Can Nuclear Magnetic Resonance be Used as a Plasma Diagnostic ?

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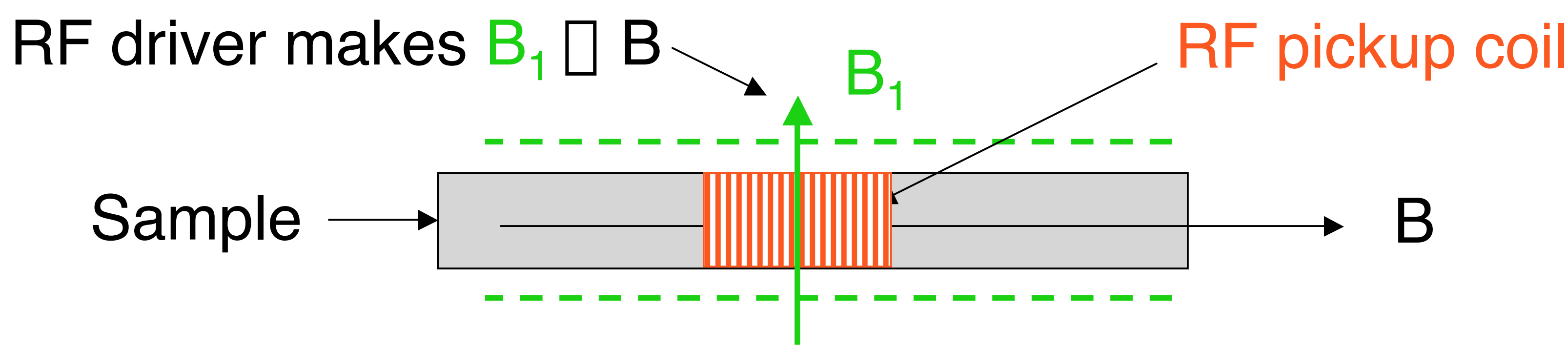
see also: Rev. Sci. Inst. 74, 11460 (2003)
from High Temperature Plasma Diagnostics Conf. 2002

Outline

- Conventional NMR in liquids and solids
- Plasma NMR *vs*. Conventional NMR
- Possible plasma NMR measurements
- Estimates of signal/noise ratios
- Conclusions and possible directions

Conventional NMR in Liquids and Solids



- Insert sample into very uniform magnetic field B (≈ 1-20 T), and apply transverse oscillating B_1 pulse at NMR frequency to rotate nuclear magnetization $\perp$ B (typically over ≈ 10 μsec)

- After B_1 field ends, measure precession of nuclear spins using RF pickup coil (“Free Induction Decay” phase)

- Frequency and amplitude of NMR spectrum in pickup coil determine type and number of nuclei in sample

NMR Nuclei and Frequencies

- **Nuclei used for NMR are of interest to fusion**
- **Frequencies are (coincidentally) in ICRH range**

Particle	**Spin**	**f_{NMR}(MHz)***	**f_{NMR}/f_{ci}****	**Sensitivity*****
Hydrogen	1/2	100	2.8	1
Deuterium	1	15.35	0.86	0.009
Tritium	1/2	106.7	9.0	1.2
He-3	1/2	76.2	3.2	0.44
Li-6	1	14.7	0.82	0.009
Li-7	3/2	38.9	2.5	0.29
Beryllium-9	3/2	14.1	0.89	0.014
Boron-10	3	10.7	0.6	0.02
Boron-11	3/2	32.1	2	0.17
Carbon-13	1/2	25.1	1.5	0.016

* at B=2.3488 T, from Abraham et al, Introduction to NMR Spectroscopy, 1988

** for fully ionized nuclei, equal to $f_{NMR}/f_{ci} = (1/2)(□/□_□)(□_i/□_p)(1/Z)$

*** relative to protons at constant B for equal number of nuclei

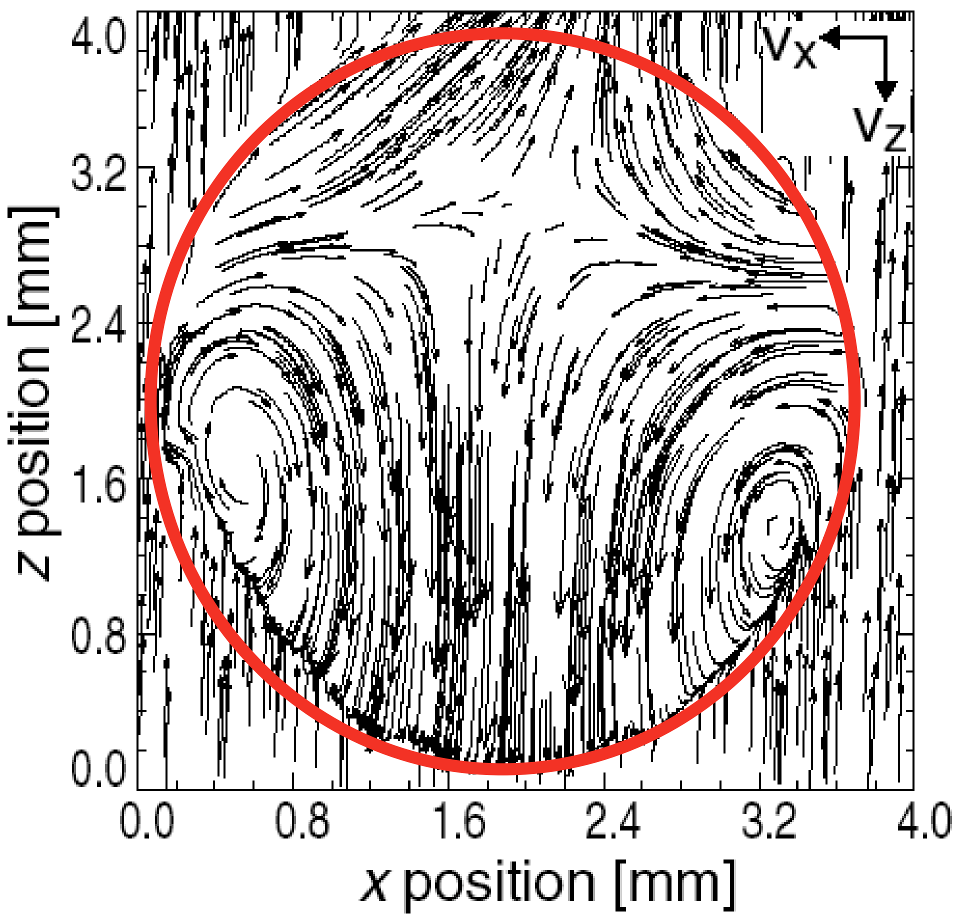
Examples of NMR Machines and Results

21 Tesla NMR machine

A 900-MHz nuclear magnetic resonance device.

Physics Today, Mar. 2002

velocity of falling water drop



Han et al, Phys. Rev. Lett. 87, 144501 (2001)

Conventional NMR vs. Plasma NMR

- In general NMR signal μ density of NMR species in sample

  => plasma signal ≈ 10^{-9} times liquid signal if they have the same fractional spin polarization

- Spin polarization fraction typically $F_{spin} \approx \mu B/kT_{room} \approx 10^{-5}$

  => in equilibrium expect $F_{spin} \approx 10^{-10}$ at T = 2.5 keV

- However, nearly 100% polarized H_2 or ^3He can be made in large quantities for use as plasma "fuel" for NMR

  => fully polarized plasma would increase NMR signal by ≈ 10^5 with respect to room temperature sample

Plasma NMR Signal with Polarized Fuel

- $V \approx 10^{-3}$ volt NMR signal from hydrogen in 1 cm^3 of water at room temperature with, B=1 T using a 10 turn coil with A=1 cm^2 at f=42 MHz (Bloch, Phys. Rev. p. 460, 1946)

- With respect to water, plasma density is smaller by $\approx 10^{-9}$, but with fully polarized H plasma, polarized spin density fraction would be larger by $\approx 10^5$

- Thus if plasma area was A=1 m^2 instead of 1 cm^2, NMR signal from plasma should be comparable to NMR signal from 1 cm^3 of water (measured in 1940's)

  expect $V_{plasma} \approx 10^{-3}$ volts => easily measurable ! ?

Possible Sources of Polarized Plasma Fuel

- Highly polarized ^3He gas (> 10^{21} atoms) produced by spin exchange with laser optically pumped alkali-metal vapor (e.g. Chupp et al, Phys. Rev. C, 2244 ‘87)

- Bottles of this gas can be transported and kept polarized for many hours if a weak magnetic field is present

- Similarly polarized hydrogen has also been created using cyrogenic methods (Cline et al, PRL 47, 1195 ‘81)

- In principle, highly polarized beams or pellets can also be created and used for plasma fueling

Spin Depolarization in Plasmas

Various processes calculated by Kulsrud et al in papers on spin-polarized fusion (e.g. Nucl. Fusion 186, p. 1443)

- Collisional depolarization negligible for fusion plasmas
- Effect of ion motion in static tokamak fields negligible
- Effect of magnetic field fluctuations near NMR frequency can cause rapid depolarization (similar to B_1 field)

  Kulsrud et al estimated $\tau_{decay} \approx .075$ sec for decay time of spin polarized tritium for assumed plasma $\delta B_{\perp} \approx 1$ Gauss at B=5T

- Effect of nuclei recycling from wall can also be significant

  typically polarization lost in ≤ 1 sec when atom resides on wall surface
  H.S. Greenside et al, J. Vac. Sci. Technol. A 2, 619 (1984)

Possible NMR Experiments on Tokamaks

1) Plasma NMR

- Measure species mix inside a fully ionized plasma
  (but needs polarized fuel for each species !)

- Measure internal □B from decay rate of polarization

2) Wall surface NMR measurement (without plasma)

- Tritium inventory inside vessel (typically ≈ 1 gram in JET)

- Low-Z surface coatings used for conditioning (Li, Be, B)

How Could This be Done ?

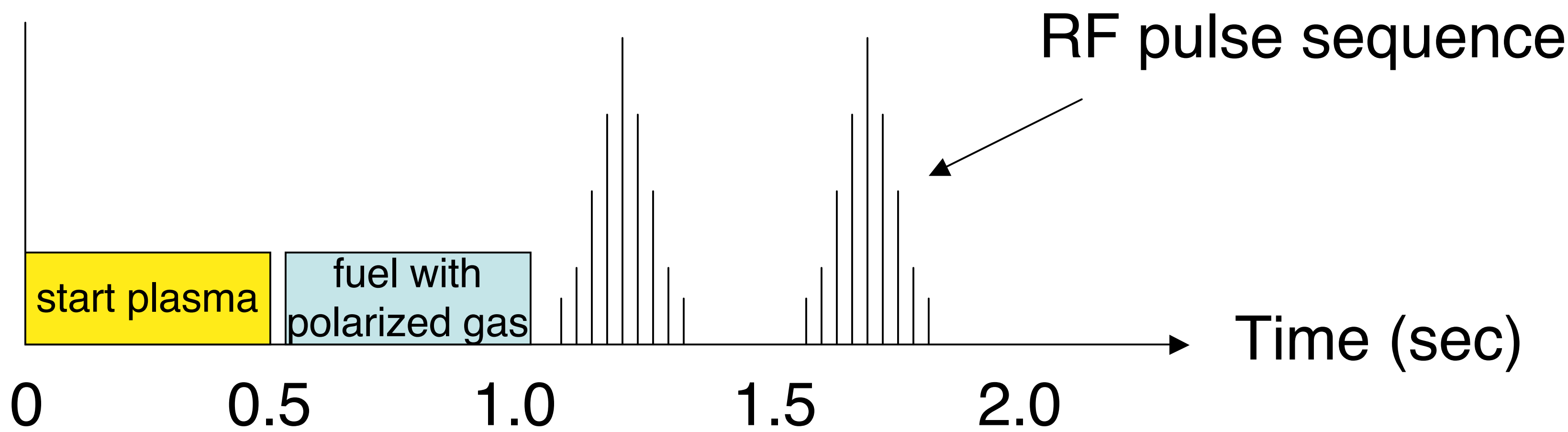
Plasma NMR measurement:

a) fuel plasma with highly polarized gas (e.g. ^3He, H, or T)
b) apply RF pulses to plasma using existing antennas
c) measure NMR spectrum using same antennas
d) vary B and RF pulse to scan resonance in plasma

Wall Surface NMR measurement:

a) apply RF pulses to empty vessel using existing antennas
b) measure spectrum of spins using same antennas
c) vary B and RF pulse to scan surface location

Scenario for Tokamak NMR Measurement



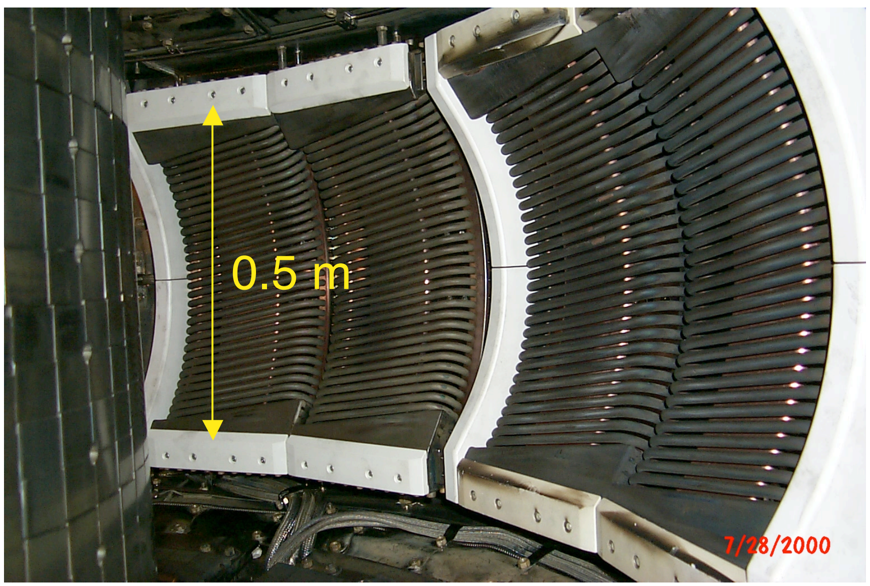
- Vary RF pulse amplitude to find maximum response
- Repeat to find timescale for plasma polarization decay
- Number of RF pulses limited by RF depolarization

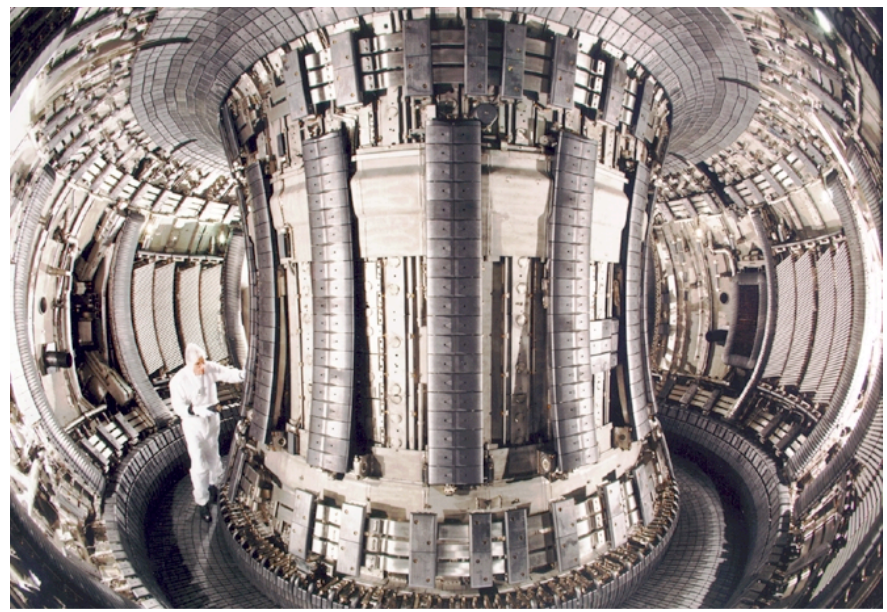
Use Existing RF Systems in Tokamaks

Note: $□_{NMR}/□_{ci}$ = 2.8 (H), 0.86 (D), 9 (T), 3.2 (^3He)

Alcator C-Mod (MIT)
$B_{toroidal} \leq 8$ T, R=0.66 m, a=0.23 m
$f_{ICRF} \approx 40\text{-}80$ MHz $P_{ICRF} \leq 5$ MW

JET (Joint European Torus)
$B_{toroidal} \leq 3.8$ T, R=3.0 m, a=1.0 m
$f_{ICRF} \approx 25\text{-}100$ MHz $P_{ICRF} \leq 20$ MW





Potential Difficulties

Plasma NMR measurement:

- Highly inhomogeneous toroidal magnetic field
- Short residence time of nuclei in a given volume
- Background due to atoms on walls
- RF propagation through plasmas
- RF noise from plasma

Wall Surface NMR measurement:

- Small thickness of surface coatings ($\approx 10\ \mu$m)
- RF skin effect in first-wall (e.g. carbon, steel)
- Coupling of RF radiation into empty vessel

Estimates of Signal / Noise

- Plasma NMR
  - expected signal in uniform B
  - expected signal in tokamak B
  - expected NMR spectrum
  - background due to atoms on wall
  - estimate of RF noise from plasma

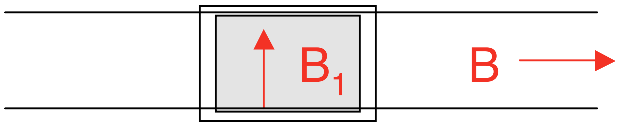
    => expected S/N for plasma NMR

- Wall surface NMR
  - expected NMR signal from T on wall
  - expected NMR signal from lithium coating
  - overlap of NMR resonances on wall

    => expected S/N for wall surface NMR

Plasma NMR Signal in Uniform B

RF driver + pickup coil



<u>"Linear" Alcator C-Mod:</u>

B=2.5 T (f=80 MHz)
n=2x10^{20} m^{-3} , T=1 keV

Assume fully polarized ^{3}He plasma with spins rotated 90º to B by RF (B_1) pulse

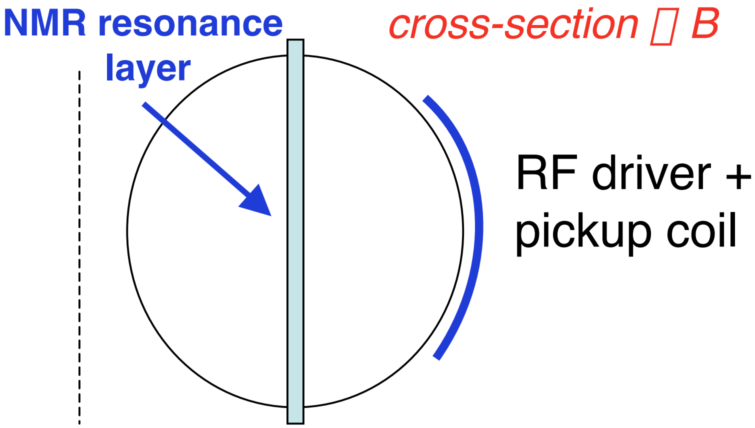
$M_{\square} = n\ \mu_{3He} = n\ (2.1\mu_N) \approx (2\text{x}10^{20}\ \text{m}^{-3})\ (2.1 \bullet 5\text{x}10^{-27}\ \text{J/T}) = 2.1\ \text{x}\ 10^{-6}$ amp-turn/m

$B_{\square} = \mu_o M_{\square} = (4\square\ \text{x}\ 10^{\square 7}\ \text{H/m})(2.1\ \text{x}\ 10^{-6}\ \text{amp-turn/m}) = 2.6\ \text{x}\ 10^{-12}$ Tesla (assumes $\mu=\mu_o$)

$V_{NMR}(\text{volts}) = (N_{coil}A_{coil})\square_{\square\square\ R}B_{\square} = (0.3\ \text{m}^2)(2.5 \bullet 2\text{x}10^8\ \text{rad/sec})\ (2.6\text{x}10^{-12}\ \text{T}) \approx$ 4x10^{-4} volts

note: fractional polarization at room temperature $f_{pol} \approx 2\mu_{3He}B/2kT \approx 6\text{x}10^{-6}$
fractional polarization at plasma temperature $f_{pol} \approx (T_{room}/T_{plasma})\ 6\text{x}10^{-6} \approx 10^{-10}$

Plasma NMR Signal in Tokamak B



Actual Alcator C-Mod:

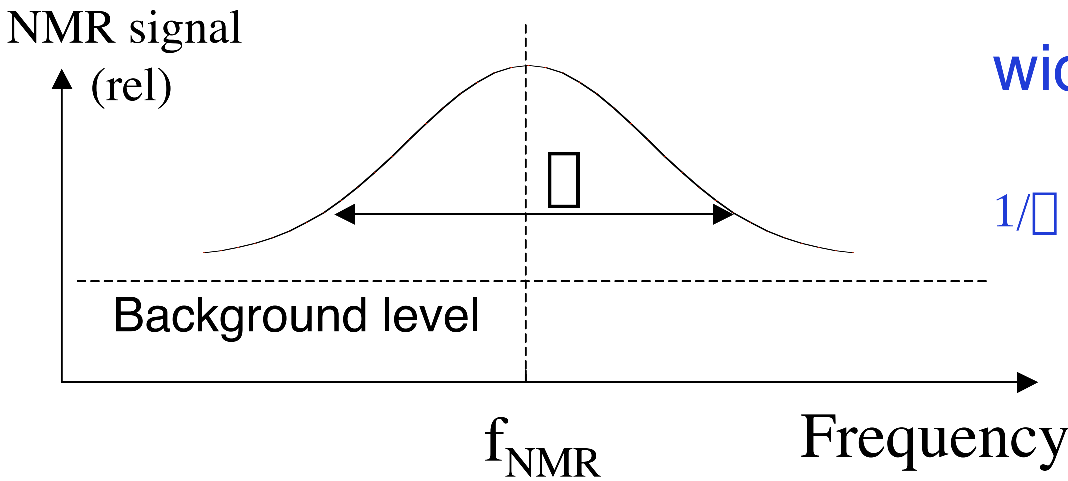
$B = B_o(R_o/R)$ where $B_o = 2.5$ T

f_{NMR} (^3He) = 80 MHz at R_o=0.67 m

n=2x10^{20} m^{-3}, T=1 keV, ρ_i=0.1 cm

- Width of NMR resonance layer: $\Delta R/R \approx \Delta B/B \approx \Delta f_{driver}/ f_{NMR}$
- Driver Δf_{driver} depends on RF pulse width: $\Delta f_{driver}\, \tau_{RF} \approx 1$
- For $\Delta R \approx 1$ cm ($\approx 10\ \rho_i$) and $f_{NMR} \approx 80$ MHz => $\tau_{RF} \approx 1\ \mu$sec
- For "filling factor" ≈ 2% of uniform B case: $V_{NMR} \approx 10^{-5}$ volts

Expected NMR Spectrum of a Tokamak



width of NMR spectrum

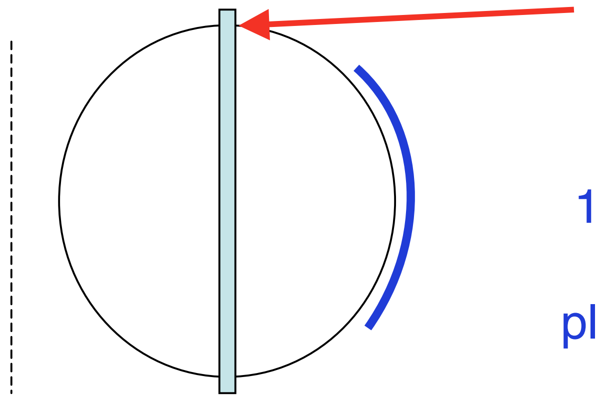
1/□ = □ all dephasing processes

$□_{□B}$	magnetic field gradients	$(□B/B)\ □_{NMR}$	≈ 1 MHz
$□_{pol}$	motion along poloidal field	$(v_i/□R)(B_{pol}/B)$	≈ 1 MHz
$□_{□}$	ion cyclotron motion	$(□_i/R)\ □_{NMR}$	≈ 0.3 MHz
$□_{□r}$	diffusion across B	$D/□R^2$	≈ 10^4 Hz
$□_v$	thermal Doppler broadening	$(v_i/c)\ □_{NMR}$	≈ 10^3 Hz
$□_{□B}$	magnetic field fluctuations	$(□B_{□}/B)^2□_{NMR}$	≈ 10 Hz

⇨ Spectrum dominated by □B and poloidal motion

Spectral width much broader than solids (≈ 1 Hz)

Background Due to Fuel Atoms on Walls



NMR resonance interacts with nuclei stuck on surface of wall

1 monolayer on wall surface ≈ 10^{15} -10^{16} atoms/cm^2

plasma “na” ≈ (2x10^{14} cm^{-3})(50 cm) ≈ 10^{16} atoms/cm^2

^{3}He probably has << 1 monolayer => negligible

However H, D, T up to ≈ 10^4 monolayers ≈ 10^{19} -10^{20} atoms/cm^2

⇨ But if only f_{pol} ≈ 10^{-5} wall atoms polarized room temperature, then wall background still < plasma signal

RF "ICE" Emission from Plasma

Spectra of RF emission as seen by a JET antenna (Cottrell & Dendy, PRL '88)

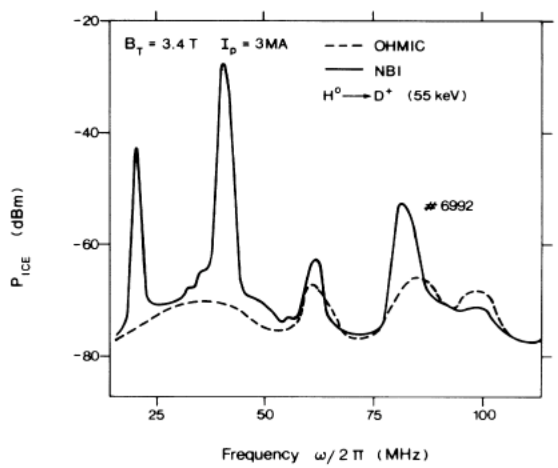
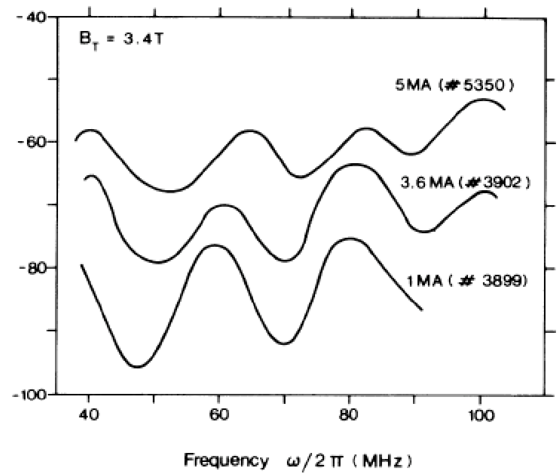


FIG. 1. ICE spectrum measured before and during 4-MW H^0 neutral-beam coinjection into a D^+ limiter plasma.



G. 2. ICE spectrum from three Ohmically heated deuteri-imiter discharges with constant toroidal field but with different plasma currents.

"ICE" lines at $n\Omega_{ci}$ of beam ions or fusion products
[McClements et al, PRL '99]

For low power Ohmic plasmas in JET the measured ICE was as low as ≈ -80 dBM

⇒ $P_{RF} \approx 10^{-11}$ Watt into ≈ 1 m^2 antenna

Arunasalam tried to explain ICE as nuclear spin-flip emission ! (Nucl. Fusion '94)

Estimated S/N for Plasma NMR

- Plasma NMR signal $V_{NMR} \approx 10^{-5}$ volts (Alcator C-Mod ^{3}He)
- Assume plasma noise $P_{noise} \approx -80$ dBm $\approx 10^{-11}$ W (approx.)
- For $R = 50\ \Omega$ antenna: $V_{noise} \approx (P_{noise}R)^{1/2} \approx 2\times10^{-5}$ volts

=> Plasma S/N ≈ 0.5

- Detector noise (Δf=1 MHz): $V_{det} = (4k_B T_{room} R\, \Delta f)^{1/2} \approx 10^{-6}$ volts

=> Detector S/N ≈ 10

=> S/N could be increased by ≈ x4 with multiple pulses/shot

NMR Wave Propagation in Tokamaks

- RF heating antennas excite the fast magnetosonic wave and a small component of the fast wave field is properly polarized to couple to (negative) ^{3}He nuclear spin

- NMR frequency of ^{3}He is ≈ $3\square_{3He}$ and ≈ $4\square_{D}$, so fast wave damping at harmonics is a possible loss mechanism

RF waves from antenna can couple to nuclear spin
Spins can couple to fast wave and back to antenna

BUT, expected $\square B_{\square}$ from NMR ≈ 10^{-8} Gauss, while expected plasma-driven magnetic fluctuations ≈ 1 Gauss !?

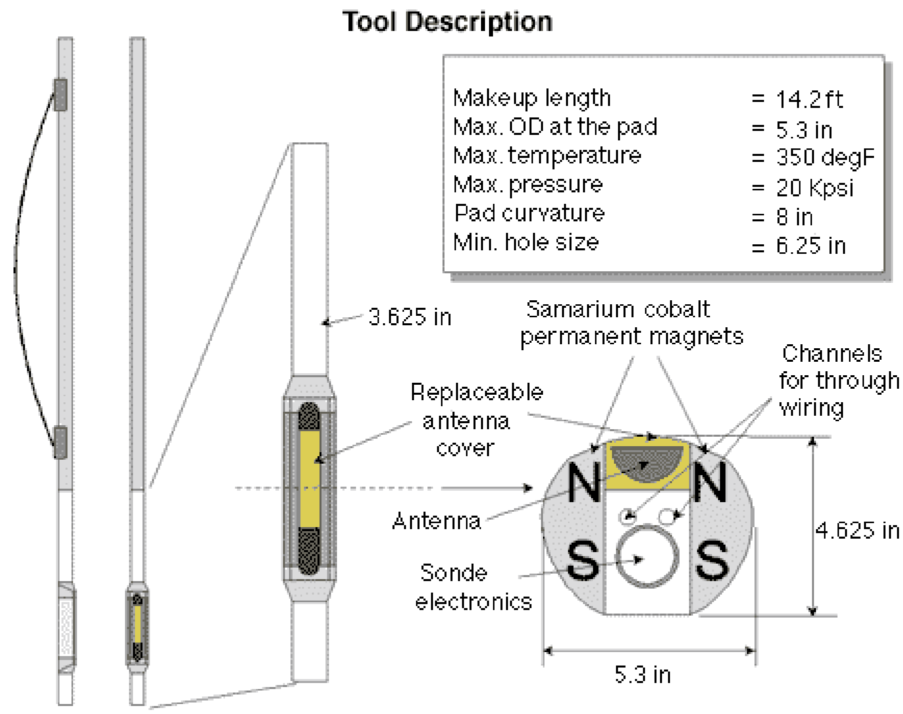
=> why can't we see the internal plasma $\square B_{\square}$ without NMR ?

Wall Surface NMR

- Measure absolute wall surface composition without plasma
- Maybe can use TF (VF?) field + RF antenna (near field only)
- Maybe can insert NMR probe into vessel with remote arm
- Should work up to RF skin depth, ≈ 10^{-2} cm at 100 MHz

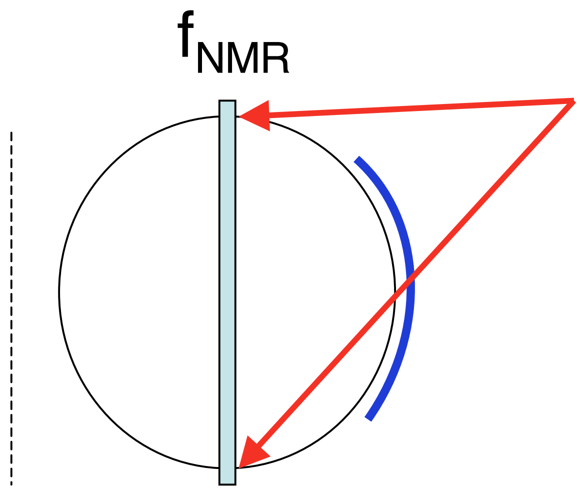
Tritium detection threshold in lab NRM ≈ 0.1 mCi, ≈ 10^{-8} of tritium levels inside JET

"Inside out" NMR used for oil exploration (Schlumberger)



http://www.slb.com/seed/en/watch/nmr/tool.htm

Measurement of Tritium on Surface



NMR resonance interacts with solid co-deposited layer on divertor surface

Assume 1 gram of T in JET is deposited on 10% of wall area

(1 gram ≈ 2×10^{23} atoms ≈ 10,000 Ci)

$B = 2.2$ T, $f_{NMR}(T) \approx 100$ MHz

$\Delta f \approx 1$ MHz, $\Delta R \approx 3$ cm

$N_T \approx (2 \times 10^{23}$ atoms$)/(2 \times 10^5$ cm$^2) \approx 10^{18}$ atoms/cm^2 on surface

Assume $f_{pol} = (\mu B_T / \mu B_{3He})(6 \times 10^{-6}) \approx 7 \times 10^{-6}$ polarized

Assume this is equivalent to distributed density in plasma of

$n \approx (10^{18}$ atoms/cm$^2)(7 \times 10^{-6})/300$ cm $\approx 2 \times 10^{10}$ atoms/cm^3

Estimated S/N for Tritium on Surface

- Assume detection of 3 cm radius with JET antenna area 1 m^2
- Signal V_{NMR} μ $(NA_{coil})n\mu\Box B$ (scaling from ^3He case in Alcator)

V_{NMR} μ $(1.0\ m^2/0.3\ m^2)(2x10^{10}\ cm^{-3}/2x10^{14}\ cm^{-3})(1.4)(100\ MHz/80MHz)(2.2\ T/2.5\ T)$

$V_{NMR} \approx (5x10^{-5})\ (10^{-5}\ volts) \approx 5x10^{-9}$ volts

- Detector noise ($\Box f$=1 MHz): $V_{det} = (4k_B T_{room} R\ \Box f)^{1/2} \approx 10^{-6}$ volts

=> $S/N \approx 5x10^{-3}$

This could be improved by multiple RF pulsing during a 10 sec long JET shot (depending on spin relaxation time in layer)

Measurement of Lithium on Surface

f_{NMR} = 63 MHz for ^{7}Li NMR at maximum B=3.8 T in JET

$N_{Li} \approx$ 5%(10^4 monolayers)(5×10^{15} atoms/cm^2) $\approx 2 \times 10^{18}$ atoms/cm^2

$f_{pol} = (\mu B_{Li}/\mu B_{3He})(6 \times 10^{-6}) \approx (3.2/2.1)(3.8/2.2)\ 6 \times 10^{-6} \approx 1.5 \times 10^{-5}$ polarized

Assume this is equivalent to distributed density in plasma of:

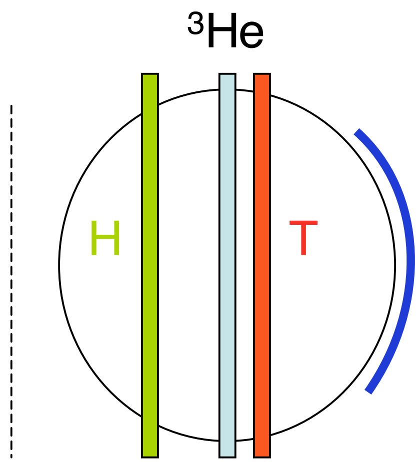
$n \approx (2 \times 10^{18}$ atoms/cm$^2)(1.5 \times 10^{-5})/300$ cm $\approx 3 \times 10^{11}$ atoms/cm^3

Signal V_{NMR} µ $(NA_{coil})n\mu$□B (scaling from T case in Alcator)

$V_{NMR}(Li) \approx (150)(3.2/3.0)(60/100)(3.8/2.2)V_{NMR}(T) \approx 2 \times 10^{-8}$ volts

=> $S/N \approx 150(5 \times 10^{-4}) \approx 7 \times 10^{-2}$

Overlap of NMR Resonances



If antenna set at f=80 MHz at 2.5 T:

Species	Resonance layer
^{3}He	R_0
H	0.76 R_0
D	6 R_0
T	1.06 R_0
^{6}Li	5 R_o
^{7}Li	2 R_0
^{13}C	4 R_0

Problem:

- H and T will probably overlap - indistinguishable ?
- D and ^{6}Li will probably overlap - indistinguishable ?

=> may be able to avoid overlap with localized NMR probe

NMR of Surface Tile Removed from Vessel

- First wall tiles are routinely removed from the tokamak for surface analysis (which can still be difficult)
- Could wall samples be analyzed in an NMR spectrometer ?
- For DT in JET or TFTR, tile has typically 5 mCi/cm^2 of tritium on surface (within upper 10^4 -10^5 monolayers)
- NMR is routinely done with 0.1-10 mCi/sample (Evans et al, "Handbook of Tritium NMR Spectroscopy", 1985, p. xii)

⇒ Looks like NMR could be done OK outside vessel

Summary of S/N Estimates

- For ^{3}He plasma NMR in Alcator C-Mod
  S/N ≈ 0.5 - 10 for one NMR pulse
  S/N ≈ 2 - 40 for ≈ 20 NMR pulses/shot

- For tritium or lithium on wall surface in JET
  S/N ≈ 10^{-2} for one NMR pulse
  S/N ≈ 1 for 10^4 NMR pulses during long TF

- For "outside the tokamak" wall tile surface analysis
  S/N >> 1 inside NMR spectrometer

Conclusions

- Measuring NMR response of fully polarized ^{3}He plasma in Alcator C-Mod seems marginally feasible

- Measurement of internal magnetic fluctuations via decay of polarization is difficult due to uncertainties about propagation of RF through plasma and ICE emission

- Measurement of low-Z composition of wall (without plasma) seems marginally feasible but potentially useful, e.g. for assessment of tritium inventory in JET or ITER

Possible Directions

- Analyze TFTR tiles for H content using NMR
  - use small sample in NMR spectrometer
  - compare with other surface analysis methods
  - develop *in situ* wall surface T diagnostic for ITER
- Do initial plasma experiments on a linear machine
  - much lower □B => much larger NMR S/N ratio
  - less RF noise and simpler RF propagation physics
  - try NMR “tagging”, flow, and diffusion experiments
- Try spin-polarized fueling on a toroidal machine
  - try to measure NMR of polarized ^{3}He in Alcator
  - if successful, try spin-polarized T fueling in JET
  - pursue x1.5 increase in DT fusion reaction rate