A New Search on the Neutron Electric Dipole Moment (nEDM)

Physics Colloquium
University of Virginia
April 6, 2007

Haiyan Gao
Department of Physics and The Triangle Universities Nuclear Laboratory
Duke University

Outline

- Introduction
- Existing measurements
- A new search for neutron EDM
- Summary

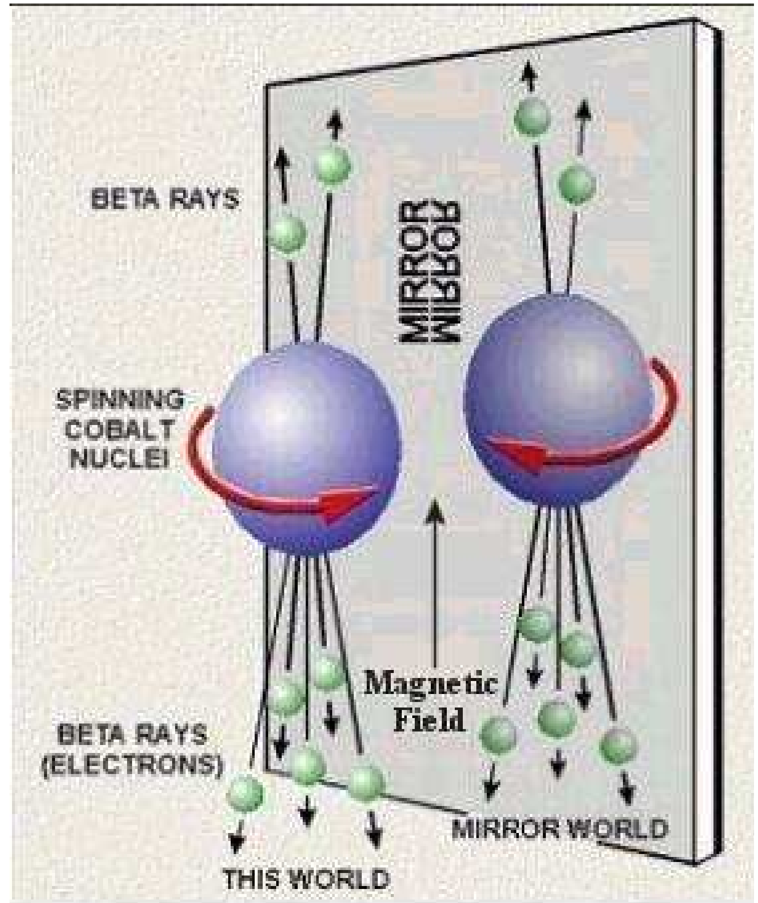
Parity-violation in weak interaction (1956)

Parity-transformation (P) : $\vec{r} \to -\vec{r}$

T. D. Lee

C. N. Yang

October 1, 1956 issue of the Physical Review



$$^{60}\vec{C}o \rightarrow {}^{60}Ni + e^{-} + \overline{\nu}_e$$

C.S. Wu, et al.
Garwin, Lederman and Weinrich
Telegdi

C: charge conjugation symmetry: particle $\rightarrow$ anti-particle

CP Violation in weak interactions

In 1964, Christenson, Cronin, Fitch and Turlay discovered at BNL that the long-lived neutral K meson with CP=-1 could decay occasionally to $\pi^+\pi^-$ with CP=+1 about once every 500 decays

$$K^o{}_L \rightarrow \pi^+\pi^-\pi^o \qquad K^o{}_L \rightarrow \pi^+\pi^-$$

CP=-1 CP=+1 0.2%

- CP violations in nuclear systems
- More CP violations in experiments:

B meson decays, SLAC and KEK

CP violation in Standard Model

– The CKM matrix: the ***complex phase*** of CKM matrix leads to CP violation

$$\Rightarrow \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \hat{V}_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \Leftarrow$$

Weak eigenstates

Mass eigenstates

For n generations:

n(n-1)/2	***angles***	***3***
(n-1)(n-2)/2	***phases***	***1***

Strong CP problem

- The strong CP problem in the Standard Model
  - The θ term in QCD Lagrangian

$$L_{QCD} = G_{\mu\nu}G^{\mu\nu} + \sum_k \bar{q}_k \gamma^\mu [\partial_\mu - igA_\mu^\alpha t_\alpha] q_k - \sum_k m_k \bar{q}_k q_k$$

$$L_{eff} = L_{QCD} + \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \tilde{G}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\kappa\lambda}G_{\kappa\lambda}$$

- Current algebra: d_n behaves like $\theta\ (m_\pi)^2 \ln\ (m_\pi)^2$

By E. Witten

d_n Neutron EDM

$$d_n \approx 1.2\times 10^{-16}\theta\ e\bullet cm \qquad \theta < 10^{-10}$$

QCD sum rule, Pospelov and Ritz, Phys. Rev. Lett. 83, 2526 (1999)

CPT Invariance

CPT is a good symmetry in a local field theory which is Lorentz invariant and has a hermitian Lagrangian

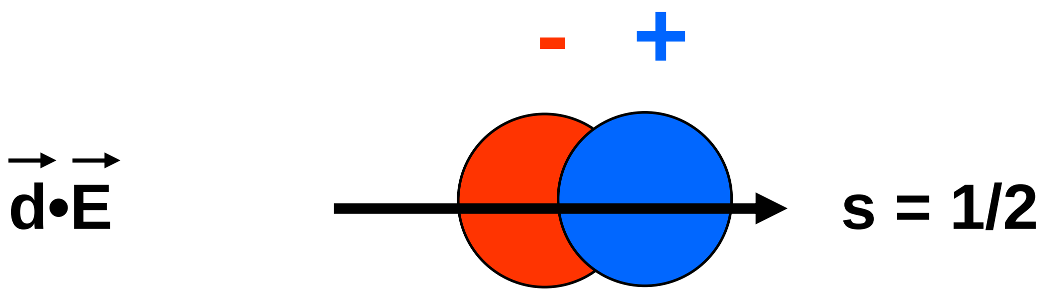
– CP violation thus implies ***time-reversal symmetry T*** violation

– Direct search for ***T violation*** is important!

- CPLEAR: semi-leptonic decay of neutral kaons
- KTev experiment $K_L \to \pi^+\pi^- e^+ e^-$
- Neutron electric dipole moment (nEDM)

T: time reversal symmetry: T -> -T

Neutron Electric Dipole Moment (EDM)



- If neutron possesses EDM, in an electric field, Hamiltonian $H = -d_n \vec{\sigma} \bullet \vec{E}$
  - changes sign under T (P) symmetry operation
- d_n is more sensitive to θ than it is to δ_{CKM}

Current algebra: $\theta\ (m_\pi)^2 \ln\ (m_\pi)^2$

By E. Witten

Predictions for Neutron EDM

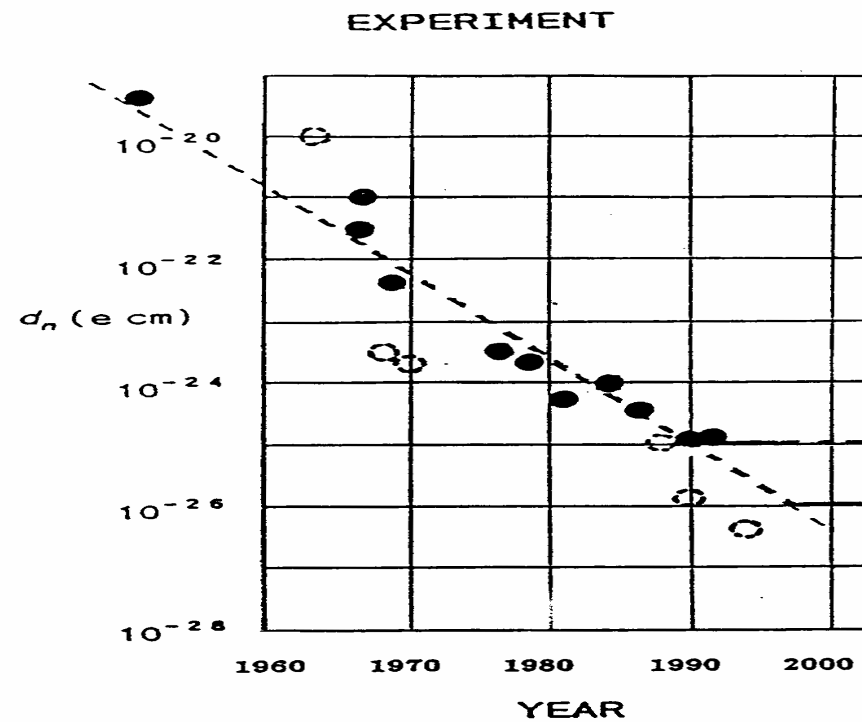
- SM: $d_n \approx 10^{-31} e \cdot cm$
  - Renormalization of QCD vacuum parameter arising from CP violation in weak interaction (CKM)
  - Strong CP: $\theta\ (m_\pi)^2 \ln\ (m_\pi)^2$
- Left-right symmetric gauge models:

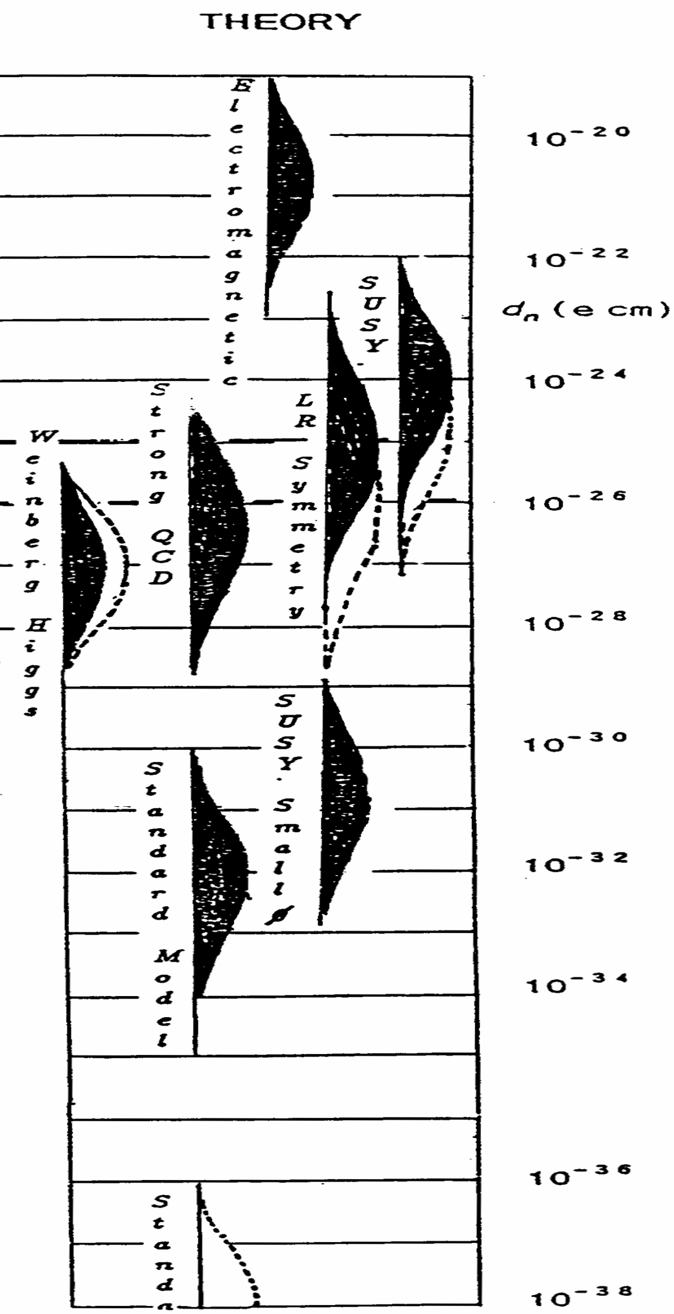
$$d_n \approx 10^{-27} e \cdot cm$$

- Non-minimal Higgs models:
  - CP odd gluonic operators inducing:

$$d_n \approx 10^{-27} e \cdot cm$$

- Supersymmetry (SUSY) models

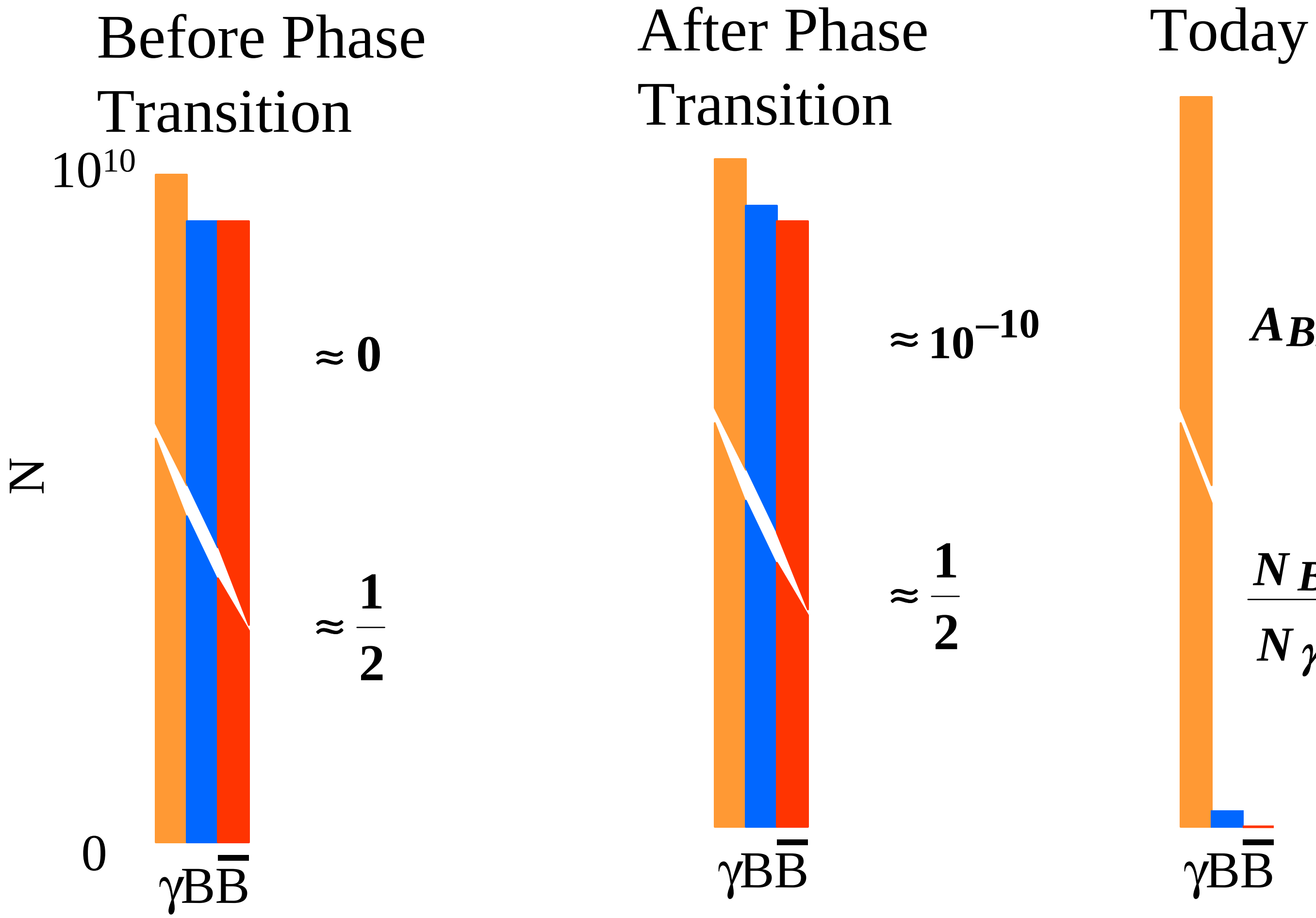




REVIEW OF PARTICLE ELECTRIC DIPOLE MOMENTS

J. Mike Pendlebury

$\bar{B}$-B *ASYMMETRY IN THE UNIVERSE*



$$A_{B\bar{B}} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 1$$

$$\frac{N_B}{N_\gamma} \approx 10^{-10}$$

CP Violation and Cosmology

- Baryon asymmetry of the universe (BAU)
- $$\frac{\Delta n_{bar}}{n_\gamma} = \frac{n_{bar(today)}}{n_\gamma} = (4-7)\times 10^{-10}$$
- To explain BAU, substantial New Physics in the CP violating sector is required
- Neutron EDM may play an important role in quantifying New Physics
- New source of CP beyond SM may have significant impact on our understanding of baryongenesis

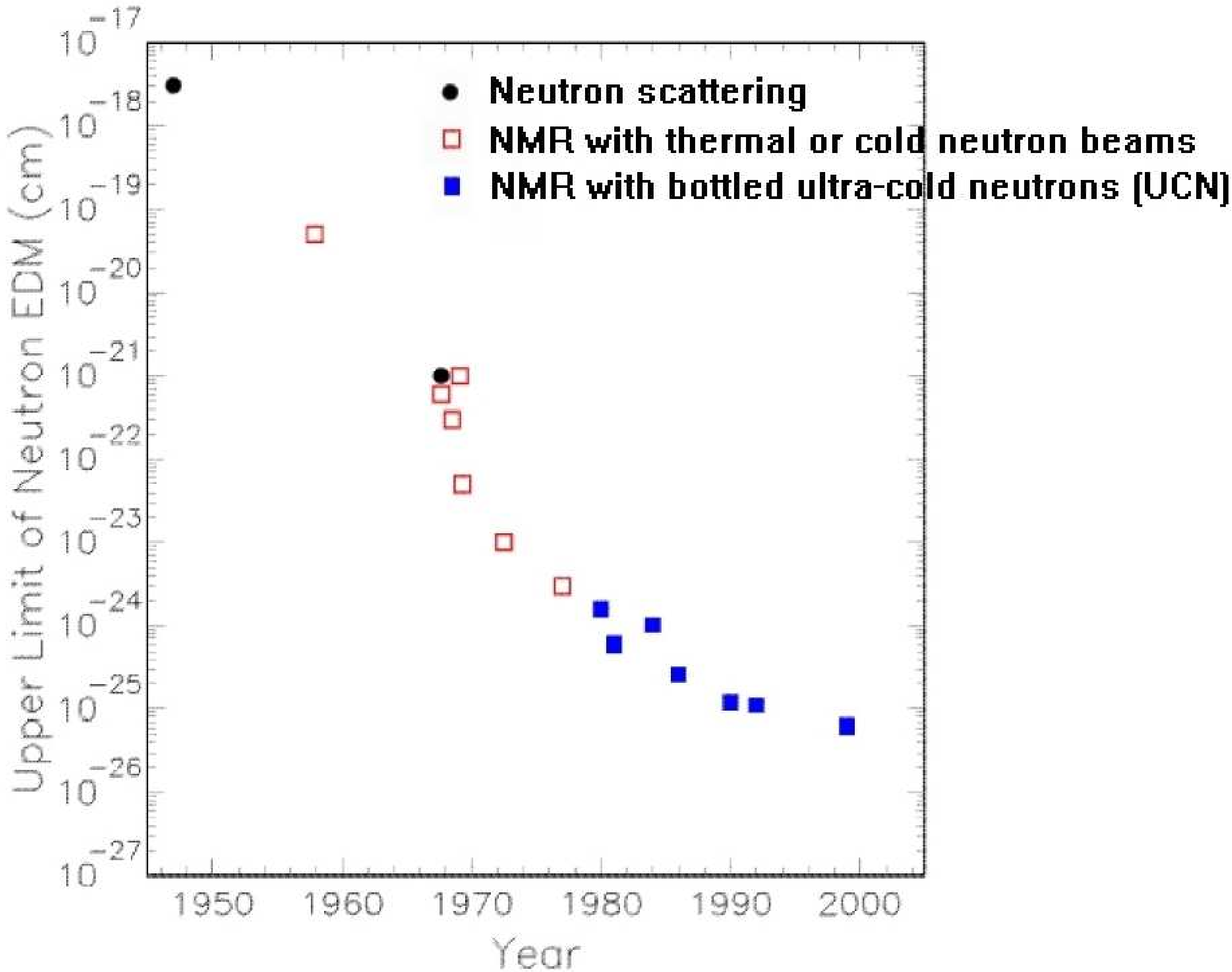
Seminar paper by A. Sakharov (1967) on calculating BAU

Existing Measurements of d_n

Experimental techniques:

- ***Neutron scattering***
  - ***Interference between neutron-nucleus and neutron-electron***
- ***Magnetic resonance technique***
  - ***thermal or cold neutron beams***
  - ***bottled ultra-cold neutrons (UCN)***

Ref: R. Golub and S. K. Lamoreaux, Phys. Report 237, 1-62 (1994)



1950, Smith, Purcell and Ramsey determined for the first time $d_n \leq 3\times10^{-18} e\cdot cm$

Current limit: $d_n < 3.0\times10^{-26} e\cdot cm$ (2006)

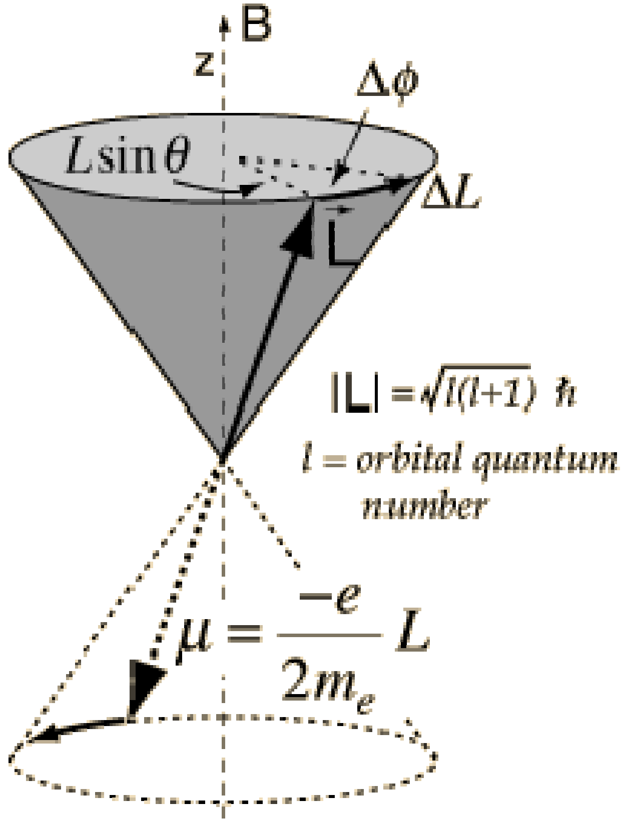
Experimental limits on the EDM of fundamental particles

Particle	Experimental EDM Value / Limit [2] ($e\cdot$cm)
Electron, e	$0.18 \pm 0.12 \pm 0.10 \times 10^{-26}$
Neutron, n	$< 0.63 \times 10^{-25}$ [90% C.L.]
Proton, p	$-3.7 \pm 6.3 \times 10^{-23}$
Lambda Hyperon, Λ	$< 1.5 \times 10^{-16}$ [95% C.L.]
Tau Neutrino, ν_τ	$< 5.2 \times 10^{-17}$ [95% C.L.]
Muon, μ	$3.7 \pm 3.4 \times 10^{-19}$
Tau, τ	$< 3.1 \times 10^{-16}$ [95% C.L.]

Current best limit on neutron EDM is from ILL reactor at Grenoble Hep-ex/0602020, published in Phys. Rev. Lett.

nEDM $< 3.0 \times 10^{-26}$ e•cm [90 % C.L.]

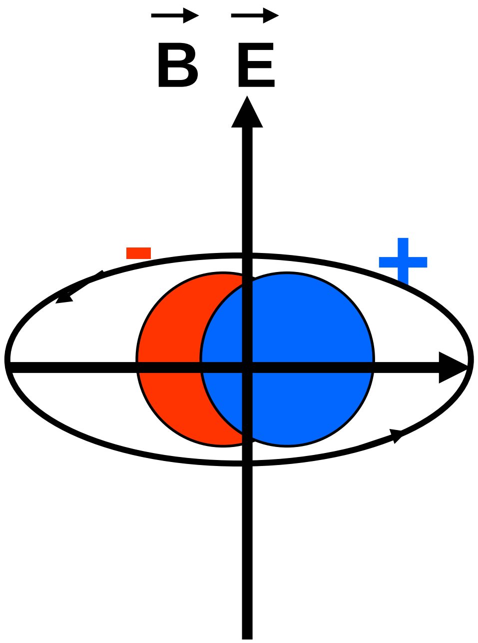
Larmor Spin Precession



$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

- The torque exerted causing the magnetic moment to precess around the direction of the B field

Magnetic Resonance Technique



Look for a precession frequency ω_d

s = 1/2 dipole moment d_n

$$\nu_n = -[2\mu_n B_0 \pm 2d_n E_0]/h = \nu_0 \pm (\Delta\nu/2)$$

$$\Delta\nu = -4d_n E_0/h$$

•A strong static electric field applied parallel (anti-parallel) to the magnetic field causes a shift in the Larmor freq.

Frequency Measurement

- Neutron spin aligned perpendicular to a static magnetic field
- The frequency shifts as the direction of E is reversed is ***from parallel to B to antiparallel to B***:

$$\Delta\nu = -4 d_n E_o / h$$

$$\begin{cases} B_0 = 10mG \\ E_0 = 0 \end{cases} \rightarrow \nu_0 = 29.2Hz$$

$$\begin{cases} E_0 = 50kV/cm \\ d_n = 4\times10^{-27} e\cdot cm \end{cases} \rightarrow \Delta\nu = 0.19\mu Hz = 0.66\times10^{-8}\nu_0$$

A new nEDM Experiment

(Spokespersons: S. K. Lamoreaux, M. Cooper)

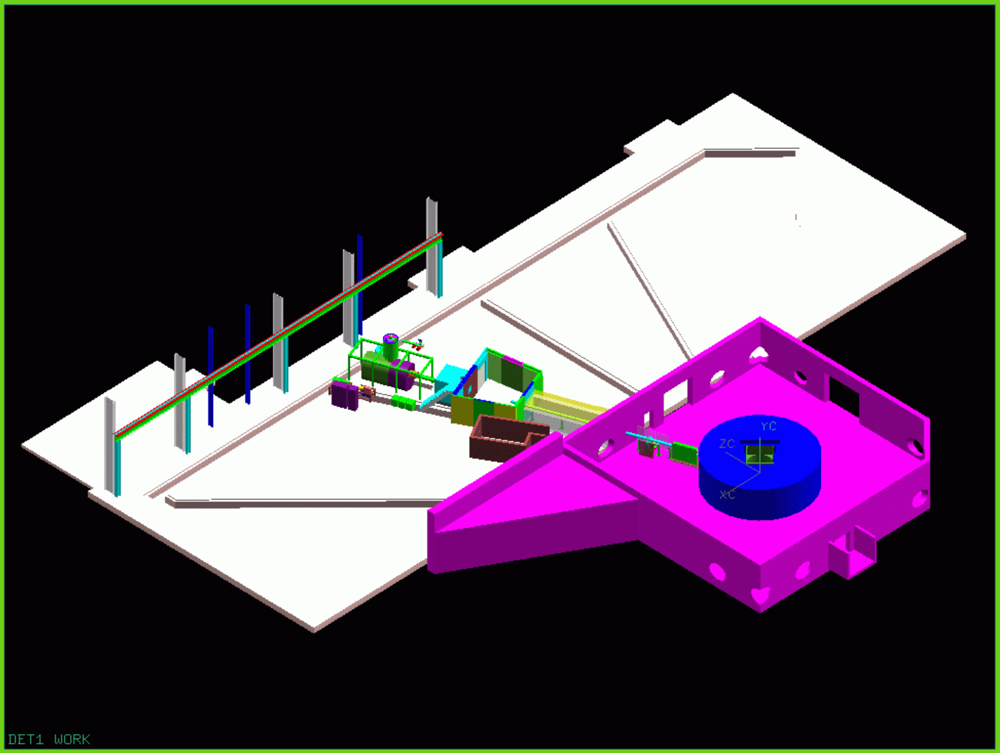


Figure of Merit for EDM Experiments ~ $E\sqrt{N\tau}$

E $\rightarrow$ 5E $\tau \rightarrow 5\tau$ N $\rightarrow$ 250 N $\rightarrow$ 175 Compared to ILL experiment

Production of Ultracold Polarized Neutrons

- Closed neutron trap filled with ultra-pure superfluid ^{4}He cooled to ~ 400 mK
- Placed in a beam of cold neutron (E=1 meV), polarized (~100%) using two total reflecting magnetic supermirror surfaces
- Neutrons interacting with the superfluid are downscattered to $E < 0.13 \mu eV, V < 5 m/s$ with a recoil phonon in the superfluid carrying away the missing energy and momentum ***(Golub, Pendelbury, 1975)***
- ***Technique has been demonstrated at a number of laboratories (France, Japan, US)***

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

How to measure the UCN Precession Frequency?

In the trap volume:

$$N_{UCN} = 2.5 \times 10^5,$$

$$N_{^3He} = 2 \times 10^{15}, \qquad \Leftarrow ?$$

$$N_{^4He} = 2.2 \times 10^{25}$$

atoms per liter of cell volume

Overview of the Experiment

– A three-component fluid of neutrons, ^{3}He atoms in a bath of superfluid ^{4}He at 300 mK
– Neutron and ^{3}He magnetic dipoles precess in a plane perpendicular to the external magnetic field
– Precision measurement of the freq.difference in the ^{3}He and neutron precession frequency modified when strong E field is turned on (or reversed) --> neutron EDM

Measurement of the UCN Precession Frequency

- UCN precession frequency beat against the ^{3}He precession frequency
- Spin dependence of the nuclear interaction cross-section:

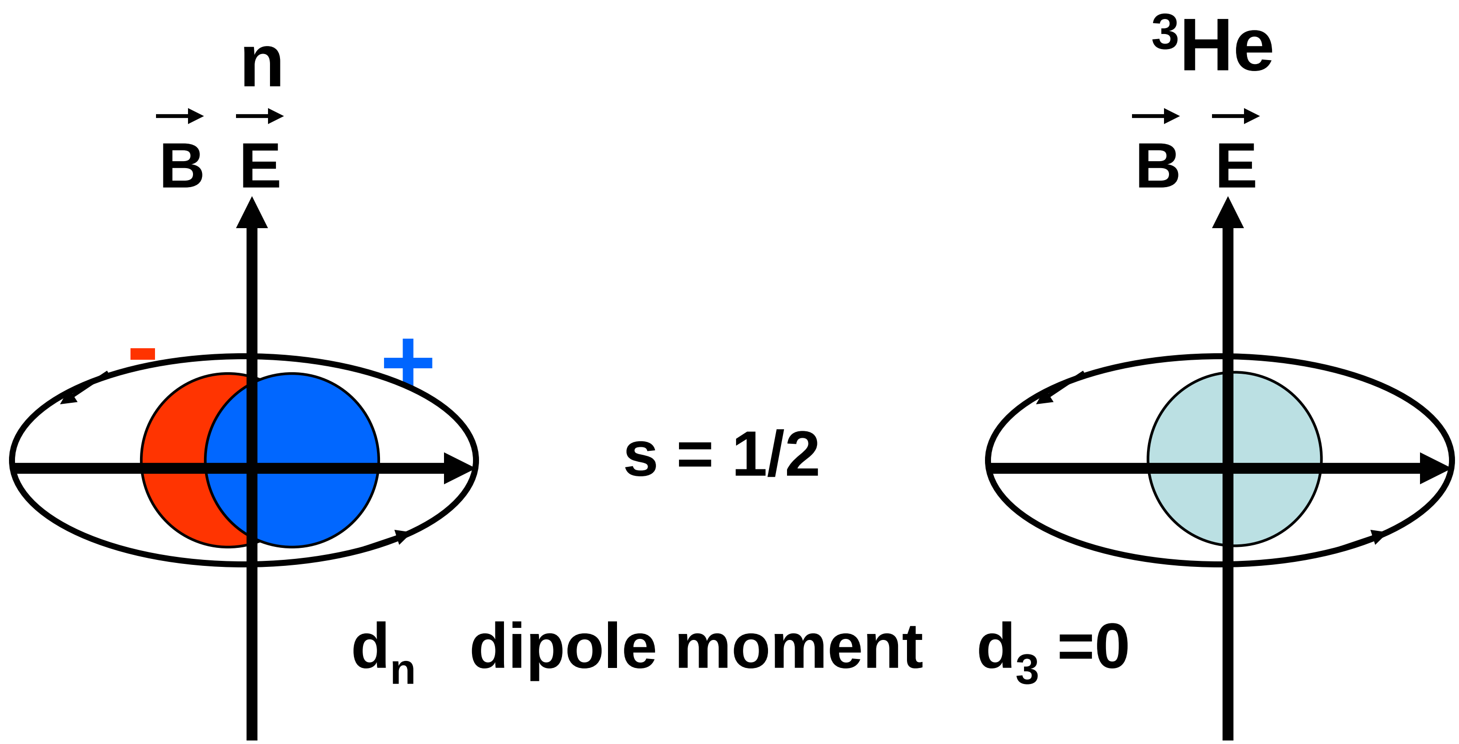
$$\vec{n} + {}^3\vec{H}e \rightarrow p + t + 772keV$$

- Scintillation light from nuclear reaction products (and beta decay products) (80 nm) can be wave-length shifted (440 nm) and detected

$$\vec{n} + {}^3He \rightarrow p + t + 772keV$$

Spin State	Cross Section (barns) (v=2200 m/sec)	Cross Section (barns) (v=5 m/sec)
J=0	$\sim 1.1 \times 10^{+4}$	$\sim 4.8 \times 10^{+6}$
J=1	~ 0	~ 0

^{3}He MAGNETOMETRY



Look for a difference in precession frequency ω_n - $\omega_3 \pm \omega_d$ dependent on E and corrected for temporal changes in ω_3

UCN Precession Frequency

The time dependent, velocity independent loss rate

$$\Phi(t) = \frac{N_o}{\tau_{abs}}[1 - \vec{P}_3 \bullet \vec{P}_n]e^{-\lambda t}$$

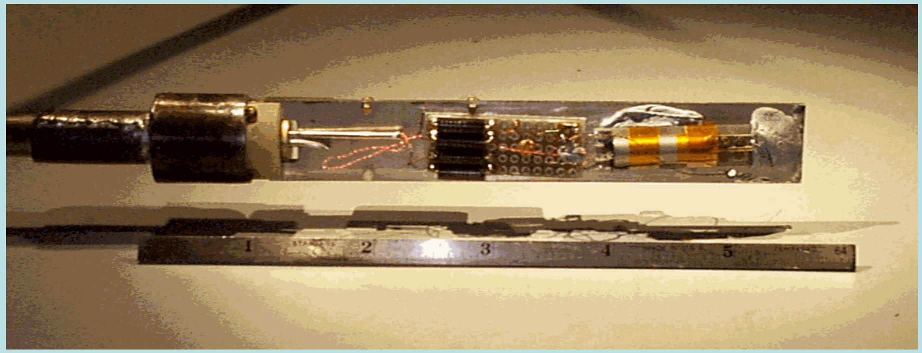
$$= \frac{N_o}{\tau_{abs}}\{1 - p_3 p_n \cos[(\gamma_{^3he} - \gamma_n)Bt + 2d_n Et]\}e^{-\lambda t}$$

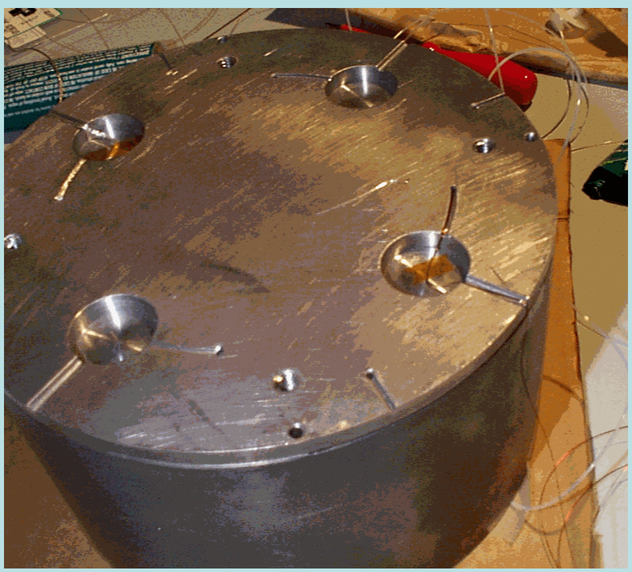
SQUIDs

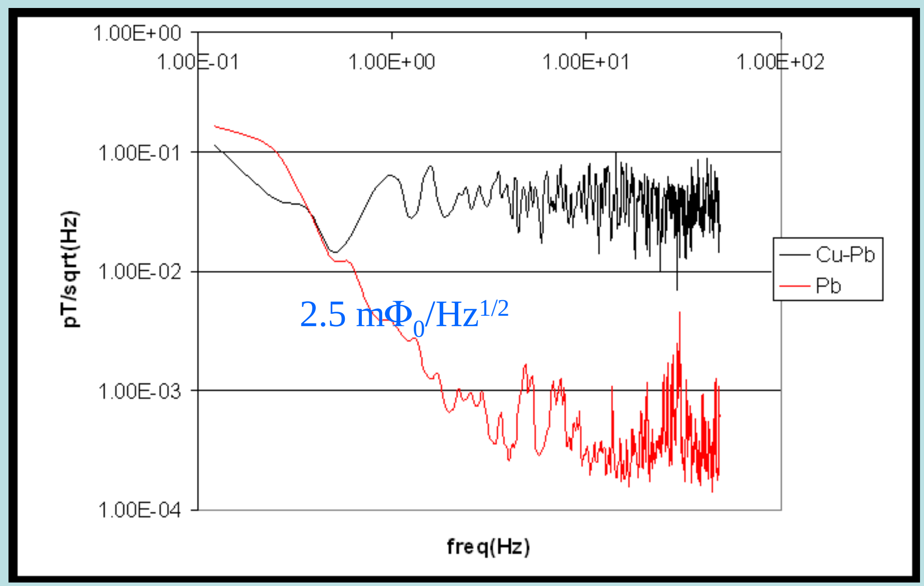
M. Espy, A. Matlachov

~100 cm^2 superconducting pickup coil

Flux = 2×10^{-16} Tm^2 = $0.1\ \Phi_0$ Noise = $4\ m\Phi_0/Hz^{1/2}$ at 10 Hz ~ $T^{1/2}$

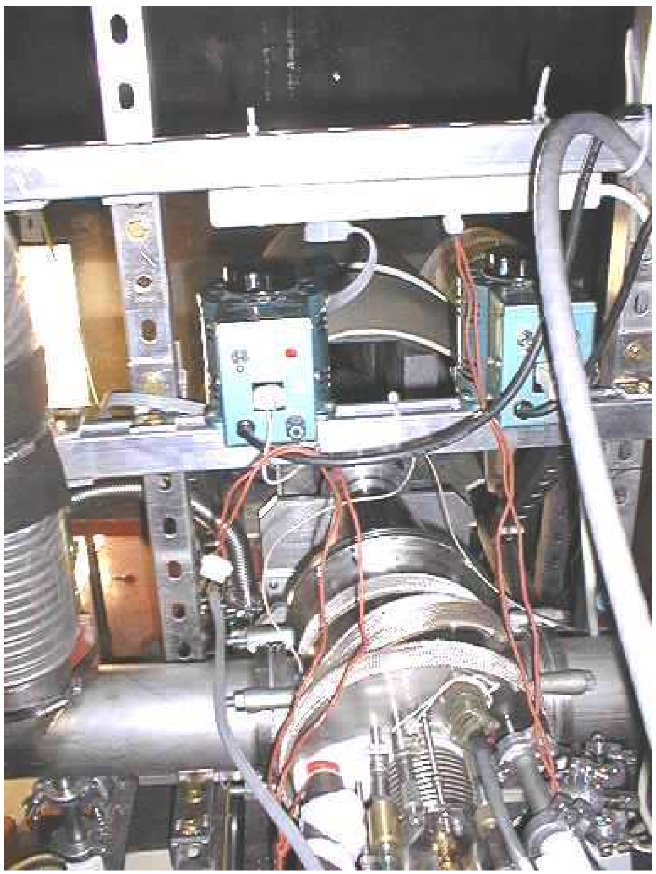


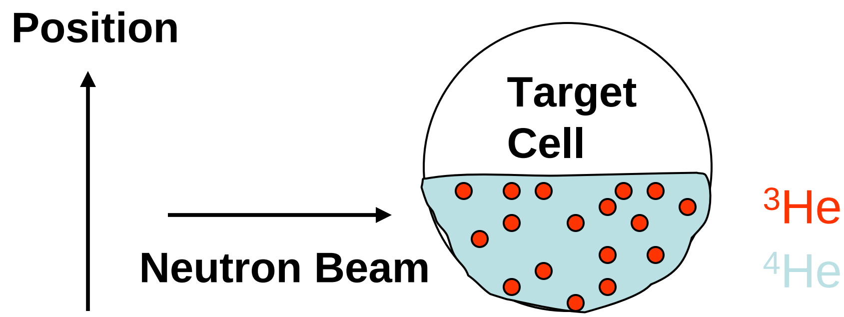


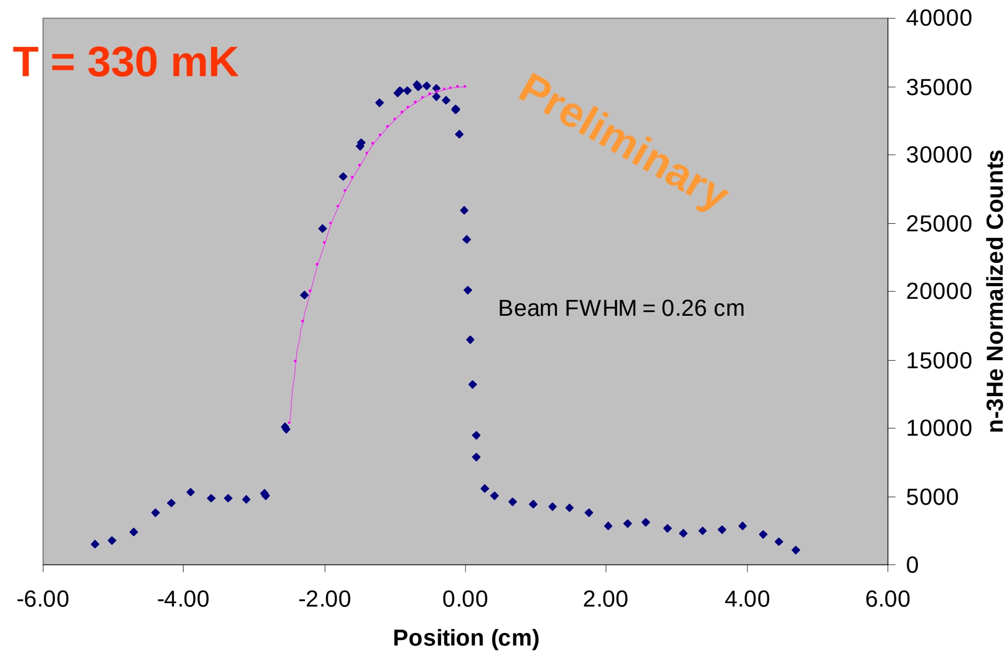


^{3}He Distributions in Superfluid ^{4}He

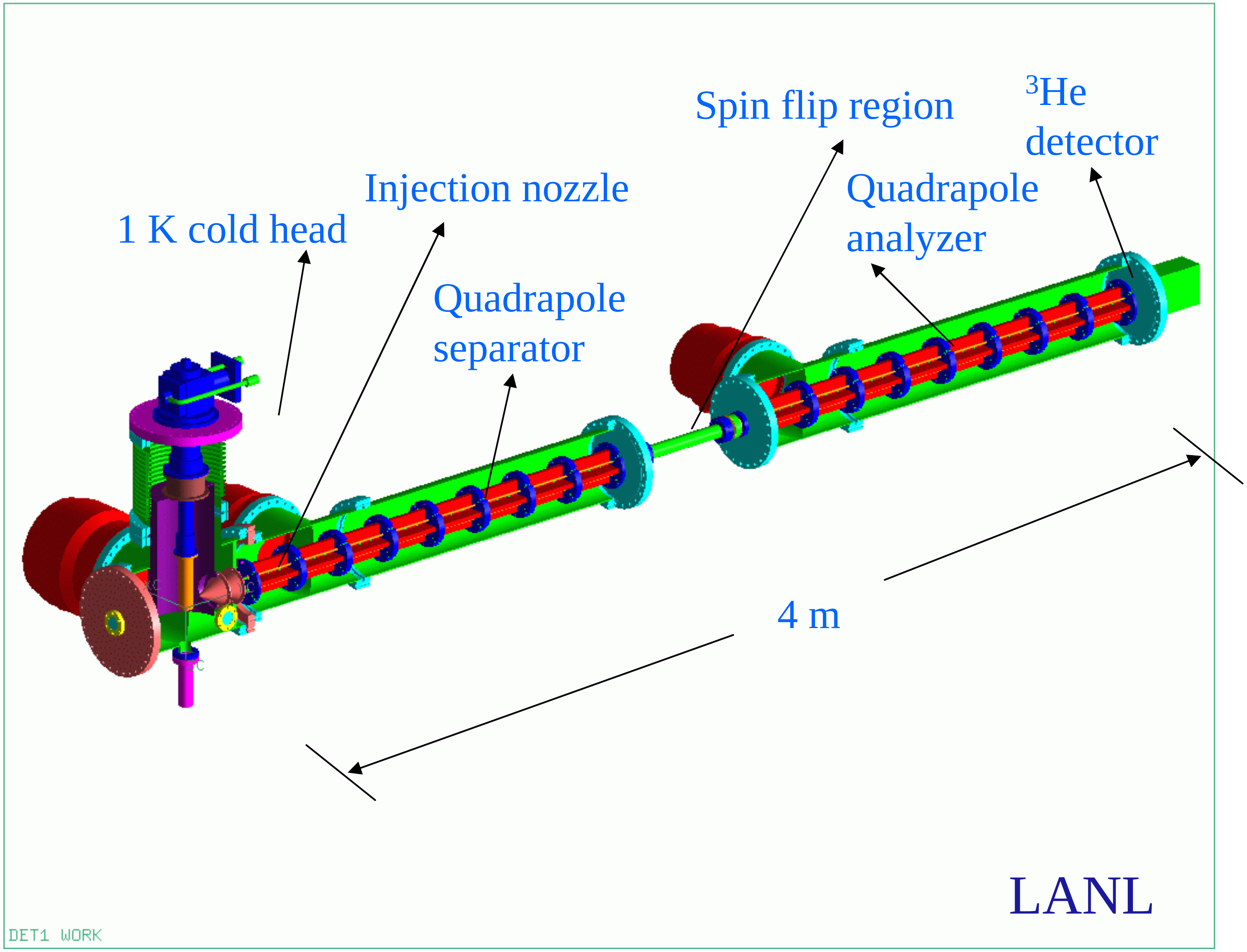
Dilution Refrigerator at LANSCE Flight Path 11a



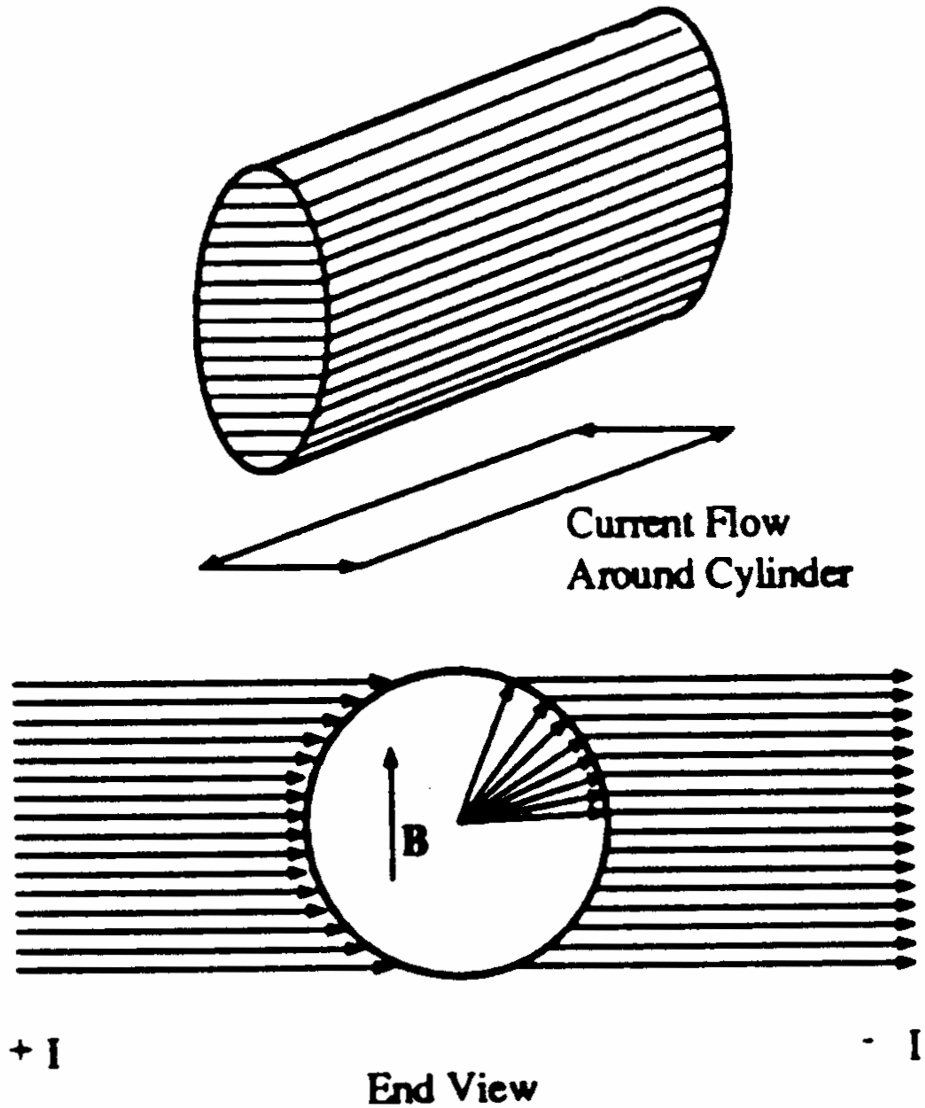




POLARIZED ^{3}He SOURCE



COSθ COIL

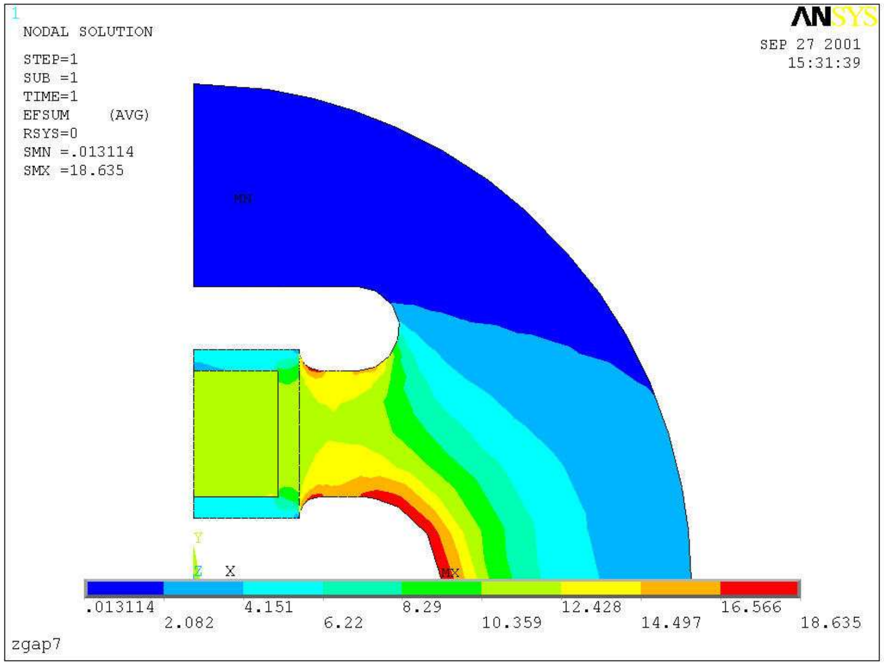


Caltech and others

ELECTRIC FIELD

Ground plate	25 x 75 x 5 cm
HV plate	30 x 80 x 10 cm
Ground shell coil	30 cm radius

designed goal of 50 kV/cm

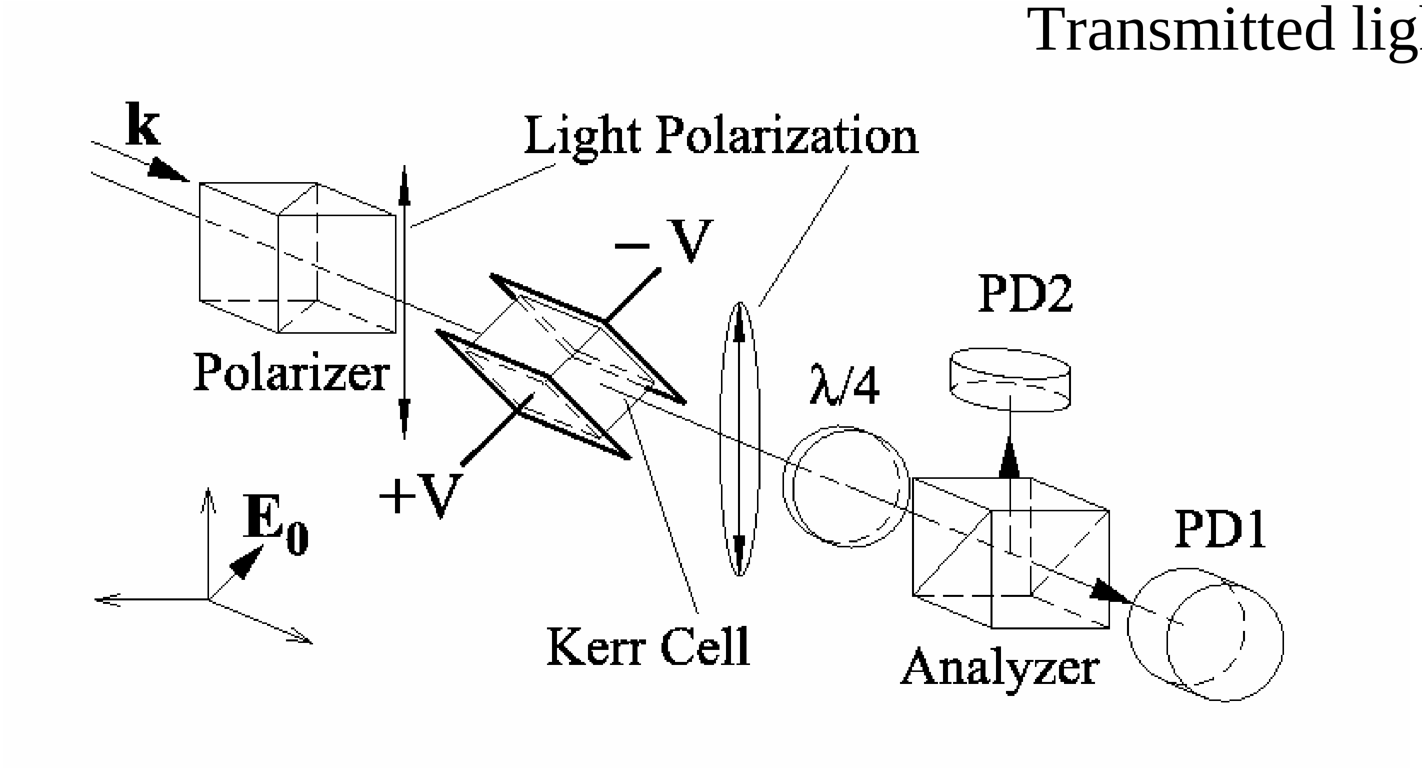


- Uniformity in cell:
  0.1% without side walls
  1% with recess
- Peak E field is ~1.5 of value in cell
- Next step - 3D model
- Cell 7.5 x 10 x 50 cm and 1.3 cm walls

LANL, IUCF

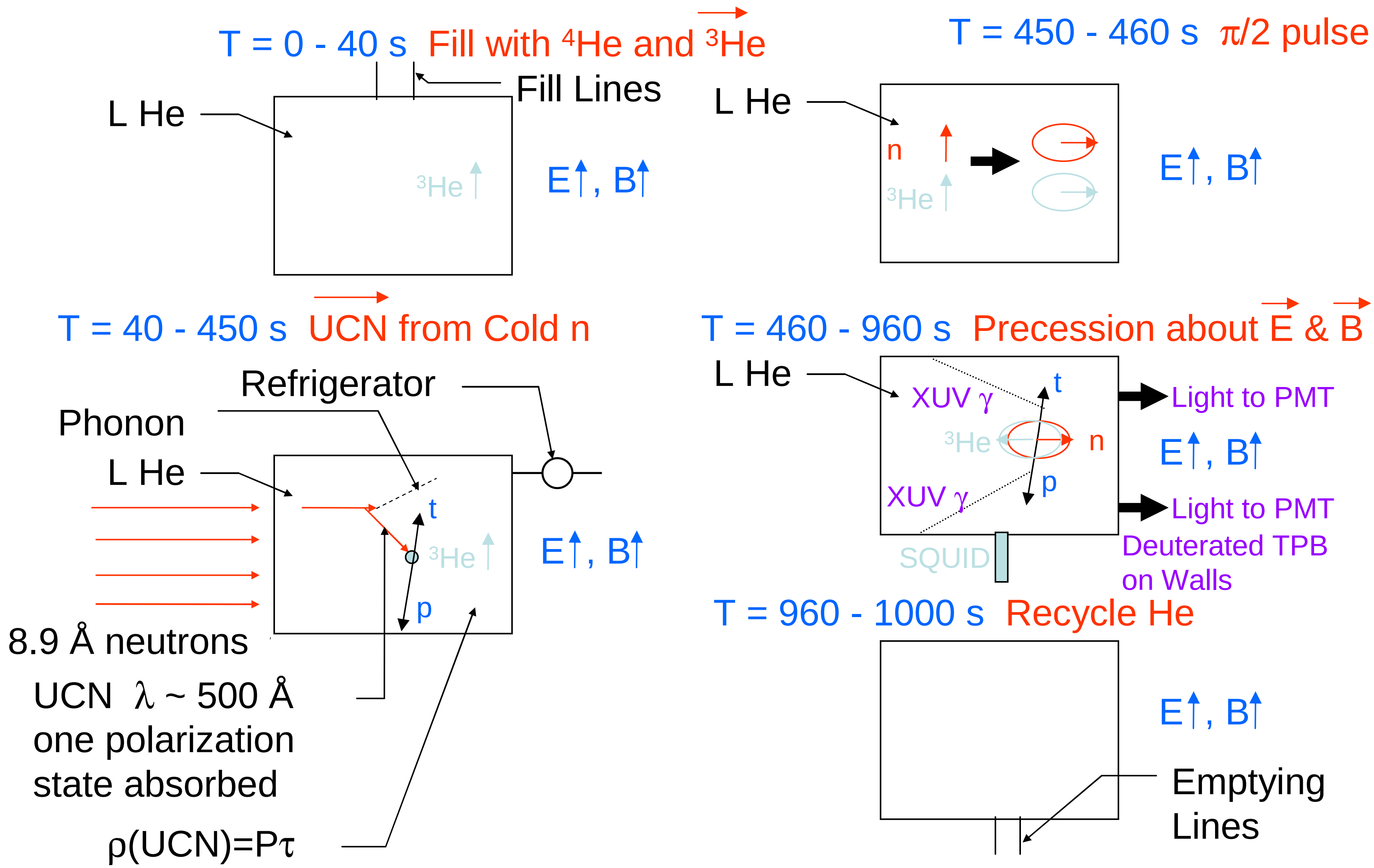
ELECTRIC FIELD MEASUREMENT

Kerr Effect $\varepsilon = \pi K l E_0^2$ ellipticity of Transmitted light

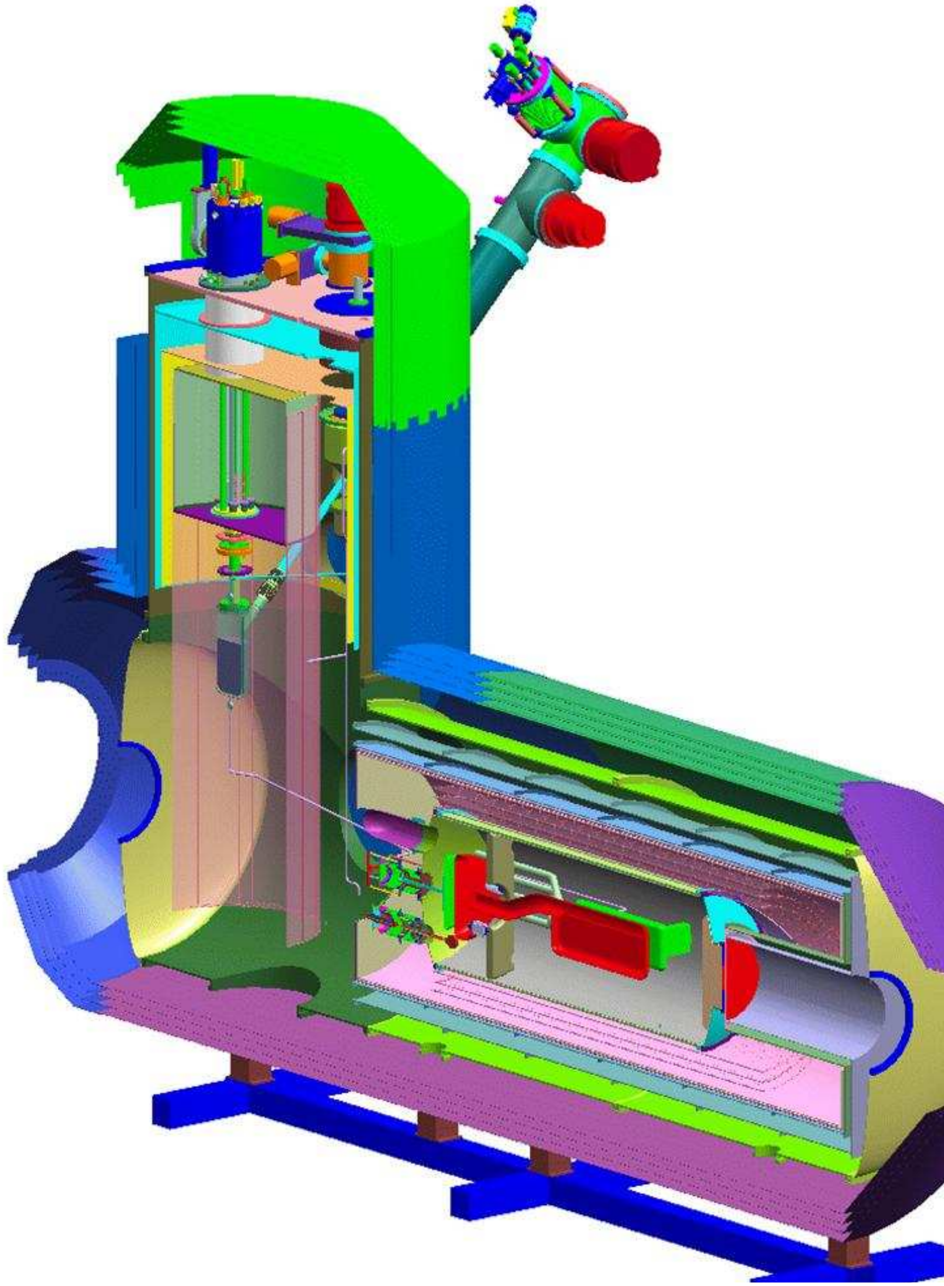


UC Berkeley and others

EXPERIMENT CYCLE



Schematic of the experiment



Polarized ^3He

Two purposes:

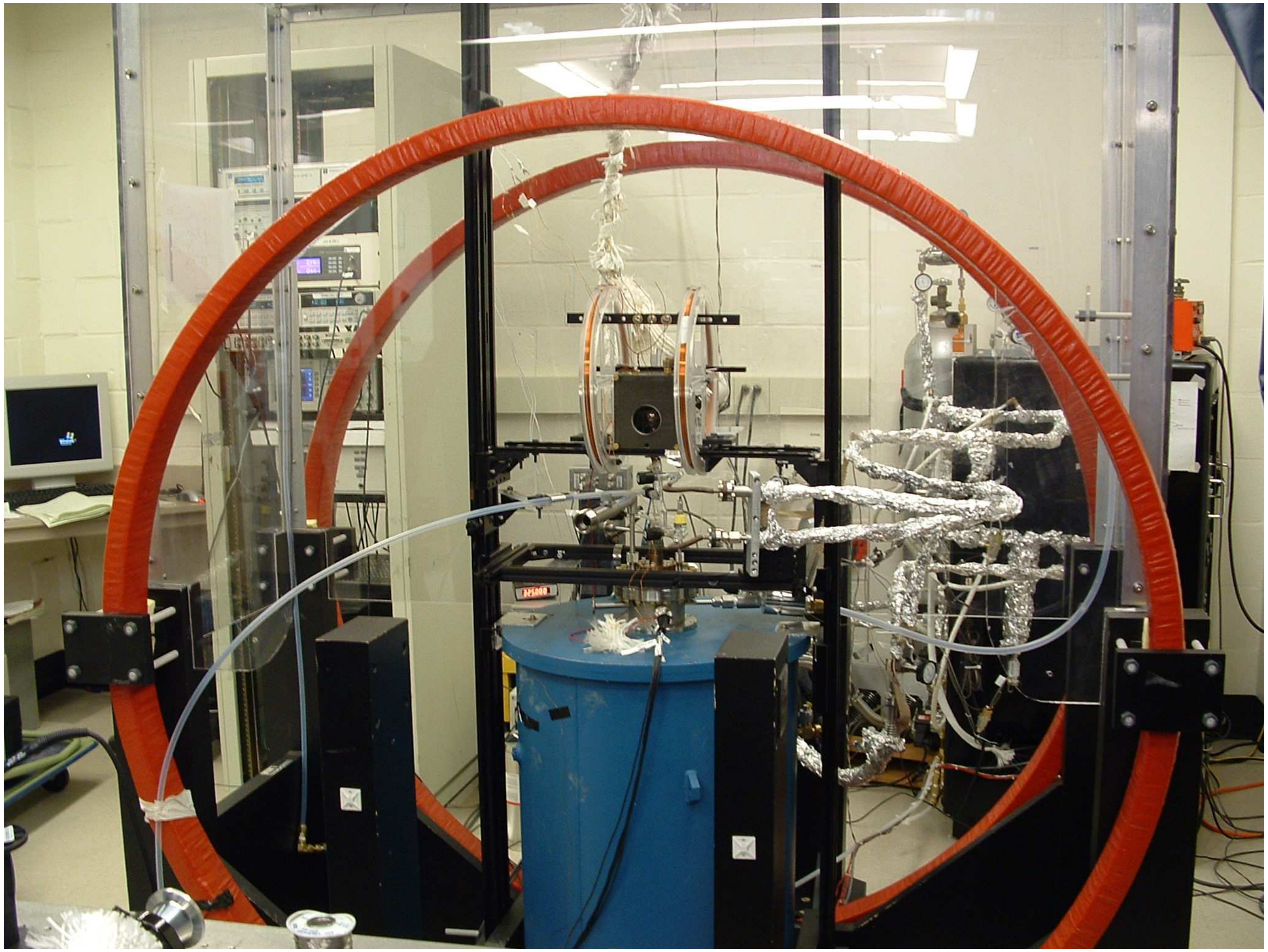
- Serve as a co-magnetometer

  Precise knowledge of B field is crucial

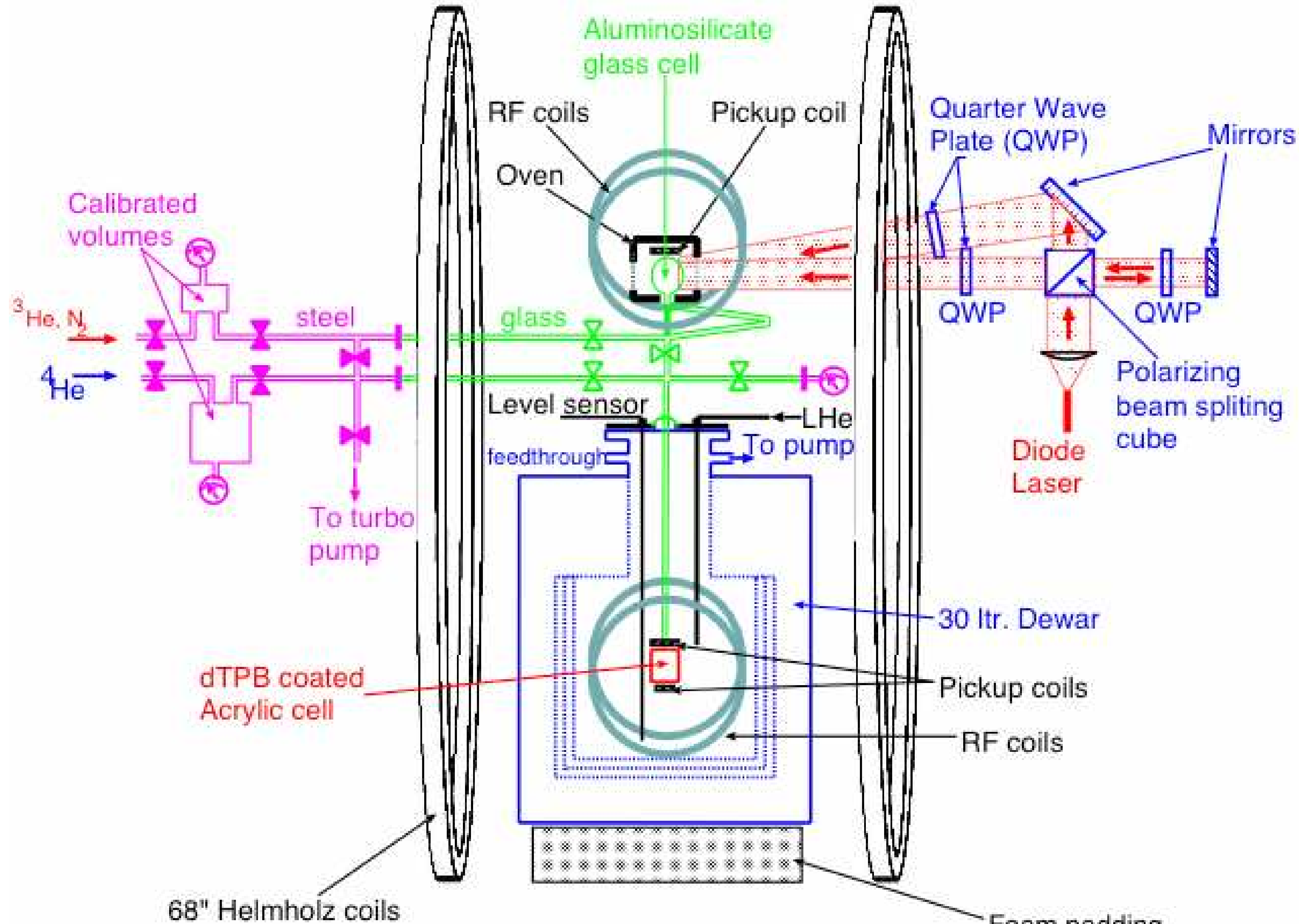
  The B field must be stable and uniform to better than 1 part in 1000 ($B_o = 10\text{mG}$)

- Nuclear reaction used for measuring the neutron precession frequency relative to ^{3}He

^{3}*He Relaxation Study at Duke University*

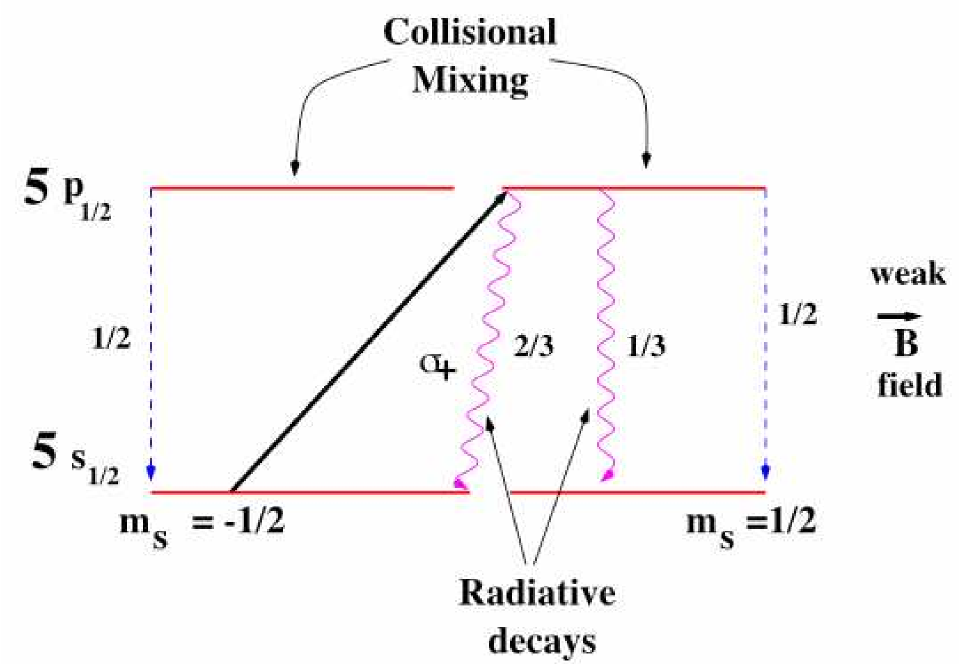


Collaborators from Caltech and NC state



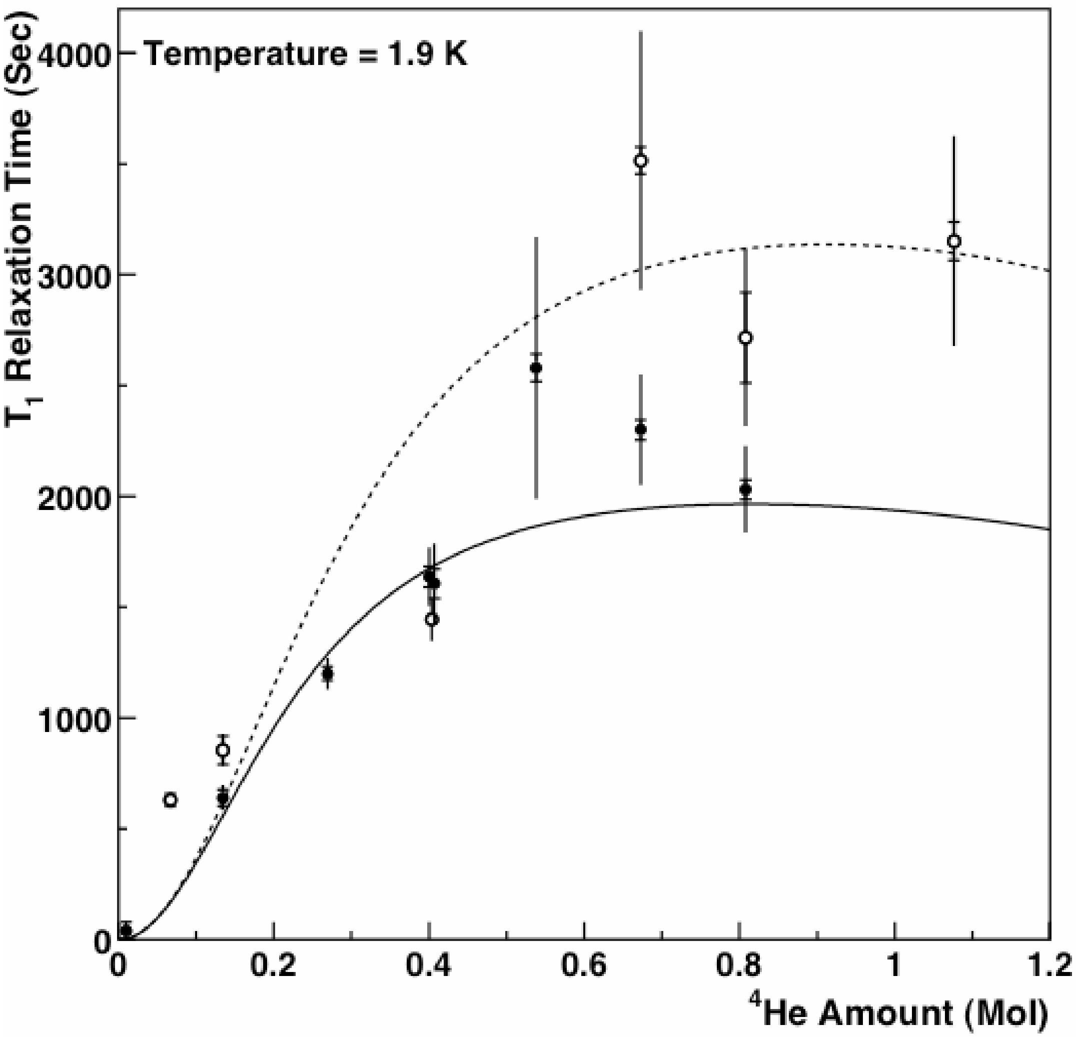
Aluminosilicate glass cell
RF coils
Pickup coil
Quarter Wave Plate (QWP)
Mirrors
Oven
Calibrated volumes
^{3}He, N_2
^{4}He
steel
glass
QWP
QWP
Polarizing beam spliting cube
Level sensor
LHe
To pump
feedthrough
Diode Laser
To turbo pump
30 ltr. Dewar
dTPB coated Acrylic cell
Pickup coils
RF coils
68" Helmholz coils
Foam padding

Spin-exchange optical pumping



- Optical pumping of alkali atoms (Rubidium)
- Spin-exchange of ^3He with Rubidium
- High pressure target, polarization ~40 to 50%

3He relaxation time at 1.9 K from dTPB coated acrylic cell



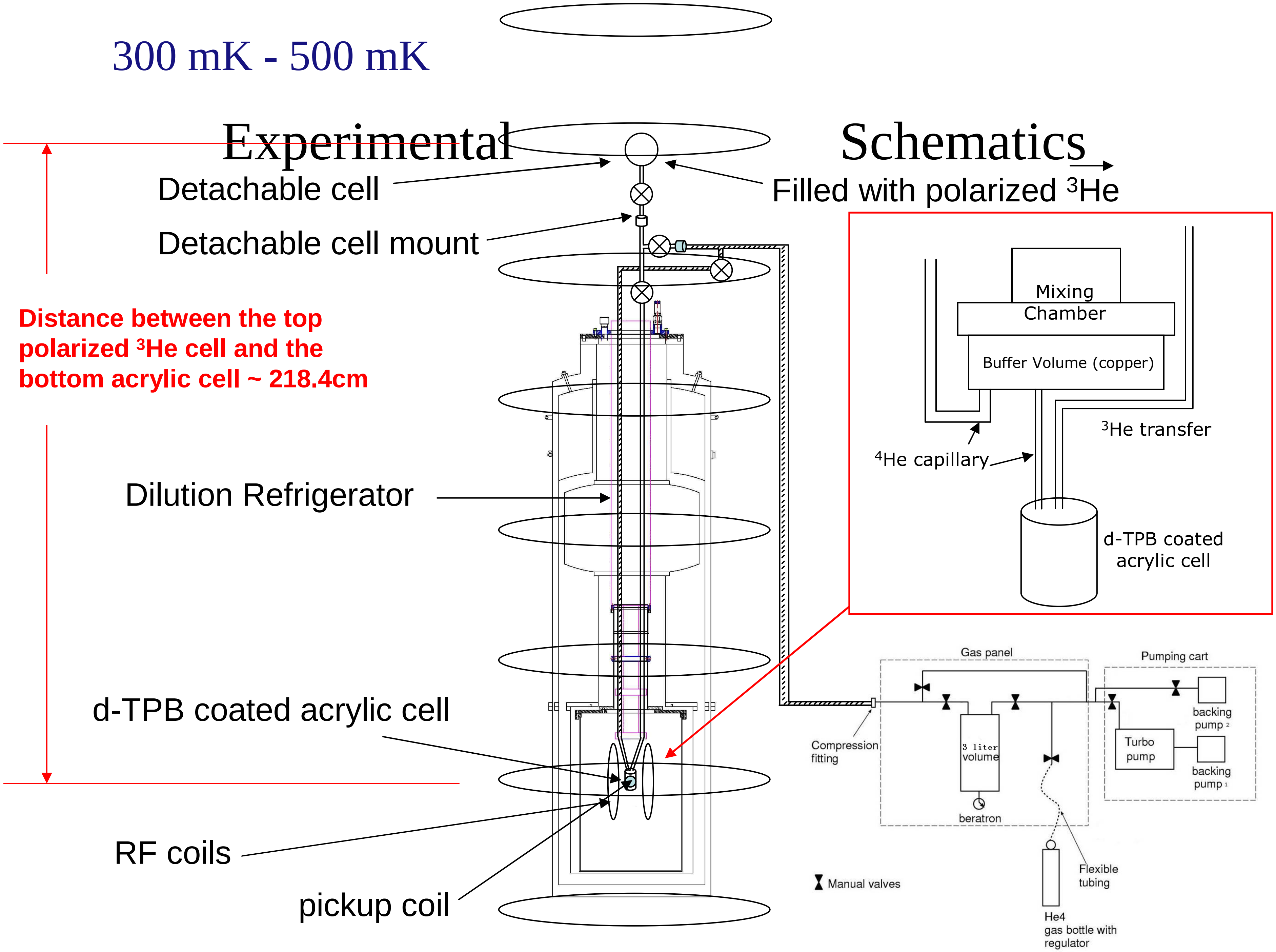
Extracted wall-relaxation coefficient from dTPB coated acrylic surface at 1.9 K in cm/sec

$$(2.0 \pm 0.12)E-04$$

Q. Ye et al., physics/0603176

300 mK - 500 mK

Experimental Schematics



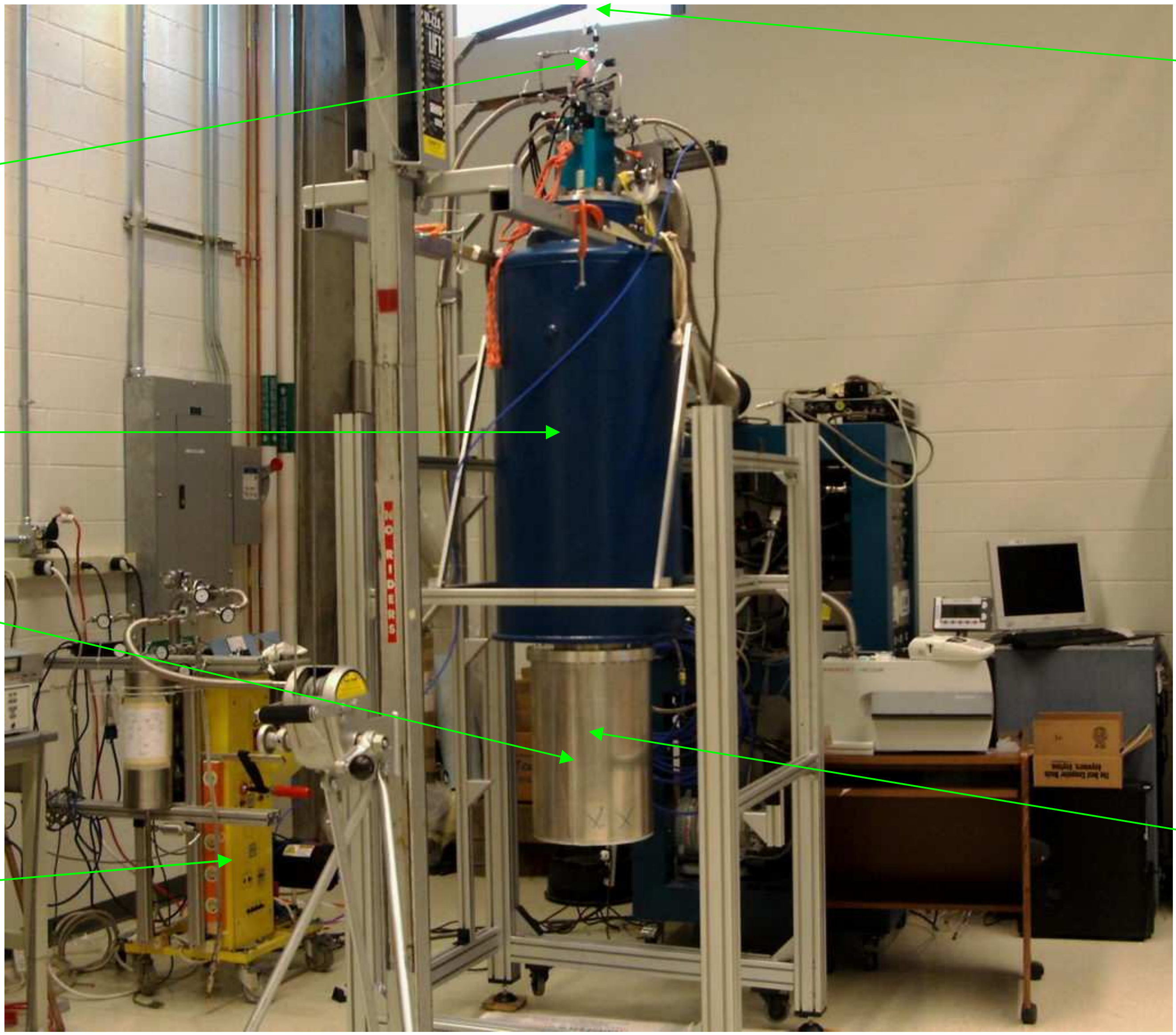
Experimental setup in French Science Building

Long piece of glass going thru dewar

Dewar

Inner Vacuum Chamber (IVC)

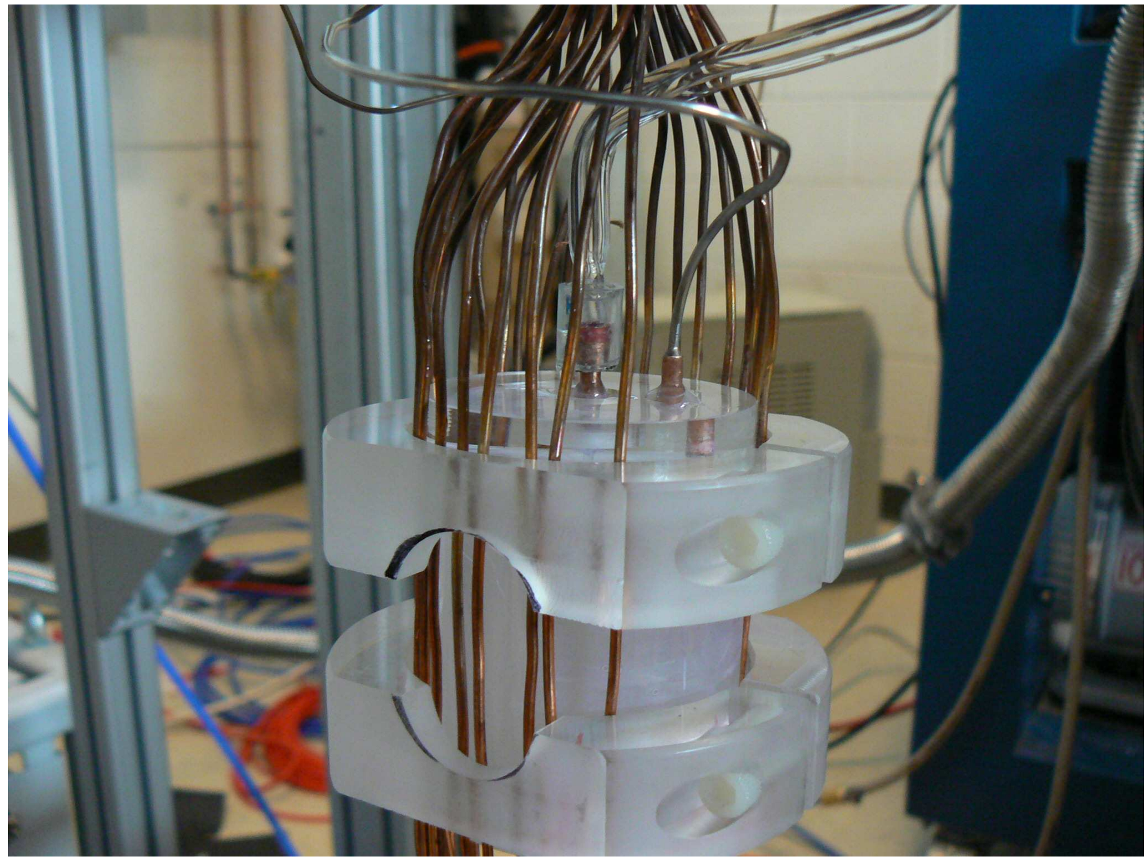
Pumping station



Polarized ^{3}He cell

8 coils will be set up around the dewar

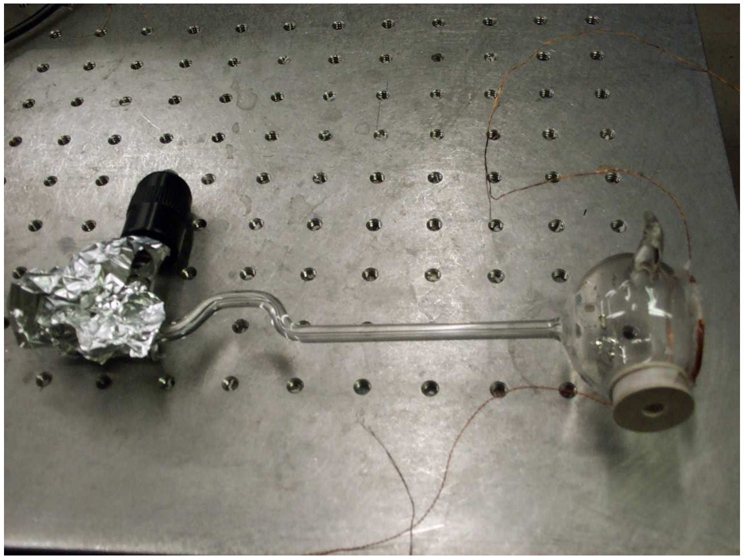
d-TPB coated acrylic cell inside

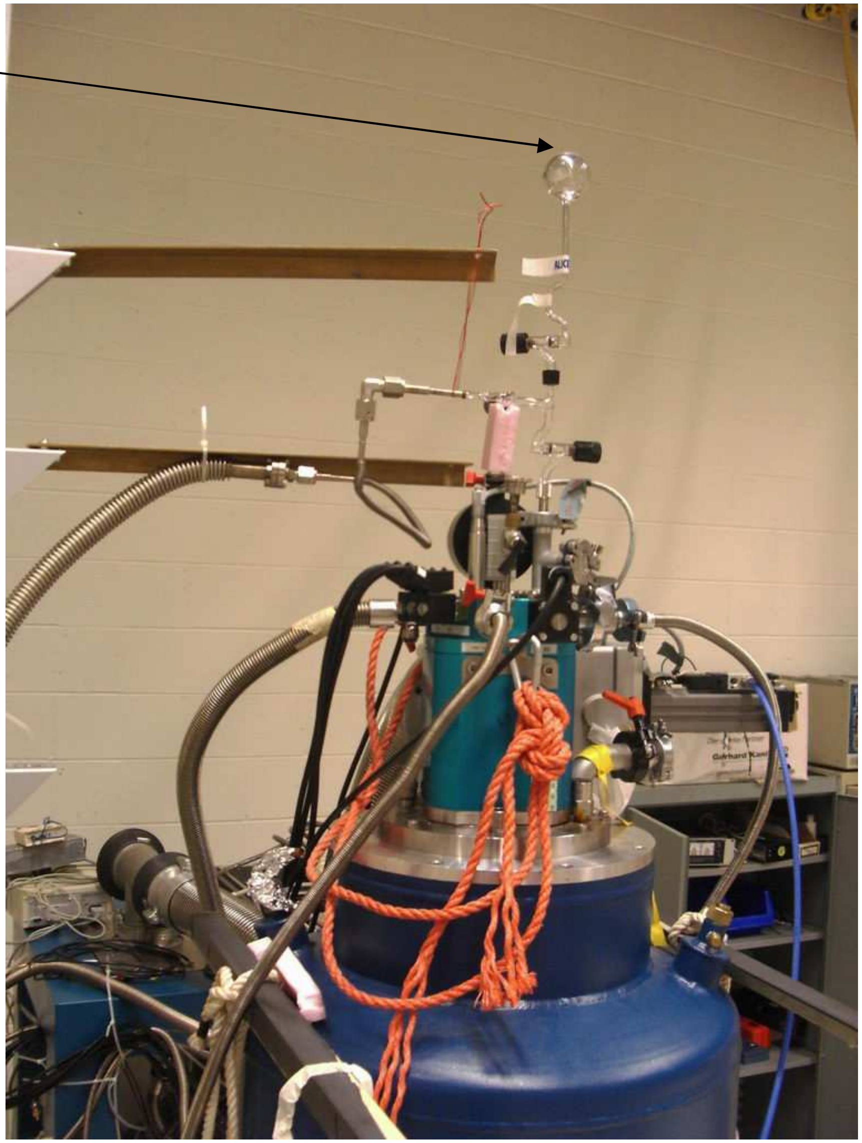


Top part of the DR

Detachable ^{3}He cell
(1.5atm ^{3}He & 200torr N_2)
T_1 ~ 40 hours

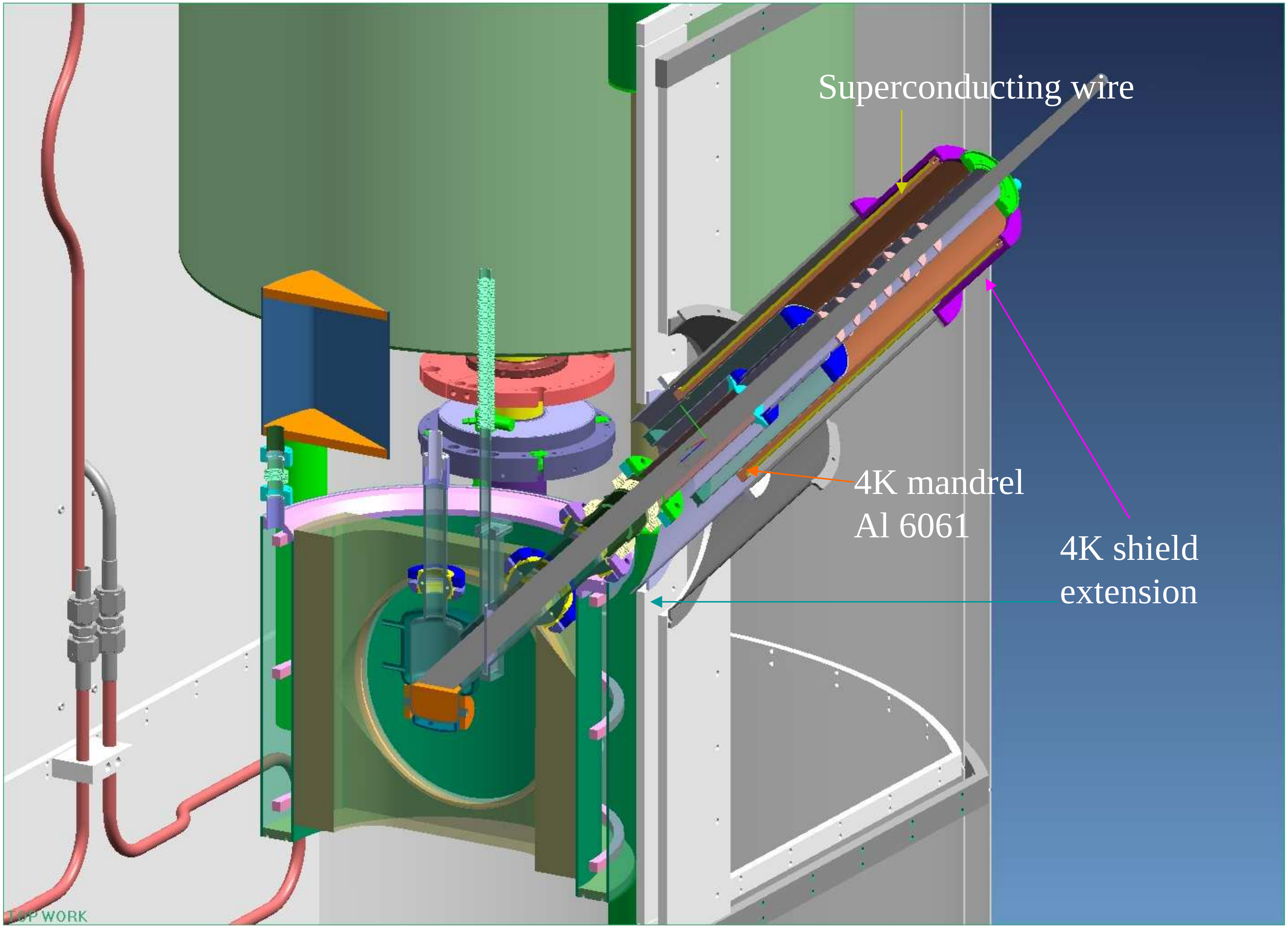
SEOP in other lab and bring over using portable magnetic field





3He injection and collection test

Duke, Caltech, Arizona, MIT



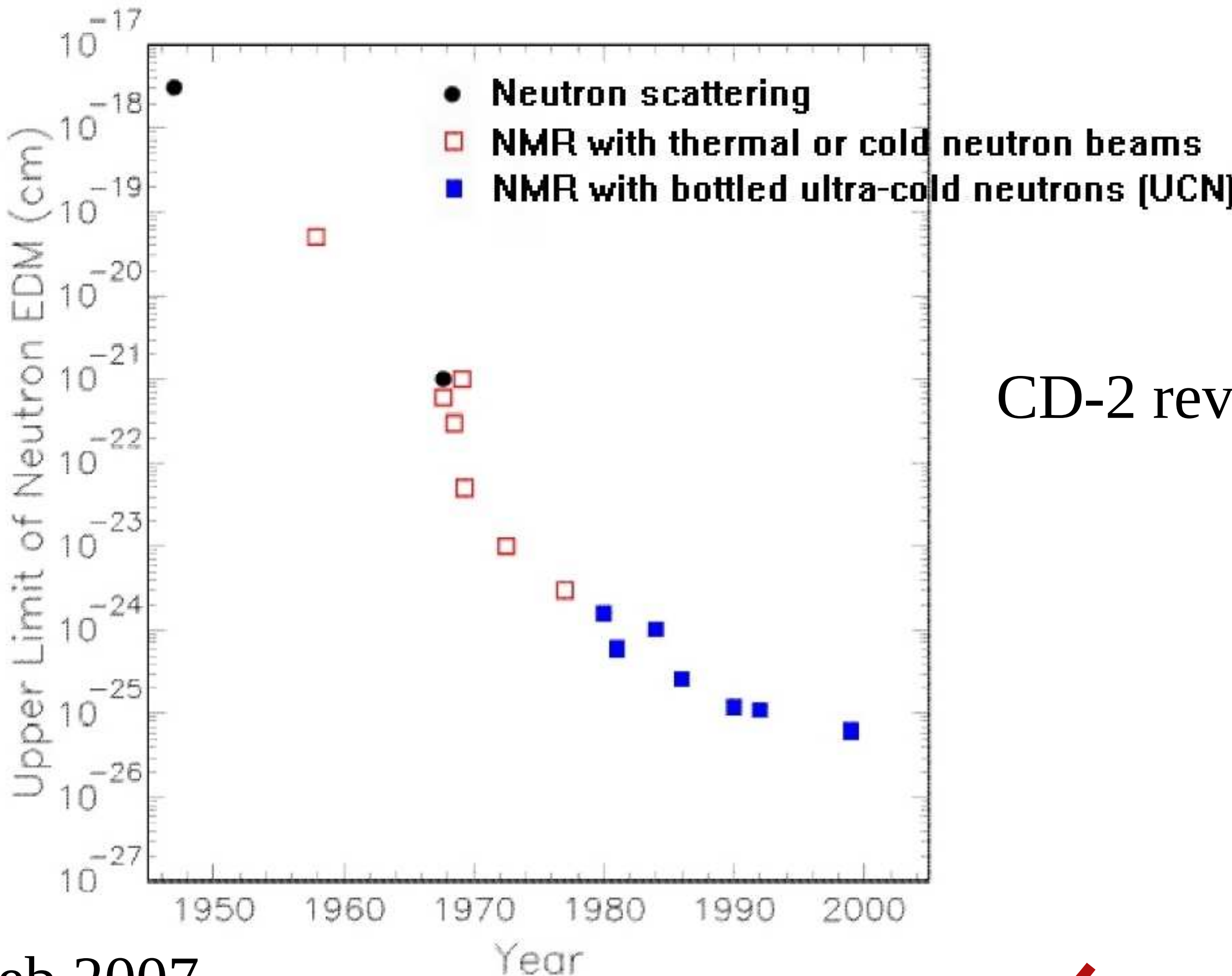
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

nEDM Collaboration List

R. Alarcon, S. Balascuta, L. Baron-Palos
Arizona State University, Tempe, AZ, USA
D. Budker, A. Sushkov
University of California at Berkeley, Berkeley, CA 94720, USA
G. Seidel
Brown University, Providence, RI 02912, USA
V. Logashenko, J. Miller, L. Roberts
Boston University, Boston, MA 02215, USA
R. Carr, B. Filippone, R. McKeown, M. Mendenhall, B. Plaster, R. Schmid
California Institute of Technology, Pasadena, CA 91125, USA
M. Ahmed, W. Chen, H. Gao, X. Qian, Q. Ye, W.Z. Zheng, X. F. Zhu, X. Zong
Duke University, Durham NC 27708, USA
F. Mezei
Hahn-Meitner Institut, D-14109 Berlin, Germany
C.-Y. Liu, J. Long, H.-O. Meyer, M. Snow
Indiana University, Bloomington, IN 47405, USA
D. Beck, A. Esler, D. Hertzog, P. Kammel, J.-C. Peng, S. Williamson, J. Yoder
University of Illinois, Urbana-Champaign, IL 61801, USA
Tim Gorringe, W. Korsch
University of Kentucky, Lexington KY 40506, USA
P. Barnes, J. Boissevain, M. Cooper, M. Espy, T. Ito, A. Matlachov, W. Sondheim, S. Tajima, J. Torgerson, P. Volegov, S. Wilburn
Los Alamos National Laboratory, Los Alamos, NM 87545, USA
E. Beise, H. Breuer
University of Maryland, College Park, MD 20742, USA
K. Dow, D. Hassel, E. Ihloff, J. Kelsey, R. Milner, R. Redwine
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
J. Dunne, D. Dutta
Mississippi State University, Starkville, MS 39762, USA
F. Dubose, R. Golub, C. Gould, D. Haase, P. Huffman, E. Korobkina, C. Swank, A. Young
North Carolina State University, Raleigh, NC 27695, USA
V. Cianciolo, S. Penttila
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
M. Hayden
Simon-Fraser University, Burnaby, BC, Canada V5A 1S6
C. Crawford, G. Greene
The University of Tennessee, Knoxville, TN 37996, USA
S. Lamoreaux, D. McKinsey
Yale University, New Haven, CT 06520, USA

Summary



CD-2 review 08

CD-1 Feb 2007

This work is supported by the US Department of Energy DE-FG02-03ER41231 and School of Arts and Science at Duke