Project 8: Progress Towards using Cyclotron Radiation Emission Spectroscopy on Atomic Tritium for a Neutrino Mass Measurement

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for
The Project 8
Collaboration

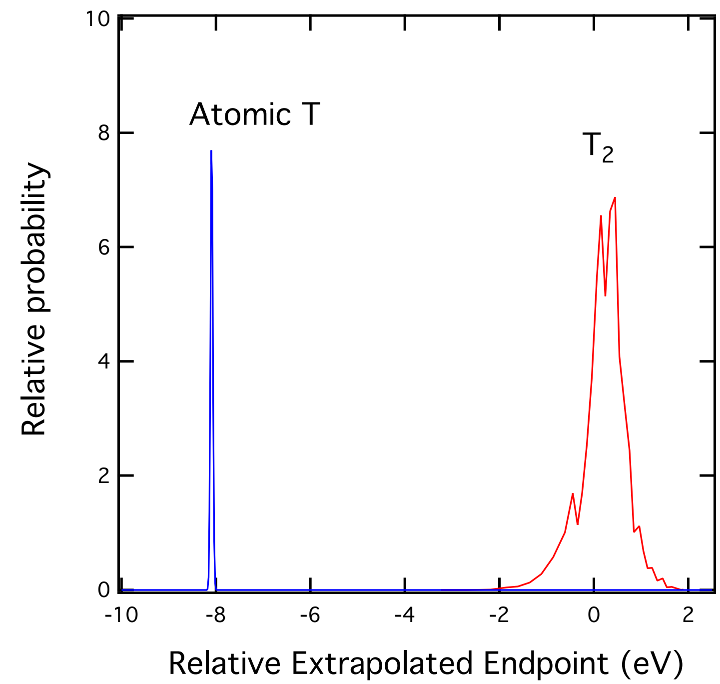
Neutrino, Heidelberg, May 2018

Motivation

How do we build on KATRIN's success and increase our sensitivity to the neutrino mass?

A fundamental systematic to any tritium beta-decay measurement is the tritium final-state distribution

We need an atomic-tritium ready technique



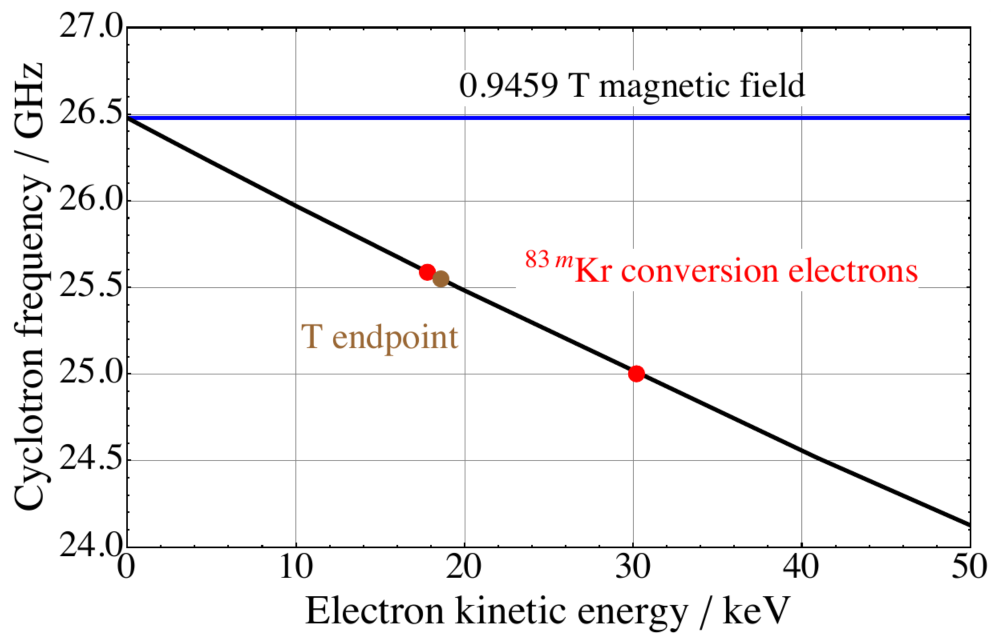
Final state energy distribution relative to tritium endpoint

Cyclotron Radiation Emission Spectroscopy (CRES)

The electron cyclotron frequency is related to the electron kinetic energy

The cyclotron frequency is encoded in cyclotron radiation

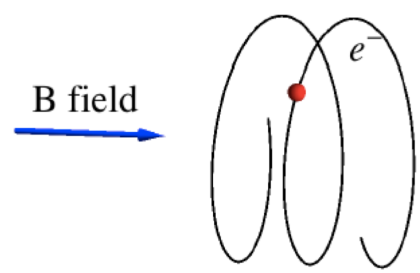
Frequency is something we can measure very precisely – eV resolution demonstrated, sub-eV resolution expected



Cyclotron motion:

$$f_\gamma = \frac{f_c}{\gamma} B = \frac{1}{2\pi} \frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

$$f_c = 27\,992.491\,10(6)\ \mathrm{MHz\,T^{-1}}$$



Project 8 Collaboration

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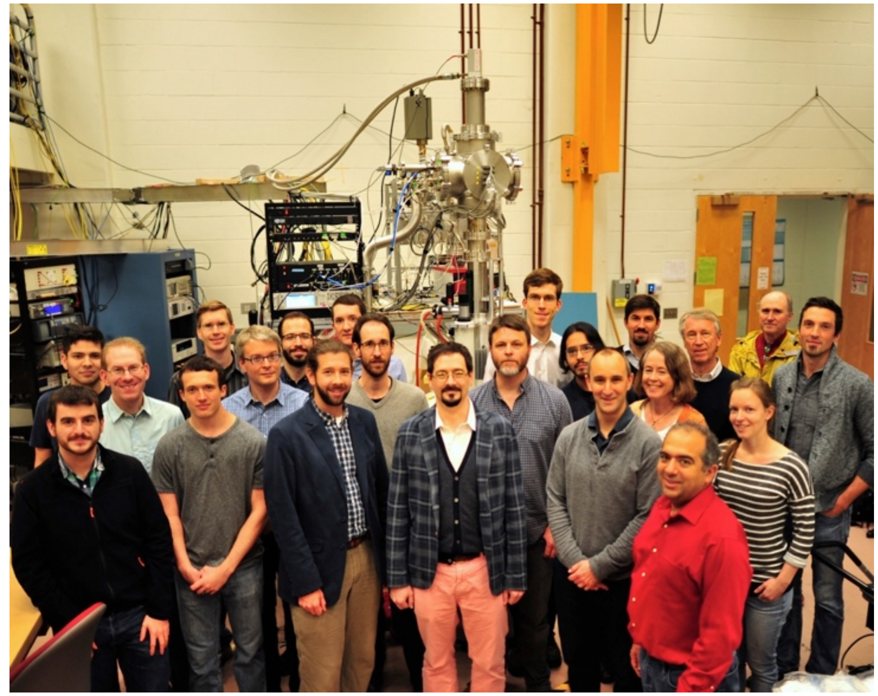

This material is based upon work supported by the following sources: the U.S. Department of Energy Office of Science, Office of Nuclear Physics, under Award No. DE-SC0011091 to MIT, under the Early Career Research Program to Pacific Northwest National Laboratory (PNNL), a multiprogram national laboratory operated by Battelle for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830, under Award No. DE-FG02-97ER41020 to the University of Washington, and under Award No. DE-SC0012654 to Yale University; the National Science Foundation under Award Nos. 1205100 and 1505678 to MIT; the PRISMA Cluster of Excellence; the Massachusetts Institute of Technology (MIT) Wade Fellowship; the Laboratory Directed Research and Development Program at PNNL; the University of Washington Royalty Research Foundation. A portion of the research was performed using PNNL Institutional Computing at Pacific Northwest National Laboratory. The isotope(s) used in this research were supplied by the United States Department of Energy Office of Science by the Isotope Program in the Office of Nuclear Physics. We further acknowledge support from Yale University, the PRISMA Cluster of Excellence at the University of Mainz, and the KIT Center Elementary Particle and Astroparticle Physics (KCETA) at the Karlsruhe Institute of Technology.

Project 8 Goals

- Demonstrate that CRES can be used to measure the tritium endpoint in a small prototype

  (right now, “Phase II”)

- Scale to a large-volume system that has sufficient statistics to contribute to the global neutrino mass effort and serve as a intermediate step for an atomic experiment

  (near future, “Phase III”)

- Transition to an atomic tritium measurement and make the most sensitive measurement of the neutrino mass possible

  (future, “Phase IV”)

Progress Demonstrating CRES with Tritium

"Phase II"

Project 8 Tritium Prototype

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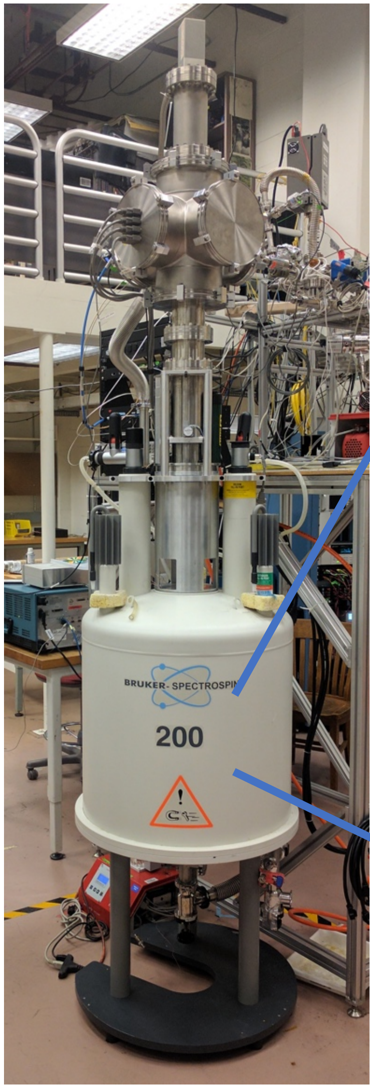
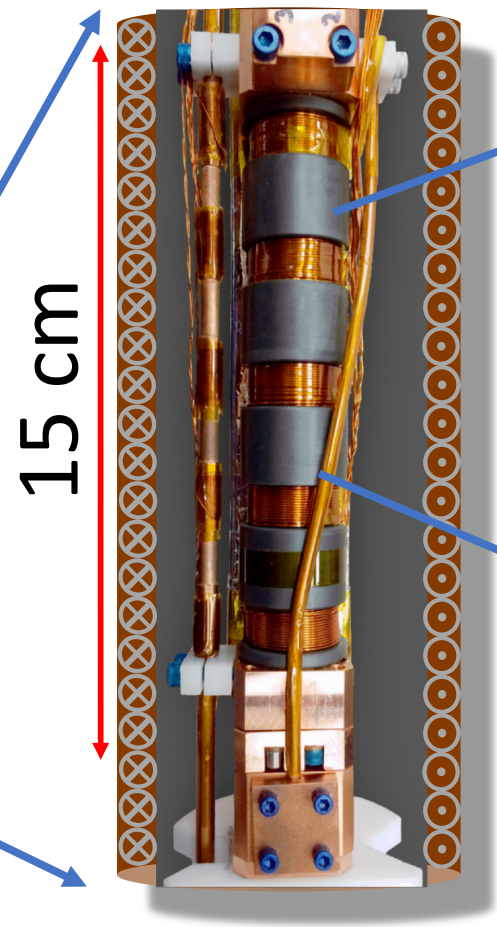
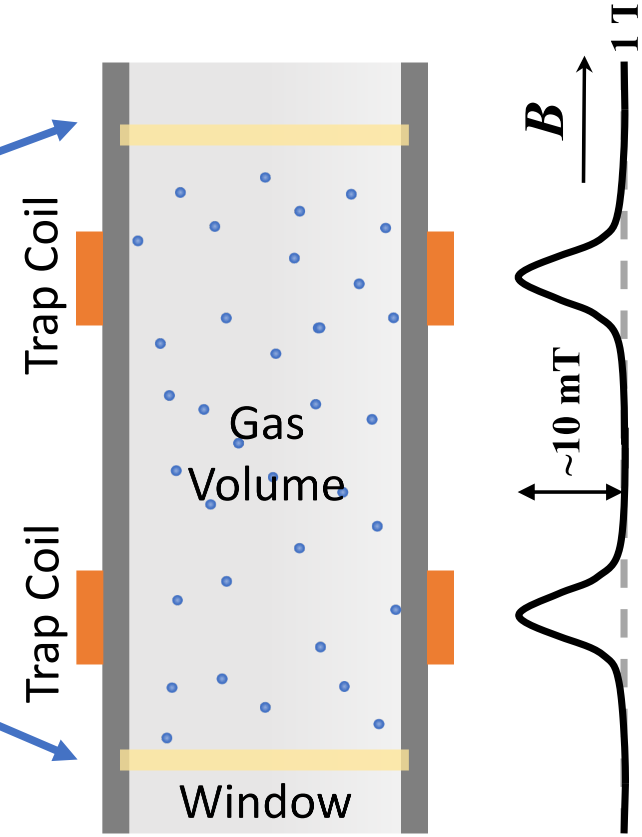






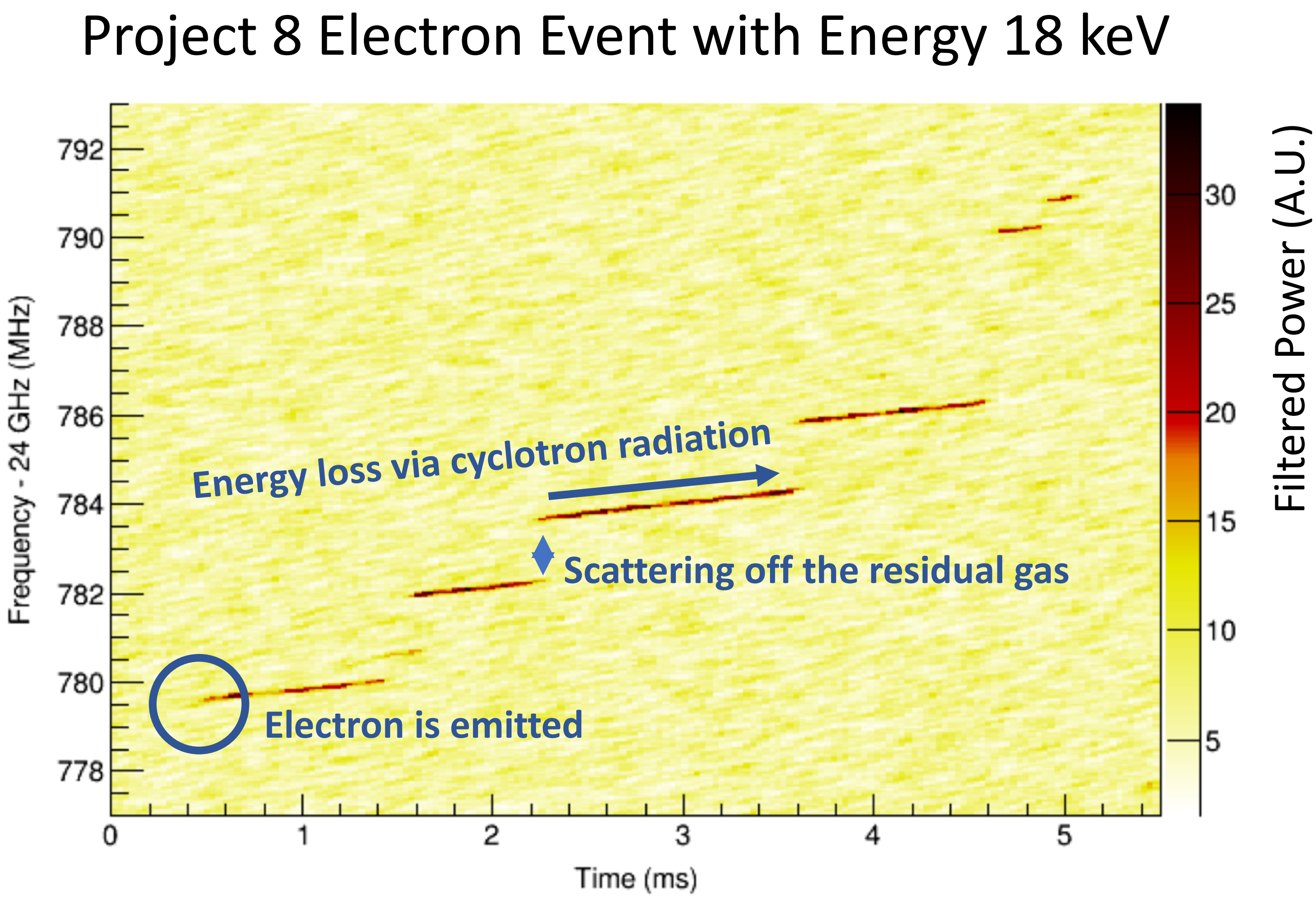
Tritium with krypton co-magnetometry

Multiple trapping coils

Circular waveguide decay region

See Poster #14 by N. Oblath

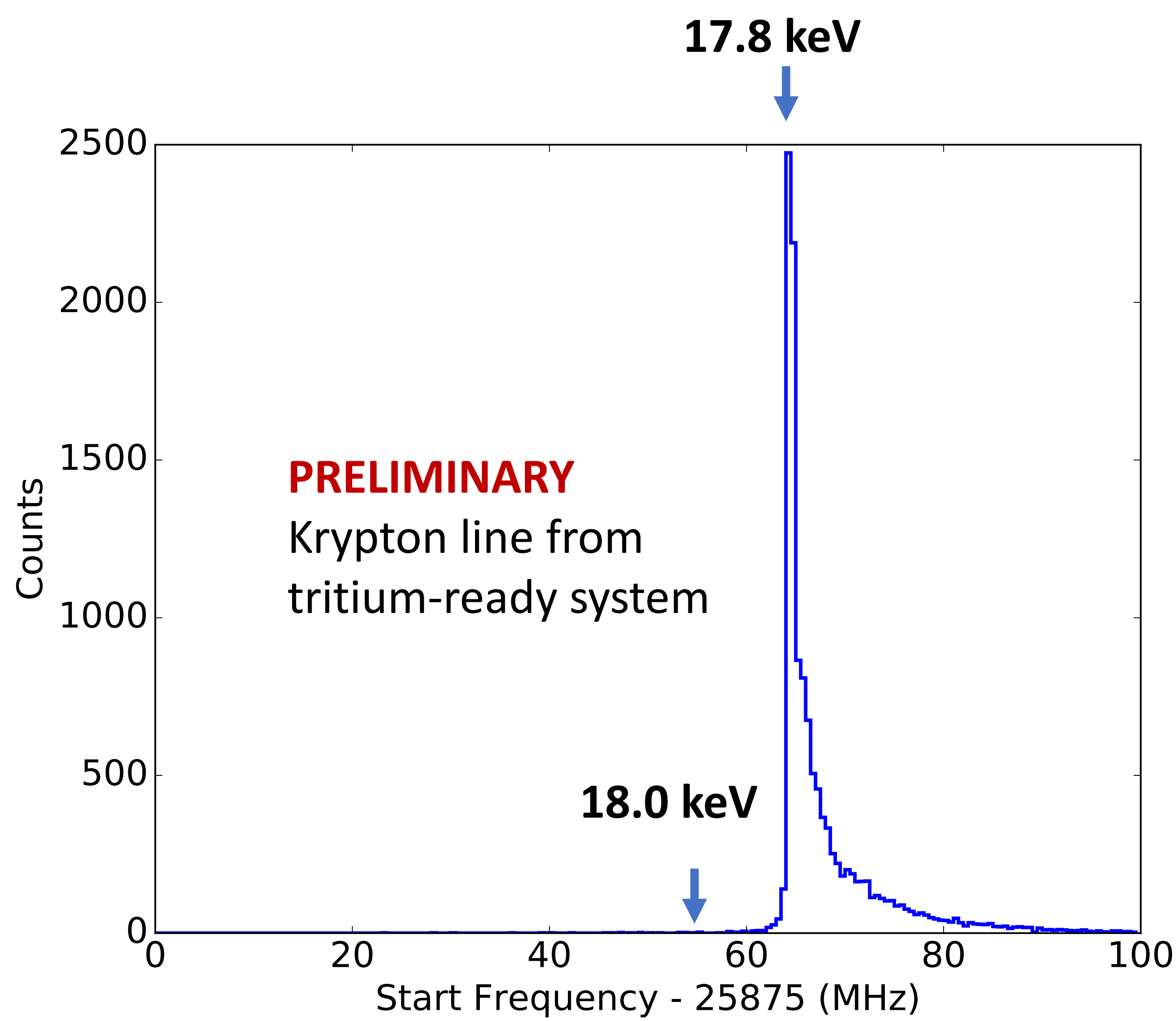
Project 8 Events



Frequency increases as energy is lost due to radiation (continuous) and collisions (discrete)

Decay Spectrum of ^{83m}Kr

- Starting frequency of track gives electron energy
- Histogram of starting energy gives decay spectrum ^{83m}Kr



Preparations for Tritium

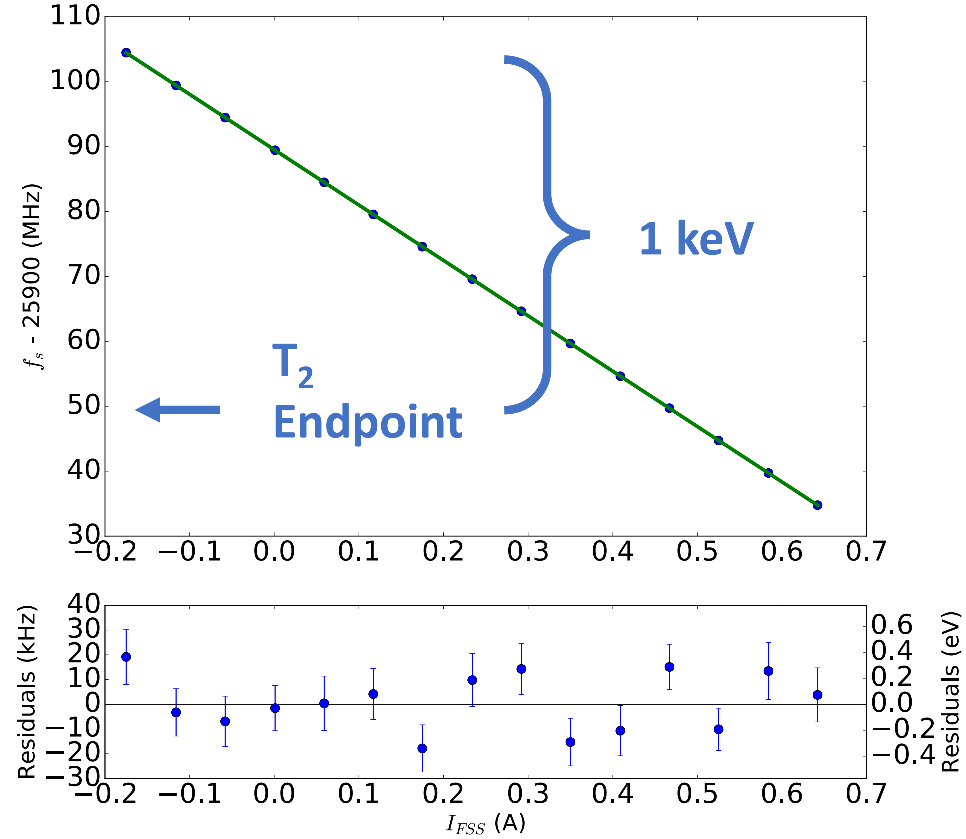
We use an additional magnetic field to move the 18 keV ^{83m}Kr line through the range where we will measure the tritium endpoint

Understanding linearity and detection efficiency is critical!

Linearity test completed, good to 0.2 eV

Efficiency data being taken right now

Once this is complete, we are ready to measure the tritium endpoint and calculate how much we need to scale up



Designs for Scaling to a Large-Volume System

"Phase III"

The Need for a Large-Volume System

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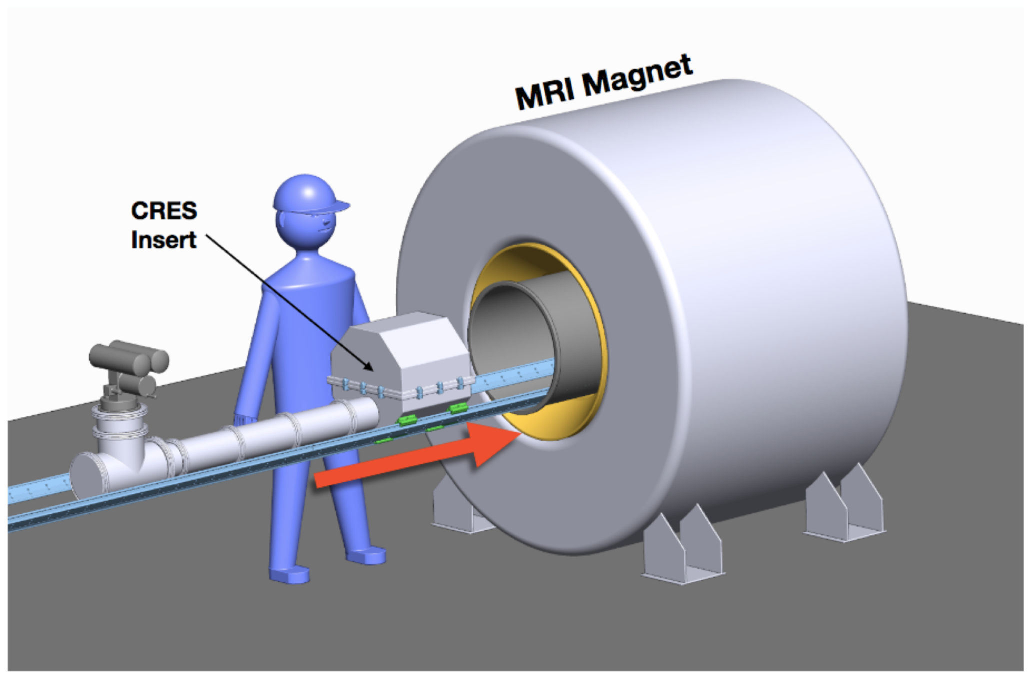
- The next apparatus needs a much larger volume for sufficient statistics
- A larger volume requires multiple readout channels

Target scale: fill the volume of a human-sized MRI magnet with tritium



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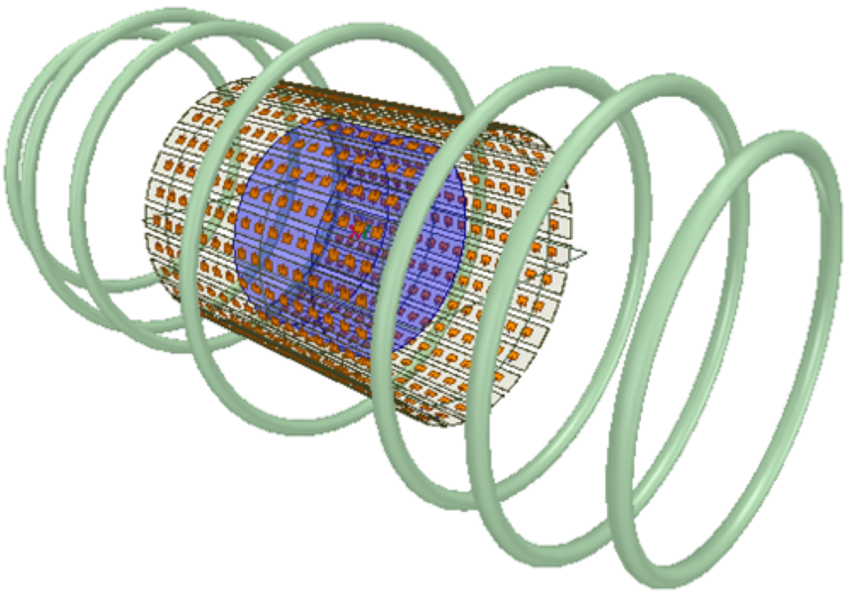
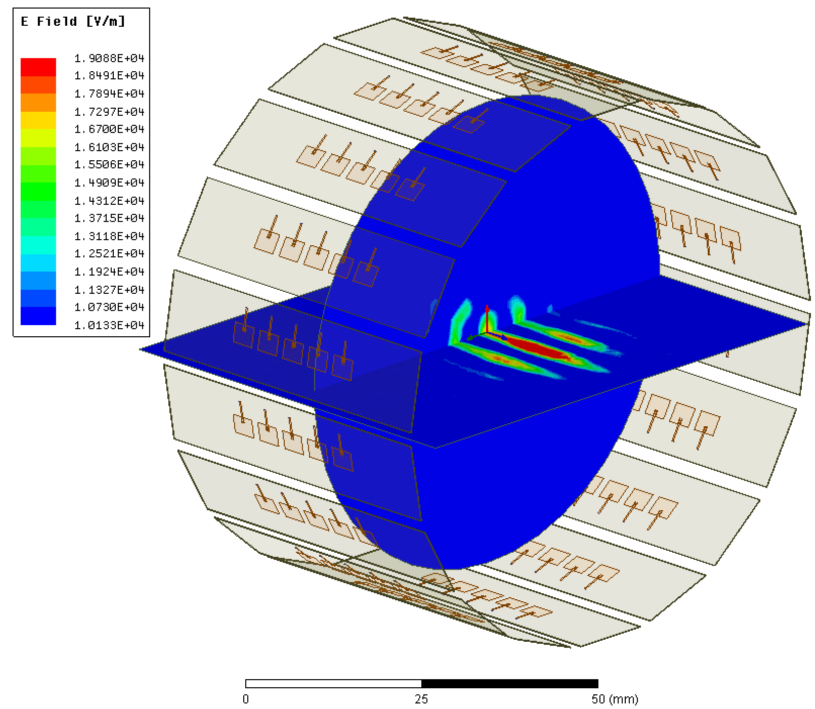
Multichannel Read-Out

We will use interferometry to localize electrons in this volume



Model of meter squared trapping volume surrounded by multiantenna array



Simulation of electron position reconstruction in antenna array

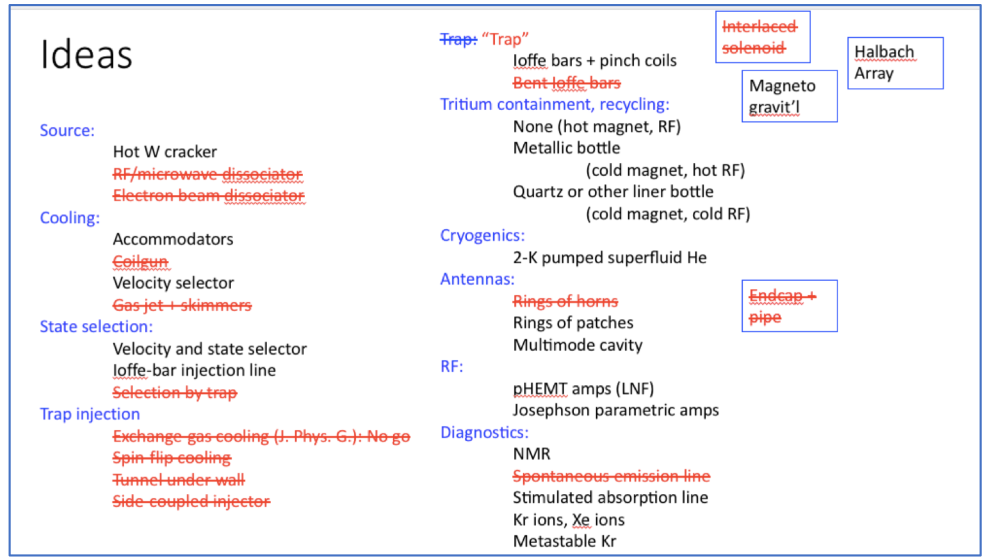
See Poster #24 by Brent VanDevender

Concept for Atomic Tritium System

“Phase IV”

Challenges for Atomic Tritium

- Produce atomic tritium
- Transport to active volume
- Maintain sufficient density
- Keep molecular contamination to $<10^{-5}$

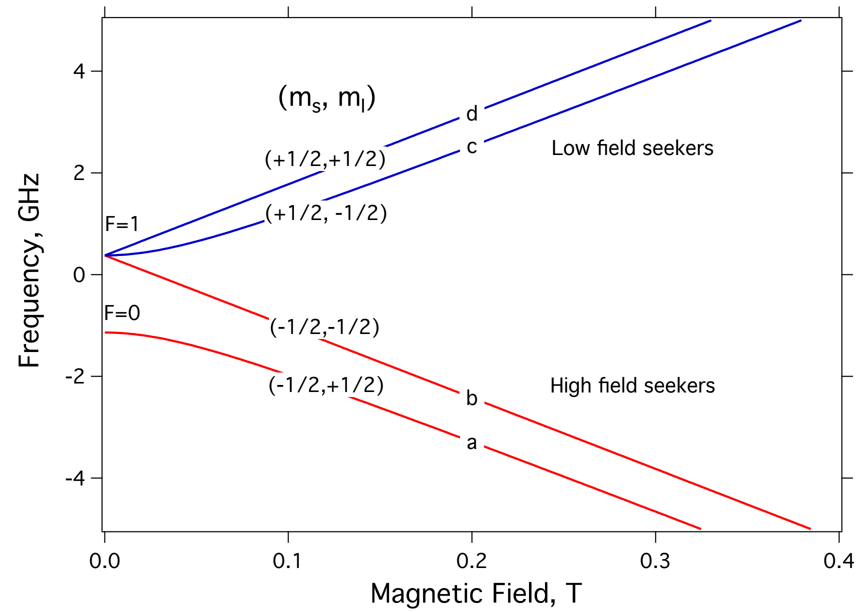


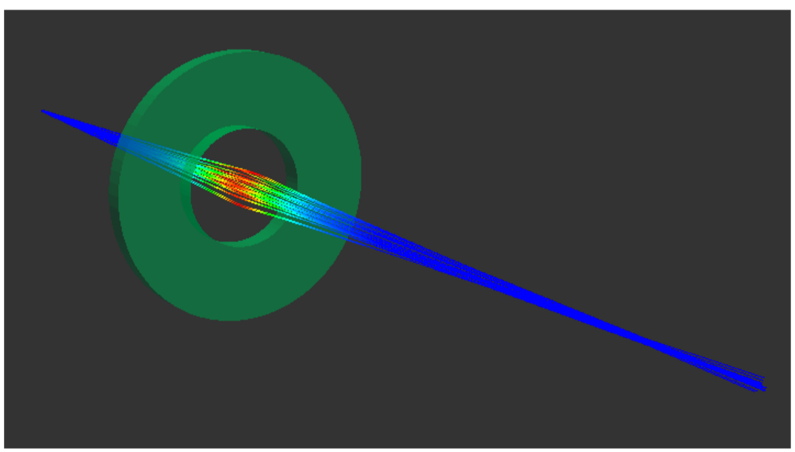
A summary slide from a recent atomic tritium report: much of the effort goes into identifying techniques that won't work.

See Poster by A. Lindman

Guiding and Selecting Tritium Atoms

Magnetic moment of atomic tritium allows atoms to be guided, cooled (to 30 mK), and trapped





Magnetic fields can be used to lens tritium beam and select preferred velocity range, as is commonly done with neutrons

Schematic Diagram of Atomic Tritium Experiment

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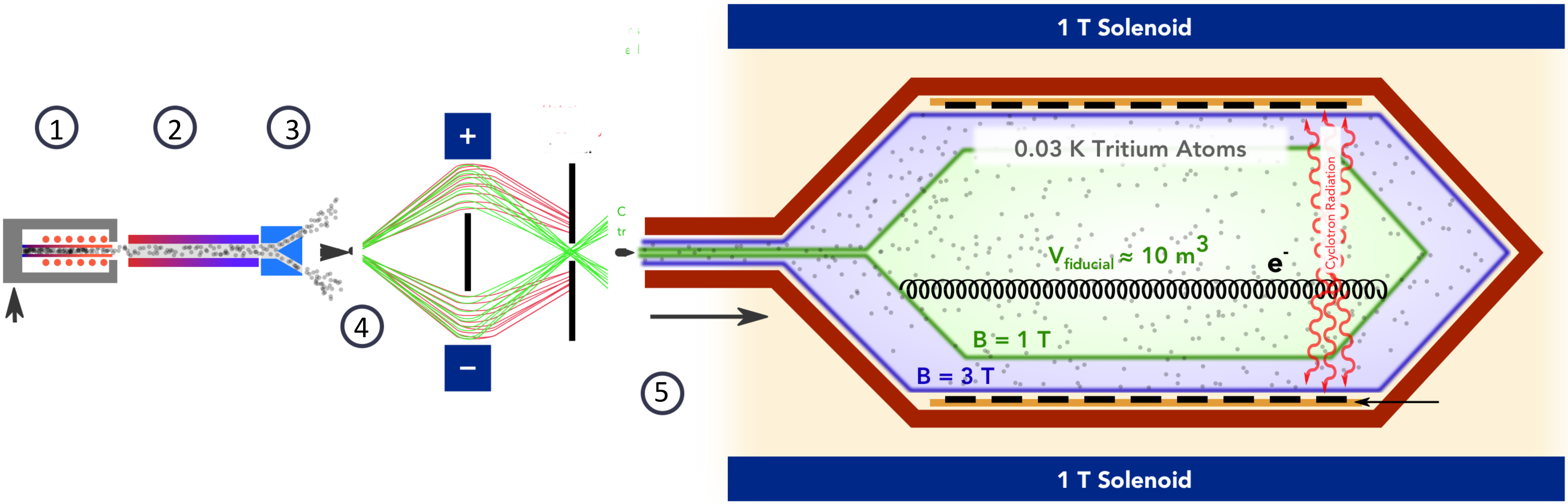

1: Molecular tritium thermally cracked

2: Atomic tritium cooled in accommodator

3: Cool atoms sprayed into velocity and state selector

4: Cold low-field seeking spin tritium selected

5: Atoms cooled to millikelvin temperatures by magnetic step, linger in decay volume

Cold Tritium Selection

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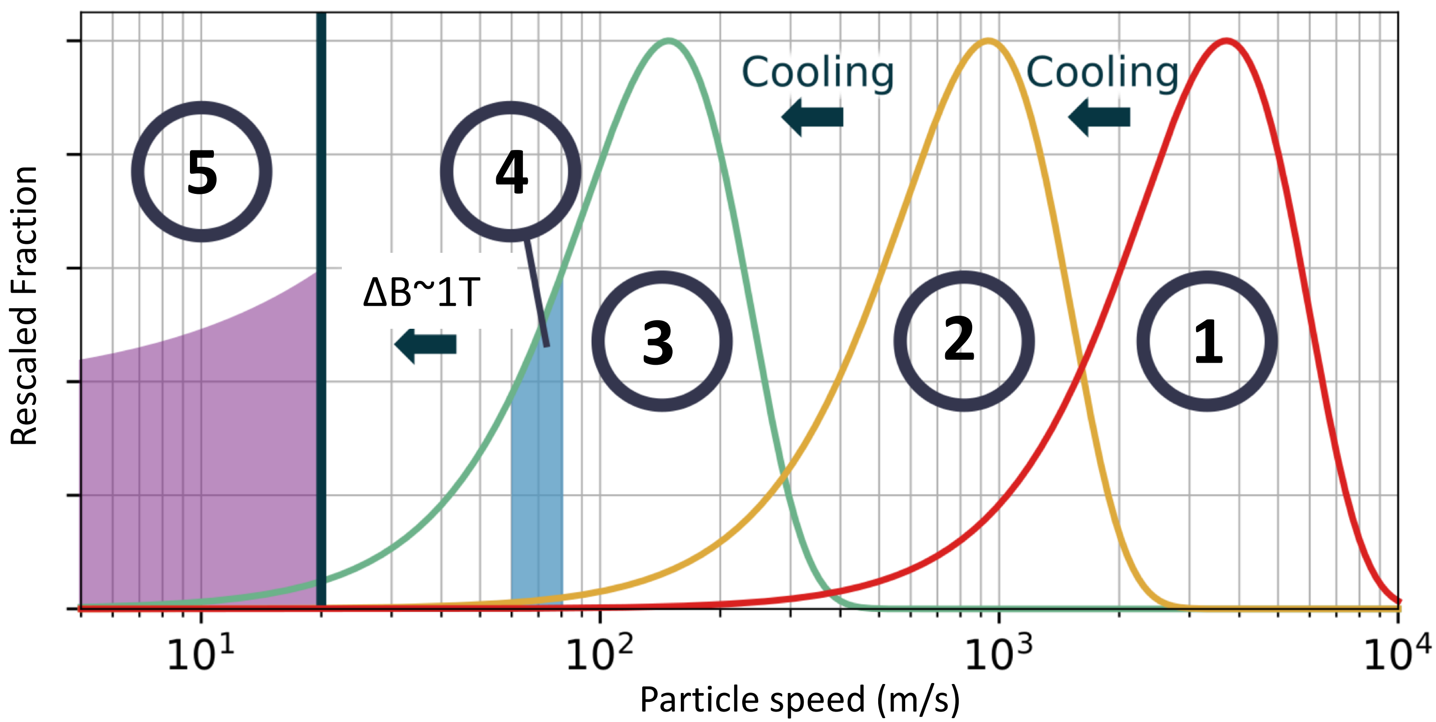


5: Atoms cooled to millikelvin temperatures by magnetic step, linger in decay volume

4: Cold low-field seeking spin tritium selected

3: Cool atoms sprayed into velocity and state selector

2: Atomic tritium cooled in accommodator

1: Molecular tritium thermally cracked

Trapping the Correct Density of Atomic Tritium

Combined Solenoid/Ioffe Trap:

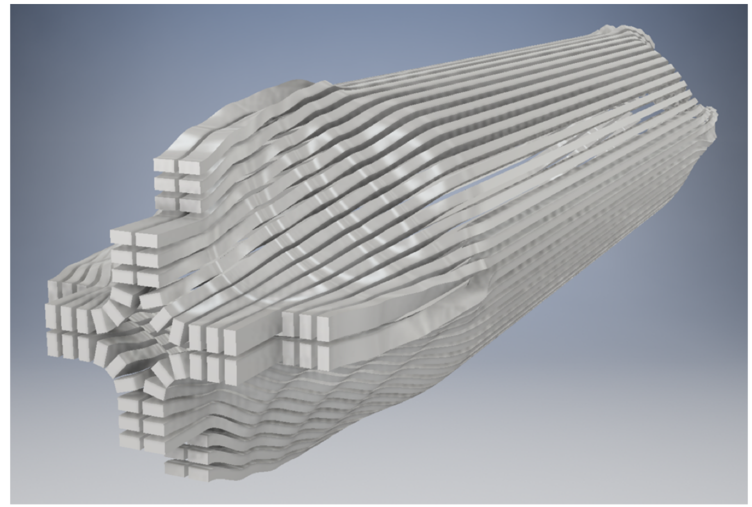
Traps atomic tritium

Molecular tritium not trapped

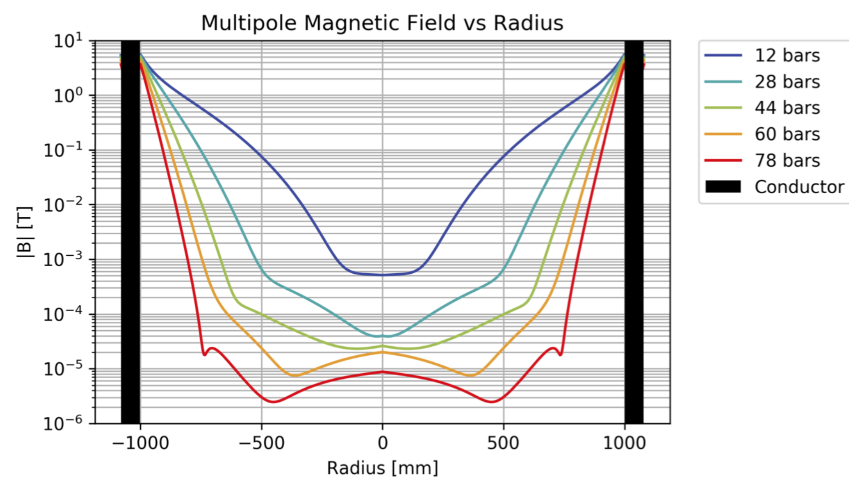
Emitted electrons are also trapped and radiate

Technique successfully used in antihydrogen experiments (e.g. ALPHA)

Status: Conceptual design stage

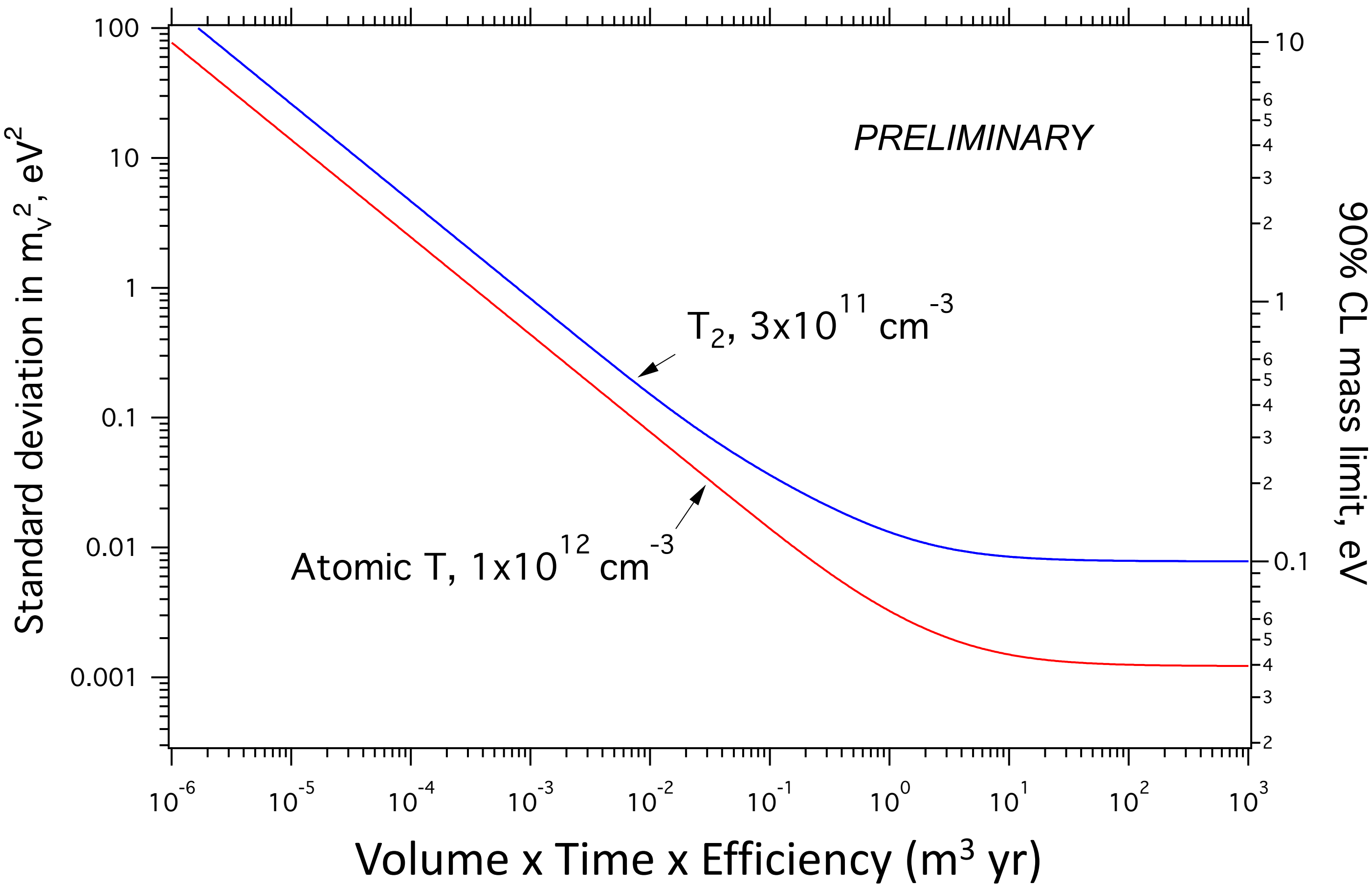


A Ioffe Conceptual Design
Scale: 10 m^3 trapping volume



Simulated containment field for Ioffe design

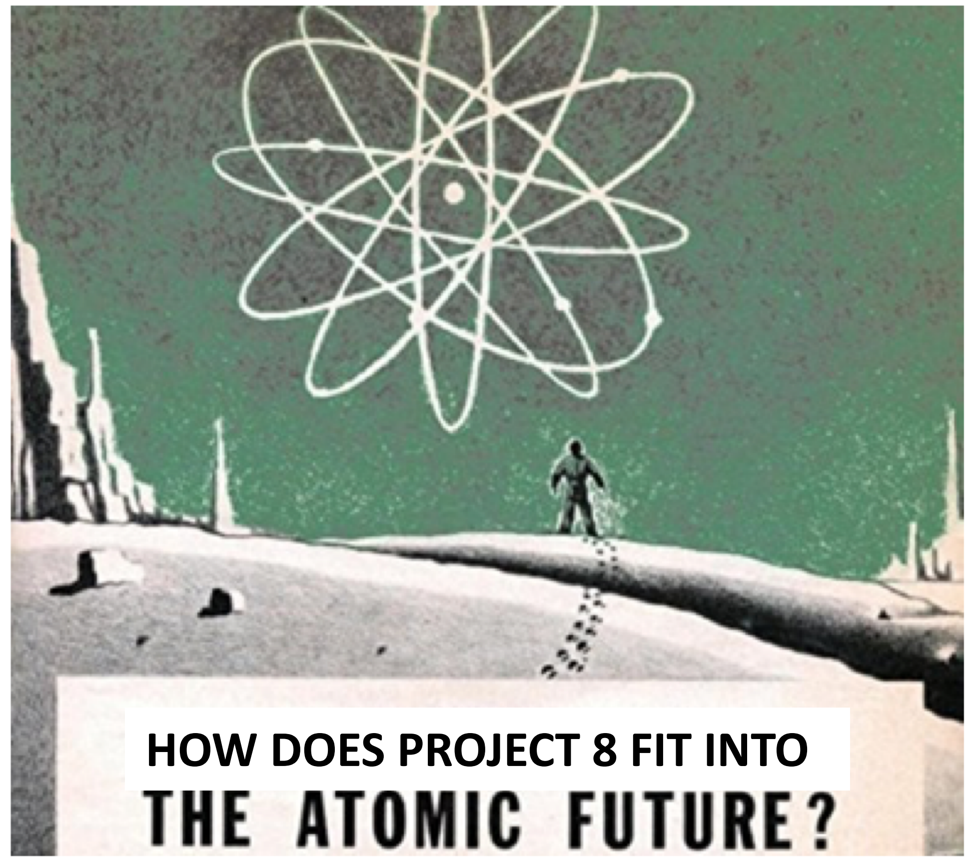
Project 8 Projected Capabilities with Atomic Tritium



Atomic tritium should allow us sensitivity to a 40 meV mass scale with 10-100 m^3-years exposure

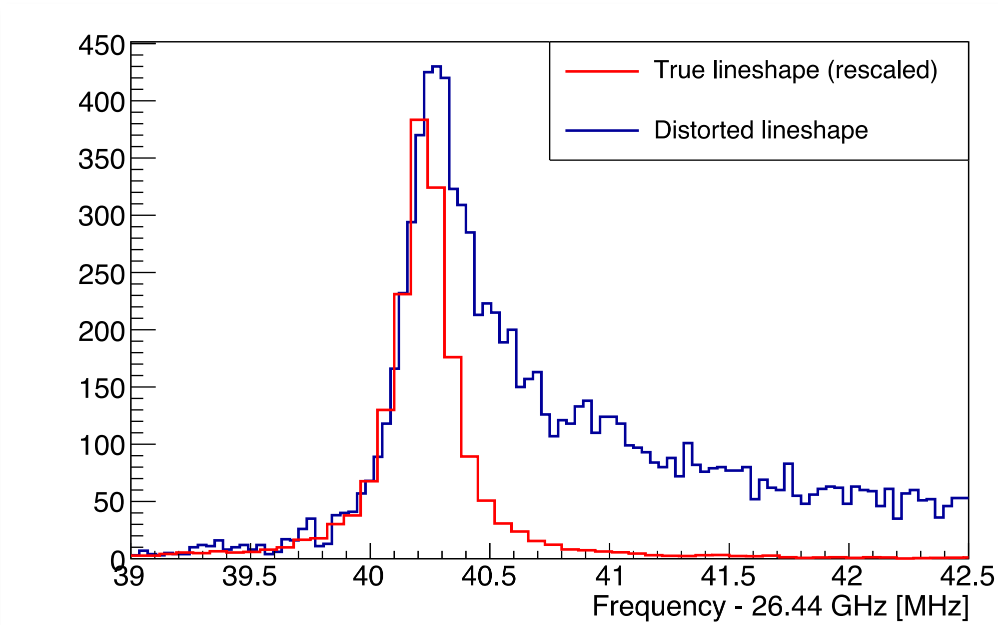
The Atomic Future

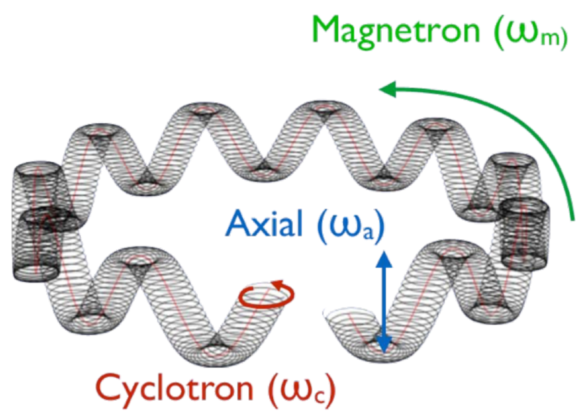
- Initial Project 8 prototype gives promising results for beta-decay electron measurement
- Conceptually, the path to atomic tritium is clear
- Engineering challenges are numerous, but approachable
- Project 8 will bring us into the Atomic (tritium) Age!



Project 8: Advances in Event Reconstruction

Distortion of Lineshape with Naïve Analysis





RF signal encodes electron motion in trap

Broadens linewidths with naïve analysis

Sophisticated analysis leverages more information for precision energy resolution

Paper describing relationship between electron signal and electron kinematics in preparation.