NMR Precision Teslameter PT2026

User's Manual

Version 2.1

(Revision 1.3)

November 2022

REVISION HISTORY

v. 1.0 r. 1.0	August 2015	First release
v. 1.1 r. 1.0	January 2016	Mention MFC API coding example Update definition of *IDN? output Add warning about NMR signal averaging Explain effect of NMR pulse parameters Add description of back panel Update specifications Miscellaneous editorial changes
v. 1.2 r. 1.0	March 2016	Change description for new recording file format API is now in LabVIEW 2015 SP1 format
v. 1.3 r. 1.0	June 2016	Add description of "Probe Info" button Update installation procedure for signed installer Fix numbering of help bullets
v. 2.0 r. 1.0	March 2017	Move safety and EMC relevant information into Installation and Safety Manual Software UIF changes: • General: colors of numeric display • General: change gyromagnetic ratio used for MHz-p units, from free to shielded proton. • Parameters > Search & Averaging: Hall Enable • Advanced > Match & Tune: new screen shot API changes: • Fetch VIs return associated measurement status • Fetch Search Progress VI returns Hall value • Add Power Off VI • Read Probe Data VI returns Designation information • Add Configure Search Hall and Configure Search Hall VIs • Add Utility/Manufacturing VIs SCPI command changes:

		• :FETCh[:SCALar]:SPRogress? returns Hall value • Add :FETCh[:SCALar]:STATus? and :FETCh:ARRay:STATus? queries • Add :CONFigure:SEARch:HALLenable and query • Add :SYSTem:POFF command • Add :ROUTe:PROBe:DESignation? query • Change :ROUT:PROBe:LOWLevel to :ROUT:LOWLevel • Add :ROUT:MMEM:DATA command and query • Add :DIAGnostic:LOG[:DATA]? Query
v. 2.1 r. 1.0	March 2017	Restructure :ROUTe:PROBe:HALL commands Add "Raw Hall" instance of Read Probe Data VI
v. 2.1 r.1.1	September 2020	Regulation status bits documented: QUESTionable:BIT12 bit 12 added OPERation:BIT11 bit 14 added OPERation:BIT12 bit 7, 12, 13, 14 & 15 added ：REGUlation command points toward the RG8026 User Manual.
v. 2.1 r.1.2	May 2022	Fix min, max and default values for SCPI commands. Fix misnamed GAUSs to GAUSS. Documents missing bits in status registers. Add explanation about the different programming options. Remove :CONFigure:SEARch:LEVel commands. Add :CONFigure:SEARch:ENABle commands. Fix "binary format" of FETCh commands.
v. 2.1 r.1.3	Nov 2022	Replace software documentation with explanation on contextual help. Remove API documentation (self documented).

CONTENTS

GETTING STARTED
1-Introduction

NOTICE

See the "Installation and Safety Manual," delivered in printed form with your instrument, for safe installation and operation of the PT2026 hardware. The most recent version of this manual is also available for download from the Metrolab website, www.metrolab.com.

The Precision Teslameter PT2026 is a magnetometer, used to very precisely measure the flux density ("field strength") of strong magnetic fields.

The PT2026 relies on Nuclear Magnetic Resonance (NMR) as measurement technique. NMR is unique in magnetometry due to its unrivalled precision and accuracy, and practically total lack of drift.[1] For these reasons, NMR magnetometers are widely used as a secondary magnetic-field standard, serving as reference to calibrate other magnetometers. They are also routinely used in scientific and industrial applications that need to measure, map, monitor or regulate magnetic fields with extreme precision.

It is important to note that NMR magnetometry also has limitations. Most importantly, the magnetic field gradients in the volume to be measured must be close to zero. In addition, NMR is best suited for measuring strong magnetic fields. Finally, NMR is a relatively slow measurement technique.

The contents of this manual are as follows:

- Chapter 2- "Quick Start Guide" and Chapter 3- "Overview" provide information to get started;
- Chapter **Error! Reference source not found.** "**Error! Reference source no t found.**" explains how to use the software;
- Chapter **Error! Reference source not found.** "**Error! Reference source no t found.**" and Chapter 4- "Host Interfaces" explain how to write instrument control software;

[1] See Chapter 5-Key Specifications for details.

- Chapter 5- "Key Specifications" lists the key instrument characteristics; and
- Chapter 6- "NMR Magnetometers" provides technical background information on NMR magnetometers.

Updates to the software, firmware and documentation are posted on the Metrolab website, www.metrolab.com, and can be downloaded free of charge. The firmware in the PT2026 Main Unit can be upgraded in the field. The easiest way to be notified of updates is to sign up for our electronic newsletter, on the News page of our site.

We hope the PT2026 will help you perform your magnetic field measurements easily and accurately. If you have problems and your reseller cannot help you further, the Metrolab team is ready to help. Even if you don't have problems, we are always interested in knowing more about how our instruments are used. Feel free to contact us at any time at contacts@metrolab.com.

GETTING STARTED
2-Quick Start Guide

This chapter describes the installation, start-up and shut-down of the PT2026 software. The hardware installation is described in the "PT2026 Installation and Safety Manual."

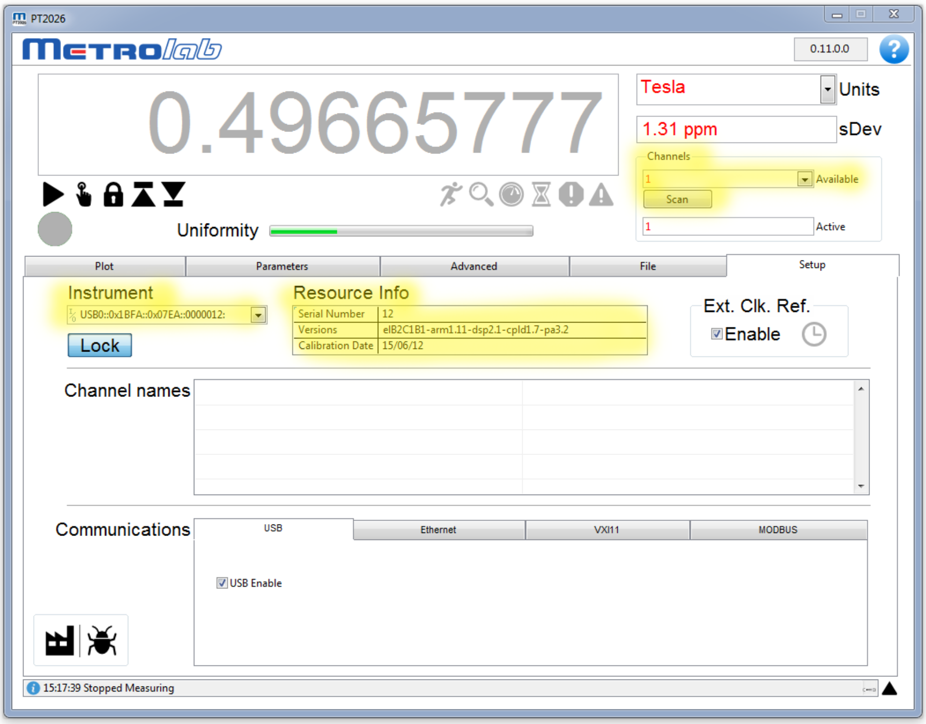
2-1 SOFTWARE INSTALLATION – WINDOWS

- Plug the USB key.
- Open the ReadMe.md file with your favorite text editor.
  Follow the instructions under "PT2026 Software Installation".

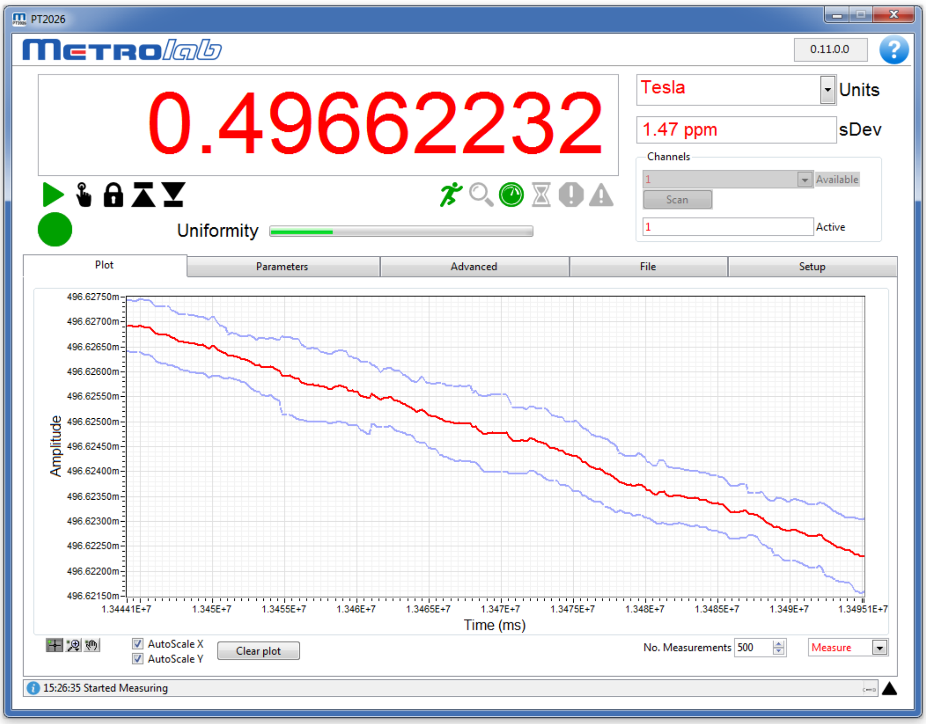
2-2 START-UP

- Power on the PT2026 as described in the PT2026 Installation and Safety Manual.
- Start the PT2026 software from the Windows Start Menu:
  Metrolab > PT2026 > Metrolab PT2026
- In the PT2026 software window, click on the "Setup" tab to select the corresponding screen. With the Instrument pull-down menu, select the VISA resource name that corresponds to your PT2026. This name should look something like "USB0::0x1BFA::0x07EA::xxxxxxx::INSTR", where "xxxxxxx" represents the serial number written on the back panel of your instrument. Verify that the software has been able to connect to your

PT2026, and that the PT2026 has been able to connect to your probe:

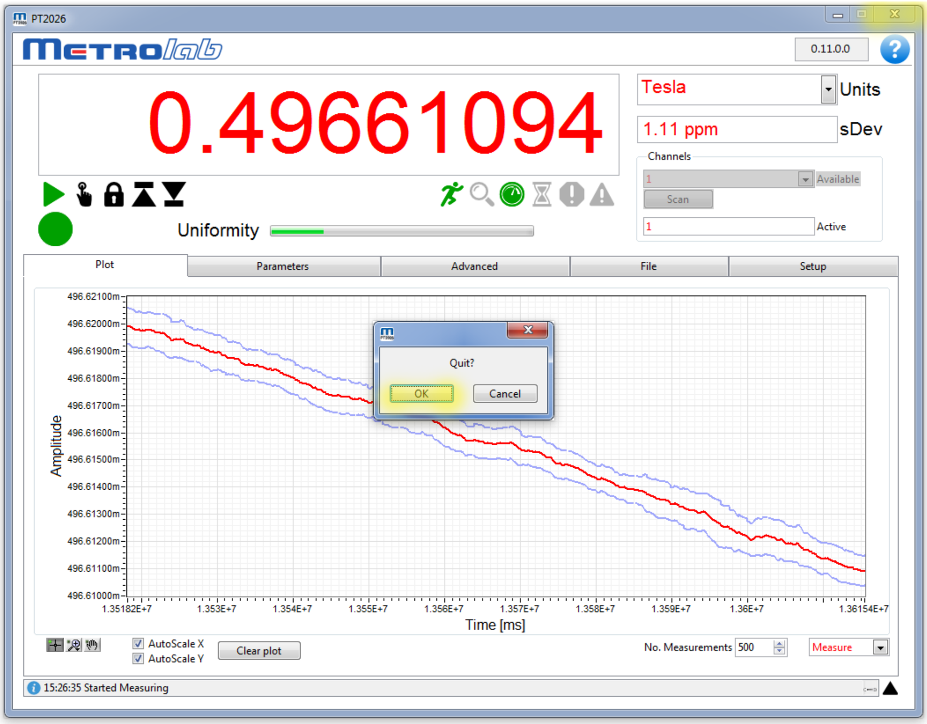


- Using the corresponding tab, return to the Plot screen and click the Measure arrow. The Search Progress bar should show the probe range being swept, searching for the NMR resonance, until your magnetic field value is reached and the instrument starts measuring:



2-3 SHUT-DOWN

- To stop the software, close the PT2026 window and confirm the "Quit?" dialog:

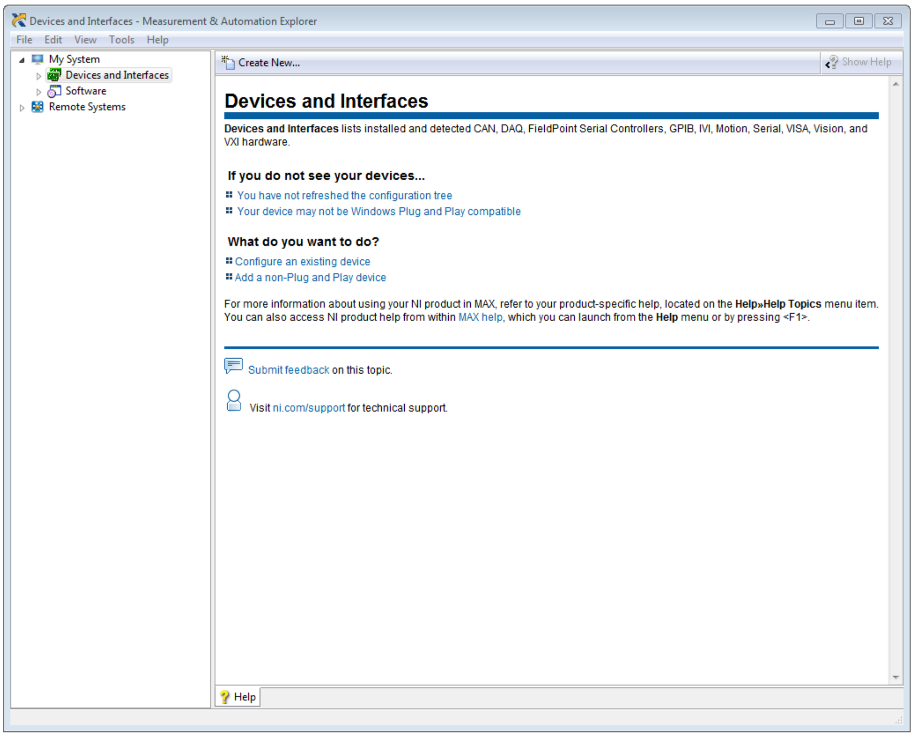


- Power off the PT2026 as described in the PT2026 Installation and Safety Manual.

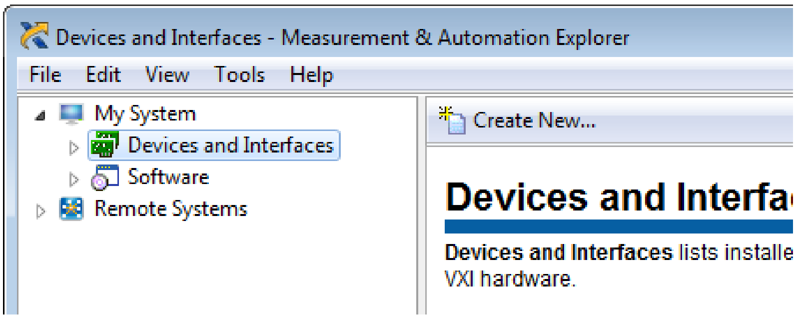
2-4 CONNECT VIA ETHERNET

To connect to the PT2026 via Ethernet, you must first create a network instrument entry for the PT2026 in the VISA database. Use the National Instruments utility, "Measurement & Automation Explorer" (MAX) to do this:

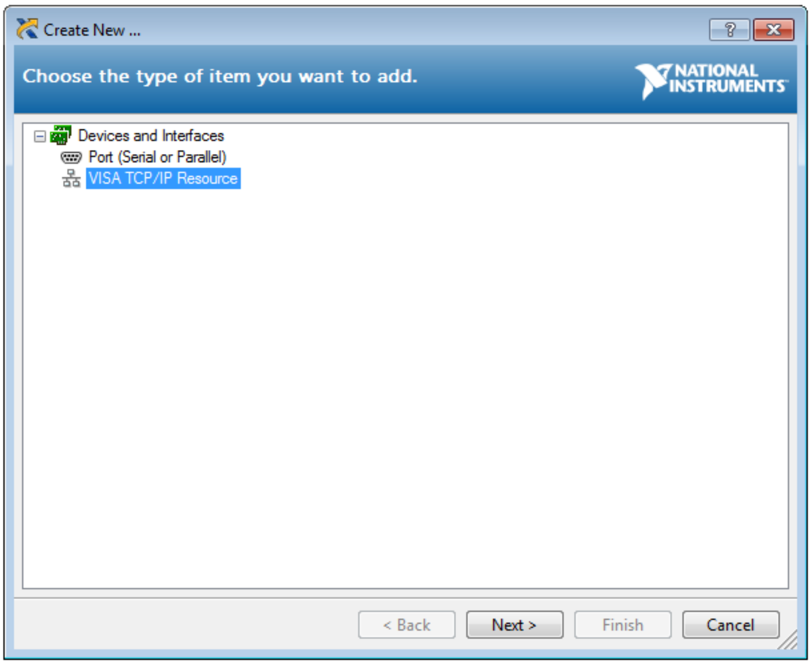
- Launch MAX: Windows Start Menu > All Programs > NI MAX:



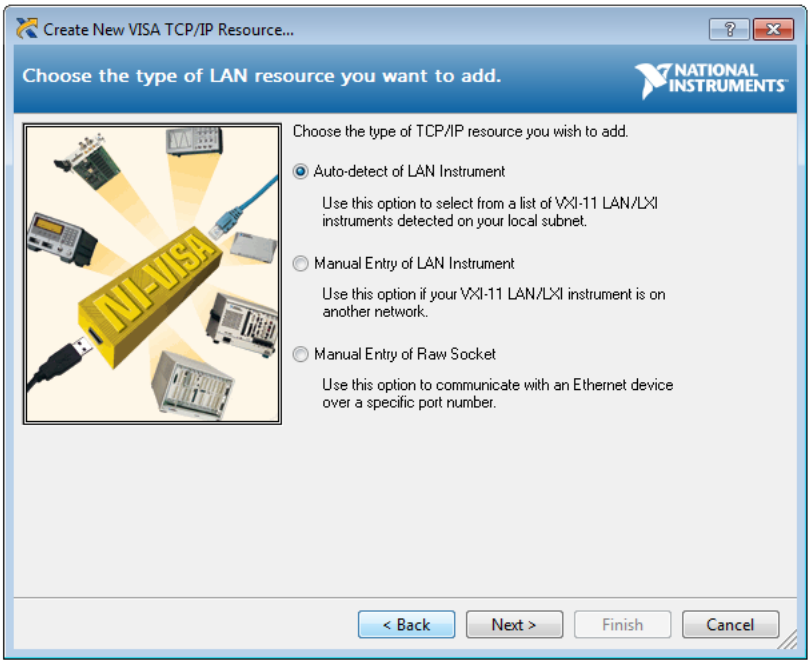
- Select "System > Devices and Interfaces" in the left-hand column, and click on "Create New…":



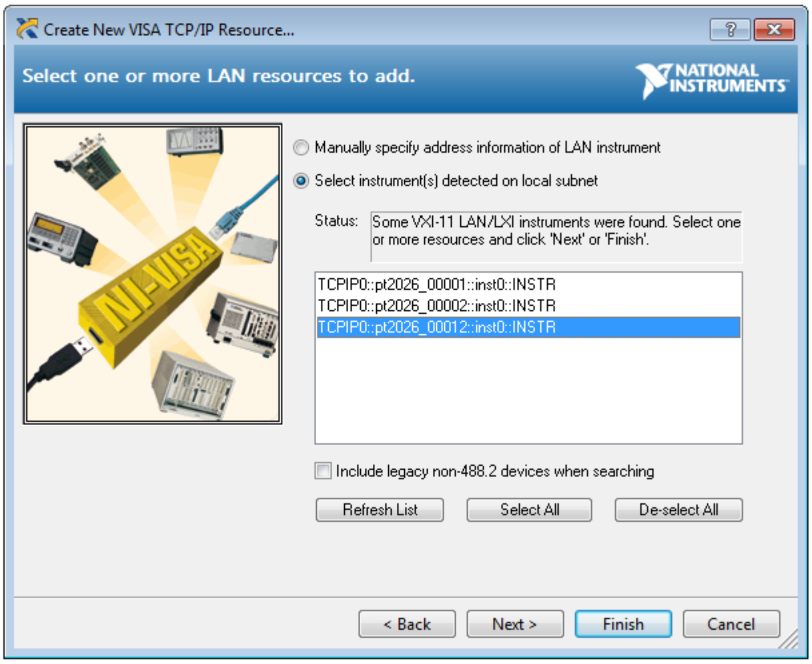
- In the resulting dialogue window, select "VISA TCP/IP Resource" and click "Next":



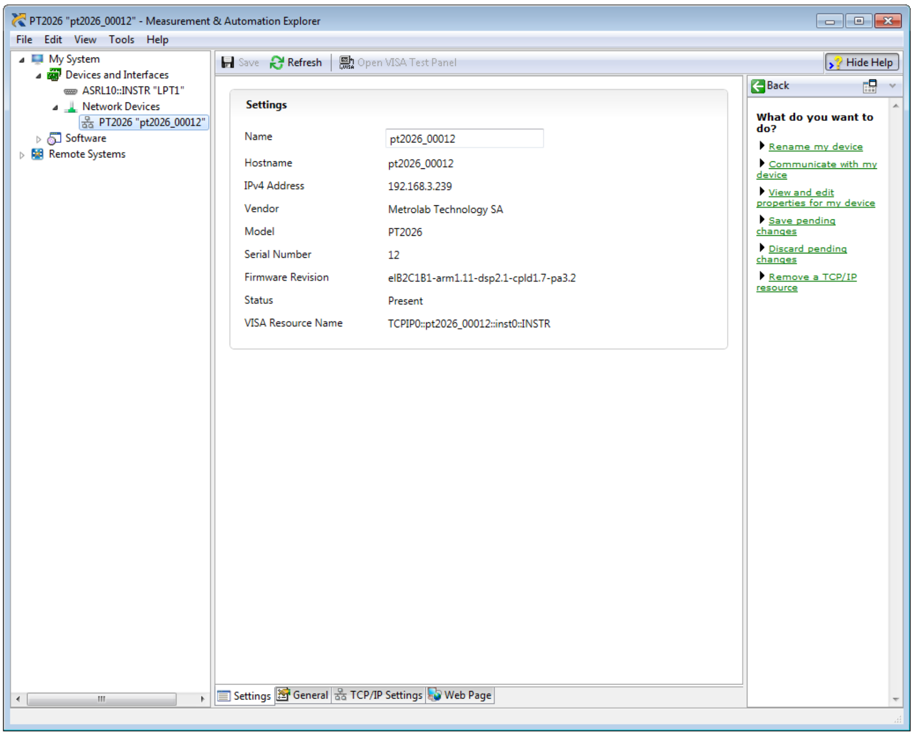
- In the subsequent dialogue, Select "Auto-detect of LAN Instrument" and click "Next":



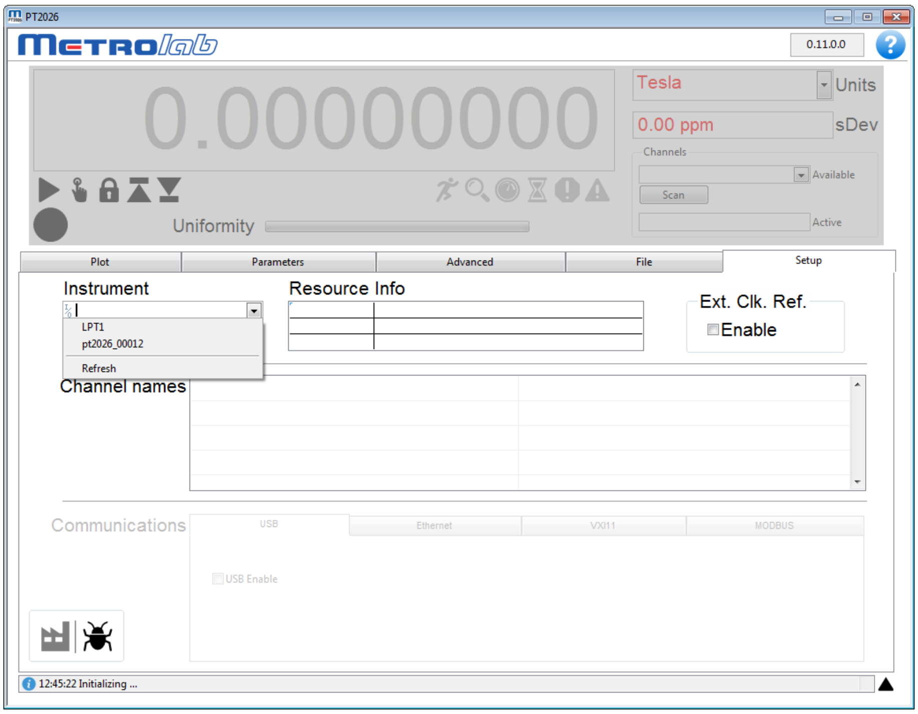
- In the last dialogue, select the entry that corresponds to your PT2026, and click "Finish":



- In the main MAX window, if you expand the item "Devices and Interfaces", then the subjacent item "Network Devices", you will now see an entry for your PT2026. Click on the entry to reveal the Settings panel for your PT2026 network device:



- Now, in the Setup panel of the PT2026 software, if you click on the Instrument pull-down menu, you will see the entry for your PT2026 network device:

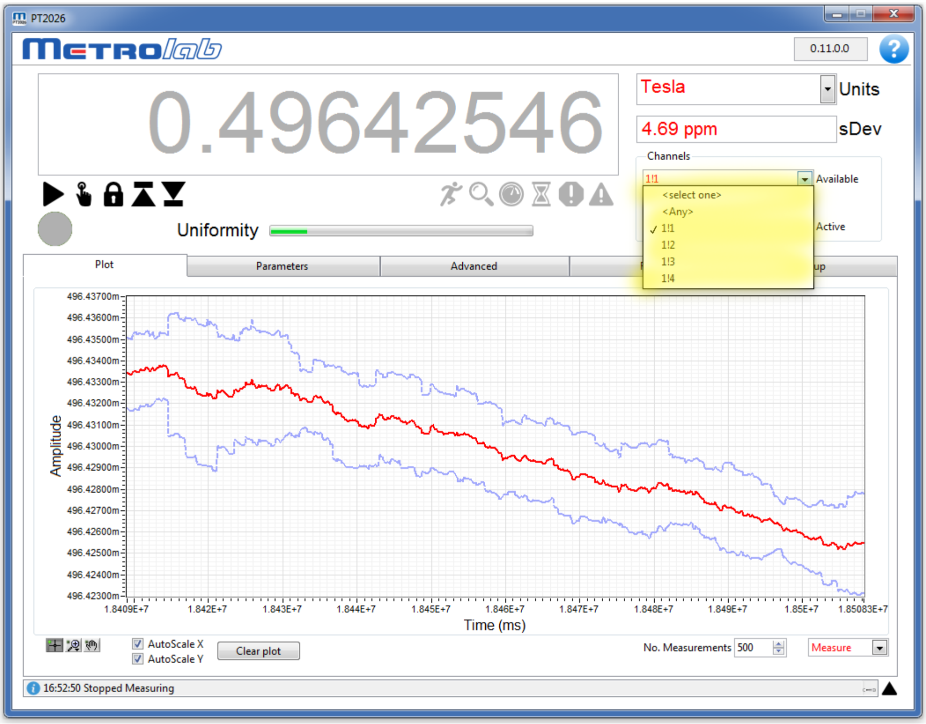


Select it and go!

2-5 USING MULTIPLEXERS

- Connect the MUX6026 multiplexer and probes as described in the PT2026 Installation and Safety Manual.

- Select the active probe from the Channels pull-down menu:



- Start measuring as described in Section 2-2.

2-6 USING SOFTWARE EMBEDDED CONTEXTUAL HELP

The PT2026 software is self-documented.

Click on the  button (top right corner of the PT2026 software) to get contextual help.

This opens a help page in your default browser, but does not require any internet connection. The page that will be open is related to the current tab opened in your PT2026 software.

USING THE PT2026
3-Overview

This chapter provides a quick overview of what you can do with the PT2026. Additional details are provided in subsequent chapters. Note that the contextual help in the PT2026 software is very useful; in fact, it is exactly the same as Chapter **Error! Reference source not found.** "**Error! Reference source not fo und.**".

3-1 MEASUREMENT

- You can measure magnetic flux density with a precision of parts per million (10^{-6}) or even better – but beware of the limitations of NMR magnetometers (see Section 6-3).
- Before starting to measure the flux density, NMR magnetometers must find the NMR resonance. The software tells you what the PT2026 is doing with a status light, a series of status symbols, a search progress bar, and a message log (see Section **Error! Reference source not found.**).
- If for some reason the PT2026 cannot find the NMR resonance, you can limit the search range (see Section **Error! Reference source not found.**). I f all else fails, you can manually force it to search at a given field strength (see Section **Error! Reference source not found.**).
- Once the NMR resonance has been found and the PT2026 is measuring, the search progress bar turns into a field-uniformity display, to help you position the probe in your magnet's "sweet spot" (see Section **Error! R eference source not found.**).
- The software will display the measurements numerically and plot the results on a strip chart. You can freeze the numeric display and change its resolution (see Sections **Error! Reference source not found.** and **Error! Re ference source not found.**), and you can manipulate many features of the plot. Some of the plot options, such as the auto-scaling controls, are evident; others, such as the cursor controls, are accessed by right-clicking on the plot (see Section **Error! Reference source not found.**).

- You can select the appropriate measurement units, such as Tesla or kGauss. The choices also include some exotic but useful units, such as MHz, MHz-proton and parts per million (see Section **Error! Reference source not found.**).
- You can enable measurement averaging and display the standard deviation of the measurements. You can control the averaging method and the filter length (see Sections **Error! Reference source not found.** and REF _Ref302221445 \r \h **Error! Reference source not found.**).
- If you are using a probe multiplexer, you use the PT2026 software to select which probe to use (see Section **Error! Reference source not found.**).
- With a multiplexer, you can also group a set of probes – for example those in a particular magnet – as a single logical channel. The PT2026 will search across the range of each probe in turn, and will start measuring with the one where it finds the NMR resonance. The PT2026 comes with one pre-configured logical channel, Any, which includes all probes that are plugged in. (See Section **Error! Reference source not found.**).
- To help you find the peak field in a volume, you can have the PT2026 software display only maximum or minimum field values (see Section **Error! Reference source not found.**).
- You can have the measurements triggered either continuously, at regular intervals, via the software interface, or via a TTL signal (see Section **Error! Reference source not found.**).
- You can also have the PT2026 generate an output trigger when a particular field value is attained (See Section **Error! Reference source not found.**). The PT2026 only has a single Trigger connector, configured either as input or output, so the output trigger cannot be used at the same time as the TTL measurement trigger.
- If need be, you can optimize the measurements by manipulating a host of internal parameters using the Advanced tab (see Sections **Error! Reference source not found.** through **Error! Reference source not found.**). Unless you are very familiar with the instrument and the principles of NMR, you probably should not touch these. A possible exception is the

Advanced > RF Pulse > Period, to increase the measurement rate (see Section **Error! Reference source not found.**).

- You can store and recall your favorite settings (see Section **Error! Reference source not found.**).
- You can record and play back measurements (see Section **Error! Reference source not found.**).
- Finally, the Setup tab embodies a host of useful utility features that deserve browsing.

3-2 INTERFACES

The interfaces are described in detail in Chapter 4- "Host Interfaces". Generally, you don't have to know anything about them, since the PT2026 software takes care of it all. If you want to know, the most important point is that the PT2026 adheres closely to industry standards:

- USB interface:
  Compliance with the USB 2.0 mechanical, electrical and protocol standard provides basic connectivity with any USB-capable computer. The instrument supports USB full-speed communication (12 Mbps).
- Ethernet interface:
  Automatically configures itself for 10 or 100 Mbps and Full or Half Duplex operation.
- Standardized USB class driver:
  Compliance with the USB Test & Measurement Class (USBTMC) allows the instrument to be connected without installing a custom USB driver. All that is required is a generic class driver for test and measurement equipment, as provided by suppliers of instrumentation software. The software supplied with this instrument includes the National Instruments USBTMC driver.
- Standardized IEEE488.2 protocol:
  Compliance with the USB488 protocol specification for USBTMC provides all the capabilities of an IEEE488 instrument on the USB bus. IEEE488, derived from HPIB/GPIB, is the world's most widely used instrumentation

protocol. IEEE488 compliance allows any VISA library (Virtual Instrument Software Architecture) to control every aspect of the instrument. The software supplied with the instruments includes the National Instruments VISA Runtime library.

- Standardized VXI-11 protocol:
  For the Ethernet interface, IEEE488 compatibility is provided by the VXI-11 standard, providing the same advantages as USBTMC for USB.
- Standardized instrument command protocol:
  The SCPI standard (Standard Commands for Programmable Instruments) is the standard developed and used by large instrumentation manufacturers such as Tektronix and HP/Agilent, and provides a programming interface familiar to many instrumentation system programmers.

PROGRAMMING THE PT2026
4-Host Interfaces

4-1 GENERAL

The PT2026 supports two physical host interfaces, USB 2.0 and Ethernet, and two host interface protocols: "native" and "MODBUS." The native protocol is based on the following standards, very widespread in the instrumentation industry:

- IEEE 488.2: device control,

- VXI-11: Ethernet device control,

- USBTMC-USB488: USB device control, and

- SCPI: command structure.

The native commands provide access to all the features of the PT2026. The same command set is supported on the USB and Ethernet interfaces.

The MODBUS protocol is commonly used in industrial automation applications. The PT2026 supports the MODBUS protocol only on the Ethernet interface, and it only provides access to a subset of the instrument's functionality.

NOTICE
• The MODBUS interface protocol is not yet implemented.

If you use the turnkey software or the LabVIEW instrument driver, it is generally not necessary to refer to the information in this chapter. You may, however, want to write a program optimized for your application, without using the LabVIEW instrument driver provided by Metrolab. This chapter will provide you with the information necessary to do so.

The PT2026 was designed to plug-and-play with a Virtual Instrument Software Architecture (VISA) compliant software library – in particular, the NI-VISA library from National Instruments (see www.ni.com). If you are not using NI-VISA, you will probably need information that is not provided in this chapter:

- USB 2.0
  See "Universal Serial Bus Specification, Revision 2.0, April 27, 2000," available from www.usb.org/developers/docs/usb20_docs.

- USBTMC and USBTMC-USB488
  See "Universal Serial Bus Test and Measurement Class Specification (USBTMC), Revision 1.0, April 14, 2003" and "Universal Serial Bus Test and Measurement Class, Subclass USB488 Specification (USBTMC-USB488), Revision 1.0, April 14, 2003," available from www.usb.org/developers/docs/devclass_docs.

- SCPI
  See "Standard Commands for Programmable Instruments (SCPI), VERSION 1999.0, May, 1999," available from www.ivifoundation.org/specifications/default.aspx.

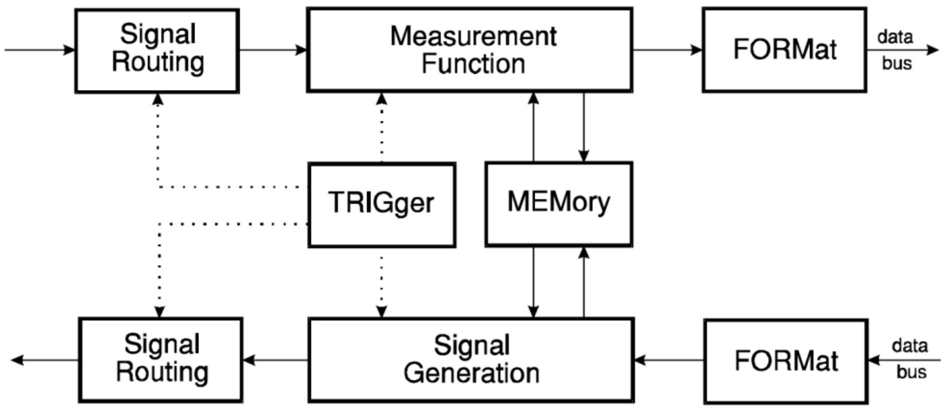
- IEEE 488.2
  See "IEEE Standard Codes, Formats, Protocols, and Common Commands for Use With IEEE Std 488.1-1987, IEEE Standard Digital Interface for Programmable Instrumentation, IEEE Std 488.2-1992," available from standards.ieee.org/reading/ieee/std_public/description/im/488.2-1992_desc.html.

- VISA
  See "VPP-4.3: The VISA Library," "VPP-4.3.2: VISA Implementation Specification for Textual Languages," "VPP-4.3.3: VISA Implementation Specification for the G Language," VPP-4.3.4: VISA Implementation Specification for COM," all Revision 2.2 (March 17, 2000) by the VXI plug & play Systems Alliance, available from www.ivifoundation.org/specifications/default.aspx.

4-2 NATIVE INTERFACES

4-2-1 SCPI instrument model

The PT2026 complies with the Standard Commands for Programmable instruments (SCPI) standard. SCPI uses a standard instrument model to organize the command structure. The diagram below shows the subsystems concerning the signal flow.



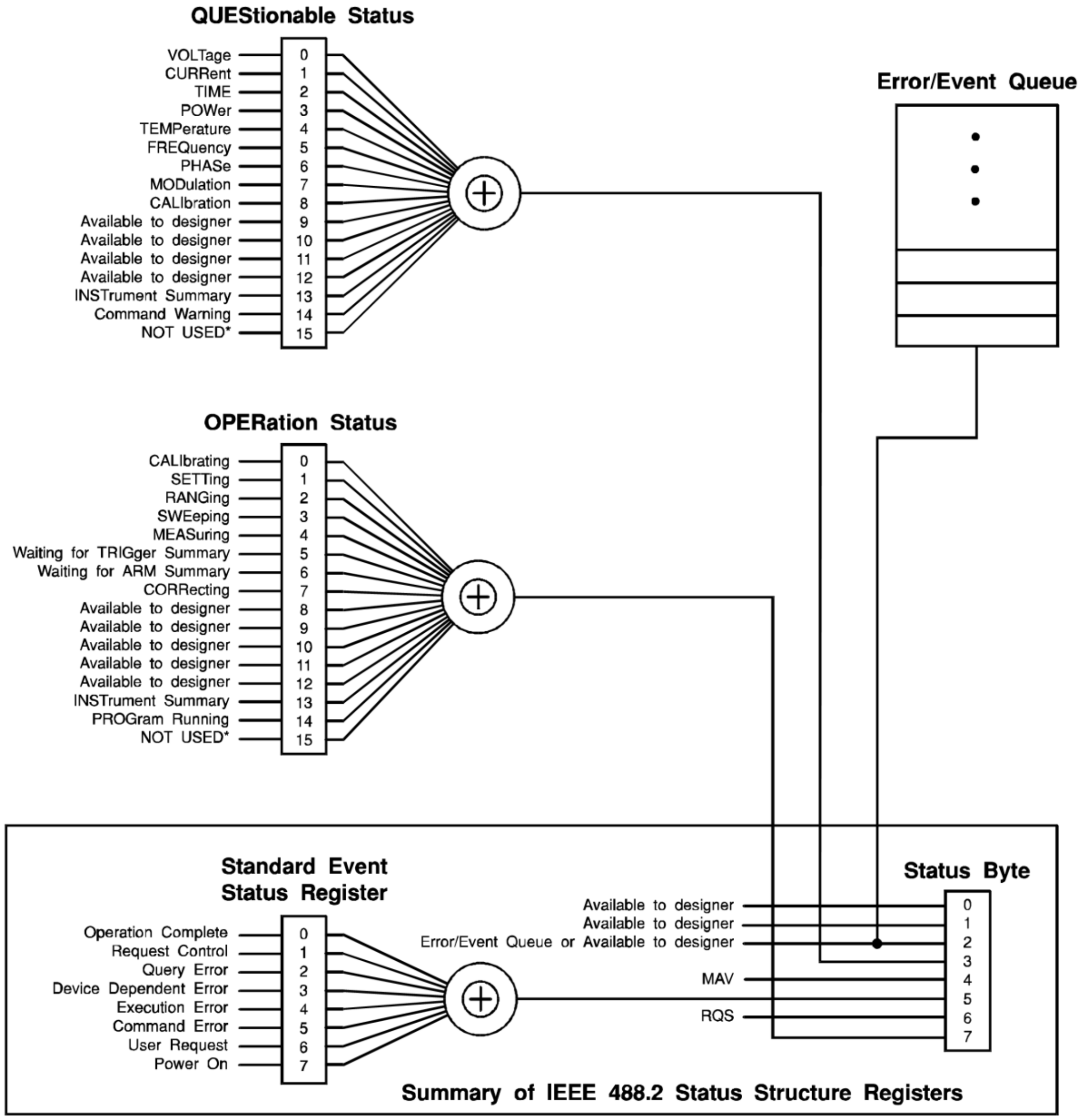
The following table provides a summary of the PT2026 capabilities, organized according to the SCPI instrument model. The supported commands include IEEE 488.2 "Common Commands" (start with "*") as well as SCPI commands – see Sections 4-2-4 through 4-2-6 for details. In addition to ASCII commands, the PT2026 also supports certain VXI-11 and USBTMC-USB488 low-level controls, also noted in this table.

Functional Block	**Command(s)**	**Function**
Measurement Function	`:MEASure …`	Measure with standard settings. Equivalent to *RST;:READ …
	`:READ …`	Measure with custom settings. Equivalent to :ABORt;:INITiate …;:FETCh …
	`:FETCh …`	Fetch measurement results previously acquired with MEASure, READ or INITiate
	`:CONFigure …`	Configure probe matching/tuning, NMR signal search, measurement and tracking
Signal Routing in	… [,<channel_list>]	Parameter for MEASure and READ
	`ROUTe`	Explicit ROUTe command
INPut	`INPut …`	Configure reference clock
SENSe	`:SENSe …`	Configure digitization parameters
CALCulate in	`:CALCulate:AVERage1` `:CALCulate:AVERage2`	NMR signal averaging NMR measurement averaging
FORMat	`:FORMat …`	Set output format
	`:UNIT …`	Set output units
TRIGger	`*TRG` `VXI-11 / USBTMC`	Generate a trigger
	`:ARM …`	Arm Trigger Out signal
	`:INITiate …`	Enable triggers

Functional Block	Command(s)	Function
	`:ABORt`	Abort triggers
	`:TRIGger:SEQuence1 …`	Initiate measurement
	`:TRIGger:SEQuence2 …`	Generate Trigger Output signal
MEMory	–	Not used in PT2026
Signal Routing out	–	Not used in PT2026
OUTPut	`:OUTPut:TRIGger …`	Configure Trigger Output signal
SOURce	`:SOURce:PULSe …`	RF pulse characteristics
CALCulate out	`*CLS`	Clear status
STATus	`*STB?, *SRE` `VXI-11 / USBTMC`	Read / enable bits in Status Byte
	`VXI-11 / USBTMC`	Request service from host
	`*ESR?, *ESE`	Read / enable bits in Standard Event Status Register
	`*OPC, *WAI`	Detect and wait for operation complete
	`:STATus …`	Read / enable bits in OPERation and QUEStionable registers
	`:SYSTem:ERRor`	Query error queue
	`VXI-11 / USBTMC`	Clear input and output buffers
SYSTem	`VXI-11 / USBTMC`	Remote/local control – ineffective since PT2026 has no local controls
	`*RST`	Perform reset
	`*TST?`	Perform self-test (not supported by PT2026)
	`*IDN?`	Return Instrument ID
	`:SYSTem:VERSion`	Return SCPI version
	`:SYSTem:HELP …`	Provide command help
	`:SYSTem:COMMunicate`	Set up Ethernet parameters
	`:SYSTem:LOCK …`	Lock out other host interfaces
MMEMory	`:MMEMory …`	Manipulate parameter files
DIAGnostic	`:DIAGnostic: …`	Initiate firmware upgrade

4-2-2 IEEE 488.2 / SCPI status registers

IEEE 488.2 compliant instruments have at least two registers: the Status Byte and the Standard Event Status Register. SCPI adds the Operation Status Register, Questionable Status Register and Error/Event Queue. The diagram below, taken from the SCPI standard, provides a good summary. This section describes how the PT2026 uses these status registers.



* The use of Bit 15 is not allowed since some controllers may have difficulty reading a 16 bit unsigned integer. The value of this bit shall always be 0.

- Status Byte

  Contains a 1-byte status summary. The PT2026 uses the following bits:

Bit	Name	Description
2	EAV	Error Available (in Error/Event Queue)
3	QSB	Questionable Summary Bit
4	MAV	Message Available: response ready to be read
5	ESB	Event Summary Bit
6	RQS	ReQuest for Service
7	OSB	Operation Summary Bit

- Standard Event Status Register

  Latches certain standardized events. The PT2026 uses the following bits:

Bit	Name	Description
0	Operation Complete	*OPC has flagged operation complete
2	Query Error	Error in preceding query
3	Device Dependent Error	Errors specific to the PT2026, including internal errors
4	Execution Error	Error detected during command execution
5	Command Error	Error in preceding command
6	User Request	A parameter has been changed
7	Power On	PT2026 has been powered up

- QUEStionable Status

  Indicates conditions that may reduce the quality of the measurement. The PT2026 sets the following bits:

Bit	Name	Description
9	Unable to measure	Unable to acquire and measure an NMR signal
10	Ignored setting	A setting was set, but is not taken into account because of other settings
11	Measurement	The quality of the measurement is questionable (e.g. Due to unknown IF in manual search mode)
12	BIT12	Summary Bit: DSP Status

- QUEStionable:BIT12

  This is a fan-out for bit 12 of the QUEStionable register, a device-specific summary bit.

Bit	Name	Description
0	External Ref Detected	External reference clock is detected
1	External Ref Locked	Locked onto external reference clock
2	Beating Detected	Measurement was rejected as spurious signal (cf. :CONFigure:MEASure:REJect command)
12	Regulator output saturated	The regulation unit isn't regulating anymore due to voltage or current having reached their physical adjustments limits.

- OPERation Status

  Captures conditions which are part of the instrument's normal operation. The PT2026 uses the following bits:

Bit	Name	Description
2	RANGing	Scanning for available probes
3	SWEeping	Searching for NMR signal
4	MEASuring	Measuring magnetic field strength
5	Waiting for TRIGger	Waiting for trigger
8	New Acq Avail	New Acquisition Data is Available
9	New Meas Avail	New Measurement Available
10	Initiated	Trigger system is initiated
11	BIT11	Summary Bit: A parameter has changed
12	BIT12	Summary Bit: Acquisition status

  Note: Bits 8 and 9 are transient pulses (immediately reset to 0 after being set to 1). This means they must be read out of the OPERation:EVENt register rather than the OPERation:CONDition register.

- OPERation:BIT11

  This is a fan-out for bit 11 of the OPERation register, a device-specific summary bit. It indicates subsystems whose configuration has changed.

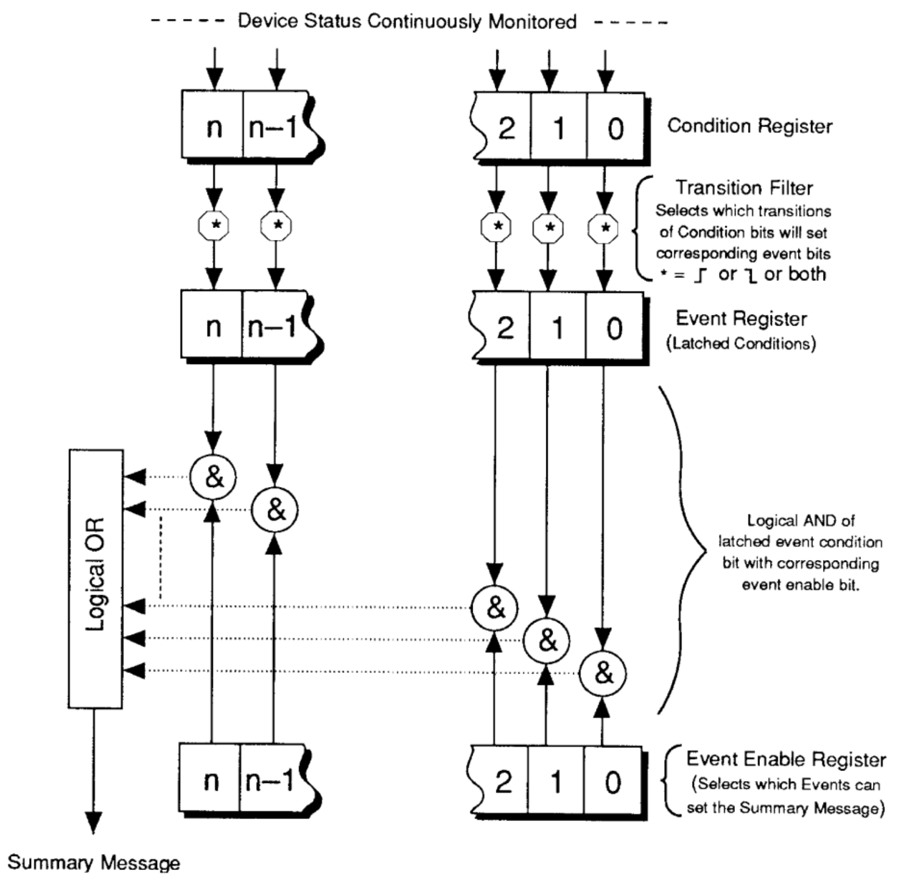
Bit	Name	Description
0	SYSTem	System: system ID, communications, lock
1	STATus	Status: enable bits
2	MEMory	Memory: parameter file loaded
3	MMEMory	Mass memory: parameters saved, created, deleted
4	CONFigure	Measurement: matching/tuning, search, tracking
5	ROUTe	Route: channel selection
6	INPut	Input: reference clock
7	OUTput	Output: trigger output signal
8	SENse	Sense: digitization
9	SOURce	Source: pulse
10	TRIGger	Trigger: measurement trigger, output trigger
11	CALCulate	Calculate: signal & measurement averaging
12	FORMat	Format: output format
13	UNIT	Units: output units
14	REGUlation	Regulation: parameter changed (needs RG8026 option)

- OPERation:BIT12

  This is a fan-out for bit 12 of the OPERation register, a device-specific summary bit.

	Bit	Name	Description
	0	`DSP_CPLD Fatal Error`	Unable to use DSP and/or CPLD
	3	`Acquisition overrun`	DSP's acquisition buffer is full
	4	`Trigger overrun`	Trigger arrived before previous acquisition complete
	5	`NMR Path Broken`	Active probe was unplugged
	6	`Peripheral Plugged`	A peripheral was plugged into the PT2026
	7	`Remote Box Start`	The start button of the remote box was pressed.
Needs RG8026 Option	12	`Regulator active`	The regulation unit is active
	13	`Regulator error`	The regulation unit is in error
	14	`Regulation on hold`	The regulation unit is active but holds the correction value.
	15	`Regulation Filter active`	The regulation filter is active.

As shown in the figure below, taken from the IEEE 488.2 standard, each of the registers above is a set of three registers:



- Condition Register
  Read-only register that is constantly updated to reflect the current state of the instrument.
- Event Register
  Transitions in a Condition Register are latched in the corresponding Event Register. Event Registers are cleared when read.
- Event Enable Register
  A mask indicating what bits in the Event Register are included in the Summary bit. The enable mask of the Status Byte is called the Status Enable register, and it determines which bits cause an RQS (ReQuest for Service).

In addition, transition filters are supported for the following register sets: QUEStionable, QUEStionable:BIT12, OPERation, OPERation:BIT11, and OPERation:BIT12. Transition filters are used to detect events with positive transitions (false to true) and/or negative transitions (true to false). By default, only positive transitions are detected.

Note that some Condition Register bits signal permanent conditions – for example Power On – and others signal transient events – for example, Command Error. Reading a Condition Register will provide no indication of transient events; only the corresponding Event Register will catch such events.

Also note that for efficiency reasons, status register updates are deferred to the extent possible, and are normally performed only at end of each sequence of commands separated by semicolons. This also means that a ReQuest for Service (RQS) is normally generated only at the end of such a sequence. There are exceptions to this deferral rule, for example if the command sequence includes a status-query command.

Finally, remark that the PT2026 supports multiple IEEE 488.2 connections, and that each connection uses its own set of status registers. Thus status bits that only affect one interface – for example Command Error – are not seen by the other interfaces. However, status bits that indicate general instrument status – in particular the QUEStionable and OPERation registers – are propagated to all interfaces. Using this feature, the OPERation:BIT11 registers can serve to broadcast parameter changes caused by any one interface.

4-2-3 IEEE 488.2 controls

The following low-level functions are defined by the VXI-11 and USBTMC-USB488 protocols. Excluded are the functions that are fundamental to the operation – e.g. in VXI-11: create_link, destroy_link, device_write, device_read, create_intr_chan, destroy_intr_chan, device_enable_srq, device_intr_srq, and device_abort.

Historically, the functions listed below correspond to dedicated hardware signals in IEEE 488.1 (HPIB or GPIB). Not all functions are supported in both VXI-11 and USBTMC-USB488. In addition, some of these functions are not supported on the PT2026; the Description column will note whether the function has no effect or whether it returns an error.

VXI-11	**USBTMC-USB488**	**Description**
`device_clear`	`INITIATE_CLEAR`	Clears the device input and output buffers
`device_trigger`	`TRIGGER`	Assert bus trigger
	`SRQ`	Requests service from host
`device_readstb`	`READ_STATUS_BYTE`	Read status byte
`device_remote`	`REN_CONTROL`	Remote Enable – no effect
`device_local`	`GO_TO_LOCAL`	Enable local controls – no effect
-	`LOCAL_LOCKOUT`	Disable local controls – no effect
`device_lock` `device_unlock`	-	Acquire or release the device's lock
`device_docmd`	-	Do special command – unsupported, returns error

4-2-4 IEEE 488.2 common commands

As any IEEE 488.2 compliant instrument, the PT2026 supports the following commands.

Command	Name	Description
*CLS	Clear status	Clear all event registers and queues (not enable registers) and error buffer
*ESE <value>	Program event enable	Program standard event enable register
*ESE?	Event enable query	Read standard event enable register
*ESR?	Event status query	Read standard event register and clear it
*IDN?	Identification query	Returns the following information: manufacturer; model; serial number; versions of hardware and firmware; and purchased options. Note: This query returns "Arbitrary ASCII Response Data" (see IEEE488.2 standard) and cannot be followed by another query in the same command sequence.
*OPC	Set operation complete	Set the operation complete bit in the standard event register after all commands have been executed
*OPC?	Operation complete query	Returns an ASCII "1" after all commands have been executed
*RST	Reset	Reset device to power-on configuration
*SRE <value>	Program status enable	Program status enable register Important: you must also enable service requests on the host. See Section 4-2-7 for details.
*SRE?	Status enable query	Read status enable register
*STB?	Status byte query	Read status byte register
*TRG	Trigger	Generate bus trigger
*TST?	Self-test Query	Perform complete self-test, return 0 if successful, 1 if not
*WAI	Wait-to-Continue	Wait until previous commands have completed

4-2-5 SCPI command syntax

In the command definitions below, the following conventions are used:

[] optional keywords or parameters

<> value

The abbreviated form of each command is written in capital letters. For example, the "MEASure" command can be written as "MEASURE" or "MEAS", or, since capitalization doesn't matter, "measure" or "meas".

Each command is presented with its subcommand(s) indented below it. For example:

:FETCh		
[:SCALar]		Fetch values acquired during last MEASure, READ or INITiate
[:FLUX]?	[<digits>]	Measured flux density
:SIGMa?	[<digits>]	Measurement deviation

According to this table, the following commands are legal:

:FETC:SCAL:FLUX?

:FETC? (same as above, omitting optional keywords)

:FETC:SIGM? (fetches measurement deviation)

The following special parameters are recognized:

MINimum

MAXimum

DEFault

The command syntax

<command>? MAXimum/MINimum[,…]

can be used to query the maximum or minimum values for all parameters of a command.

Some commands take a channel list parameter, to specify the probes to be used. The syntax of a channel list is specified in Section 8.3.2 of Volume 1 of the SCPI standard. In brief:

- Each channel is specified as a list of multiplexer ports separated by exclamation marks. For example "1!2" refers to the probe plugged into channel 2 of a second-level multiplexer plugged into channel 1 of the top-level multiplexer.
- A range of channels can be specified by separating the starting and ending channels with a colon. For example, "1!4:1!6" specifies channels 4 through 6 on the second-level multiplexer.
- An arbitrary list of channels and channel ranges can be specified by separating them with commas. For example, "1!2,1!4:1!6" specifies channels 2, 4, 5 and 6 on the second-level multiplexer.

- The channel list is opened by "(@" and closed by ")". For example: "(@1!2,1!4:1!6)".

Command parameters may be set to their default values by omitting them. To use a parameter after an omitted parameter, keep the commas as placeholders. For example, to measure channels 1 and 2 with the default search range:

MEASURE? ,,(@1,2)

Numeric parameters usually require units. Analogously, the values returned by queries contain units, as specified by the UNIT command. In addition, some units can have prefixes:

N = nano (10^{-9})

U = micro (10^{-6})

M = milli (10^{-3})

K = kilo (10^{3})

MA = mega (10^{6})

G = giga (10^{9})

The PT2026 recognizes the following units:

Base unit	**Multiplier**	**Description**
`T`	`N, U, M`	Tesla (default for magnetic field strength)
`GAUSS`	`U, M, K`	Gauss
`PPM`		Parts Per Million deviation: magnetic field strength, relative to a reference value set with the `:UNIT:PPMReference` command
`HZP`	`K, MA, G`	Magnetic field strength measurements: equivalent proton NMR resonant frequency
`HZ`	`K, MA, G`	Frequency. For magnetic field strength measurements: NMR resonant frequency for the probe being used.
`S`	`M, U, N`	Seconds
`V`	`M`	Volts

Any parameters whose units indicate magnetic field strength (T, GAUSS, PPM, HZP, HZ) use the units currently selected by the UNIT command.

4-2-6 SCPI command summary

The following tables list the legal commands for the PT2026, in alphabetical order:

Command	Parameters	Description
`:ABORt`		Stop execution of a command

Command	Parameters	Description
[:CALCulate]		Averaging control.
:AVERage1		NMR signal averaging. This is intended to reduce noise in the NMR signal. Measurements are performed on the averaged NMR signal. All subcommands are as for :CALCulate:AVERage2. Note: This command should only be used with very stable fields. Averaging signals with different frequencies can lead to very confusing behavior.
:AVERage2		NMR measurement averaging. This permits an estimate of the measurement stability. Without measurement averaging, :FETCh:SIGMa? returns NaN ("Not a Number"). A measurement is returned only after averaging.
:COUNt?	[MINimum|MAXimum|DEFault]	Query averaging count.
:COUNt	<value>| MINimum|MAXimum|DEFault	Set number of signals in average. The measurement is performed after this number of acquisitions. min = 1; max = 1000; default = 1.
[:STATe]?	[DEFault]	Query averaging enabled/disabled.
[:STATe]	<boolean>|DEFault	Enable/disable averaging. The default state is OFF.
:TCONtrol?		Query the termination control setting.

:TCONtrol	EXPonential|MOVing|REPeat	Specify action after <avg_count> signals: - EXPonential: $AVG_n = \frac{1}{k} X_n + \frac{k-1}{k} AVG_{n-1}$ where k = <avg_count> - MOVing: Moving window: oldest measurement is subtracted from average, and newest measurement is added. This action is not supported for :AVERage1. - REPeat: Clear the average and repeat. This is the default action.

<table>
<tr><th>Command</th><th>Parameters</th><th>Description</th></tr>
<tr><td>:CONFigure?</td><td></td><td>Returns string "<function><parameters>" with configuration set by the last CONF command or MEAS? query.</td></tr>
<tr><td>:CONFigure</td><td></td><td>Configure measurement and search parameters</td></tr>
<tr><td>[:MEASure]</td><td></td><td></td></tr>
<tr><td>:MODE?</td><td></td><td>Query measure mode.</td></tr>
<tr><td>:MODE</td><td>AUTO|MANual</td><td>- Automatic measure mode uses the default measurement settings.
- Manual mode uses the values set with the :CONFigure[:MEASure] commands.</td></tr>
<tr><td>:REJect?</td><td>[DEFault]</td><td>Query reject setting</td></tr>
<tr><td>:REJect</td><td><boolean>|DEFault</td><td>Enable or disable spurious signal rejection. The default state is ON.</td></tr>
<tr><td>:LEVel?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query detection level [V].</td></tr>
<tr><td>:LEVel</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Minimum level of NMR peak relative to average spectral noise [V].
min = 0, default = probe dependent, max = 32V.</td></tr>
<tr><td>:BANDwidth?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query frequency range [Hz].</td></tr>
<tr><td>:BANDwidth</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Frequency range around peak value used to fit response [Hz].</td></tr>
<tr><td>:POINts?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query number of fit points</td></tr>
<tr><td>:POINts</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Number of points used to fit the response.
min = 3, default = 8, max = 32.</td></tr>
<tr><td>:HYSTeresis?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query measurement hysteresis</td></tr>
<tr><td>:HYSTeresis</td><td><value>|
MINimum|MAXimum|DEFault</td><td>How many missing measurements to allow before aborting measurement mode.
min = 0, max = 100, default = 5.</td></tr>
<tr><td>:PROBe</td><td></td><td></td></tr>
<tr><td>:MODE?</td><td></td><td>Query matching/tuning mode.</td></tr>
</table>

:MODE	AUTO|MANual	- Automatic matching/tuning uses the probe's characteristic curves. - Manual matching/tuning sets the voltages manually
:MATChing?	[MINimum|MAXimum|DEFault]	Query matching voltage [V].
:MATChing	<value>| MINimum|MAXimum|DEFault	Set matching voltage [V]. min = 0, max = 30, default = 15.
:TUNing?	[MINimum|MAXimum|DEFault]	Query tuning voltage [V].
:TUNing	<value>| MINimum|MAXimum|DEFault	Set tuning voltage [V]. min = 0, max = 30, default = 15.
:SEARch		Configure search parameters.
:ENABle?	[DEFault]	Query search enable.
:ENABle	<boolean>	Enable or disable search. When enabled, the system sweeps frequency until it found an NMR signal. When disabled, the system operates at fixed frequency defined by :CONFigure:SEARch[:LIMit]:VALue. default = true.
:MODE?		Query search mode.
:MODE	AUTO|CUSTom|MANual	- Auto search mode steps through the specified search range with default search parameters. - Custom search mode is as the Auto mode but uses the custom user search level and frequency step parameters. - Manual search mode sets the RF frequency where a search is to be performed.
:FSTEp?	[MINimum|MAXimum|DEFault]	Query frequency step [Hz].
:FSTEp	<value>| MINimum|MAXimum|DEFault	Frequency step, used in CUSTom search mode [Hz]. Zero indicates default step size, as computed from probe data. min = 1e3, max = 60e3, default = 10e3, digits = 3

<table>
<tr><td>:HALLenable?</td><td>[DEFault]</td><td>Query Hall enable.</td></tr>
<tr><td>:HALLenable</td><td><boolean></td><td>Enable or disable using the Hall value to assist the NMR resonance search.
default = true.</td></tr>
<tr><td>[:LIMit]</td><td></td><td>min, max, default: those for the active probe.</td></tr>
<tr><td>:HIGH?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query maximum field value [UNIT?].</td></tr>
<tr><td>:HIGH</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Maximum field value [UNIT?].</td></tr>
<tr><td>:LOW?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query minimum field value [UNIT?].</td></tr>
<tr><td>:LOW</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Minimum field value [UNIT?].</td></tr>
<tr><td>:VALue?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query fixed field value [UNIT?].</td></tr>
<tr><td>:VALue</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Fixed field value, when search is disabled [UNIT?].</td></tr>
<tr><td>:TRACking</td><td></td><td>Field-tracking parameters.</td></tr>
<tr><td>[:LIMit]</td><td></td><td>min, max, default: those for the active probe.</td></tr>
<tr><td>:HIGH?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query maximum IF [Hz].</td></tr>
<tr><td>:HIGH</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Max intermediate frequency [Hz].
min = 800, max = 150e3, default = 150e3</td></tr>
<tr><td>:LOW?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query minimum IF [Hz].</td></tr>
<tr><td>:LOW</td><td><value>|
MINimum|MAXimum|DEFault</td><td>Min intermediate frequency [Hz].
min = 800, max = 150e3, default = 800</td></tr>
<tr><td>:HYSTeresis?</td><td>[MINimum|MAXimum|DEFault]</td><td>Query tracking hysteresis.</td></tr>
<tr><td>:HYSTeresis</td><td><value>|
MINimum|MAXimum|DEFault</td><td>How many measurements to allow outside the range before correcting the RF frequency.
min = 0, max = 1000, default = 0.</td></tr>
</table>

Command	Parameters	Description
:DIAGnostic :UPGRade [:INITiate]		Initiate a firmware upgrade. The PT2026 will disconnect from the USB bus and reconnect as a DFU (Device Firmware Upgrade) device,[2] with the following alternate settings: CODE, DATA, CPLD and HWINFO.
:LOG[:DATA]?		Read the debug log. Note: if the PT2026 detects an irrecoverable error, it attempts to write the debug log to non-volatile memory. (/yaffs/user/DebugLog.txt).

NOTICE
The :DIAGnostic commands are intended for use by the manufacturer only. They can cause your PT2026 to become nonoperational.

[2] See "Universal Serial Bus Device Class Specification for Device Firmware Upgrade," Version 1.1, Aug 5, 2004, available from www.usb.org/developers/devclass_docs/DFU_1.1.pdf.

Command	Parameters	Description	Binary Format
:FETCh			
[:SCALar]		Fetch data values acquired during last MEASure, READ or INITiate. The following actions invalidate previously acquired data: - Reset; - Continuous trigger initiation; and - Changing trigger parameters. <digits>: return at least the requested number of significant digits. min = 1, max = 16, default = Flux 9, Sigma 4, Uniformity 3	
[:FLUX]?	[<digits>]	Measured flux density [UNIT?].	f64
:SIGMa?	[<digits>]	Standard deviation of measurement [ppm]. Standard deviation of measurement. [ppm]. Note: Returns NaN ("Not a Number") if :CALCulate:AVERage2 is not enabled.	f32
:UNIFormity?	[<digits>]	Rough measure of field uniformity (0 to 1).	f32
:CHANnel?		Channel selected for measurement [FORMat?].	u8, 0 separated
:TIMestamp?		Time stamp [ms].	u64
:STATus?		1 if measurement was questionable, 0 otherwise.	u8
:IFRequency?	[<digits>]	Measured intermediate frequency [Hz]	f64
:RELaxation?	[<digits>]	Measured relaxation time [s]	f32
:RFFRequency?	[<digits>]	Radio frequency [Hz]	f64

:SPRogress?		Search progress: percentage done, and Hall value if present, -1 otherwise. Only useful when a search is initiated. [%, UNIT?].	u8, f32

:ARRay		Fetch values acquired during the last MEASure:ARRay or READ:ARRay. <size> must be no greater than the acquisition size. If FORMat is ASCii, returns a comma-separated list of values. The other parameters are as for :FETCh:SCALar.	
[:FLUX]?	<size>[,<digits>]	Measured flux density [UNIT?].	f64
:SIGMa?	<size>[,<digits>]	Standard deviation of measurement. [ppm]. Note: Returns NaN ("Not a Number") if :CALCulate:AVERage2 is not enabled.	f32
:UNIFormity?	<size>[,<digits>]	Rough measure of field uniformity (0 to 1).	f32
:CHANnel?	<size>	Channel selected for measurement [FORMat?].	u8, 0 separated
:TIMestamp?	<size>	Time stamp [ms].	u64
:STATus?	<size>	For each measurement: 1 if questionable, 0 otherwise.	u8
:NMRSignal?	<size>	Return <size> samples of the last NMR IF signal acquired. The first datum returned is the sample period in seconds.	Period: f32 Sample: f32
:FFTBuffer?	<size>	Return <size> samples of the last FFT buffer. The first datum returned is the frequency resolution in Hz.	Resolution: f32 Sample: f32
:SPECtrum?	<size>	Return <size> samples of the peak spectrum. The first two data returned are the center frequency and the frequency resolution in Hz.	Center: f32 Resolution: f32 Sample: f32
:FIT?	<size>	Return <size> polynomial coefficients, starting at degree 0. The first datum returned is the residue.	Residue: f32 Coeffs: f32

Command	Parameters	Description
:FORMat		
[:DATA]?		Query data output format
[:DATA]	ASCii|INTeger	Set format for returned data. ASCii by default. INTeger returns an IEEE488.2 definite-length block, consisting of an 8-byte header of the form "#6nnnnnn" and followed by nnnnnn bytes of binary data. For the flux density and standard deviation, binary data consists of 64-bit little-endian floating-point values. The binary representation of a channel is a 16-bit little-endian unsigned integer, with channel numbers as defined in Section 4-3-2. The relevant commands are flagged with "[FORMat?]". The binary representation of a timestamp is a 64-bit unsigned integer [ms].

Command	Parameters	Description
:INITiate		Start measurements. Note: This command is overlapped; in other words, other commands can be processed while initiated. Moreover, it does not affect the No Operation Pending Flag; in other words, it does not force *OPC, *OPC? and *WAI to wait for the INITiate to complete.
[:IMMediate]		
[:ALL]		Enable trigger with trigger source, trigger count and trigger period set by TRIGger commands
:CONTinuous?	[DEFault]	Query continuous-trigger state
:CONTinuous	<boolean>|DEFault	Set continuous-trigger state, where the trigger is automatically re-enabled after each acquisition. OFF by default.

Command	Parameters	Description
:INPut		
:CLOCk[:SOURce]?		Queries the clock source.
:CLOCk[:SOURce]	INTernal|EXTernal	Selects the source of the reference clock. If configured as INTernal, the output from the OCXO, divided by 2, is presented at the Clock connector. For EXTernal, the Clock connector is configured as input. The default is EXTernal; thus if an external clock is connected, it is used; otherwise the OCXO is used.

Command	Parameters	Description
:MEASure		Abort any pending triggers and perform measurements using the default search and measurement parameters.
[:SCALar]		
[:FLUX]?	[<expected_value>] [,<digits>] [,<channel_list>]	Perform a single measurement. <expected_value> serves to constrain the NMR signal search; by default the full range of all active probes is searched [UNIT?]. <digits> defines the number of significant digits to return for ASCii FORMat; the default is 9. The PT2026 searches for an NMR signal on each channel in <channel_list>, in order, and will start measuring on the first channel where it finds a signal. The default channel list is defined by the ROUTe command, or else contains all connected probes.
:ARRay		
[:FLUX]?	<size> [,<expected_value>] [,<digits>] [,<channel_list>]	Perform a series of <size> measurements. The other parameters are as for the :MEASure:SCALar command.

Command	Parameters	Description
:MMEMory		Manipulate parameter files.
[:CATalog]?		Read the file directory. Returns: - Total bytes used - Total bytes available - File entries consisting of: - File name - File type - File size
:DATA?	<filename>	Read the contents of the given file.
:DATA	<filename>,<data>	Write the contents of the given file. Note: <filename> must be a path starting with "/yaffs/user/".
:DELete	<filename>	Delete the given file.
:LOAD		
[:STATe]	<value>,<filename>	Load the given parameter file. Since the PT2026 does not support the *SAV/*RCL commands, <value> must be 0.
:STORe		
[:STATe]	<value>,<filename>, ALL|COMMunication|MEASure|TRIGger|REFClk|UNITs	Store the specified subset of the current parameters. <value> must be 0.

Command	Parameters	Description
:OUTPut[:TRIGger]		Configure Trigger Output signal. The output is initiated by TRIGger:SEQuence2.
[:STATe]?	[DEFault]	Query the Trigger Output state.
[:STATe]	<boolean>|DEFault	Enable or disable the Trigger Output signal.
:IMMediate		Force Trigger Output signal, as if the field had gone above the threshold.
:SHAPe?	[DEFault]	Query Trigger Output shape
:SHAPe	DC|PULSe|DEFault	Set Trigger Output signal shape: - DC: Logic level, depending on POLarity - PULSe: Pulse at transition, as defined by WIDTh and POLarity
:POLarity?	[DEFault]	Query trigger polarity
:POLarity	NORMal|INVerted	Set the polarity of the trigger signal. For pulse output, NORMal is a positive-going pulse. For DC output, NORMal is low level when the field is below the threshold, high level when it is above.
:WIDTh?	[MINimum|MAXimum|DEFault]	Query trigger pulse width [s]. Valid only if SHAPe = PULSe.
:WIDTh	<value>| MINimum|MAXimum|DEFault	Pulse width [s]. min = default = 1 ms, max = $2^{32} – 1$ ms
:DELay?	[MINimum|MAXimum|DEFault]	Query trigger output signal hold-off [s]
:DELay	<value>| MINimum|MAXimum|DEFault	Output signal hold-off [s]. min = default = 0 ms, max = $2^{32} – 1$ ms

Command	Parameters	Description
:READ		Abort any pending triggers and perform measurements using the current search, measurement and routing parameters.
[:SCALar]		
[:FLUX]?	[<expected_value>] [,<digits>] [,<channel_list>]	Perform a single measurement. <expected_value> serves to constrain the NMR signal search; by default the full range of all active probes is searched [UNIT?]. <digits> defines the number of significant digits to return for ASCii FORMat; the default is 6. The PT2026 searches for an NMR signal on each channel in <channel_list>, in order, and will start measuring on the first channel where it finds a signal. The default channel list is defined by the ROUTe command, or else contains all connected probes.
:ARRay		
[:FLUX]?	<size> [,<expected_value>] [,<digits>] [,<channel_list>]	Perform a series of <size> measurements. The other parameters are as for the :READ:SCALar command.
:REGUlation	Regulation unit related commands are described in the **RG8026 User Manual**. The Regulation unit is an option that isn't part of the standard PT2026 and must be ordered separately.	

Command	Parameters	Description
:ROUTe		Multiplexer control
:CLOSe	<channel_list>	Select active channels. The PT2026 will search for an NMR signal on each of these channels, in order, and will start measuring on the first channel where it finds a signal.
:STATe?		Returns list of selected channels [FORMat?].
:ACTive?		Returns the current active probe [FORMat?].
:PROBe		Returns information for the probe connected to the given channel(s)
:MODel?	<channel_list>	Model
:SERialno?	<channel_list>	Serial number
:DESignation?	<channel_list>	Designation
:MINimum?	<channel_list>	Minimum field [UNIT?].
:MAXimum?	<channel_list>	Maximum field [UNIT?].
:SCAN?		Returns an array of all channels which have a probe connected [FORMat?].
:HALL		Return the Hall sensor reading. If the probe has no Hall sensor, this command returns an error.
[:CALibrated]?		Return Bx, By, Bz, B, calibrated
:RAW?		Return Bx, By, Bz, B, uncalibrated
:LOWLevel?	<message>	Send the given message to the probe/multiplexer system, and return the response. The message is encoded as "arbitrary block program data" (see Section 7.7.6 of IEEE 488.2 standard). The first byte of the response is the returned status: 0 = No error 11 = Write error 12 = Read error 47 = Firmware failure

`:MMEMory:DATA?`	<channel_list>	Read a peripheral's rewritable memory. Note: channel list must contain exactly one channel.
`:MMEMory:DATA`	<channel_list>,<data>	Write a peripheral's rewritable memory. The data is encoded as "arbitrary block program data" (see Section 7.7.6 of IEEE 488.2 standard). Note: channel list must contain exactly one channel.

NOTICE
The :ROUTe:LOWLevel?, :ROUTe:MMEMory:DATA?, and :ROUTe:MMEMory:DATA commands are intended for use by the manufacturer only. It can cause your PT2026 to become nonoperational.

Command	Parameters	Description
[:SENSe]		
:SWEep		Set/query digitization parameters
[:MODE]?		Query sweep mode
[:MODE]	AUTO|MANual	Compute the sweep time automatically, or set it manually.
:OFFSet		Set/query offset used to mask the transient at the beginning of the NMR signal, caused by the transmit pulse.
:TIME?	[MINimum|MAXimum|DEFault]	Query offset [s].
:TIME	<value>| MINimum|MAXimum|DEFault	Set offset [s]. min = 0, max = 100 ms, default = 70 us
:TIME?	[MINimum|MAXimum|DEFault]	Query sweep time [s].
:TIME	<value>| MINimum|MAXimum|DEFault	Set sweep time [s]. min = 1 µs, max = 100 ms, default = 10 ms
:FREQuency?	[MINimum|MAXimum|DEFault]	Query digitization rate [Hz].
:FREQuency	<value>| MINimum|MAXimum|DEFault	Set digitization rate [Hz]. min = 1 kHz, max = 1 MHz, default = 1 MHz

Command	Parameters	Description
[:SOURce]		
:PULSe		Set/query the RF pulse parameters
[:MODE]?		Query pulse mode.
[:MODE]	AUTO|MANual	Determines whether the pulse width and period are calculated automatically from the probe information, or set manually.
:PERiod?	[MINimum|MAXimum|DEFault]	Query RF pulse period [s].
:PERiod	<value>| MINimum|MAXimum|DEFault	Set RF pulse period [s]. min = 30 ms, max = 5 s, default = 100 ms
:WIDTh?	[MINimum|MAXimum|DEFault]	Query RF pulse width [s].
:WIDTh	<value>| MINimum|MAXimum|DEFault	Set RF pulse width [s]. min = 1 µs, max = 200 µs, default = 25 µs

Command	Parameters	Description
:STATus		
:OPERation | :OPERation:BIT<n> | :QUEStionable | :QUEStionable:BIT<n>		Register set to query/set
[:EVENt]?		Read and clear event register
:CONDition?		Read condition register
:ENABle?		Query enable register
:ENABle	<numeric_value>	Set enable register
:NTRansition?		Query negative transition filter
:NTRansition	<numeric_value>	Set negative transition filter
:PTRansition?		Query positive transition filter
:PTRansition	<numeric_value>	Set positive transition filter
:PRESet		Reset OPERation and QUEStionable enable registers

Command	Parameters	Description
:SYSTem		
:CDATe?		Return calibration date in the following: YYMMDD
:CDATe	<date>	Set new calibration date, given in the following format: YYMMDD
:COMMunicate		Definitions for communication
:ETHernet		Ethernet parameters
[:ENABle]?	[DEFault]	Query whether Ethernet is enabled
[:ENABle]	<boolean>|DEFault	Enable or disable Ethernet default = enabled
:IDENtifier?		Query system identifier
:IDENtifier	<string>	Set system identifier, used for DNS and NBNS
:ADDRess?		Query IP network address
:ADDRess	AUTO|<IP_address>	Set IP network address If AUTO, use DHCP to obtain the IP address, network mask, broadcast address, gateway address, and DNS server address.
:MASK?		Query IP network mask
:MASK	<network_mask>	Set IP network mask
:BROadcast?		Query IP broadcast address
:BROadcast	<broadcast_address>	Set IP broadcast address
:GATeway?		Query IP gateway address
:GATeway	<gateway_address>	Set IP gateway address
:DNSServer?		Query DNS server IP address
:DNSServer	<DNS_server_address>	Set DNS server IP address
:DOMain?		Query domain name
:DOMain	<domain_name>	Set domain name
:NBNS?	[DEFault]	Query whether NBNS is enabled
:NBNS	<boolean>|DEFault	Enable or disable NBNS default = enabled
:RESTart		Restart with new parameters
:MODBus		

[:ENABle]?	[DEFault]	Query whether the MODBUS interface is enabled.
[:ENABle]	<boolean>|DEFault	Enable or disable the MODBUS interface. default = disabled
:HOSTs?		Query allowed host IP numbers
:HOSTs	<string>	Set allowed host IP numbers. List separated by spaces.
:NCONnections?	[MINimum|MAXimum|DEFault]	Query allowed number of connections
:NCONnections	<value>| MINimum|MAXimum|DEFault	Set allowed number of connections default = 1
:F32?	[DEFault]	Query whether 32-bit floating-point numbers are returned.
:F32	<bool>|DEFault	Select whether 32-bit floating-point numbers are returned. default = false
:USBTmc		
[:ENABle]?	[DEFault]	Query whether the USBTMC-USB488 interface is enabled.
[:ENABle]	<boolean>|DEFault	Enable or disable the USBTMC-USB488 interface. This interface is always enabled at system startup. default = enabled.
:VXI11		
[:ENABle]?	[DEFault]	Query whether the VXI-11 interface is enabled.
[:ENABle]	<boolean>|DEFault	Enable or disable the VXI-11 protocol on the Ethernet interface. default = enabled
:ERRor		
[:NEXT]?		Query error queue
:HELP		Instrument's help utilities for programmer
:HEADers?		Lists all available commands
:SYNTax?	<command_header>	Lists syntax for a command

:LOCK		Lock out other host interfaces
:REQuest?		Attempts lock and returns 1 if successful, 0 if it fails
:RELease		Release lock
:MDATe?		Return manufacturing date in the following: YYMMDD
:POFF	<boolean>|DEFault	If true, reboot the system; if false, power it off. default = false.
:TEMPerature?		Query the temperature inside the instrument case
:VERSion?		Query SCPI version (e.g. 1999.0)

Command	Parameters	Description
:TRIGger		
[:SEQuence1]		TRIGger:SEQuence1 initiates a measurement.
:COUNt?	[MINimum|MAXimum|DEFault]	Query trigger count
:COUNt	<value>| MINimum|MAXimum|DEFault	Set the number of triggers required to complete an acquisition. min = 1, max = 2048, default = 1 Note: Resets the trigger system.
:SLOPe?		Query the trigger slope for External trigger.
:SLOPe	POSitive|NEGative	The trigger slope for External Trigger.
:SOURce?	[DEFault]	Query trigger source
:SOURce	IMMediate|TIMer|BUS| EXTernal|DEFault	Trigger source: - IMMediate = no wait - TIMer = periodic trigger - BUS = VXI-11 or USB488 - EXTernal = trigger input default = IMMediate Note: Resets the trigger system.
:TIMer?	[MINimum|MAXimum|DEFault]	Query trigger timer [s].
:TIMer	<value>| MINimum|MAXimum|DEFault	Set period for Timer trigger [s]. min = 1 ms; max = 86400 ms; default = 200 ms; resolution = 1 ms Note: Resets the trigger system.

Command	Parameters	Description
:TRIGger		
:SEQuence2		TRIGger:SEQuence2 generates a Trigger Output signal. Note: TRIGger:SEQuence2 (Trigger Out) is mutually exclusive with TRIGger:SEQuence1:SOURce = EXTernal (Trigger In).
:LEVel?	[MINimum|MAXimum|DEFault]	Query the trigger level [UNIT?].
:LEVel	<value>| MINimum|MAXimum|DEFault	The measurement value at which Trigger Output is activated [UNIT?]. min = 0, max = 100, default = 0
:SLOPe?		Query the trigger slope.
:SLOPe	POSitive|NEGative|EITHer	Select Trigger Output on a rising measurement, a falling measurement, or either.

Command	Parameters	Description
:UNIT?	[DEFault]	Query units
:UNIT	T|MT|GAUSS|KGAUss|PPM|MAHZP|MAHZ|DEFault	Set units for the measurement results, or any flux-density parameter (marked as "[UNIT?]"). Supported units: T: Tesla mT: mTesla (1T=10^3 mT) G: Gauss (1T=10^4 G) kG: kGauss (1T=10 kG) ppm: parts per million (relative to value set in "Configure PPM Reference.vi") MHz: NMR frequency (depends on gyromagnetic ratio of sample material) MHz-p: proton equivalent NMR frequency (1T ≈ 42.5775 MHz-p) default = T
:ALL?		Return a list of all the units supported by this instrument, followed by the divisor for each set of units. The divisor converts T to the associated units.
:PPMReference?	[MINimum|MAXimum|DEFault]	Query reference value for ppm [UNIT?].
:PPMReference	<value>| MINimum|MAXimum|DEFault	Set reference value for ppm [UNIT?]. min = 0, max = 100, default = 1

4-2-7 Programming hints

Here are a few notes on how the native command set is intended to be used:

- For simple measurements with the standard settings, use the MEASure? command. MEASure:ARRay? is the same, except it returns a time series.
- The "expected value" parameter can be used to minimize the search.
- When given a channel list, MEASure? tries to measure on each of the specified channels. This is useful for groups of probes with different field ranges used to measure a single magnet. Preference is given to channels

with previous successful measurements, and the result from the first channel with a successful measurement is returned. Use :FETCh:CHANnel? to know which channel was measured.

- Use the UNIT command to set the units in which the results are returned, and the "digits" parameter to control the number of significant figures returned (assuming FORMat is ASCii).
- For measurements with non-standard parameters, do a CONFigure, INPut, ROUTe, SWEep, SOURce and/or PULSe, followed by a READ. As with MEASure, READ:ARRay? returns a time series. The optional parameters act as for MEASure.
- Use the TRIGger:SEQuence1 commands to control the measurement timing. As trigger source, you can select "IMMediate", an internal timer, a trigger command sent from the host, or an external Trigger In signal. After setting up the trigger source, you initiate a measurement using the INITiate command. The CONTinuous option immediately re-initiates an acquisition when the previous one has completed.
- Use the :CALCulate:AVERage commands to control averaging. The PT2026 supports averaging of the NMR signal, or averaging of the resulting measurement. Any combination of signal- and measurement averaging is supported. Averaging is only effective for a stable field.
- The measurement integration time depends on the trigger and the measurement averaging options:
- If CALCulate:AVERage2:TCONtrol = REPeat, the measurement average is computed from a block of new measurements initiated by the trigger.
- Otherwise, for EXPonential and MOVing mode averaging, the average is computed from one new measurement, initiated by the trigger, plus older measurements that have been acquired in the course of signal tracking (and may never have been returned to the user).
- Use the :OUTPut[:TRIGger] commands to configure an output trigger signal when the measured field value crosses a certain threshold. Use the TRIGger:SEQuence2 commands to initiate the output trigger. Note that the

Trigger In function (TRIGger:SEQuence1:SOURce = EXTernal) is mutually exclusive with the Trigger Out function.

- Use the FETCh command to retrieve all data corresponding to a preceding MEASure?, READ? or INITiate command, or FETCh:ARRay for the data corresponding to a MEASure:ARRay?, READ:ARRay? or INITiate with TRIGger:COUNt > 1. The NMR signal and intermediate signal analysis results corresponding to the last measurement can be retrieved with the FETCh:ARRay:NMRSignal? / FFTBuffer? / SPECtrum? / FIT? commands.
- The ROUTe:CLOSe command does the same thing as the channel list in the MEASure and READ commands. The syntax of the channel list is specified by Volume 1 of the SCPI standard, Section 8.3.2. For example, ROUTe:CLOSe (@1) selects channel 1, and ROUTe:CLOSe (@2!3) selects channel 3 on a secondary mux attached to channel 2 of the primary mux. Colons are used for ranges of channels; for example, ROUTe:CLOSe (@3:5) sets up to measure channel 3, 4 or 5. Commas are used to enumerate several channels or channel ranges; for example, ROUTe:CLOSe (@1,2) sets up to measure channel 1 or channel 2.
- Use ROUTe:SCAN? to find all channels with a probe attached. Use ROUTe:PROBe to retrieve information about a probe.
- To determine whether an NMR signal has been found, check the OPERation status register. By setting the appropriate Operation Status Enable bit, plus the OSB (Operation Summary Bit) in the Status Enable register, you can generate a ReQuest for Service (RQS) when the PT2026 enters a given state.
- Using the *OPC command, you can also generate a ReQuest for Service (RQS) when a measurement (or any other action) is complete. Set bit 0 of the Standard Event Enable register and the ESB (Event Summary Bit) in the Status Enable register. Now, the execution of an *OPC command will generate an RQS.
- Be sure to check the status after every command. The Standard Event Status register provides a general idea of what went wrong, and the message on the Error/Event Queue (retrieved by SYSTem:ERRor?)

provides a detailed diagnostic. See Section 4-2-8 for the exact interpretation of these error messages. It may be convenient to set up the Enable bits to generate a ReQuest for Service (RQS) when an error is encountered.

- On the USBTMC host interface, if you program the instrument to generate an RQS, it is very important to Enable Service Requests on the host. This posts a read on the appropriate USB endpoint, the Interrupt endpoint. In the USB protocol, the host initiates all transfers; so if the host has not posted a read, the instrument cannot complete its RQS transfer. This will block the Interrupt endpoint, and any other commands using this endpoint – notably the USBTMC-USB488 Read Status Byte function – will fail.
- The MMEMory commands are used to manipulate XML-format parameter files. The user can store custom parameters – e.g. user-friendly channel names – that they would like to store with the instrument.
- Two host interfaces can be synchronized using the STATus:OPERation:BIT11 register. Enable the bits of interest in STATus:OPERation:BIT11, bit 11 in STATus:OPERation, and the OSB in the Status Byte; now, a Service Request (SRQ) will be generated whenever the configuration of one of the corresponding subsystems changes. The application must then read STATus:OPERation:BIT11 to identify which subsystem is affected. Finally, the updated value of these parameters can be read back using the appropriate query. Note that since reading the STATus:OPERation:BIT11 register also resets it, this technique does not work for more than two host interfaces.

4-2-8 Error codes

Error codes returned by the native host interfaces are numbered according to the SCPI standard. Sections 21.8.9 through 21.8.16 of Volume 2 of the SCPI manual, "Command Reference", provide a generic description of all possible error codes. In general, the codes are between -800 and 300. This chapter describes only the error codes produced by the PT2026, and the circumstances that might produce each error.

0	**NO ERROR**	Zero indicates no error.
-100	**COMMAND ERRORS**	
-102	Syntax error	The command header did not match any of the known commands.
-104	Data type error	A parameter within the command was of a type invalid for the command.
-115	Unexpected number of parameters	The wrong number of parameters was given in the command.
-120	Numeric data error	<value> parameter to :MMEMory:LOAD or STORe is non-zero.
-123	Exponent too large	The command contains a numeric parameter that was too large to be stored internally. This occurs if the value has an exponent greater than ±43.
-151	Invalid string data	The parameters in the command contain an unmatched single or double quote, or invalid setting type in :MMEMory:STORe.
-171	Invalid expression	The parameters in the command contain an unmatched bracket.
-200	**EXECUTION ERRORS**	
-200	Execution error	*CLR or :ABORt has failed, for an unknown reason.
-210	Trigger error	Input trigger failed, for an unknown reason.
-221	Settings conflict	Indicates that a legal program data element was parsed but could not be executed due to the current device state: • Conflicting parameters – see Figure 1. • Received bus trigger, but not in bus trigger mode. • Changing Trigger Out parameters while measuring. • Changing clock source while measuring. • Starting a measurement while already measuring. • Changing measurement parameters while measuring. • Loading new parameters while measuring. • Scanning probes or changing channels while measuring. • Disabling the active interface. • Setting ppm reference in ppm units.
-222	Data out of range	Indicates that a legal program data element was parsed but could not be executed because the interpreted value was outside the legal range as defined by the device.
-225	Out of memory	The device has insufficient memory to perform the requested operation.
-240	Hardware error	DSP firmware failed to boot.

-257	File name error	• Filename parameter of :MMEMory:DATA? query is empty. • Filename parameter of :MMEMory:DATA command does not start with "/yaffs/user/". • Filename parameter of :MMEMory:DELete command does not start with "/yaffs/". • Filename parameter of :MMEMory:LOAD command does not start with "/yaffs/settings/". • Filename parameter of :MMEMory:STORe command is a path.
-300	**DEVICE-DEPENDENT ERRORS**	
-350	Queue overflow	A specific code entered into the queue in lieu of the code that caused the error. This code indicates that there is no room in the queue and an error occurred but was not recorded.
-365	Time out error	DSP is not responding.
-400	**QUERY ERRORS**	
-400	Query error	Generic query error: reset in progress?
-410	Query INTERRUPTED	The host has sent a new command before finishing reading the response to a preceding query.
-420	Query UNTERMINATED	The host is trying to read a response without having sent a complete query.
-440	Query UNTERMINATED after indefinite response	Indicates that a query was received in the same program message after a query requesting an indefinite response was executed. On the PT2026, the only command returning an indefinite response ("Arbitrary ASCII Response Data") is *IDN.
100	**INSTRUMENT-DEPENDENT COMMAND ERRORS**	
101	Invalid value in list	One or more values in a numeric list parameter are invalid, e.g. floating point when not allowed.
102	Wrong units for parameter	A parameter within the command has the wrong type of units for the command.
103	Invalid number of dimensions in channel	The channel list provided refers to more layers of multiplexers than allowed.
104	Error in channel list	The channel list provided is not valid.
105	Numeric suffix invalid	Too many numeric suffixes, or one or more numeric suffix in the command is invalid, e.g. out of range.
200	**INSTRUMENT-DEPENDENT EXECUTION ERRORS**	
200	Software Error	The firmware has encountered an unexpected error.
201	No probe	No probe is plugged in.
202	No selected channel	No channel has been specified.
203	Invalid channel list	Channel specification is invalid.
204	Data not all available	The user is trying to fetch more data than was acquired.

205	Topology changed	The channel topology has changed: probes and/or multiplexers have been plugged or unplugged.

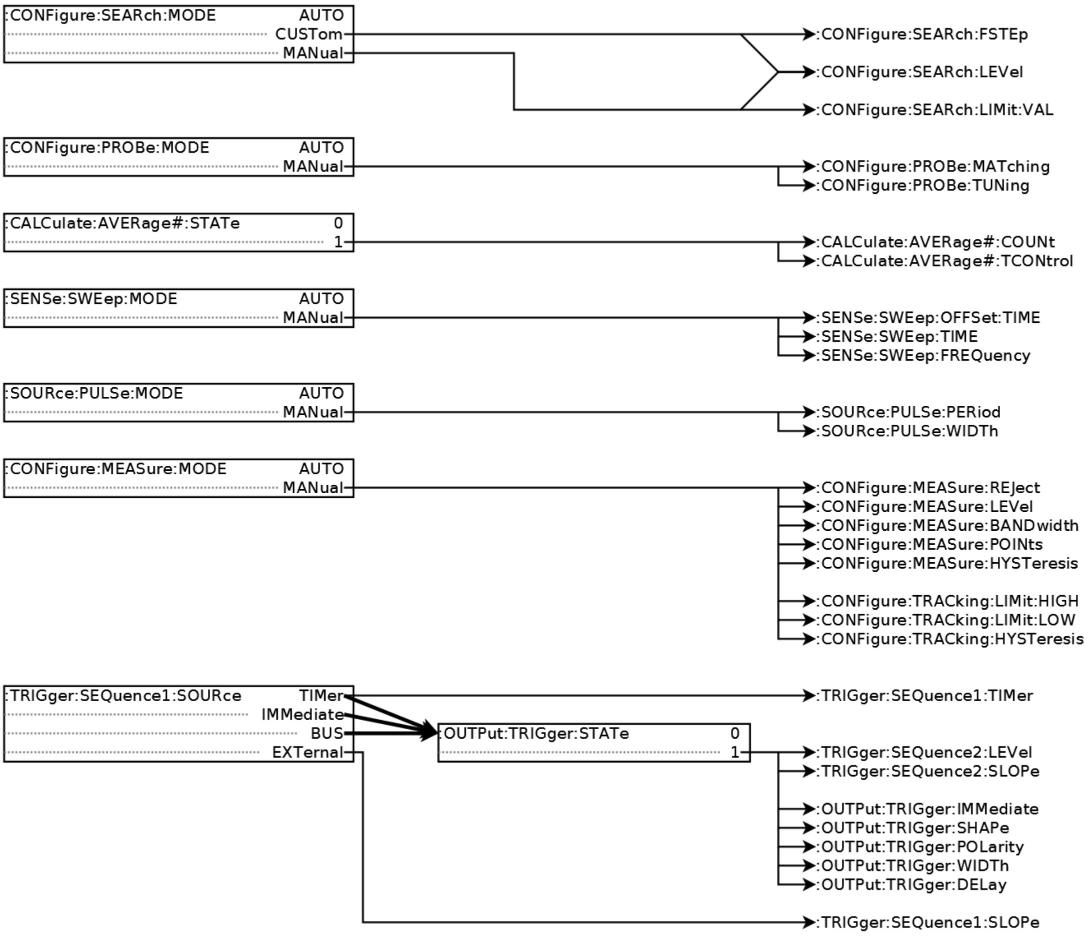


Figure 1. Parameter compatibility matrix.

4-3 MODBUS INTERFACE

NOTICE
• The MODBUS interface protocol is not yet implemented.

4-3-1 Operational overview

- The PT2026 acts as a MODBUS TCP/IP server.
- For each channel to be measured, a set of Holding Registers contains the corresponding parameters for INPut, SOURce:PULSe, SENSe:SWEep, CONFiguration, CONFigure, CALCulate:AVERage1 and CALCulate:AVERage2. Each channel is mapped to a known Holding

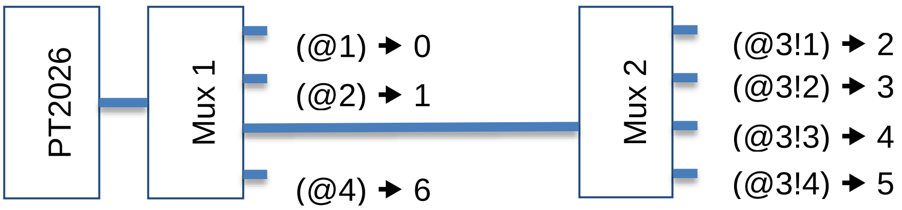
Register address according to a well-defined channel map (see Section 4-3-2).

- The MODBUS module in the PT2026 will continuously scan the specified channels. The results of these measurements consist of:
    - the field value
    - the standard deviation
    - the time stamp.
- These results are stored in a set of Input Registers, available at any time for read-out. The Input Registers are mapped to channels in the same order as the Holding Registers. Initially, the Input Registers will return a time stamp of zero, allowing the host to determine whether a valid measurement is available yet.
- The Input Registers also contain the model and serial number of the attached probe. By reading these, the host can determine which channels can be activated.
- Bit-access, via "Discrete Inputs" and "Coils," is not used.
- Floating-point numbers are by default IEEE 64 bit format, and are mapped onto four 16-bit MODBUS registers using the big-endian convention. Optionally, they can be returned in IEEE 32 bit format; in this case, each floating-point number is mapped into the 32 MSBs of the allotted 64-bit slot. No assumption should be made concerning the contents of the unused 32 bits.
- Integers are mapped onto a single 16-bit register.
- The time stamp, indicating the end of the measurement, is an unsigned 32-bit tick count, where each tick is a ms. It is mapped onto two 16-bit registers, using the big-endian convention.
- Strings – for example the probe model – are written into successive 16-bit registers, using the big-endian convention, and are terminated by a null character.
- The MODBUS interface provides the following security features:

    - Other interfaces (VXI-11 and USBTMC) can be disabled. The USBTMC interface will be automatically re-enabled upon power-up, to avoid locking up an instrument completely.
    - The PT2026 can be constrained to accept MODBUS commands only from a limited set of IP addresses. This configuration option must be set through the native interface.
    - The number of simultaneous connections is limited, by default to one. This parameter can be changed through the native interface. Attempted connections that exceed this limit will be refused. Each connection is maintained until terminated by the client.
- A saved instrument configuration can be read out and written back via one of the native interfaces. The output is an XML file that the PT2026 writes to flash memory to save its state. Using this file, a clever programmer could also automatically generate a SCADA configuration corresponding to the PT2026 configuration. Note, however, that the XML file is an undocumented internal interface whose format may change in future releases of the firmware.
- The following PT2026 features are not supported by the MODBUS interface:
    - Control over the time of measurement – be it programmatically, via a timer, via a bus trigger, or via the Trigger Input signal.
    - Detailed status of each measurement
    - Service requests (interrupts)
    - Results in units other than Tesla
    - Results in a format other than binary
    - Reading the NMR signal
    - Generating a Trigger Output signal
    - Changing the Ethernet communications parameters
    - Firmware upgrades
- Note that all these features continue to be available via the native VXI-11 or USBTMC interfaces.

4-3-2 Channel mapping

If one considers the multiplexers and their channels as a tree rooted at the PT2026, the channels are mapped to MODBUS registers in the order of a depth-first traversal of this tree. A simple example with two levels of multiplexers illustrates the relation of the SCPI "channel list" notation to the MODBUS channel map:



The same channel map is used for the Holding and Input Registers. The PT2026 MODBUS module supports up to 511 channels.

4-3-3 Holding register map

The Holding Registers are read/write registers that control the overall system operation and the operation of each channel. Each register is 16 bits. MODBUS supports up to 64K Holding Registers; this address space is divided into 512 blocks of 128 registers.

The first block controls overall system parameters:

Address	**Content**
0 – 9	System Identifier (`:SYSTem:IDENtifier?`)
100	Operation mode:
	0 = Standby, 1 = Measure, 2 = Reset, 3 = Reset to factory defaults
110	Security options (may be cumulated):
	0x0001 = Disable USBTMC interface
	0x0002 = Disable VXI-11 interface
120	Other options (may be cumulated):
	0x0001 = Return 32-bit floats instead of 64
	0x0002 = Enable external reference clock input

Blocks 1 through 511 control the search and measurement parameters for each possible channel:

Relative address	**Content**
0-3	Probe matching voltage [V] (`:INPut:MATChing?`) Zero means automatic mode.
4-7	Probe tuning voltage [V] (`:INPut:TUNing?`) Zero means automatic mode.

8-11	Pulse frequency [Hz] (`:SOURce:PULSe:FREQuency?`) Zero means automatic mode.
12-15	Pulse width [s] (`:SOURce:PULSe:WIDTh?`) Zero means automatic mode.
16-19	Acquisition sweep time [s] (`:SENSe:SWEep:TIME?`) Zero means automatic mode.
20-23	Acquisition rate [Hz] (`:SENSe:SWEep:FREQuency?`)
24-27	Acquisition offset [s] (`:SENSe:SWEep:OFFSet:TIME?`)
28-31	Search threshold (`CONFigure:SEARch:LEVel?`)
32-35	Search frequency step (`CONFigure:SEARch:FSTEp?`) Zero means default value.
36-39	Search lower limit [UNIT?] (`CONFigure:SEARch:LIMit:LOW?`) Zero means default value.
40-43	Search upper limit [UNIT?] (`CONFigure:SEARch:LIMit:HIGH?`) Zero means default value.
44-47	Search manual value [UNIT?] (`CONFigure:SEARch:LIMit:VALue?`)
48-51	Measurement threshold (`CONFigure:MEASure:LEVel?`)
52-55	Analysis bandwidth (`CONFigure:MEASure:BANDwidth?`)
56-59	Minimum IF for tracking [Hz] (`CONFigure:TRACking:LOW?`)
60-63	Maximum IF for tracking [Hz] (`CONFigure:TRACking:HIGH?`)
100	Search mode (`CONFigure:SEARch:MODE?`) 0 = Auto, 1 = Custom, 2 = Manual
101	Frame size (`CONFigure:MEASure:FRAMe?`)
102	Number of analysis points (`CONFigure:MEASure:POINts?`)
103	Signal averaging enable (`:CALCulate:AVERage1:STATe?`): 0 = Disable; 1 = Enable
104	Signal averaging termination control (`:CALCulate:AVERage1:TCONtrol?`): 1 = EXPonential, 2 = REPeat
105	Signal averaging count (`:CALCulate:AVERage1:COUNt?`)
106	Measurement averaging enable (`:CALCulate:AVERage1:STATe?`): 0 = Disable; 1 = Enable
107	Measurement averaging termination control (`:CALCulate:AVERage2:TCONtrol?`): 1 = EXPonential, 2 = REPeat, 3 = MOVing
108	Measurement averaging count (`:CALCulate:AVERage2:COUNt?`)
109	Hysteresis for tracking (`CONFigure:TRACking:HYSTeresis?`)
127	Channel state: 0 = Not present, 1 = Disabled, 2 = Enabled

4-3-4 Input Register Map

The Input Registers are read-only registers that provide information about the system as a whole and about each channel, including the measurement results. Each register is 16 bits. MODBUS supports up to 64K Input Registers; this address space is divided into 512 blocks of 128 registers.

The first block returns information about the system as a whole:

Address	Content
0 – 99	System model, version information (*IDN?)
100	System options: 0x0001 External reference clock is enabled

Blocks 1 to 511 return information from each channel, including the measurement results:

Relative address	Content
0-9	Probe Model (`:ROUTe:PROBe:MODel?`)
10-19	Probe Serial Number (`:ROUTe:PROBe:SERialno?`)
20-23	Measured flux density [UNIT?] (`:FETCh:SCALar:FLUX?`)
24-27	Standard deviation [UNIT?] (`:FETCh:SCALar:SIGMa?`)
28-31	Field uniformity [0 to 1] (`:FETCh:SCALar:UNIFormity?`)
32-33	Time stamp [1 ms ticks] (`:FETCh:SCALar:TIMestamp?`) 0 = measurement not yet valid

REFERENCE
5-Key Specifications

See the PT2026 Installation and Safety Manual for Dimensions, Ratings and Back Panel Connections.

5-1 MEASUREMENT

Frequency range	1 MHz – 1 GHz
Resolution	± 0.1 Hz (stable field, low gradient, no averaging)
Accuracy	± 5 ppm, independent of temperature
Max gradient	> 1000 ppm/cm
Measurement rate	Up to 33 Hz
Trigger modes	Immediate, Timed, Bus, External

5-2 PROBES

Ranges	0.19 – 0.52 T (4 mm Ø p sample) 0.42 – 1.29 T (3 mm Ø p sample) 1.13 – 3.52 T (3 mm Ø p sample) 3.29 – 10.57 T (3 mm Ø p sample) 8.00 – 22.8 T (3 mm Ø D sample) Custom ranges upon request
Search time	Full range typ. < 10 s
Multiplexer (optional)	Self-powered; 4 or 8 channels; up to 3 levels (512 probes max)

5-3 SOFTWARE

Supported platforms	Microsoft Windows XP SP3 or higher
API	Access to all system features; LabVIEW® 2015 SP1
Licenses	Metrolab (including source code for API) National Instruments (LabVIEW® and NI-VISA run-times)

REFERENCE
6-NMR Magnetometers

(This section is adapted from an article published in Magnetics Technology International 2011, pp. 78-71.)

Amongst a dozen physical phenomena exploited to measure magnetic field strength, NMR (Nuclear Magnetic Resonance) is by far the most accurate. In addition, NMR magnetometers are immune to temperature- or age-related drift. For these reasons, they are widely used as a reference for calibrating other magnetometers, such as the common Hall "gaussmeter." However, due to technological constraints, their use beyond calibration has been limited to research and a few industrial applications. This may start to change. We review the principles of operation of NMR magnetometers, their benefits and constraints, and recent developments that aim to bring these fantastic instruments into more common use.

6-1 NMR: A DISCOVERY DESTINED FOR GREATNESS

Building on fifty years of physics research, Nuclear Magnetic Resonance (NMR) was experimentally demonstrated in late 1945 by two independent teams, led by Felix Bloch at Stanford and Edward Purcell at Harvard. Bloch and Purcell received the Nobel Prize in 1952, but industrialization of NMR had already started in 1948, when Russel Varian, a colleague of Bloch's, founded his company to use NMR for chemical analyses. NMR spectrometers are now an essential tool in chemistry. Similarly, Magnetic Resonance Imaging (MRI), first commercialized in 1978, has quickly developed into one of medicine's most important imaging modalities.

Commercial NMR magnetometers became available about the same time as MRI. The principle is straightforward: if a nucleus has spin, it will act like a little compass needle and align itself in a magnetic field. Quantum-mechanically speaking, the nucleus has two energy states: the lower-energy state where the nuclear magnetic moment is aligned with the external field, and the higher-energy state where it is opposed. The gap between these two energy states depends only on the magnitude of the magnetic moment and that of the magnetic field. Since the nuclear magnetic moment is a constant, this energy gap is a perfect measure of magnetic field strength.

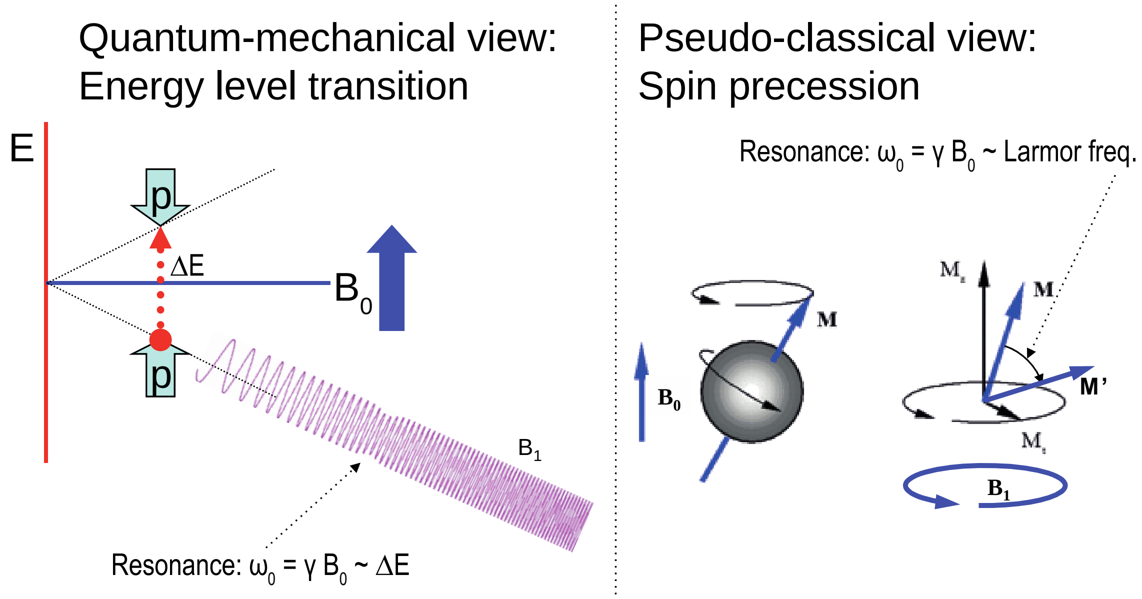


Figure 2. Principles of NMR.

As in spectroscopy, injecting just the right amount of energy will cause the nucleus to transition from the lower to higher energy level. The injected energy is proportional to its frequency, so a magnetic measurement via NMR consists of searching for the frequency – the resonant frequency – that cause the nuclear spins to flip.

The energy is injected by an AC magnetic field (usually called B_1), perpendicular to the field being measured (B_0). Just like the angular momentum vector of a spinning top precesses around the direction of gravity, the nuclear magnetic moment precesses around $\mathbf{B_0}$; resonance occurs when the frequency of B_1 exactly matches the precession, or Larmor, frequency. At resonance, B_1 rotates the spin away from B_0 – even though B_1 is generally orders of magnitude smaller than B_0.

6-2 THE INGREDIENTS FOR AN NMR MAGNETOMETER

Practically speaking, an NMR magnetometer has five main elements:

- **NMR sample**: The sample material must have a nuclear spin; many common isotopes, such as ^{12}C or ^{16}O, have zero spin and are transparent to NMR. The material must also exhibit a sharp resonance; in a molecule, the NMR resonance is broadened by interactions with the other nuclei and electrons. Finally, the nuclei must "relax" to their initial, spin-aligned state in a "reasonable" amount of time: too short a relaxation time prevents us from detecting the resonance, but too long renders repeated measurements more difficult. The most readily available sample material is water (NMR resonance of ^{1}H, or proton).

- **B_1 excitation coil**: The B_1 coil must be perpendicular to the field being measured – more or less. Unlike Hall magnetometers, imperfect alignment does not change the measurement result; it simply reduces the effective B_1, causing some loss of sensitivity.
- **RF generator**: The key parameters are bandwidth (≈ 1 MHz to 1 GHz for ^{1}H), stability (≈ ppb/day), and suppression of spurious frequencies (<≈ -80 dB). Producing such a generator economically is one of the major challenges in designing an NMR magnetometer.
- **Detector**: Various techniques exist to detect the NMR resonance:
    - Marginal oscillator: the B1 coil is part of a marginally stable oscillator. At resonance, the NMR sample absorbs energy, acting like a resistance, thus lowering the Q and killing the oscillation.
    - Continuous wave (CW): because of the same resistance-like effect, the driving voltage on the B_1 coil dips slightly at resonance. An alternate CW technique is the inductive bridge, where a pick-up coil perpendicular to the B_1 coil detects when, at resonance, spins are rotated by 90°.
    - Pulsed-wave (PW): the sample is excited with a short, wide-band pulse applied to the B_1 coil; then, in a second step, the B_1 coil is used to detect the Larmor precession during the relaxation time.
- **Modulator**: All but the PW technique require some sort of modulation, to detect a change when crossing the resonance. The most obvious solution is to modulate the frequency, but it is often more practical to add a small coil to modulate B_0, taking care to synchronize the measurement with the modulation zero-crossing.

Figure 3. The Metrolab Precision Teslameter PT2025.

Figure 4 shows the architecture of an actual instrument, Metrolab's Precision Teslameter PT2025. A detailed functional description can be found in the manual; here we just want to point out the five key elements: the Sample, B_1 Coil and Detector are all physically located in the probe; the RF Generator consists of a Voltage Controlled Oscillator (VCO) and frequency dividers, located in the main unit; and the Modulator consists of a current generator in the main unit connected to a field modulation coil in the probe. Other important features of this architecture are the tracking loop that automatically adjusts the VCO to stay centered on the resonance, and the auto-tuned variable capacitance, forming a resonant tank circuit with the B_1 coil and thus greatly improving the SNR. The basic design dates from 1985, and these instruments now represent the overwhelming majority of the world's installed base of NMR magnetometers.

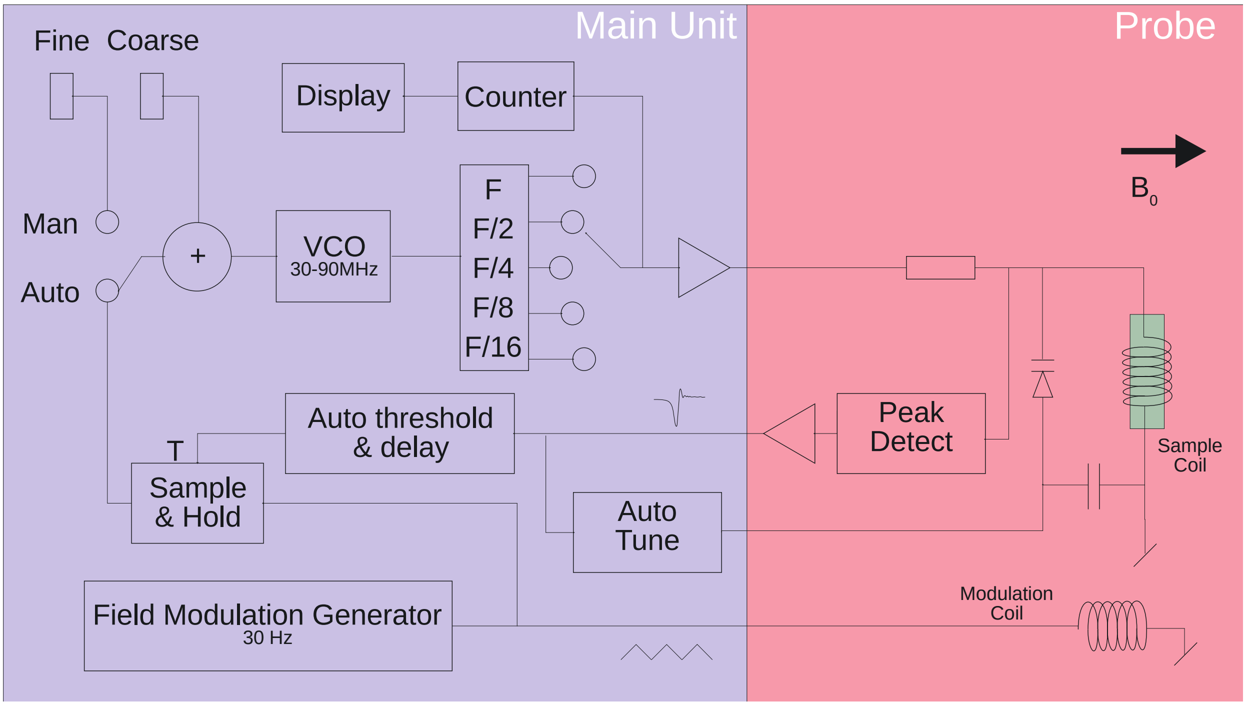


Figure 4. PT2025 functional block diagram.

6-3 PROS AND CONS

Compared to other magnetometer technologies, NMR has obvious benefits. First and foremost is the astounding precision and accuracy. The resolution is essentially limited by the stability of the RF generator and the sample's resonance width; for existing instruments such as the PT2025, this is around 0.1 parts per million (ppm). The absolute accuracy is limited by low-level field distortion caused, for example, by the susceptibility of materials surrounding the NMR sample; for the PT2025, this is around 5 ppm, which is more than enough to calibrate other magnetometers. It also allows researchers to measure minute magnetic effects such as the "training" of superconducting filaments. Last but not least, NMR is the only way to create a field map with enough resolution to guarantee the uniformity needed for MRI or NMR spectroscopy – NMR magnetometry serving its NMR sister technologies.

NMR is also essentially drift-free. Drift of the RF generator reference clock is important, but can be readily maintained at extremely low levels – parts per billion (ppb) or better. Finally, unlike Hall- or coil/integrator based magnetometers, NMR measures the total field B, regardless of the exact probe orientation.

Obviously, NMR magnetometers also have limitations. The most important is that it only works in a uniform magnetic field. The reason is simple: the sample has a finite size (≈ 4 mm diameter); a magnetic field gradient causes one end of the sample to resonate at a different frequency than the other, and the higher the gradient, the harder it becomes to determine "the" resonant frequency. Today's limit is a field gradient on the order of 100 to 1000 ppm/cm. Most magnets are very far from this level of field uniformity.

Since NMR is a relatively slow technology – on the order of 10 to 100 ms per measurement – it is of limited use for rapidly varying fields. Finally, the field needs to be relatively strong for the spin-flip energy gap to rise significantly above the room temperature thermal noise. For example, the range of PT2025 probes starts at 40 mT, or roughly 1000x the earth's field. Sadly, many interesting and useful applications fall into that three-order-of-magnitude "NMR no-fly zone."

NMR magnetometers have continued to evolve since 1985. Many changes simply follow industry trends in terms of electronic components, microprocessors, displays, controls and computer interfaces. However, some improvements allow us to push back key limitations, opening the way for a more widespread use of NMR magnetometers. Let us take a look at some of these.

6-4 MORE IS BETTER

The first major step came in 1992, with the introduction of multi-probe systems for mapping MRI magnets – what eventually became Metrolab's Magnetic Field Camera MFC3045. Up to 32 NMR probes functioning in parallel addressed the need for faster field maps. Other key improvements include the use of a Direct Digital Synthesizer (DDS) as RF Generator, which allows using frequency modulation and eliminating the field modulation coils. Also, the auto-tuning circuit with a varactor diode was replaced with a simple trim cap, reducing the measurement range from 300% per probe for the PT2025 to around ±2% – a perfectly acceptable simplification for MRI magnets, where the target field is exactly known. Finally, the mechanical aspects of the instrument were optimized for MRI production, with robust housing and connectors, remote control, etc.

Figure 5. The Magnetic Field Camera probe array:
(a) cut-away showing the probe positions; (b) as installed in a horizontal MRI magnet.

With this instrument, the time to map a magnet was reduced from many hours to around five minutes. Productivity gains add to technical benefits: less magnet drift and fewer human errors, combined with improved positioning precision, meant more self-consistent maps and better convergence of the entire magnet-tuning process. It is fair to say that without the development of multi-probe NMR systems, MRI would not be what it is today.

6-5 BETTER IS BETTER

For almost a decade, Metrolab has been working on a new-generation, "all digital" NMR magnetometer, the PT2026. As we can see from Figure 6, the term "all digital" is to be taken with a grain of salt: "all digital control" is more accurate. Other important technical improvements include:

- **RF Generator**: up to around 1 GHz, instead of 90 MHz for the PT2025. Absolute frequency control simplifies the architecture and improves stability.
- **Detection**: support for either continuous-wave (CW, like PT2025) or pulsed-wave (PW, as shown in Figure 6). Improved performance in poor-SNR environments due to sophisticated Digital Signal Processing (DSP).
- **Modulation**: field modulation for CW probes, or none for PW probes.
- **Multi-probe capability**: up to 512 PW channels, or 16x the MFC3045.
- **Probe tuning**: variable, like PT2025, or fixed, like MFC3045. For PW probes, dynamic matching improves power transfer.
- **Search of NMR resonance**: assisted by 3-axis Hall probe.

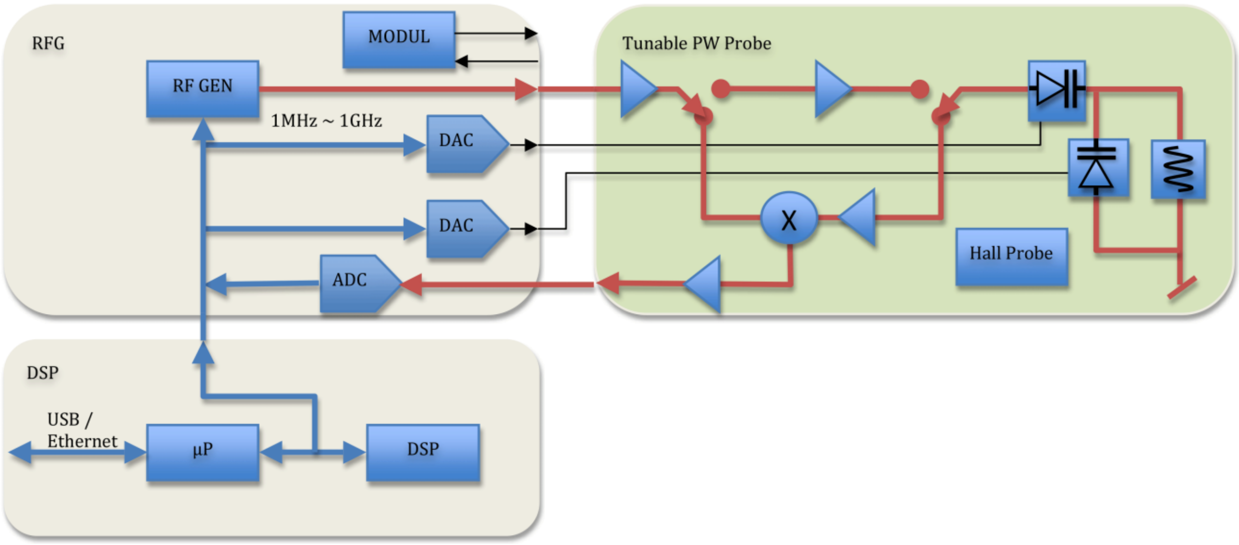


Figure 6. PT2026 functional block diagram.

What will change from a user's standpoint? For measurements above 2 T, delicate heavy water (^{2}H, or deuterium) based probes will be replaced with robust rubber (^{1}H) based probes. The maximum field will go from not quite 14 T to over 20 T – or practically unlimited if one accepts deuterium probes. The measurement resolution remains around 1 Hz, but the measurement rate will be an order of magnitude faster. With optional signal averaging, measurement speed can be traded off against resolution; for typical NMR spectroscopy magnets, the resulting resolution starts to approach the parts per billion.

Massively parallel multi-probe systems allow us to conceive fixed, 3D probe arrays rather than rotating 2D probe arrays – resulting in even faster mapping and better positioning accuracy. In addition, the new PW probe arrays will share one set of electronics for all probes, making the actual array simpler and smaller. We have already demonstrated probe arrays that fit into the 40 mm bore of a conventional NMR spectrometry magnet – almost an order of magnitude smaller than currently possible.

In addition to maximum field, resolution, speed and multiple probes, the PT2026 promises another key improvement: tolerance of non-uniform fields, where we expect the combination of higher SNR and a DSP to provide close to an order of magnitude improvement. This, combined with usability improvements like fast search assisted by a 3-axis Hall probe, will significantly push back the limitations of NMR magnetometers.

6-6 EVEN LESS CAN BE BETTER

The PT2026 leaves one major barrier untouched: that for fields below 40 mT. There are four basic approaches to address this problem:

- Larger sample: provides more nuclei and thus a better SNR. However, the large probe size is a great practical hindrance.
- Electron-Spin Resonance (ESR): very similar to NMR, except based on electron spin instead of nuclear spin, with a gyromagnetic ratio in the GHz/T instead of the MHz/T. Currently known ESR probe materials are chemically unstable and/or have wide resonance widths, making them unsuitable for an industrial instrument.
- Pre-polarization: improve the SNR by aligning the spins in a strong magnet before measuring the resonance in the weak field. Requires physically transporting the sample material – for example water – from the polarization magnet to the B_1 coil.
- Higher pick-up sensitivity: replace the coil with a more sensitive pick-up, such as a superconducting coil or Superconducting Quantum Interference Device (SQUID).

In the past, Metrolab has shipped PT2025 probes with large samples and with ESR samples; neither proved to be entirely satisfactory. Metrolab is now pursuing the third option, a flowing water system, specifically for calibrating Hall probes over a wide range of fields (±2 T) with a single probe. We also continue to search for innovative ESR sample materials. High-sensitivity pickups may be a promising long-term solution, but the technological complexity is currently daunting.

Metrolab earned their dominant position in NMR magnetometry by making a delicate piece of laboratory equipment work in the rough-and-tumble manufacturing environment. Our equipment goes from the arctic cold of an airplane hold to the sauna-like Singapore summer, gets dropped by the baggage handlers, yanked into place by a burly technician pulling on the probe cable – and is then expected to deliver parts-per-million accuracy. More than twenty years later, such systems are still returned for calibration (and occasionally, repair). We are committed to continuing to push back the limitations as far as physics and good engineering allow.