R&D on Microwave Transparent Thermal Insulation for the Project 8 experiment

Arina Telles
Yale University
TIPP conference - May 27th, 2021
What is this talk about?

Detector subsystem R&D for a neutrino mass experiment

**Signal:** microwave frequency emitted from a spiraling electron

**Detector:** Antennas (slotted waveguides)

- Introduction: neutrino mass measurement via a radio-frequency based technique
- Detector design: antennas & thermal management
- R&D in progress: Microwave-transparent thermal insulation
Why measure neutrino mass?

• Motivations:
  • Fundamental science!
  • Parameter for cosmological models of how the universe began
  • Neutrino mass remains mysterious as compared to other particles
Neutrino mass: global experimental status

• Direct methods:
  • Current experimental limit is from KATRIN: $1.1 \text{ eV}/c^2$, $0.8 \text{ eV}/c^2$. Projected sensitivity is $0.2 \text{ eV}/c^2$ (the current limit from cosmology is $\sim 0.12 \text{ eV}/c^2$)
  • Next generation experiments necessary to be sensitive below KATRIN limit, where neutrino mass is likely to be

• Indirect methods:
  • Neutrinoless double beta decay
  • Cosmology
Direct neutrino mass measurements

- Measurement of the endpoint of the tritium beta decay spectrum. Spectral shape at the highest energies set limits on neutrino mass
How to measure electron energy?

- A new method for measuring the energy of the electron: Cyclotron Radiation Emission Spectroscopy (CRES)

- Cyclotron motion of electron emits radiation at frequency related to its energy

- Proof-of-concept shown by Project 8 inside a waveguide (Phases I & II)

\[ f = \frac{f_0}{\gamma} = \frac{1}{2\pi m_e + \frac{E_{\text{kin}}}{c^2}} eB \]
How to measure electron energy?

- Electrons are trapped magnetically, bouncing in an axial trap for sufficiently long observation times.
- For increased statistics, goal is to move to larger free-space volume surrounded by antennas.
- Trapped pitch angles up to ~5°-7° below 90° (⊥ to B-field).
Free-space CRES Demonstrator (FSCD)

Fused silica vessel, containing gaseous $^3\text{H}_2$

Slotted waveguide antennas

Medical MRI magnet (1T)

Low-noise cryo amps

Magnetic Trap coils

Magnet bore $\approx 90$ cm
• In 1 T field, electron radiates ~1 fW at 26 GHz

• Seeing small signal above noise -> low temperature for antennas to minimize thermal noise, ~2 K

• Keep tritium from freezing out -> source temperature ~30 K
Signal & Detector Characteristics

• In 1 T field, electron radiates ~1 fW at 26 GHz

• Seeing small signal above noise -> low temperature for antennas to minimize thermal noise, ~2 K

• Keep tritium from freezing out -> source temperature ~30 K

Signal loss must be minimized
Thermal insulation necessary
Potential solution: frequency-selective surfaces

• A patterned, metallized layer that acts as a filter: shape determines electromagnetic behavior

• Originally developed for radar and stealth applications

• One recent application: thermally efficient windows that let through 5G cell signal
Microwave-transparent thermal insulation

• Goal: best trade-off between thermal insulation and RF-transparency

• Leads to “patch-style.” Squares chosen as simple starting point

• Squares must be small enough to act as low-pass filter (small compared to RF signal wavelength ~11.5 mm)

Simulation done in ANSYS High Frequency Structure Simulator (HFSS)
Proof of concept

Anechoic chamber to avoid extraneous reflections

Slotted waveguide antenna prototypes

Linear stage for varying antenna field regimes

Data collected with vector network analyzer

Aluminized mylar glued onto a pane of glass, laser-etched pattern

1 mm periodicity
Etching width: 0.11 ± 0.02 mm
=> 76%-83% coverage
Initial Results

\[ dB(S_{21}) = 20 \times \log\left( \frac{V_{\text{rec}}}{V_{\text{trans}}} \right) \]
Initial Results

\[ \text{dB}(S_{21}) = 20 \times \log\left( \frac{V_{\text{rec}}}{V_{\text{trans}}} \right) \]

![Graph showing frequency response with different materials: nothing, holder only, glass, glass + fully al. mylar, glass + etched al. mylar. Each curve peaks at different frequencies and the overall trend shows a ~0.9 dB loss.](image)

~0.9 dB loss
Summary & Outlook

• Next steps:
  • Test angular & distance dependence -> ultimately insulation must cover a cylinder in the near-field of the antennas
  • Evaporate custom patterns on mylar to isolate from glass effects
  • Optimize for best design

• This, along with various R&D projects, will lead to conceptual design for the next phase of Project 8 experiment. And ultimately to a neutrino mass measurement!
This work is supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all institutions.
BACKUP
Antenna testing in the lab

Water-jet cut slots

All bolted together, modular

WR-34-shaped groove machined out

Commercial launcher
Slotted Waveguide Gain

Bore-sight Gain of Slotted WG Antennas

- Gain (dB)
- Freq (GHz)

Graph showing the bore-sight gain of slotted waveguide antennas with different lines representing different antennas and a simulation.
Characterization

- Tested antennas in our anechoic chamber setup
- Used VNA to make 2-port S-parameter measurements
- Standard gain horn to benchmark gain
- Boresight gain only (for now)

Standard gain horn
(Microwave Vision Group, WR-34, 24 dB, 22-33 GHz)