# Optimization of a Three-Axes Teslameter for the Calibration of the Athos Undulators at PSI


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*Project done in collaboration with the* ***Paul Scherrer Institute*** *and* ***SENIS AG***

L-Università ta' Malta

Malta University Consulting

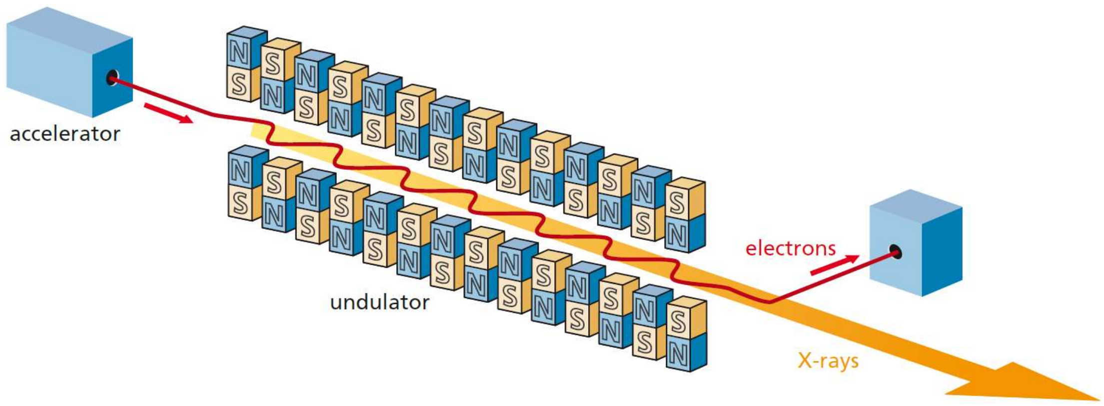
PAUL SCHERRER INSTITUT PSI

SENIS magnetic & current measurement

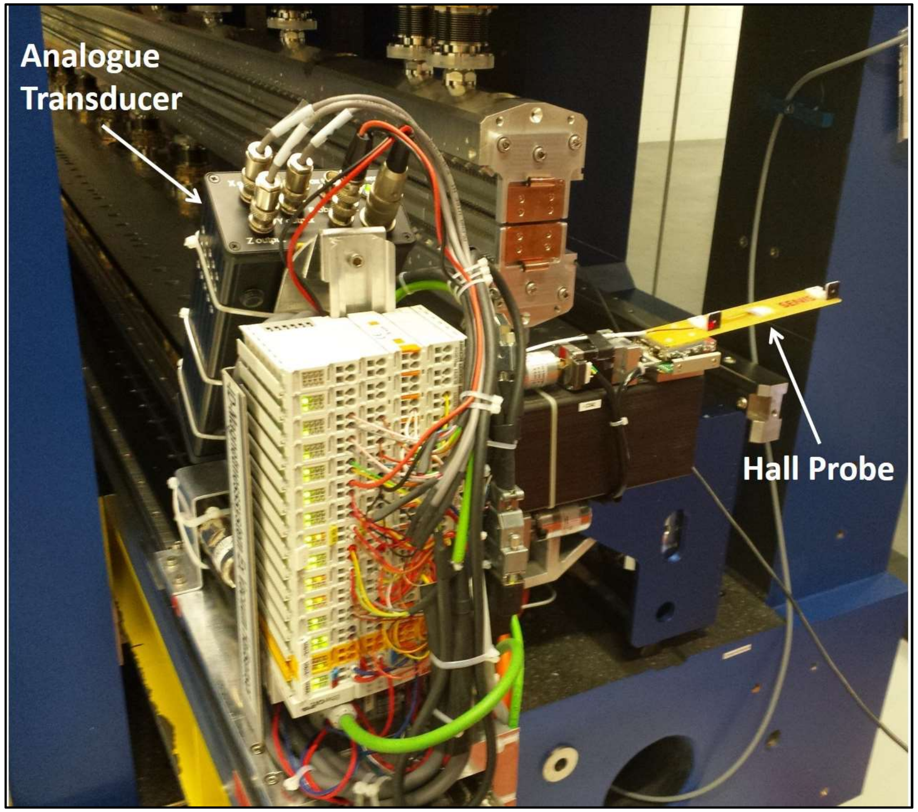
# Presentation Outline

- **Background and Problem Definition**
- **Instrumentation Technology**
- Instrument Architecture
- Instrument Development
- Final End Product
- Instrument Calibration
- Instrument Performance
- Conclusion
- Demonstration Videos

# Background and Problem Definition



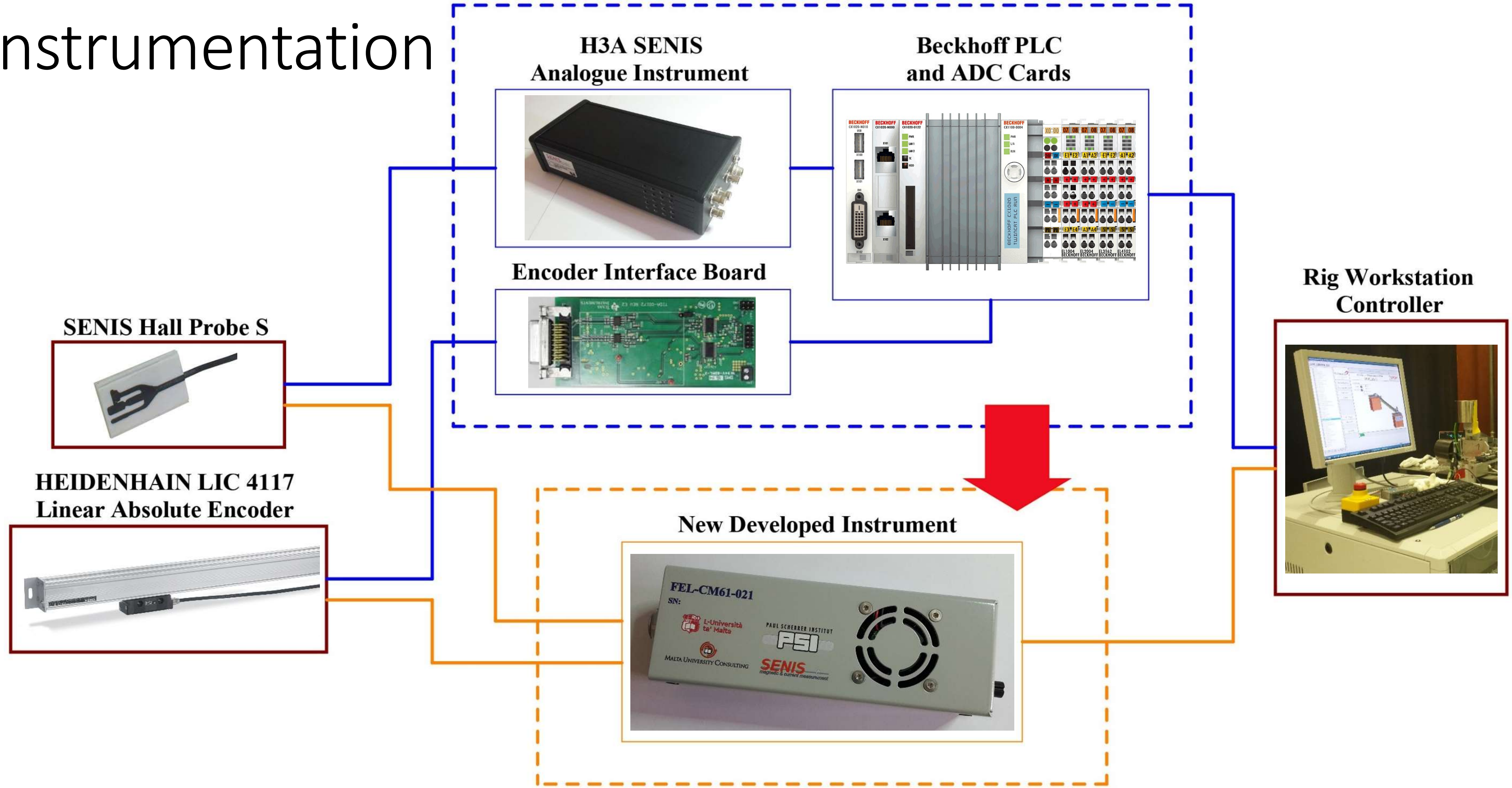

[1]




| Hall Probe Advantages | Hall Probe Disadvantages |
|---|---|
| Fast Measurement | Offset |
| Very Small in Size | Highly Non-Linear |
| Simultaneous Measurement of 3 Axes | Temperature Sensitivity |
| Suitable for mapping non-uniform fields | Drift with Time |


[1] P. Scherrer Institut (2012), *"SwissFEL Concept Design Report"*, p. 5.

# Instrumentation



# Instrumentation Comparison

| OLD Teslameter | NEW Teslameter |
|---|---|
| Bulky in size (separate blocks) | Substantial Reduction in size |
| ONLY Analogue Instrument | Fully Integrated Analogue and Digital Instrument |
| External 16 Bit Resolution Digitisation | 22 Bit Resolution Digitisation |
| Hardware Gain Calibration | No Hardware Gain Calibration |
| **Offline** Software Calibration | **On Board** Software Calibration |
| **Separate** Interface via a PLC system to Heidenhain Absolute Linear Encoder | **Integrated** Interface to Heidenhain Absolute Linear Encoder |
| Interface to PC via PLC system | micro SD Card interface |
| | USB 2.0 interface |
| Off-the-Shelf Instrumentation System | Application Tailored Instrument |



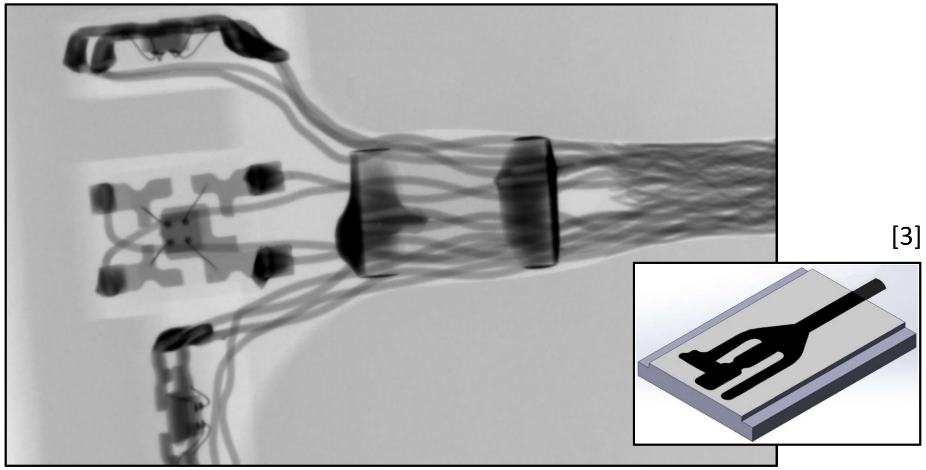
**220 mm x 103 mm x 53 mm**
**ANALOGUE**

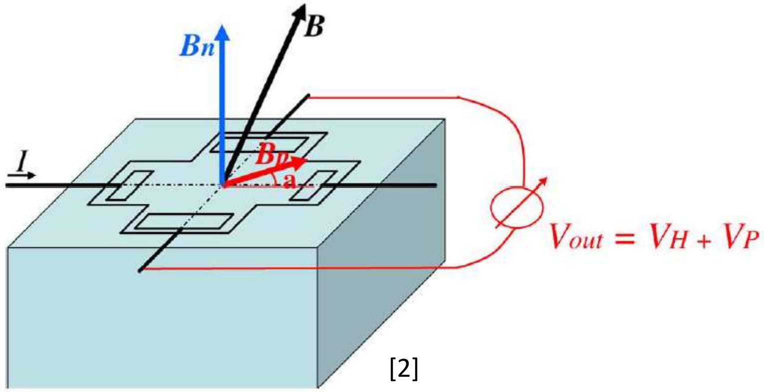
→

**150 mm x 50 mm x 45 mm**
**ANALOGUE + DIGITAL**

≈ 7 times REDUCTION of
**ANALOGUE CIRCUITRY**

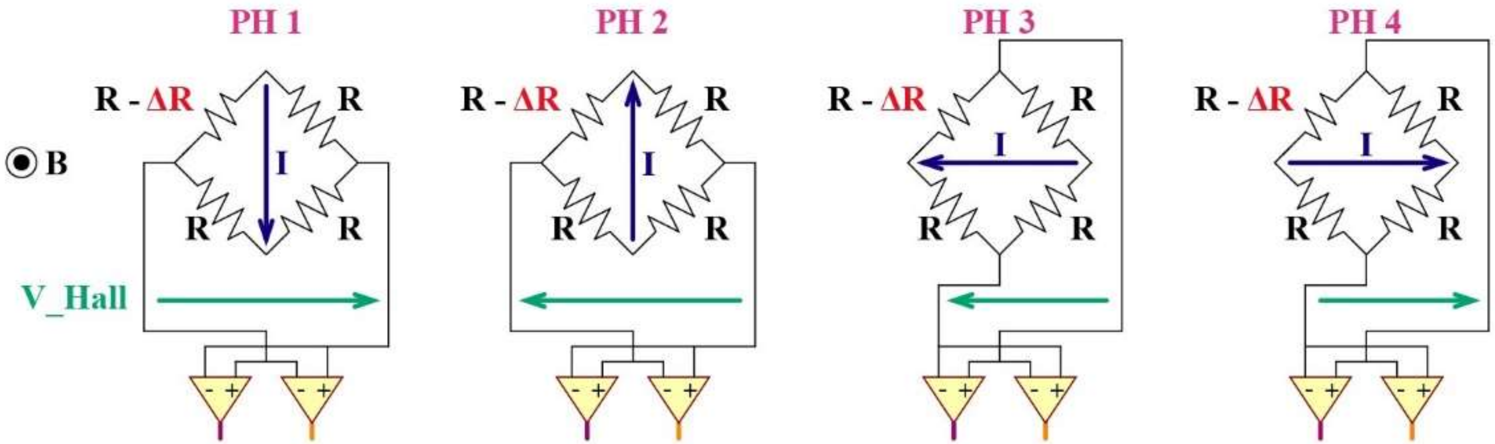
# Hall Probes - Theory of Operation




## Spinning Current Technique

- True Hall Voltage
- Planar Hall Voltage
- Offset Voltage at Zero Field
- 1/f noise





[2] D.R. Popovic et al, “Three-Axis Teslameter With Integrated Hall Probe,” *IEEE Trans on Instrumentation and Measurement,* vol. 56, *(4),* pp. 1396-1402, 2007.
[3] "Hall Probe S for H3A Magnetic Field Transducers," SENIS, Neuhofstrasse, Baar, Switzerland, May 2014.

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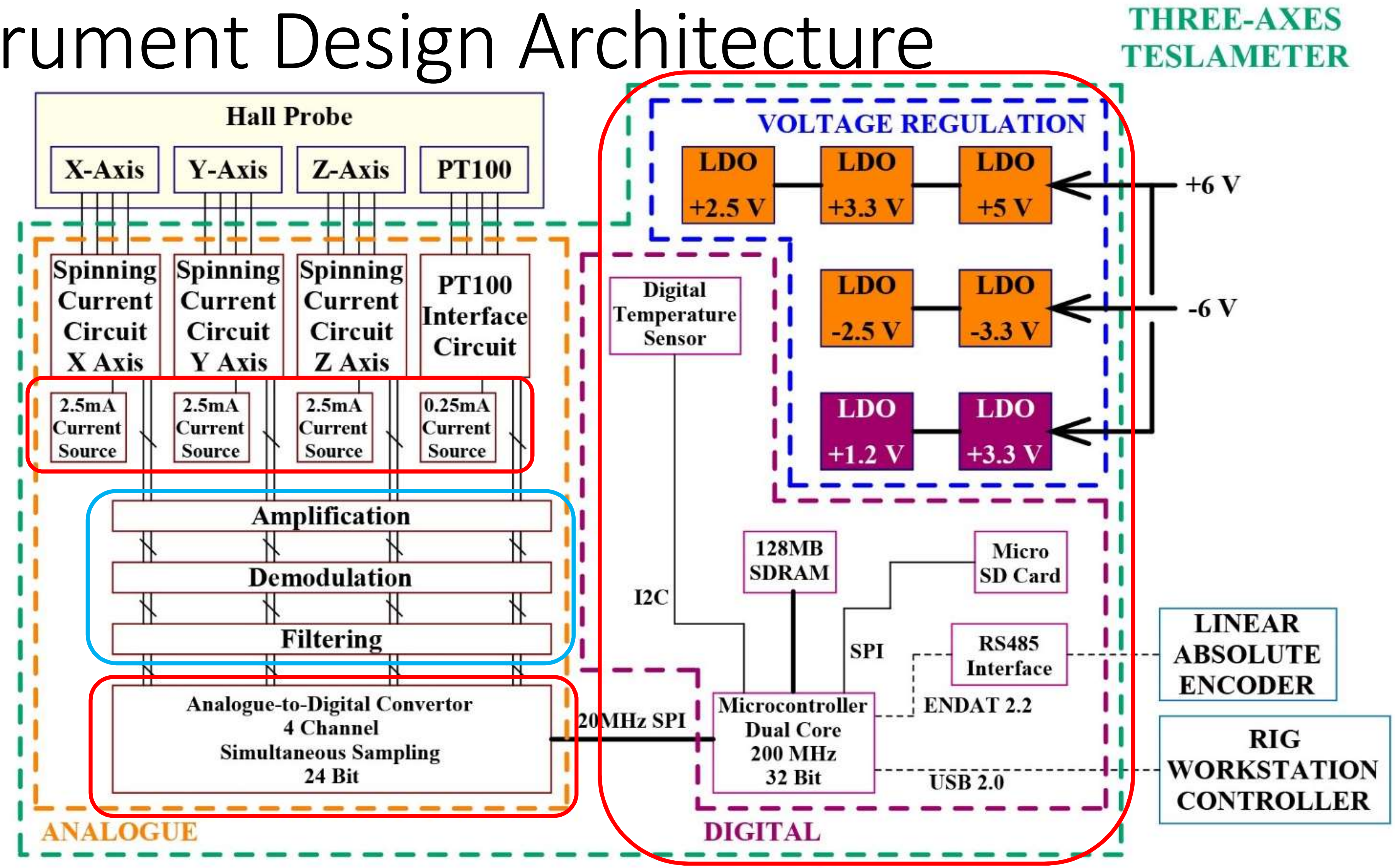
# Instrument Design Architecture

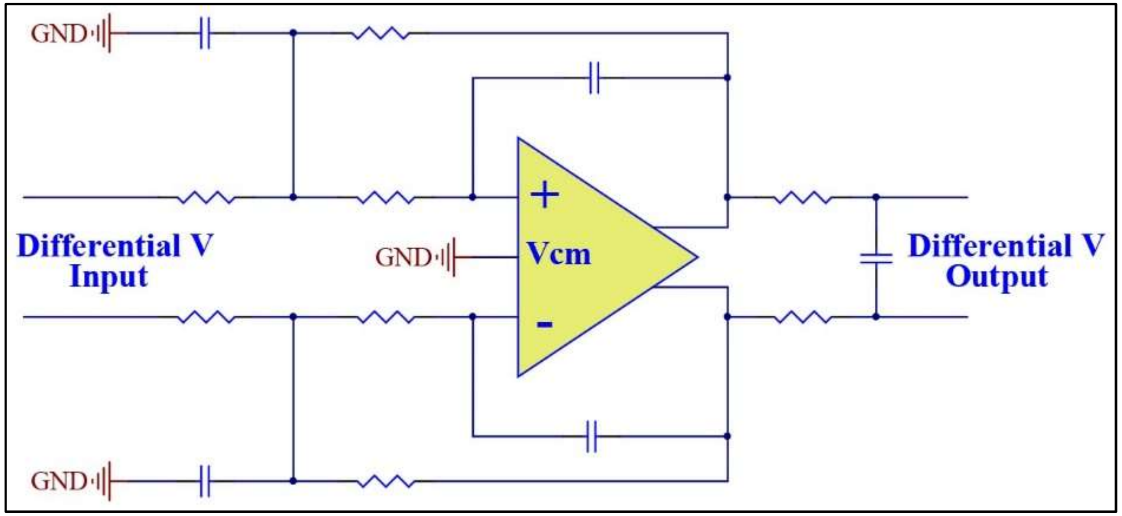


# Antialiasing Filter and Analogue to Digital Converter

**Analogue 3$^{rd}$ Order Low Pass Differential Butterworth**

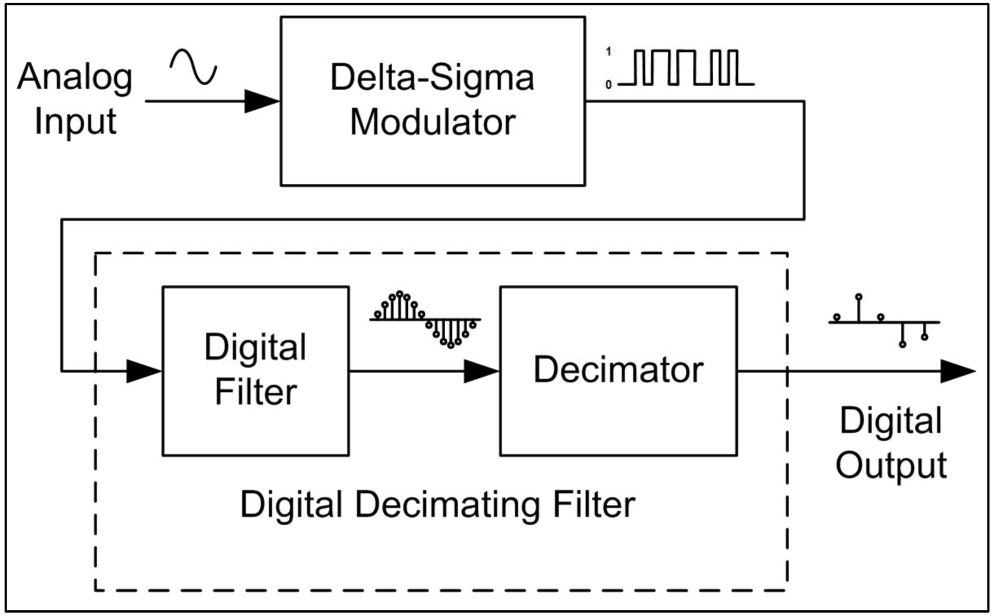
**Antialiasing Filter**

- Filter Bandwidth: 500 Hz
- Attenuation of 51 dB at 7.8 kHz Switching Frequency




**24 Bit, 4 Channel Delta-Sigma ADC (ADS131A04)**

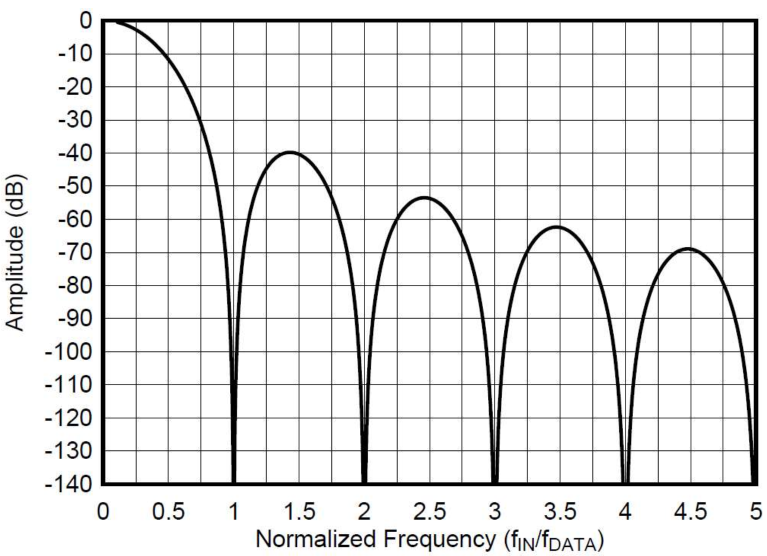
- Simultaneous Sampling of 4 Independent Channels
- No Hardware Multiplexing
- **22 Bits Effective Resolution at 1 kHz Acquisition Frequency**
- Internal Sinc$^3$ Filter Design



# Analogue to Digital Converter - Sinc$^3$ Filter

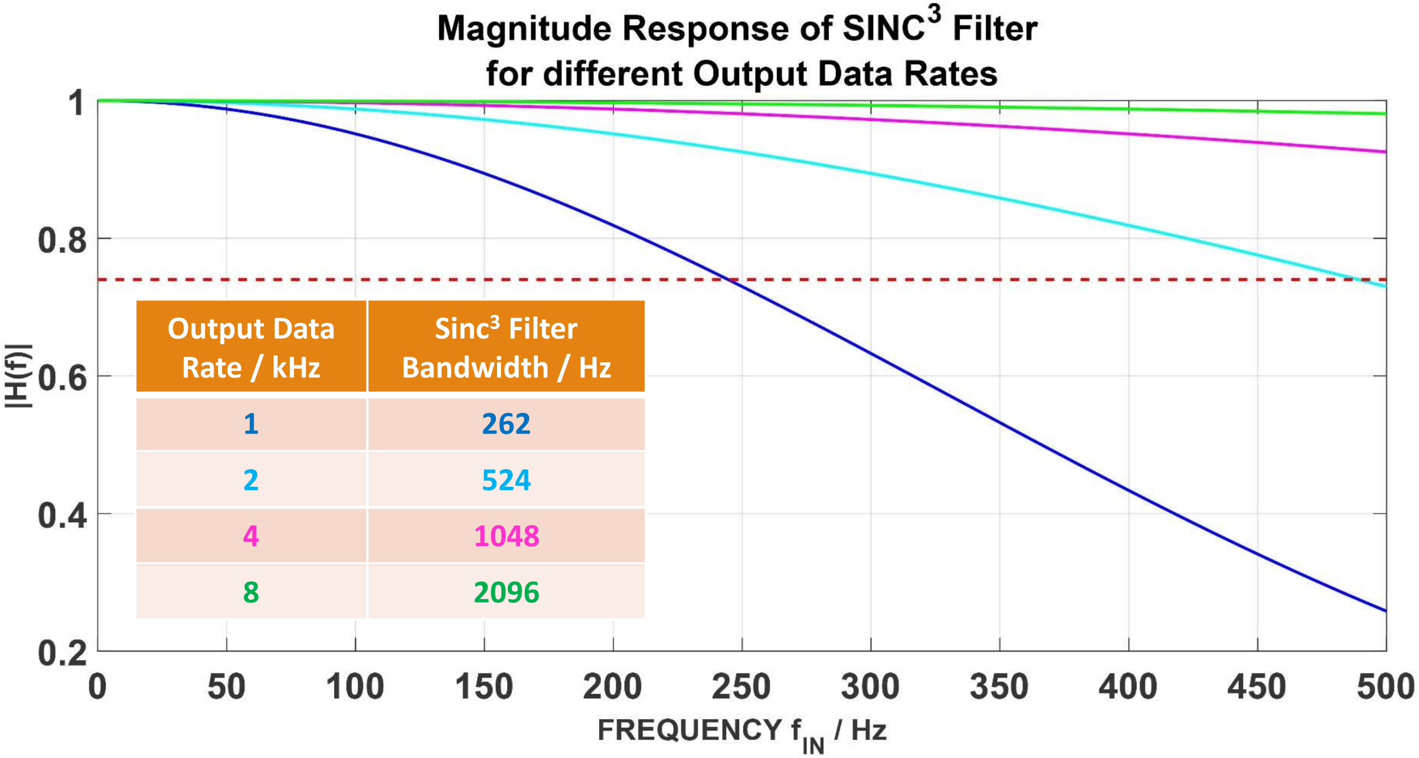
### Sinc$^3$ Filter Phase Response

- Group Delay caused by the Linear Phase Response.




### Sinc$^3$ Filter Magnitude Response

- Different Bandwidth Response according to Output Data Rate




| Output Data Rate / kHz | Sinc$^3$ Filter Bandwidth / Hz |
|---|---|
| 1 | 262 |
| 2 | 524 |
| 4 | 1048 |
| 8 | 2096 |

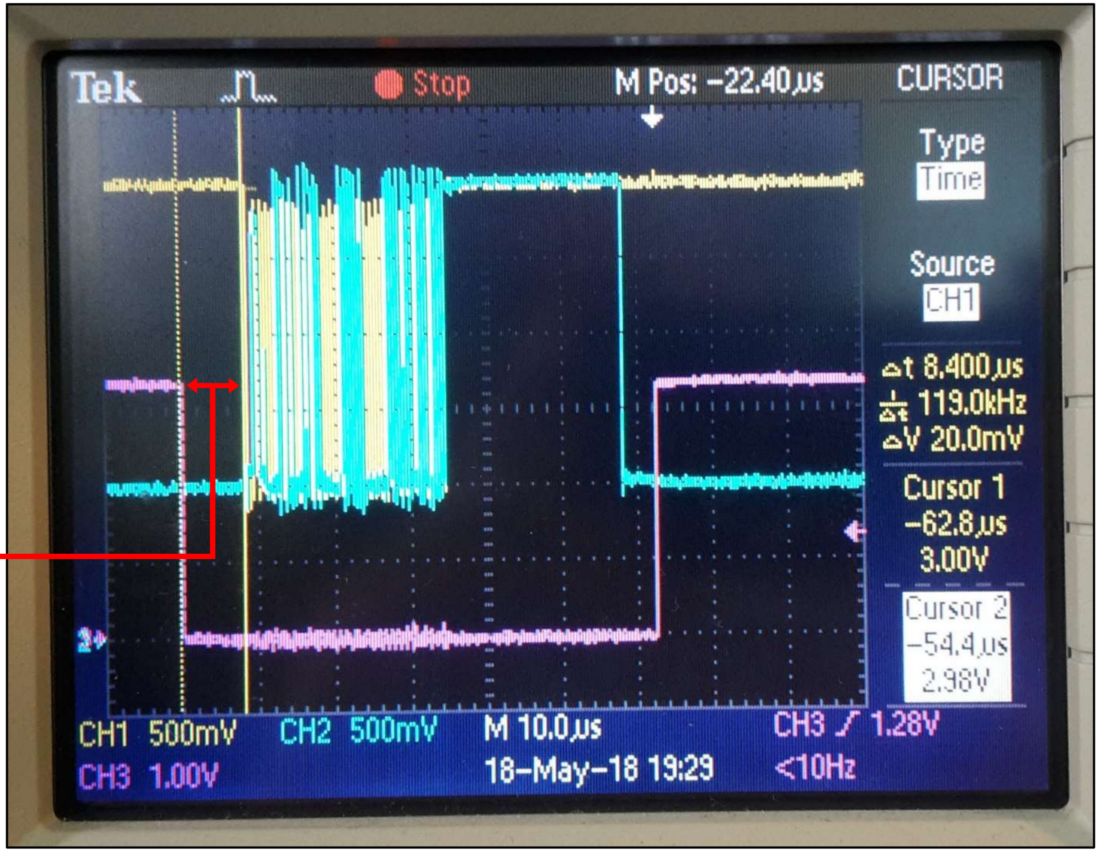
[4] "Data Sheet for ADS131A0x 2- or 4-Channel, 24-Bit, 128-kSPS, Simultaneous-Sampling, Delta-Sigma ADC," TI, Dallas, TX, USA, Rep. SBAS590D, Mar. 2016 [rev. Jan. 2018].

# Encoder Interface Synchronization

Synchronization between Magnetic Field Readings and Encoder Position reading occurs at a jitter free delay of 8.4 µs.

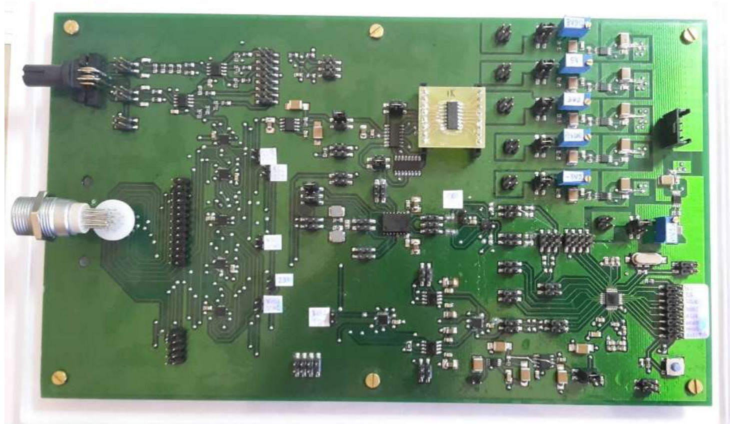
This delay is equivalent to 1680 clock cycles for the microcontroller to establish communication with the encoder on the ADC falling edge interrupt.

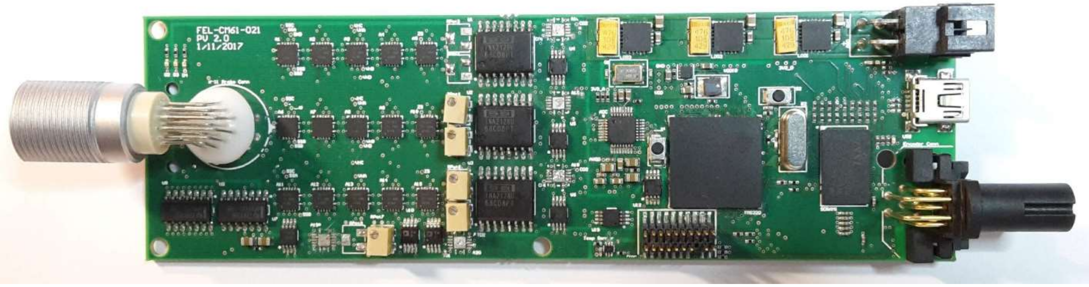
**8.4 µs**




# Instrument Development

**First Prototype Board**
2 Layer PCB Analogue Circuitry ONLY
**FUNCTIONALITY TESTING**



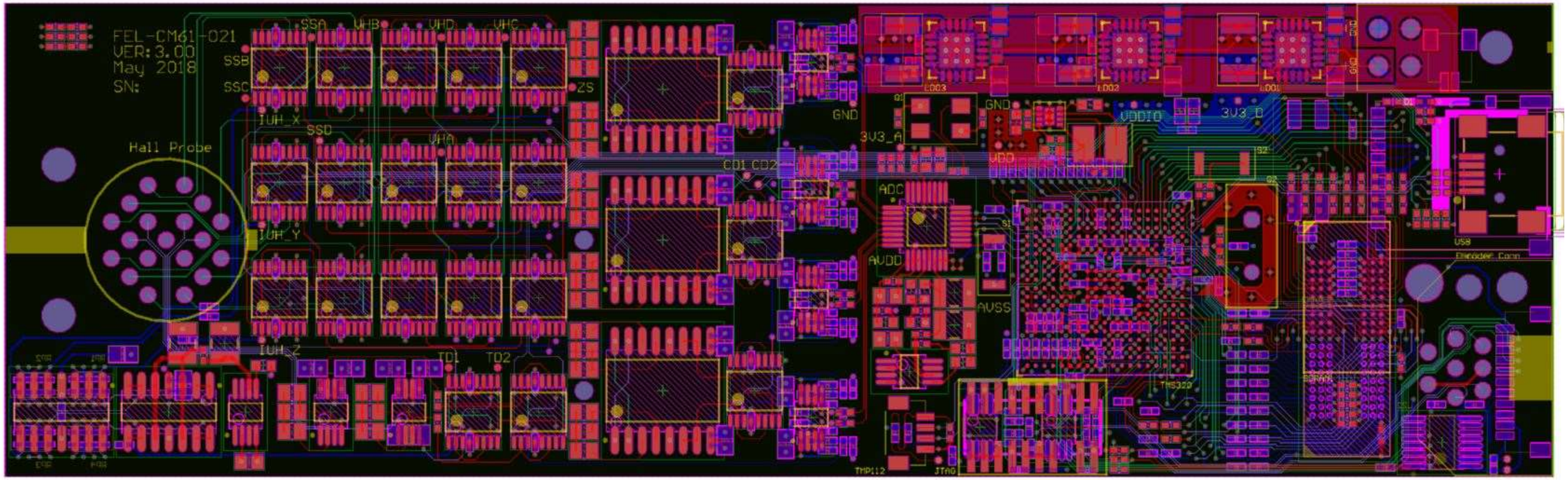


**Second Prototype Board**
8 Layer PCB Analogue Circuitry + Digital Circuitry
**PERFORMANCE TESTING**

**Third Final Board**
8 Layer PCB
**OPTIMIZATION PERFORMANCE TESTING**

# 8 Layer PCB Design

- Layer 1 - SIGNALS
- Layer 2 - POWER
- Layer 3 - GROUND
- Layer 4 - SIGNALS
- Layer 5 - SIGNALS
- Layer 6 - GROUND
- Layer 7 - POWER
- Layer 8 - SIGNALS




**Analogue Circuitry** | **Digital Circuitry**

# Final End Product Instrument


**Instrument Dimensions: 150 mm x 50 mm x 45 mm**

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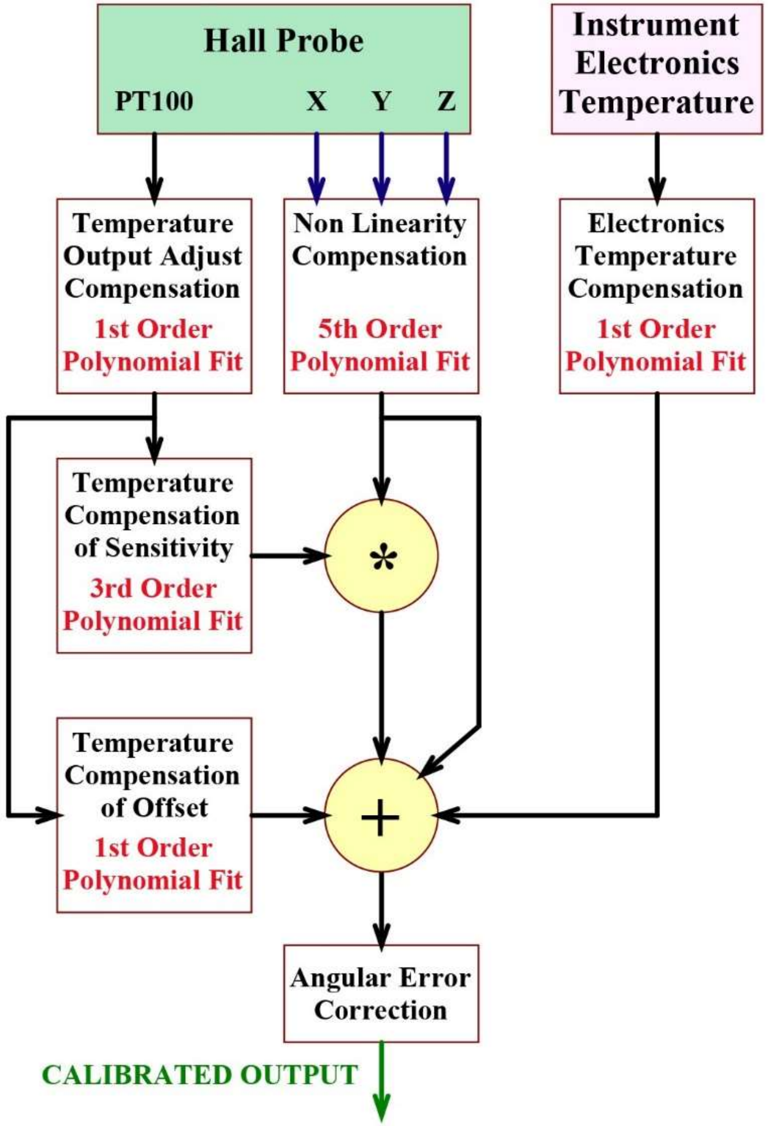
# Instrument Calibration


The sequence of the tests performed are:

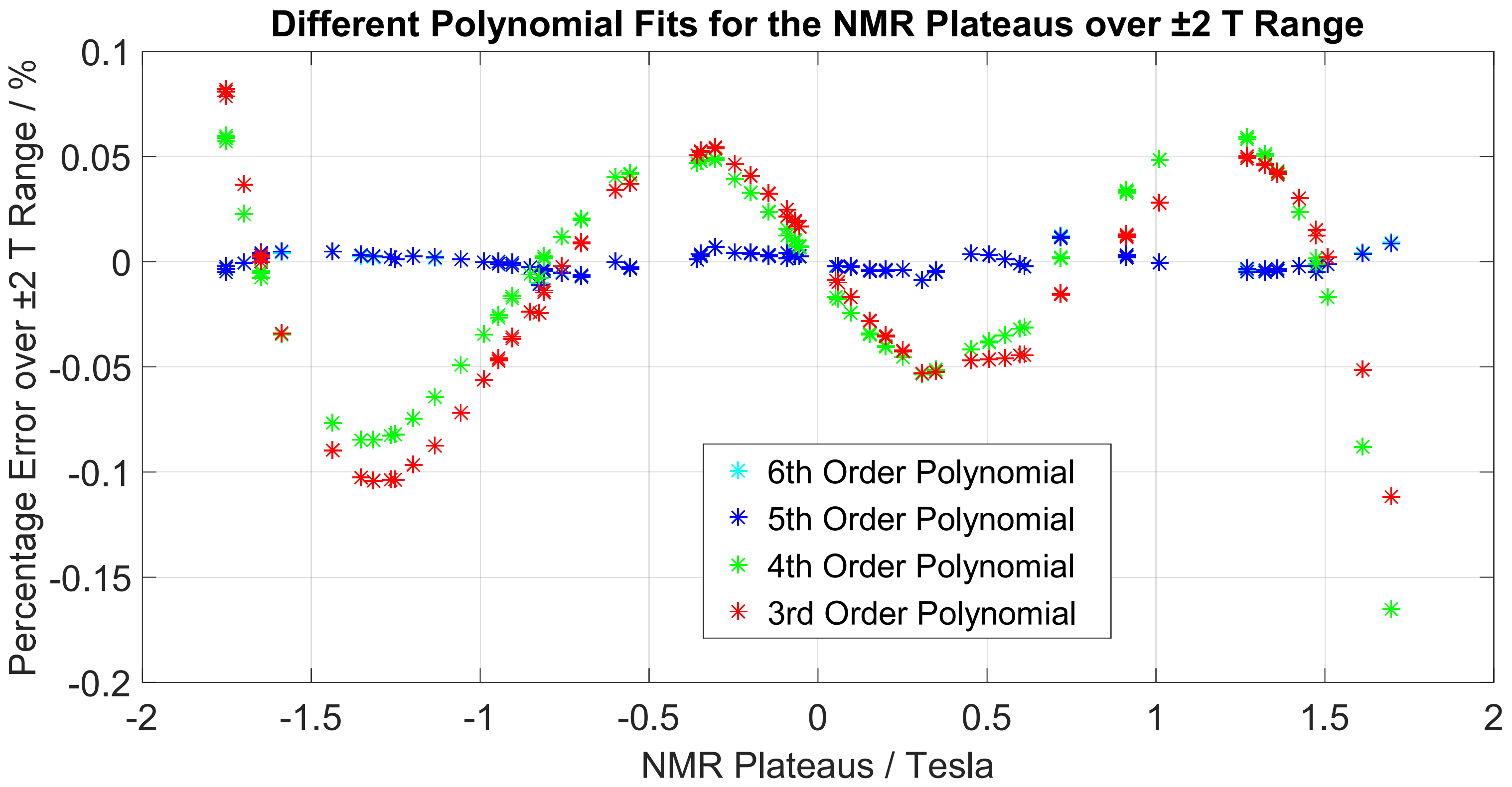
1. **Non Linearity Compensation**
2. **Temperature Output Adjust Compensation**
3. **Temperature Compensation of Offset**
4. **Temperature Compensation of Sensitivity**
5. **Electronics Offset Temperature Compensation**



# Instrument Calibration - Non Linearity

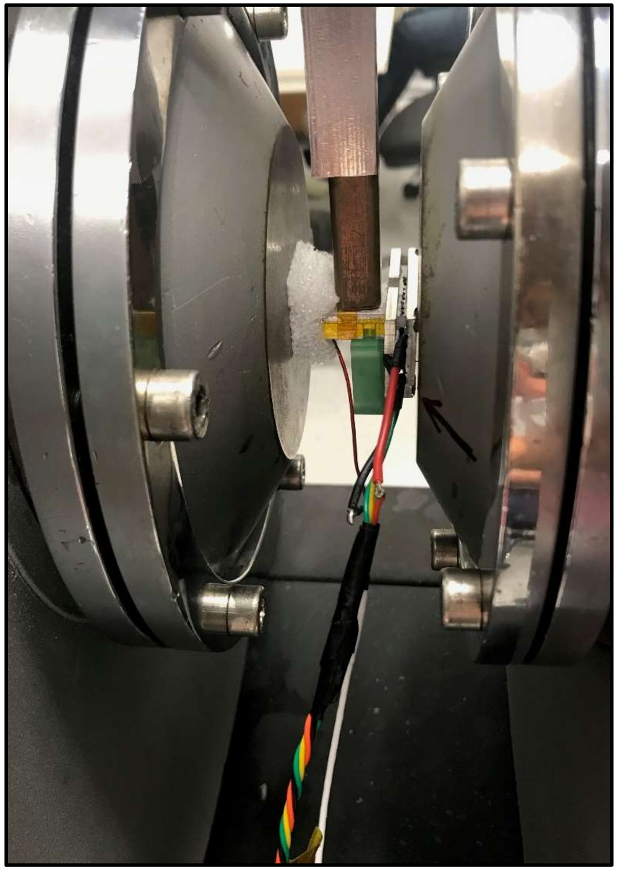
**Hall Probe is exposed to the whole ±2 T range in 50 mT steps at Ambient reference temperature of 24 °C.**

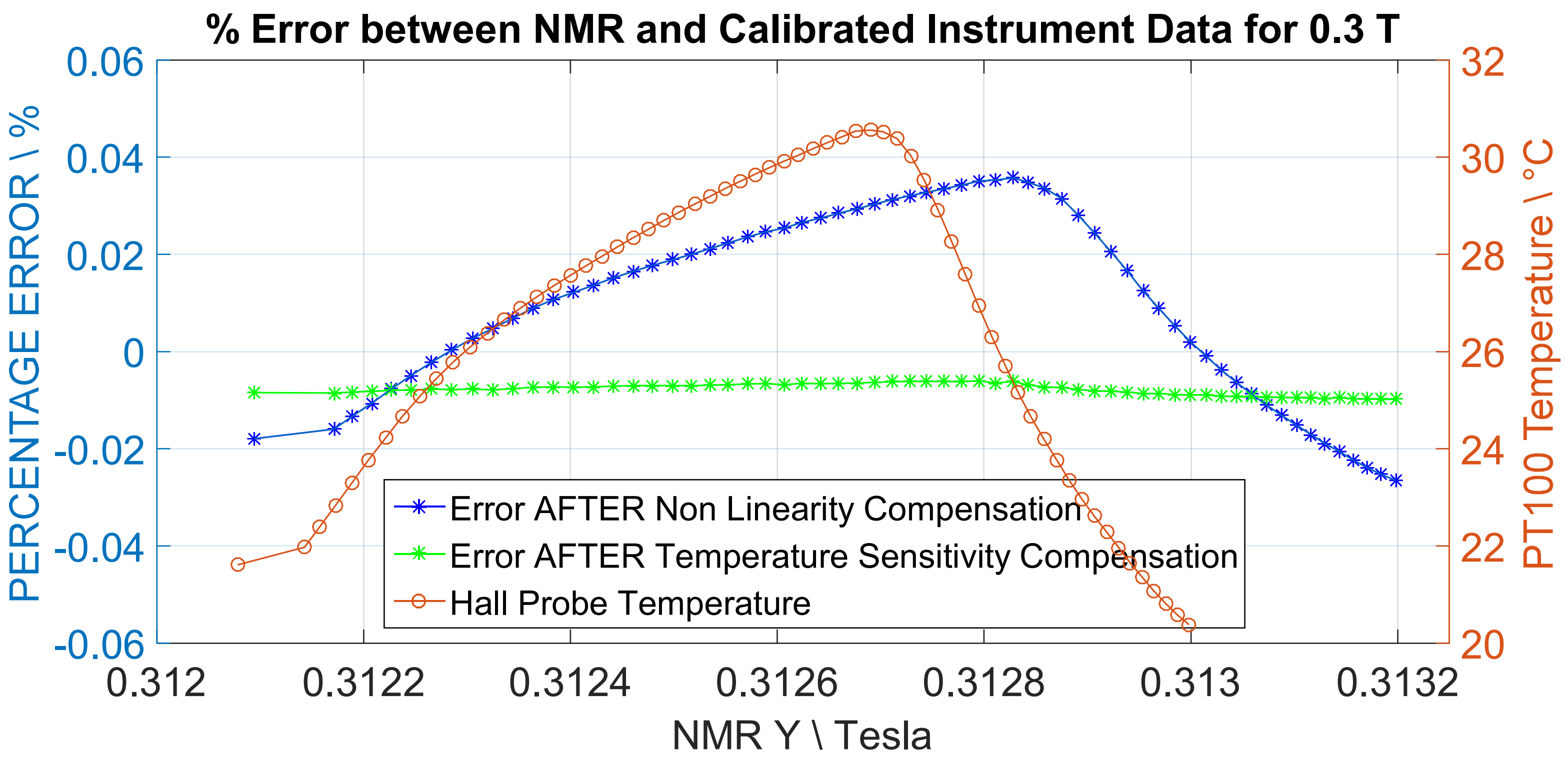
The non linear relation can be modelled using different orders of polynomial fits.



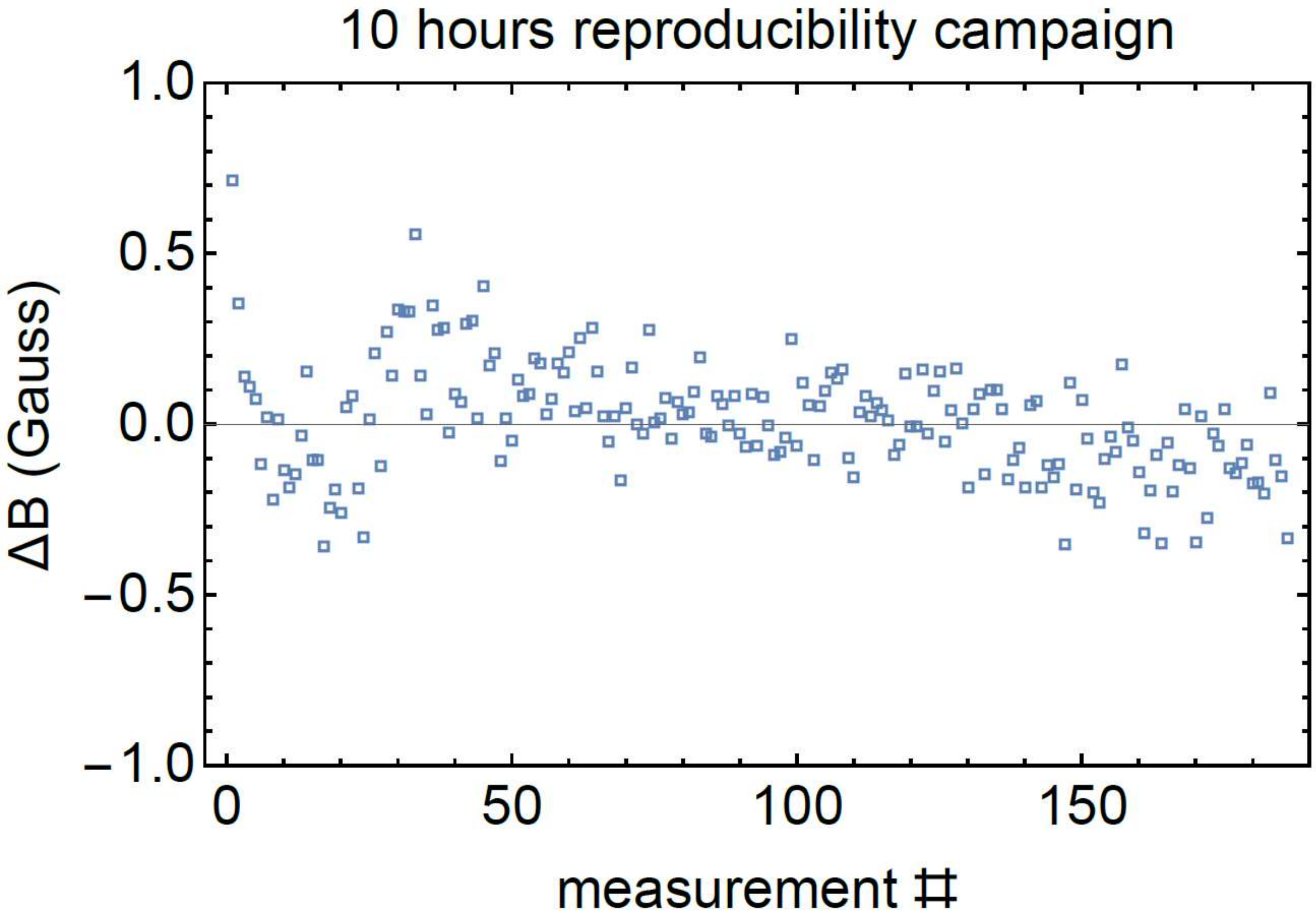

| Polynomial Fit Order | AVERAGE / % Error |
|---|---|
| Before Compensation | 1.173 |
| 1st Order Fit | 0.926 |
| 2nd Order Fit | 0.880 |
| 3rd Order Fit | 0.042 |
| 4th Order Fit | 0.040 |
| **5th Order Fit** | **0.004** |
| 6th Order Fit | 0.004 |

# Instrument Calibration - Temperature Compensation of Offset and Sensitivity





# Instrument Performance Reproducibility




**10 hours → 185 Undulator Traversal Runs**

**Reproducibility : ± 0.5 Gauss → 0.005 %**

**Peak MF of Undulator is ± 1 Tesla**

# Noise Performance Figures of Merit

$$V_{rmsB} \approx \left[ NSD_{1/f}^2 . 1Hz . ln\frac{f_H}{f_L} + 1.22 . NSD_W^2 . f_H \right]^{1/2}$$

**Offset Fluctuation and Drift**

- **1/f noise** at quasi DC measurement conditions.
- Bandwidth from **0.1 Hz to 10 Hz ($f_L$ to $f_H$).**
- Calibrated data over a 10 s period at **ZERO GAUSS.**

**Broadband Noise**

- **White noise** at full measurement bandwidth.
- Bandwidth from **10 Hz to 500 Hz.**
- Calibrated data over a 10 s period at **ZERO GAUSS.**

| Output Data Rate / kHz | Offset Fluctuation and Drift (0.1 Hz – 10 Hz) / $\mu T_{pp}$ | Broadband Noise (10 Hz - $f_T$) / $\mu T_{pp}$ |
|---|---|---|
| 1 | 4.69 | 9.36 |
| 2 | 6.56 | 12.3 |
| 4 | 6.96 | 14.34 |
| 8 | 7.59 | 17.16 |

# Conclusion: Project Challenges and Achievements (1)

| Challenges | Achievements |
| --- | --- |
| **Instrument Physical Size Restriction** | |
| Maximum Enclosure Dimensions:<br>**50 mm x 60 mm x 150 mm** (W x H x L) | Instrument Aluminium Enclosure External Dimensions:<br>**50 mm x 45 mm x 150 mm** (W x H x L) |
| | |
| **Optimization of Analogue Circuitry** | |
| Improved Analogue Interface to the 3 Axes SENIS Hall Probe | Very Fast Analogue Switches<br>3$^{rd}$ Order Butterworth LPF<br>Improved Temperature Stability of Pre-Amp Stage |
| | |
| **Excellent Noise Specifications in the µTesla Range** | |
| Analogue Circuitry must be very noise immune<br>Very High Resolution on Digitisation | Very Low Noise Amplifiers<br>24 bit Delta-Sigma ADC |

# Conclusion: Project Challenges and Achievements (2)

| Challenges | Achievements |
|---|---|
| **Temperature Drift Effects and Compensation** | |
| Control and Monitoring of Temperature inside Instrument Enclosure | Temperature Monitoring: **Digital Temperature Sensor**<br>Temperature Stabilization: **Cooling Fan** |
| | |
| **Microcontroller Interface Capability to numerous Peripherals** | |
| 13 PWM Control Signals<br>SPI Interface to ADC<br>SPI Interface to SD Card<br>$I^2C$ Interface to Digital Temperature Sensor<br>USB Interface to Raspberry Pi<br>EnDat 2.2 Protocol to Heidenhain Encoder | 200 MHz, 32 bit floating point Microcontroller<br>Enhanced PWM Modulator<br>3 High Speed SPI channels<br>2 $I^2C$ Interfaces<br>USB 2.0 Interface<br>Configurable Logic Block for interfacing of Encoder |
| | |
| **On Board Calibration Implementation** | |
| Calibrated Magnetic Field value output from the instrument | On Board Programmed Calibration Algorithm with 32 bits floating point precision |

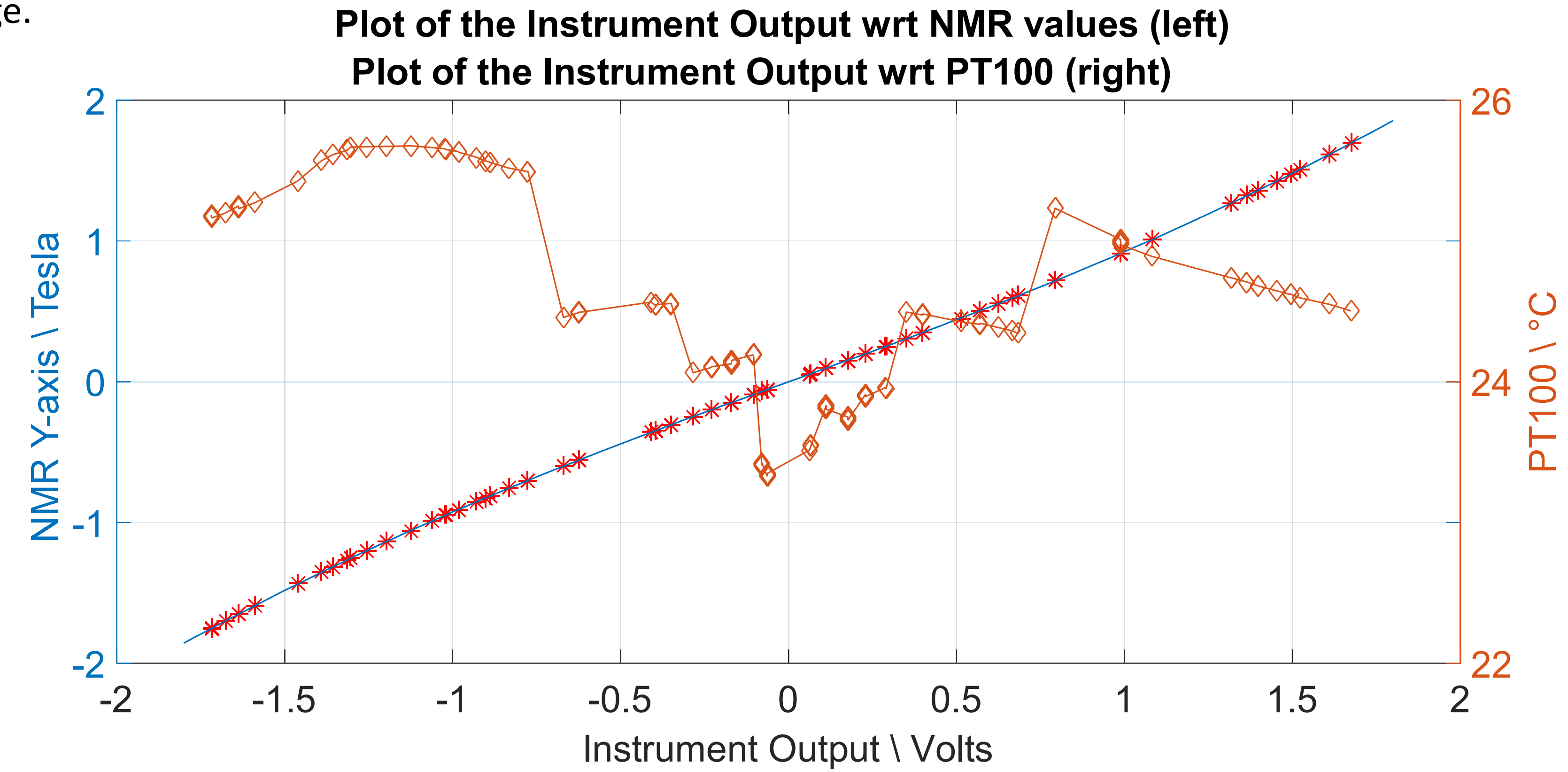
# Conclusion: Specifications Comparison

| Old Analogue Teslameter (H3A SENIS Transducer) | | New Analogue & Digital Teslameter | |
|---|---|---|---|
| **Bandwidth** | | | |
| 2 kHz Output Data Rate | 500 Hz | 1 kHz Output Data Rate | 262 Hz |
| | | 2/4/8 kHz Output Data Rate | 500 Hz |
| **Offset Fluctuation and Drift (0.1 Hz – 10 Hz)** | | | |
| 2 kHz Output Data Rate | 4 $\mu T_{pp}$ | 2 kHz Output Data Rate | 6.56 $\mu T_{pp}$ |
| **Broadband Noise (10 Hz – 500 Hz)** | | | |
| 2 kHz Output Data Rate | 7.2 $\mu T_{pp}$ | 2 kHz Output Data Rate | 12.3 $\mu T_{pp}$ |
| **Instrument Physical Size** | | | |
| 220 mm x 103 mm x 53 mm | | 150 mm x 50 mm x 45 mm | |

# Conclusion: Calibration Possible Improvements

**Electronics Temperature Compensation of Sensitivity:** Calibration of the effect of the change in the electronics temperature for the full ±2 T range.

**Non Linearity Calibration:** Better control of the Ambient Temperature Stability.

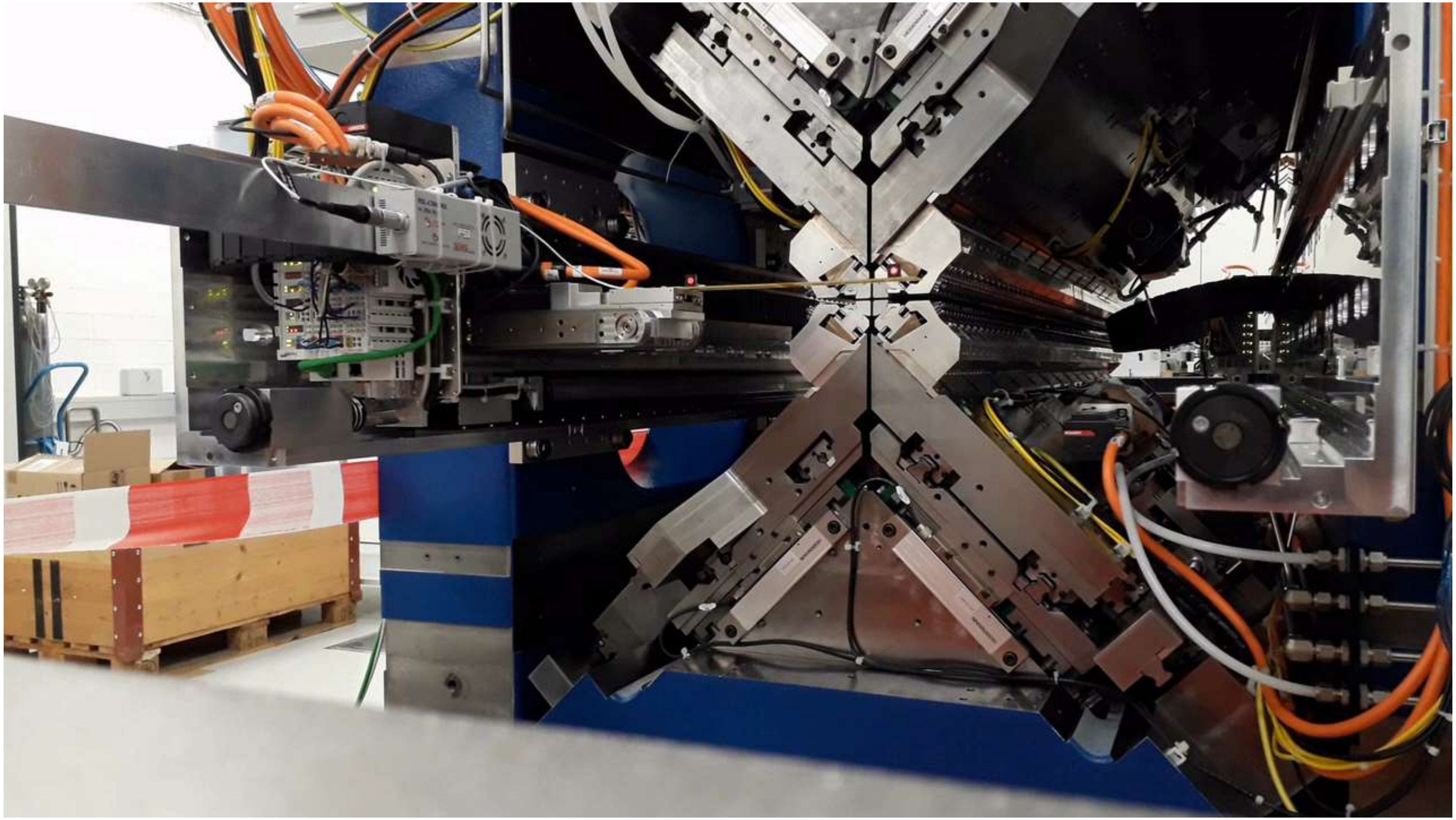


# Conclusion: Further Suggestions for Additional Improvements and Future Work

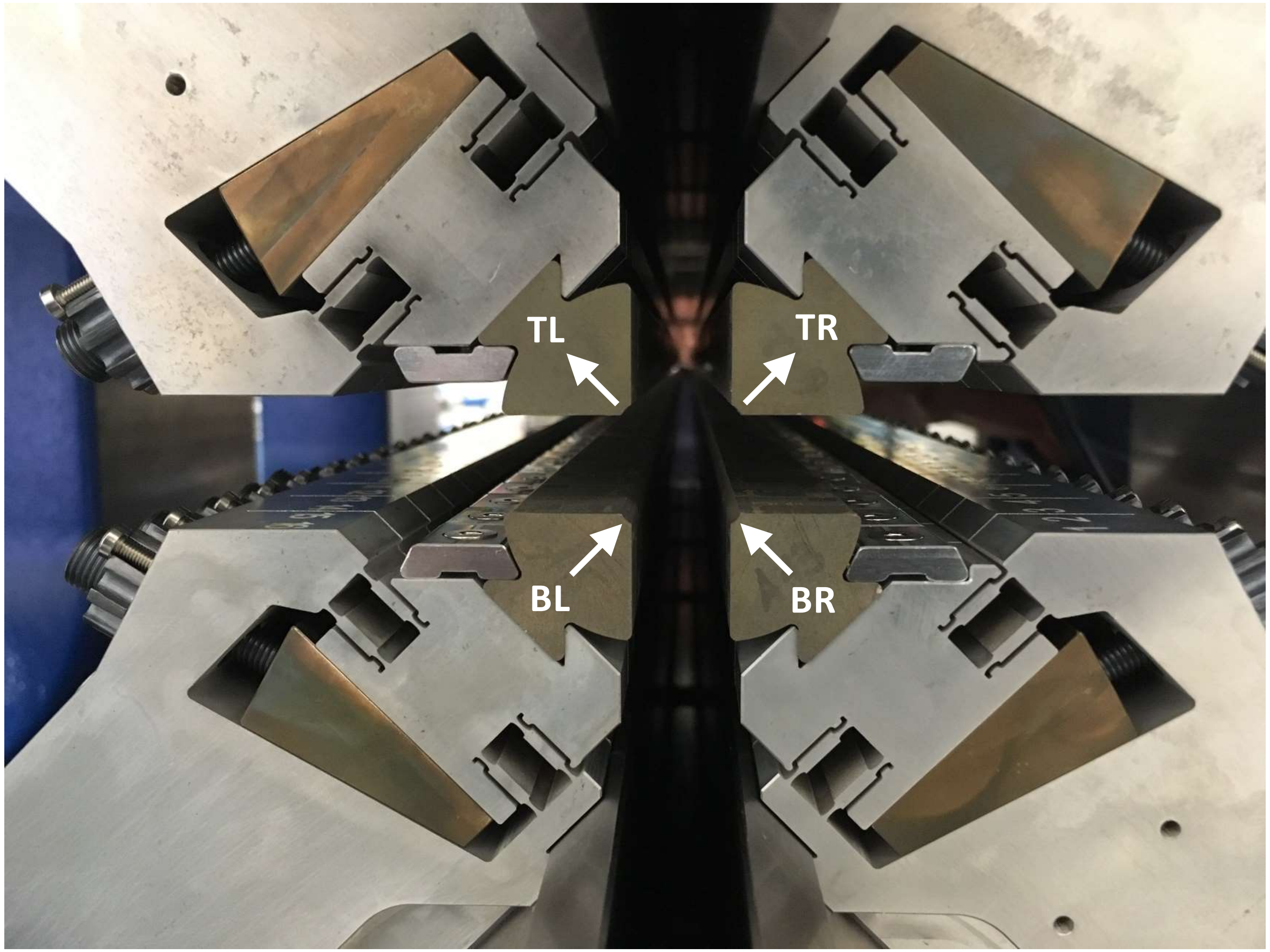
- Implementation of the proper **Compensation** for the difference in the spatial position of the sensor dies that are slightly **Offset** from the centre of the **Undulator Geometrical axis**.
- Improvement in the **Bandwidth response** of the on board Sigma-Delta ADC.

- Investigation for **alternative bias methods** of the Hall Probe rather than the **Spinning Current technique** due to switching noise spikes that set the major performance limitation.
- **On-the-fly data transfer** from the SDRAM to the micro SD card and USB for the reduction of data transfer time.

# Video Demonstration

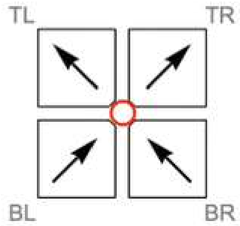


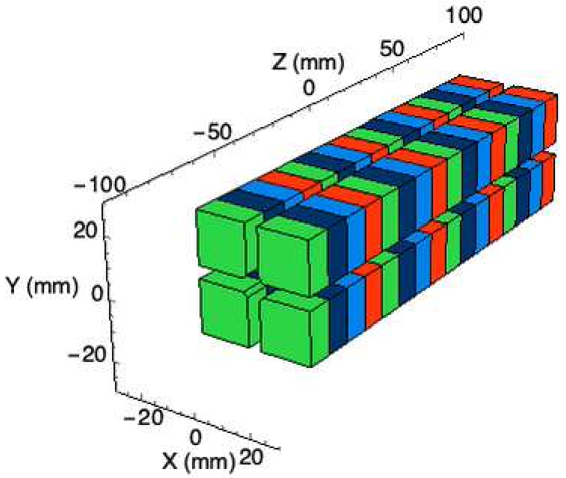
# Athos Prototype - AppleX

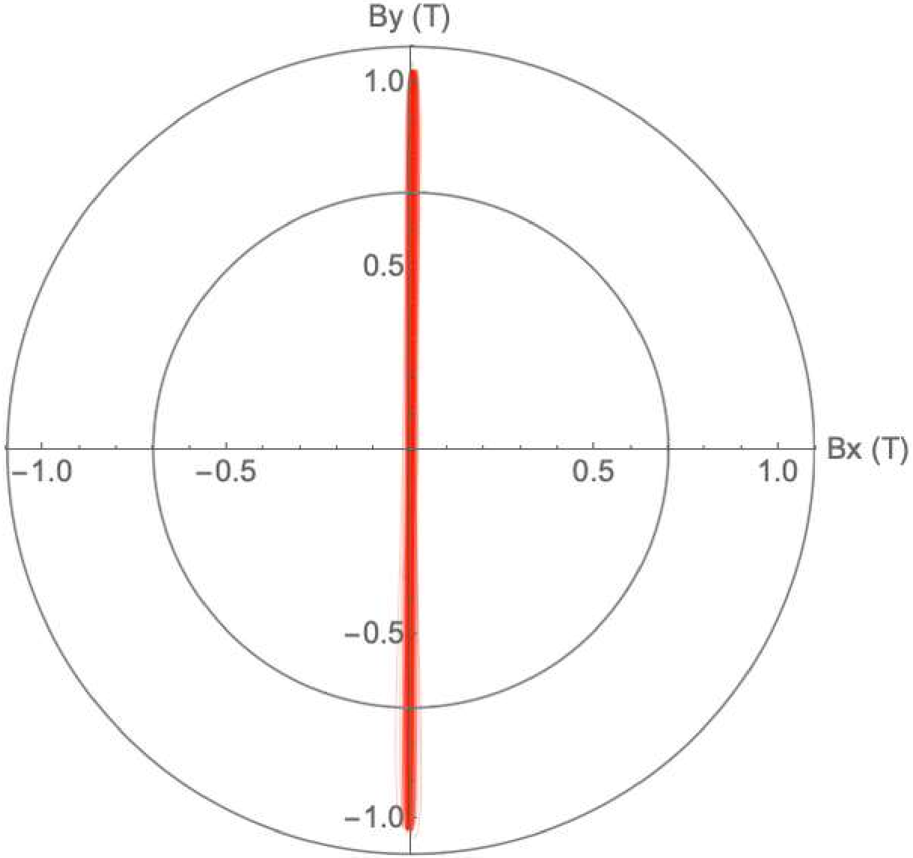


# Linear Horizontal - LH

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 3.250 | 3.250 | 3.250 | 3.250 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

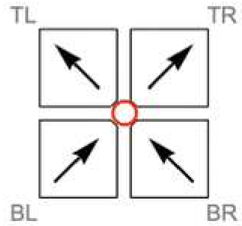


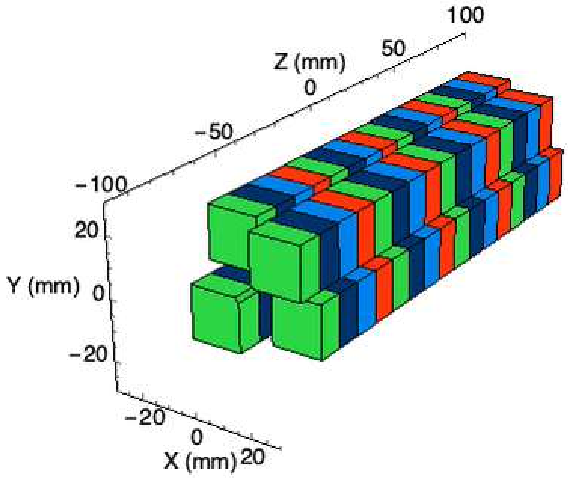



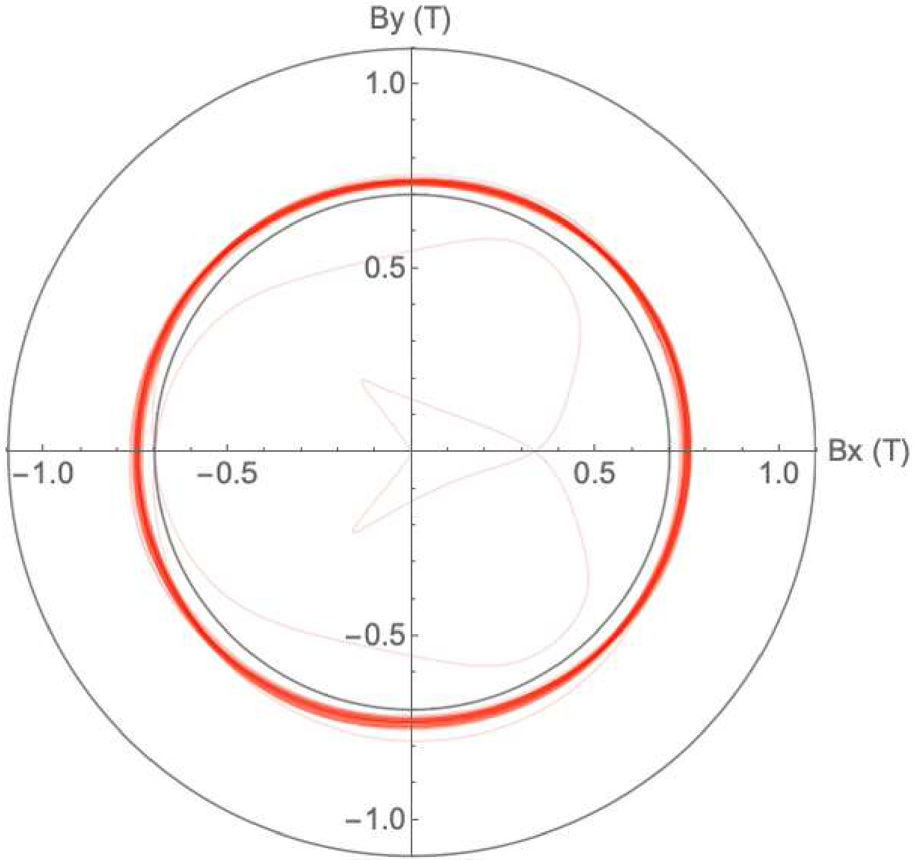



# Circular Plus – $C^+$

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 3.250 | 3.250 | 3.250 | 3.250 | mm |
| Longitudinal Shift | 4.750 | −4.750 | −4.750 | 4.750 | mm |

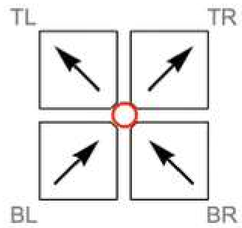


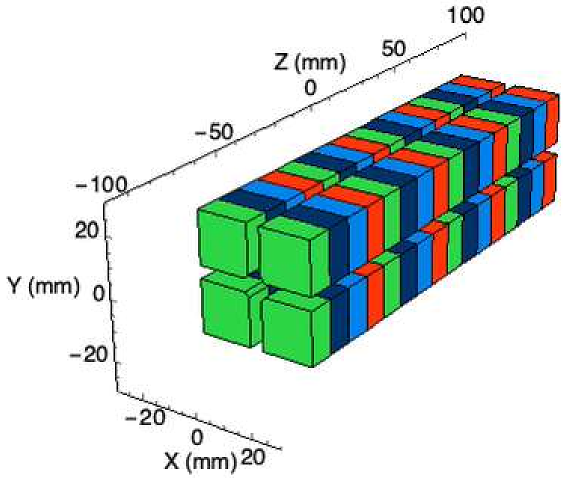



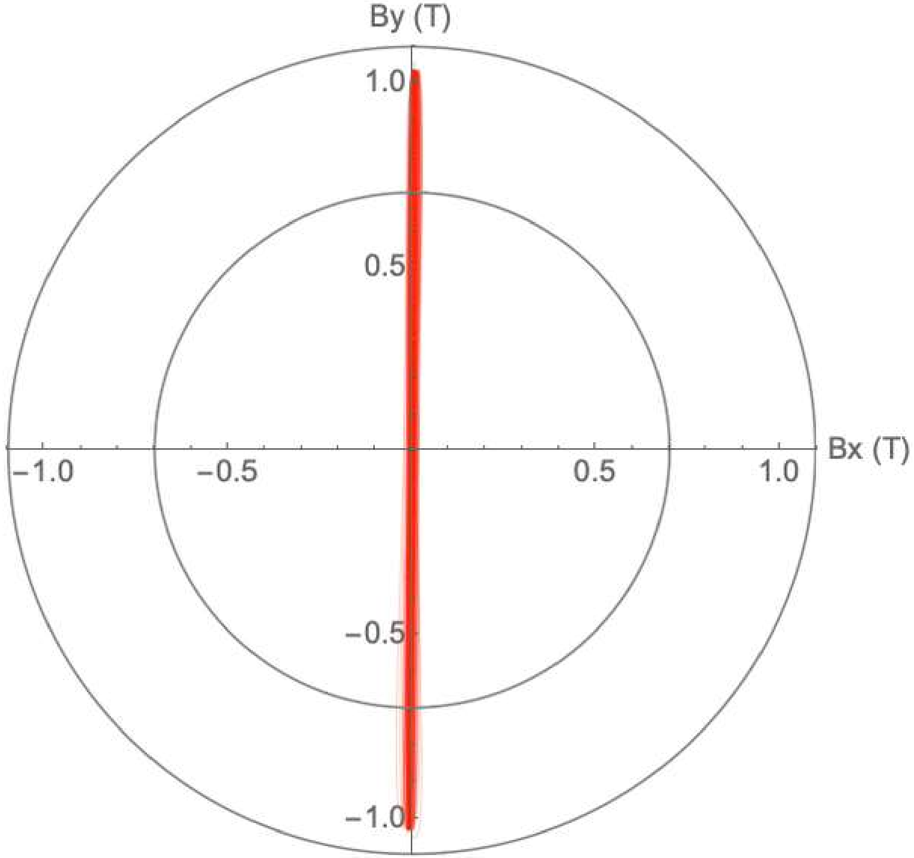



# Linear Rotation – 0 - 90°

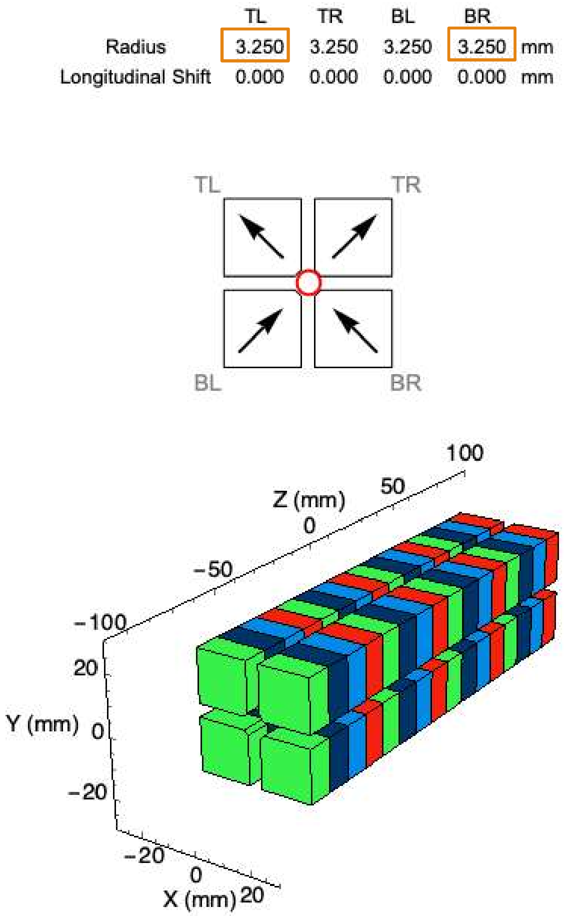
| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 3.250 | 3.250 | 3.250 | 3.250 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

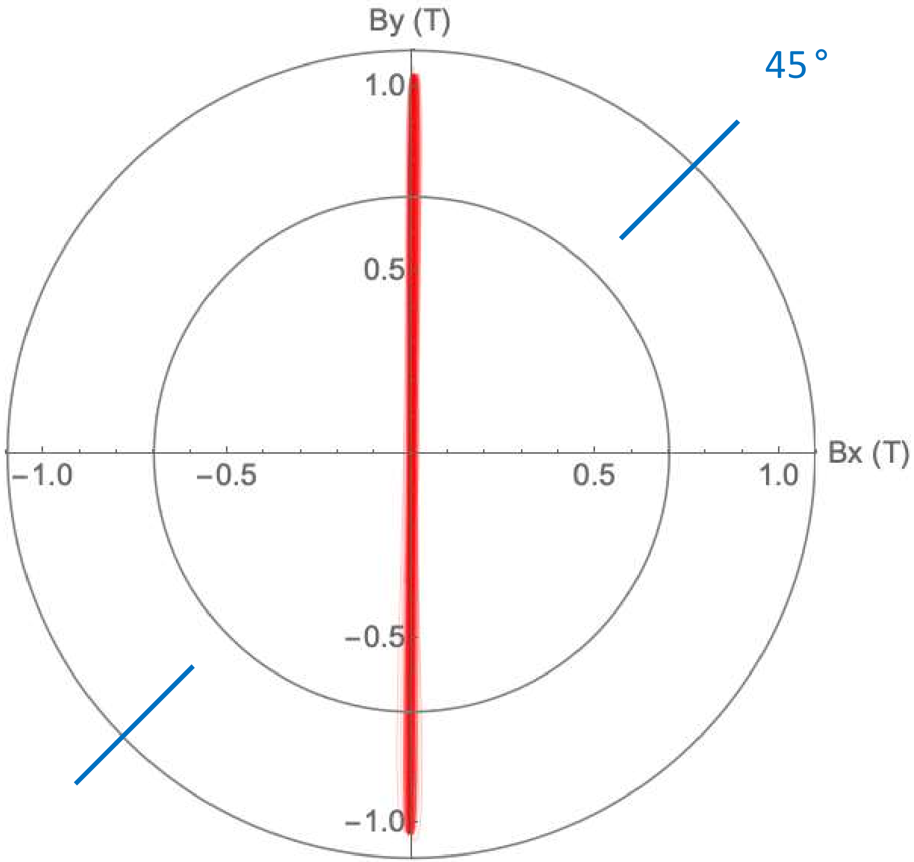


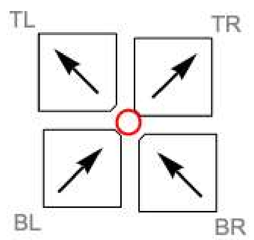
# New Linear Rotation – ONLY for AppleX (1)

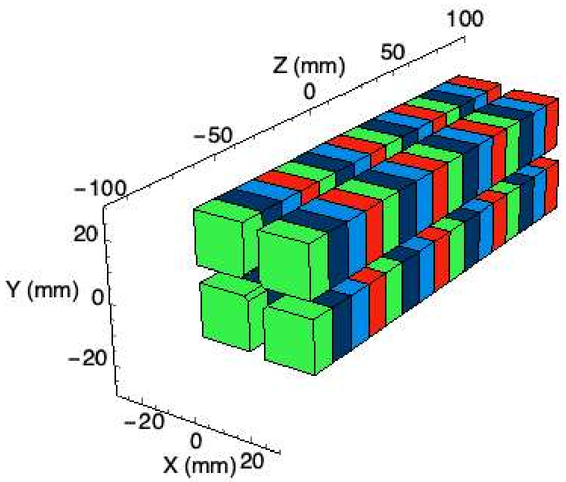


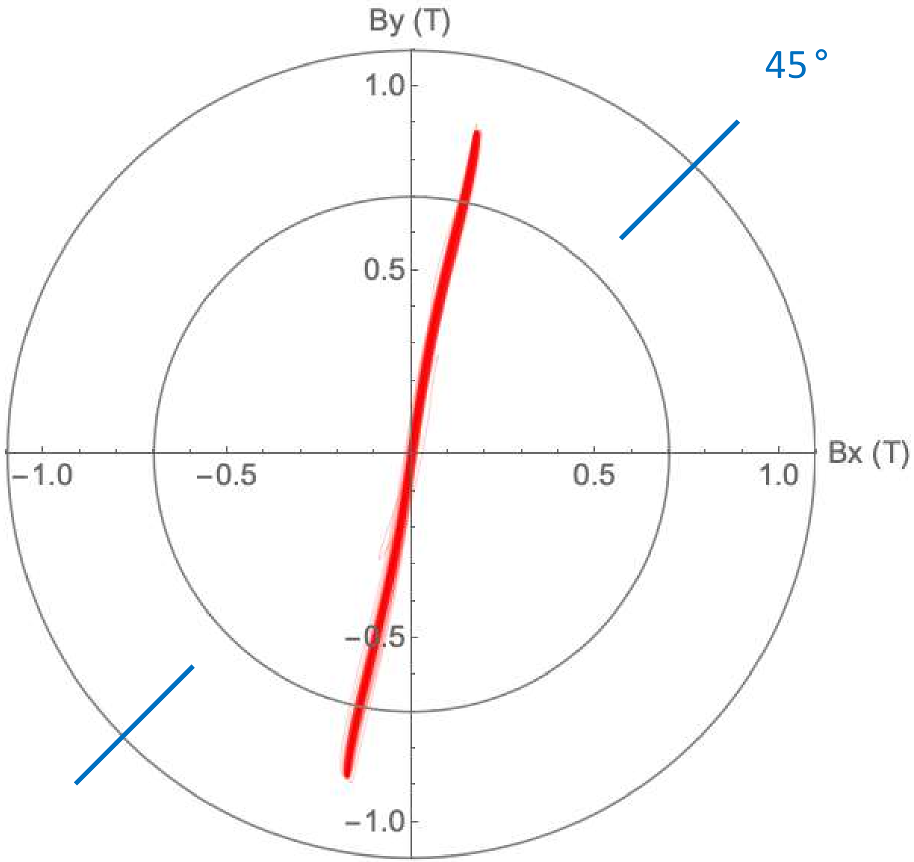



# New Linear Rotation – ONLY for AppleX (2)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 4.750 | 3.250 | 3.250 | 4.750 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

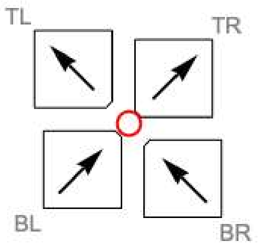


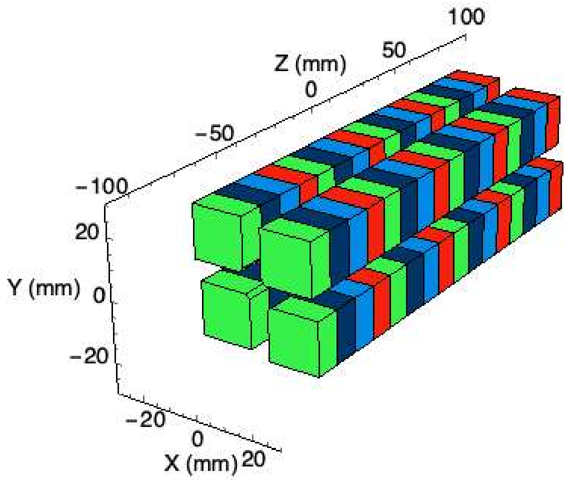



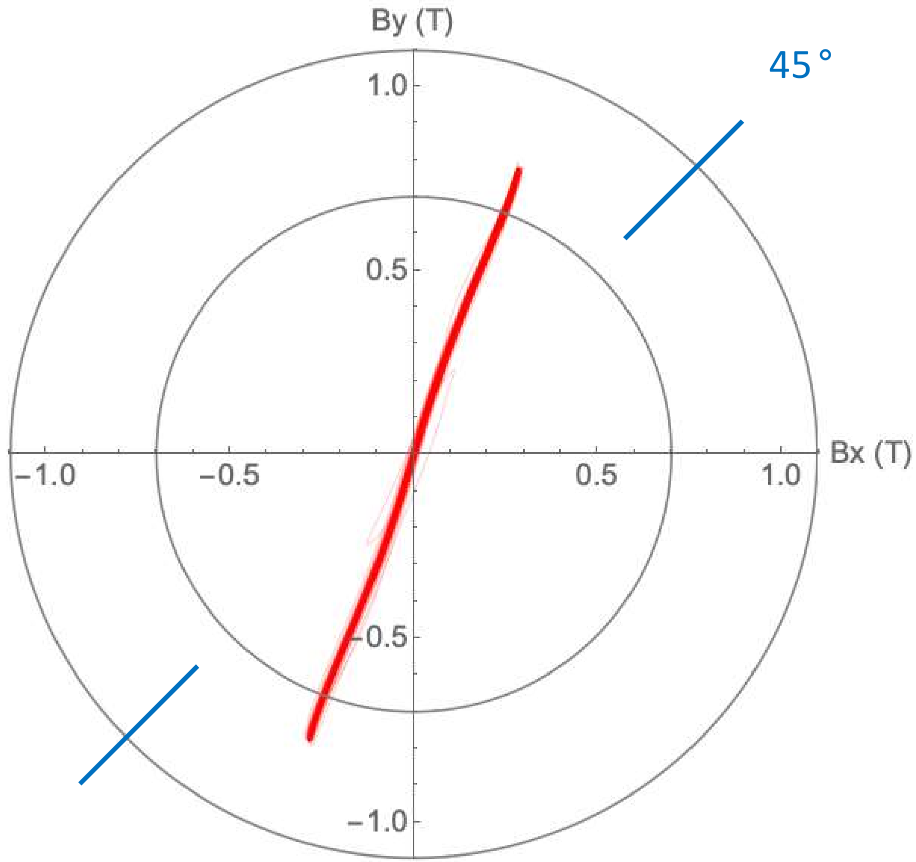



# New Linear Rotation – ONLY for AppleX (3)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 6.250 | 3.250 | 3.250 | 6.250 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

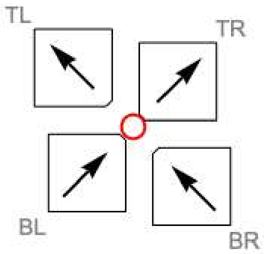


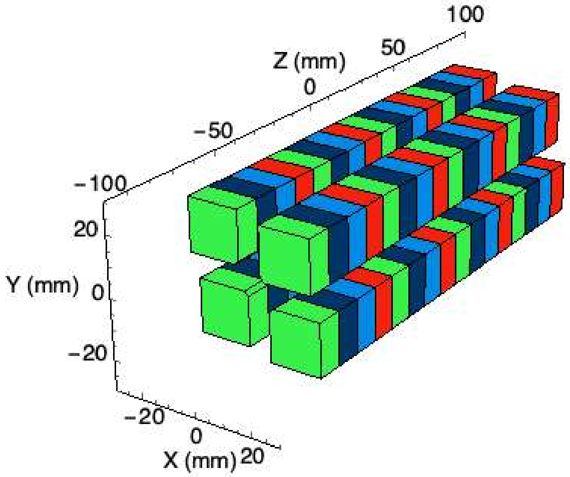



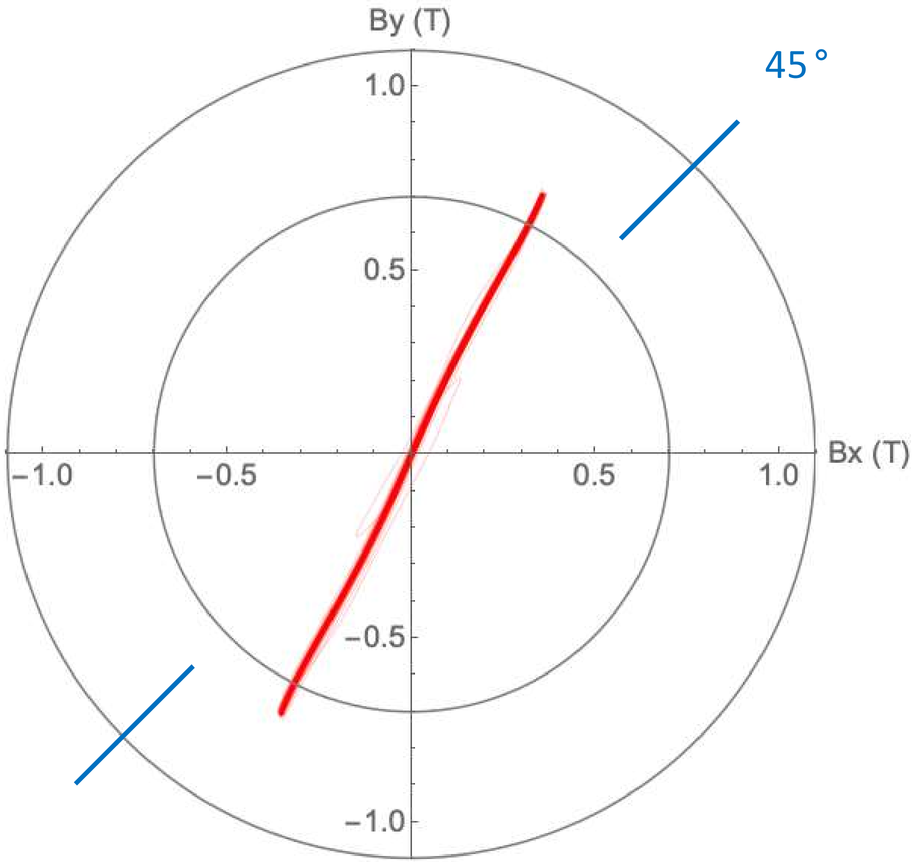



# New Linear Rotation – ONLY for AppleX (4)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 7.750 | 3.250 | 3.250 | 7.750 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

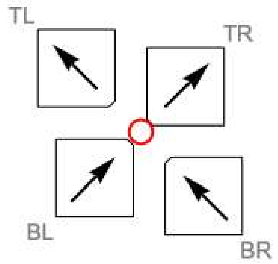


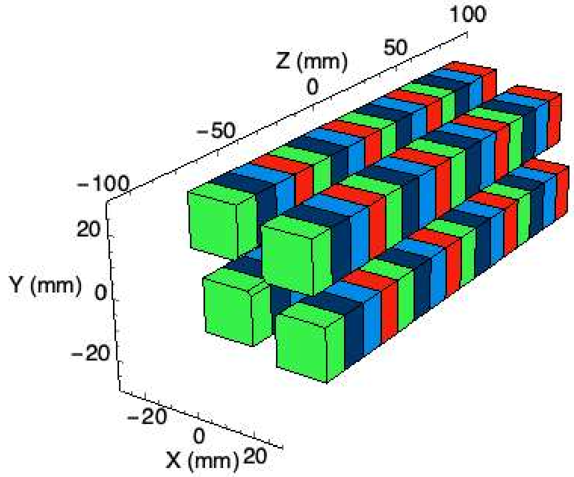



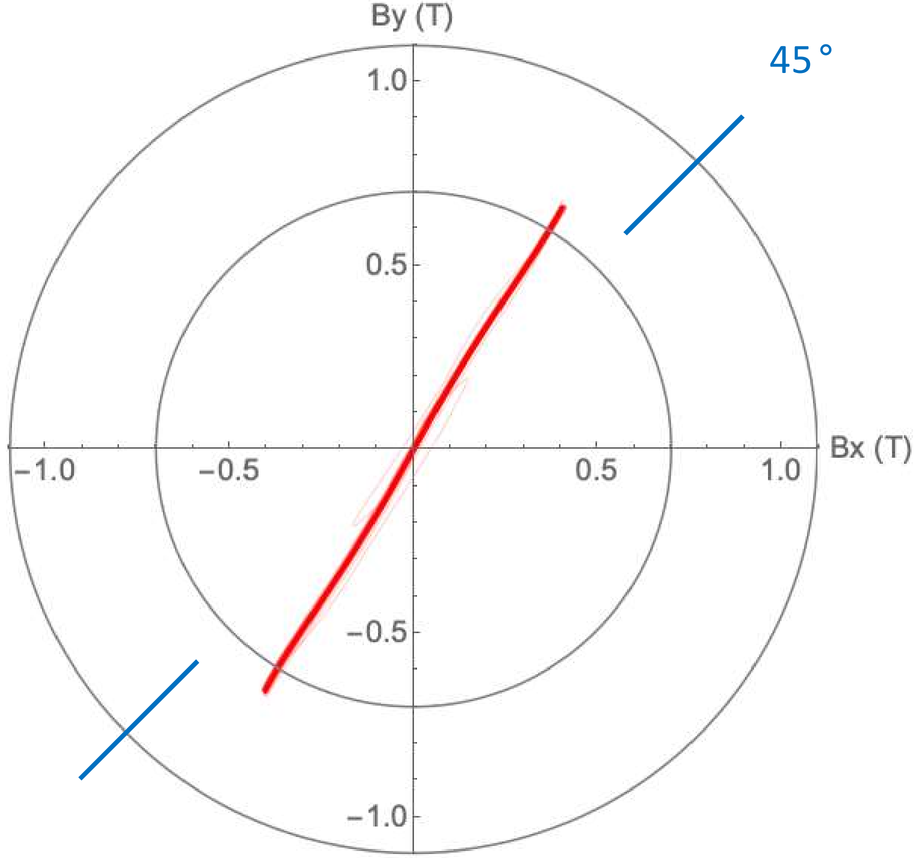



# New Linear Rotation – ONLY for AppleX (5)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 9.250 | 3.250 | 3.250 | 9.250 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

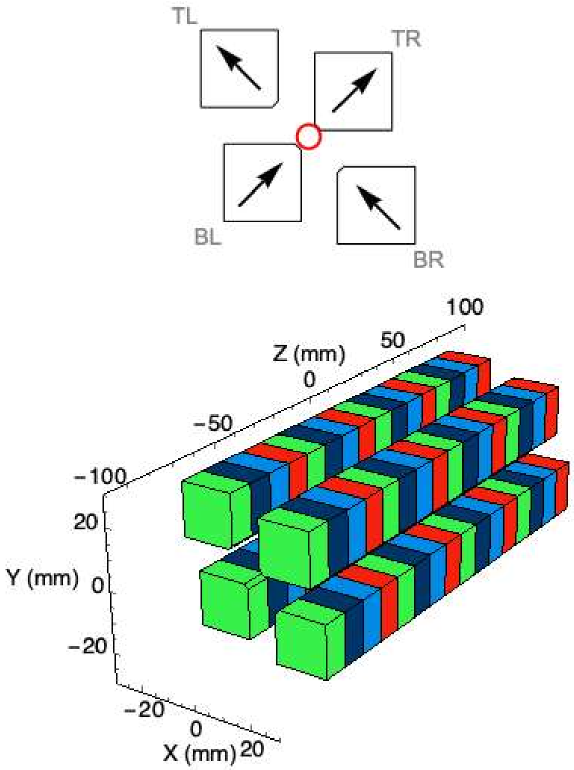


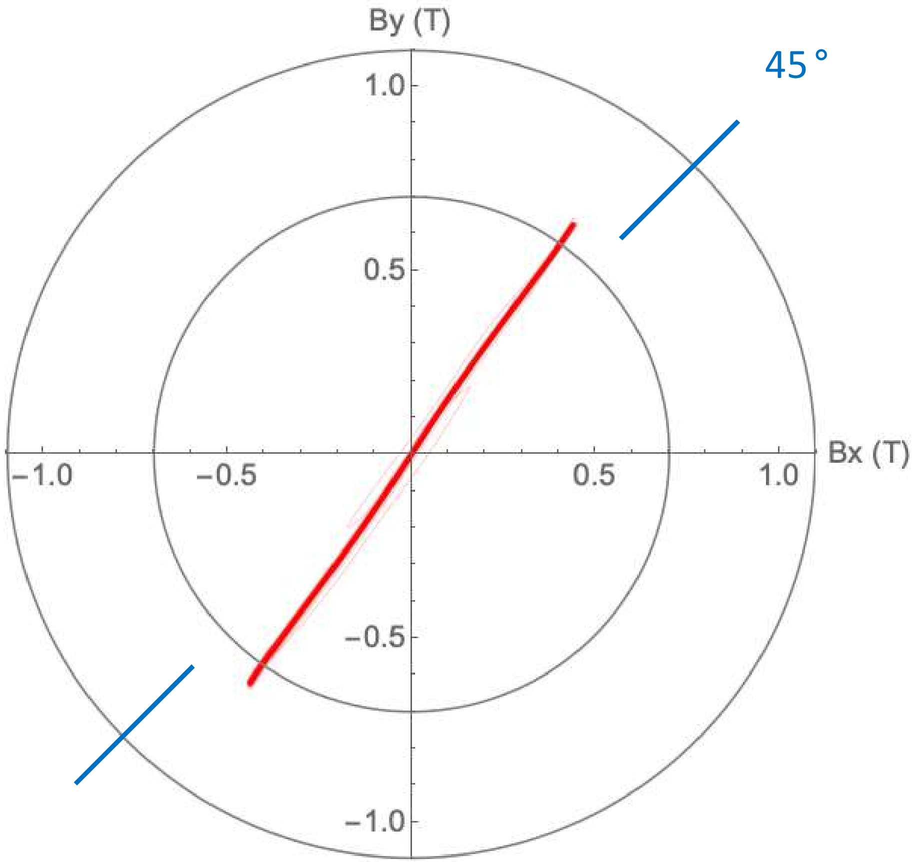



# New Linear Rotation – ONLY for AppleX (6)

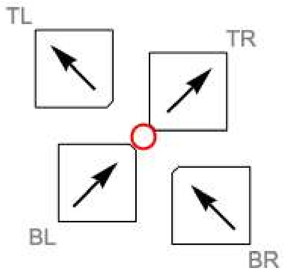
| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 0.000 | 0.000 | 0.000 | 0.000 | mm |

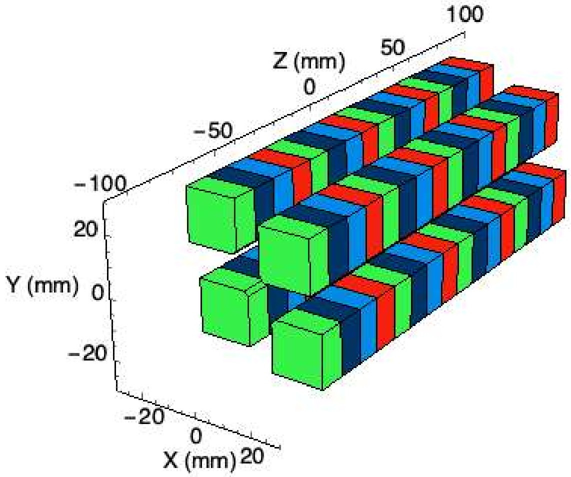


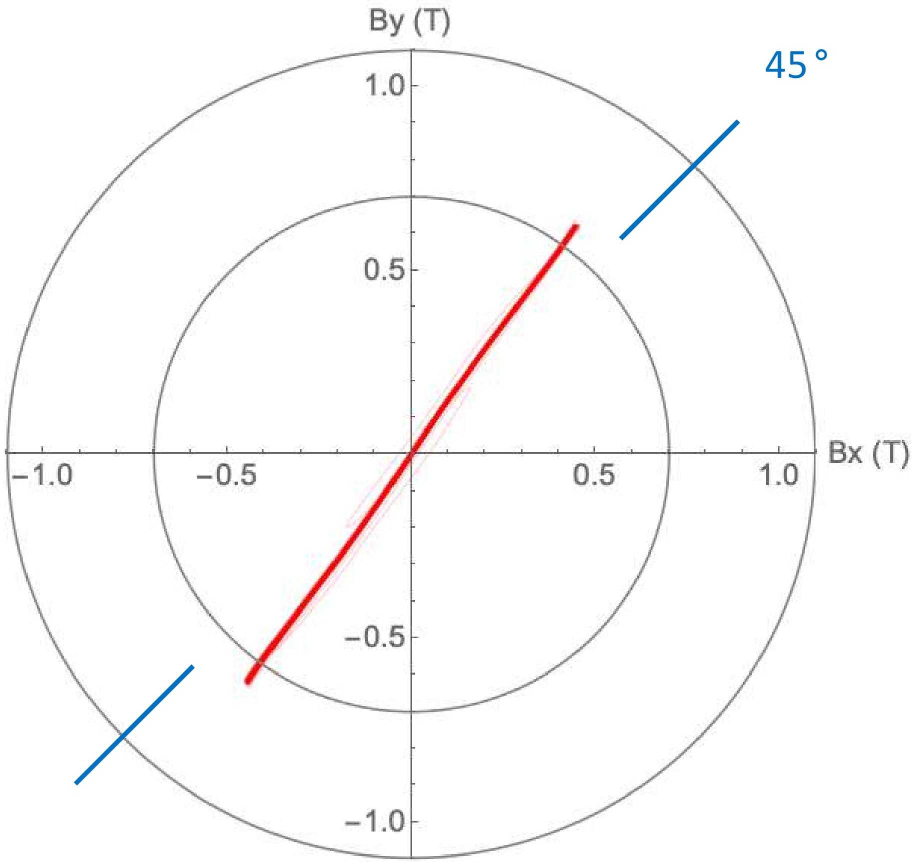



# New Linear Rotation – ONLY for AppleX (7)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 1.900 | 0.000 | 0.000 | −1.900 | mm |

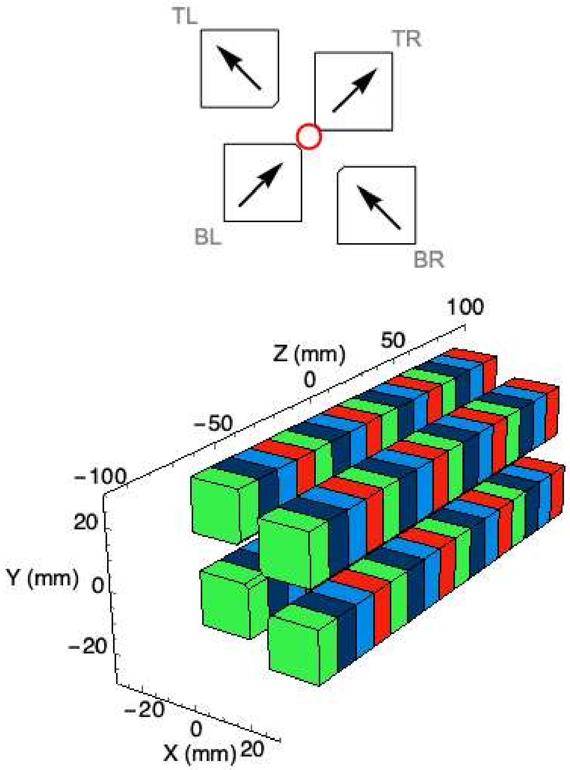


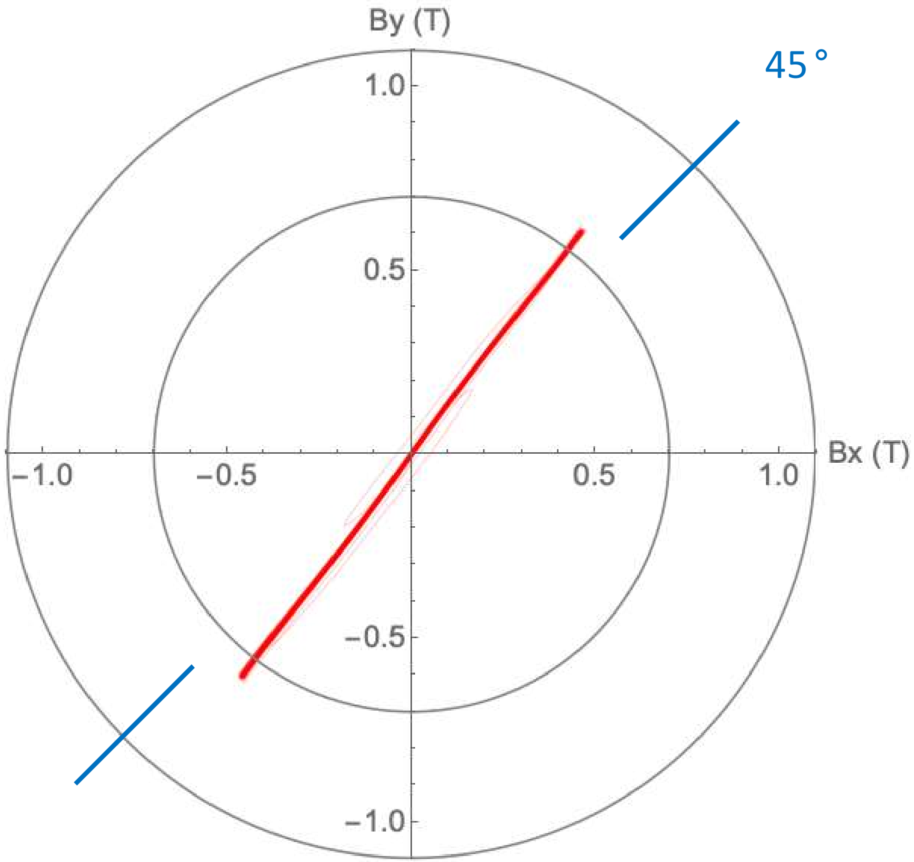



# New Linear Rotation – ONLY for AppleX (8)

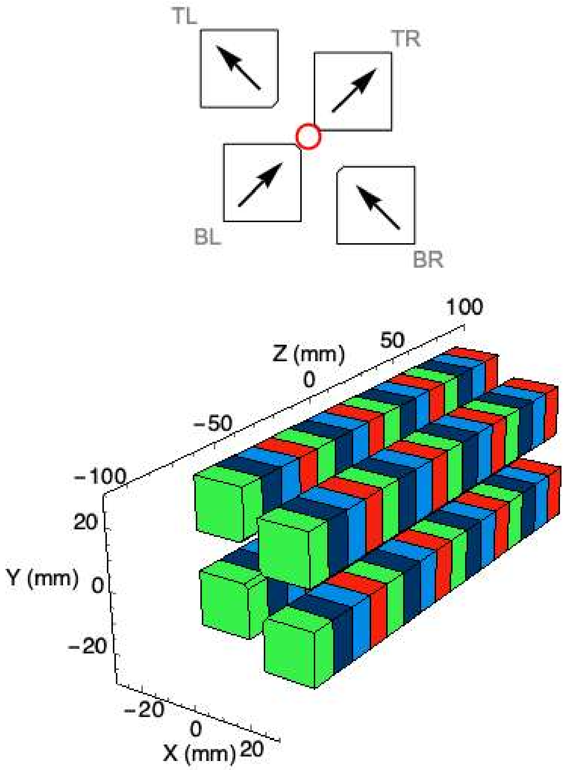
| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 3.800 | 0.000 | 0.000 | −3.800 | mm |

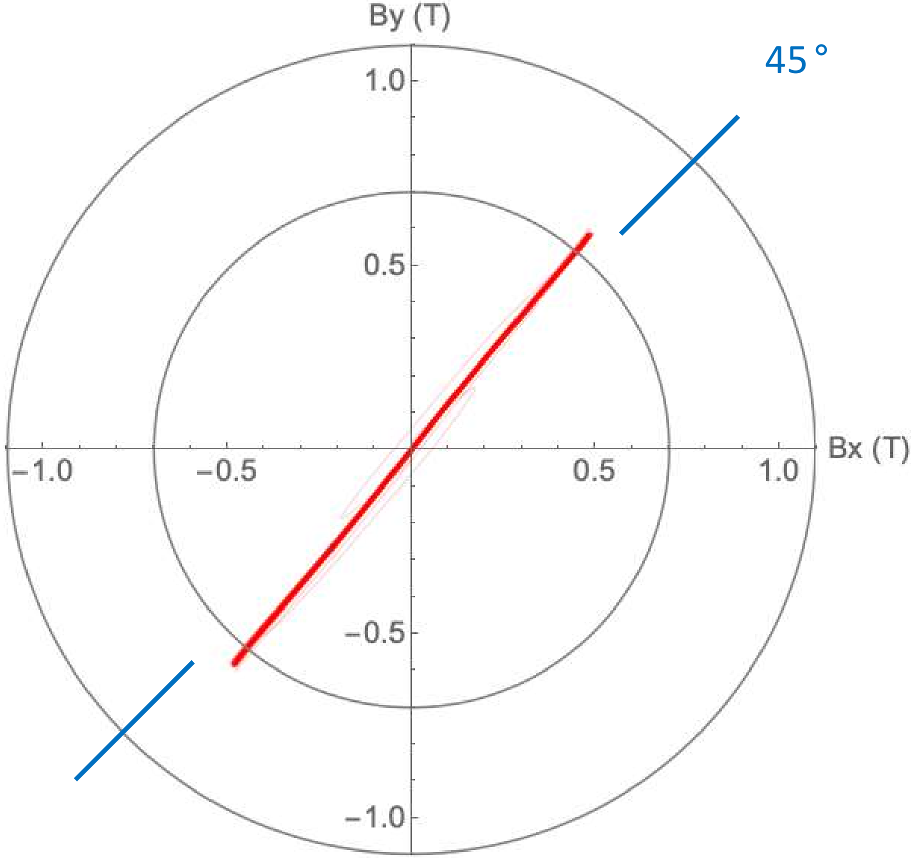


# New Linear Rotation – ONLY for AppleX (9)

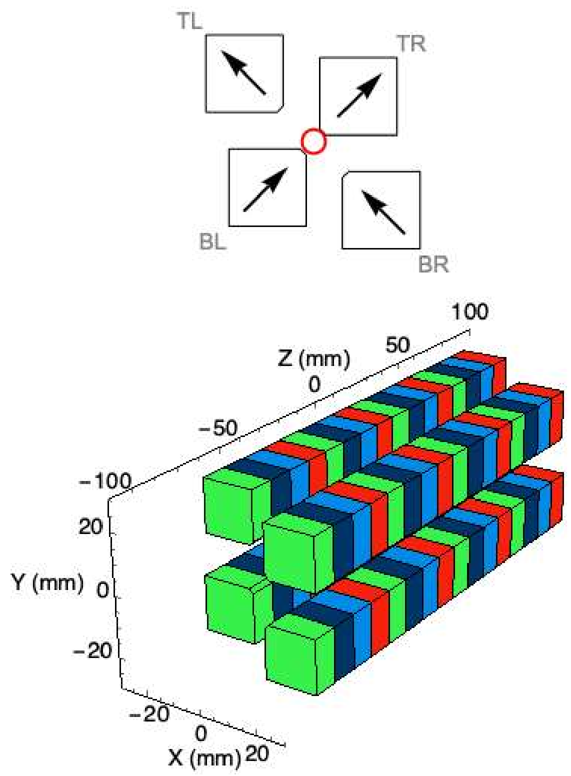
| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 5.700 | 0.000 | 0.000 | −5.700 | mm |

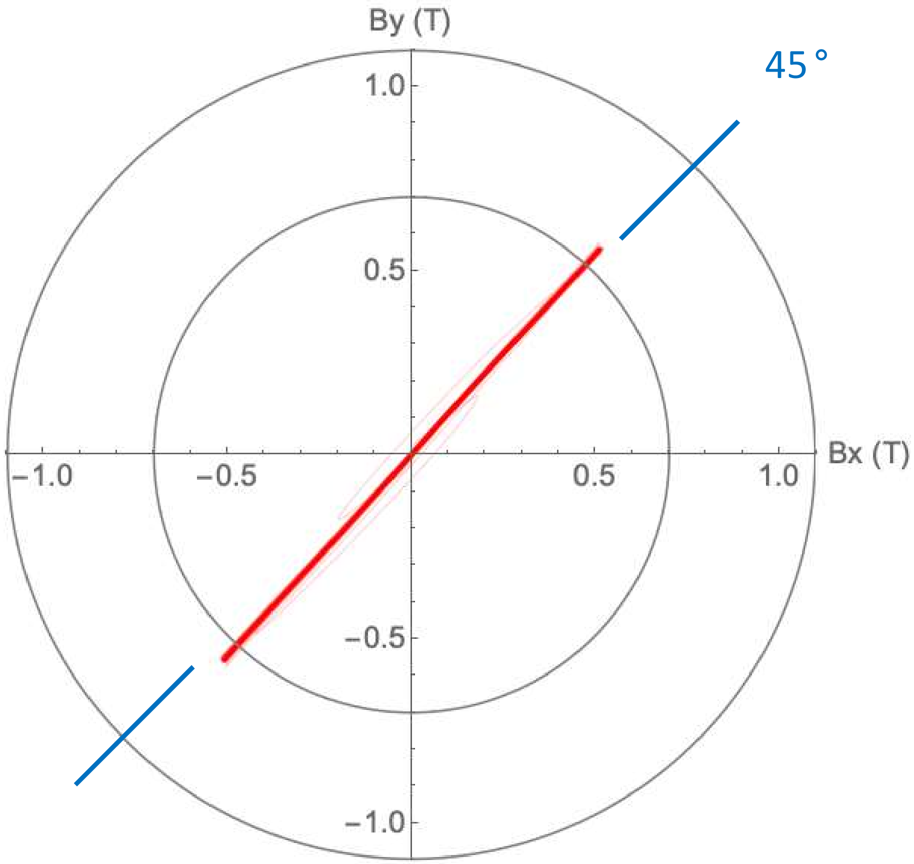


# New Linear Rotation – ONLY for AppleX (10)

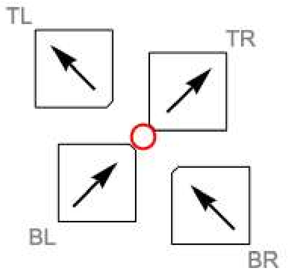
| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 7.600 | 0.000 | 0.000 | −7.600 | mm |

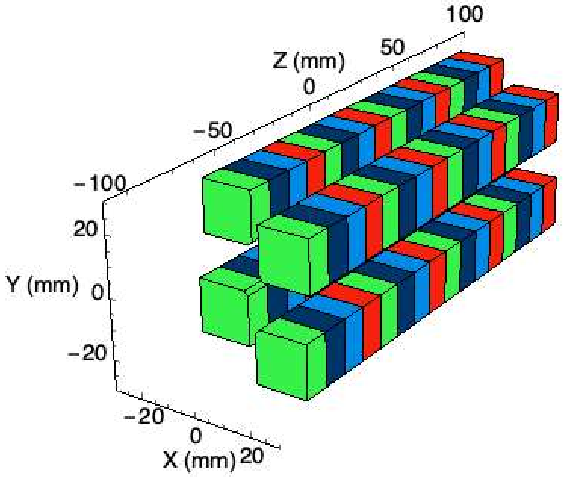


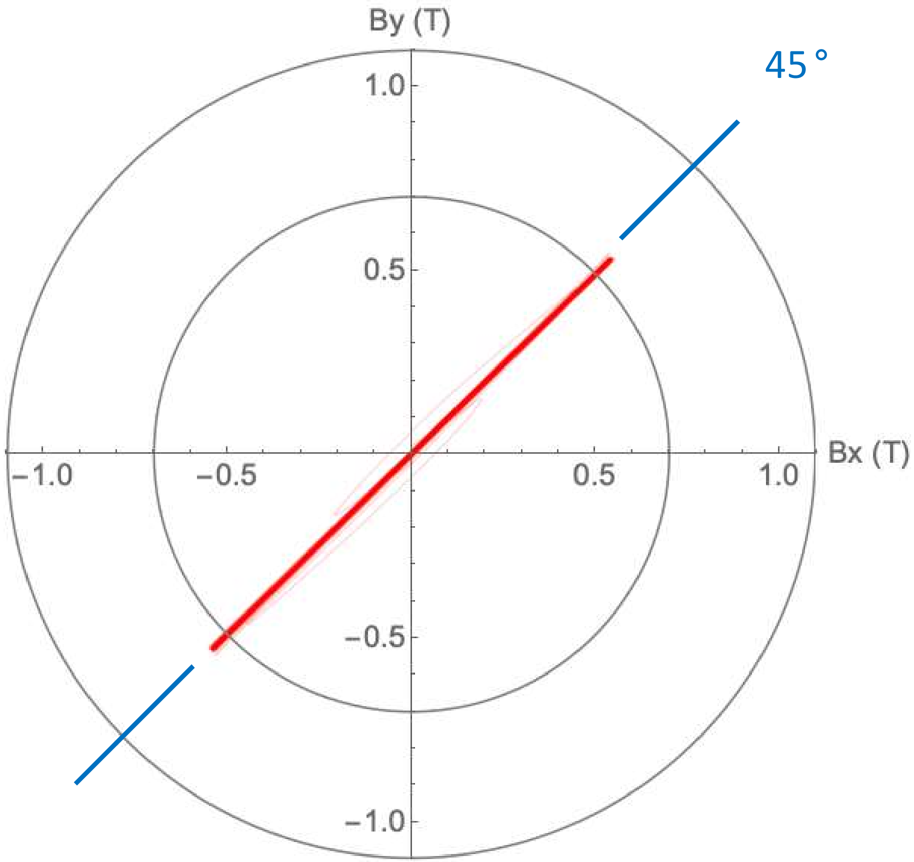



# New Linear Rotation – ONLY for AppleX (11)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |

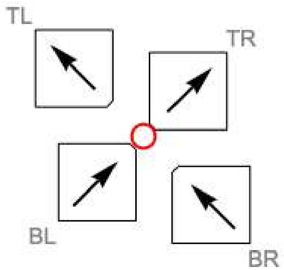


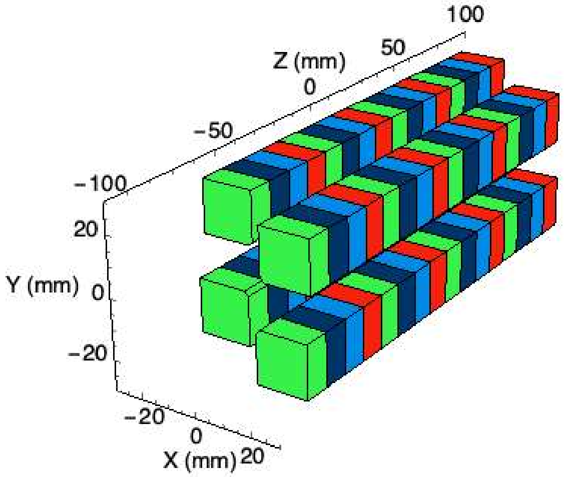



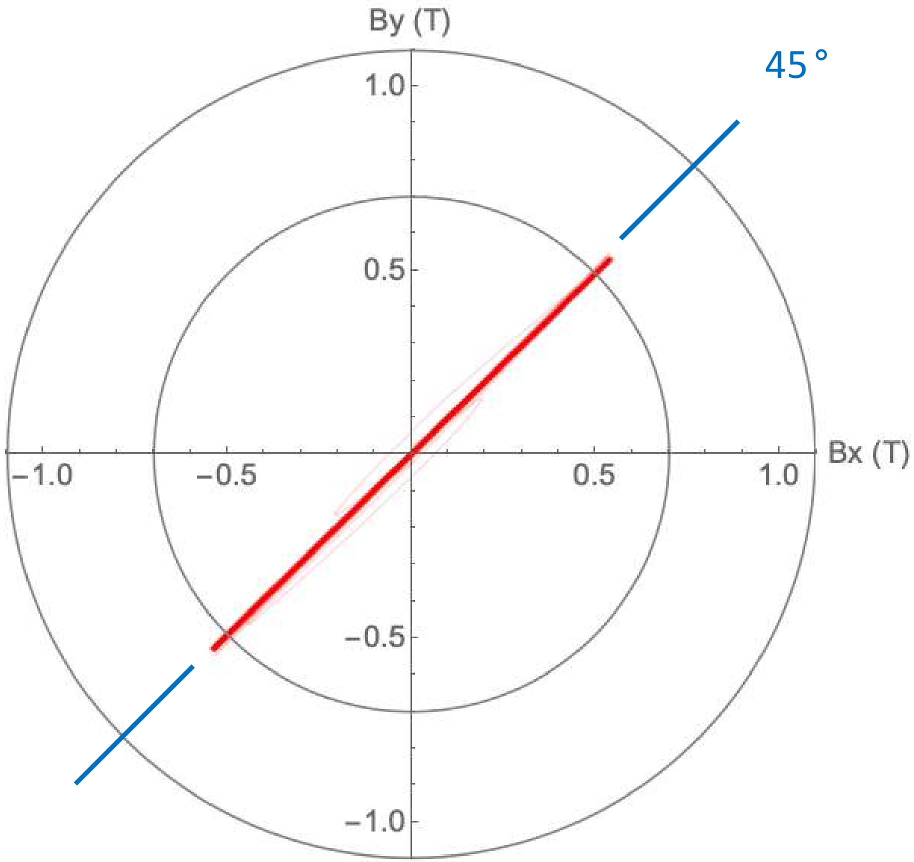



# New Linear Rotation – ONLY for AppleX (12)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 10.750 | 3.250 | 3.250 | 10.750 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |

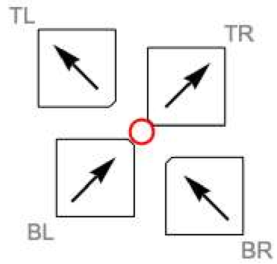


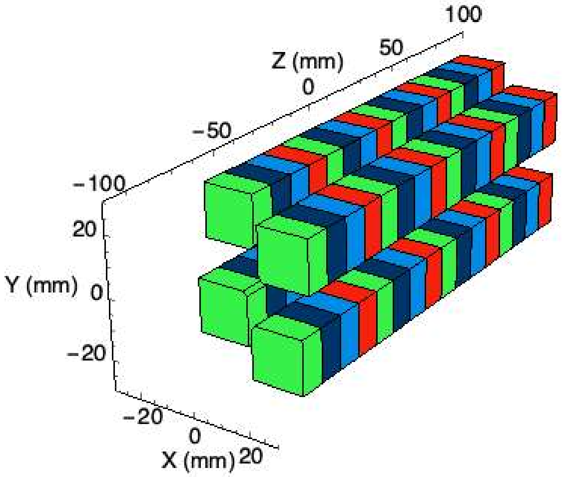



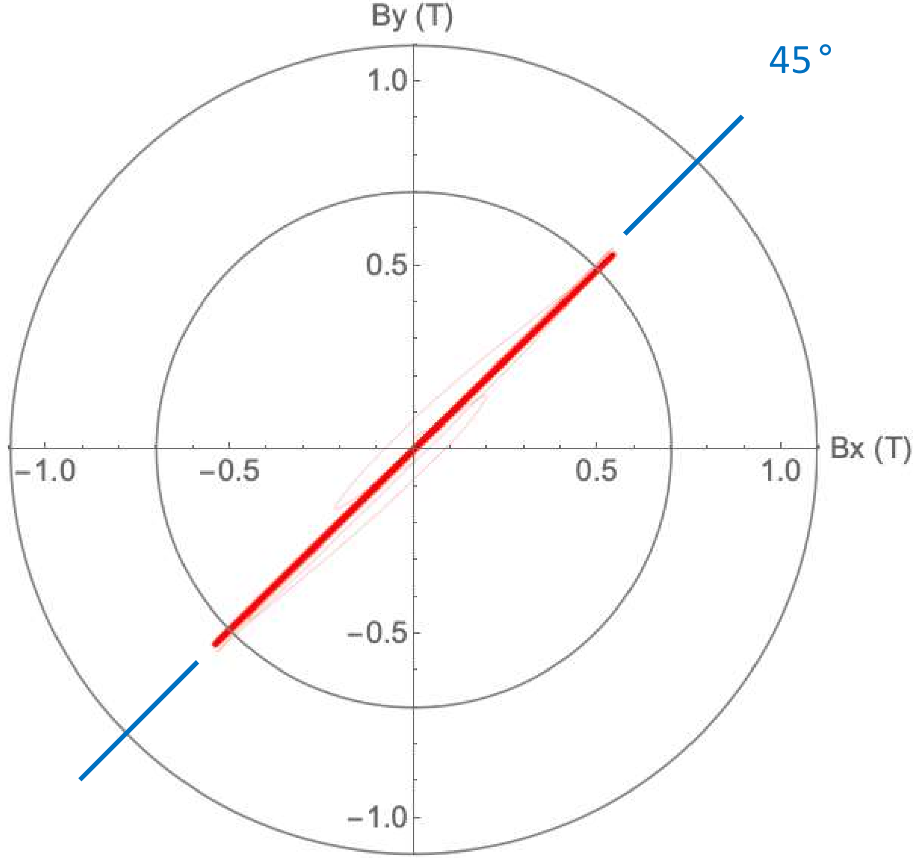



# New Linear Rotation – ONLY for AppleX (13)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 9.250 | 3.250 | 3.250 | 9.250 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |

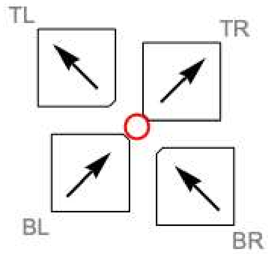


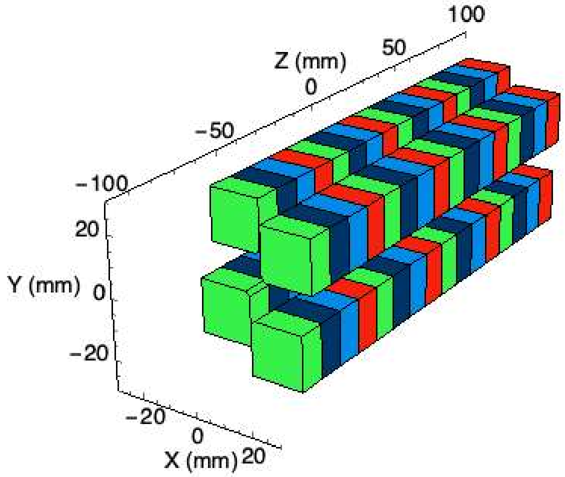



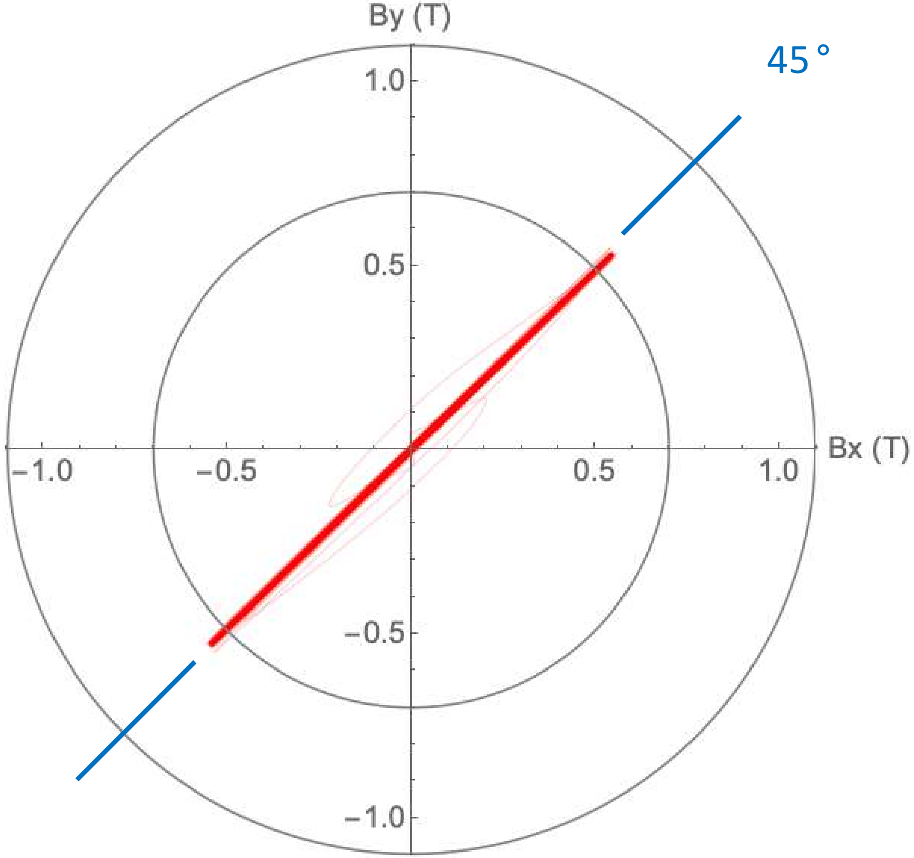



# New Linear Rotation – ONLY for AppleX (14)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 7.750 | 3.250 | 3.250 | 7.750 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |

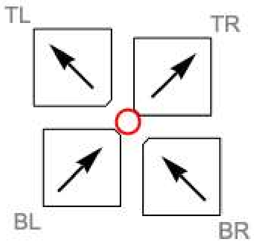


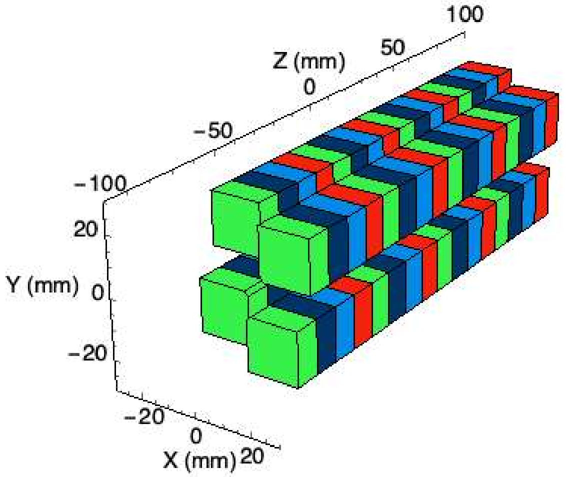



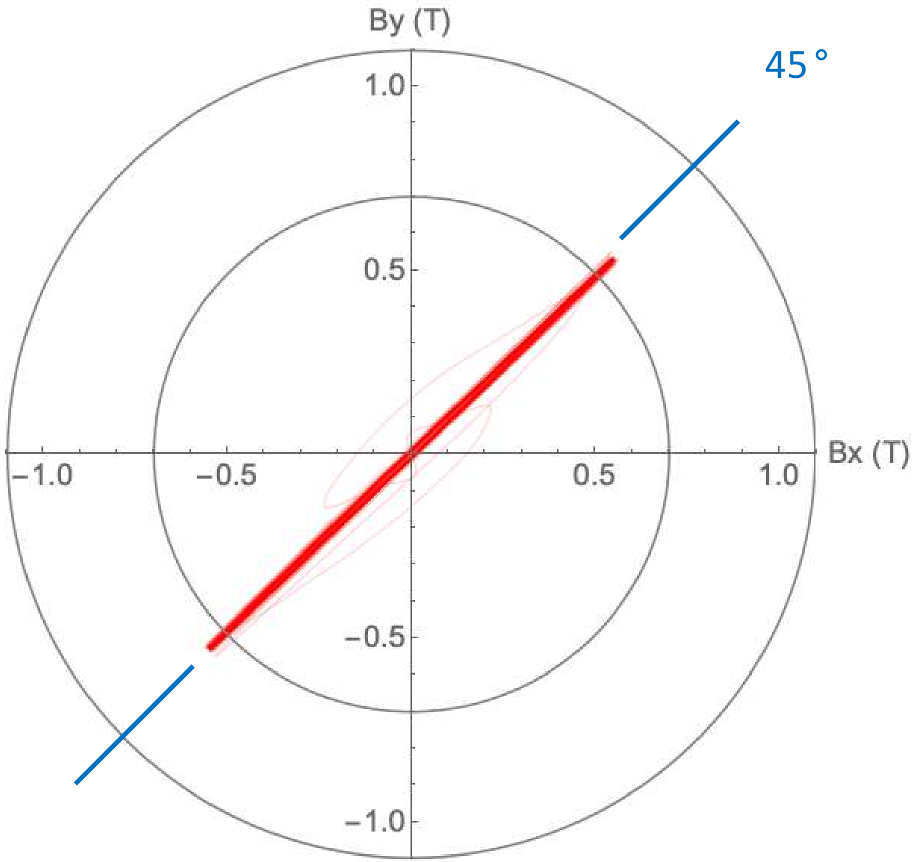



# New Linear Rotation – ONLY for AppleX (15)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 6.250 | 3.250 | 3.250 | 6.250 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |

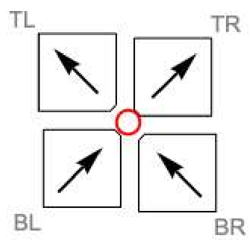


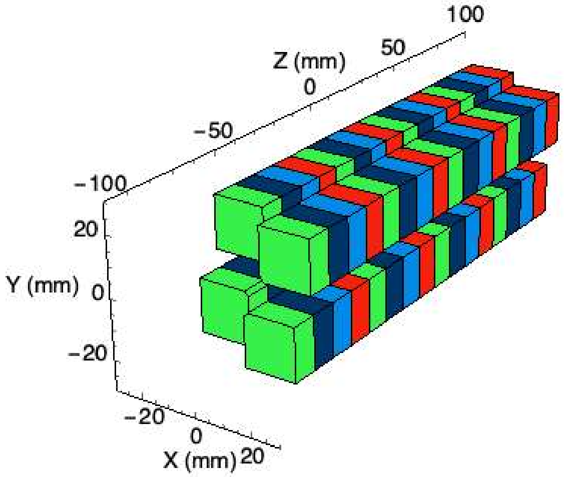



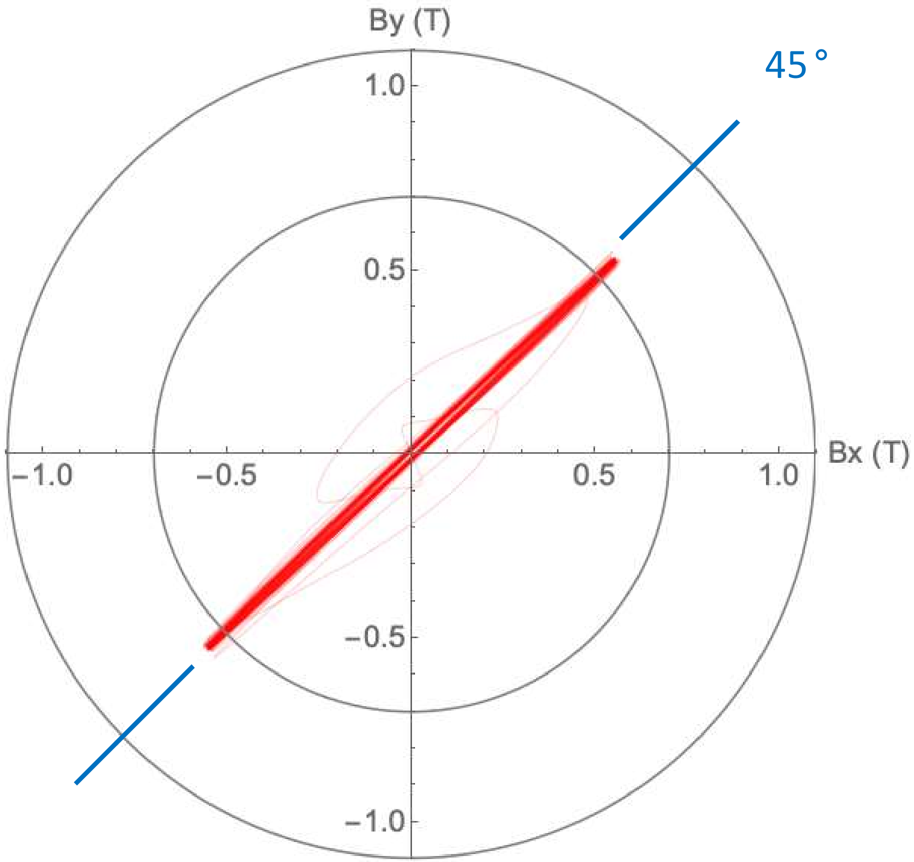



# New Linear Rotation – ONLY for AppleX (16)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 4.750 | 3.250 | 3.250 | 4.750 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |

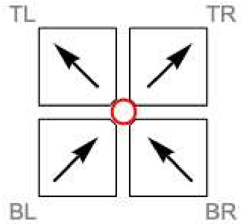


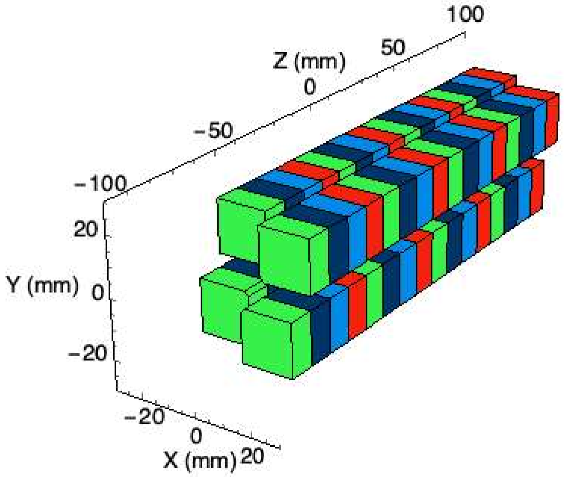



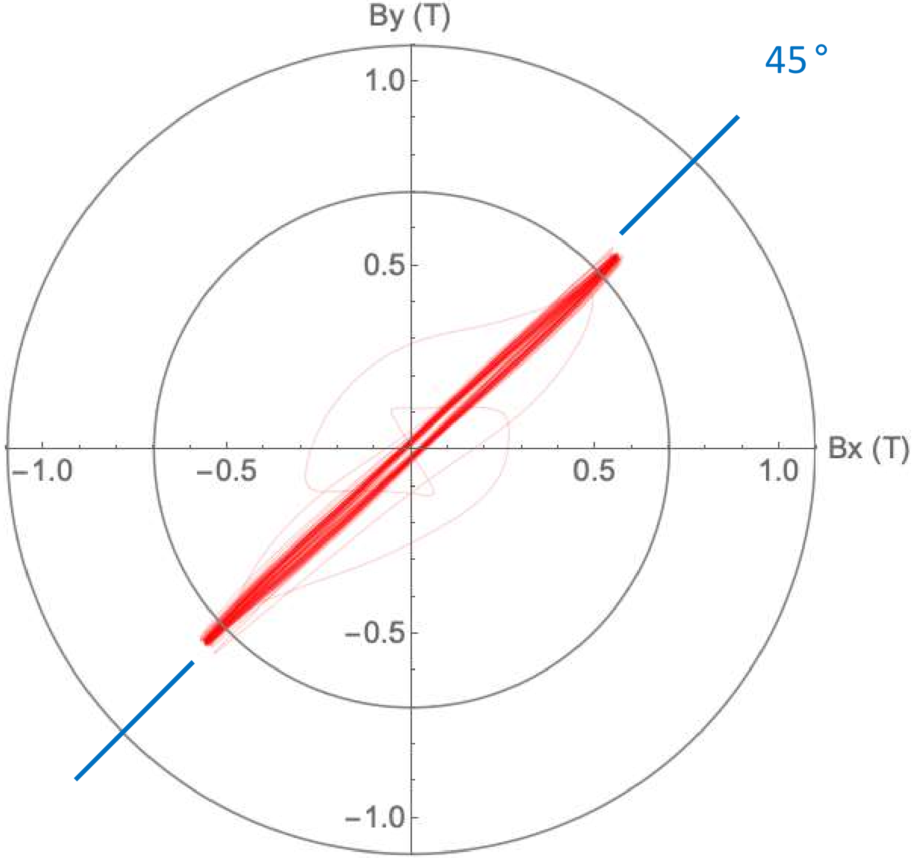



# New Linear Rotation – ONLY for AppleX (17)

| | TL | TR | BL | BR | |
|---|---|---|---|---|---|
| Radius | 3.250 | 3.250 | 3.250 | 3.250 | mm |
| Longitudinal Shift | 9.500 | 0.000 | 0.000 | −9.500 | mm |



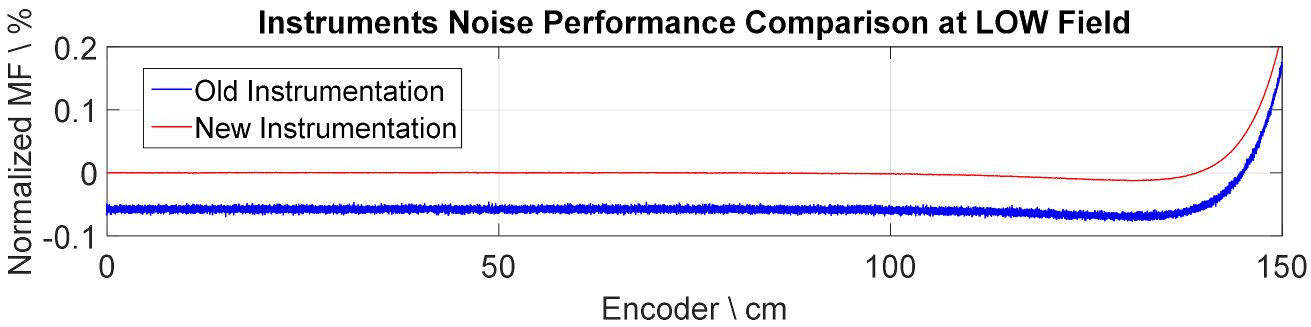



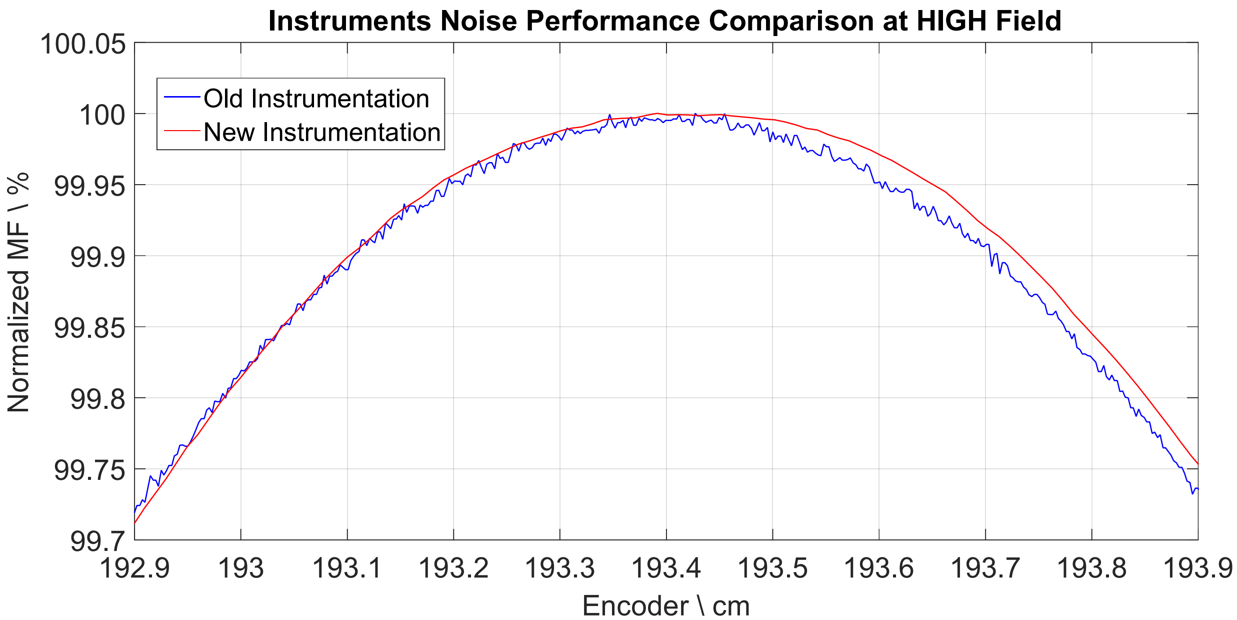
THANK YOU

ANY QUESTIONS ?

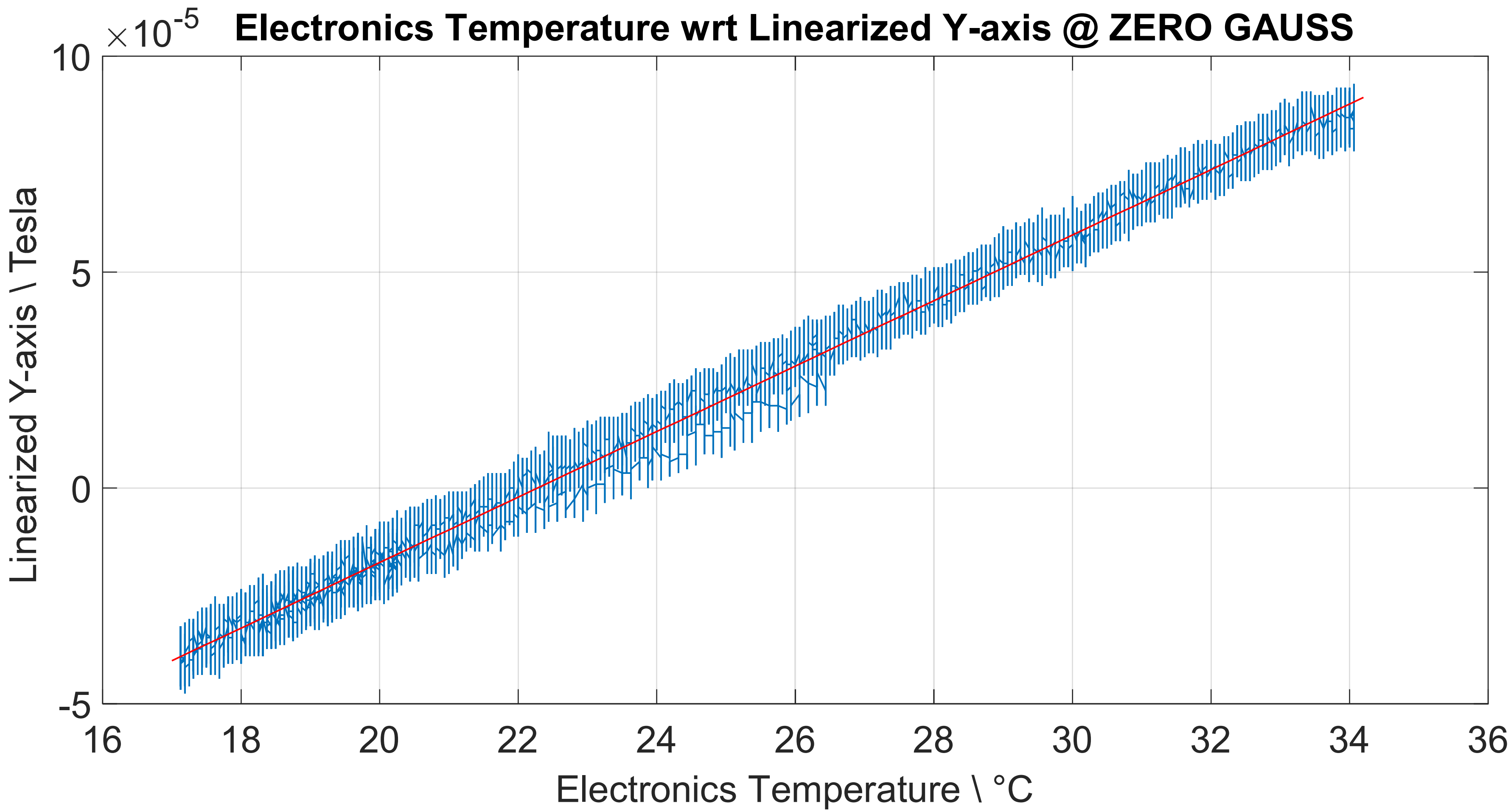
# Extra Slides

# Performance Comparison of the Old and New Instrumentation

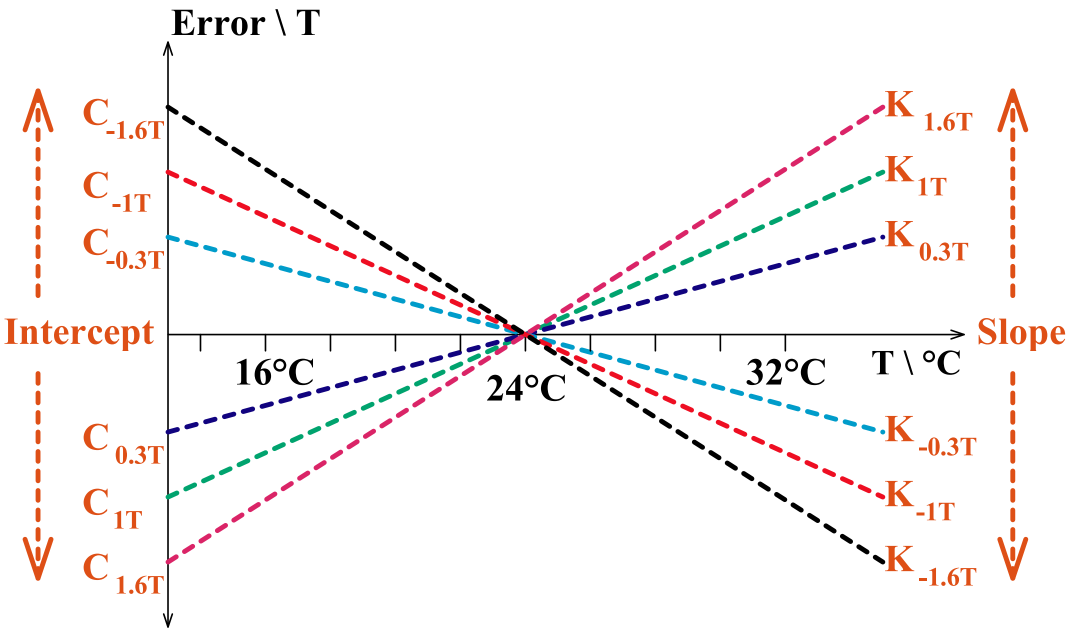


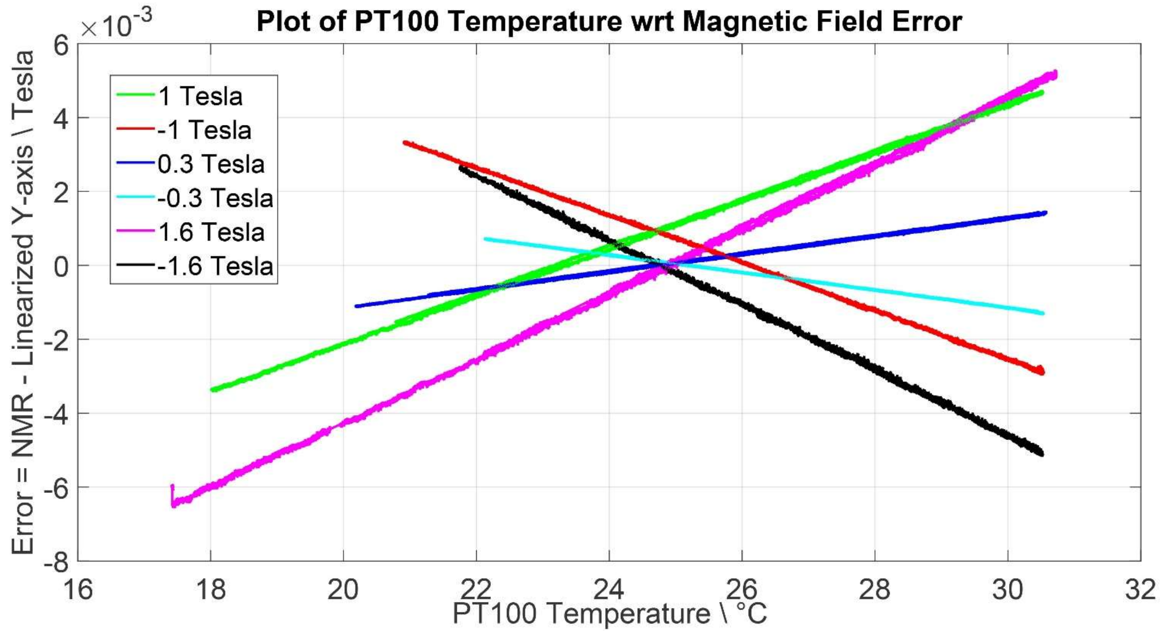



# Electronics Temperature Compensation



# Instrument Calibration - Temperature Compensation of Offset and Sensitivity (2)



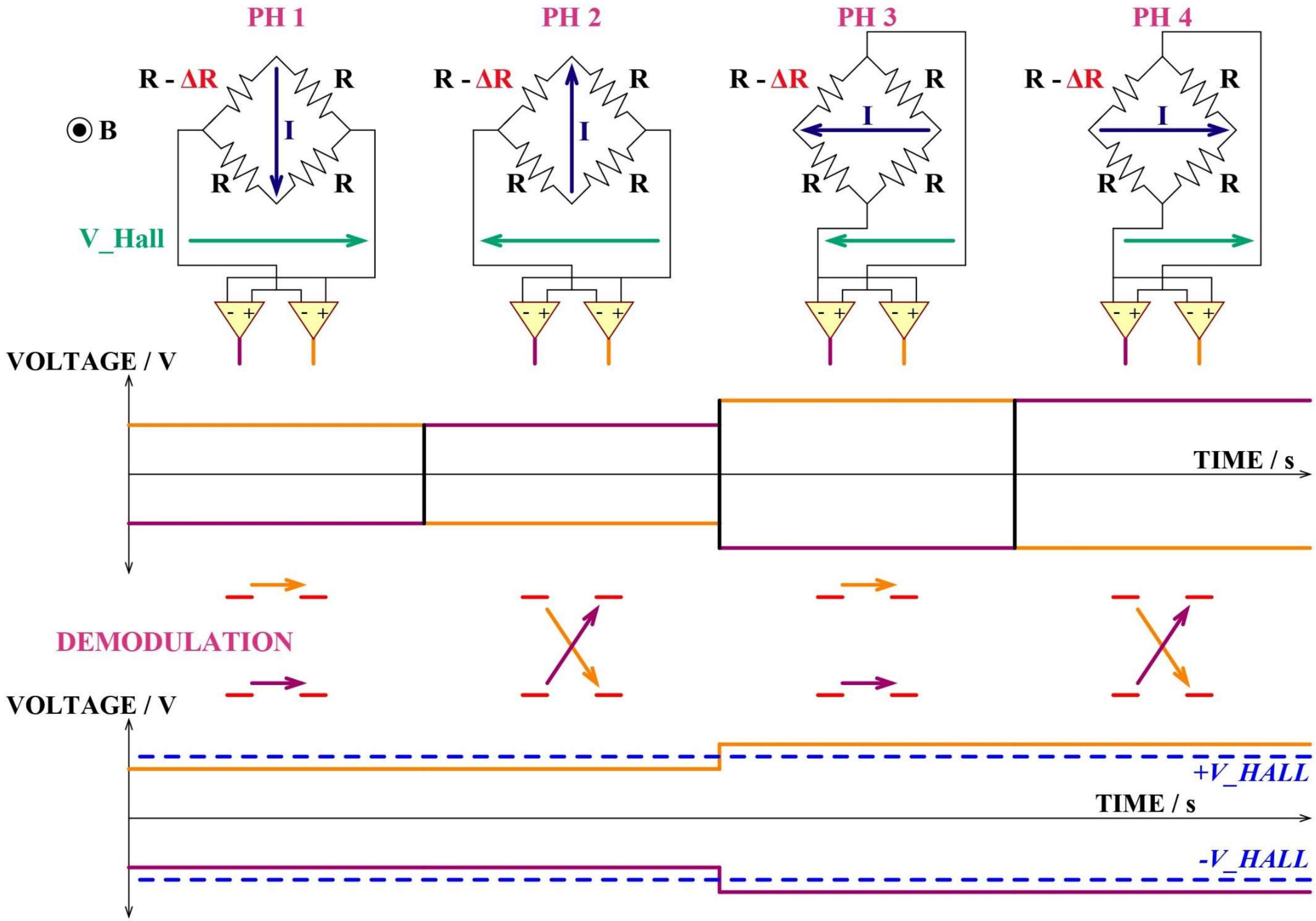

**Calibration Verification**

- Uncalibrated Output Peak Error of **1.93 %** over the Full Range.
- Calibrated Output Peak Error of **0.02 %** over the Full Range.

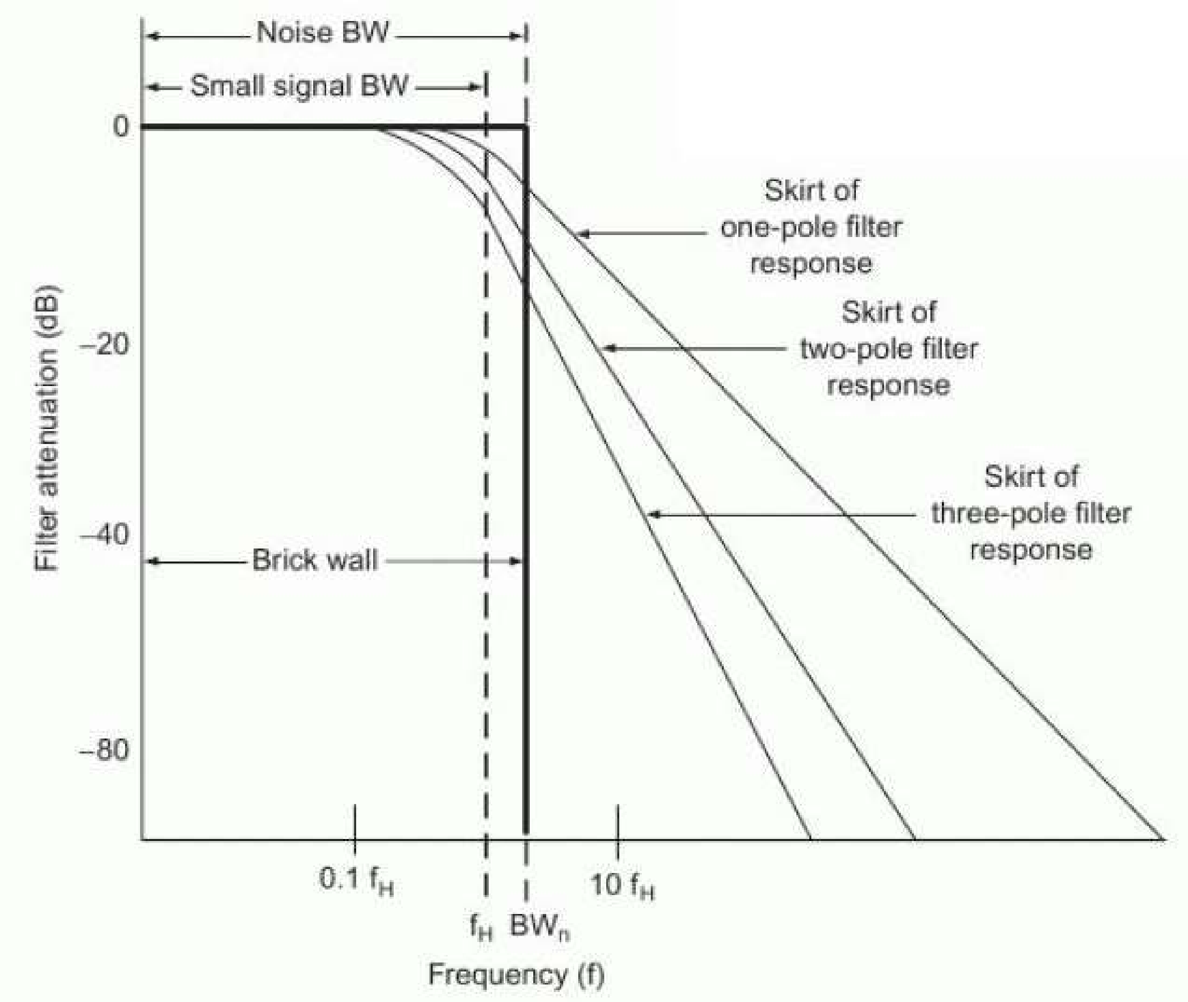
# Spinning Current Technique

**Spinning Current Suppression:**

- Hall Offset Voltage
- PA Offset Voltage
- Planar Hall Voltage
- 1/f noise



# Noise Performance (1)




$$BW_n = f_H . K_n$$

$BW_n$ *is the Effective Noise Bandwidth*

$f_H$ *is the Upper Cutoff Frequency*

$K_n$ *is the Brick Wall Conversion Factor*

| Number of Poles in Filter | $K_n$ AC Noise Bandwidth Ratio |
|---|---|
| 1 | 1.57 |
| 2 | 1.22 |
| 3 | 1.16 |
| 4 | 1.13 |
| 5 | 1.12 |

# Noise Performance (2) – 1/f noise

**Derivation of *1/f* region noise**

$E_n$ *is the Normalized RMS Noise Voltage* $(V/Hz)$

$e_{normal}$ *is the Noise Voltage Spectral Density* $(V/\sqrt{Hz})$

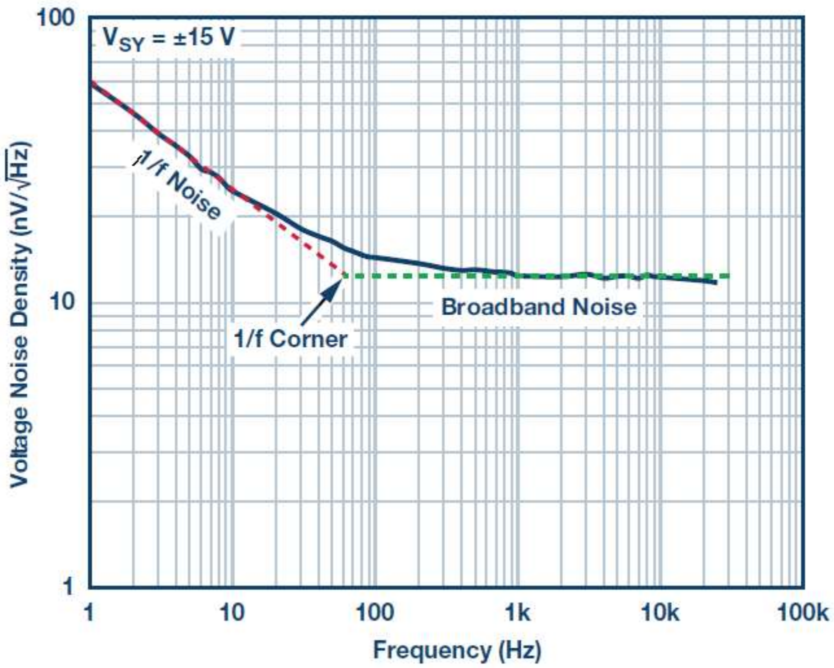
$E_{nf}$ *is the Total* $1/f$ *RMS Noise Voltage* $(V)$

$$E_n = \frac{e_{normal}}{\sqrt{f}}$$

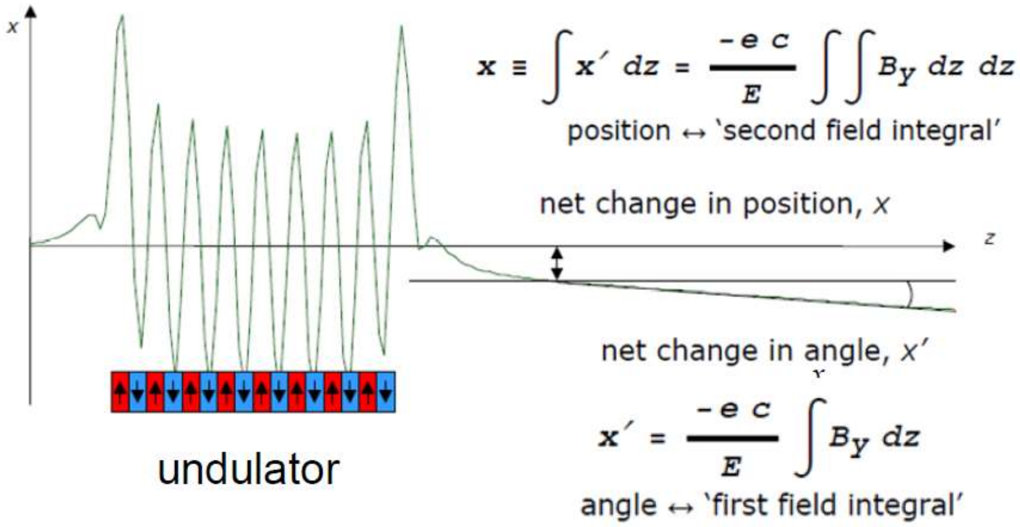
$$E_n^2 = \frac{e_{normal}^2}{f}$$

$$E_{nf}^2 = \int_{f_L}^{f_H} \frac{e_{normal}^2}{f}\, df = e_{normal}^2 . (\ln(f_H) - \ln(f_L)\,)$$

$$E_{nf} = e_{normal} . \sqrt{\ln\left(\frac{f_H}{f_L}\right)}$$

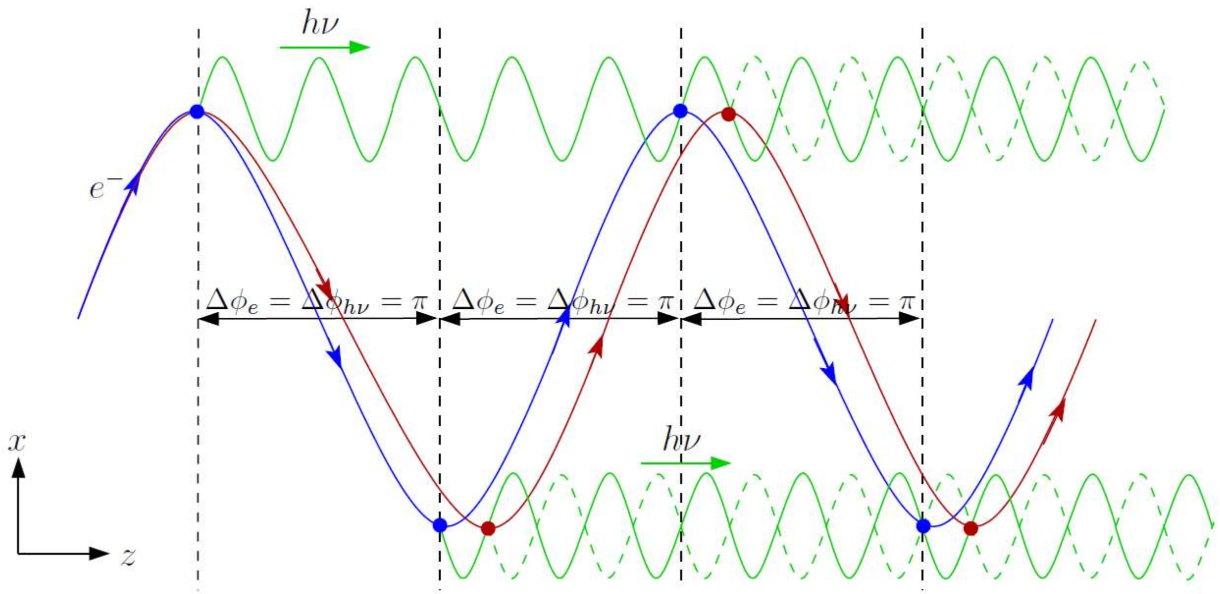


# Magnetic Field Errors in Undulators

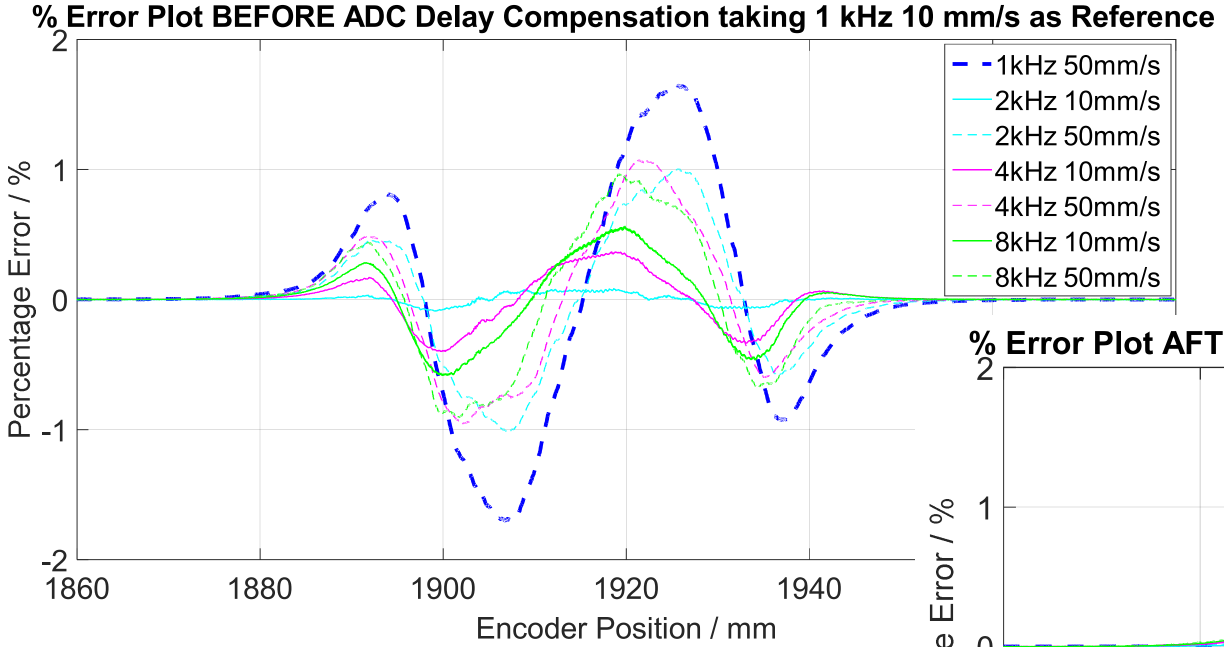



**First and Second Field Integral Errors** measured by Stretched Wire Technique

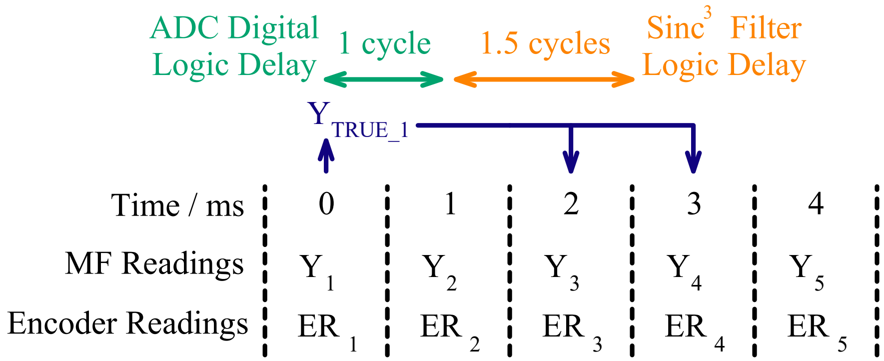
**Phase Error** measured by Hall Probe traversal along Undulator length

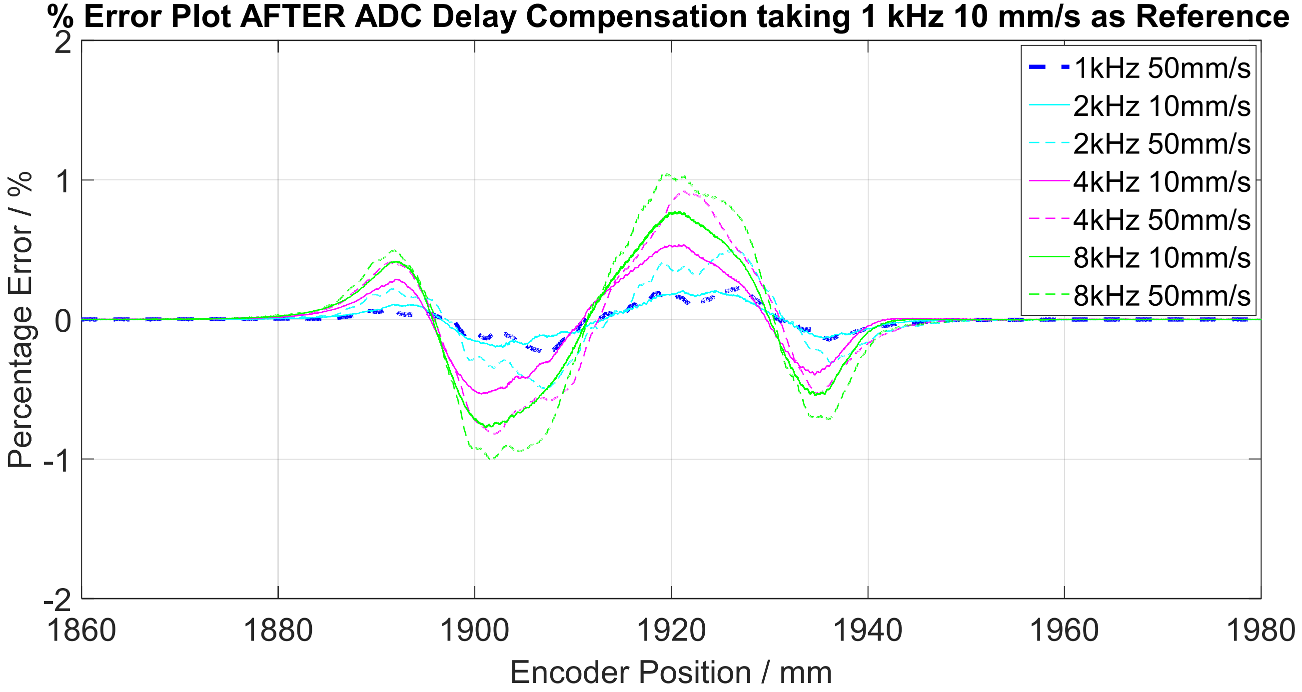


# ADC $Sinc^3$ Filter Phase Delay Compensation




**Reference Traversal : 1 kHz 10 mm/s**



# ADC Sinc$^3$ Filter Magnitude Analysis - Aliasing