Møller Polarimetry
for PV Experiments at 12 GeV

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SoLID Meeting

Outline

Outline

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1. Introduction
2. Ferromagnetic Targets
3. Møller with Atomic Hydrogen Target
4. Conclusion
5. Appendix

Outline

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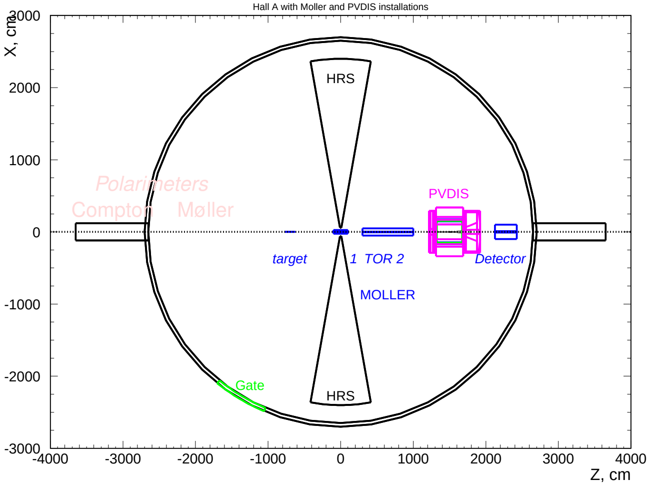
Installation in Hall A



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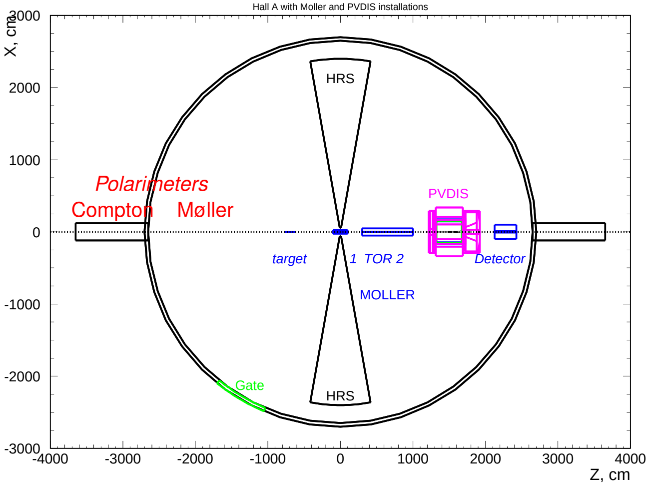

Error Budget of Møller and SoLID Experiments

Møller

Source of error	% error
Q^2 absolute value	0.5
beam polarization	0.4
beam second order	0.4
inelastic *ep*	0.4
elastic *ep*	0.3
other	0.5
total	1.0

SoLID

Source of error	% error
beam polarization	0.4
radiative corrections	0.3
Q^2 absolute value	0.2
statistics	0.3
total	0.6

0.4% - can it be done?

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Electron Polarimetry for PV at JLab: Features

- Energy range $E_{beam} = 6.6 - 11\ GeV$
- Current range $\mathcal{I}_{beam} = 40 - 90\ \mu A$

Additional features to consider

- Time needed to achieve $\sim 0.4\%$ statistical error
- Difficult to evaluate systematic errors from:
  - Polarimetry uses a different beam regime than the experiment (energy, current, location)
  - Intermittent (invasive?) measurements in contrast with the continuous one

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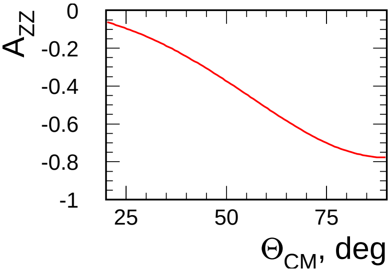
Møller Polarimetry

- Rad. corrections to Born $< 0.3\%$
- Detecting the e^- at $\theta_{CM} \sim 90^\circ$
- $\frac{dA}{d\theta_{CM}}|_{90^\circ} \sim 0$ - good systematics
- Beam energy independent
- Coincidence - no background
- Ferromagnetic target $\mathcal{P}_T \sim 8\%$
  - Heating $\frac{d\mathcal{P}}{dT} \sim 1\%/100^\circ C$ $\langle I_B \rangle < 3\ \mu A$
  - Levchuk effect (atomic e^-)
  - Low $\mathcal{P}_T \Rightarrow$ dead time
  - Syst. error $\sigma(\mathcal{P}_T) \sim 2\%$ (0.5%?)

$\vec{e}^{\,-} + \vec{e}^{\,-} \rightarrow e^- + e^-$ QED.



$A(E) = -\frac{7}{9}$

$\sigma_{lab} \sim 180\,\frac{mb}{ster}$

Møller Polarimetry - Ferromagnetic Targets

Polarized electron targets: magnetized ferromagnetic foils

- Iron: polarized *d*-shell (6 positions occupied out of 10)
- $\mathcal{P}_e$ not calculable: derived from measured magnetization
- Spin-orbital corrections ($\sim 5\%$) - measured in bulk material
- Magnetizing field is along the beam

Field 20 mT, foil at $\sim 20^\circ$

- Magnetization along the foil
- Magnetization can be measured
- A few % from saturation
- Sensitive to annealing, history
- Polarization accuracy $\sim 2-3\%$

Field 3-4 T, foil at $\sim 90^\circ$

- Magnetization perp. to the foil
- Magnetization - from world data
- Foil saturated
- Polarization is robust.
- Polarization accuracy $\sim 0.5\%$

Attempts to use iron in 50-100μA beam

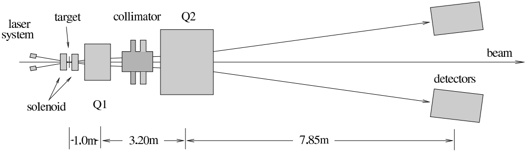
- Hall C: a mesh target, a wire target, a kicker magnet and a foil band
- Hall A: a beam duty cycle - the “tune” beam with bunch suppression.

Not successful so far

Møller Polarimeter with Saturated Iron foil (Hall C)

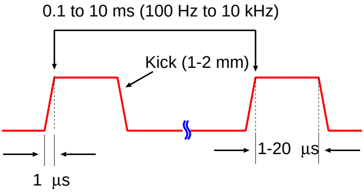
JLab, Hall C, M. Hauger *et al.* NIM A **462**, 382 (2001), talk on PAVI09 by S.Page

- External $B_Z \sim 3-4\ T$
- Target foils 1-10 μm, perp. to beam
- $\mathcal{P}_t$ not measured
- Levchuk: 3% correction



Tests at high beam current

- Half-moon shape foil
- Kicker magnet

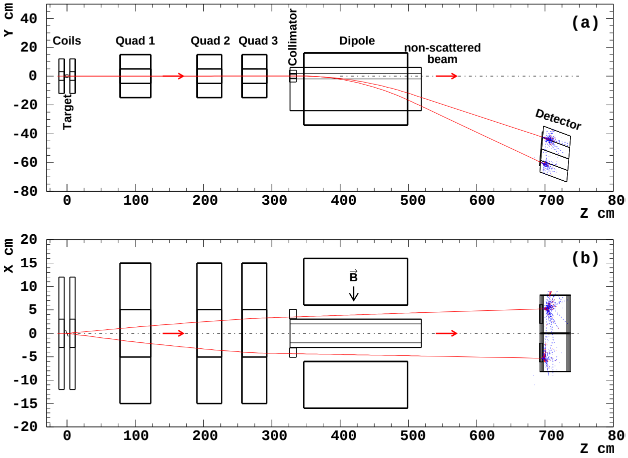


source	$\sigma(A)/A$
optics, geometry	0.20%
target	0.28%
Levchuk effect	0.30%
total at 3 μA	0.46%
$\Rightarrow$ 100 μA	?

A 1μm thick half-foil: mech. problems:

- Foil unstable: holder design
- Thicker foil - high rate
- At 20μA - accidentals/real≈0.4

Hall A Møller polarimeter with high field iron target



- Minimal Levchuk
- $\sigma_{stat} = 1\%$ in $\sim$2–3 min
- $B_Z \sim 3 - 4$ mT field
- Foil at 0° to field
- Foils 1–10μm
- Beam <3μA
- Systematics $\sim 1\%$

Hall A high field iron target: lessons learned

Used for PREX (∼1 GeV) and DVCS (∼5 GeV)

- Coils - strong beam steering
    - No remote motion/steering of the magnet
    - Elaborate attempts to align the magnet with the help of the survey group - little success
    - Can the coils move inside the cryo-vessel?
- Optimal Q1 current is about 15% off the mark at 1 GeV
  No explanation so far ⇒ systematic error on analyzing power
- Variation between targets ∼0.5-1.0% - material or the field angle? (3° ⇒ 1% at 3 T, 0.3% at 4 T)
- No full saturation visible (∼1% level) at 3-4 T ⇐ Levchuk effect depends on the field

Møller Systematic Errors

Variable	Hall C	Hall A	
		Low B Fe	High B Fe
Material Polarization	0.25%	0.30%	0.25%
Target variation	0.00%	1.50%	0.50%
Target angle	0.00%	0.50%	0.00%
Analyzing power	0.24%	0.30%	0.30%
Levchuk effect	0.30%	0.30%	0.30%
Target temperature	0.05%	0.00%	0.02%
Dead time	?	0.30%	0.30%
Background	?	0.30%	0.30%
Others	0.10%	0.30%	0.30%
Beam extrapolation	?	larger	?
Total	0.47%	1.75%	$\sim$0.90%

Possible Breakthrough in Accuracy

Møller polarimetry with 100% polarized atomic hydrogen gas, stored in a ultra-cold magnetic trap.

E.Chudakov and V.Luppov IEEE Trans. on Nucl. Sc., 51, 1533 (2004)

`http://www.jlab.org/~gen/hyd/loi_3.pdf`

Advantages:

- 100% electron polarization
  - very small error on polarization
  - sufficient rates $\sim \times 0.005$ - no dead time
  - false asymmetries reduced $\sim \times 0.1$
- Hydrogen gas target
  - no Levchuk effect
  - low single arm BG from rad. Mott (×0.1 of the BG from Fe)
  - high beam currents allowed: continuous measurement

Operation:

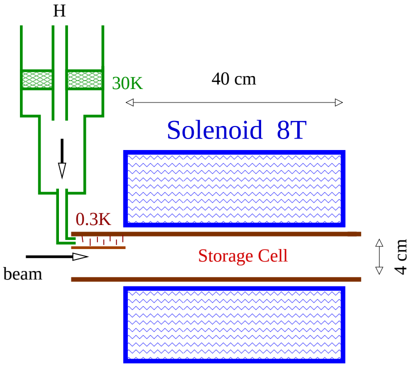
- density: $\sim 6 \cdot 10^{16}$ atoms/cm^2
- Stat. error at 50 μA: 1% in $\sim$10 min

Møller Systematic Errors

Proposed: 100%-polarized atomic hydrogen target ($\sim 3 \cdot 10^{16}$ atoms/cm^2).

Variable	Hall C	Hall A		
		Low B Fe	High B Fe	High B ^{1}H
Material Polarization	0.25%	0.30%	0.25%	0.01%
Target variation	0.00%	1.50%	0.50%	0.00%
Target angle	0.00%	0.50%	0.00%	0.00%
Analyzing power	0.24%	0.30%	0.30%	0.10%
Levchuk effect	0.30%	0.30%	0.30%	0.00%
Target temperature	0.05%	0.00%	0.02%	0.00%
Dead time	?	0.30%	0.30%	0.10%
Background	?	0.30%	0.30%	0.10%
Others	0.10%	0.30%	0.30%	0.30%
Beam extrapolation	?	larger	?	0.00%
Total	0.47%	1.75%	∼0.90%	0.35%

Storage Cell



First: 1980 (I.Silvera,J.Walraven)
$\vec{p}$ jet (Michigan)
Never put in high power beam

- 4 states, $\mathcal{P}_e$: $|a\rangle$,$|b\rangle$=-1 $|c\rangle$,$|d\rangle$=+1
- $-\vec{\nabla}(\vec{\mu_H}\vec{B})$ force in the field gradient
  - pulls $|a\rangle$, $|b\rangle$ into the strong field
  - repels $|c\rangle$, $|d\rangle$ out of the field
  - $\mathcal{P}_e = 1 - \delta$, $\delta \sim 10^{-5}$
- H+H→H_2 recombination (+4.5 eV) high rate at low T
  - parallel electron spins: suppressed
  - gas: 2-body kinematic suppression
  - gas: 3-body density suppression
  - surface: strong unless coated $\sim$50 nm of superfluid ^{4}He
- Density $3 \cdot 10^{15} - 3 \cdot 10^{17}$ cm^{-3}.
- Gas lifetime > 1 h.

Contaminations and Depolarization of the Target Gas

Ideally, the trapped gas polarization is nearly 100% ($\sim 10^{-5}$ contamination).
Good understanding of the gas properties (without beam).

Gas Properties

- Atom velocity $\approx$ 80 m/s
- Atomic collisions $\approx 1.4\ 10^{5}\ \mathrm{s}^{-1}$
- Mean free path $\lambda \approx 0.6$ mm
- Wall collision time $t_R \approx 2$ ms
- Escape (10cm drift) $t_{es} \approx 1.4$ s

CEBAF Beam

- Bunch length σ=0.5 ps
- Repetition rate 497 MHz
- Beam spot diameter $\sim$0.2 mm

Contamination and Depolarization

No Beam

- Hydrogen molecules $\sim 10^{-5}$
- Upper states $|c\rangle$ and $|d\rangle < 10^{-5}$
- Excited states $< 10^{-5}$
- Helium and residual gas $<$0.1%
  - measurable with the beam

100 μA Beam

- Depolarization by beam RF $< 2 \cdot 10^{-4}$
- Ion, electron contamination $< 10^{-5}$
- Excited states $< 10^{-5}$
- Ionization heating $< 10^{-10}$

Expected depolarization $< 2 \cdot 10^{-4}$

R&D and initial design - before major commitments

- Proof of principle
  - How to make electrodes in the 0.3 K copper cell with He film to provide E$\sim$1 V/cm?
  - Revisiting some calculations: new calculations/data on atomic cross sections at 0.3 K?
- Adapting to Hall A polarimetry
  - How to make thermal shielding from the beamline?
  - Cooling: He consumption - do we have enough power?
  - How to align the magnet and avoid the beam steering?
  - How to detect trajectories before Q1 (needed to identify the interaction position - essential to identify the residual gas contribution)
  - Optics at 12 GeV
  - What space along the beam is needed? Do we have enough space on the beamline?

Conclusion

New PV experiments require a ∼0.4% polarimetry.
Two options for the Møller polarimetry:

Iron foil in strong field

- Not continuous
- Invasive
- Certain: 0.8%
- Potential: 0.5% with R&D
  - manpower ∼ 4 FTE*Y
  - low material cost (∼ 50k)

Atomic hydrogen

- Continuous
- Not invasive
- Novel instrument
- Potential: 0.25%!
- Possible steps:
  - R&D - cell with electrodes 1 FTE*Y, 50k
- Interest expressed:
  - UVA (Don Crabb)
  - Mainz (Frank Maas)

Hall A Møller Polarimeter: high field iron target

Motivated by PREX requirements:

- High field magnetization (Hall C target clone)
- High instantaneous beam current:
  reduce heating by introducing a beam duty cycle $< 5\%$
  - Beam rep. rate 500 MHz/4 - $\mathcal{F}_{laser} \cdot (n+1) = \mathcal{F}_{RF} \cdot n$ “beat”
  - “Tune beam”: 4 ms pulses at $\sim$60 Hz
  - Instantaneous counting rate at 50μA will be $\times 3$ higher
  - More invasive than a kicker scheme
- Electronics upgrade to digest higher rates

Target heating with the real raster

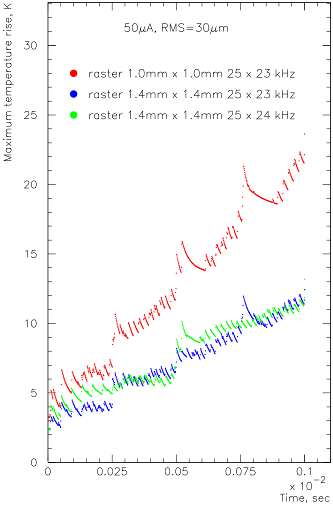
Average heating by 1.5 μA

- $\Delta T_{max} \sim 22$ K no raster
- $\Delta T_{max} \sim 12$ K raster 1×1 mm^2

Instantaneous heating by 50 μA

50 μA, $\sigma_X \sim 30$ μm, $\Delta t = 1$ ms
Raster $\sim 1.4 \times 1.4$ mm^2, 25×24 kHz

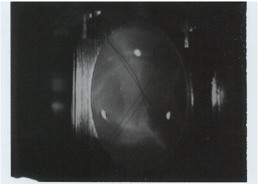
- In pulse $\Delta T_{max} \sim 12$ K
- Total $\Delta T_{max} \sim 24$ K - acceptable!



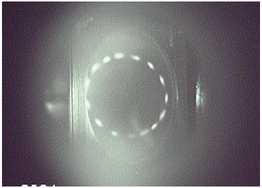
Bunch suppression

Options (from the draft of a paper by M.Poelker et al)

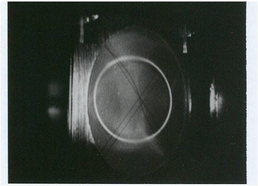
- G0: laser running at $499/16 MHz$ - too long to install
- For regular bunch charges: laser at $\mathcal{F}_{laser} < \mathcal{F}_{RF}$ bunch suppression on the chopper.
  Beat frequency condition ($\mathcal{F}_{RF} = 499 MHz$):
  $\mathcal{F}_{laser} \cdot (n+1) = \mathcal{F}_{RF} \cdot n$,
  $n = 3, 4, 7, 15, 31, ...$ - “magic” numbers



regular $\mathcal{F}_{laser} = \mathcal{F}_{RF}$



$n = 15$

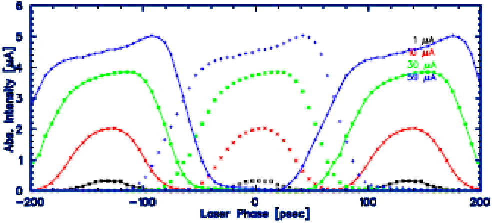


continuous

Beat frequency mode - leak through

Pulses overlap

- τ_{pulse} ~200 ps @50 μA
- τ_{pulse} grows with $\mathcal{I}_{beam}$ (electro-repulsion)
- Fully open slit 110 ps
- No leak: $\Delta\tau > 160$ ps



Optimization

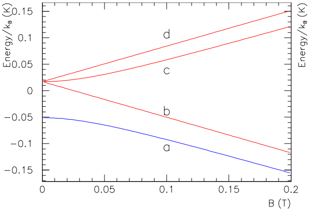
- n=15 same slit $\Delta\tau = 133$ ps, contamination $\sim 5\%$ - bad
- n=7 same slit $\Delta\tau = 285$ ps, no contamination; other slit $\Delta\tau = 95$ ps leak $\sim 30\%$ - invasive for other halls
- n=4 other slit $\Delta\tau = 166$ ps non-invasive?

Hydrogen Atom in Magnetic Field

H_1: $\vec{\mu} \approx \vec{\mu_e}$;
H_2: opposite electron spins

Consider H_1 in $B = 7\ T$ at $T = 300\ mK$
At thermodynamical equilibrium:
$n_+/n_- = exp(-2\mu B/kT) \approx 10^{-14}$

Complication from hyperfine splitting:



Low energy	High energy
$\lvert b\rangle = \lvert \downarrow ⤈\rangle$	$\lvert d\rangle = \lvert \uparrow ⤉\rangle$
$\lvert a\rangle = \lvert \downarrow ⤉\rangle \cdot \cos\theta - \lvert \uparrow ⤈\rangle \cdot \sin\theta$	$\lvert c\rangle = \lvert \uparrow ⤈\rangle \cdot \cos\theta + \lvert \downarrow ⤉\rangle \cdot \sin\theta$

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where $\tan 2\theta \approx 0.05/B(T)$, at 7 T $\sin\theta \approx 0.0035$
Mixture ∼53% of $|a>$ and ∼47% of $|b>$:
$\mathcal{P}_e \sim 1 - \delta, \qquad \delta \sim 10^{-5}$,
$\mathcal{P}_p \sim\ -0.06$ (recombination ⇒ ∼80%)

Dynamic Equilibrium and Proton Polarization

Proton polarization builds up, because of recombination of states with opposite electron spins:

$|a\rangle = |\downarrow\text{⍏}\rangle\alpha + |\uparrow\text{⍖}\rangle\beta$ and

$|b\rangle = |\downarrow\text{⍖}\rangle$

As a result, $|a\rangle$ dies out and only $|b\rangle = \downarrow\text{⍖}$ is left!

$\mathcal{P} \rightarrow 0.8$

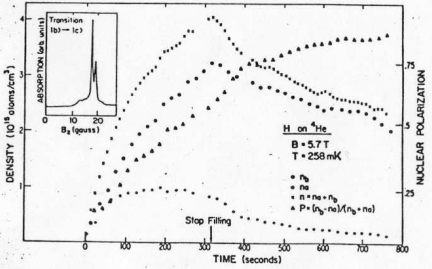


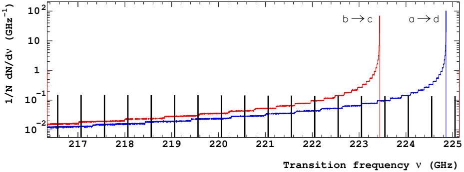
Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).

Contamination and Depolarization of the Target Gas

100 μA CEBAF beam:

Beam RF influence

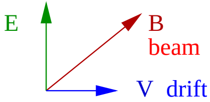
- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle$ $\sim$200 GHz
- RF spectrum: flat at $<$300 GHz



- $\sim 10^{-4}$ s^{-1} conversions (all atoms)
- $\sim$ 6% s^{-1} conversions (beam area)
- Diffusion: contamination $\sim 1.5 \cdot 10^{-4}$ in the beam area
- Solenoid tune to avoid resonances

Gas Ionization

- 10^{-5} s^{-1} of all atoms
- 20% s^{-1} in the beam area
- Problems:
  - No transverse diffusion
  - Recombination suppressed
  - Contamination $\sim$40% in beam
- Solution: electric field $\sim$1 V/cm
  - Drift $v = \vec{E} \times \vec{B}/B^2 \sim$ 12 m/s
  - Cleaning time $\sim$ 20 μs
  - Contamination $< 10^{-5}$
  - Ions, electrons: same direction
  - Beam $\overline{E_r}(160\mu\text{m}) \approx 0.2$ V/cm



Summary on Atomic Hydrogen for Møller Polarimetry

Potential for Polarimetry

- Systematic accuracy of $< 0.3\%$
- Continuous measurements
- Tools for systematic studies:
  changing the electrical field (ionization)
  changing the magnetic field (RF depolarization)

Problems and Questions

- Electrodes in the cell: R&D is needed
- Residual gas 0.1% accurate subtraction
  Coordinate detectors: the interaction point?
- Atomic cross section (mean free path...) needs verification
- Cost and complexity

Potential Improvement of Systematic Accuracy

Fe at 3T: potential improvement (quite optimistic):

- Better understanding of magnetization in thin foils (find experts)
- More extensive MC and beam studies
- Measurements: 0.1% stat ⇒ *3-5h beamtime* ⇒ beam stability?

Variable	Hall C	Hall A		
		Fe at 3T		H_1 gas
Target polarization	0.25%	0.50%	0.25%	0.01%
Target angle	0.00%	0.00%	0.00%	0.00%
Analyzing power	0.24%	0.30%	0.20%	0.15%
Levchuk effect	0.30%	0.20%	0.20%	0.00%
Target temperature	0.05%	0.02%	0.02%	0.00%
Dead time	-	0.30%	0.15%	0.10%
Background	-	0.30%	0.15%	0.10%
Others	0.10%	0.30%	0.15%	0.15%
Beam extrapolation	?	0.15%	0.15%	0.00%
Total	0.47%	0.82%	0.48%	0.25%