High-precision magnetic fields for 40 meV neutrino mass sensitivity in Project 8

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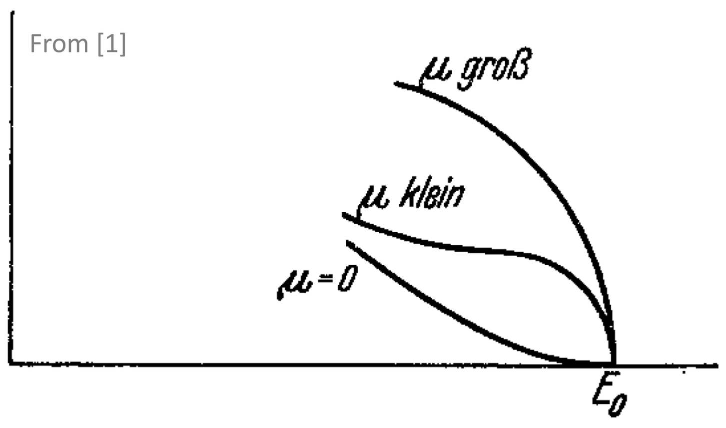
PROJECT 8

Neutrino Mass

Measure electron energy in tritium β-decay: pure kinematic measurement

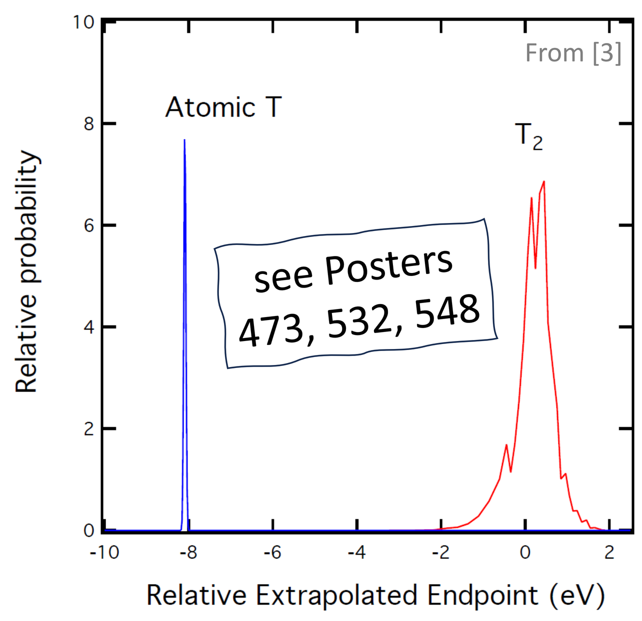
Challenges
- sub-eV energy resolution
- high statistics
- low background



and Atomic Tritium

With T_2 decay, rotational and vibrational excitation of final state molecule leads to energy broadening leading to dominant systematic at ~0.2 eV

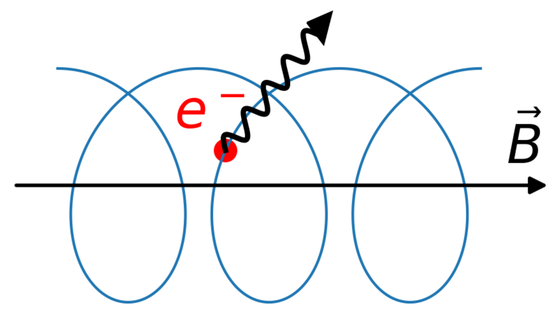
→ atomic tritium required for 40 meV sensitivity



with Cyclotron Radiation Emission Spectroscopy

Electron in magnetic field radiates at cyclotron frequency

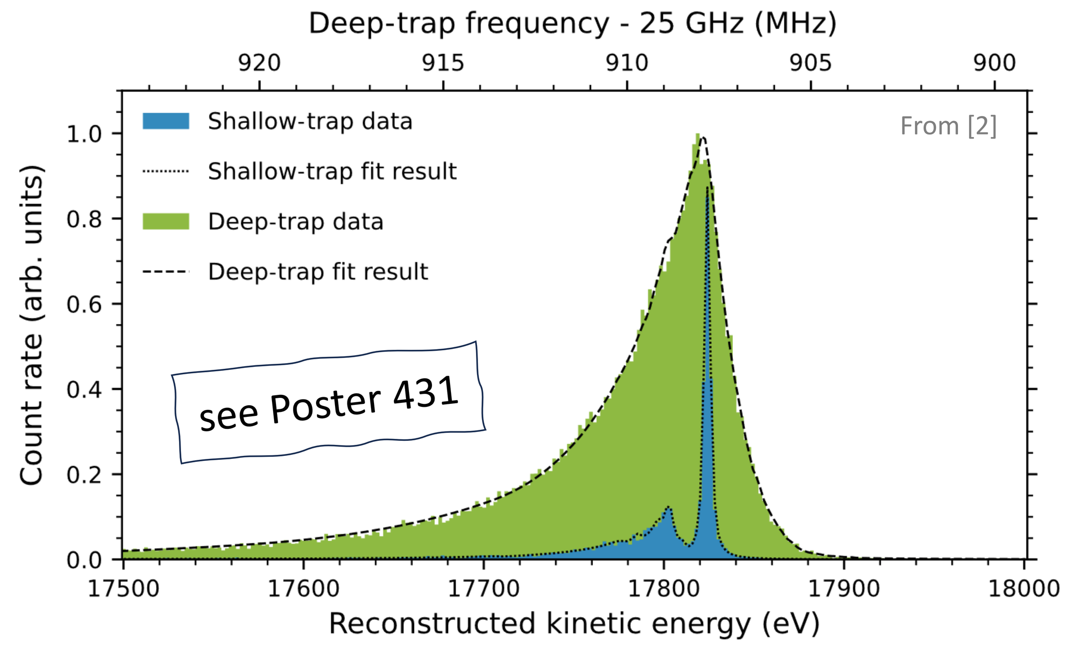
$$E_{\text{kin}} = \frac{ec^2\langle B\rangle}{2\pi f_{\text{meas}}} - m_e c^2$$



Precision measurement of cyclotron frequency and magnetic field needed

CRES demonstrated in small volumes at 1 T field and 25.9 GHz frequency with molecular tritium [2]

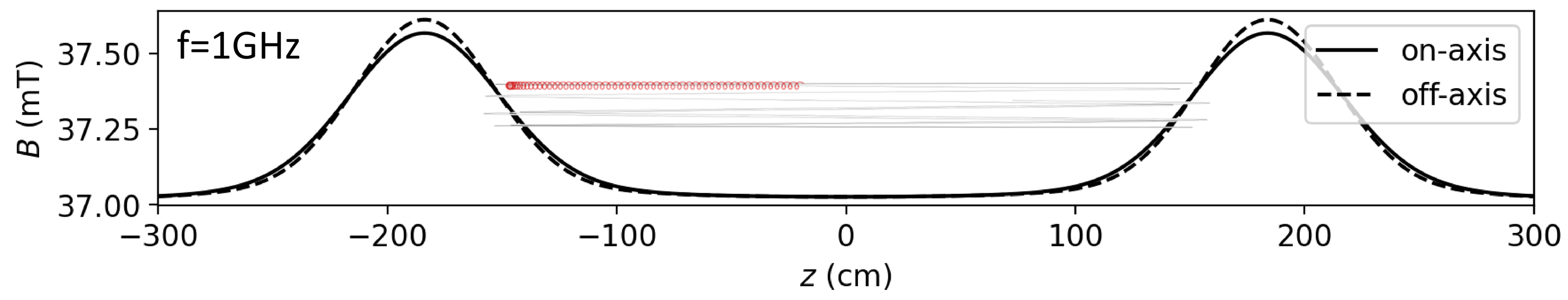
Energy resolution dominated by magnetic field variation caused by electron trap



Demonstrate CRES compatibility with atomic trap and large volume

CRES Electron Trap

Confine beta decay electrons in detector volume by magnetic bottle trap

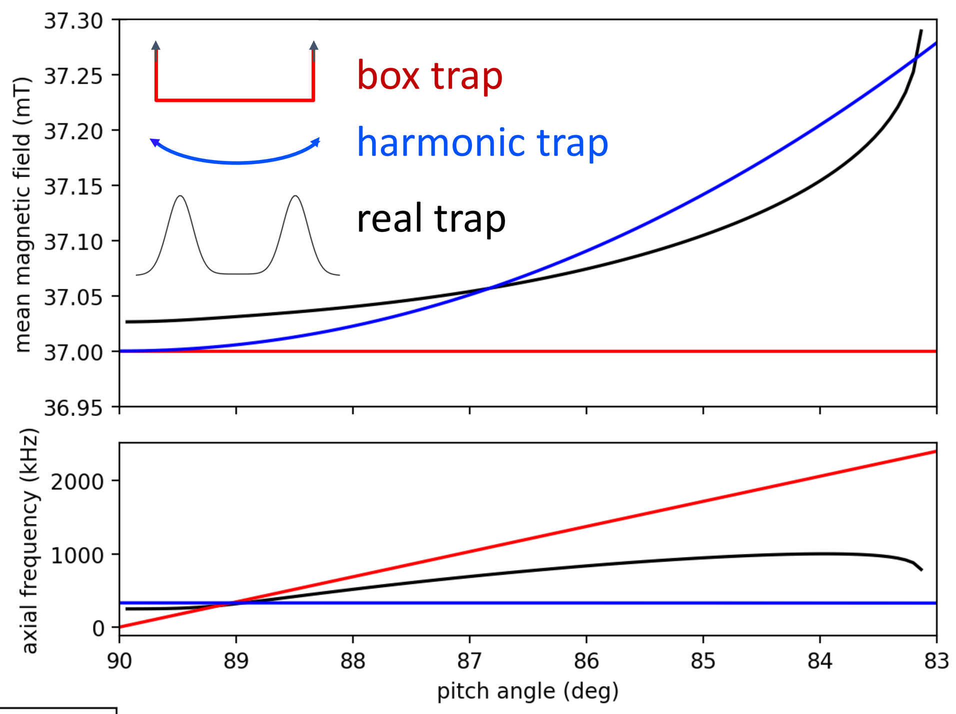


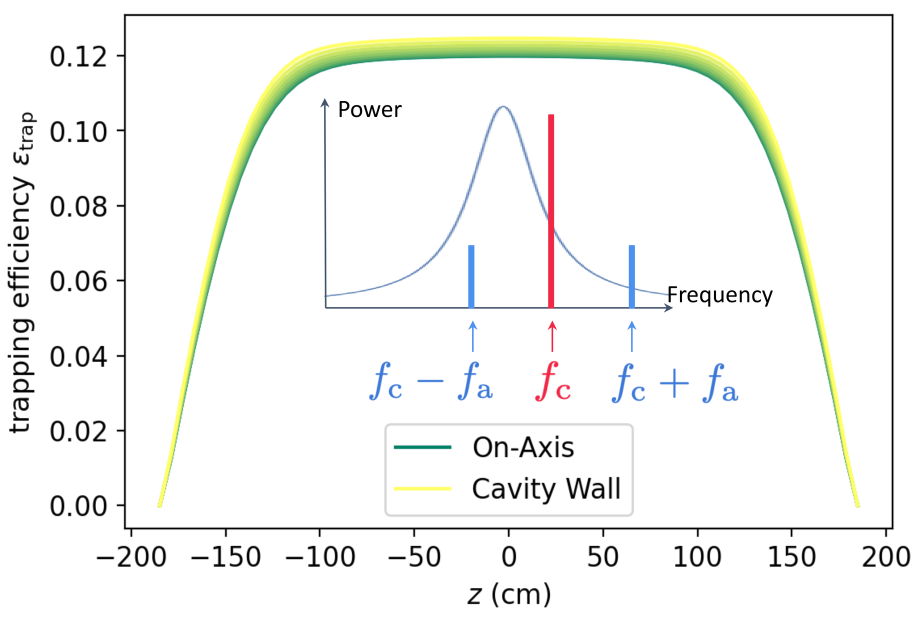
Trap Shape

Trap shape determines electron axial and drift motion

Mean magnetic field depends on electron position and pitch angle

Mean magnetic field can be pushed off resonance from cavity

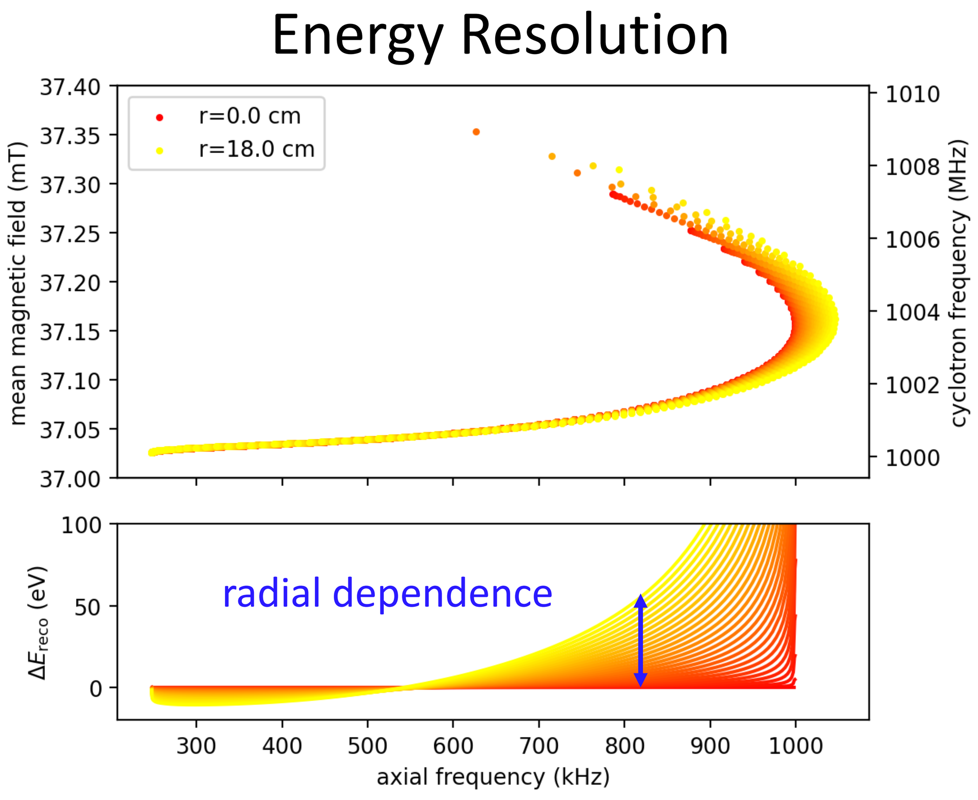




Efficiency

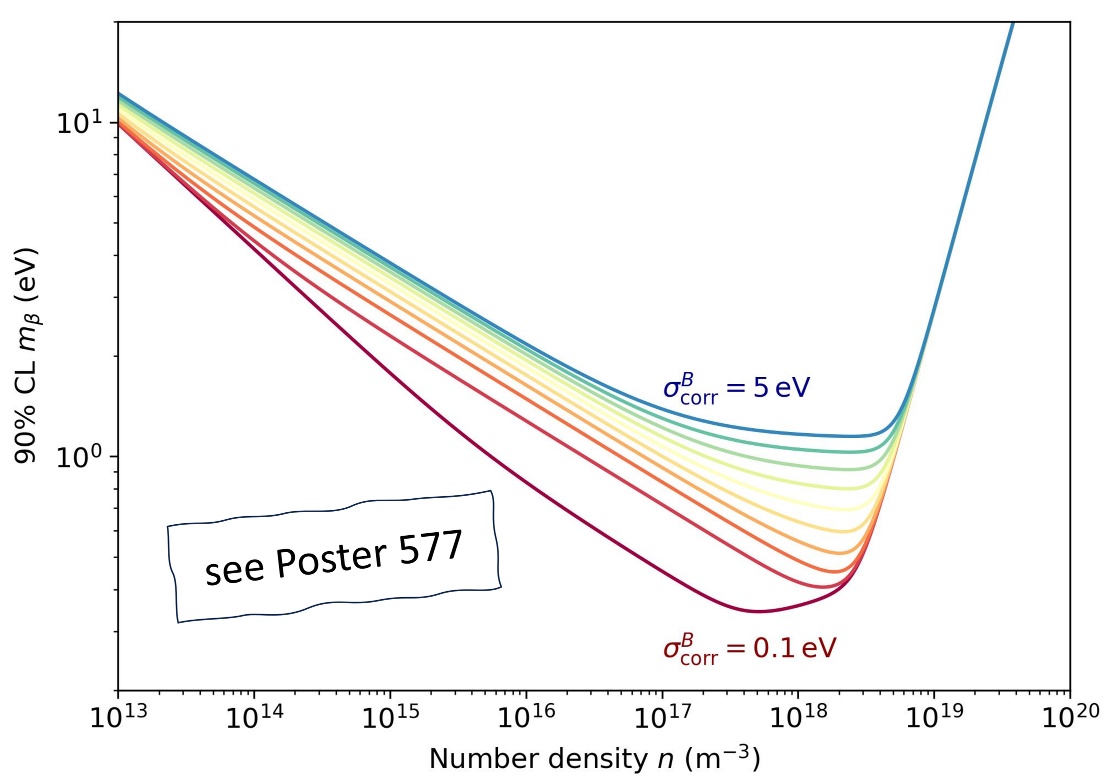
Deeper trap increases trapping efficiency but shifts frequencies off cavity resonance which reduces SNR

Energy Resolution



Mean magnetic field shift and axial frequency depend on radial position which broadens energy resolution if not accounted for in reconstruction

Neutrino Mass Sensitivity

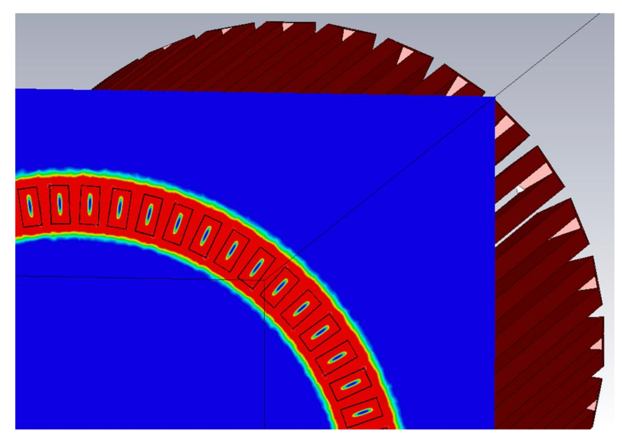


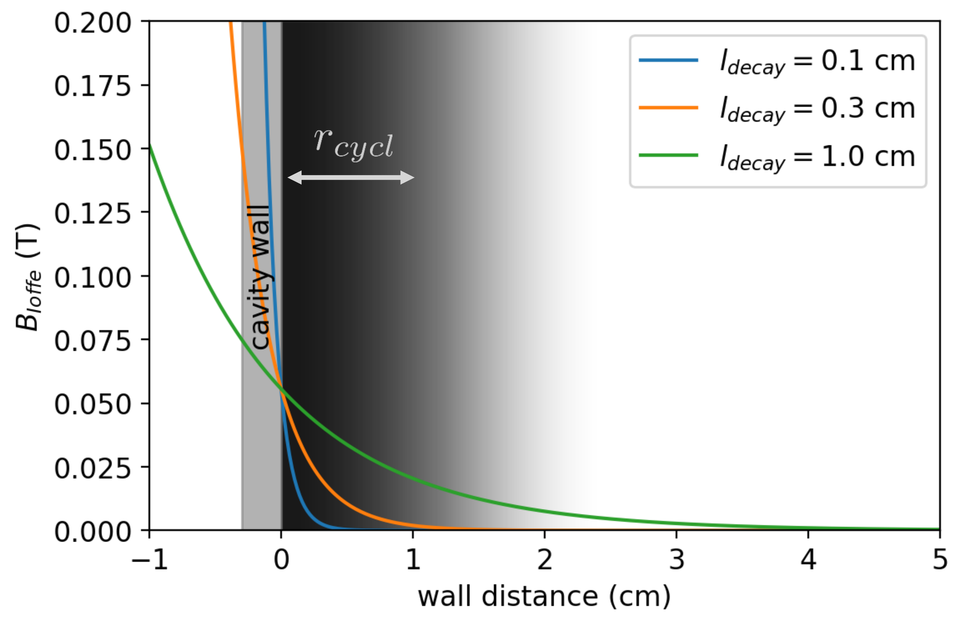
Depends on energy resolution due to magnetic field variation

Atom Trap

Confine atomic tritium by magneto-gravitational trap

To confine atomic tritium at 1mK in a 3m tall magnet, a field wall of ~35 mT is needed



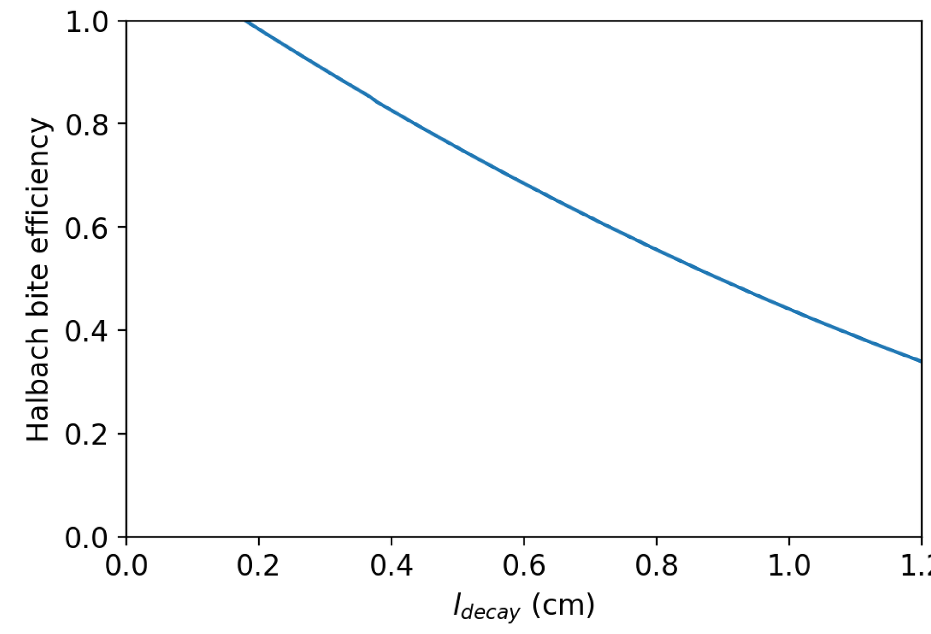


Atom trap field must decay quickly to reach ppm homogeneity in detection volume

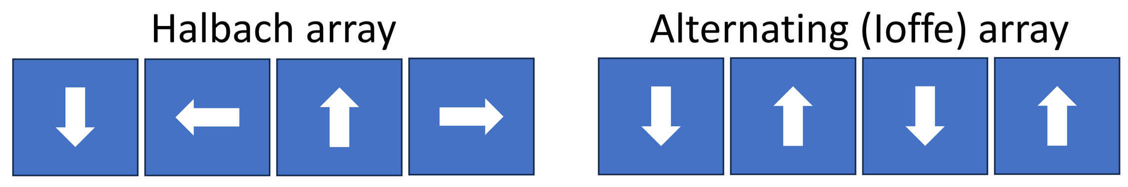
Field of magnet needs to be significantly higher than 35 mT since field decays in cavity wall

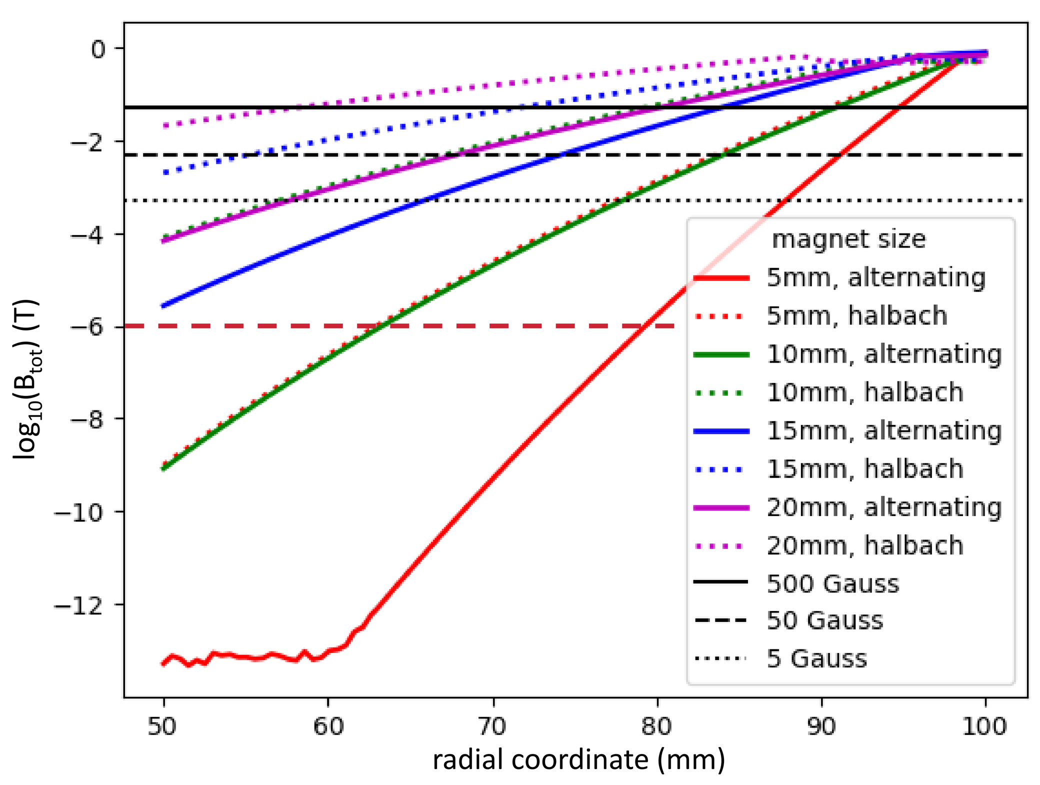
Electrons within one cyclotron orbit radius from the wall are lost to wall interaction

Efficiency loss if atom trap does not decay quickly enough and influences CRES electrons



Studied decay length of Halbach and Ioffe style magnet arrangement





Ioffe magnet arrangement provides fast wall field decay

References
[1] E. Fermi, Z. Physik **88**, 161–177 (1934)
[2] A. Ashtari Esfahani *et al.* Phys. Rev. Lett. **131**, 102502 (2023)
[3] A. Ashtari Esfahani Snowmass 2021 arxiv:2203.07349

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