# Magnetometry for the Nab Experiment

E. Mae Scott for the Nab Collaboration

University of Tennessee, Knoxville

2020 DNP

# Nab is an Unpolarized Measurement

## Parametrization of Neutron Beta Decay

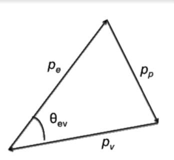
$$\frac{\partial^3\omega}{\partial E_e \partial\Omega_e \partial\Omega_\nu} \propto \frac{1}{\tau_n} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b\cancel{\frac{m_e}{E_e}} + \cancel{\langle\vec{\sigma_n}\rangle \cdot \left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + \ldots\right)}\right]$$

To extract $a$, we use an unpolarized neutron beam and set the spin correlation terms to zero. The Fierz interference term, $b$, is zero in the Standard Model.

$$\frac{\partial^3\omega}{\partial E_e \partial\Omega_e \partial\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu}\right]$$

# Extracting *a* in the Nab Experiment

$$\Gamma = f(E_e)\left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu}\right] = f(E_e)\left[1 + a\beta_e cos\theta_{e\nu}\right] = f(E_e)\left[1 + a\beta_e \frac{p_p^2 + p_e^2 + p_\nu^2}{2p_e p_\nu}\right]$$



## Determining $cos\theta_{e\nu}$

- Known Q value of neutron beta decay
- $E_e$
- $p_p$

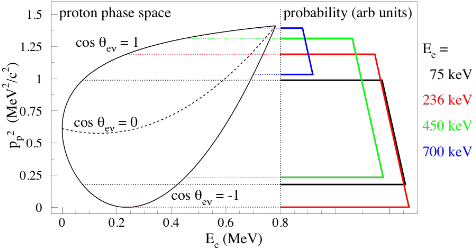
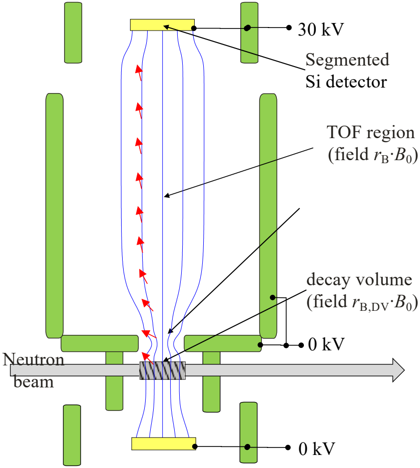
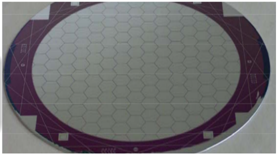


Figure: Pocanic et al, NIMA 611 (2009) 211, Baessler et al, AIP Conf Proc 1560 (2013) 114

# Nab Experimental Design



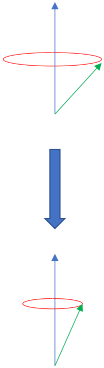
$E_e \leq 783 keV$
$E_p \leq 30 keV$

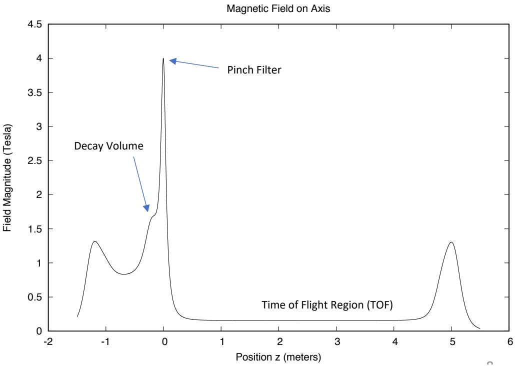


## Observables

- $E_e$ - electron energy
- $t_p$ - proton time of flight

# Nab Experimental Design

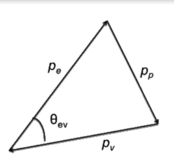




$$\frac{1}{t_p^2} = \frac{p_0^2}{m_p^2}\left[\int_{z_0}^{l} \frac{dl}{\left(1 - \frac{e(V - V_0)}{T_0} - \frac{B}{B_0} sin^2\theta_0\right)^{1/2}}\right]^{-2}$$

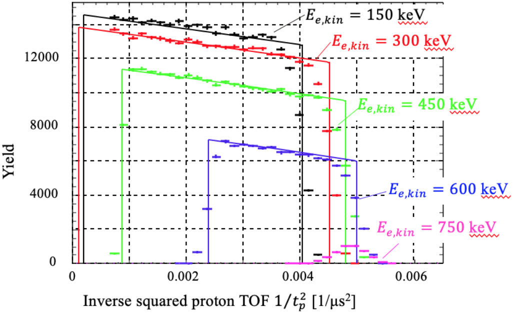
# Extracting *a* in the Nab Experiment

$$P_p(p_p^2) = \begin{cases} 1 + a\beta_e \dfrac{p_p^2 + p_e^2 + p_\nu^2}{2p_e p_\nu} & \text{for} \left| \dfrac{p_p^2 + p_e^2 + p_\nu^2}{2p_e p_\nu} \right| < 1 \\ 0 & \text{otherwise} \end{cases}$$

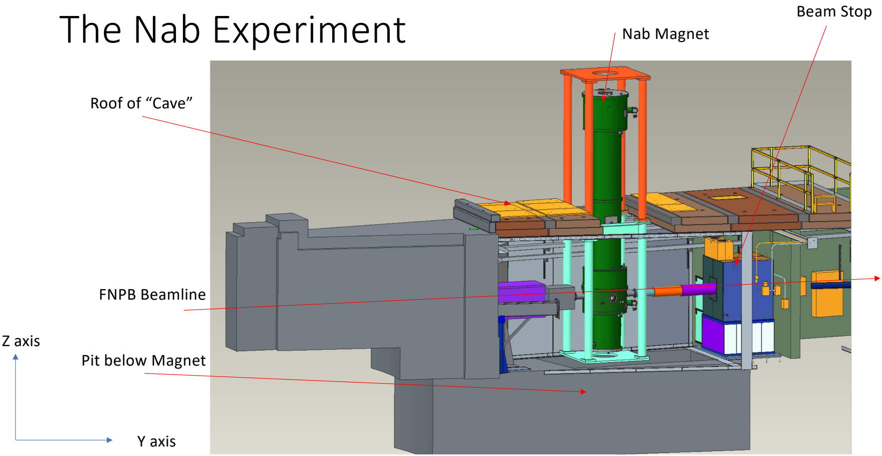


## Determining $cos\theta_{e\nu}$

- Known Q value of neutron beta decay
- $E_e$
- $p_p$



# The Nab Experiment



# Precision Requirements

**Nab systematic uncertainties**

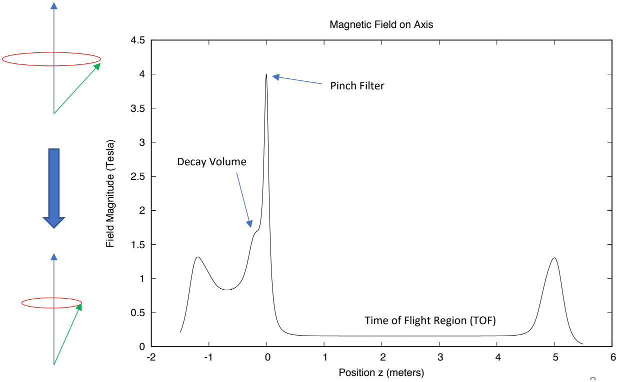
| Experimental Parameter | Principle specification | $(\Delta a/a)_{syst}$ |
|---|---|---|
| **Magnetic Field:** | | |
| curvature at pinch | $\Delta\gamma/\gamma = 2\%$ with $\gamma = (d^2B_z(z)/dz^2)/B_z(0)$ | $5.3 \times 10^{-4}$ |
| ratio $r_B = B_{TOF}/B_0$ | $(\Delta r_B)/r_B = 1\%$ | $2.2 \times 10^{-4}$ |
| ratio $r_{B,DV} = B_{DV}/B_0$ | $(\Delta r_{B,DV})/r_{B,DV} = 1\%$ | $1.8 \times 10^{-4}$ |
| $L_{TOF}$, **length of TOF region** | | (* Free fit parameter) |
| **U inhomogeneity:** | | |
| in decay / filter region | $\|U_F - U_{DV}\| < 10$ mV | $5 \times 10^{-4}$ |
| in TOF region | $\|U_F - U_{TOF}\| < 200$ mV | $2.2 \times 10^{-4}$ |
| **Neutron beam:** | | |
| position | $\Delta\langle z_{DV}\rangle < 2$ mm | $1.7 \times 10^{-4}$ |
| profile (incl. edge effect) | slope at edges <10% / cm | $2.5 \times 10^{-4}$ |
| Doppler effect | analytical correction | small |
| unwanted beam polarization | | measure |
| **Adiabaticity of proton motion** | | $1 \times 10^{-4}$ |
| **Detector effects:** | | |
| $E_e$ calibration | $\Delta E_e < 200$ eV | $2 \times 10^{-4}$ |
| proton trigger efficiency | $\Delta N_{tail}/N_{tail} \leq 1\%$ / cm | $3.4 \times 10^{-4}$ |
| TOF shift (det./electronics) | $\epsilon_p < 100$ ppm/keV | $3 \times 10^{-4}$ |
| shape of $E_e$ response | | $4.4 \times 10^{-4}$ |
| **TOF in acceleration region** | $r_{\text{electrods}}$ (prelim) | $3 \times 10^{-4}$ |
| **electron TOF** | analytic correction | small |
| **BGD/accid. coinc's** | (will subtract out of time coinc) | small |
| **Residual gas** | $P < 2 \cdot 10^{-9}$ torr | $3.8 \times 10^{-4}$ |
| **Overall sum** | | $1.2 \times 10^{-3}$ |

# Spectrometer Uncertainties

**Spectrometer systematic uncertainties**

| Experimental Parameter | Principle specification | $(\Delta a/a)_{syst}$ |
|---|---|---|
| **Magnetic Field:** | | |
| curvature at pinch | $\Delta\gamma/\gamma = 2\%$ with $\gamma = (d^2B_z(z)/dz^2)/B_z(0)$ | $5.3 \times 10^{-4}$ |
| ratio $r_B = B_{TOF}/B_0$ | $(\Delta r_B)/r_B = 1\%$ | $2.2 \times 10^{-4}$ |
| ratio $r_{B,DV} = B_{DV}/B_0$ | $(\Delta r_{B,DV})/r_{B,DV} = 1\%$ | $1.8 \times 10^{-4}$ |
| $L_{TOF}$, **length of TOF region** | | (* Free fit parameter) |
| **Overall sum** | | $6.0 \times 10^{-4}$ |

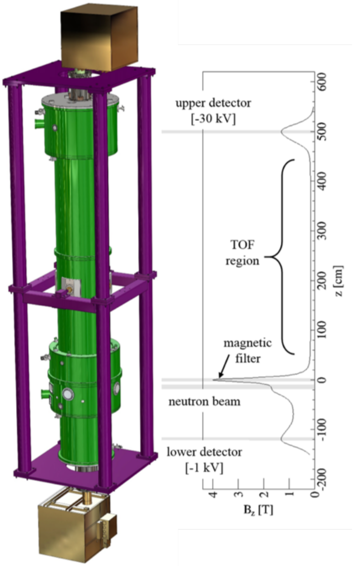
# Mapping Requirements



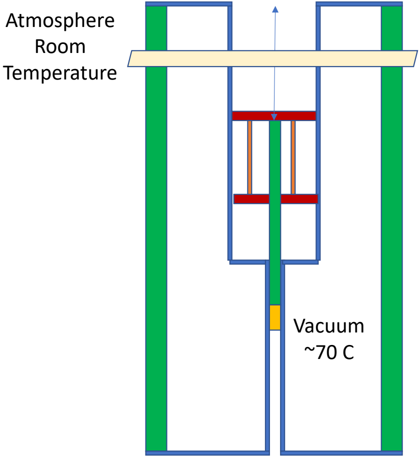
$$\frac{1}{t_p^2} = \frac{p_0^2}{m_p^2}\left[\int_{z_0}^{l} \frac{dl}{\left(1 - \frac{e(V-V_0)}{T_0} - \frac{B}{B_0} sin^2\theta_0\right)^{1/2}}\right]^{-2}$$

# Mapping the Field: Physical Challenges

- The range of field strength requires the use of a Hall Probe, which **must operate at room temperature**.
- The hall probe position **must be measured with respect to the magnet**.
- We must **align the probe normal to the field** to measure the magnitude of the field to a $10^{-4}$ precision.

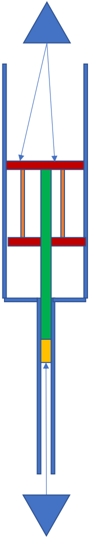


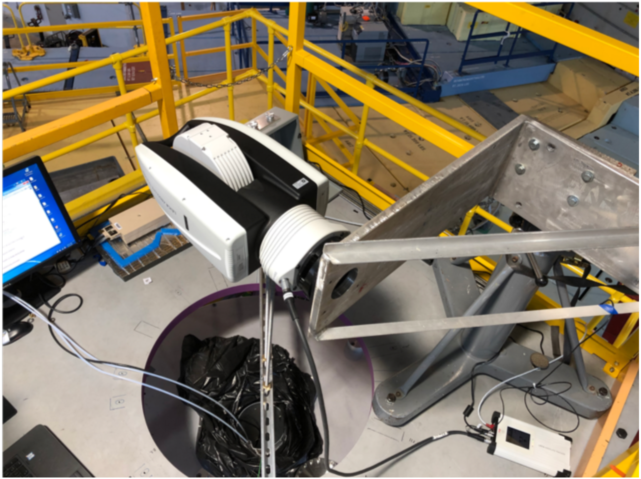
# Solution: Insertion of an Inverted Dewar



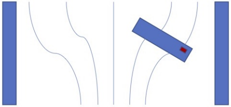
- We inserted an aluminum dewar wrapped in mylar superinsulation to create an ”inverse dewar” inside the magnet.
- While the magnet is cold, we can access most of the field inside this room temperature dewar.

# Solution: Connecting Calibrated Hall Probe and Leica Laser Tracker





# Solution: Design of the Off Axis Hall Probe Holder



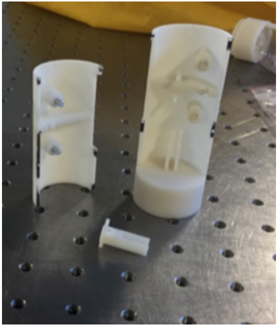
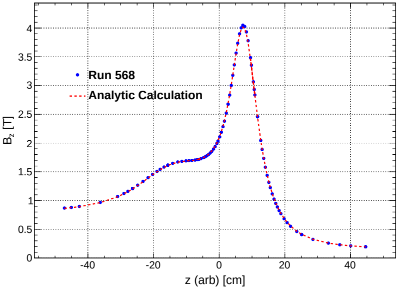


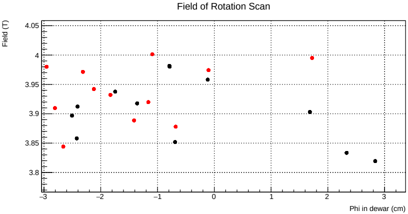
Figure: Iteration 15 tilt table.

- Since our field is cylindrically symmetric, on axis fields will align vertically.
- For off axis fields, I designed a "tilt table" that rotates the Hall probe radially and measures the peak magnitude of the field.
- This tilting can be done from a distance of about 6 meters using a cable system similar to bike brakes.

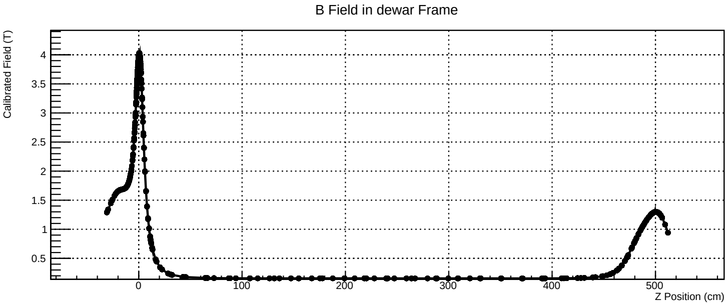
# Dewar Data



$B_z$ vs z, Main and UDet energized



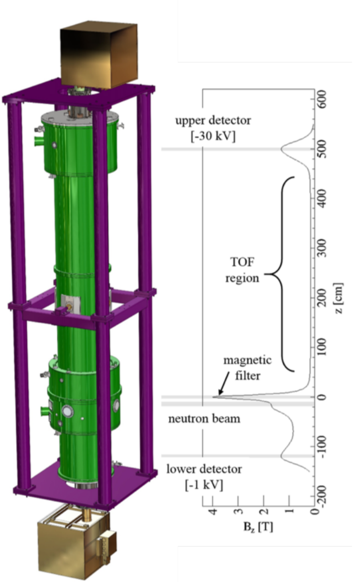
Field of Rotation Scan



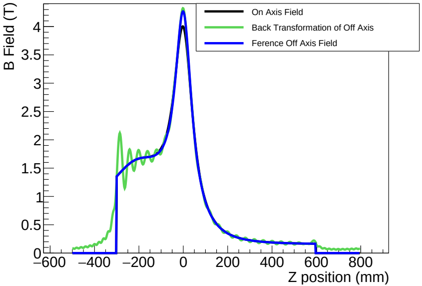
B Field in dewar Frame

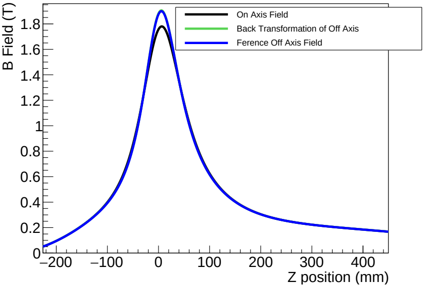
# Mapping the Field: Analysis Challenges

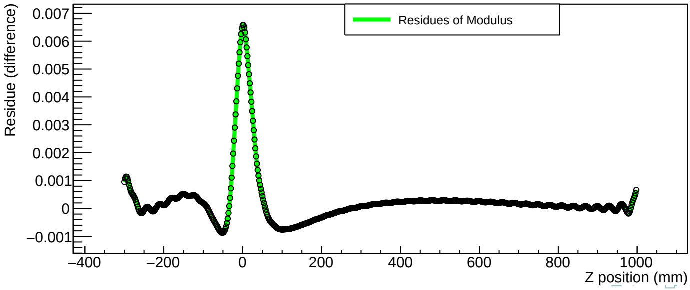
- We need to **use the data to find a full field expansion** from the on axis data.
- We must **find the magnetic field axis**, not the mechanical axis of the magnet can.



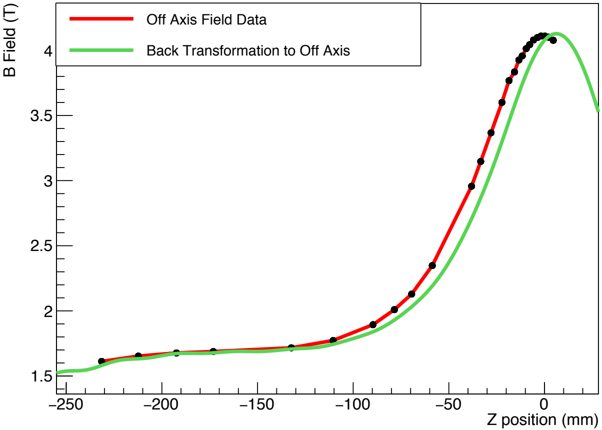
# Theoretical Off Axis Expansion


A trimmed FFT with Hann Windowing


A trimmed FFT with Hann Windowing

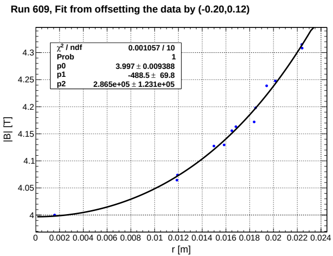

Residue between the FFT and Theoretical Data

# Off Axis Expansion of Real Data



Performing the off axis expansion shows that there is some discrepancy between the expected off axis field and the measured field.

# Finding the Magnetic Field Axis



**We have two agreeing methods for determining the magnetic axis!**

- Radial: $(-0.21 \pm 0.03, 0.12 \pm 0.02)$ cm
- Bessel: $(-0.186 \pm 0.007, 0.105 \pm 0.007)$ cm

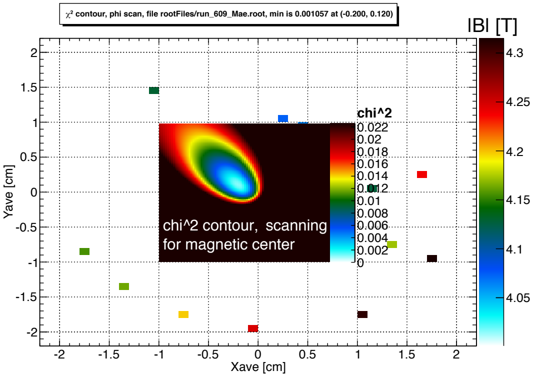
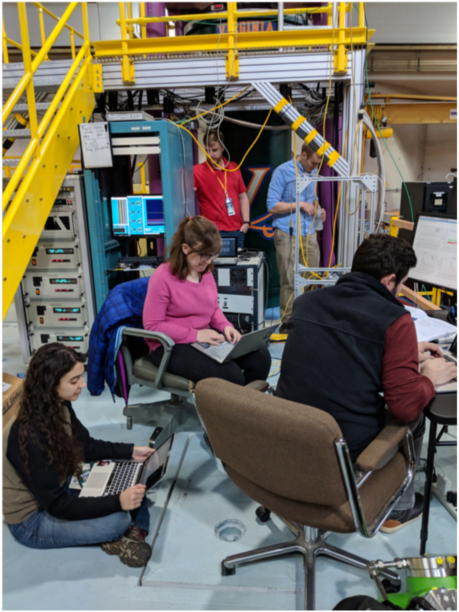
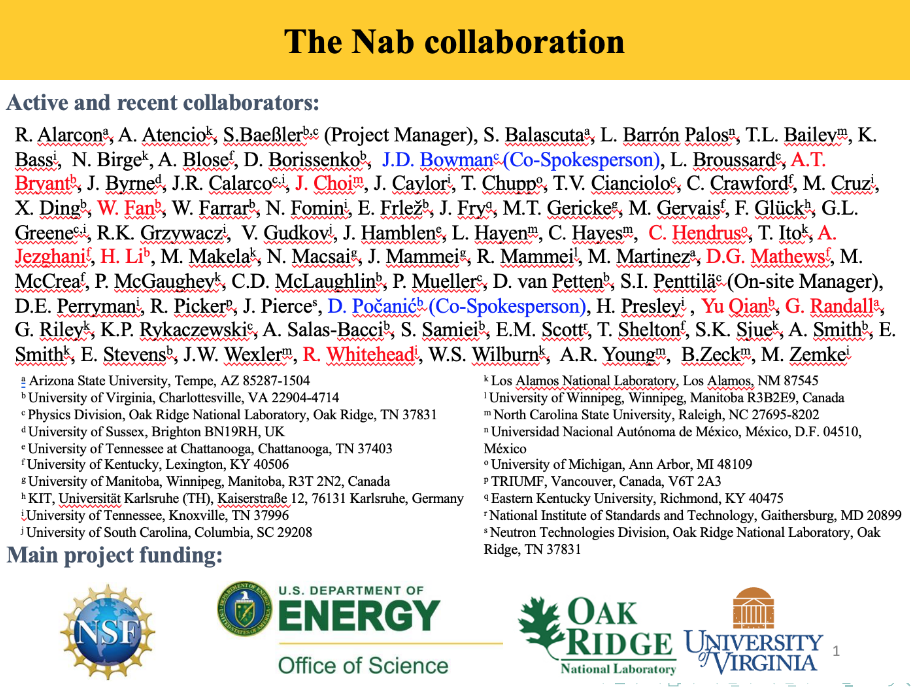


Figure: Courtesty of J.Fry

# Conclusions and Future Work



- We have a method for expanding the field from on axis data that is good to $10^{-2}$
- We also have two agreeing independent methods for determining the magnetic axis from the filter region.
- Analysis of data to find offset in other parts of the field is in progress.



# The Nab collaboration

## Active and recent collaborators:

R. Alarcon[a], A. Atencio[k], S.Baeßler[b,c] (Project Manager), S. Balascuta[a], L. Barrón Palos[n], T.L. Bailey[m], K. Bass[i], N. Birge[k], A. Blose[f], D. Borissenko[b], J.D. Bowman[c] (Co-Spokesperson), L. Broussard[c], A.T. Bryant[b], J. Byrne[d], J.R. Calarco[c,i], J. Choi[m], J. Caylor[i], T. Chupp[o], T.V. Cianciolo[c], C. Crawford[f], M. Cruz[i], X. Ding[b], W. Fan[b], W. Farrar[b], N. Fomin[i], E. Frlež[b], J. Fry[q], M.T. Gericke[g], M. Gervais[f], F. Glück[h], G.L. Greene[c,i], R.K. Grzywacz[i], V. Gudkov[j], J. Hamblen[e], L. Hayen[m], C. Hayes[m], C. Hendrus[o], T. Ito[k], A. Jezghani[f], H. Li[b], M. Makela[k], N. Macsai[g], J. Mammei[g], R. Mammei[l], M. Martinez[a], D.G. Mathews[f], M. McCrea[f], P. McGaughey[k], C.D. McLaughlin[b], P. Mueller[c], D. van Petten[b], S.I. Penttilä[c] (On-site Manager), D.E. Perryman[i], R. Picker[p], J. Pierce[s], D. Počanić[b] (Co-Spokesperson), H. Presley[i] , Yu Qian[b], G. Randall[a], G. Riley[k], K.P. Rykaczewski[c], A. Salas-Bacci[b], S. Samiei[b], E.M. Scott[r], T. Shelton[f], S.K. Sjue[k], A. Smith[b], E. Smith[k], E. Stevens[b], J.W. Wexler[m], R. Whitehead[i], W.S. Wilburn[k], A.R. Young[m], B.Zeck[m], M. Zemke[i]

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## Main project funding:

1

# Thank you for Listening

Any Questions?

CRYOGENIC

ACTIVELY SHIELDED NAB SPECTROMETER

THE LARGEST CRYOGEN-FREE SYSTEM IN THE WORLD

- Used to make precision neutron decay measurements and test the weak interaction in the Standard Model of particle physics.
- The results will provide important inputs for astrophysical processes.
- Key measurements will be of the electron-neutrino correlation parameter, and the Fierz interference term in neutron beta decay.

**Key Features:**

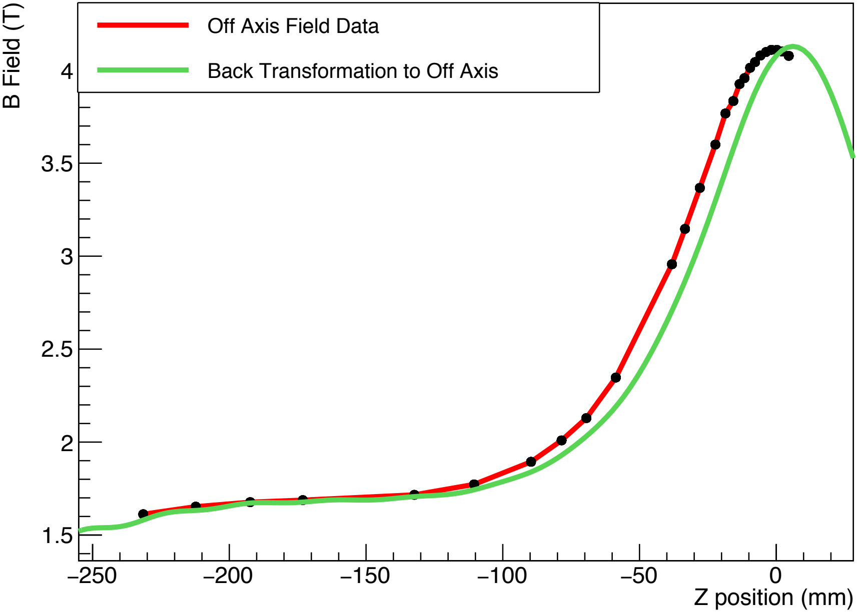
- Detector is housed in a cryogen-free magnet system 7.5 m long and ø1.4 m.
- Magnet cold mass > 1 tonne, cooled by four Gifford McMahon cryocoolers.

Bz, Field along magnet axis

www.cryogenic.co.uk

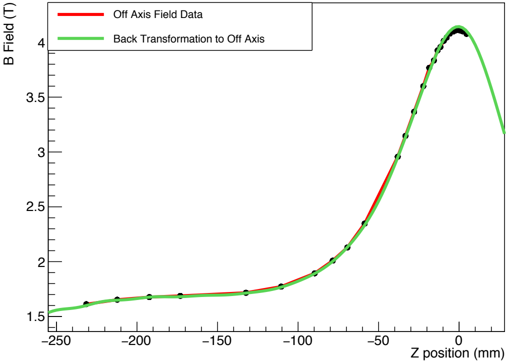
## Bonus Slides

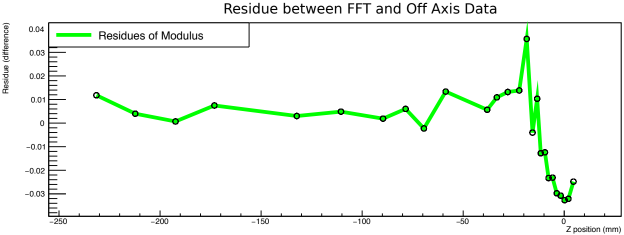
# Off Axis Expansion of Real Data



# Off Axis Expansion of Real Data

If the off axis data is shifted by 8mm...





# Solution: Expansion of Field using Modified Bessel Functions

The interior of the spectrometer is free of current and can be modeled as a solution to Laplace's equation:

$$\vec{H} = -\nabla\Phi \rightarrow \nabla^2\Phi = 0$$

Assuming cylindrical symmetry, this is separable into radial and axial variables.

$$\frac{\partial^2 Z}{\partial z^2} = -k^2 Z \quad \rightarrow \quad Z(z) = a_1 \sin(kz) + a_2 \cos(kz)$$

$$\rho^2 \frac{\partial^2 R}{\partial \rho^2} + \rho \frac{\partial R}{\partial \rho} - k^2 \rho^2 R = 0 \quad \rightarrow \quad R(\rho) = b_1 I_0(k\rho) + b_2 K_0(k\rho)$$

# Solution: Expansion of Field using Modified Bessel Functions

## Bessel Function Expansion

$$B_z(\rho, z) = \frac{\delta \Phi}{\delta z} = \sum_{-\infty}^{\infty} ikI_0(k\rho) f_k e^{ikz}$$

$$B_\rho(\rho, z) = \frac{\delta \Phi}{\delta \rho} = \sum_{-\infty}^{\infty} kI_1(k\rho) f_k e^{ikz}$$

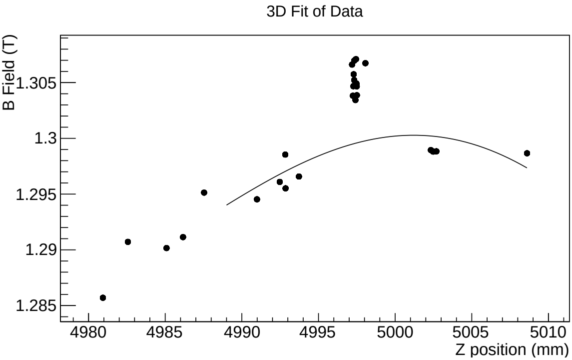
At $\rho = 0$, the $B_z$ reduces to a Fourier series. If the transform is discretized as $k = 2\pi n/L$, $z = m\delta z$, and $L = N\delta z$

$$F[n] = \frac{1}{N} \sum_{m=0}^{N-1} B[m] e^{-i2\pi nm/N}$$

$$F_z[n] = I_0(\frac{2\pi n\rho}{L}) F[n] \rightarrow \quad B_z[m] = \sum_{n=0}^{N-1} F_z[n] e^{i2\pi nm/N}$$

$$F_\rho[n] = -iI_1(\frac{2\pi n\rho}{L}) F[n] \rightarrow \quad B_\rho[m] = \sum_{n=0}^{N-1} -F_\rho[n] e^{i2\pi nm/N}$$

# The data is not as good for fitting the upper detector...



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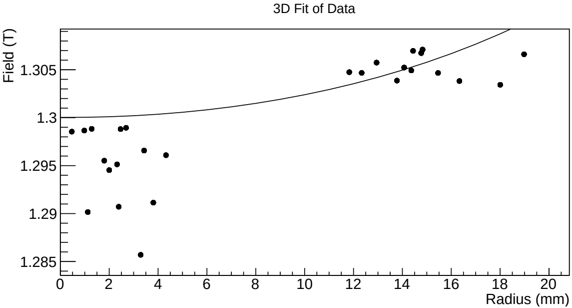
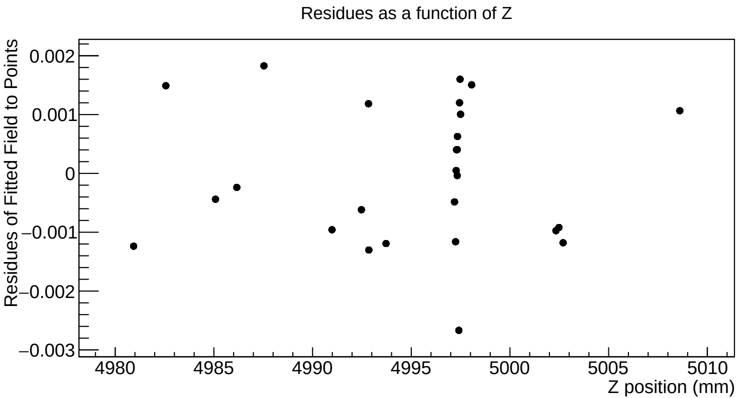


# The data is not as good for fitting the upper detector...



This 3 dimensional fit determined that the offset in x and y is $(0.299 \pm 1.79, -2.665 \pm 2.17)$ mm.

# Solution: Mapping the Field and Testing for Cylindrical Symmetry

By expanding the field in terms of sine and cosine, we can have a fit function with $2n+1$ parameters, consisting of the Fourier coefficients and the offset in x and y.

$$B_{mod}(z) = \sqrt{B_z^2 + B_\rho^2}$$

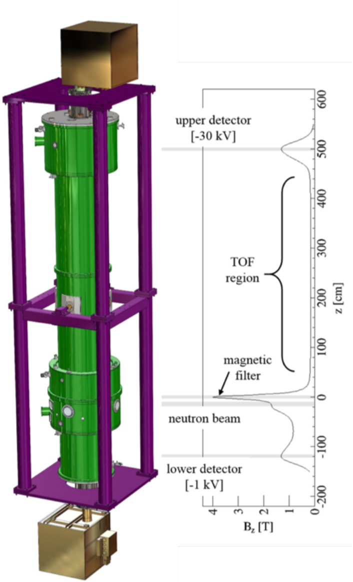
$$B_z(z) = \sum_{n=0} I_0(2\pi n\rho/L)\Big[C[n]\cos(2\pi nz/L) - D[n]\sin(2\pi nz/L)\Big]$$

$$B_\rho(z) = \sum_{n=0} I_1(2\pi n\rho/L)\Big[C[n]\sin(2\pi nz/L) + D[n]\cos(2\pi nz/L)\Big]$$

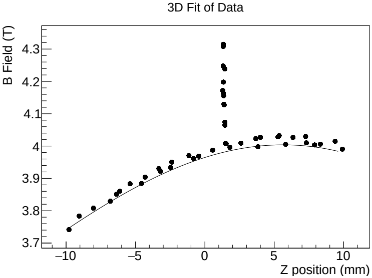
Choosing a sufficiently large L will restrict high wavenumber effects. This is optimized manually.

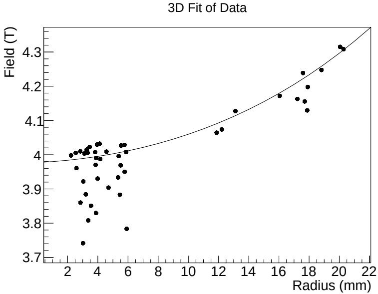
# Mapping the Field: Analysis Challenge 2

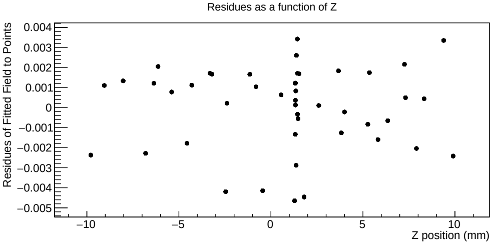
- The spectrometer magnet is a series of solenoids.
- It is possible that the coils are offset from the physical flanges of the magnet.



# Solution: Mapping the Field and Testing for Cylindrical Symmetry

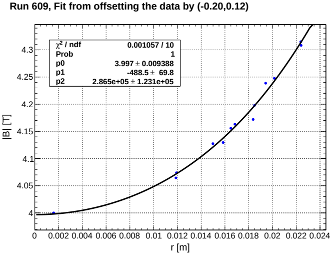






This 3 dimensional fit determined that the offset in x and y is $(-1.86 \pm .07, 1.05 \pm 0.07)$ mm.

# Solution: Mapping the Field and Testing for Cylindrical Symmetry



**This agrees with the radial series fit of the magnetic axis!**

- Radial: $(-0.21 \pm 0.03, 0.12 \pm 0.02)$ cm
- Bessel: $(-0.186 \pm 0.007, 0.105 \pm 0.007)$ cm

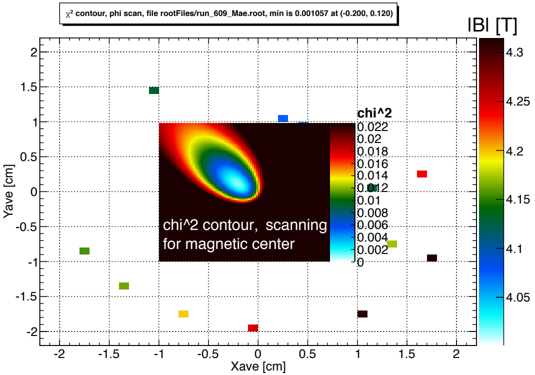
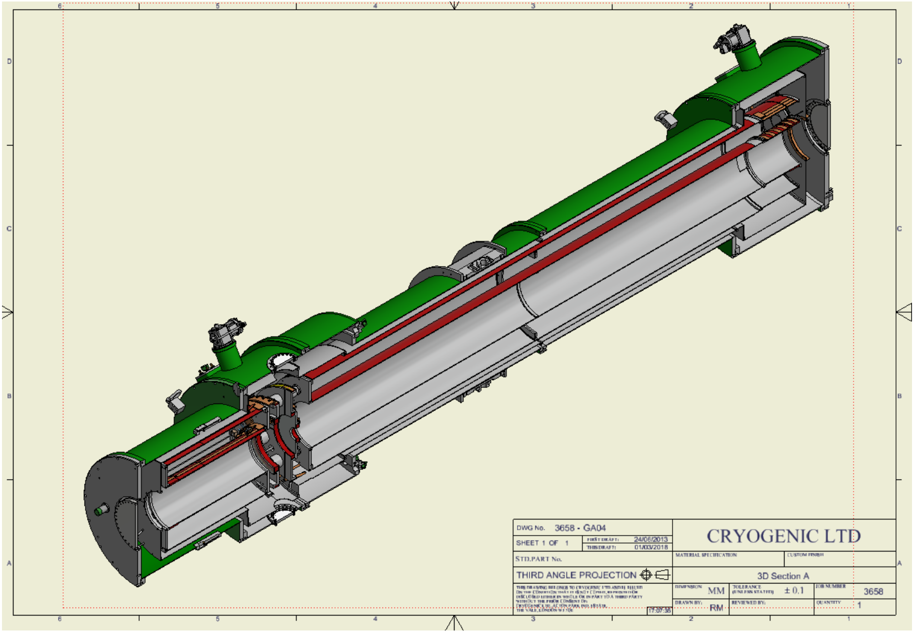


Figure: Courtesty of J.Fry



DWG No. 3658 - GA04

SHEET 1 OF 1

FIRST DRAFT: 24/06/2013

THIS DRAFT: 01/03/2018

STD.PART No.

THIRD ANGLE PROJECTION

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