Effectiveness of a superconducting lead endcap in minimizing magnetic field gradients for the nEDM search

Aritra Biswas
Filippone Group, Kellogg Radiation Laboratory

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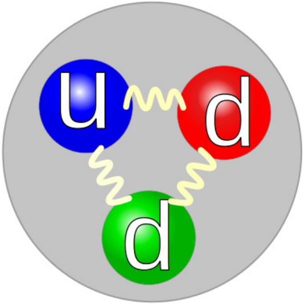
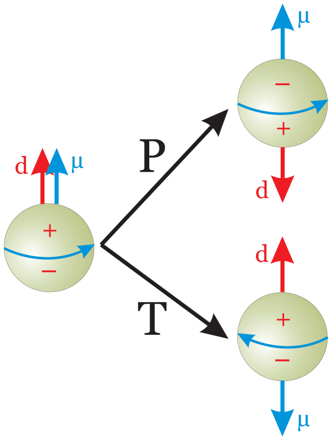
nEDM = neutron electric dipole moment

- up quark: $\frac{2}{3}e$
- each down quark: -$\frac{1}{3}e$
- electric dipole moment: vector measuring separation between + and - charges and their orientation



Horvath A. Quark structure neutron. Wikimedia.

why does the nEDM matter?



- $C : q \mapsto -q$
- $P : (t, x, y, z) \mapsto (t, x, -y, z)$
- $T : (t, x, y, z) \mapsto (-t, x, y, z)$

- *CPT* symmetry
  $+$ *P* violation
  $+$ *T* violation
  $\Rightarrow$ *CP* violation

- reformulations of Standard Model
- matter-antimatter asymmetry

Knecht A. 22 May 2008. Parity and time reversal violation. Wikimedia. Public domain.

how do we measure the nEDM?

- put ultra-cold neutrons (UCN) in **E** and **B** fields
- neutron will precess at frequency ω

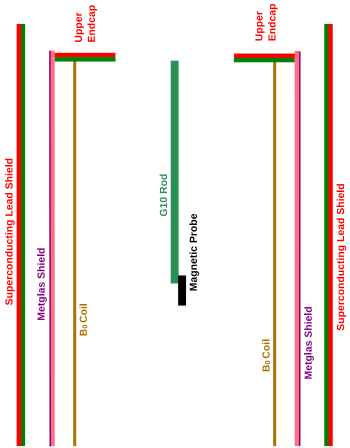
$$\omega_{\uparrow\uparrow} = -\frac{\mu_n B + d_n E}{J\hbar}, \quad \omega_{\uparrow\downarrow} = -\frac{\mu_n B - d_n E}{J\hbar} \tag{1}$$

$$\Delta\omega = \pm\frac{2d_n E}{J\hbar} \pm \Delta\omega_{geo} \tag{2}$$

- $\frac{\partial \mathbf{B}}{\partial(x,y,z)} \neq 0 \Rightarrow \frac{\partial \mathbf{B}}{\partial t} \neq 0 \Rightarrow$ effect of **E** field $\Rightarrow \Delta\omega_{geo}$
- geometric phase $\Rightarrow$ false measurement!

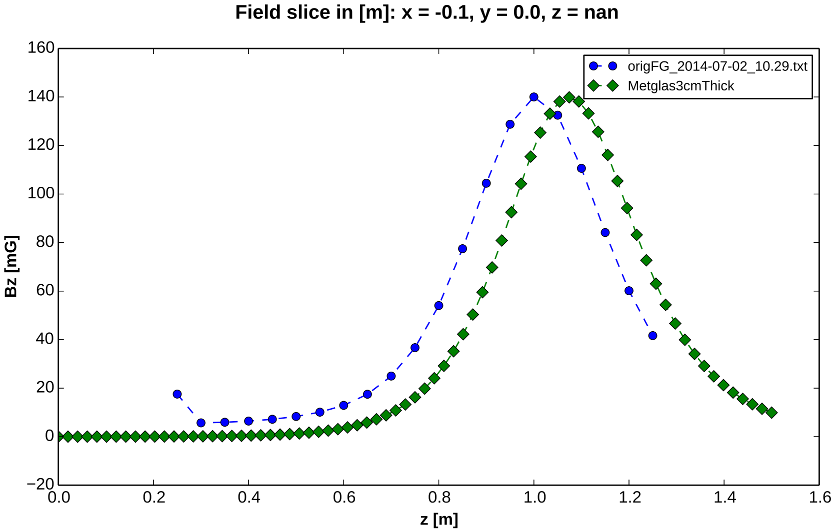
Pendlebury et. al. Geometric-phase-induced false electric dipole moment signals for particles in traps. Phys. Rev. A. 70, 032102 (2004).

creating an uniform magnetic field

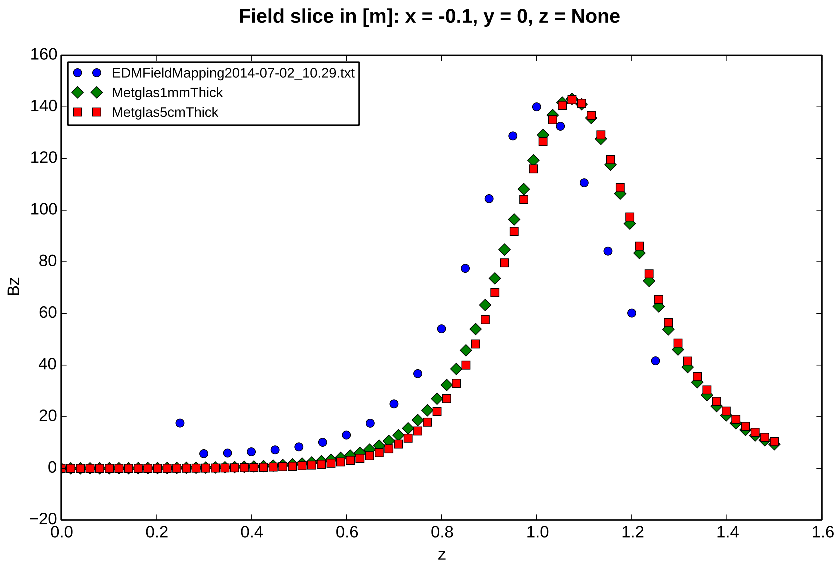


- B_0 coil: $\cos\theta$ coil geometry, emulates sheet current
- ferromagnetic Metglas shield
- superconducting axial shield
- superconducting upper endcap

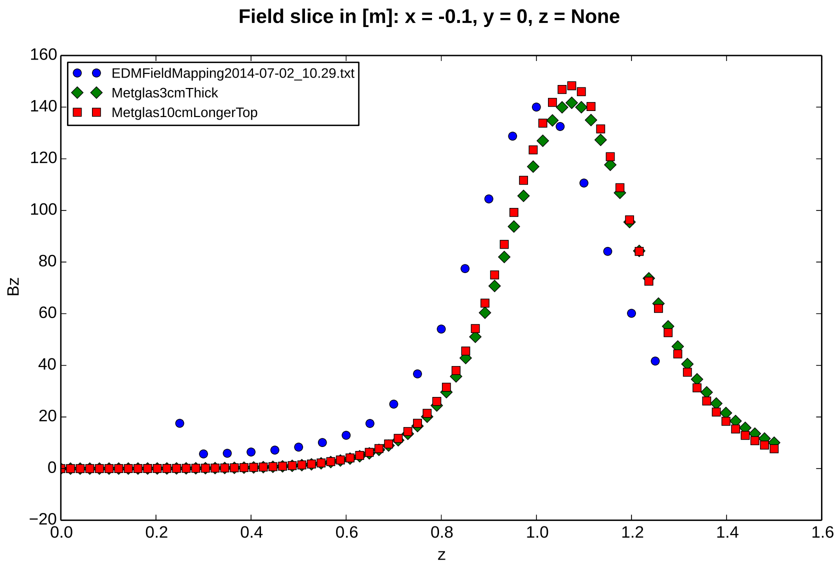
original comparison, warm



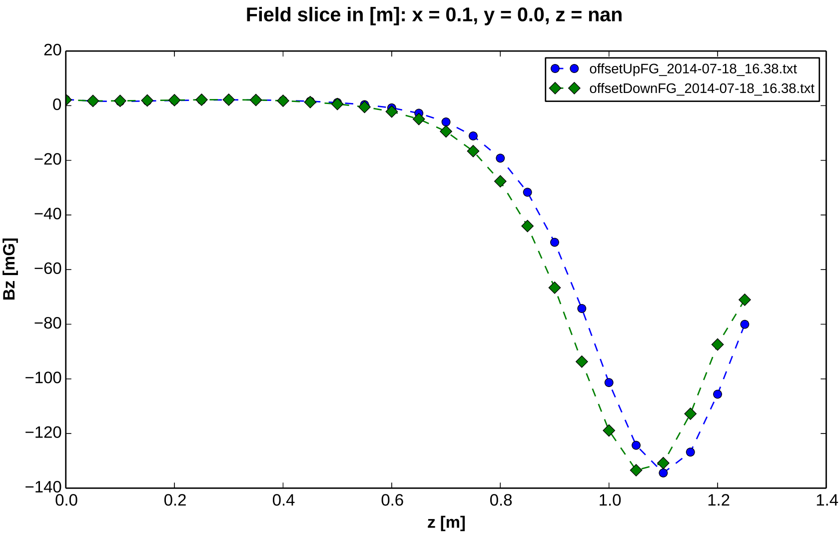
Metglas thickness



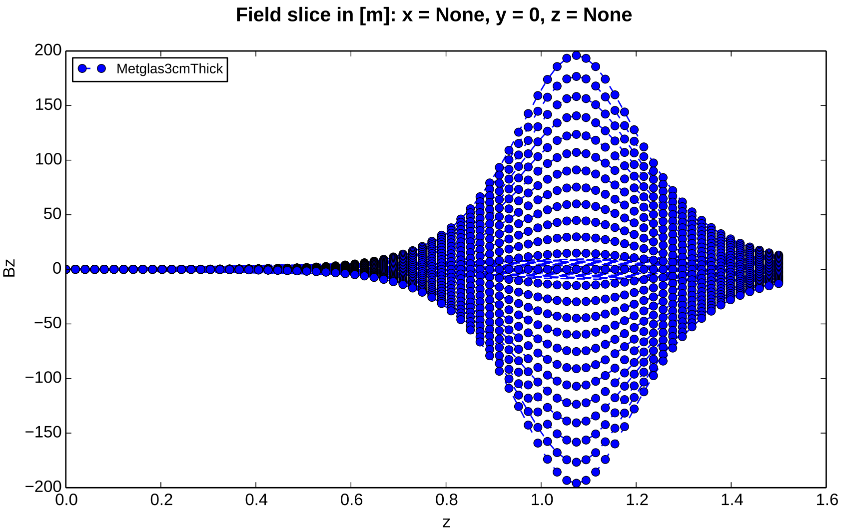
Metglas 10 cm longer on top



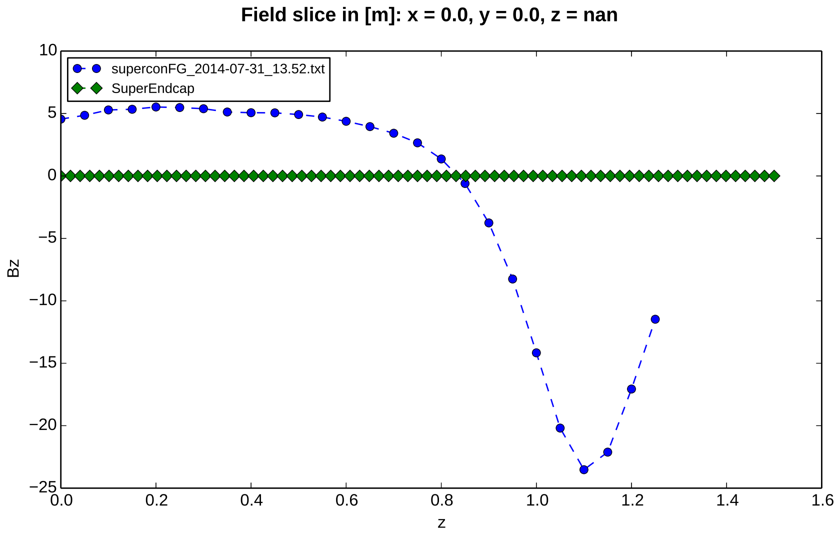
correction 1: probe measurement time



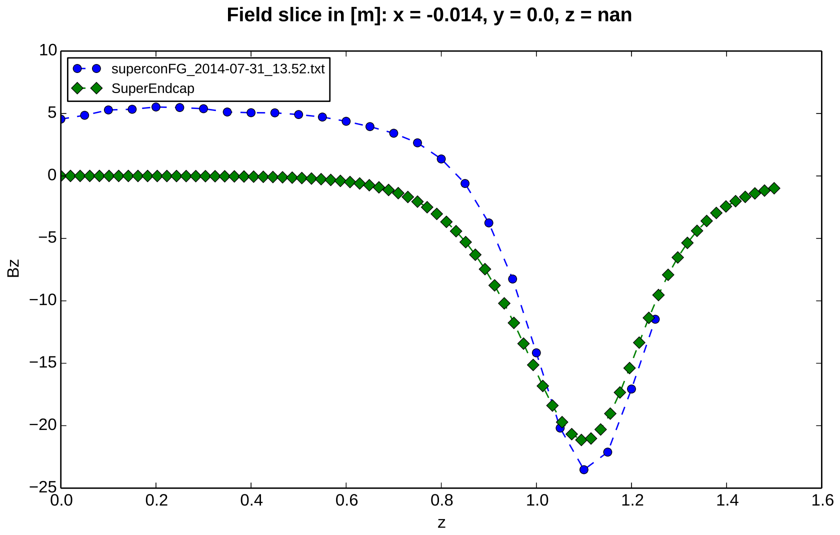
correction 2: x centering



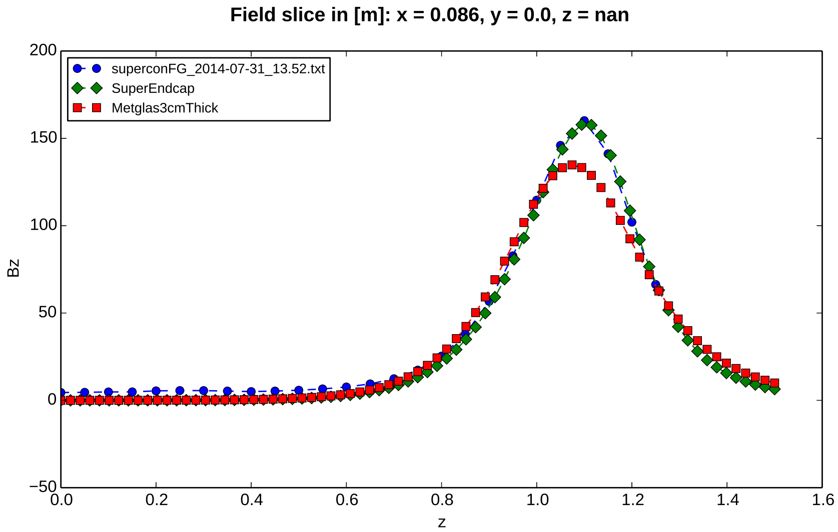
correction 2: x centering, superconducting



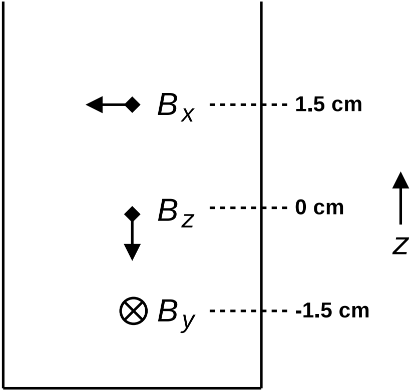
correction 2: x centering, superconducting, 1.4 cm offset



comparison, superconducting

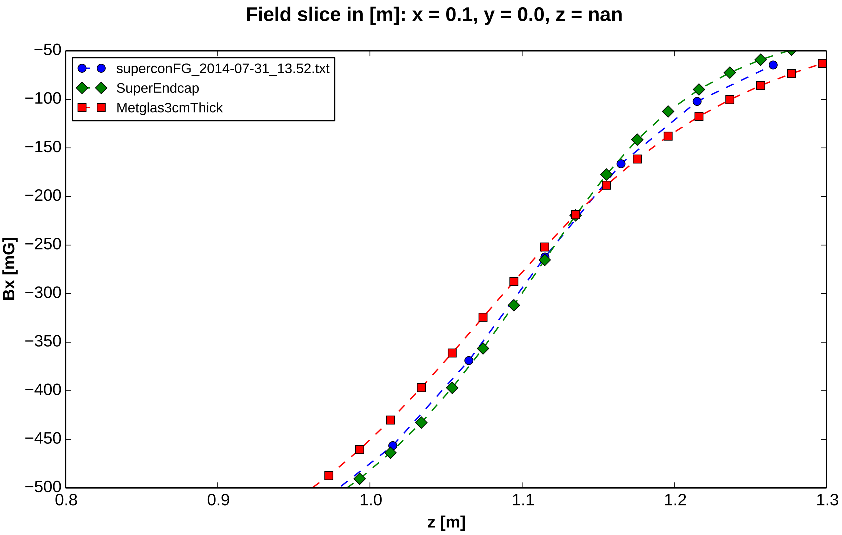


correction 3: probe axis offset

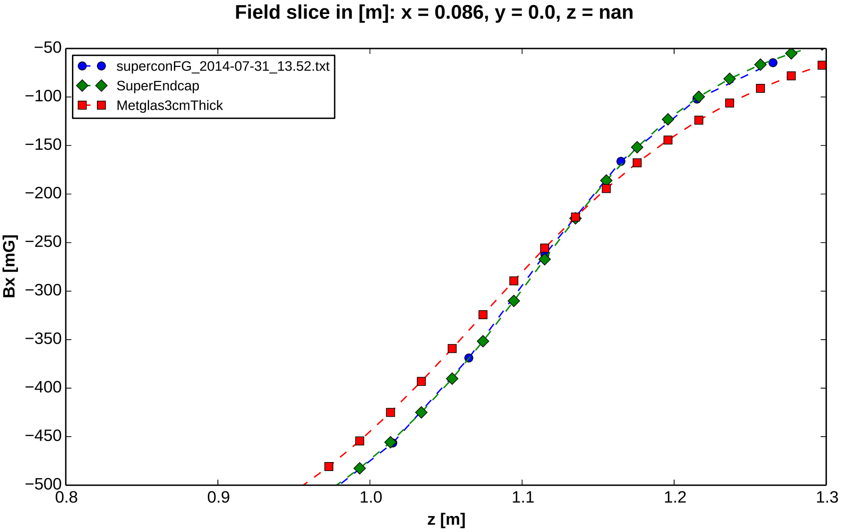


- 3 separate 1-axis probes
- incomplete vector map
- need to store z-axis offset vector along with z array
- `OffsetAxis` class to return proper spatial axis array based on desired vector component

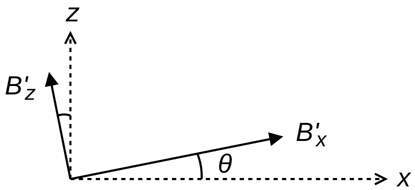
comparison, superconducting, no probe axis offset



comparison, superconducting, probe axis offset



correction 4: probe tilt



$$B_x = B'_x \cos\theta - B'_z \sin\theta, \quad B_z = B'_z \cos\theta + B'_x \sin\theta \qquad (3)$$

1. θ is small:

$$B_x = B'_x - B'_z\theta, \quad B_z = B'_z + B'_x\theta$$

2. $B_z = 0$ at center:

$$\theta = -\frac{B'_z}{B'_x}$$

comparison, superconducting