Fermilab

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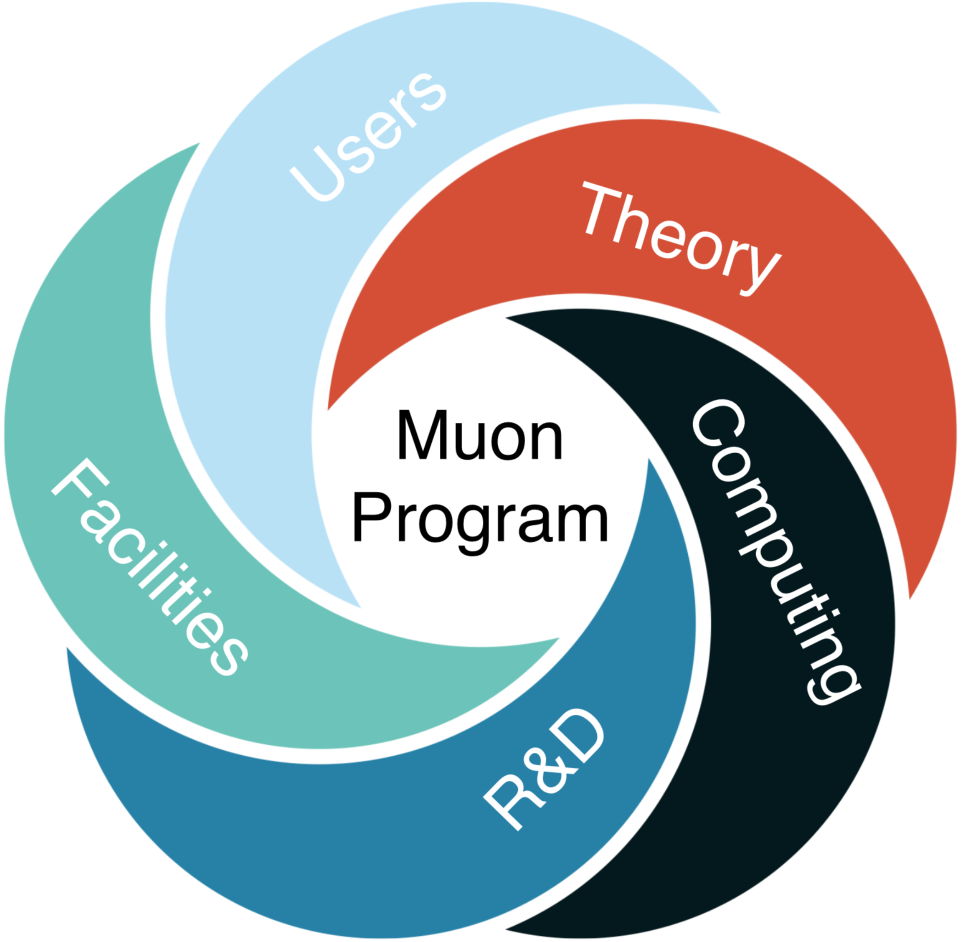
Muon g-2 Scientific Highlights

Brendan Kiburg
Particle Physics Division
Fermilab Institutional Review
12 February 2015

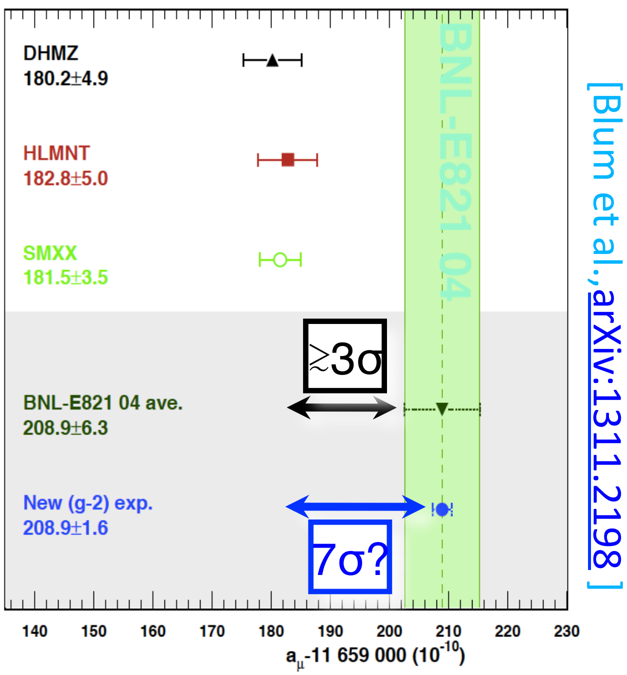
Overview

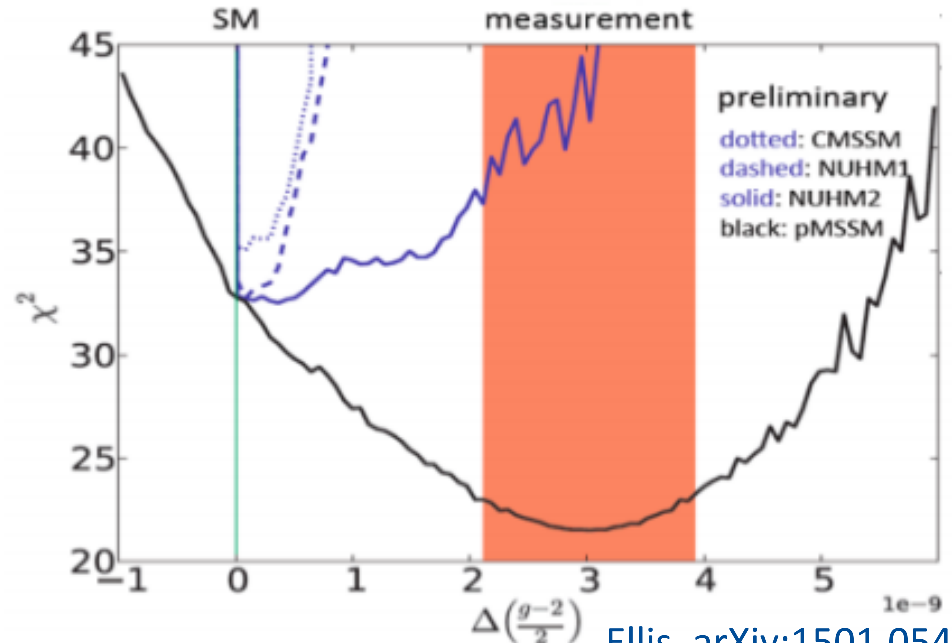
- Motivation, Technique, Goals
- Community: Theory, Experiment, Collaboration
- Recent Highlights: Theory, R&D, Commissioning
- Analysis Preparations: Field



Muon g-2 : Motivation

- The discrepancy between muon g-2 calculations and measurement hints at potential new physics





Ellis. arXiv:1501.05418v1

Post-LHC-Run 1 phase space that can accommodate a_μ

Precision measurement potentially sensitive to new physics at high energies or dark matter

LHC ←→ a_μ Interplay

1 or 2 Field Extensions of SM

Studied models constrained by 8 TeV run or within reach of 14 TeV run

Scenario	Production	LHC8	LHC14
$V^\pm$	$pp \to V^+V^-$	$M_V > 398$ GeV	$M_V > 676$ GeV
$\phi^0 + \psi^\pm$	$M_\psi < M_\phi$: $pp \to \psi^+\psi^-$ $M_\psi > M_\phi$: $pp \to \psi^+\psi^- \to \ell^+\phi^0\,\ell^-\phi^0$	– ×	× ×
$\phi^0 + \psi_D$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$ $M_\psi > M_\phi$: $pp \to \psi^+\psi^- \to \ell^+\phi^0\,\ell^-\phi^0$	× ×	× ×
$\phi_D + \psi^\pm$	$M_\psi < M_\phi$: $pp \to \psi^+\psi^-$ $M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	– ×	× ×
$\phi_D + \psi_A$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$ $M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	× ×	× ×
$\phi_D + \psi_T$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$ $M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	$M_\psi > 258$ GeV $M_\phi > 380$ GeV	$M_\psi > 420$ GeV ×
$\phi_A + \psi_T$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$ $M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	$M_\psi > 258$ GeV ×	× ×
$V^\pm + \psi^0$	$M_V < M_\psi$: $pp \to V^+V^-$ $M_V > M_\psi$: $pp \to V^+V^- \to \ell^+\psi^0\,\ell^-\psi^0$	$M_V > 398$ GeV $M_V > 373$ GeV	$M_V > 676$ GeV $M_V > 716$ GeV
$V^\pm + \psi_D$	$M_V < M_\psi$: $pp \to V^+V^-$ $M_V > M_\psi$: $pp \to V^+V^- \to \ell^+\psi^0\,\ell^-\psi^0$	$M_V > 398$ GeV $M_V > 476$ GeV	$M_V > 676$ GeV $M_V > 903$ GeV
$V_A + \psi_D$	$M_V < M_\psi$: $pp \to V^+V^-$ $M_V > M_\psi$: $pp \to \psi^\pm\psi^0$	$M_V > 398$ GeV $M_\psi > 296$ GeV	× ×

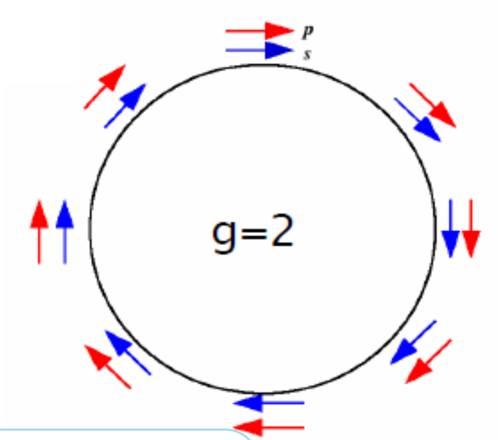
Decay			
Decay	$\phi^0 \to \ell^+\ell^-$ $\phi^\pm \to \ell^\pm\nu$	$V^0 \to \ell^+\ell^-$ $V^\pm \to \ell^\pm\nu$	$\psi^0 \to \nu Z,\ \nu H,\ \ell^\pm W^\mp$ $\psi^\pm \to \ell^\pm Z,\ \ell^\pm H,\ \nu W^\pm$

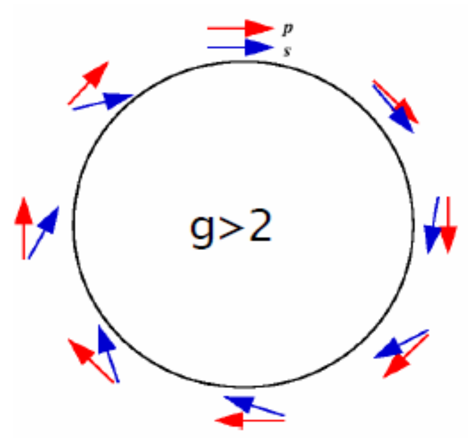
Table 2: LHC production (top) and typical decay process (bottom) for the new particles in the one- and two-field scenarios that can explain the muon magnetic moment anomaly. Cases that are excluded at two sigma by 8-TeV LHC data or can be probed conclusively at 14 TeV are marked by a cross. Wherever the two-sigma range of Δa_μ is not fully covered, we display the lower mass bounds as obtained from the analyses described in the text.

Freitas et al. arXiv:1402.7065v3
Sep 2014
(Joe Lykken)

Experiment Basics: Muons in a storage ring

1. Start with polarized muon beam (from pion decay)
2. Cyclotron frequency : $\omega_c = \frac{e}{m\gamma}B$
3. Spin precession frequency : $\omega_S = \frac{e}{m\gamma}B\left(1+\gamma a_\mu\right)$ Larmor + Thomas precession



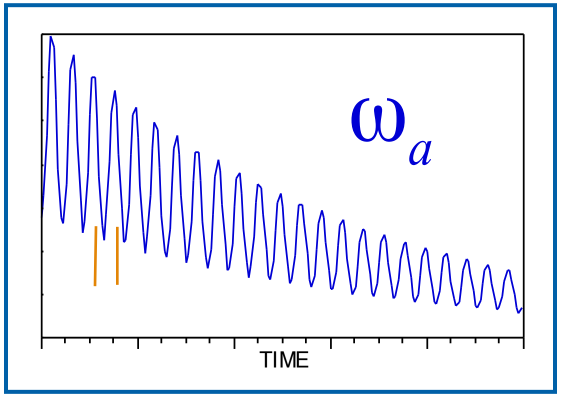


momentum

spin

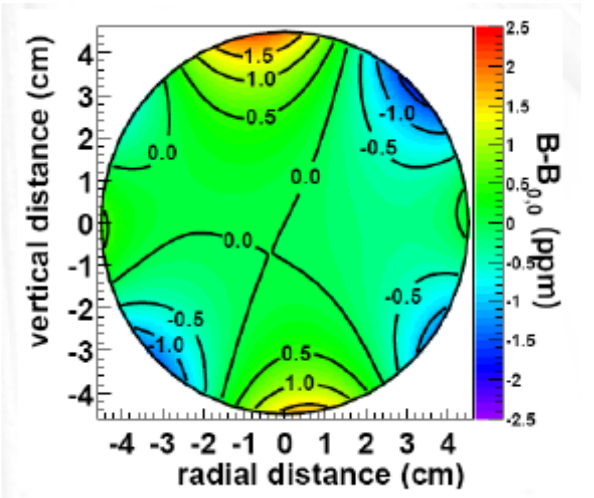
$$\omega_a = \omega_S - \omega_c = \frac{eB}{m}a_\mu$$

Muon g-2 Measurement Responsibilities



$$\omega_a = \frac{eB}{m} a_\mu$$

B field measured via NMR thus useful to write in terms of proton precession frequency

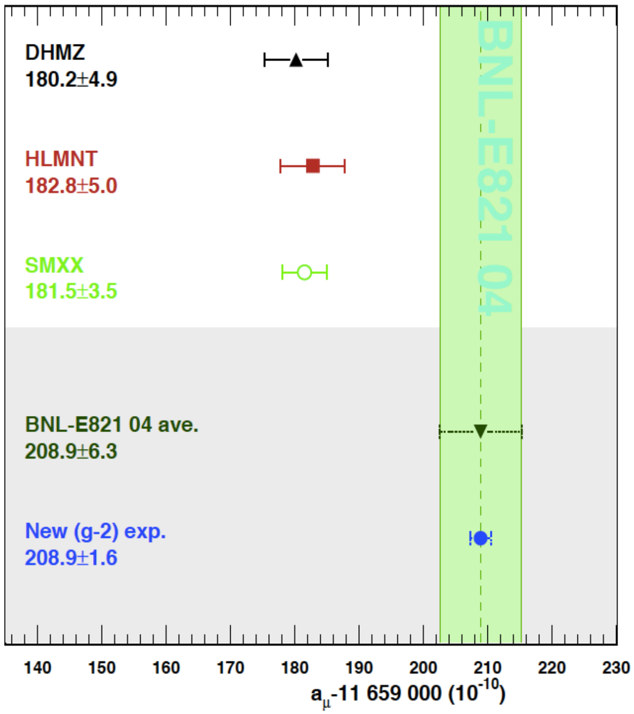


$$a_\mu = \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

8 ppb , 25 ppb, 0.3 ppb uncertainty contributions

- Measure muon precession frequency via electrons
- Measure proton precession frequency via NMR
- Measure muon distribution in the storage region (beam dynamics)

Anticipated Improvements to the g-2 Uncertainty



[Blum et al., arXiv:1311.2198]

- Must address many challenging topics in parallel as a community

Uncertainty Source	Status 2015 [ppb]	Projected after E989 [ppb]	Goal for lattice QCD [ppb]
ω_a	180	70	
ω_p	170	70	
Statistical	460	100	
Total Exp.	**540**	**140**	**140**
Had. Vac. Pol	360	215 *	100
Had LBL	225	225	100
Total Theory	**420**	**310**	**140**

* Projected error anticipating input from e+/e- BES III, VEPP2000, etc.

E989 Collaboration: 34 Institutes; 155 Members

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Russia:
- Dubna
- Novosibirsk

England
- University College London
- Liverpool
- Oxford

Korea
- KAIST

Summary of Scientific Roles - Experiment

Name	Div.	Project and Scientific Roles
Chris Polly	PPD	Project Manager, E821 Collaborator
Mary Convery	AD	Deputy Project Manager, L2 Accelerator
Brendan Casey	PPD	L2 Detector, Early Career Award for Straw Tracker
Adam Lyon	SCD	G-2 computing liaison, leads g-2 *art*-based simulation team
Mandy Rominsky *	PPD	T1042 spokesperson, L3 Tracker, developed straw prototypes
Brendan Kiburg *	PPD	L3 Field Shimming, Proton Precession Meas. Tools and Software
Tammy Walton *	PPD	Leads *art*-based tracking code team
Hogan Nguyen	PPD	L2 Ring, Ring Reassembly and Field Simulations
Emanuela Barzi	TD	Superconducting Inflector Shield R&D
Vladimir Kashikhin	TD	Superconducting Inflector Magnet Design
Erik Ramberg	PPD	Strain Gauges, Silicon Entrance Detectors
Carol Johnstone	AD	Accelerator Beamline Design
John Johnstone	AD	Accelerator Beamline Design

* Postdoc

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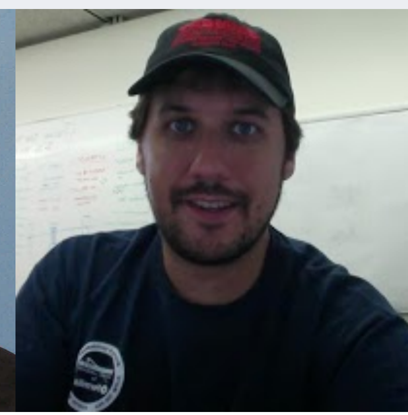
Hogan Nguyen	PPD	L2 R
Emanuela Barzi	TD	Supe
Vladimir Kashikhin	TD	Supe
Erik Ramberg	PPD	Strai
Carol Johnstone	AD	Acce
John Johnstone	AD	Acce


* Postdocs (pictured)

Summary of Scientific Roles - Theory

Name	Project and Scientific Roles
Ruth Van de Water	(with HPQCD & MILC) now undertaking first complete four-flavor lattice-QCD calculation of the hadronic vacuum polarization term
Andreas Kronfeld	
Paul Mackenzie	
Ran Zhou *	Central to hadronic light-by-light calculation innovations
Prateek Agrawal *	Investigating connections between muon g-2 and leptophilic dark matter in simplified models. Investigating simplified models connecting muon g-2 and Higgs Sector
Fady Bishara **	Investigating simplified models connecting muon g-2 and Higgs Sector
Felix Yu * (→ Mainz)	

USQCD US Lattice Quantum Chromodynamics

Lattice QCD Meets Experiment 2014

Fermilab

March 7-8, 2014

* Postdoc ** Graduate Student Fellow

- Leadership role for charged lepton groups in Snowmass
- Organizing important lattice workshops to connect with experiment

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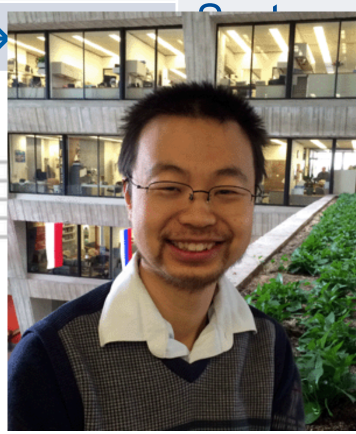
USQCD




n

connect with experiment

* Postdoc ** Graduate Student Fellow (pictured)

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Recent Highlights

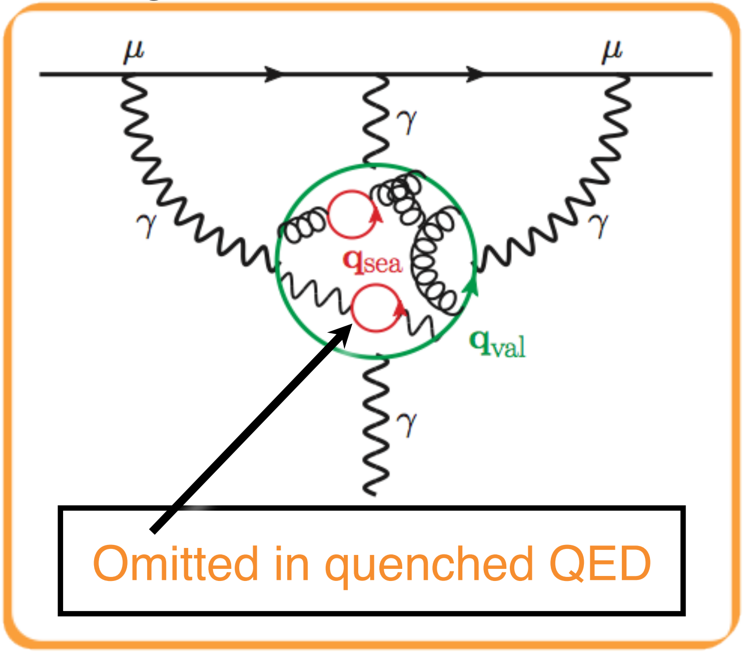
Recent Highlights: Hadronic Vacuum Polarization

- Current status: a_μ^{HVP} = 6949 (43) x 10^{-11} [0.6 %]
- Projected w/ e+/e- updates = 6949 (26) x 10^{-11} [0.4 %] [Blum et al., arXiv:1311.2198]
- Lattice QCD δa_μ^{HVP} Roadmap
  - Currently ~5% → 1% next several years→ 0.2% goal

- Fermilab Lattice Theorists now undertaking first complete four-flavor lattice-QCD calculation of a_μ^{HVP}
  - Higher-precision new methods
  - Anticipate determining a_μ^{HVP} to 1% or better with existing four-flavor ensembles in the next few years
  - Goal precision requires the direct inclusion of isospin-breaking and EM effects

Recent Highlights: Hadronic Light-by-Light

- Current status: a_μ^{HLbL} = 105(26) [25 % or 225 ppb]
- Must be obtained from theory, as the current error estimate from QCD models is subjective and not systematically improvable
- Reduction of theory uncertainty to 10-15% would match exp. goals
- Fermilab Lattice Theorists are devising and testing methods for HLbL
  - Significant human effort and computing resources are required **
  - Innovative approach uses new QED +QCD gauge-field ensembles that include dynamical quarks, gluons, and photons to calculate contributions omitted from all previous efforts
  - Premature to give quantitative error projection timeline, but will sustain effort until the needed precision is reached



** Van de Water submitted Early Career proposal for additional RAs and computing resources

Recent Highlight: The Big Move from BNL to FNAL

Recent Highlights: Muon Campus 1 Construction

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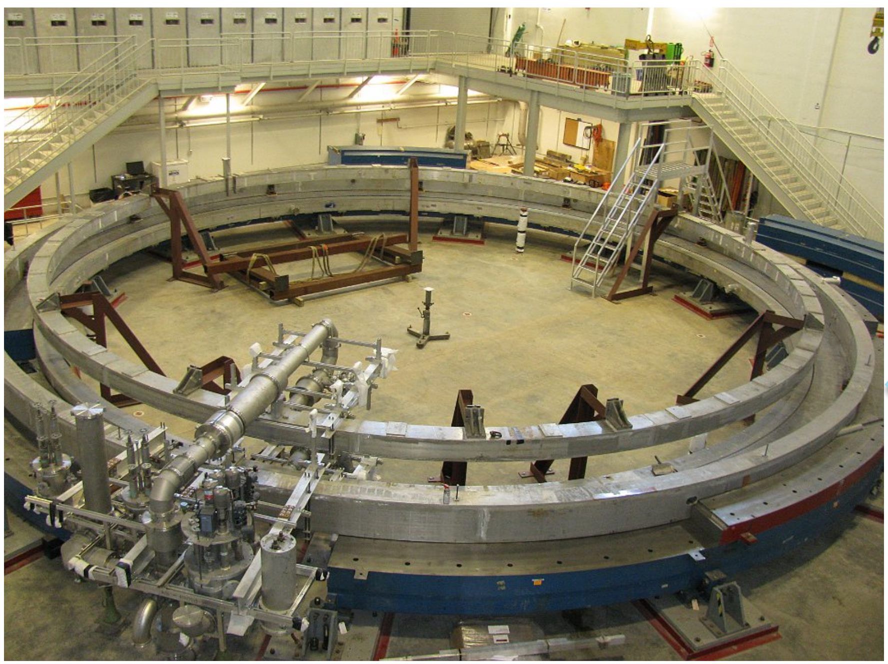
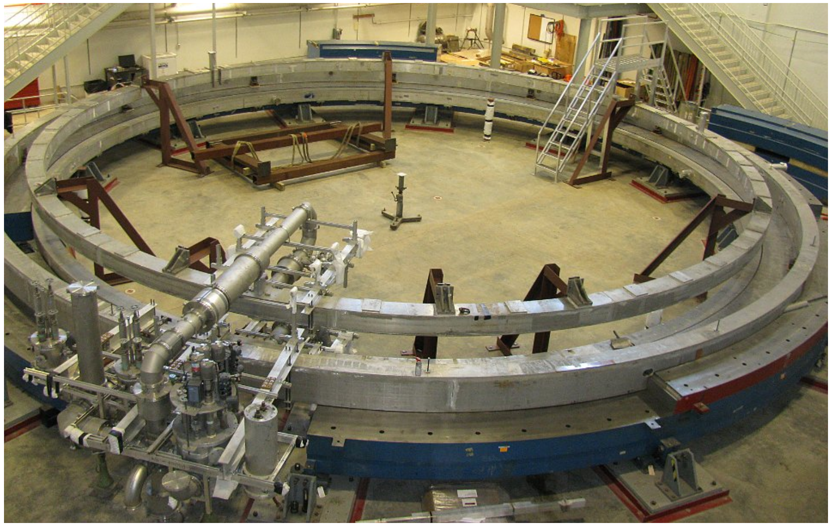
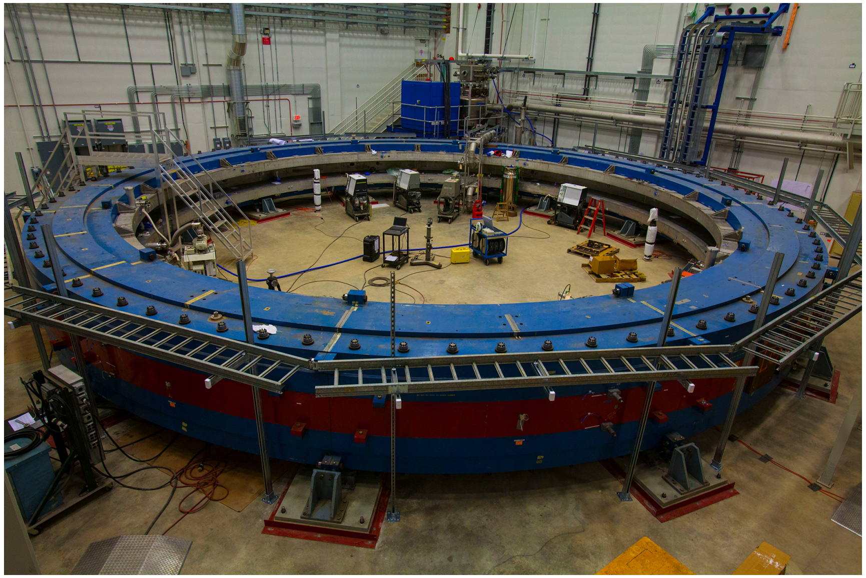
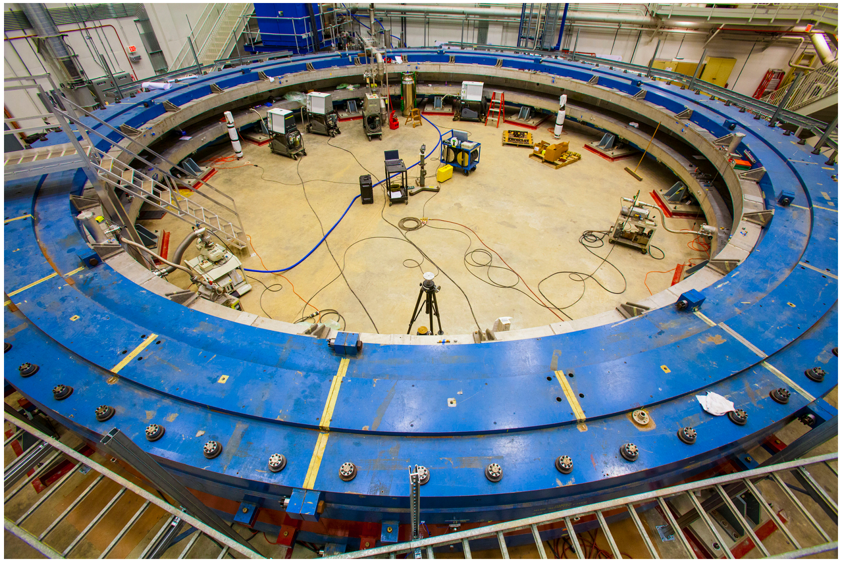
Recent Highlights : The Little Move Across Site to MC-1



Recent Highlights: Ring Reassembly







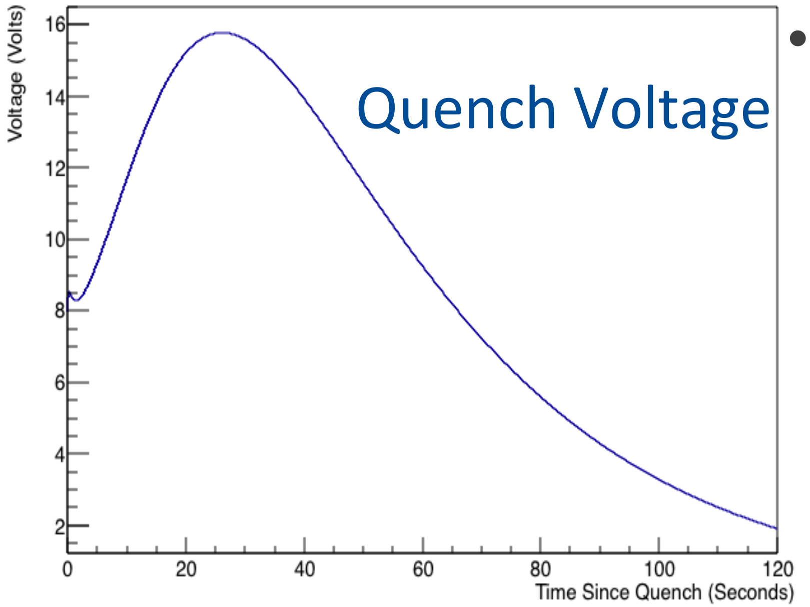
Highlights: Student Involvement

- The disassembly and reassembly provided university students the opportunity to participate in the construction of the experiment and develop a sense of ownership

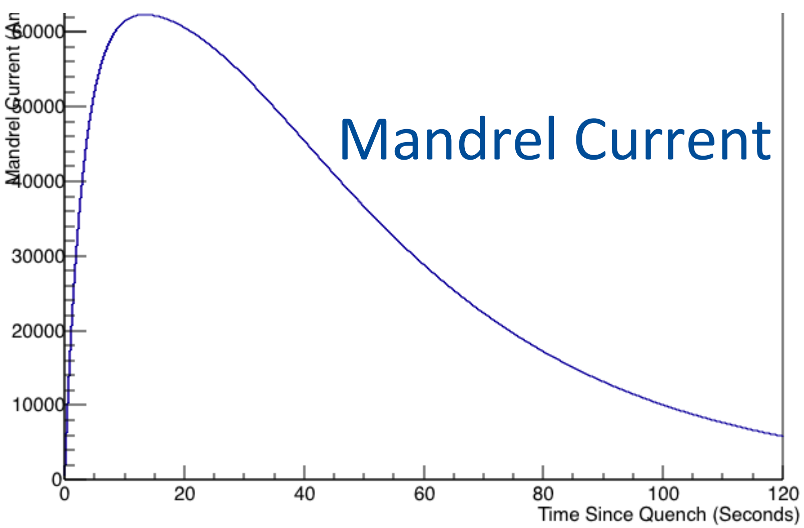
Robin Bjorkquist, Cornell & Nathan Froemming, UW, @ BNL

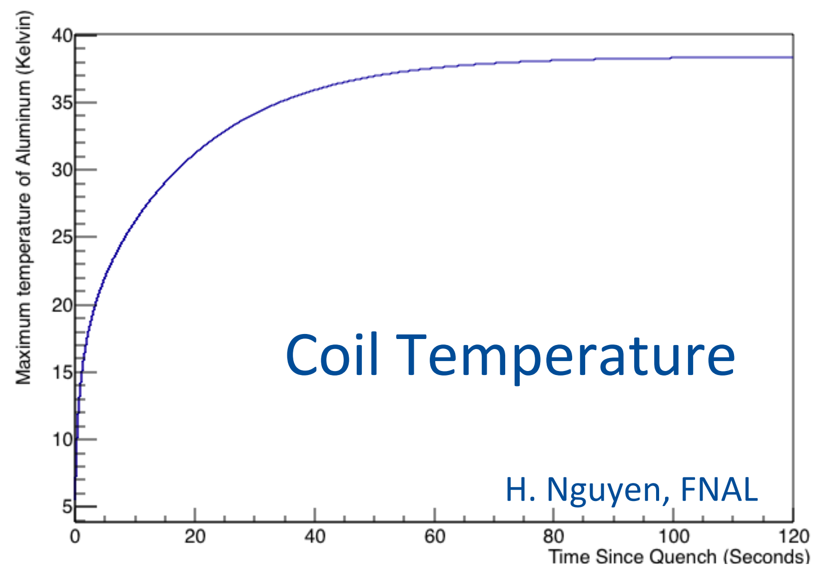
Mary Shenk, Mike McEvoy NIU @ FNAL

Recent Highlights: Storage Ring Quench Analysis



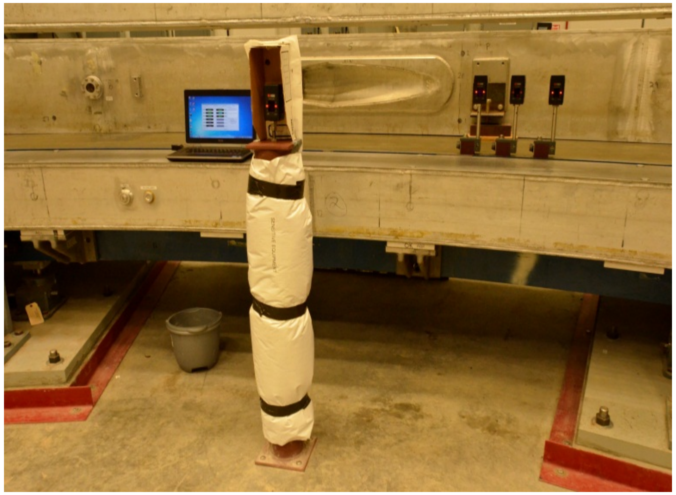
- **Enables design of proper quench protection to avoid destroying coils**
  - Reproduced E821 Studies
  - Understand time evolution of current and temperature in the coils and mandrels

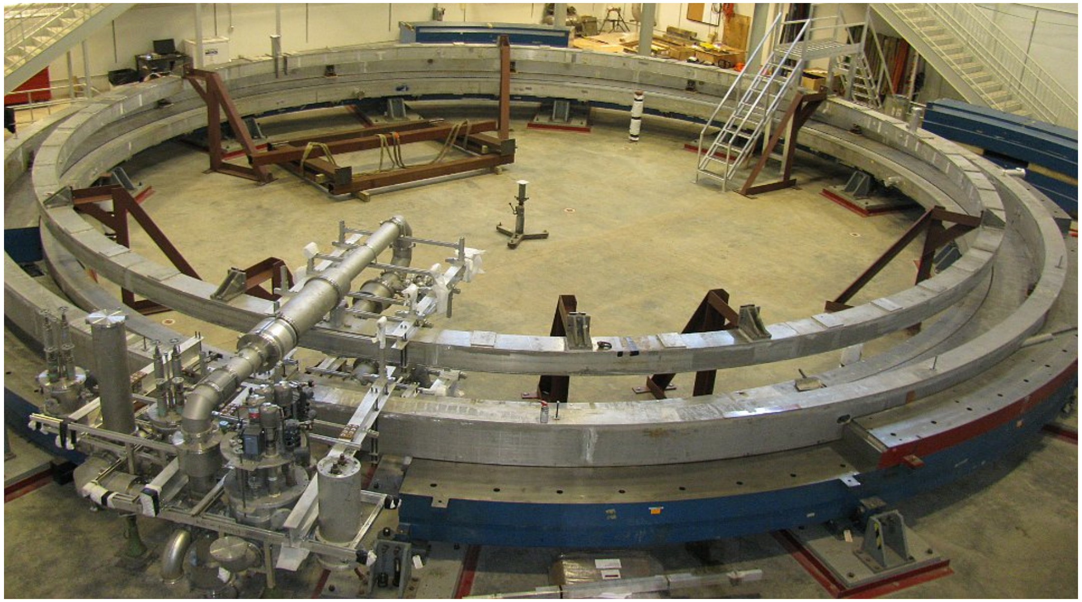




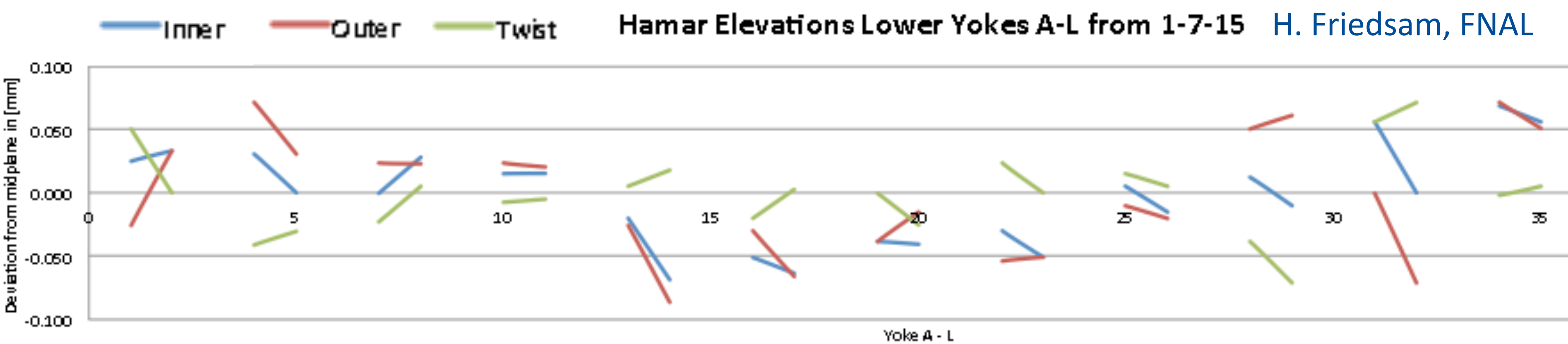
Recent Highlights: Hamar Laser Alignment of yokes, coils

- A misalignment of a pole piece by ~10 microns leads to large non-uniformities in the magnetic field. (ΔB ~100 pppm)

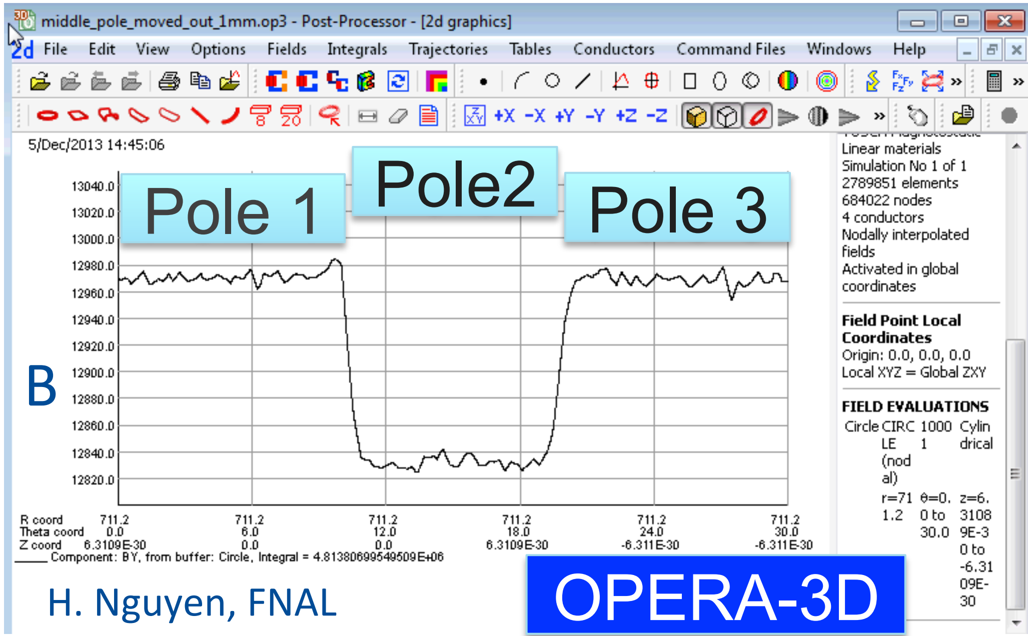




Recent Highlights: Hamar Laser Alignment of yokes, coils



- Yokes within < 100 microns of horizontal
- Fermilab Alignment Group interfacing with ANL, FNAL scientists
  - monitor stability and progress during the shimming phase

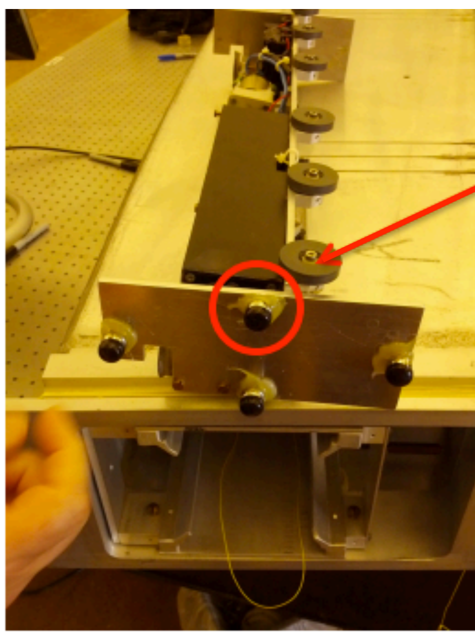


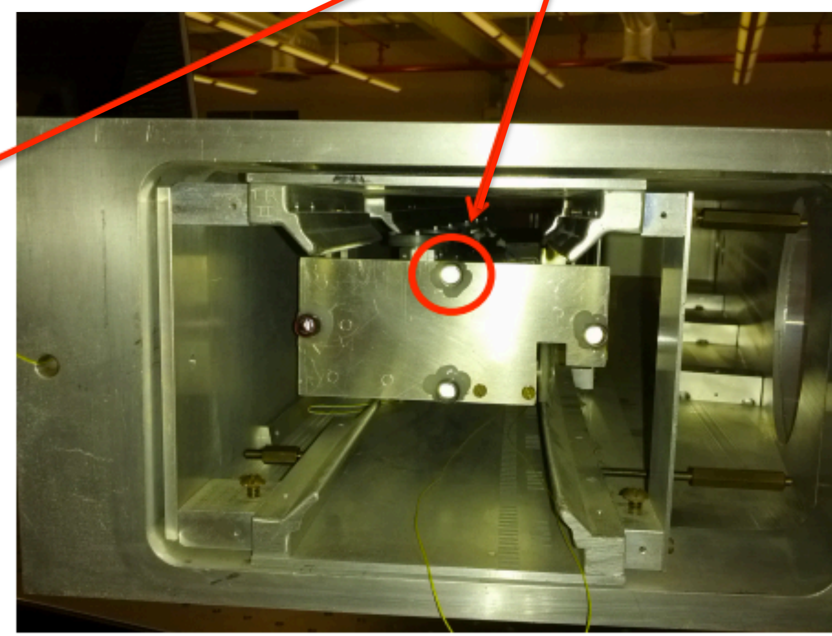
H. Nguyen, FNAL
B. Kiburg, FNAL

Recent Highlights: Vacuum Chamber Rail Alignment

- Knowledge of the NMR trolley probe position was a leading uncertainty for E821 proton precession frequency measurement.
- Thus we survey the rails before and after installation

4 reflecting spheres

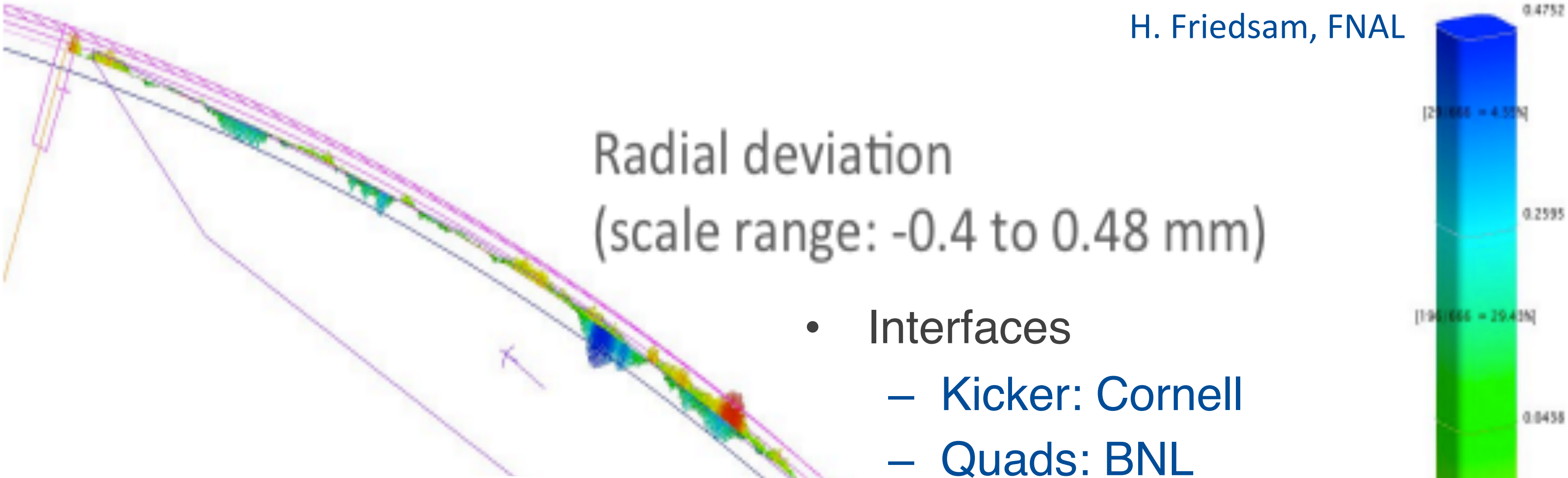


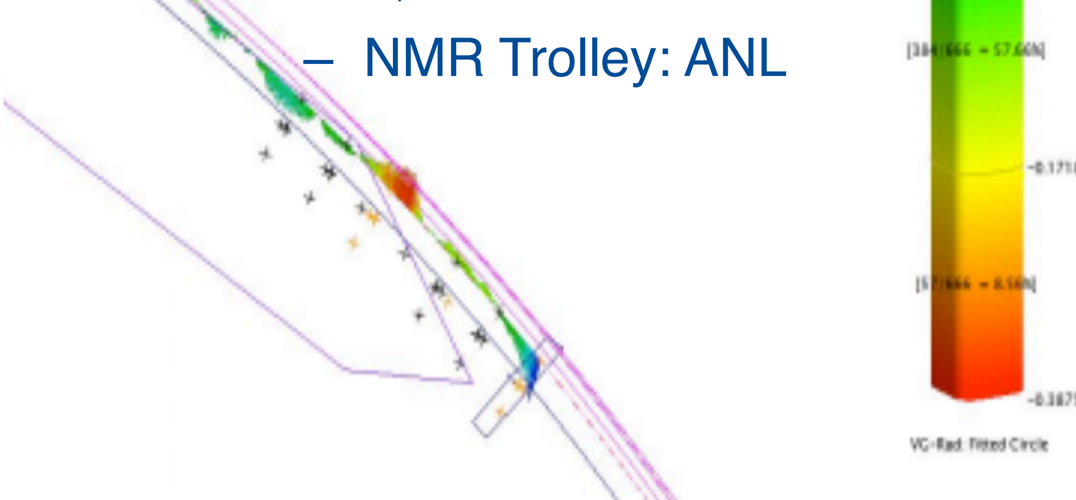


H. Friedsam, FNAL
P. Winter, ANL
J. Grange, ANL

Recent Highlights: Vacuum Chamber Rail Alignment

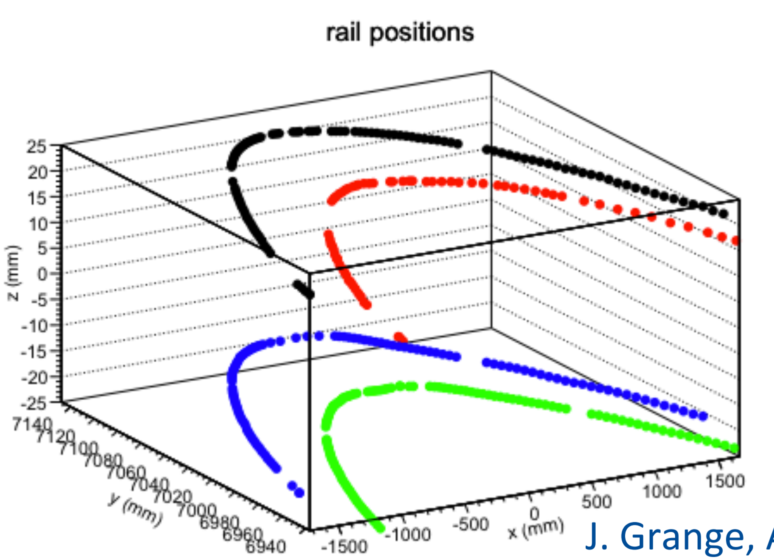
H. Friedsam, FNAL





Radial deviation
(scale range: -0.4 to 0.48 mm)

- Interfaces
  - Kicker: Cornell
  - Quads: BNL
  - NMR Trolley: ANL

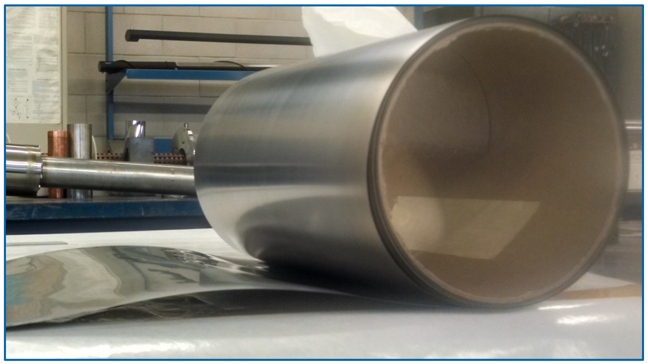


J. Grange, ANL

Recent Highlights: Superconducting Inflector Magnet

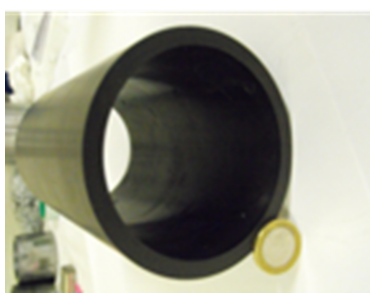
- Inflector: prevents incoming muons from deflecting in the fringe field.
- Critical object → Developing an upgrade→ Testing shield materials

2014 Luvata 100-μm-thick NbTi foil

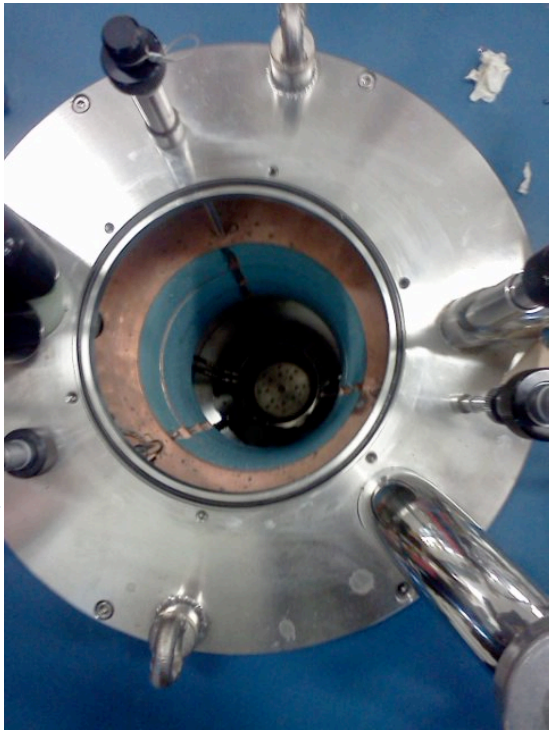


E821 shield material

Novel Bulk MgB_2

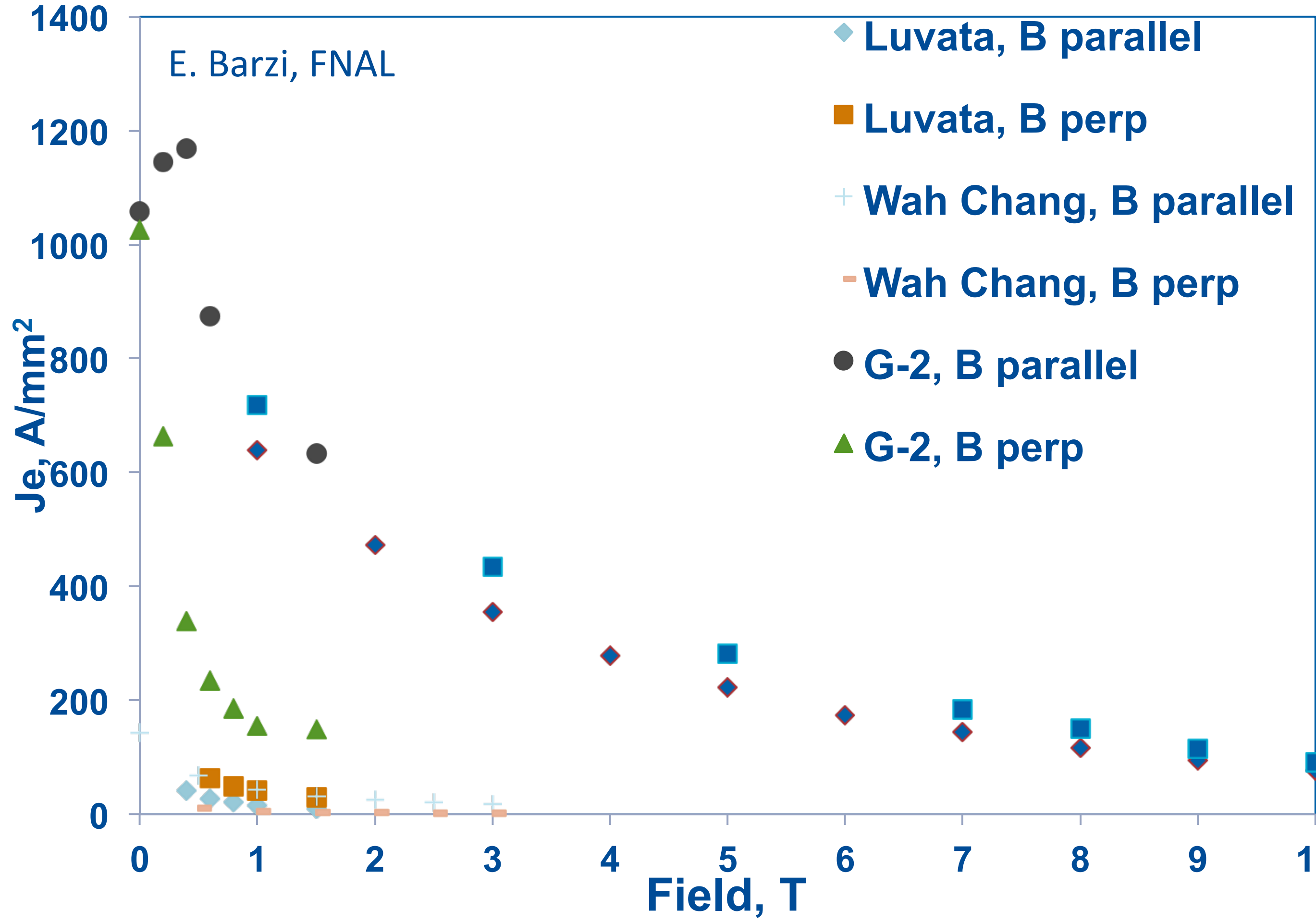


Test Shield Properties



TD “Teslatron”

Recent Highlights: Superconducting Inflector Magnet

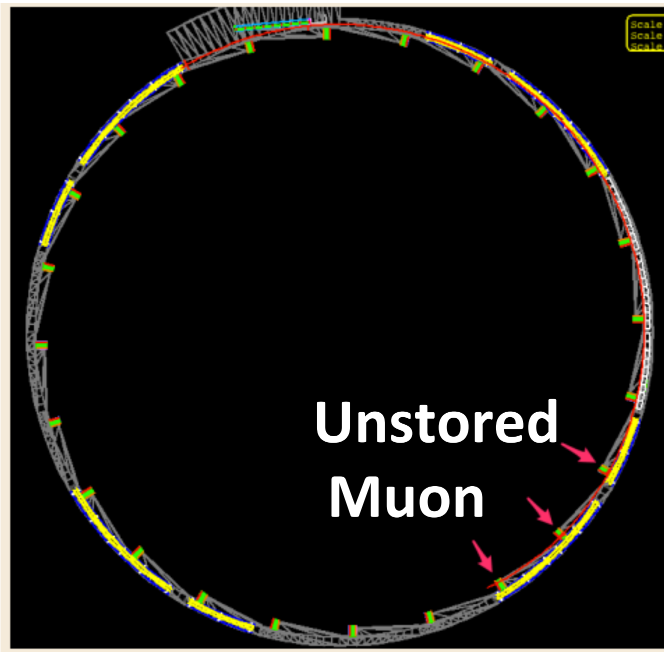


Data shown for current parallel to rolling direction, i.e. highest in the g-2 shield.R

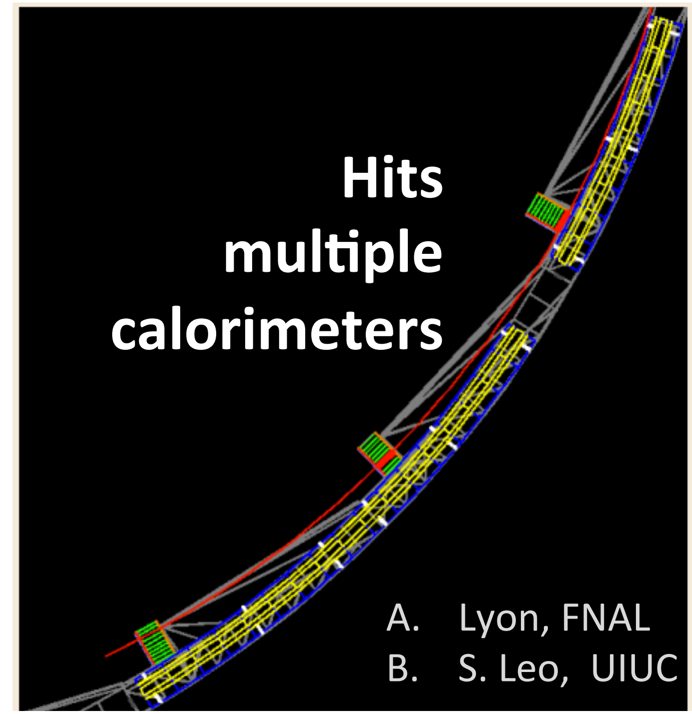
R&D effector to evaluate MgB_2 and E821 g-2 Shield Material

Recent Highlights: Lost Muons Studies

- Potential systematic error if "lost muons" have different ensemble spin



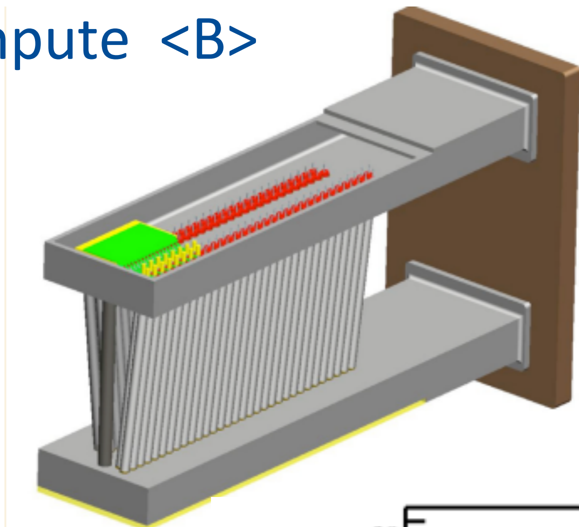
FNAL and Illinois

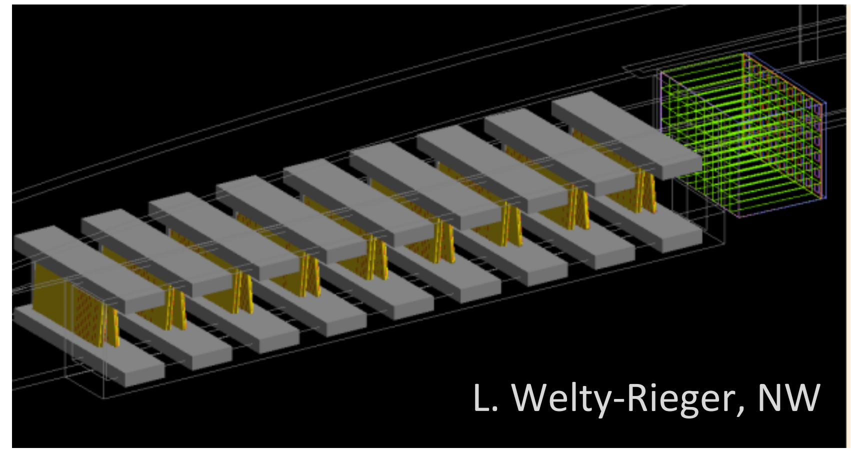


- *art*-based simulation : Adam Lyon and Harvey Mudd undergraduate Tasha Arvanitis combined the Geant-4 simulation with the *art* framework.
- Team of lab and university postdocs and students ported the code
- Weekly simulation meetings, several workshop/schools each year

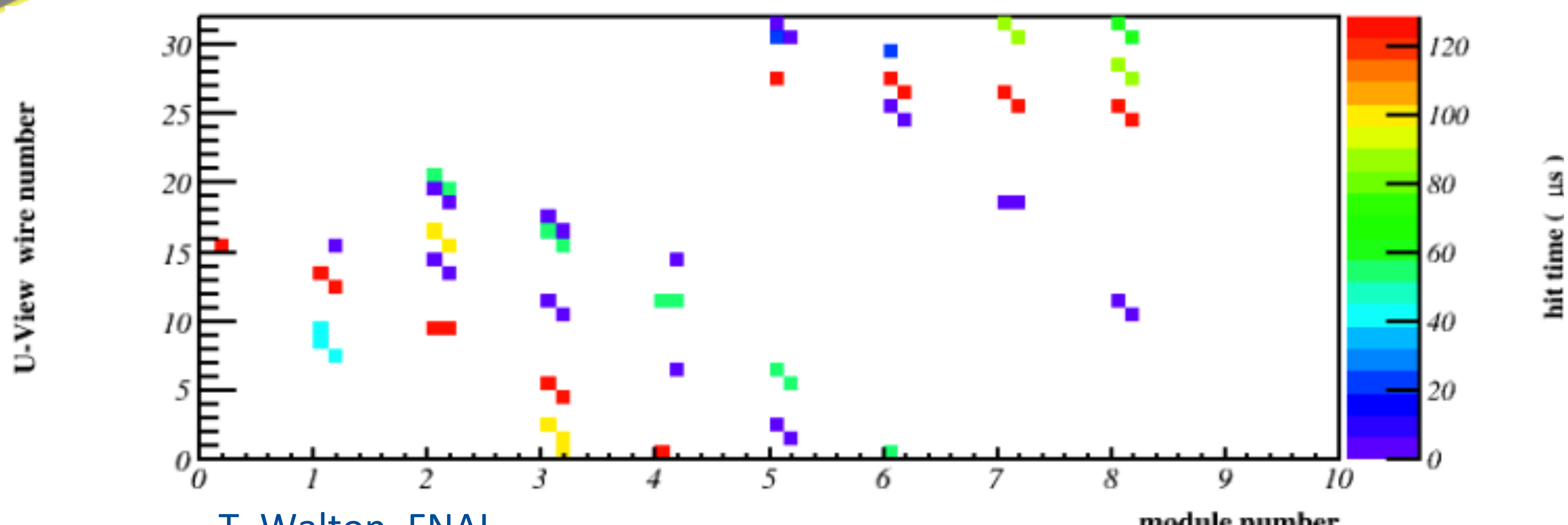
Recent Highlights: Simulating Tracker Performance

Tracker needed to understand muon beam profile so we can compute <B>





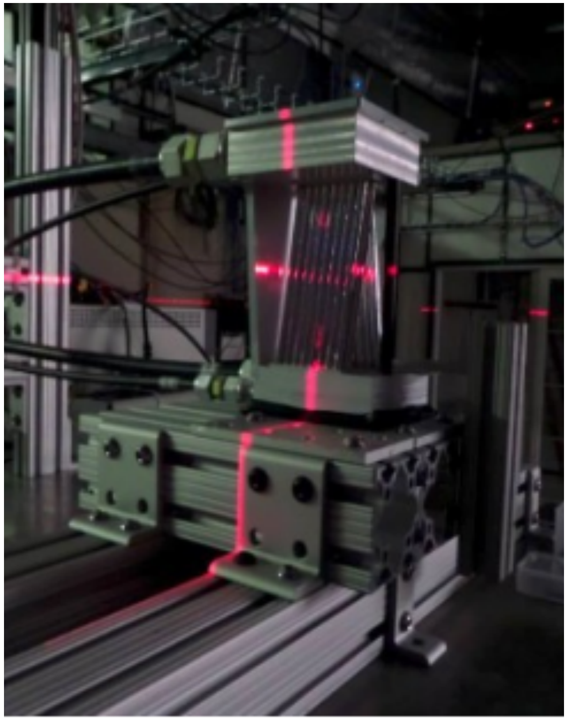
art-based simulation FNAL,NW, UCL

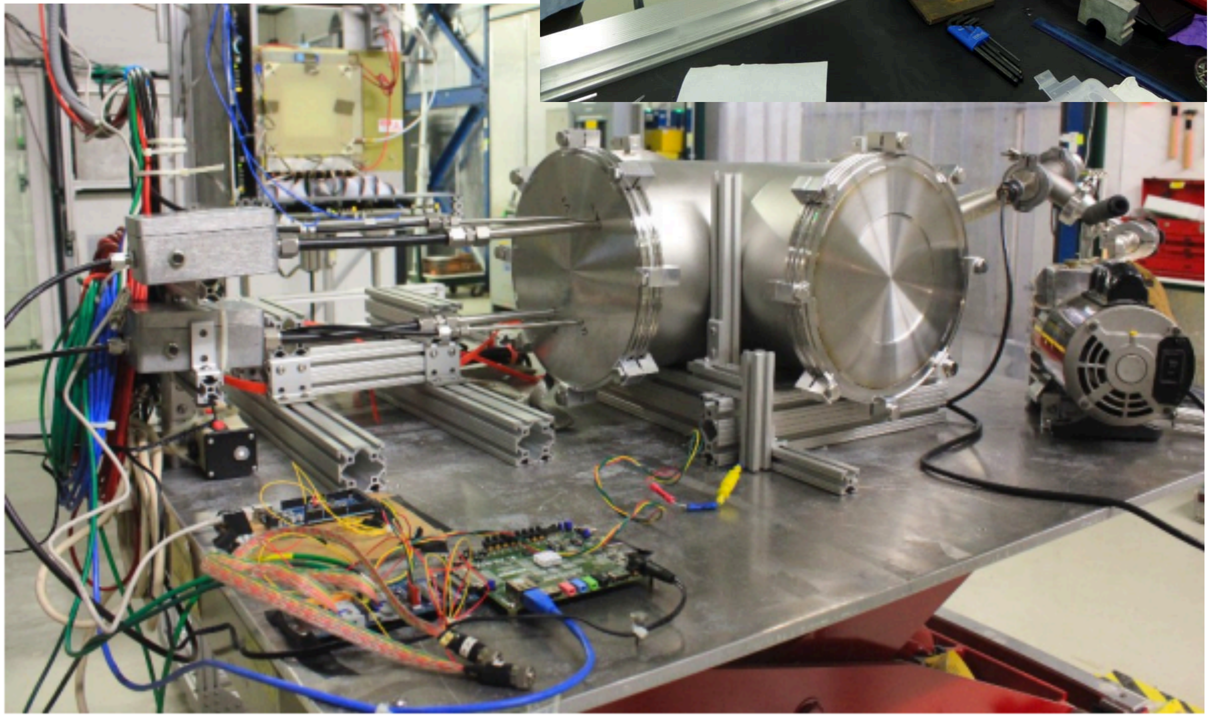


T. Walton, FNAL

Recent Highlights: Straw Tracker Tests

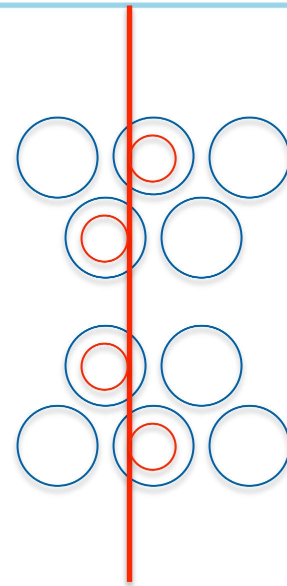
- Two week runs in Jan and May 2014 to test prototype in air and vacuum

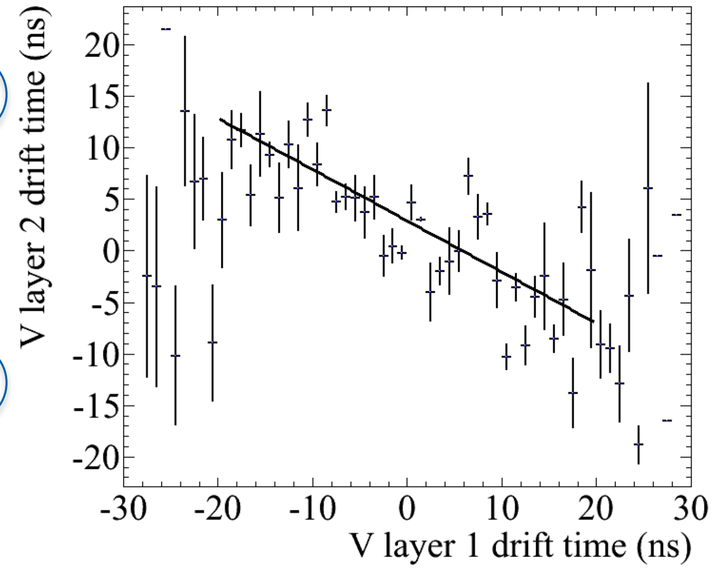


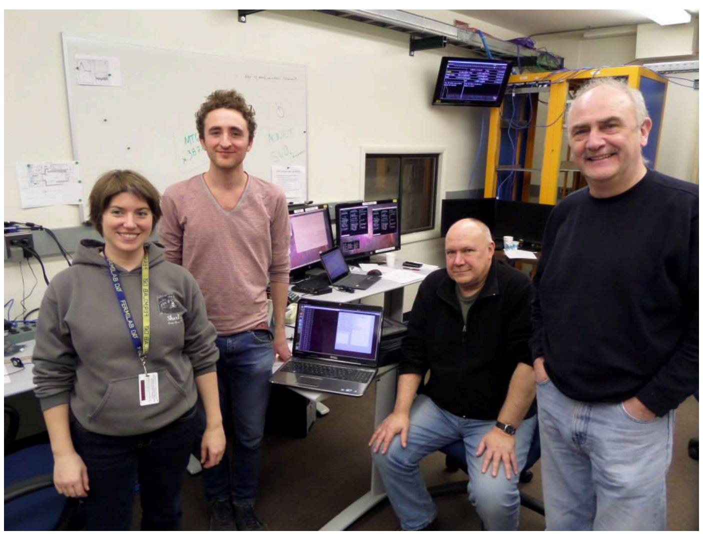


Recent Highlights: Straw Tracker Tests

- Collaborative effort
  - Straws constructed by FNAL/ Liverpool
  - End pieces designed by NIU Senior Design
  - BU frontend electronics
  - UCL Readout Electronics
  - Liverpool + UCL test Beam



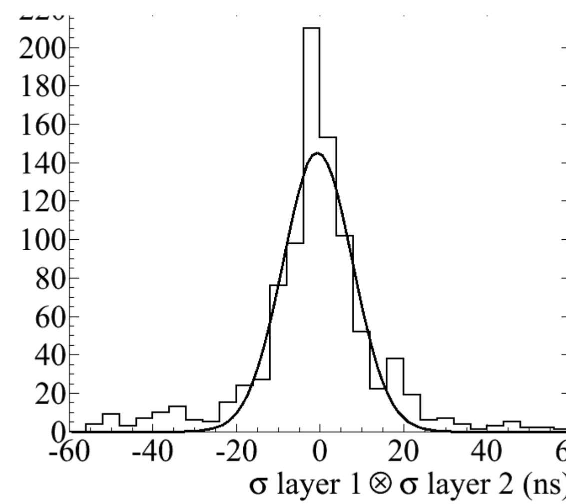




8ns res in data

9ns in GARFIELD after applying effective threshold from beam

Corresponds to 270 μm resolution



Field Highlights

The 4T Oxford OR66 magnet from Minnesota to ANL

- Facility needed to study B-Field Measurement Systematics
- Nearby (Argonne)
- Homogeneous field while storage ring is in use
- Enables study of delicate transfer of probe calibration
- Enables development of new calibration probes (e.g. He-3)

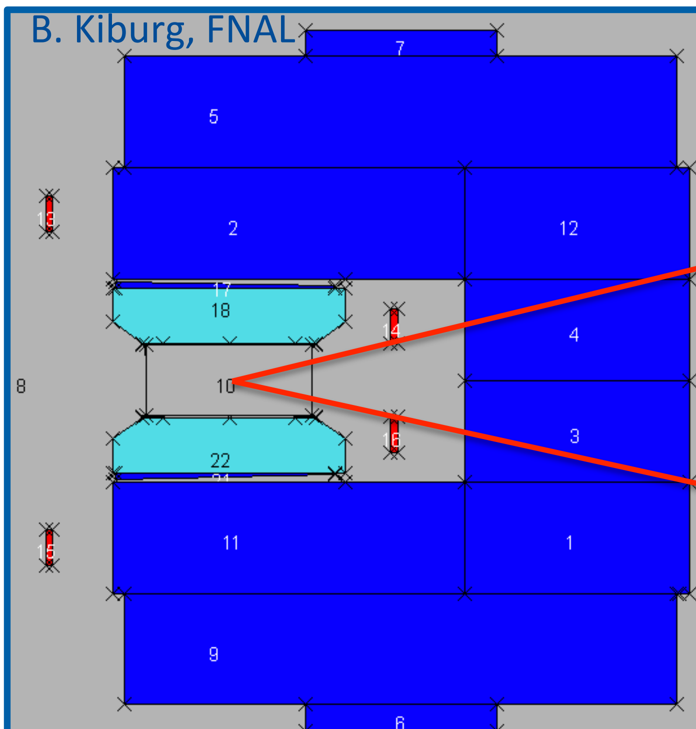
Bore size (without active coils)	Homogeneity	Drift
68 cm (90 cm)	7ppb/cm	~90ppb/hr

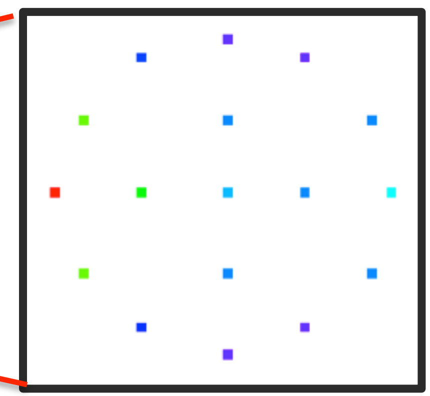
OR66 magnet from Minnesota arrived at ANL in April

Recent Highlights: Field Analysis

- Magnet Cold + Powered ~Spring 2015 → Start of proton precession frequency measurement begins now.
- Joe Grange of Argonne and BK of FNAL lead this analysis
  - JG examining and fitting E821 data
  - BK generating and fitting OPERA simulations

Ring center ←





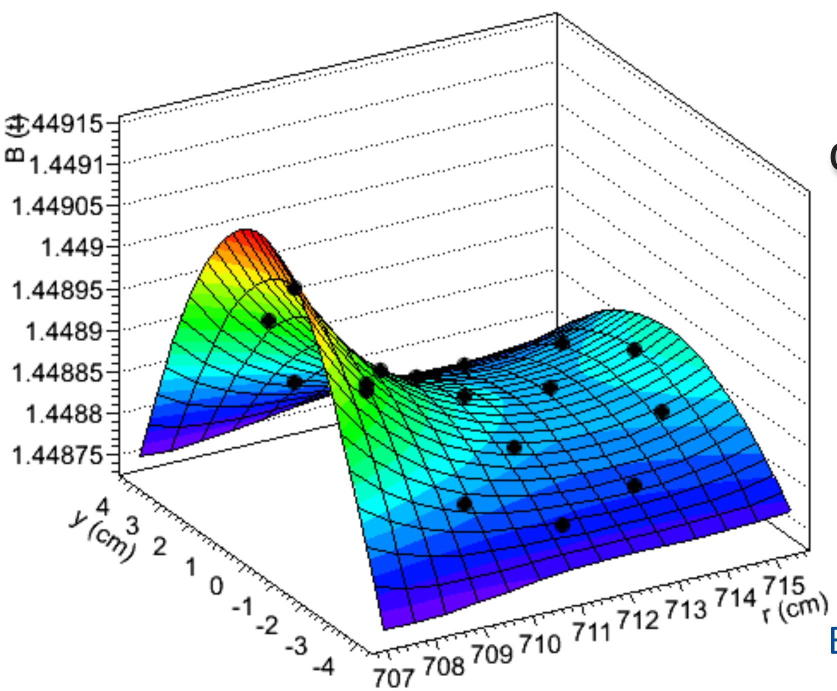
Extract Field at Trolley Points

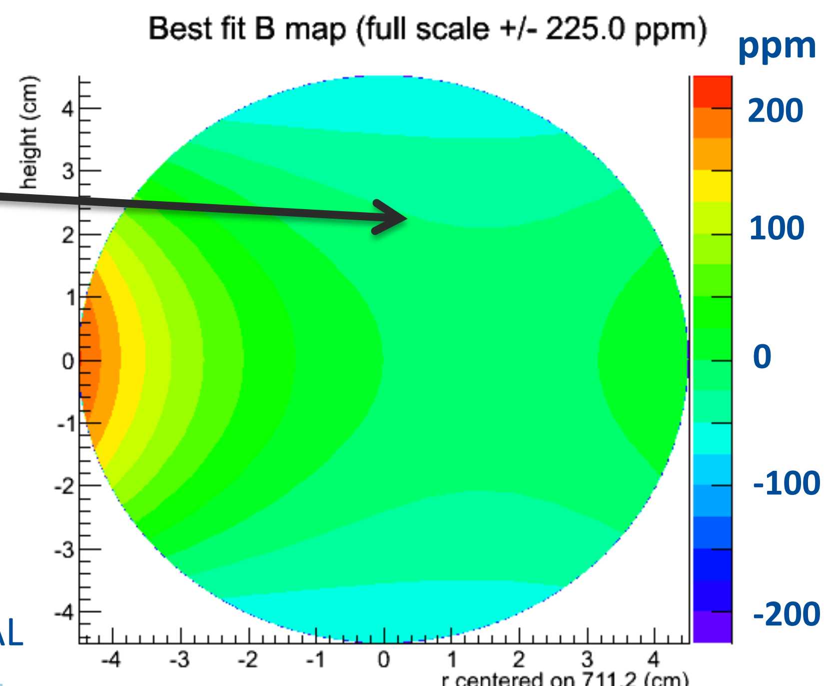
Modify Shimming Knobs to make field more uniform

$$B(x,y) = B(r,\theta) = B_0 + \sum_{i=1}^{n} \left(\frac{r}{r_0} \right)^i \left[a_i \cos(i\theta) + b_i \sin(i\theta) \right]$$

- Points = “Data”
- Colored Curve = Best Fit

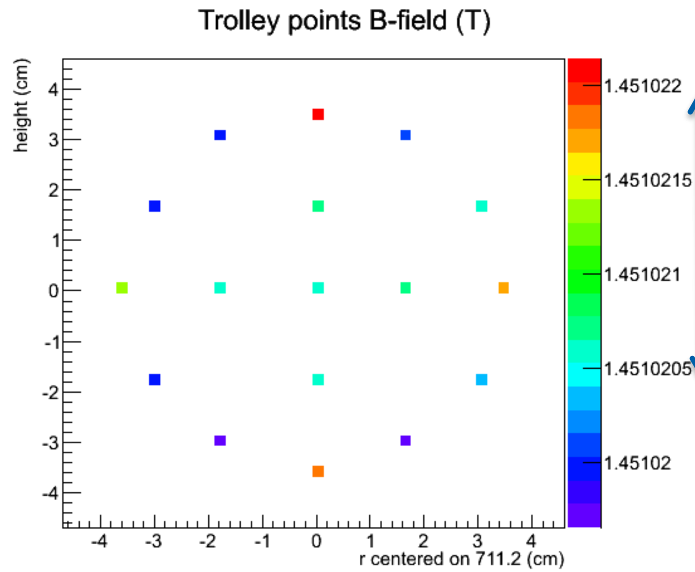
- Reconstruct Muon Storage Region
- Quantify Multipole Component at r=4.5 cm



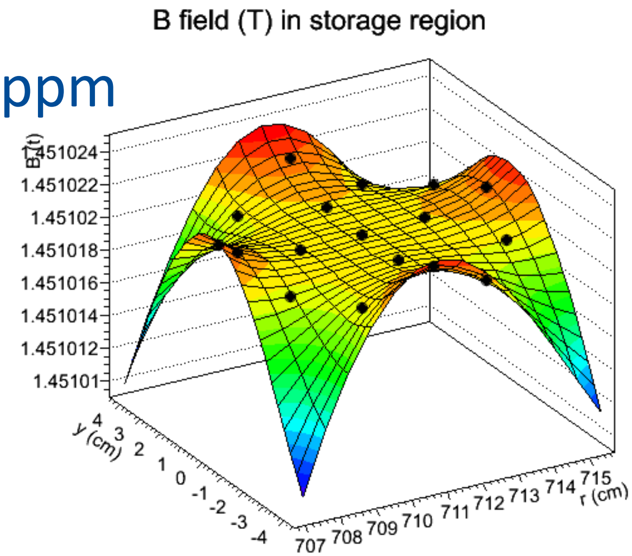


B. Kiburg, FNAL

Modify Shimming Variables to make field more uniform

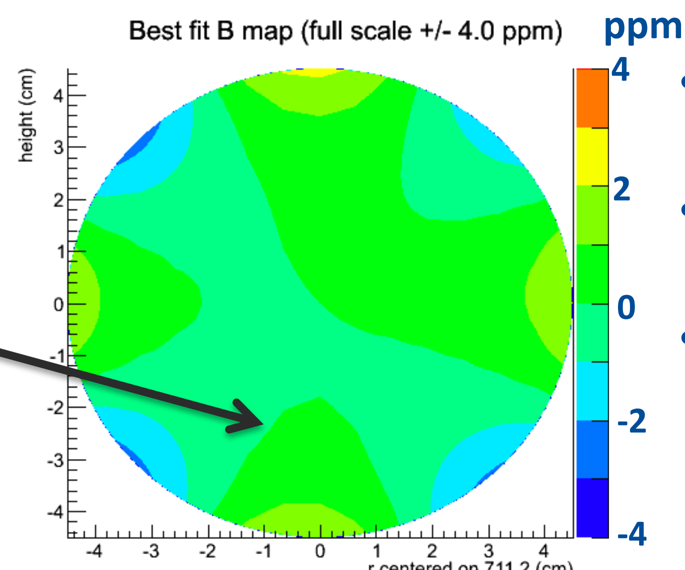


~1 ppm



- Parameterize mechanical variations → Matrix-based analysis solution for shimming

1 ppm contours

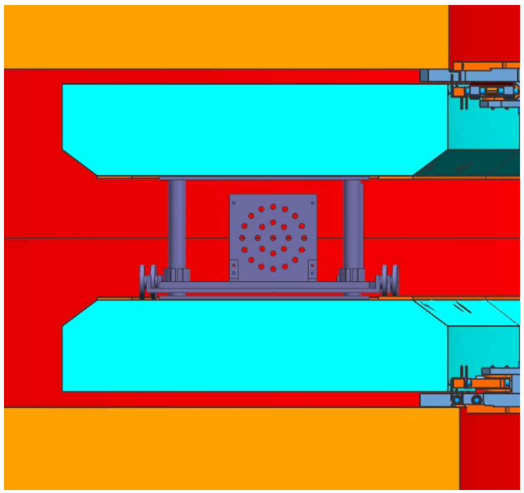


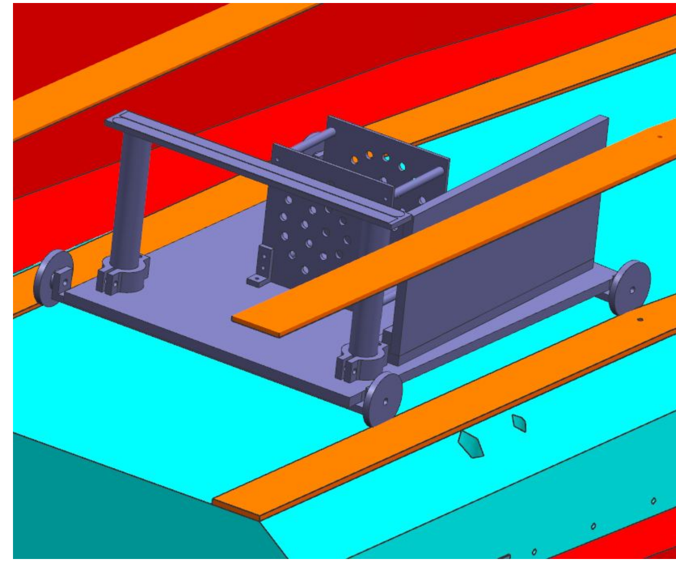
- 1 ppm contours
- LO Moments <0.3 ppm
- Decupole ~2ppm

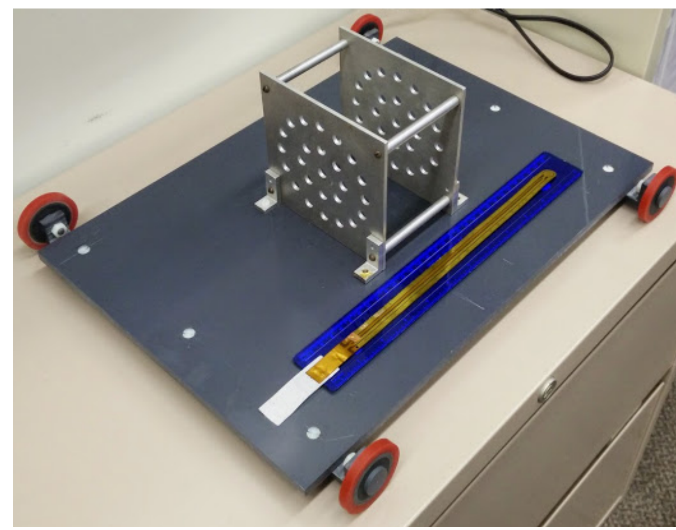
Fermilab

Recent Highlights: Shimming Platform

- Goal: Use mechanical knobs to shim B Field to 10 ppm, measure it with NMR prior to installation of vacuum chambers







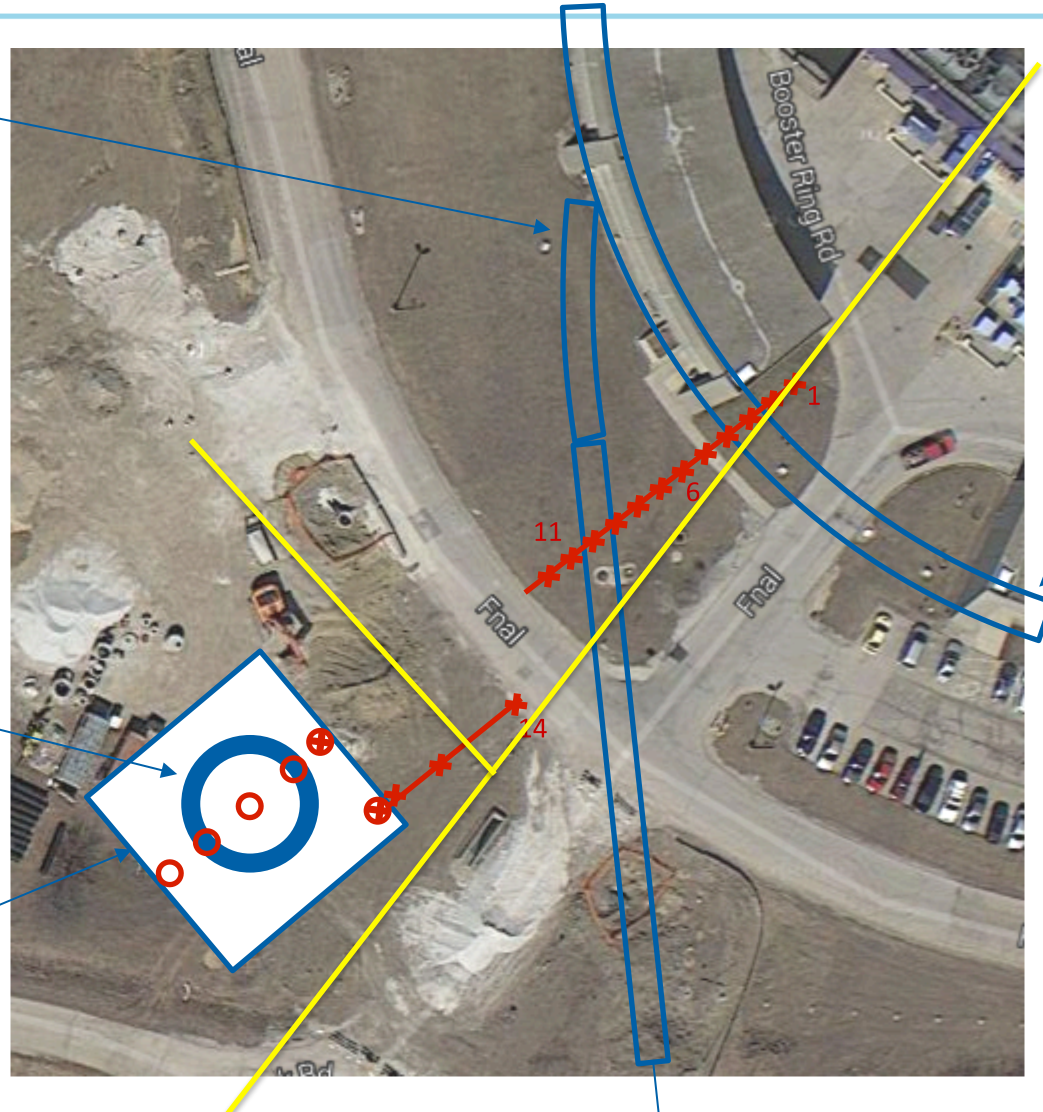
- Establish Pole-Pole Gap and Laser Tracker Pos.
- Spring – Summer 2015
  - D. Kawall UMass, E. Swanson UW (IF Fellowships)
  - ANL, FNAL local teams
  - Grad Students: UW, UCL, Cornell
  - Small Team of Young Scientists from UK Royal Institute

Fermilab

Recent Highlights : Transient Field Analysis

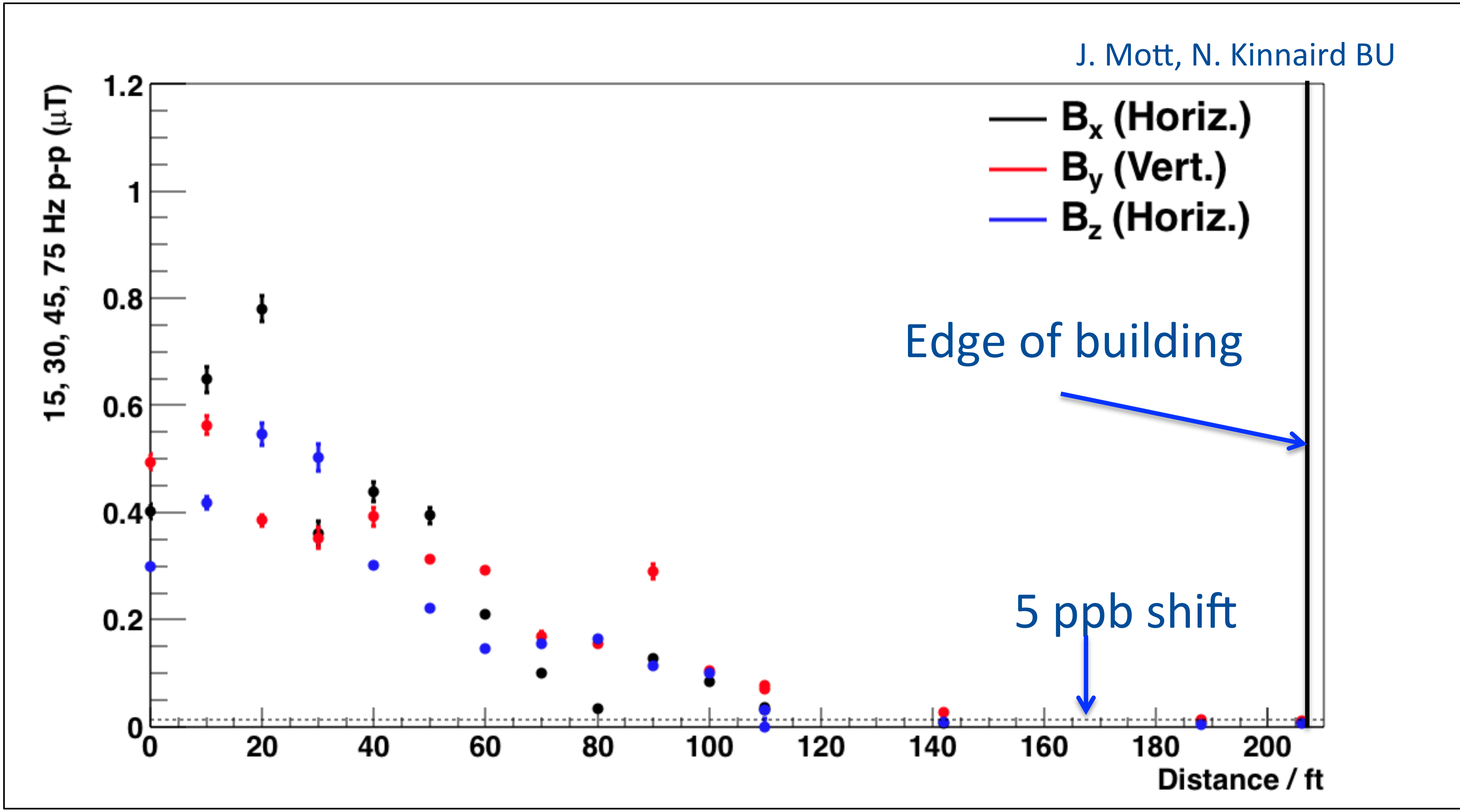
- If a time-dependent field source is coupled to the muon arrival, then muons (ω_a) could sample a different average field than the NMR Probes (ω_p) → Systematic Error
- Possible sources
  - Booster Field
  - Power Lines
  - Vehicular Traffic
  - Other Magnets
- Boston Fermilab took measurements
  - J. Mott N. Kinnaird (BU) with H. Nguyen, B. Kiburg (FNAL)

Measurement Locations



Fluxgate magnetometer measures the magnetic field in 3 dimensions.

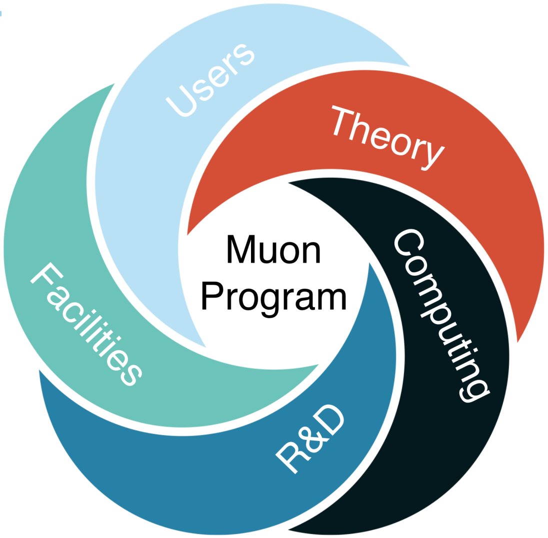
Booster Field vs. Distance



The booster harmonics fall off nicely with distance.

Fermilab

Conclusions



- Clear theory and experimental roadmap to achieve proposed precision
  - Strong relationship with theory department at the lab
  - Cooperative efforts between divisions at the lab to use tools and expertise available to their maximum extent
  - Coordinating complex systems development with universities to achieve prototypes
  - Robust simulation efforts using Fermilab-based *art* framework, utilized by a large fraction of collaborating institutes

Thank You!