Preliminary Design of the Continuous ADRs for the Primordial Inflation Explorer (PIXIE)

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PIXIE Architecture

- Orbit
  - L2
  - Zenith-pointing
  - 1 rpm spin
  - Continuous sky scan

- Cryogenic system
  - 2 radiatively cooled shields
  - 2 actively cooled shields
  - Stirling/JT cryocooler
  - ADR system
    - 2.725 K telescope (iADR)
    - 100 mK detectors (dADR)
    - Continuous cooling required
PIXIE Optical Path

- **Calibrator (580 mm)**
- **Sky**
  - A Beam
  - B Beam
  - V Polarization
  - H Polarization
- **Primary Mirror**
  - 550 mm f/1.7
- **Secondary Mirrors**
  - 50 mm f/7.5
- **Polarizer A**
- **Folding Flats**
- **Transfer 1**
  - 125 mm f/2.4
- **Split Polarizations**
- **Mix Beams**
  - Transfer 2
  - 125 mm f/4.4
- **Inject Phase Delay**
  - Transfer 3
  - 125 mm f/4.4
- **Re-Combine Beams**
  - Transfer 4
  - 125 mm f/4.4
- **Split polarizations**
  - Transfer 5
  - 125 mm f/4.4
- **Measure Fringes**

**Dimensions**
- **Beams to Sky**
  - 79 cm
- **Primary Mirror**
  - 115 cm
- **Fourier Transform Spectrometer**
Measurement Strategy

• PIXIE operates as a nulling polarimeter which is sensitive only to the differences between two nearly identical sources

• FTE produces a rotating fringe pattern at twice the s/c spin rate (4 rpm)
  – Allows separation of instrumental effects that appear at the spin rate

• Optical components and calibrator are systematically varied in temperature to identify any effect on detector output
Thermal Map

- Heat inputs to 2.7 K
  - 1.2 mW from 17 K
  - 1.0 mW from dADR
  - 2.5 mW from temperature control of optics
  - Total of 4.7 mW

- Current design has 100% margin on 100 mK and 2.7 K loads

- iADR will output 12 mW at 4.5 K

NOTE: Heat flow values in mW.
• Parallel configuration for iADR can achieve near continuous heat rejection
  – Maximizes cooling power at 2.6 K
• Carnot efficiency: 9.4 mW in at 2.6 K -> 16 mW at 4.5 K
  – Goal is peak heat rejection rate of 20 mW
• 3-stage dADR uses constant 2.6 K heat sink
• 2 μW detector heat load at 100 mK
Optics Temperature Control

- Telescope/optics are connected to the 2.6 K thermal bus with a tailored $k$ value.
  - Temperature controlled to $2.725 \pm \Delta$
    - $\Delta$ varies from 5-10 mK for most components, 20-100 mK for calibrator.
  - Transition time must be shorter than period of temperature variations.

- Optimize thermal bus temperature to give smallest entropy usage ($\dot{Q}/T$).
  - Peak heat load (all optics at elevated temperature) is 2.5 mW.

$$\dot{Q}_1 = (2.725 - T_{bus}) \cdot k_1$$

$$\dot{Q} = \sum_{n} \dot{Q}_n = 2.5 \text{ mW}$$

For $T_{bus} = 2.66 \text{ K}$.
## ADR Design Parameters

### PIXIE ADR

<table>
<thead>
<tr>
<th>Stage</th>
<th>Refrigerant</th>
<th>B field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60 g, CPA</td>
<td>0.2</td>
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<tr>
<td>2</td>
<td>60 g, CPA</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>60 g, GLF</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>60 g, GLF</td>
<td>3</td>
</tr>
<tr>
<td>4a</td>
<td>150 g, GLF</td>
<td>3</td>
</tr>
<tr>
<td>4b</td>
<td>150 g, GLF</td>
<td>3</td>
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</tbody>
</table>

### Hitomi ADR

<table>
<thead>
<tr>
<th>Stage</th>
<th>Refrigerant</th>
<th>B field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270 g, CPA</td>
<td>2</td>
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<tr>
<td>2</td>
<td>150 g, GLF</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>150 g, GLF</td>
<td>3</td>
</tr>
</tbody>
</table>

- Detectors are not sensitive to magnetic fields, so magnets have only basic shielding to minimize interactions between stages.
• iADR was modeled for 9.4 mW continuous heat input
  – Peak heat reject rate is ~20 mW
• iADR and dADR are purposely synchronized to maintain stable temperature pattern
Summary

• Continuous cooling of the detectors and telescope are key requirements for PIXIE

• Two 3-stage ADR assemblies provide continuous cooling at 100 mK and 2.66 K

• High efficiency and near-continuous heat rejection are key to meeting power allocation for Stirling/JT cryocooler
  – Drives choice of parallel upper stages