Energy stabilization of the PIP-II LINAC

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Overview

• Brief review of the PIP-II LINAC design
• Development of a suitable simulation tool
• Benchmarking
• Initial results
• Summary and way forward
Overview of the LINAC

- 120 RF cavities
  - 4 bunchers (red)
  - 8 HWR (green)
  - 16 SSR1 (blue)
  - 35 SSR2 (cyan)
  - 33 LB650 (yellow)
  - 24 HB650 (magenta)
- Accelerating voltage (blue)
- Synchronous phase (red)

<table>
<thead>
<tr>
<th>Cavity type</th>
<th>Frequency</th>
<th>$Q_L$</th>
<th>$r/Q$</th>
<th>$K_p/K_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buncher</td>
<td>162.5 MHz</td>
<td>5210</td>
<td>700</td>
<td>2.5/3e5</td>
</tr>
<tr>
<td>HWR</td>
<td>162.5 MHz</td>
<td>$2.7 \times 10^6$</td>
<td>275</td>
<td>665/4e7</td>
</tr>
<tr>
<td>SSR1</td>
<td>350 MHz</td>
<td>$3.7 \times 10^6$</td>
<td>242</td>
<td>455/4e7</td>
</tr>
<tr>
<td>SSR2</td>
<td>350 MHz</td>
<td>$5.2 \times 10^6$</td>
<td>296</td>
<td>713/4e7</td>
</tr>
<tr>
<td>LB650</td>
<td>650 MHz</td>
<td>$11.3 \times 10^6$</td>
<td>375</td>
<td>695/4e7</td>
</tr>
<tr>
<td>HB650</td>
<td>650 MHz</td>
<td>$11.5 \times 10^6$</td>
<td>609</td>
<td>707/4e7</td>
</tr>
</tbody>
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Simulation code development

- Trace-win has an RF simulation tool
  - Missing some key features: integral feedback loop, feed-forward compensation, arbitrary drive function for beam-loading
  - Calculations are time consuming
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  – For electrons (assumes particle velocities are the speed of light)
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• Develop a code that supplements existing beam-dynamics codes and has all the features we need
  – A parser interoperates the lattice file from these codes
  – Simpler calculations make for fast execution
  – Suitable for any particle species
Simulation code development

- Feedback model has arbitrary beam-loading compensation and arbitrary beam disturbances
Simulation code development

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- Assume the cavity is at steady state when the beam arrives

\[
V_{\text{cav}}(t) = V_{\text{set}} + \int_{-\infty}^{\infty} (V_{\text{beam}}(t - \tau) + V_{\text{ff}}(t - \tau)) \frac{-ae^{-bt}}{k} \left( e^{-\frac{kt}{2}} - e^{\frac{kt}{2}} \right) d\tau
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- Calculate phase advance in drift and kick from RF cavities

\[
\delta\phi(t) = \frac{\omega_0 L}{\beta(t)c} \quad \Delta E = V_{\text{cav}}(t) \cos(\phi_s + \delta\phi(t))
\]
Benchmarking: beam dynamics model

• Perturbation study
  – Perturb each cavity by one degree and observe the resultant change in energy and phase at the end of the LINAC
  – Compare with parmela simulation
Benchmarking: beam dynamics model

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• Parmela phase convention slightly different then the developed code
  – The new code uses the frequency of the proceeding cavity for the phase advance of each drift
  – Parmela uses a global frequency clock and computes the cavity phase relative to that clock

\[ \phi = \phi_{\text{cav}} + \Phi \frac{f_{\text{cav}}}{f_0} \]
  – For comparison we use both phase conventions in our code
Energy sensitivity as a function of cavity number for a one degree perturbation in each along the LINAC

Phase sensitivity as a function of cavity number for a one degree perturbation in each along the LINAC
Benchmarking: RF feedback system model

- The RF model does not currently incorporate a feedback delay
  - try to understand how this affects our calculations
- Left: Cavity voltage as a function of time for the five types of SRF cavities due to an uncompensated beam-loading transient
- Right: Cavity phase as a function of time for the five types of SRF cavities due to uncompensated beam-loading transient
Benchmarking: RF feedback system model

- A similar model has been used on the bunching cavity at PI-Test
- Right: measured RF waveform with a beam-loading-like disturbance driven from the LLRF system compared with simulations
Combined RF and Beam simulations

Energy modulation along the beam pulse as a function of time for uncompensated beam-loading transients

Phase modulation along the beam pulse as a function of time for uncompensated beam-loading transients
Combined RF and beam simulations

Evolution of the energy deviation from nominal along the LINAC for four beam slices along the beam pulse

Evolution of the phase deviation from nominal along the LINAC for four beam slices along the beam pulse
Non-ideal current distribution

- Current distributions have been treated as “top-hat”
- The code can handle arbitrary current distributions at some sample interval
- Right: Measured current profile (timing scan) along the beam pulse from the MEBT beam dump
Non-ideal current distributions and feed-forward

- Left/Right: Energy/Phase modulation along the beam pulse for a top-hat beam current profile (green), the measured beam current profile (blue), the measured beam current profile with a poorly timed feed forward compensation pulse (red), and a mostly compensated transient (teal)
Summary and way forward

• Developed a tool for providing estimates of the impact of RF transients on the beam throughout the LINAC
• Benchmarked against measured data and existing accelerator codes
• Initial calculations indicate that fast beam-based feedback is probably not necessary
• Next steps
  – Incorporate the transfer line
  – Add transverse dynamics
  – Study schemes for global RF control