

# Low Field (10 mT) Pulsed Dynamic Nuclear Polarisation

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## INTRODUCTION

Dynamic Nuclear Polarisation (DNP) associated with standard MRI permits the detection of stable nitroxide free radicals in large animals (1-2). The majority of DNP experiments have been performed with continuous wave (CW) irradiation of the Electron Paramagnetic Resonance (EPR) transitions. Recently, pulsed DNP has been proposed (3) for spectroscopic studies at very high field (5 T).

## AIMS OF THIS STUDY

We present a pulsed DNP ( $\pi$ DNP) apparatus operating at very low field (10 mT) suitable for free radicals detection on large samples. Direct experimental evidence of the  $\pi$ DNP technique is shown with a triarylmethyl (TAM) single electron contrast agent. The main goal of this  $\pi$ DNP technique is to increase the signal-to-noise ratio and/or to decrease the average microwave power deposited in the sample.

## EXPERIMENTAL METHODS

**The paramagnetic sample.** To reduce the hardware constraints paramagnetic samples with relaxation times  $T_{1e} \approx T_{2e} \geq 1 \mu\text{s}$  are required. TAM is a water soluble paramagnetic probe with very narrow EPR line ( $\sim 14 \mu\text{T}$ ). The structure, synthesis, characterisation and use of TAM has been reported elsewhere (4-5). A small amount was obtained as a gift from Nycomed Innovation AB (Malmo, Sweden) for preliminary  $\pi$ DNP. A 1 mM de-oxygenated water solution of TAM (17 ml sample tube of dia. 23 mm) was used.

**RF Hardware.** The apparatus designed and tested for  $\pi$ DNP at 10 mT is composed as follows. A pulse generator (Lyon Instruments, model PG71) generates a TTL gating signal with width of 500 ns and variable period of 1  $\mu\text{s}$  to 20  $\mu\text{s}$ . A RF source (Gigatronics, model 610) provides the EPR pulses with maximum output of +17 dBm. A directional coupler (Mini Circuit, ZAD-10-1) inserted between the RF source and the power amplifier (Kalmus, 400 FC, bandwidth 1.5 MHz to 400 MHz, gain 50 dB, maximum power 60 W) permits to monitor the TX pulses via a high frequency oscilloscope (Philips, PM 3295A). The measured rise and fall times of the pulses were less than 10 ns. A home-built, high-power directional coupler was used for power calibration and monitoring of the TX and reflected RF pulses. The NMR hardware for the detection of the water proton signal at 10 mT is equipped with a 70 turns solenoidal transmit/receive coil tuned to 425 kHz (dia 7.5 cm, length 7 cm, cylindrical copper shield dia 20 cm and length 30 cm).

**EPR resonator.** A one-loop one-gap resonator (LGR) (6) (dia 38 mm, length 30 mm) tuned to 280 MHz and with quality factor  $Q_L \approx 173$  was used. The measured efficiency parameter,  $\Lambda$ , for the empty LGR was  $\Lambda \approx 13 \mu\text{T}/\text{W}^{1/2}$ . This efficiency factor value and RF power limitations restricted the use of RF pulses widths of 500 ns. The applied  $\pi$  pulse produces a decay of  $B_{1e}$  in the LGR with time constant  $\tau$  of about 160 ns for the empty LGR and about 110 ns with 11 ml of deionised water. Assuming that for  $\pi$ DNP experiments the resonator dead time is  $T_D \approx 5 \cdot \tau$ , the repetition time of the pulses should be longer than  $\sim 1 \mu\text{s}$ .

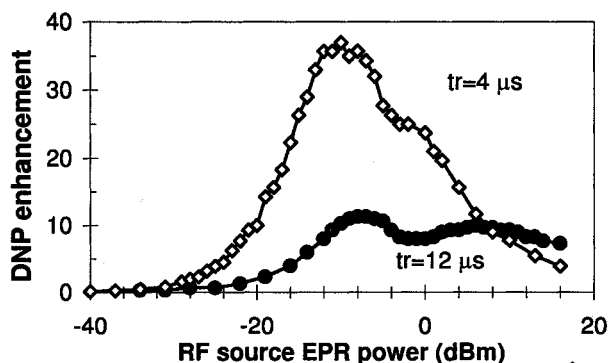
## RESULTS

$\pi$ DNP experiments were carried out using the 1 mM aqueous solution of TAM. The proton FID was acquired: (i) without EPR irradiation to obtain the reference signal; (ii) after a train of  $\pi$  pulses with EPR irradiation frequency 279.65 MHz, EPR power -8 dBm,  $T_{\text{EPR}} > 500$  ms,  $t_p = 500$  ns,  $t_r = 20 \mu\text{s}$ . The FID showed a

significant increase of the amplitude and the  $\pi$ DNP enhancement was about -6.

$\pi$ DNP experiments were performed with a wide range of EPR power (between -40 dBm and +17 dBm) using repetition times of 12  $\mu\text{s}$  and 4  $\mu\text{s}$ . The pulse width was maintained at a constant value of 500 ns. The FID amplitude was sensitive to the power level of the irradiating EPR pulses and the measured DNP enhancement is reported in Fig. 1. Using repetition times of 12  $\mu\text{s}$  it was found that: (i) the  $\pi$ DNP enhancement follows a steady increase from zero to about -8 for EPR power level up to -12 dBm; (ii) for higher power the enhancement shows an oscillating behaviour with a first maximum of -11 obtained at power of -8 dBm and a second maximum of -10 at power of +7 dBm. A similar behaviour was obtained with pulses of repetition time of 4  $\mu\text{s}$  and the measured maximum DNP enhancement was -35 at power of -8 dBm. These experimental results demonstrated that actually  $\pi$ DNP was being used and not merely discontinuous EPR irradiation.

The comparison of the enhancement between  $\pi$ DNP (repetition time of 4  $\mu\text{s}$ ) and CW DNP was made using the same average EPR power in the sample. The FID with CW irradiation ( $T_{\text{EPR}} > 500$  ms) was acquired at an EPR power of -19 dBm and the enhancement was  $A_{\text{CW}} \approx -65$ . With the present apparatus it was not possible to reduce the repetition time because of the dead time of the LGR (about 2  $\mu\text{s}$ ). Experimental methods to decrease the resonator dead time at low field have been recently proposed (7).



## CONCLUSIONS

An apparatus for pulsed DNP at 10 mT has been designed and tested. The enhanced FID of protons after a train of inverting EPR pulses has been detected by using a water soluble single electron contrast agent with a very narrow ( $\sim 14 \mu\text{T}$ ) EPR line. A maximum DNP enhancement of about -35 with inverting EPR pulses (repetition time 4  $\mu\text{s}$ , width 500 ns) was measured. The use of this  $\pi$ DNP technique makes it possible to reduce the average EPR power deposited in the sample with a modest loss of signal amplitude with respect to CW DNP. This should be particularly relevant for future applications of  $\pi$ DNP with large biological samples.

## REFERENCES

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