Introducing the Next Generation Metrolab Magnetic Field Camera, the MFC2046

Contents

1. MFC2046 description

The MFC2046 Main Unit comprises an NMR Precision Teslameter PT2026 with the Camera firmware option, a Field Camera Amplifier FCA7046, a 3026-10M Cable, and the MFCTool software. In addition, you will need to plug in a probe array MFC9046. The model of the MFC9046 depends on the geometry and the field strength of your MRI magnet.

In a move towards greater efficiency and convenience, the MFC2046 integrates the PT2026 for single probe use, effectively replacing both the MFC3045 and the PT2025. This seamless integration streamlines workflow processes, allowing researchers to focus more on their experiments and less on instrument management.

1.1. Enhanced Precision and Accuracy

The MFC2046 sets a new standard for precision and accuracy in NMR analysis, boasting an impressive **accuracy of 1 part per million** (ppm) compared to the 5-ppm accuracy of its predecessor. This fivefold improvement ensures that researchers can rely on the MFC2046 to deliver consistently precise results, which is essential for the most demanding research applications.

1.2. Enhanced versatility: single-point as well as mapping

The MFC2046 offers the flexibility to accept either NMR Probe-Arrays MFC9046 or single-point NMR probes 1326, 1426 or 1526 models. This unprecedented versatility means that your manufacturing and service personnel now only require one instrument for field mapping or single-point measurements. The latter option provides update rates of up to 33 Hz, enabling the real-time detection of low-frequency magnetic noise.

The MFC2046 offers versatility in analysis, allowing for single-mode operation either by utilizing a single probe or by connecting to one of the probes within the MFC9046 probe array. Users can seamlessly operate the PT2026 software, capitalizing on its full suite of analytical capabilities. This capability is particularly advantageous in research and development environments and manufacturing settings where understanding complex situations is crucial for issue resolution.

2. Enabling Insights into the characteristics of the magnetic field

The Free Induction Decay (FID) and Fast Fourier Transform (FFT) are crucial pulsed mode NMR magnetometry components that provide unique insights into the magnetic field characteristics. These aspects cannot be acquired in frequency sweep NMR magnetometry. Here's how they contribute:

2.1. Free Induction Decay (FID):

In pulsed mode NMR magnetometry, after applying an RF pulse, the nuclear spins in the sample are tipped in the transverse plane. As they precess while returning to their equilibrium state, they induce a decaying signal in the detector coil called the Free Induction Decay (FID).

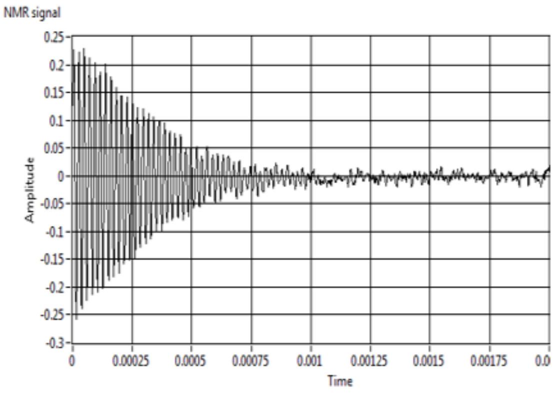
The FID contains information about the frequencies present in the NMR signal and the relaxation processes occurring in the sample. The decay rate of the FID is related to the T2* relaxation time of the sample.

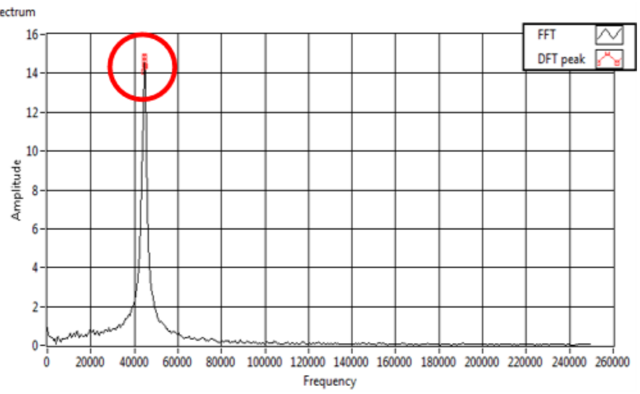
2.2. Fast Fourier Transform (FFT):

The FID is a time-domain signal, but to interpret the frequencies present in the signal, it is converted into the frequency domain using the Fast Fourier Transform (FFT).

The FFT decomposes the time-domain FID signal into its constituent frequencies, revealing the NMR peaks. Each peak in the spectrum corresponds to a specific resonance frequency, which depends on the local magnetic field strength for a given nucleus.

A significant advancement in the MFC2046 is its incorporation of pulsed NMR technology, which enables the analysis of Free Induction Decay (FID) signals. This feature, not present in the previous generation MFC3045 with its legacy frequency sweep magnetometry technology, is pivotal for cutting-edge research and development projects.





2.3. Calculations of T2* and determining field inhomogeneity

The T2* relaxation time characterizes the decay of the transverse magnetization. The decay rate is directly related to the inhomogeneity of the magnetic field. Only Pulsed NMR enables the acquisition of the T2* relaxation time.

The PT2026, hence the MFC2046 follows these steps:

Acquisition: The PT2026 applies an RF pulse to the probe to excite the nuclear spins, followed by monitoring the decay of the transverse magnetization signal.

Fitting Decay Curve: Fit the decay curve of the transverse magnetization to an exponential decay function. The decay time constant obtained from this fit corresponds to the T2* relaxation time. T2* is composed of the sample decaying constant T2 and the inhomogeneity of the field T2' through the relation:

$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T2'}$$

The inhomogeneous time constant T2' is related to the magnetic field inhomogeneity (ΔB) by the formula:

$$T2' = 1/(\gamma \cdot \Delta B)$$

where γ (gamma) is the gyromagnetic ratio, which is a fundamental constant specific to the nucleus being studied.

Solve for Inhomogeneity: Rearrange the equation to solve for the magnetic field inhomogeneity (ΔB):

$$\Delta B = 1/(\gamma \cdot T2')$$

Plug in the value of γ for the specific nucleus being studied (e.g., for protons, γ ≈ 42.58 MHz/T) and the measured T2* value to calculate the magnetic field inhomogeneity.

Interpretation: The calculated magnetic field inhomogeneity represents the spatial variations in the static magnetic field (B0) experienced by the sample. Higher values indicate greater field inhomogeneity, which can arise from factors such as magnetic susceptibility variations in the sample or imperfections in the magnet. An increase of magnetic field gradient will result in a faster decay of the time-domain signal which will translate into a widening of the frequency-domain peak resonance.

By analyzing the T2* relaxation time, you can quantitatively assess the magnetic field inhomogeneity, which is crucial for various NMR applications such as imaging and spectroscopy.

3. Enhanced Probe Range and Versatility

The MFC2046 excels in mapping magnetic fields ranging from 0.2 T to 30 T (1.1 GHz), a significant advancement compared to the legacy system MFC3045, which was limited to 7 T.

An outstanding feature of the probe arrays MFC9046 is their expanded probe range, offering a remarkable ±3% range of the nominal field (ranging from 2.91 T to 3.09 T for a 3.0 T nominal field probe array), as opposed to the 1% range provided by the MFC3045. This extended range not only facilitates more flexible measurements but also opens up new avenues for diverse applications, such as field decay analysis.

Moreover, the MFC2046 introduces the option of including a 3-fold wide-range probe in the center of the probe array (ranging from 1.0 T to 3.0 T for a 3.0 T nominal field probe array), offering researchers even greater flexibility in experimental design and sample analysis. This innovation allows for direct monitoring of the magnet's ramp-up process using the probe array, enhancing experimental control and accuracy.

4. Optimizing Normalization: Ensuring Precision in Magnetic Field Camera Readouts

Enhancing its performance, the MFC2046 incorporates advancements in component selection within the probe arrays. These enhancements minimize susceptibility and improve homogeneity, resulting in more consistent normalization of probe arrays. This ensures dependable and reproducible outcomes across experiments.

Normalization is a pivotal procedure in magnetic field camera (MFC) operations, compensating for the susceptibility effects of materials surrounding the probes. The legacy MFC3048 and the new MFC9046 can compensate for each probe, yielding a signal readout within a mere ±0.2 parts per million (ppm) from the nominal field value. However, the introduction of the MFC9046 marks a new era of precision and performance in normalization.

With advancements in component selection, geometry optimization, and overall performance, the MFC9046 achieves a remarkable level of tightness in the distribution of compensated values compared to its predecessor. This tighter distribution ensures greater uniformity and reliability in normalization across probe arrays, enhancing precision and consistency in magnetic field measurements.

Probe array type	MFC9046-3T	MFC3048-3T	MFC9046-1.5T	MFC3048-1.5T
AVG StdDev	8.23E-03	1.43E-02	1.03E-02	1.52E-02

Table 1: Averages of the variation of the deviation from the nominal field for the data displayed in figures 1 to 4.

Data obtained from figures 1 to 4 has been acquired during the normalization process of probe arrays manufactured according to Philips Medical Systems specifications. These arrays consist of 24 points over an elliptical probe array measuring 225 mm by 250 mm, operating at fields of 1.5 T and

3.0 T for both MFC9046 and legacy MFC3048 probe arrays. During each instance, operators adhered to the normalization procedure developed by Metrolab technology, employing an averaging parameter of 5 for the MFC9046 and 70 for the MFC3048. The values presented represent the deviation between the corrected magnetic field readout of each probe and the average magnetic field in parts per million (ppm). Each probe reading undergoes correction during the normalization process to mitigate the impact of susceptibility in the proximity of the probe.

To illustrate this improvement, four graphs depicting the normalization performance of individual probes at two different field values will be presented. These visual representations will demonstrate the superior normalization capabilities of the MFC9046, reinforcing its status as the pinnacle of magnetic field camera technology.

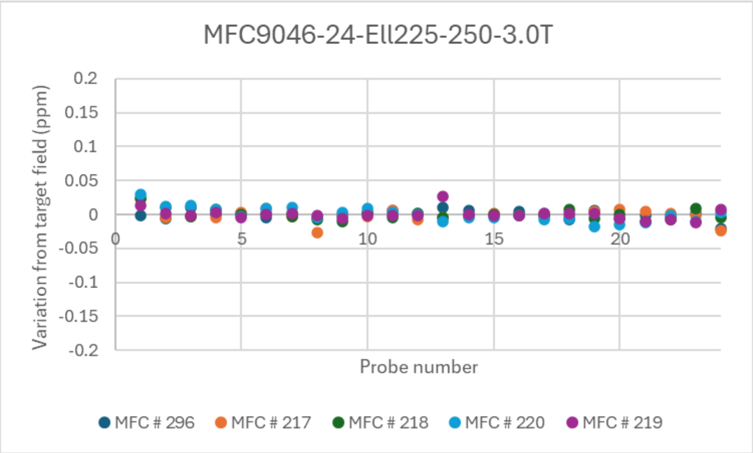


Figure 1: Production data of compensated reading for MFC9046-24-Ell225-250-3.0T

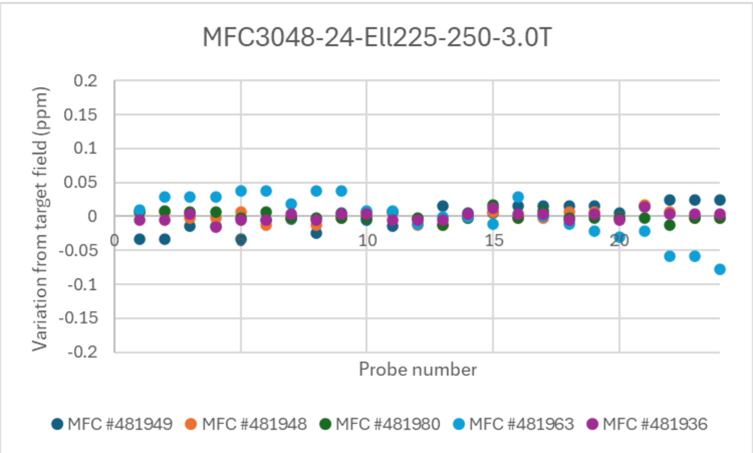


Figure 2: Production data of compensated reading for MFC3048-24-Ell225-250-3.0T

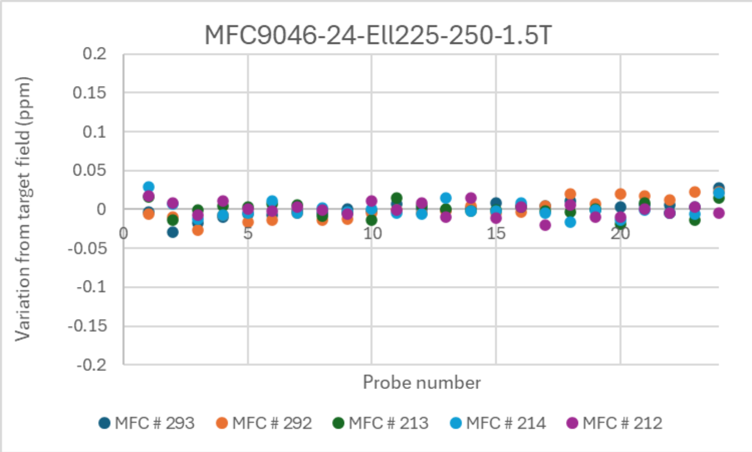


Figure 3: Production data of compensated reading for MFC9046-24-Ell225-250-1.5T

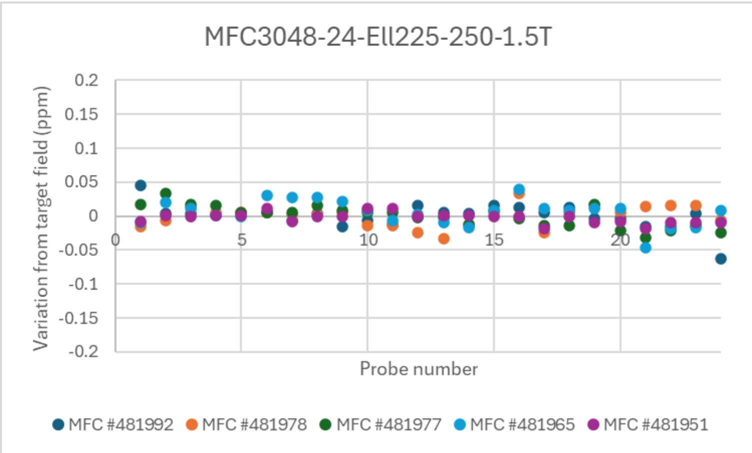


Figure 4: Production data of compensated reading for MFC3048-24-Ell225-250-1.5T

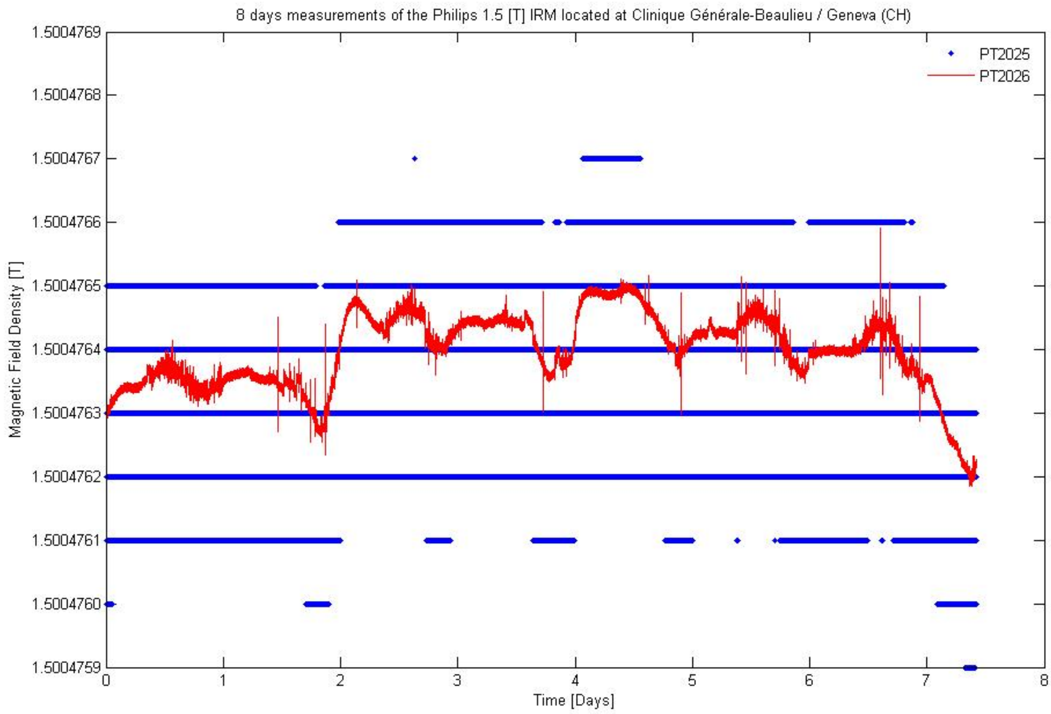
By prioritizing normalization precision, the MFC9046 not only enhances the quality of magnetic field measurements but also instills confidence in researchers relying on its data for critical scientific endeavors. With tighter distribution and improved performance, the MFC9046 establishes a new standard for normalization excellence, further solidifying its position as the premier choice for advanced NMR applications.

5. Performance Comparison Between Metrolab's PT2025, MFC3045 and PT2026 Magnetometers

5.1. Introduction

Comparing the previous generation PT2025 and MFC3045 NMR Magnetometer to the new generation PT2026 is not as straightforward as it may initially appear. This is because the PT2025 and the MFC3045 produce results as fixed-point ASCII-encoded numbers that are discreet and limited in resolution, whereas the PT2026 results are in the form of 64-bit floating-point numbers. Quantization occurs at such a low-resolution level that the limiting factor is not the measurement encoding but the measurement principle.

To examine the effects of these differences and to elucidate any practical consequences, we performed a survey of the magnetic field of a 1.5 [T] Magnetic Resonance Imager (MRI) over several days. The results shown in the graph below clearly demonstrate that the PT2026 is an impressive improvement on the PT2025.



5.2. NMR Measurement Principle

In the following paragraphs, we will explain the measurement principle and the measurement limits of the PT2025, MFC3045, and PT2026.

Obtaining the Nuclear Magnetic Resonance (NMR) signal

As the topic of NMR functioning is well covered by others [1][2], we will focus on what is directly relevant to our paper. Metrolab magnetometers use three common methods to obtain an NMR signal: continuous wave modulation with a steady radio frequency (RF) (field modulation), continuous wave modulation with a variable RF (frequency sweep), and pulsed waves (pulsed modulation). The signal is detected when a sample within the magnetic field is briefly stimulated by an oscillating perpendicular magnetic field. If the oscillation frequency matches the resonance, the nuclei in the sample will interact with the stimulation.

The Metrolab PT2025 uses continuous wave modulation to obtain an NMR signal. The sample is continuously stimulated with an RF set to that of the NMR frequency. To obtain accurate readings, the stimulation must be brief. However, briefly stimulating the sample at the NMR frequency may affect the magnetic field being measured (perturbation). To mitigate this effect, we employ an external coil and the principle of superposition. This creates a total magnetic field equal to the sum of the one being measured plus the perturbation field. When the total magnetic field matches the RF that stimulates the sample, the NMR signal is detected.

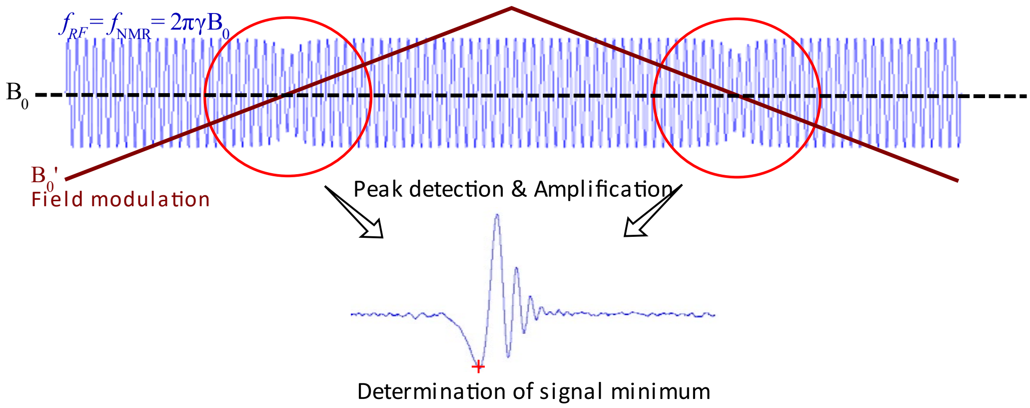


Figure 1. NMR signal obtained with field modulation.

The MFC3045 Magnetic Field Camera employs a different method for continuous wave stimulation: the sample is stimulated with a radio frequency that continuously varies around the NMR frequency. When the RF matches the NMR frequency the NMR signal is detected.

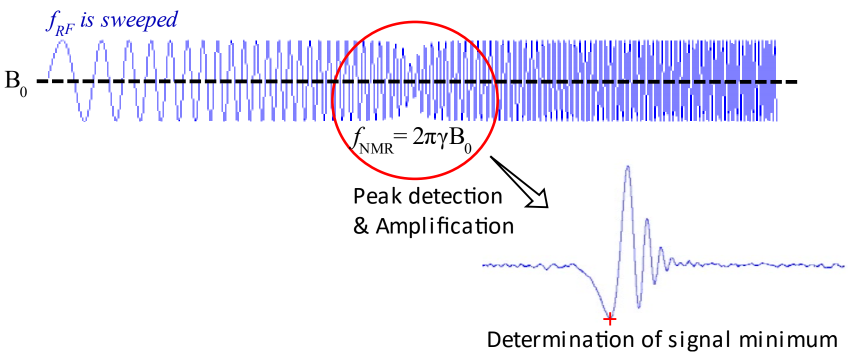


Figure 2. NMR signal obtained with frequency sweep.

Finally, the PT2026 uses pulsed NMR. In this case, the sample is stimulated with a brief pulse of RF set to match the NMR frequency. When the stimulation stops, the NMR signal is detected.

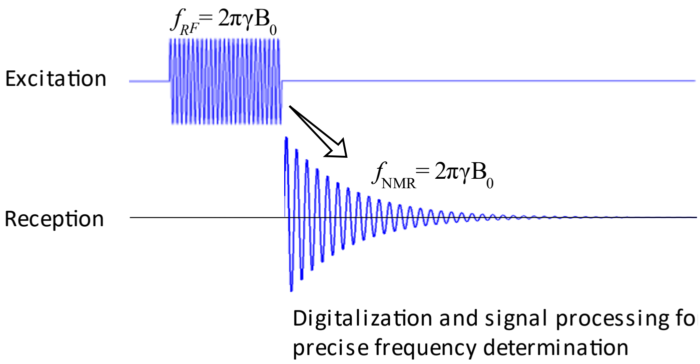


Figure 3. NMR signal obtained with pulse modulation.

Sample shape and excitation

An important aspect of NMR analytics is identifying the precise location of the measurement taken. The NMR signal is created by the participation of every single nucleus in the sample [1][2]. The overall effect is either constructive when in the presence of a homogeneous magnetic field or destructive in the presence of an inhomogeneous magnetic field. When the gradient is too strong, the NMR signal might disappear completely.

The intensity at which a nucleus contributes to the final signal is relative to the flip angle produced by the excitation coil, a simple wire surrounding the sample. For a maximum intensity signal, every single nucleus should be flipped to 90°. However, the excitation coil does not stimulate the sample with a constant power because the strength of the electromagnetic field varies across its entire volume; it also diverges. These conditions impact the perpendicularity of the oscillating magnetic field (**B_1**) and reduce the NMR signal emitted by the nuclei.

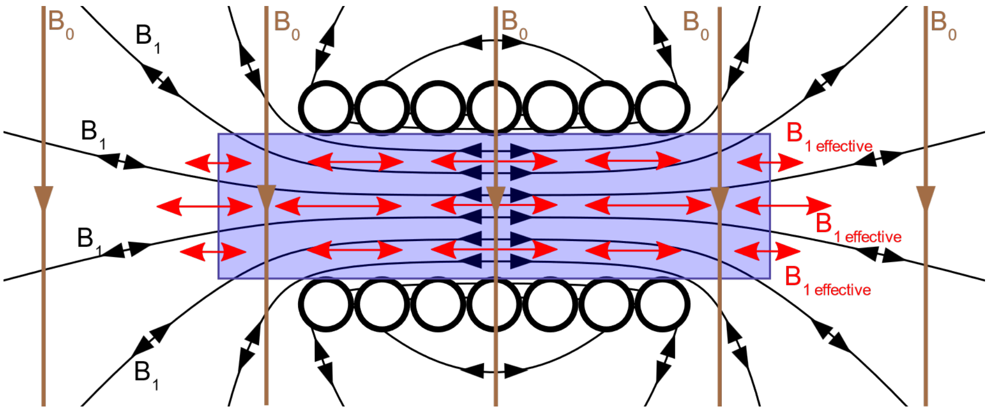


Figure 4. NMR sample and coil (adapted from [5])

If the magnetic field is homogenous, the measurement's precise location is the sample's center. Indeed, the geometrical construct of the measuring head is designed for this specification. However, other intrinsic factors need to be considered to determine the exact location of the magnetic measurement returned by the instrument. These factors include gradient measurement, the shape of the excitation coil, and the shape of the sample. Furthermore, inhomogeneity produces a weaker NMR signal, which results in higher noise on the final measurement, thus blurring its exact location.

5.3. PT2025 Principle of Operation

The PT2025 operates a continuous wave measurement scheme, i.e., continual stimulation at the NMR frequency of the coil surrounding the NMR sample. An envelope detector follows the amplitude of the RF signal, which is amplified, and the variation is used to detect the NMR absorption signal. As previously outlined, stimulating the sample with a fixed frequency is not an option. We need to create variation, either by sweeping the RF around the estimated NMR frequency or by creating a local variation of the magnetic field using a modulation coil, as with the PT2025.

As an external field is created, we must be certain that the NMR frequency is related to the measured magnetic field and is not a shifted version of it. This problem is solved by ensuring that the NMR absorption peak occurs when the current injected in the modulation coil is null.

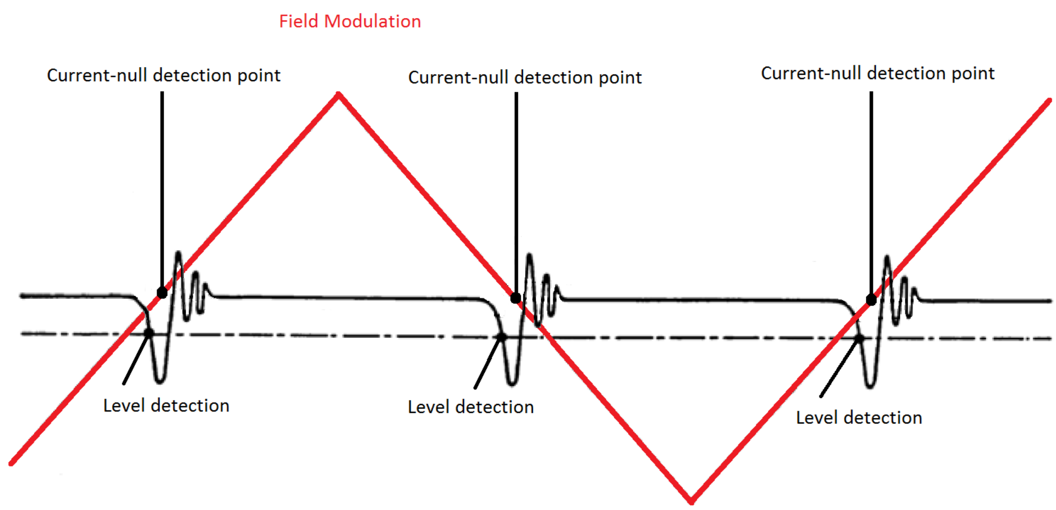


Figure 5. PT2025 field modulation

Maintaining the position of the absorption peak at the instant where the modulation coil induces no magnetic field is achieved by constantly adjusting the RF. An additional analog mechanism ensures that the detected signal has the correct voltage and works as a lock detector. If the peak is detected, the RF is fed to a counter gated for a duration related to the units in which the measurement is displayed, thus averaging the frequency using a timed window.

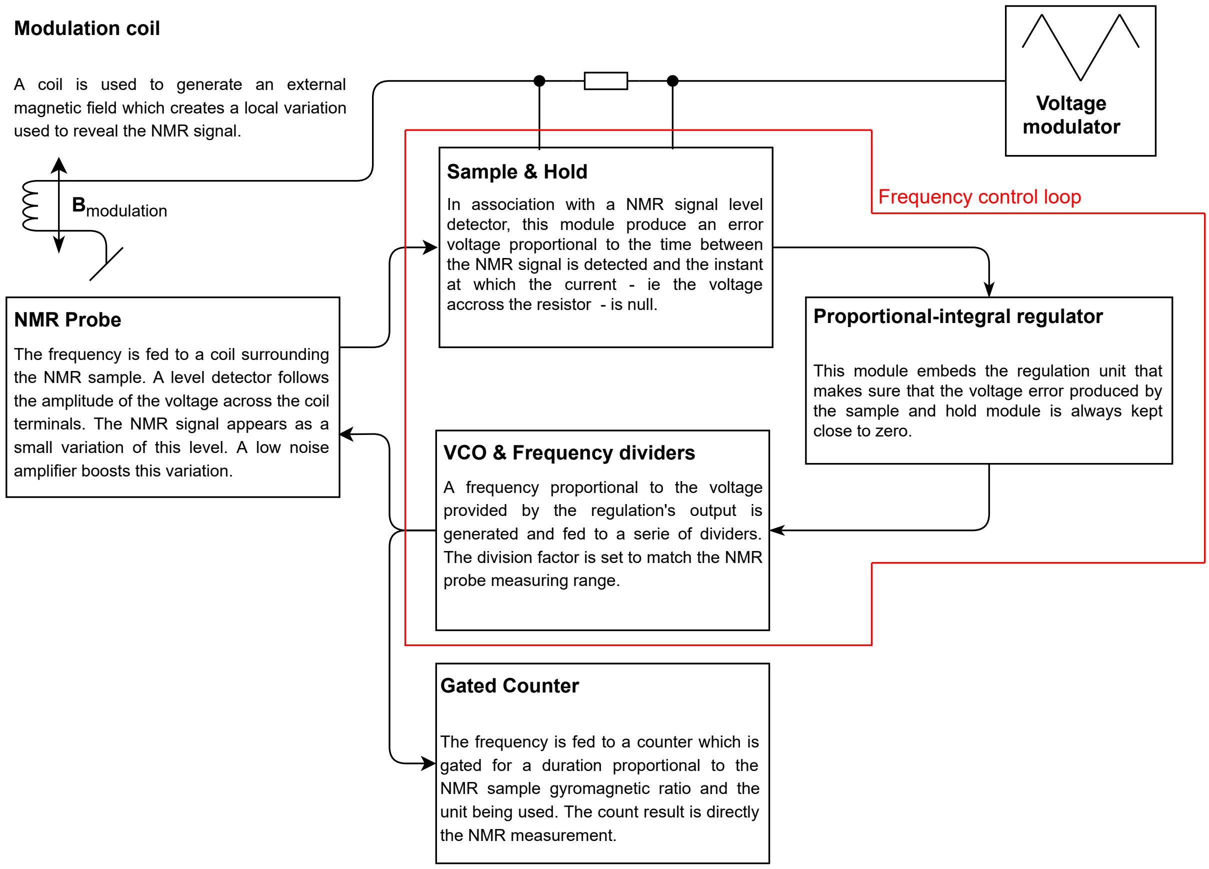


Figure 6. PT2025 simplified bloc diagram.

However, there are drawbacks to this design.

- A modulation coil is needed to make a measurement, creating a local perturbation that may be harmful in the customer environment. Furthermore, the loop that follows the measured magnetic field dynamics is affected by a time lag, resulting in an absolute error if the field is not static.
- The NMR signal is revealed by a change in the RF voltage amplitude as it appears across the coil terminals. The noise that affects the detected signal directly impacts the error voltage fed to the proportional-integral regulator, resulting in a slight frequency shift.
- Any noise on the voltage-controlled oscillator (VCO) input immediately translates into small frequency variations.
- The gyromagnetic ratio is created using a time window gate. The clock used to generate that window has a granularity of 100 ns. As explained in [4], when the units are set to T, this windowing leads to the digitization of the gyromagnetic ratios, which impacts the time taken between each measurement and the resolution. For ^1H probes, the resolution for T units is close to four times poorer than with MHz units.

Sample	Unit	Effective time window	Gyromagnetic ratio
^{1}H	Tesla	0.939 491 [s]	$\gamma''_p(eff)/2\pi$= 42.576 246 073 671 800 MHz/T
^{2}H	Tesla	1.530 060 [s]	$\gamma''_d(eff)/2\pi$= 6.535 691 410 794 350 MHz/T
^{1}H & ^{2}H	MHz	1.000 000 [s]	N.A.

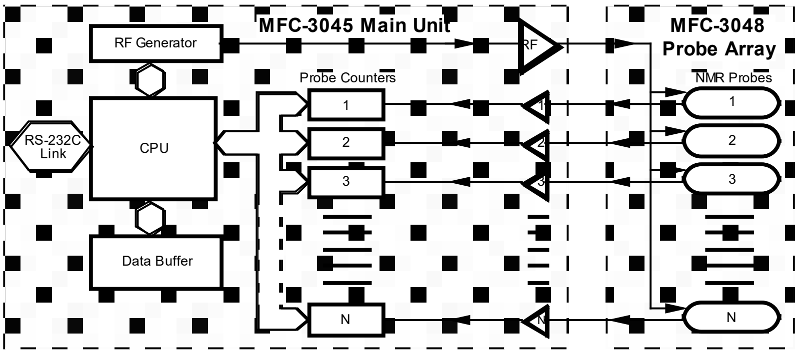
- During the time window, the counter holding the NMR measurement acts as a fixed float register, in which the last digit directly determines the resolution.

5.4. MFC3045 Principle of Operation

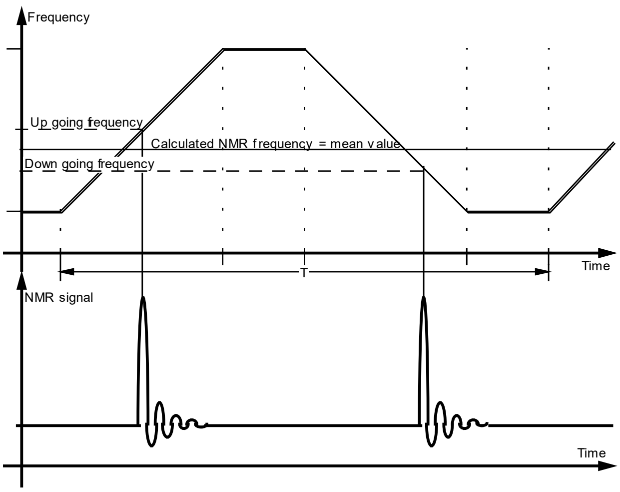
The MFC3045 operates using a frequency modulation scheme. That kind of measurement falls into the continuous wave stimulation mode but instead of revealing the NMR signal using an external modulation coil, it is the frequency that is modulated around the NMR frequency.

As for any continuous wave system, it is the absorption of the excitation signal that is detected. For this detection to be perceptible, an envelope detector follows the amplitude of the RF signal, which is amplified, and the variation is used to detect the NMR absorption signal. This modulation scheme is a key difference between the PT2025 and the MFC3045 as the measured magnetic field isn't perturbated by the excitation magnetic field the PT2025 uses.

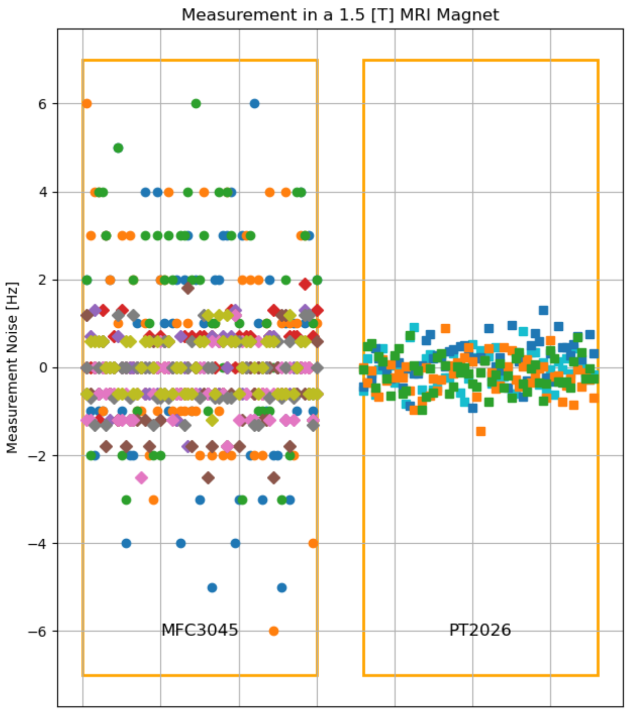
Another important difference is relative to the fact that the MFC3045 is meant to measure several probes in parallel. The same RF generator is used to stimulate in parallel all the probes that are located on the probe-array. In conjunction with the generation of the frequency modulated ramp, a counter is started. Each probe signal is amplified and, using a voltage threshold, a signal is generated when the NMR resonance appears which stops the counting.

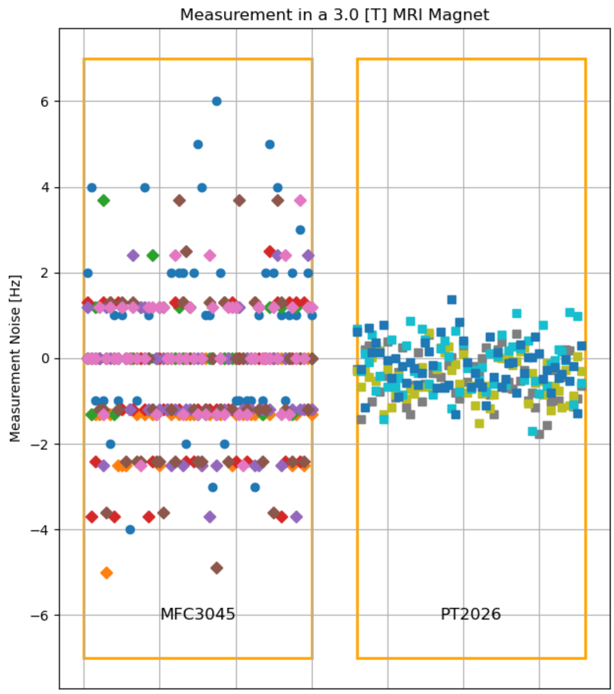


A proportional operation is then performed that relates the frequency to time, allowing the determination of the frequency that led to a resonance. To prevent any accuracy error relative to the voltage threshold, the average of the two frequencies measured during the modulation ramp up and down are used to compute a measurement. In the presence of a stable magnetic field, it is interesting to proceed to a measurement averaging. Would this averaging be performed; it is by averaging results of several up-down cycles that the operation would be made, ensuring that the accuracy isn't impacted.



Due to internal limitations related to the technology used – the MFC3045 was designed in the early 90s – the result provided to the user is expressed in decihertz with a resolution that isn't higher than 0.5 Hz. As such, in the presence of a very homogeneous and stable magnetic field, the results delivered by the unit will tend to be very similar to one another. This creates a numerical bias of the standard deviation. This effect can be seen in the following graphics, where the decimated value extracted from the MFC3045 unit is clearly visible.





5.5. PT2026 Principle of Operation

The PT2026 operation is based on pulsed NMR, where the NMR sample is stimulated with an RF sent to the coil that surrounds it, for a duration that causes most of the nuclei to reach a flip angle of 90°.

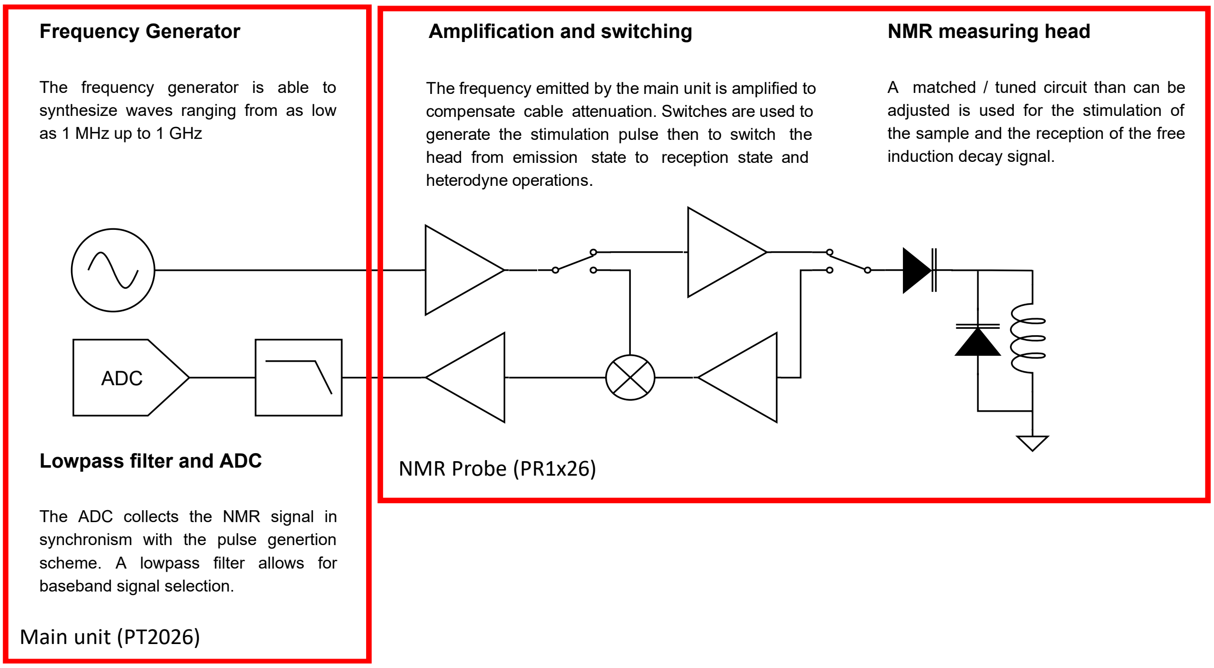
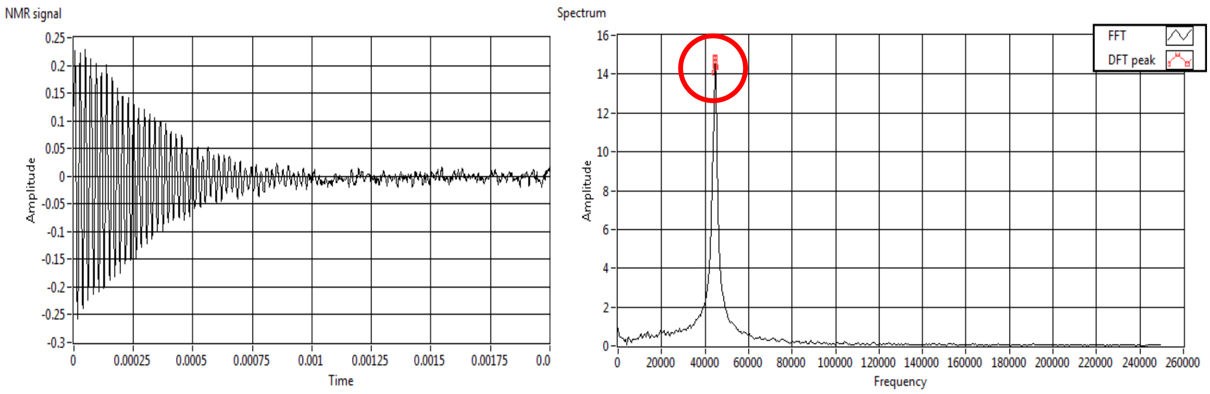


Figure 7. PT2026 simplified bloc diagram

When the stimulation ceases, the nuclei are drawn to their initial state by the magnetic field being measured. During this state restoration, an NMR signal can be measured using the same coil. As this signal is very small, a high gain amplification is required. An Analog-to-Digital Convertor (ADC) collects the free induction signal, which is then processed using Fourier transform techniques, to determine its frequency.



The PT2026 embeds the latest RF integrated circuits as well as a novel Application-Specific Integrated Circuit (ASIC) developed in collaboration with EPFL / Lausanne [6]. All the measurements are made at a very precise rate, limited mainly by the spin-lattice relaxation time. The probe's gyromagnetic ratio is stored as a 64-bit float directly in the probe, allowing any NMR probe sample usage.

Resolution Comparison

Before performing any measurements, we used a Metrolab TFM1176 Magnetic Field Probe to determine the distance to which the magnetic field induced by the modulation scheme of the PT2025 would not affect the PT2026. We determined that at 10 cm, the PT2026 measurements would not be impacted, so the probes were set 10 cm apart, each positioned 5 cm from the magnet center.

We accessed a 1.5 T MRI magnet from a private medical facility in Geneva. The resident building was being retrofitted and during this time, clinical access to the MRI was not possible. We installed both a

PT2025 and a PT2026 within the MRI, in order to perform long term measurements within the same magnet. Out of fairness for the PT2026 and to prevent a huge dataset, we configured the instrument to report a measurement based on a 1s block average, which gives a measurement rate almost identical to that of the PT2025.

Results

We found that with the PT2026, 99.7 % of the measured values are 7.3 times better than the theoretical resolution of the PT2025, not taking its noise into account. Please refer to Figure 8 below.

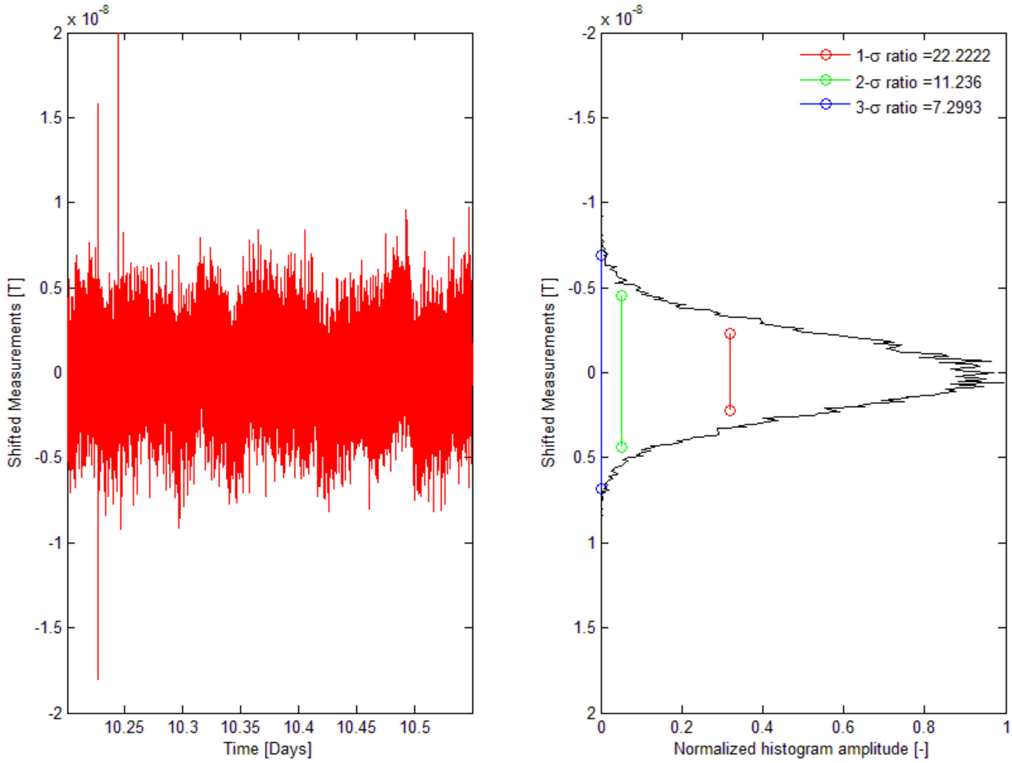


Figure 8. PT2026 histogram and standard deviations

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