Chapter 3

Pulsed and Field Cycling NMR Relaxometry

NMR experiments can be carried out either in frequency domain or in time domain. In the early days of its development, continuous wave (CW) spectrometers were used to perform frequency domain experiments where one sees the frequency dependence of the real and imaginary parts of the susceptibilities either by sweeping rf frequency or the static field through the resonance. These were better suited for direct observation of static aspects of the microscopic environment. With the advent of pulsed rf techniques, time domain experiments were possible which readily focus on dynamic aspects as well. In a typical pulsed experiment one measures the time evolution of magnetization followed by an rf pulse. With the development of fast Fourier transform (FFT) algorithm, such a classification is only of academic interest, since the two outcomes of these two experiments are closely related by FT as

\[ f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)e^{-i\omega t} \, d\omega \quad (3.1) \]

\[ F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t)e^{i\omega t} \, dt \quad (3.2) \]

Hence the same spectral information can in principle be obtained from both the methods. However, the large majority of NMR experiments currently are best performed with pulse spectrometers owing to their advantages over the CW type. There are three principal advantages of pulsed over CW-swept excitation.

i. In the pulsed experiment nuclei within the frequency band width of the pulse are excited simultaneously so that the spectral information obtained per unit time is enhanced.

ii. As the signal detection takes place in the absence of rf excitation, NMR signal is free from oscillator noise, leading to an improvement of the signal-to-noise ratio.
ratio \( \frac{S}{N} \).

iii. The measurement of signal becomes easier as signal follows by a pulse which provides the phase coherence.

Despite these advantages, applications of pulse experiments are limited due to poor \( \frac{S}{N} \) as the signal strength weakens with the decrease in applied static field \( \frac{S}{N} \propto H_0^3 \) for proton typically about 4 MHz Larmor frequency. The significance of field-cycling technique emerges here. In this technique the nuclei are polarized at suitably high static fields and allowed to relax at the desired low field by switching the static field suddenly. The magnetization remaining after a delay time is detected again at a higher field, providing a good signal to noise ratio since the detection system operates under the favourable conditions of high enough frequency. The advent of fast field-cycling NMR (FFCNMR) technique practically leveled the low field limit of NMR experiments only limited by the earth’s field. Thus field-cycling relaxometry enables one to investigate the frequency dependence of NMR phenomena covering several decades of frequency with the same instrument. This feature makes it a most powerful tool for the study of molecular dynamics in complex systems. To cover Larmor frequencies ranging from 60 MHz to 10 kHz we augmented the commercial FFCNMR relaxometer (Spinmaster, Stelar, Italy) covering the range 10 kHz to 20 MHz, with a conventional field variable pulsed spectrometer (10 - 60 MHz).

This chapter provides briefly the principles and methodology of pulsed NMR measurements, including field cycling technique. This also gives certain technical details of the instruments useful to appreciate the results reported in this thesis.

### 3.1 Conventional Pulsed NMR Methodology

The equation of motion of the total nuclear magnetic moment \( \mathbf{M} \), in the presence of a magnetic field \( \mathbf{H} \) can be written, as (Abragam 1961, Slichter 1978)

\[
\frac{d\mathbf{M}}{dt} = \gamma (\mathbf{M} \times \mathbf{H}) \tag{3.3}
\]

In order to solve the equation readily, it is convenient to transform the reference to a rotating coordinate system. It can be shown that the time derivative of any time dependent vector \( \mathbf{M}(t) \), computed in the laboratory frame (say, \( \{x,y,z\} \)) is related to such a derivative computed from a rotating frame with an angular velocity \( \omega \), (say, \( \{x',y',z'\} \)) as

\[
\frac{d\mathbf{M}}{dt} = \frac{\delta \mathbf{M}}{\delta t} + (\omega \times \mathbf{M}) \tag{3.4}
\]
where \( \frac{\delta M}{\delta t} \) describe motion of \( M \) in the rotation coordinate system or in detail rate of change of \( M \) with respect to \( \{x',y',z'\} \) frame. Combining Eqns. 3.3 and 3.4 the equation of motion of \( M \) in the rotating frame can be written as

\[
\frac{\delta M}{\delta t} = \gamma M \times \left( H + \frac{\omega}{\gamma} \right)
\]  

(3.5)

Thus in the rotating frame the magnetic moment experiences an effective field which is the sum of the applied field \( H \) and a fictitious field \( \frac{\omega}{\gamma} \). Considering a special case appropriate to our experiments, where a dc magnetic field \( H_o \) is applied along \( z \)-direction and a rotating field \( H_1 \) around \( x \)-axis, the corresponding equation in a rotating frame, where \( H_1 \) appears stationary, is given by

\[
\frac{\delta M}{\delta t} = \gamma M \times \left( H_o + \frac{\omega}{\gamma} \right) k + H_1 i
\]

(3.6)

where \( i \) and \( k \) are the unit vectors along \( x' \) and \( z' \) axes, respectively, in the rotating frame. (Here \( x' \) axis in the rotating frame is chosen to be along \( H_1 \)). If \( H_1 \) is applied at Larmor frequency equation 3.6 becomes

\[
\frac{\delta M}{\delta t} = \gamma (M \times H_1)
\]

(3.7)

Thus at resonance, the effective field seen by the nuclear magnetic moment, from the frame where the applied rf field is stationary, is only due to \( H_1 \) and hence it precesses around \( H_1 \) with a frequency \( \omega_1 = \gamma H_1 \). Then the angle, through which \( M \) precesses in a time \( t \) is

\[
\theta = \gamma H_1 t
\]

(3.8)

If the rf pulse is applied for a chosen time so that \( \theta = \frac{\pi}{2} \), then the pulse is called \( \frac{\pi}{2} \) pulse. Similarly, if the pulse width is long enough to rotate the magnetization by an angle \( \pi \) (i.e. to flip the total magnetization into \(-z\) direction), then the pulse is called \( \pi \) pulse. The total magnetization, thus flipped into transverse plane by a \( \frac{\pi}{2} \) pulse is stationary in the rotating frame. But, because of the spin-spin interaction there is a spread \( (\Delta H) \) in the net magnetic field experienced by the individual magnetic moments. This results in a spread in the Larmor frequencies \( (\Delta \omega = \gamma \Delta H) \) of individual magnetic moments and they start dephasing resulting in the decay of the net magnetic moment as observed from the \( x'-y' \) plane. An rf pick-up coil, in the laboratory frame, outputs an oscillatory emf at the Larmor frequency corresponding to the net magnetization. After rf detection, the envelope of this signal is a decaying curve (Free induction decay, FID), with a time constant of \( T_2 \) (spin-spin relaxation time). But in practice, there are two contributions to the spread in the Larmor frequency:
the first due to the spin-spin interaction and the second due to the inhomogeneity in
the applied magnetic field. Hence one always finds that the FID decays with a time
constant $T_2^*$ which is shorter than $T_2$.

3.2 Measurement of Relaxation Times

To measure various relaxation times ($T_1$ and $T_2$), different pulse sequences, corre-
sponding to the different initial non-equilibrium conditions required to be created,
are necessary. The details of such pulse sequences used in the present studies are
given below.

3.2.1 $T_1$ Measurements

3.2.1.1 Saturation Recovery Sequence ($\frac{\pi}{2} - \tau - \frac{\pi}{2}$)

In this sequence the first $\frac{\pi}{2}$ pulse makes the magnetization, in the z-direction, zero.
The magnetization, developed after a time $\tau$ is again sampled by another $\frac{\pi}{2}$ pulse
(Farrar and Becker 1971, Fakushima and Roeder 1981). Magnetization recovery after
the first $\frac{\pi}{2}$ pulse is described by

$$M_z(t) = M_o \left[1 - \exp\left(-\frac{t}{T_1}\right)\right]$$  \hspace{1cm} (3.9)

The amplitude, $A(t)$ of the FID observed after the second $\frac{\pi}{2}$ pulse applied after a time
$\tau$ (see Fig. 3.1), is representatative of the instantaneous $M_z$ component developed till
that instant as a result of spin-lattice relaxation process. The time evolution of this
FID amplitude is thus provided by the above equation. (Eqn.3.9), and hence $T_1$ value
can be computed.

![Figure 3.1: Saturation recovery sequence](image-url)
3.2. Measurement of Relaxation Times

3.2.1.2 Inversion Recovery Sequence \((\pi - \tau - \frac{\pi}{2})\)

This sequence is also used for \(T_1\) measurements. The first \(\pi\) pulse flips the magnetization to -z direction, which is allowed to evolve for a time \(\tau\) and then sampled by another \(\frac{\pi}{2}\) pulse. (Farrar and Becker 1971, Fakushima and Roeder 1981). The amplitude of the FID, \(A(t)\), after this sampling pulse, representing the instantaneous \(\mathbf{M}-z\) component, increases from a negative value to its equilibrium value covering the zero value in the process. The detected amplitude of the FID evolves as

\[
A(t) = A(\infty) \left[ 1 - \exp \left( -\frac{t}{T_1} \right) \right]
\]

as shown in the Fig. 3.2. Using this sequence, it is convenient to make a rough estimation of the \(T_1\) value by observing the zero crossing point.

![Inversion recovery sequence](image)

Figure 3.2: Inversion recovery sequence

The advantage of this sequence compared to the saturation recovery sequence is the apparent increase in the signal to noise ratio. The total variation of the magnetization is \(M_o\) in the saturation recovery sequence whereas it is \(2M_o\) in the inversion recovery sequence. But this sequence assumes that before the first pulse (preparation pulse) is applied the spin system is completely in equilibrium and hence the magnetization is \(M_o\) along z-direction. So before repeating the sequence, it is necessary to wait until complete equilibrium is achieved, usually for a period of about \(5T_1\). This will become very time consuming if \(T_1\) is more than few hundreds of ms. Saturation recovery sequence does not have this problem since the preparation pulse only has to make the magnetization in the z-direction zero and it does not matter what the magnetization is before this pulse. One disadvantage of these two sequences is that, if the preparation pulse width is not exactly \((\pi\) or \(\frac{\pi}{2}\)) the initial conditions of the magnetization \((-M_0\) or zero, respectively) are not met.
3.2.1.3 Saturation Burst Sequence

This sequence employs a number of $\frac{\pi}{2}$ pulses (say, $n$) (usually $5 < n < 10$) followed by a sampling ($\frac{\pi}{2}$) pulse. The spacing between two $\frac{\pi}{2}$ pulses in the burst ($\tau$) is so chosen that the $T_2$ process is complete but $T_1$ process has not effectively taken place (i.e. $T_2 < \tau \ll T_1$). This burst generates zero magnetization in the x-y plane even if the pulses slightly deviate from $\frac{\pi}{2}$ and even if $H_1$ is slightly inhomogeneous. The magnetization recovery again satisfies Eqn. 3.9 and $T_1$ can be calculated as explained above. Since the FID amplitude is measured after saturating the spin system, it is not necessary to wait till the spins completely relax to equilibrium, before the next sequence is applied. The sequence can be repeated immediately after recording the FID amplitude. In fact, in an actual experiment, the first pulse in the next burst can be used as the sampling pulse. The recovery of the magnetization, in this experiment, is shown in Fig. 3.3.

$$\pi /2 \quad \ldots \ldots \pi /2 \quad \tau \quad \pi /2$$

![Saturation burst sequence](image)

Figure 3.3: Saturation burst sequence

3.2.2 $T_2$ Measurements

3.2.2.1 Spin-Echo Method

Due to the spatial inhomogeneity in the applied dc field, the time constant associated with the FID decay ($T_2^*$) is shorter than $T_2$ and hence the FID after a single $\frac{\pi}{2}$ pulse can not be used to measure $T_2$. Instead, the spin echo method with a $\frac{\pi}{2} - \tau - \pi$ sequence (Hahn 1950) is used. The effect of this pulse sequence on the spin system is shown in Fig. 3.4, which can be understood as follows. The first $\frac{\pi}{2}$ pulse puts the magnetization in the transverse plane (say along $x'$-axis, if the pulse is applied along $y'$-axis). The magnetization starts de-phasing due to the spread in the Larmor frequencies. Next $\pi$ -pulse (along the same $y'$-axis) at time $\tau$ inverts all individual magnetic moments (to lie along -$x'$ axis) thereby inverting the sequence of dephasing
as shown in Fig. 3.4.

Therefore the spins refocus again after the time interval $\tau$ from the $\pi$ pulse forming an echo. If the $\pi$ pulse can invert the direction of the dephasing of all spins then the echo will have the same magnitude as that of the FID. This means that the phase relations among these spins have not changed during the time $2\tau$. But these phase relations may change for some spins during the time $2\tau$ (e.g., if the dephasing is due to time varying local fields) and such spins do not coalesce with the other spins and so their contribution to spin echo will be missing. Thus any process which causes individual spins dephase in a irreversible manner will reduce the amplitude of the echo, and one obvious example of such process is spin-flip due to spin-spin interaction. Thus by measuring the amplitude of the echo as a function of $\tau$ one can measure $T_2$ since the spin echo amplitude decreases as $\exp\left(-\frac{\tau}{T_2}\right)$.

### 3.2.2.2 Carr Purcell Sequence

If there is a rapid diffusion in the inhomogeneous magnetic field, the spin echo amplitude is further reduced (Slichter 1978) and the above sequence is not useful for measuring $T_2$. A sequence suggested by Carr and Purcell (1964) is well suited in such cases. This sequence consists of a $\pi/2$ pulse followed by a series of $\pi$ pulses at $t$, 

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**Figure 3.4: Spin-Echo Sequence**

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3t, 5t etc. The spin echoes arising out of this sequence is shown in Fig.3.5. It can be shown (Ailion 1983)

\[ \frac{\pi}{2}, \pi, \pi, \pi \]

Figure 3.5: CPMG Pulse sequence.

that this sequence makes the contribution of diffusion due to the field inhomogeneity negligible. In this sequence error in setting the width of pulse does lead to some error in \( T_2 \) but this can be rectified by the insertion of a 90° phase shift between the \( \frac{\pi}{2} \) pulse and successive \( \pi \) pulses, as suggested by Meiboom and Gill (1958).

3.3 Fast Field-Cycling NMR (FFCNMR) Methodology

Molecular processes in complex fluids, for example the collective motions in liquid crystals are very slow in nature. Typical range of such motional frequencies fall in sub MHz to kHz regime. At such low frequencies conventional pulsed NMR methods are technically impracticable or even impossible. The difficulties are primarily due to the related well-known weakening of the NMR induction signal, which goes approximately as \( H_o^{3/2} \). In this context field-cycling (FC) technique is very effective and overcomes this limit extending the scope of field dependent measurements to very low Larmor frequencies while still allowing the convenience of high field signal detection. Thus field-cycling NMR (FCNMR) complements and enables one to extend investigations of molecular processes over a wide band width spacing several decades, in conjunction with conventional pulsed NMR technique.
3.3.1 FC Principle

In a FC experiment sample generally undergoes three evolution phases namely polarization period (P), evolution or relaxation period (E) and detection period (D). Fig. 3.6 illustrates these three periods. The cycle starts with $\tau$ where samples are polarized at relatively high fields ($B_{oP}$) and allowed to relax at a lower field ($B_{oE}$). The remaining magnetization after pre-defined delay is detected at a higher field $B_{acq}$. The field switching rate must be large enough to avoid excessive relaxation losses of the magnetization during the switching process and also it should be slow enough to permit adiabatic field changes in case the relaxation field is perceptibly superimposed by local fields (of arbitrary directions other than that of the polarizing field). For this purpose in early FC experiments sample shuttling technique was used. In this, the sample under study is shuttled fast from $B_{oP}$ to $B_{oE}$ and further to $B_{acq}$ mechanically normally pneumatically. Even though this mechanical field-cycling is very simple, it has considerable drawbacks.

![Typical field cycle](image)

Figure 3.6: Typical field cycle, with polarization, evolution and detection periods separated by the transit intervals $t_{ON}$ and $t_{OFF}$

The switching is relatively slow and cannot be applied if the $T_1$ is shorter than 100 ms. In addition, reliable temperature control seems to be almost impossible. In these circumstances the electronic field switching emerged, where the magnetic field cycling takes place by controlling the electrical current through the magnet coil fast compare to the relaxation times. In this technique field switching takes place within 3 ms or even less. For this reason it is often called fast field-cycling (FFC) NMR technique. For achieving this fast switching, one uses energy storage principle discussed in detailed in a review article (Noack 1986, Kimmich and Anardo 2004)
3.3. Fast Field-Cycling NMR (FFCNMR) Methodology

Figure 3.7: Field cycle for low relaxation fields (pre-polarization).

Figure 3.8: Field cycle for high relaxation fields (non-polarization). Shaded part shows the variable relaxation interval. Vertical arrow indicates the time when signal is detected. The 'down' and 'up' field switching times are indicated by the intervals (dt)d and (dt)u respectively. (Kimmich 2004).

3.3.2 \(T_1\) measurements using FCNMR

On FCNMR instrument \(T_1\) measurements are made using two standard protocols: pre-polarized sequence and non-polarized sequence. Pre-polarized sequence is used for operation with below the magnetic fields corresponding to 4 MHz of proton Larmor frequency while non-polarized sequence is used for operating at Larmor frequencies equal to or above 4 MHz. The two pulse sequences are shown in Figs. 3.7 and 3.8. In a pre-polarized sequence nuclei are polarized at sufficiently high field \(B_{oP}\)
3.4 The NMR Spectrometer

The NMR spectrometer broadly consists of three units (i) transmitter (ii) matching network or probe and (iii) receiver. The block diagram of the experimental setup used in the field variable pulsed NMR spectrometer is given in Fig. 3.9. The transmitter generates appropriate pulsed rf radiation, amplifies and delivers it to the matching network (probe). The probe consists of passive elements including the sample coil. The receiver picks up the weak signal from the NMR coil and amplifies it in stages. This amplified signal is detected by the phase sensitive detector and processed through a low pass filter and a video amplifier. Finally a signal averager is used to improve the $S/N$.

![Figure 3.9: Block diagram of NMR set up](image)

Here we employed an automated NMR hardware, (Spinmaster from Stelar, Italy) to take care of all rf operations. Spinmaster encapsulates transmitter and receiver
3.4. The NMR Spectrometer

parts of the NMR spectrometer into a single console. It consists of RF and Digital unit, power supply and variable temperature controller. The variable magnetic field in this instrument is generated by a commercial magnet (Bruker make, model Bruker B-E 25), with a variable pole gap. The pole pieces are 12” in diameter providing a good spatial homogeneity. The time stability of the field is better than one point in $10^6$. The magnet is cooled by circulating chilled water under pressure. The probe assembly was supplied by Bruker covering the range of 4 - 90 MHz. The temperature is controlled by a home-built facility with an estimated stability of within ±0.1°C. Block diagram of the setup of Stelar’s fast field-cycling NMR relaxometer is shown in Fig. 3.10. Details of these instruments are briefly prosecuted below.

3.4.1 RF and Digital Unit

The latest generation of direct digital synthesizers (DDS), programmable logic and fast A/D and D/A converters are implemented in the RF electronics of Spinmaster. The unit operates in the 2.2 to 80 MHz band and all pertinent settings are under digital control. The RF and digital unit further consists of

1. Direct digital synthesizer (DDS) rf unit
2. RF power transmitter
3. RF receiver unit
4. Acquisition Manager (AQM)

The direct digital synthesizer (DDS) rf unit consists of (i) clock generator (ii) a digital synthesizer with its control circuitry and (iii) an rf modulator. The clock generator sends a sinusoidal reference signal at 80 MHz as output. This clock output is divided by a factor of 2 and the resultant 40 MHz clock output is available for Acquisition Manager. The DDS controller is used to control the system frequency and phase difference between two channels. RF and pulse modulator produce the pulsed rf output which is to be fed to the transmitter. The level of this pulsed RF output can be varied from 0.25 V to 2.5 V. The rf power transmitter of Spinmaster delivers up to 300 W in the pulse mode. The maximum power level can be adjusted through the Acq NMR software. The receiver amplifies the emf induced by the nuclear magnetization from its initial level (of order microvolt) to the level required for data handling and display (of order volts). In the process, the nuclear signal is demodulated (i.e., the rf frequency removed) by an appropriate detector (normally a phase-sensitive detector).
The receiver is capable of withstanding overloaded voltages and also recovers fast from these overload voltages (due to leakages during pulse ON periods). This is a quadrature receiver with an additional diode detection channel and programmable amplifier filters. Acquisition manager (AQM) is the heart of the Spinmaster. It is connected to a standard PC parallel port which transmits logical commands called interface primitives. It has an inbuilt CPU (Z180) which decodes the instructions into a set of commands to be sent to the hardware interface at planned time intervals. Furthermore, this CPU, reports the current status of the hardware and of the experiment to the PC, programs the hard ware units through a proprietary parallel, bi-directional 8-bit bus (Stelar bus) and sends the acquired data to the host PC. At boot time, the Z180 executes a configuration routine and establishes communication with the PC. In practice, the time-critical instructions are executed by the pulser, which are loaded by the Z180. The host may stop/start the Z180 and the flow of instructions under its control, but the AQM executes the instructions related to configuration and sequence independently.

### 3.4.2 Probe

The probe or the matching network which houses the sample coil plays an important role in the performance of the spectrometer. An ideal probe must effectively couple the sample coil to the transmitter during pulse ON time and to the receiver during pulse OFF time for signal detection. It should also decouple the receiver from the transmitter during the pulse ON period. For the present experiments we used a single-coil probe. The single-coil probe arrangement is simpler and has many advantages and some disadvantages with respect to the crossed-coil probe. Probably the main advantage of the single-coil is its much high power efficiency since the coil can be tightly wound around the sample, in contrast to the crossed-coil probe in which the transmitter coil must be considerably larger and adjusted for minimum coupling to the receiver coil. Probe is tuned to desired frequency by adjusting tuning and matching capacitors. If the probe is not properly tuned and/or matched, rf power is not optimally transferred, thus lengthening the 90 pulse width and worsening signal to noise. Tuning a probe is obviously necessary when a different nucleus is to be observed. Not so obviously, it is often necessary after changing the sample. This is due to the sample’s rf-properties. To tune a probe, directional coupler is used as an impedance sensor. The output is displayed on a dip meter.
3.5 Specifications of Pulsed NMR Spectrometer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency range</td>
<td>3.5 MHz to 60 MHz</td>
</tr>
<tr>
<td>Field stability</td>
<td>1 in $10^6$</td>
</tr>
<tr>
<td>Field homogeneity</td>
<td>1 in $10^{-6}$</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 MHz at a given frequency</td>
</tr>
<tr>
<td>Pulsed rf power</td>
<td>up to 300 W</td>
</tr>
<tr>
<td>ON/OFF ratio of the gated pulse</td>
<td>100 dB modulator</td>
</tr>
<tr>
<td>Typical $\frac{\pi}{2}$ pulse width</td>
<td>2-4 $\mu$s for proton</td>
</tr>
<tr>
<td>Pulse sequence used</td>
<td>Inversion recovery, Saturation burst</td>
</tr>
<tr>
<td>Method of detection</td>
<td>Single coil parallel resonance type</td>
</tr>
<tr>
<td>Transmitter isolation</td>
<td>60 dB minimum</td>
</tr>
<tr>
<td>Recovery time</td>
<td>15 $\mu$s</td>
</tr>
<tr>
<td>rf gain of the receiver</td>
<td>typically 80 dB, adjustable over a range of 40 dB</td>
</tr>
<tr>
<td>Temperature range</td>
<td>25°C to 120°C (with 0.2 °C stability over one hour)</td>
</tr>
</tbody>
</table>

Table 3.1: Specifications of pulsed NMR spectrometer
### 3.6 Specifications of FFCNMR Relaxometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>Aluminum air coil system</td>
</tr>
<tr>
<td>Maximum operating frequency</td>
<td>21 MHz</td>
</tr>
<tr>
<td>Field switching time</td>
<td>$&lt; 0.15$ ms/MHz</td>
</tr>
<tr>
<td>Field stability</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>Field homogeneity</td>
<td>$1 \times 10^4$ over 1 cm$^3$</td>
</tr>
<tr>
<td>Bandwidth of the rf spectrometer</td>
<td>2 MHz</td>
</tr>
<tr>
<td>Pulsed rf power</td>
<td>up to 300 W</td>
</tr>
<tr>
<td>ON/OFF ratio of the gated pulse</td>
<td>100 dB modulator</td>
</tr>
<tr>
<td>Typical $\frac{\pi}{2}$ pulse width</td>
<td>5-10 $\mu$s for proton</td>
</tr>
<tr>
<td>Method of detection</td>
<td>Single coil parallel resonance type</td>
</tr>
<tr>
<td>Transmitter isolation</td>
<td>60 dB minimum</td>
</tr>
<tr>
<td>Recovery time</td>
<td>20 $\mu$s</td>
</tr>
<tr>
<td>Interface bus with PC</td>
<td>LPT</td>
</tr>
<tr>
<td>rf gain of the receiver</td>
<td>typically 80 dB, adjustable over a range of 40 dB</td>
</tr>
<tr>
<td>Temperature controller</td>
<td>Gas flow type PID, VTC90 (Stelar made)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-140°C to 140°C, with 0.1°C stability over a day</td>
</tr>
</tbody>
</table>

Table 3.2: Specifications of FFCNMR relaxometer