Operation-Readiness Clearance of the polarization measurement system for the SpinQuest Experiment at NM4

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Abstract

The E1039 polarized target setup comprises collection of several relatively independent systems. Among others, there is a NMR-based polarization measurement system consisting of a constant-current series-resonant Q-meter and an integrated data acquisition system (DAQ). This document along with supplemental materials provides information necessary for the electrical safety assessment.

Contents

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1. Introduction

This document will give the information that is necessary to conduct the Fermilab Operational Readiness Clearance (ORC) review with the focus on electrical safety. It contains a brief description of the system, an overall system layout, specifications for each subsystem and power consumption estimates. Supplemental materials are attached and include printed circuit board (PCB) layouts and RF component lists. The principles of operations [1, 2] and operational manual are provided elsewhere.

The polarization measurement or NMR system is one of the critical systems of the SpinQuest target. It is based on the principle of continuous wave nuclear magnetic resonance (CW-NMR), where a sweeping RF field, applied perpendicular to the axis of the holding field, drives the nucleon spin-flip transitions. The corresponding energy gains or losses are detected by a specially tuned resonant RF circuit (Q-meter). The circuit itself and the integrated DAQ are made of a number of commercially available and custom-made elements discussed in the following sections. The system components are spread from the target cave to the cryo-platform and further to the control room.

2. General scheme

The main sensing element is a one- or a three-turn NMR coil, which constitutes a single readout channel. NMR coils are embedded in the target material and are held at a temperature of 1K in the target cryostat. The target material is contained in a 8 cm-long target cup. A single target cup can host up to three NMR coils, while the target ladder has a maximum capacity of holding up to three target cups. Thus, the NMR system is capable of reading up to nine NMR channels in total. Currently, the target ladder is expected to host two target cups with three NMR coils in each cup. Each NMR coil connects to a tuned RF-resonant LCR circuit, which is located on the cryo-platform, through a semi-rigid coaxial transmission cable. The electronics for one NMR channel is represented by a set of three custom-made PCB boards: *external frequency tuner*, *analog NMR signal processor*, and *digital processor board*. Boards are housed in a VME crate, which can held up to four independent NMR channels per crate. In addition, there are two more additional custom-made PCB boards required for crate operation: *RF switch* and *crate controller*. An external (commercial) frequency synthesizer is required to provide the input RF power.

Simultaneous three-coil operation in an asynchronous mode implies that each corresponding NMR channel has to be operated independently from a separate VME crate. Thus, for expected 3 coils $\times$ 2 cups configuration, the NMR rack has to be equipped with three RF synthesizers and three VME crates, which host two NMR channels each. A network switch and an Ethernet-to-USB device server connect the system to a dedicated target computer installed in the counting room for the crate and synthesizer remote control operations. Communication between the target computer and the NMR rack is done over the private E1039 Ethernet network.

Fig. 1 depicts the schematic view of the polarization measurement setup for a **single** NMR channel in standard configuration (213 MHz variant, see Sec. 3). Fig. 1 is also included in the supplemental materials as a separate file `nmr_scheme_0.pdf`. An additional set of *external frequency tuner*, *analog NMR signal processor*, and *digital processor board* would have to be added for every subsequent NMR channel in a given VME crate. The only boards that require VME power (+5 V, ±12 V) are *analog NMR signal processor*, *digital processor board* and *crate controller*. The VME backplane connector for each board follows the VME 96 Pin DIN Connector pinout convention. A list of interconnecting cables used in the setup is discussed in Sec. 6.

The NMR rack configuration for a standard (213 MHz variant) 3 coils $\times$ 2 cups setup is shown in Fig. 2. Each of three VME crates is organized according to schematics that are shown in Fig. 1. The internal connections between the analog NMR signal processor and digital processor board are routed through a cut-out part of the digital processor board and are not visible in Fig. 2. A network switch connects NMR rack electronics to the E1039 private network and makes it accessible to the host target PC located in the counting room.

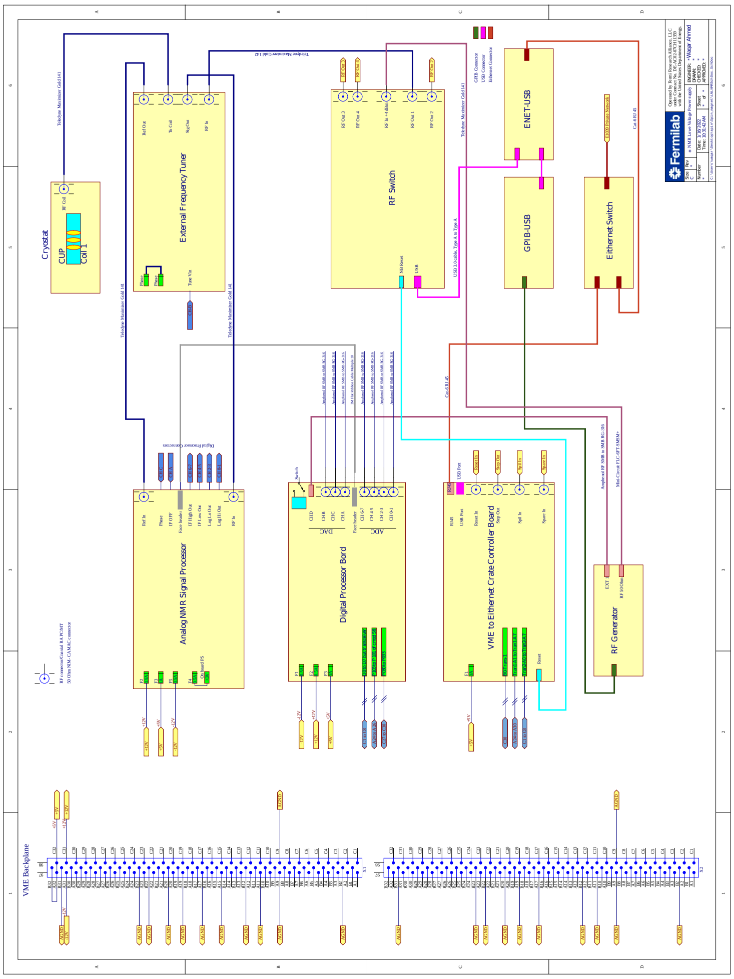

Figure 1: Schematic diagram of the E1039 polarization measurement system. Connections for a single NMR channel are shown. This diagram is also included in the supplemental materials as a separate file *nmr_scheme_0.pdf*. The power and ground connections for the VME 96 Pin DIN Connector are equivalent for the *analog NMR signal processor*, *digital processor board* and *crate controller*.

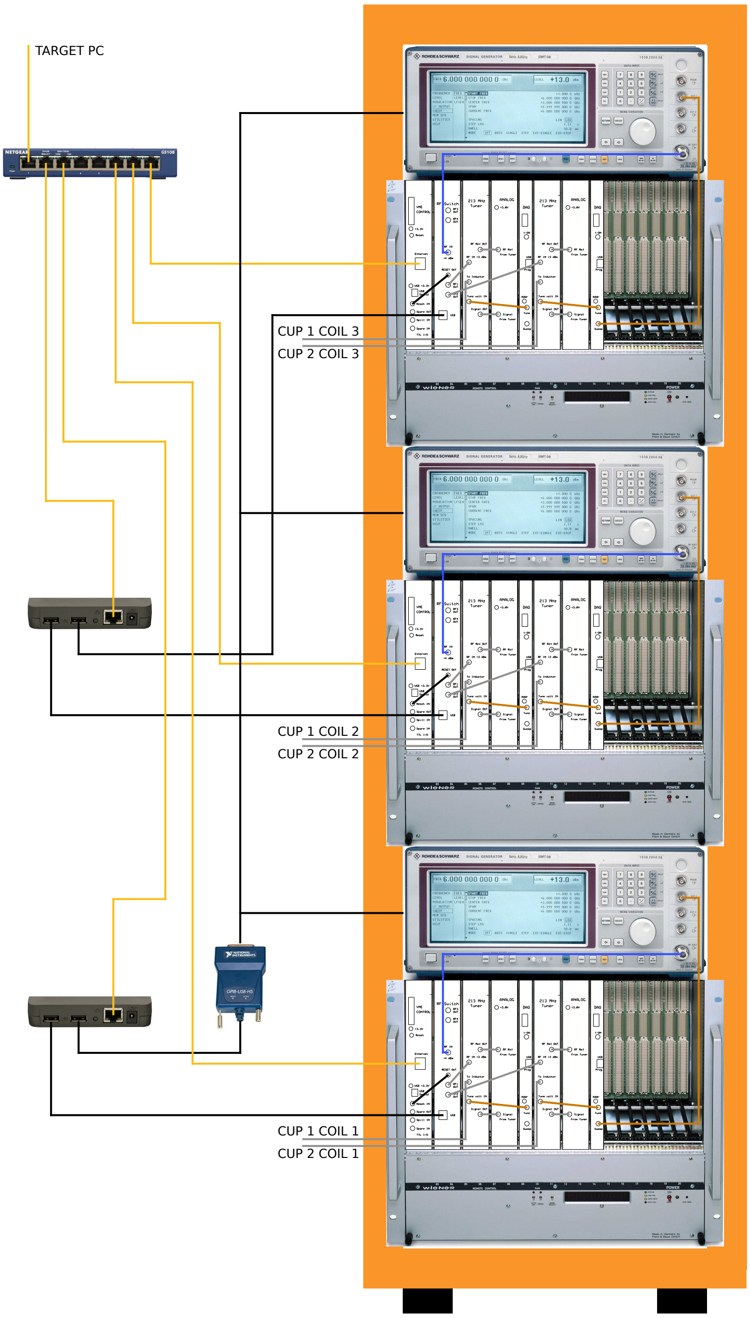

Figure 2: Schematic diagram of the E1039 NMR rack. Each VME crate hosts (from left to right)): crate controller board, RF switch, two (*external frequency tuner*, *analog NMR signal processor*, and *digital processor board*) NMR channels. A network switch, two Ethernet-to-USB device servers and GPIB-to-USB converter are shown on a side for clarity.

3. Analog boards

There are two boards that process RF and LF NMR signals before they are passed for digitization. These boards, the external frequency tuner and the analog NMR signal processor, together with NMR coils and transmission cables constitute a Q-meter. An additional RF switch board is responsible for distributing RF power over several NMR channels residing in one VME crate.

3.1. External frequency tuner

The RF tuner is a part of the Q-meter that together with a NMR coil forms a series RF-resonant LCR circuit. The custom-built external frequency tuner circuit diagram can be found in the supplemental materials (files: `AB_tuner_schematic.*`). It receives the incoming RF from the generator and converts it to a constant current source of about 0.3 A. For proper operation and to satisfy the NMR resonance condition, the Q-meter has to be tuned to a corresponding proton (deuteron) Larmor frequency. A varactor diode, which is adjusted by an applied $0.5\,\mathrm{V} - 10\,\mathrm{V}$ voltage with a negligible amount of current, is used for tuning purposes. Otherwise, this board does not require a power supply for its operation. A short description of the corresponding supplemental materials is given in Table 1.

#	File name	Comment
1	`AB_tuner_schematic.*`	circuit diagram
2	`AB_tuner_pcb*`	PCB layout
3	`AB_tuner_photo.pdf`	assembled PCB photograph
4	`AB_tuner_front_panel_photo.jpeg`	VME front panel shielding

Table 1: Supplemental materials description for the external frequency tuner.

Since the NMR signals are extremely small, a number of improvement are required to address signal-to-noise degradation and signal instabilities. The transmission cable, which connects the remote coil in the cryostat and RF tuner, is a part of the RF-resonant circuit and is one of the major sources of signal degradation. Thus, reducing the cable length or eliminating it completely significantly improve the NMR signal quality. Such measures imply two modes of operation - *warm* and *cold* mode NMR, which are discussed below.

3.1.1. Warm mode NMR

In this (standard) mode, the RF tuner is held at room temperature. It is installed in a dedicated shielding enclosure for noise reduction and is mounted behind a standard 6U dual slot plank inside of the VME crate.

To further improve Q-meter performance, the shielded enclosure with the RF tuner (or the entire NMR rack) can be moved as close to the cryostat as radiation environment allows. In this case the length of the RF-resonant cable between the tuner and the NMR coil is decreased while the interconnecting cables between the tuner and the rest of the Q-meter are lengthened. No additional power is needed for this configuration.

3.1.2. Cold mode NMR

Cold mode NMR implies that the RF turner is moved to closest vicinity of the NMR coil and is, thus, held at cryogenic ($\sim$ 1 K) temperature. The RF tuner had to be miniaturized in order to fit the limited space on the target insert ladder. This miniaturized tuner is known as cold NMR board. It carries a regular variable (mechanical) capacitor, as it is expected that semiconductor radiation damage will prevent the use of a varactor diode. In addition, elimination of the coil-tuner cable comes with a price of requiring two non-resonant cables per coil inside of the cryostat. No power is carried over these cables. A standalone document will be produced to perform a separate ORC review for the cold mode NMR.

3.2. Analog NMR signal processor

This analog board contains majority of the Q-meter's post-LCR electronics, including a phase shifter, phase-sensitive demodulator, magnitude detection units as well as a number of post-RF amplification stages. The analog NMR signal processor board schematics can be found in the supplemental materials (file: `AB_sig_processor_V4_schematic.*`). The analog printed circuit board has a 6U VME format with eight metal layers and occupies one VME slot. Most traces carrying RF are 50 Ω strip-lines, providing required shielding.

The board resides inside of the VME crate. The VME crate supplies the +5 V and ±12 V rails. The expected power consumption is less than 0.25 A at +5 V and less than 0.1 A at ±12 V which is fused with a 1 A and 0.5 A fuses respectively. An on-board low-noise voltage regulator generates the critical +3.3 V used by the MMICs. While two connectors on a front panel connects the board to the RF tuner, a ribbon and a number of coaxial cables carry the amplified output signals to the digital processor board.

There are two (proton and deuteron) variants of the board designed to operate at 213 MHz and 32.7 MHz frequencies. The difference is due to the part of the circuit that performs phase adjustment of the reference signal with respect to the NMR signal. The phasing is controlled remotely using an electronic line stretcher and directional coupler. The Mini-Circuits ELS-210 (see file: `AB_sig_processor_ELS-210.pdf`) is used for near 213 MHz operation while a dedicated phase shifter was designed to operate at lower 32.7 MHz frequency (see 3.1.2). A short description of the corresponding supplemental materials is given in Table 2.

#	File name	Comment
1	`AB_sig_processor_V4_schematic.*`	circuit diagram
2	`AB_sig_processor_V4_pcb.*`	PCB layout
3	`AB_sig_processor_V4_photo.jpg`	assembled PCB photograph
4	`AB_sig_processor_front_panel_photo.jpg`	VME front panel shielding
5	`AB_sig_processor_ELS-210.pdf`	phase shifter ELS data-sheet

Table 2: Supplemental materials description for the analog NMR signal processor.

3.3. RF switch

The four-channel RF switch board is used to provide an RF power to a desired NMR channel while ensuring there is no RF power delivered to the neighboring channels to prevent the cross-talk. It is based on a Mini-Circuits ZSDR-425 four-channel RF switch and a DLP-IO20 Design USB-based DAQ module. The ZSDR-425 RF switch requires a +5 V power source and two TTL-based input signals for control logic, both of which are supplied by the DLP-IO20 DAQ. The DLP-IO20 itself is USB-powered. The expected power consumption is less than 0.5 A at 5 V. A short description of the corresponding supplemental materials is given in Table 3.

#	File name	Comment
1	AB_rf_switch_schematic.pdf	circuit diagram
2	AB_rf_switch_photo.jpg	assembled PCB photograph
3	AB_rf_switchfront_panel_photo.jpeg	VME front panel shielding
4	AB_rf_switch_ZSDR-425+.pdf	Mini-Circuits ZSDR-425 RF switch data-sheet
5	AB_rf_switch_dlp-io20-ds-v10.pdf	DLP Design DLP-IO20 DAQ manual

Table 3: Supplemental materials description for the RF switch board.

4. Digital boards

There are two digital boards that constitute an integrated data acquisition system. The main purpose of these boards is to perform a digitization of the amplified LF output signals from the Analog NMR signal processor, to pass information to the host computer, as well as to provide a number of control signals for analog boards.

4.1. Digital processor board

The digital processor is a custom-built board which contain majority of the DAQ electronics. Its schematics can be found in the supplemental materials (file: `DB_dig_processor_schematic_0[1-3].*`). In order to digitize the analog board outputs, it provides the on-board four-channel 16-bit bipolar ADC interfaced to VME bus. A separate dual-channel ADC monitors the system temperature and MMIC power supply voltage. The four-channel 16-bit bipolar DAC is used to supply the varactor tune, phase shifter and DC offset control voltages. In addition, the DAC produces voltages to control an RF sweep on external RF synthesizer (see below). Communication between the digital processor and the VME back-plane is guided by a Spartan-6 FPGA daughter-board, which serves as a multiplexer switching signals to the appropriate device.

The physical layout is a four-layer single-slot VME (6U) printed circuit board. The VME crate provides a +5 V with an estimated consumption of 0.25 A and protecting fuse of 1 A. Another VME power source is a ±12 V rail with an estimated consumption of 0.1 A and protecting fuse of 0.5 A. A precision voltage reference supplies +2.5 V to the ADC and DAC. The ADC performs differential voltage measurements over the ±5 V range. The FPGA uses the Digilent Cmod S6 48-pin DIP form factor board, which includes a USB connection for configuration, test and communications interfaces. A short description of the corresponding supplemental materials is given in Table 4.

#	File name	Comment
1	DB_dig_processor_schematic_0[1-3].*	circuit diagram
2	DB_dig_processor_pcb*	PCB layout
3	DB_dig_processor_photo.pdf	assembled PCB photograph
4	DB_dig_processor_front_panel_photo.jpeg	VME front panel shielding
5	DB_dig_processor_FPGA.pdf	Digilent Cmod S6 manual
6	DB_dig_processor_ribbon_cable_pinout.pdf	Face header pinout

Table 4: Supplemental materials description for the digital processor.

4.2. Crate controller board

Another 6U, dual-slot custom-built VME board is used to create reliable VME system. Its schematics can be found in the supplemental materials (file: `DB_crate_controller_schematic.pdf`). It utilizes the Netburner MOD5270 industrial module built around the 32-bit processor with integrated 10/100 Ethernet. The processor with a real time operating system controls a 16-bit bi-directional data bus connected to the VME back-plane. A telnet server running on the processor passes data to a remote computer. The board is VME powered by a +5 V with an estimated consumption of 0.5 A and protecting fuse of 1 A. A short description of the corresponding supplemental materials is given in Table 5.

#	File name	Comment
1	`DB_crate_controller_schematic.pdf`	circuit diagram
2	`DB_crate_controller_pcb*`	PCB layout
3	`DB_crate_controller_photo.jpg`	assembled PCB photograph
4	`DB_crate_controller_front_panel_photo.jpeg`	VME front panel shielding
5	`DB_crate_controller_mod5270.pdf`	NetBurner mod5270 data-sheet
6	`DB_crate_controller_backplane_pinout.pdf`	VME back-plane pinout

Table 5: Supplemental materials description for the crate controller board.

5. External devices

A number of commercially available devices are exploited in the polarization measurement setup.

5.1. VME crate

In the standard configuration for two target cups, where three NMR coils inside of each cup has to be operated asynchronously, three VME crates are necessary to host corresponding NMR electronics. The WIENER VME 6021 (6023) series full size chassis crate is used in the setup. It has a steel-aluminum enclosure for 21 VME64 bus 6U×160 mm cards, UEL 6020 EX fan tray, and UEP 6021 power supply. The UEP 6021 PS is self protected against under/over voltage, over current, over temperature and uses 94 V – 260 V world-wide auto-range AC input with power factor correction. The crate is rated for a maximum load of 100 VAC – 240 VAC (50 Hz – 60 Hz, max. 16 A). A short description of the corresponding supplemental materials are given in Table 6.

#	File name	Comment
1	`ED_vme_crate_6021_datasheet.pdf`	WIENER VME 6021 crate data-sheet
2	`ED_vme_crate_6201_manual.pdf`	WIENER VME 6021 crate manual

Table 6: Supplemental materials description for the WIENER VME 6021 series crate.

5.2. RF generator

An external frequency synthesizer is required to provide the input RF power for the Q-meter circuit. Similarly, three synthesizers are needed for asynchronous running. The commercially available Rohde & Schwarz SMT series (SMT0[2,3,6]) signal generators or, alternatively, its modern SMB100B variant are typically used for this purpose as they offer exceptionally high signal quality and outstanding level accuracy.

Frequency modulation is achieved by supplying an external, with respect to the synthesizer, signal source. This signal, which is generated by one the digital processor boards inside VME crate discussed above, is a linear triangle $[-1, 1]$ V wave that corresponds to a frequency sweep of about 0.8 MHz. The modulated output at 213 MHz (32.7 MHz) is then sent to the input of the RF switch board via semi-rigid coaxial cable. The unit power supply uses a standard AC power input with the following ratings: 100 VAC – 240 VAC, 50 Hz – 400 Hz, 2.7 A – 1.1 A. A short description of the corresponding supplemental materials are given in Table 7.

#	File name	Comment
1	`ED_rs_smt020306_specs.pdf`	R&S SMT series specifications
2	`ED_rs_smt020306_manual.pdf`	R&S SMT series manual
3	`ED_rs_smb100b_specs.pdf`	R&S SMB100B series specifications
4	`ED_rs_smb100b_manual.pdf`	R&S SMB100B series manual

Table 7: Supplemental materials description for the Rohde & Schwarz SMT series signal generator.

5.3. USB-to-GPIB converter

The R&S SMT0x or SMB100B generators can be remotely controlled via GPIB interface. The National Instruments GPIB-USB-HS (GPIB-USB-HS+) controller offers a plug-and-play GPIB interface. It is an USB bus-powered device with a typical (maximum) power consumption of 80 mA (200 mA). A short description of the corresponding supplemental materials are given in Table 8.

#	File name	Comment
1	`ED_gpib_usb_hs+_specs.pdf`	NI GPIB-USB-HS+ specifications
2	`ED_gpib_usb_inst_specs.pdf`	NI GPIB hardware specifications
3	`ED_gpib_usb_ni488.2_manual.pdf`	NI-488.2 manual

Table 8: Supplemental materials description for the National instruments GPIB-USB-HS+ controller.

5.4. Ethernet-to-USB device server

The Ethernet-to-USB device servers are designed to connect and share USB devices over a network. The Silex DS-510 gigabit USB device server is integrated into the E1039 private network to provide access to the RF generators (via NI GPIB-USB-HS+) from the counting room. The DS-510 power supply uses a standard AC power input with the following ratings: 100 VAC – 240 VAC, 50 Hz/60 Hz, DC 5 V 2 A. The maximum power consumption is 3.5 W, which does not include USB bus power. A short description of the corresponding supplemental materials are given in Table 9.

#	File name	Comment
1	`ED_ether_usb_ds-510_specs.pdf`	Silex DS-510 specifications
2	`ED_ether_usb_ds-510_manual.zip`	Silex DS-510 manual

Table 9: Supplemental materials description for the Silex DS-510 Ethernet-to-USB gigabit device server.

5.5. Network switch

A standard Netgear GS108 8-port gigabit Ethernet unmanaged switch connects all network devices in the polarization measurement system with the E1039 target PC located in the counting room. The GS108 power adapter uses a standard AC power input with the following ratings: 12 V at 1 A DC input. If the cable length is greater than 10 m, the maximum power consumption is about 5 W. A short description of the corresponding supplemental materials are given in Table 10.

#	File name	Comment
1	`ED_net_switch_GS108_datasheet.pdf`	Netgear GS108 data-sheet
2	`ED_net_switch_GS108_inst_guide.pdf`	Netgear GS108 installation guide

Table 10: Supplemental materials description for the Netgear GS108 8-port network switch.

6. Cable summary

A set of cables to carry analog and digital signals and other information is used throughout the system. The RF signals are predominantly transmitted via Teledyne Storm Maximizer Gold semi-rigid coaxial tin-platted copper 50 Ω cable of 141 (or 086) diameter. The amplified RF signals, as well as a number of service digital signals, transmitted between the analog NMR signal processor and digital processor boards are carried by the Amphenol 145104-01-12.00 RF fixed-length (12 in) cable assemblies with the SMB-type connectors. The 3M 1700/20 100SF flat ribbon cable with a 3M 89120-0001 connectors carry a number of additional control signals between these boards.

Table 11 lists port's names and corresponding cable type for each custom-made board in the setup. The pinout of the flat ribbon cable and the pinout of the VME back-plane bus are given in tables of Sec. 4 and Sec. 5 respectively. Besides cables presented in Table 11, the setup exploits standard NI GPIB, USB_A-micro_USB, USB_A-USB_B and Ethernet cables. A short description of the corresponding supplemental materials is given in Table 12.

7. Power summary

The custom-built boards and commercial instruments in the E1039 polarization measurement system require variety of power sources. The detailed information on power specifications of the individual component can be found in the supplemental materials of the corresponding section. Table 13 gives a quick overview of estimated consumption.

#	Port 1	Port 2	Type
1	EFT “To Coil”	NMR coil	Teledyne Maximizer Gold 141
2	EFT “RF In”	RFS “RF OUT N”	Teledyne Maximizer Gold 141
3	EFT “Ref Out”	ASP “Ref In”	Teledyne Maximizer Gold 141
4	EFT “Sig Out”	ASP “RF In”	Teledyne Maximizer Gold 141
5	EFT “Phase 1”	EFT “Phase 2”	Teledyne Maximizer Gold 141
6	EFT “Tune Vin”	DPB “CHB”	Amphenol RF SMB-to-SMB RG-316
7	ASP “IFHI OUT”	DPB “CH0-1”	Amphenol RF SMB-to-SMB RG-316
8	ASP “IFLO OUT”	DPB “CH2-3”	Amphenol RF SMB-to-SMB RG-316
9	ASP “LOGLO OUT”	DPB “CH4-5”	Amphenol RF SMB-to-SMB RG-316
10	ASP “LOGHI OUT”	DPB “CH6-7”	Amphenol RF SMB-to-SMB RG-316
11	ASP “IF OFF”	DPB “CHA”	Amphenol RF SMB-to-SMB RG-316
12	ASP “PHASE”	DPB “CHC”	Amphenol RF SMB-to-SMB RG-316
13	ASP “Header”	DPB “face header”	3M Flat Ribbon Cable Multiple 20
14	DPB “CHD”	RFG “EXT 1”	Amphenol RF SMB-to-SMB RG-316
15	RFG “RF 50Ω”	RFS “RF In”	Mini-Circuits FLC-6FT-SMSM+

Table 11: Connection cables between the custom-built components of the E1039 polarization measurement system. The abbreviations used in the diagram are: Coil - one of the NMR coils embedded in the target material, EFT - external frequency tuner, ASP - analog NMR signal processor, RFS - RF switch, DPB - digital processor board, RFG - RF signal generator.

#	File name	Comment
1	`CS_semi_rigid_maximizer_specs.pdf`	Teledyne Storm Maximizer data-sheet
2	`CS_coax_amphenol_specs.pdf`	Amphenol data-sheet
3	`CS_flat_ribbon_3Mcable_specs.pdf`	3M cable data-sheet
4	`CS_flat_ribbon_3Mconnector_specs.pdf`	3M connector data-sheet
5	`CS_test_miniciruit_FLC-6FT_specs.pdf`	Mini-Circuits FLC data-sheet

Table 12: Supplemental materials description for the types of connection cables used in the setup.

#	Component	Power	Consumption	Fuse	Comment
1	External frequency tuner	0.5 V – 10 V	< 1 W	-	16-bit DAC-powered
2	Analog signal processor	+5 V, ±12 V	~ 3 W	1 A, 0.5 A	VME-powered
3	RF switch	+5 V	~ 2 W	-	DLP-IO20, USB-powered
4	Digital processor board	+5 V, ±12 V	~ 3 W	1 A, 0.5 A	VME-powered
5	Crate controller board	+5 V	~ 5 W	1 A	VME-powered
6	VME crate	94 V – 260 V AC	~ 75 W	external	over T, V, I protection
7	R&S RF generator	100 V – 240 V AC	~ 300 W		
8	USB-to-GPIB	100 V – 240 V AC	~ 80 mA	-	USB-powered
9	Ethernet-to-USB	100 V – 240 V AC	~ 10 W	-	
10	Network switch	12 V	~ 5 W	-	12 V PS-powered

Table 13: Power specifications of the E1039 polarization measurement system.

References

[1] McGaughey, P. and Yurov, M. and Klein, A. and Kleinjan, D. and Liu, K. and Mirabal-Martinez, J., A modern Q-meter system to measure the polarization of solid polarized targets, Nucl. Instrum. Meth. A 995 (2021) 165045. doi:10.1016/j.nima.2021.165045.

[2] M. Yurov, P. L. McGaughey, J. Mirabal-Martinez, A New Target Polarization Measurement System for the Fermilab Polarized Drell-Yan SpinQuest Experiment, PoS PSTP2019 (2020).