Performance of Laser-Polarized ^{3}He in Tokamak Fuel Pellets

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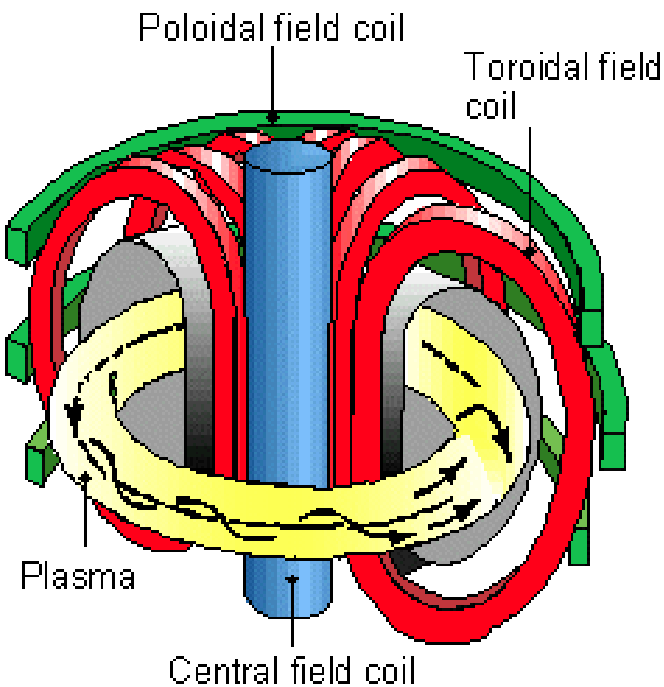
Nuclear Fusion: The ultimate green energy source?

- Despite decades of research, self-sustained energy production remains elusive.
- The use of spin-polarized fuel in a tokamak reactor would provide a significant boost.
- The cross section for the fusion reaction

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow \alpha + n$$

is enhanced by 50% if the deuterium and tritium nuclei are fully polarized along the local magnetic field.

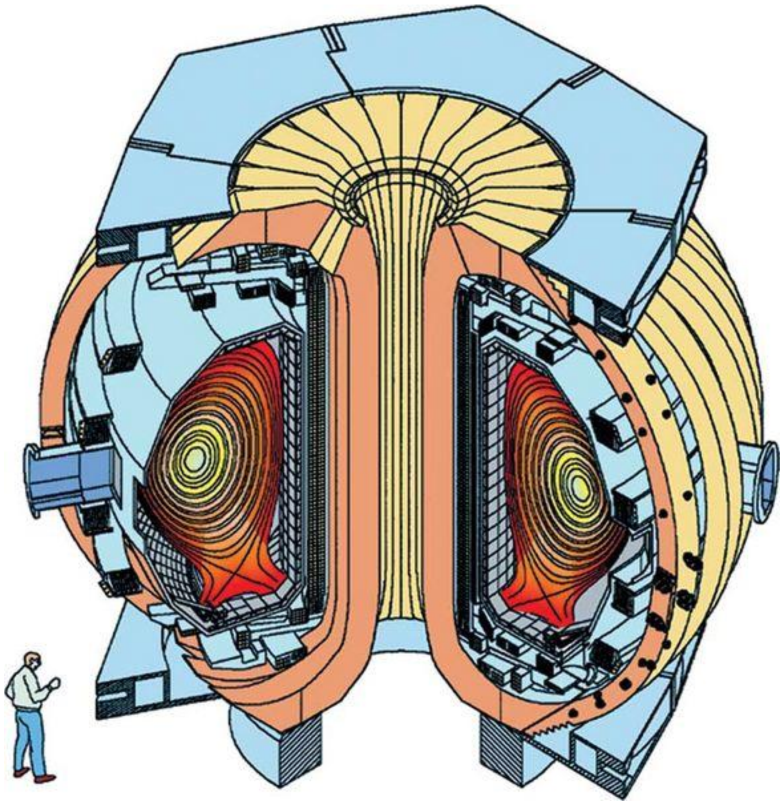


Tokamak fusion reactor

Plenary Session: 3 PM Wednesday (Today!)
Sterling Smith – "Polarized fusion, its implications, and plans for direct measurements in a Tokamak plasma.

Planning first direct test of polarization survival

- Realizing the benefits of polarized fusion requires the polarization to survive in the plasma environment for the energy containment time (a few seconds).



DIII-D tokamak (San Diego, CA)

- Multi-center collaboration, including: Jefferson Lab, DIII-D/General Atomics, University of Virginia

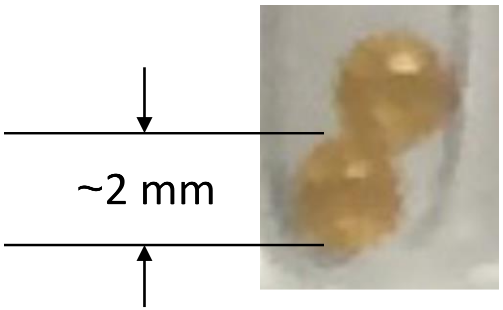
- Study mirror reaction:

$$^{2}\mathrm{H} + {}^{3}\mathrm{He} \rightarrow \alpha + p$$

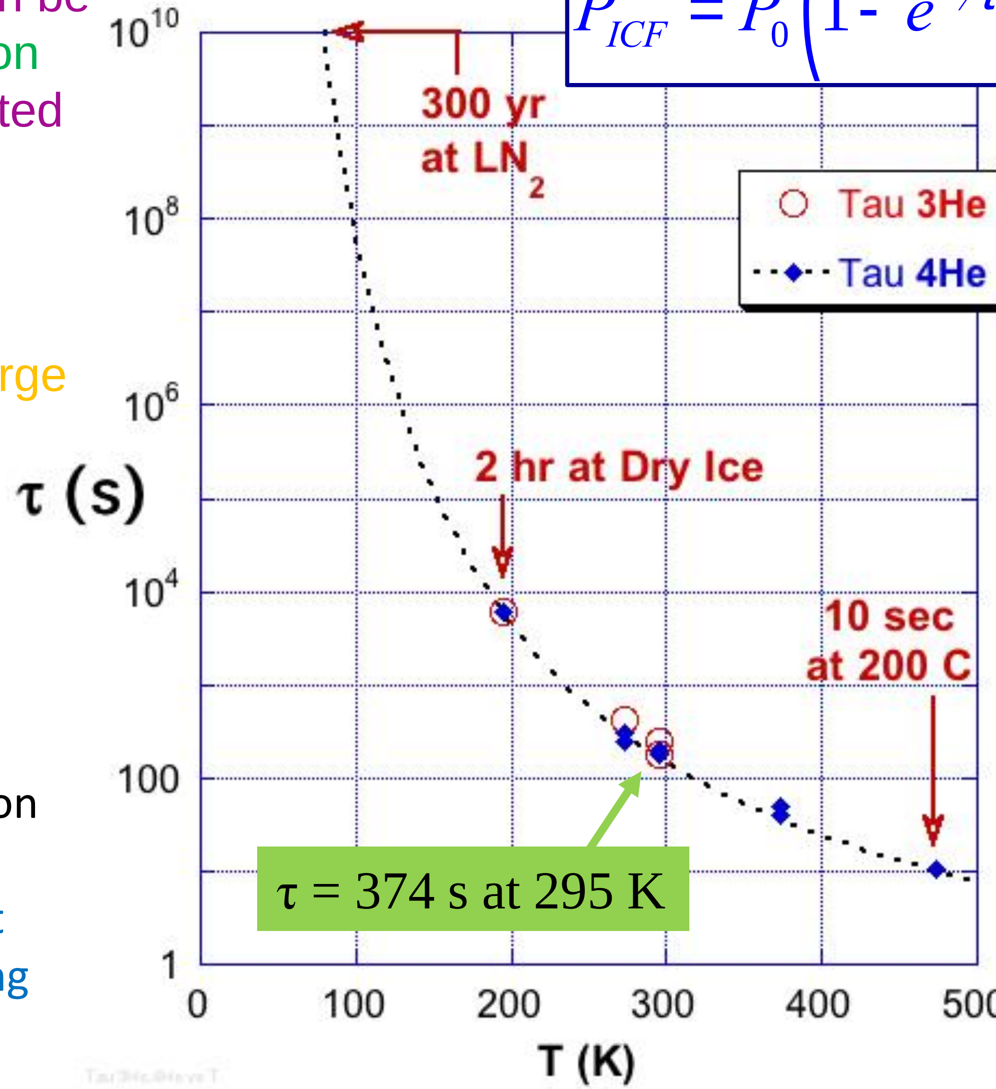
Inertial Confinement Fusion (ICF) pellets

$$P_{ICF} = P_0\left(1 - e^{-t/\tau}\right)$$

ICF pellets are polymer shells that can be filled with gas by passive permeation through the shell wall and then injected directly into plasma core



GDP (glow discharge polymer)



- D can be polarized after permeation of HD into the pellet
- ^{3}He must be polarized *before* permeation
- Recipe: Permeate laser-polarized ^{3}He at room temperature, seal inside by cooling with LN_2

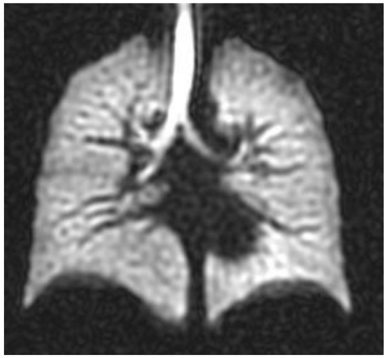
Apparatus normally used for hyperpolarized ^{3}He lung imaging

^{3}He polarizer at UVa Medical School

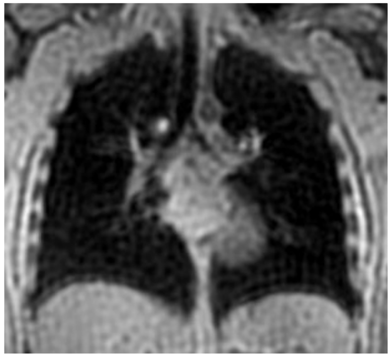
Built by Gordon Cates and Wilson Miller, based on polarized ^{3}He target design developed for JLab

- Hybrid (Rb + K) spin-exchange optical pumping
- Maximum ^{3}He polarization ~65%

^{3}He MRI



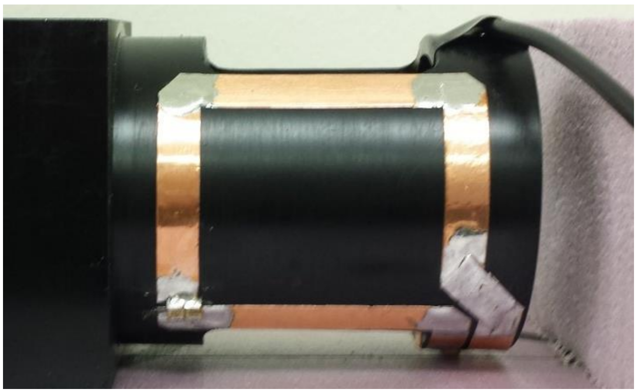
Conventional MRI



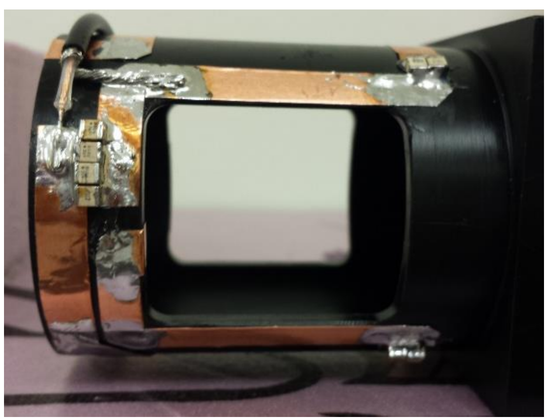
Siemens Avanto 1.5 T clinical MRI scanner

- Magnetic field inhomogeneity < 1 ppm
- ^{3}He resonance frequency 48.5 MHz

Transmit/receive RF coil



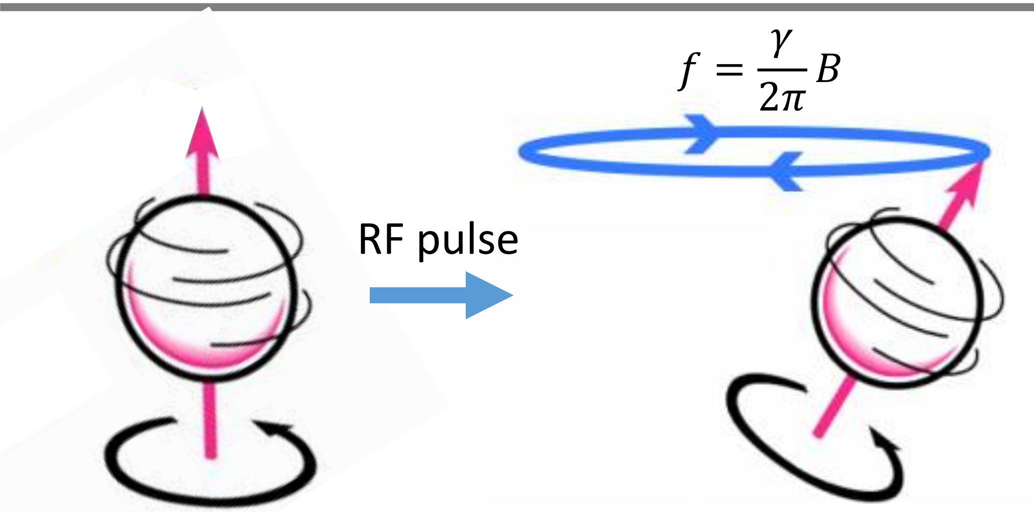
side view

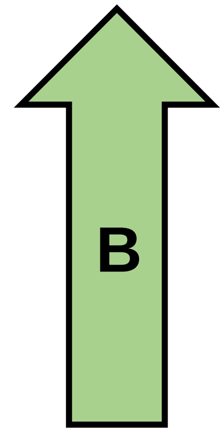


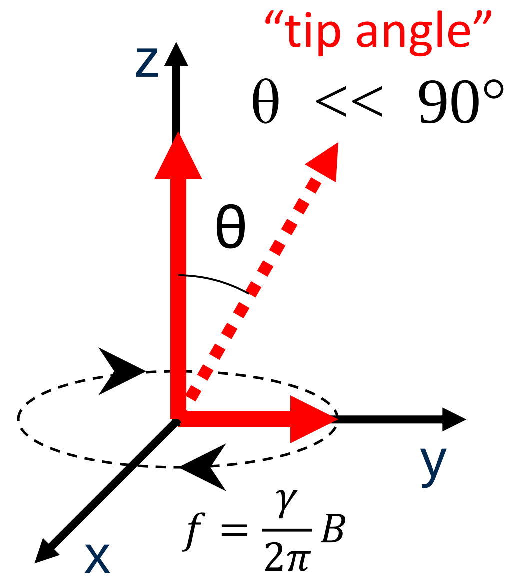
bottom view

our setup

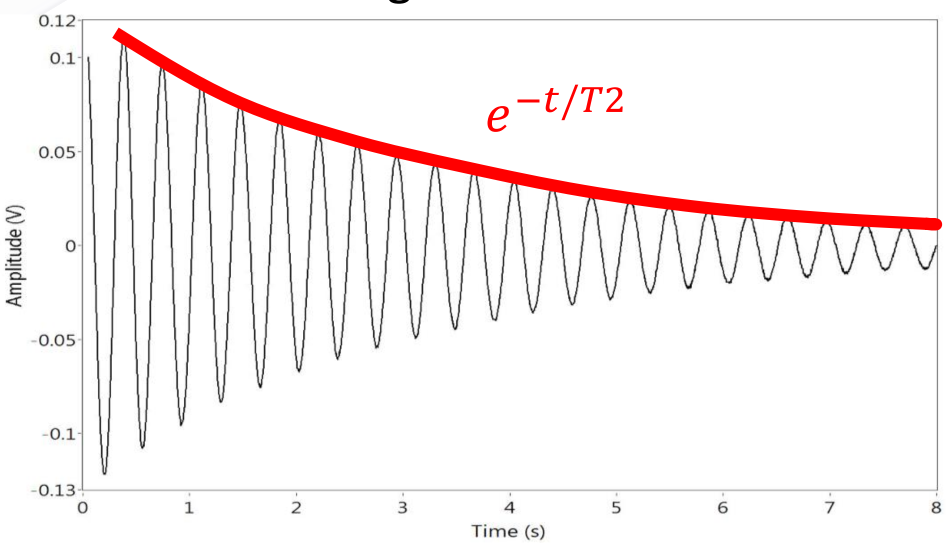
"Pulsed" Nuclear Magnetic Resonance (NMR)





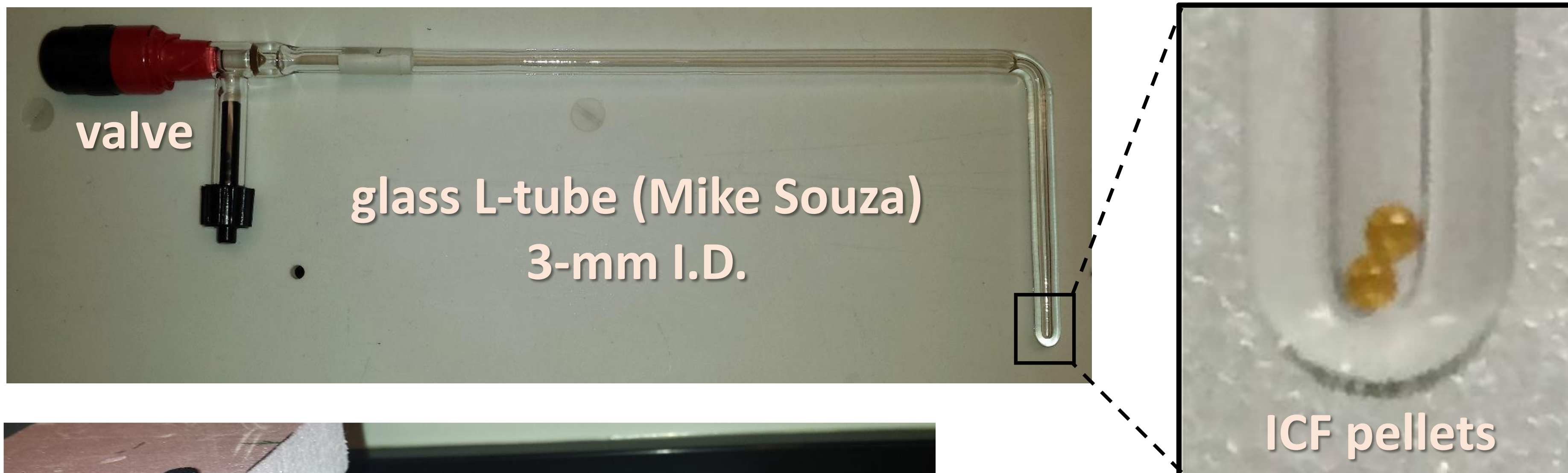


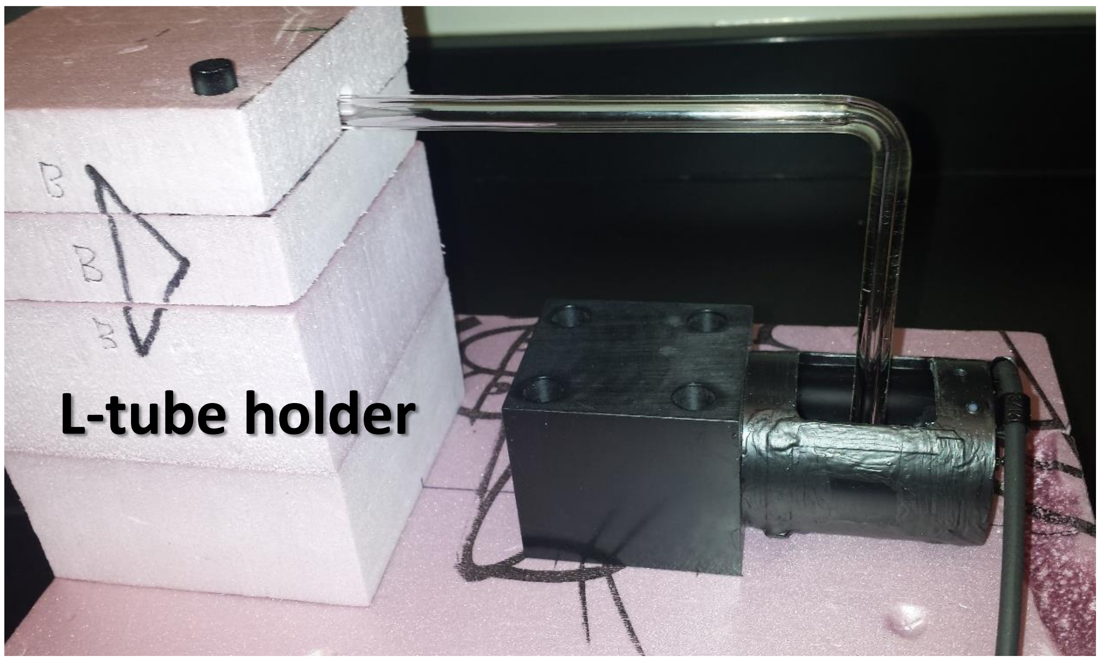
NMR signal in receiver coil



- Pulses of RF electromagnetic waves used to excite the polarized spins
- Precessing spins induce oscillating current in a nearby RF coil
- Spin precession frequency (a.k.a. resonance frequency) proportional to magnetic field

Permeation and imaging of ICF pellets was performed inside a glass cell





Spatial encoding: Magnetic Resonance Imaging

All spatial localization in MRI is accomplished by applying linear magnetic field gradients to map spatial position to resonance frequency.

- The gradient is superimposed on the main magnetic field, can point in any direction:

$$B = B_0 + (xG_x + yG_y + zG_z)$$

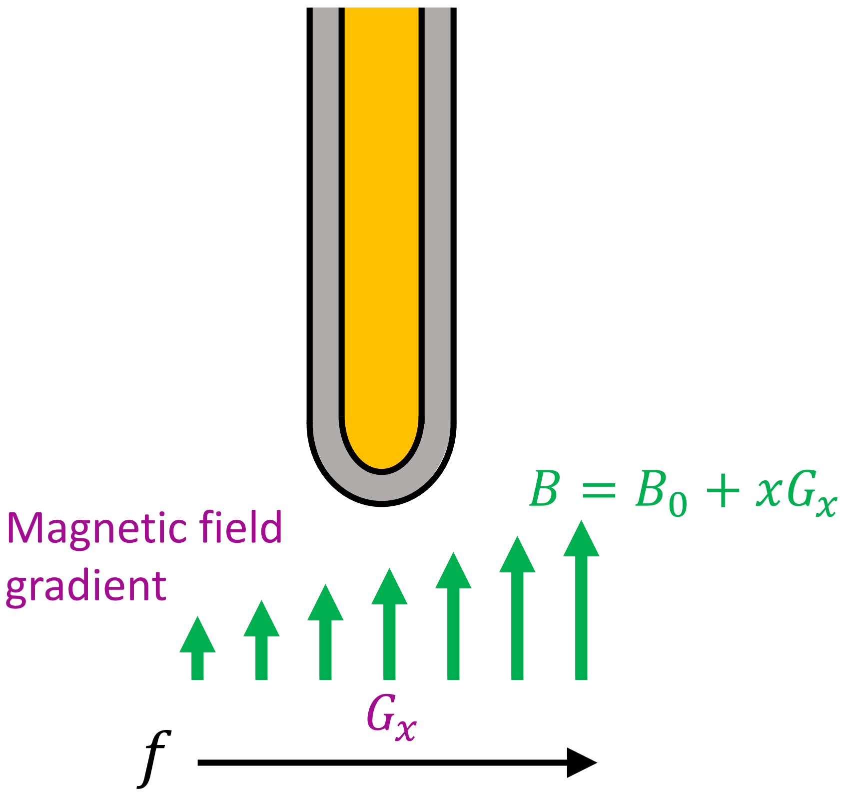
- Causes resonance frequency to vary linearly along that direction:

$$f = f_0 + \frac{\gamma}{2\pi}(xG_x + yG_y + zG_z)$$

- MR signal measured in the presence of a gradient G is the weighted sum of all these frequency components:

$$S(t) \propto \int \rho(\vec{r}) e^{-i2\pi f_0} e^{-i\gamma \vec{G}\cdot\vec{r}}$$

L-tube filled with hyperpolarized ^3He



Spatial encoding: Magnetic Resonance Imaging

We sample the NMR signal in the presence of magnetic field gradients in order to measure the Fourier components of the image in *k* space.

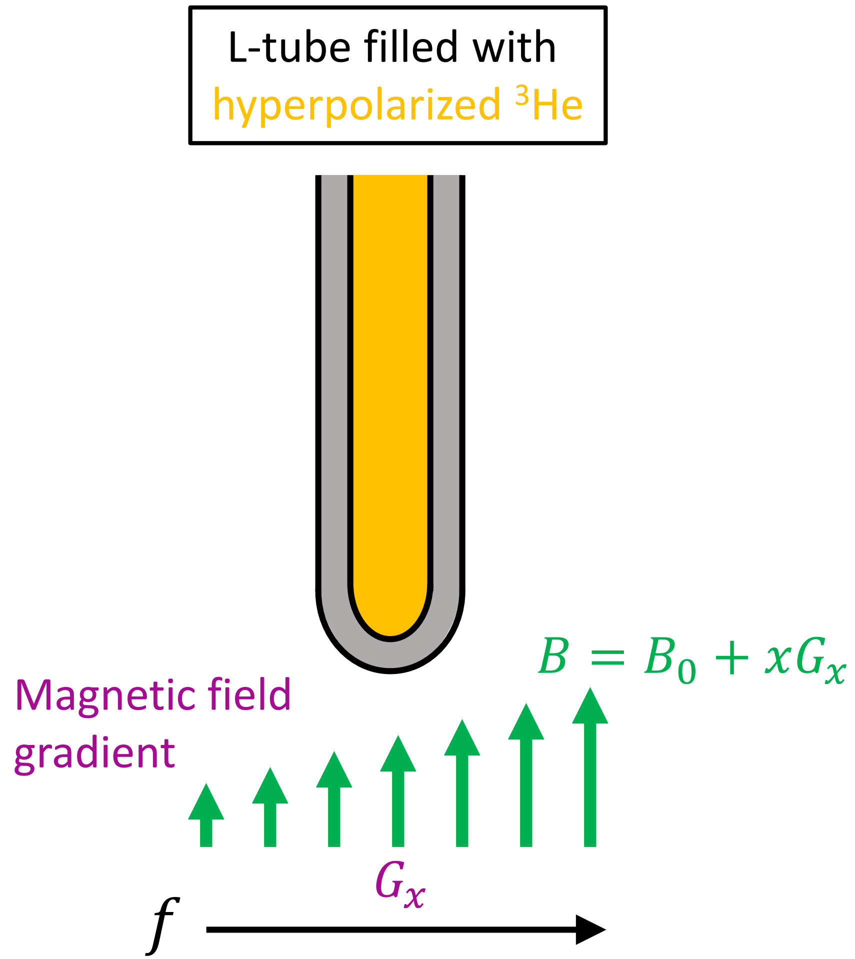
- If we define $\vec{k}$ to be the time-integral of the applied gradient $\vec{G}$:

$$\vec{k} \equiv \frac{\gamma}{2\pi} \int \vec{G}(t)dt$$

- Then there is a Fourier relationship between $\vec{k}$ and the spin density $\rho(\vec{r})$:

$$\rho(\vec{r}) \propto \int S(\vec{k}) e^{-2\pi i \vec{k}\cdot\vec{r}}$$

The image of the spin distribution is recovered by taking the inverse Fourier transform of the *k*-space data matrix!



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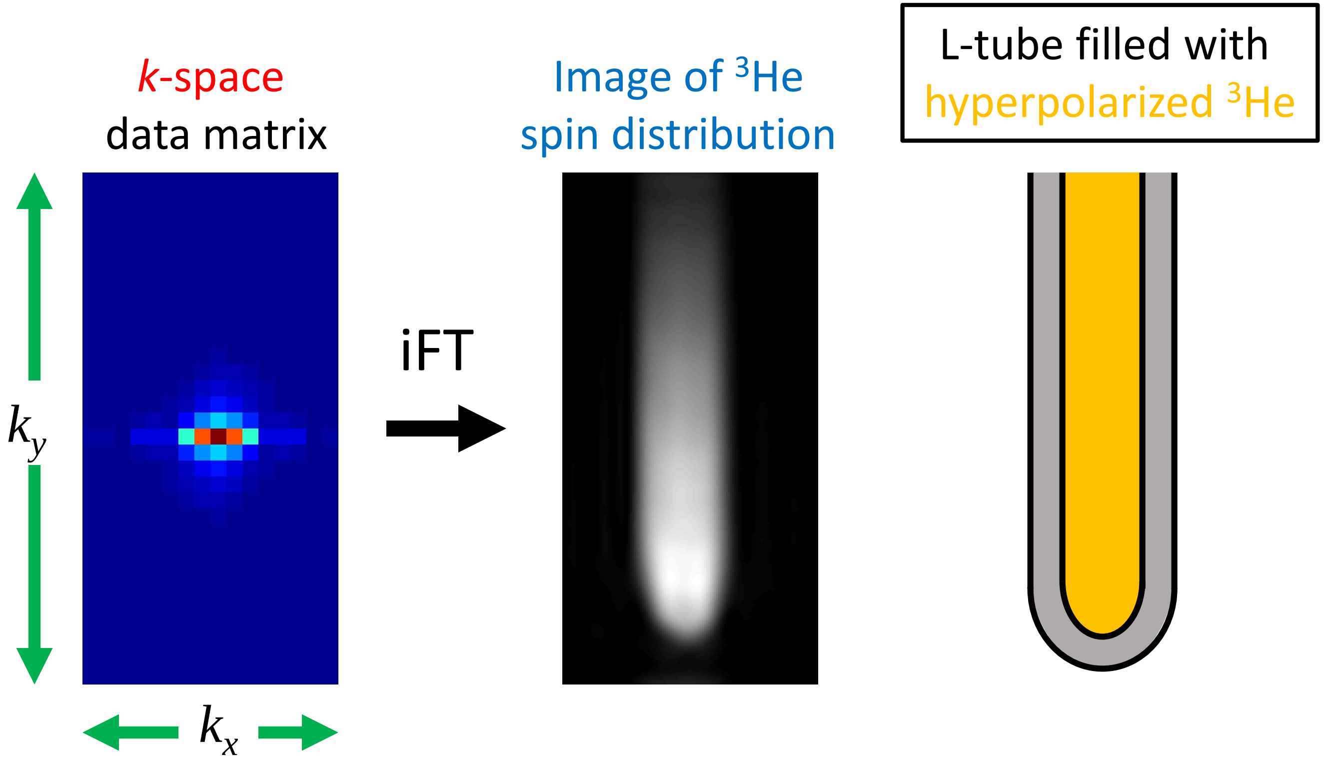


The image of the spin distribution is recovered by taking the inverse Fourier transform of the *k*-space data matrix!

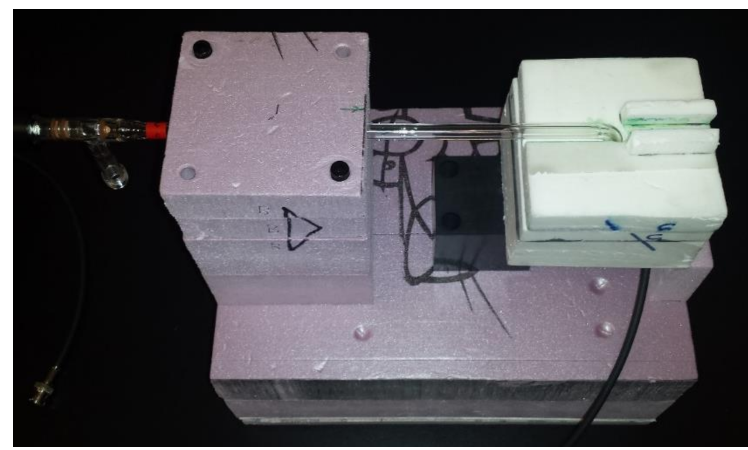
First permeation test: Polarization survives?

Experimental procedure:

1. L-tube containing pellets connected to output manifold of ^{3}He polarizer
2. Cell evacuated (and pellets, via permeation out)
3. Tube filled with up to 8 atm of ~60% polarized ^{3}He
4. Wait ~10 min for ^{3}He to permeate through pellet wall
5. L-tube carried down the hall and placed in the scanner, end immersed in LN_2 bath
6. Acquire image

Two ICF pellets placed inside L-tube

MRI scanner



L-tube holder w/LN_2 bath

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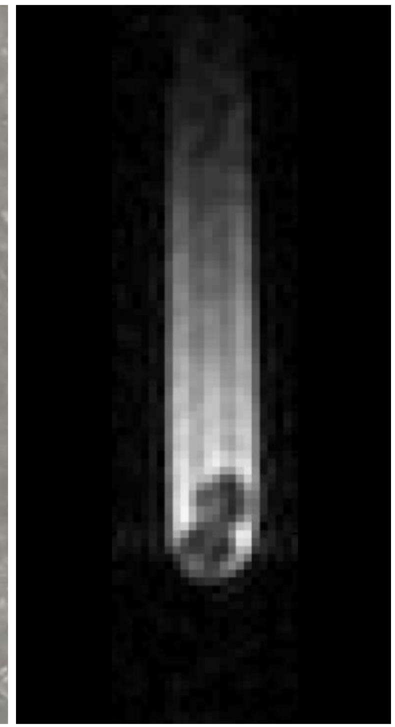
Two ICF pellets placed inside L-tube

Image acquired ~10 min after cell filled with ^{3}He



Polarization survives permeation??

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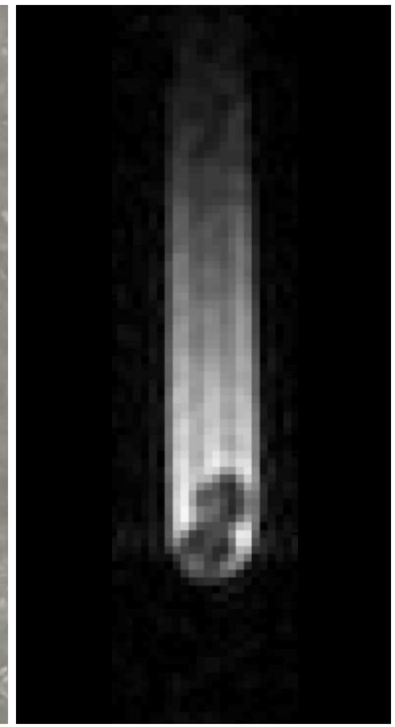
4. Wait ~10 min for ^{3}He to permeate through pellet wall
5. L-tube carried down the hall and placed in the scanner, end immersed in LN_2 bath
6. Acquire image
7. Evacuate ^{3}He outside the pellet
8. Acquire image

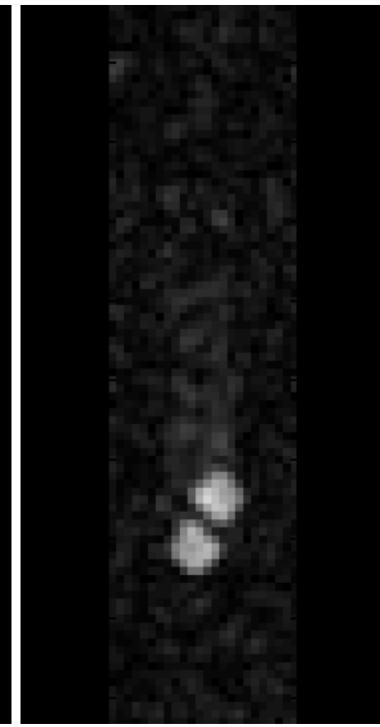
Two ICF pellets placed inside L-tube

Image acquired ~10 min after cell filled with ^{3}He



Polarization survives permeation??

Image acquired after evacuating ^{3}He from L-tube

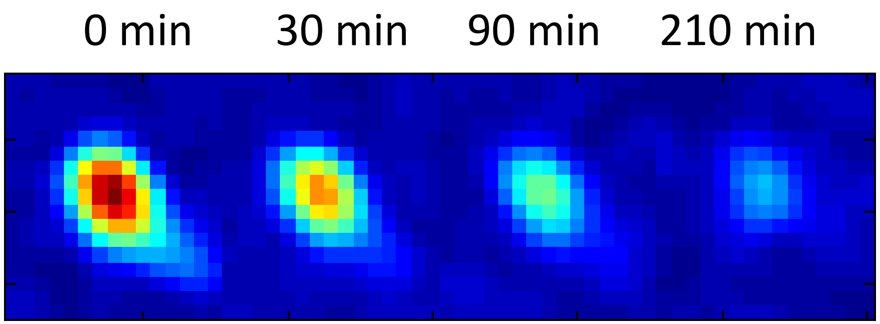


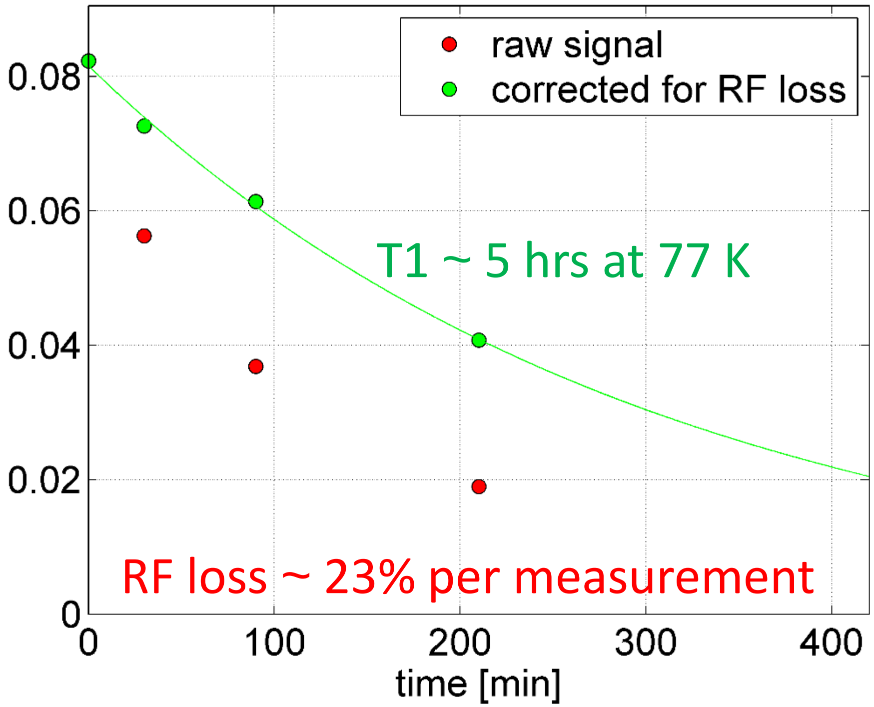
Polarization survives permeation!!

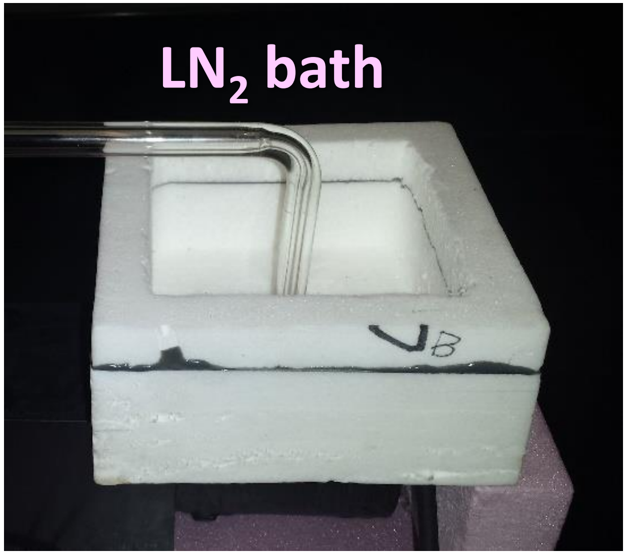
Second permeation test: T1 inside pellet

For all this to work, the ^{3}He polarization must not only survive permeation, but also have a sufficiently long spin relaxation time (T1) inside the shell.

Pellet images
L-tube immersed in LN2, evacuated after permeation





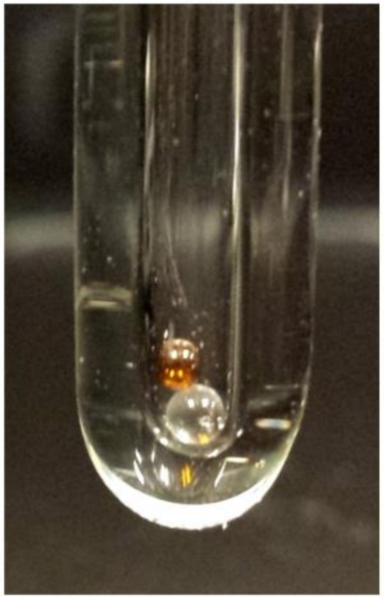


Third permeation test: Image during permeation

Special MRI pulse sequence: Chemical-Shift Imaging (CSI)

- Maximizes SNR by taking full advantage of long T2 in gas phase
- Minimizes signal loss associated with gas diffusion during gradient application
- Provides sensitivity to NMR frequency shifts due to magnetic field disturbances

ICF pellet
placed on top of glass bead



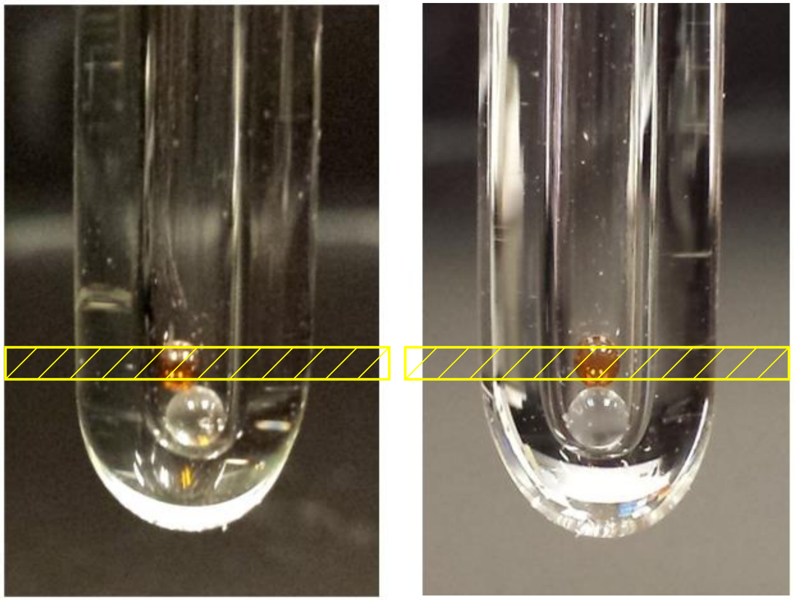
Front view

Side view

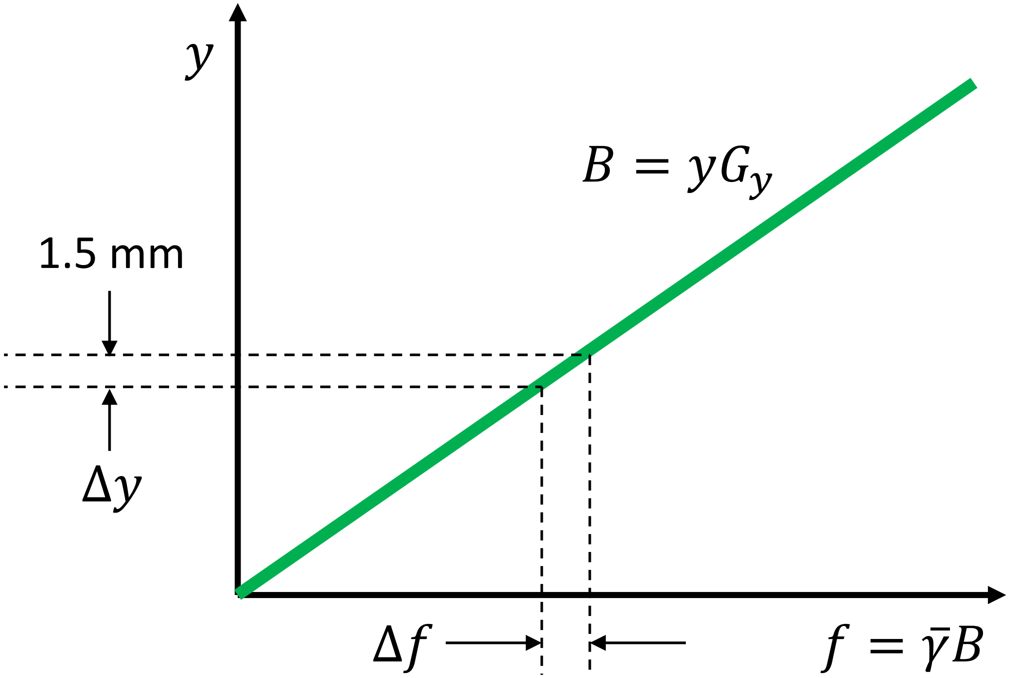
Only excite thin plane through the pellet

Slice-selective excitation achieved by applying shaped RF pulse in the presence of a magnetic field gradient

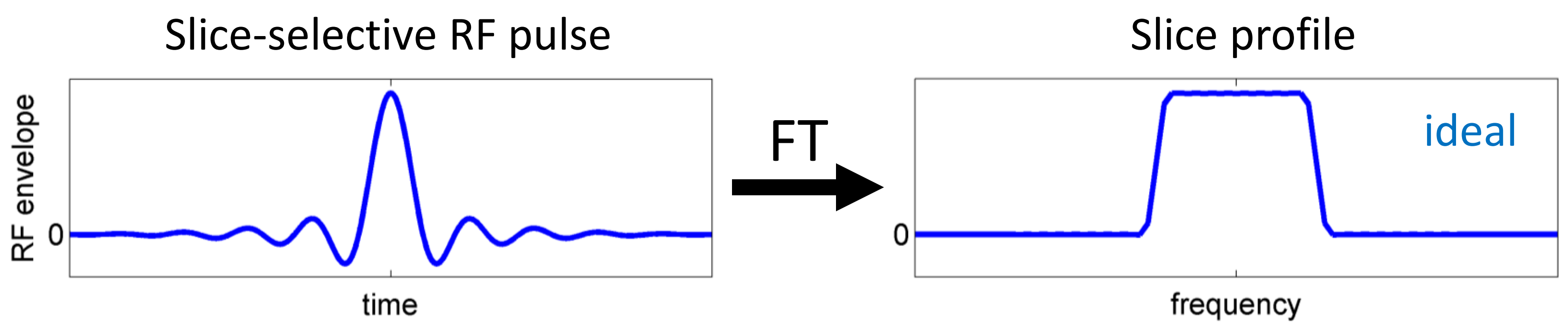
ICF pellet
placed on top of glass bead

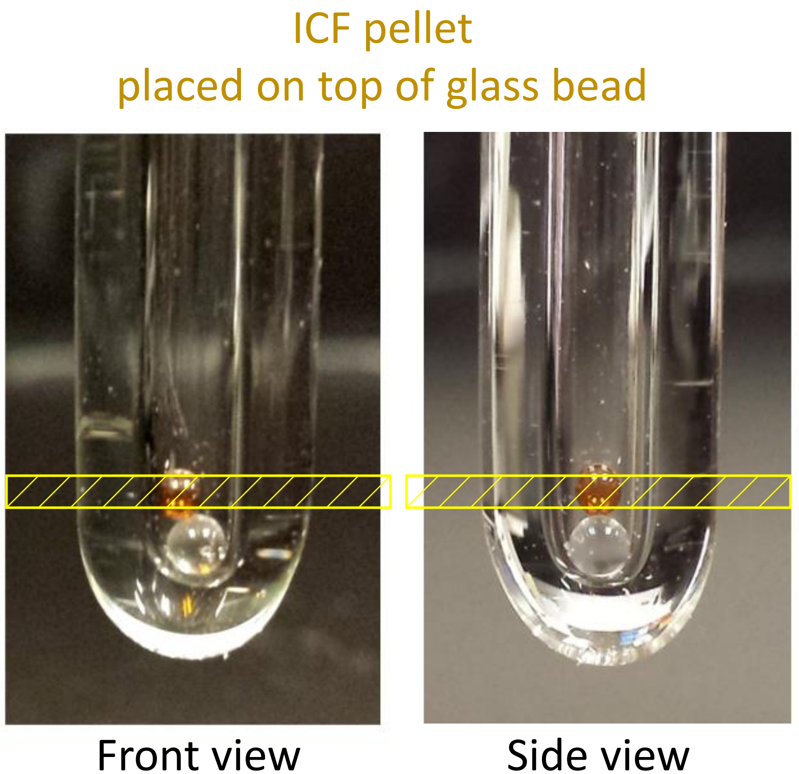


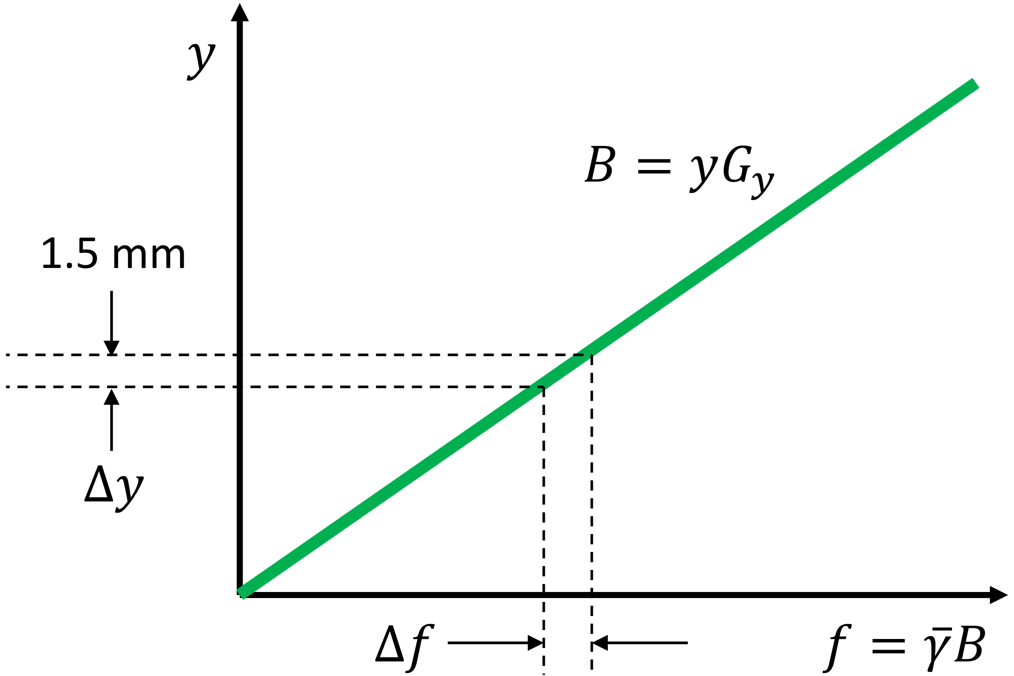
Front view   Side view



Only excite thin slice through the pellet







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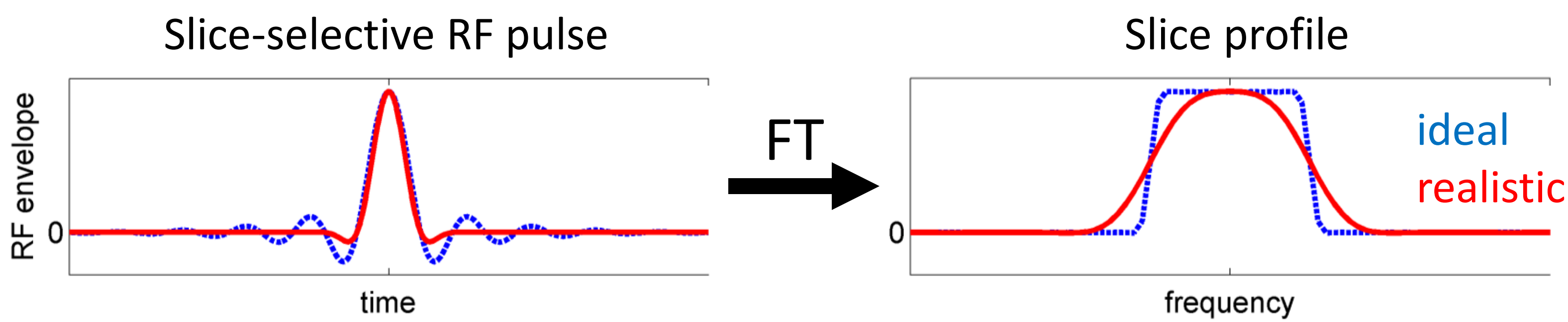
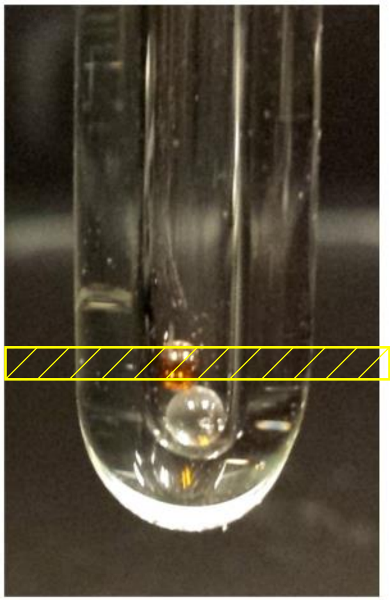
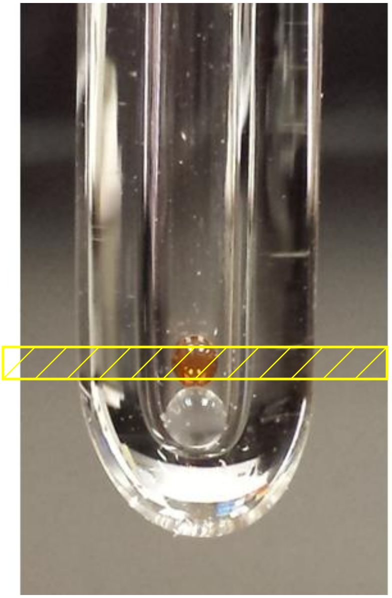


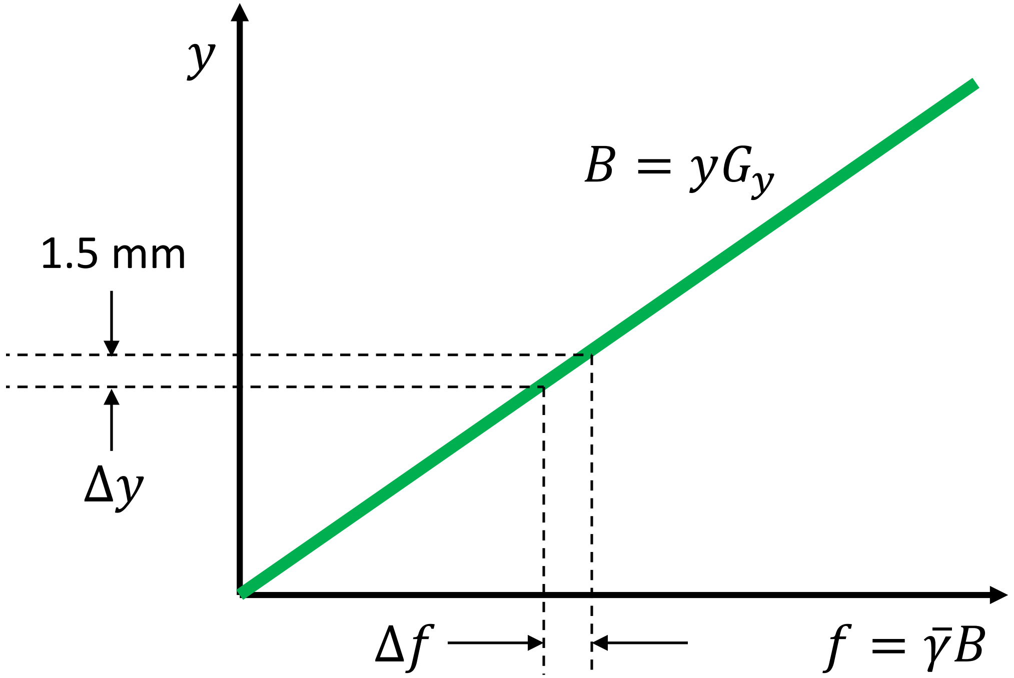
ICF pellet
placed on top of glass bead



Front view



Side view

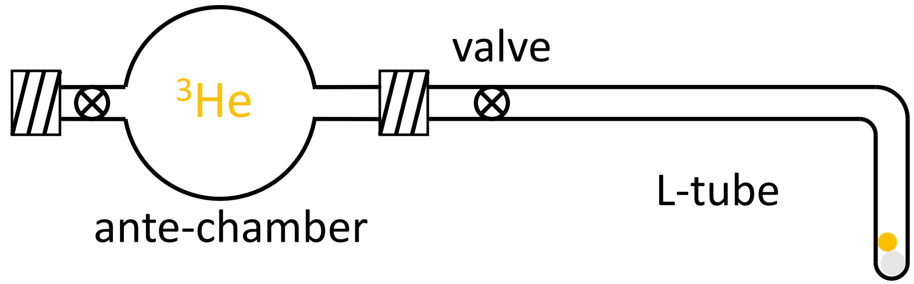


Third permeation test: Image during permeation

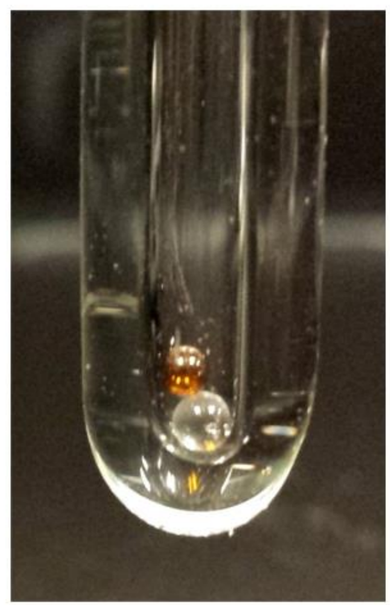
Experimental procedure:

1. Assembly connected to output manifold of ^3He polarizer
2. Cell & ante-chamber evacuated
3. With L-tube valve closed, ante-chamber filled with ~8 atm of ~60% polarized ^3He
4. Assembly carried down the hall and placed in the scanner
5. Open valve between ante-chamber and L-tube; permeation begins
6. Acquire quick "scout" image for slice positioning
7. Acquire time series of images during permeation

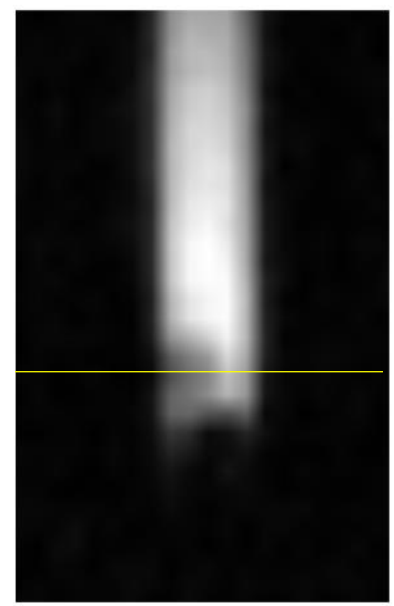
^3He released into L-tube immediately before imaging



ICF pellet placed on top of glass bead



Quick 2D "scout" image used for slice positioning

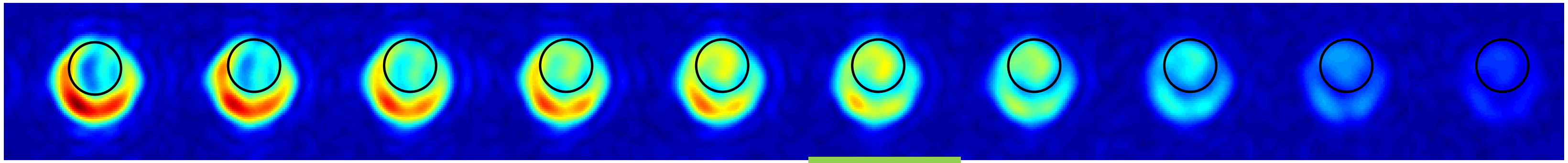


Dynamic imaging of ^{3}He permeation into ICF pellet

Permeation

T1 decay

Circle shows pellet location

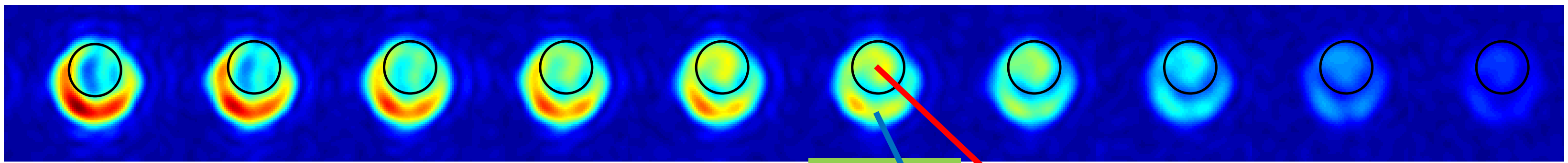


30 s | 1.5 min | 3.5 min | 5 min | 9 min | 15 min | 23 min | 35 min | 52 min | 75 min

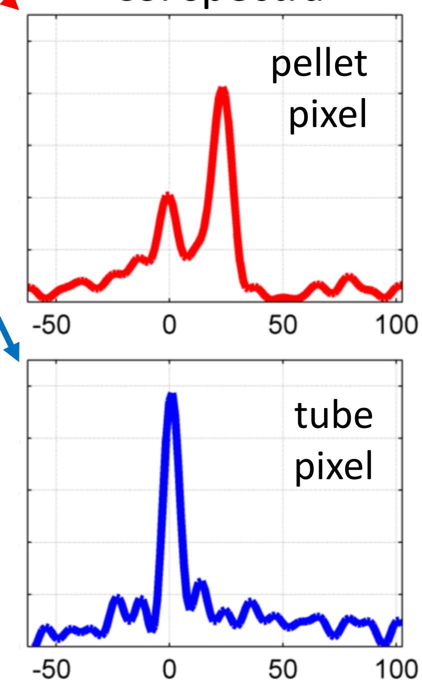
Dynamic imaging of ^{3}He permeation into ICF pellet

Permeation → T1 decay →

Circle shows pellet location



30 s | 1.5 min | 3.5 min | 5 min | 9 min | 15 min | 23 min | 35 min | 52 min | 75 min



In addition to excellent SNR, the Chemical Shift Imaging technique provides spatially resolved frequency spectra

Chemical Shift Imaging of ^3He permeation

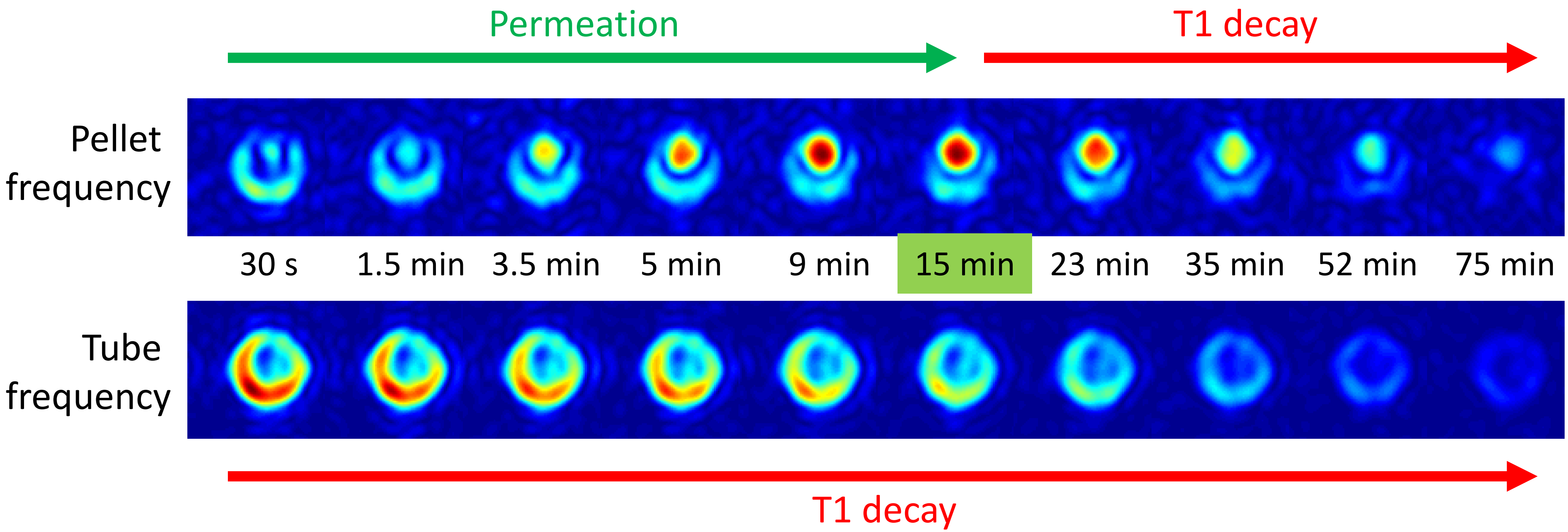


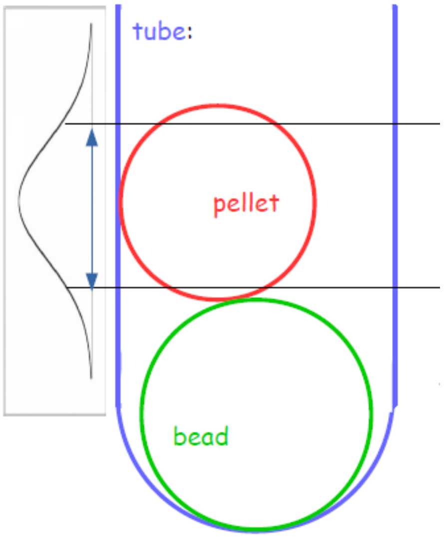
Image intensity depends on many factors

- T1 inside the pellet
- T1 in L-tube (outside the pellet)
- Permeation rate
- Polarization loss during permeation
- Excitation tip angle
- Excitation slice profile

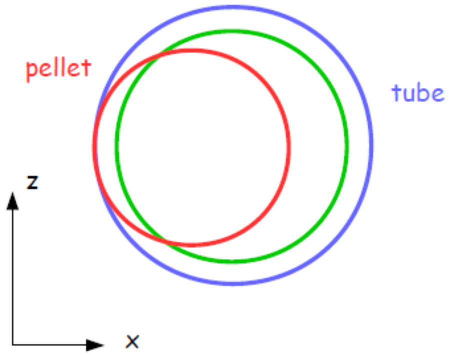
Built model of signal evolution inside and outside pellet, based on these factors.

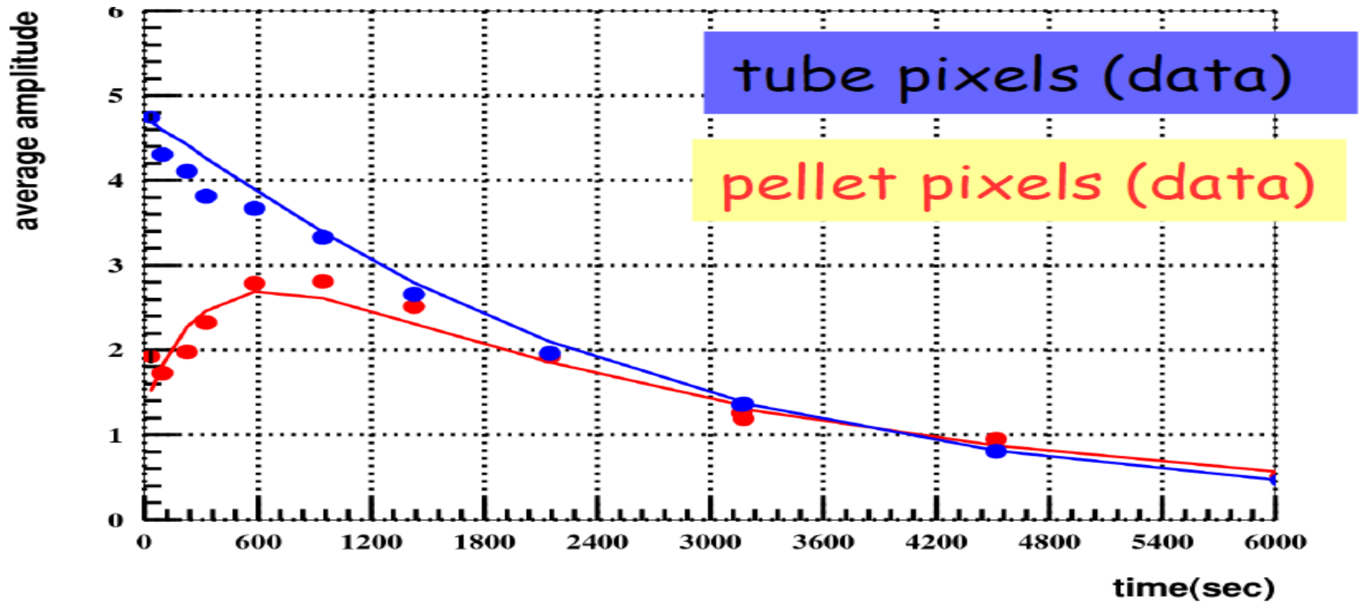
Fit measured signal evolution to extract the desired parameters.

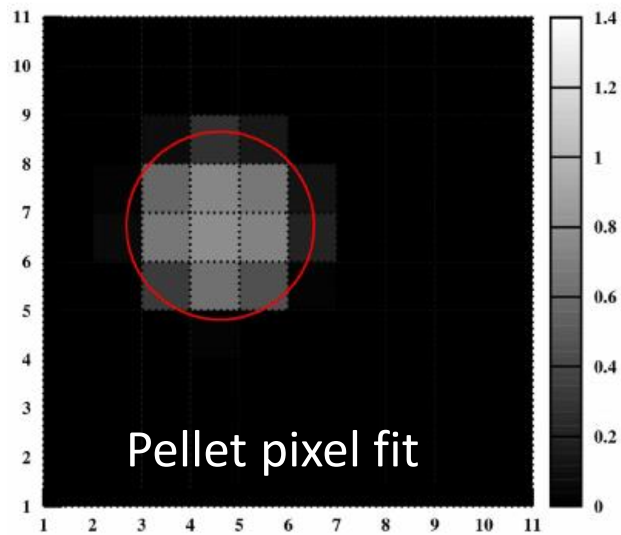
Pellet Permeation Measurements

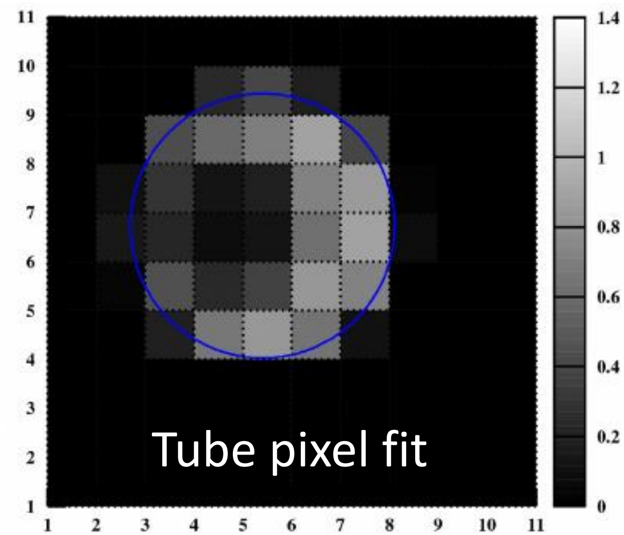


thickness integrated over y using a Gaussian weight, within ± 5σ range

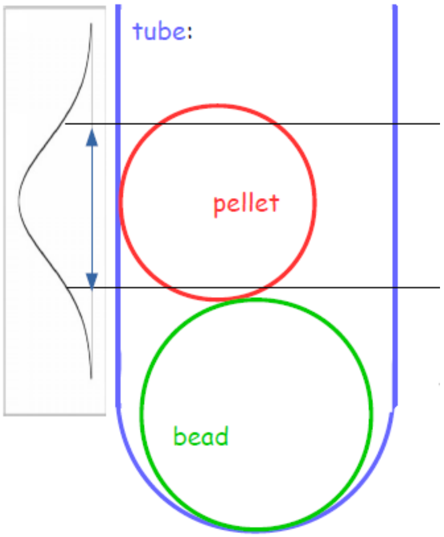








Pellet Permeation Measurements



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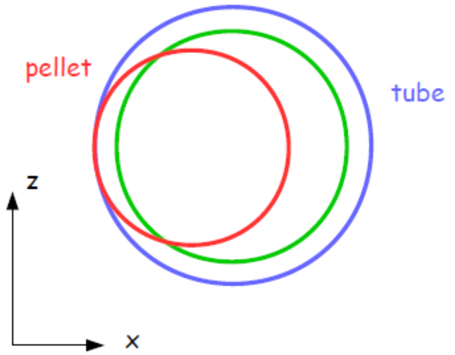
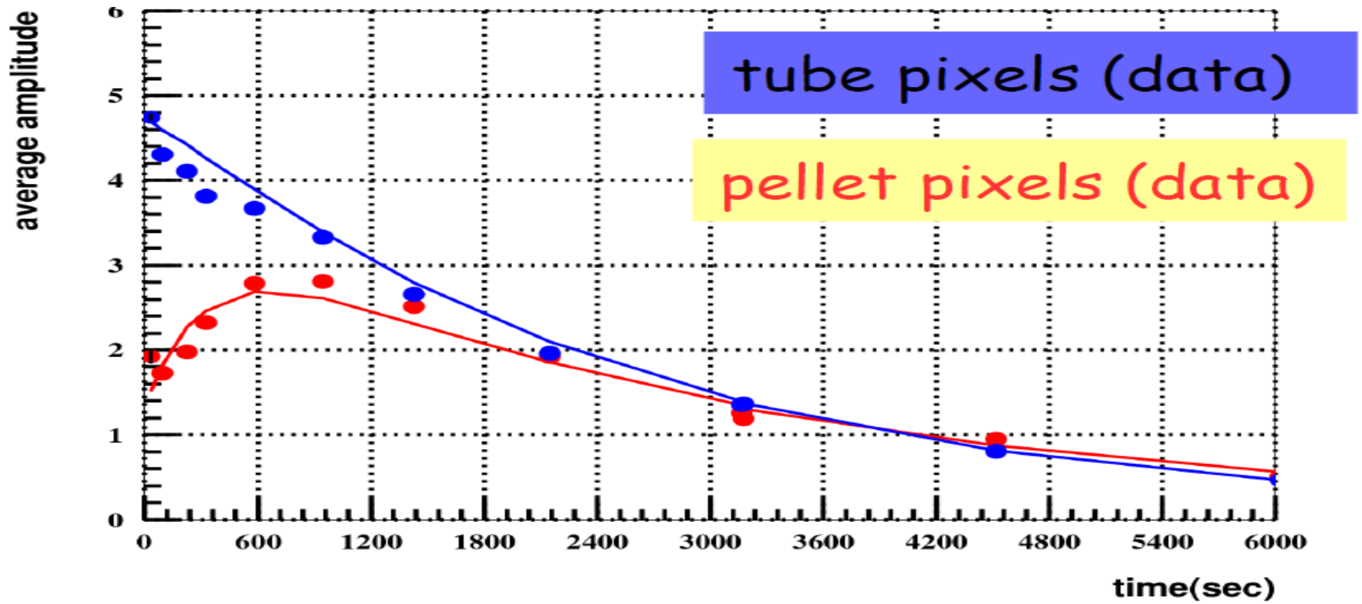
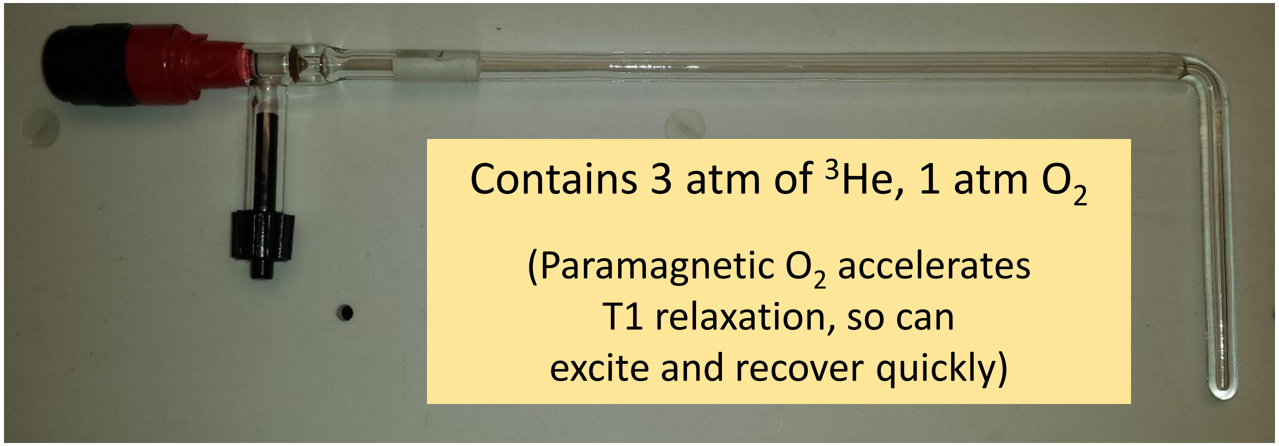




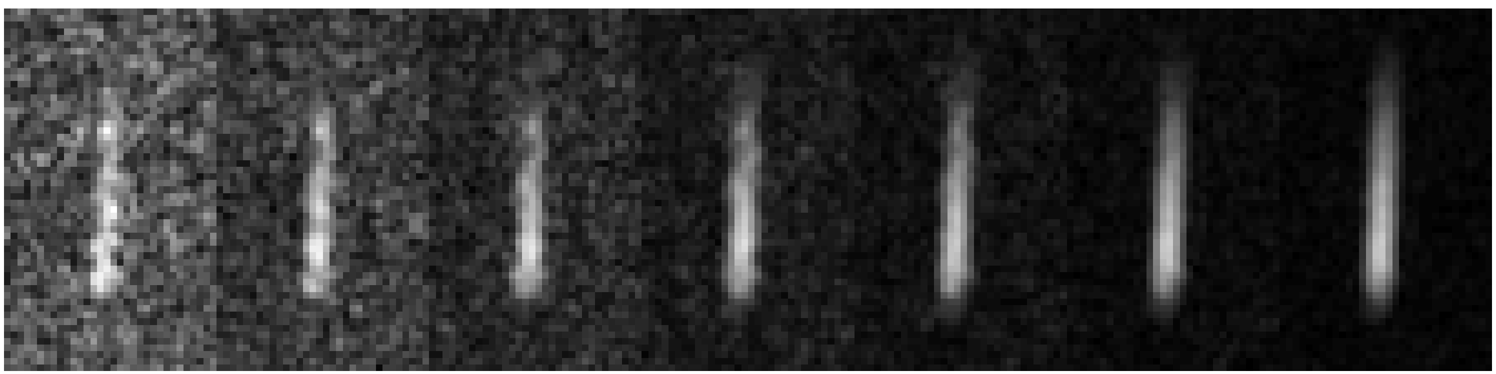
FIT RESULTS	
T1 inside pellet	67 ± 3 min
T1 in tube (outside pellet)	41 ± 1 min
Permeation time constant	387 ± 2 sec
Fraction of polarization that survives permeation	67 ± 1 %

Absolute polarimetry: Thermal Equilibrium signal comparison



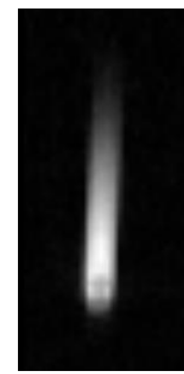
Prepared dedicated L-tube for thermal equilibrium studies.

Thermally polarized ^{3}He: $P \sim 3$ ppm at 1.5 Tesla



1 hr 2 hrs 4 hrs 8 hrs 16 hrs 32 hrs 64 hrs

Hyperpolarized ^{3}He
$P \sim 40\%$



< 1 sec

Absolute polarimetry is a work in progress!

The future is bright (and green)!

This initial round of tests showed that 1/3 of the ^{3}He polarization was lost during permeation into the ICF pellets. This is sufficient for our immediate purposes, but we wish to note:

- There is significant room to optimize permeation procedure
- More polarization-friendly shell materials exist

T1 relaxation time inside pellet > 1hour at room temperature, > 5 hours at 77K

- Plenty of time to fill a pellet and get it into the Tokamak, even if the polarizer is not right next door.

Absolute polarimetry appears feasible, by calibrating hyperpolarized ^{3}He signal against thermally polarized ^{3}He signal.

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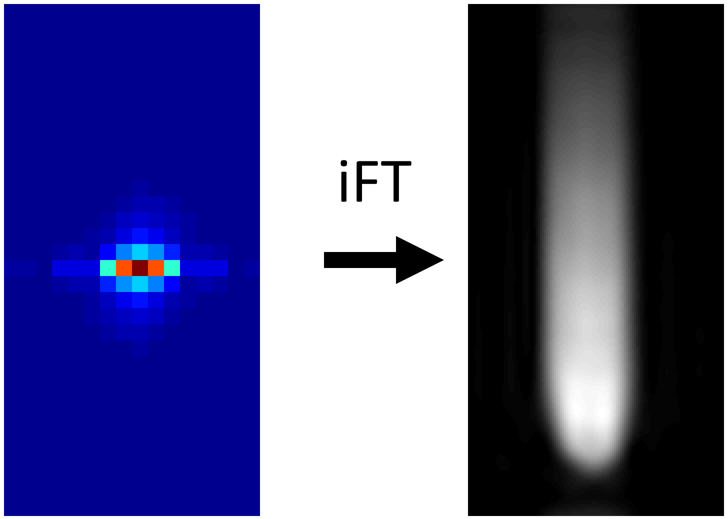
Thermally polarized vs. hyperpolarized NMR

Thermal Polarization	Hyperpolarization
Large magnetic field induces net spin alignment and sets the resonance frequency	Magnetic field only sets the resonance frequency
P ~ 5 ppm at 1.5 T	P ~ 50%
Time constant T1 characterizes the rate at which longitudinal magnetization (polarization, net alignment) regrows after excitation RF pulse	Time constant T1 characterizes the rate at which the hyperolarized magnetization decays to zero.
Time constant T2 characterizes signal decay following excitation RF pulse	same
Large RF tip angles used	Very small RF tip angles used

Magnetic Resonance Imaging: K space

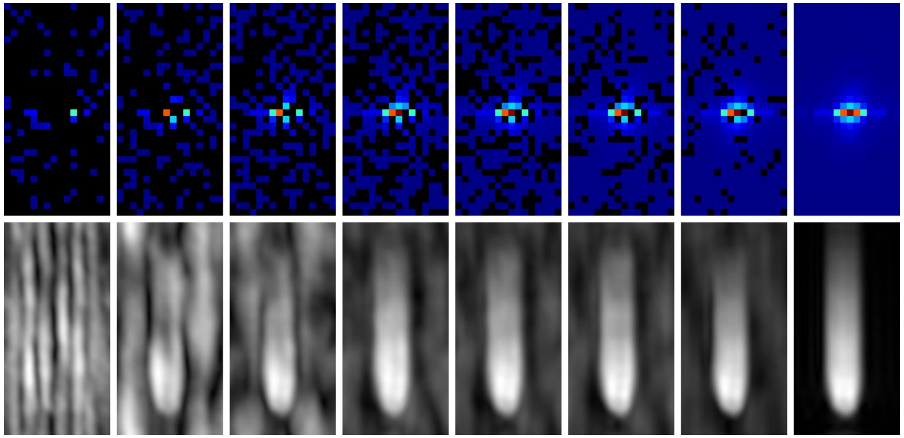
- We sample the NMR signal in the presence of magnetic field gradients, to measure the “spatial frequency” components of the magnetization distribution in “*k* space”
- Then reconstruct an image of the magnetization distribution by applying the inverse Fourier transform to the *k*-space data matrix.



k-space amplitudes

magnitude image

Random Points selected in k space



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