Results of the ATLAS Solenoid Magnetic Field Map

CERN mapping project team

Martin Aleksa, Felix Bergsma, Laurent Chevalier, Pierre-Ange Giudici, Antoine Kehrli, Marcello Losasso, Xavier Pons, Heidi Sandaker

Map fitting by

John Hart (RAL)

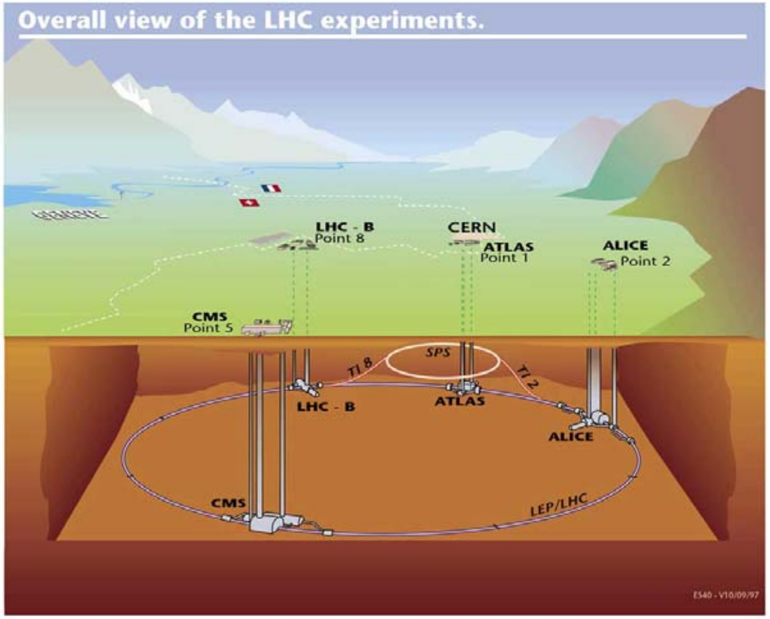
Paul S Miyagawa, Steve Snow (Manchester)

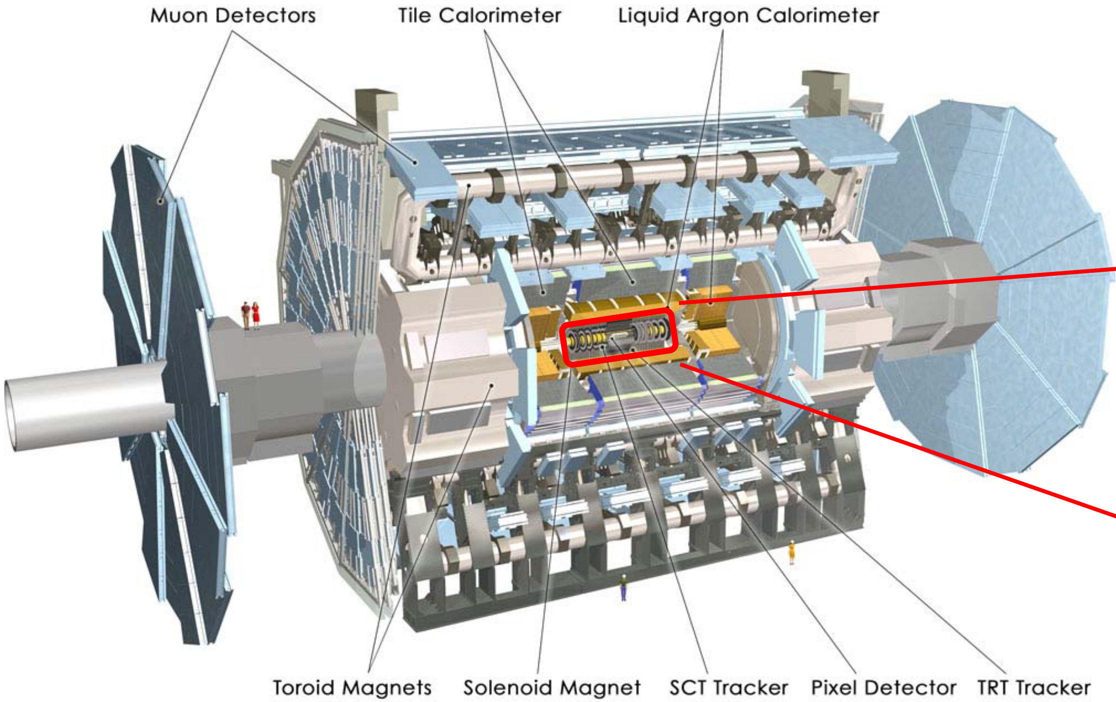
Outline

- Overview of mapping campaign
- Corrections to data
- Geometrical fit results
- Geometrical + Maxwell fit results
- Systematic errors
- Conclusions

ATLAS Experiment

- LHC will produce proton-proton collisions:
  - cms energy 14 TeV
  - 25 ns bunch spacing
  - 1.1×10^{11} protons/bunch
  - design luminosity 10^{34} $cm^{-2}s^{-1}$
- ATLAS is a general-purpose detector:
  - diameter 25 m, length 46 m
  - overall mass 7000 tonnes
- ATLAS solenoid provides 2 T field for Inner Detector
  - length 5.3 m, diameter 1.25 m, 1159 turns
  - operated at 7730 A



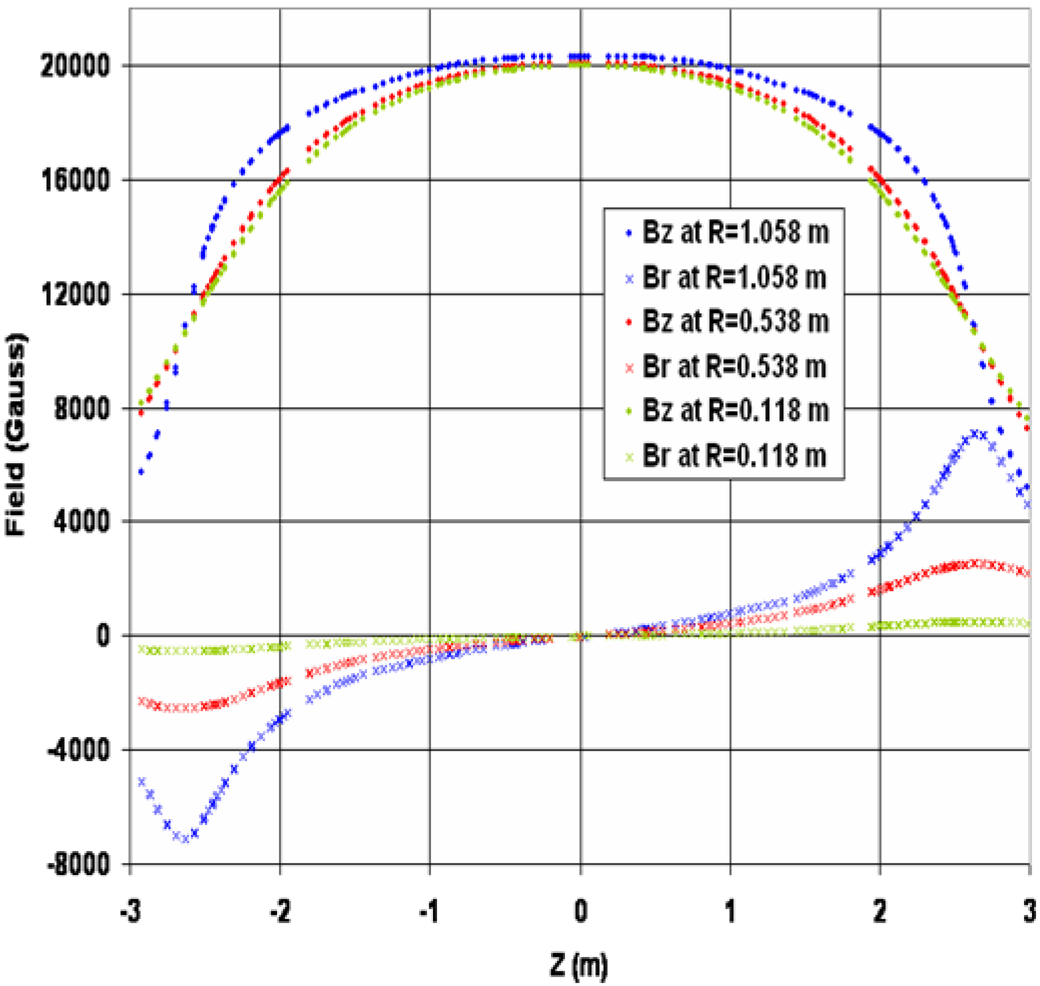


MANCHESTER 1824

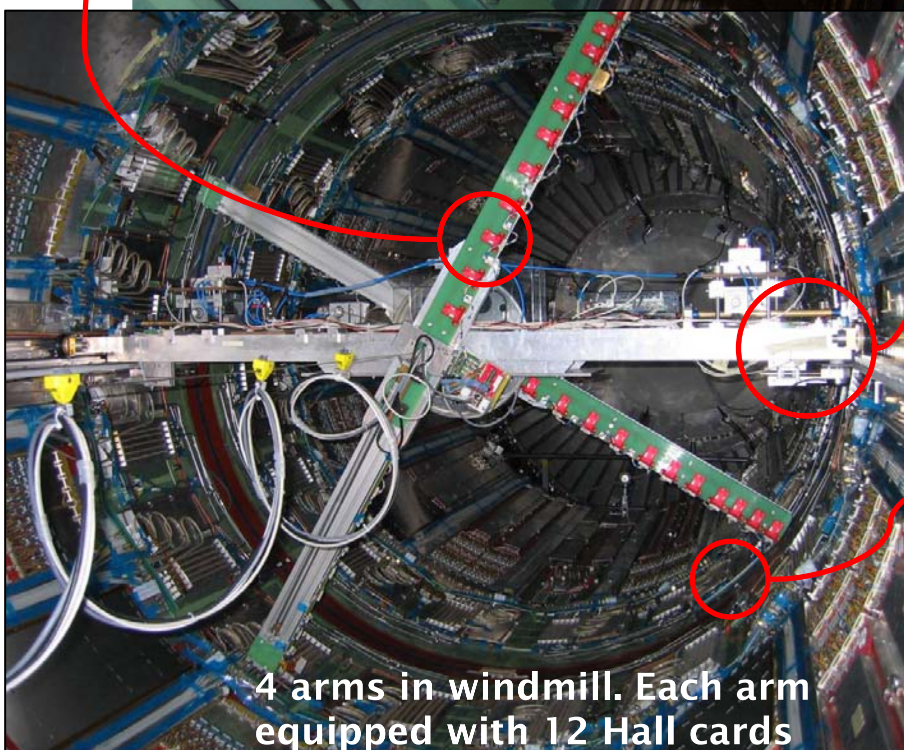
The University of Manchester

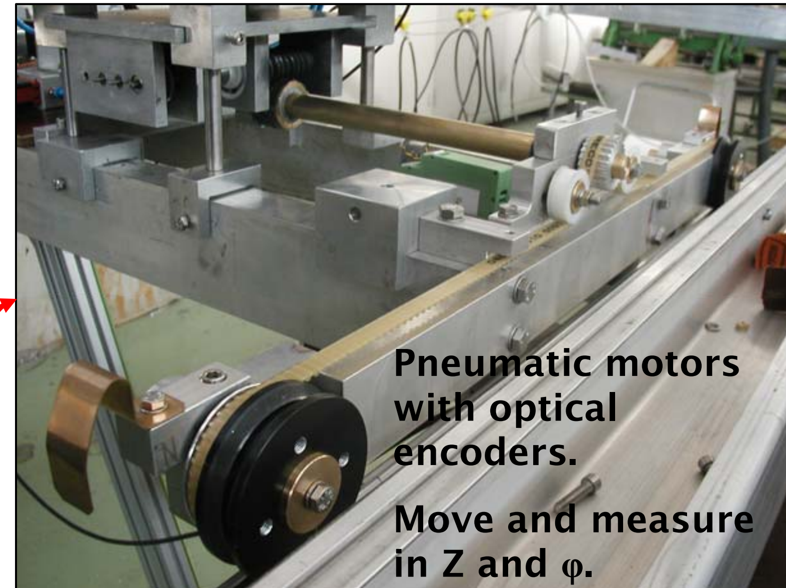
Overview of the task

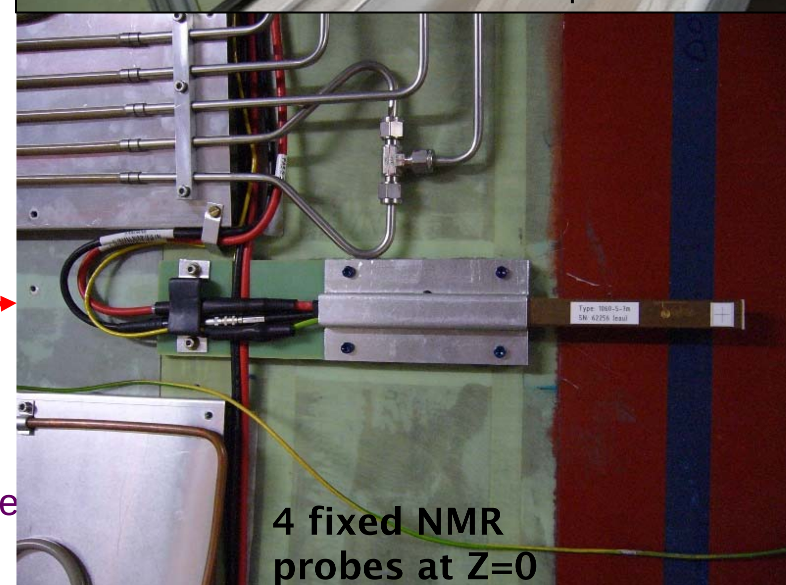
- Mapping 6m long x 2m diameter cylindrical volume
- 2 Tesla (20000 Gauss) at Z=0, dropping to 0.8 T at Z=3m
- Require track sagitta error due to field uncertainty < 0.05%
  - Motivated by targets on uncertainty for measurement of *W* mass



The field mapping machine







Data sets recorded

- Data taken at four different solenoid currents
  - Nominal current (7730 A) gives 2 T at centre
  - Low current (5000 A) gives 1.3 T and is used with low-field probe calibration
- Fine phi scans used to measure the (tiny) perturbation of the field by the mapping machine
- Total data collected ~0.75M
  - Statistical errors will be negligible

Date in August	Current (A)	Number of φ steps	Number of Z steps
2nd-3rd	7730	16	99
3rd	7730	64	1
4th	7850	16	25
	7000	16	44
	5000	16	76
	5000	64	1
7th	7730	16	8
	7730	24	26
	7730	12	35

Corrections to data

Geometrical effects

- Plenty of survey data taken before and after mapping campaign
  - Positions of individual Hall sensors can be determined to ~0.2 mm accuracy
- Mapping machine skew recorded in data
- Carriage tilts determined from data

Probe calibrations

- Response of Hall sensors calibrated as function of field strength, field orientation and temperature using test stands at CERN and Grenoble
  - Low-field calibration (up to 1.4 T) has expected accuracy of ~2 G, 2 mrad
  - High-field calibration (up to 2.5 T) has expected accuracy of ~10 G, 2 mrad
- NMR probes intrinsically accurate to 0.1 G
- Absolute scale of high-field Hall calibration improved using low-field Hall calibration and NMR values
- Relative Hall probe normalisations and alignments determined from data

Other effects

- Effects of magnetic components of mapping machine corrected using magnetic dipoles

Fit quality measures

- We fit the map data to field models which obey Maxwell's equations
  - The volume covered has no currents and has effects of magnetic materials removed
  - Maxwell's equations become

$$\nabla \cdot B = 0\,; \quad \underline{\nabla} \times \underline{B} = \underline{0}$$

- Our fit uses Minuit to minimise

$$\chi^2 = \sum_{\substack{i=\text{data points}\\ c=Z,R,\phi}} \left(\frac{B_{c,i}^{\text{measured}} - B_{c,i}^{\text{fit}}}{5\,\text{Gauss}} \right)^2$$

- Our aim is to know the track sagitta, which is proportional to (c_r and c_z are direction cosines)

$$S = \int_0^{r_{\max}} r\left(r_{\max} - r\right)\left(c_r B_z - c_z B_r\right) dl$$

- Our fit quality is defined to be $\delta S/S$ where

$$\delta S = \int_0^{r_{\max}} r\left(r_{\max} - r\right)\left(c_r\left(B_z^{\text{meas}} - B_z^{\text{fit}}\right) - c_z\left(B_r^{\text{meas}} - B_r^{\text{fit}}\right)\right) dl$$

Geometrical fit

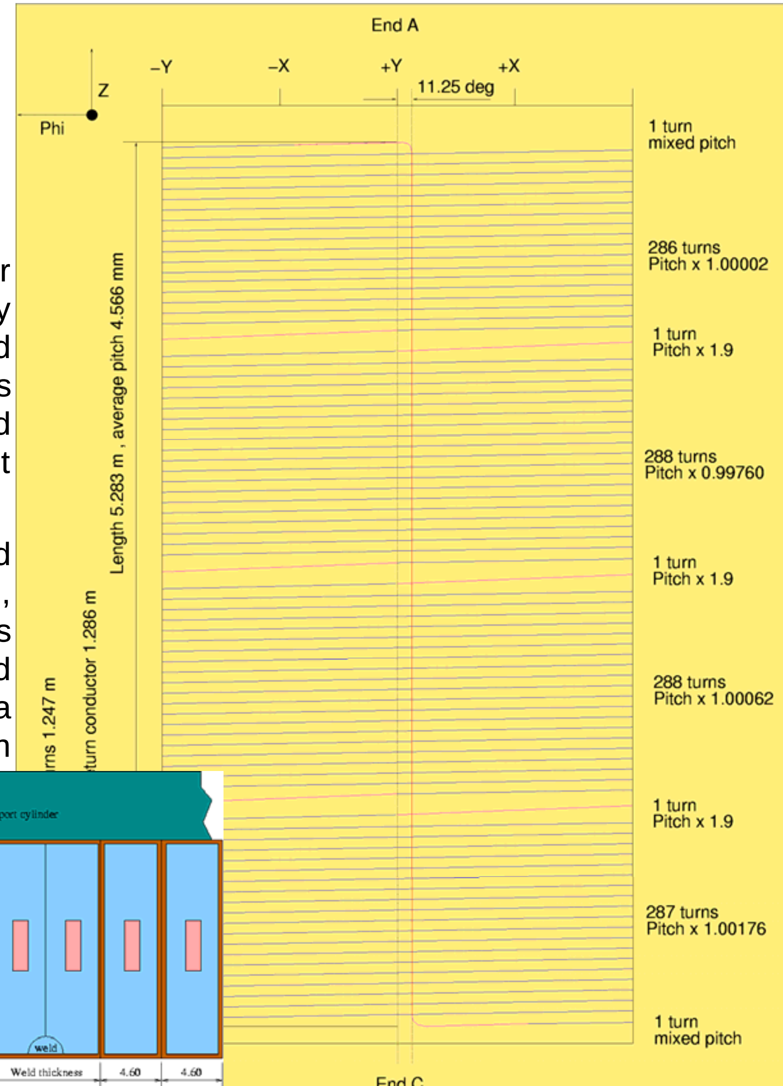
- 96% of the field is directly due to the solenoid current
  - We use a detailed model of the conductor geometry and integrate Biot-Savart law using the known current
  - 7 free parameters
    - Scale factor and aspect ratio (length/diameter) of conductor model
    - Position and orientation of conductor model relative to IWV
- 4% of field is due to magnetised iron (TileCal, girders, shielding discs etc)
  - Parametrised using 4 free parameters of Fourier-Bessel series with length scale=2.5m

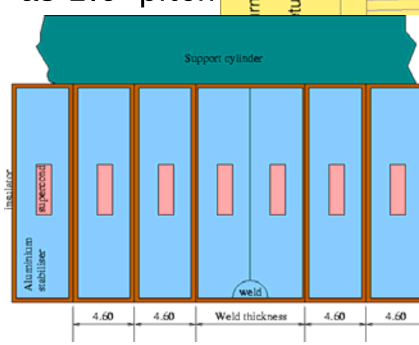
$$B_z = \sum_{i=1}^{4} C_i \cos\left(\frac{zi}{s}\right) I_0\left(\frac{ri}{s}\right)$$

$$B_r = \sum_{i=1}^{4} C_i \sin\left(\frac{zi}{s}\right) I_1\left(\frac{ri}{s}\right)$$

Conductor geometry determined by surveys of solenoid as built

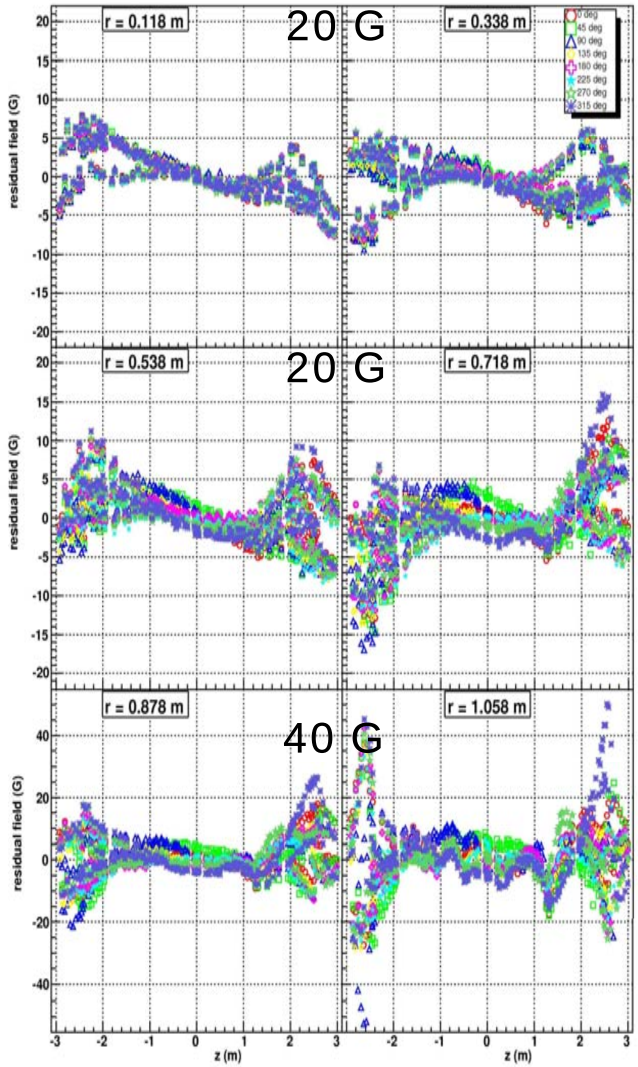
except weld thickness, which was determined from data as 1.9×pitch



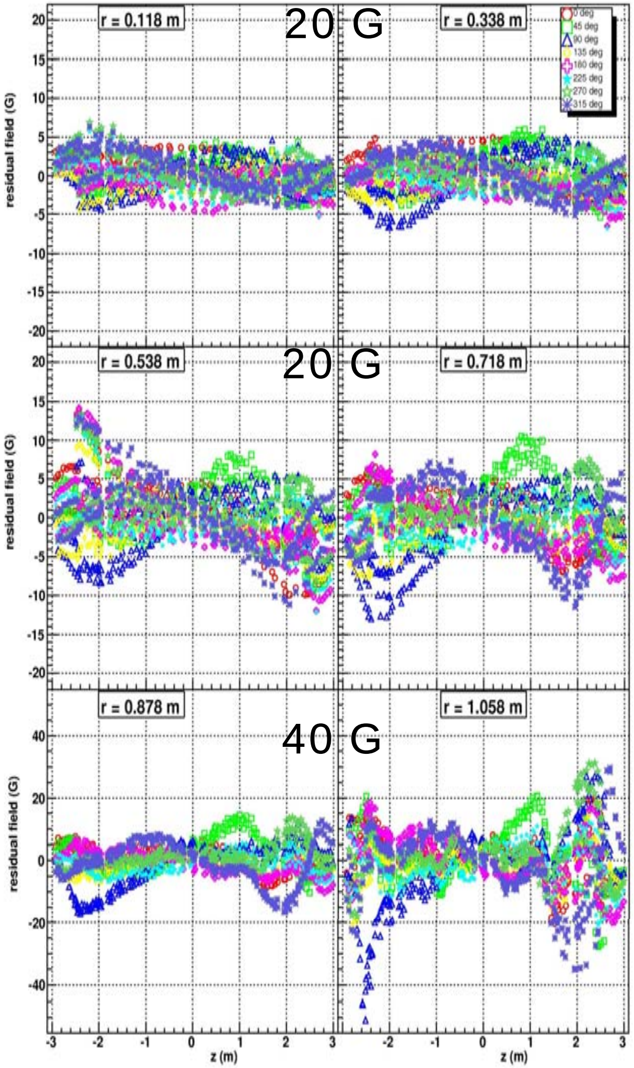


Results from geometrical fit

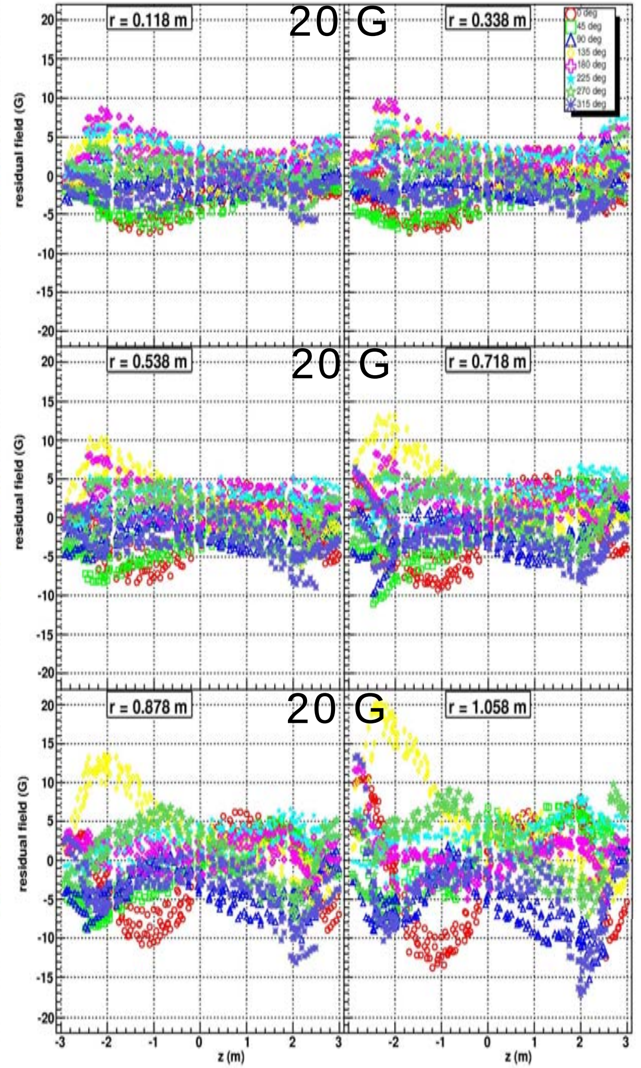
B_Z



B_R



B_φ



Full fit (geometrical + Maxwell)

- A few features remain in the residuals from the geometrical fit
  - Ripples for |Z|<2m believed to be due to variations in the coil winding density
  - Bigger features at |Z|>2m believed to arise from the coil cross-section not being perfectly circular
    - These effects are more pronounced at the ends of the solenoid
- These features cannot be determined accurately enough to be included in the geometrical model
  - However, they are real fields which should obey Maxwell's equations
- We apply a general Maxwell fit to the residuals to account for these features

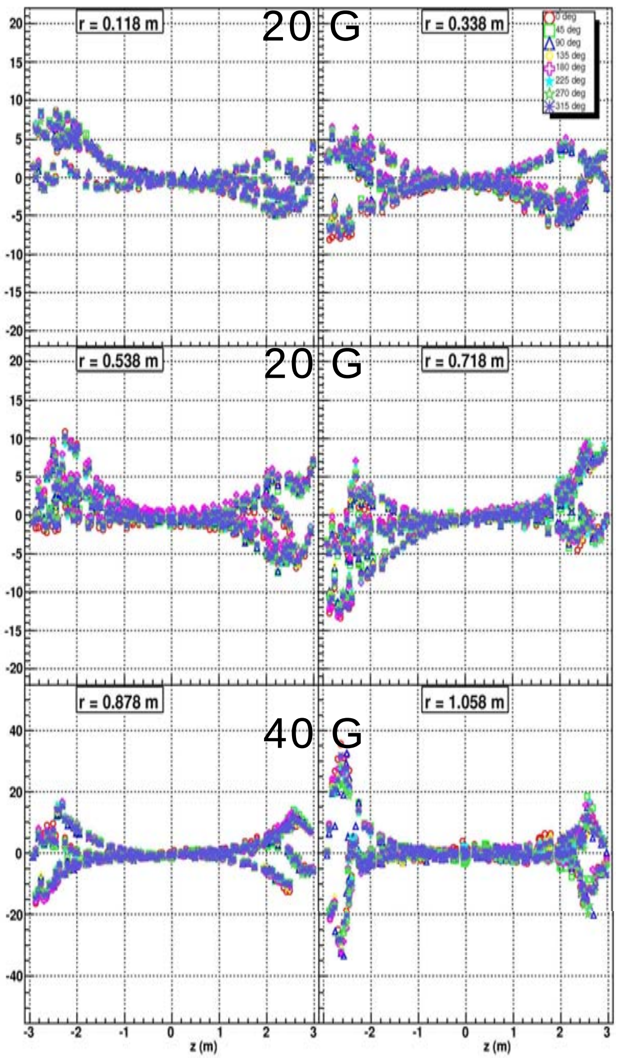
General Maxwell fit

- General fit able to describe any field obeying Maxwell's equations.
- Uses only the field measurements on the surface of a bounding cylinder, including the ends.
- Parameterisation proceeds in three stages:

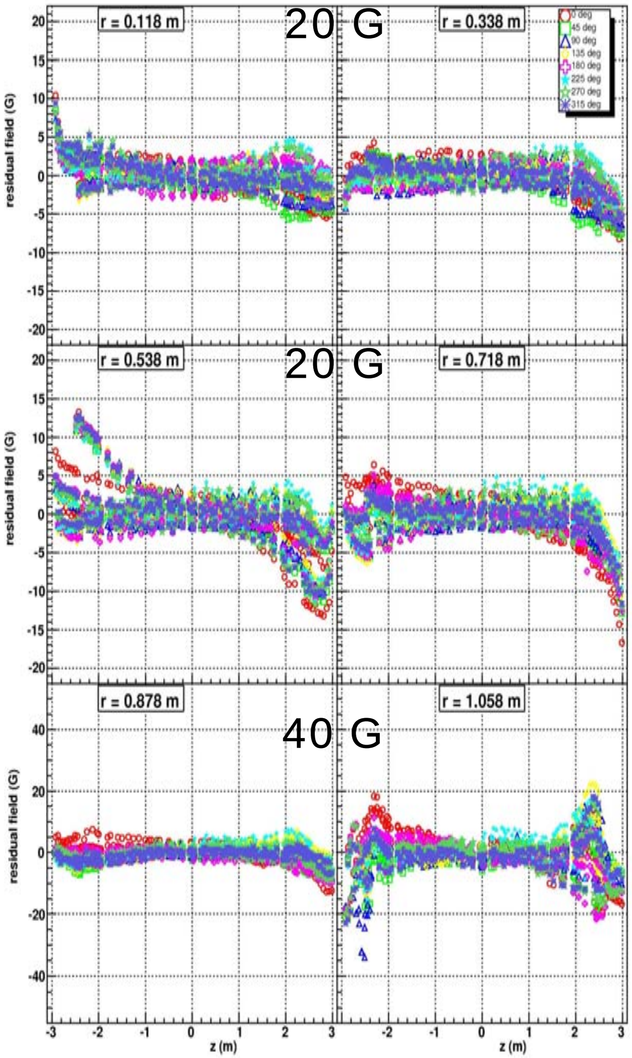
  1. B_z on the cylindrical surface is fitted as Fourier series, giving terms with φ variation of form $\cos(n\varphi+\alpha)$, with radial variation $I_n(\kappa r)$ (modified Bessel function).
  2. $B_z^{\text{meas}} - B_z^{(1)}$ on the cylinder ends is fitted as a series of Bessel functions, $J_n(\lambda_j r)$ where the λ_j are chosen so the terms vanish for $r = r_{\text{cyl}}$. The z-dependence is of form $\cosh(\mu z)$ or $\sinh(\mu z)$.
  3. The multipole terms are calculated from the measurements of B_r on the cylindrical surface, averaged over z, after subtraction of the contribution to B_r from the terms above. (The only relevant terms in B_z are those that are odd in z.)

Results from full fit I

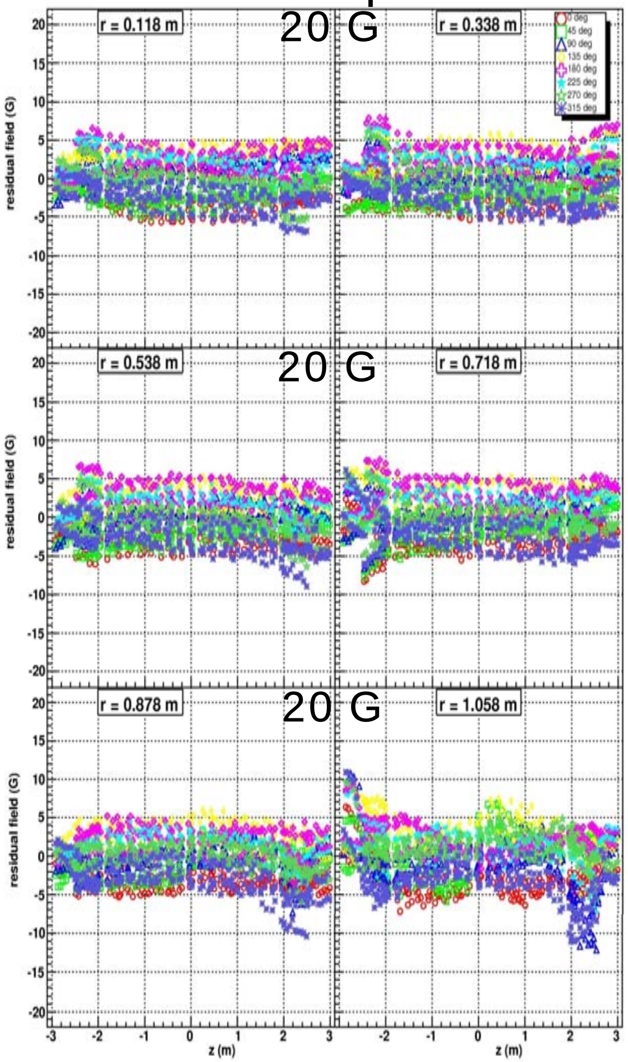
B_Z



B_R



B_ϕ



The University of Manchester

MANCHESTER 1824

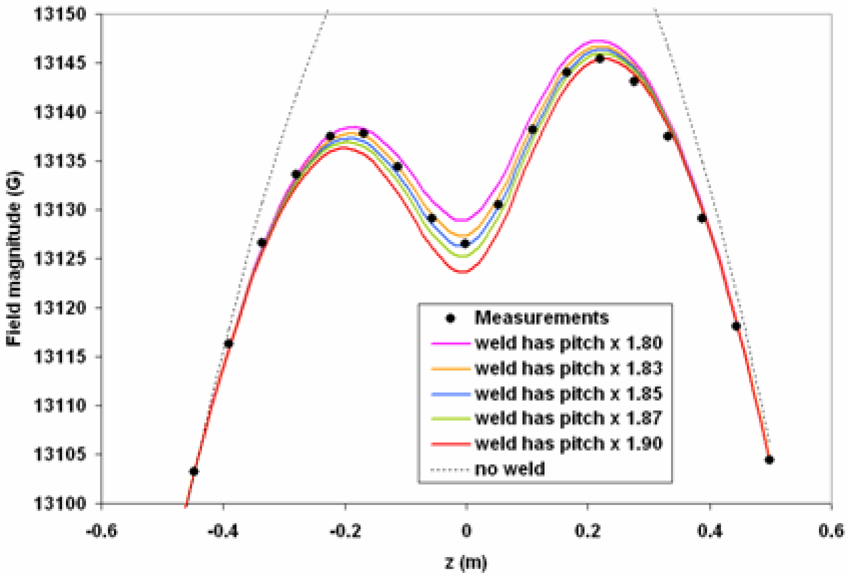
Results from full fit II

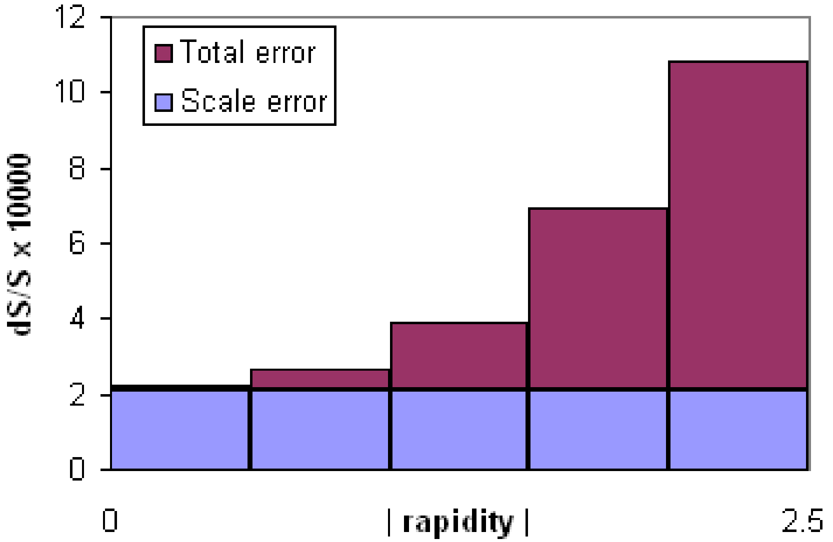
- All geometrical fit parameters (length scale, position, etc) consistent with expected results
- With full fit, residuals of all probes reduced significantly
  - Recall that Maxwell fit is made using outermost probes only
  - Fact that the fit matches inner probes as well shows strong evidence that the difference between data and geometrical model is a real field
- With geometrical fit alone, rms of relative sagitta error $\delta S/S$ already within target of 5×10^{-4}
  - Adding Maxwell fit improves $\delta S/S$, especially at high η

Fit	B_Z (G)		B_R (G)		B_φ (G)		$\delta S/S$ ($\times10^{-4}$)	
	rms	extreme	rms	extreme	rms	extreme	rms	extreme
Geom	5.23	-51.5	5.14	-49.9	4.60	+22.1	3.35	+10.9
Full	4.34	-37.1	3.52	-33.8	2.90	+15.2	1.29	+6.5

Systematic errors

- Uncertainty in overall scale
  - Comparison between Hall and NMR probes
  - Weld thickness, which influences the Hall-NMR comparison
  - Overall scale error 2.1×10^{-4}
- Uncertainty in shape of field
  - Dominant factor is 0.2 mrad uncertainty in orientation of the mapping machine relative to ATLAS physics coordinates
  - Overall shape error 5.9×10^{-4}
- Total uncertainty varies from 2–11 $\times10^{-4}$
  - Dominated by scale error at low η, shape error at high η





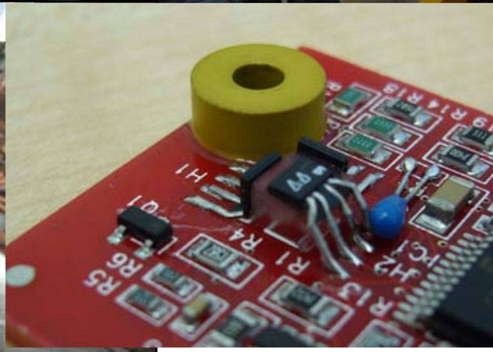
Conclusions

- The ATLAS solenoid field mapping team recorded lots of high quality data during a successful field mapping campaign
- All possible corrections from surveys, probe calibrations and probe alignments have been applied to the data
- We have determined a fit function satisfying Maxwell's equations which matches each component of the data to within 4 Gauss rms
- Using this fit, the relative sagitta error ranges from $2\text{–}11 \times 10^{-4}$
- At high rapidity, the systematic errors are dominated by a 0.2 mrad uncertainty in the direction of the field axis relative to the ATLAS physics coordinate system

Backup slides

Surveys

- Survey of mapping machine in Building 164
  - Radial positions of Hall cards
  - Z separation between arms
  - Z thickness of arms
- Survey in situ before and after mapping
  - Rotation centre and axis of each arm
  - Position of Z encoder zero
  - Positions of NMR probes
- Survey of ID rails
  - Gradient wrt Inner Warm Vessel coordinates
- Survey of a sample of 9 Hall cards
  - Offsets of BZ, BR, Bf sensors from nominal survey point on card
- Sensor positions known with typical accuracy of 0.2 mm



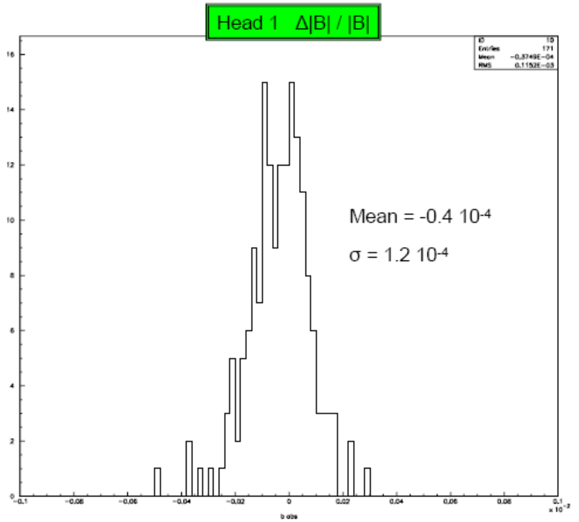
Probe calibrations

Hall sensors

- Response measured at several field strengths, temperatures and orientations (θ,φ)
- Hall voltage decomposed as spherical harmonics for (θ,φ) and Chebyshev polynomials for |B|,T

$$V(|B|, Temp, \theta, \varphi) = \sum_{k} \sum_{n} \sum_{l} \sum_{m=0}^{l} c_{klm} T_k(|B|) d_{nlm} T_n(Temp) Y_{lm}(\theta, \varphi)$$

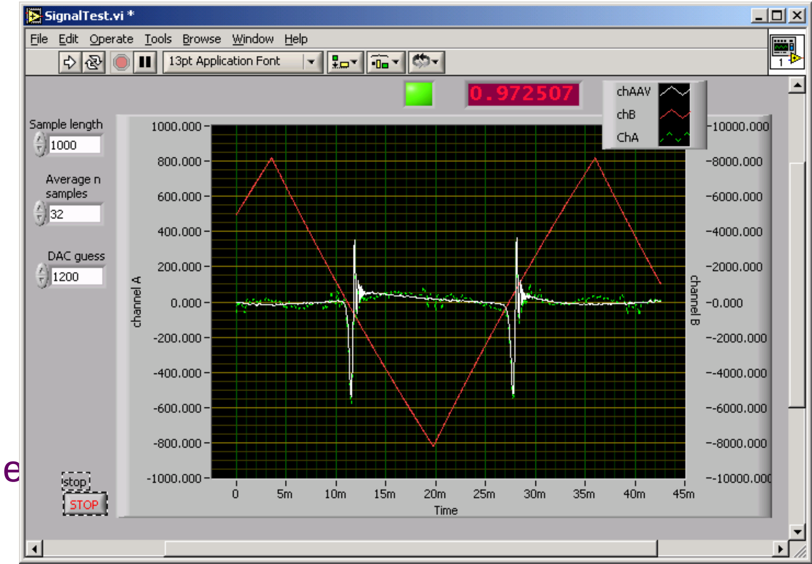
- **Low-field calibration (up to 1.4 T):** expected accuracy ~2 G, 2 mrad
- **High-field calibration (up to 2.5 T):** expected accuracy ~10 G, 2 mrad



B measured by NMR compared to B from sensors at 0.885 Tesla

NMR probes

- No additional calibration needed (done by whoever measured Gp = 42.57608 MHz/T)
- Compare proton resonance frequency with reference oscillator
- **Intrinsically accurate to 0.1 G**

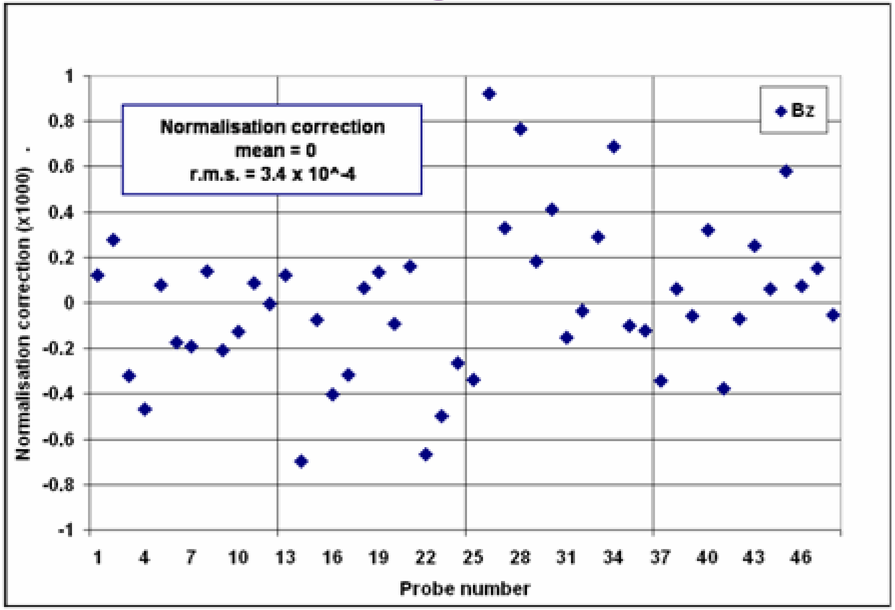


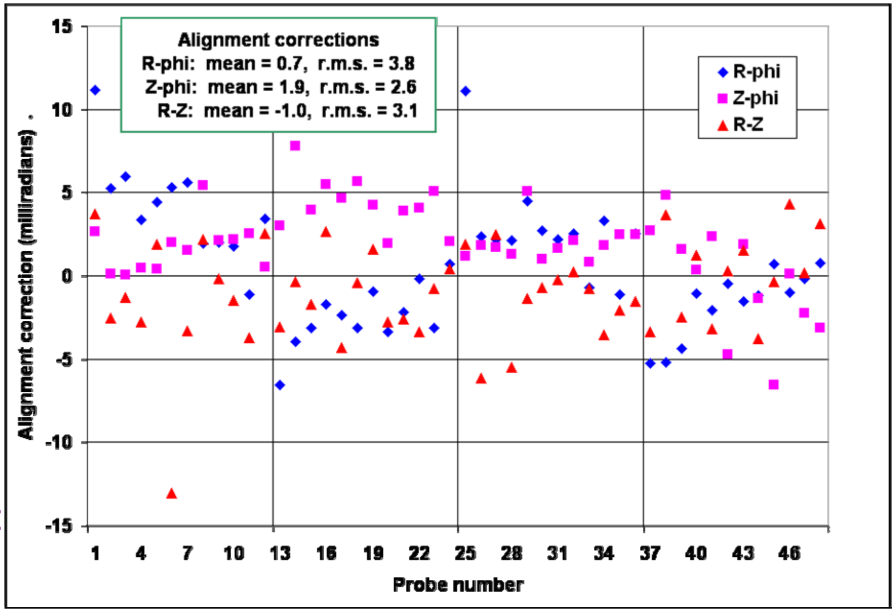
Probe normalisation and alignment

- Exploited the mathematics of Maxwell's equations to determine relative probe normalisations and alignments
- B_Z normalisation:
  - Uses the fact that each probe scans the field on the surface of a cylinder
  - B_Z at centre determined for each probe
  - All probes were then normalised to the average of these values
- Probe alignment:
  - Uses curl **B** = **0** and

$$B_\varphi^m = B_\varphi + A_{\varphi z} B_z - A_{r\varphi} B_r$$

  - Integrate $\oint B_\varphi \, ds = 0$
  - Tilt angles A_{ij} of probe were determined from a least squares fit
  - The third alignment angle comes from div B = 0



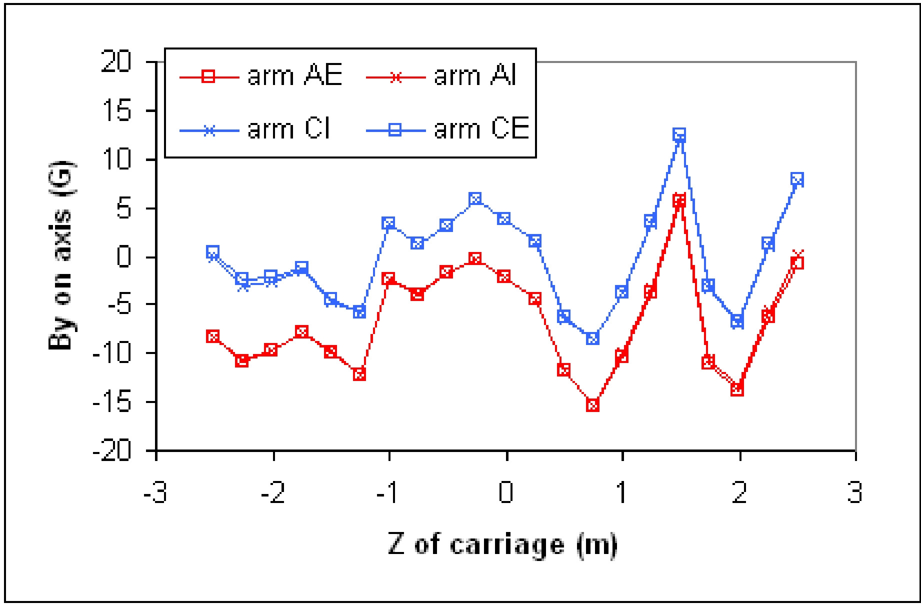


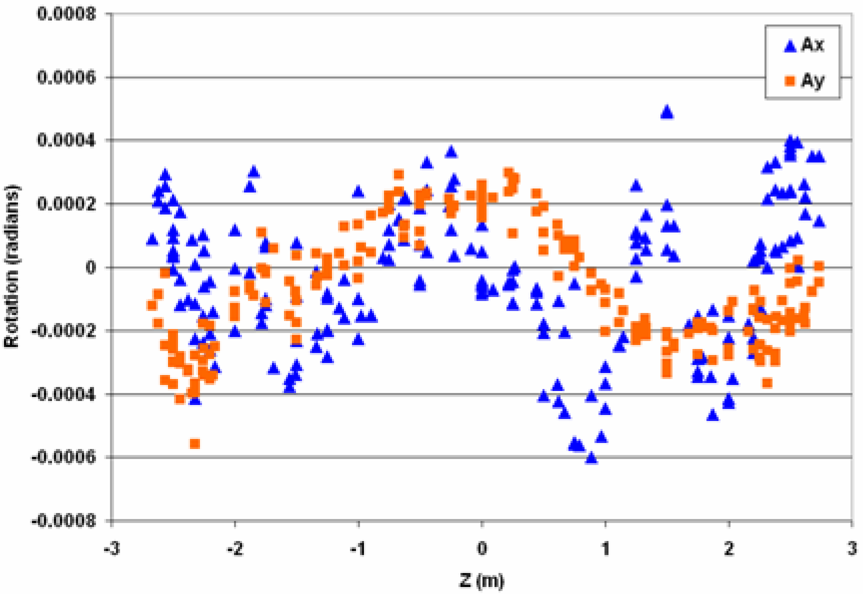
Carriage tilts

- Another analysis which exploited mathematics of Maxwell
- B_x and B_y on the z-axis evaluated from average over φ for probes near centre of solenoid
- Plots of B_x,B_y versus Z of carriage show evidence that entire carriage is tilting
- Degree of tilt can be calculated by integrating to find expected B_x,B_y value

$$\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x}$$

- Jagged structure of tilts suggest that machine is going over bumps on the rail of ~0.1 mm



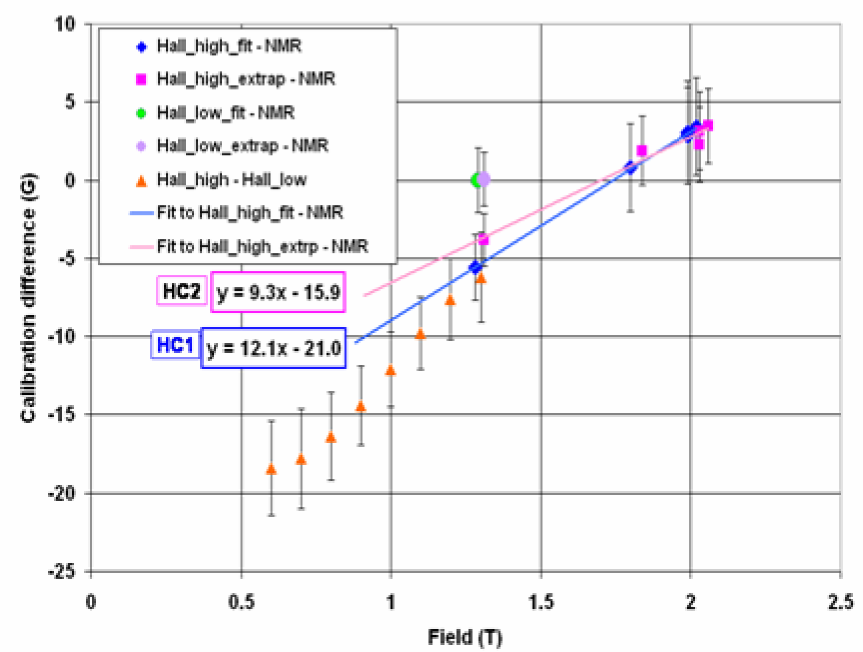


MANCHESTER 1824

The University of Manchester

Absolute Hall scale

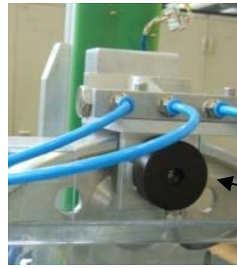
- Absolute scale of high-field Hall calibration (10 G) is greatest uncertainty
  - Can be improved using low-field Hall calibration (2 G) and NMR value (0.1 G)
- Low-field Hall values and NMR values are equal for 5000 A data
  - Low-field Hall values are considered accurate in low-field region
- Discrepancy between low- and high-field Hall values in low-field region

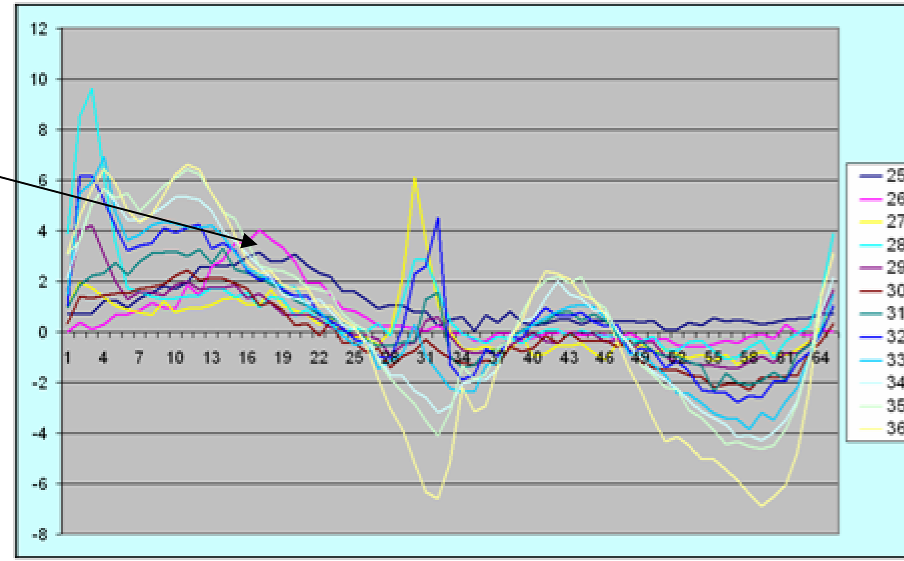


- Discrepancy between high-field Hall values (derived from field fits) and NMR value in high-field region
  - This discrepancy lines up with the discrepancy from low-field region
- Alternative high-field Hall values from extrapolation give estimate of systematic error

Magnetic machine components

- Perturbation of the magnetic field by the mapping machine was not anticipated





- Some spikes in the data were clearly attributed to components of the mapping machine
- A dipole was subtracted at each component position with field strength chosen to make residuals look smooth

Object	Z (m)	R (m)	Phi (deg)	Strength
Phi encoder	-0.02	0.190	90	0.0090
Phi motor bearings	-0.13	0.378	164	0.0023
Z motor bearings	-0.13	0.772	171	0.0023
Magnetic plug on ESB	-0.04	0.457	9	0.0182
Z encoder	-0.04	1.080	188	0.0056
Z encoder	0.00	1.080	352	0.0056
electrical valve	-0.08	0.865	18	0.0032
electrical valve	-0.08	0.830	162	0.0032
Z motor bearings	-0.13	0.830	8	0.0023