Development of an Ultra Fast RF Kicker for an ERL-based Electron Cooler

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Fast kicker requirements for the JLab MEIC

- The Jefferson Lab Medium Energy Electron-Ion Collider (MEIC) utilizes electron cooling of ions for reduced emittance, high luminosity
  - Staged approach to electron cooling employs **bunched beam cooling** in ion collider ring for suppressing IBS-induced emittance growth, maintaining design emittances
  - Single-pass ERL to accelerate/decelerate high current, high power bunches
  - Luminosity upgrade requires higher current for more intense electron cooling
  - ERL with full circulator ring
Fast kicker requirements for the JLab MEIC

- An **ERL with full circulator ring** relaxes the current requirement from the injector
- At top energy with 3 nC electron bunches at 476 MHz
  - Single-pass: 1.5 A from source, 3 MW at dump
  - Multi-pass in ring: 60 mA from source, 120 kW at dump for 25 turns

- Beam kicker to deflect bunches into and out of circulator ring needs rise and fall times ~ 1 ns at MHz repetition rates
  - **Beyond current driver technology**
Kicker waveform generation

- For n turns in the circulator ring, kicker needs to deflect every n-th bunch in bunch train into/out of circulator ring

- \(~\) Periodic delta function with frequency \(f_{\text{eff}} = \frac{476}{n} \text{ MHz}\)
  - Use this approximation to generate a suitable waveform

476 MHz pulse train in circulator ring

Few kV

\(~\)ns \quad \sim \quad \sim \text{tens of ns} \quad \sim
Kicker waveform generation

- **Subharmonics of the electron bunch frequency*** summed to generate a continuous waveform with peaks at the effective frequency $f_{\text{eff}} = \frac{476}{n} \text{ MHz}$
- Relative phases and amplitudes of subharmonics manipulated to shape waveform according to desired characteristics

- Rise and fall times == bunch spacing
- Magnitude of kicking pulse == zero for non-kicked bunches that continue in circulator ring
- Gradient of kicking pulse == zero for non-kicked bunches

* [A. Hutton, B. Terzic]
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Non-uniformity of kicking pulse

- Sharp rise and fall times create a narrow pulse that is not uniform over the length of the electron bunch
- “Flat-top” kicking pulse formed by adjusting subharmonic amplitudes and phases appropriately
- For full beam size of 2 mm transverse, 600 ps longitudinal (+/- 3σ)
  - \( V = 0.934 \ V_{\text{peak}} \) for \( f = 476 \text{ MHz} \)
Simulations of transverse effects

- Transverse effects on kicked and unkicked bunches in a circulator ring simulated using ELEGANT
- Circulator ring approximated with 1 turn linear transfer matrix
- Kicker waveform generated using a series of zero-length RF deflectors with appropriate frequencies, phases, and amplitudes

### Nominal parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ [MeV/c]</td>
<td>55.5086</td>
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<tr>
<td>$\varepsilon_x$, $\varepsilon_y$ [nm]</td>
<td>10</td>
</tr>
<tr>
<td>$\beta_x$, $\beta_y$ [m]</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_s$ [cm]</td>
<td>3</td>
</tr>
<tr>
<td>$\sigma_{\Delta\rho/\rho}$</td>
<td>$3 \times 10^{-4}$</td>
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<tr>
<td>$f$ [MHz]</td>
<td>476</td>
</tr>
<tr>
<td>$n$</td>
<td>25</td>
</tr>
<tr>
<td>$V_{\text{kick}}$ [kV]</td>
<td>50</td>
</tr>
</tbody>
</table>

ELEGANT verification of kicker waveform generation
Transverse effects for zero-gradient pulse

- **Zero-gradient pulse**: $V=0$ and $dV/dt=0$ at bunch arrival times for any non-kicked bunch
  - No relative phase offset between subharmonics
  - Kicking pulse non-uniformity 6.6%

- At time $t=0$, bunch is kicked into ring
- With each turn, bunch sees different part of intermediate kicker waveform
- After 25\textsuperscript{th} turn, bunch again sees kicking pulse and is kicked out of ring
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- 4% emittance growth due to non-uniformity of kick
- Negligible emittance growth due to residual voltages seen as bunch circulates
- Larger growth seen after bunch receives second kick
  - Less significant as bunch heads toward energy recovery
Transverse effects for flat-top pulse

- Immediate 4% emittance growth due to non-uniformity of zero-gradient pulse
- **Flat-top pulse**: adjust relative phase offsets, amplitudes of subharmonics while maintaining $V=0$ at bunch arrival times for non-kicked bunches
  - $dV/dt\neq 0$
  - Kicking pulse non-uniformity 0.1%

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$n=11$ for illustration only

Phase space distortion more apparent
Transverse effects for flat-top pulse

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- 0.4% emittance growth due to non-uniformity of kick
- Large emittance growth due to large gradients seen by bunches during first few turns
  - Very large emittance growth as bunch prepares to exit ring
  - ~2x increase due to gradients on first turn, additional 2x increase due to gradients on $(n-1)^{th}$ turn

![Turn-by-turn normalized horizontal emittance](image-url)
Compensation of phase space distortion

- For flat-top pulse, transverse phase space distortion is amplified by large gradients, resulting in large emittance growth that degrades cooling efficiency
- Phase space distortion is well-defined – we know our kicking pulse
- **Pre-distort** the distribution to send a matched bunch into the circulator ring

![Diagram showing phase space distortion compensation](image)
Compensation of phase space distortion

- Compensation of phase space distortion reduces emittance growth for the flat-top pulse to ~5%
  - Comparable to non-compensated zero-gradient pulse
Possible cavity structures for fast kicker

- PEP-II fast feedback transverse kicker on loan from SLAC – strip line kicker designed for lower frequency
- Initial CST simulations (J. Guo, TUPF10) indicate high power consumption to drive the SLAC kicker with this type of kicker waveform ( > 10 kW)
- Design and simulation of resonant cavity structure supporting the flat-top pulse with 100 W total power consumption
Summary

• Bunched beam cooling is an integral component to attaining high luminosity in the JLab MEIC

• An ERL + circulator ring complex for possible luminosity upgrade requires fast RF kickers that are beyond current driver technology

• Simulations indicate that kicking waveform with ~ns rise and fall times and MHz repetition rates can successfully kick suitable electron bunches without major degradation of bunch quality
  – 4% transverse emittance growth due to kick

• Possible cavity structures and experimental measurements are being pursued

• We are optimistic about the prospects of an ultra fast RF kicker!