Center for Exploration of Energy and Matter

Behind the Magic:

Building Better Magnetic Fields

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COMSOL Conference
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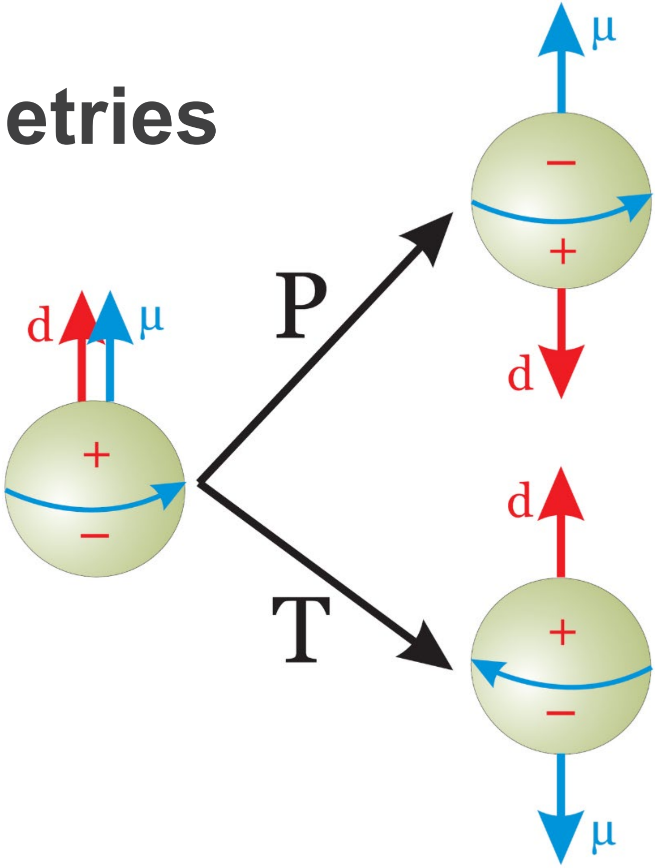
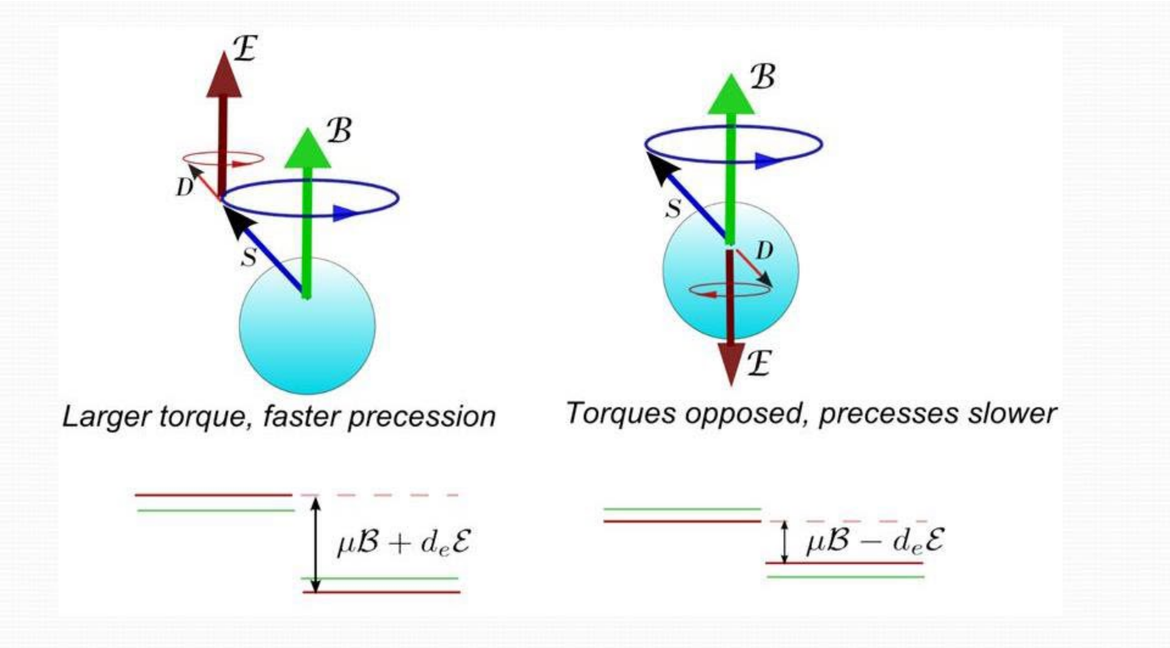
EDM Violates Several Symmetries

$$H = \mu \hat{J} \cdot \vec{B} + d\hat{J} \cdot \vec{E}$$

	C	P	T
$\vec{B}$	-	+	-
$\hat{J}$	-	+	-
$\mu \hat{J} \cdot \vec{B}$	+	+	+

	C	P	T
$\vec{E}$	-	-	+
$\hat{J}$	-	+	-
$d\hat{J} \cdot \vec{E}$	+	-	-





Larger torque, faster precession

Torques opposed, precesses slower

$$H = \mu\hat{J} \cdot \vec{B} + d\hat{J} \cdot \vec{E}$$

$$\omega = \gamma B \pm 2ed_n\, E/\hbar$$

NMR on neutrons

1. Initial polarization can be close to 100%
2. Apply fields (static and RF)
3. Measure final polarization
   n.b. Can only measure polarization destructively

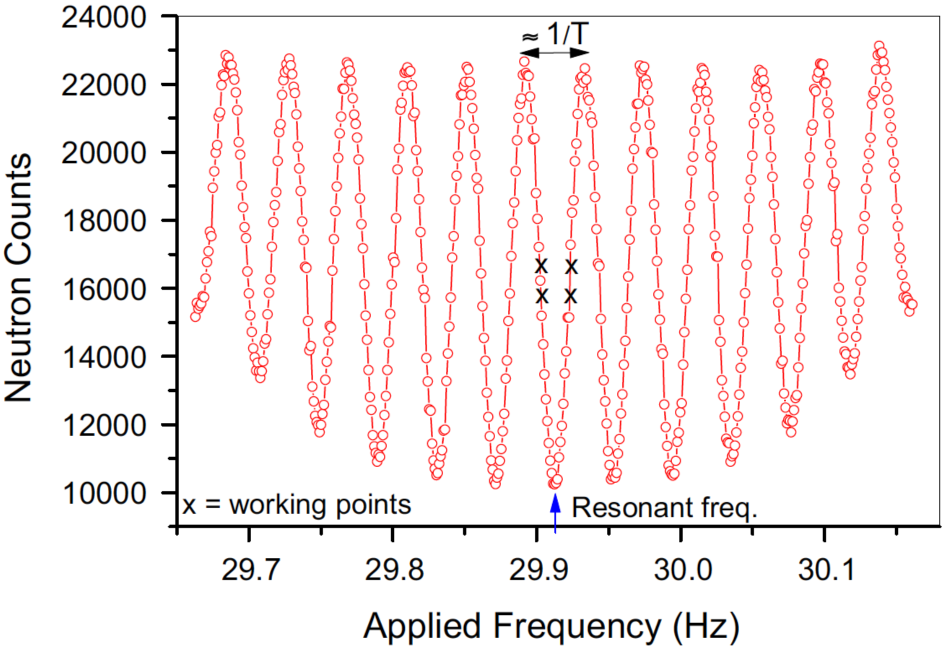
Precision NMR with Ramsey

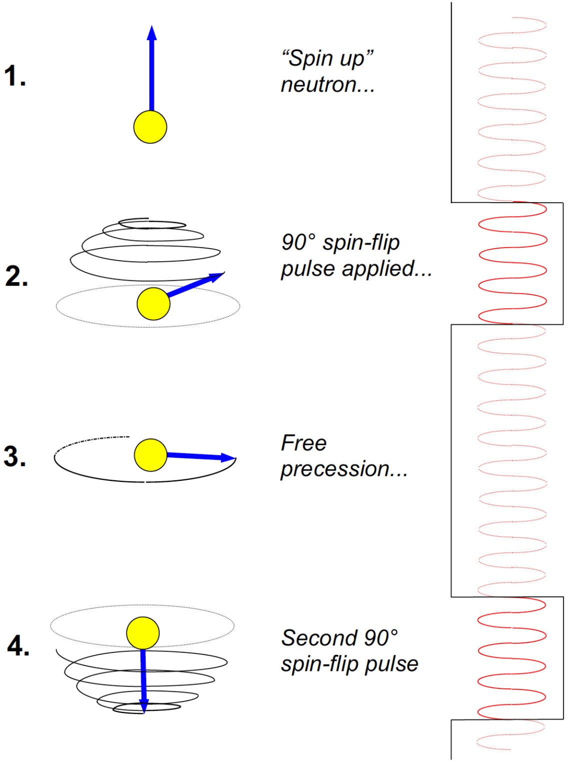
1.

2.

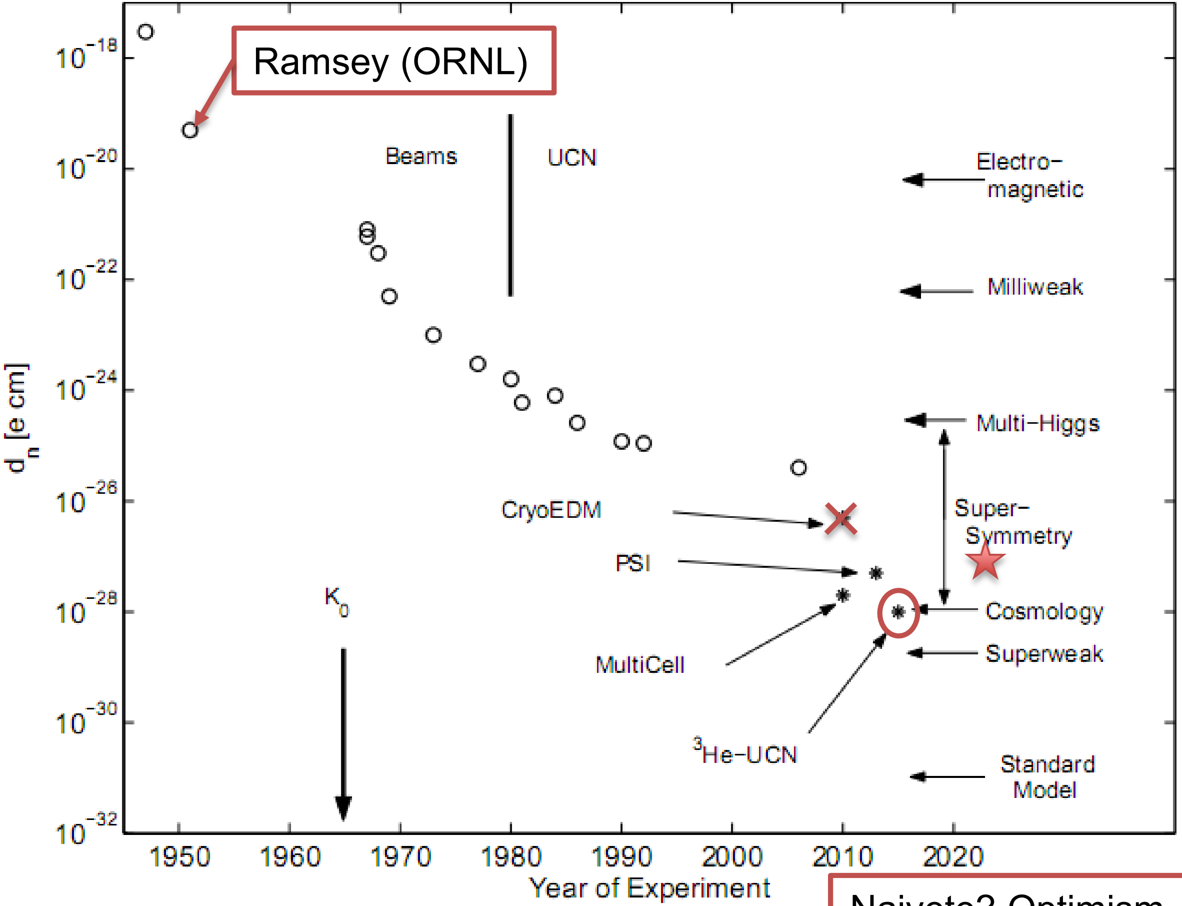
3.

4.





$$\delta d_n = \frac{\hbar}{2\alpha T E \sqrt{N}}$$



Naivete? Optimism.

Better Measurements Through Statistics

1. α: polarization*analyzing power
2. T: precession Time
3. E: Electric field strength
4. N: observed particle number

$$\delta d_n = \frac{\hbar}{2\alpha T E \sqrt{\mathbf{N}}}$$

Ultra-Cold Neutrons (UCN)

UCN?

- <300 neV
- Extremely slow neutrons
- $v < 8\,{}^{m}/{}_{s} \quad \lambda > 50\,nm$

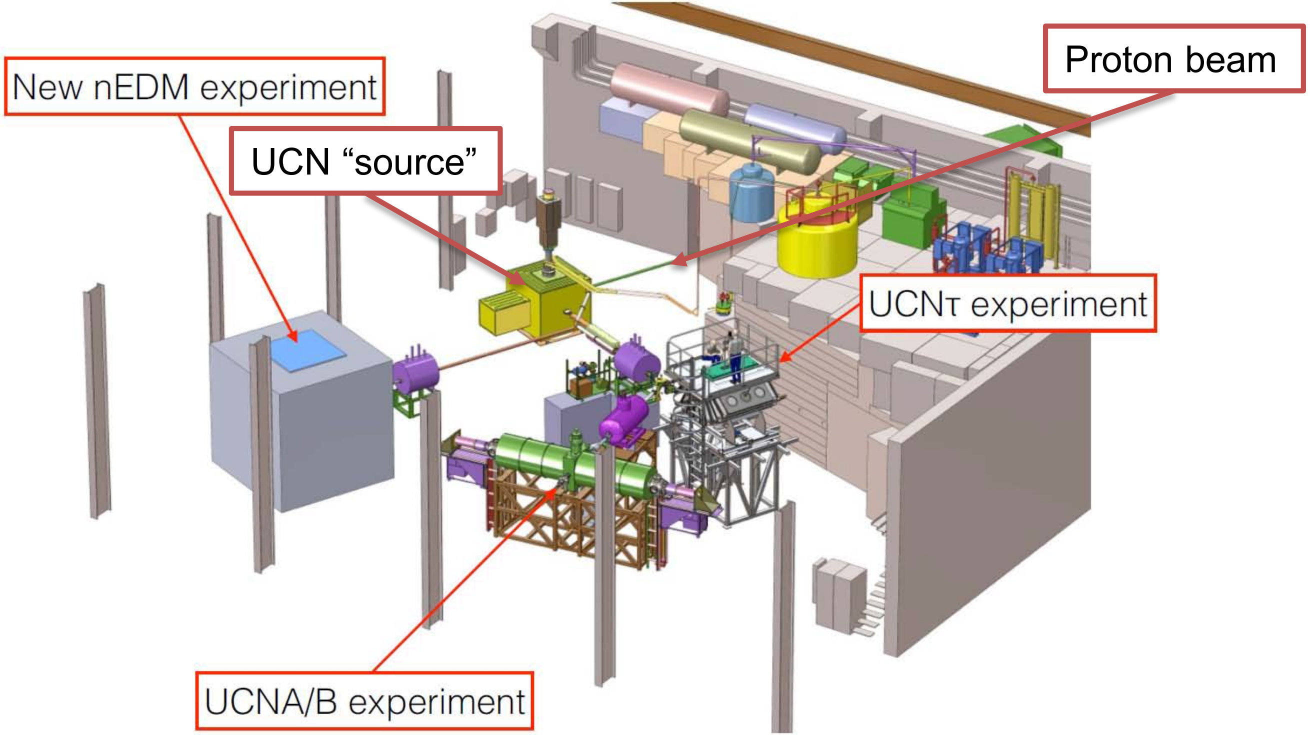
Neutron + Gravity: 102 neV/m

Neutron + Magnetism: 60 neV/T

Benefits?

- Long storage time (β limited)
- Low radiation background
- 100% polarization

Area B layout with the proposed nEDM Experiment



New nEDM experiment

UCN “source”

Proton beam

UCNτ experiment

UCNA/B experiment

Slide thanks to Takeyasu Ito

Systematics

Reducing v increases observation time and improves $B' \approx B - \frac{\vec{v}\times\vec{E}}{c^2}$

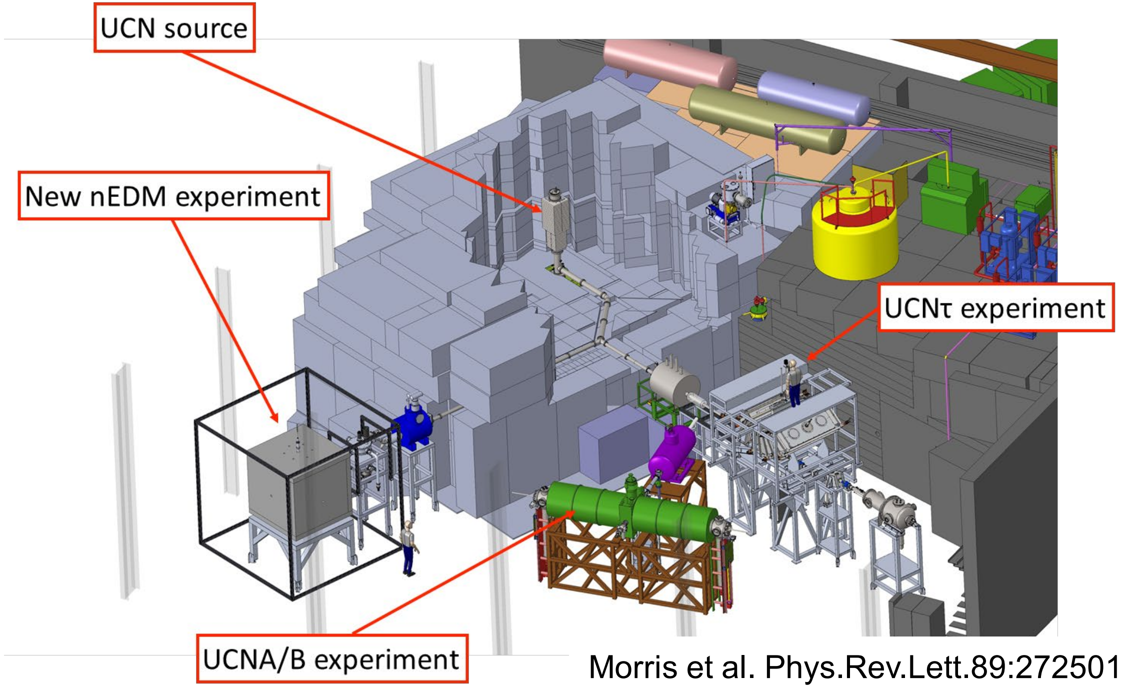
Bottled neutrons: $\langle v \rangle = 0 \quad \overset{?}{\Rightarrow} \quad \langle \vec{v} \times \vec{E} \rangle = 0$

Magnetic field gradients: $\nabla \cdot B = 0 \quad \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0$

Some math happens: $\delta\omega \propto E\,\frac{\partial B_z}{\partial z}$

$$\boxed{\delta\omega = \frac{4 d_n E}{h}}$$

UCN Physics at LANSCE



Source upgrade:
- Better moderator cooling
- NiP guides
- Optimized geometry

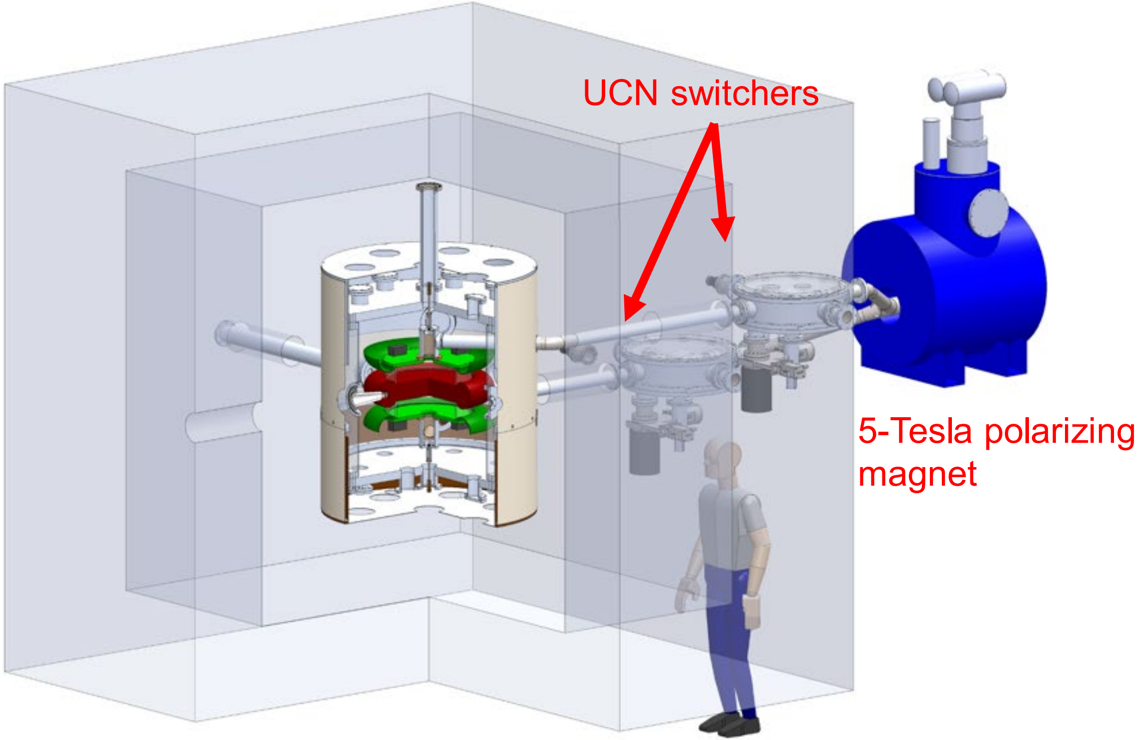
Morris et al. Phys.Rev.Lett.89:272501 (2002)
Saunders et al. RSI 84, 013304 (2013)
Ito et al., Phys. Rev. C 97, 012501 (2018)

nEDM@LANL

Design features:

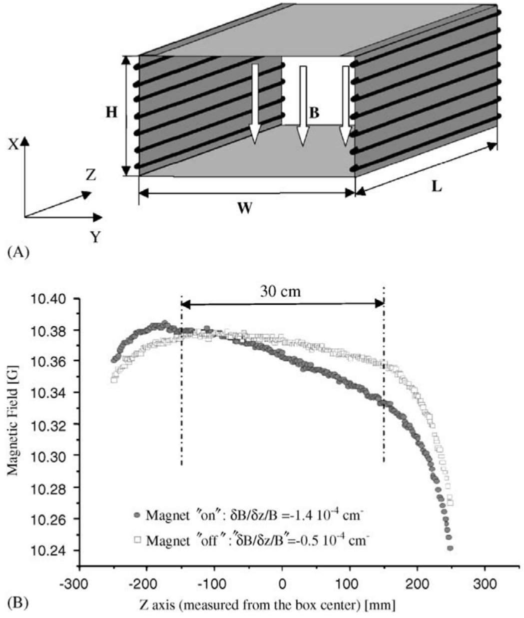
- Double cell
- Hg co-magnetometer
- Cs external magnetometers
- Magnetically shielded room
- Room temperature operation

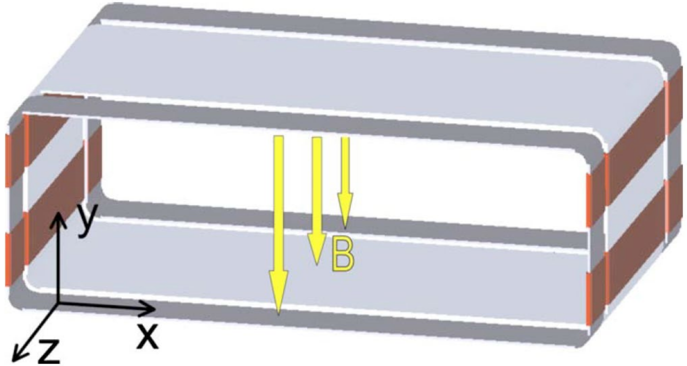
- Construction: 2018-2021



Slide thanks to Chen-Yu Liu

Flux Capacitors, aka Magic Boxes





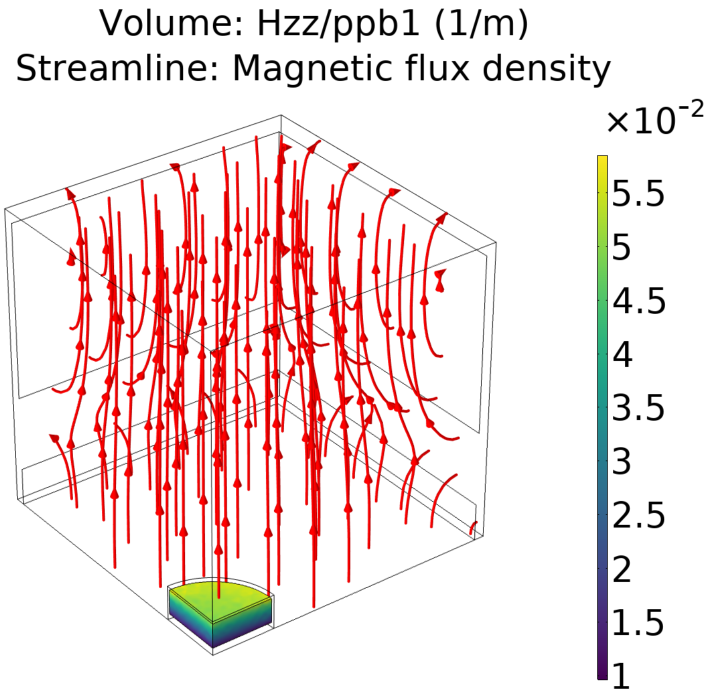
Left: Petoukhov et al. 2006
Above: McIver et al. 2009

Building better B fields

- For B ~ 10mG, ν = 30 Hz
- For E = 10kV/cm and d_n= $3\text{x}10^{-27}$ e·cm,
  δν = 30 nHz
- Part per Billion precision!
- Minimize $\frac{\mathrm{d}B_0}{\mathrm{d}t}, \frac{\partial B_z}{\partial z}$

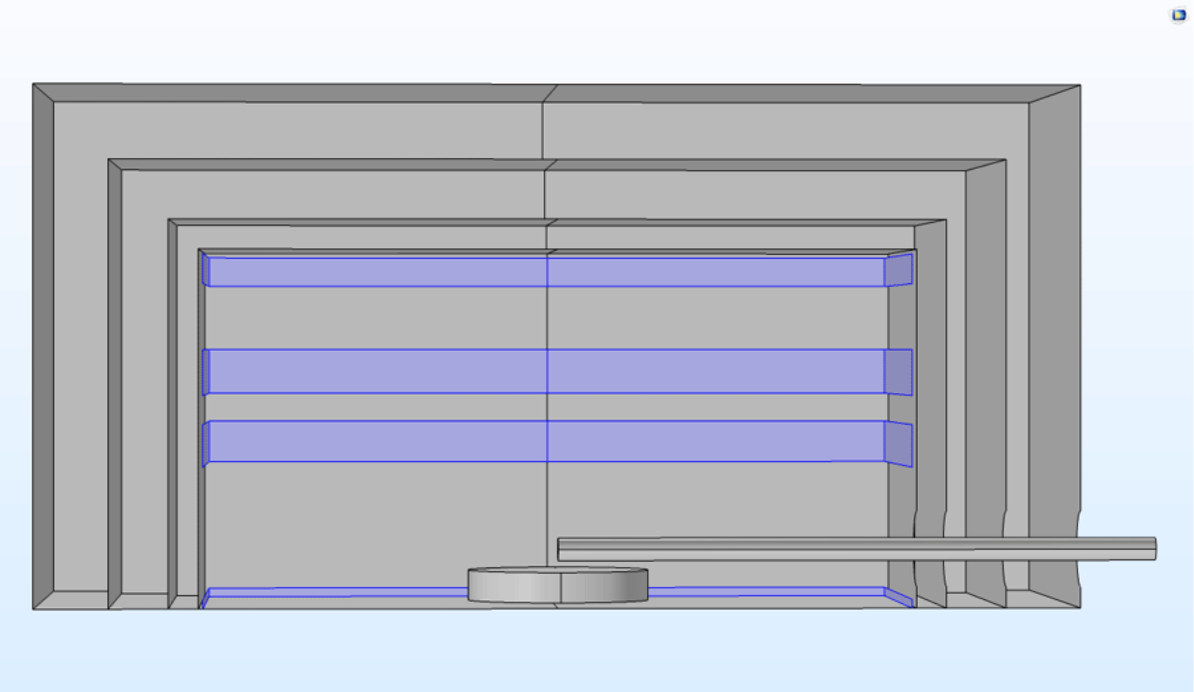
The Optimization Problem

1. Perfect Solenoid
2. Split Solenoid
3. Balanced Solenoid



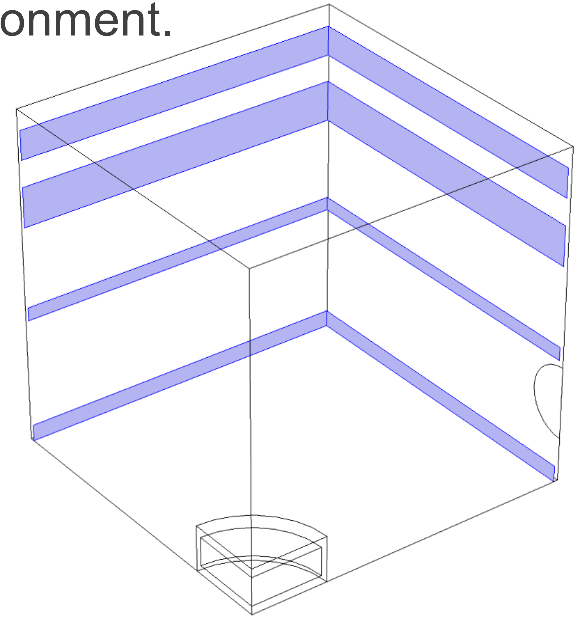
COMSOL Geometry

Cubic shells
3.5m Outer W
2.4m Inner W



The Optimization Problem

1. Assume inner shell is decoupled from external environment.
2. Innermost shell is soft MuMetal far from saturation
3. There are four large penetrations for guides
4. Current sheets are uniform and not intersecting
5. Minimize $\left\langle \frac{\partial_z B_z}{B_0} \right\rangle_V$ over the central 20 l volume

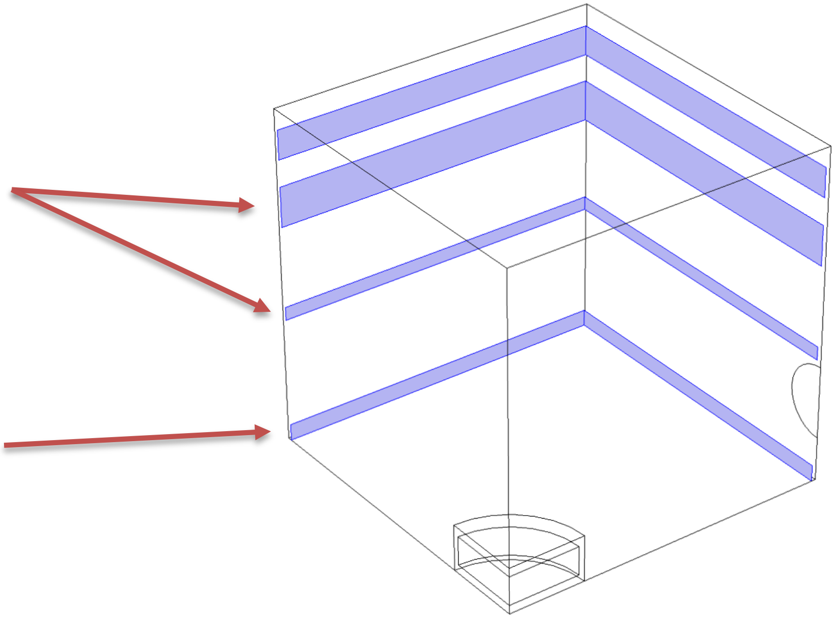


Optimization (in detail)

1. Unknown Bzz landscape
2. 8 free parameters
3. 4.5 min solve time

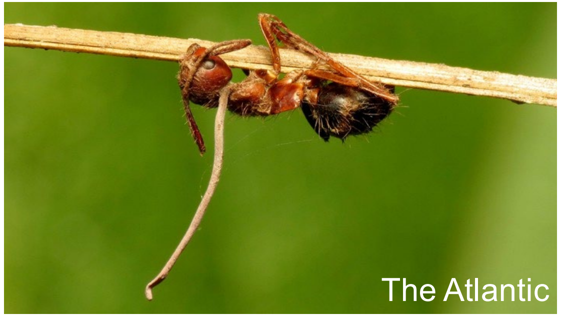
- Width
- Current
- Height

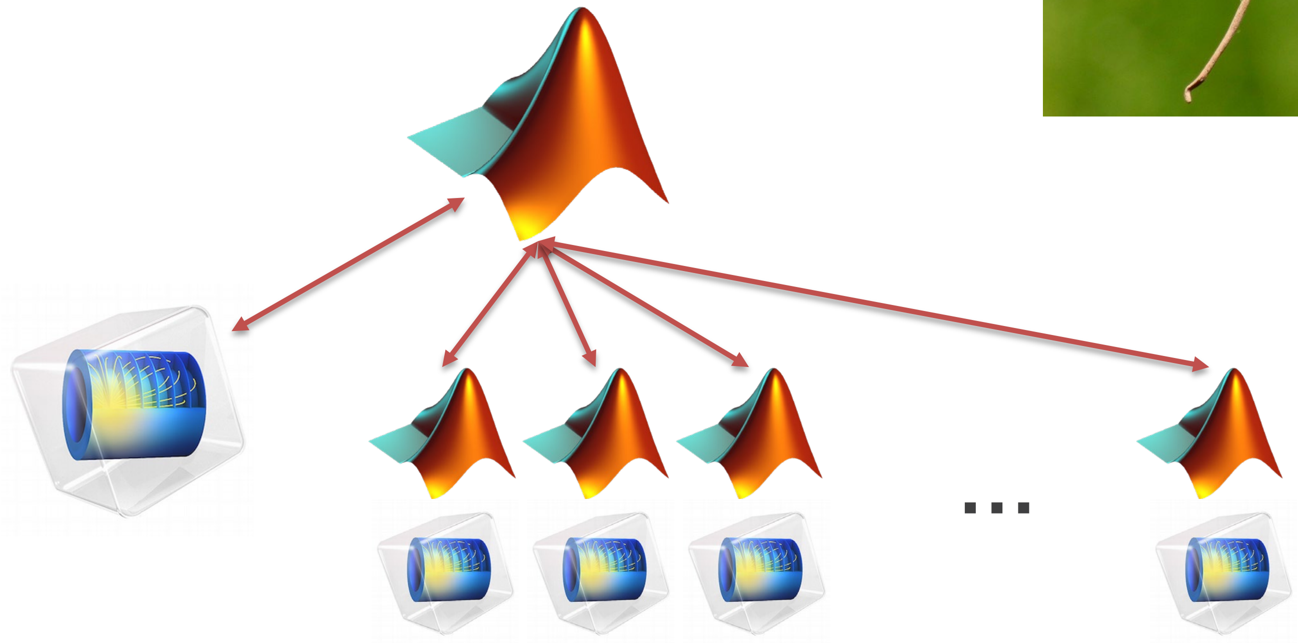
- Width
- Current



MATLAB <3 COMSOL

Think for yourself

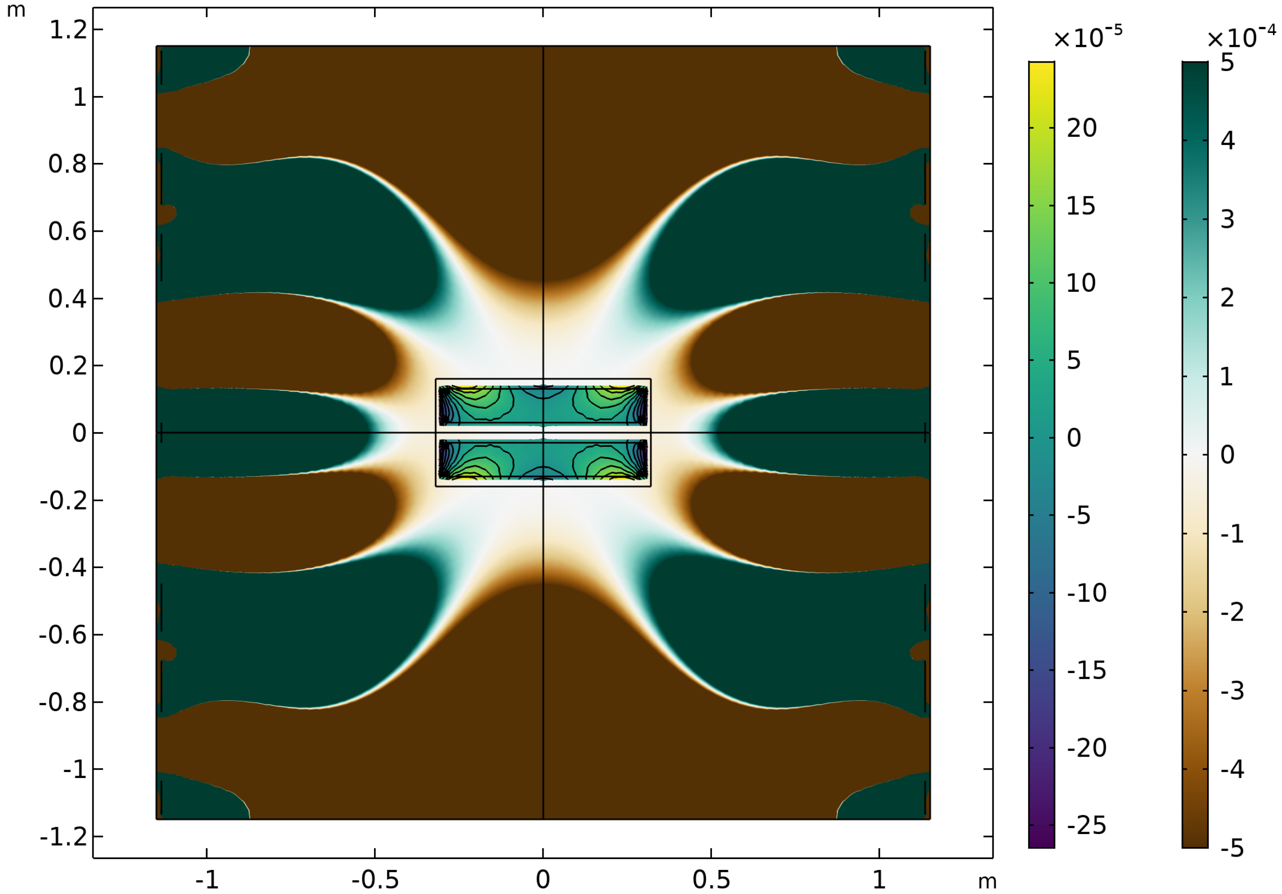

The Atlantic



Not zero, but close!

1. Precondition MATLAB parameters
2. 4 days for optimizer to converge
3. $\left\langle \frac{\partial_z B_z}{B_0} \right\rangle_V < 1.02 \times 10^{-4}$

Magic Box with guide holes: rms(Hzz)/<Hz> = 1.02E-4 Bulk: H/<Hz>
Cells: (dHz/dz)/<Hz> (1/m)



nEDM@LANL Collaboration

Los Alamos National Laboratory: S. Clayton, S. Currie, S. MacDonald, T. Ito, M. Makela, C. Morris, C. O'Shaughnessy, A. Saunders, A. Urbaitis

UCN source operation + precession cells + HV

IU is the lead institution of the MRI-consortium grant

Indiana University: C.-Y. Liu, J. Long, W. Snow, Y. Chen, A. Reid, D. Wong, J. VanderWerp, P. Smith

MSR requisition, spin analysis, slow control Hg co-magnetometer, He-3 magnetometer

University of Kentucky: A. Aleksandrova, J. Brewington, R. Dadisman, B. Plaster

Magnetic coils

University of Michigan: N. Sashdeva, T. Chupp

External magnetometry

Yale University: S. Lamoreaux

Hg co-magnetometer

Joint Institute of Nuclear Research: E. Sharapov

Caltech: C. Swank

East Tennessee State University: R. Pattie

DAQ, data storage

Tennessee Technol. University: A. Holley

Spin transport simulation

Mississippi State University: D. Dutta

NV diamond magnetometer

Chinese Spallation Neutron Source: T. Xin

He-3 magnetometer; Surface coating R&D

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Thank you! Questions?

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FULFILLING *the* PROMISE