Search for a neutron EDM at the SNS

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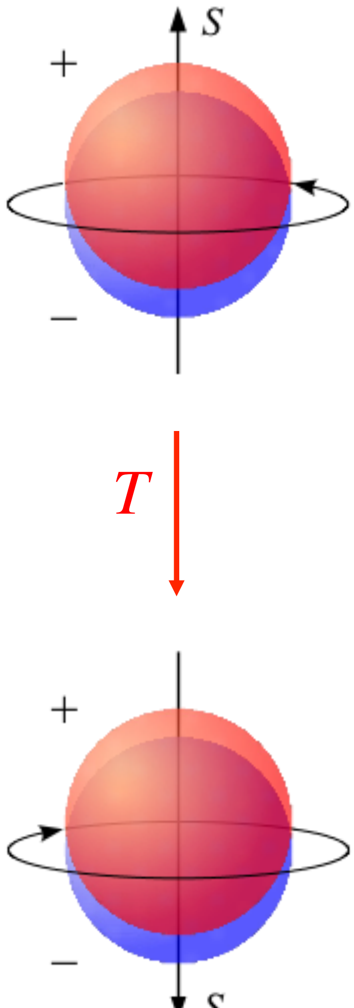
Outline

- Motivation
  - EDMs and CP violation
  - searches in atoms, molecules, neutron
- SNS nEDM experiment
  - experiment overview
  - measurement cell construction/UCN measurements
  - dTPB light conversion measurements
  - E-field effect on scintillation
  - cryogenic light production test
  - PULSTAR

The Search for an EDM

A permanent EDM violates T :

with CPT theorem, implies CP violation



Standard Model CP violation generates EDMs far too small to measure.

Therefore, finding an EDM would be proof of new physics.

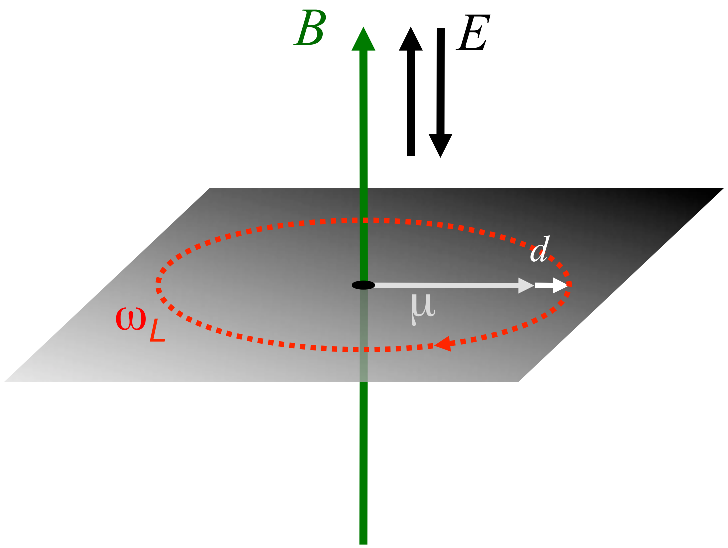
Search for an EDM of the neutron began nearly 60 years ago, so far no luck.

Theories of physics beyond the Standard Model → EDMs large enough to see with current experiments.

Therefore, keep on looking!

Measuring an EDM via Larmor precession

$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$



$$\omega_1 = \frac{2\vec{\mu} \cdot \vec{B} + 2\vec{d} \cdot \vec{E}}{\hbar}$$

$$\omega_2 = \frac{2\vec{\mu} \cdot \vec{B} - 2\vec{d} \cdot \vec{E}}{\hbar}$$

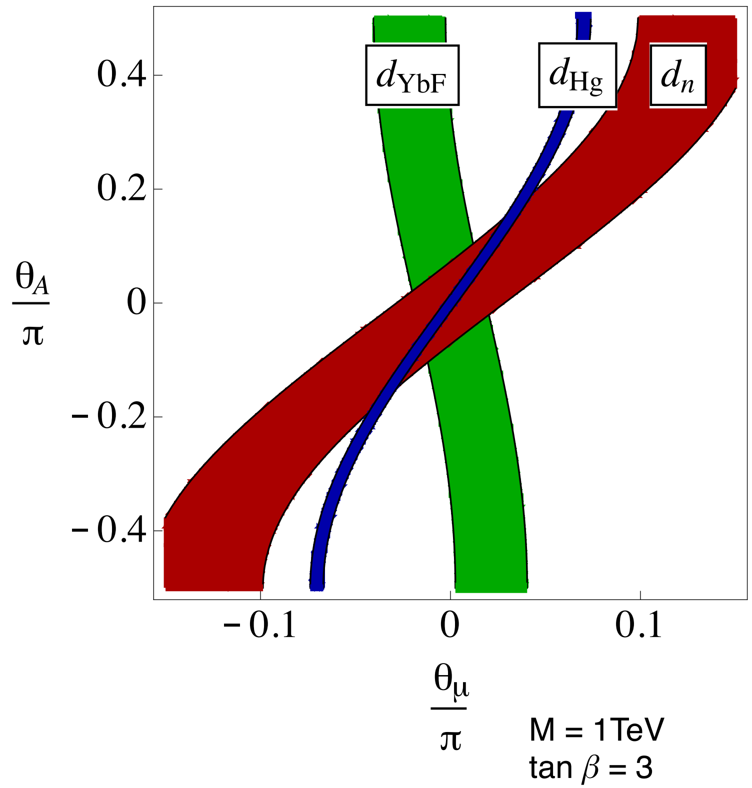
$$\Rightarrow \quad \omega_1 - \omega_2 = \frac{4\,d\,E}{\hbar}$$

larger E-fields give better sensitivity, need to control magnetic fields very well, guard against any B-fields correlated with E

EDM searches

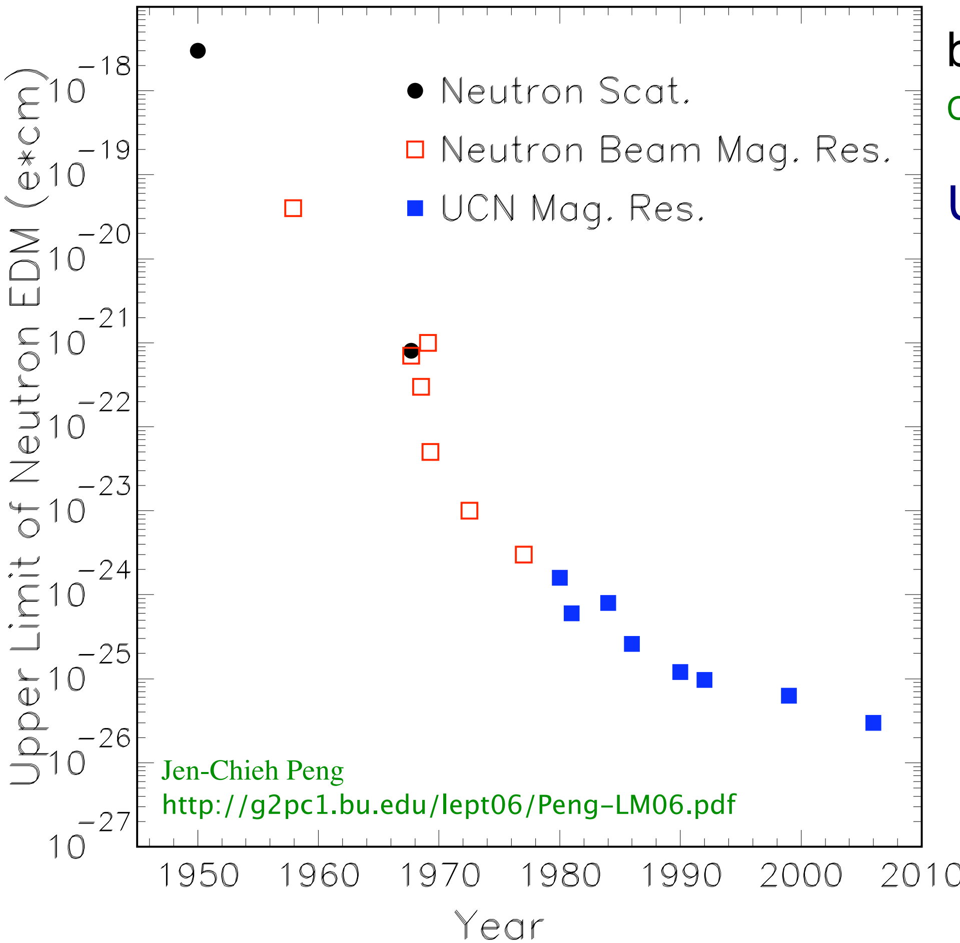
- paramagnetic atoms and molecules
  - mainly sensitive to EDM of the electron
  - large enhancement for heavy atoms (d(Tl) ~ 600 d_e)
  - even larger for polar moleculeslike YbF (~10^6)
- diamagnetic atoms (^{199}Hg, ^{129}Xe)
  - mainly sensitive EDM associated with CP-violating nucleon-nucleon interactions
- neutron
  - upper bounds from nEDM measurements have ruled out more theoretical models than any other experiment
  - could be generated from standard model QCD theta term
    - nedm limit implies $\theta_{QCD} < 10^{-10}$, smallness of this phase can be explained by introducing axions, a possible DM candidate

EDM limits on MSSM CP violating phases



T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999). Update A. Ritz (2011).

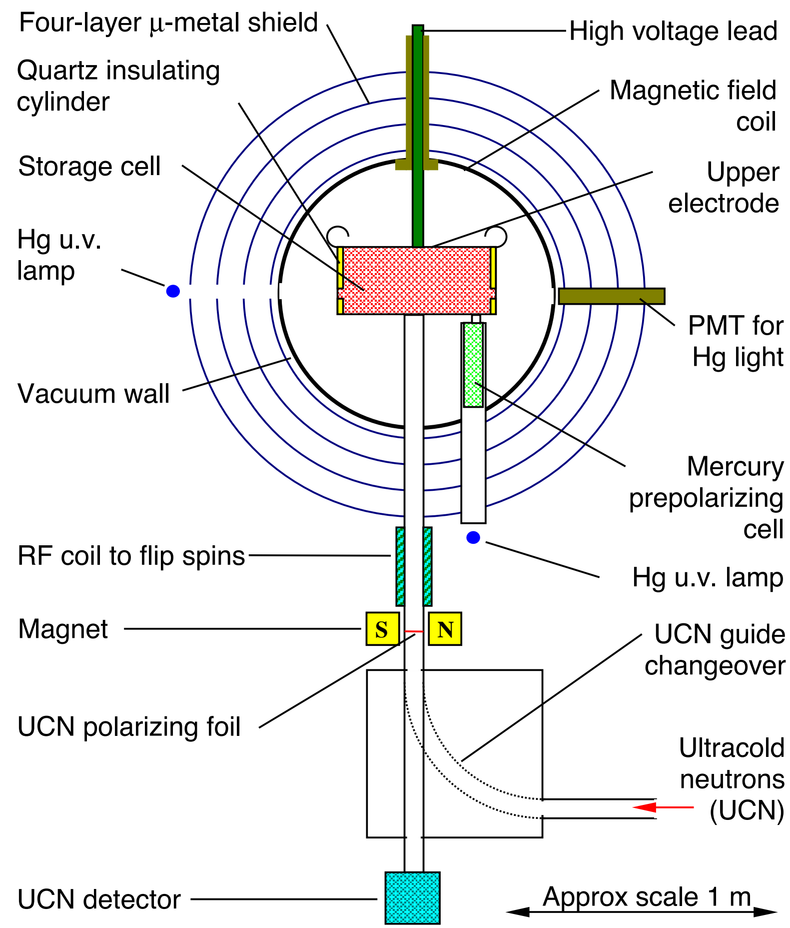
Search for the neutron EDM



best limit: $|d_n| < 3.0 \times 10^{-26}\ e\ \mathrm{cm}$ (2006)

C. A. Baker *et al*, PRL **97**, 131801 (2006).

UCN+^{199}Hg comagnetometer (Sussex/ILL)



Current nEDM searches

- many new experiments hope to improve the nEDM sensitivity to 10^{-27} e cm and beyond

- Room temperature:
  - PSI: continue to operate the UCN+^{199}Hg apparatus at PSI's new UCN source
  - TRIUMF/RCNP: Xe comagnetometer
  - Munich (FRM II): adjacent ^{3}He magnetometer cells

- cryogenic experiments: perform experiment in superfluid ^{4}He – Sussex/ILL CryoEDM, Oak Ridge SNS
  - create high UCN density by superthermal production, higher electric field breakdown strength in LHe (> 50kV/cm), superconducting magnetic shielding and magnetic coils give higher stability field environement
  - Oak Ridge SNS: superfluid ^{4}He with small amount of polarized ^{3}He ($\rho_3/\rho_4 \sim 10^{-10}$)
    - 3He acts as neutron spin analyzer

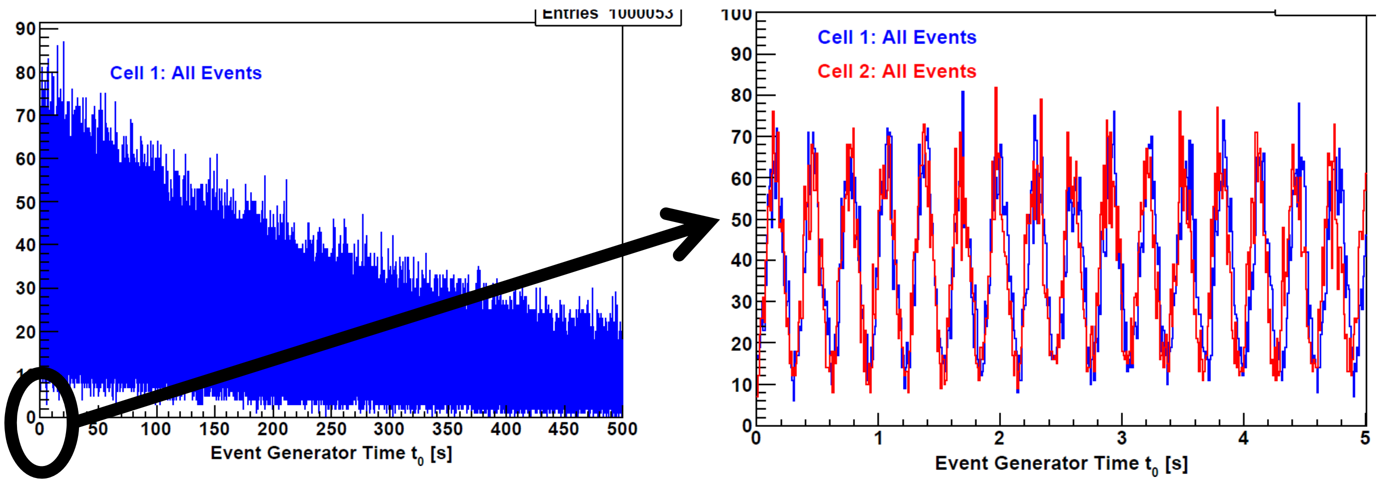
$$\vec{\mathrm{n}} + {}^{3}\vec{\mathrm{He}} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV} \quad (\sigma_{\uparrow\downarrow} \gg \sigma_{\uparrow\uparrow})$$

      - UV scintillation light shifted to visible by tetraphenyl butadiene (TPB) on cell walls, cell walls act as light guides to PMTs
    - detection of ^{3}He precession with SQUIDs gives comagnetometer signal

Precession signal

- modulated scintillation signal
  - magnetic moments of n and ^{3}He are different
  - scintillaiton signal oscillates at $(\omega_3 - \omega_n)$

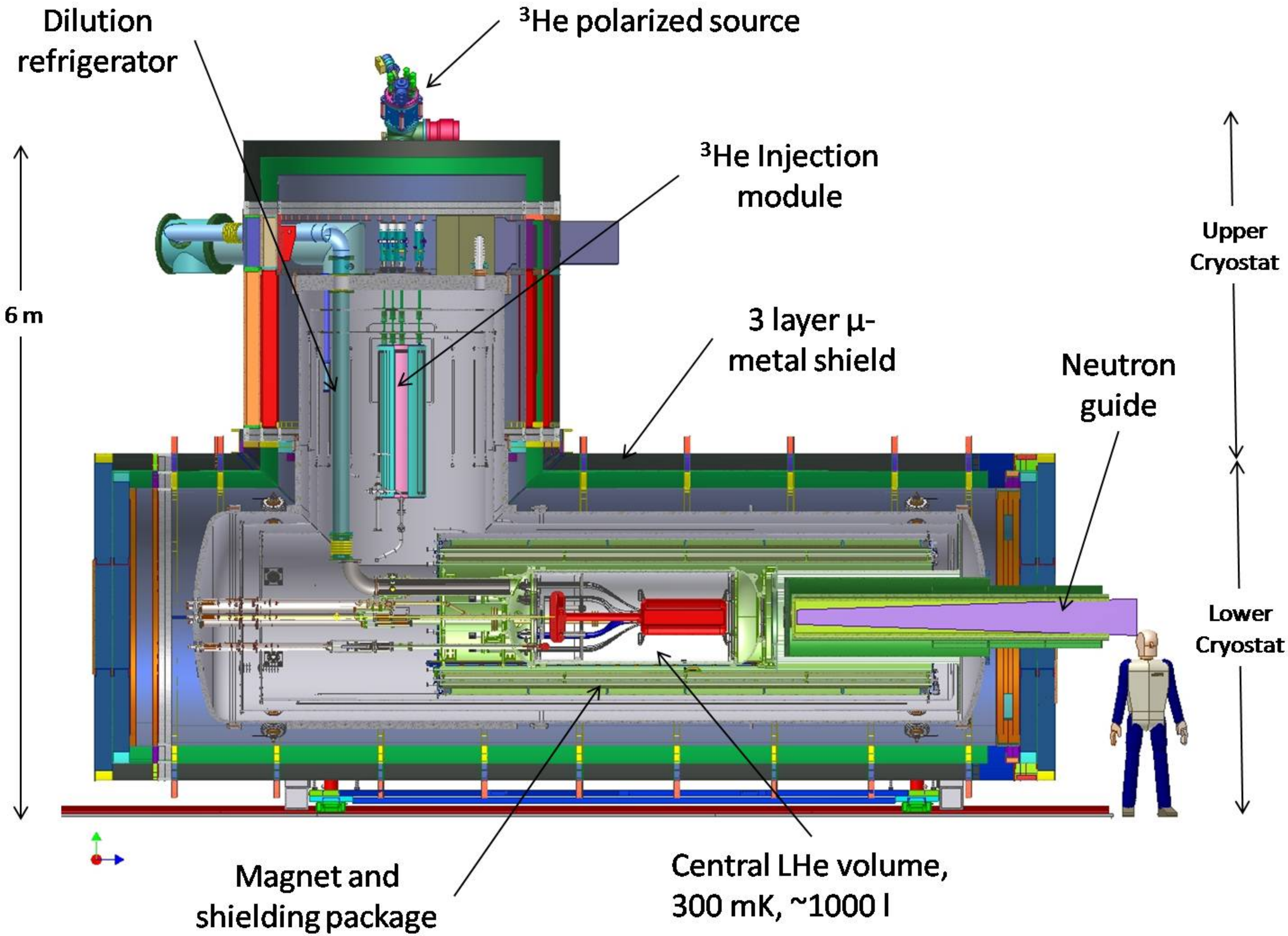
$$\frac{\gamma_3}{\gamma_n} = 1.11$$



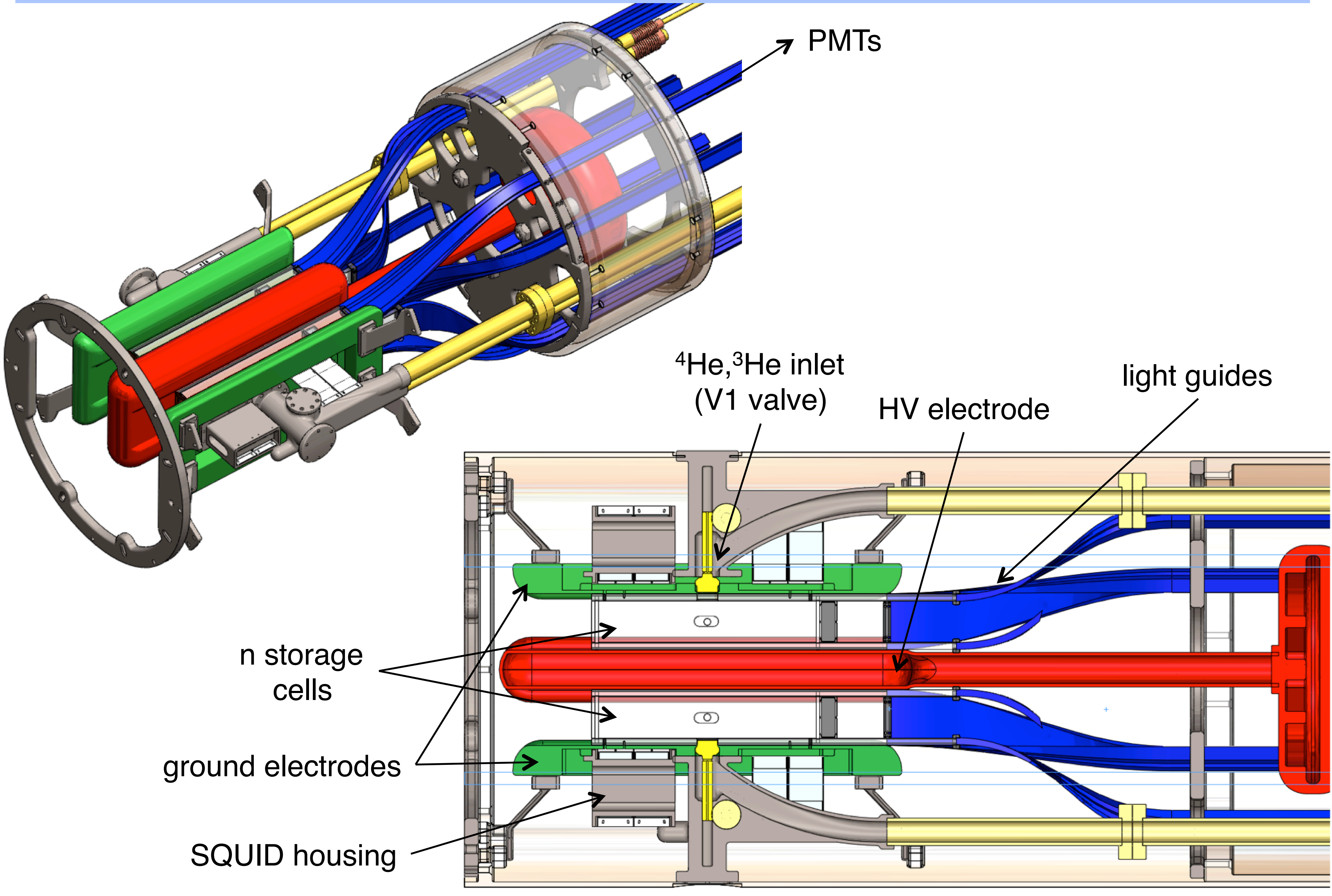
simulated data (B. Plaster)

- alternate method: dressed spin technique
  - apply appropriate RF field that modifies effective gyromagnetic ratio γ'
  - critical dressing achieved if $\gamma_n' = \gamma_3'$
    - ^{3}He and n precess in unison – less affected by *B* fluctuations
    - EDM signal: change in critical dressing field when *E* is flipped

nEDM apparatus



Central detector system



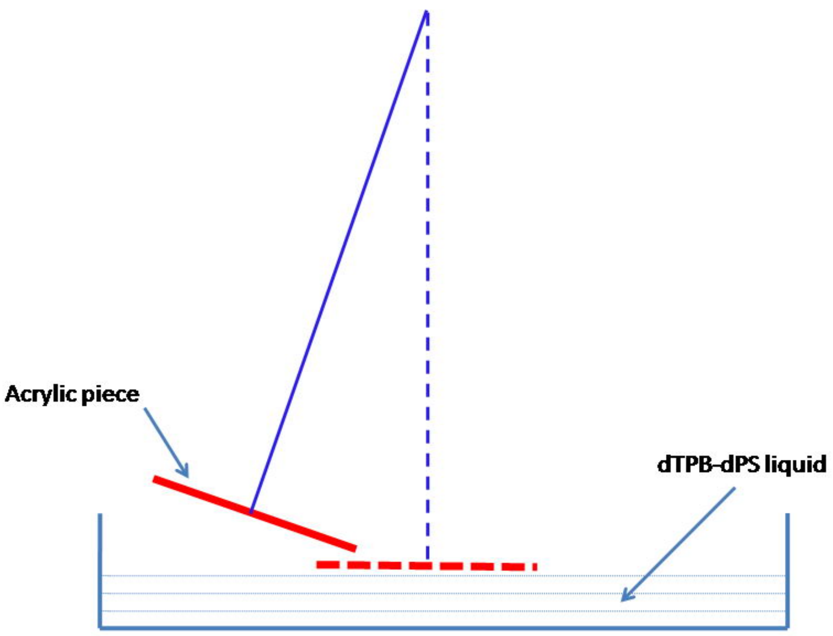
Experimental challenges and R/D areas

- Cryogenics – central detector module at 0.3-0.45 K, magnet module at 4 K
- Electric field – breakdown strength in superfluid He, electrode materials, field amplification, need to measure/control leakage currents
- Magnetic field – crucial for sensitivity and systematics, ½ scale magnet coils/shields, SQUID readout sensitivity tests, SQUID survivability near HV, spin dressing RFfields can generate eddy current heating
- ^3He services – injection/transport/removal, measurement cell materials and ^3He transport system must have very long ^3He polarization lifetime, superfluid tight plastic valves, superfluid film burner for the atomic beam source
- neutrons – UCN production in situ can lead to high backgrounds, FNPB beamline simulations to predict UCN production numbers, measurement cell needs long UCN storage time
- light readout – TPB/light guide efficiency of the measurement cell, long curved light guides from cell to PMTs, scintillation yield in a strong E-field
- …

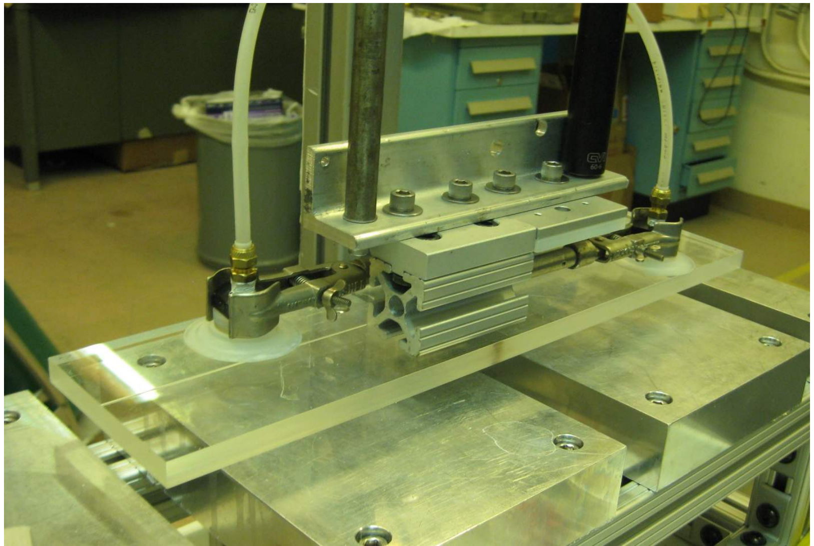
nEDM measurement cells

- nEDM cells are planned to be constructed from UVT acrylic, coated with deuterated-polystyrene (dPS, C_8D_8) + deuterated-TPB ($C_{28}D_{22}$)
  - 7.5 x 10 x 40 cm box, ½" thick walls
- It is crucial that the cell walls:
  - have a long ^{3}He polarization lifetime (verified to be ~ 25000 s for dPS +dTPB in separate measurements)
  - have a long UCN wall loss time (goal ~ 2000 s, 10^{-5} loss per bounce)
  - must act as efficient light guides
- coating strategy:
  - 30% dTPB + 70% dPS (M_W=100-300k) dissolved in deuterated toluene
  - dip coat the acrylic plates
  - then glue into a 6-sided box with deuterated MC-Bond acrylic cement
    - 81% dichloromethane, 14% methyl methacrylate, 5% acetic acid
    - need to control any gaps to < 1 mm^2

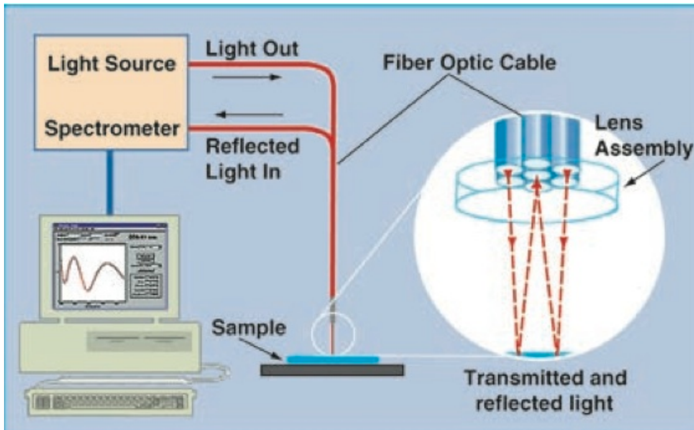
Swing coating

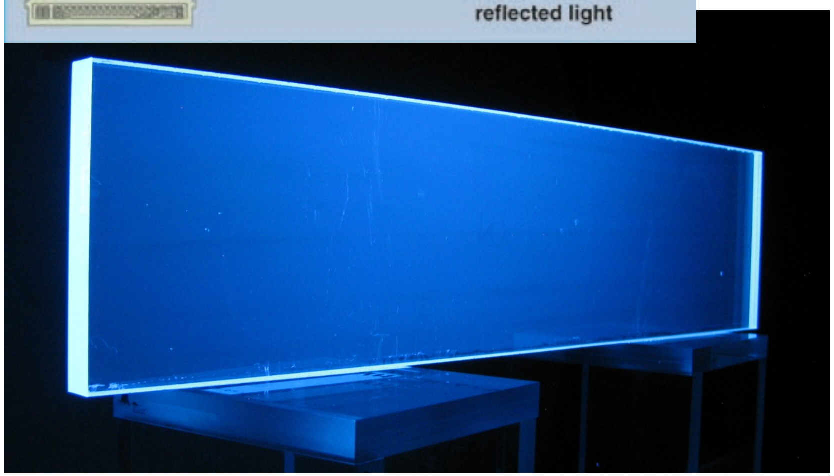


- technique developed during ^{3}He wall depolarization studies (Gao, Golub, Ye)
- plate is dipped into d-toluene +dPS/dTPB solution, swung out very slowly and smoothly

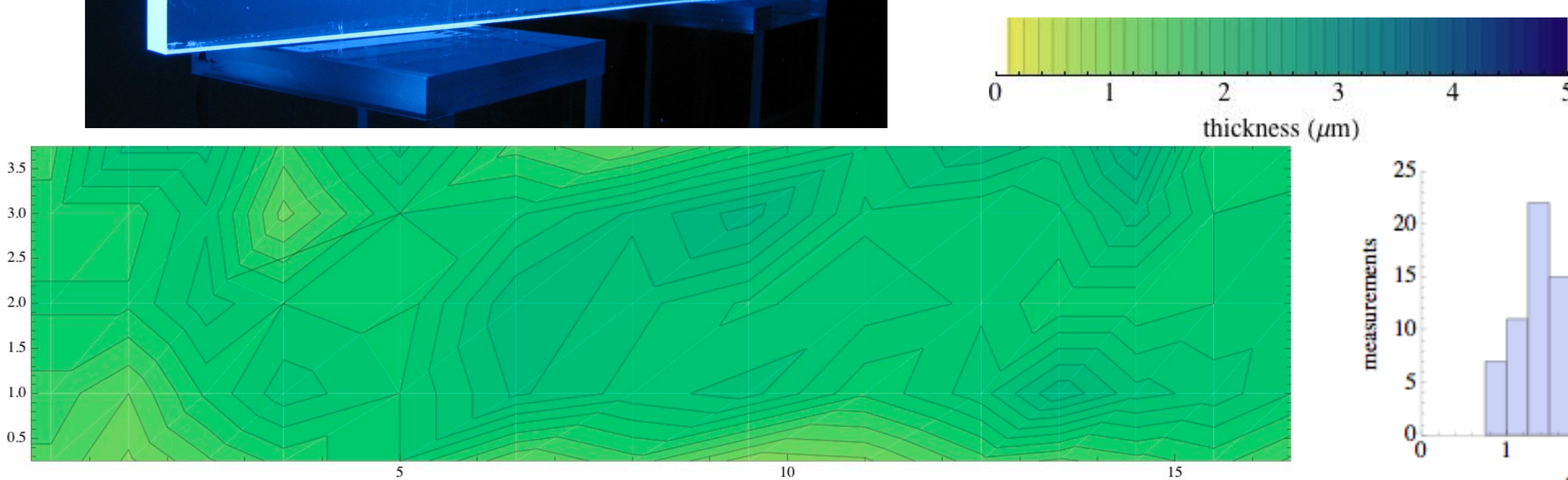


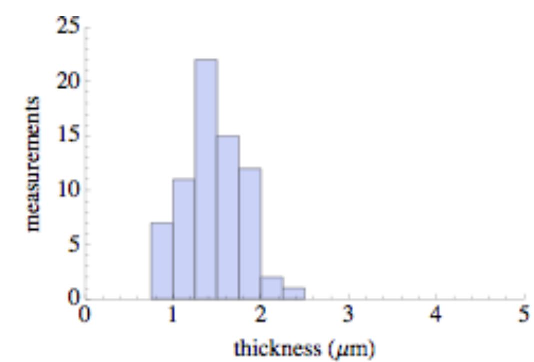
Coating thickness





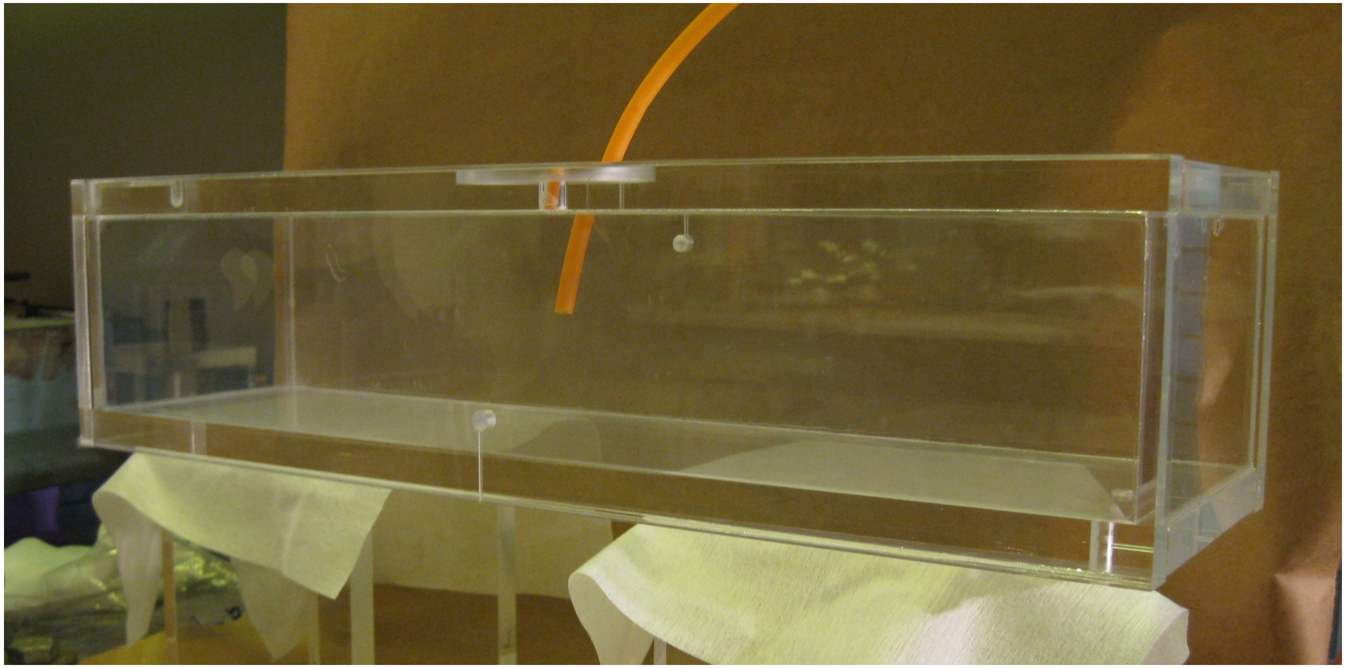
- coating thickness is checked with a spectral reflectometer
- thickness > 100 nm to avoid UCN tunneling losses
- 1-2 microns is adequate for light production
- have seen crazing after temperature cycling when > 4 microns



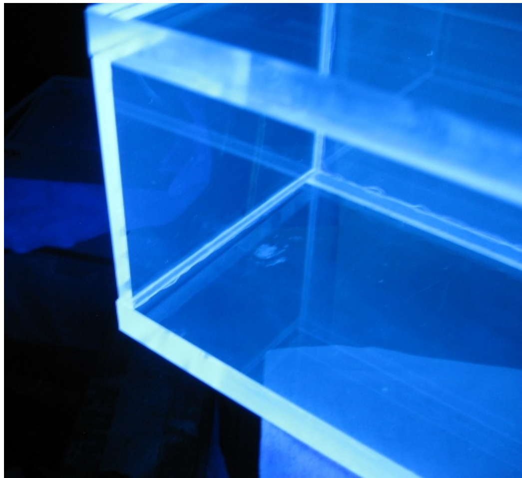


Cell gluing

- joints are optically clear – transmission tests show no significant losses due to joint, mostly bubble-free
- need to flush out glue vapors or coating becomes cloudy
- heat treating the glued cell at 90-100 C also causes cloudiness/crystalization
  - some concern that the gluing process introduces some stress that could be reduced by annealing post-gluing
  - non-annealed boxes have survived multiple cryogenic temperature cycles without cracking/crazing

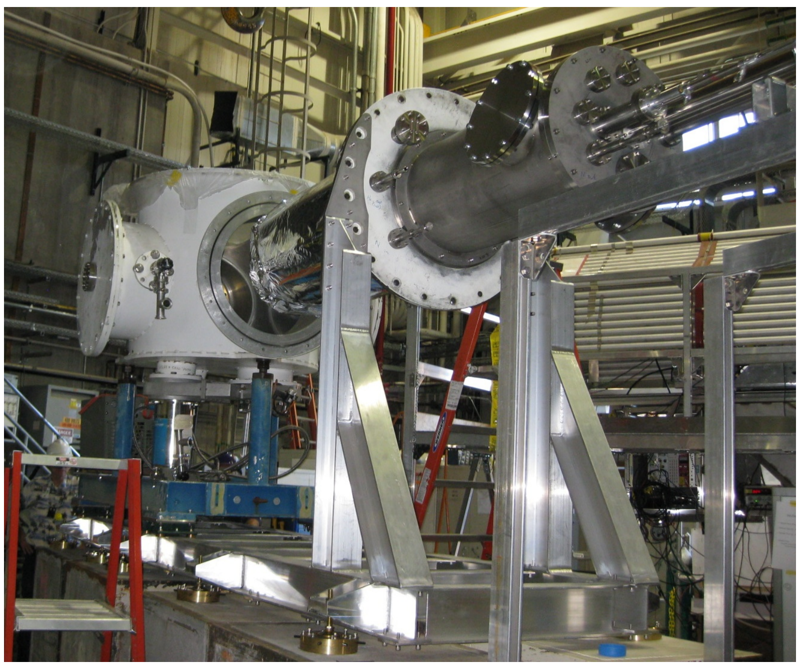


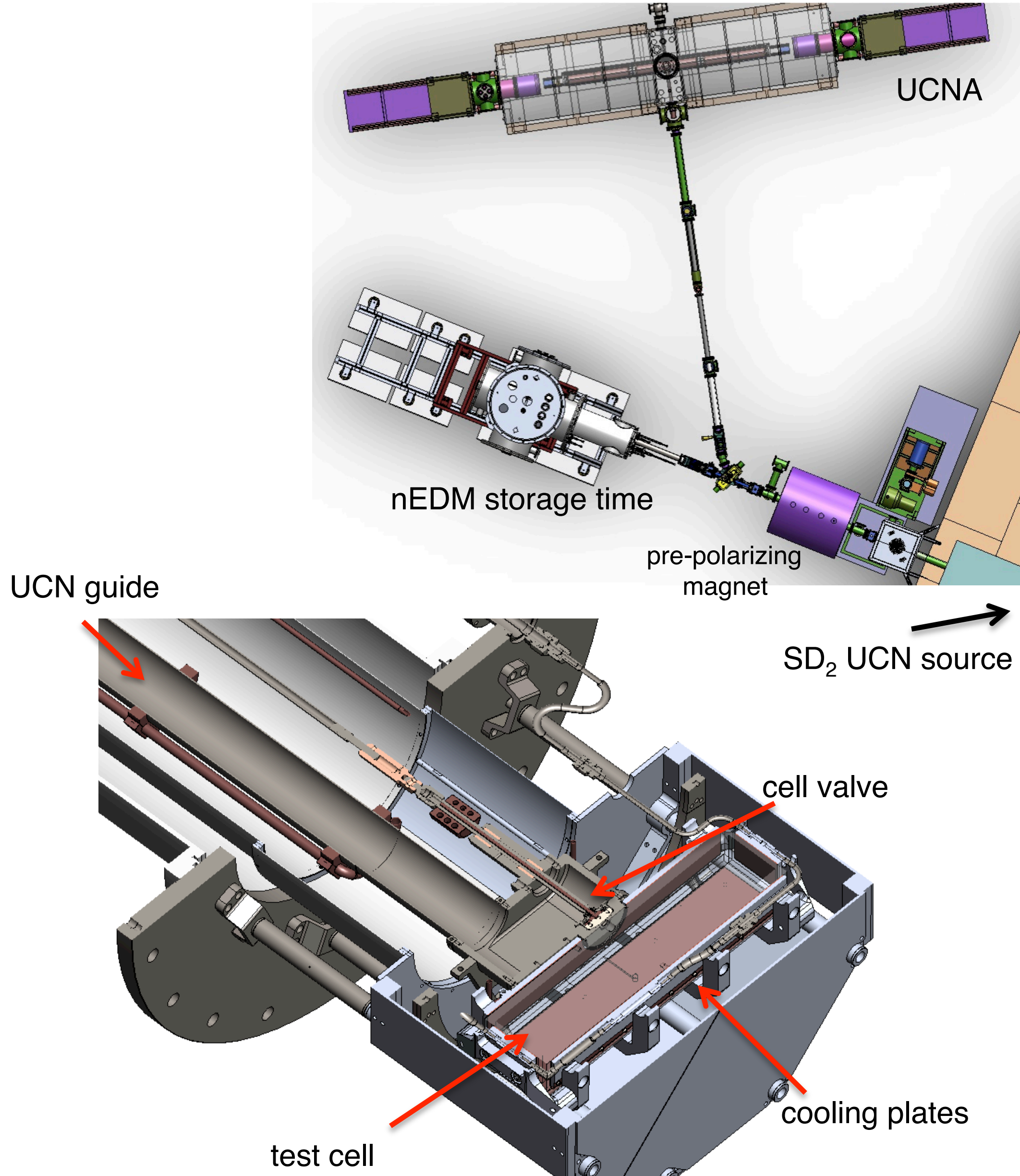
dTPB fluorescing under a UV lamp:



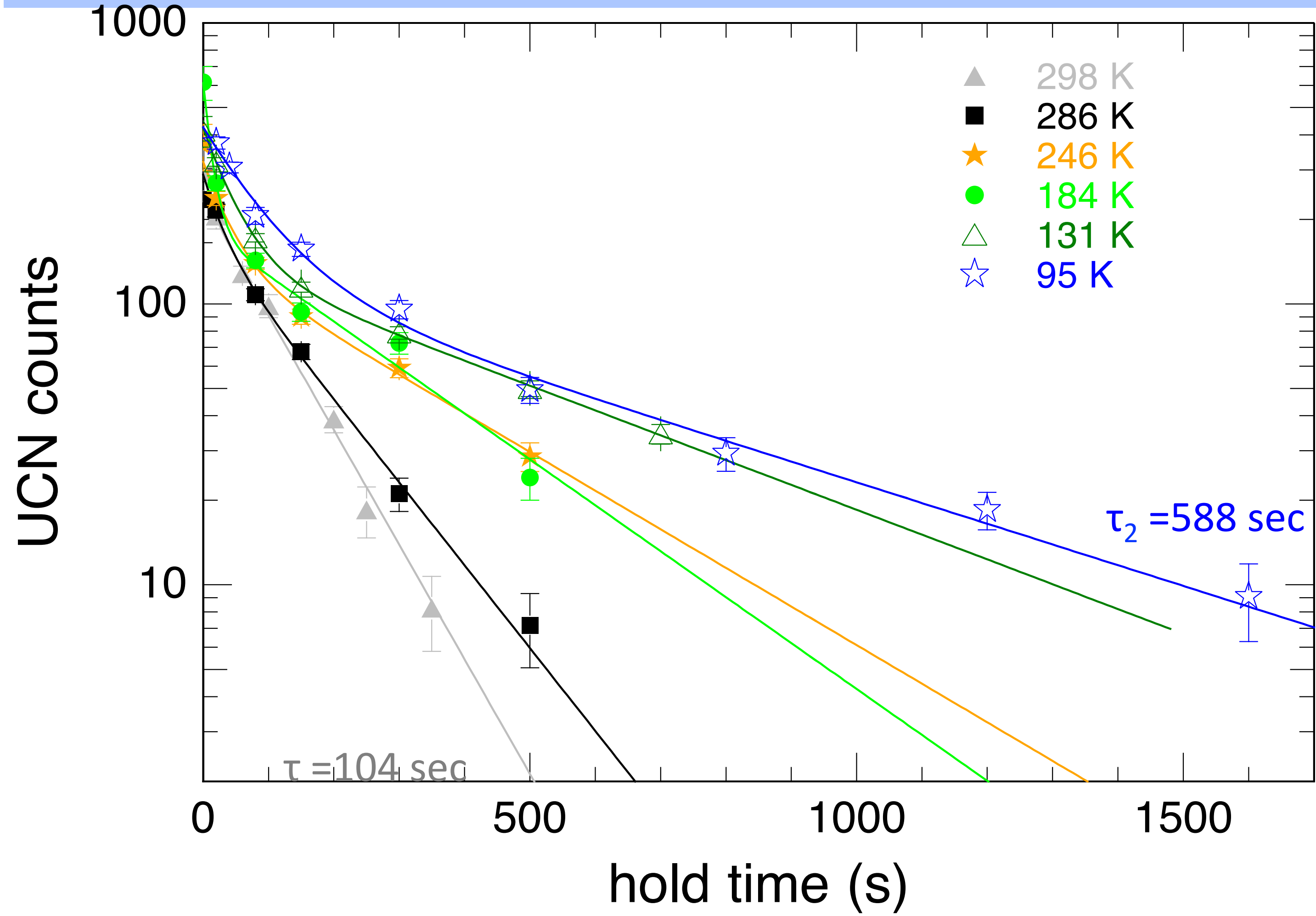
LANL UCN storage time tests

- utilizes currently operating LANSCE UCN source
- test wall coatings and cell construction for UCN storage in vacuum down to 15 K





UCN storage data



assuming,
$1/\tau_{bottle} = 1/\tau_n + 1/\tau_{wall}$

τ_{wall} = 1800 sec

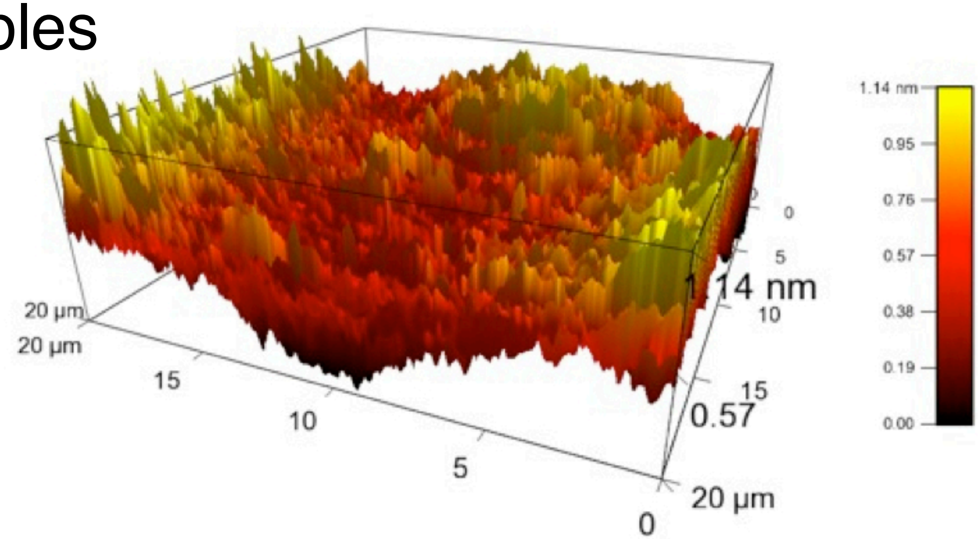
solid lines are double exp. fits: $A_1*\exp(-x/tau_1)+A_2*\exp(-x/tau_2)$

1800 sec wall time is close to our goal, but initial faster drop indicates higher velocity UCN are not being stored as well

– may be an issue with the d-dichloromethane in the acrylic cement

Further coating development at NCSU

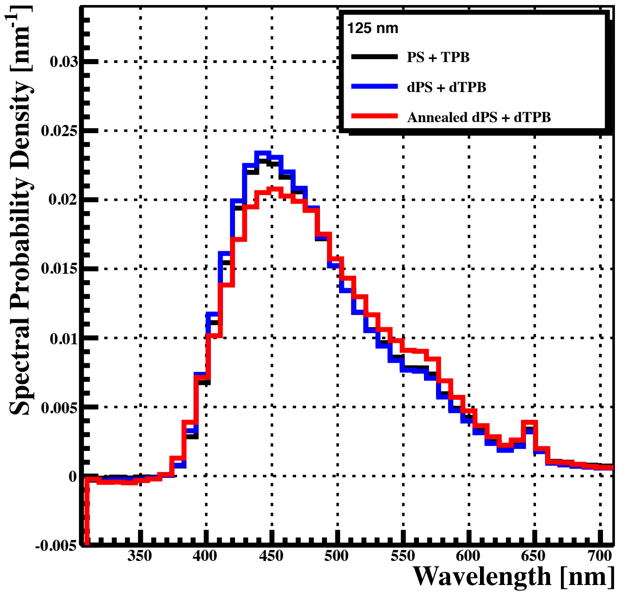
- alternate cell design that will hide glue joints from UCN
- NCSU is acquiring a DispenseMate applicator/robot to apply dPS/dTPB coating (sprayed or dripped)
    - also using to apply acrylic glue
- AFM scans of coated samples show ~1 nm roughness

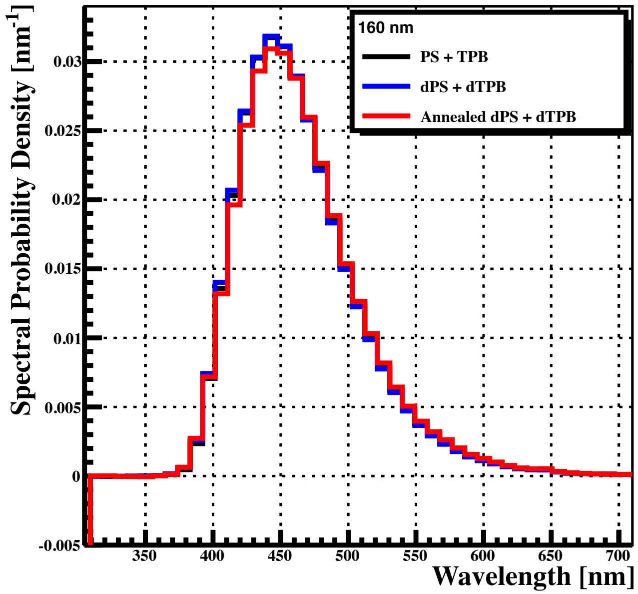


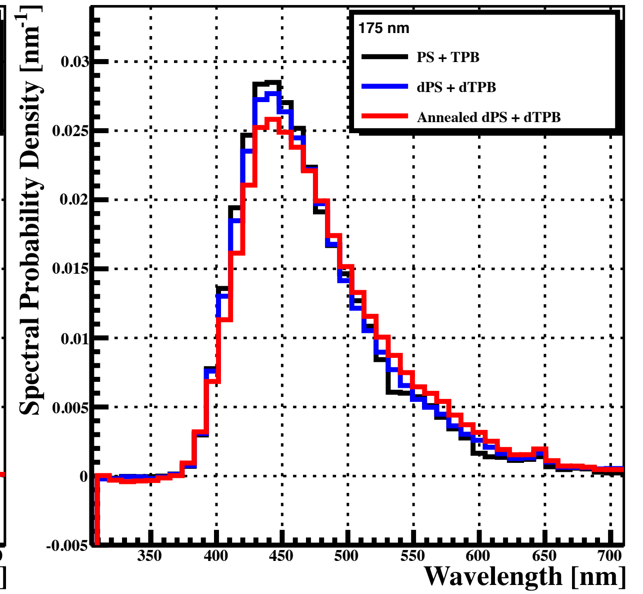
dTPB light conversion

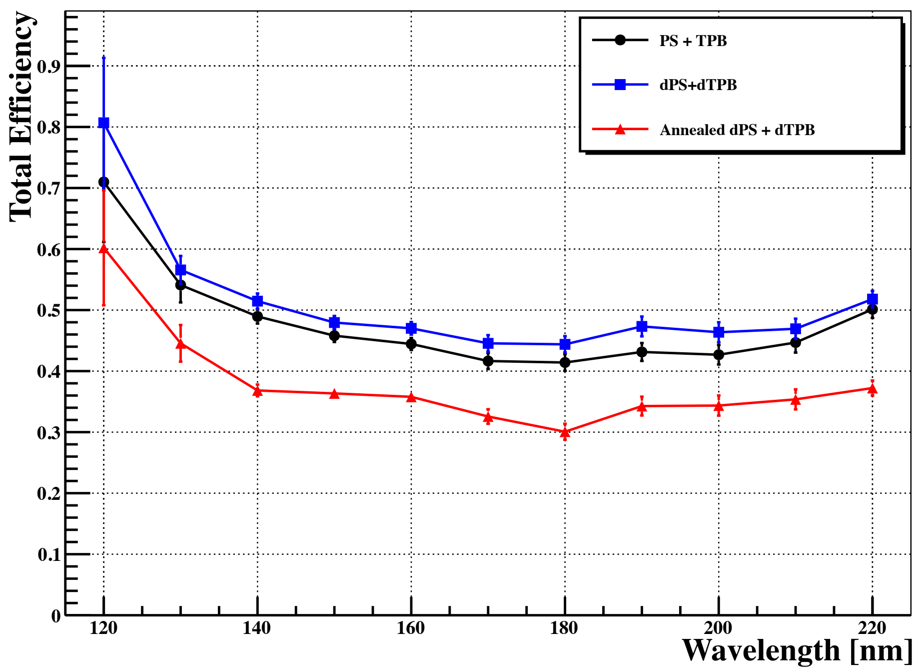
- recent paper: V.M. Gehman, T.M. Ito, W.C. Griffith, and S.R. Seibert, J.of Inst., **8** P04024 (2013).
- wanted to check conversion efficiency for nedm coating
  - any difference for deuterated vs. "regular" ?
  - does annealing the coating affect light production?
    - would like to anneal glued/coated boxes to relieve stresses
    - "baking" the test cells tends to improve UCN storage
- samples prepared at LANL:
  - PS + TPB
  - dPS + dTPB
  - dPS + dTPB annealed at 75 C for 12 hours after coating

dTPB light conversion measurements by Vic





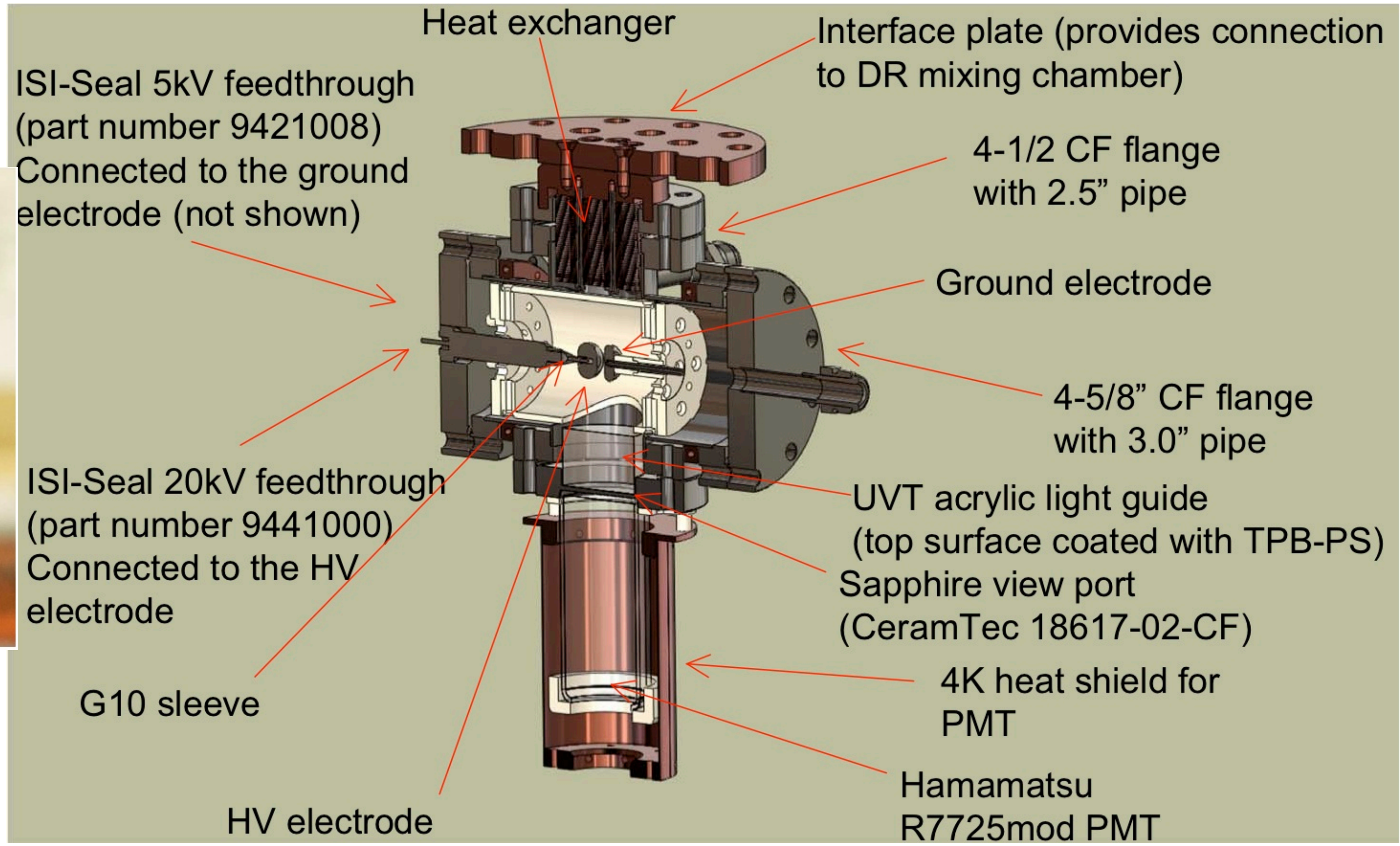




- dPS+dTPB looks pretty similar to regular PS +TPB
- heat treated sample has ~25% reduction

Liquid He scintillation in an E-field

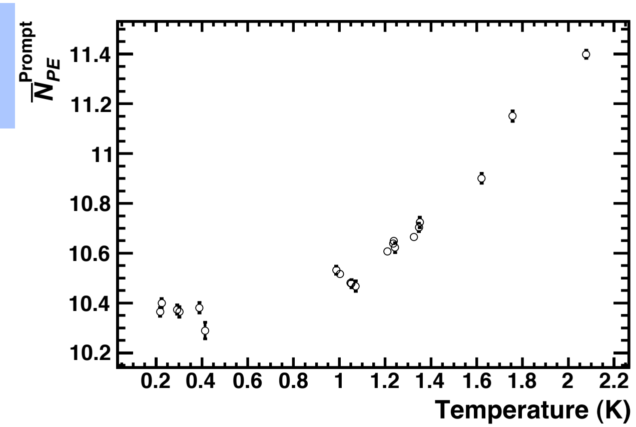
- LANL, Indiana U, Brown — T. Ito et al, Phys Rev A 85, 042718 (2012).
- small HV test cryostat mounted on IU dilution fridge



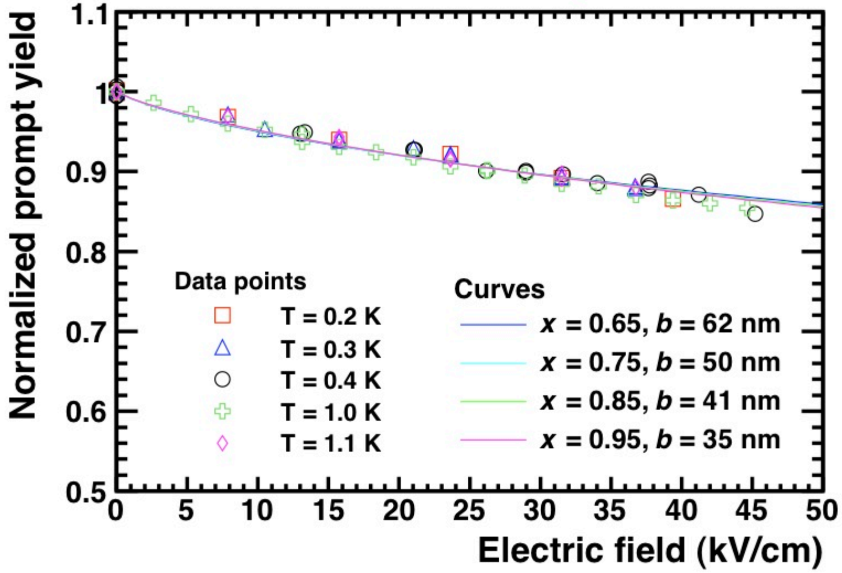
- ^{241}Am α-source electroplated on ground electrode

Liquid He scintillation in an E-field

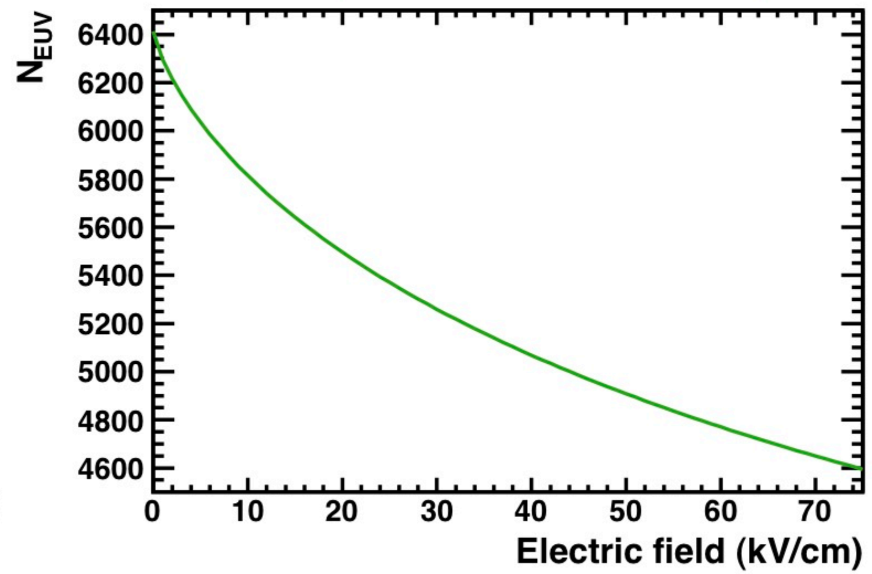
T. Ito et al, Phys Rev A 85, 042718 (2012).



Data taken with α particles

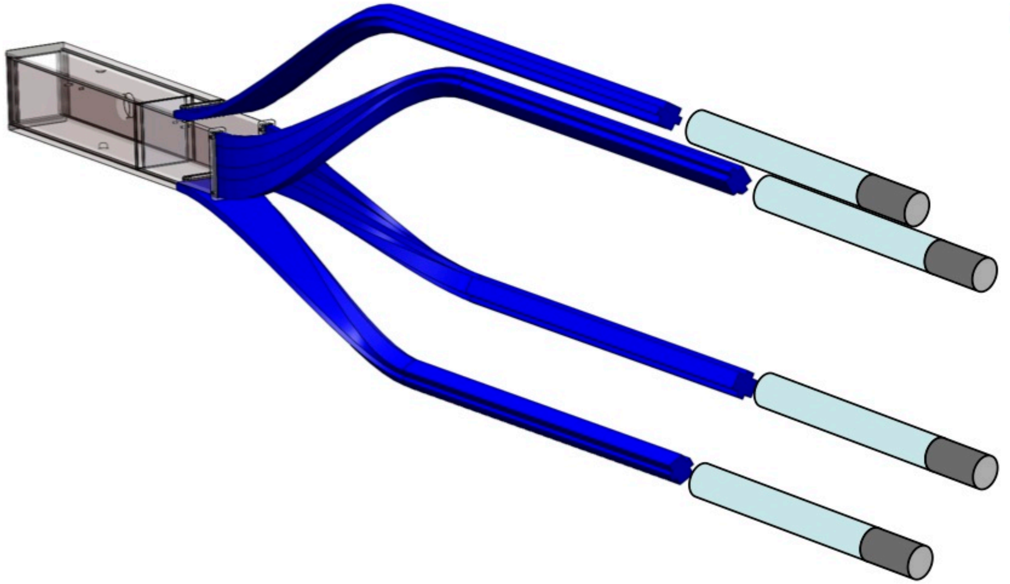


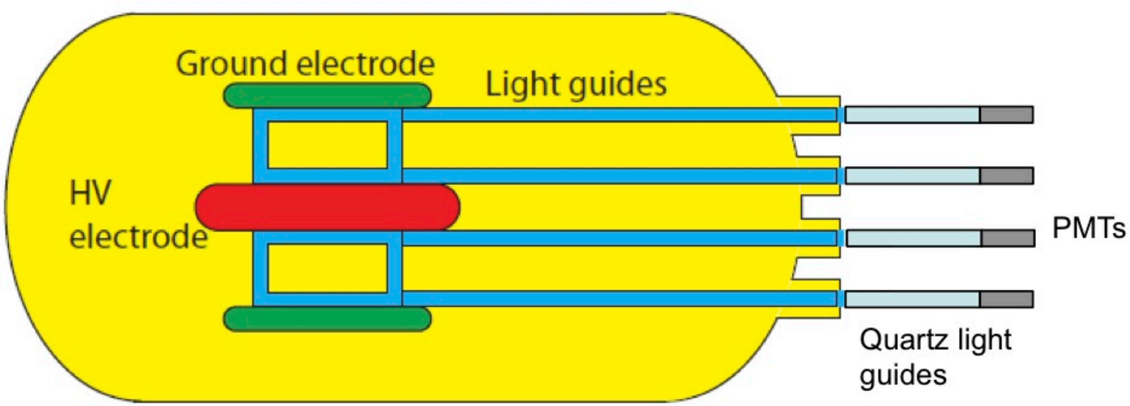
Model prediction for n capture



- The scintillation yield reduces by ~ 15% @ 50 kV/cm.
- The data can be well described by the Jaffe-Kramers columnar theory of recombination (G. Jaffe (1913), H. A. Kramers (1952)).
- The data were used to make a prediction on N_{Euv} for $^3He(n,p)^3H$.

Expected # of photoelectrons





Current estimate of the #PE

- Based on calculations and measurements of individual loss factors

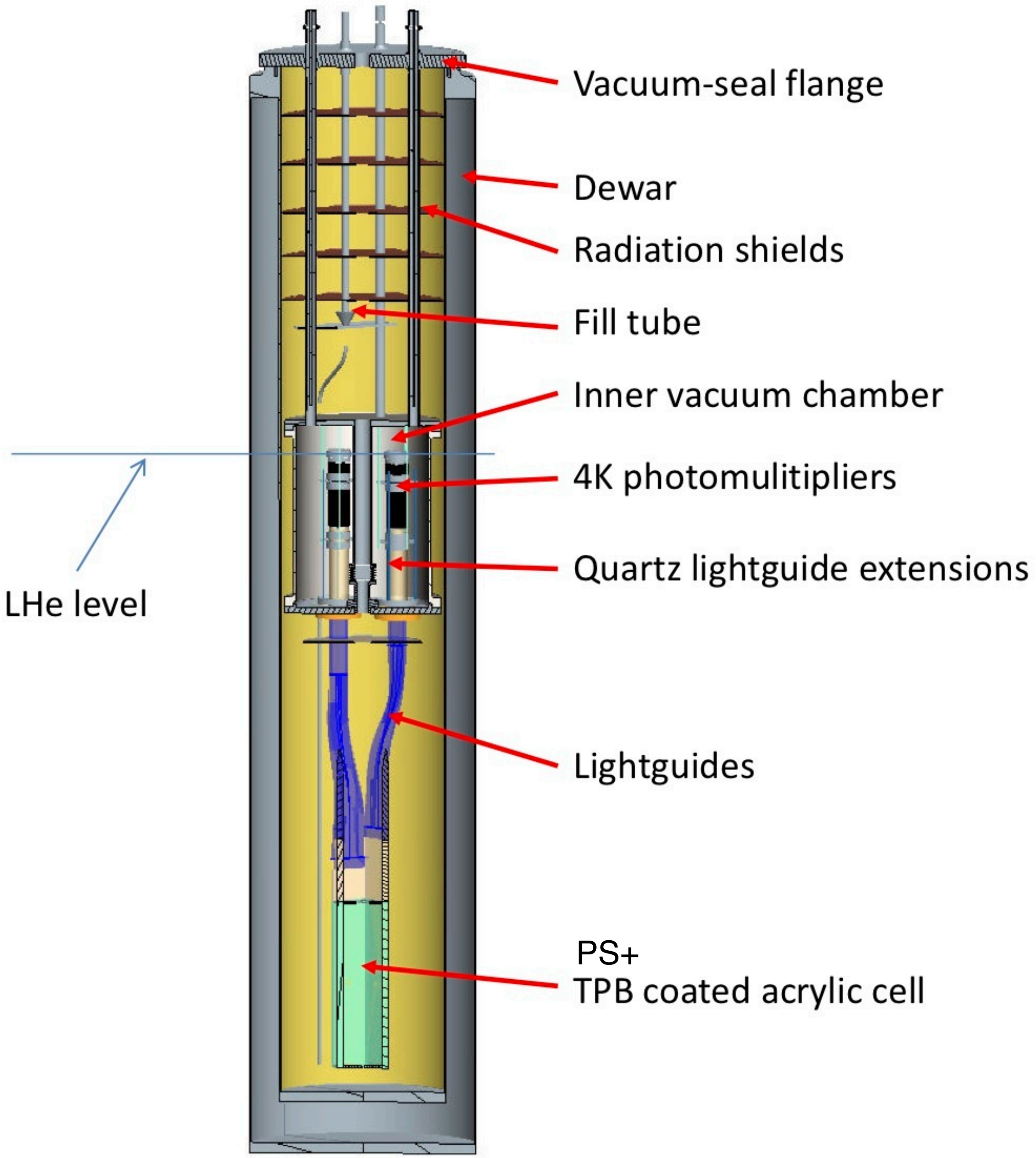
Factor	Value	% Error
N_{XUV}	4800	15
ε_{HV}	0.76	5
$\Omega_{TPB}/4\pi$	0.90	1
ε_{conv}	0.33	19
$\varepsilon_{collect}$	0.21	5
ε_{coated}	0.92	5
$\varepsilon_{endcaps}$	0.87	1
ε_{holes}	0.97	10
ε_{gaps}	0.78	5
g_{AR}	1.05	4
$\varepsilon_{straight\text{-}guide}$	0.64	3
ε_{bend}	0.88	10
ε_{PMT}	0.18	10
#PE	**14.8**	**32**

Directly measured

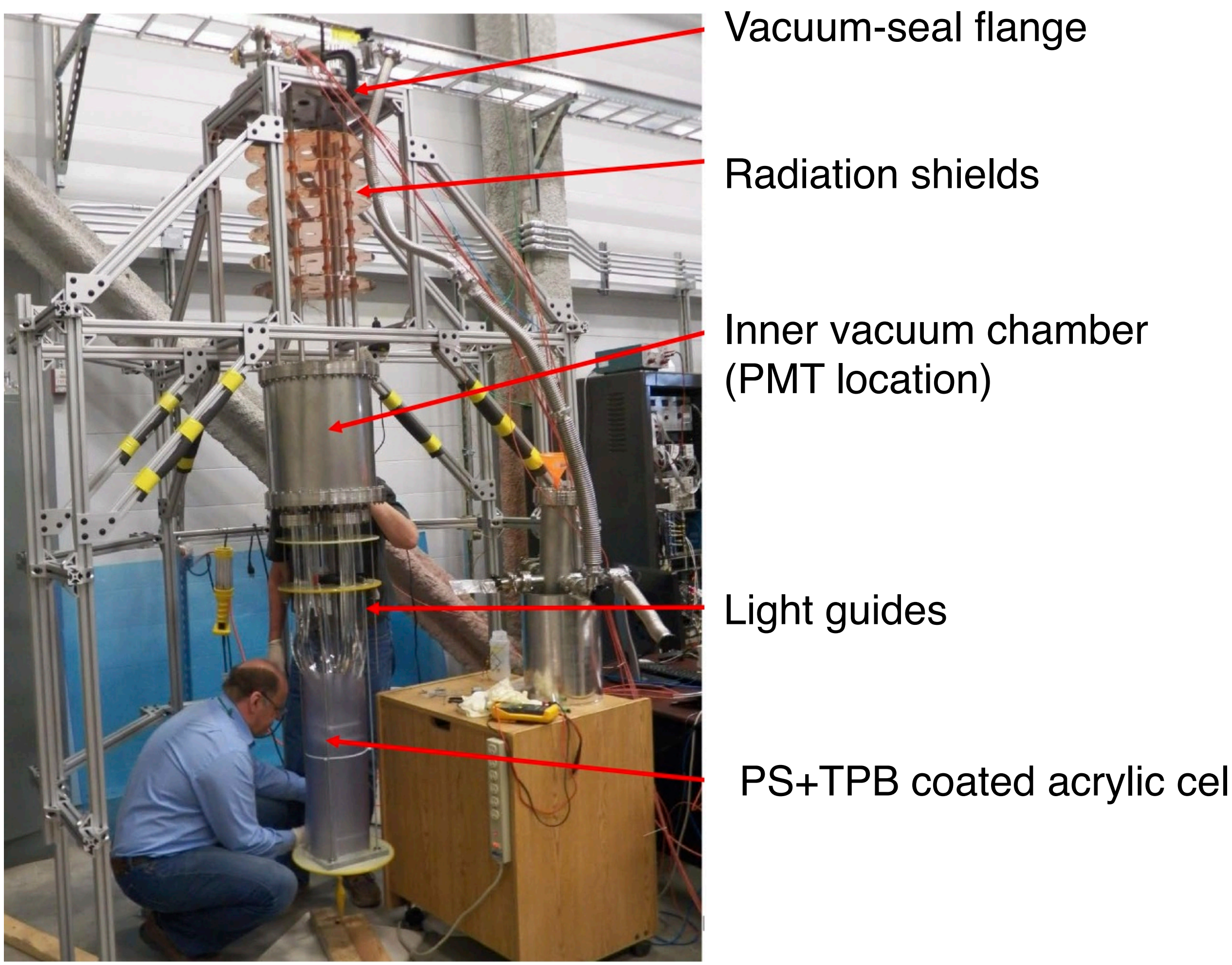
Indirectly measured

Cryogenic light collection test

- Goal: near full size test of light collection system in LHe
- cross-check of the estimate based on table of individually measured/calculated loss factors
- 80 nm scintillation from ^{210}Po α-source, vertically scannable



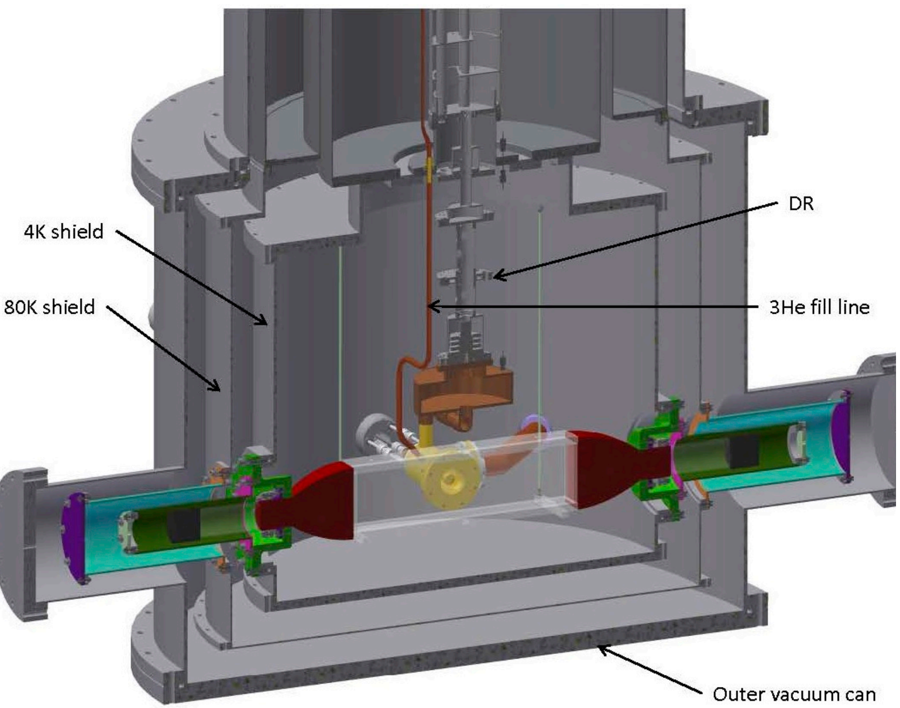
Cryogenic light test

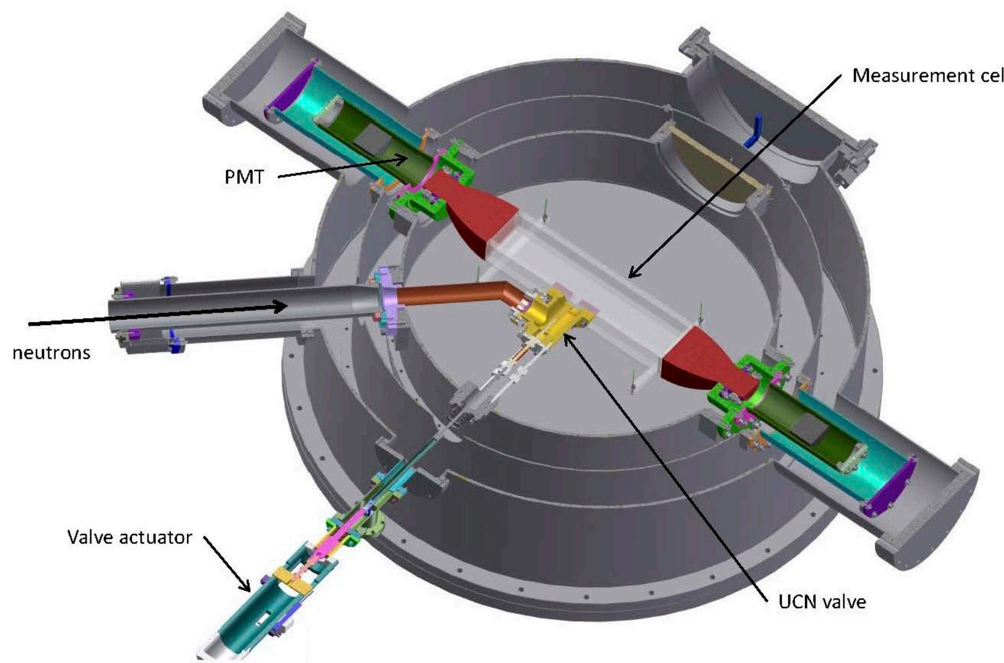


- apparatus in place at Oak Ridge
- room temperature tests with UV-LED indicate things working as expected
- first cryogenic measurements in progress…

PULSTAR nedm systematic studies apparatus

- a nedm test apparatus is planned for a new solid deuterium UCN source at the NCSU PULSTAR reactor
  - will include UCN in LHe, polarized ^{3}He, magnetic coils/shields
  - further light generation/collection tests, UCN storage, spin dressing optimization…





Summary

- EDM searches in the neutron, paramagnetic, and diamagnetic systems provide a valuable test for new sources of *CP*-violation.
- neutron EDM efforts should improve sensitivity by 1-2 orders of magnitude in next 5-10 years
- SNS nEDM experiment development is ongoing
  - only nEDM approach using LHe scintillation light detection
  - hopefully moving towards final design and construction 2014-2018