The cryo EDM Experiment at ILL

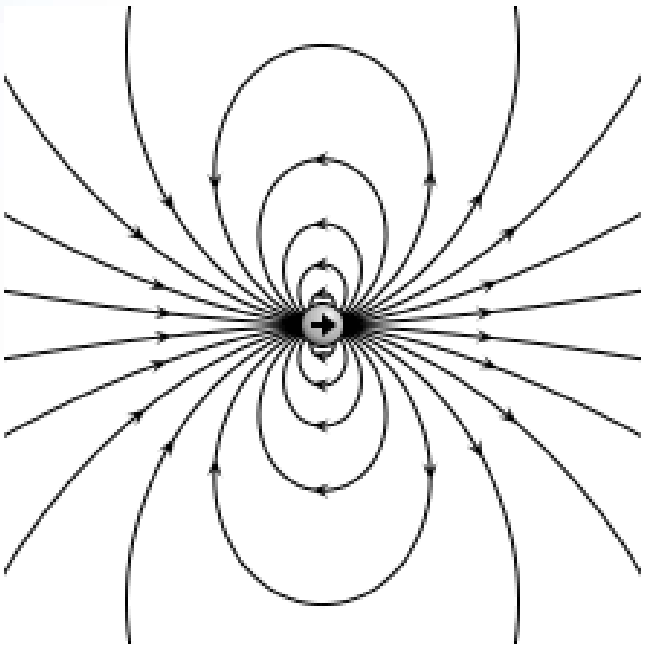
Melissa George

Seminar, Queen Mary University of London, Nov 30th 2012

Let's Start at The Beginning

- The neutron EDM is a measure of the distribution of positive and negative charges inside the neutron.
- Such an EDM would violate P, T and CP symmetry.
- Neutron EDM is predicted to exist by ~all models including the standard model.

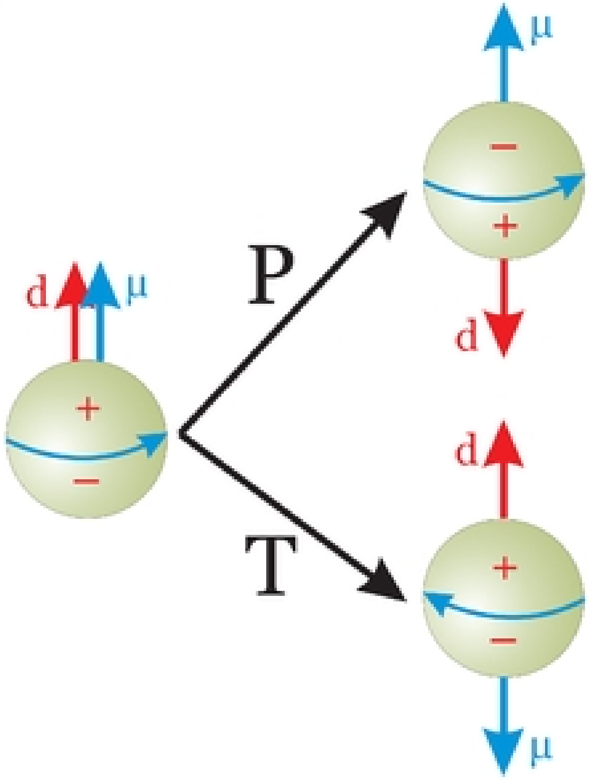
The electric Dipole Moment



Courtesy of Wikipedia:
A transformation from a point-shaped dipole to a finite-size electric dipole is shown.
Imagine yourself zooming in and out.

Electric Dipole Moments

- Under parity, the electric dipole moment changes its direction but not the magnetic dipole moment.
- Under T reversal, the magnetic dipole moment changes its direction, whereas the electric dipole moment stays unchanged.
- Having also CPT symmetry, the combined symmetry CP is violated as well
  - Important to test with other systems than K, B



- Clean system
  - background free: SM predicts tiny EDMs, other models typically 10^6 larger.
- Can be used to place tight constraints on models of new physics.

Baryogenesis

Sakharov Conditions

- **Baryon number Violation.**
  - To produce an excess of baryons.
- **CP Violation.**
  - To prevent annihilation of the baryon excess.
- **Departure from thermal equilibrium.**
  - Prevent washout by inverse processes.

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

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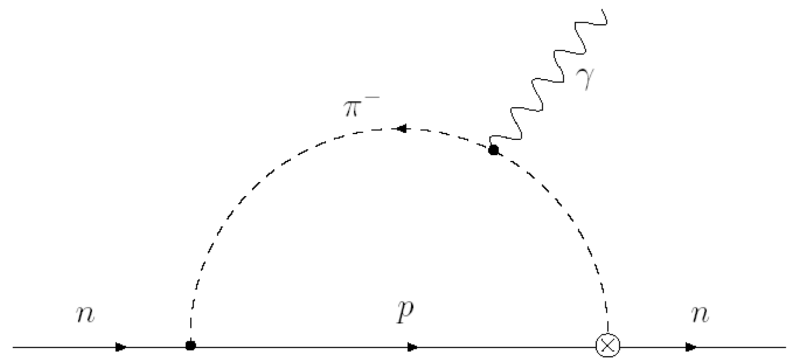
CP Violation

Standard Model CP violation is orders of magnitude too small to explain observed asymmetry – we need new physics.

Larger-than-SM CP violation tends to predict larger-than-SM EDMs

Standard Model EDM

- EDMs are zero-momentum limit of fermion-fermion-photon 3-point function:



- SM CPv related to single phase in CKM, flavour change
- EDM is flavour conserving CPv, “flavour change squared”
- In fact >3 loops; v. suppressed

$$d_n^{\rm KM} \simeq 10^{-32} e\ {\rm cm}.$$

$$d_e^{\rm KM} \leq 10^{-38} e\ {\rm cm},$$

Standard Model EDM

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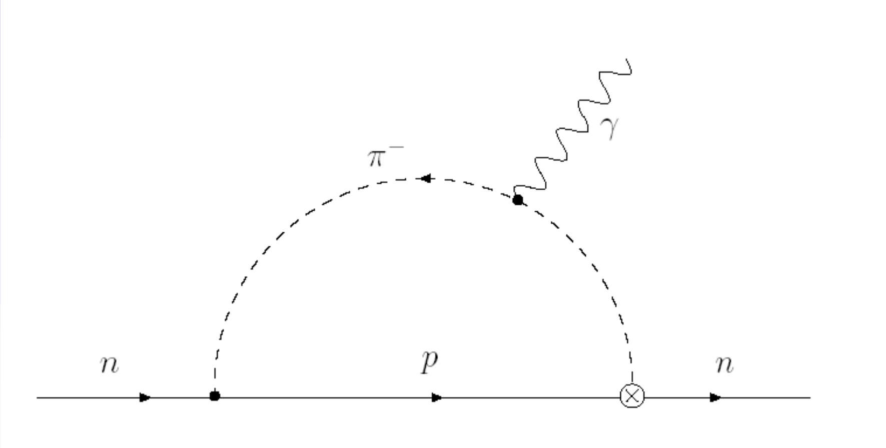

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$$d_e^{\rm KM} \leq 10^{-38} e \text{ cm,}$$

Strong CP Problem

- Due to its quark content the neutron is susceptible to CP violation from the strong interaction.
- QCD naturally includes a neutron EDM of:

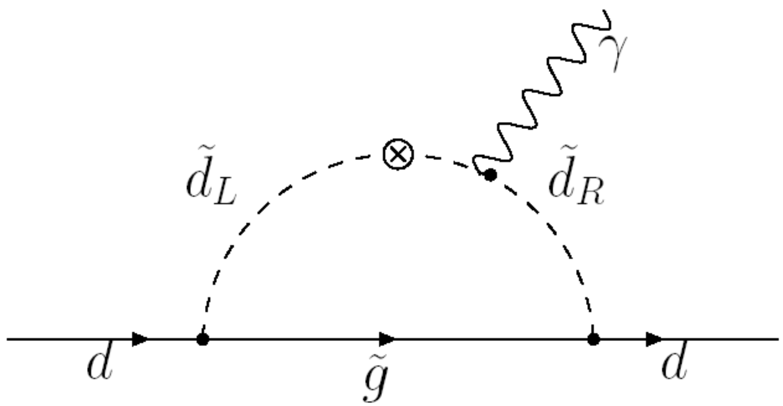
$$d_n \sim 10^{-16}\ \theta\ \text{e.cm}$$

$$\Rightarrow \theta < 2\times10^{-10}\ \text{rads}$$

- Thus limiting θ from its natural value of order 1 rad.
  - Why is θ so small?
  - Peccei-Quinn: Axions?

Supersymmetry / SUSY CP Problem

- MSSM without corrections gives: EDM = 10^{-23-25} e.cm ALREADY RULED OUT!! Current World Limit = 2.9 x 10^{-26} e.cm (90% CL)
- SUSY breaking introduces new CPv phases
- EDMs appear at 1-loop level



$$\kappa_i = \frac{m_i}{16\pi^2 M_{\rm SUSY}^2} = 1.3 \times 10^{-25}{\rm cm} \times \frac{m_i}{1{\rm MeV}} \left(\frac{1{\rm TeV}}{M_{\rm SUSY}}\right)^2,$$

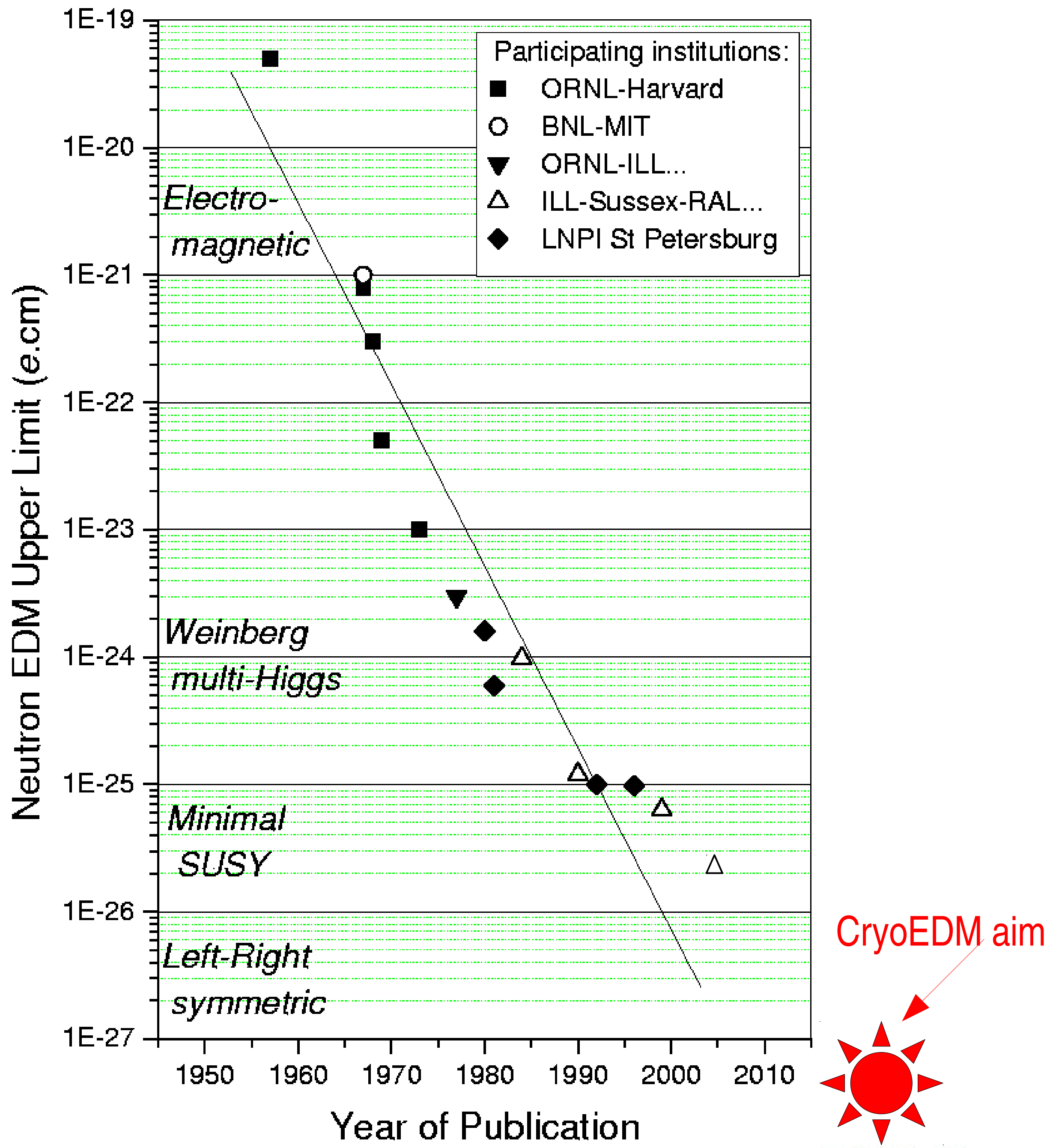
- SUSY with extensions: EDM = 10^{-28} e.cm NEARLY WITHIN AIM OF cryoEDM!!

History

Factor 10

per decade

on average



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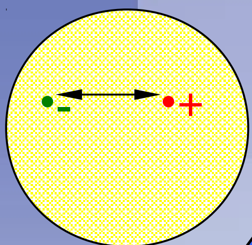
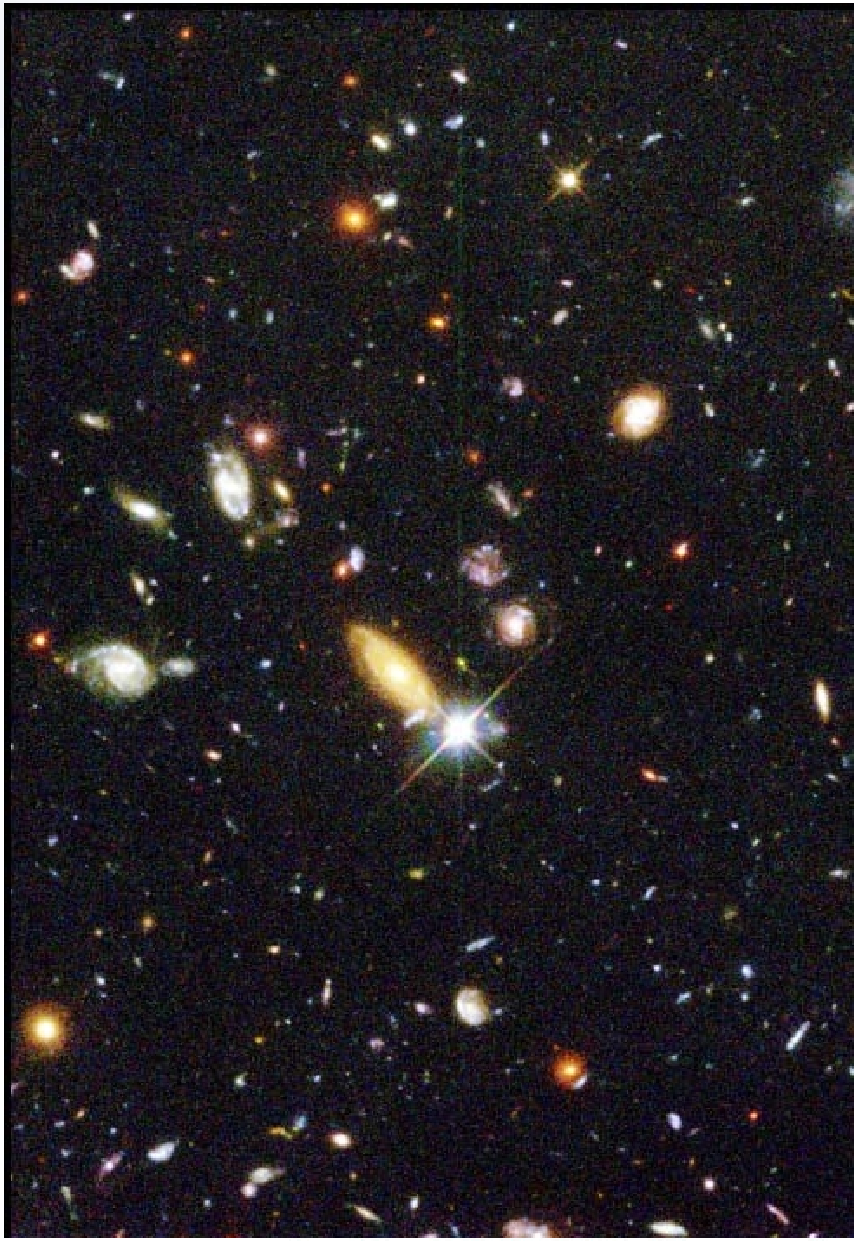
Reality Check

If the EDM we could see was expanded
to the size of, e.g., a football



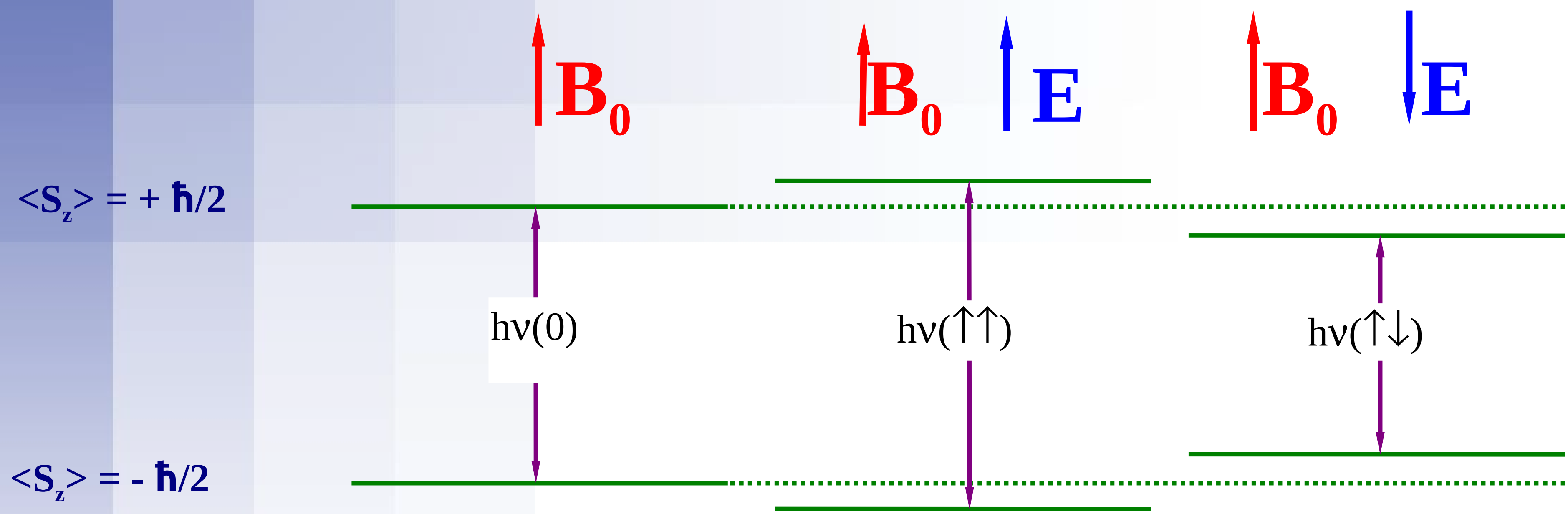
...then a football enlarged by the same amount
would expand to the size of ....

the visible Universe.



Measurement Principle

Use NMR on ultracold neutrons in **B, E** fields

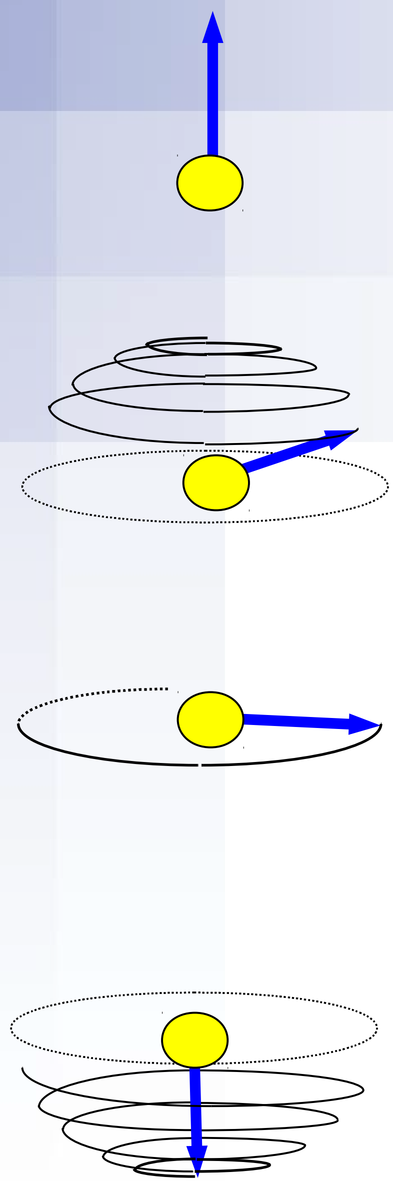


$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/h$$

assuming **B** unchanged when **E** is reversed.

Energy resolution of our detector: $<10^{-21}$ eV

Ramsey Method of Separated Oscillating Fields

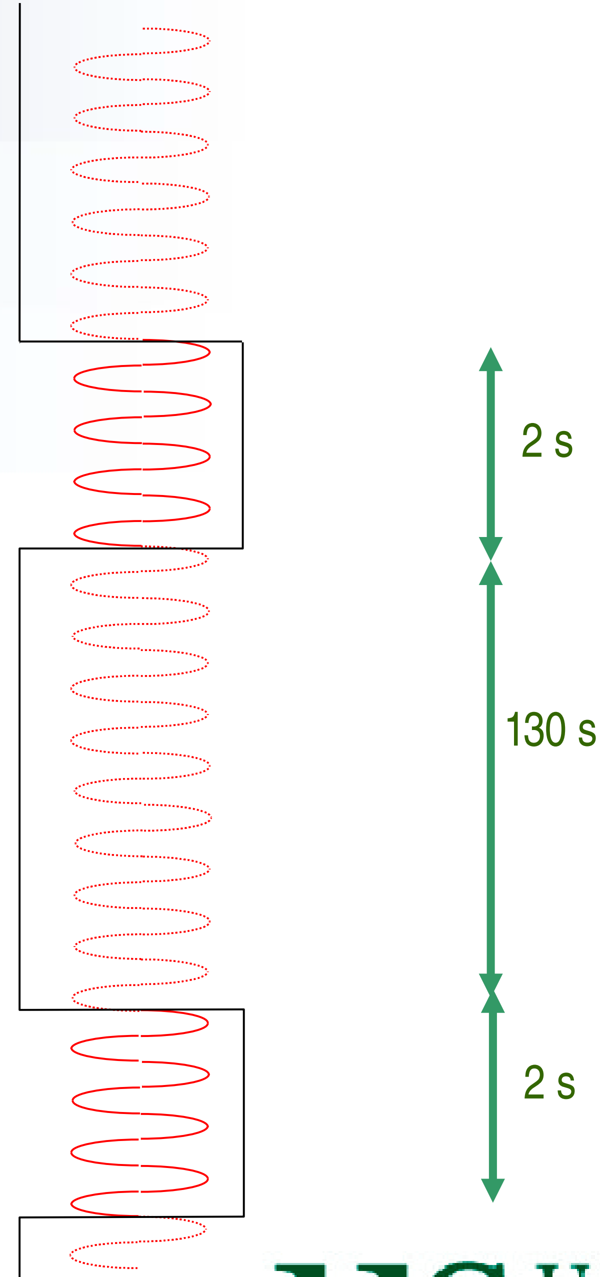


1. *"Spin up" neutron...*

2. *Apply $\pi/2$ spin-flip pulse...*

3. *Free precession...*

4. *Second $\pi/2$ spin-flip pulse*



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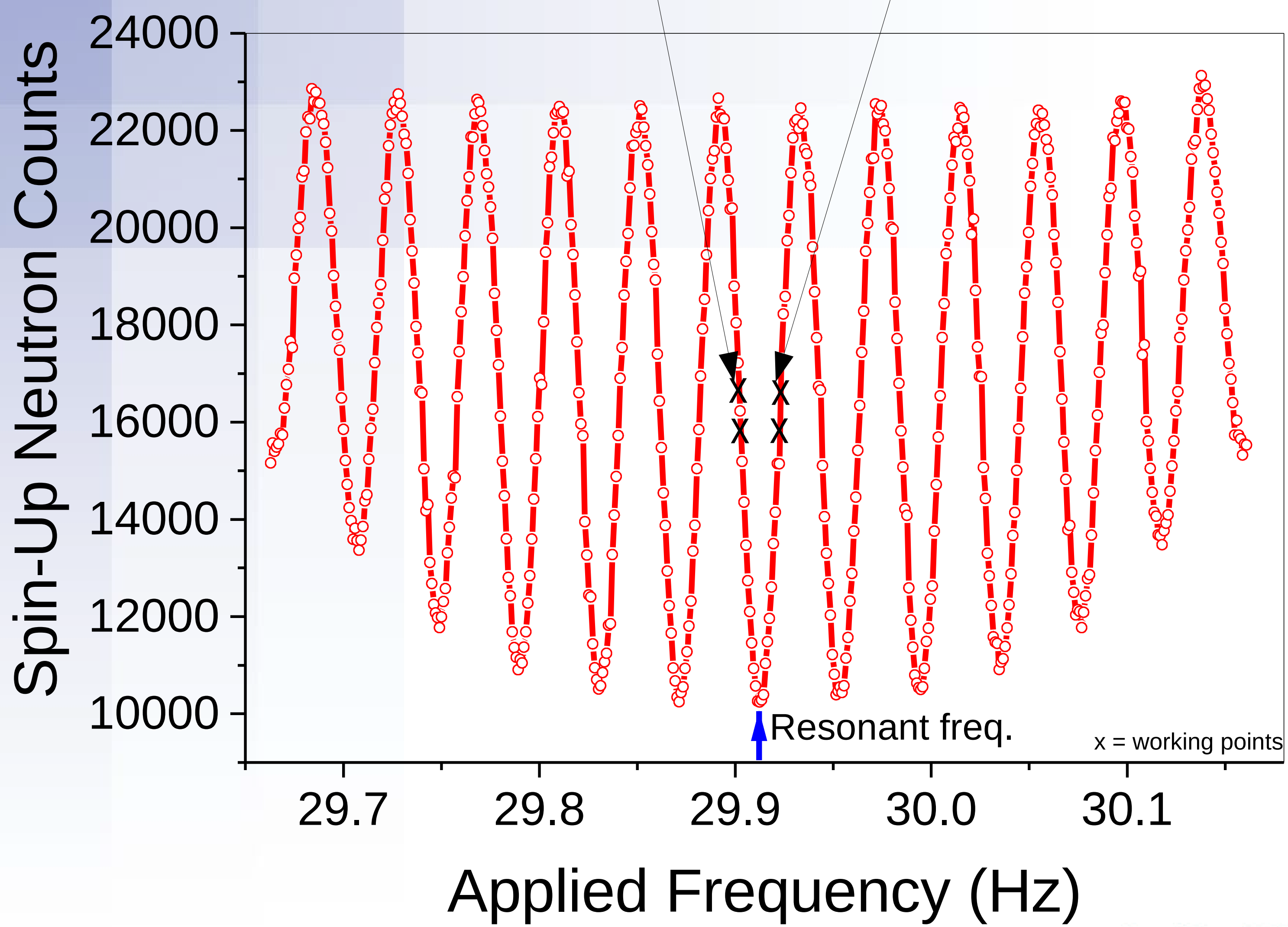
Ramsey Resonance

Phase gives frequency offset from resonance



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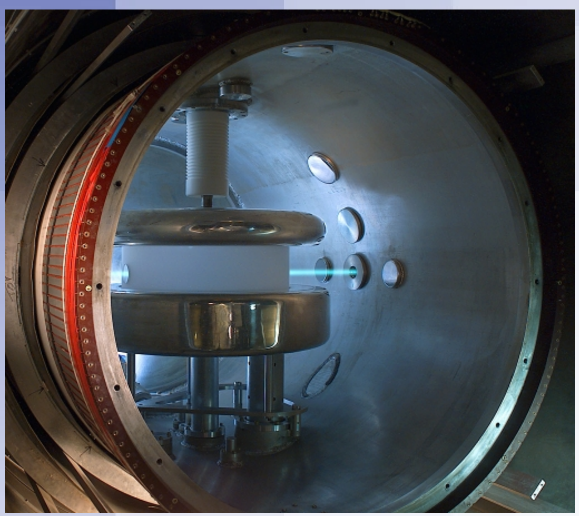
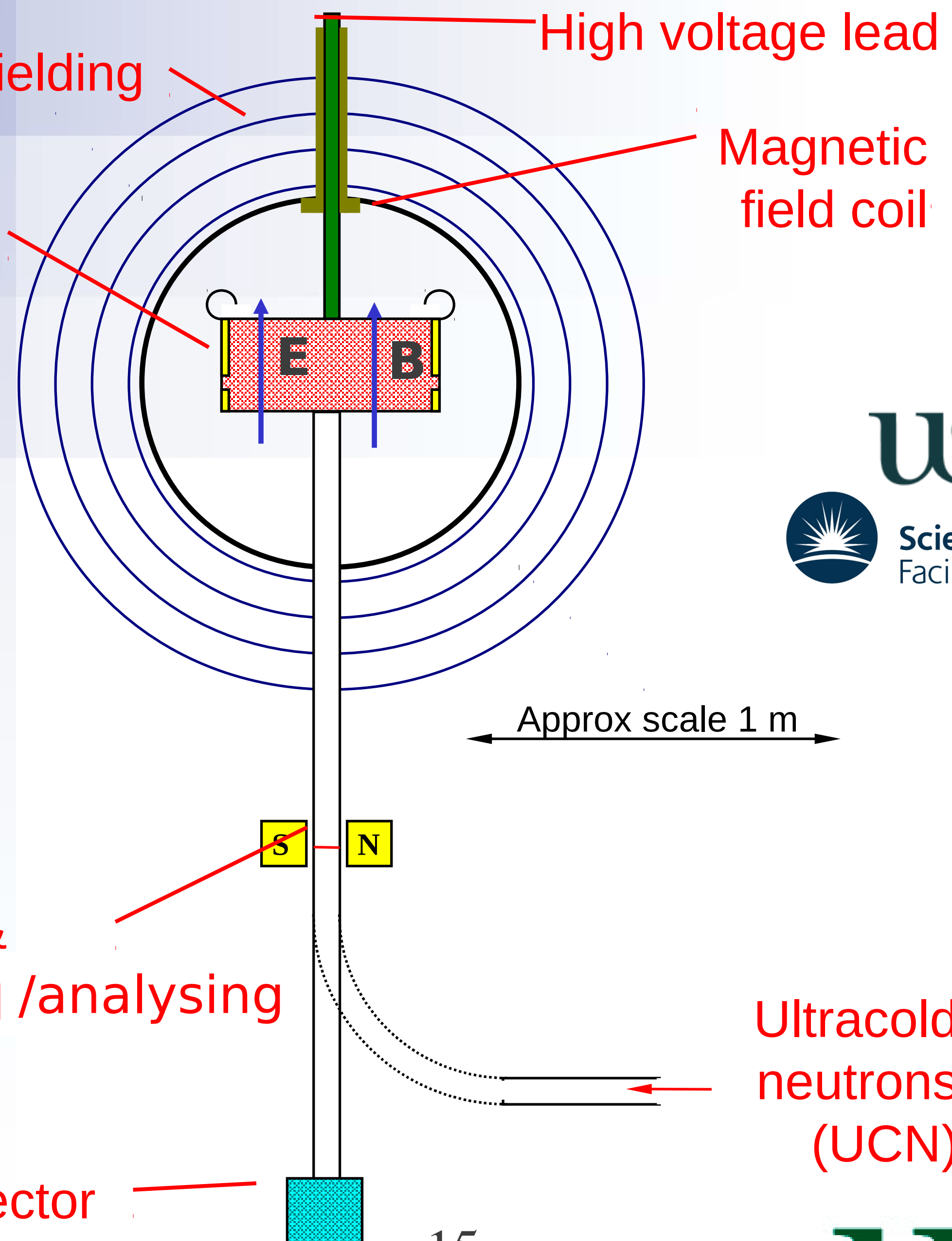
Room Temperature nEDM Experiment





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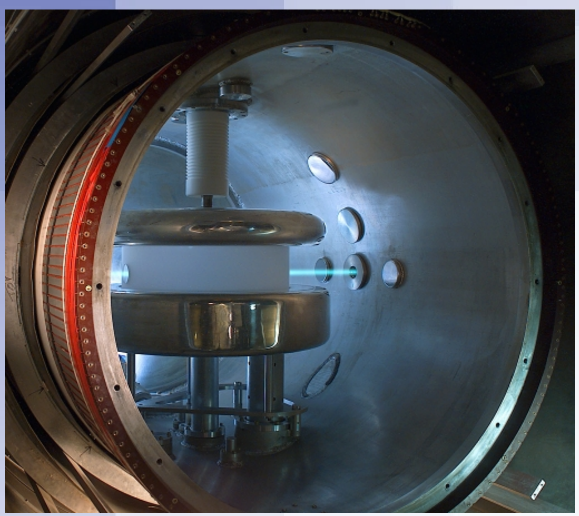
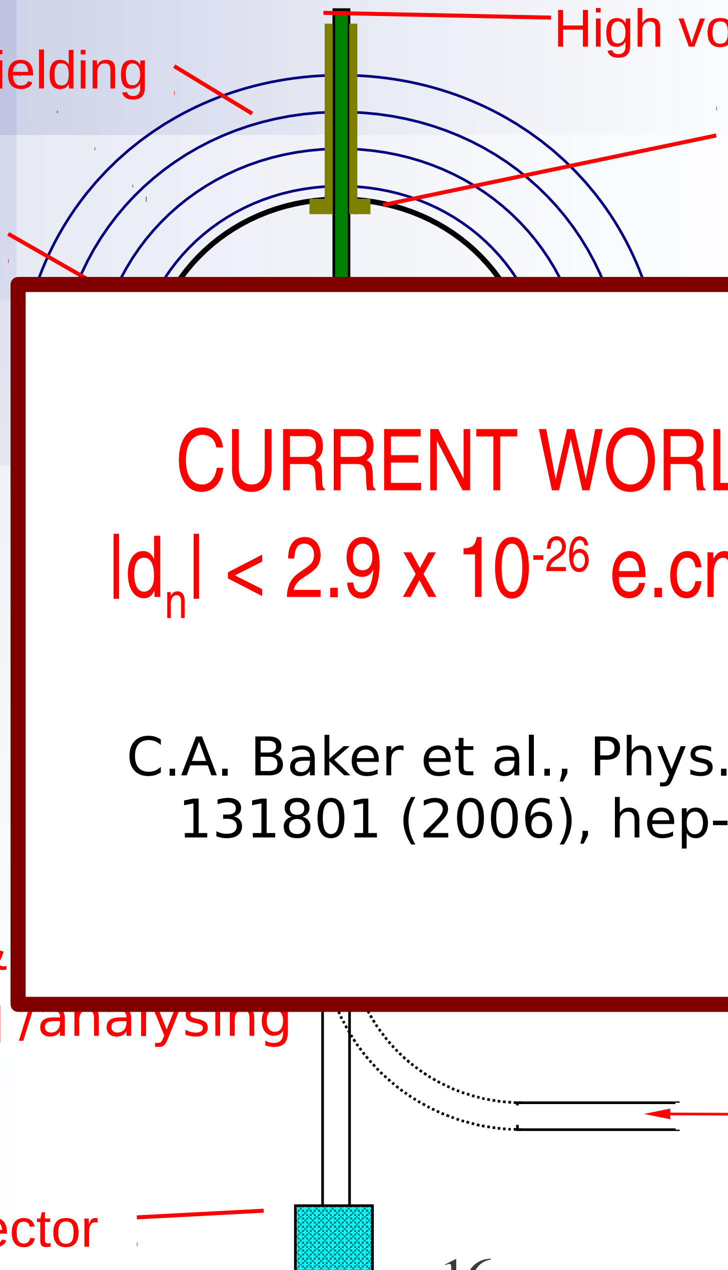




CURRENT WORLD LIMIT:

$|d_n| < 2.9 \times 10^{-26}$ e.cm (90% CL)

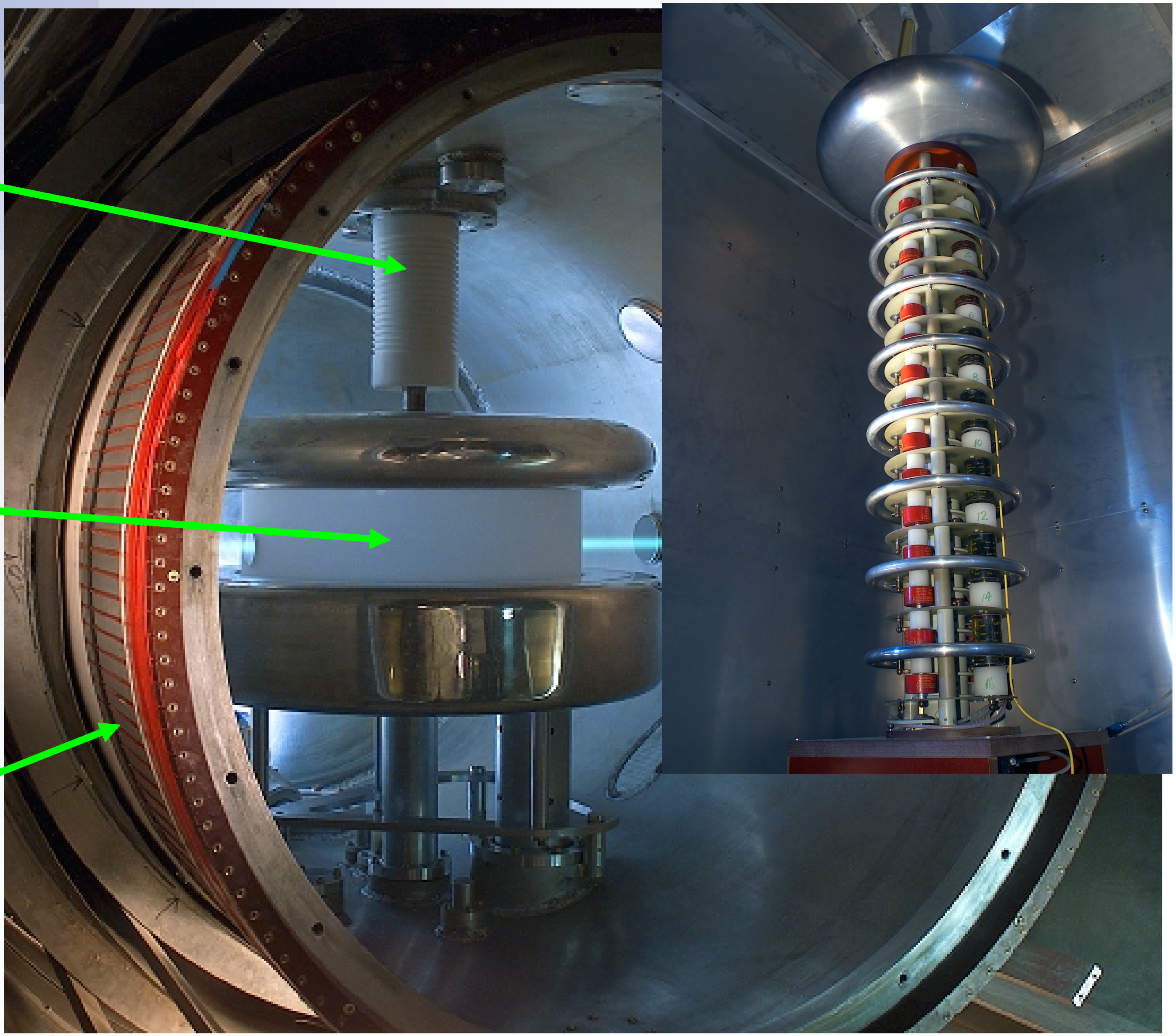
C.A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006), hep-ex/0602020

The Real Thing

HV feedthru

Neutron storage chamber

B-field coils



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ILL, Grenoble

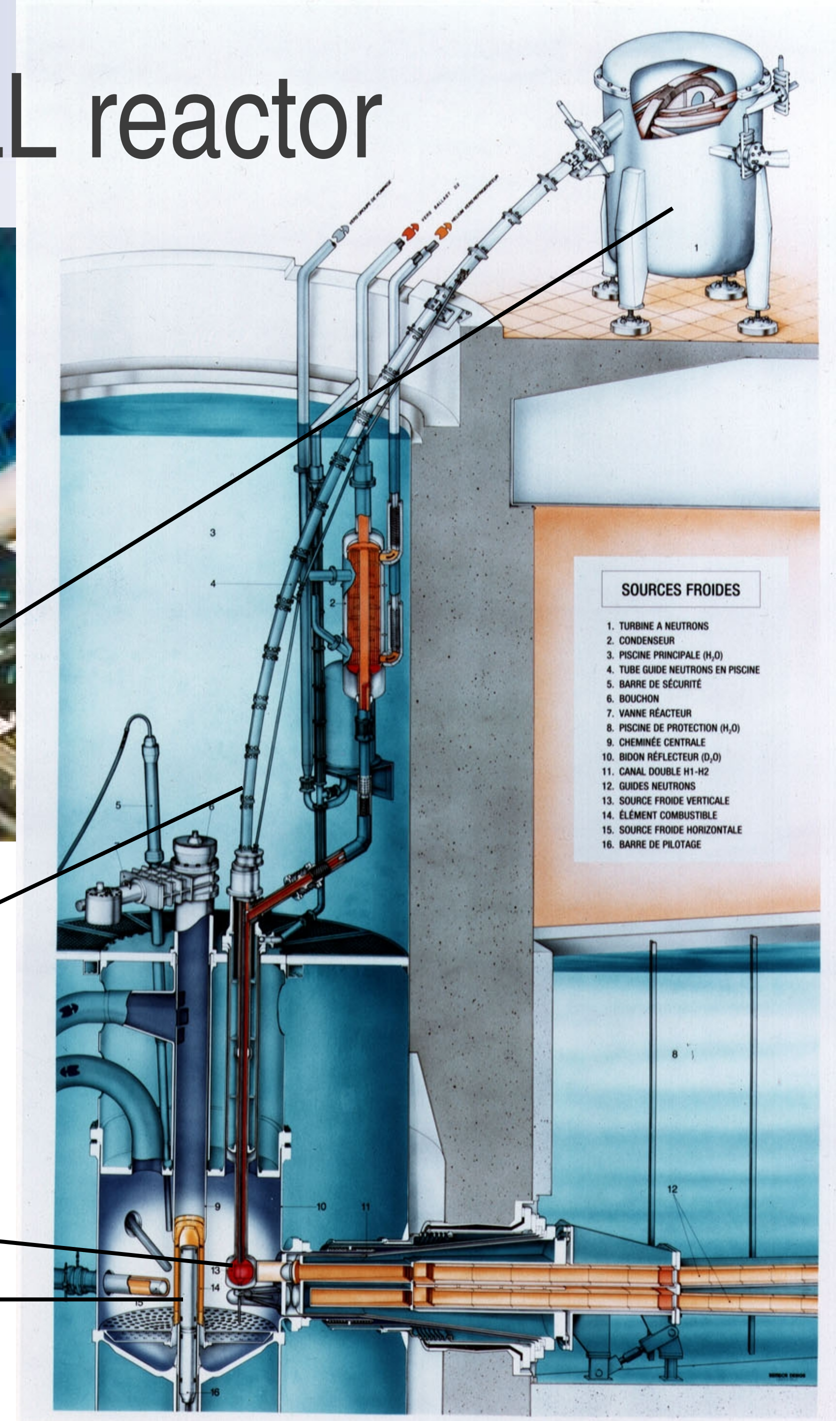
NEUTRONS FOR SCIENCE

The CryoEDM Collaboration

- Involves 5 institutions from 3 Countries.

- RAL
  - Neutron Production and detection
  - cryogenics
- Sussex
  - Analysis and Software
  - DAQ and MC
  - Cryogenics
  - HV, inc in liquid Helium
  - B field control
- Oxford
  - SQUID systems
- ILL
  - Reactor Neutrons
- Kure
  - Cryogenic apparatus

The ILL reactor



Neutron turbine
A. Steyerl (TUM - 1986)

Vertical guide tube

Cold source

Reactor core

Neutron Energies

Ultracold Neutrons have an energy less than 3×10^{-7} eV.

Slow neutrons have a kinetic energy less than or equal to 0.4 eV.

Epithermal neutrons have an energy from 1 eV to 10 keV.

Hot neutrons have an energy of about 0.2 eV.

Thermal neutrons have an energy of about 0.025 eV.

Cold Neutrons have an energy from 5×10^{-5} eV to 0.025 eV.

Very cold neutrons have an energy from 3×10^{-7} eV to 5×10^{-5} eV.

Fast neutrons have kinetic energies greater approximately 1 MeV.

Continuum region neutrons have an energy from 0.01 MeV to 25 MeV.

Resonance region neutrons have an energy from 1 eV to 0.01 MeV.

Low energy region neutrons have an energy less than 1 eV.

The ILL reactor

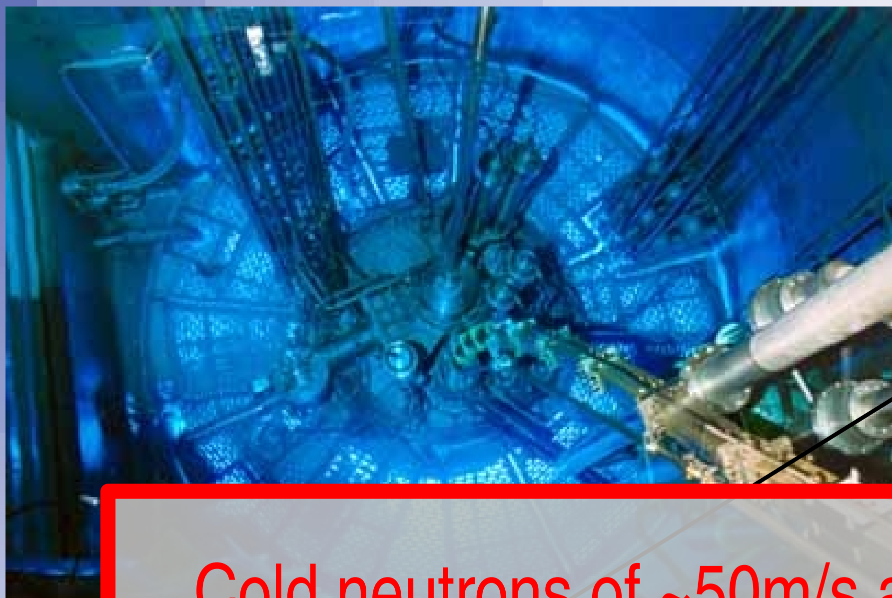
Neutron turbine
A. Steyerl (TUM - 1986)

Vertical guide tube

Cold n source

Reactor core

The ILL reactor



Neutron turbine
A. Steyerl (TUM - 1986)

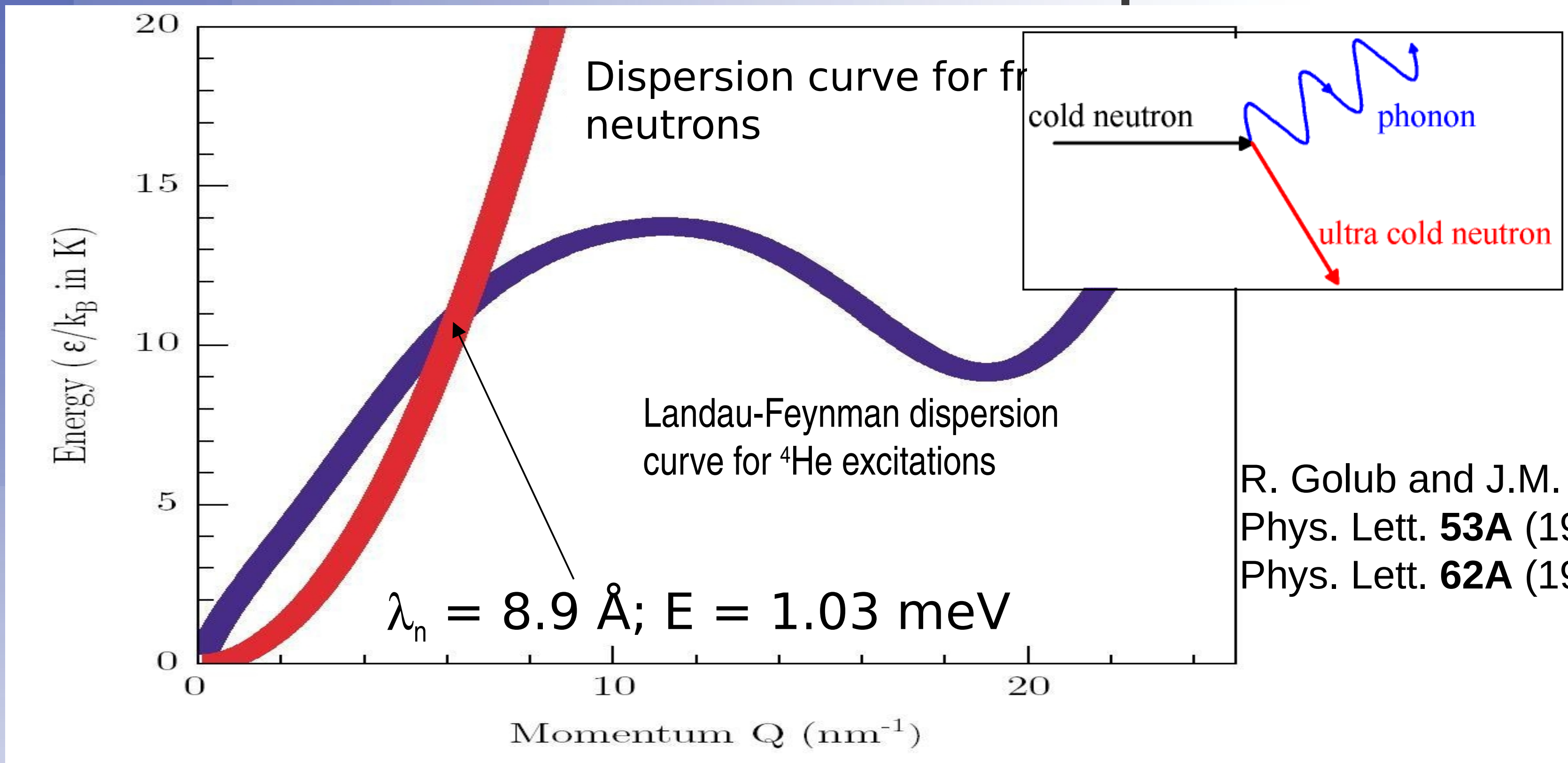
Vertical guide tube

Cold n source

Reactor core

Cold neutrons of ~50m/s are produced with a liquid D2 moderator near the core of the nuclear reactor at ILL.

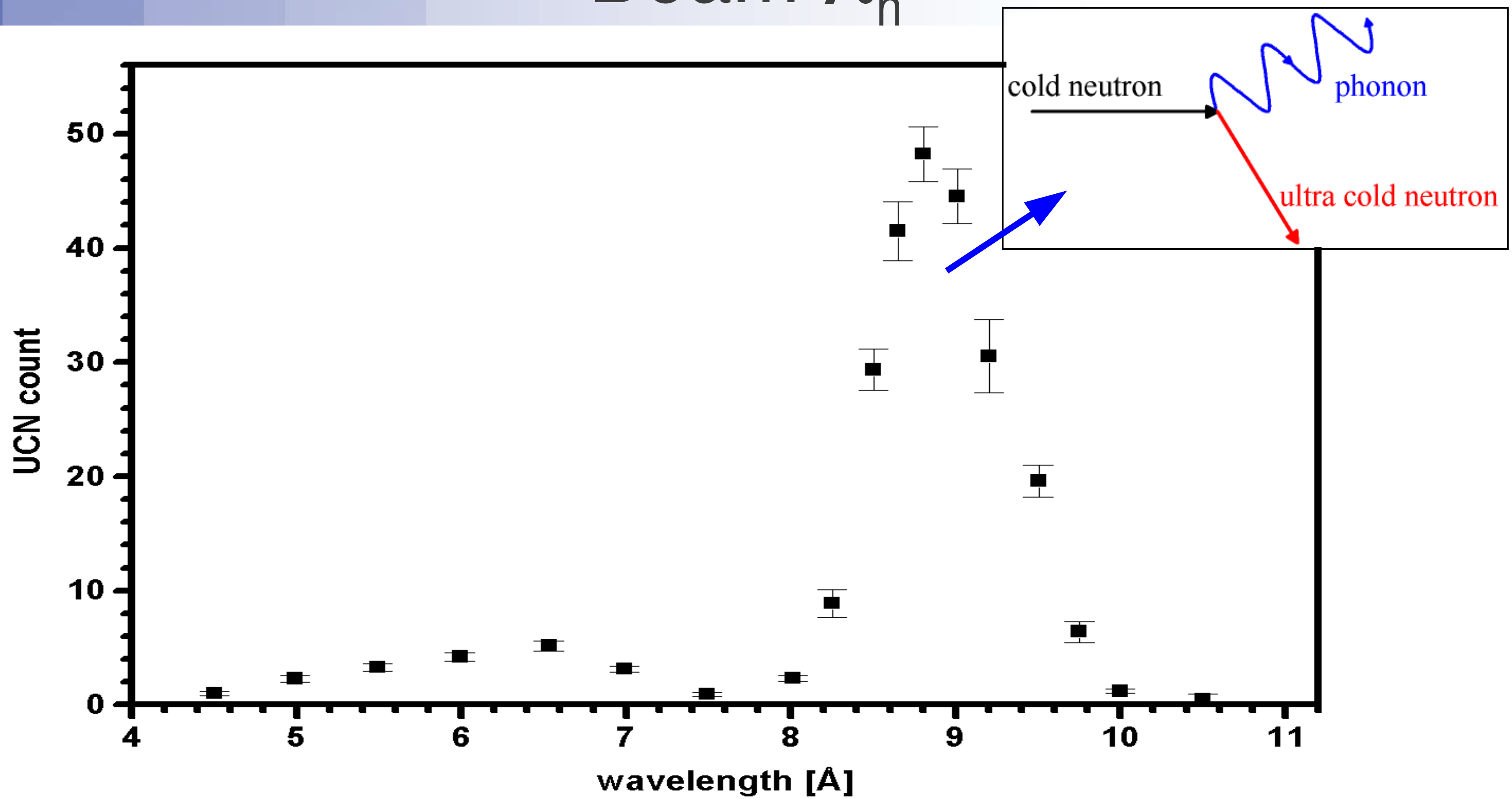
UCN Production In Liquid Helium



R. Golub and J.M. Pendlebury
Phys. Lett. **53A** (1975),
Phys. Lett. **62A** (1977)

- In liquid helium at 11K a 9A neutron will downscatter by emission of phonon in helium atom, loose its energy coming to a stop and hence becoming a UCN.
- Upscattering suppressed: Boltzmann factor $e^{-E/kT}$ means not many 11 K phonons present.

UCN production rate vs Wavelength of Neutron Beam λ_n

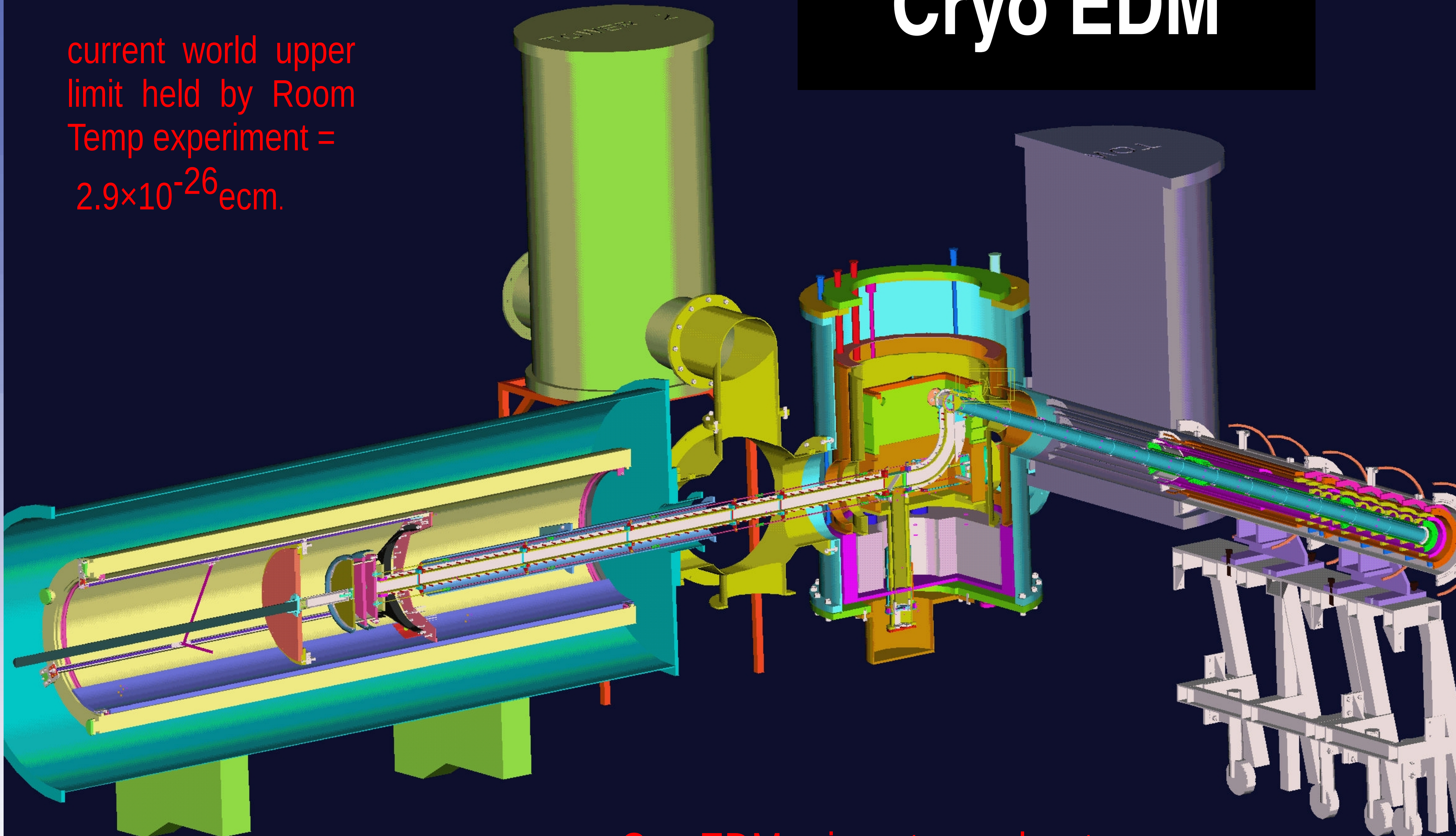


1.19±0.18 UCN cm^{-3} s^{-1} expected, 0.91± 0.13 observed

C.A.Baker et al., Phys.Lett. **A308** 67-74 (2002)

Cryo EDM

current world upper limit held by Room Temp experiment = 2.9×10^{-26}ecm.



CryoEDM aims to probe to 10^{-28}ecm

Neutrons and The Source

- Neutrons go through a polariser to polarise the neutrons before they enter the source.
- Only the 9 Å neutrons are fed into our detector.
- Neutrons enter the source as fast moving thermal neutrons.
- These neutrons are then transformed in the liquid helium to slow moving (~8ms^{-1}) Ultracold Neutrons UCN.
- Giving us an anticipated production rate of 1.4 n/cc/s and a resulting density in the source of 30 n/cc.
- UCN are needed as they have long wavelengths compared to the inter-nuclei spacings in a solid. This means that for many materials the neutrons cannot travel through the walls of the material (we use beryllium coated copper).

The Physics Bit
Calculating The Neutron EDM

N_1 = Neutrons spin up, N_2 = Neutrons spin down, $\uparrow\uparrow$ = E and B fields parallel, $\uparrow\downarrow$ = E and B fields anti-parallel

$$d_n = \frac{N_1\uparrow\uparrow - N_2\uparrow\uparrow - N_1\uparrow\downarrow + N_2\uparrow\downarrow}{2\alpha E T \sqrt{N}}$$

Neutron EDM

Polarisation x analysing efficiency

Electric Field

Storage time in Ramsey cells

Total neutrons

Sensitivity

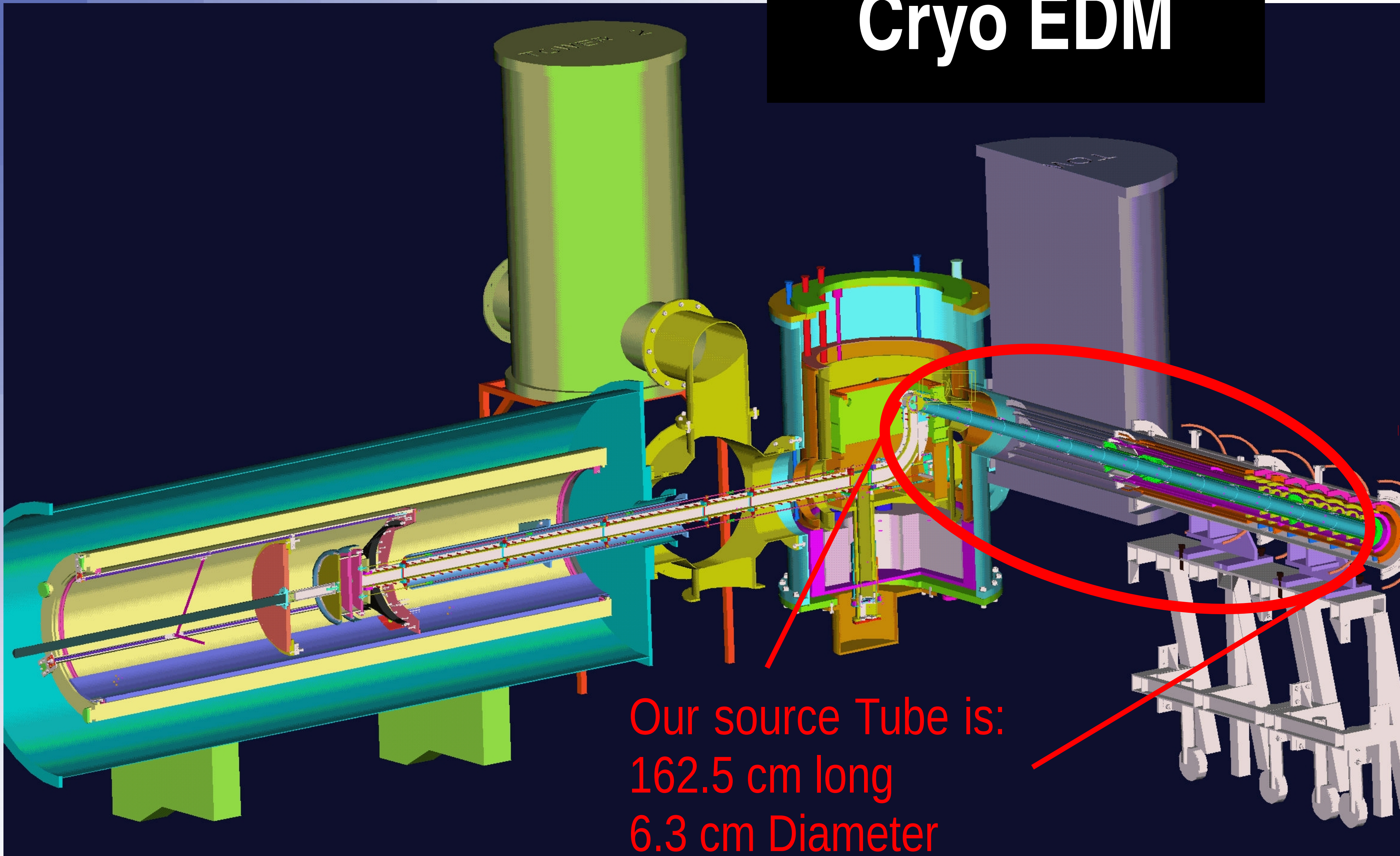
$$\sigma_d = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

(NB sensitivity/day is actually closer to $\sigma_d = \frac{\hbar}{2\alpha E \sqrt{TN}}$)

A Precision Experiment

- Number of neutrons
  - As sensitivity depends on √N.
- Lifetime
  - The neutron lifetime of ~881.5±1.5 can be greatly reduced in the experiment.
- Polarisation
- Constant Magnetic Field
  - Inhomogeneities in the field causes in different parts of the apparatus to precess with different frequencies, hence reducing polarisation.
- Field control and Monitoring
  - We must be able to either reduce stray fields or accurately map them so as to reduce their affect in analysis.
- Electric Field
  - Sensitivity has a linear dependence on E, this fields should therefore, be as great as poss.

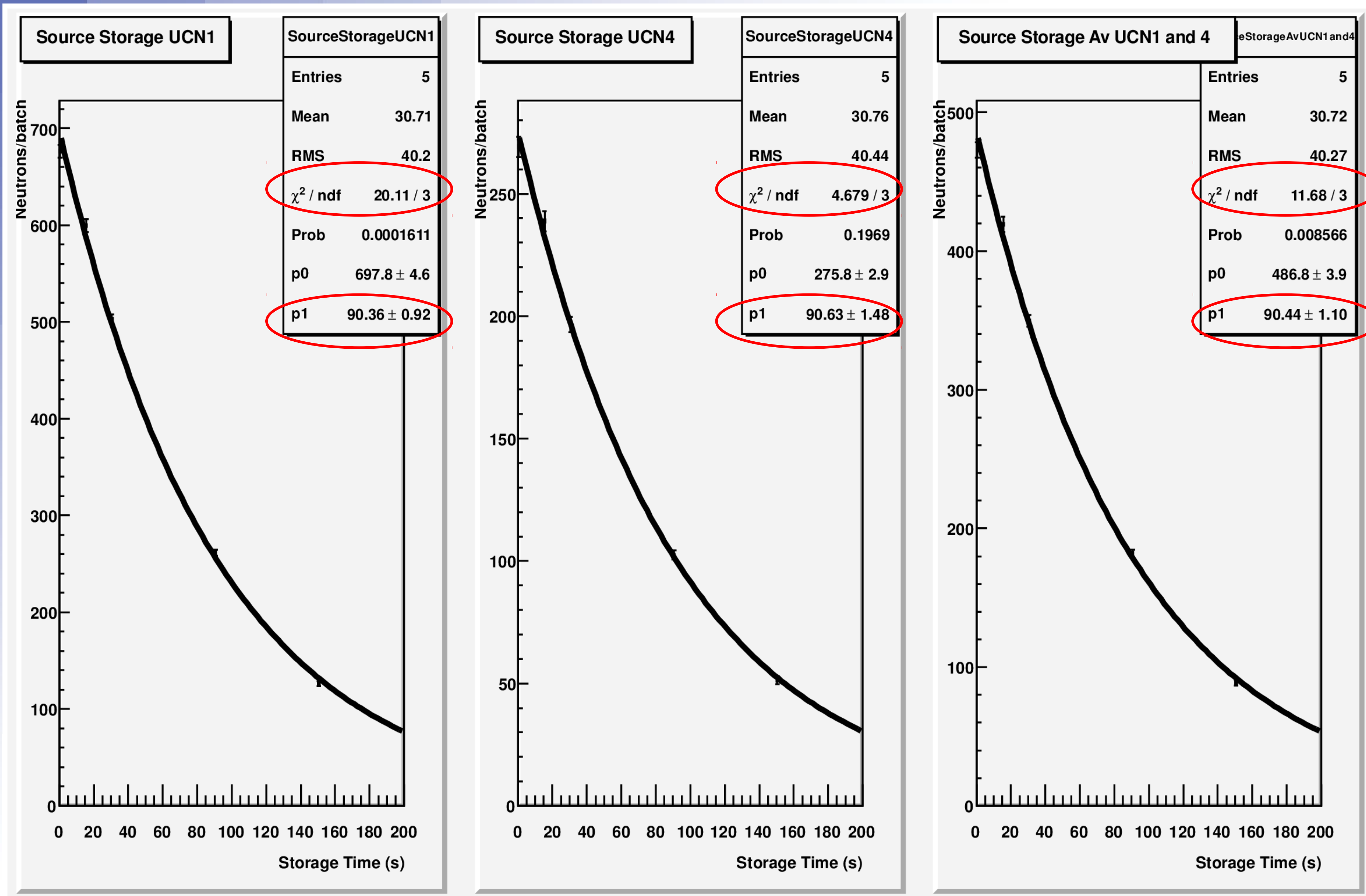
Cryo EDM



Our source Tube is:
162.5 cm long
6.3 cm Diameter
In 13 sections
Beryllium copper

Source Lifetime

~ 90.44 +/- 1.1s



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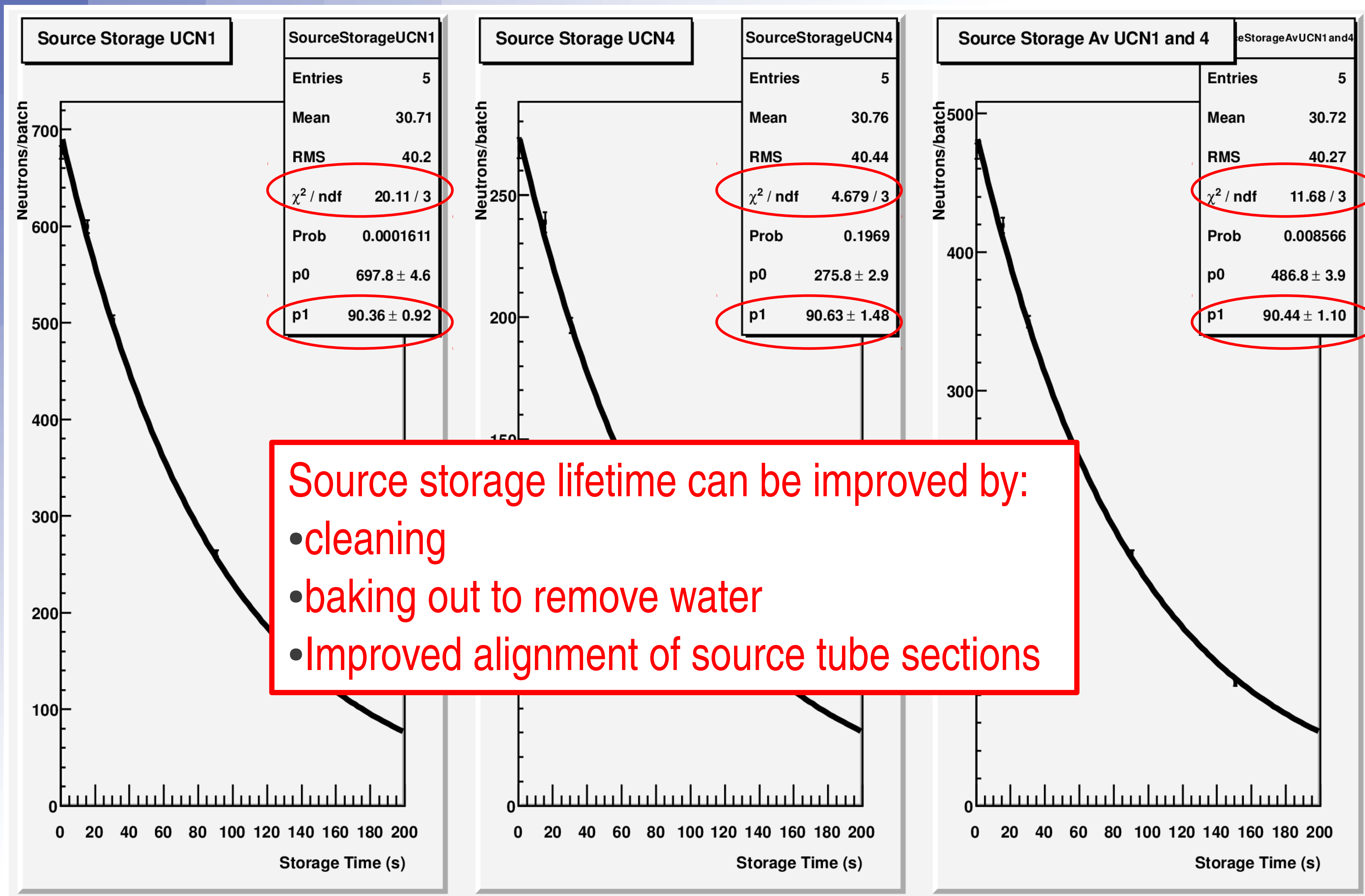
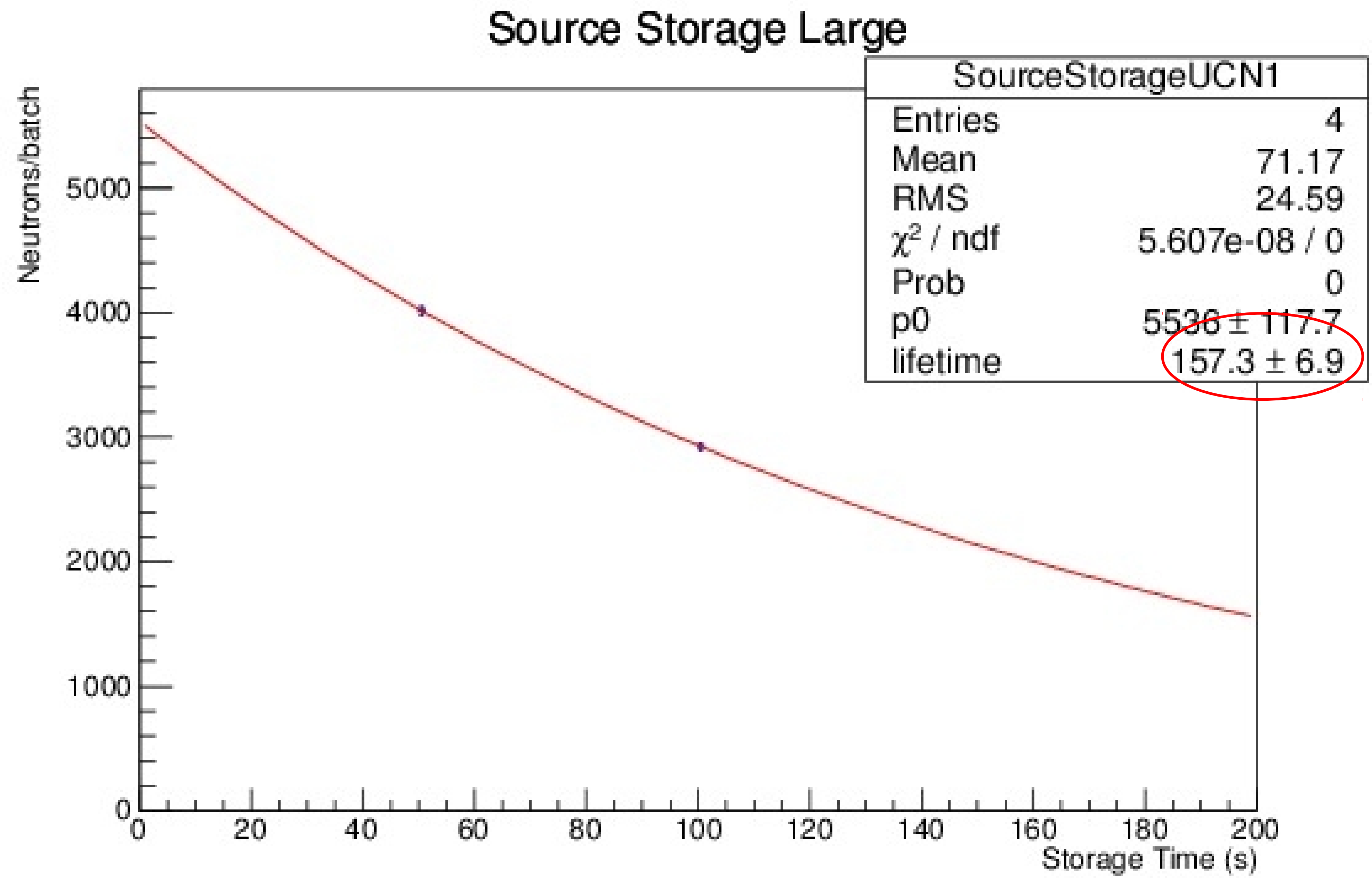


Source storage lifetime can be improved by:

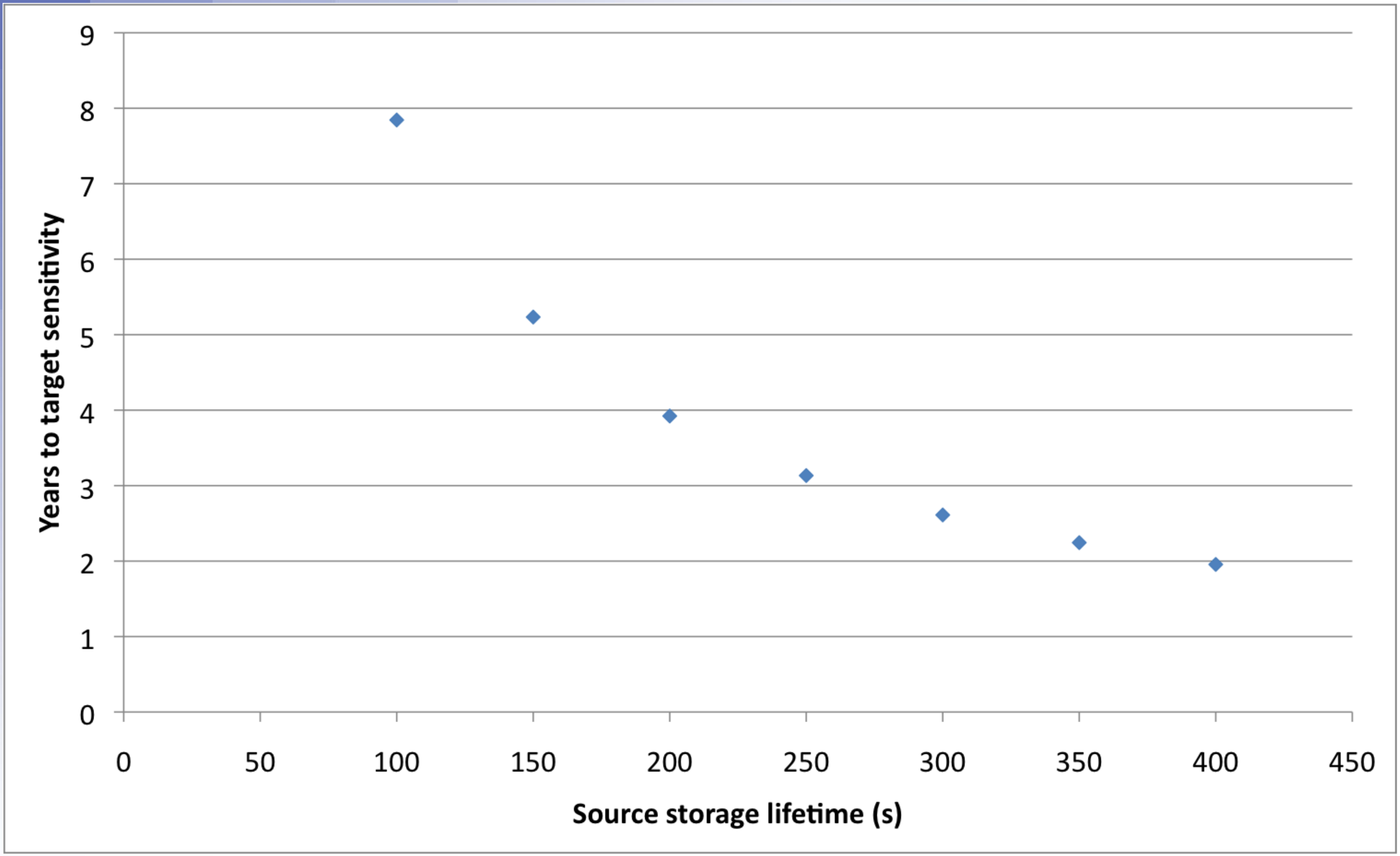
- cleaning
- baking out to remove water
- Improved alignment of source tube sections

Source Lifetime

157.3 +/- 6.9s



Source Storage Lifetime vs Sensitivity



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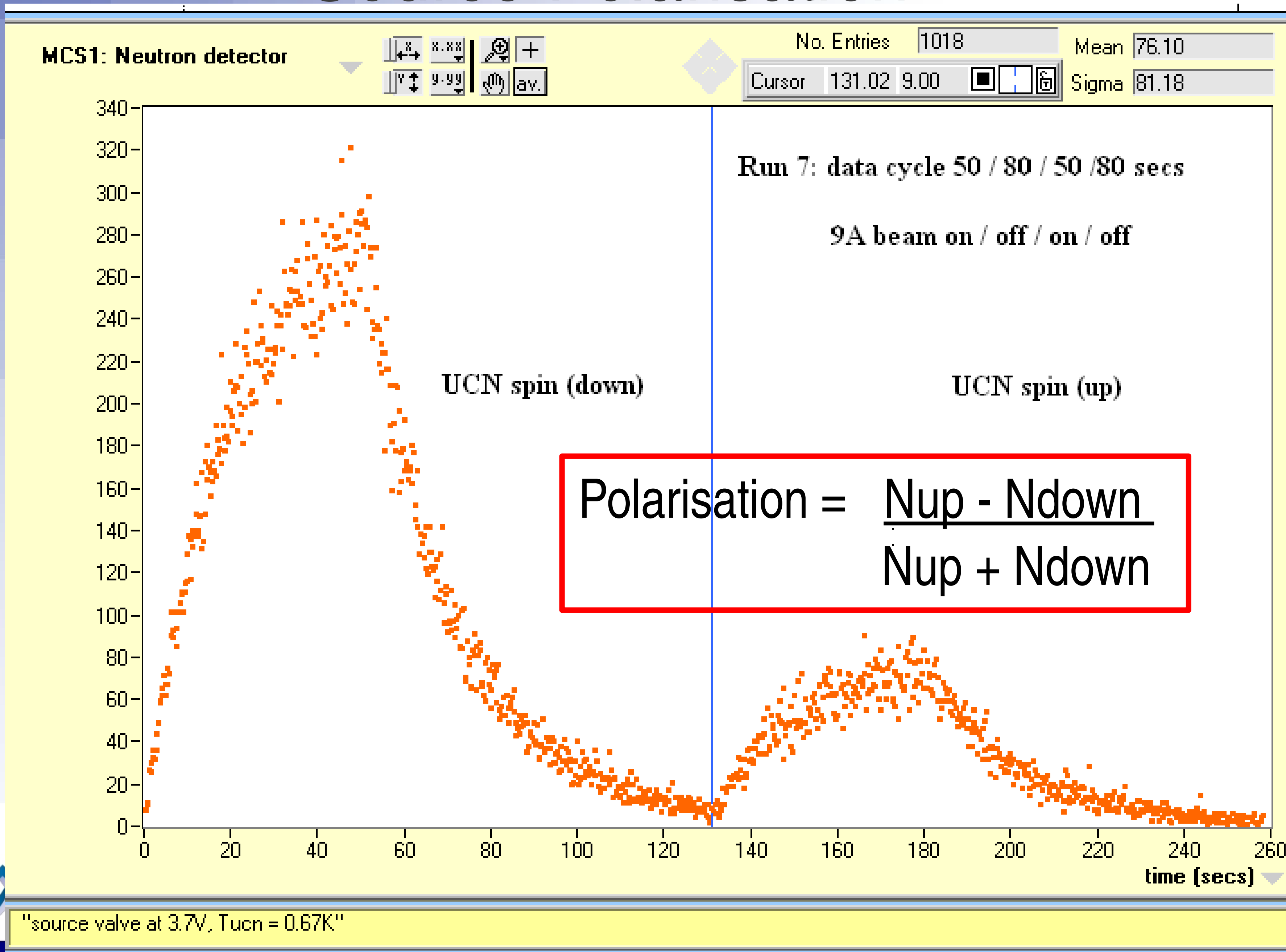
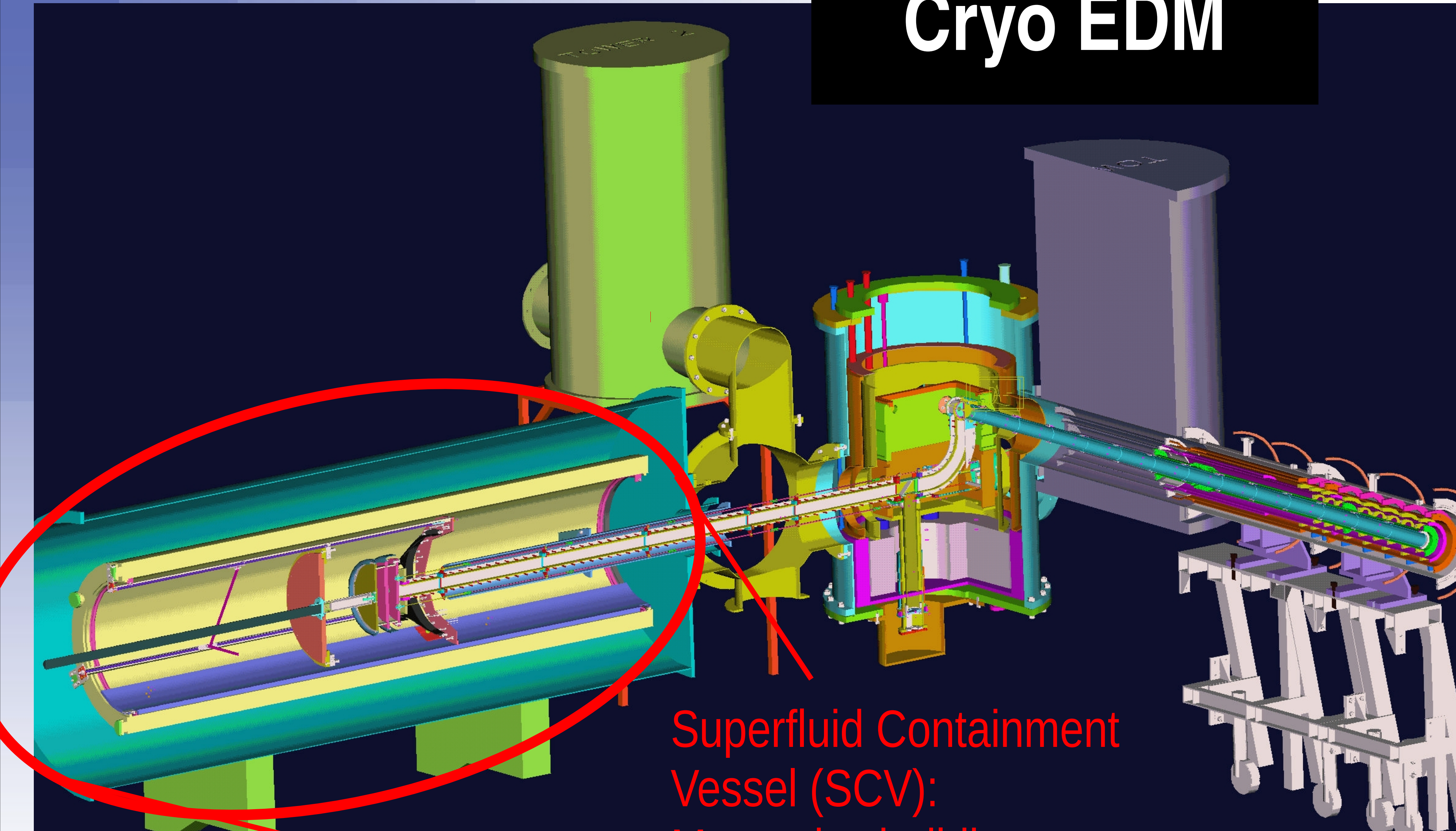
Source Polarisation

~66 +/- 4s



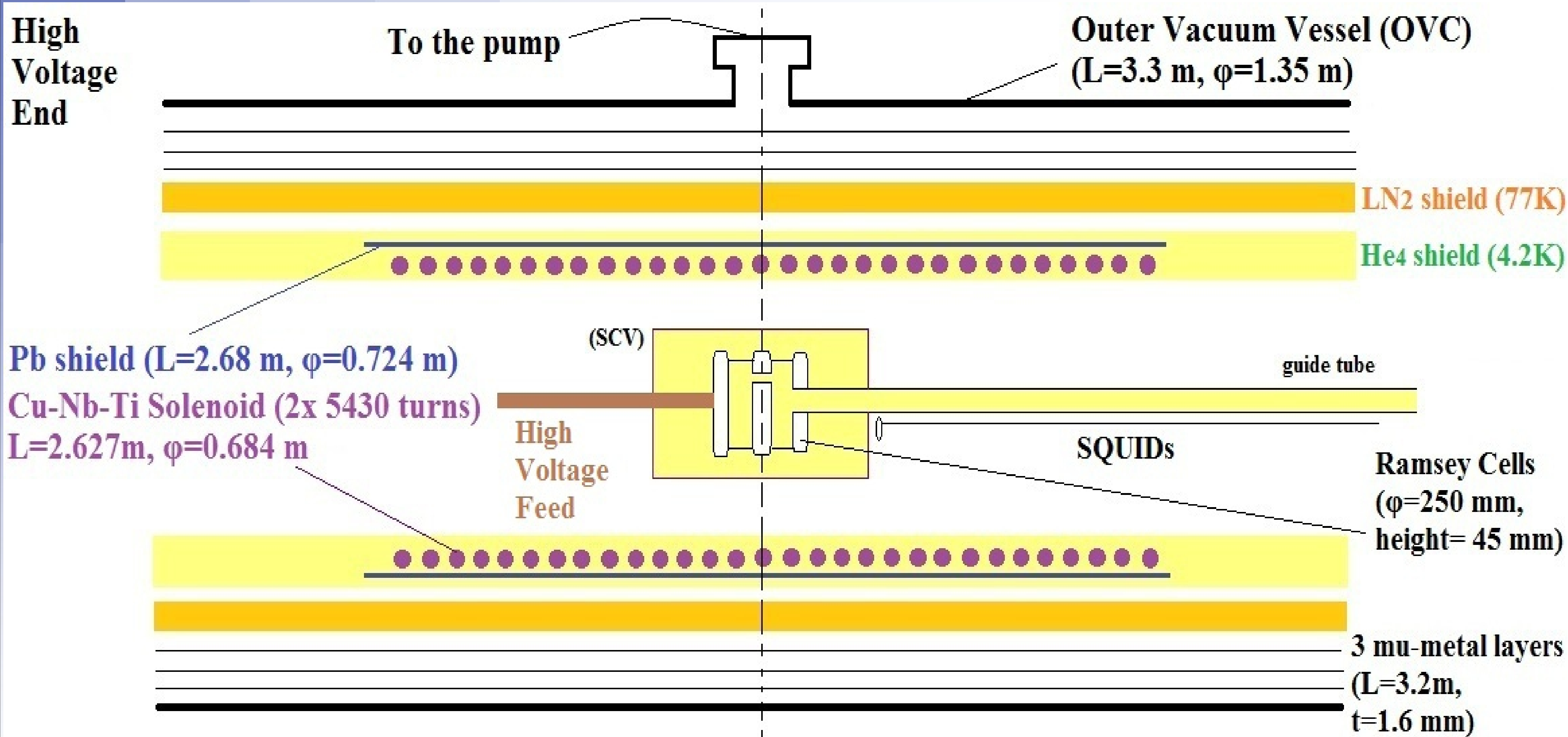
$$\text{Polarisation} = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$$

Cryo EDM



Superfluid Containment Vessel (SCV):
Magnetic sheilding
Compensation coils
N guides and Ramsey Cells

Outer Vacuum Chamber (OVC) and Superfluid Containment Vessel (SCV)



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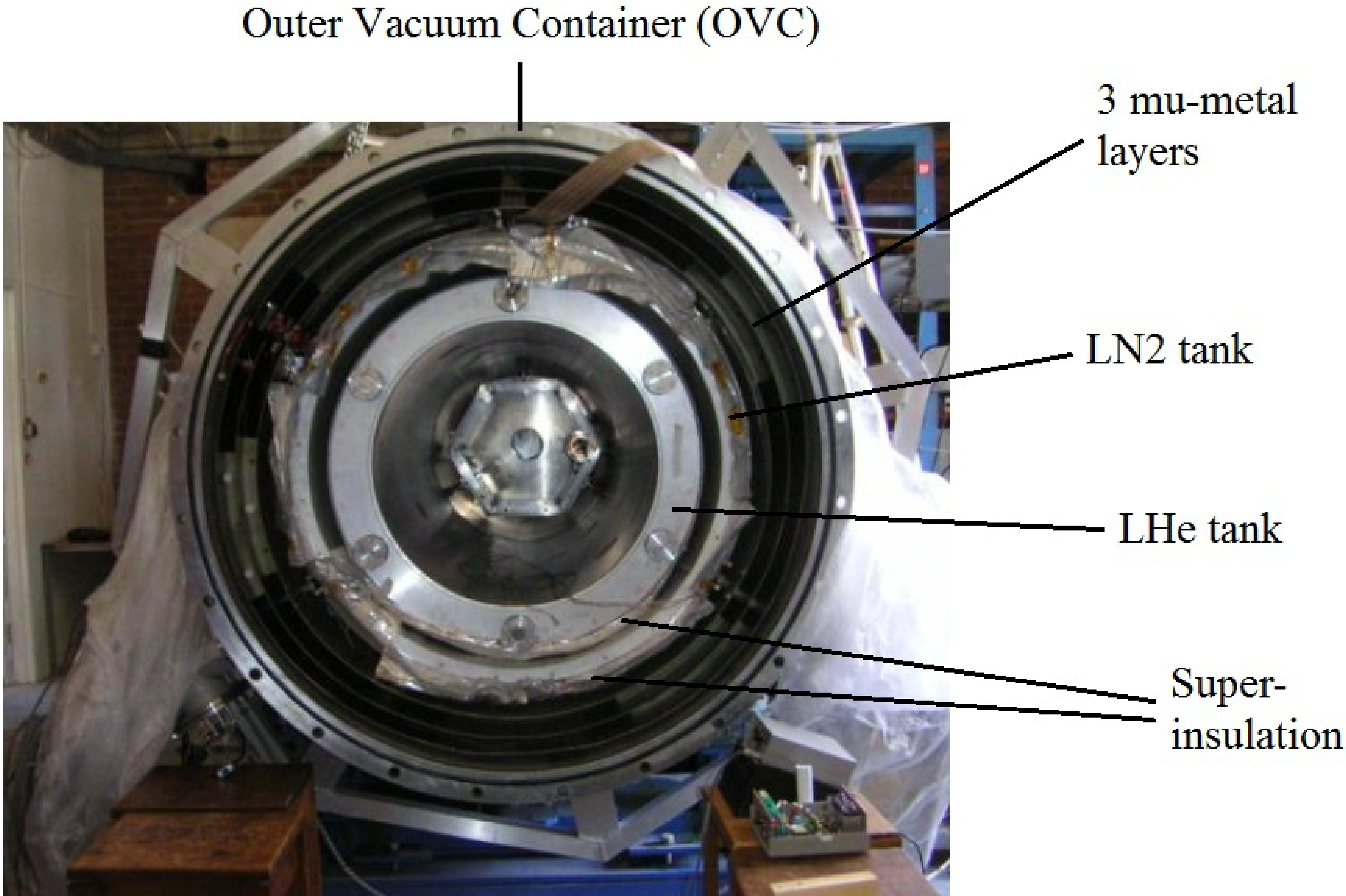

Outer Vacuum Container (OVC)
3 mu-metal layers
LN2 tank
LHe tank
Super-insulation

OVC / SCV. Improvements

Lab tests have shown that increasng the length of the shield we can increase the shielding factor by ~500.

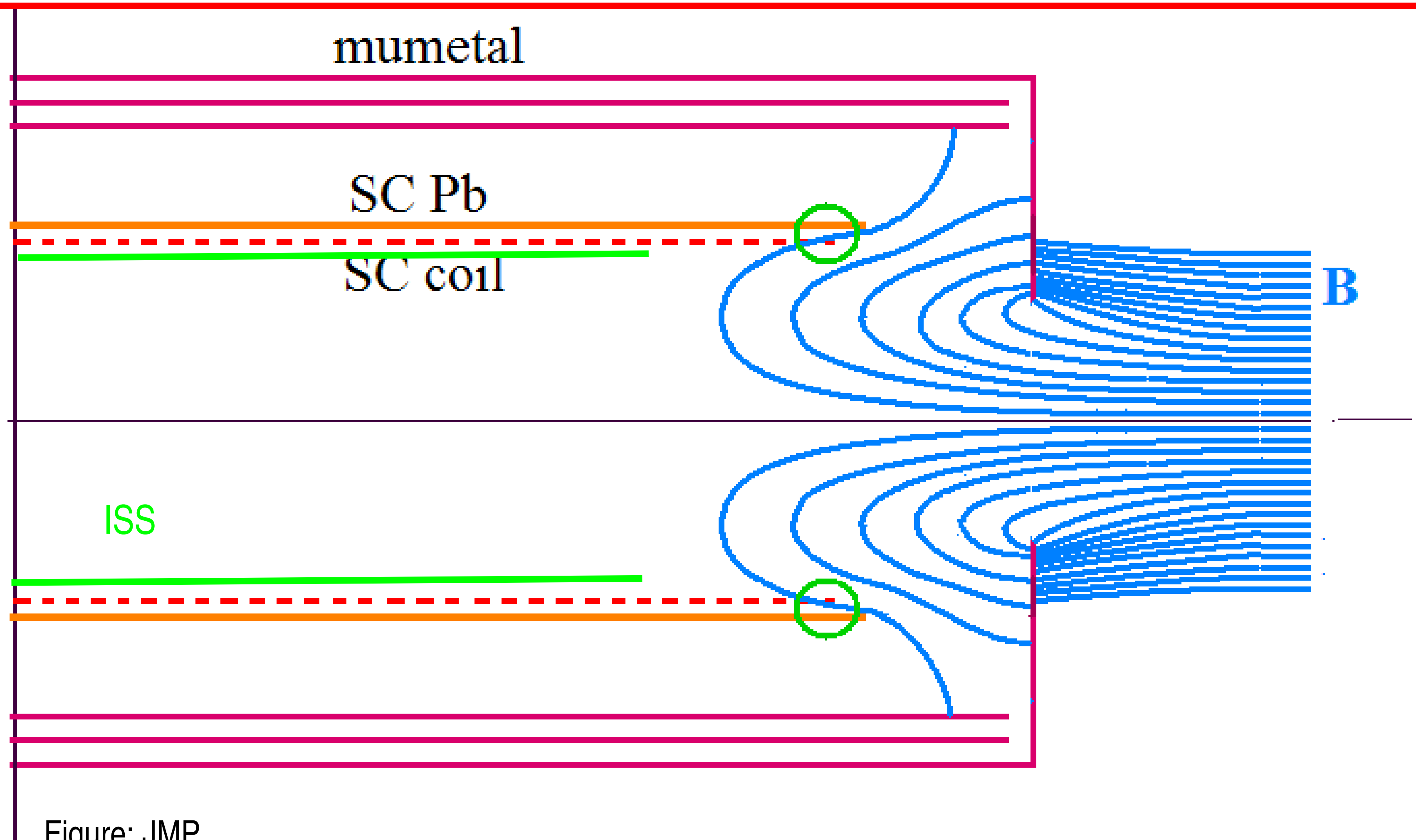
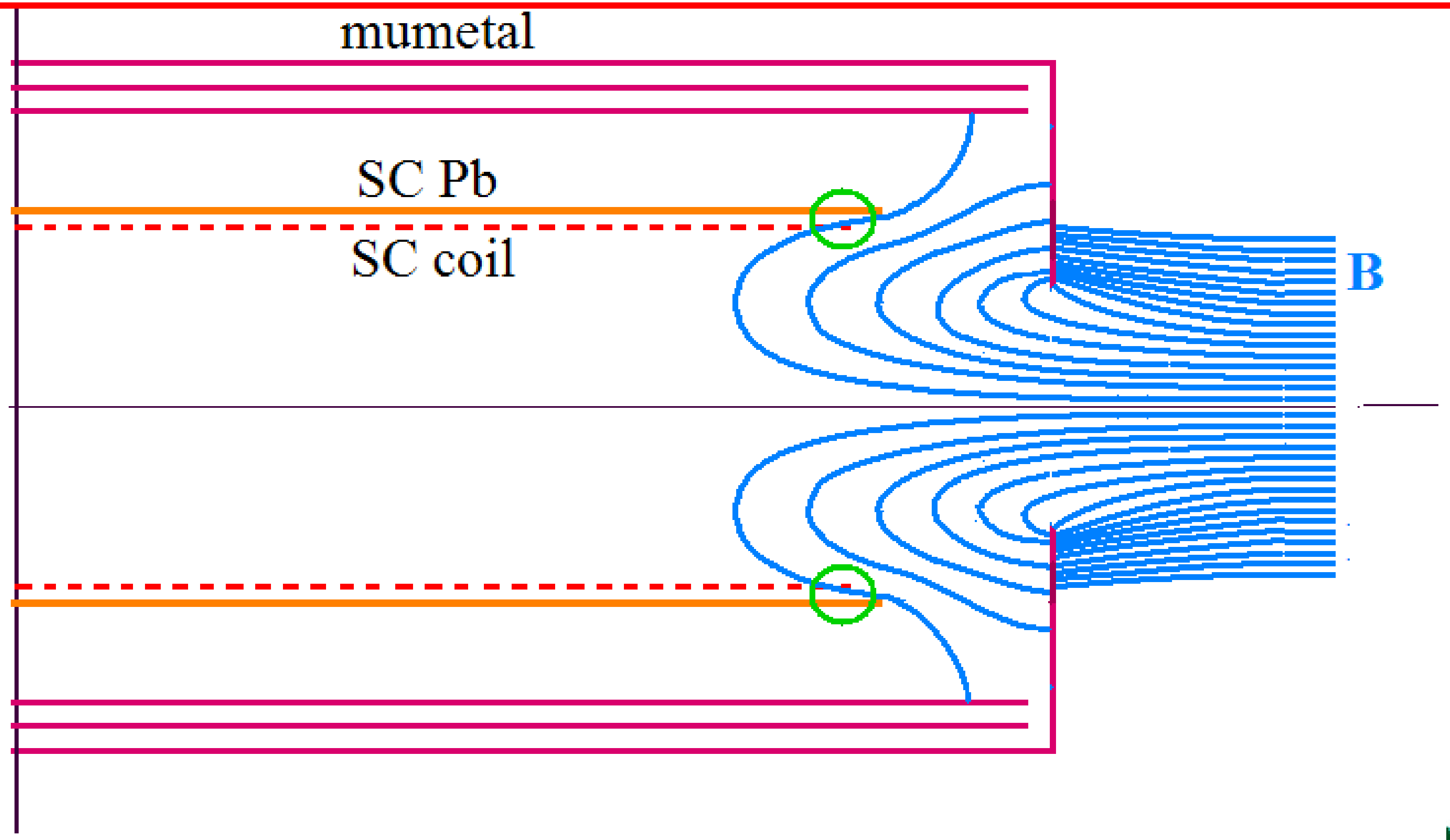


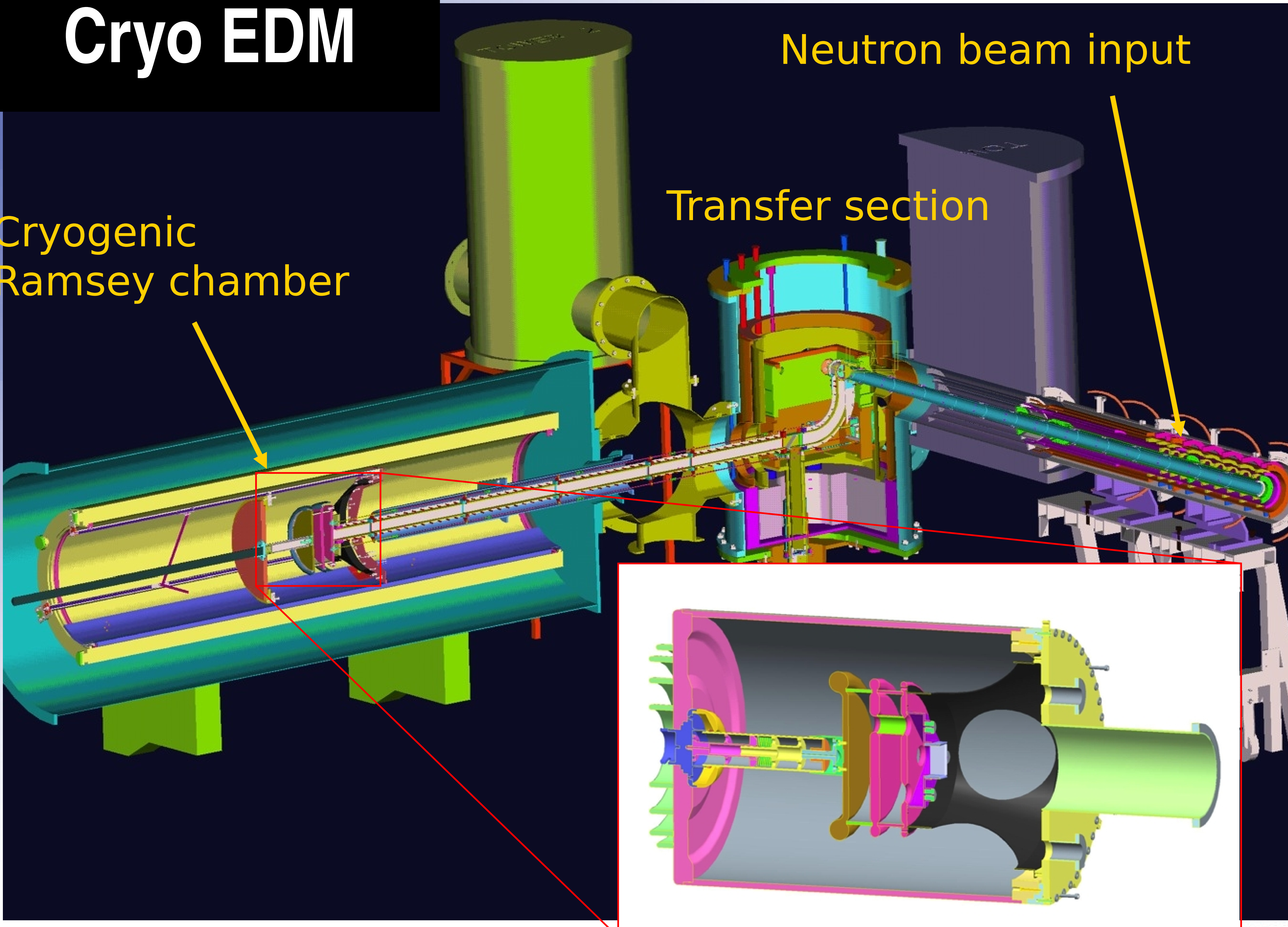
Figure: JMP

OVC / SCV, Improvements

At present, Pb shield too short: flux lines clip coil end, inducing current in whole coil.
Introduces common-mode noise, limiting sensitivity to 1E-27 e.cm.

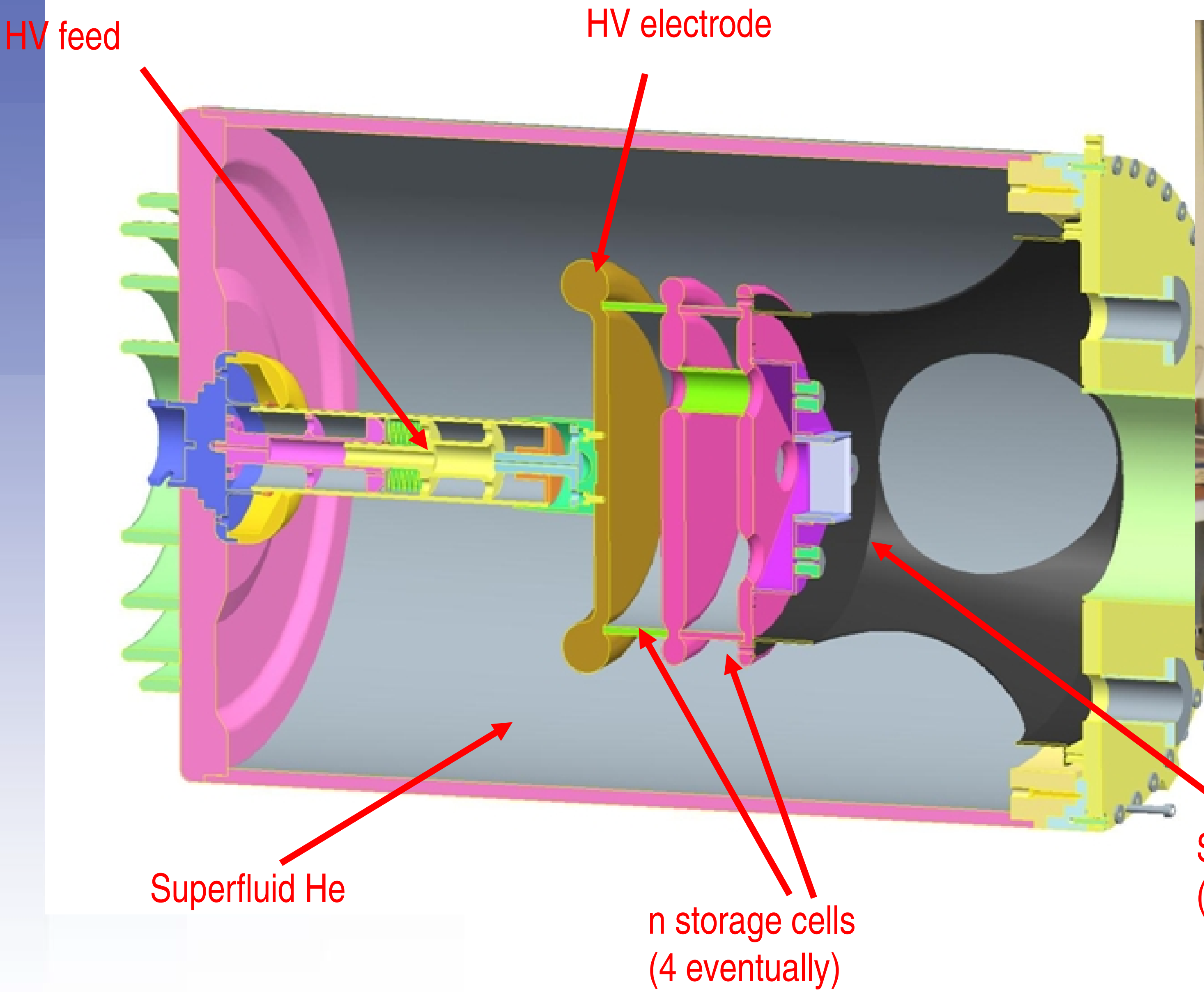


Cryo EDM



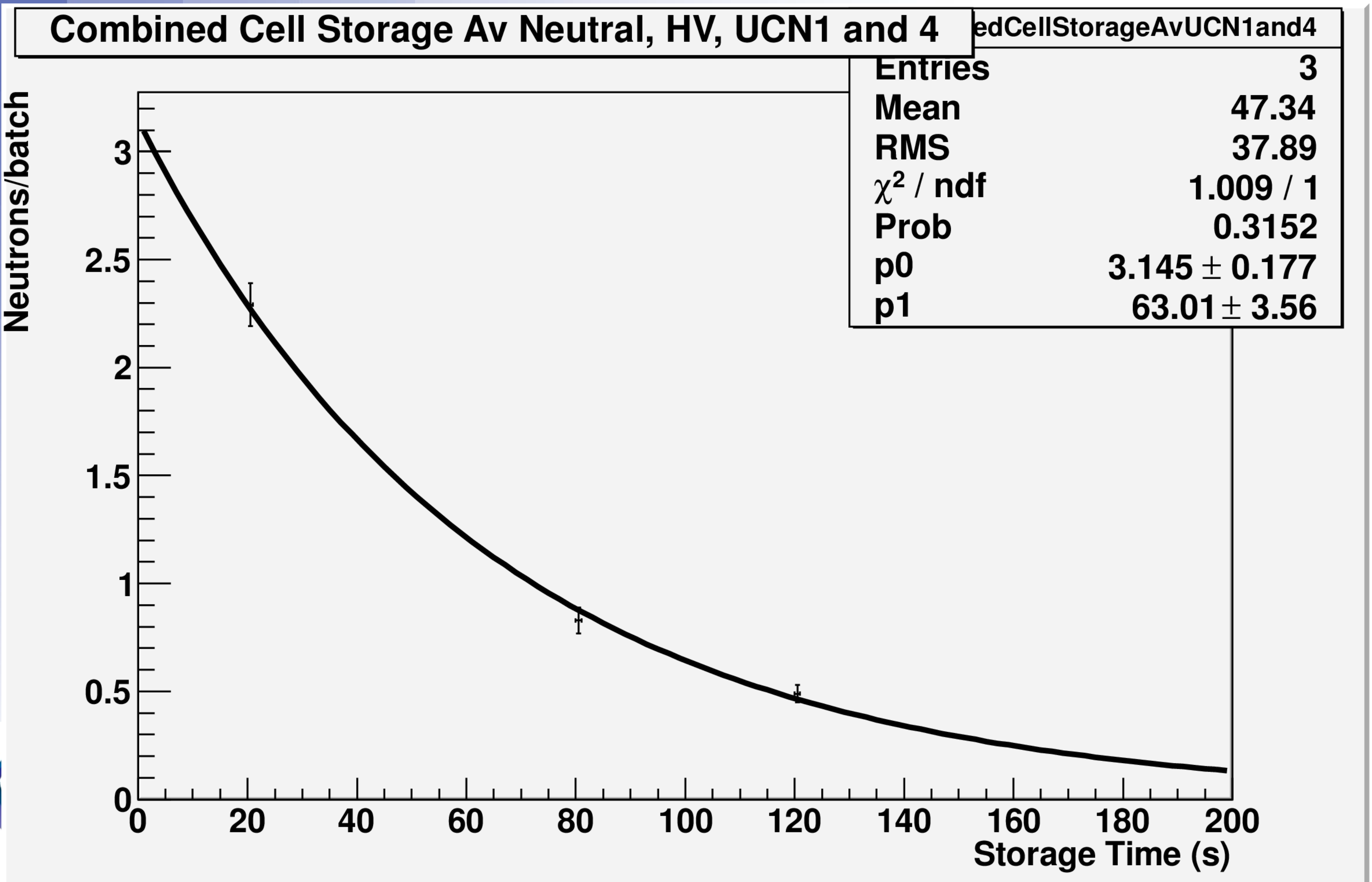
Neutron beam input
Transfer section
Cryogenic
Ramsey chamber

Cryogenic Ramsey Chamber



Cell Lifetime

63.01 +/- 3.56s



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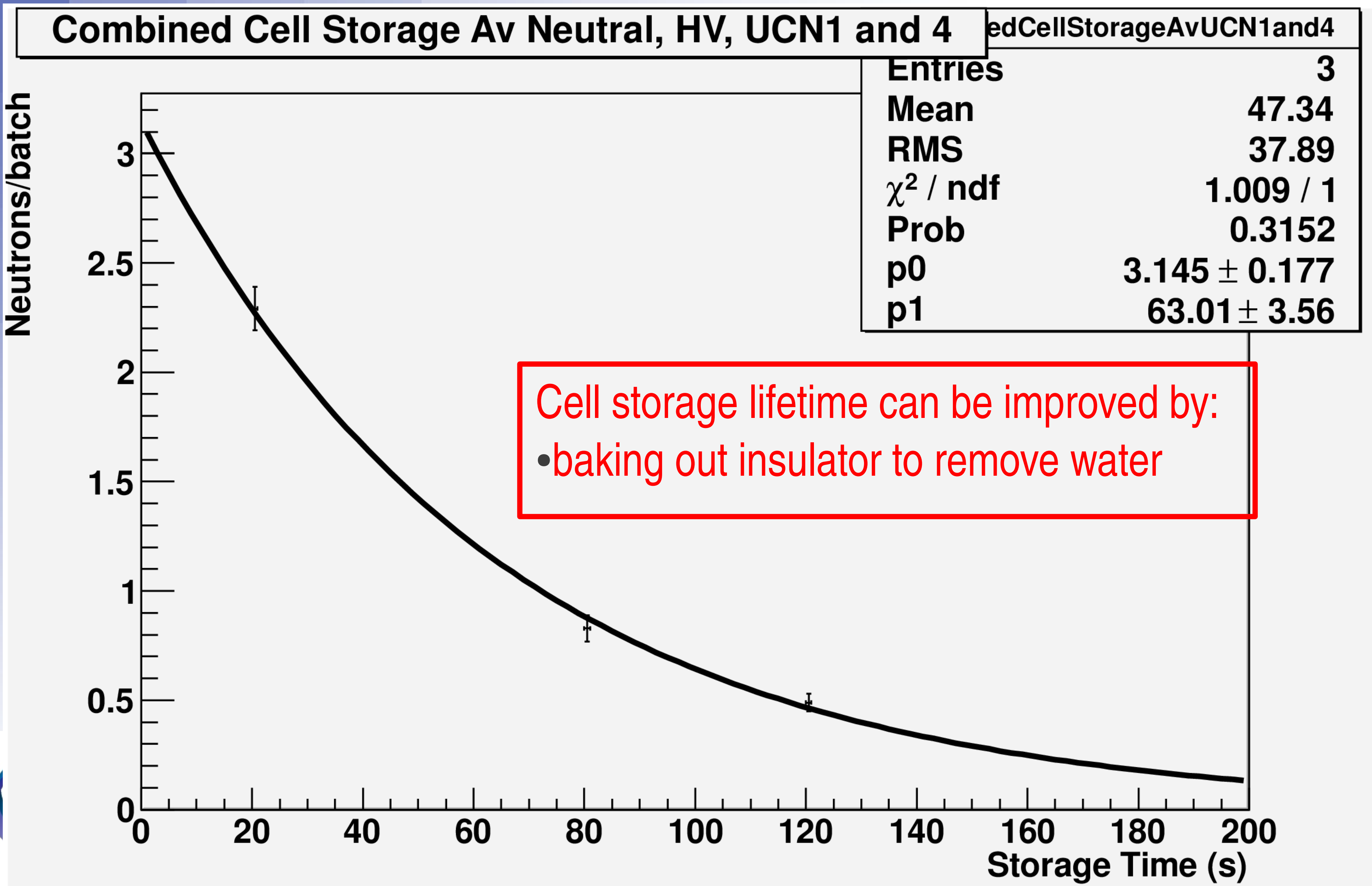
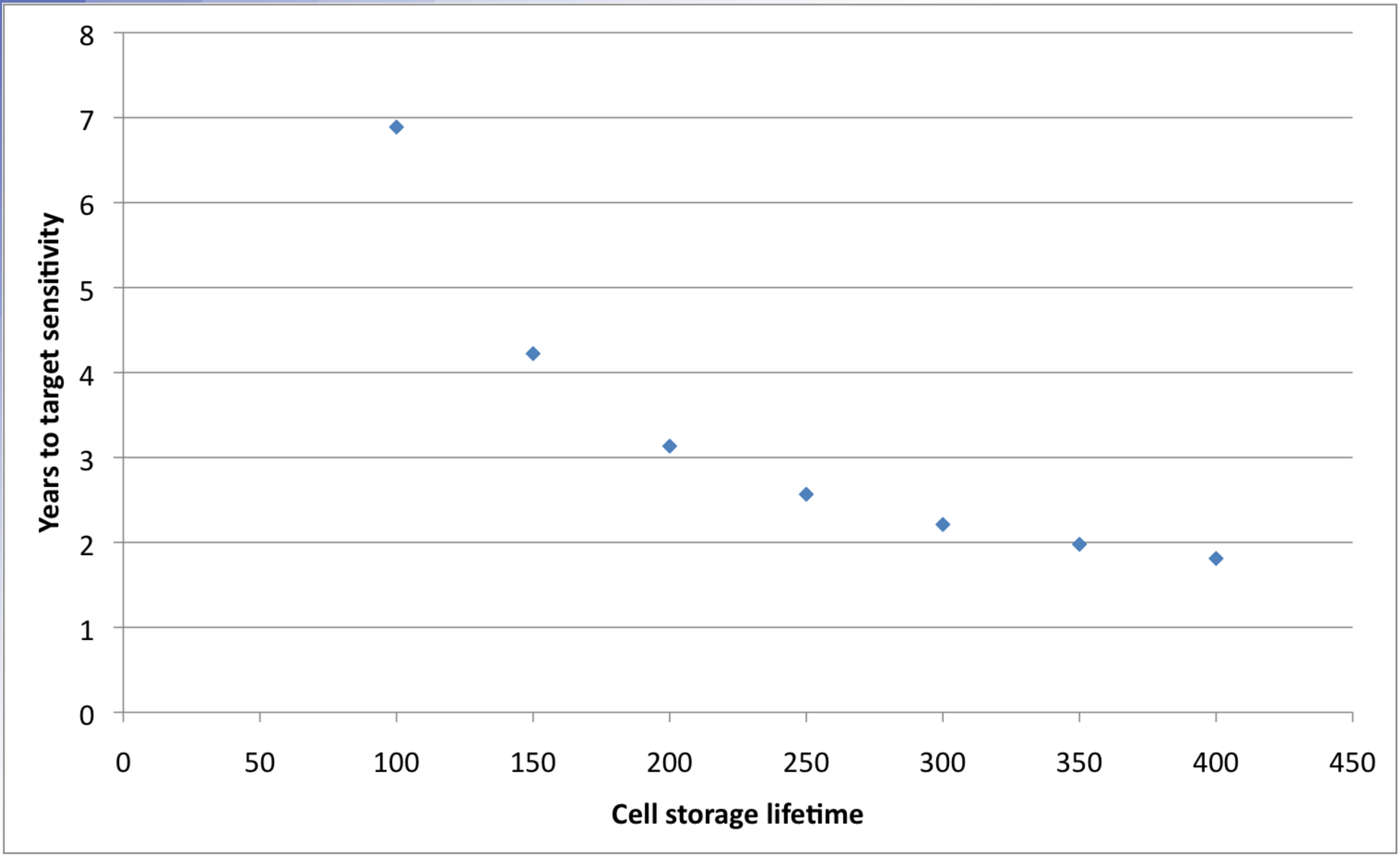
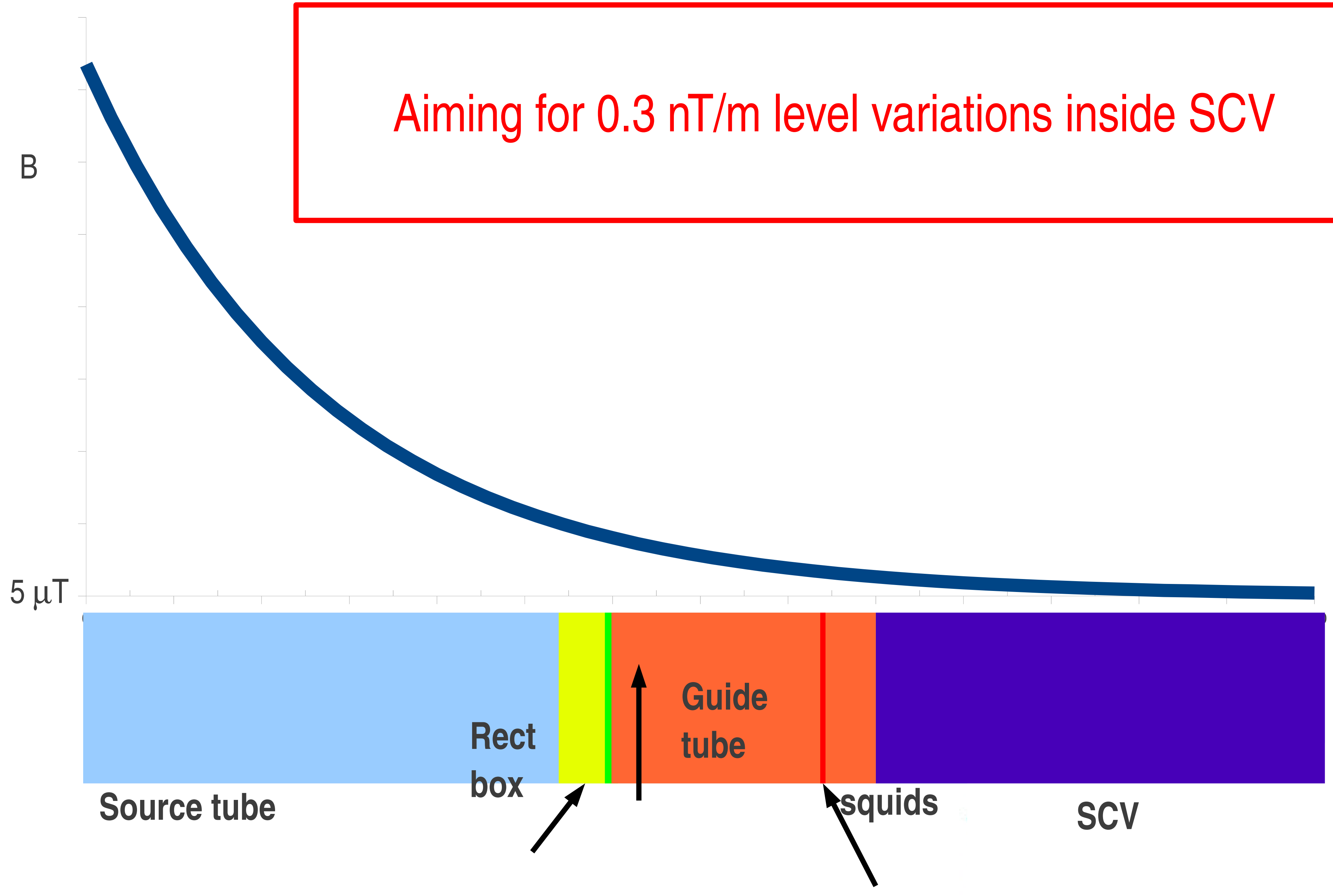


Cell Storage Lifetime vs Sensitivity

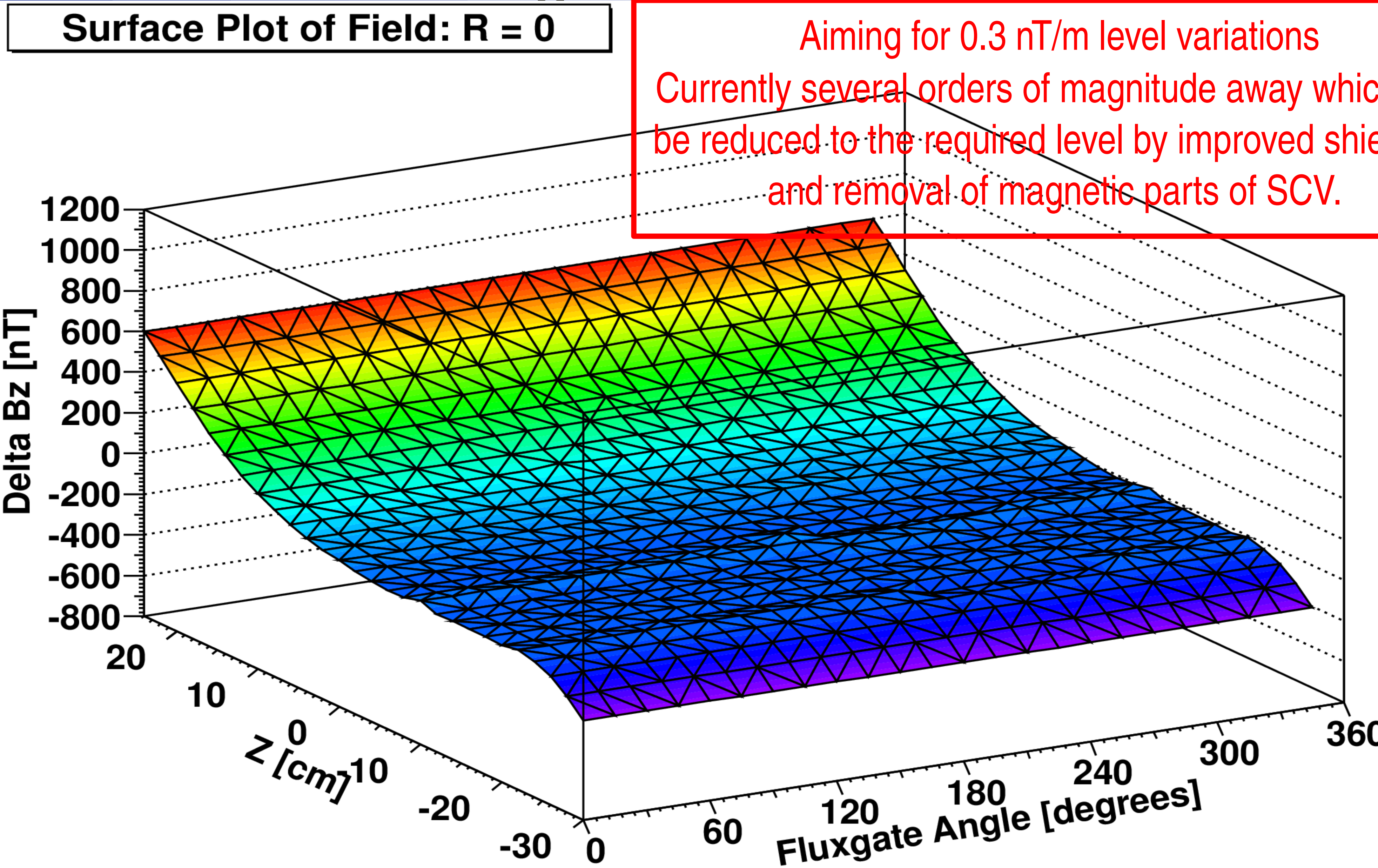


Ideal Magnetic Environment

Aiming for 0.3 nT/m level variations inside SCV



Magnetic Environment

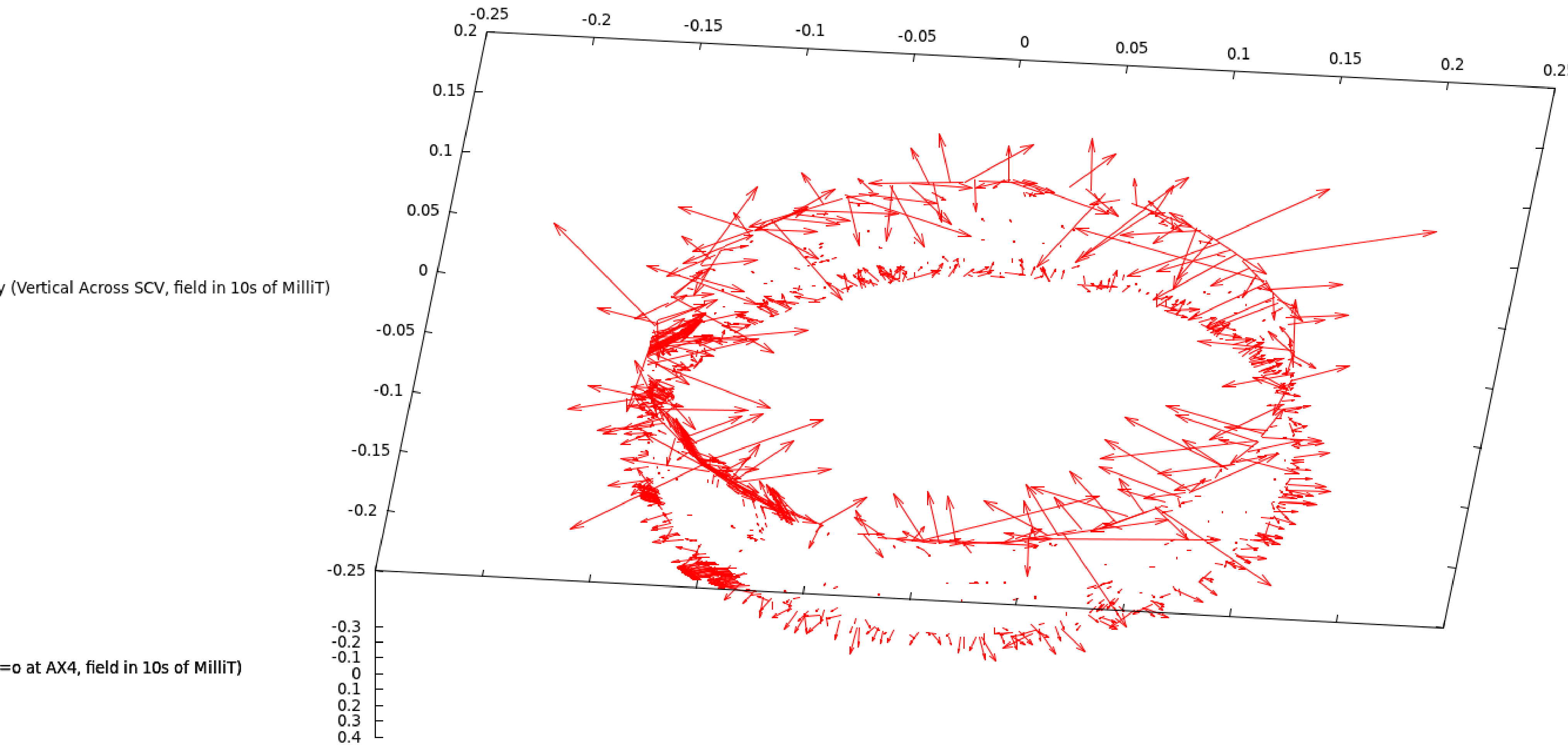


Aiming for 0.3 nT/m level variations
Currently several orders of magnitude away which will be reduced to the required level by improved shielding and removal of magnetic parts of SCV.

We have already identified many of these magnetic parts to remove and improve, such as baseplates with magnetic inclusions...

Vector Bz Field over SCV

Data taken July 2012, BxByBz Calculated from Br, Bθ and Bz
Field shown is at R=150 mm



NB// Field is given in 10s of milliT

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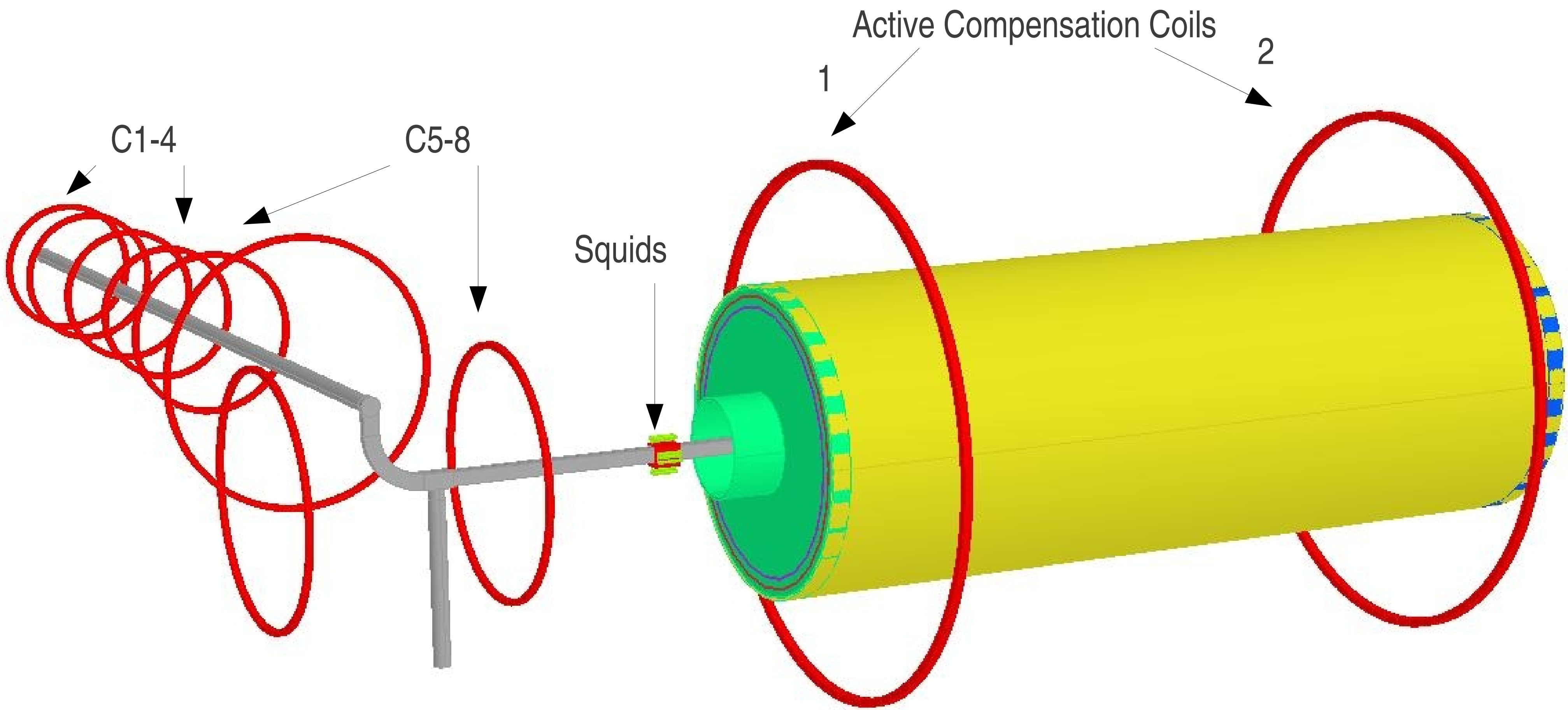
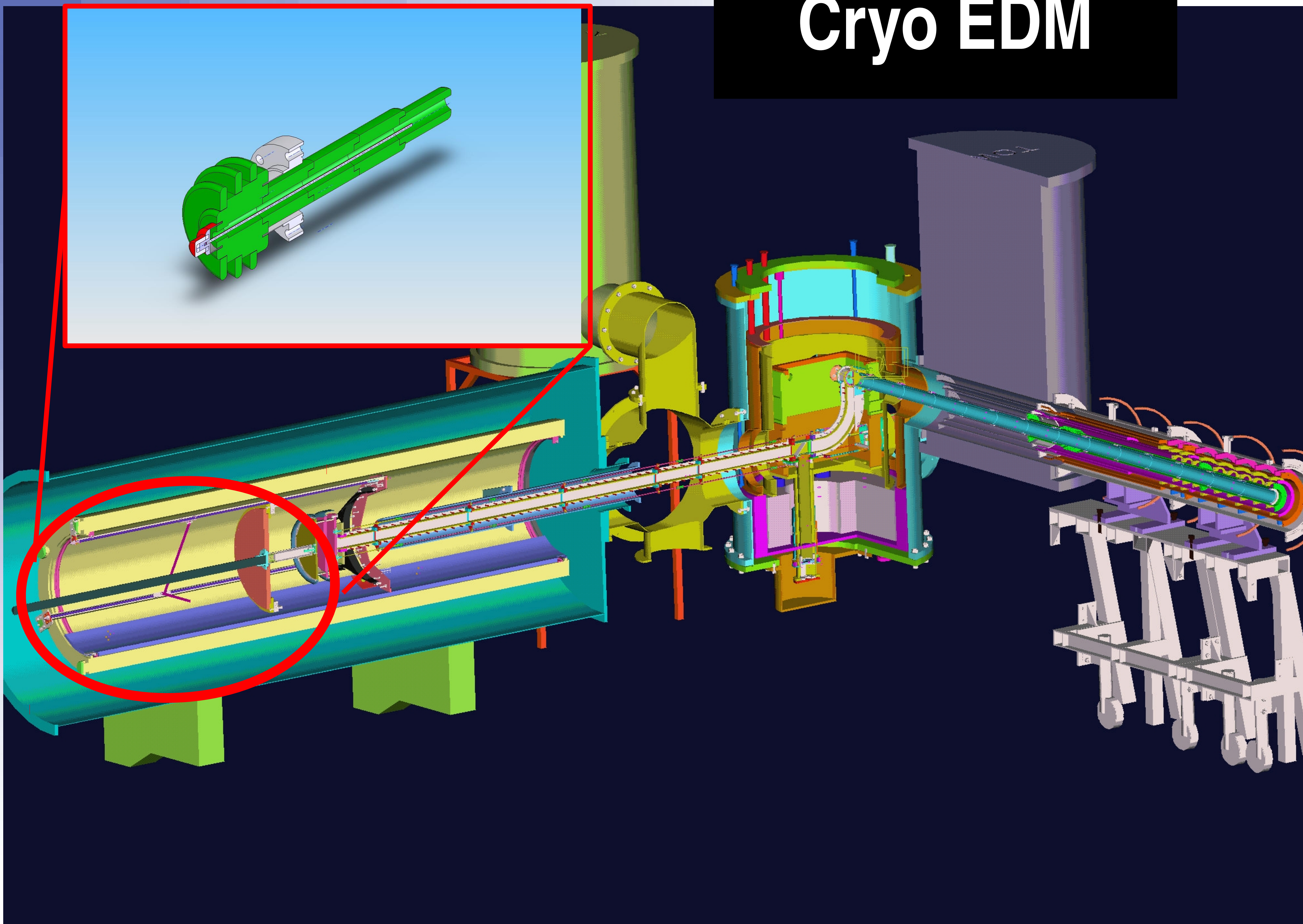
Coils



Cryogenics

- Base temperature in Ramsey cells = 0.5 K.
- This is reached in 4 weeks from room temperature.
- Has been achieved many times and is well understood.
- Poss improvements to include recirculation of helium.

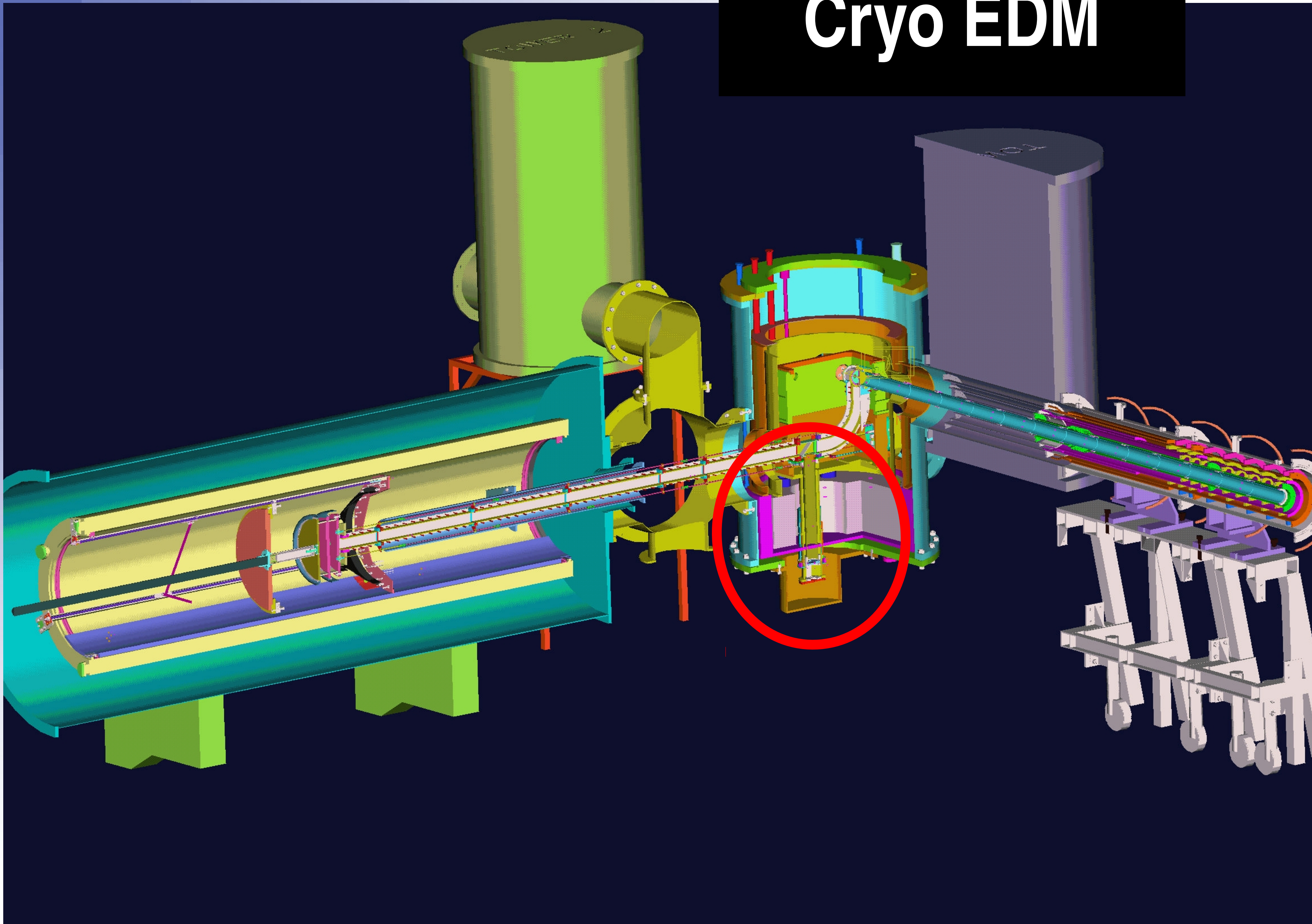
Cryo EDM



HV

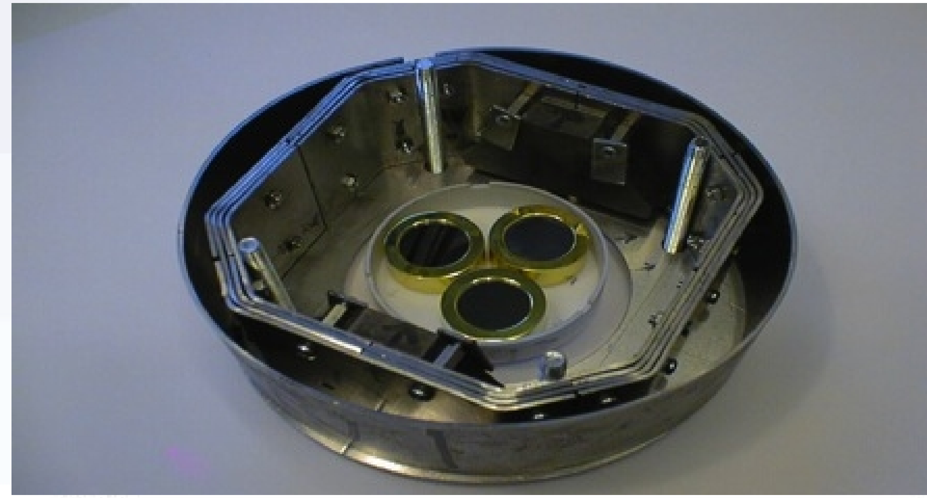
- Latest HV designed for 30 KV and tested up to 45 kV.
- 10 KV/cm has been achieved.
- Laboratory tests show that a field of 20 kV/cm should be readily achievable.
- 30 KV/cm can be attained by pressurising the helium to ~1.2 bar.

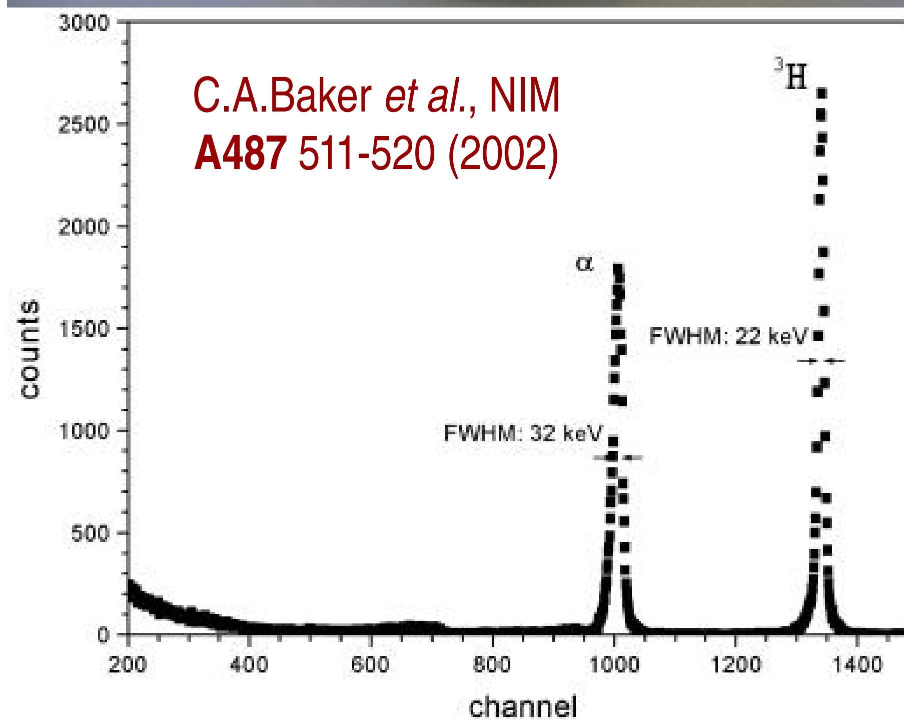
Cryo EDM



Detectors

- Solid state detectors developed for use in Liquid helium.
- Thin surface film of ^{6}LiF: $n + {}^{6}Li \rightarrow \alpha + {}^{3}H$; 82% eff.
- Currently α peak hidden under γ background
- Now moving to detector with 10x area, to cover entire guide.
- Testing completed 2012 neutron numbers increasing as expected.





Sensitivity

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

Achieved 60% polarisation in source, but must improve

Successfully produced, transported, stored UCN, but need to reduce losses

Successfully applied 10 kV/cm (same as previous expt); aiming for 20-30 kV/cm

RT-edm: 130 s. So far we have 62 s cell storage time. (aim ~200s)

(NB sensitivity/day is actually closer to $\sigma_d = \frac{\hbar}{2\alpha E \sqrt{TN}}$)

Upgrade 2013-15: Shutdown and Move to New Beamline

- Mid-2013: ILL will shut down for a year; we will move to new dedicated beamline.
  - New beam 4x more intense; and dedicated
  - Due to become operational mid-2014
  - Beam must then be characterised (9A flux, divergence, stability, polarisation)
  - We will then have access to the area (late 2014) to move our apparatus into it.
- Major experimental Upgrade:
  - Cryogenics upgrade including pressurising the liquid helium to increase E field x 2-3.
  - Move from 2 to 4 Ramsey cells
  - Installation of 1 m inner superconducting magnetic shield: giving a 500x improvement in B field stability.
  - Construction of non-magnetic SCV: to Improve depolarisation time and overcome geometric-phase systematic error
- Net result:
  - Order of magnitude improvement in sensitivity
  - Commensurate improvement in systematics

Sensitivity Timeline

Date	Item	factor	ecm/year	Comment
2002	RT-edm		1.7E-26	Baseline
2010	CryoEDM commission		1.7E-24	
2012	Large-area detector	3.5	4.9E-25	Proven
2012	HV to 70 kV	1.6	3.1E-25	OK to 50 kV, lab tests suggest should work at 70 kV
2012	Repair detector valve	1.3	2.5E-25	Repair – should be fine
2012	Polarisation 60%	1.5	1.7E-25	Seen in source. Should transfer ok to cells.
2012	Aperture to 50 mm	1.2	1.4E-25	Will increase radiation levels slightly, but should be ok
2012	Ramsey time to 60 s	1.8	7.7E-26	Almost certain – undergoing mag. scan now to confirm
2013	See alpha peak	1.4	5.5E-26	Quite likely by 2012, but we do not count on it by then
2014	New beam	2.0	2.7E-26	ILL produced this estimate
2014	Recover missing input flux?	2.2	1.2E-26	Depends on geometry match to new beam.
2014	Improve cell storage lifetime to 100 s	1.5	8.3E-27	Not guaranteed, but haven't yet tried most obvious solutions (e.g. bakeout), so improvement likely
2014	Match aperture to beam	1.3	6.4E-27	Likely
2015	HV to 135 kV	1.9	3.3E-27	Requires pressurisation. Lab tests show this is realistic.
2015	Four-cell system	1.4	2.3E-27	Guaranteed part of upgrade
2015	Polarisation to 90%	1.5	1.6E-27	No known reason why not
2013-15	Inner supercond. shield			Lab tests on scale model shows factor 500
2013-15	Cryogenics			Included in upgrade
2013-15	Non-magnetic SCV			Included in upgrade
2017				

Summary

- Current world limit for nEDM held by predecessor to cryoEDM
  $|d_n| < 2.9 \times 10^{-26}$ e.cm (90% CL)
- CryoEDM aims for 10^{-28} e.cm following ILL upgrades.

- Successfully produced, transported, stored neutrons, currently working to reduce losses.
- Successfully applied 10 kV/cm HV; aiming for 20-30 kV/cm
- Polarisation observed and is being improved
- Detection efficiency set to improve significantly.
- Magnetic field stability can improve factor 1000 – we know how to do this.

Challenges remain, but we are on the way.

Questions?

University of Sussex

Backup slides

False EDM

Mechanism	False EDM Uncertainty	Assumptions
Non-zero $(B_0\uparrow\uparrow - B_0\uparrow\downarrow)$ from mu-metal hysteresis	$10^{-2} \times 10^{-28}$ e cm	$(B_0\uparrow\uparrow - B_0\uparrow\downarrow)$ outside the super-conducting shield is that previously experienced in our nEDM experiments
Electric forces - cell displacement - dB_0/dr	1.0×10^{-28} e cm	$dB_0/dr = 3\times10^{-8}$ G/mm Rigidity of radial displacement of cells = 100 kg/mm
Electrical leakage currents caused by E	1.0×10^{-28} e cm	Current of 1 nA at 40 kV/cm An asymmetric tangential flow of 50 mm
DC B- and E-fields directly from the high voltage supply	$10^{-5} \times 10^{-28}$ e cm	DC current 1 mA in 40 cm diameter circuit 1.6 m from the shield end – current reverses with sign of HV
AC B-fields from the high voltage and dE/dt	0.05×10^{-28} e cm	Ripple on the high voltage 0.04 % - manufacturers figure. 10 kHz and 50 Hz considered.
$(\mathbf{E}\times\mathbf{v})/c^2$ 1st order UCN ensemble translation of CM	0.2×10^{-28} e cm	Upwards displacement of the UCN due to warming in storage = 1 mm. Volume ave. angle **E** to $\mathbf{B_0}$ = 0.1 radian
$(\mathbf{E}\times\mathbf{v})/c^2$ 1st order UCN ensemble net circulation about CM	0.3×10^{-28} e cm	**Circulation decay τ = 1s** $\Delta E_r = E/10$ in outer 30 mm UCN enter at $R/4$ 2s wait before 1^{st} $\pi/2$ flip
$((\mathbf{E}\times\mathbf{v})/c^2)^2$ 2nd order affects all individual trajectories	0.3×10^{-28} e cm	Gives E^2 shift $(E\uparrow - E\downarrow)/\langle E\rangle = 0.05$ $\langle E\rangle$ = 60 kV/cm used Two cells cancel effect to 10%
$(\mathbf{E}\times\mathbf{v})/c^2$ & dB_0/dz geometric phase affects all individl. trajectories	0.8×10^{-28} e cm	dB_0/dz = 1 μG/m after trimming. B_0 = 25 mG Rms v (UCN) = 5 m/s

Overall systematic error	1.7×10^{-28} e cm	All the above errors are uncorrelated

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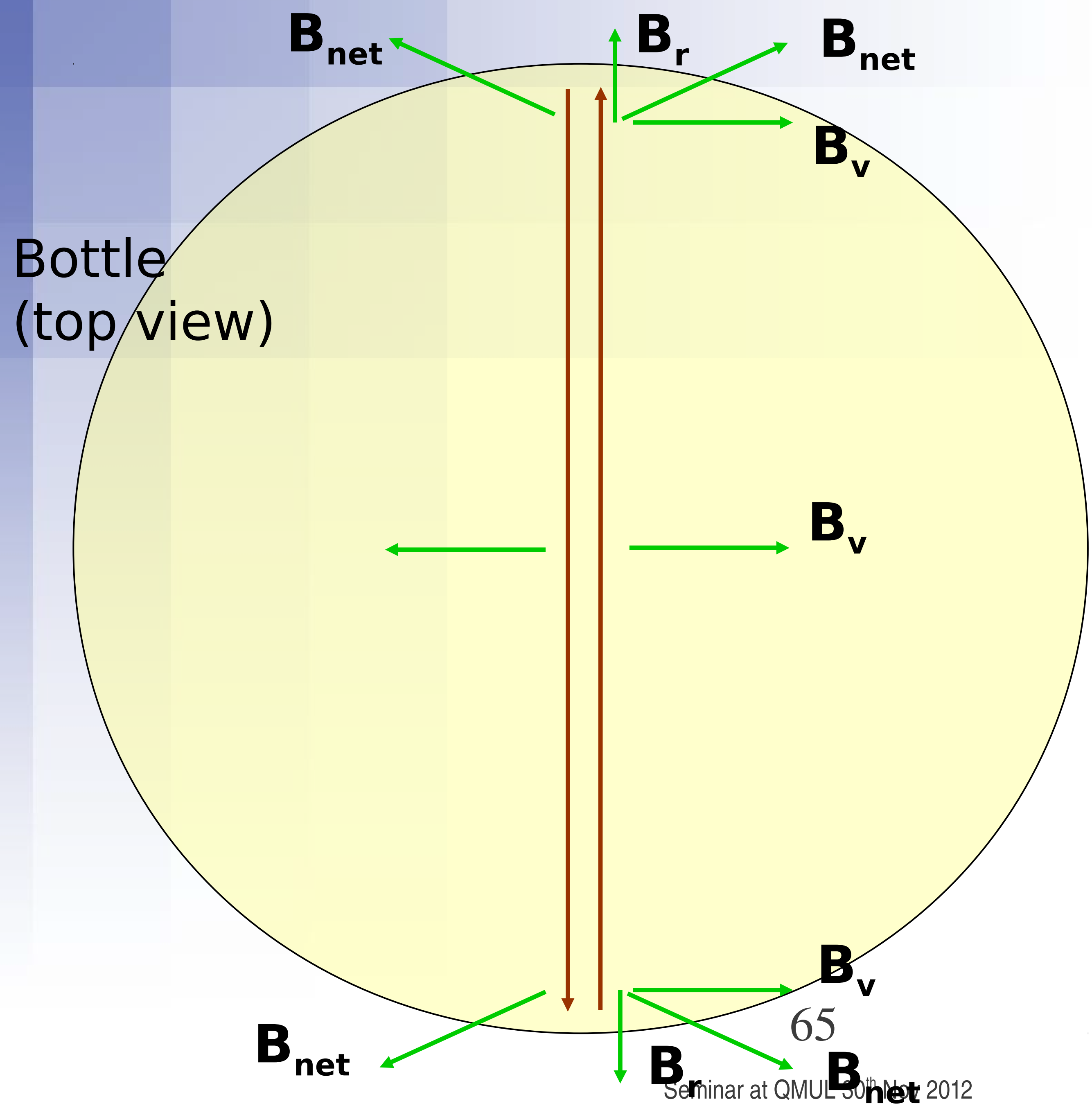
ex

Systematics Summary

Effect	Size (e.cm)
B fluctuations	1×10^{-30}
Geometric phase	3×10^{-29}
Ex**v** translational	2×10^{-29}
Ex**v** rotational	1×10^{-29}
Ex**v** 2^{nd} order	3×10^{-29}
μ metal hysterisis	1×10^{-30}
E-induced cell movement	1×10^{-28}
Leakage currents	5×10^{-29}
HV line contamination	1×10^{-29}

Systematics: Geometric Phase



... so particle sees additional rotating field

Frequency shift ∝ E

Looks like an EDM, but scales with dB/dz

Systematics: Geometric Phase

- For neutrons, $d_f \propto \frac{\partial B_z / \partial z}{B_z^2}$.
- Scales as $1/B^2$; increase B 5x to obtain factor 25 protection
- $\partial B_z / \partial z$ <1 nT/m $\rightarrow$ 3E-29 e.cm

Systematics: E x v

- Translational:
  - Vibrations may warm UCN, cause CM to rise ~1 mm in 300 s → 3E-6 m/s
  - If **E**, **B** misaligned 0.05 rad., gives 2E-29 e.cm
- Rotational:
  - Net rotation damped quickly (~1 s): matt walls
  - Delay before NMR pulses allows rotation to die away
  - Neutrons enter E-field cells centred horizontally; no preferred rotation
  - Below 1E-29 e.cm

Systematics: E x v 2nd Order

- Perpendicular component, adds in quadrature to **B**.
- Prop. to **E**^{2}; gives signal if **E** reversal is asymmetric
- Cancellations (back-to-back cells; **B** reversals) reduce effect to < 3E-29 e.cm

Systematics: Mu Metal Hysteresis

- The system depends not only on its current state but on its past state.
- Room-temp expt: Pickup in B coil from E field reversals; return flux causes hysterisis in μ metal
- Coil here is SC, not power-supply driven
- Inner shield is SC also
- Small effect from trim coils, enhanced by any misalignments
- Net estimate < 1E-30 e.cm

Systematics: E induced Cell Movement

- Electrostatic forces of order 20 N; $\propto E^2$
- Radial gradients of order 3 nT/m
- Must keep displacement on E reversal to ~ 0.01 μm
- Cancellation with double cell
- Symmetric voltages to ~2%
- Net effect < 1E-28 e.cm

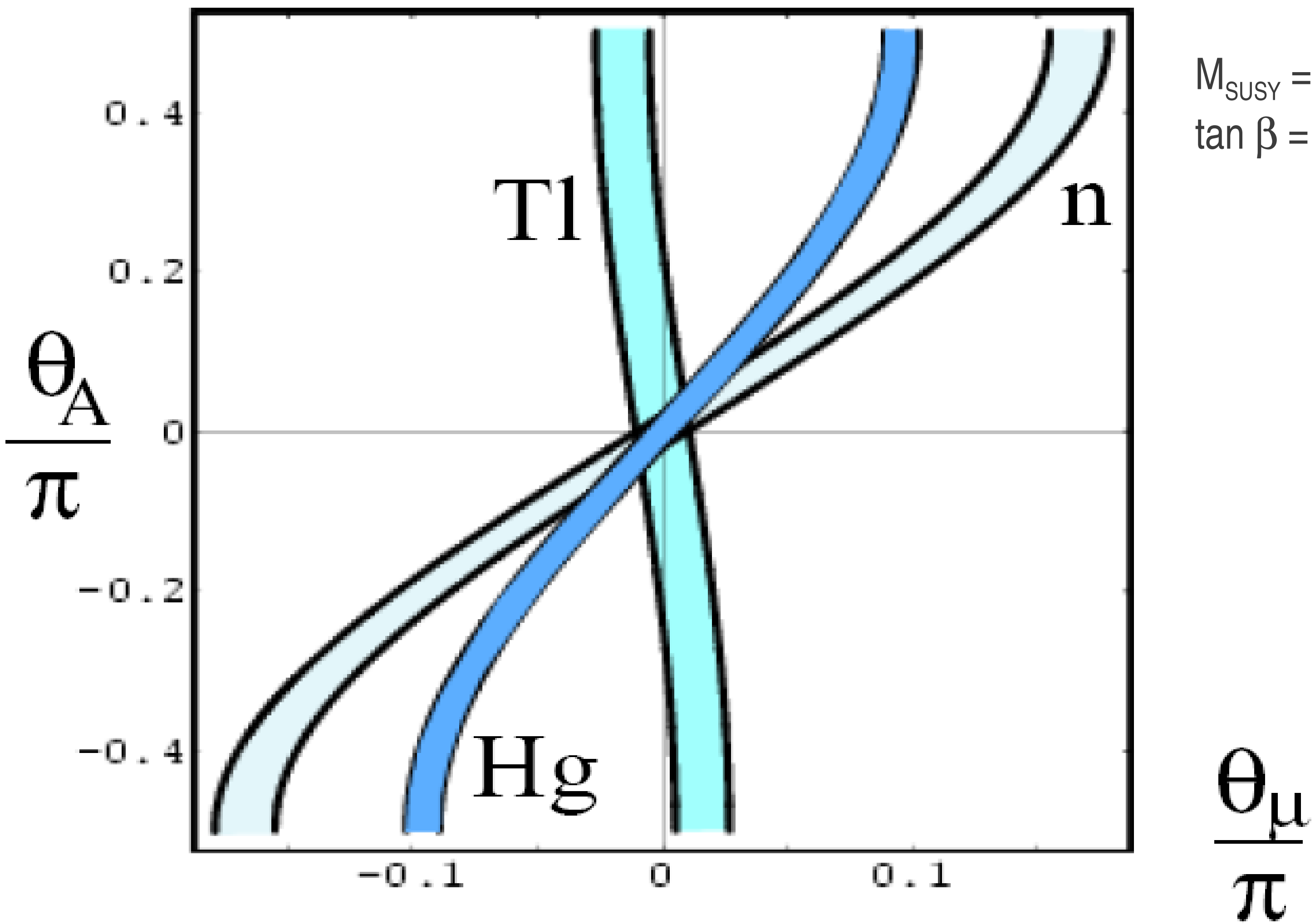
Systematics: Leakage Currents

- Azimuthal current components generate axial contributions to B
- Cancellation in adjacent cells
- Conservative estimate: 1 nA $\rightarrow$ 5E-29 e.cm
- In reality LHe should keep currents much below this?
- New source of current: ionisation from UCN decay electrons

Systematics: HV Supply Contamination

- HV circuit isolated as far as possible to minimise earth contamination. Separate computer control.
- 10 kHz ripple on HV line can “pull” resonant freq. Estimate 1E-30 e.cm
- Likewise 50 Hz ripple: estimate ~1E-29 e.cm
- Directly generated AC **B** fields negligible

SUSY Constraints



M_{SUSY} = 500 GeV
$\tan\beta = 3$

Pospelov & Ritz, hep-ph/0504231