High Luminosity Polarized ^3He Targets For Electron Scattering Experiments

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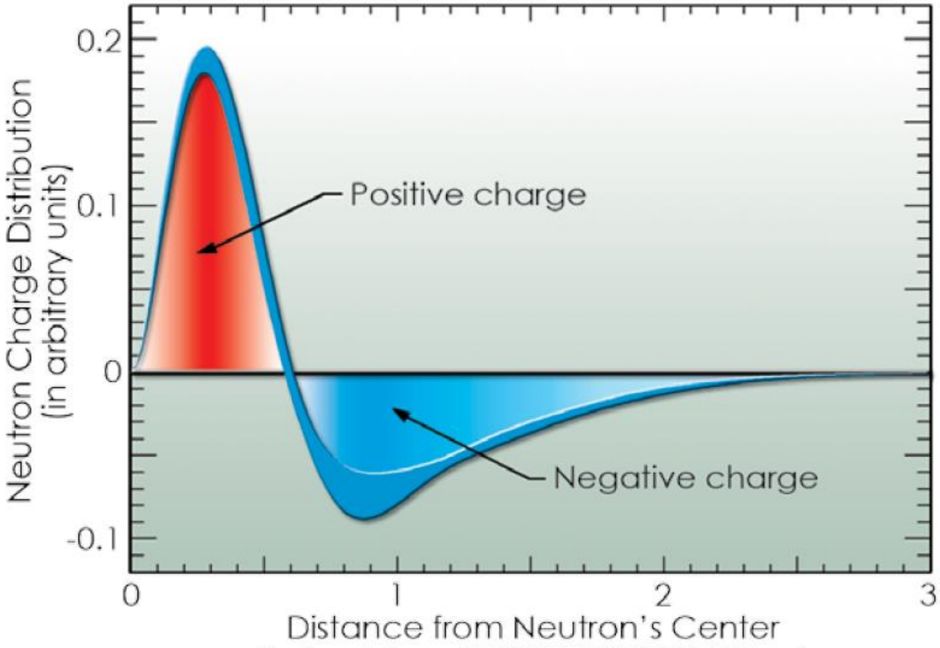
University of Virginia

5/01/2014

Elastic form factors of the neutron

Among the reasons they are important,

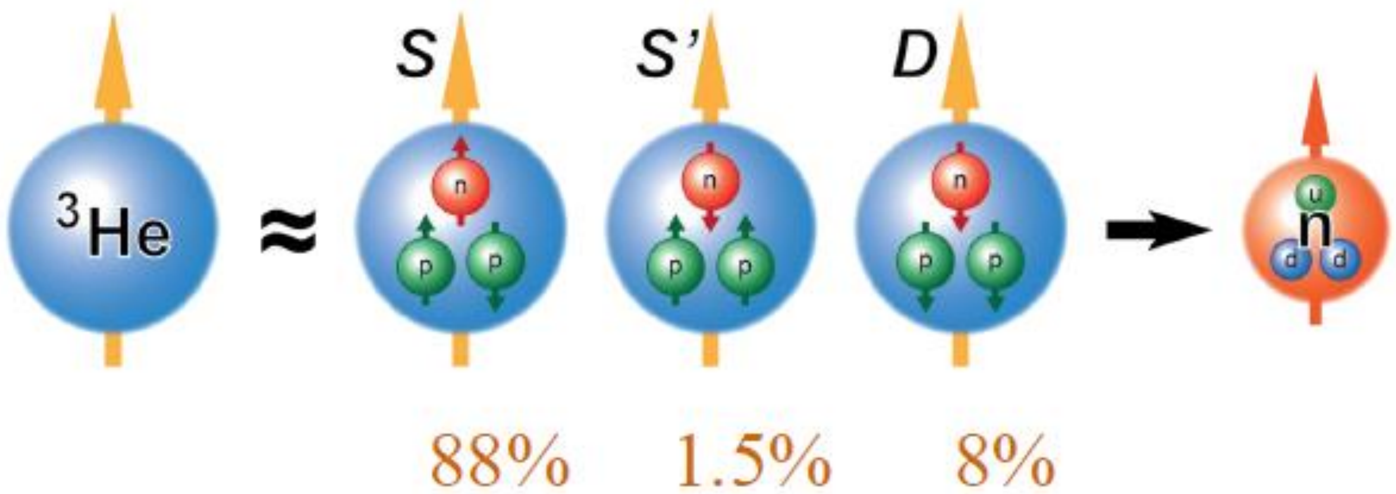
- A fundamental property of the neutron
- Provides information on the charge density inside neutron
- Tests models of neutron structure
- Provides critical constraints on generalized parton distributions (GPD's)



in fm, 1 fm = 10^{-15} m

Neutron Target

- Neutron mean lifetime is just under 15 mins.
- ^{3}He nucleus has two protons whose spins are paired, and a single neutron that accounts for most of the nuclear spin.
- So, ^{3}He is an effective polarized neutron target.



F. R. P. Bissey, A. W. Thomas, and I. R. Afnan, Phys. Rev. C64, 024004 (2001)

Effective Luminosity

In a double-spin asymmetry experiment

$$A_{measured} = P_e P_{He} A_{physical}$$

Relative error of Asymmetry is given by,

$$\frac{\delta A_{physical}}{A_{physical}} = \frac{1}{\sqrt{N} P_e P_{He}}$$

$$N \propto Lt$$

$$L = I_{beam}[\mathrm{He}]l$$

$$\left(\frac{\delta A_{physical}}{A_{physical}}\right)^2 \propto \frac{1}{L P_{He}^2}$$

← Effective Luminosity

The performance of polarized ^{3}He targets has increased by roughly a factor of 30 since SLAC E142

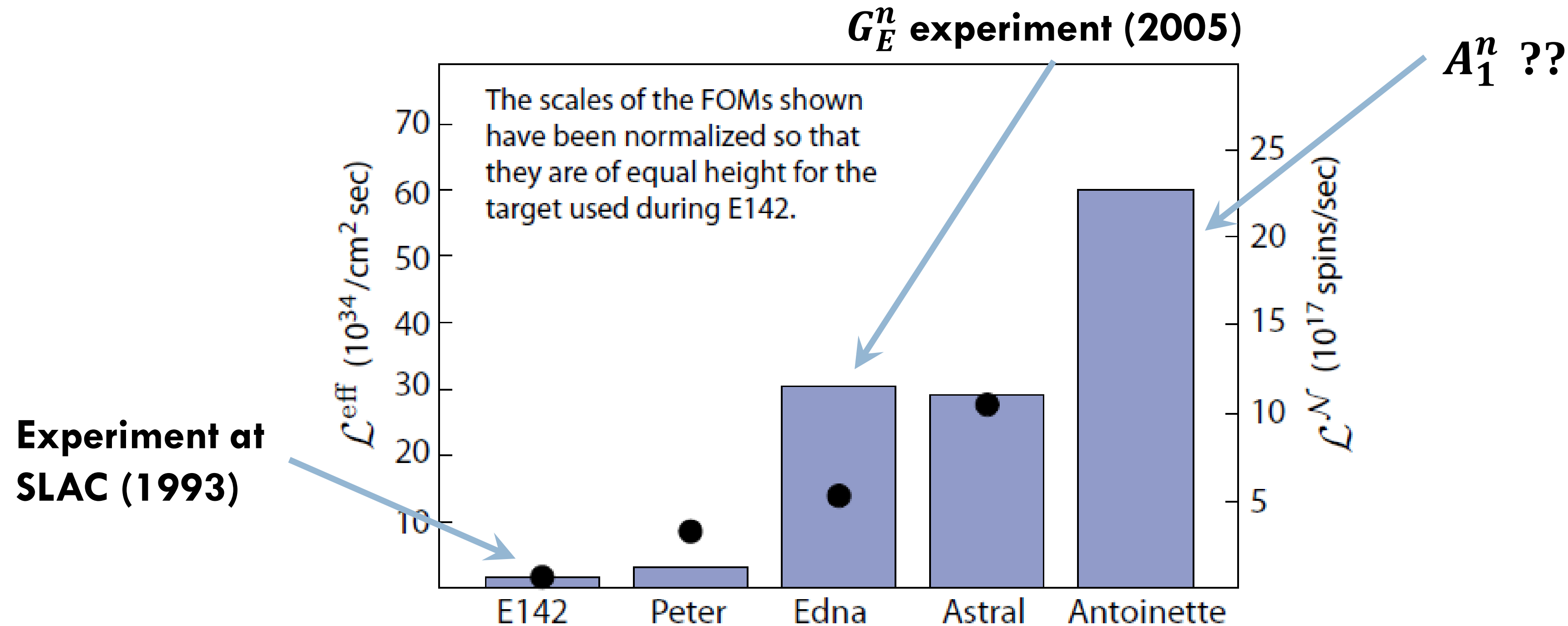


FIG. 1: Shown are two figures of merit (FOM) for five polarized ^{3}He targets. The solid circles (left-hand scale) indicate the luminosity weighted by ^{3}He polarization squared (P_{He}^2) achieved in beam. The shaded columns (right-hand scale) show a FOM proportional to the total number of spins polarized per second, again weighted by P_{He}^2.

^{3}He target cell

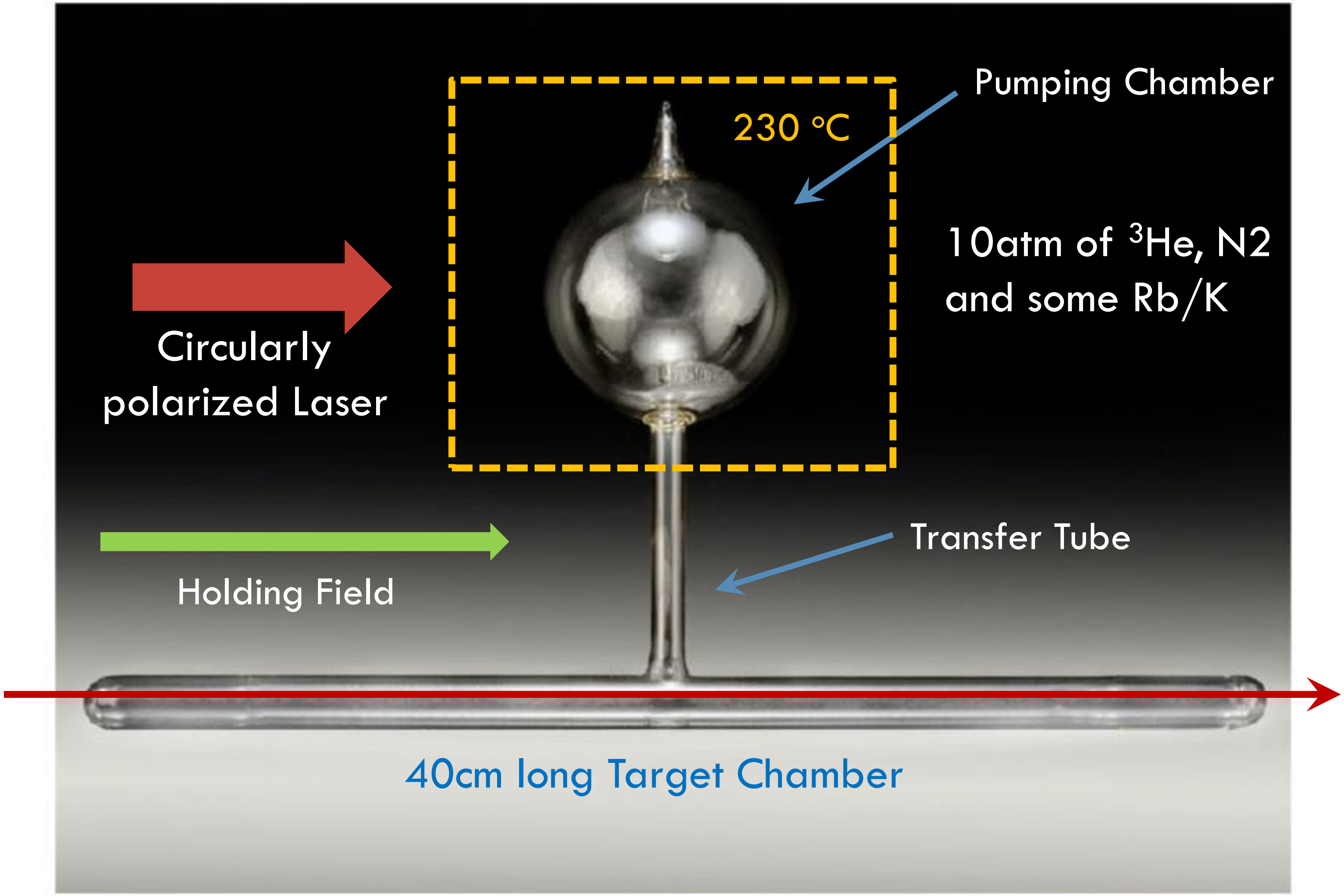


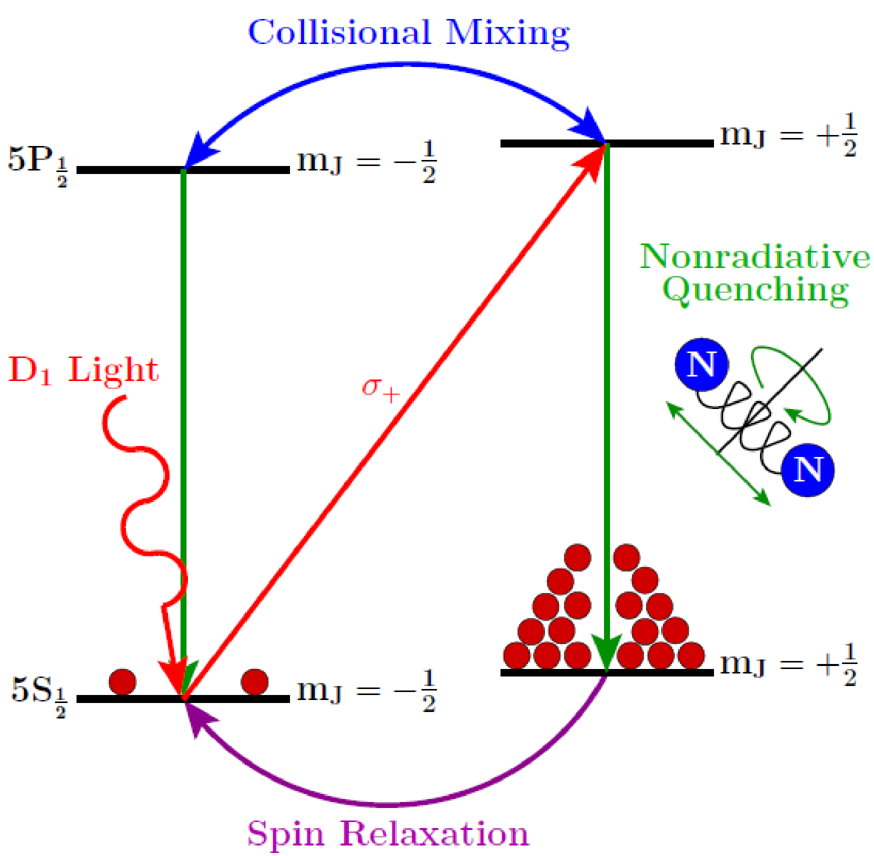
Photo Credit: A. Gavalya

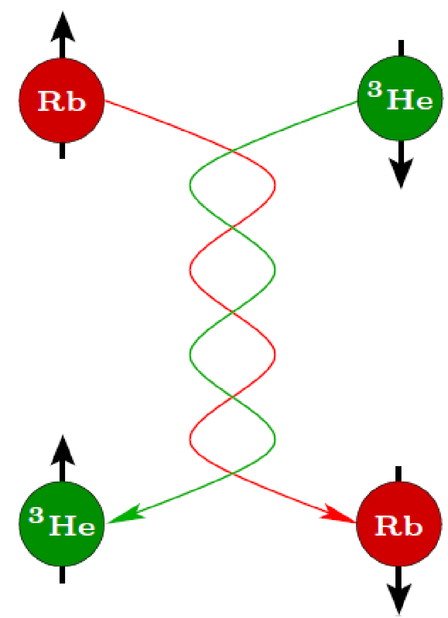
High Luminosity Polarized ^{3}He Targets For Electron Scattering Experiments

- <u>Techniques</u>
- Convection based Cells
- Targets with metal target windows

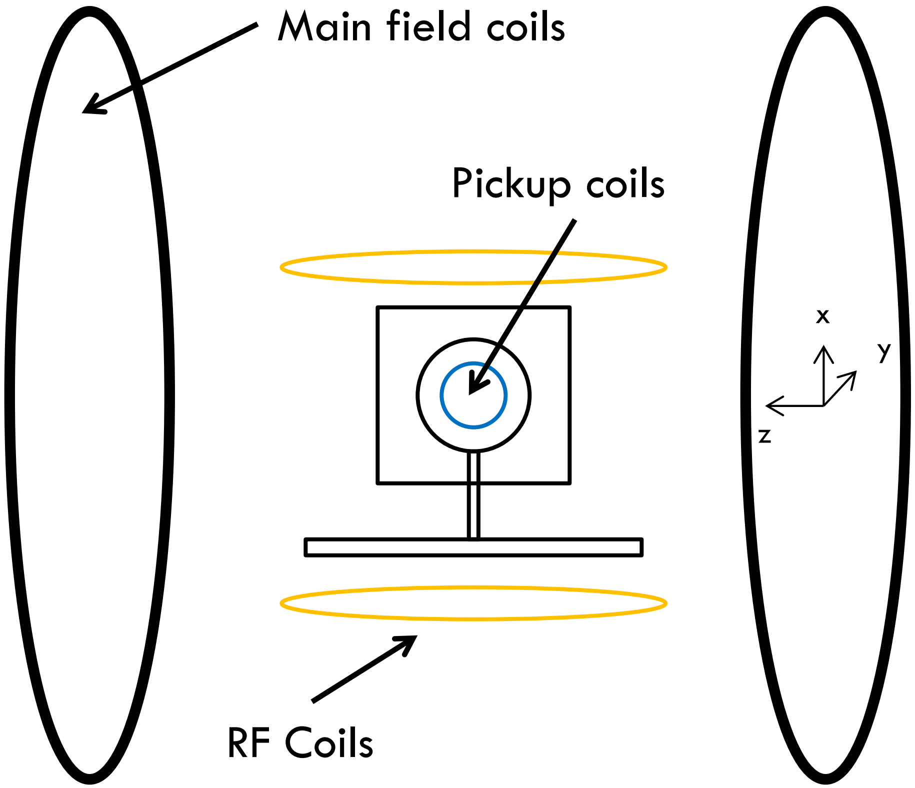
Spin Exchange Optical Pumping

- Use Spin Exchange Optical Pumping (SEOP) method to polarize the target.
  1. an alkali-metal vapor is polarized by optical pumping using lasers.
  2. the polarized alkali-metal atoms transfer spins to ^{3}He atoms.





Adiabatic Fast Passage (AFP)



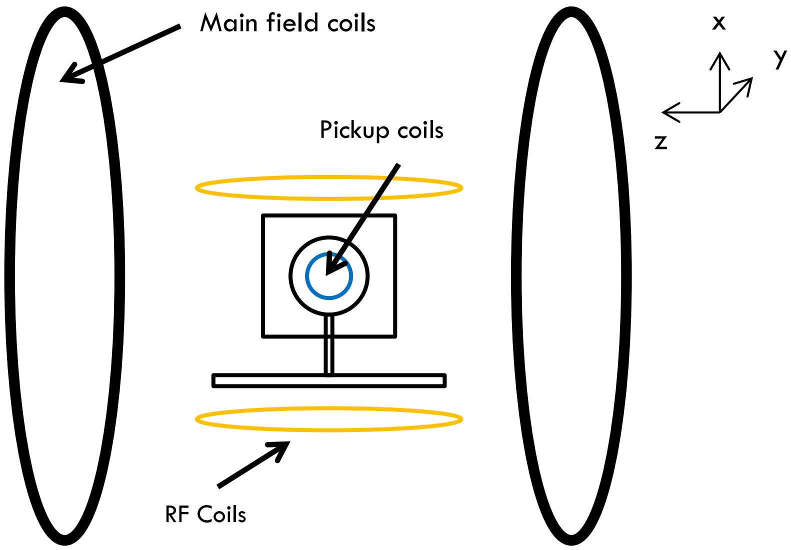
$$\vec{B}_0 = B_0 \hat{z}$$

$$\vec{B}_1 = B_1 \cos\omega t \ \hat{x}$$

In rotating coordinates

$$B = (B_0 - \omega/\gamma)\hat{z} + B_1\hat{x}$$

Adiabatic Fast Passage (AFP)



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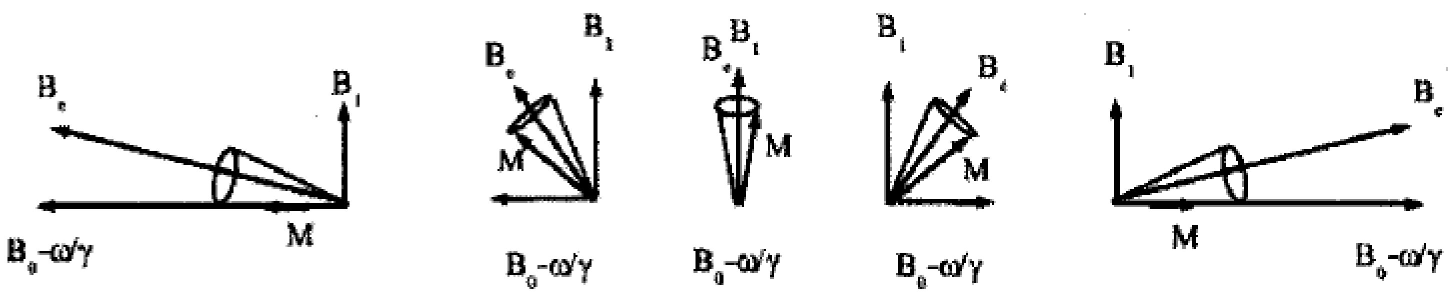
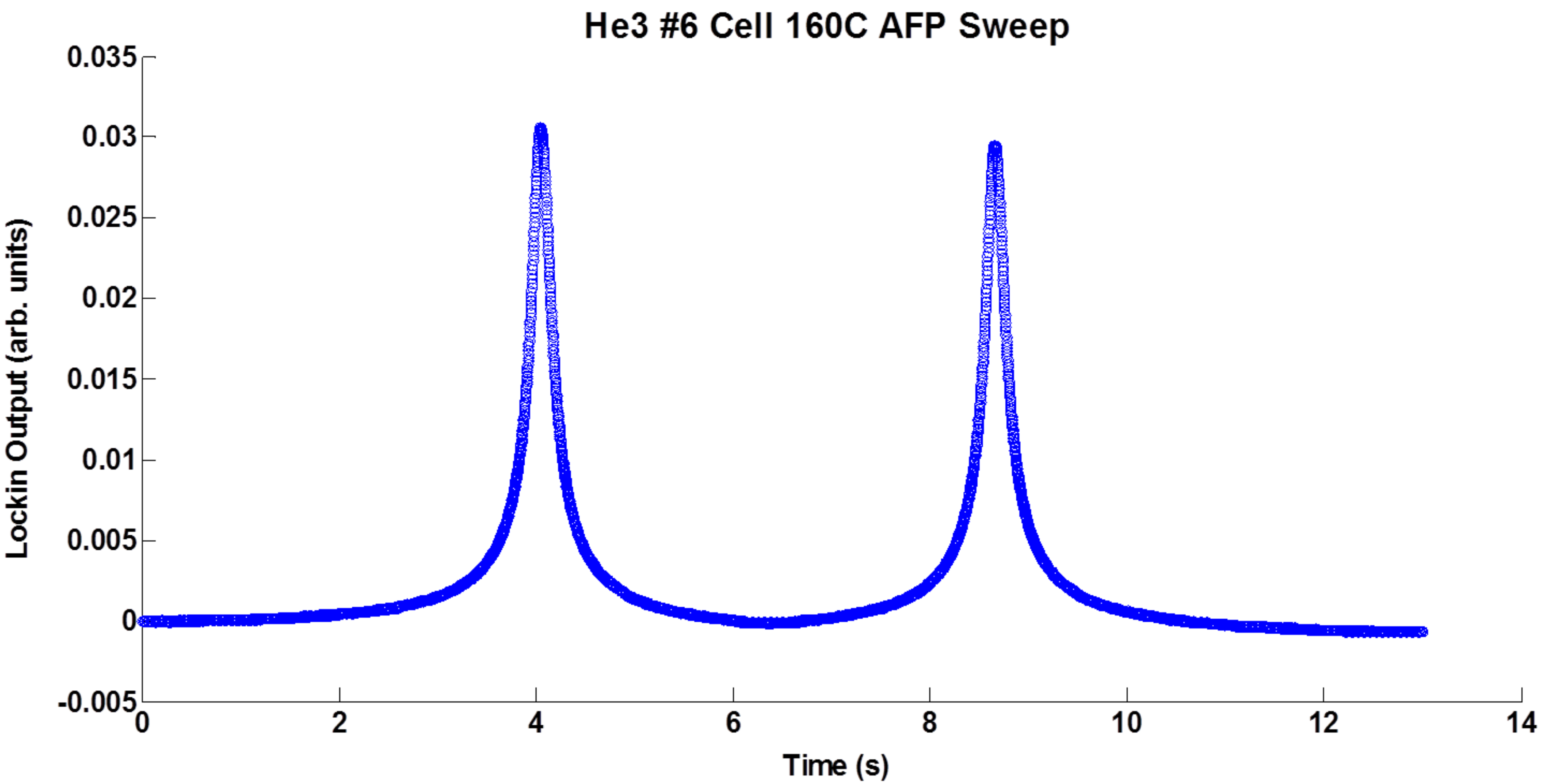


- Net magnetization follows effective magnetic field.

AFP Signal


He3 #6 Cell 160C AFP Sweep
Lockin Output (arb. units)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
2
4
6
8
10
12
14
Time (s)

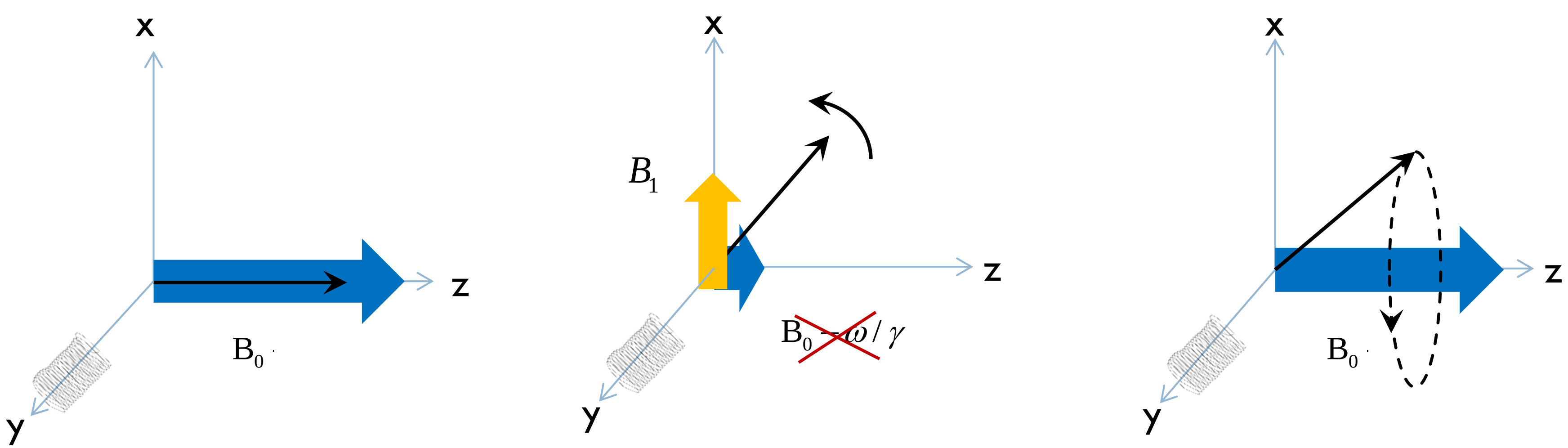
Pulse NMR

- Radio frequency energy is applied in the form of a short pulse on resonance which tips ^3He spins and make them precess around holding field.

In rotating coordinates

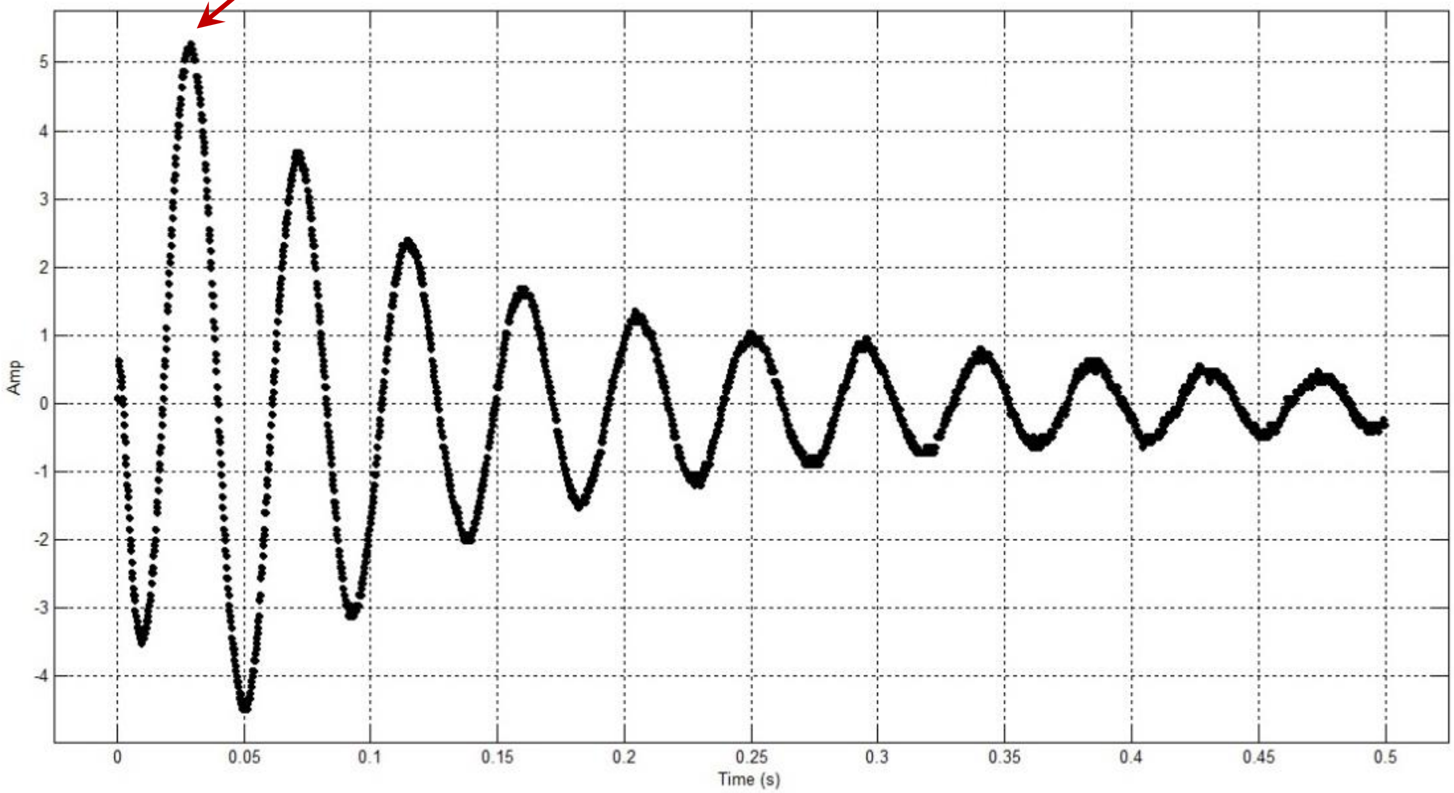
$$B = (B_0 - \omega/\gamma)\hat{z} + B_1\hat{x}$$

$$\vec{B}_1 = B_1 \cos \omega t \ \hat{x}$$

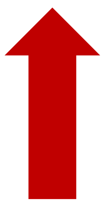


Pulse NMR Signal

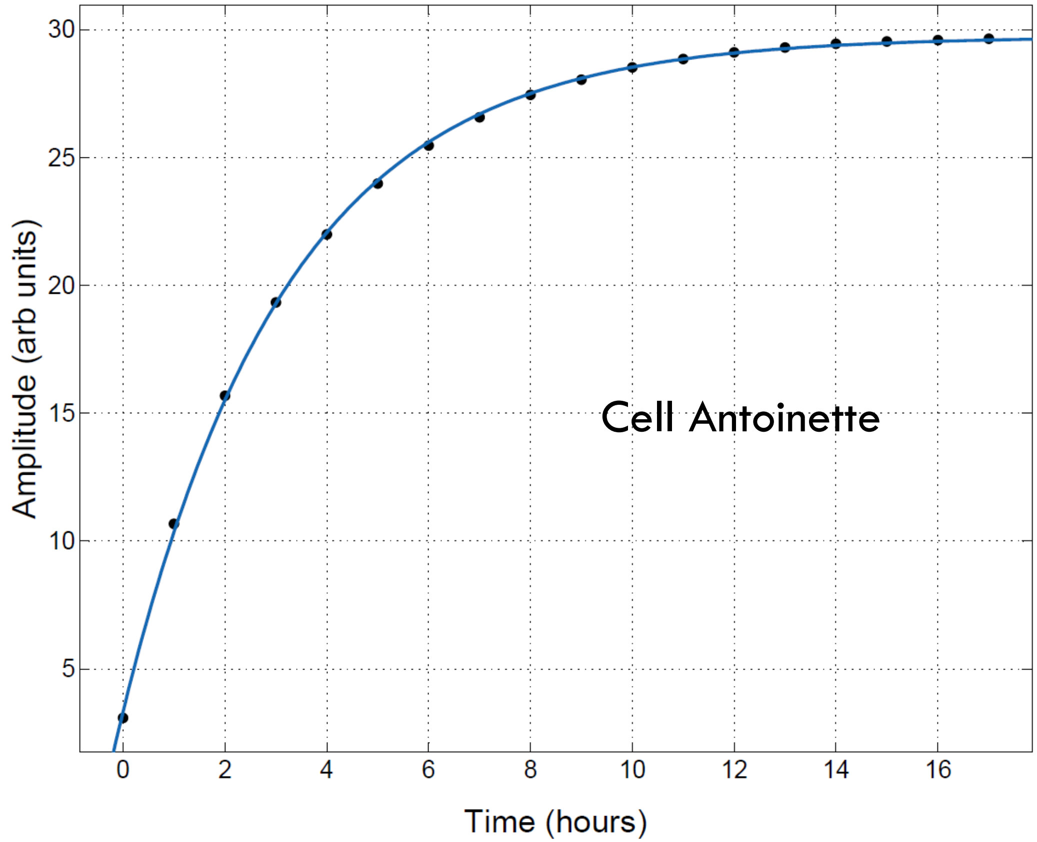
Initial amplitude is taken as a measure of polarization



Spin Up Curve



Polarization



Polarization measured as a function of time, while cell is pumped up.

De-polarization or Spin Relaxation

Sources of ^{3}He spin relaxation $\Gamma = \Gamma_{dipolar} + \Gamma_{field} + \Gamma_{wall}$

- Dipolar Relaxation

$$\Gamma_{dipolar} = \frac{\left[{}^3He\right]}{744} hrs^{-1}$$

- Static magnetic field inhomogeneity

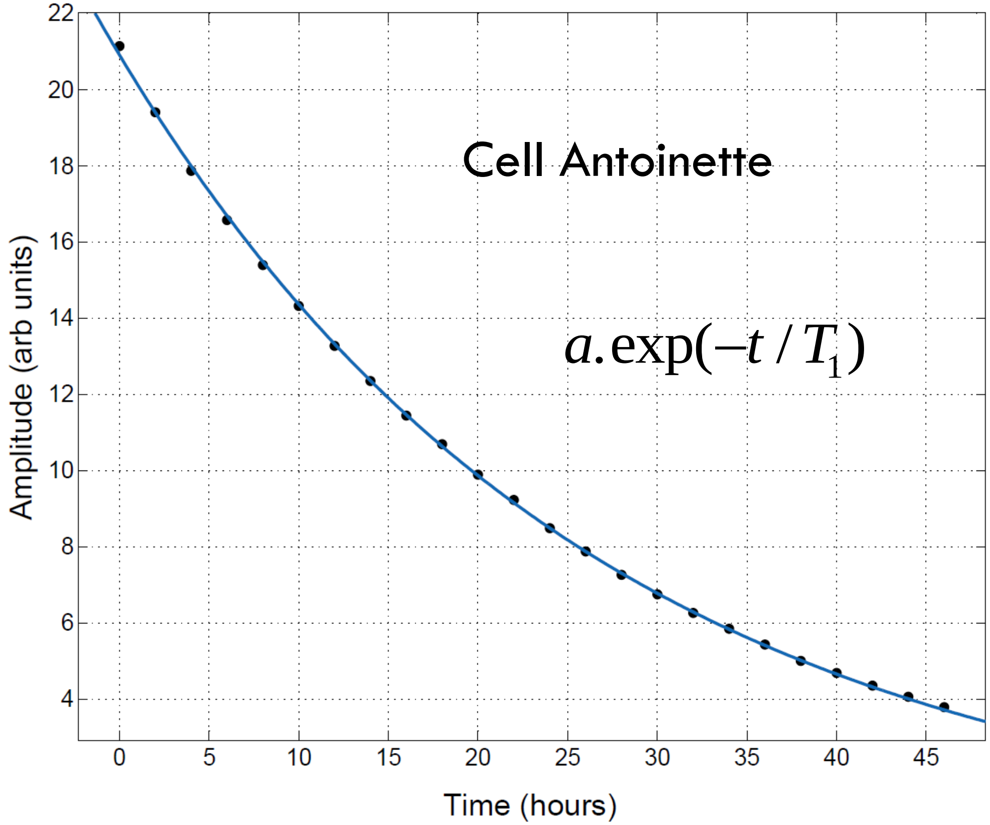
$$\Gamma_{field} = D\frac{\left|\nabla B_x\right|^2 + \left|\nabla B_y\right|^2}{B_0^2}$$

- Wall Relaxation

$$\Gamma_{wall} = \rho \frac{A}{V}$$

Spin Down Curve

Polarization



$$\Gamma = \frac{1}{T_1}$$

Polarization vs. time as spins relax.

Spin down measurement is used to determine life time of a cell.

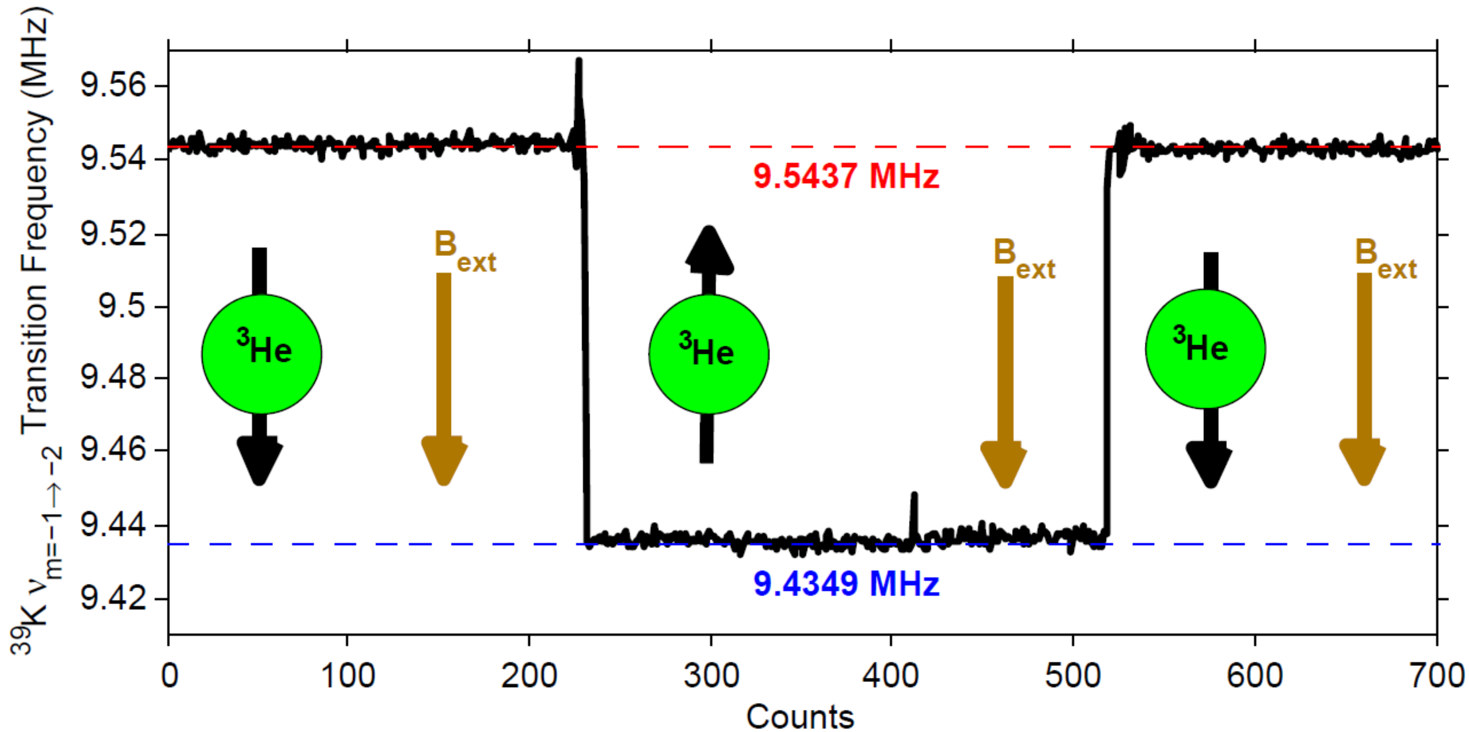
Electron Paramagnetic Resonance (EPR)

- Rb/K Zeeman splitting is proportional to the size of the field.

- Alkali metal atoms experience a small “effective” field due to the presence of polarized ^3He gas.

- We can isolate this field due to the ^3He gas by flipping the ^3He spins.

Electron Paramagnetic Resonance (EPR)



Adapted from P.A.M. Dolph et al.,2011

$$\Delta\upsilon \propto P\left[He\right]$$

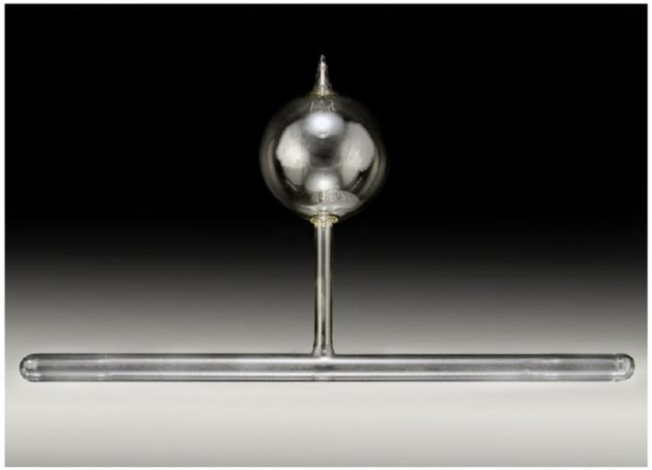
High Luminosity Polarized ^{3}He Targets For Electron Scattering Experiments

- Techniques

- Convection based Cells

- Targets with metal target windows

Diffusion based Cell



Historically used single transfer tube.

$$\frac{P_{tc}}{P_{pc}} = \frac{1}{1+\Gamma_{tc}/d_{tc}}$$

Γ_{tc} - Spin relaxation rate in TC

d_{tc} – rate atoms leave TC

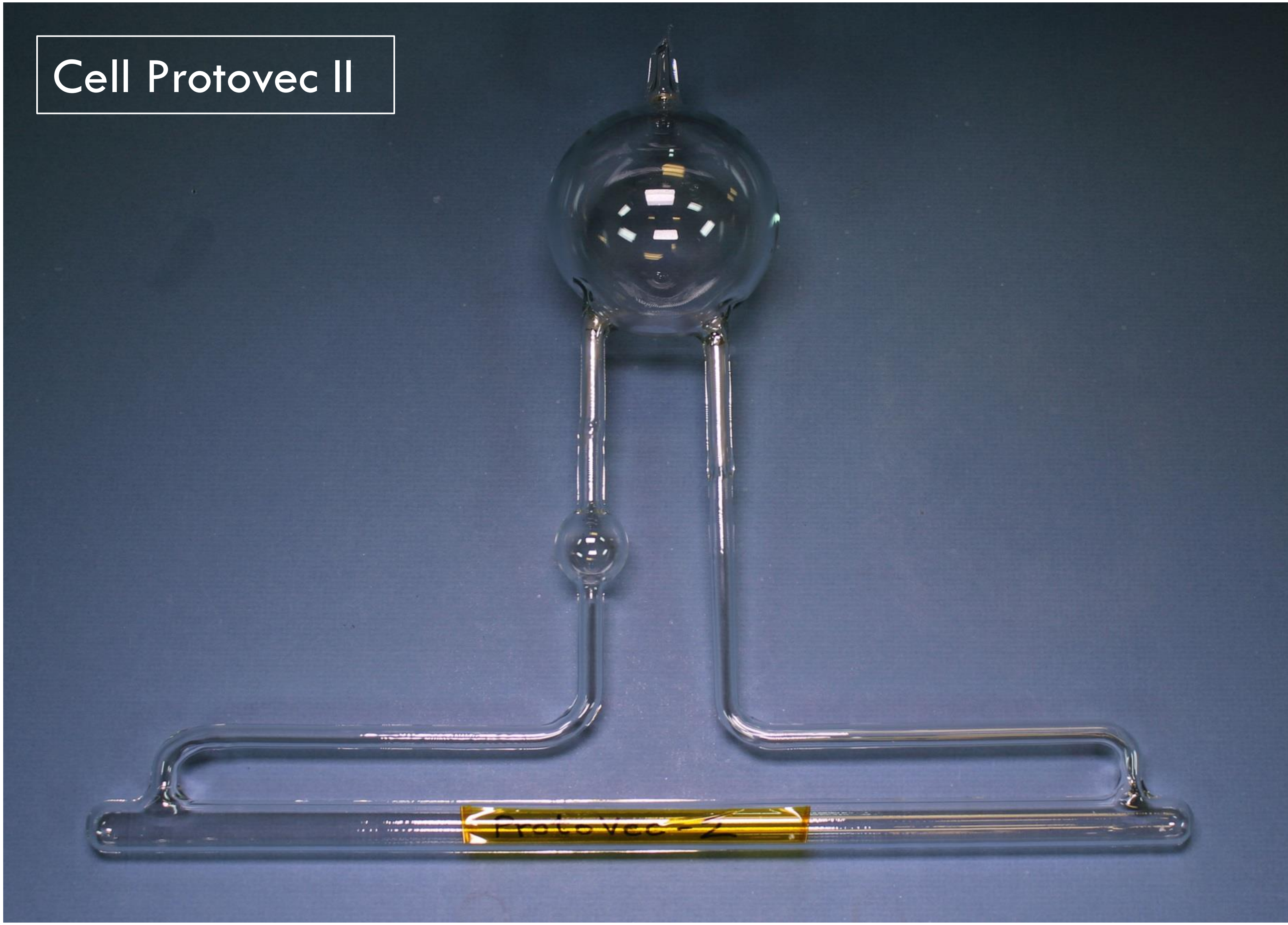
$$\Gamma_{tc}/d_{tc} << 1$$

Difficult to maintain as beam current increases.

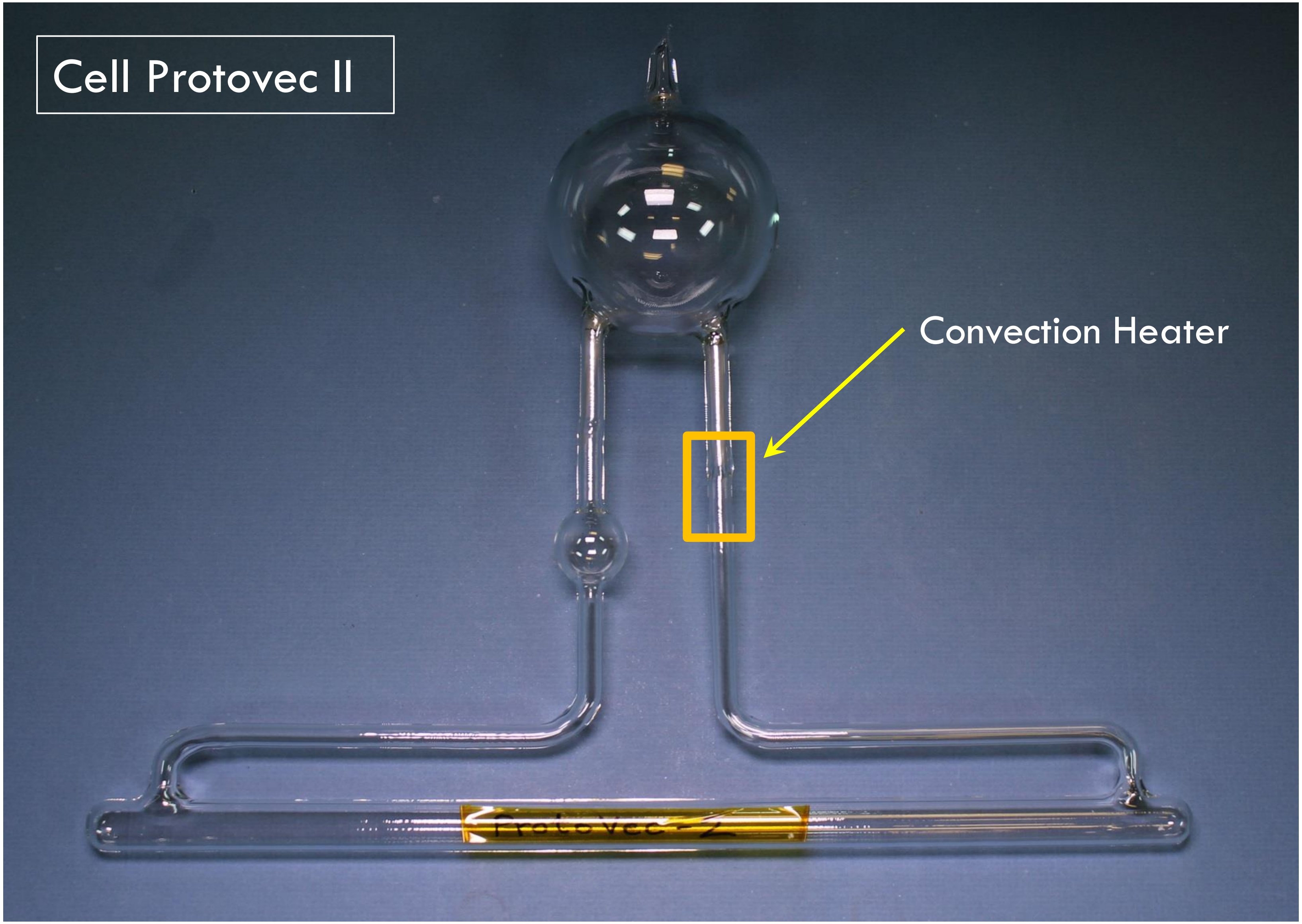
Results in lower target chamber in-beam polarization.

Since PC & TC are close to each other – risk for radiation damage.

Convection Cell

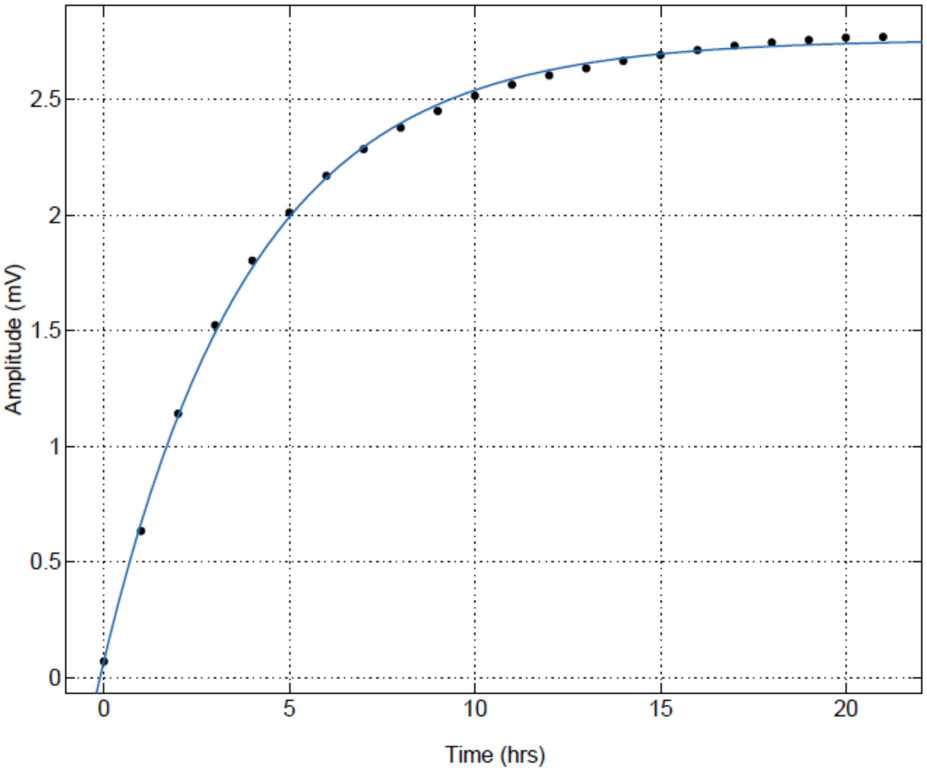


Convection Cell

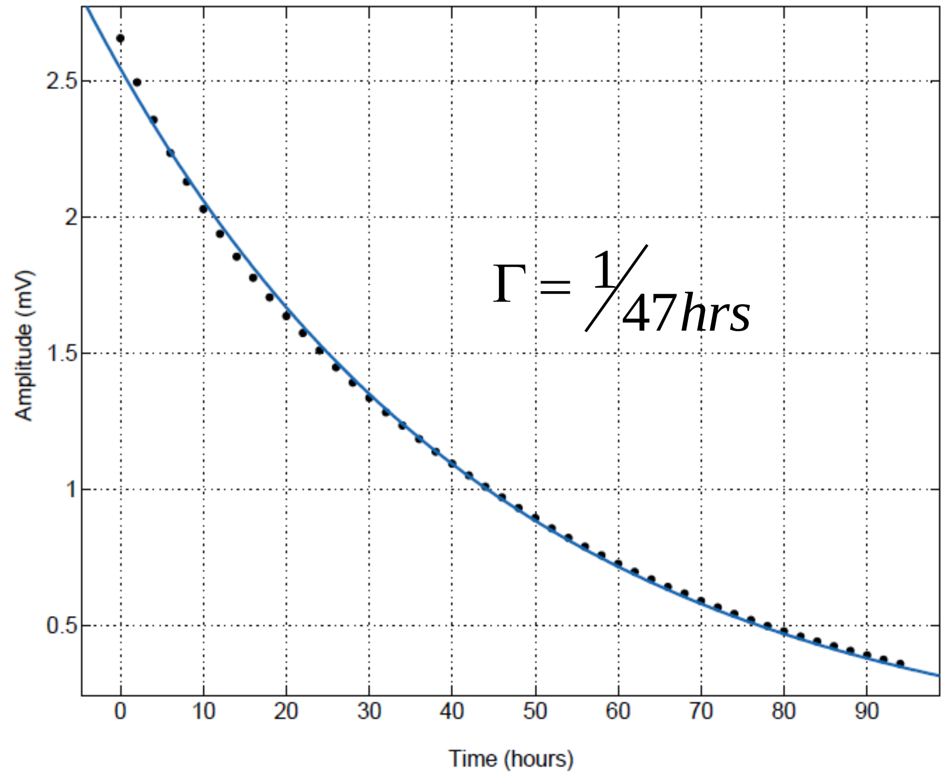


Protovec II Results

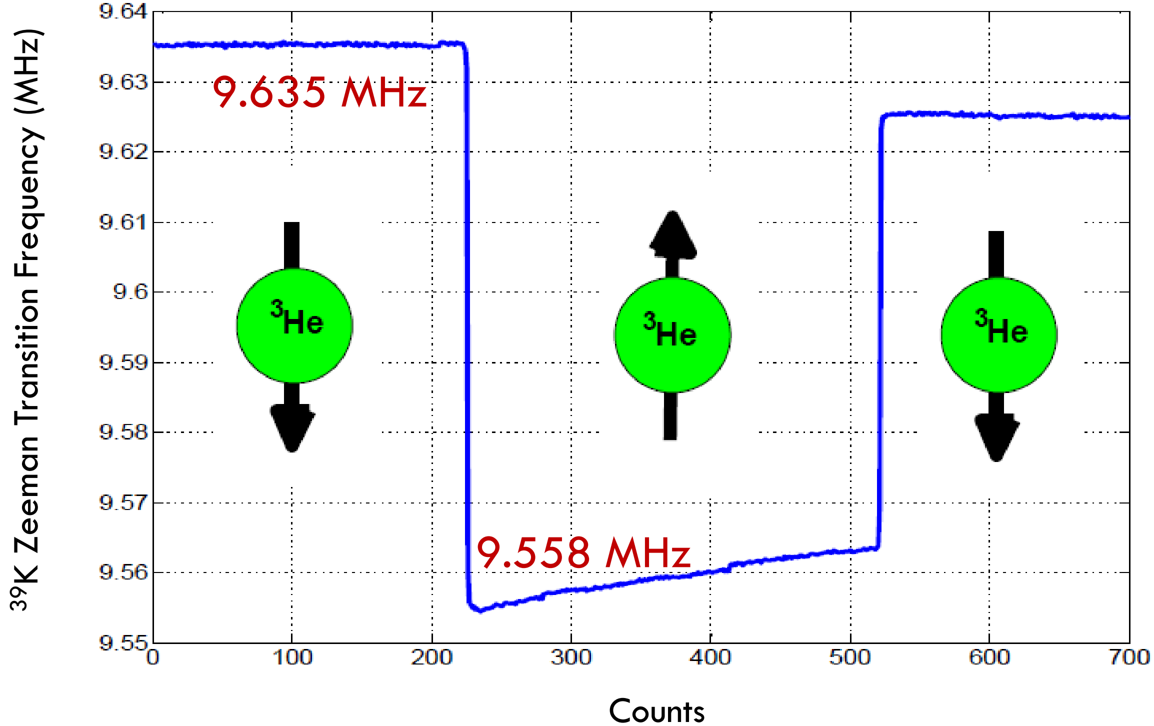
Spin Up at 235 ^{0}C



Spin Down

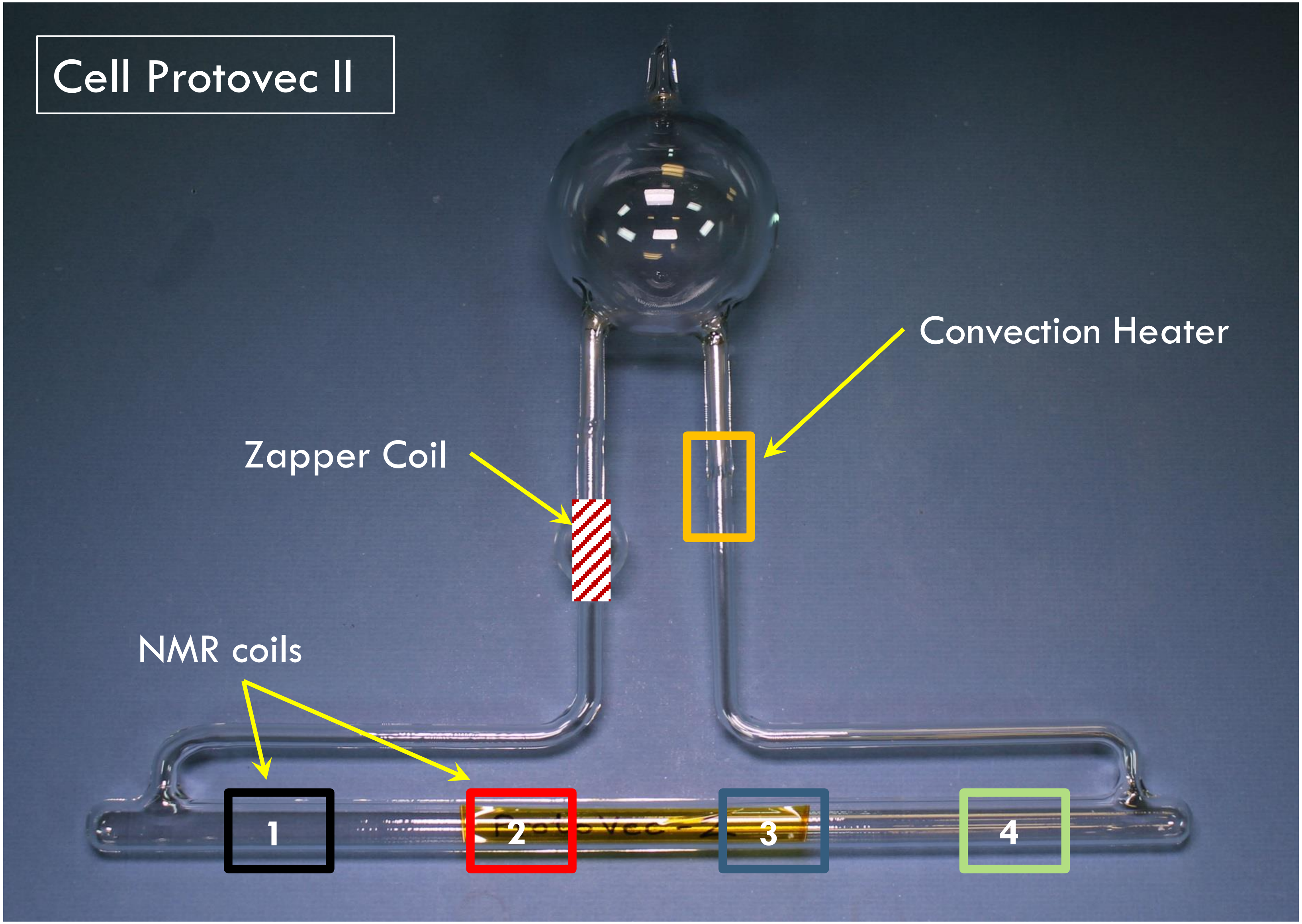


Protovec II Results

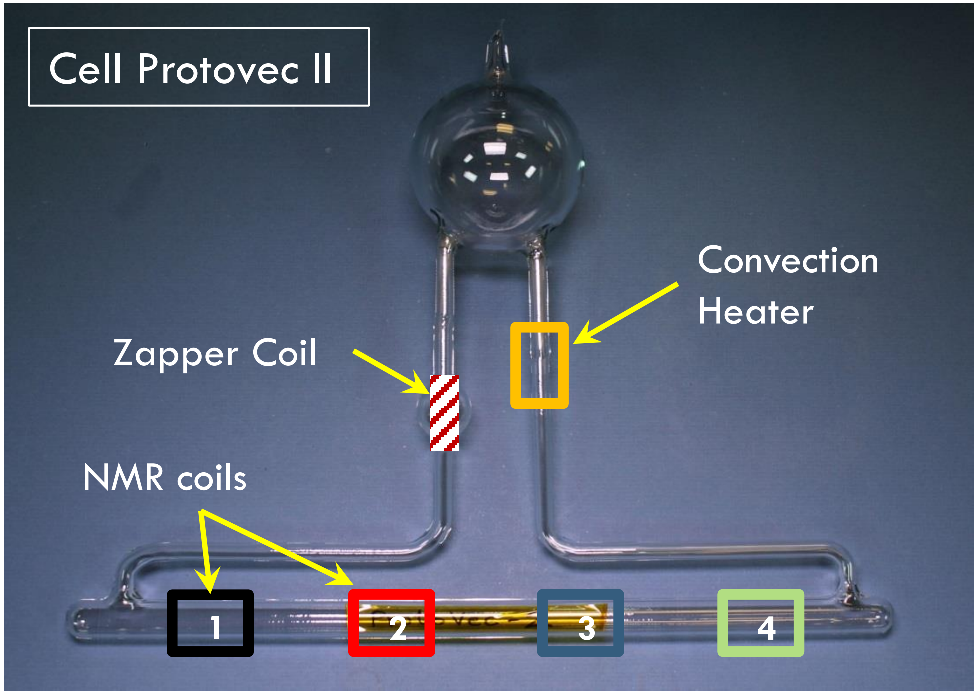


EPR calibration shows a ~ 80% saturated ^{3}He Polarization

Convection-driven gas-flow test

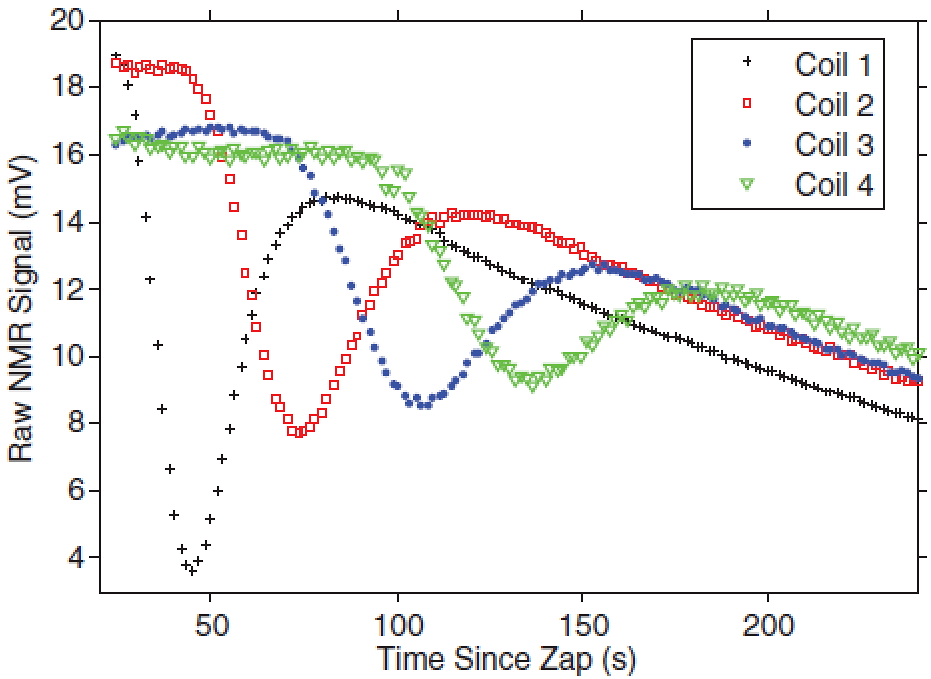


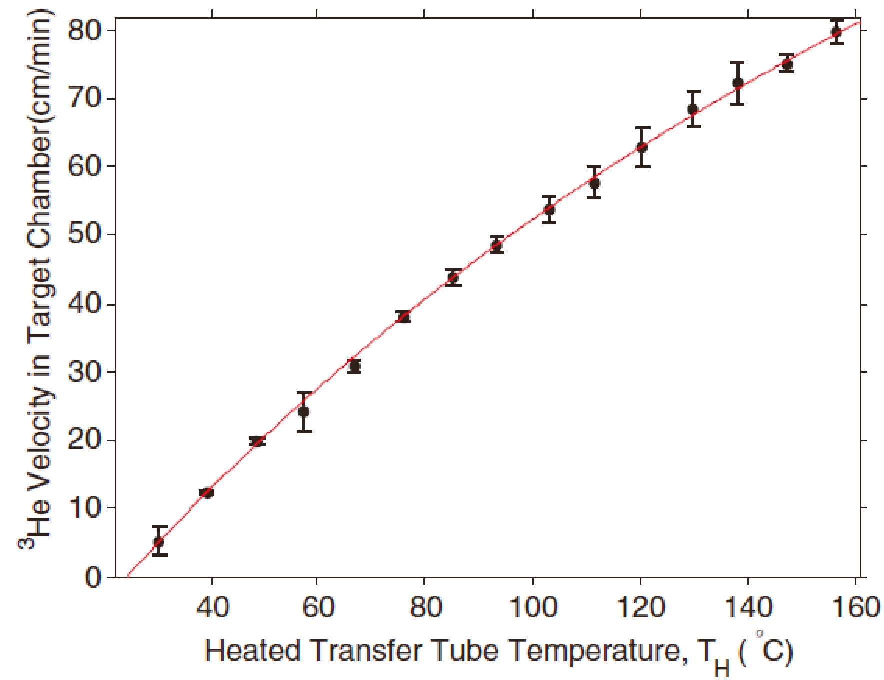
Convection-driven gas-flow test



- Heater drives convection
- Zapper coil depolarizes slug of gas
- Coils #1 - #4 monitor passage of depolarized slug.
- Heater temperature can be changed to adjust speed of gas.

Convection-driven gas-flow test





Adapted from P. A. M. Dolph et al., Phys. Rev. C **84**, 065201 (2011).

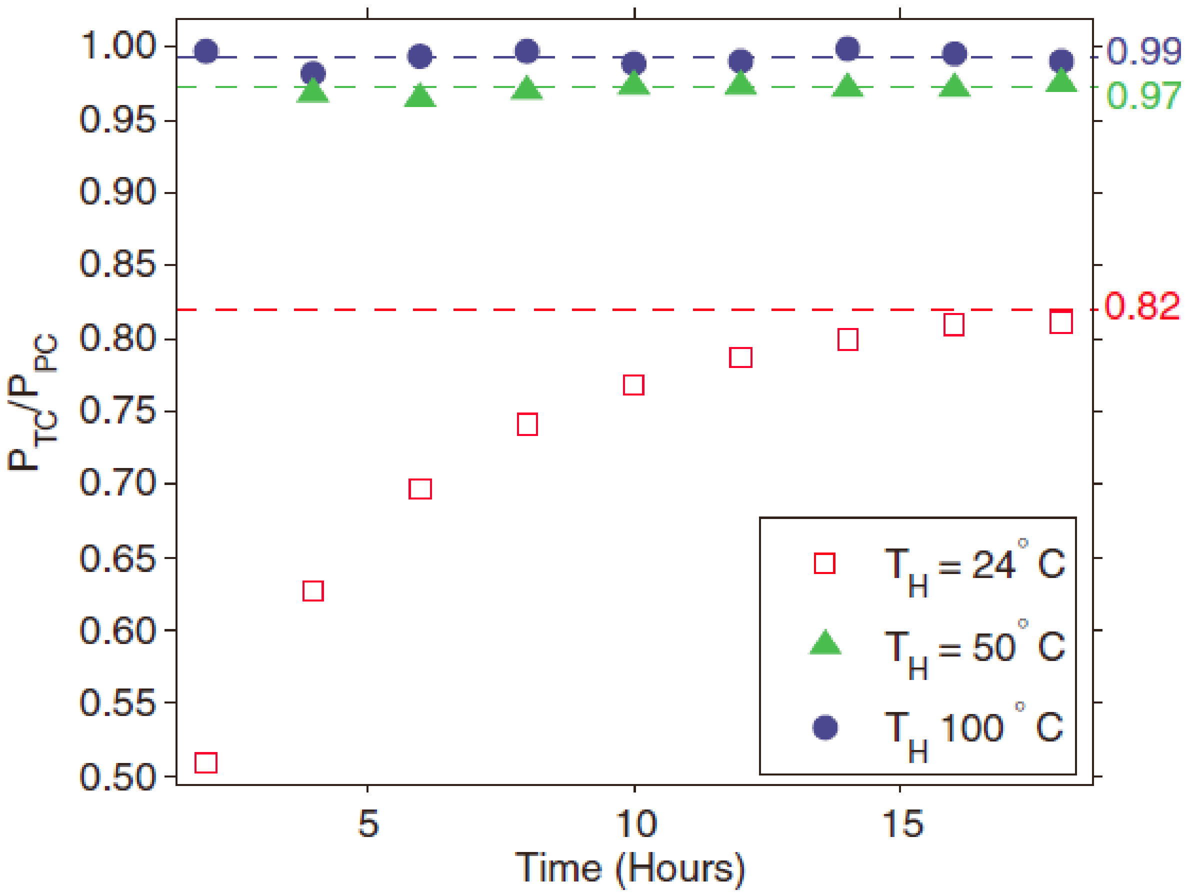
Unheated transfer tube was at 24 ◦C.

The data indicate a gas flow velocity up to 80 cm/min.

d_{tc} for the diffusion based cell 0.72 h^{-1}

d_{tc} for the convection based cell 4.9 - 81 h^{-1}

Convection drives polarization gradient to zero.



Adapted from P.A.M. Dolph et al.,2011

Ratio of polarizations of the target chamber to the pumping chamber quickly reaches unity with convection driven gas circulation.

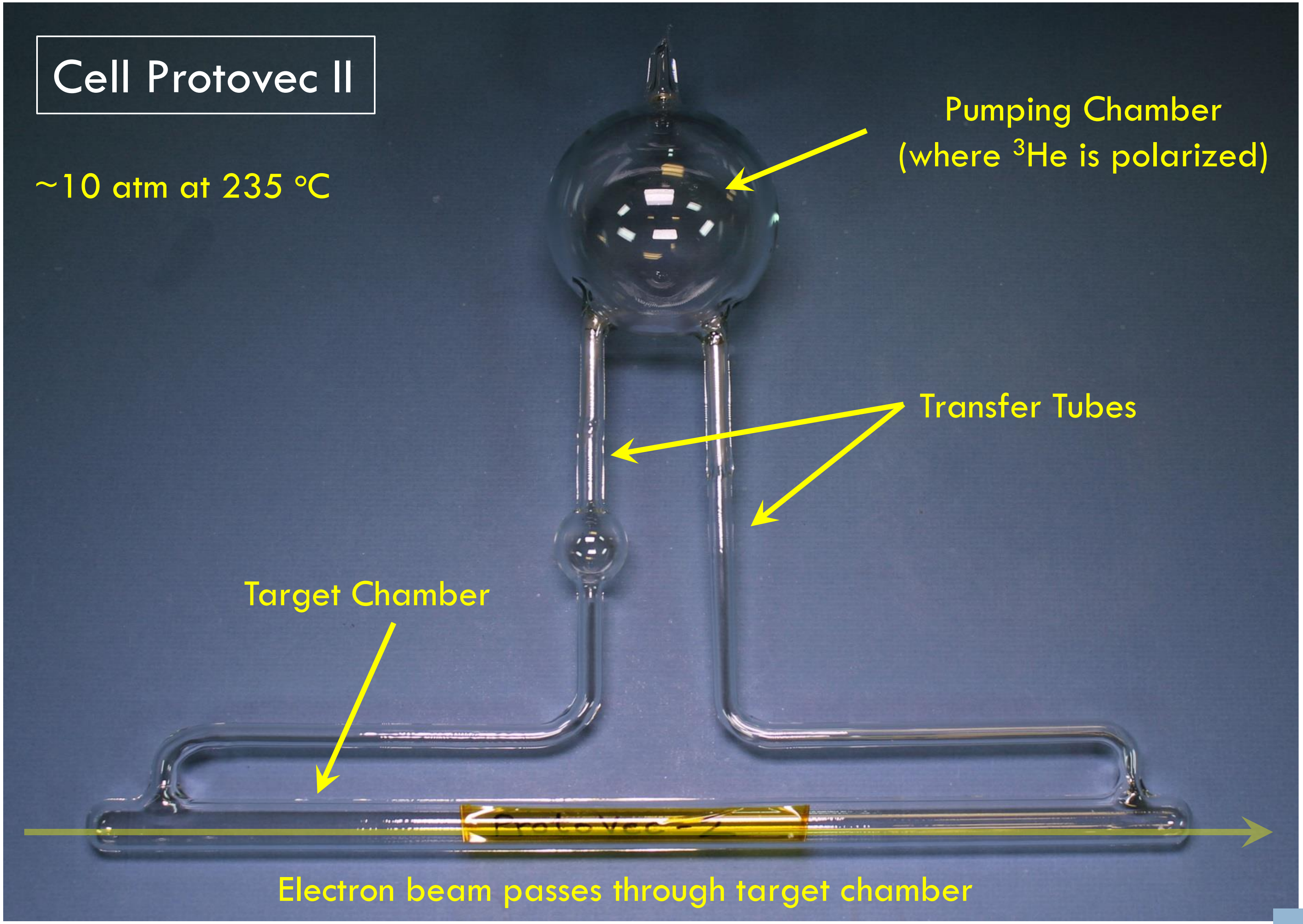
High Luminosity Polarized ^{3}He Targets For Electron Scattering Experiments

- Techniques

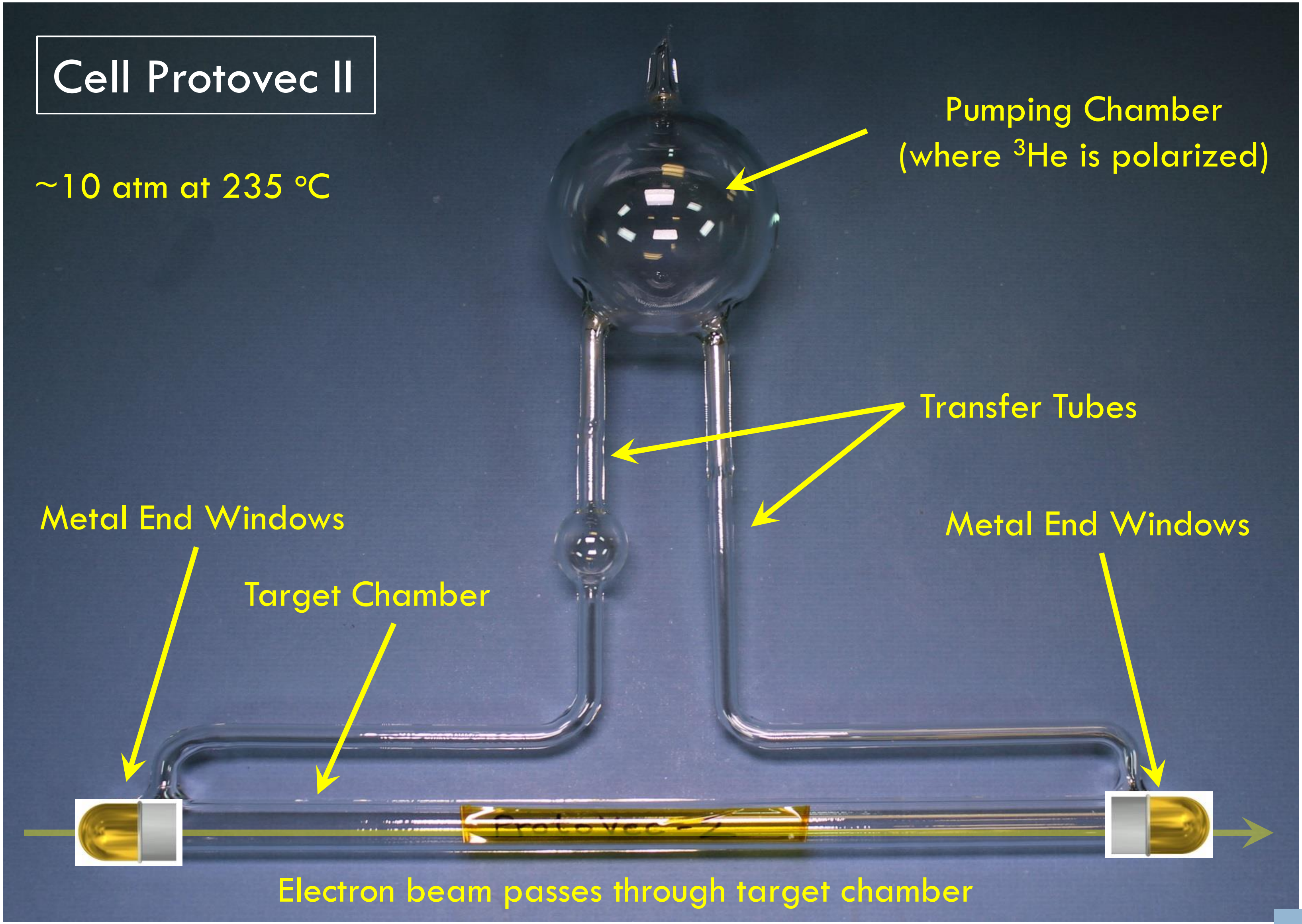
- Convection based Cells

- <u>Targets with metal target windows</u>

Polarized ^{3}He Target



Polarized ^{3}He Target



Numbers on Gold from the literature look encouraging for making metal end windows.

Paramagnetic relaxation of spin polarized ^{3}He at coated glass walls

Part II

A. Deninger[1], W. Heil[1,a], E.W. Otten[1], M. Wolf[1], R.K. Kremer[2], and A. Simon[2]

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[2] Max-Planck-Institut für Festkörperforschung, 70569 Stuttgart, Germany

THE EUROPEAN PHYSICAL JOURNAL D

Eur. Phys. J. D **38**, 439–443 (2006)
DOI: 10.1140/epjd/e2006-00051-1

5 Other coatings

In the course of 3 thesis works [18,23,27] we have briefly examined also a number of other coatings on various glass substrates and measured their ^{3}He relaxation times (in brackets): metals: Mg (6 h), Al (6 h), Zn (12 h), Se (5 h), Ag (5 h), Sb (7 h), Te (10 h), Au (20 h), Pb (26 h), Bi (50 h); salts: LiF (8 h), MgF_2 (8 h), CsF (25 h), CsCl (18 h); oxides: Al_2O_3 (4 h); hard covalent coatings: diamond (3 h), titanium nitride (2 h). Most of the more volatile species have been evaporated in situ by a removable oven and ^{3}He relaxation has been measured without breaking the vacuum in between [18]. This might have in-

Wall Relaxation Rate

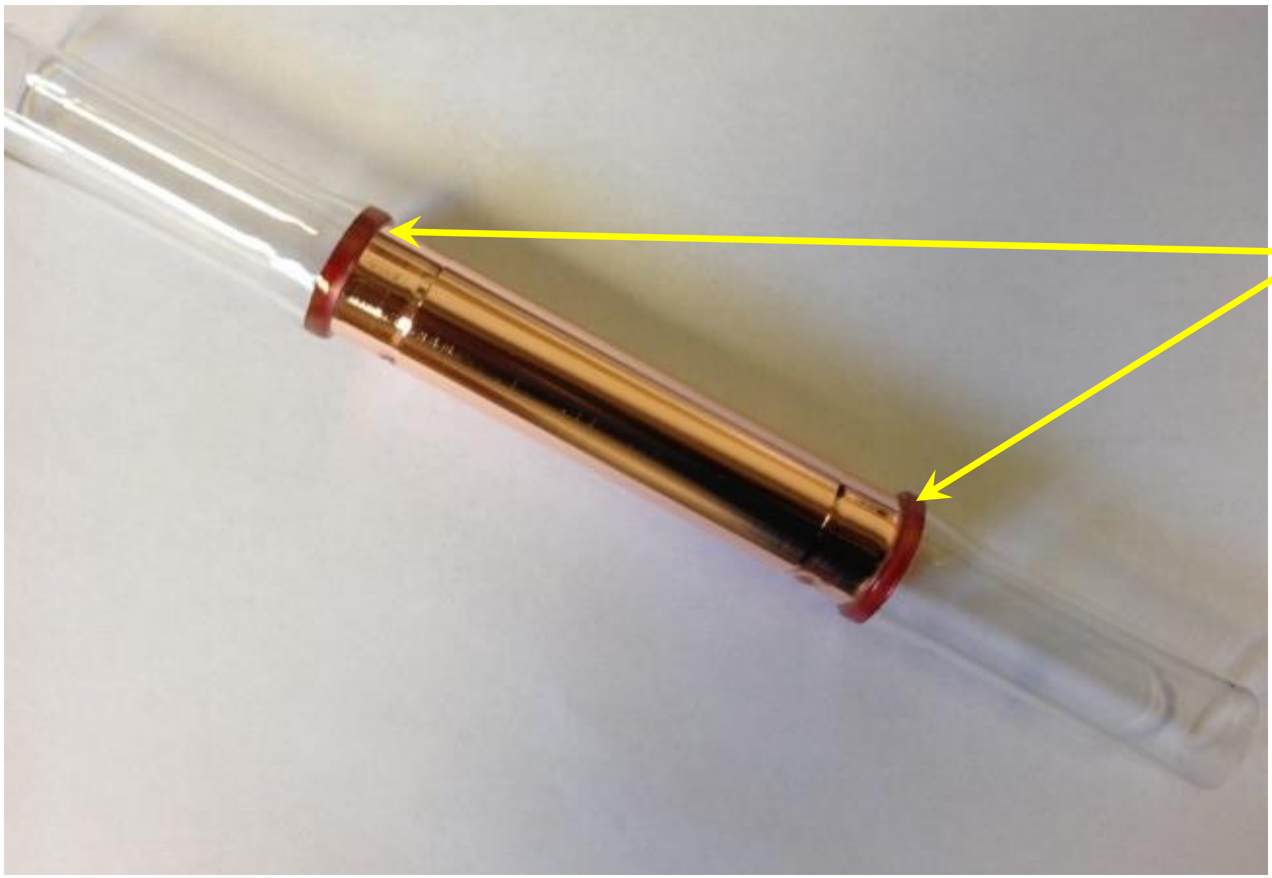
$$1/T_1^{wall} = \rho A/V$$

ρ - Surface relaxivity
A - Area
V – Total Volume

Preparation of Pyrex-Copper-Pyrex tubes

Larson Glass-Metal Seals

LARSON
ELECTRONIC GLASS



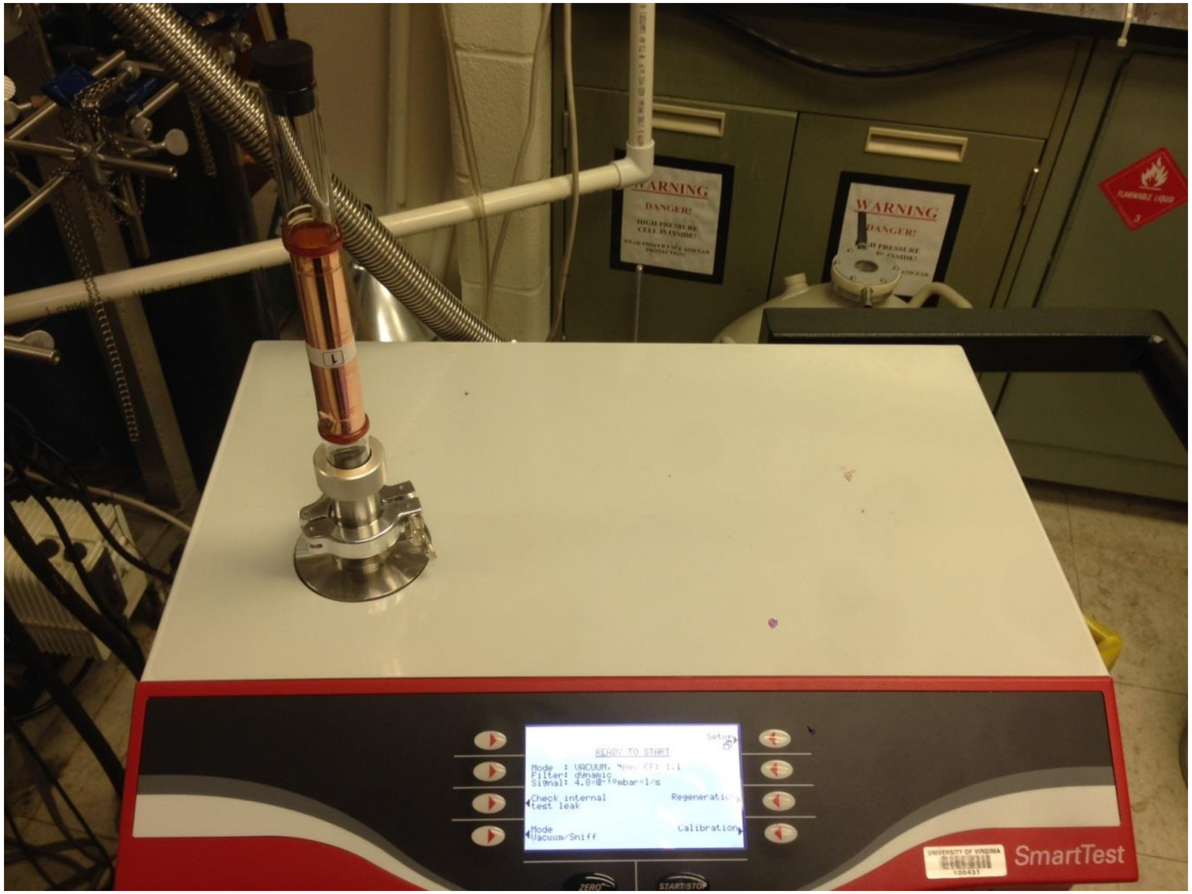
Housekeeper Seals

Preparation of Pyrex-Copper-Pyrex tubes

Pressure tested Glass-Metal Seal. It survived pressures greater than 20 atm.

Preparation of Pyrex-Copper-Pyrex tubes

Leak tested the seals. Leak Rate about 10^{-9}-10^{-10} mbar l/s.



Preparation of Pyrex-Copper-Pyrex tubes

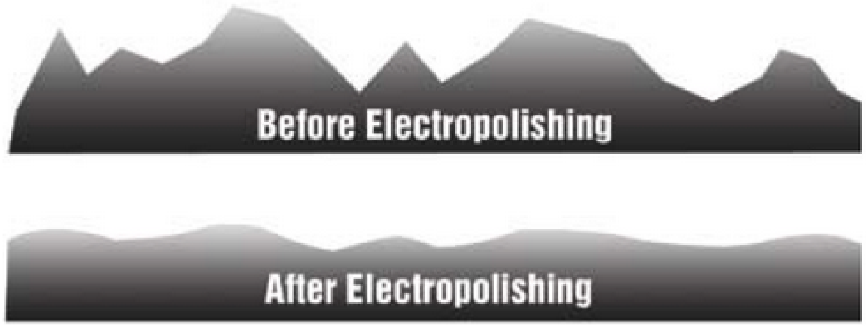


Illustration A

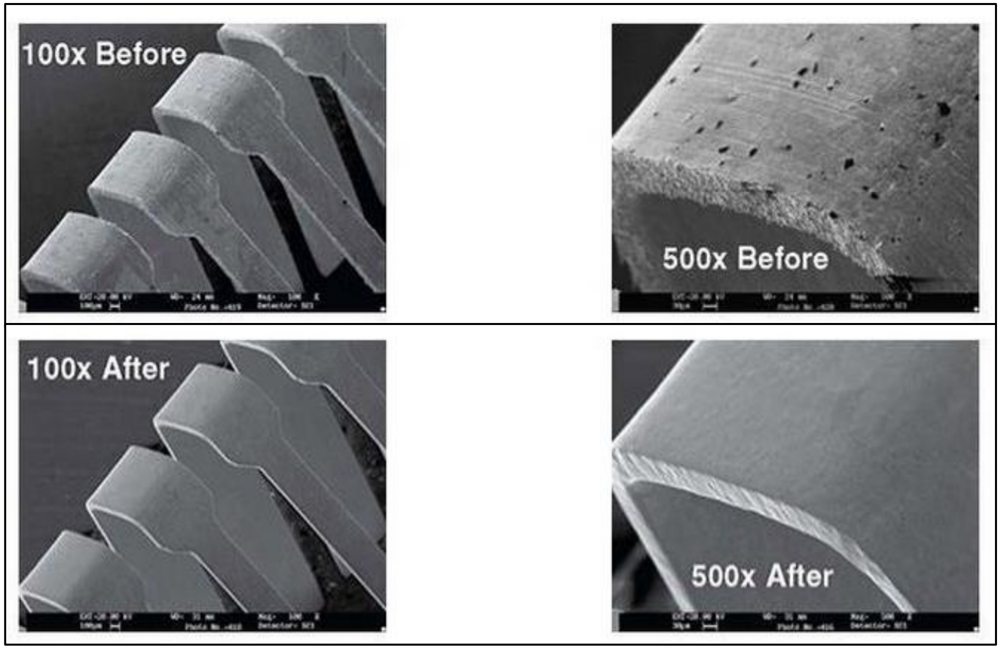
In general terms, when properly applied, electropolishing can reduce microfinish values by 50% with a removal of .0005″ from each surface. Chart B clearly shows that maximum benefit is achieved in this area, and that removing much more metal does not continue to improve surface finish.

ABLE®

Electropolishing

Advanced Metal Improvement Technologies

② Electro-polished



http://www.ableelectropolishing.com/

Preparation of Pyrex-Copper-Pyrex tubes

EPNER TECHNOLOGY INC. Accredited Nadcap

Plating Specialist Since 1910

Laser Gold

Laser Gold plating is a proprietary, pure, hard, electrochemically deposited gold coating that combines the theoretical reflectivity and emissivity of gold, with a surface that can *actually be physically cleaned!*

Nd-Yag laser pump cavity reflectors, brass substrate.

A process that has been refined for more than twenty years, Laser Gold has been the sole and single NIST standard (#2011) for infrared reflective material. Epner Technology is also proud of the fact that Laser Gold has been specified on some of our nation's most advanced military and space programs.

http://epner.com

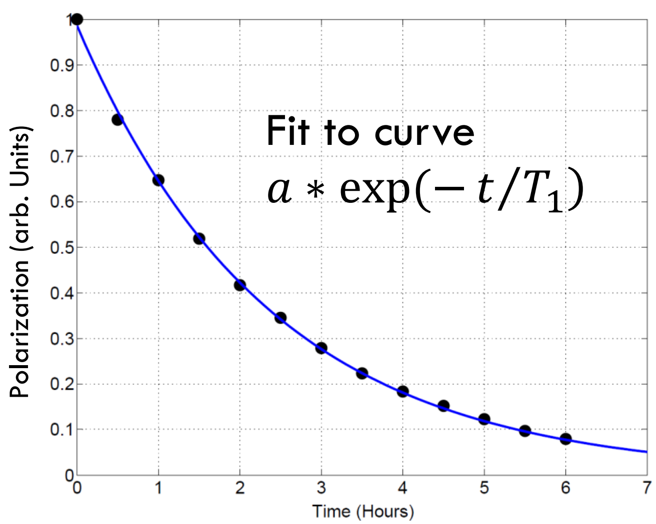
③ Gold plated inside surface (for some tubes)

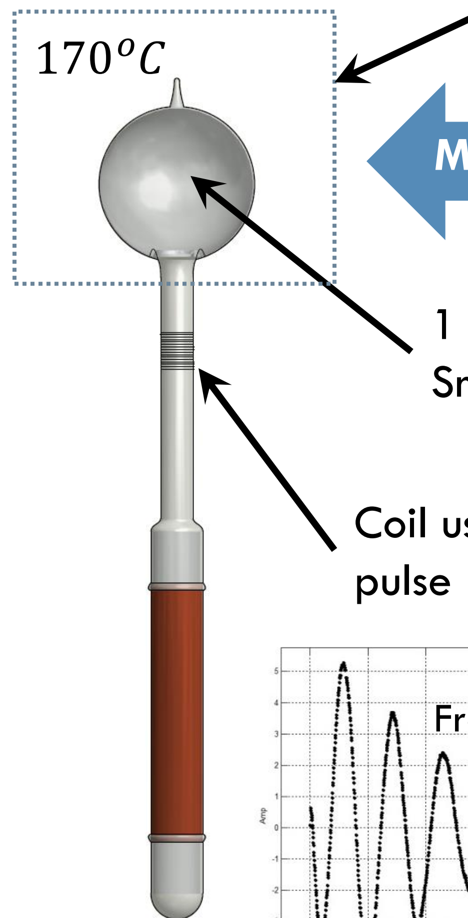
Preparation of Pyrex-Copper-Pyrex tubes

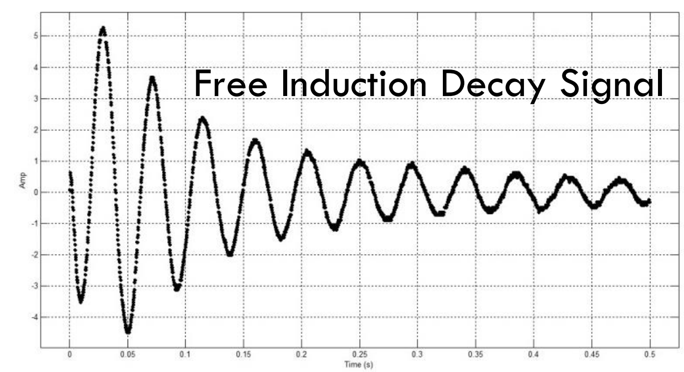
④ Cleaned tubes using ultra-sonic cleaner.

Method for testing samples

- ^{3}He test cells built using tubes
- ^{3}He polarized using spin-exchange optical pumping (SEOP)
- Polarization monitored using Pulse NMR
- Polarization measured as a function of time.



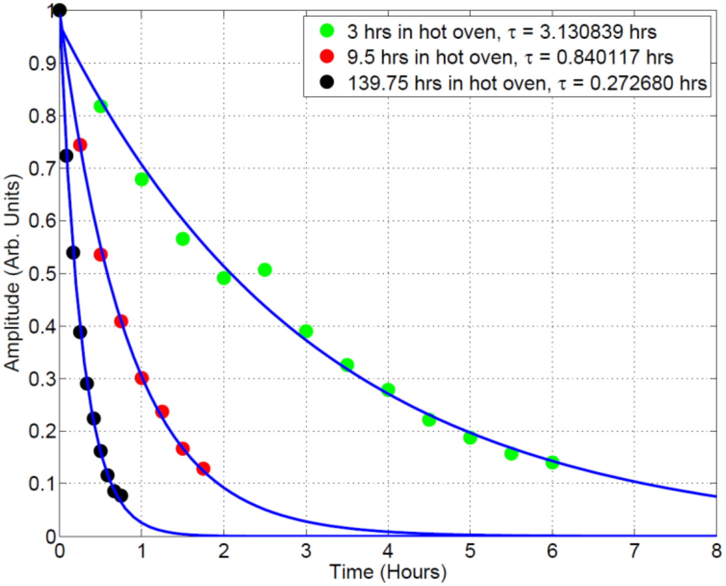




Results with and without Gold

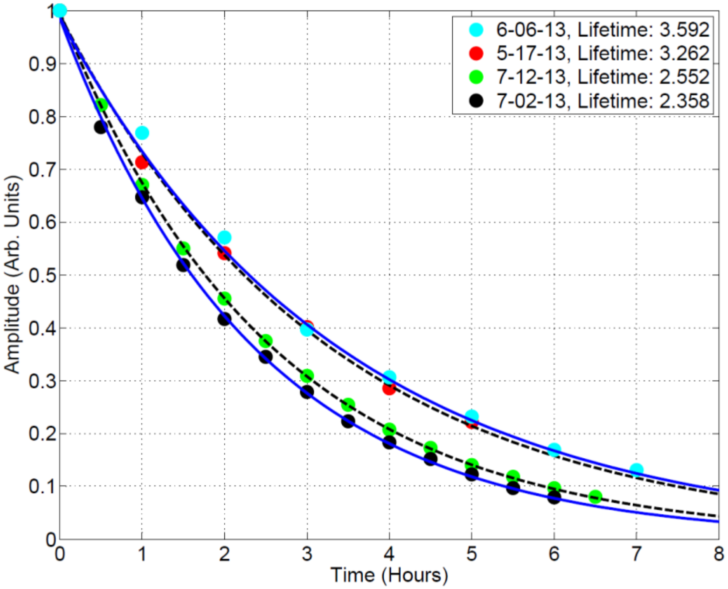
Cell Gold Finger

“Cupid” - Copper-only



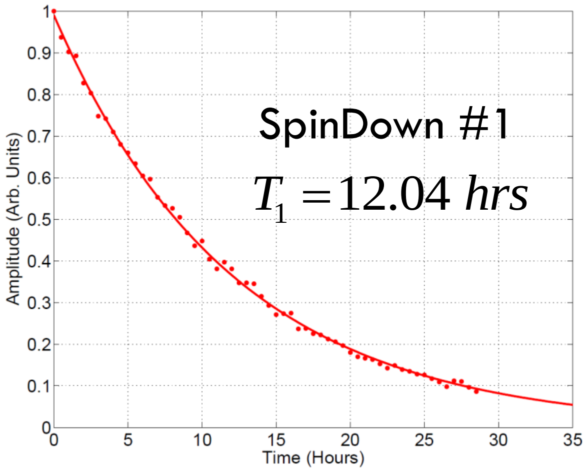
Lifetimes degrade from 3.1 hrs to 0.3 hrs. We believe Rb exposure degraded our surfaces.

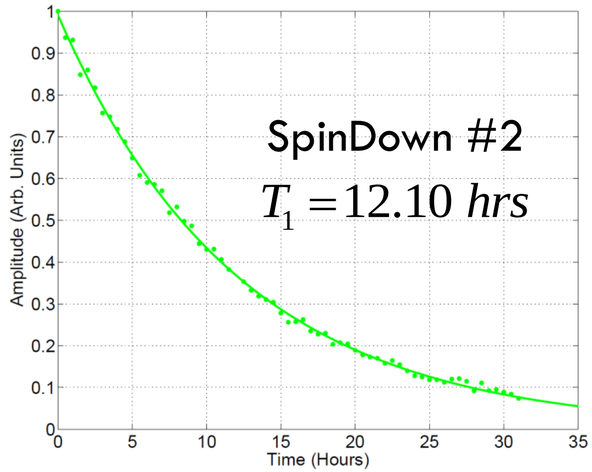
“Goldfinger” - Gold-coated copper

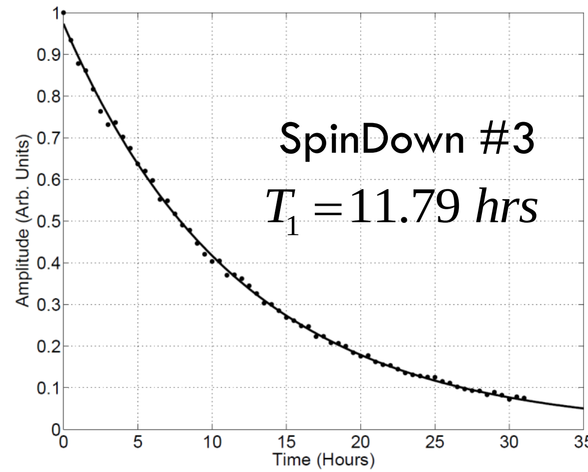


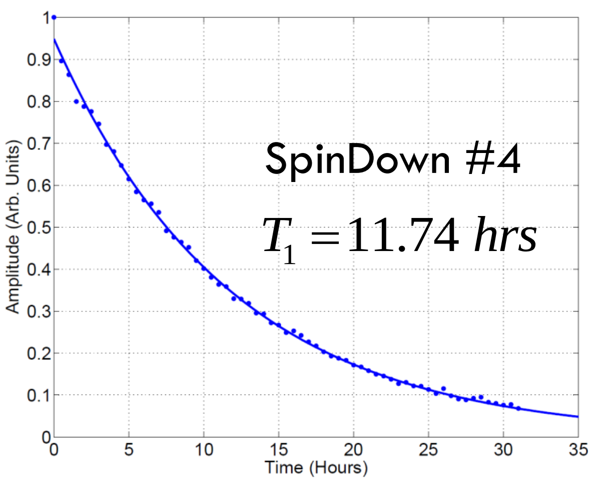
Lifetime degraded only slightly from 3.6 hrs to 2.4 hrs.

Tests of "GoldRush"









a) No significant degradation of lifetime was observed over four spin downs

b) The observed lifetimes were the longest we had measured to date.

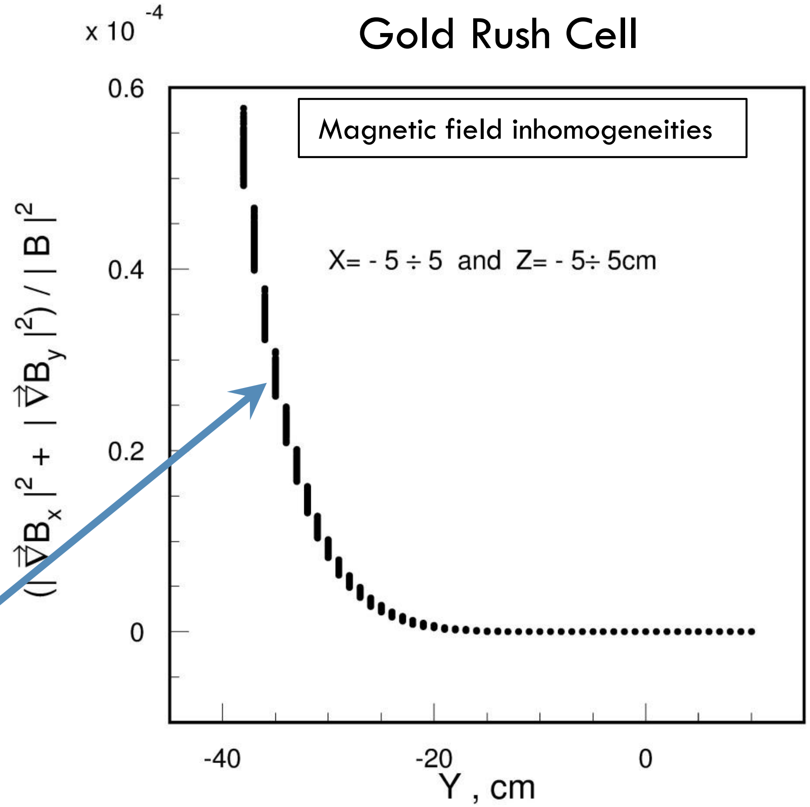
c) We further discovered these lifetimes were limited by magnetic field inhomogeneities (more on this to come)

Calculations indicated lifetime of "GoldRush" was at least partially limited by magnetic field inhomogeneities

Relaxation Time ~ 300 – 700 hrs

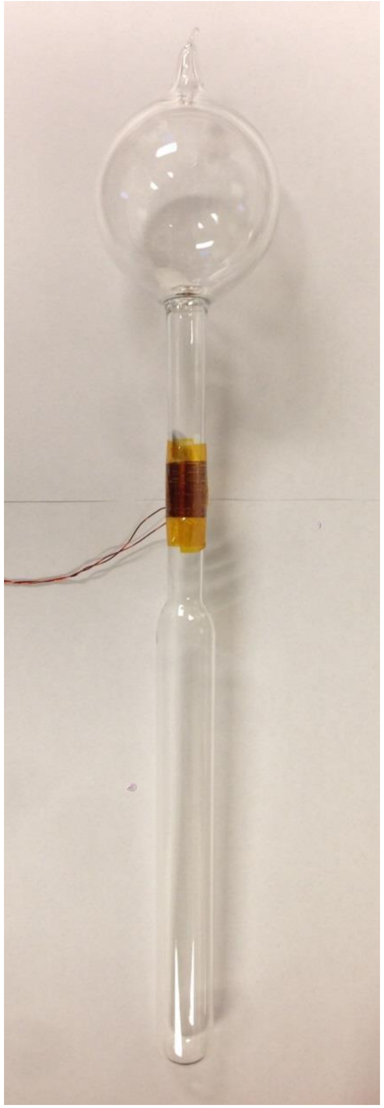
36 cm

Relaxation time ~ 1-5 hrs

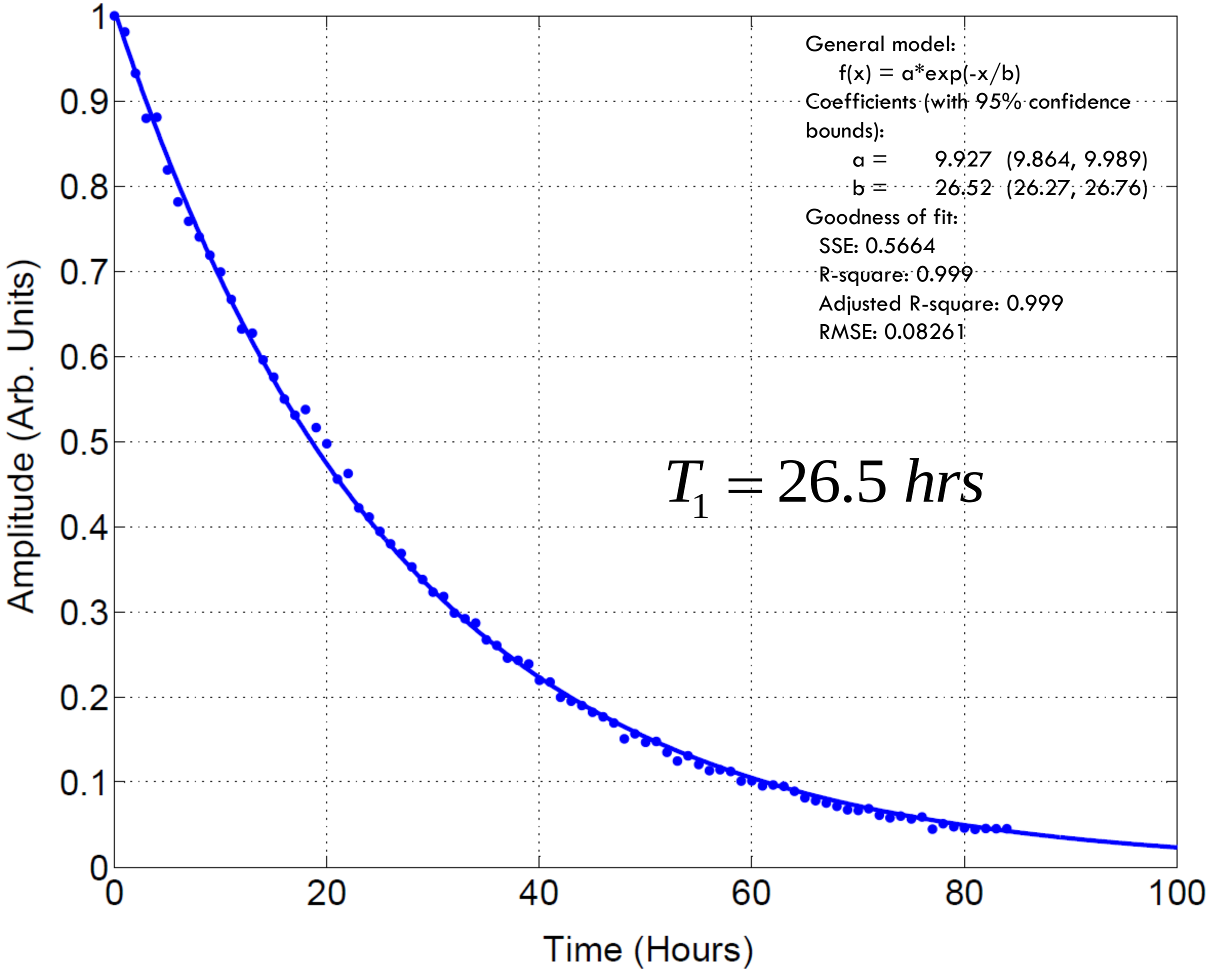


Lifting the cell by ~ 5 cm improved lifetime of GoldRush from around 11 to 15 hrs.

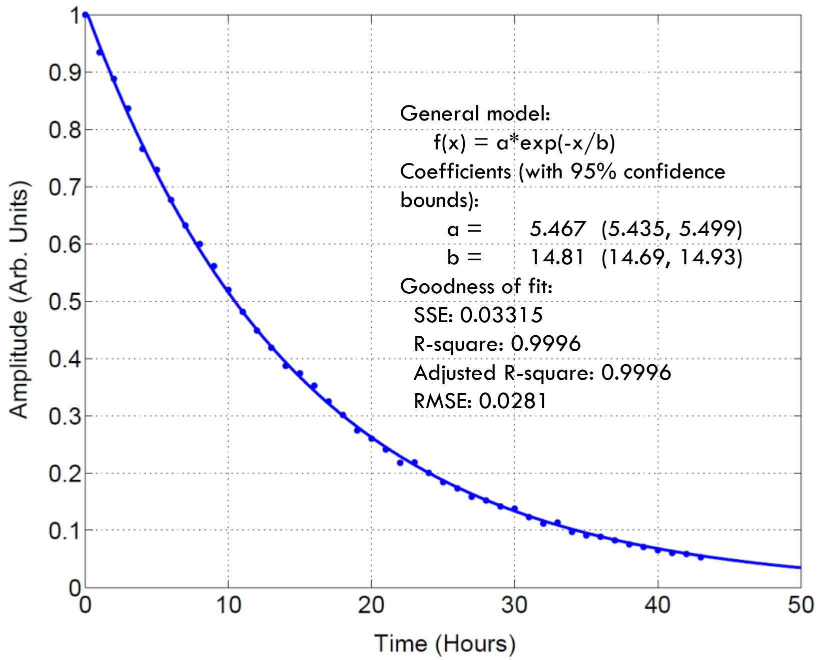
Control Cell "Pyrah" for glass-metal cell tests



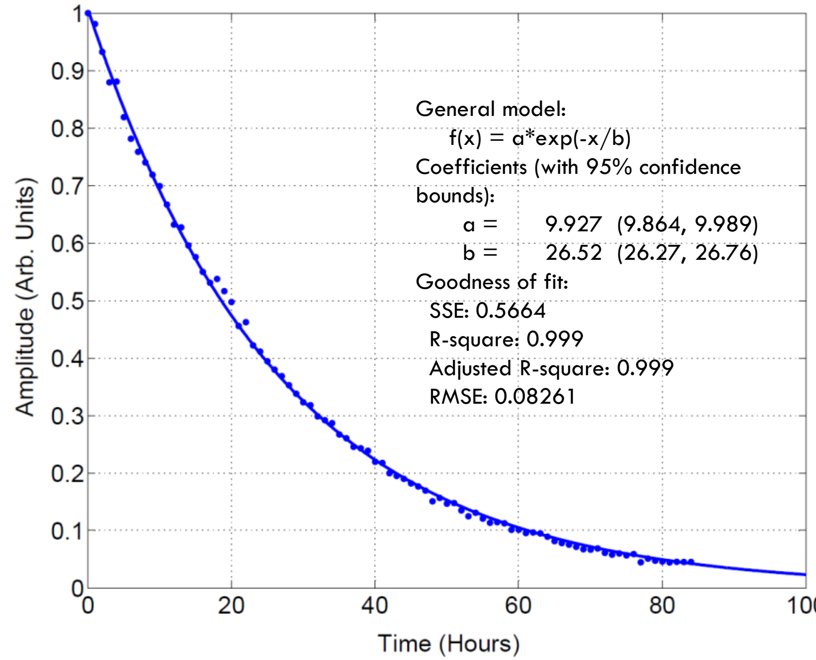
Cell Pyrah



"GoldRush" and "Pyrah" in Elevated position
(lower average magnetic field inhomogeneities)



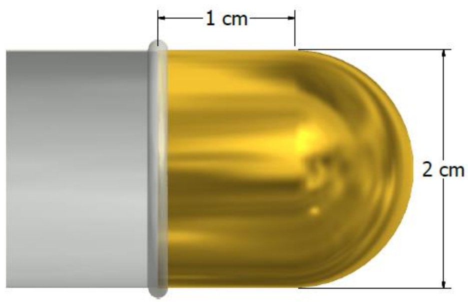
Gold Coated Cell $T_1 = 14.81\ hrs$



Control Cell $T_1 = 26.5\ hrs$

Comparing the control with Goldrush suggests the metal introduces additional relaxation (in this size cell) of 1/25 hrs !!!

Conclusion: Metal end caps appear feasible



OFHC Copper coated with gold appears to give excellent results.

Two end caps like this on Protovec would only contribute ~1/135 hrs for relaxation.

Currently Developing a target cell with these end windows.

Also exploring “Titanium” coated with gold or platinum

Summary

- Convection based cells reduce polarization gradients between pumping and target chambers.

- Convection based cells avoid radiation damage to pumping chamber due to electron beam.

- Targets with metal end windows allow us to use higher beam currents.

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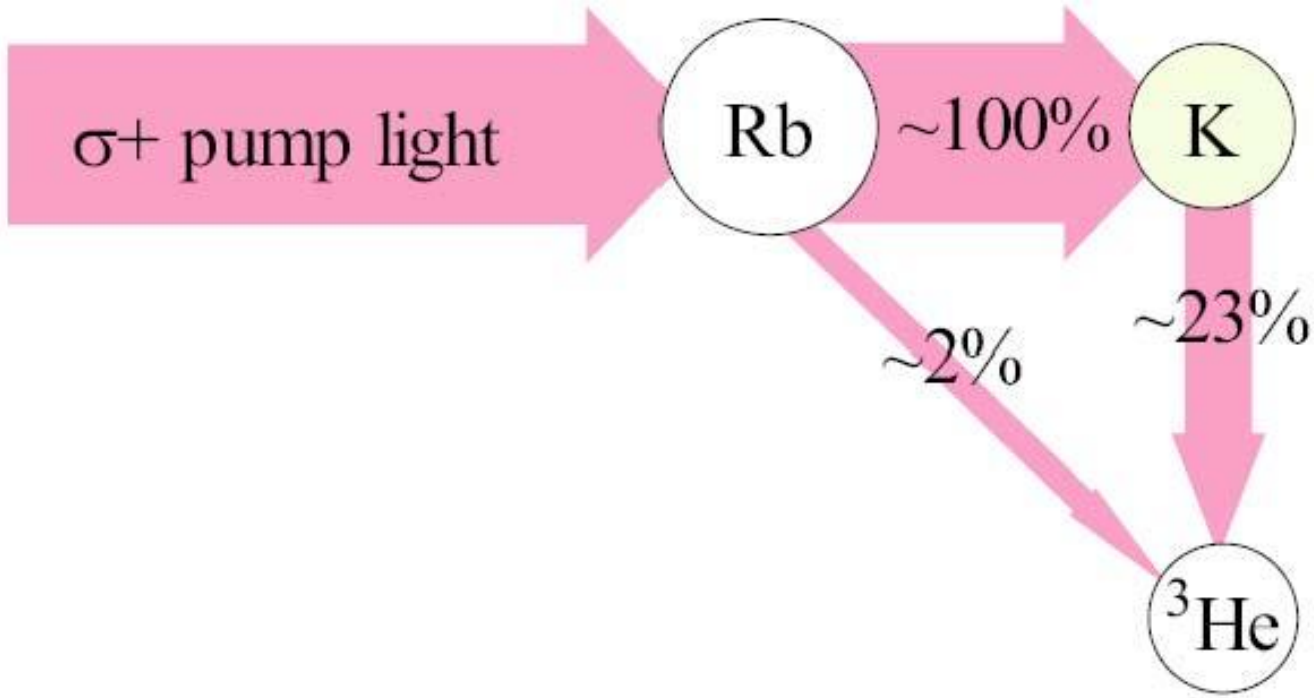
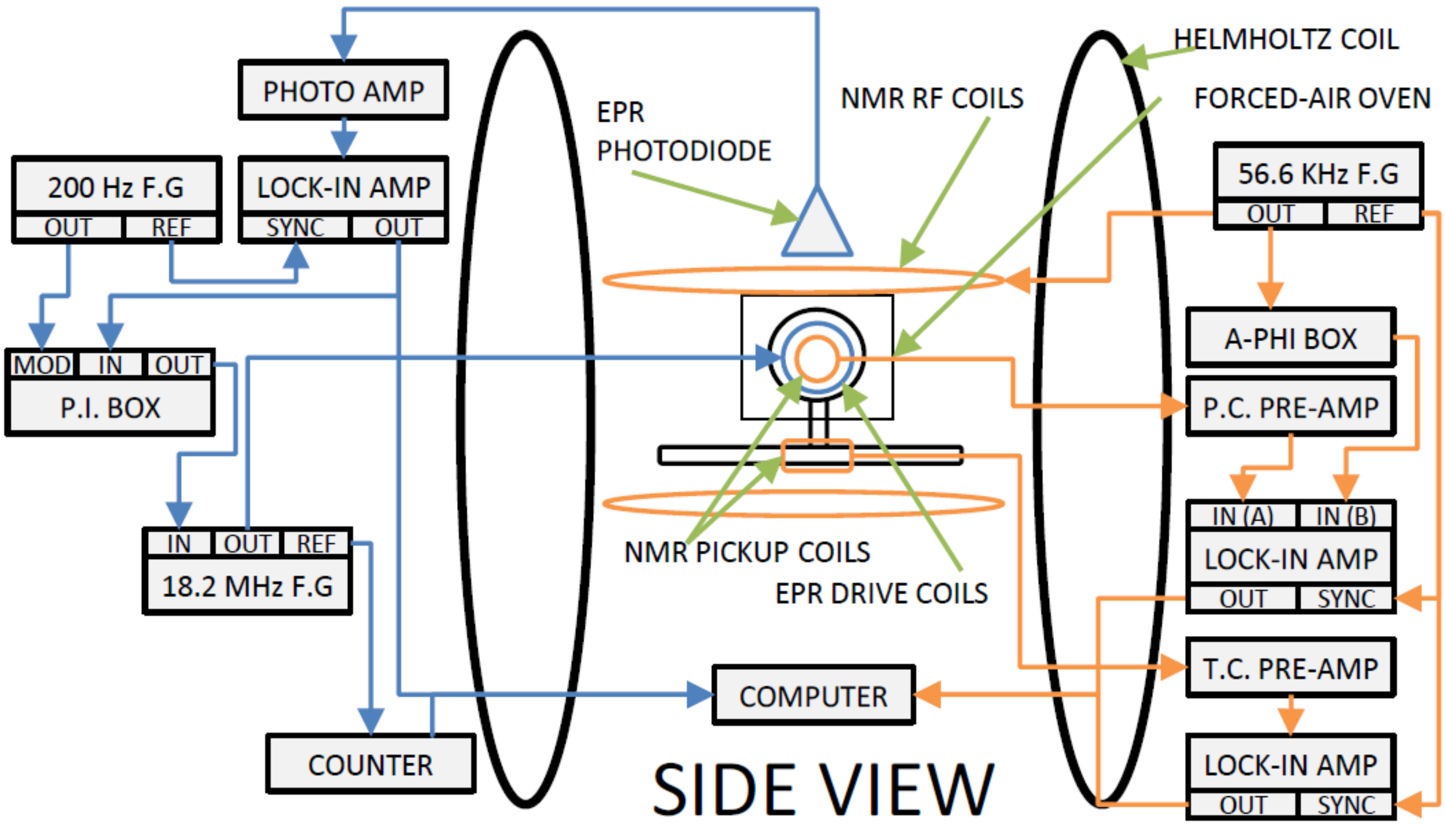
Backup Slides

Reason to use Alkali Hybrid Mixture



NMR and EPR setup



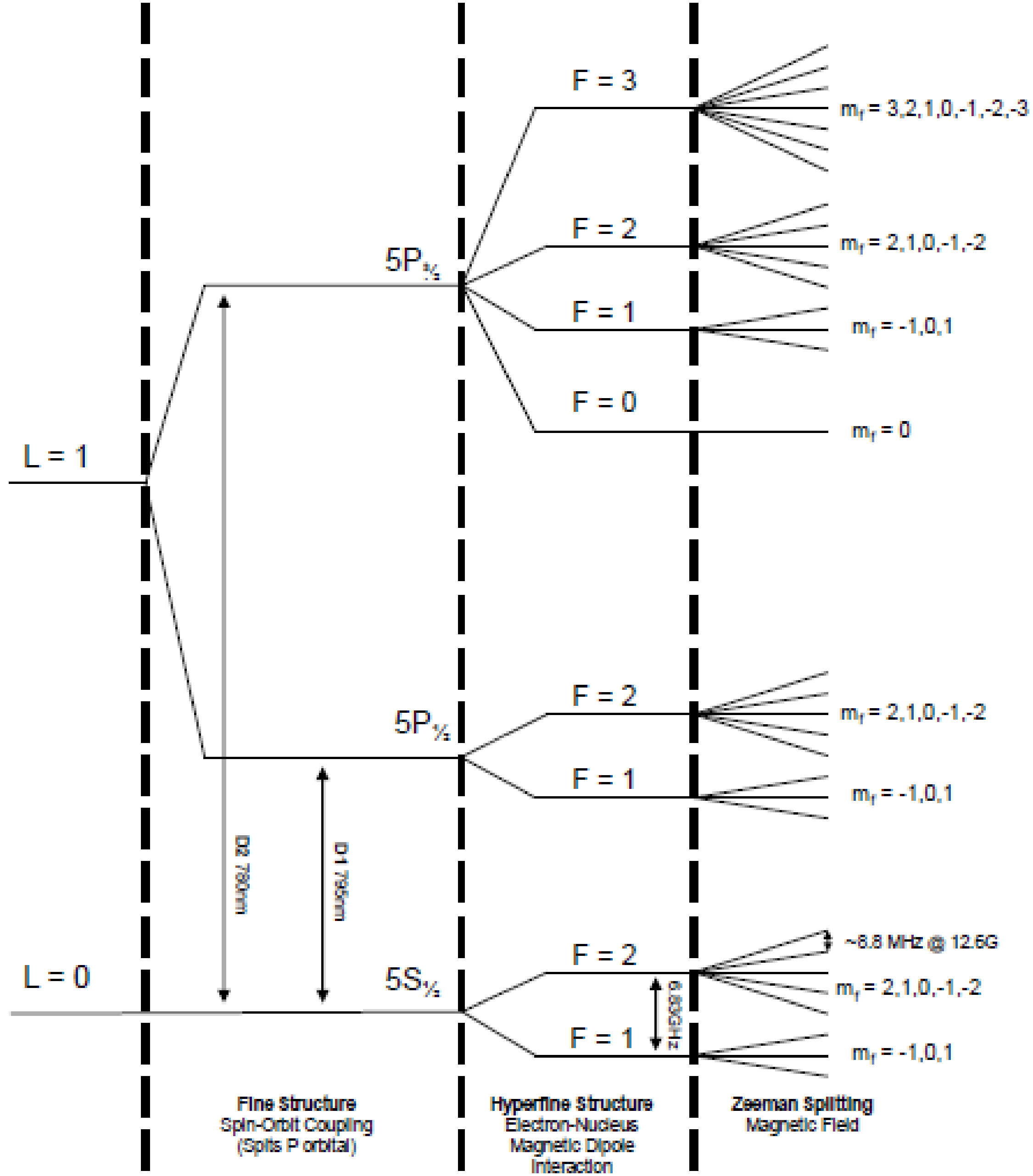


Figure 2.2: Energy-level diagram of 87-Rb, (I = 3/2, not to scale) showing full hyperfine structure

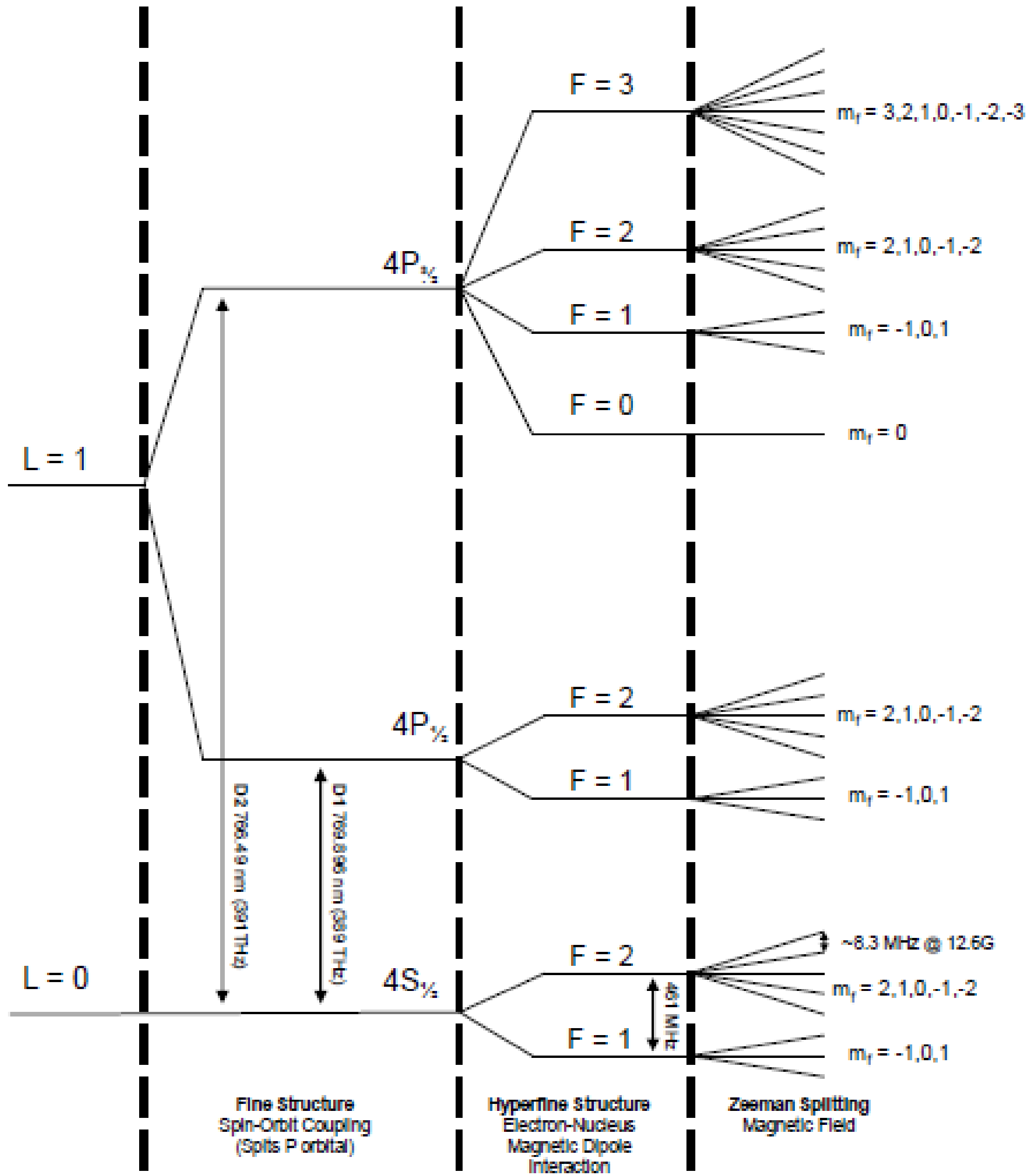


Figure 3.4: Energy-level diagram of 39-K, (I = 3/2, not to scale)