Explosives Detection at LANL Based on Novel Magnetic Resonance Methods

Larry Schultz (LANL P-21)

for Michelle Espy and the Squid Team

ADSA09

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In a Nutshell: Liquid Explosives Screening

- WHAT: Integrated Nuclear Magnetic Resonance and X-ray (MagRay)
- WHY: Could provide for liquids screening with almost no additional headaches for air travelers, well integrated with existing CONOPS.
- HOW: NMR / X-ray signature is highly selective relative to deployed solutions.
- HOW: Can handle diverse packaging & multiple bottles in a conveyor fed stream.

In a Nutshell: Explosives Detection
(in partnership with ALERT)

- WHAT: Nuclear Quadrupole Resonance (NQR) with polarization enhancement.
- WHY: Non-invasive, safe detection of 14N based IED's in ground, packages, or in the body.
- HOW: NQR has demonstrated sensitivity but signal is weak.
- HOW: Polarization enhancement boosts signal such that practical application is enabled.

NMR and NQR Basics

NMR:

Apply polarization field B_p

½ spins align

ULF only: reduce field to $B_m << B_p$

Apply RF "spin flip" pulse

Spins flip to orthogonal to B_m…

…and precess about B_m

Resulting in signal at frequency proportional to B_m

NQR:

≥ 1 spins align naturally within electron cloud

Apply RF excitation pulse at material NQR frequency

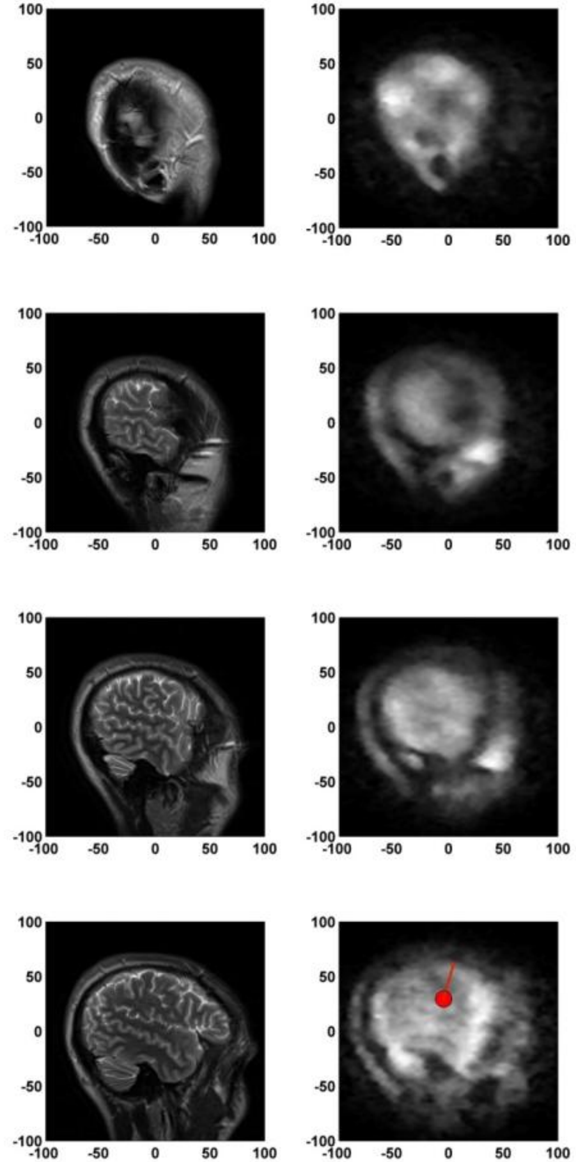
Spins flip…

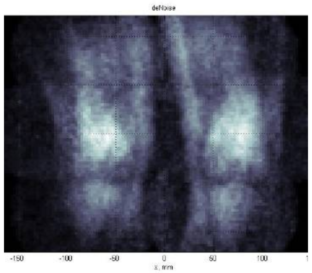
…and precess

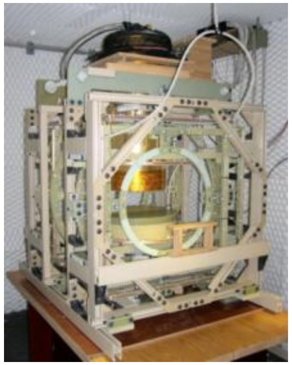
Resulting in signal at material NQR frequency

Ultra Low Field NMR/MRI at LANL

- Ultra low field enables integration of MRI and other brain diagnostics.
- Polarization (B_p) at ~100 mT rather than 1.5-3T.
- Readout (B_m) at μT (Earth's field level)
- Safe, tolerant to metal, inexpensive.

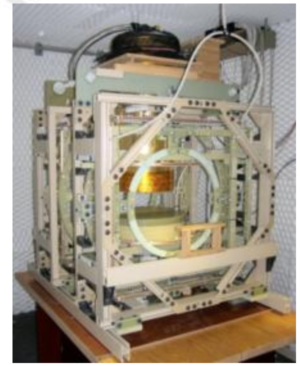






“Battlefield” and portable MRI

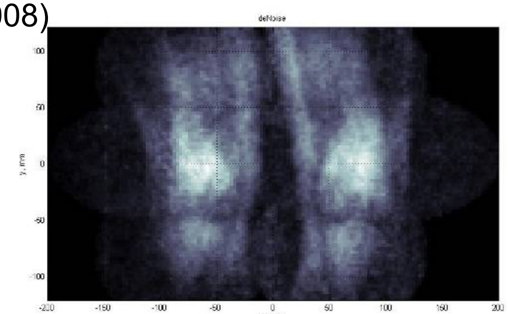
Design Goals / Performance Metrics	
Image Quality	SNR 20, 2x2x4 mm^3
Image Time	< 20 min
Size	2x2x2 m^3
Cost	< $500k
Cryo. refill	> 6 months
Weight	< 1 ton



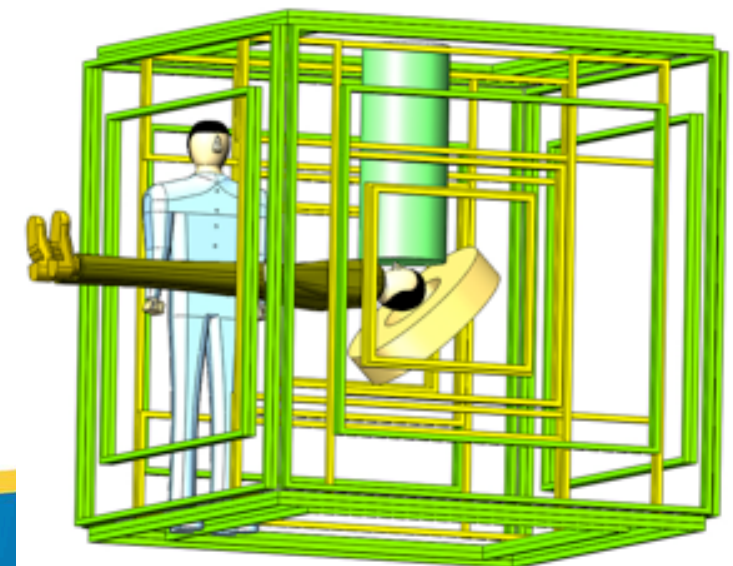
Compact MRI suitable for rapid deployment to field hospitals and emergency rooms: a path forward for a new generation of low resource MRI diagnostics.

MRI can be delivered this way!

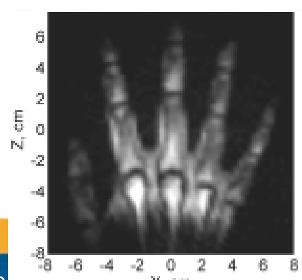
First MRI ULF image of Espy’s knees (2008)

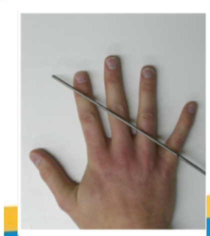


Preliminary design of the LANL “battlefield MRI” system

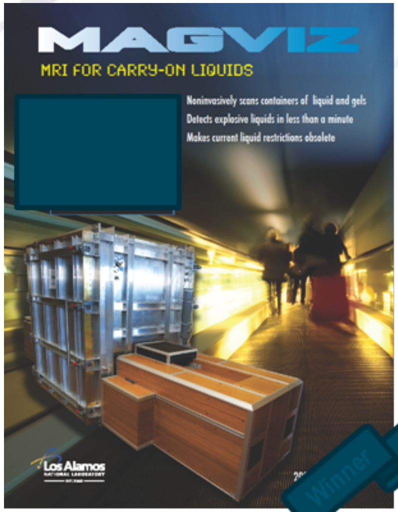


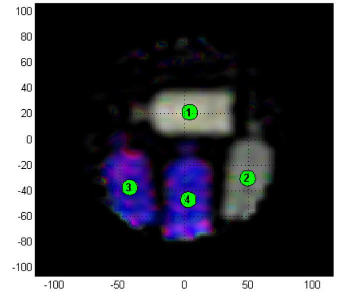
Safe in the presence of metal

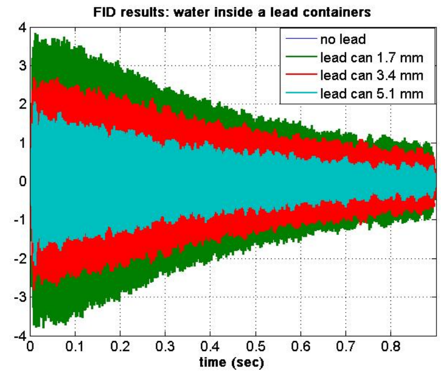




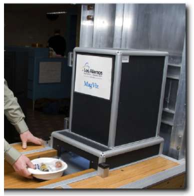
Ultra-low field NMR/MRI for detection of liquid explosives: MagViz (NMR relaxometer)



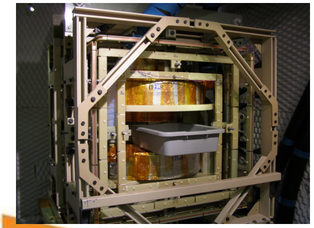





MagViz in the Albuquerque Airport, 2008



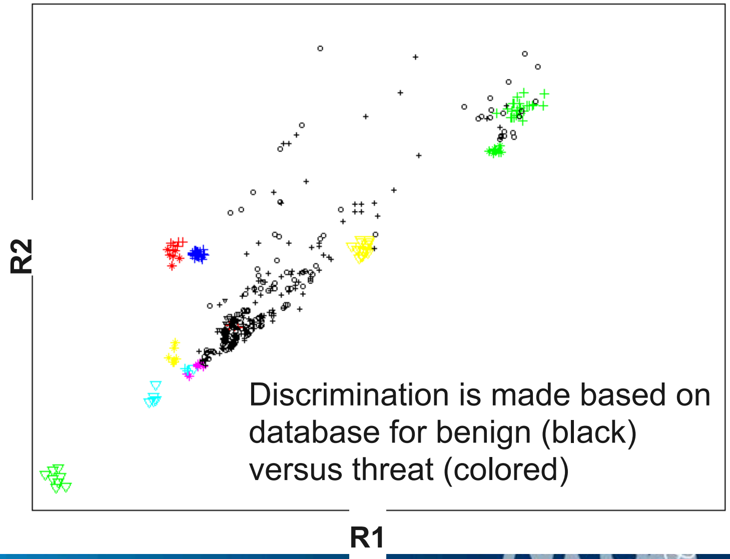
MagViz "2B" July 2010, screening large volumes



Espy et al., Supercond. Sci. Technol. 23 (2010) 034023 Ultra-low-field MRI for the detection of liquid explosives

Espy et al., "Progress on Detection of Liquid Explosives Using Ultra-Low Field MRI," IEEE Trans. Appl. Supercond., IEEE Trans. Appl. Supercond. (2011) Vol.21, iss.3 PART 1, p.530-533.

Espy et al., Applications of Ultra-Low Field Magnetic Resonance for Imaging and Materials Studies IEEE Trans. Appl. Supercond. (JUN 2009) Vol.19, iss.3, pt.1, p.835-838



Discrimination is made based on database for benign (black) versus threat (colored)

MagRay Timeline

June 2006: first ultra-low field MRI of brain

Sept 2006: Proof of concept for detection of liquids. HSARPA "MagViz" project begins

Dec 2008: First MagViz unit at airport for 3-1-1 bags

- Field ability of ULF demonstrated.
- Multiple bottle screening.
- Stream of commerce packaging.
- Slow (~1 min), large footprint.
- Cryogens required.
- Limited threat list.

July 2010: MagViz screens small suitcases and segregated tubs of liquids

Ocobter 2010: cryogen free MagViz BLS at airport

- No cryogens!
- Small footprint BLS.
- Moderate scan time: ~30 sec.
- Greatly expanded threat list.
- About 5% P_{fa} at TSL.
- Notable gaps in threat list.

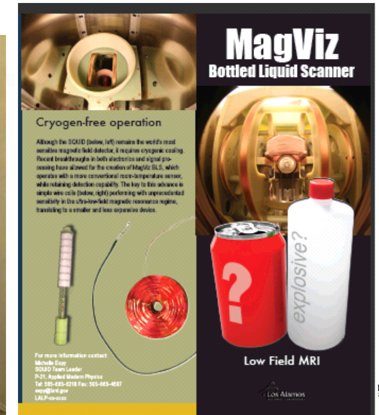
August 2011: MagViz BLS for DT&E at TSL

March 2013: Demonstration of MagRay combined NMR and X-Ray

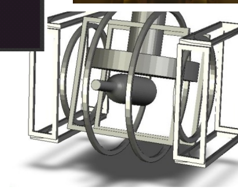
- Comprehensive threat list – excellent selectivity.
- Low scan time: <20 sec.
- Lab demo only – not fully integrated.
- Multiple bottle capable (though not yet demonstrated).

ULF NMR based BLS





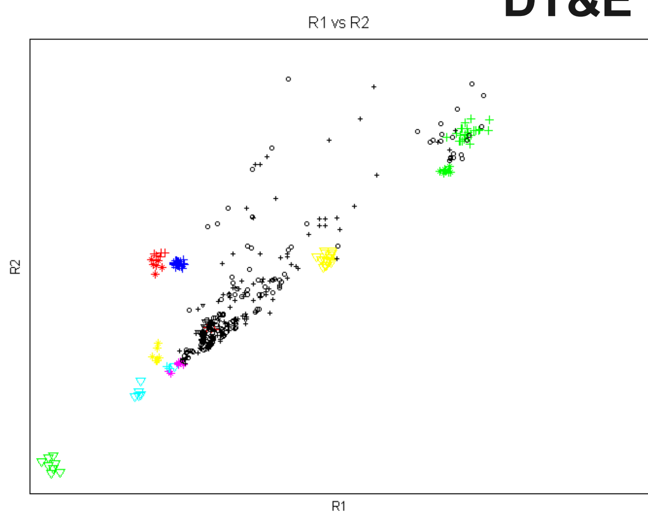



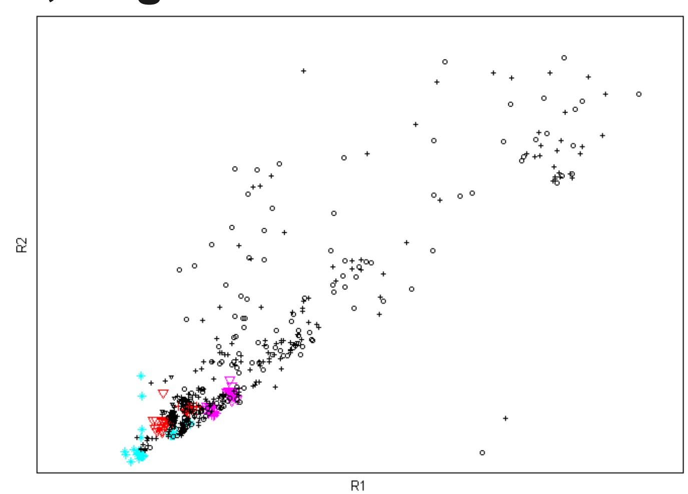
MagViz BLS, Albuquerque Airport October 2010. Screen a 3-1-1 exemption within 30 seconds.

DT&E at TSL, August 2011

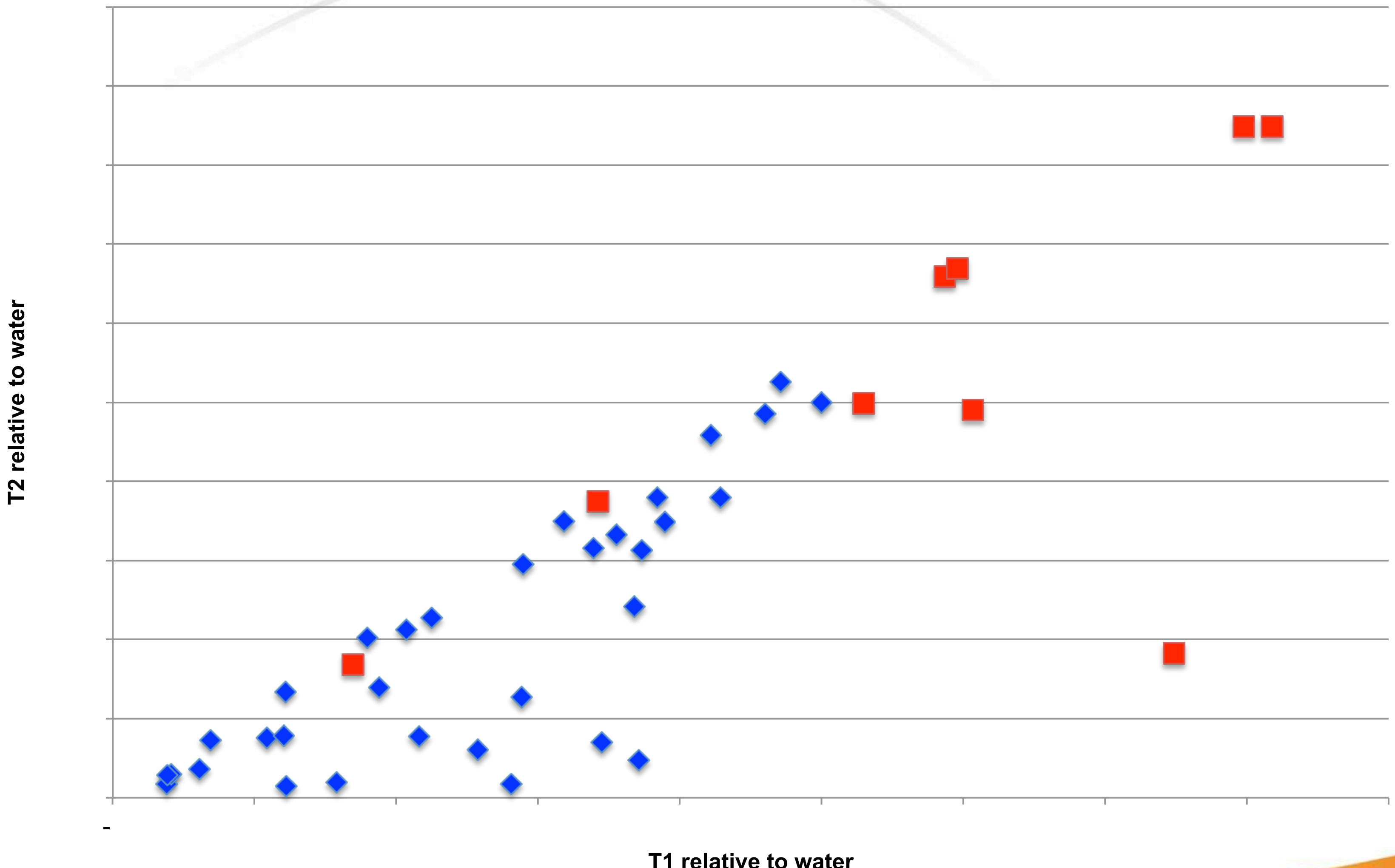
August 2011
~ 500 benign items
(black symbols)

~ 12 threats
(colored)





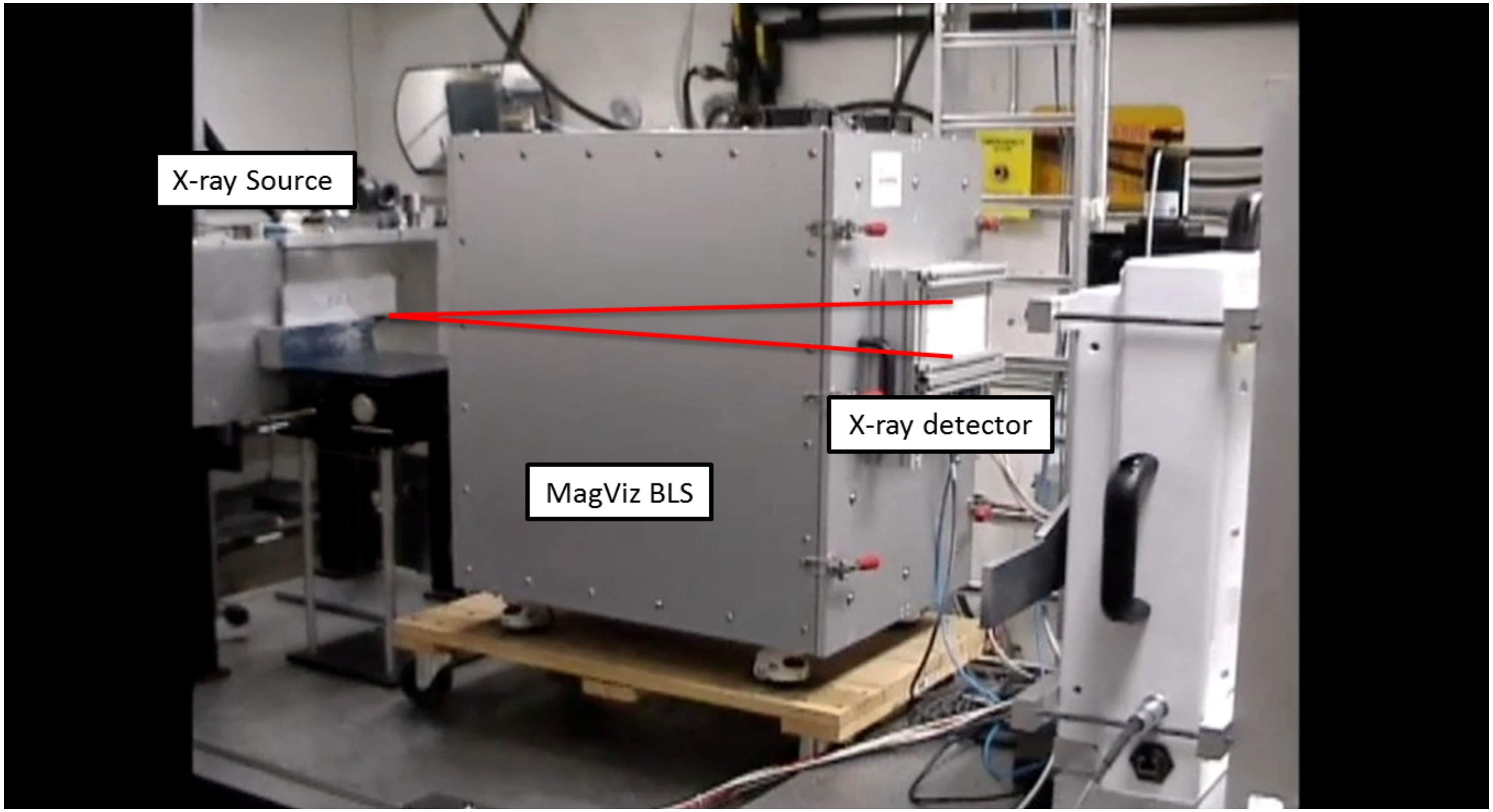
Signature is solid for some materials, not for others



Improving Selectivity

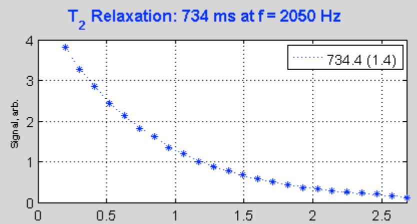
- X-ray imaging allows extraction of volume dependent NMR information.
- X-ray attenuation is also informative.
- An integrated NMR / X-ray dataset provides much better selectivity than does either mode individually.
- Dual energy or multispectral X-ray could enhance signature even further.

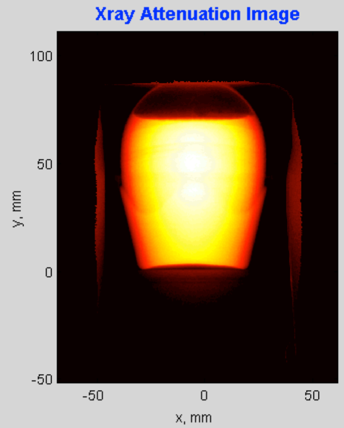
MagRay: combined ULF NMR and X-ray

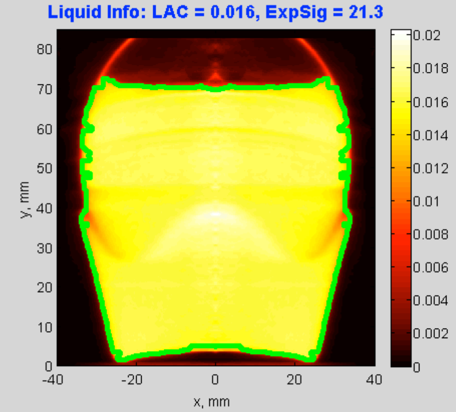


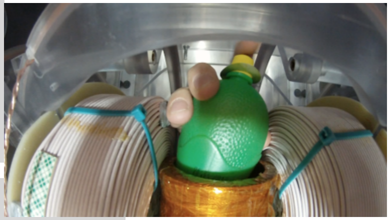
Setup of the MagRay demonstration experiment. The existing X-ray source is shown on the left. The X-ray detector is attached to the rear of the MagViz BLS.

Combined ULF NMR and X-ray









Classification Information

Benign

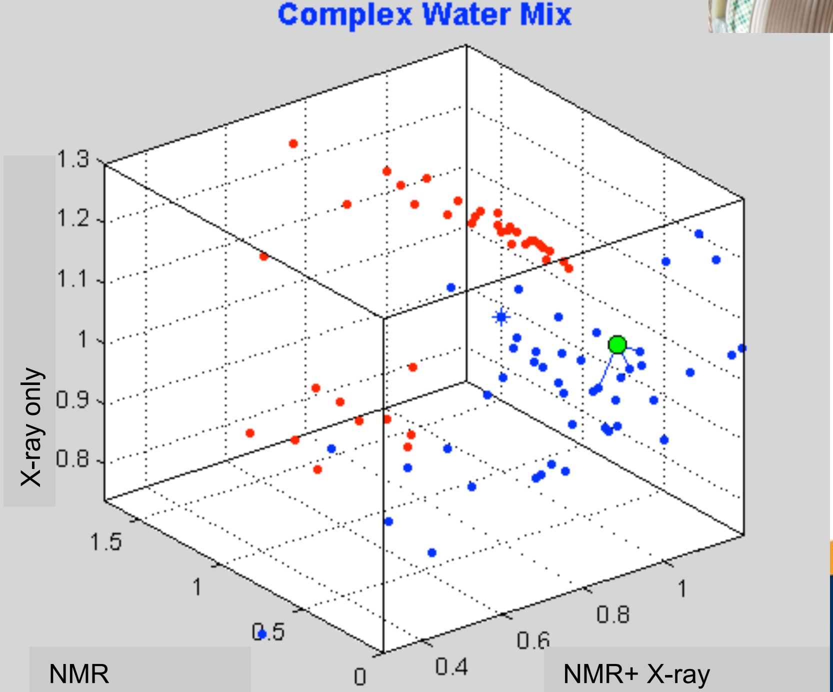
Group: Complex Water Mix

Likely: OrangeJuice / Lotion / WhiteWine

Reliability: 0.36 / 0.22 / 0.17

T1: 0.47, T2: 0.32, RNS: 1.01, LAC: 1.05

Subject ID: LimeJuice



Performance Estimate

Detection of threat liquids	P_d
All but nine threat liquids	>99.9%
Two neat threats, two HME's,	>99%
Four HME's	>90%
One HME	>80%
OVERALL PROBABILITY OF DETECTION	**97.4%**
Screening of benign liquids	Pfa
Nine benign liquids	<0.1%
Eleven benign liquids	<1%
Six benign liquids	1-5%
Four benign liquids	5-10%
Six benign liquids	10-25%
OVERALL PROBABILITY OF FALSE ALARM	**4.2%**

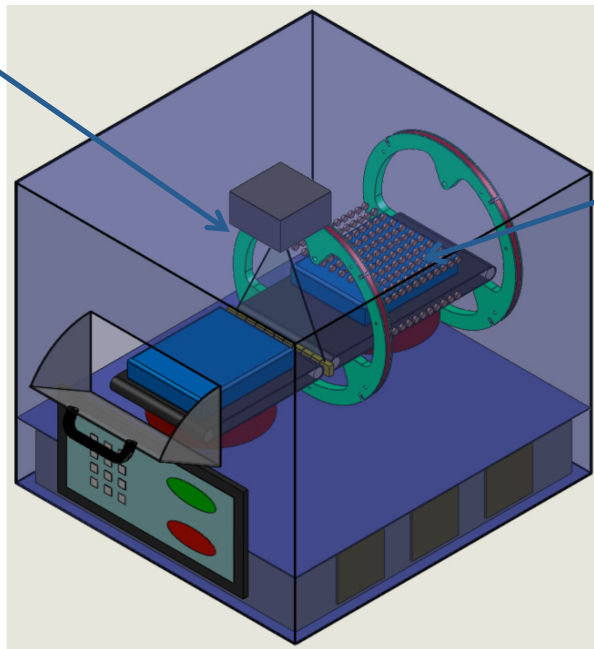
Simulated 1,000 scans of each liquid in our study, assuming a mean signature per our experimental measurements and assuming conservative measurement errors of 5% for X-ray and NMR.

We classified each simulated run as threat or benign based on the closest signature from our experimental library.

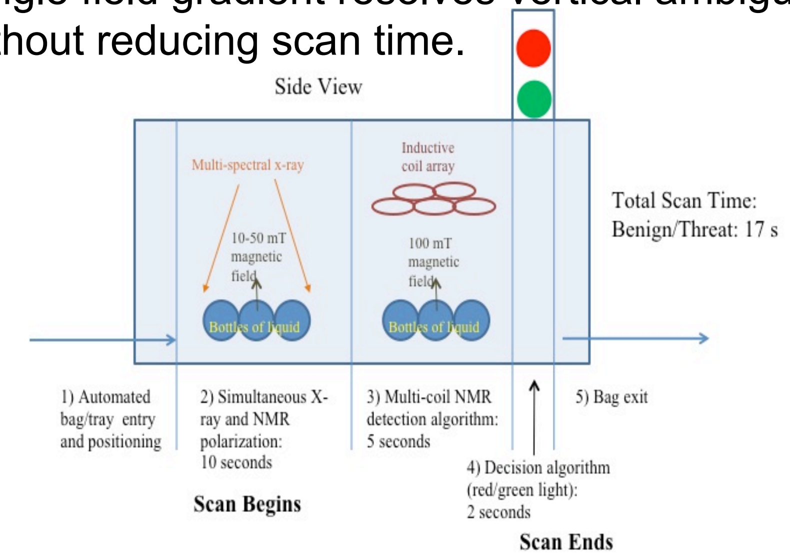
Based on this simulated study, for the liquids studied herein, **we estimate a probability of detection of 97.4%, with a false alarm rate of 4.2%.**

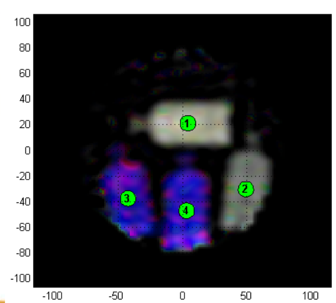
Back to 3-1-1 / multiple bottles: Concept

- X-ray image acquired via linear array as bag transits



- Low-cost NMR hybrid: single gradient and multi-coil detection
  - Detector coil array encodes NMR signal to assign signature to particular bottles.
  - Single field gradient resolves vertical ambiguity without reducing scan time.

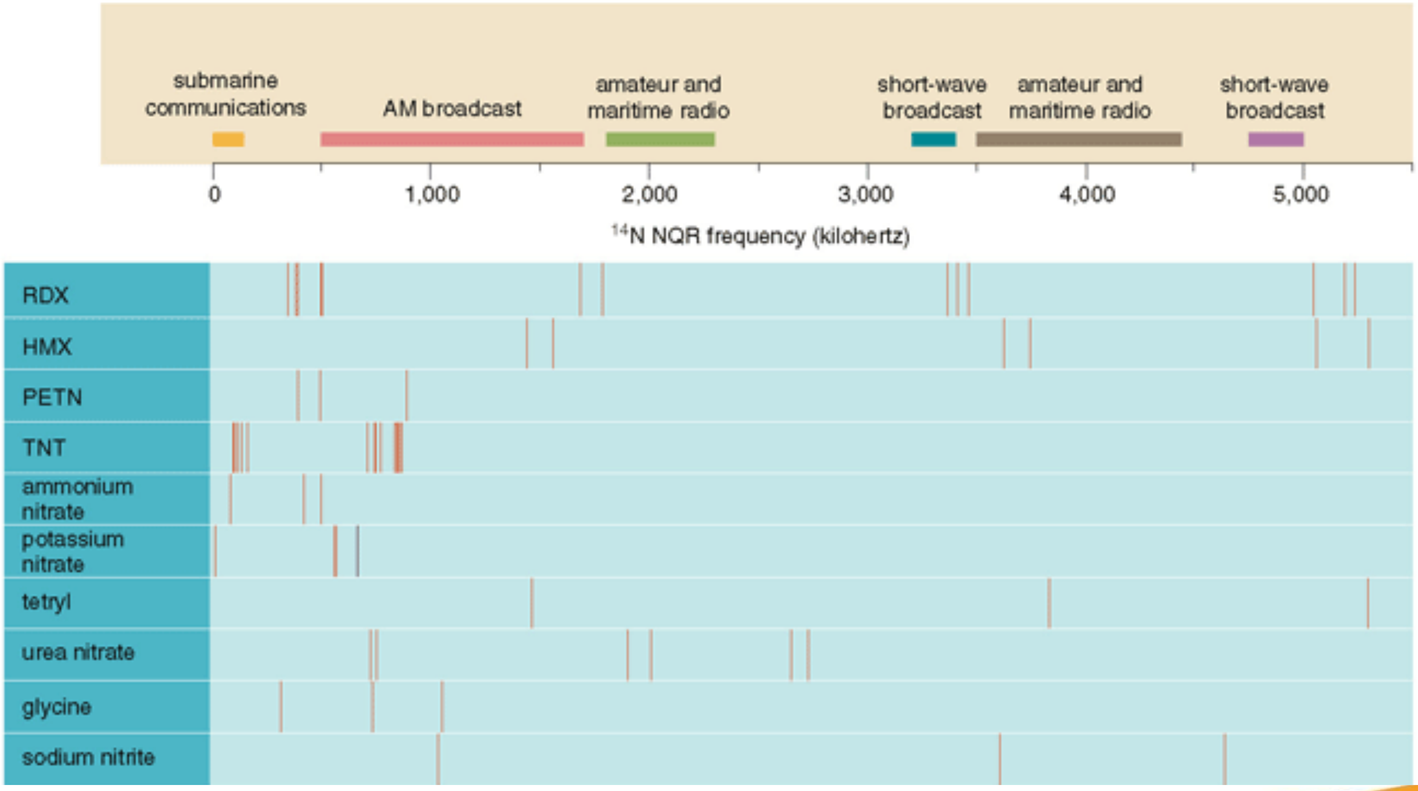




- Add-on to end of existing baggage scanners?

NQR for solid explosives detection

DARPA project: Non-contact detection of explosives at stand-off (~ 10cm) in high water content opaque media

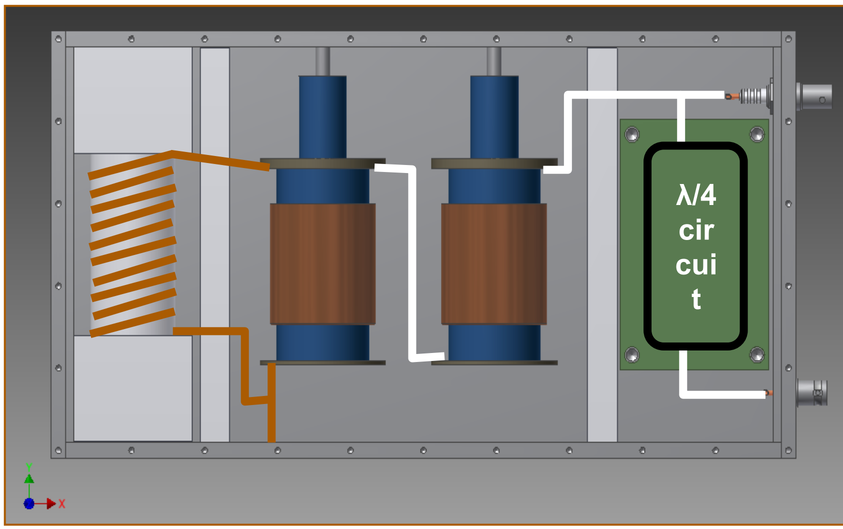


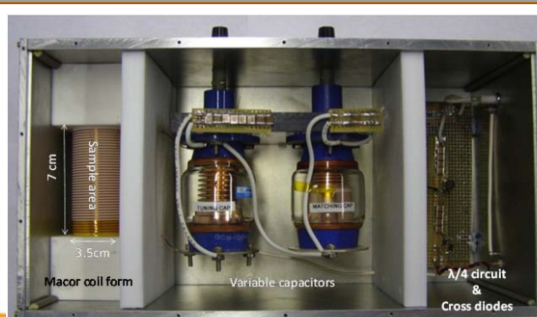
NQR capability development at LANL

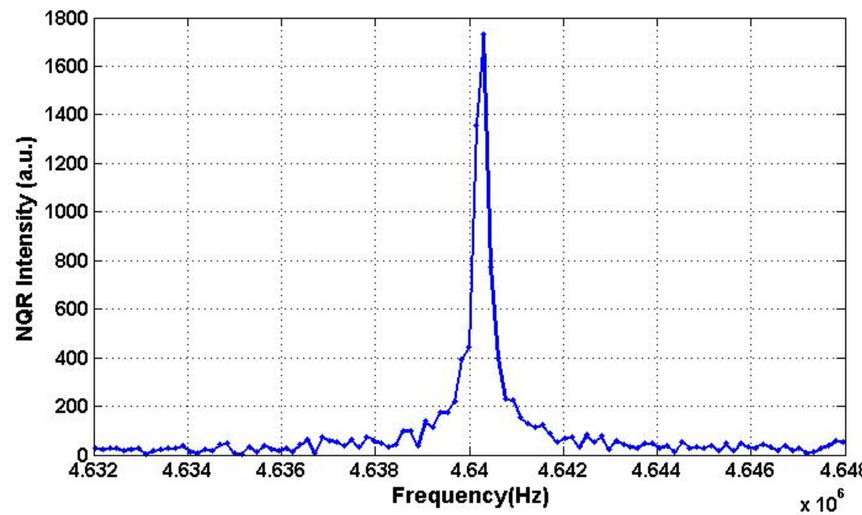
Performance test: NQR signal with $NaNO_2$

$$(\text{pseudo}\,180^0) - \tau - (\text{pseudo}\,90^0) - Acq$$

- Pulse duration of 1st and 2nd pulse = 185μs and 86μs, respectively. Power =250 W.
- Acquisition at 180μs after the second pulse.
- Sequence repeated **50** times (repetition time= 400ms).
- τ =300 ms



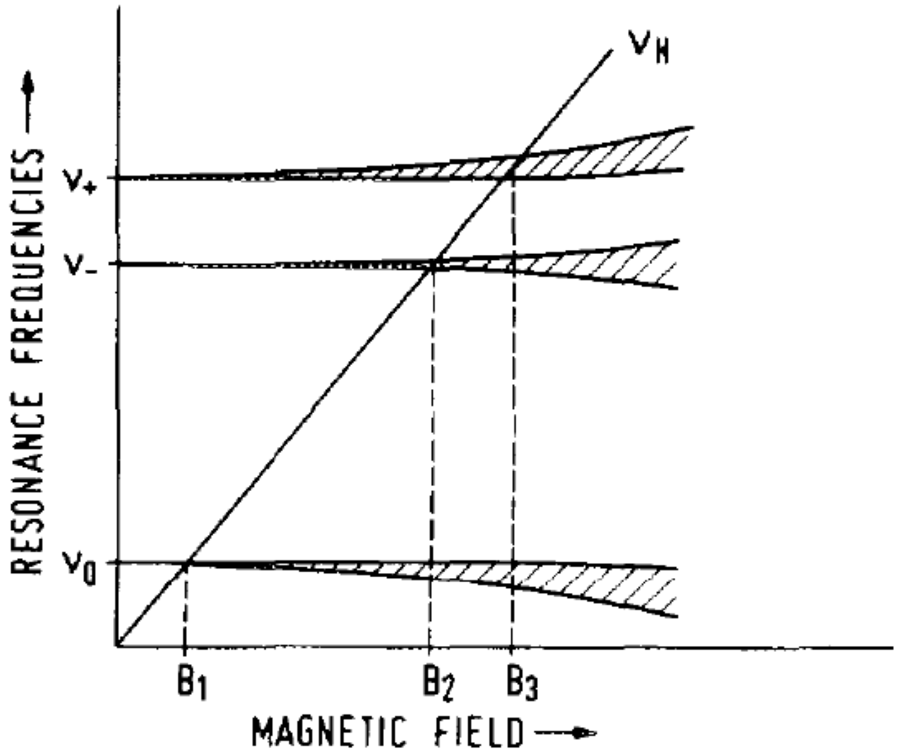




Polarization enhanced NQR

When spin 1 nucleus is near a spin ½ nucleus, double resonance may occur when the Larmor frequency of the spin ½ nucleus equals the NQR frequency of the spin 1 , the two spin populations can become linked.

- Sweeping an applied field through the overlap region of Larmor and NQR frequencies can transfer polarization to spin 1 nucleus, enhancing NQR signal.
- Because spin populations are mixed during the overlap, the relaxation rate of the spin ½ nuclei are typically altered
  - Measuring relaxation time vs. magnetic field can reveal NQR frequencies.

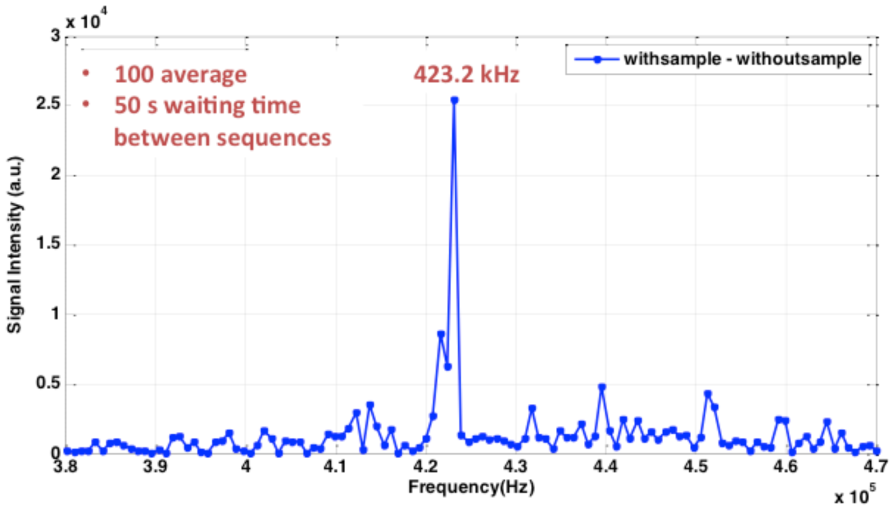


Plot showing conditions for double resonance.

Ammonium Nitrate: polarization enhancement helps significantly!

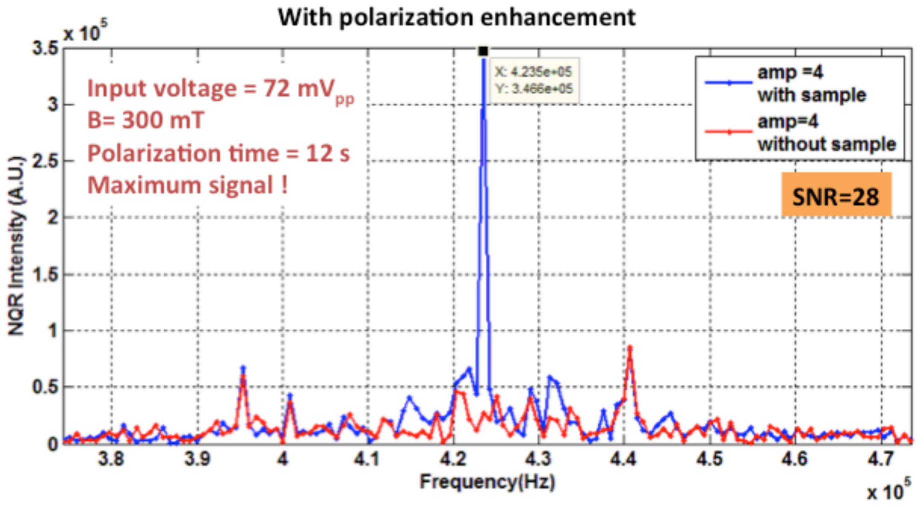
423 kHz: an order of magnitude lower SNR than $NaNO_2$

No PE: ~1.5 hour scan



With PE: ~15 second scan

Total measurement time = 2.3 s



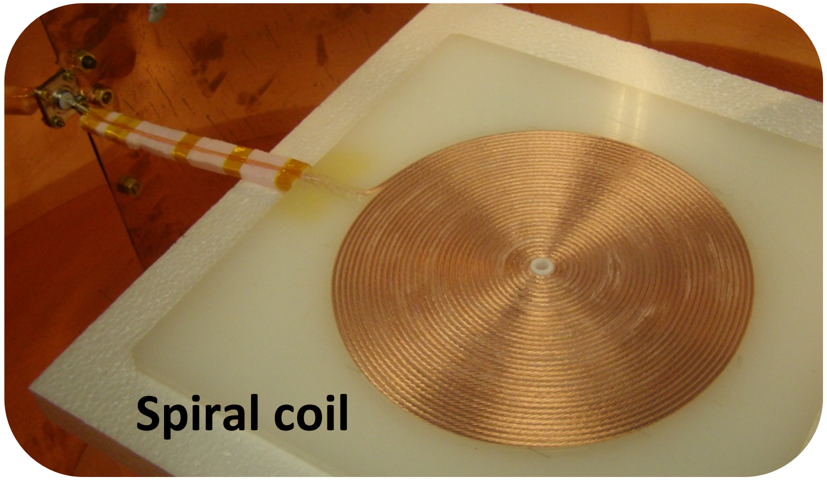
Implementing a practical geometry

4-Nitrotoluene (PNT) ($CH_3C_6H_4NO_2$):

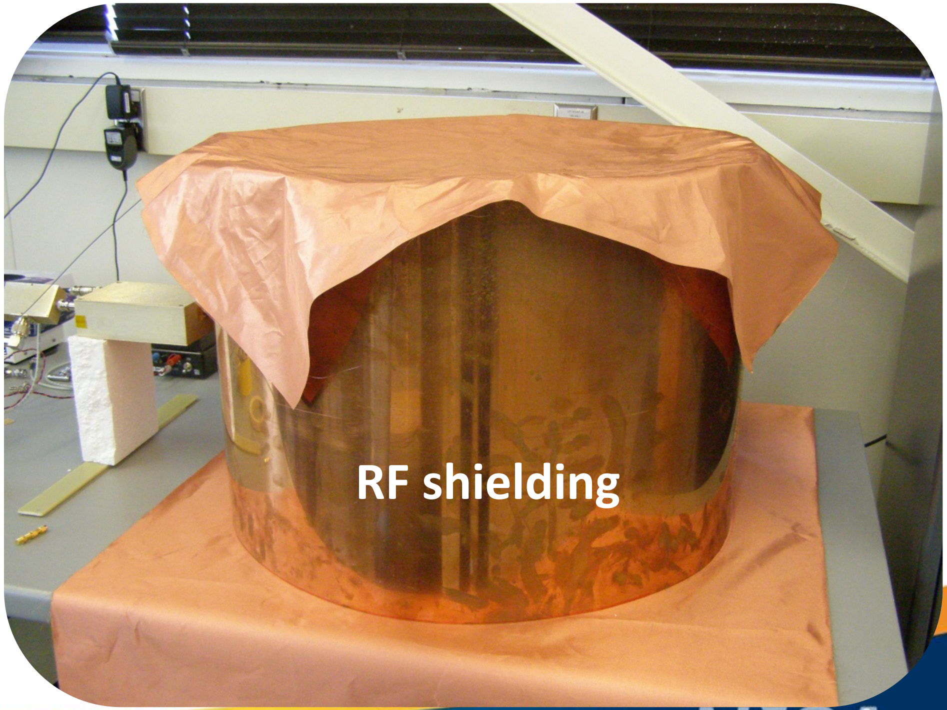
Molecular Weight 137.14, Density: 1.392 g/cc, $N = 6.1\times10^{21}$ 14N/cc

The NQR frequencies of PNT are : f_+ = 1.2 MHz and **f_- = 887 kHz (we used this transition frequency)**

- **Spiral coil has been made.**
- **Copper RF shielding houses the coil.**

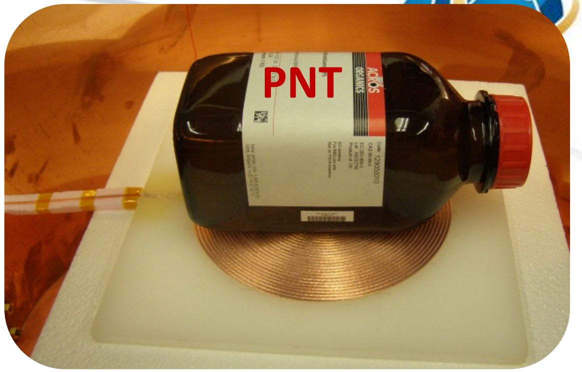


ID = 9.57 mm; OD = 178.11 mm
Number of turns = 34 turns; Wire gauge = 15 AWG
L ≈ 79 μH



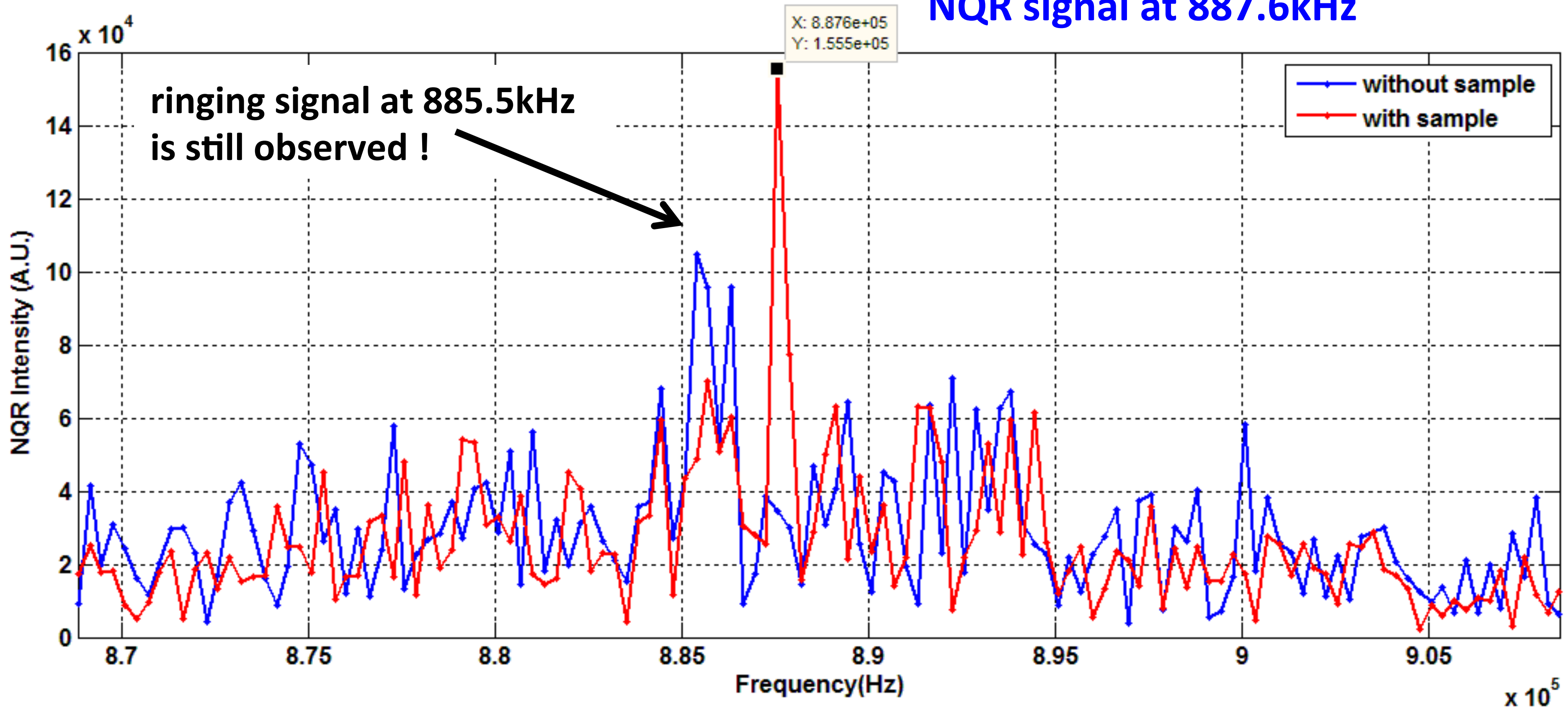
NQR signals from PNT

~6 sec scan, no PE



Pulse width ~ 100 μs, Current ~ 4.3 A_{peak}

NQR signal at 887.6kHz



Questions?

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