_{56}^{thz}$</td>
<td>Bates arcs $R_{56}$ [cm]</td>
<td>variable</td>
</tr>
</tbody>
</table>
Measuring Energy Loss

BPM readings from each side of 180° bend average to remove any betatron offset.

Averaged reading taken in 1\textsuperscript{st} and 2\textsuperscript{nd} arc. Common jitter is removed by subtracting out the measurement from arc 1.
Falling RF Measurement
Falling RF Measurement
Falling RF Measurement
Falling RF Measurement
Falling RF Measurement
Rising RF Measurement

Did not sweep far enough to see full compression in the 1st arc.

Impact of sextupoles shown in this measurement.

Changing strength of quadrupoles in first arc.
Rising RF Measurement

Impact of sextupoles shown in this measurement

Did not sweep far enough to see full compression in the 1st arc
Rising RF Measurement

Did not sweep far enough to see full compression in the 1st arc

Impact of sextupoles shown in this measurement
Linearization

Sextupoles On - Linearized Bunch

Compressible region

Sextupoles Off

optical cavity chicane

IR wiggler

THz suppression chicane
When bunch is compressed, energy redistribution from CSR/LSC is observed. This redistribution is dependent on the degree of compression.

Please note: The animation can be viewed on the next slide.
When bunch is compressed, energy redistribution from CSR/LSC is observed. This redistribution is dependent on the degree of compression.
Energy Distribution Simulation
Energy Distribution Simulations

Chicane End

After CSRdrift

(a) $R_{56}^{A1} = 0.87 \text{ m}$
(b) $R_{56}^{A1} = 0.71 \text{ m}$
(c) $R_{56}^{A1} = 0.68 \text{ m}$

(d) $R_{56}^{A1} = 0.64 \text{ m}$
(e) $R_{56}^{A1} = 0.60 \text{ m}$
(f) $R_{56}^{A1} = 0.55 \text{ m}$

optical cavity chicane
IR wiggler
THz suppression chicane

2nd Bates bend
In Arc 2
Can fit a parabola to the longitudinal phase space:

$$\delta(z; h) = -\left(\frac{1}{h} + R_{56}\right) \frac{1}{2T_{566}} \pm \frac{1}{2T_{566}} \sqrt{\left(\frac{1}{h} + R_{56}\right)^2 + 4T_{566}z}$$

Average energy of the head of the bunch will shift as compression is changed.

CSR wake strongest at head of the bunch. Causes fragmentation of the energy spectrum dependent on compression.
Compensating Non-Linear Compression

Curvature Induced by RF:
\[ z_1 = z_0 \]
\[ \delta_1 = \delta_0 + R_{65} z_0 + T_{655} z_0^2 \]

Transport through a longitudinally dispersive region:
\[ z_2 = z_1 + R_{56} \delta_1 + T_{566} \delta_1^2 \]
\[ \delta_2 = \delta_1 \]

Can remove curvature by correctly setting \( T_{566} \) in the first arc with the sextupoles:
\[ R_{56} T_{655} + T_{566} R_{65}^2 = 0 \]
Impact of Sextupoles

Sextupoles Off

Sextupoles On

Charge Distribution

Energy Distribution
Conclusions

- Better understanding of CSR will be critical for the success of many upcoming accelerators.
- Measurements show good qualitative agreement to 1-D CSR model.
- CSR in drifts after a bunch compressor can have a large impact on the energy distribution.
- Important to control longitudinal curvature to keep energy distribution uniform.
  - Leads to greater energy loss overall due to better compression.
Further Work

- Perform a better analysis of simulations for microbunching.
- Include longitudinal space charge in simulation
  - Underway currently
  - Leads to large enhancement of fragmentation in energy spectrum
- Further experiments?
  - Better test sextupole impact
  - Measure emittance
THANK YOU!