Validation of Garfield with Test-Beam Data of ATLAS Muon Drift-Tube Chambers in Magnetic Fields

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drift tube: Ar:CO$_2$ (93:7), gas gain $2 \cdot 10^4$ (3080 V)

Spatial resolution:
- single tube: 80 µm
- chamber: 35 µm

Required r–t accuracy: 20 µm
Motivation for the study

Average magnetic field: 0.4 T.

Goal:
- conversion of drift times into drift radii with an accuracy $\leq 20 \ \mu \text{m}$.

In chambers on the toroid coils:
- large gradients of the magnetic field along a tube,
  $\Rightarrow$ large variations of the maximum drift time $t_{\text{max}}$ along a tube.

This goal requires a formula to correct for these variations with an accuracy of $\sim 1 \ \text{ns}$. 
Set-up for the test-beam measurements

Location: Gamma Irradiation Facility at CERN.

Position accuracy of silicon tracker: $< 20 \, \mu m$. 

$B = 0.3 \, T, \ 0.6 \, T, \ 0.9 \, T$. 

silicon detectors for $\mu$ track measurement

MDT chamber on rotation table

MNP-17 dipol magnet

$\beta$, $\alpha$, $\mu$
A simple model

Equation for the electron drift (special case: $\vec{B} \parallel$ wire)

\[ \ddot{y} = - \left( \frac{\dot{y}}{\tau_\epsilon} \right)^{1+\epsilon} - \frac{e}{m} E_y - \frac{e}{m} \dot{z} B \]

\[ \ddot{z} = - \left( \frac{\dot{z}}{\tau_\epsilon} \right)^{1+\epsilon} - \frac{e}{m} E_z + \frac{e}{m} \dot{y} B. \]

$\epsilon = 0$: Langevin equation.

$\epsilon > 0$: allow for larger friction.

Larger friction can be caused by inelastic electron-molecule scattering.

$E_{rot}(CO_2) \sim E_{kin}(e^-) \Rightarrow$ rotations of CO$_2$ can be excited.

$\Rightarrow$ Inelastic electron-molecule scattering is expected for Ar:CO$_2$(93:7).
Predictions by the simple model

Solution of the differential equation

\[
t(r, \vec{B}) = t(r, \vec{B} = 0) + \Delta t(r, \vec{B}) \\
\approx t(r, \vec{B} = 0) + B^{2-\epsilon} \int_{r_{min}}^{r} \frac{v_{B=0}^{1-\epsilon}(r')}{{E'}^{2-\epsilon}(r')} \, dr'.
\]

Accuracy of the approximation for \( \Delta t(r, \vec{B}) \): \( \approx 1\% \).
Comparison with test-beam measurements

- Langevin equation with linear friction term ($\epsilon = 1$) insufficient to describe the measurements.
- Inelastic scattering of drifting electrons off CO$_2$ molecules must be taken into account!
Role of Garfield simulations

- Inelastic scattering of drifting electrons off CO$_2$ molecules are important.
- Since CO$_2$ has no dipole moment rotational excitations can only exist on top of vibrational excitations. CO$_2$ molecules are thermally excited to vibrational states.
- Test-beam measurements are taken at a single CO$_2$ content (7%) and a single temperature. Expect temperature spread in ATLAS: 15 K.
- Reliable Garfield calculations are needed to extrapolate from the test-beam operating point to other operating points, especially different temperatures.
The predictions of the two latest Garfield versions were compared with our test-beam measurements: Garfield-8 and Garfield-9.

Main difference: Garfield-9 uses new calculations of cross sections for electron-CO$_2$ scattering.
Comparison of Garfield with Measurements

First case: no magnetic field

No magnetic field
p=2.99 bar
T=295 K
7% CO$_2$
93% Ar

Garfield-8
Drift velocity too high!

Garfield-9
Excellent agreement between test-beam measurement and data!

Garfield-8 can be matched to test-beam data by increasing the CO$_2$ content to (the wrong value of) 7.1%.
Comparison of Garfield with Measurements

Second case: magnetic field switched on

Garfield-8: Too small drift velocity even after matching of $t(r)$ at $B=0$ by adjusting the CO$_2$ content!

Garfield-9: Good agreement between test-beam measurement and data!
Test-beam studies of the space-drift-time relationship of ATLAS MDT chambers in magnetic fields show that inelastic collisions of drift electrons with the CO\textsubscript{2} molecules of the drift gas must be taken into account.

Comparisons of the test-beam measurements with the predictions of the two latest Garfield versions show that only the most recent version (9) treats collisions with CO\textsubscript{2} molecules appropriately.