Low Level RF for PIP-II

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PIP-II LLRF Team

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What is PIP-II

- PIP – II is a 20Hz, 800 MeV, superconducting H- LINAC that will replace the existing 400 MeV copper LINAC
- The primary goal of this upgrade is to increase the beam power available to neutrino experiments to 1.2 MW
- As part of the PIP-II R&D plan we are also building a test stand
  - Warm front end, HWR, and SSR1
  - Goal to test the chopper and the transition from NC to SC as well as prove out accelerator technology
Overview of the PIP-II LINAC

- RF field control of all LINAC Cavities capable of pulsed and CW operation
- Multi-frequency Master Oscillator and Phase Reference lines
- Beam Chopper Waveform Generator
  - RF locking source for Booster during beam fill
  - Timing source
- Resonance control (microphonics and LFD)
## Overview of the PIP-II LINAC

| RFQ | 162.5 | 1 | 2 | CW | 75 | 1 (special) |
| Bunching Cavities | 162.5 | 4 | 1 | CW | 3 | 1 |
| HWRs | 162.5 | 8 | 1 | CW | 3,7 | 2 |
| SSR1s | 325 | 16 | 1 | Pulsed | 7 | 4 |
| SSR2s | 325 | 35 | 1 | Pulsed | 20 | 9 |
| LB650s | 650 | 33 | 1 | Pulsed | 40 | 9 |
| HB650s | 650 | 24 | 1 | Pulsed | 70 | 6 |
Challenges for PIP-II

- Individual cavities regulated to 0.01%, 0.01 deg. RMS → Energy regulated to $10^{-4}$
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- LFD for four different cavity types
  - Superconducting cavities are narrow band
  - Operated in pulsed mode at 20 Hz
  - Power overhead is limited
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• International collaboration
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  - Static errors: Caused by calibration errors and drifts
  - Dynamics errors: Beam-loading disturbances and cavity detuning
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Energy and phase sensitivity at the end of the LINAC caused by perturbations to the phase of individual cavities.
**LINAC Energy Stability Simulations**

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Energy sensitivity along the LINAC for phase errors introduced at frequency transitions: Here the phase errors are applied uniformly for each frequency type.
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Assuming we can calibrate phase and amplitude to ±0.5° and ±1% respectively, we can stabilize the energy to $10^{-4}$ through pulse-to-pulse beam-based feedback using the last cryomodule.
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Resonance Control

- Resonance control specifications for each cavity type

<table>
<thead>
<tr>
<th></th>
<th>HWR</th>
<th>SSR1</th>
<th>SSR2</th>
<th>LB650</th>
<th>HB650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity to He pressure (FRS), ( \frac{df}{dP} ), Hz/Torr</td>
<td>&lt;25</td>
<td>&lt;25</td>
<td>&lt;25</td>
<td>&lt;25</td>
<td>&lt;25</td>
</tr>
<tr>
<td>... (measurements), ( \frac{df}{dP} ), Hz/Torr</td>
<td>13</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Estimated LFD sensitivity, ( \frac{df}{dE^2} ), Hz/(MV/m)^2</td>
<td>-</td>
<td>-5.0</td>
<td>-0.8</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>... (measurements), ( \frac{df}{dE^2} ), Hz/(MV/m)^2</td>
<td>-1.5*</td>
<td>-4.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Estimated LFD at nominal voltage (FRS), Hz</td>
<td>-</td>
<td>-500</td>
<td>-192</td>
<td>-136</td>
<td></td>
</tr>
<tr>
<td>... (measurements) at nominal voltage, Hz</td>
<td>-122.4</td>
<td>-440</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Two cavities were measured in a test stand. The results are: -1.82 and -1.3 Hz/(MV/m)^2.

- Meeting these specifications will be challenging
  - Passive measures to reduce \( \frac{df}{dp} \) looks promising
  - Active compensation currently being tested on SSR1 type cavities
Active Resonance Control Testing

- PIP-II nominal operating conditions
  - 12.5 MV/m
  - 20 Hz repetition rate
  - 15% duty cycle, 0.5ms flattop
- STC operating condition
  - Greater than 12.5 MV/m
  - 25 Hz repetition rate
  - 7.5 ms fill, 7.5 ms flattop
- 7.4 Hz RMS detuning on the flattop
  - Specification is a peak detuning of 20 Hz: Further improvement is needed
Active Resonance Control Testing

- Significant progress has been made toward PIP-II specification of detuning.

- Plan for incoming test at STC:
  - Improvements in feedback (automation of filter bank coefficients) should improve performance
  - May be possible to automatically extract optimal coefficients from delay scan data
  - Further firmware improvements should allow more detailed studies of pulse structure
System conceptual design

Rack layout and module descriptions
LLRF System for PIP-II
LLRF Signal Chain for 4 cavities

[Diagram showing the LLRF signal chain with various components including SOC FPGA Board, LLRF Controller, FPGA, RF Protection Interlock, Cavity 1, 2, 3, and 4.]
Phase Reference Lines (162.5, 325, 650, 1300 MHz)

Multi-frequency Phase References and Local Oscillators
Being prototyped at BARC
Chopper program generator

- 1.3 GHz RF Ref
- PC GUI (LabVIEW)
- Trig Sync
- Analog Filter
- Amp & Comparator
- Kicker Driver
- PS
- Upper Helix
- Lower Helix
- Oscilloscope

162.5 RF Ref
Controls Trigger
+600 V
-600 V
Chopper program generator

Time Resolution <50 ps

- Delay with respect to synchronized trigger
  - Compensate for cable lengths
  - Compensate for kicker driver delay
  - Internal delay of Arbitrary Waveform Generator (AWG)
- Differential delay
  - Different characteristics of kicker switches
Hardware status to date

Prototype measurements
4-Channel Up-converter

- 20 MHz IF input -2 dBm max
- 162.5, 325, and 650 MHz Output, +11 dBm max
- 13 dB IF to RF Conversion Gain typ.
- Channel to Channel Isolation > 88 dB
- Spurious Signal Suppression > 80 dB
- High isolation (>68 dB) TTL RF switch
- Power Supply 6V, 1.8 Amp

![RF Output vs IF Input](chart1.png)

![RF Output Linearity](chart2.png)
**PIP-II LLRF 8-Channel Downconverter Prototype**

- RF input 162.5 MHz – 650 MHz
- Less than 1% non-linearity up to 10 dBm RF input
- 1.8, 2.1, 2 dB conversion loss @ 162.5, 325, 650 MHz respectively
- Better than 82 dB Channel to Channel Isolation
- RF, LO, IF monitor ports
- Absorptive IF output low pass filter
- Noise output floor of -161 dBc/sqrt(Hz)
- Integrated output 1/f noise < 1.84 fsec, (0.02 to 20 Hz)
- LO Input power of 3.1, 3.8, and 5.7 dBm @ 162.5, 325, 650 MHz respectively
- Power Supply 6V, 2.25 Amps
Measurements from PIP-II injector test

- To date we have operational experience with the RFQ and three bunching cavities
- Left: Models of the RFQ LLRF system match well with measurements
- Right: Phase and amplitude ripple on the amplifiers complicate frequency tracking mode (modified frequency tracking loop for copper cavities)
Measurements from PIP-II injector test

- Feed-forward is used to reduce the beam-loading transient in the RFQ
- Initial specification of $10^{-3}$ is met
- Amplifier phasing is necessary to ensure proper match into the RFQ
Progress of the IIFC collaboration

- Seven joint FRSs Approved (two more near approval)
  - TRS in process
- 8-Channel Down-Converters
  - BARC version is in manufacturing process
- 4-Channel Up-Converters
  - FNAL version tested
  - BARC version is in manufacturing process
- FPGA Board
  - In schematic review process
- ADC-DAC FMC Module
  - Ready for manufacturing
- Resonance Control Chassis
  - Leverage from FNAL LCLS-II design and is in progress
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Conclusions

• PIP-II LLRF design conceptual design is mature and leveraged off of existing designs and past experience
  – Gaining experience from PIP2—IT as well
  – While specifications are tight, simulations indicate we will be able to meet these requirements
  – Our biggest challenge is LFD compensation