The future of direct neutrino mass measurements
Project 8 and beyond

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Pre-Snowmass Neutrino Mass Working Group
Mar. 6, 2013

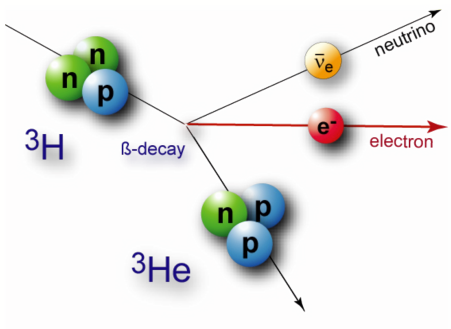
Measuring the Neùtrino Mass Scale

Cosmology

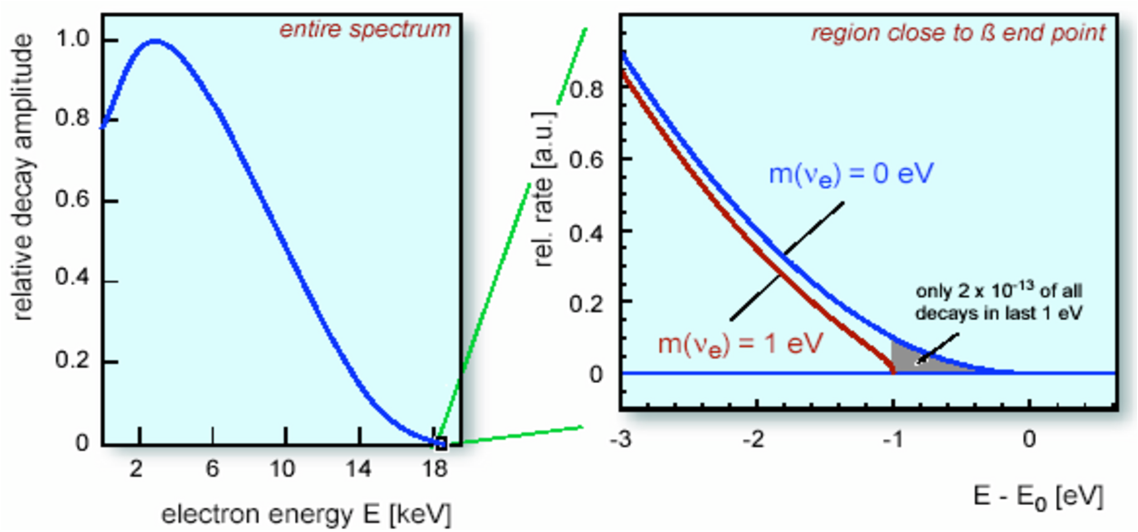
0υββ

Direct β decay

Beta Decay Review



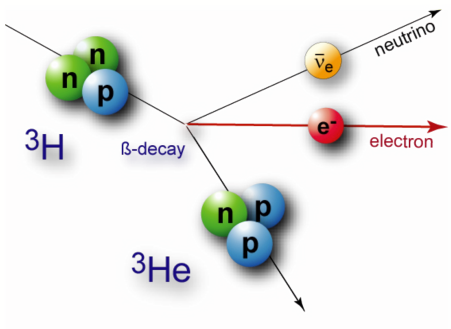
$^3H \rightarrow {}^3He^+ + e^- + \nu_e$



Beta decay spectrum enpoint is sensitive to neutrino mass

Present Limit $m_\nu < 2$eV Aseev et al. Phys. Rev D 84 112003 (2011)

Challenges in Beta Decay Measurements



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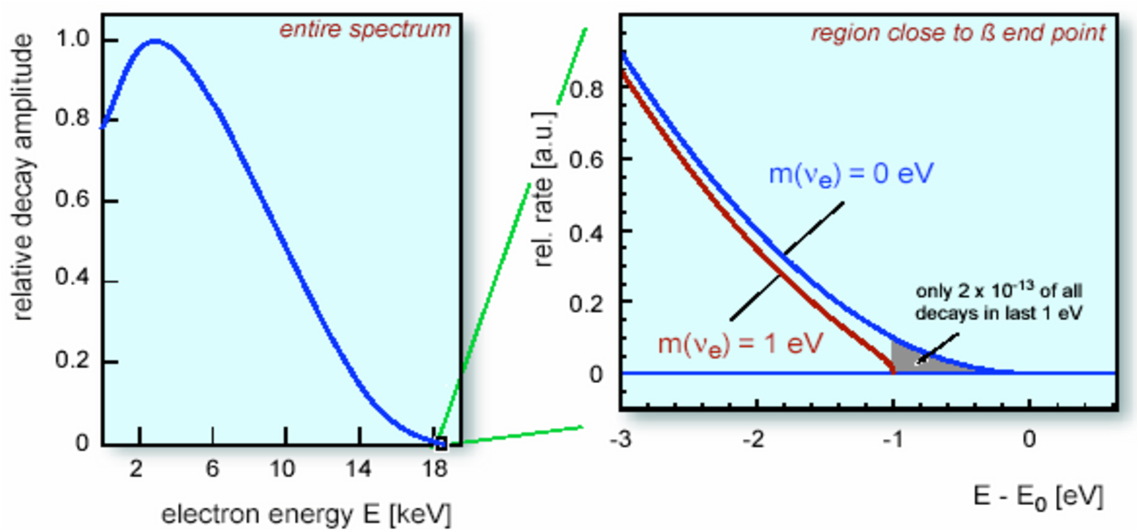
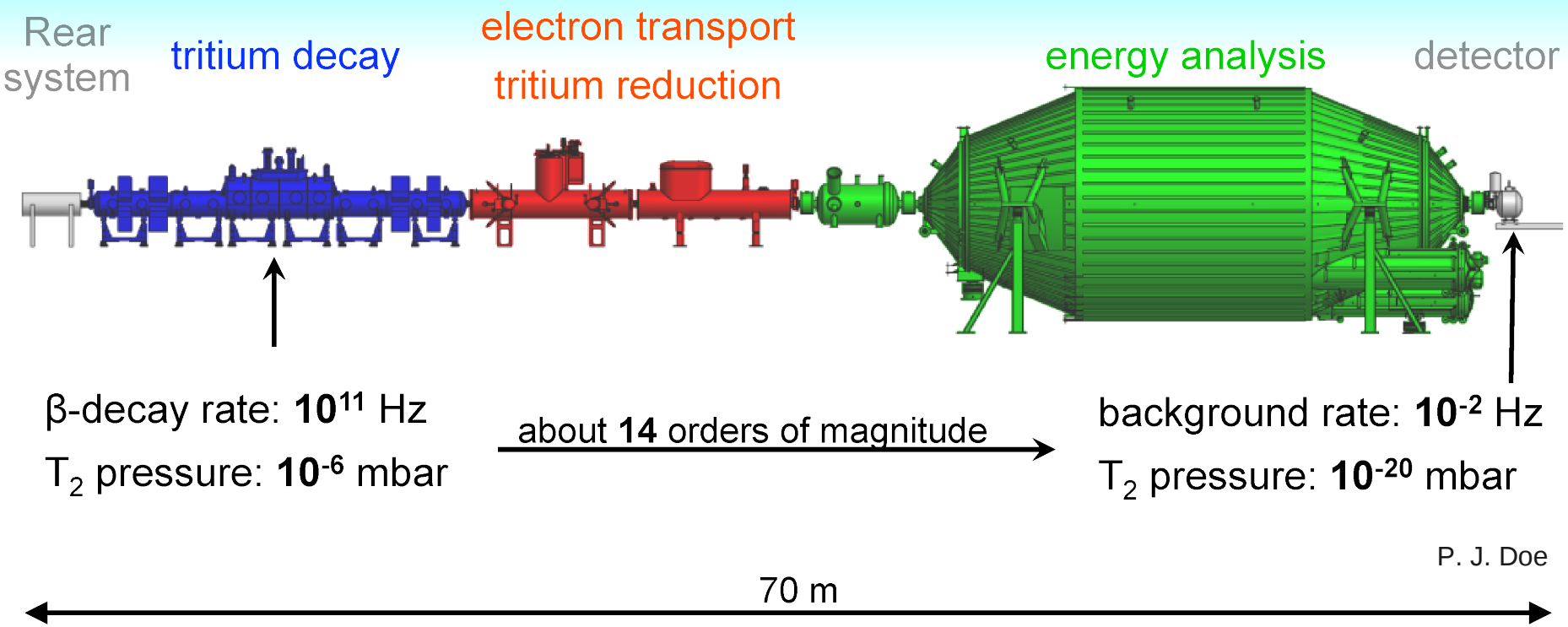


Only 1 in 10^{13} decays are useful (for Tritium)

Need to measure 10's of keV energies with eV resolution

Excitable molecular states can modify electron energy

KATRIN as an Example



Electrons from Tritium decay are filtered electrostatically and counted

Presently under construction, expected final m_ν sensitivity of 0.2 eV

Cannot be scaled up sensibly any further

Ideas for More Sensitive Measurements

Upgrade Katrin with Time-of-Flight

N. Steinbrink, Thesis, Munster 2012

^{187}Re Bolometer – MARE

Gatti et al. MARE proposal, 2006

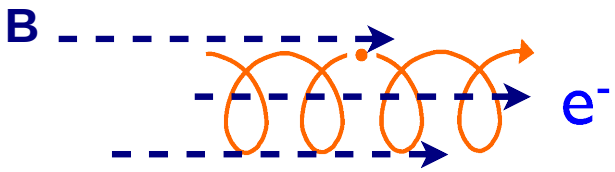
^{163}Ho Bolomoter – ECHO

L. Gastaldo et al, arxiv:1206.5647

New Spectrometer: Project 8

B. Monreal and J Formaggio, PRD 80:051301 2009

Cyclotron Motion



$$f_{cyc} = 27.922 \times B \frac{m_e}{m_e + KE} \quad \text{GHz}$$

magnetic field (T) electron mass electron energy

An electron's cyclotron frequency tells us its energy

Frequency can be measured very accurately

Trapping Electrons

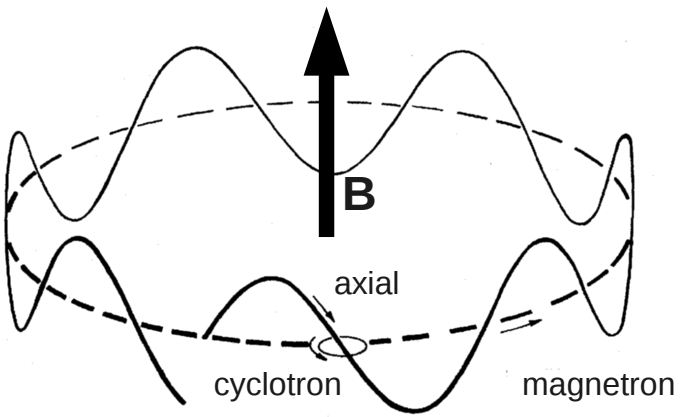
For an energy resolution of 1 eV in a field of 1 telsa, the frequency resolution needed is 50 kHz, and the electron must be observed for 20 μs.

A free electron with a pitch of 1 degree will travel 35 meters in this time

The electrons must be contained

Electrostatic traps will alter electron energy

Magnetic traps will cause nontrivial motion



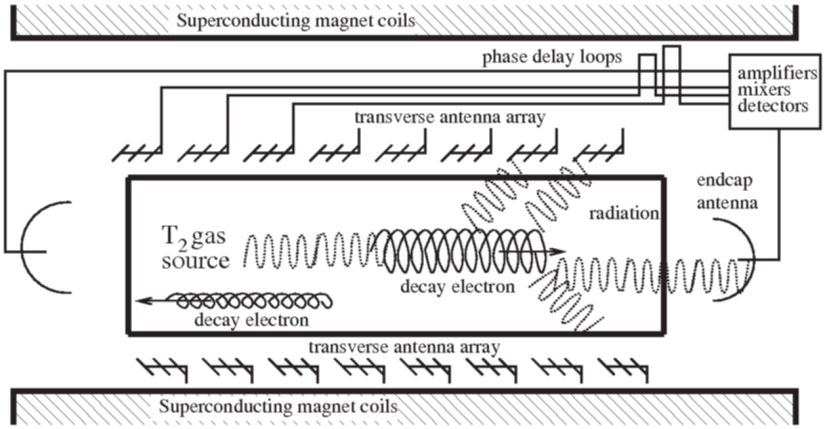
Cyclotron Power Collection

An 18 keV electron in a 1 T field emits 1 fW

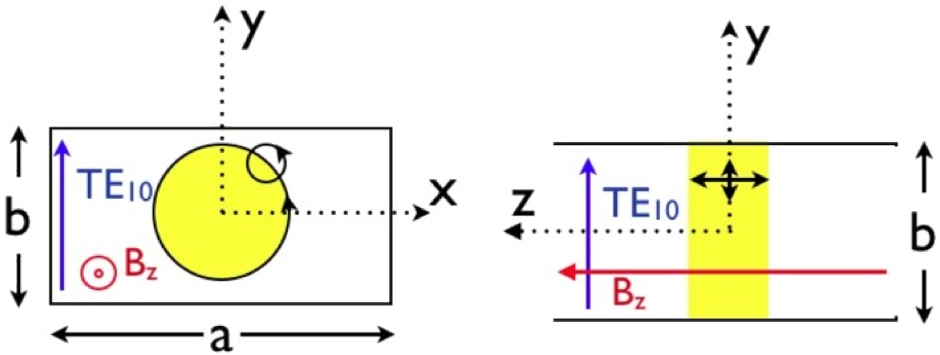
A 300K blackbody emits 0.2 fW in a 50 kHz bandwidth

The vast majority of the power must be collected

surround volume with antennas



couple motion to a waveguide



Project 8

University of Washington
PNNL
MIT & Haystack Observatory
UC Santa Barbara
NRAO
Caltech

Goal:
Develop cyclotron radiation technology for the next generation tritium beta decay experiment

The Plan

1) Demonstrate we can use cyclotron radiation to measure the energy of a radioactive decay

2) Demonstrate we have the sensitivity necessary to make a tritium measurement

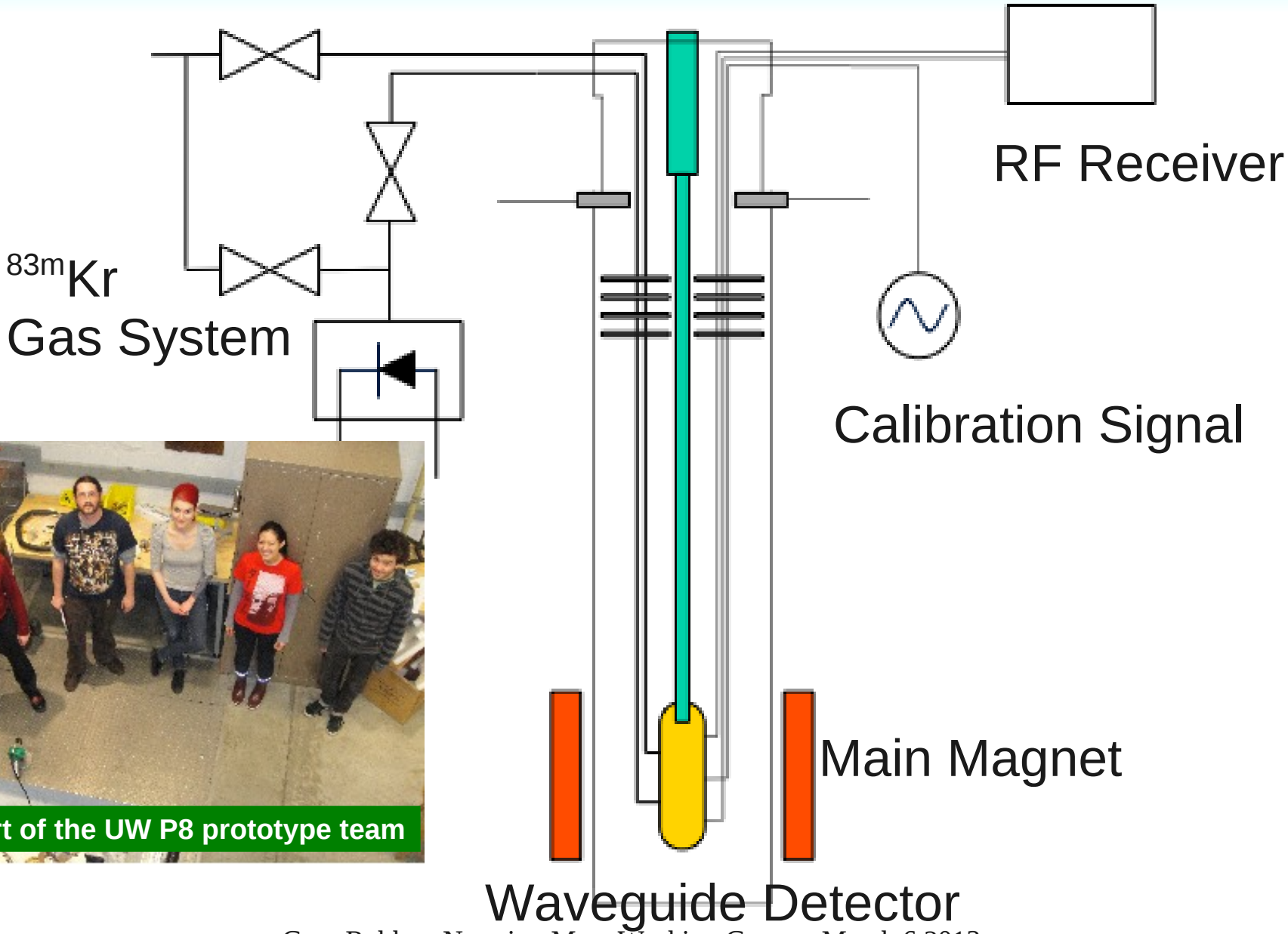
3) Scale the system to the necessary volume

Prototype Goals

Use cyclotron radiation to measure electron energy of ^{83m}Kr decay

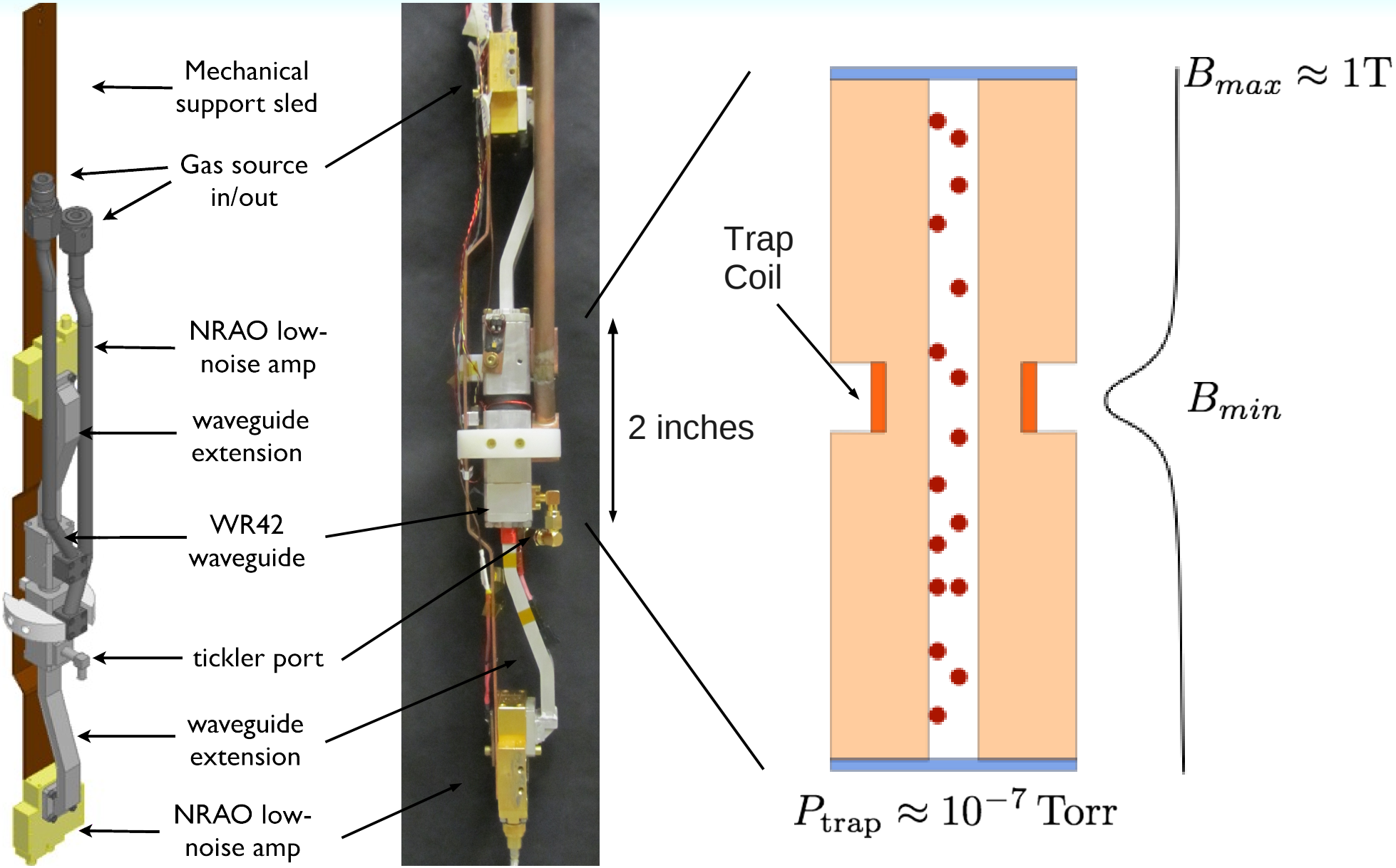
- Refine analysis of cyclotron RF signal
- Identify potential backgrounds to a Tritium measurement

Prototype Overall Design

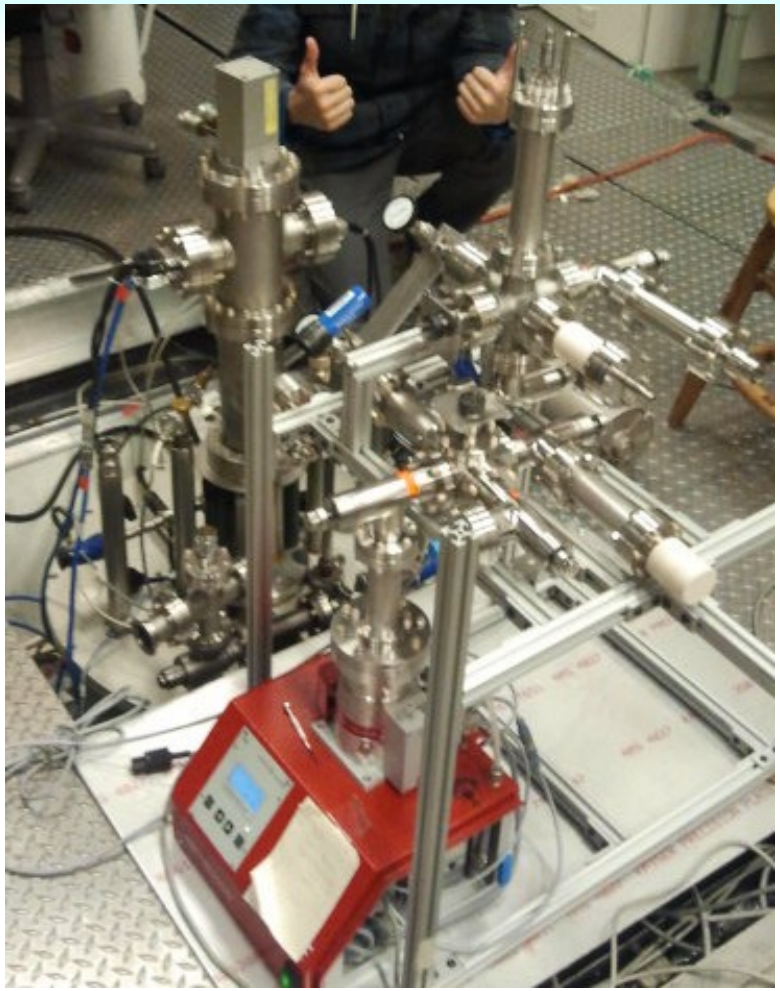


Part of the UW P8 prototype team

Waveguide Detector

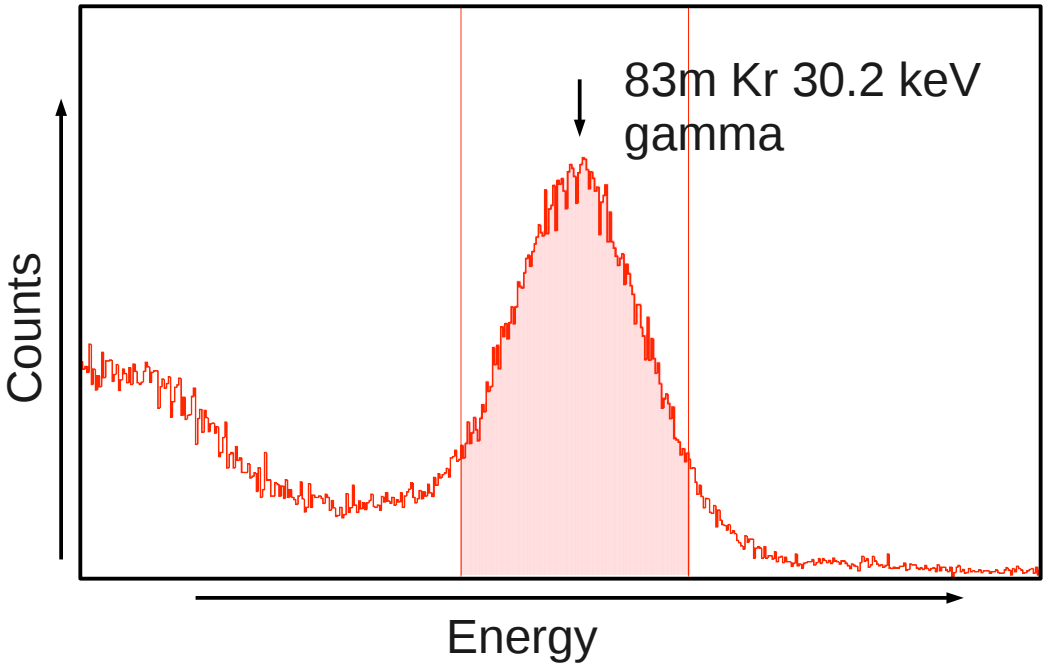


Gas System



Gas system attached to insert

Kr Spectrum on PIPS detector shows active source in waveguide trap



Challenges

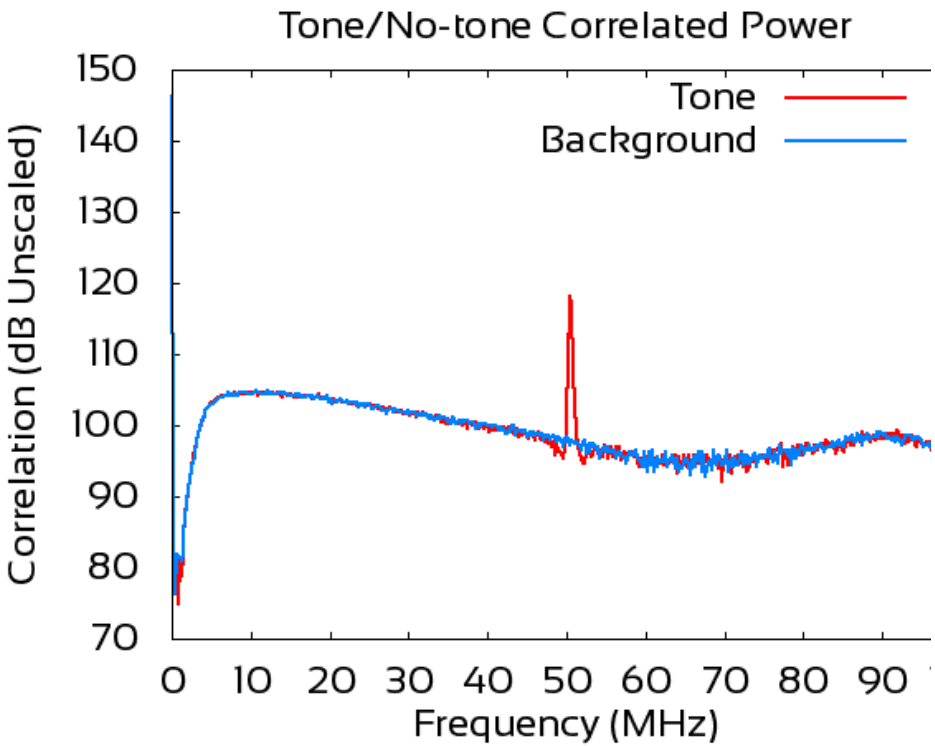
Containment pressure > 10^{-6} torr ruins trapping time

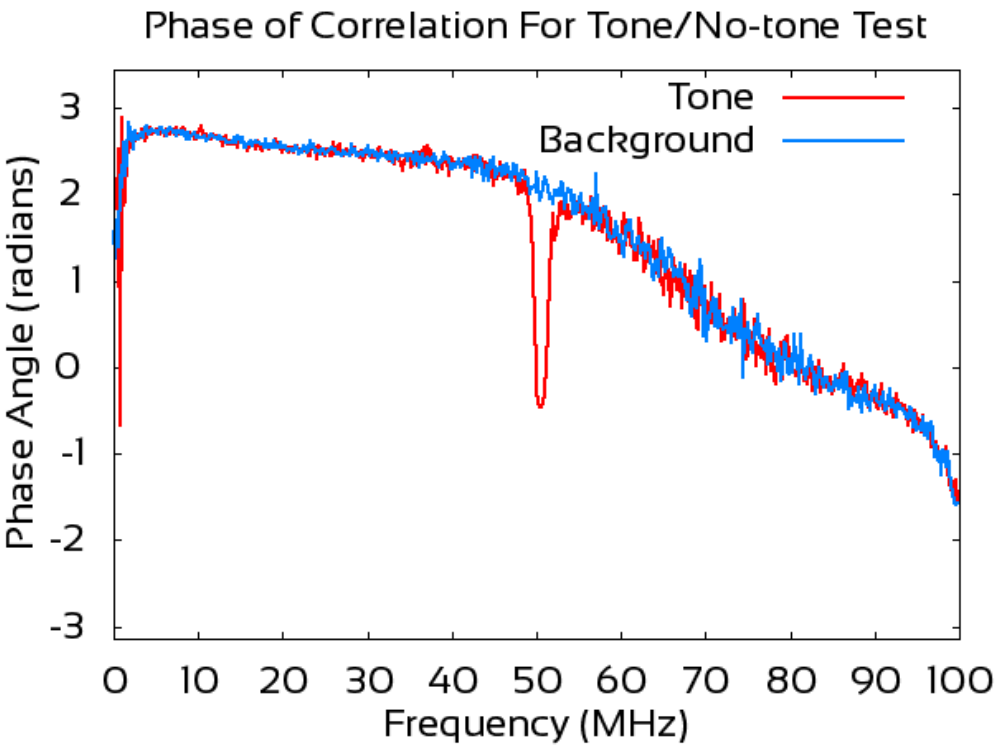
Target Kr activity density 1 Bq/mm^3

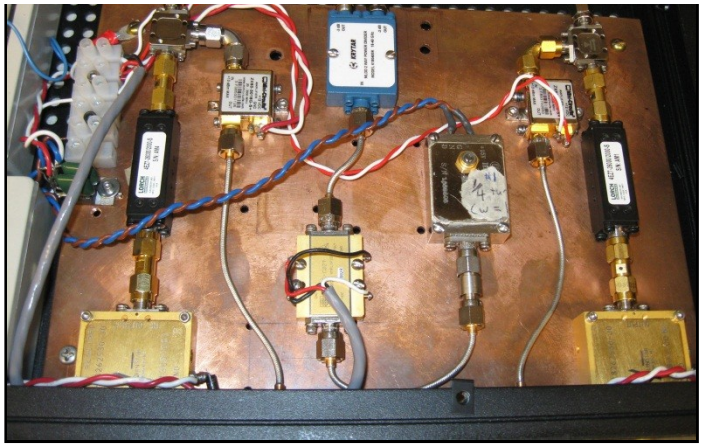
Below 110K, Kr source freezes out

Minimize system volume

RF System



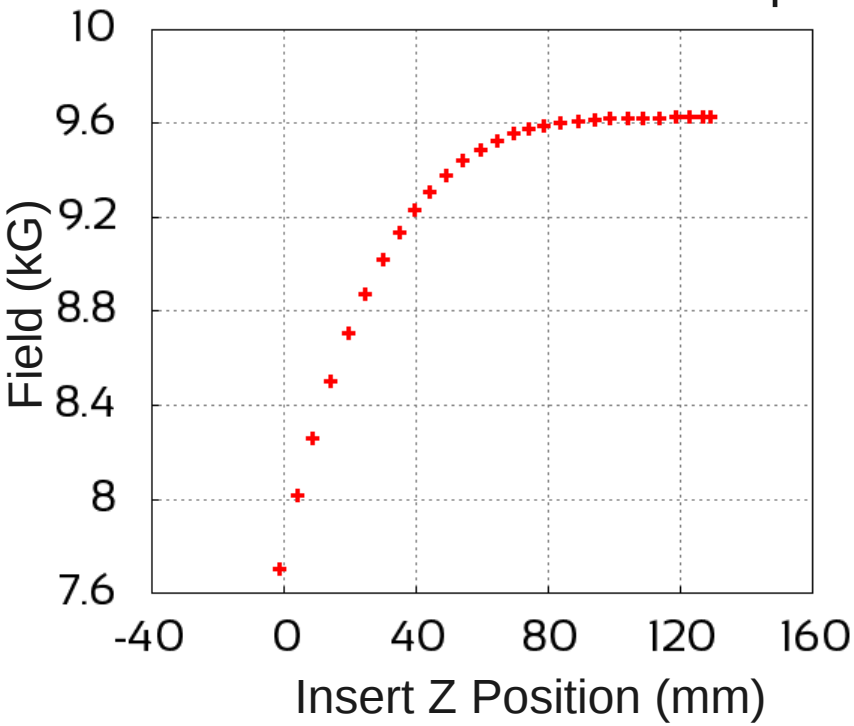




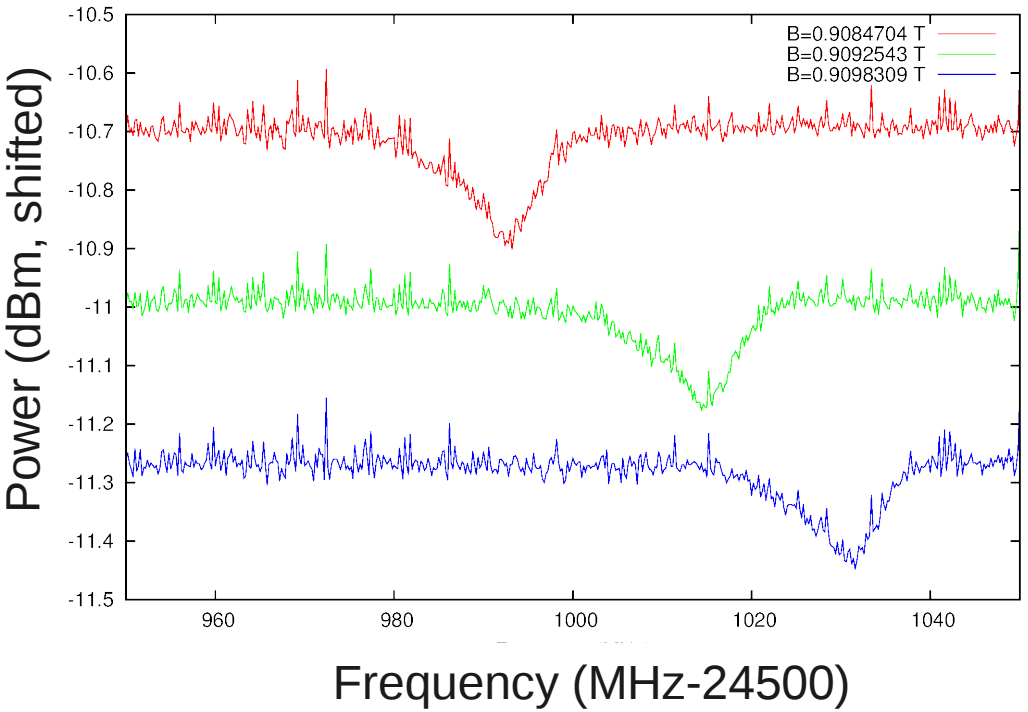
2 channels
100 MHz Bandwidth

Magnetic Field System

In-situ Hall Probe Field Map

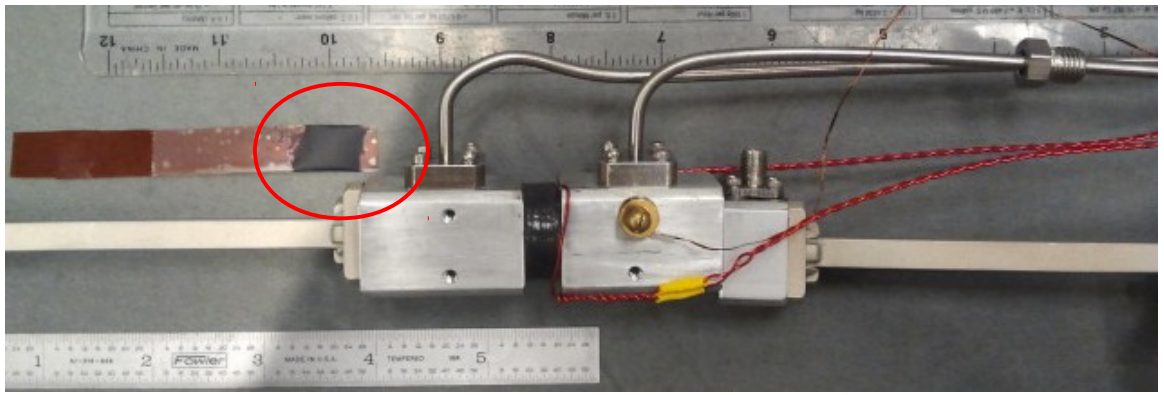


Ex-situ ESR Demonstration

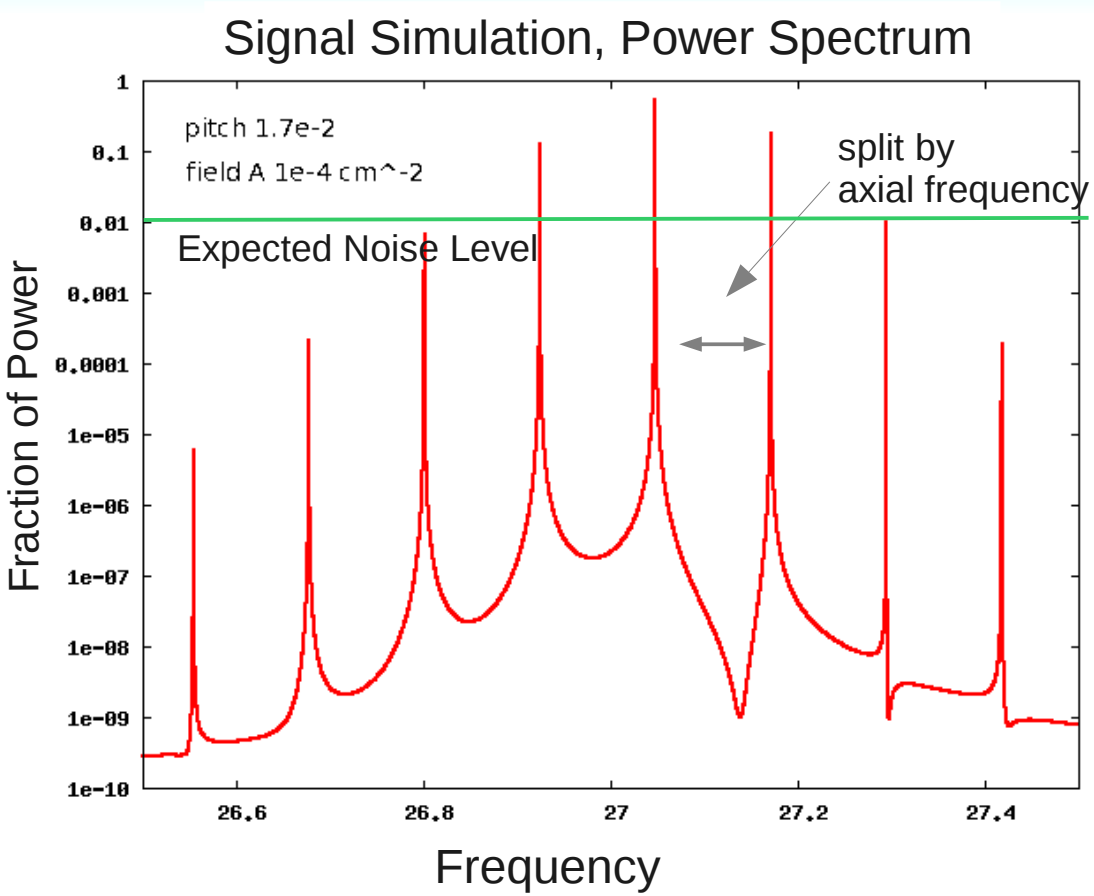


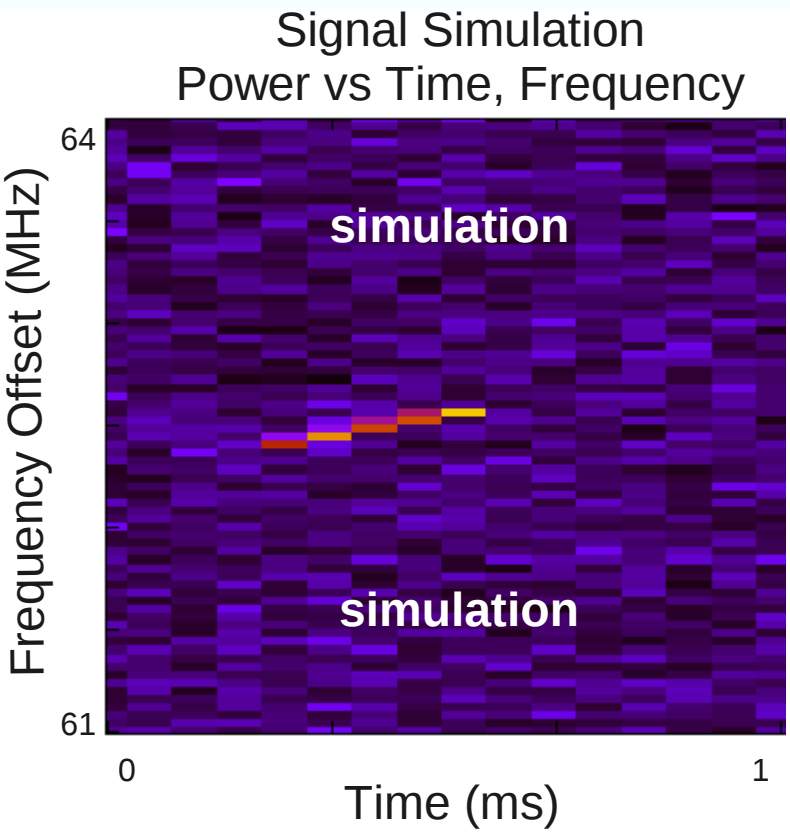
Hall probe indicates field uniform to 1 in 10^3

ESR will measure to 1 in 10^5



Expected Signals and Backgrounds





Trap motion causes sidebands
First set of sidebands must be measured for full energy resolution

Initial analysis focuses on locating central peak

Prototypȅ Status

Done

- Gas source constructed, functional
- Magnet Field Mapped
- Insert assembled, installed
- RF system characterized

Underway

- ESR Field Measurement
- Identification of Electron Signal

Scaling Challenges

What do we have to solve to scale from a small prototype to a neutrino mass experiment?

Increase active volume to ~10 m^3

Handle 1 to 10^{13} useful to useless event rate

Increasing Volume

Lower Frequency Resonant Structures

Resonant power enhancement
Natural Filter
Power loss with scaling

vs

Multiantenna Instrumented Volumes

Large volumes
Event reconstruction
Many channels, intereferometry is hard

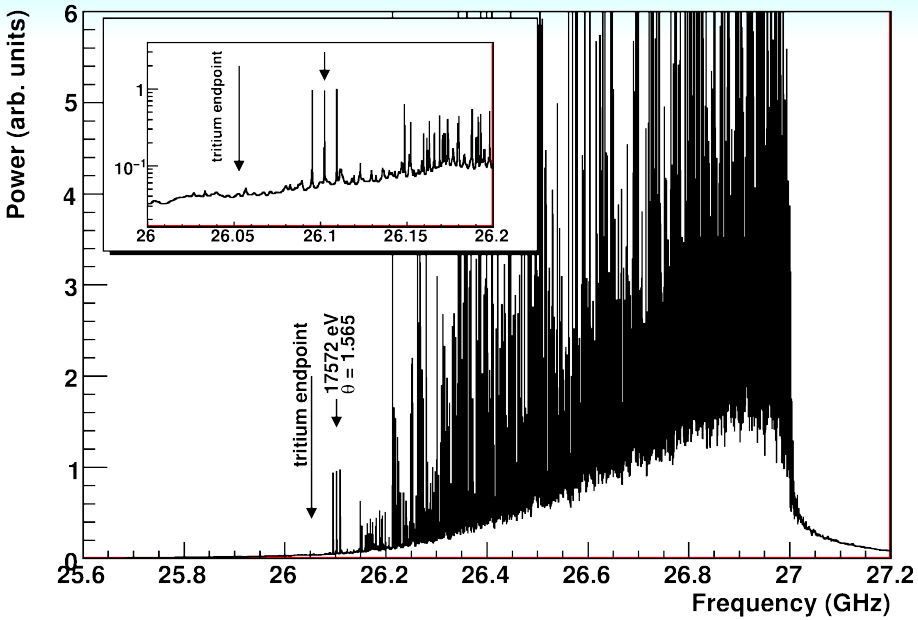
Handling Event Rate

Events well separated in frequency space

Low energy electrons emit less power

Current estimation ~ 1 Ci per channel to significantly affect noise level

However, highly dependent on design parameters



Monreal & Formaggio, Phys. Rev D 80, 051301(R) (2009)

Monte Carlo showing combined spectra of 10^5 events from tritium distribution + 1 endpoint event

Electron energy identification key design issue

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So what will Project 8 full neutrino mass experiment look like?

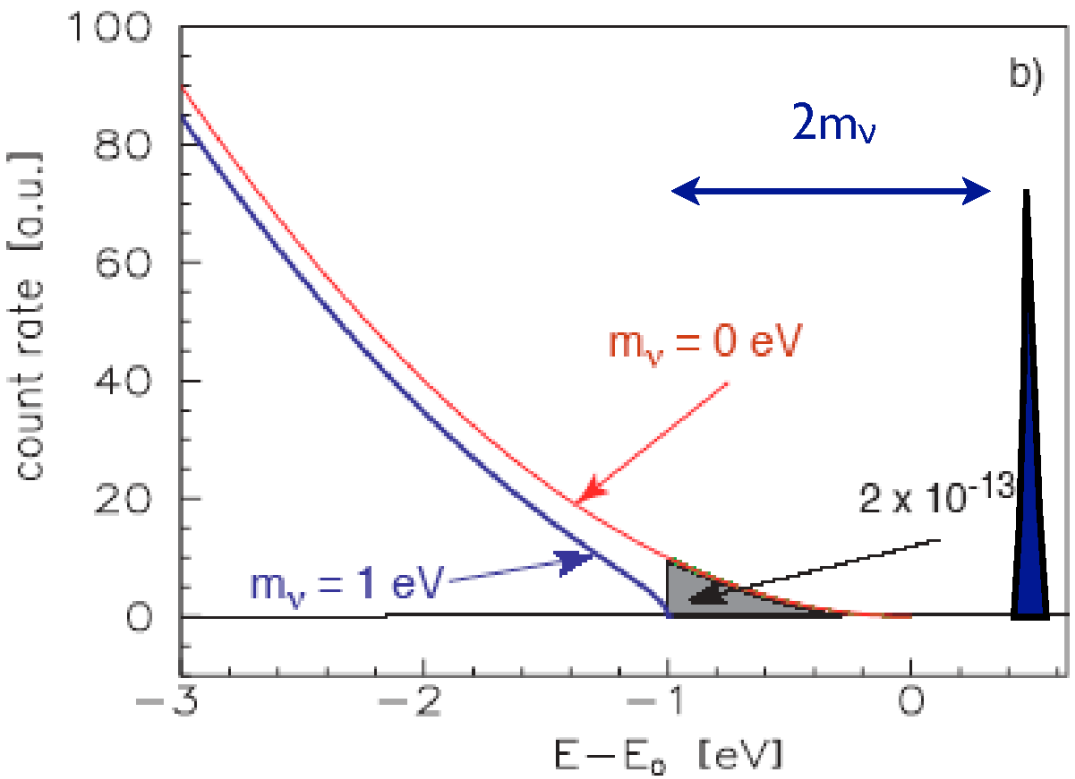
(we're working on that)

Beyond Project 8

Molecular effects will soon become the dominant uncertainty for β decay experiments

Can we use an atomic T source?

Beyond Beyond – Relic Neutrinos



β decay is sensitive to relic neutrinos

1 MCi of Tritium needed

8 orders of magnitude beyond current capability*

*See A. Kaboth, J. Formaggio, and B. Monreal Phys Rev. D 82 062001

Conclusions

Cyclotron radiation frequency measurement is a promising idea for neutrino mass beta spectrometers

A demonstration experiment is underway

As we build the prototype, we refine our ideas about a full scale neutrino mass experiment

Backup Slides Follow

Increasing SNR

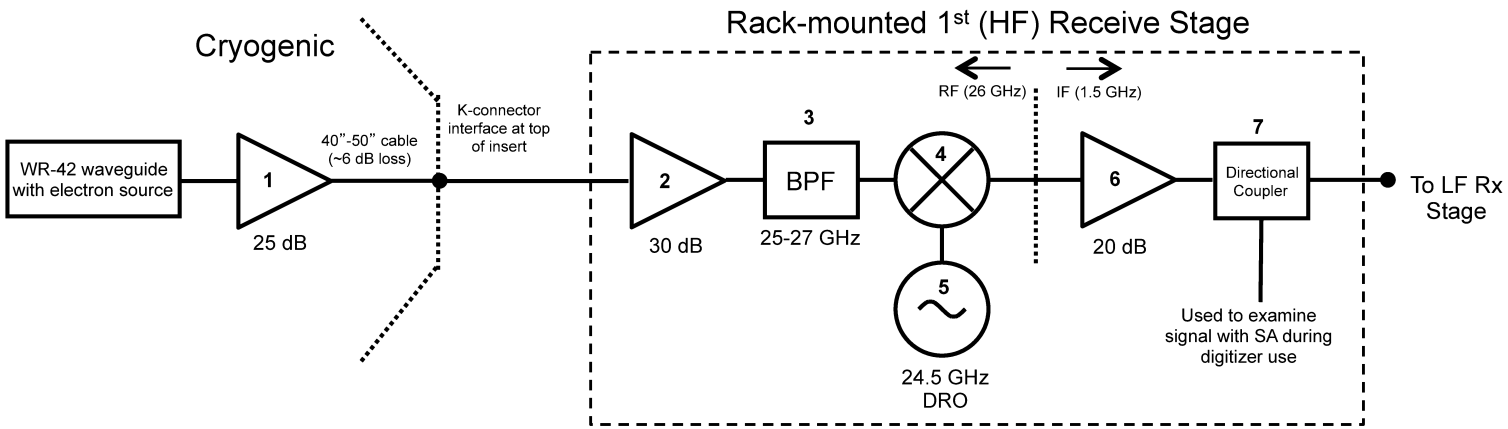
Lesson from prototype: physical temperature != noise temperature
waveguide does not contribute significantly to noise temperature

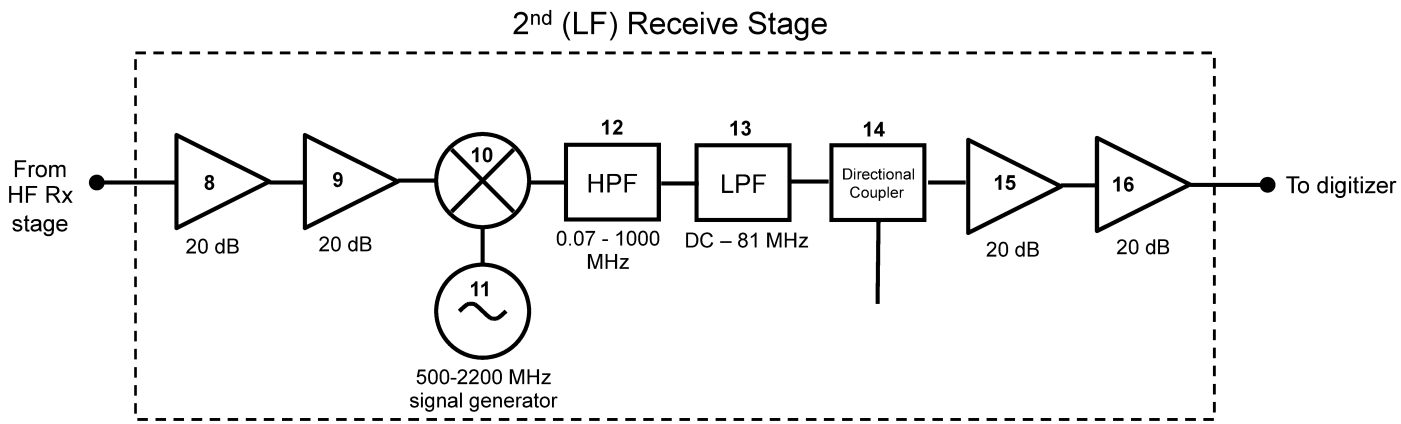
Resonant structures enhance Signal

Move to quantum limited amplifiers

Interferometry decreases noise

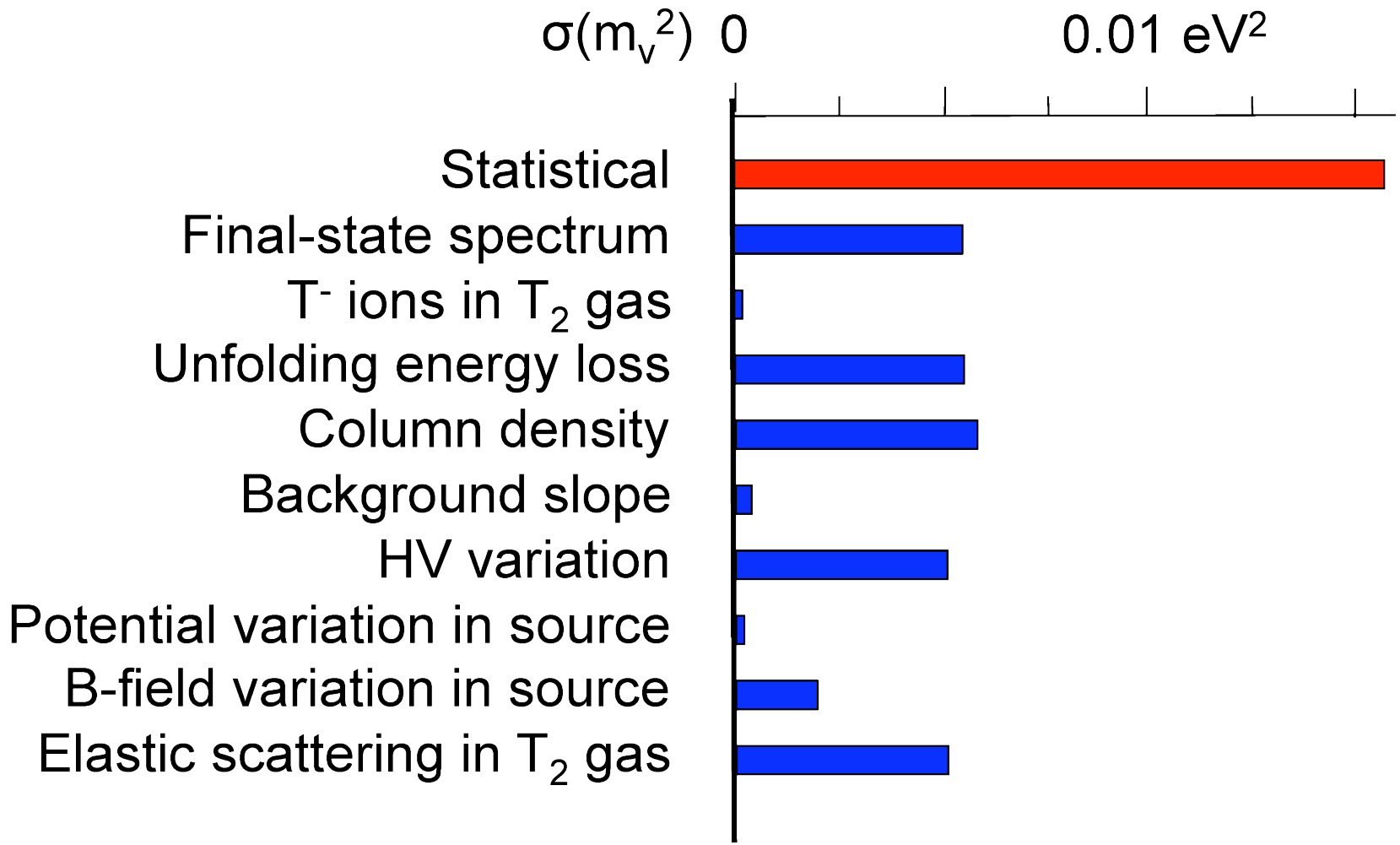
Recèiver


Cryogenic
Rack-mounted 1st (HF) Receive Stage
WR-42 waveguide with electron source
1
25 dB
40"-50" cable (~6 dB loss)
K-connector interface at top of insert
2
30 dB
3
BPF
25-27 GHz
4
5
24.5 GHz DRO
RF (26 GHz)
IF (1.5 GHz)
6
20 dB
7
Directional Coupler
Used to examine signal with SA during digitizer use
To LF Rx Stage


2nd (LF) Receive Stage
From HF Rx stage
8
20 dB
9
20 dB
10
11
500-2200 MHz signal generator
12
HPF
0.07 - 1000 MHz
13
LPF
DC – 81 MHz
14
Directional Coupler
15
20 dB
16
20 dB
To digitizer

Sources of Uncertainty

KATRIN's uncertainty budget*



P8
No
Yes
Yes
No
Maybe
Maybe
No
Maybe
Yes
Maybe

+?

$\sigma(m_\nu^2)_{total} = 0.025\ eV^2$

* KATRIN Budget from H. Robertson