# A New NMR System

## for JLab Solid Polarized Targets

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for the Jefferson Lab Target Group

Jefferson Lab

TARGET Group

Tensor Spin Observables Workshop
Trento, Italy
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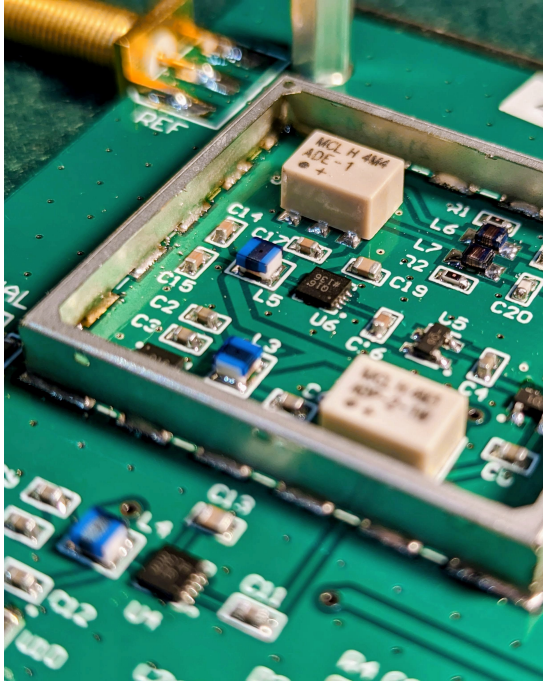

# Outline


1. NMR and JLab Solid Targets
   - Introduction
2. Cold Board NMR
3. A New JLab Q-Meter System
   - Qmeter Design
   - DAQ Design
   - Software Design
4. Results
5. Future Effort

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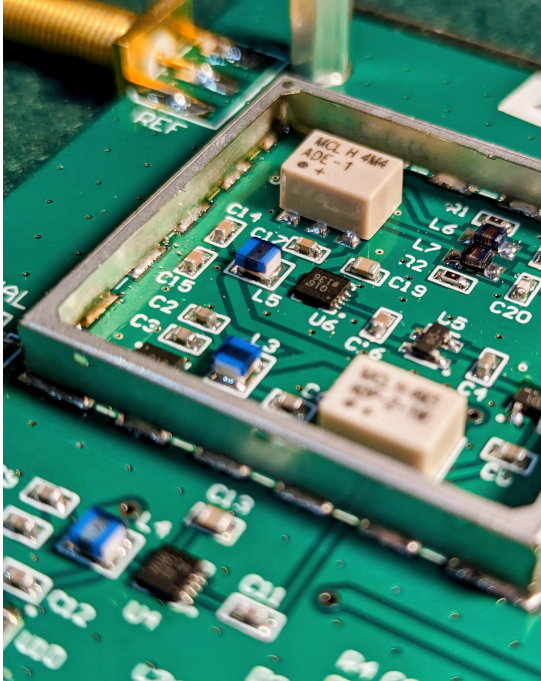

# Measuring Polarization in Polarized Solids

- NMR in field $B_0$ at $\omega_0$, apply RF field to material
- Coil of $L_0$ applies field perpendicular to $B_0$ to induce spin flip
- Material polarization modifies the effective inductance of a coupled coil, with filling factor $\eta$:

$$L(\omega) = L_0(1 + 4\pi\eta\chi(\omega))$$

- Polarized nuclei give the target material a complex susceptibility, a function of applied frequency ($\omega$):

$$\chi(\omega) = \chi'(\omega) + i\chi''(\omega) \quad \text{and} \quad P = K\int_0^\infty \chi''(\omega)d\omega$$

- $\chi(\omega)$ is non-zero only close to the Larmor frequency $\omega_0$

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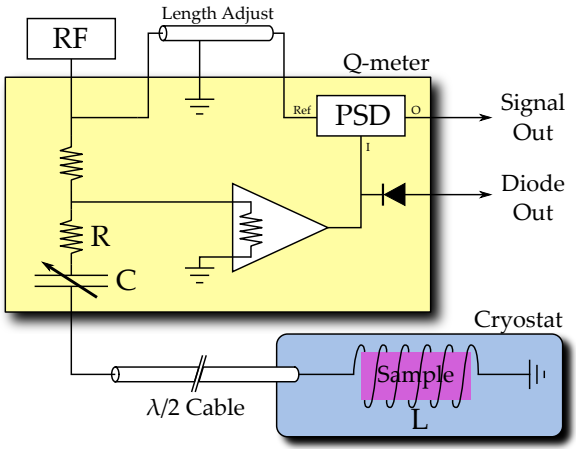
# Continuous-wave NMR Electronics: Q-meter

- Choose $L$, $C$: $\omega_0 = 1/\sqrt{LC}$
- Complex impedance of circuit $\sim i\omega L_0 \Delta L(\omega)$
- Compare signal to reference with mixer for real portion, must match phase
- Away from $\omega_0$, coil impedance has reactive components, makes Q-curve
- Sweep frequency around $\omega_0$ to integrate in $\omega$



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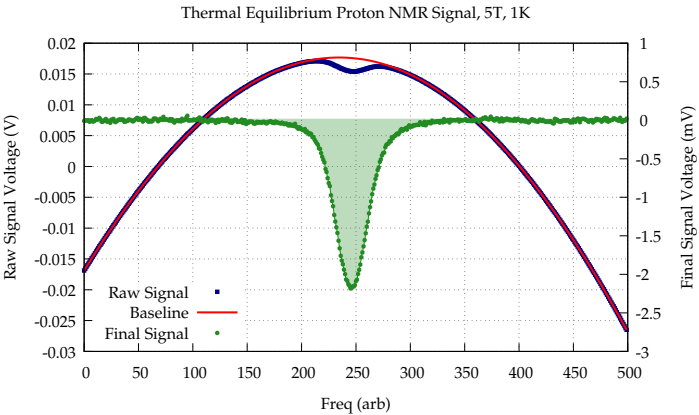
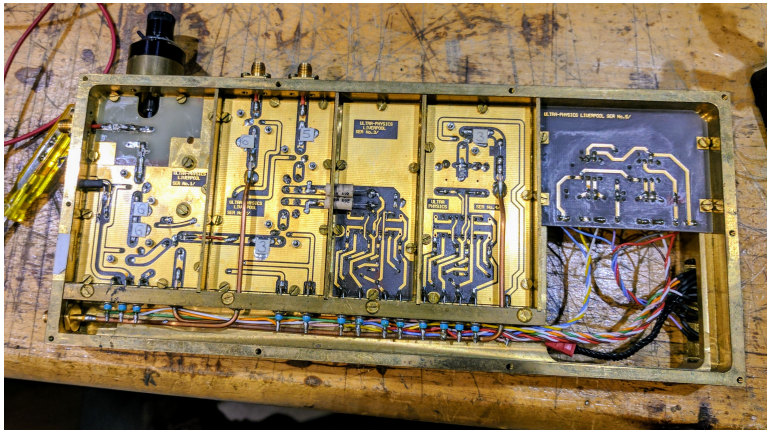
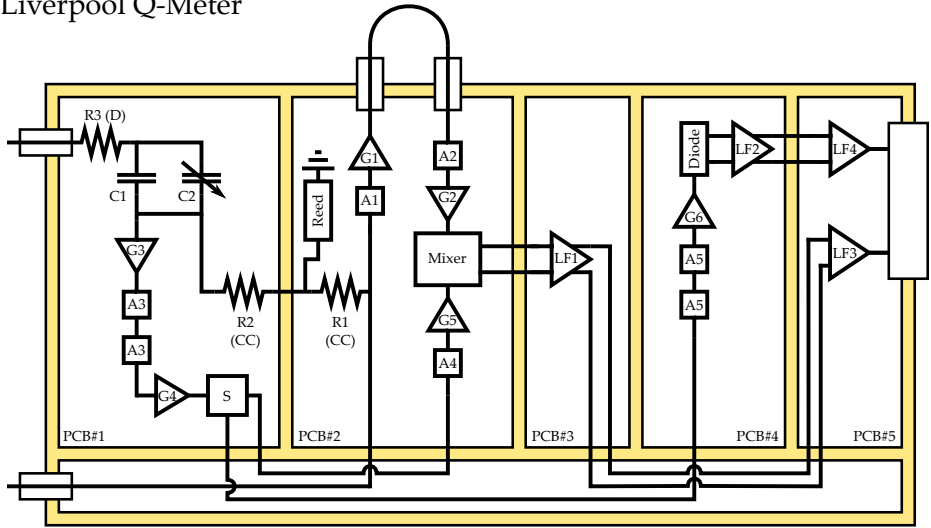


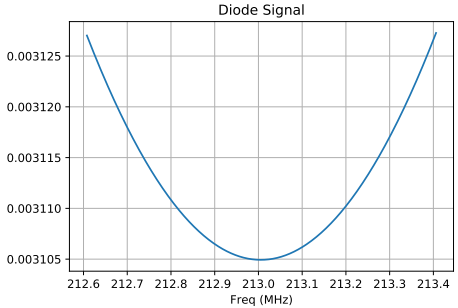
# Liverpool Q-meter

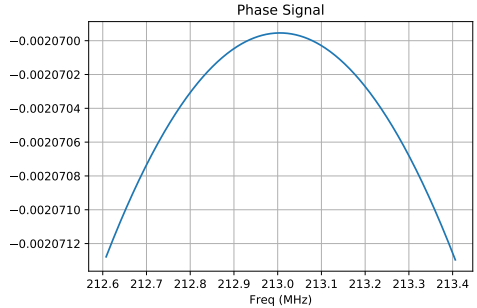
- Liverpool Q-meter used for decades.
  G.R. Court, NIM A324 (1993)
- Designed for excellent RF performance for DNP applications.
- Five 2-sided boards:
  1. Tank and splitter
  2. Mixer
  3. Phase amplification
  4. Diode amplification
  5. Final amplification



## Liverpool Q-Meter






## Traditional Tuning for Continuous-wave NMR

- Determine length cable $(n\lambda/2)$ to run from Q-meter to coil within cryostat
- Set $C$ (trimmers) to center power response (diode) minimum at $\omega_0$
- Choose phase cable to center real portion maximum at $\omega_0$

## JLab NMR Wishlist

- Remote capacitor tuning
  - Convenience, Accommodate 2 opposing cells, Synchronous Tuning
- Electronic phase tuning
- Cold circuit NMR
  - Noise reduction, Non-resonant cable circuit
- Address aging of Liverpool Q-meter
  - New Q-meters using off-the-shelf components
- Software Overhaul
- Bespoke Data Acquisition?

Focus on Enabling, Ease of Use Improvements

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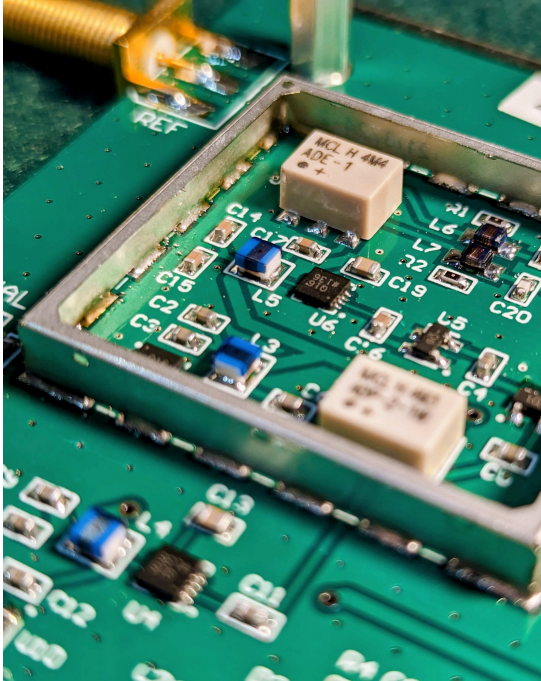
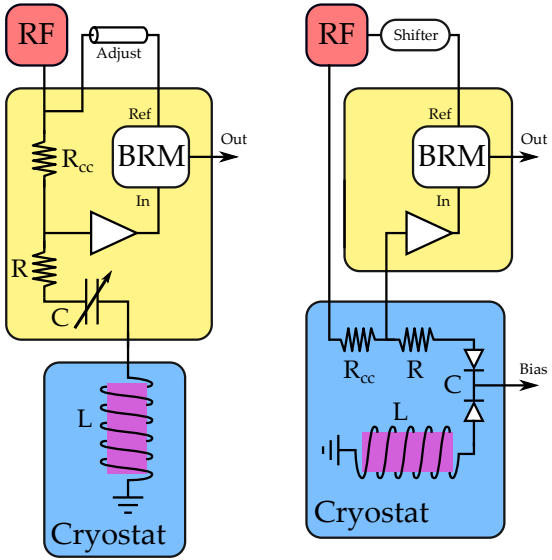


# Put Tank Circuit inside Cryostat?

- Traditionally, $R$ and $C$ inside Q-meter, $L$ in the cryostat
- Moving $R$ and $C$ into the cryostat, $\lambda/2$ no longer separates $L$. (Court, NIM A 2004.)
  - Q-curve shallower
  - Thermal noise reduction
  - Requires components that can handle cold, microwaves, radiation
- Varactor diodes vary $C$ vs. voltage
- Electronic phase shifters replace phase cable
- GaAs Varactors for cryogenic applications



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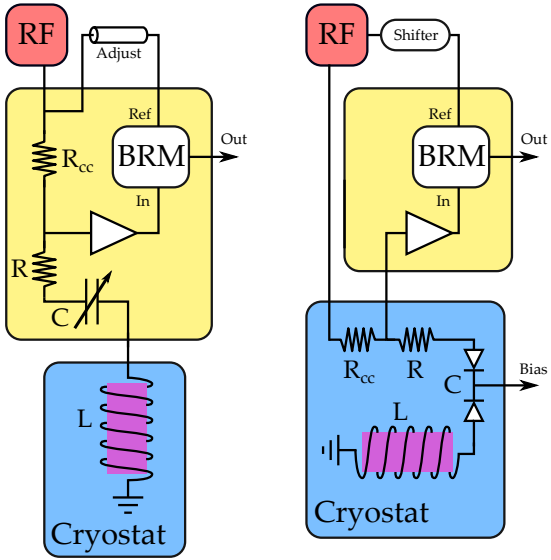

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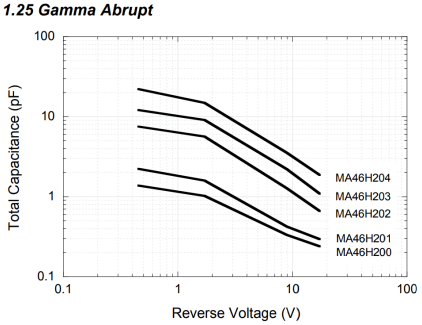
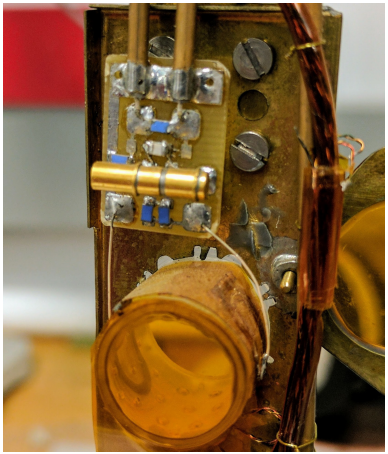


# Cold NMR Boards

- Cold NMR method most recently used at JLab for EG1-DVCS deuteron
  - Trim cap and high $C$ for 5 T D: 32.7 MHz
  - Tune performed warm, anticipating the change with temperature
- Introducing GaAs varactor diodes
  - Tested at 213 MHz to 3.2 K
  - Minimal changes seen at high B, low T
- Final Board: Tuning Range Expanded
  - 2 parallel varactors in series with a large capacitor
  - Thermometry and heater
  - Temp held around 15 K to avoid film creep



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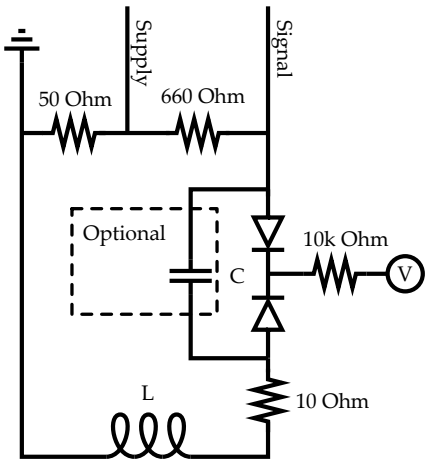

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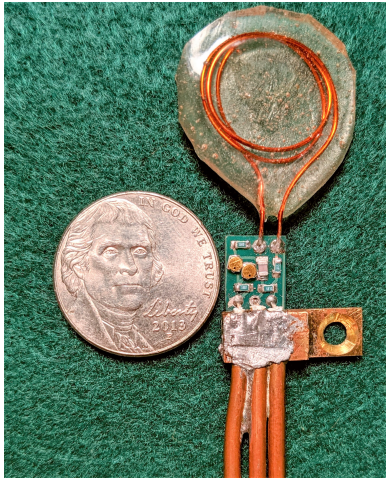

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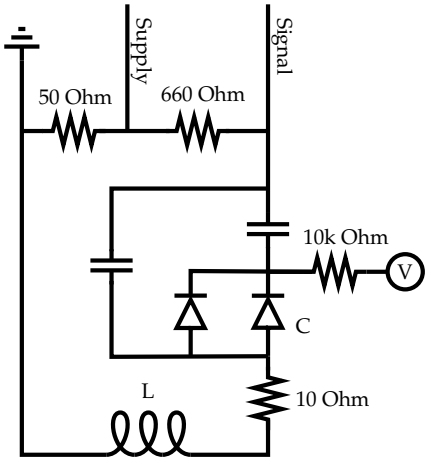

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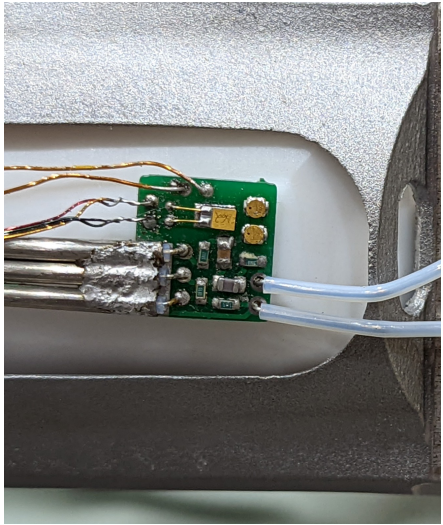
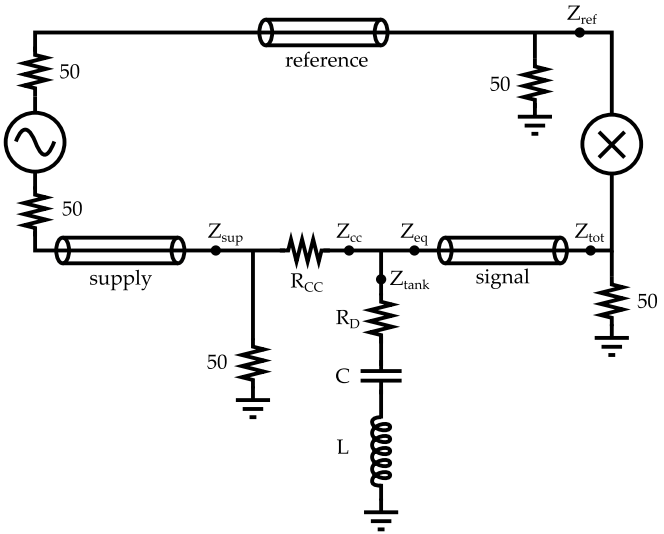


# Q-meter Simulation

- Using remote tank circuits, varactors and phase shifters introduces unfamiliar effects
- Python simulation expanded from MathCAD code by Houlden, Court
- Understand how cable lengths and mistune can affect signal
- Allow fits to baseline (lmfit)



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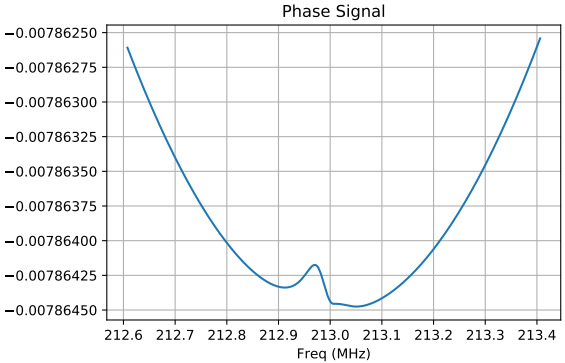


Signal cable: $1.2 \cdot \lambda/2$, retuned

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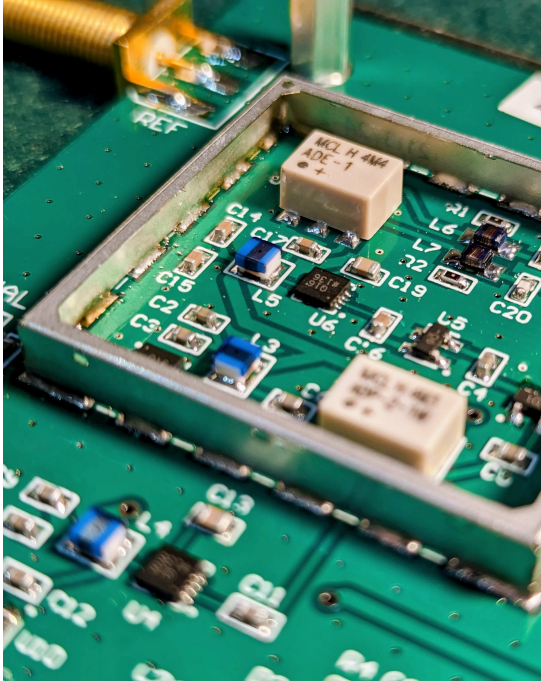
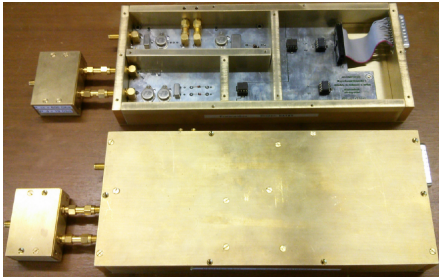


# A New Liverpool Q-meter?

- Q-meters now limited commodity, replacements scarce
- Target group at Bochum already building new Q-meters in the Liverpool style with new components J. Herick Thesis, Bochum, 2016.



## Aims for JLab Q-meter

- Follow Liverpool meter's successful design as closely as possible
- Replace components when modern parts superior (amplifiers)
- As modular as possible and all off-the-shelf components
- Simplify power supply to just $\pm 5\,\mathrm{V}$

# JLab Q-meter Design

- JLab Q-meter consists of 2 boards in Al enclosure
- Single layer boards with ground plane shielding
- “Stitching” for ground planes
- Mixer enclosed in board shield
- Biggest change: Analog Devices RF and Diff amplifiers
- Layout: JM, H. Dong

1. Amplifier Board
2. Mixer/Diode Board

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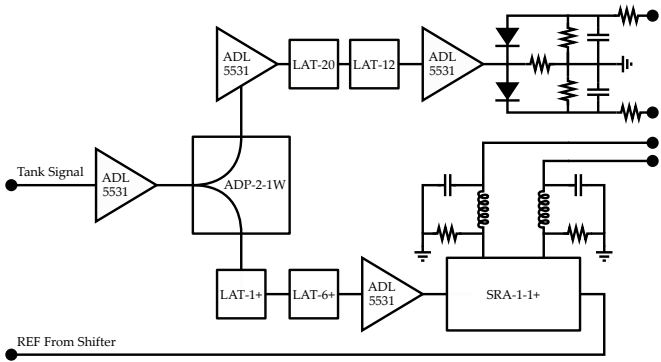

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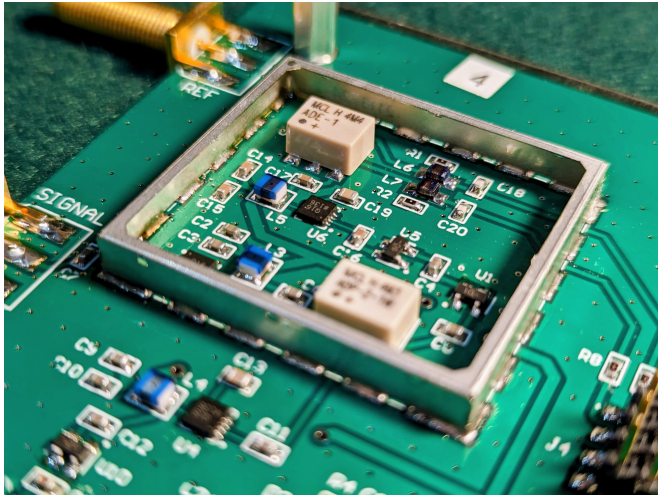

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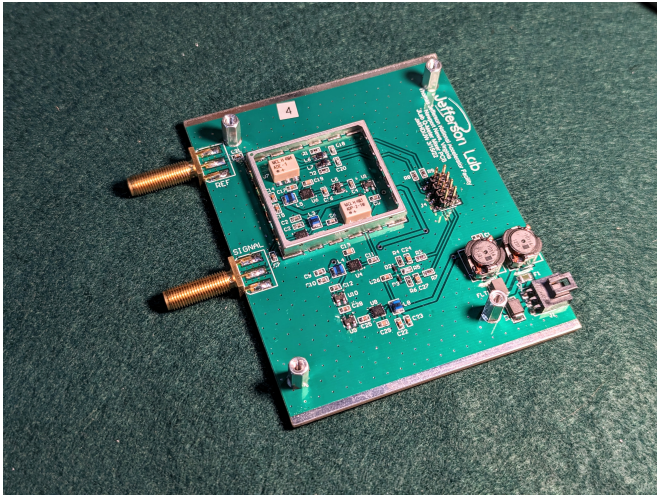

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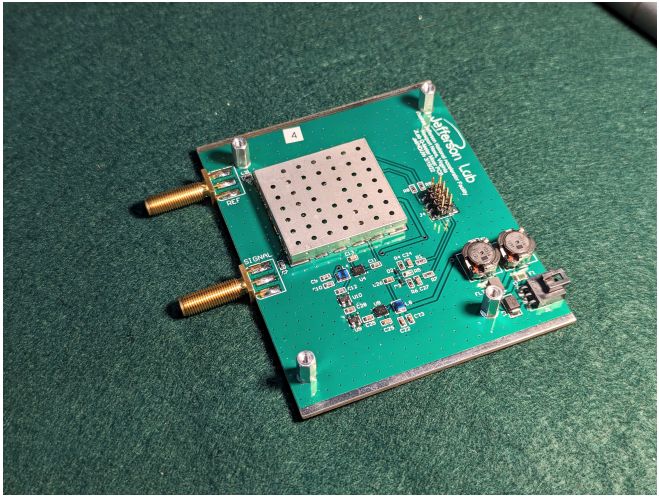

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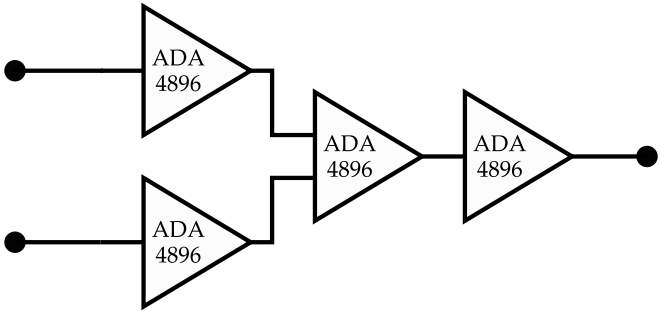

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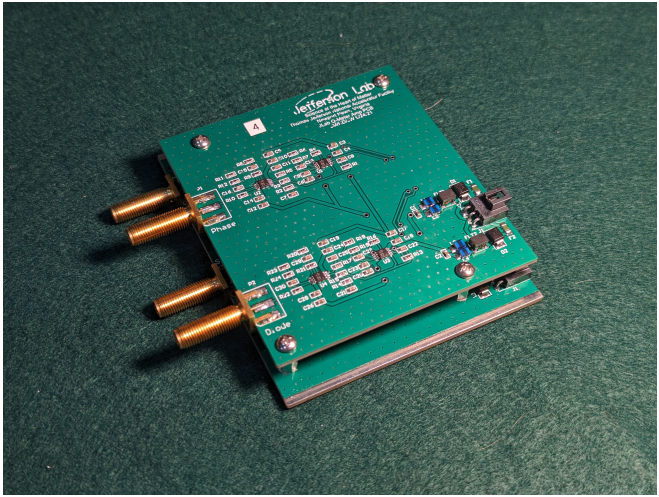

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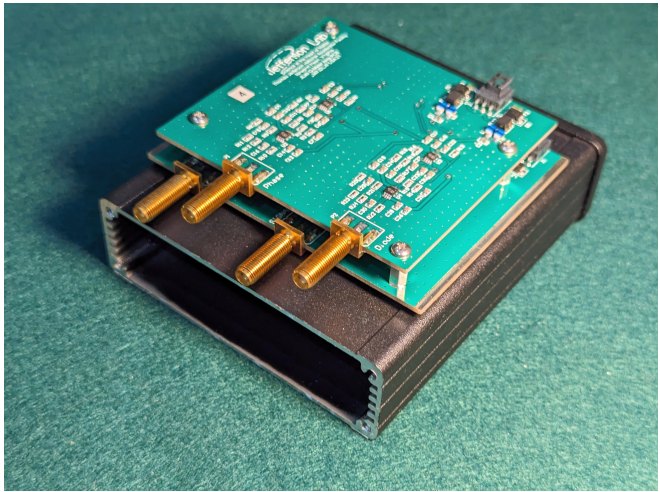
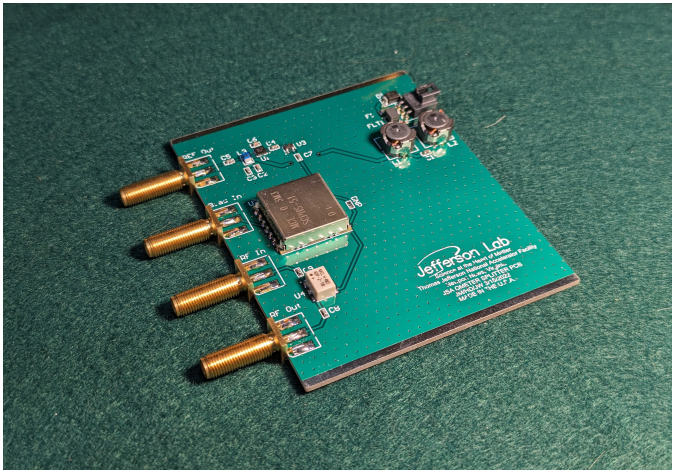
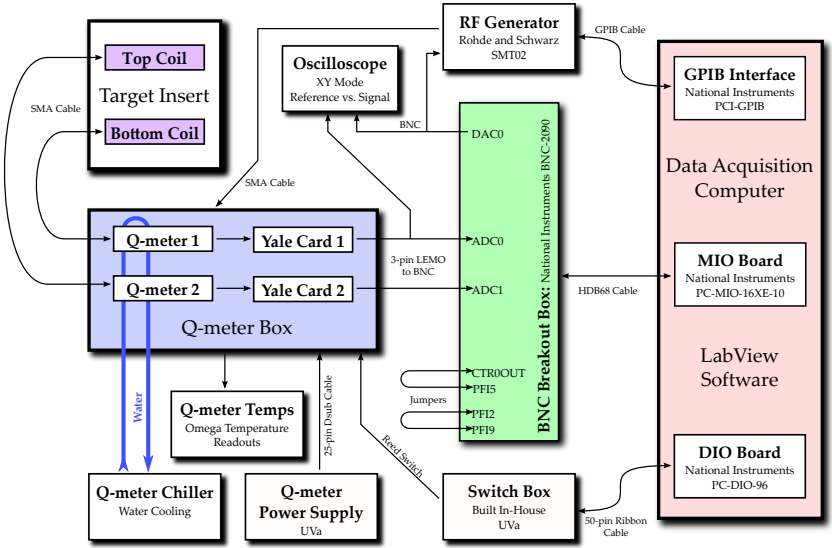


# Auxiliary Box Design

- Split RF-in to send to tank board and phase shifter
- Amplify RF to send as REF to Q-meter
- Accommodate either electronic phase shifter or phase cable
- Turn off RF power to Q-meter through relay when not in use




Top Coil
Target Insert
Bottom Coil
SMA Cable
SMA Cable
Oscilloscope
XY Mode
Reference vs. Signal
BNC
RF Generator
Rohde and Schwarz
SMT02
GPIB Cable
GPIB Interface
National Instruments
PCI-GPIB
Data Acquisition
Computer
DAC0
ADC0
ADC1
Q-meter 1
Yale Card 1
Q-meter 2
Yale Card 2
Q-meter Box
3-pin LEMO
to BNC
BNC Breakout Box: National Instruments BNC-2090
HDB68 Cable
MIO Board
National Instruments
PC-MIO-16XE-10
LabView
Software
CTR0OUT
PFI5
Jumpers
PFI2
PFI9
Water
Q-meter Temps
Omega Temperature
Readouts
25-pin Dsub Cable
Reed Switch
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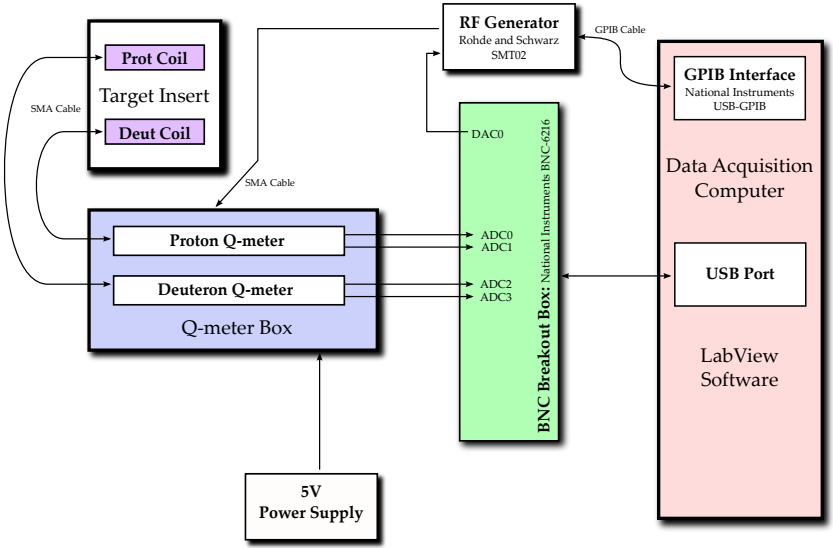
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Target Insert
Deut Coil
SMA Cable
SMA Cable
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Data Acquisition
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Deuteron Q-meter
Q-meter Box
ADC0
ADC1
ADC2
ADC3
BNC Breakout Box: National Instruments BNC-6216
USB Port
LabView
Software
5V
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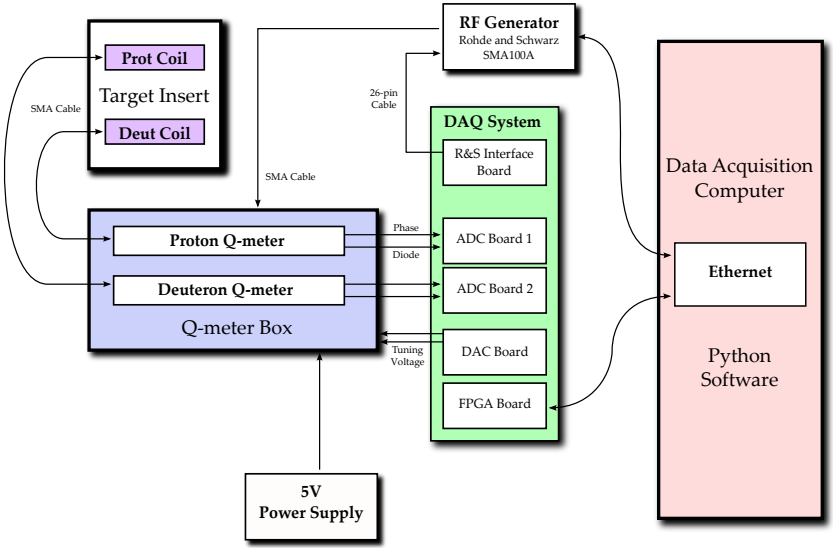
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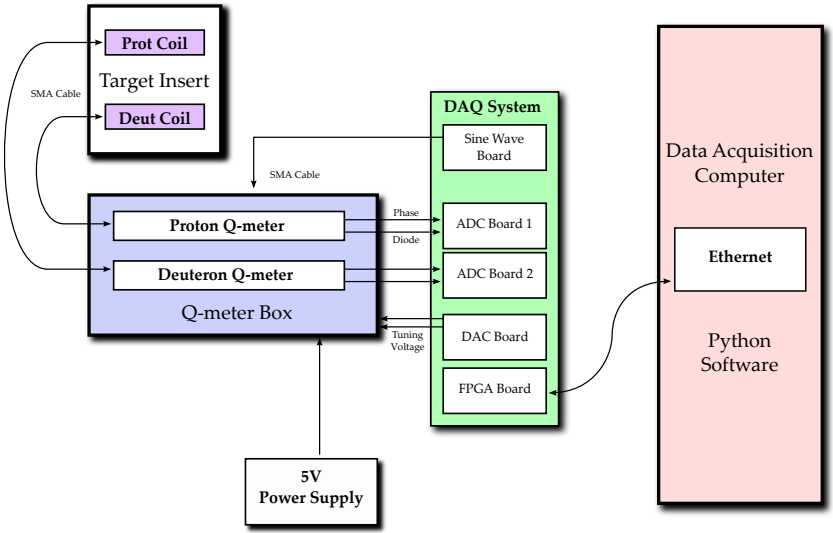
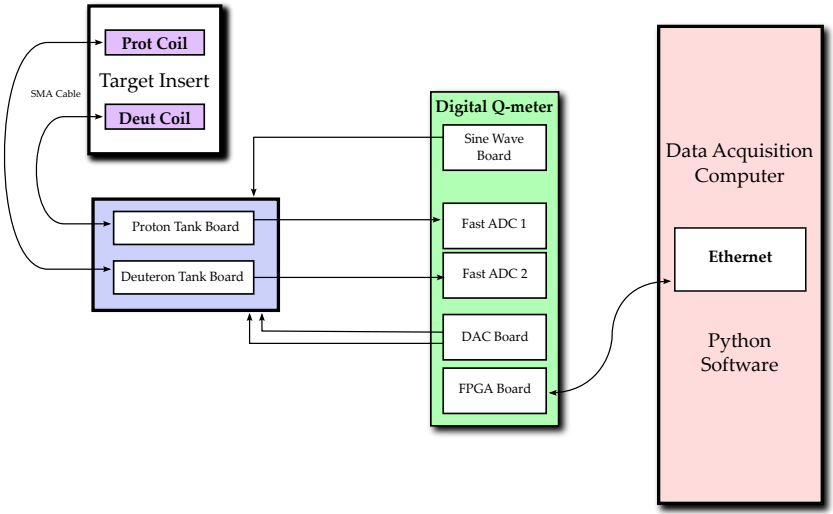
Computer
Proton Q-meter
Deuteron Q-meter
Q-meter Box
Phase
Diode
ADC Board 1
ADC Board 2
Ethernet
Tuning
Voltage
DAC Board
FPGA Board
Python
Software
5V
Power Supply


Prot Coil
Target Insert
Deut Coil
SMA Cable
SMA Cable
Proton Q-meter
Deuteron Q-meter
Q-meter Box
Phase
Diode
Tuning Voltage
DAQ System
Sine Wave Board
ADC Board 1
ADC Board 2
DAC Board
FPGA Board
Data Acquisition Computer
Ethernet
Python Software
5V Power Supply


Prot Coil
Target Insert
Deut Coil
SMA Cable
Proton Tank Board
Deuteron Tank Board
Digital Q-meter
Sine Wave Board
Fast ADC 1
Fast ADC 2
DAC Board
FPGA Board
Data Acquisition Computer
Ethernet
Python Software

# Q-meter DAQ Improvements

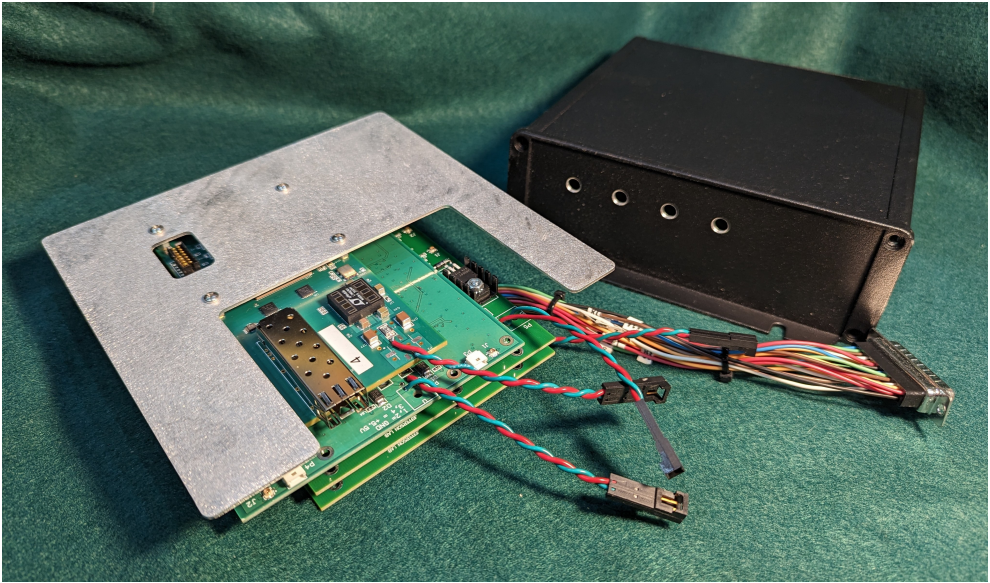
The biggest weakness of previous system is not the venerable Liverpool Q-meter!

## NI PC-MIO-16XE-10

- 16-bit
- 100 kSps
- $\pm$ 36 $\mu$V
- 30 $\mu$s frequency switching
- Triangle freq sweep
- PCI board, GPIB to R&S
- LabView

## New System

- 24-bit
- 625 kSps
- $\pm$ 1 $\mu$V
- 10 $\mu$s switching
- Arbitrary freq sweep
- Ethernet
- Python



# FPGA Sweeping Algorithm in VHDL

- Initialize via UDP
  - Set center frequency, modulation, number of steps, number of sweeps to take, dwell time per step, points per step, ADC settings
  - Also change DAC voltage out for tuning (synchronous tuning one day)
- Takes sweeps
  - Change frequency, take ADC value, sum for that bin, repeat
  - Repeat for multiple sweeps through the range, continuing sums
  - After last sweep, return summed bins and number of sweeps to average
  - PC listens for FPGA response on TCP, divides to form averaged sweep
- Communicates with signal generator directly with 16-bit word on 16 pin cable
  - Allows 10 $\mu$sec setting time for generator
  - Limits this device to Rohde & Schwarz SMA110A
- Written by H. Dong

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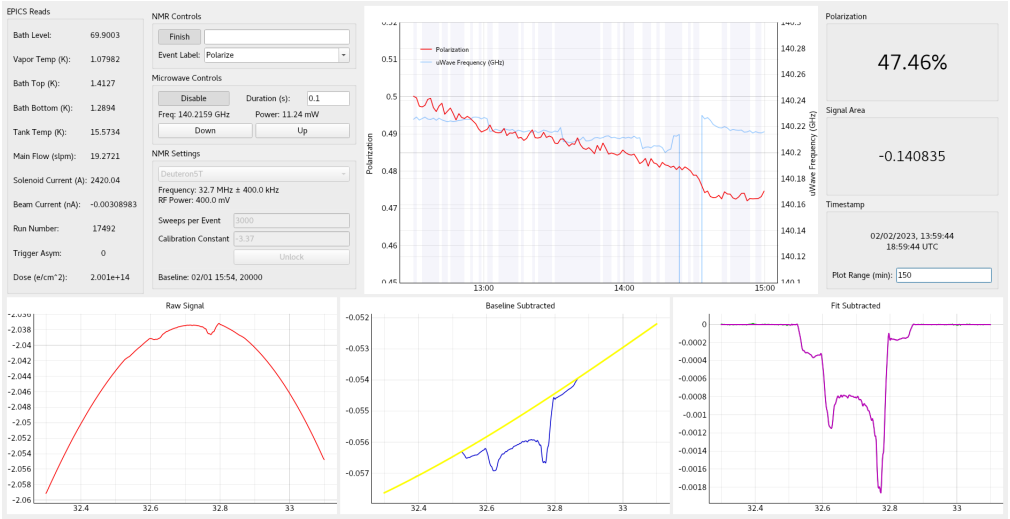
# Leaving LabView Behind...

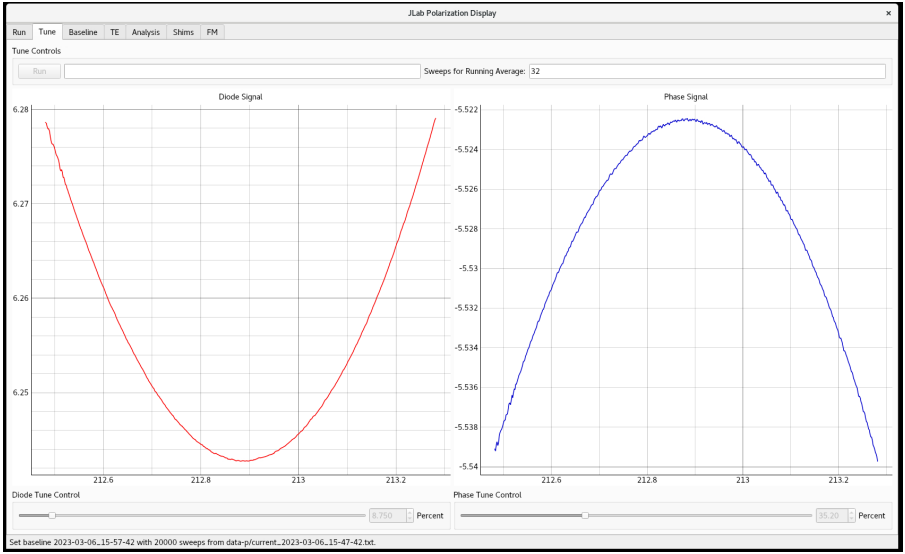
## Software Revamp Goals

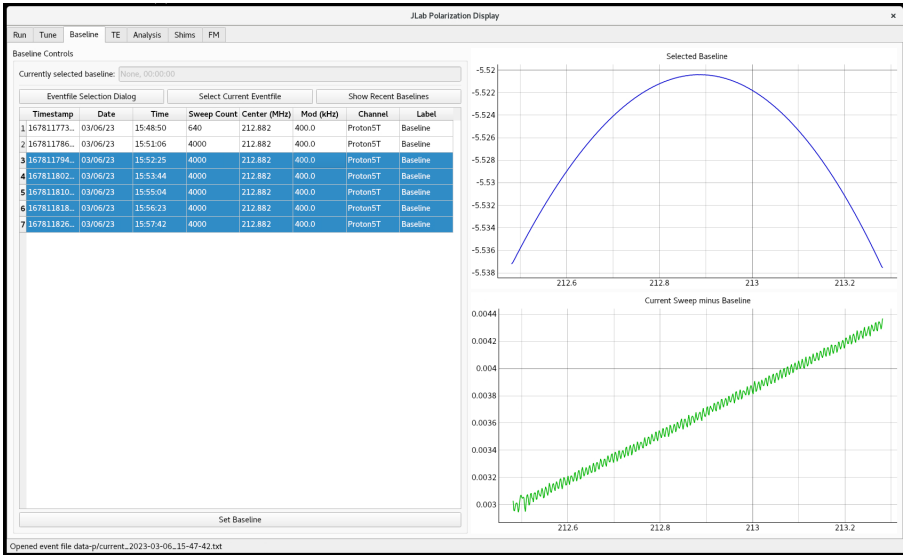
- Modernize, improve ease of use
  - Lightweight and cross-platform compatibility
- Incorporate Python circuit simulation for fits
- Flexibility to use new FPGA or old NI DAQ
- Include traditionally off-line tools: TE, fits, event viewer
- Allow arbitrary sweep frequency lists
- Interface with numerous instruments, EPICS

# JLab PyNMR

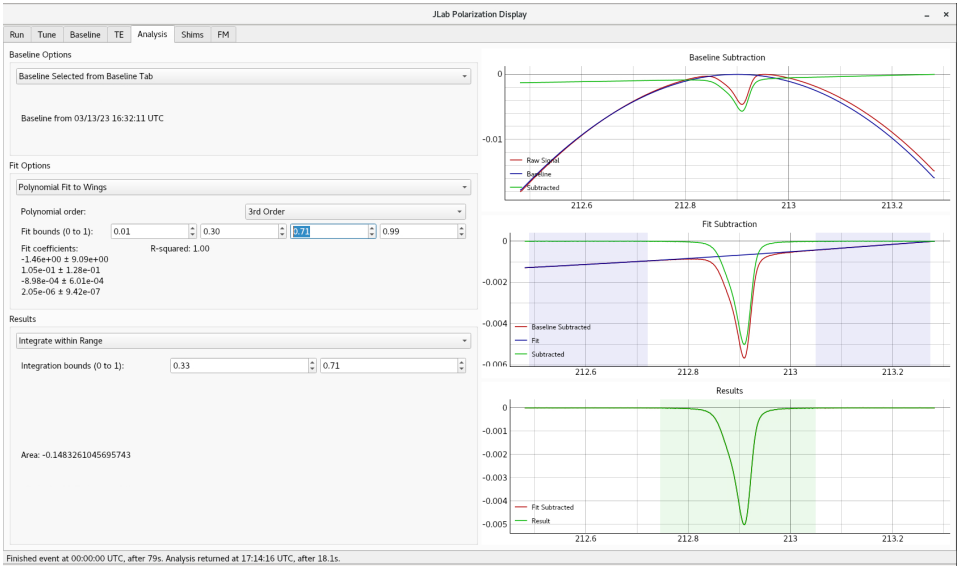
- New software based on Python, PyQt5
  - Uses Numpy, Scipy, pyqtgraph to be fast
  - Sockets for TCP, UDP communication
  - EPICS slow controls archiving over ethernet
  - Config file in YAML, JSON data files, Log files
  - Controls for microwave frequency and modulation
- Modular online signal analysis
- Documentation here, Github here.

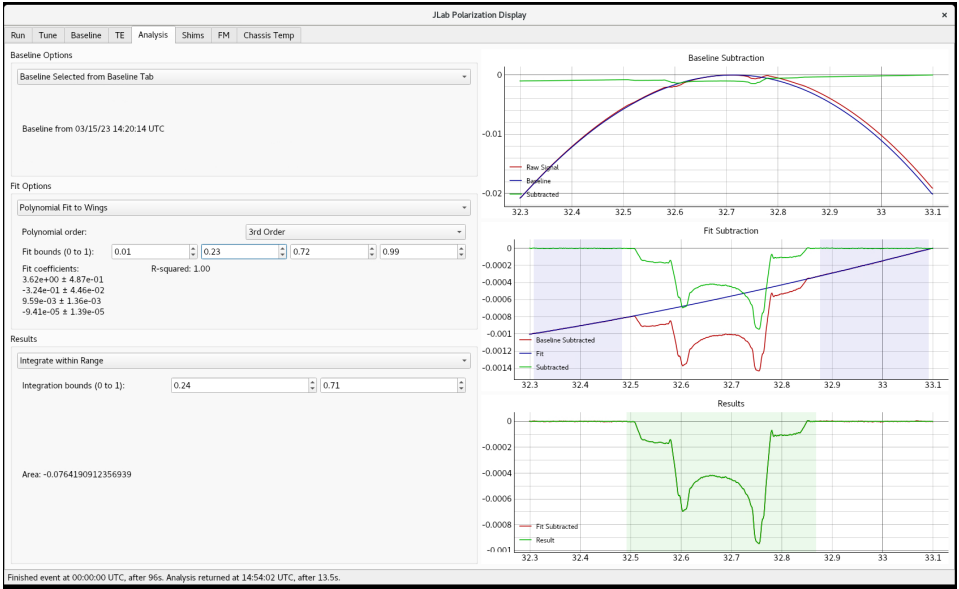

EPICS Reads
Bath Level: 69.9003
Vapor Temp (K): 1.07982
Bath Top (K): 1.4127
Bath Bottom (K): 1.2894
Tank Temp (K): 15.5734
Main Flow (slpm): 19.2721
Solenoid Current (A): 2420.04
Beam Current (nA): -0.00308983
Run Number: 17492
Trigger Asym: 0
Dose (e/cm^2): 2.001e+14
NMR Controls
Finish
Event Label: Polarize
Microwave Controls
Disable
Duration (s): 0.1
Freq: 140.2159 GHz
Power: 11.24 mW
Down
Up
NMR Settings
DeuteronST
Frequency: 32.7 MHz ± 400.0 kHz
RF Power: 400.0 mV
Sweeps per Event 3000
Calibration Constant -3.37
Unlock
Baseline: 02/01 15:54, 20000
Polarization
uWave Frequency (GHz)
Polarization
uWave Frequency (GHz)
13:00
14:00
15:00
Polarization
47.46%
Signal Area
-0.140835
Timestamp
02/02/2023, 13:59:44
18:59:44 UTC
Plot Range (min): 150
Raw Signal
Baseline Subtracted
Fit Subtracted

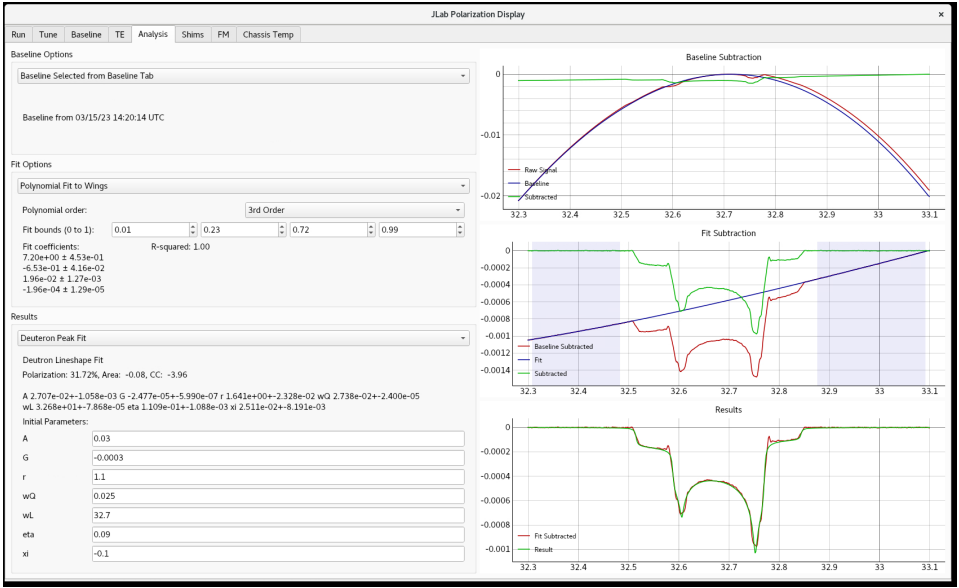

JLab Polarization Display
Run
Tune
Baseline
TE
Analysis
Shims
FM
Tune Controls
Run
Sweeps for Running Average:
32
Diode Signal
6.28
6.27
6.26
6.25
212.6
212.8
213
213.2
Phase Signal
-5.522
-5.524
-5.526
-5.528
-5.53
-5.532
-5.534
-5.536
-5.538
-5.54
212.6
212.8
213
213.2
Diode Tune Control
8.750
Percent
Phase Tune Control
35.20
Percent
Set baseline 2023-03-06_15-57-42 with 20000 sweeps from data-p/current_2023-03-06_15-47-42.txt.


JLab Polarization Display
Run
Tune
Baseline
TE
Analysis
Shims
FM
Baseline Controls
Currently selected baseline:
None, 00:00:00
Eventfile Selection Dialog
Select Current Eventfile
Show Recent Baselines
Timestamp
Date
Time
Sweep Count
Center (MHz)
Mod (kHz)
Channel
Label
1 167811773... 03/06/23 15:48:50 640 212.882 400.0 Proton5T Baseline
2 167811786... 03/06/23 15:51:06 4000 212.882 400.0 Proton5T Baseline
3 167811794... 03/06/23 15:52:25 4000 212.882 400.0 Proton5T Baseline
4 167811802... 03/06/23 15:53:44 4000 212.882 400.0 Proton5T Baseline
5 167811810... 03/06/23 15:55:04 4000 212.882 400.0 Proton5T Baseline
6 167811818... 03/06/23 15:56:23 4000 212.882 400.0 Proton5T Baseline
7 167811826... 03/06/23 15:57:42 4000 212.882 400.0 Proton5T Baseline
Set Baseline
Selected Baseline
-5.52
-5.522
-5.524
-5.526
-5.528
-5.53
-5.532
-5.534
-5.536
-5.538
212.6
212.8
213
213.2
Current Sweep minus Baseline
0.0044
0.0042
0.004
0.0038
0.0036
0.0034
0.0032
0.003
212.6
212.8
213
213.2
Opened event file data-p/current_2023-03-06_15-47-42.txt


Area History
History to Show (min): 360
Fit relaxation time 1e+04 secs ± inf, asymptote -0.00 ± inf.
TE Calculator
Species: Proton
B Field (T): 5.00
Double click to remove point. Fit slope 3.99e-09 ± 7.68e-09.
Date/Time
Area
Temp (K)
7 18:06:21 -0.0010039... 1....
8 18:09:39 -0.0009028... 1....
9 18:12:57 -0.0009630... 1....
10 18:16:15 -0.0008986... 1....
11 18:19:33 -0.0008506... 1....
12 18:22:51 -0.0009388... 1....
13 18:26:09 -0.0009109... 1....
14 18:29:27 -0.0010337... 1....
15 18:32:45 -0.0009542... 1....
16 18:36:03 -0.0008472... 1....
17 18:39:21 -0.0009074... 1....
18 18:42:39 -0.0009495... 1....
19 18:45:57 -0.0009370... 1....
20 18:49:15 -0.0008858... 1....
21 18:52:33 -0.0008498... 1....
22 18:55:51 -0.0008696... 1....
23 19:02:27 -0.0009745... 1....
24 19:05:45 -0.0009422... 1....
25 19:09:03 -0.0009355... 1....
26 19:12:21 -0.0008811... 1....
27 19:15:39 -0.0009559... 1....
Calculate TE from Points
Save Results & Use CC
TE Results
Material type: Proton
Number of Points: 27
Average Area: -0.0009197 ± 0.0000528
Average Temperature: 1.4908 ± 0.0019
Average Polarization: 0.00343 ± 0.00000
Average Calibration Constant: -3.7382742 ± 0.2175881
Area vs. Time
-0.001
-0.002
-0.003
-0.004
11:00
12:00
13:00
14:00
Select for TE
-0.0008
-0.0009
-0.0010
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
Finished event at 00:00:00 UTC, after 198s. Analysis returned at 19:22:16 UTC, after 0.1s.

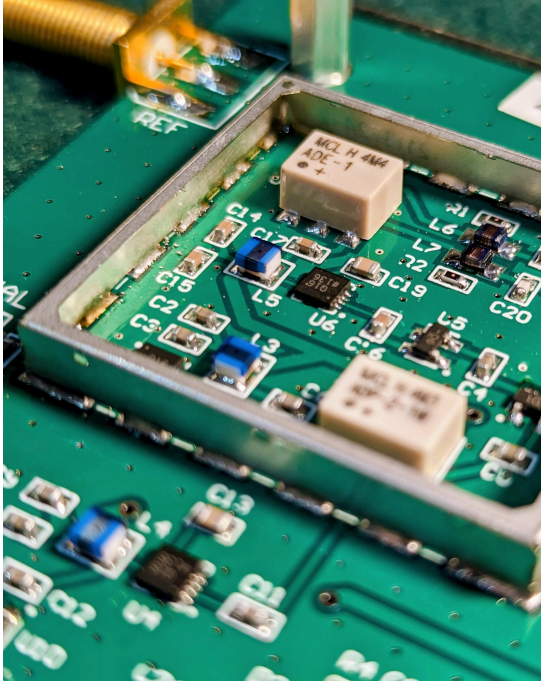

JLab Polarization Display
Run
Tune
Baseline
TE
Analysis
Shims
FM
Baseline Options
Baseline Selected from Baseline Tab
Baseline from 03/13/23 16:32:11 UTC
Fit Options
Polynomial Fit to Wings
Polynomial order:
3rd Order
Fit bounds (0 to 1):
0.01
0.30
0.71
0.99
Fit coefficients:
-1.46e+00 ± 9.09e+00
1.05e-01 ± 1.28e-01
-8.98e-04 ± 6.01e-04
2.05e-06 ± 9.42e-07
R-squared: 1.00
Results
Integrate within Range
Integration bounds (0 to 1):
0.33
0.71
Area: -0.1483261045695743
Baseline Subtraction
Raw Signal
Baseline
Subtracted
Fit Subtraction
Baseline Subtracted
Fit
Subtracted
Results
Fit Subtracted
Result
Finished event at 00:00:00 UTC, after 79s. Analysis returned at 17:14:16 UTC, after 18.1s.


JLab Polarization Display
Run
Tune
Baseline
TE
Analysis
Shims
FM
Chassis Temp
Baseline Options
Baseline Selected from Baseline Tab
Baseline from 03/15/23 14:20:14 UTC
Fit Options
Polynomial Fit to Wings
Polynomial order:
3rd Order
Fit bounds (0 to 1):
0.01
0.23
0.72
0.99
Fit coefficients:
3.62e+00 ± 4.87e-01
-3.24e-01 ± 4.46e-02
9.59e-03 ± 1.36e-03
-9.41e-05 ± 1.39e-05
R-squared: 1.00
Results
Integrate within Range
Integration bounds (0 to 1):
0.24
0.71
Area: -0.07641909123569 39
Baseline Subtraction
Raw Signal
Baseline
Subtracted
Fit Subtraction
Baseline Subtracted
Fit
Subtracted
Results
Fit Subtracted
Result
Finished event at 00:00:00 UTC, after 96s. Analysis returned at 14:54:02 UTC, after 13.5s.


JLab Polarization Display
Run
Tune
Baseline
TE
Analysis
Shims
FM
Chassis Temp
Baseline Options
Baseline Selected from Baseline Tab
Baseline from 03/15/23 14:20:14 UTC
Fit Options
Polynomial Fit to Wings
Polynomial order:
3rd Order
Fit bounds (0 to 1):
0.01
0.23
0.72
0.99
Fit coefficients:
7.20e+00 ± 4.53e-01
-6.53e-01 ± 4.16e-02
1.96e-02 ± 1.27e-03
-1.96e-04 ± 1.29e-05
R-squared: 1.00
Results
Deuteron Peak Fit
Deutron Lineshape Fit
Polarization: 31.72%, Area: -0.08, CC: -3.96
A 2.707e-02+-1.058e-03 G -2.477e-05+-5.990e-07 r 1.641e+00+-2.328e-02 wQ 2.738e-02+-2.400e-05
wL 3.268e+01+-7.868e-05 eta 1.109e-01+-1.088e-03 xi 2.511e-02+-8.191e-03
Initial Parameters:
A
0.03
G
-0.0003
r
1.1
wQ
0.025
wL
32.7
eta
0.09
xi
-0.1
Baseline Subtraction
Raw Signal
Baseline
Subtracted
Fit Subtraction
Baseline Subtracted
Fit
Subtracted
Results
Fit Subtracted
Result

# Outline


1. NMR and JLab Solid Targets
   - Introduction
2. Cold Board NMR
3. A New JLab Q-Meter System
   - Qmeter Design
   - DAQ Design
   - Software Design
4. Results
5. Future Effort

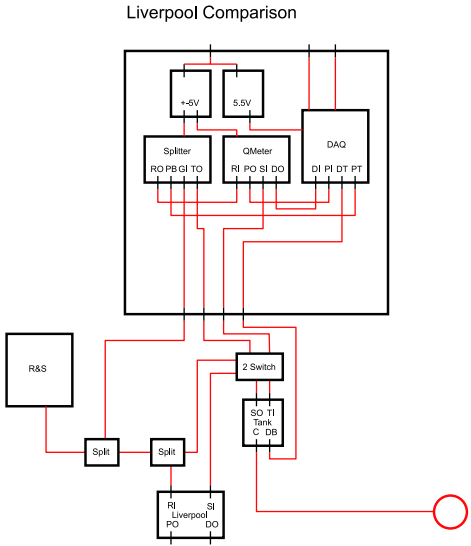



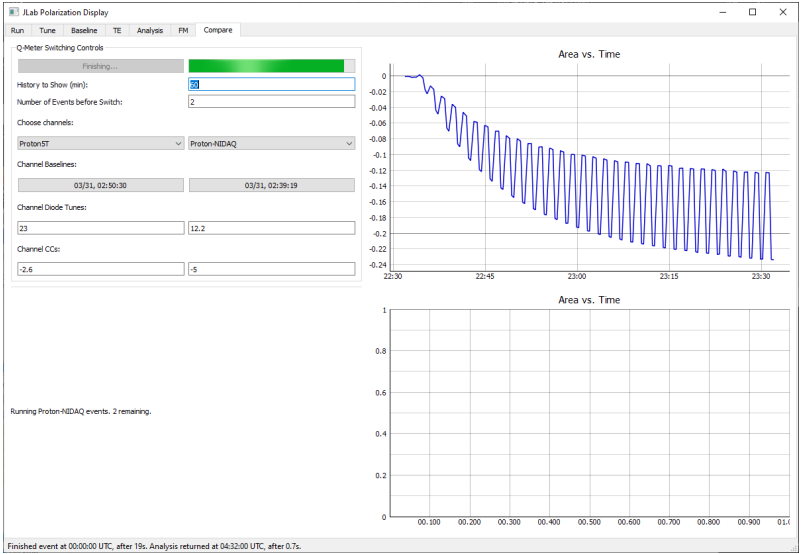
"Upgrading from the Liverpool to JLAB q-meter greatly increased the sensitivity and stability of the NMR system, allowing us to measure signals from very small samples."

-J. Pierce, Oak Ridge National Lab

# Comparing with Liverpool

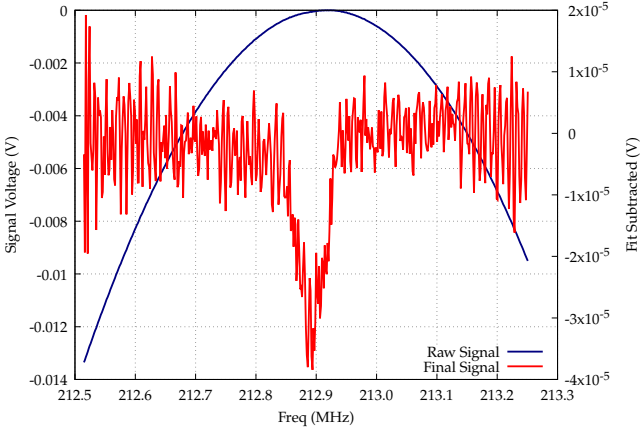
- Direct comparison to Liverpool useful
  - Liverpool is gold standard
  - Linearity is crucial
- Ethernet double RF switch, Python Software
- Same material, coil and tank circuit
- This is an unfair comparison!
  - Unavoidable noise introduced to both systems with switching
  - JLab gets benefit of new DAQ, shielding
  - JLab is faster, (1/3 switching time)
  - Liverpool set up with NI DAQ board




JLab Polarization Display
Run
Tune
Baseline
TE
Analysis
FM
Compare
Q-Meter Switching Controls
Finishing...
History to Show (min):
20
Number of Events before Switch:
2
Choose channels:
ProtonST
Proton-NIDAQ
Channel Baselines:
03/31, 02:50:30
03/31, 02:39:19
Channel Diode Tunes:
23
12.2
Channel CCs:
-2.6
-5
Running Proton-NIDAQ events. 2 remaining.
Area vs. Time
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
-0.18
-0.2
-0.22
-0.24
22:30
22:45
23:00
23:15
23:30
Area vs. Time
1
0.8
0.6
0.4
0.2
0
00.100
00.200
00.300
00.400
00.500
00.600
00.700
00.800
00.900
Finished event at 00:00:00 UTC, after 19s. Analysis returned at 04:32:00 UTC, after 0.7s.

# Comparing with Liverpool

- Test: Proton TE, tiny signal!
- Noise roughly 2-3 times worse in switching configuration
- 3000 sweeps through frequency
  - Takes JLab 60 sec
  - JLab takes 2 times as many points
  - Takes Liverpool 91 secs
- Noise comparison maybe not conclusive here
- Under polarization, performs well
- Linearity comparison




JLab

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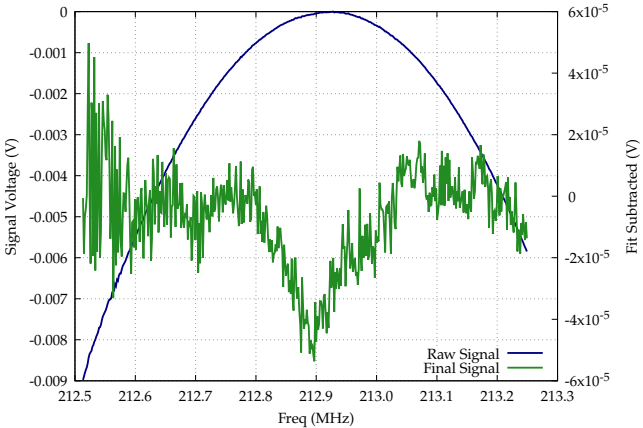


Liverpool

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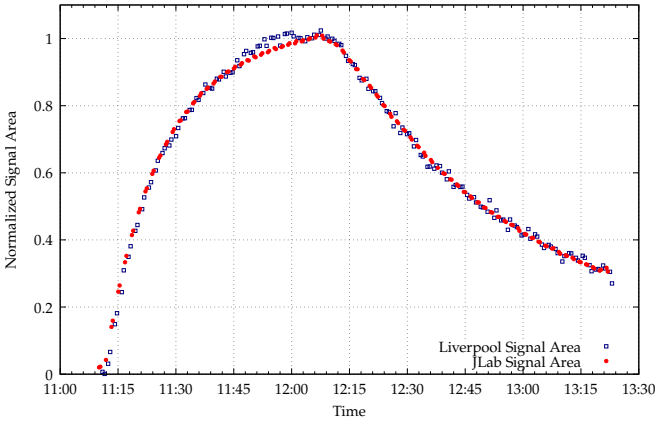

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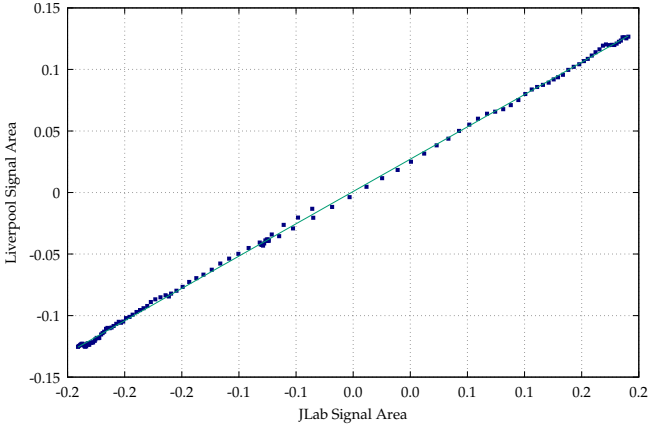

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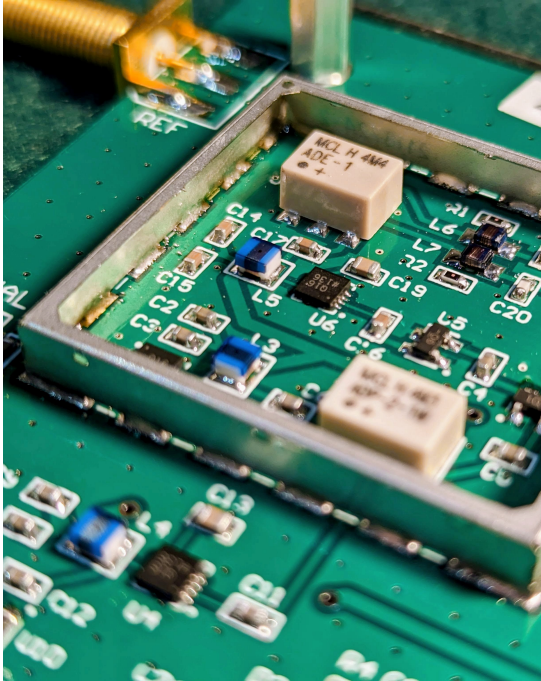


# Future Paths of Research

- Sine wave board: replace R&S signal generator
- All Digital Q-meter
  - Use fast ADCs to digitize before down-mixing
  - Perform algorithmic down-mix to get signal
  - Patent Awarded for Design (J. Maxwell, 2422U (JSA))
- Machine Learning DOE grant awarded for polarized target control
  - ML methods for polarization extraction from NMR also to be investigated
  - Focus first on baseline determination, signal isolation
- Quadrature measurements with existing system

# Summarizing New JLab NMR System

- Significant ergonomic improvements:
  - Cheaper to build, more flexible, better supported by software, easier to use
- Direct improvement of measurement accuracy
  - Faster, less noisy
- Used with success for Run Group C
- Publication forthcoming
- Schematics and code available to all

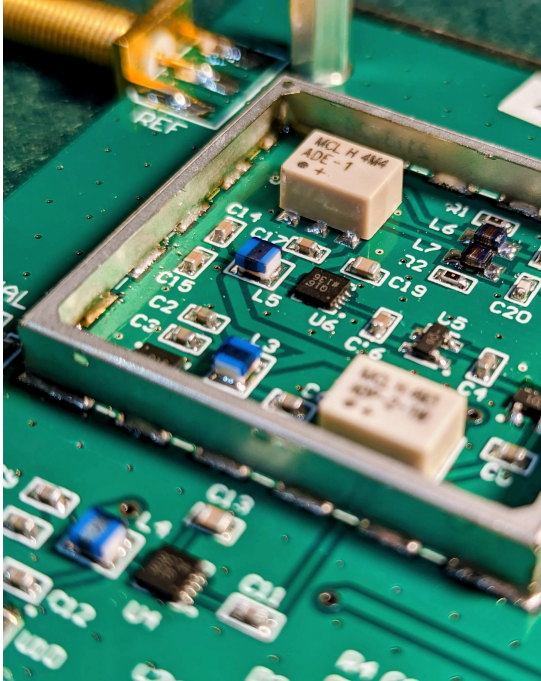
Jefferson Lab Polarized Target Group:

- C. Keith, J. Maxwell, D. Meekins
- J. Brock, C. Carlin, D. Griffith, M. Hoegerl, P. Hood

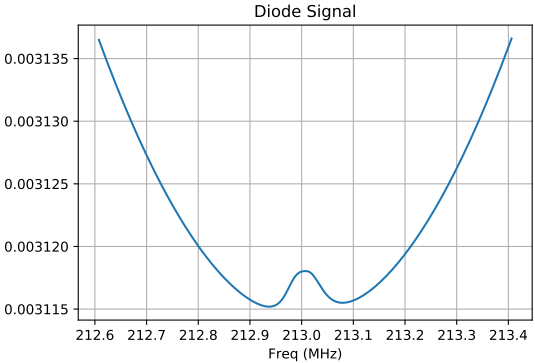
Special thanks:

- H. Dong, J. Wilson
  (JLab Electronics Group)
- J. Pierce (ORNL)
- V. Lagerquist (ODU)

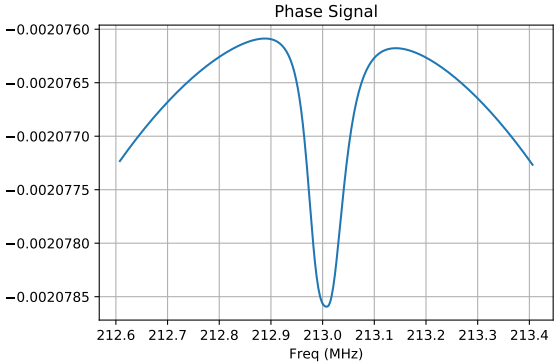
Thank you for your attention!



# Q-curve and Signal Response, 400 kHz Range

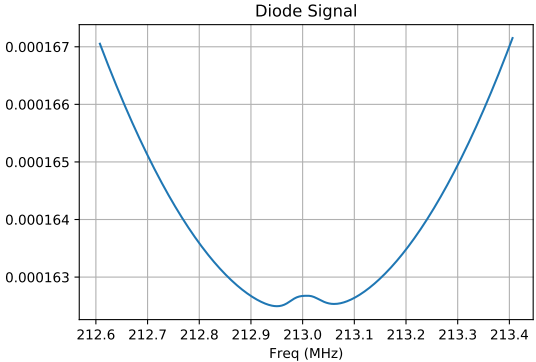



Signal cable: short

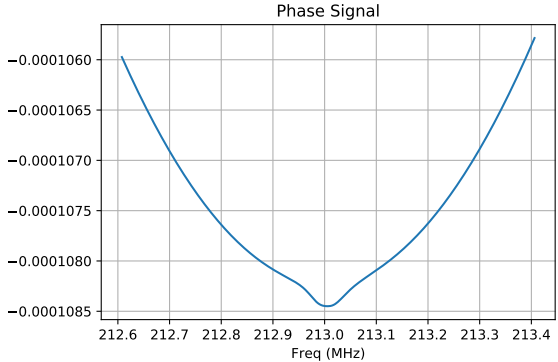



Signal cable: short

# Q-curve and Signal Response, 400 kHz Range

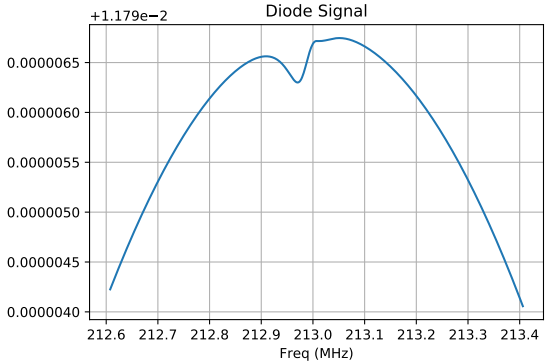



Signal cable: $1.5 \cdot \lambda/2$

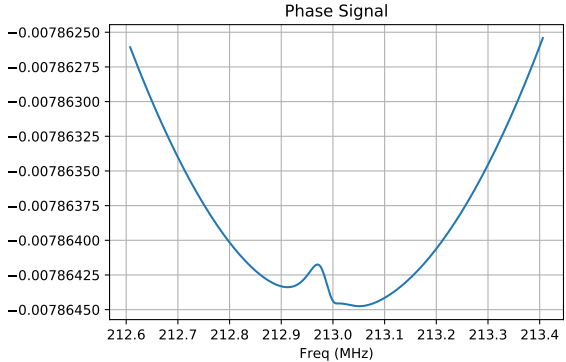



Signal cable: $1.5 \cdot \lambda/2$

# Q-curve and Signal Response, 400 kHz Range




Signal cable: $1.2 \cdot \lambda/2$, retuned




Signal cable: $1.2 \cdot \lambda/2$, retuned