Measurements of Correlation Coefficients in Pulsed Neutron Beams

NPP @ LPS 2013

Grenoble, March 25th -27th 2013

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Physikalisches Institut
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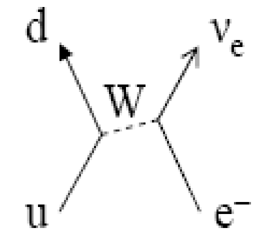
Contents

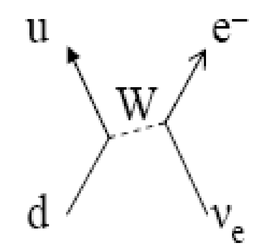
- Why we investigate neutron beta decay
- Beta asymmetry as an example
- Pulsed beam measurements with
  - PERKEO III
  - Proton Electron Radiation Channel
- Benefits of pulsed beams

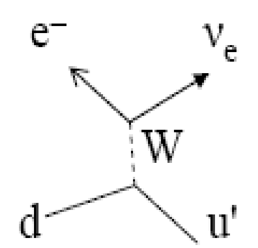
Neutron Decay Data are useful…

- Many processes share the same Feynman diagram.
- Neutron decay measurements **required** to measure couplings.

Primordial element formation	$n + e^+ \rightarrow p + \nu'_e$
(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$
	$n \rightarrow p + e^- + \nu'_e$
Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$
	$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.
Neutron star formation	$p + e^- \rightarrow n + \nu_e$
Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$
Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$
Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.
W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.







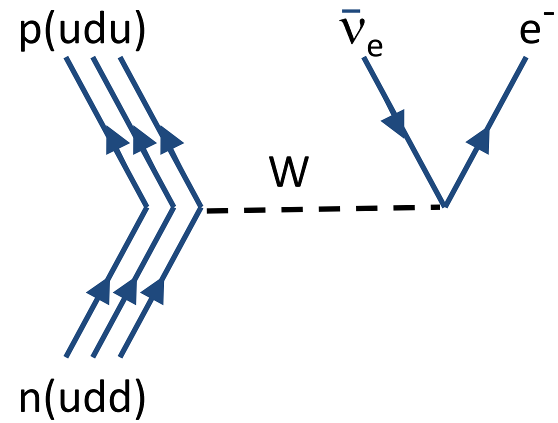
D. Dubbers

Neutron Decay

- Simplest semi-leptonic decay

$$n \rightarrow p + e^- + \overline{\nu}_e$$

long lifetime ~ 15 min
e^- endpoint energy 782 keV



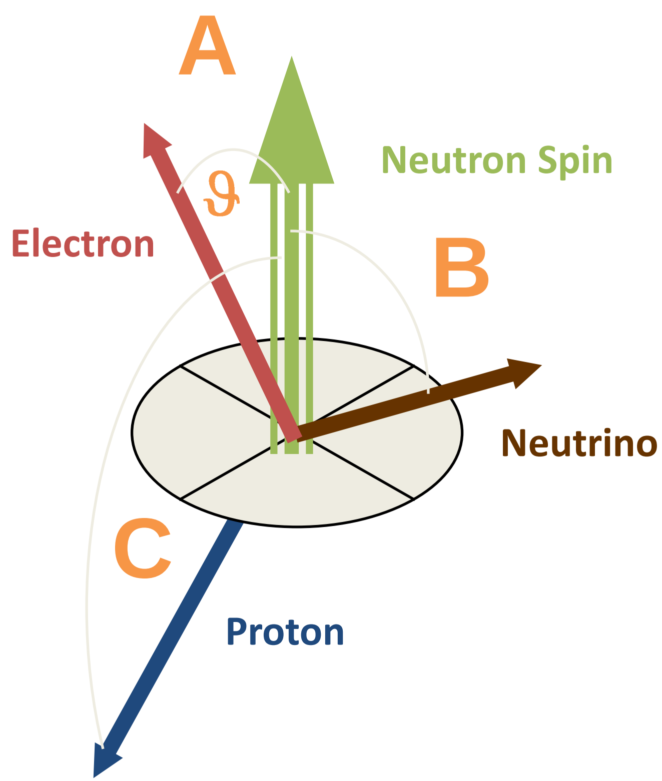
- Only 2 free parameters in standard model

lifetime: $$\tau^{-1} = G_F^2 |V_{ud}|^2 (1+3\lambda^2) \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7}$$

  - **Ratio** of coupling constants $\lambda = \frac{g_A}{g_V}$
  - **Quark mixing** from the Cabibbo-Kobayashi-Maskawa matrix V_{ud}

Only small radiative corrections, no nuclear structure

Correlations Coefficients



Beta Asymmetry A $A \approx -12\%$

UCNA, arXiv:1210.7048 (2013)
PERKEO II, PRL in print (2013) arXiv:1204.0013
PERKEO III, dissertation Mest (2011)

Neutrino Asymmetry B $B \approx 98\%$

PERKEO II, PRL 99 (2007)

Proton Asymmetry C $C \approx -24\%$

PERKEO II, PRL 100 (2008)

Electron-Neutrino Correlation a $a \approx -10\%$

Byrne et al., J. Phys. G 28 (2002)
***a*Spect** – running @ ILL
aCORN – running @ NIST

Triple Coefficient *D* $D = 0$

TRINE, PLB 581 (2004)
emiT, PRL 107 (2011)

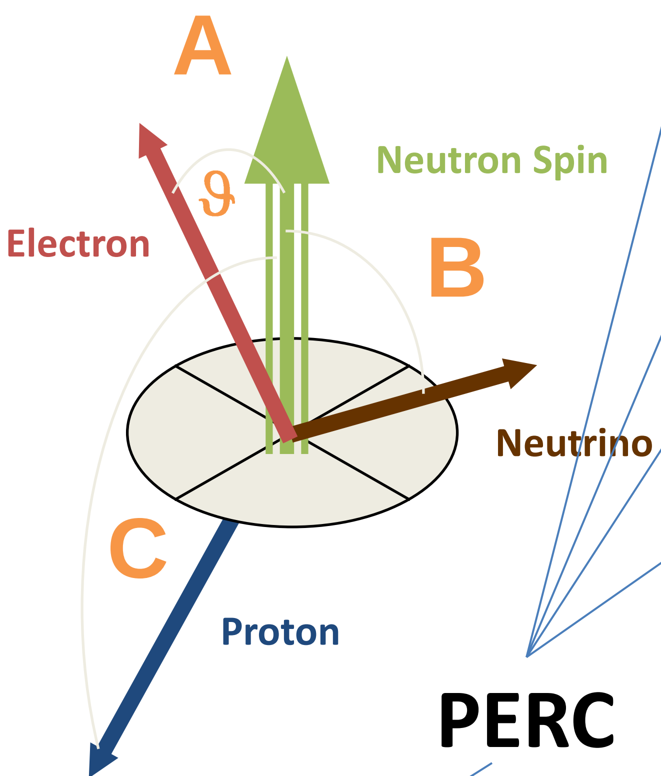
Electron-spin correlations

N, ***R*** – Kozela et al., PRL 102 (2009)

Unmeasured:

Fierz interference term ***b***
Weak magnetism f_2
Electron helicity ***h***

Correlations Coefficients



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Search for New Physics

→ <u>Combine</u> measurements of different observables

- Unitarity test of **quark mixing matrix** (Cabibbo-Kobayashi-Maskawa, CKM)
  e.g. supersymmetry, leptoquarks

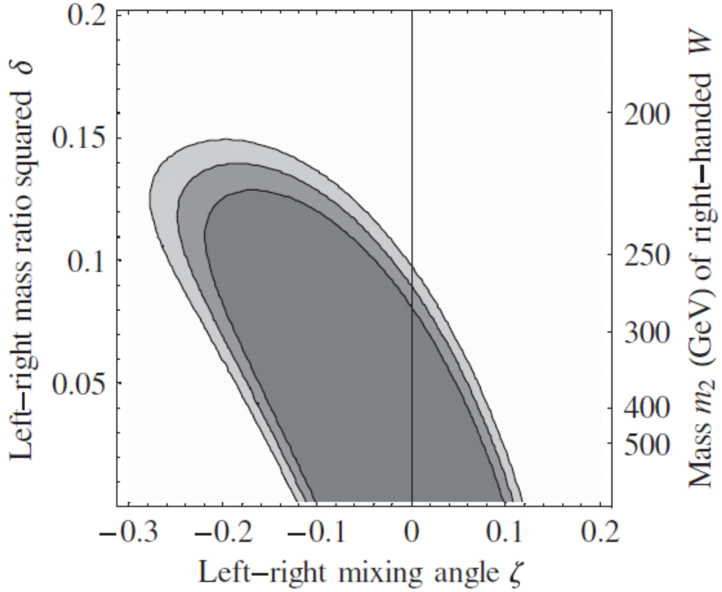
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \varepsilon$$

- **Right handed currents**
  e.g. left-right symmetric models, exotic fermions

- **Scalar** and **tensor** couplings
  e.g. supersymmetry

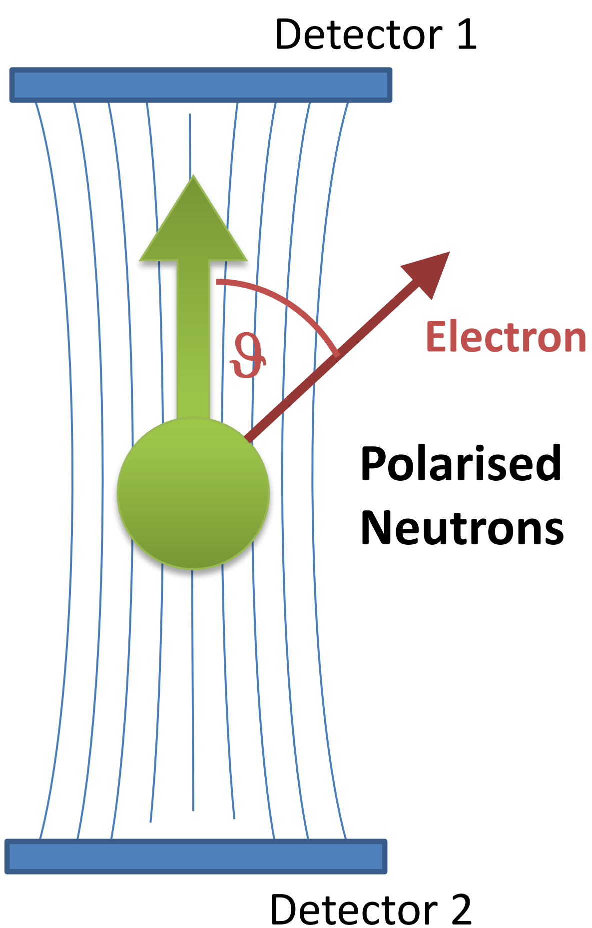
For future limits see also
Konrad et al., arXiv:1007.3027

Current neutron limits on r.h.c –
Manifest left-righ symmetric model
Parameters A, B, C



Dubbers, Schmidt, Rev. Mod. Phys 83

Measuring Beta Asymmetry



- Electron Angular Distribution:

$$W(\vartheta, E) = 1 + \frac{v}{c} A \cos\vartheta$$

- Within Standard Model:

$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \qquad \lambda = \frac{g_A}{g_V}$$

- Magnetic Field to as Quantisation Axis
- Integration over Hemispheres: $\cos\vartheta = 1/2$
  2 × 2π detection
- Experimental Asymmetry

$$A_{\exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2}\frac{v}{c} P A$$

Beta Asymmetry - Experimental Challenges

- **Electron Spectroscopy**

  Magnetic field design

  time-of-flight of backscattered electrons

- **Neutron Polarisation P**

  Analysis with ILL's „Magic Box" – ^{3}He spin filter

$$A_{exp} = \frac{1}{2}\frac{v}{c} P A$$

- **Counting Statistics**

  Long lifetime 15 min, velocity of cold neutrons v ~ 700 m/s

  Large (long) active volume, strong cold beam

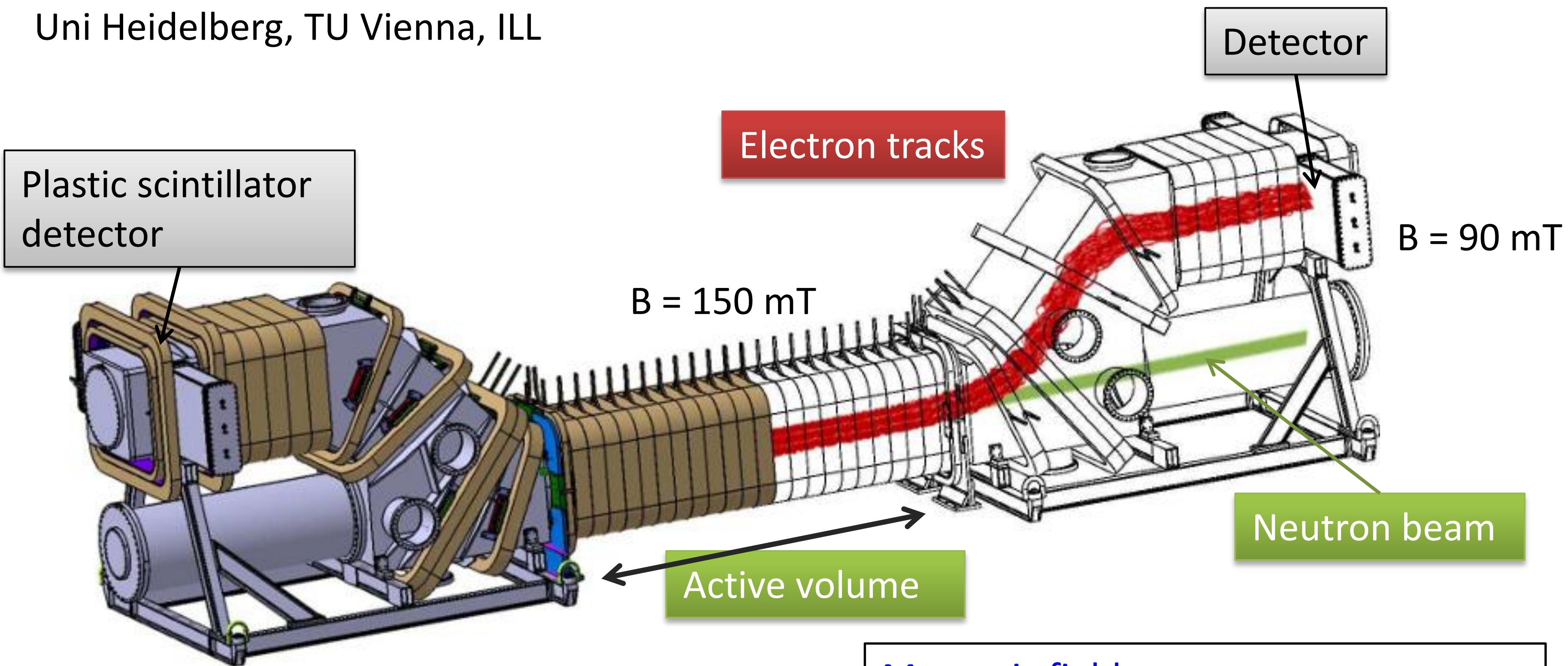
- **Background**

  Only few neutrons decay, others potentially cause background: Pulsed Beam

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow} + \mathrm{Bg}}$$

Spectrometer PERKEO III

Uni Heidelberg, TU Vienna, ILL



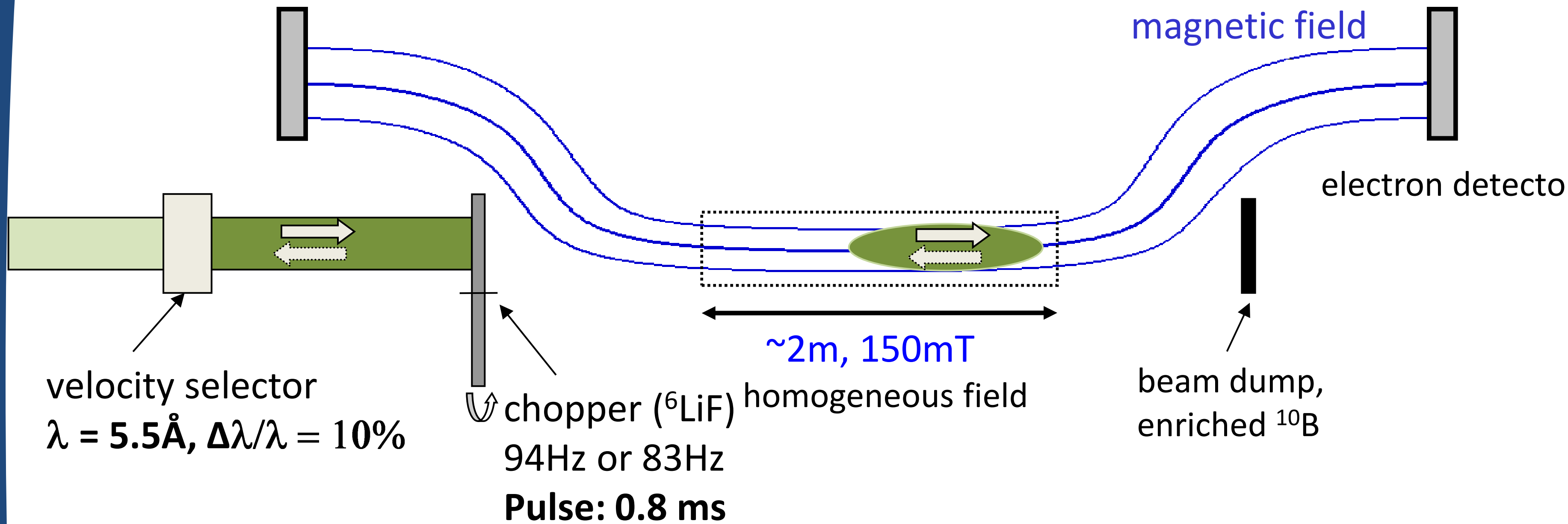
Total length: 8 m
Event rate CW, polarised: 50 000 s^{-1}
Installation at cold beam PF1b, ILL

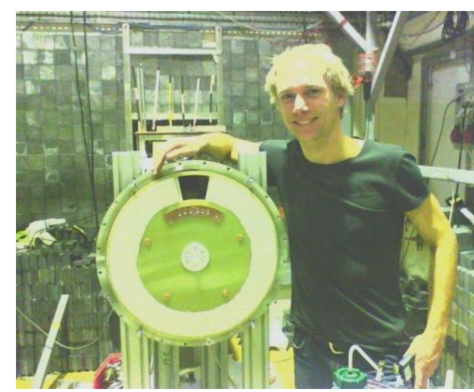
B. Märkisch et al., NIM A 611 (2009) 216–218

Magnetic field :

- alignment of n–spin
- guide e^-, p onto detectors
  $\Rightarrow$ 2 x 2 π detector
- separation into hemispheres

Pulsed Cold Neutron Beam at ILL



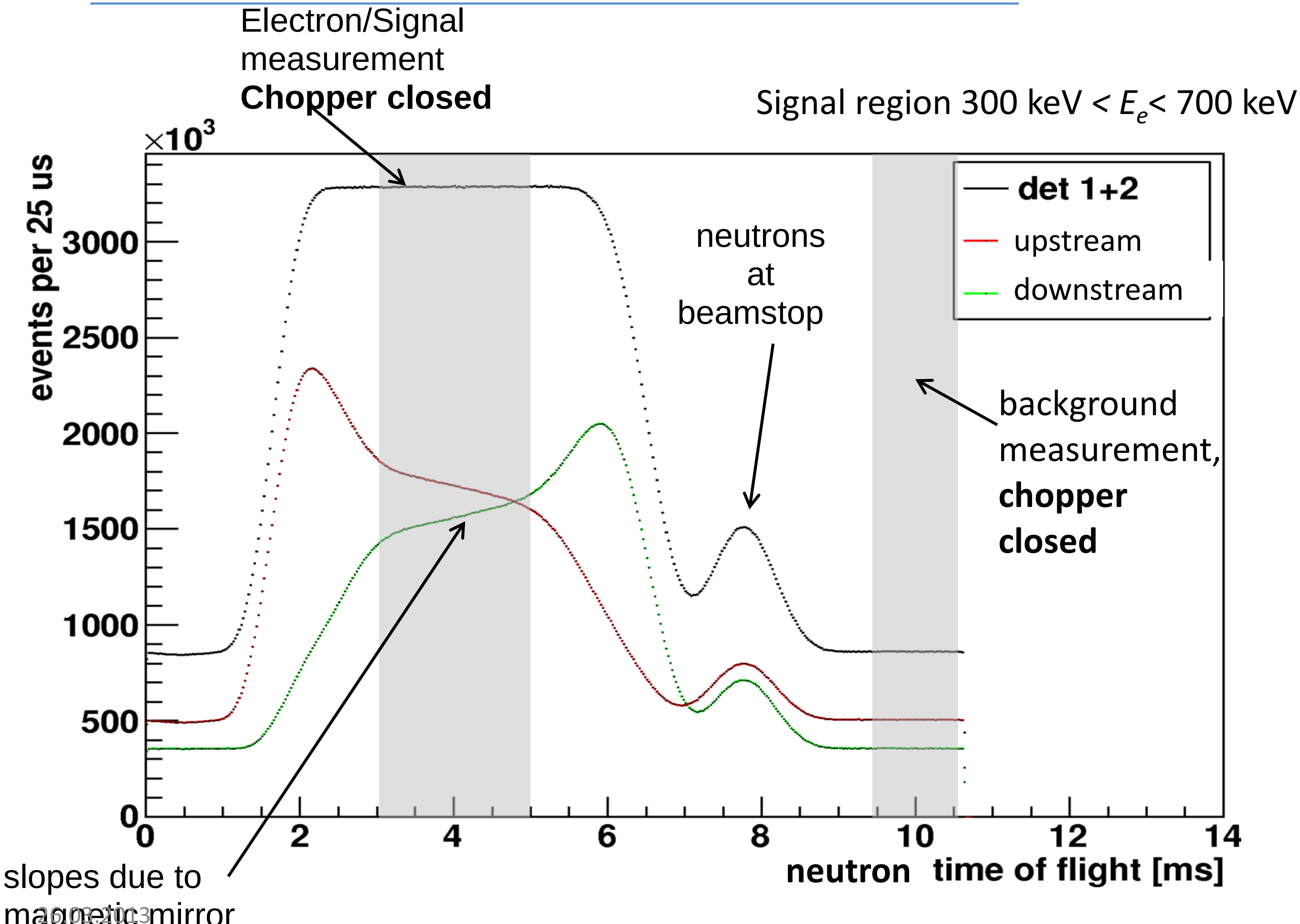


Eliminate leading sources of error:

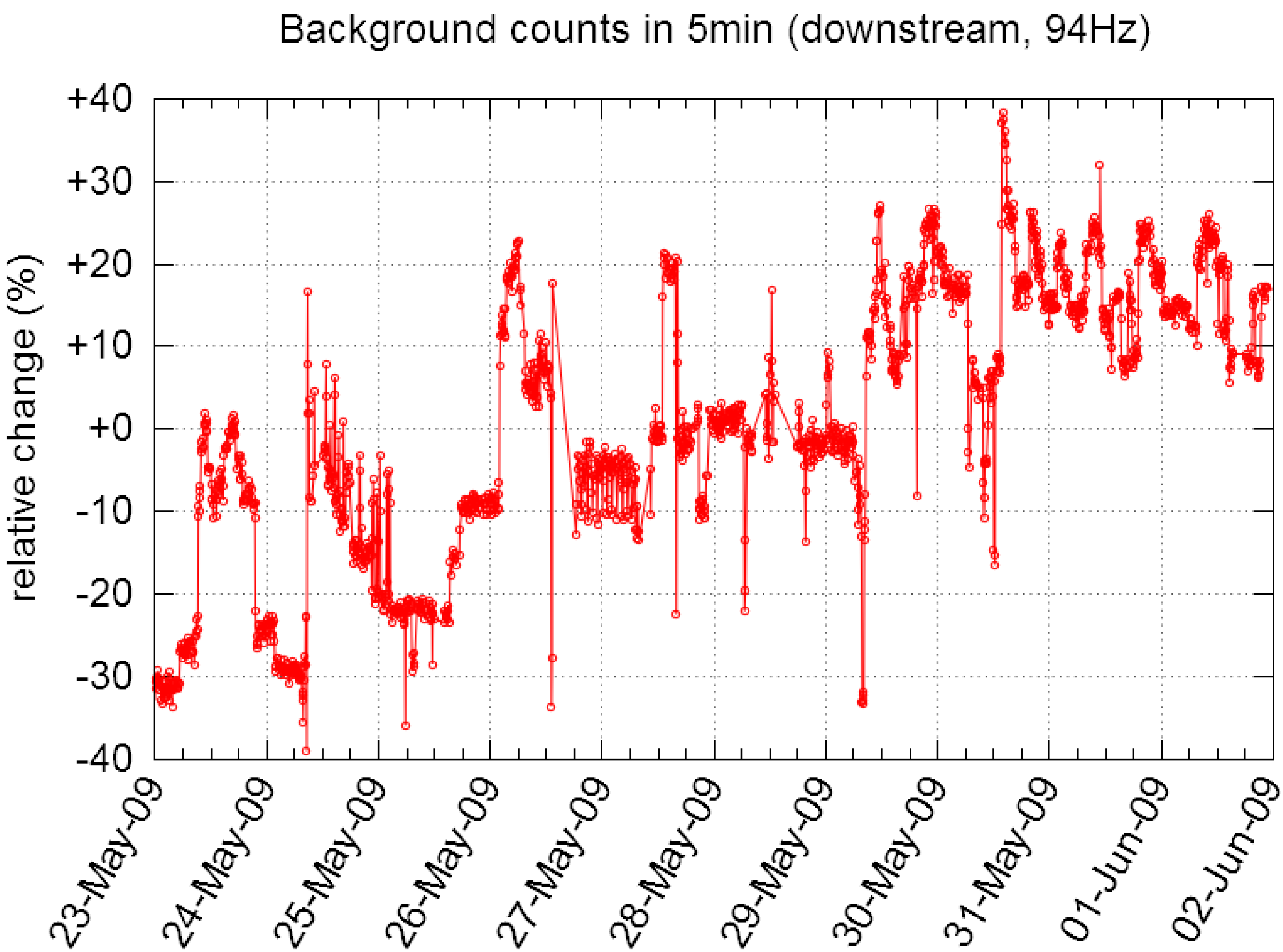
- *Edge-free projection* onto detectors:
  full 2 x 2π detection without distortions
- Background *fully measured and subtracted*
- Control *magnetic mirror effect*

B. Märkisch et al., NIM A 611 (2009) 216–218

Pulsed Neutron Beam



Background Produced by Neighbours

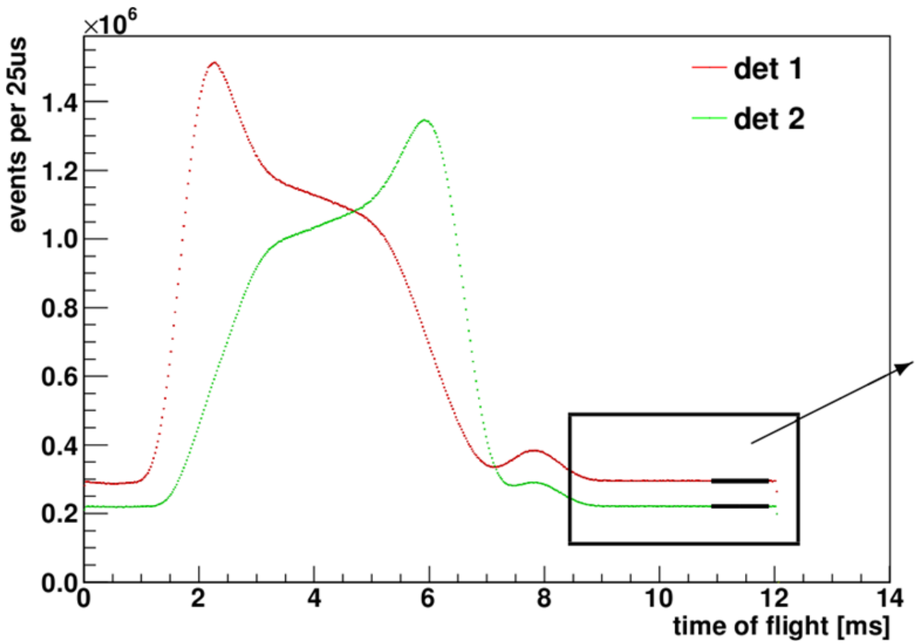


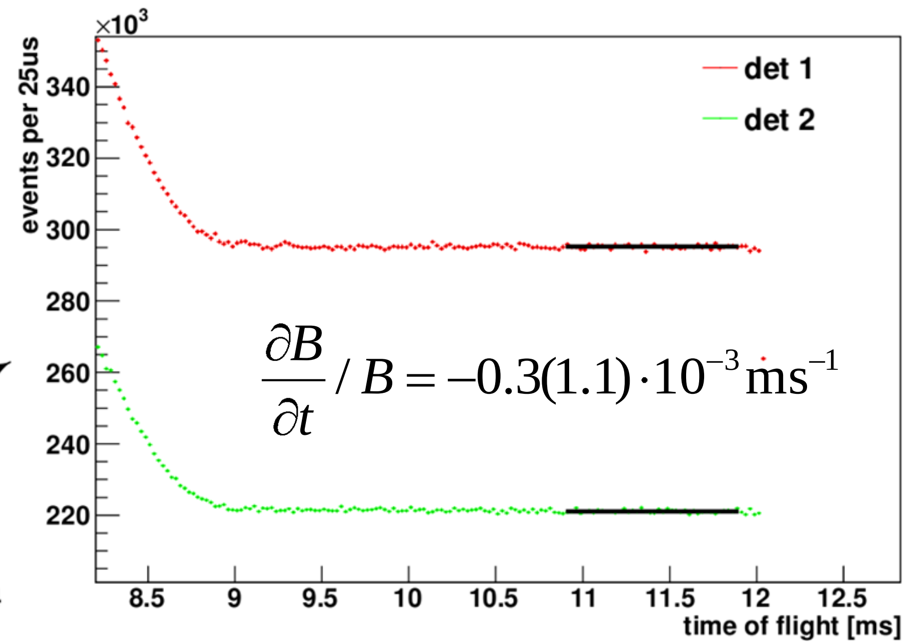
Background Subtraction

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow} + \mathrm{Bg}}$$

No time variation of measured background! (neutron TOF)

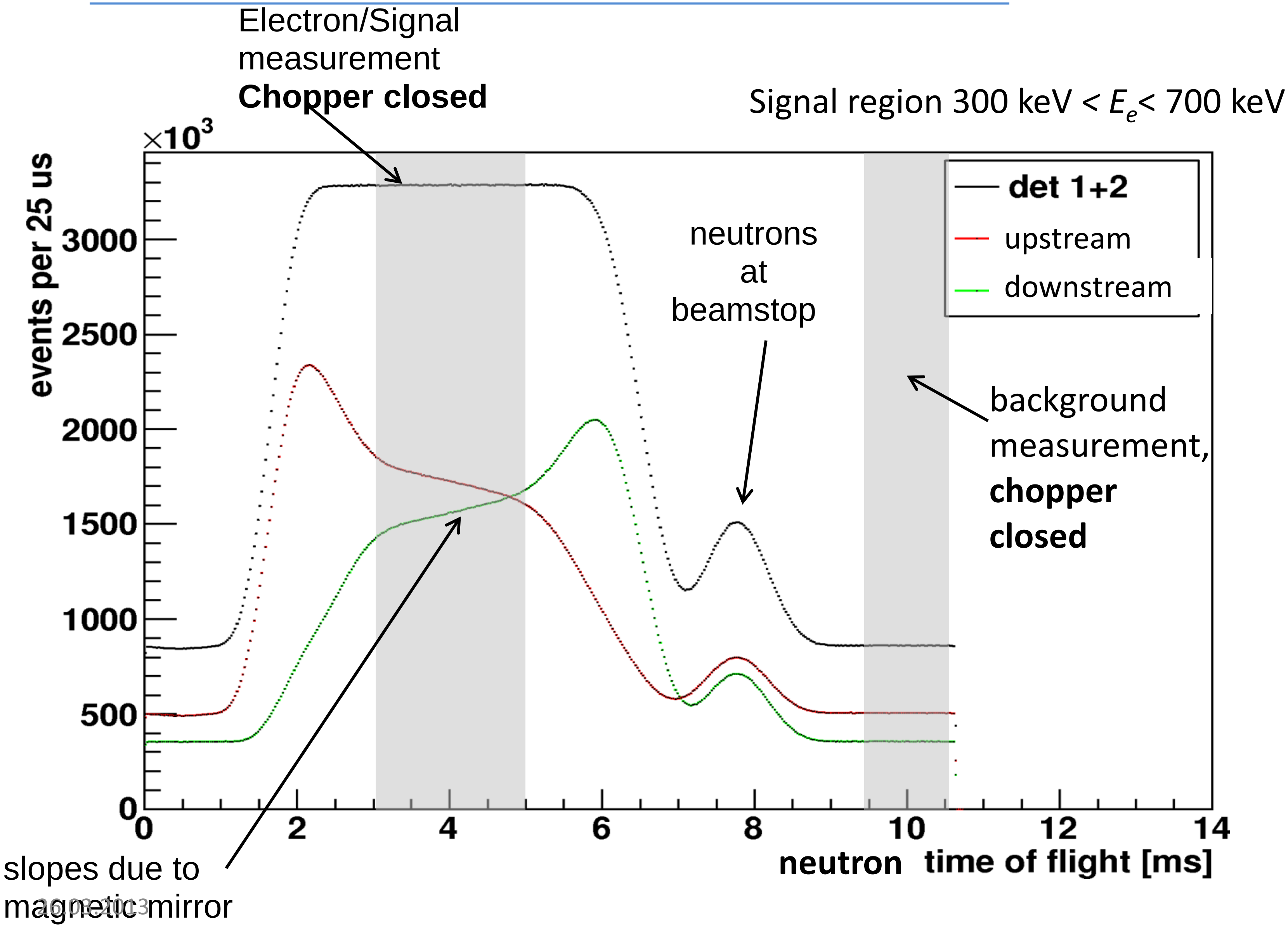
-> Total uncertainty on background: $\frac{\Delta A}{A} = 1 \cdot 10^{-4}$





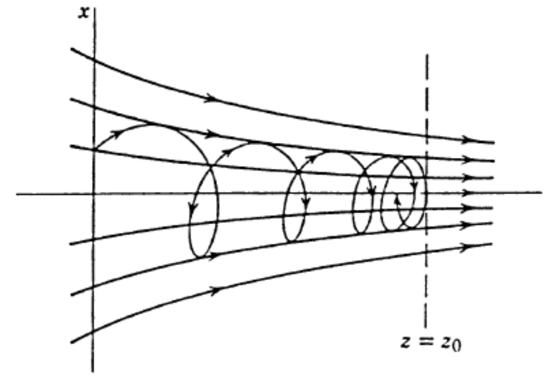
Signal region 300 keV < E < 700 keV

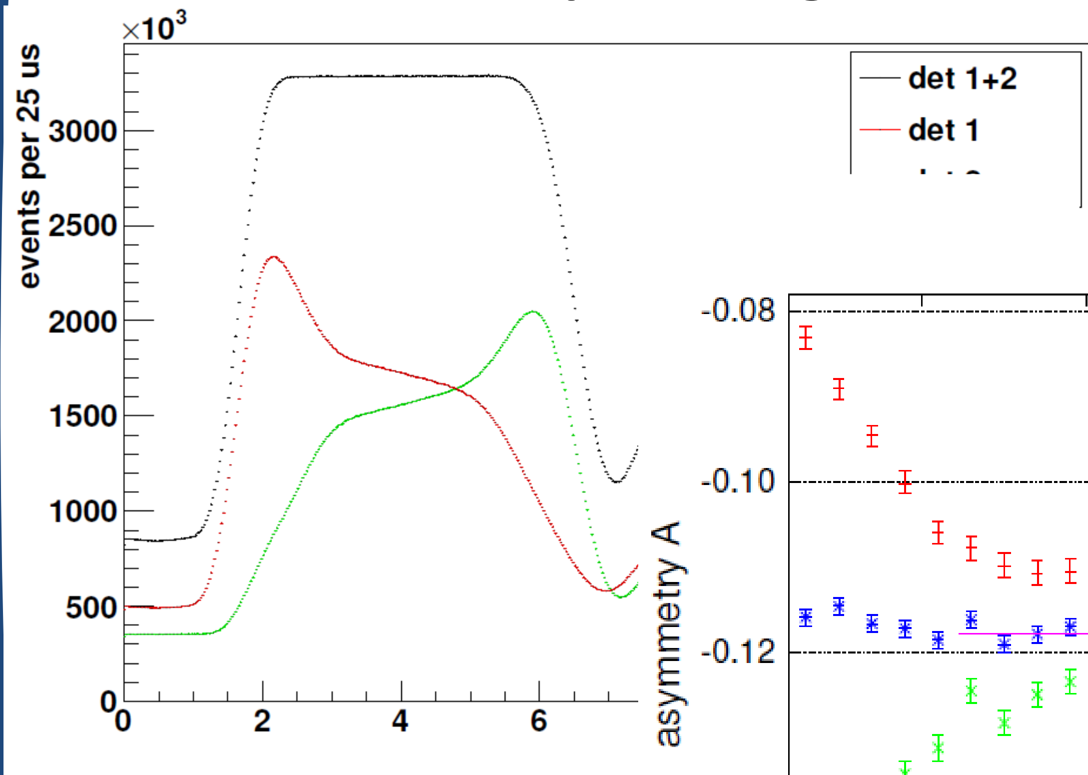
Pulsed Neutron Beam

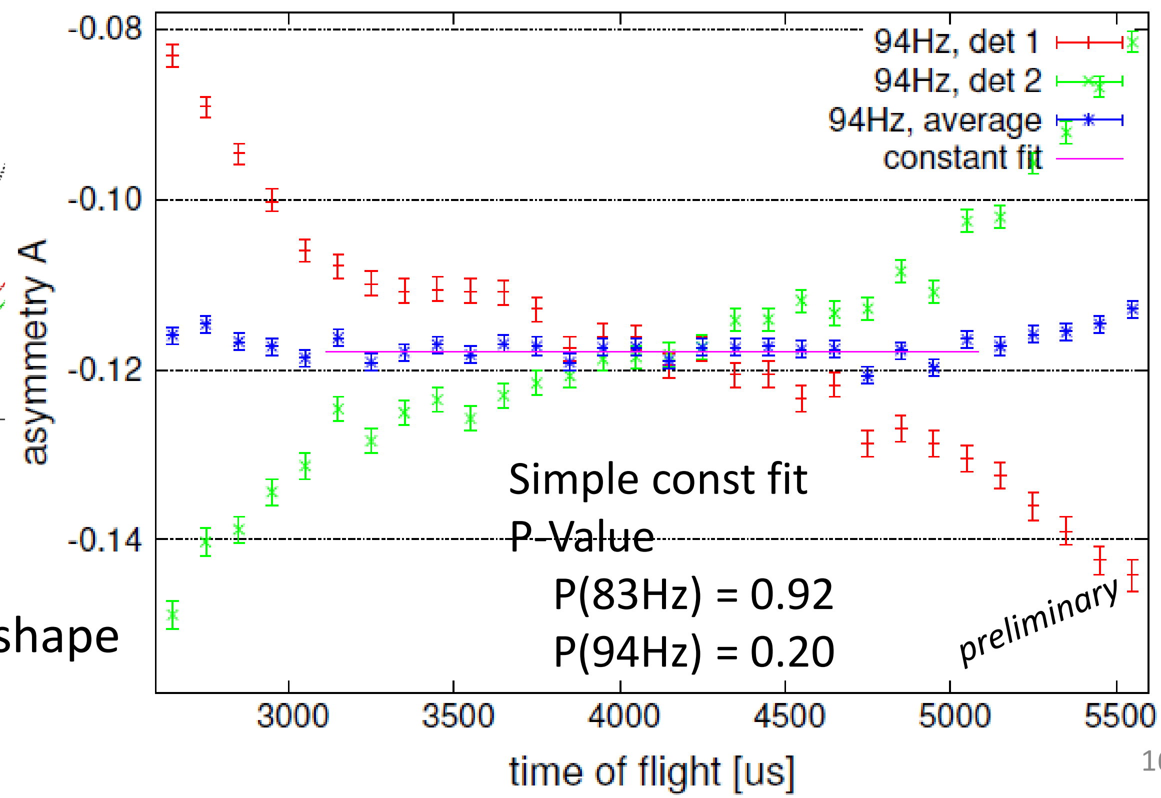


Magnetic Mirror Effect

Effect due to **shape of magnetic field**:



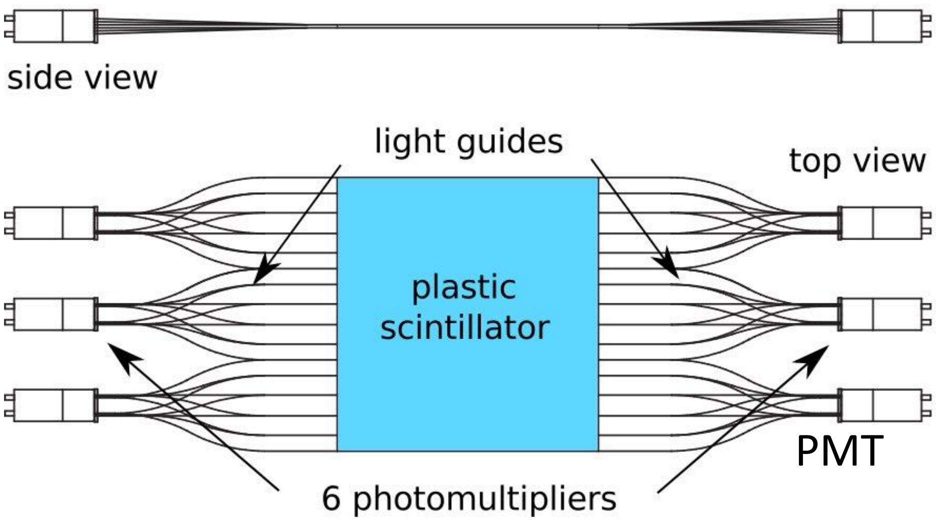




O(1%) Correction, known:

- measured neutron pulse shape
- magnetic field map

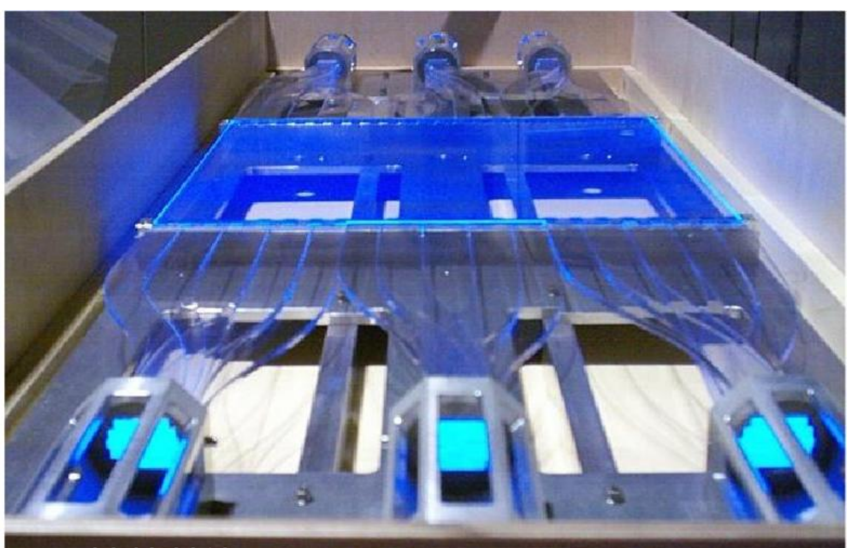
Electron Detector



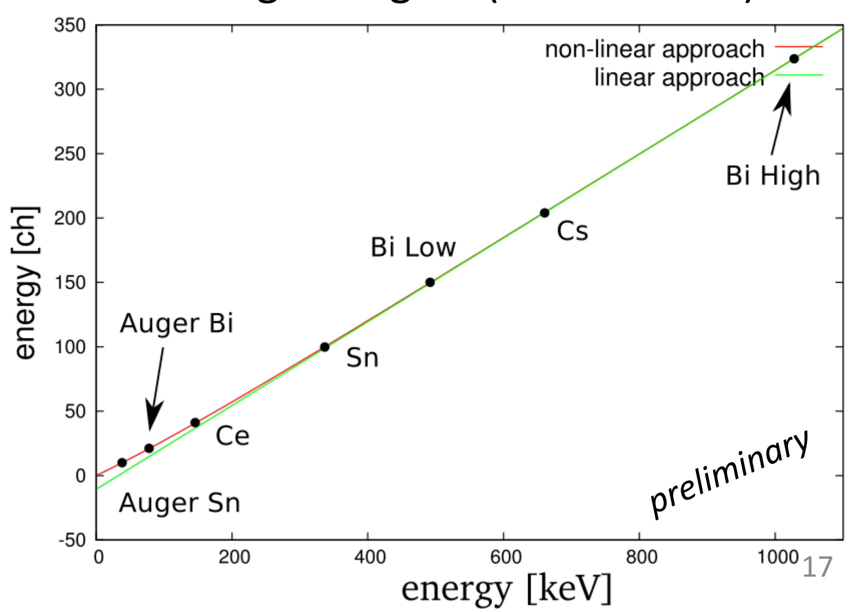
Area ~ 40 x 40 cm²,
Light output >160 PE/MeV

Electron Conversion Calibration Sources:

- ^{207}Bi – 500 keV, 1.06 MeV, 2 Auger
- ^{137}Cs – 630 keV, 2 beta spectra
- ^{113}Sn – 370 keV, Augers
- ^{139}Ce – 130 keV



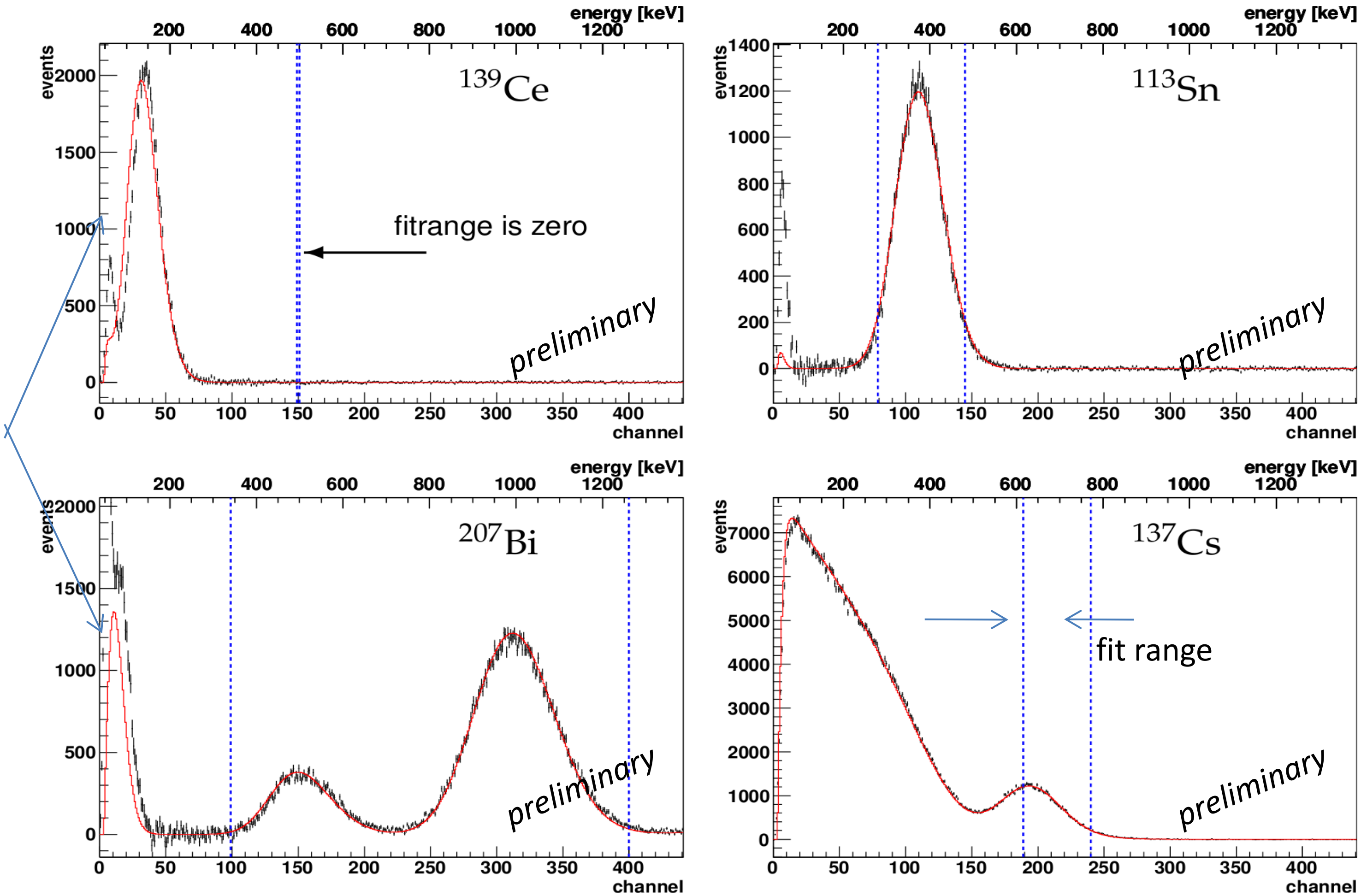
Linear in signal region (300-700 keV)



Detector Calibration

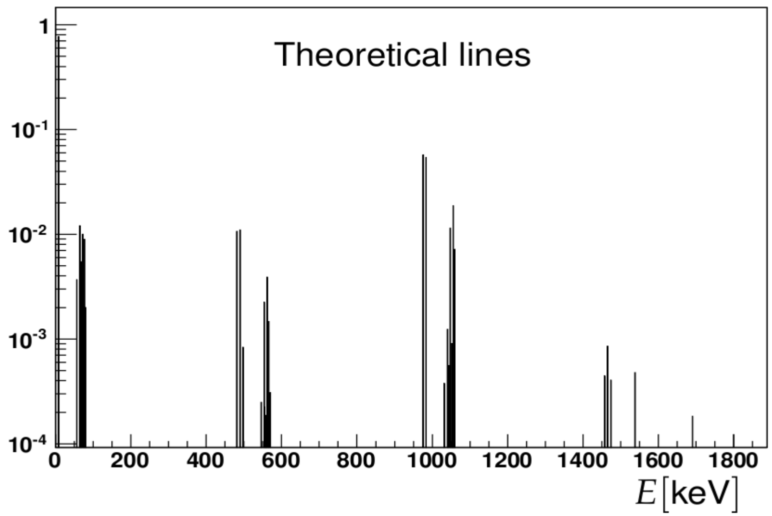
Simultaneous fits; No gamma background from sources!

non-
linearity



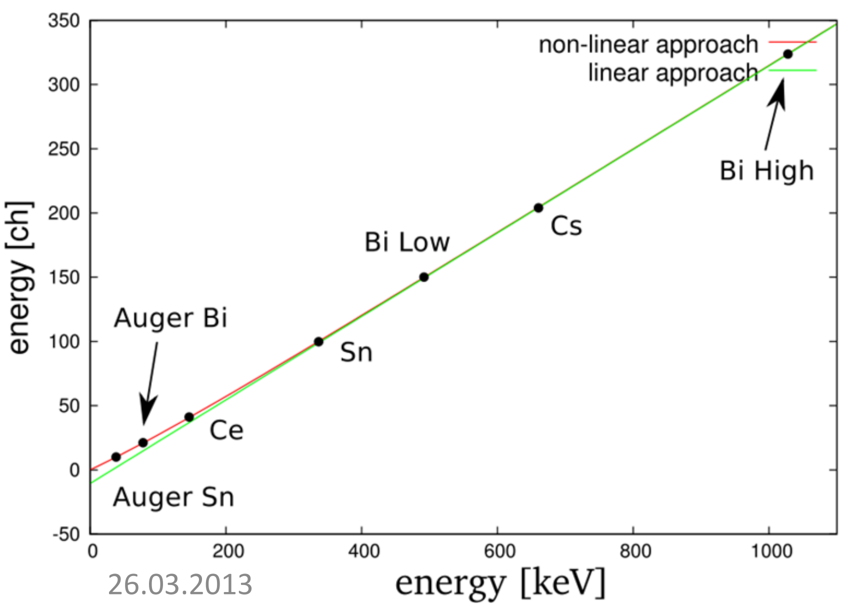
Hourly calibration measurements to control drifts, full calibration twice a day

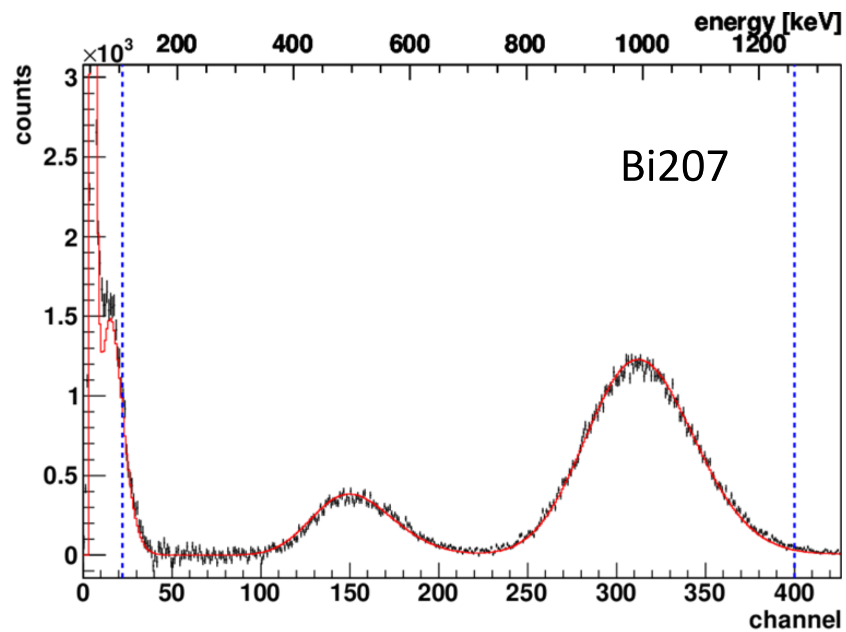
Detector Linearity



Model Detector Properties
(Photoelectron statistics,
Noise, non-linearity)

Response is linear in signal region



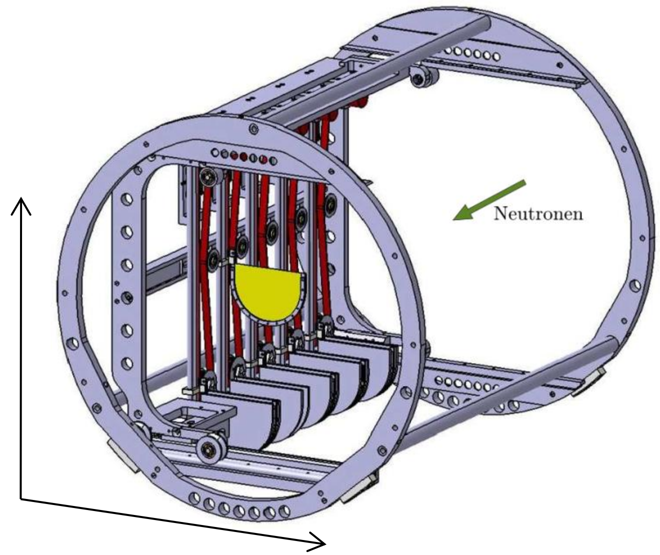


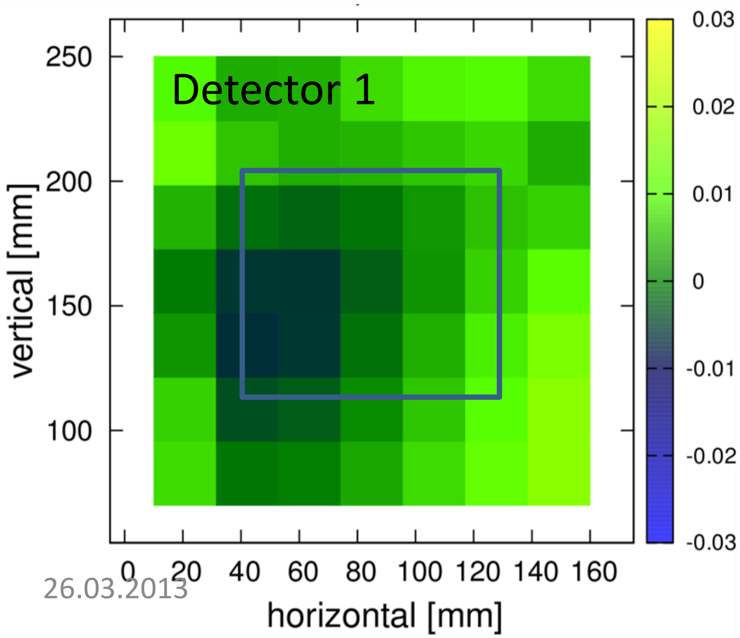
Uniformity of Light Output

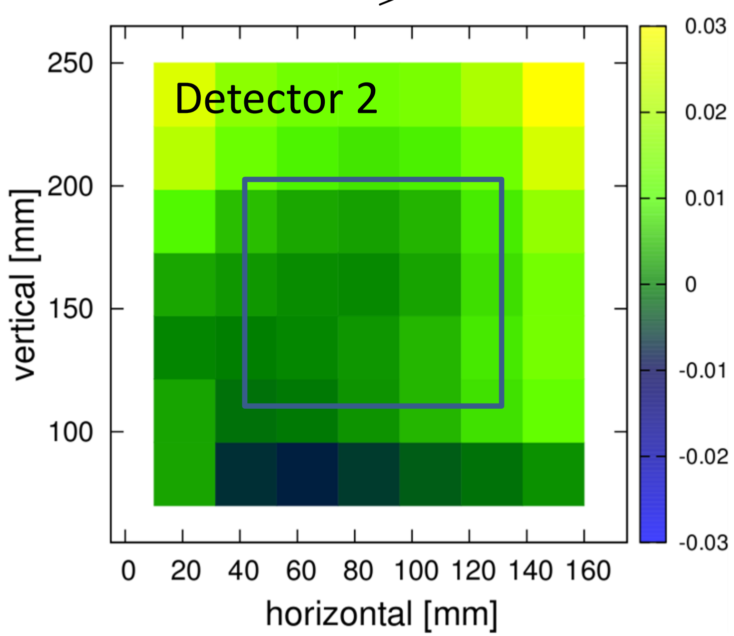
Verification of uniformity with calibration sources:

better than ±1%

Measured attenuation length: 670 mm
Intrinsic 1600 mm

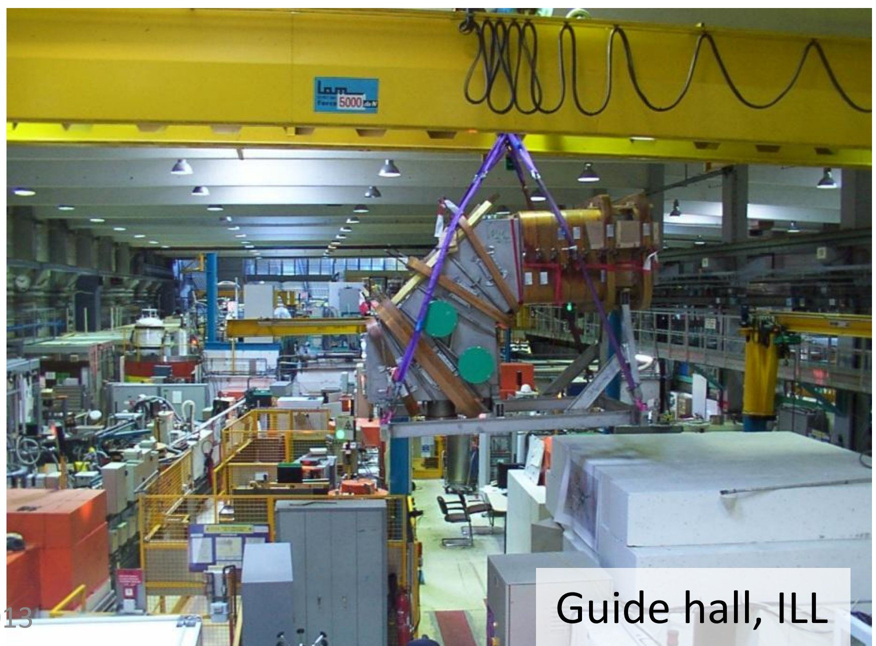






Installation at PF1B, ILL

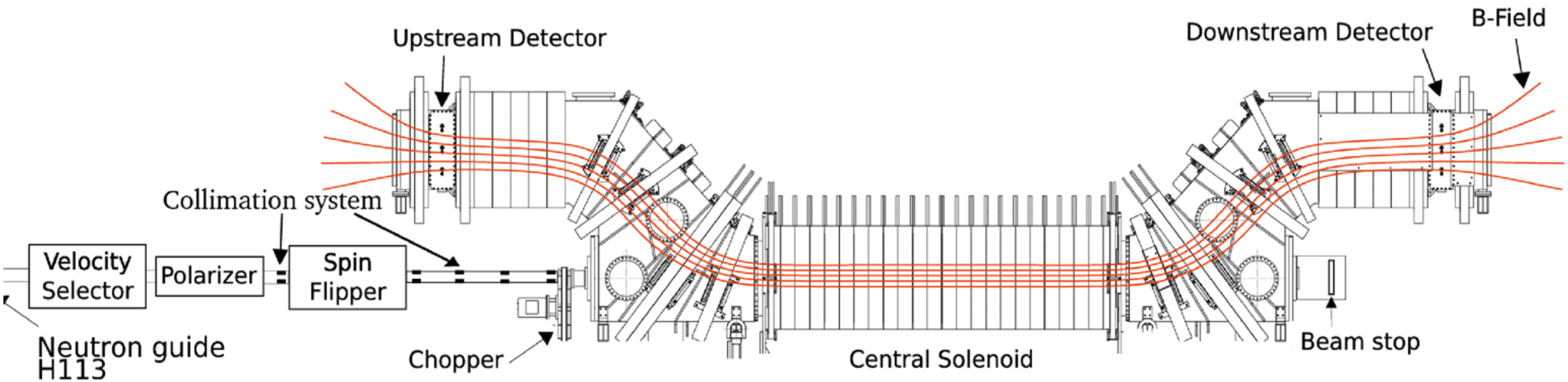
One of two trucks



Guide hall, ILL

Experimental Zone

Installation at ILL, PF1B, 2009



- Unpolarised capture flux density $\phi_c = 2 \cdot 10^{10} \frac{1}{\mathrm{s\,cm}^2}$
- Single supermirror polariser, max. transmission
- Velocity selector, 5.5 Å, FWHM ~10%
- Adiabatic Fast Passage spin flipper (RF)
- LiF collimation system 6x6cm²
- LiF chopper, 83 Hz or 94 Hz

Total 140 days of beamtime
55 days setup, characterization, optimisation
25 days polarization measurements (*)
60 days beta decay measurement

96% of data acquired in analysis
$6 \cdot 10^8$ neutron decay events detected

Perkeo III - Error Budget, Preliminary

Thesis Holger Mest, Uni HD

Effect on Asymmetry A	Relative Correction	Relative Uncertainty $\Delta A / A$
•Polarisation $\mathcal{P}$	separate analysis	$\leq 10 \cdot 10^{-4}$ (Polarisation and Spinflip efficiency combined)
•Spinflip efficiency $\mathcal{F}$		
•Magn. mirror effect	separate analysis	$\leq 8 \cdot 10^{-4}$
*Background (measured)	$-2.0 \cdot 10^{-4}$	$0.9 \cdot 10^{-4}$
*Deadtime	$-5.0 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
*Detector drift		$4 \cdot 10^{-4}$
*Detector calibration		$5 \cdot 10^{-4}$
*Short gate time		$1.4 \cdot 10^{-4}$
*•Systematics	to be finalised	$\leq 14.6 \cdot 10^{-4}$
†Ext. radiative corr.	- $9 \cdot 10^{-4}$	$5 \cdot 10^{-4}$
*Statistics		$13.7 \cdot 10^{-4}$
Total		$\leq 2.1 \cdot 10^{-3}$

$$A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

Preliminary Result:

$$\frac{\Delta A}{A} = 2.1 \cdot 10^{-3}$$

$$\frac{\Delta \lambda}{\lambda} = 5.3 \cdot 10^{-4}$$

Total correction ~ 2 %

PERKEO III Collaboration

University of Heidelberg

D. Dubbers, B. Märkisch, H. Mest, C. Roick, D. Werder

TU Vienna, TU Munich

H. Abele, H. Saul, X. Wang

Institut Laue Langevin, Grenoble

T. Soldner, A. Petoukhov

Perkeo III Team, ILL 2009

Proton Electron Radiation Channel

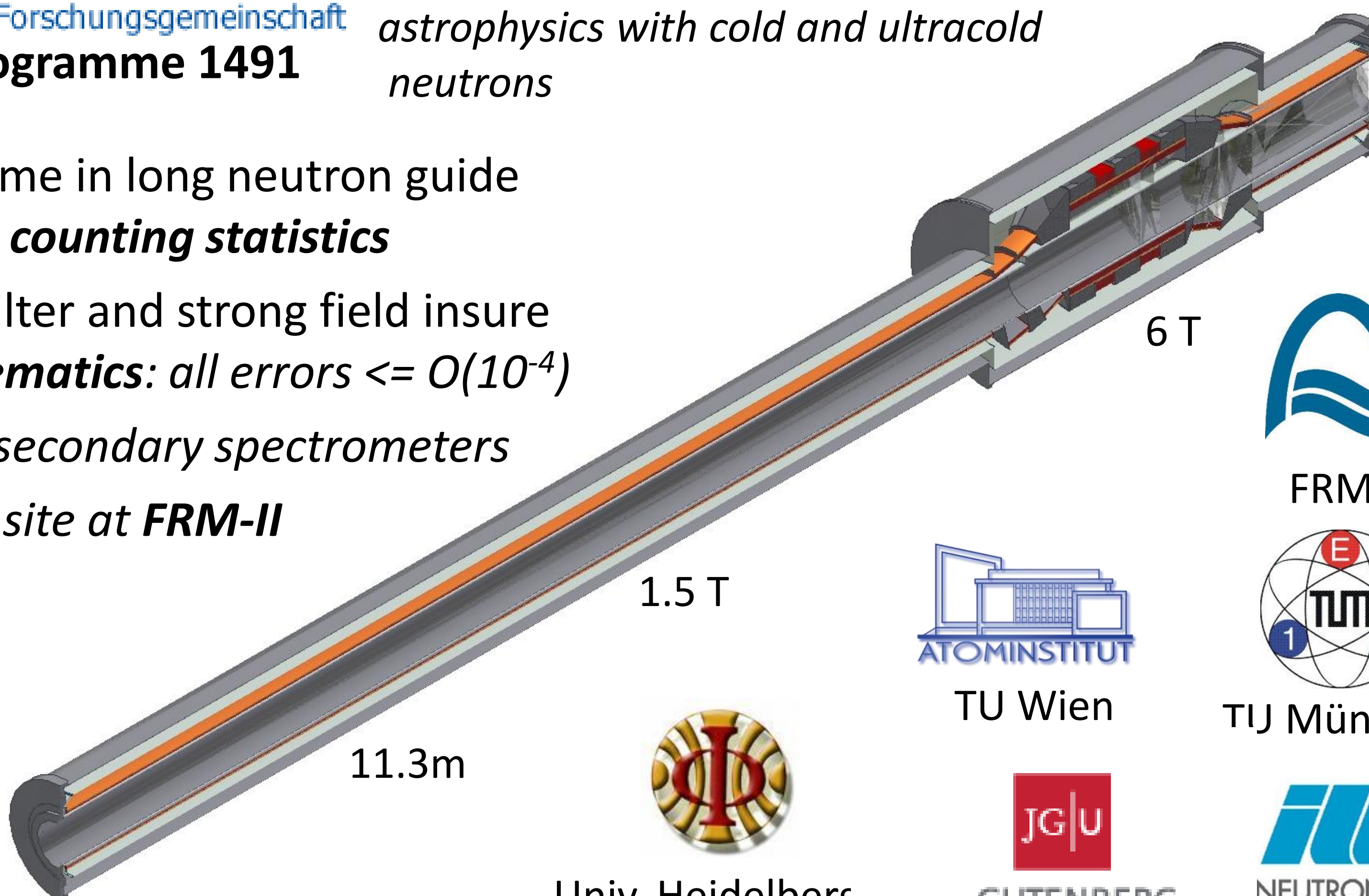
PERC

DFG Deutsche Forschungsgemeinschaft

Priority Programme 1491

Precision experiments in particle and astrophysics with cold and ultracold neutrons

- Active volume in long neutron guide ***maximises counting statistics***
- Magnetic filter and strong field insure ***clean systematics****: all errors <= O(10^{-4})*
- ***Source*** *for secondary spectrometers*
- *New beam site at* ***FRM-II***



Preliminary Magnet Design

FRM-II

ATOMINSTITUT

TU Wien

TU München

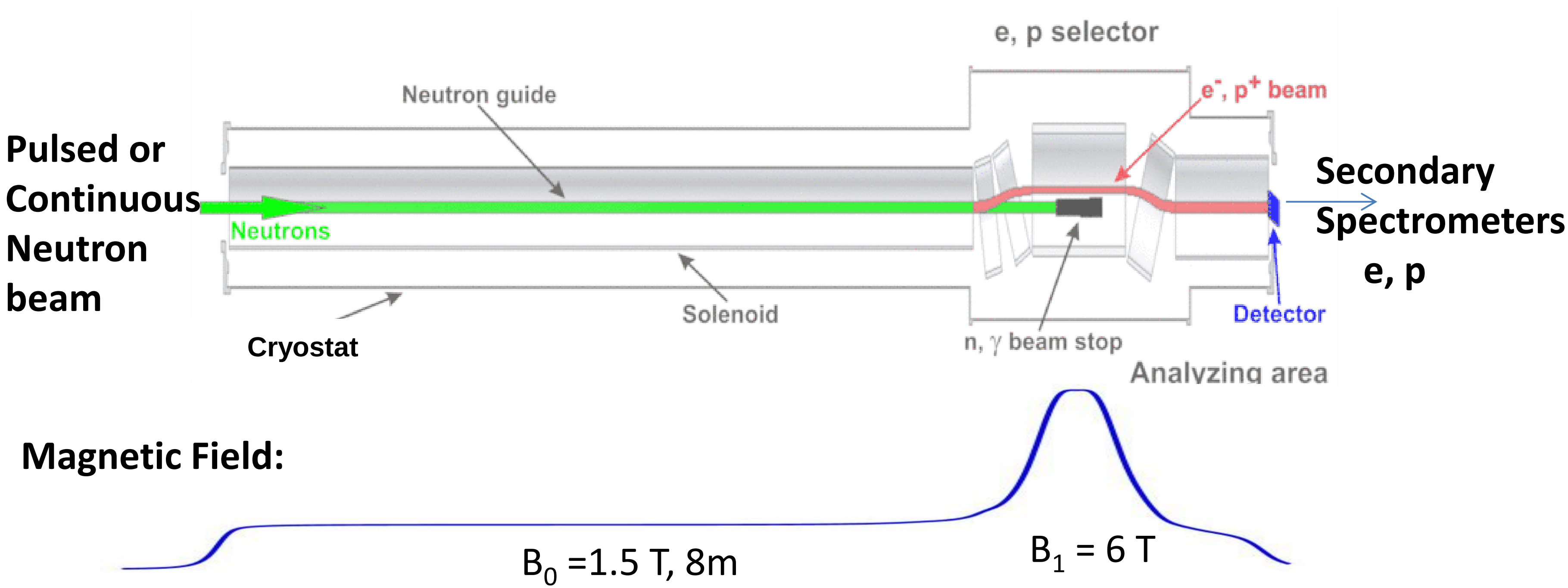
Univ. Heidelberg

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

ill NEUTRONS FOR SCIENCE

D. Dubbers *et al.*, *Nucl. Instr. Meth. A* **596** (2008) 238 and arXiv:0709.4440

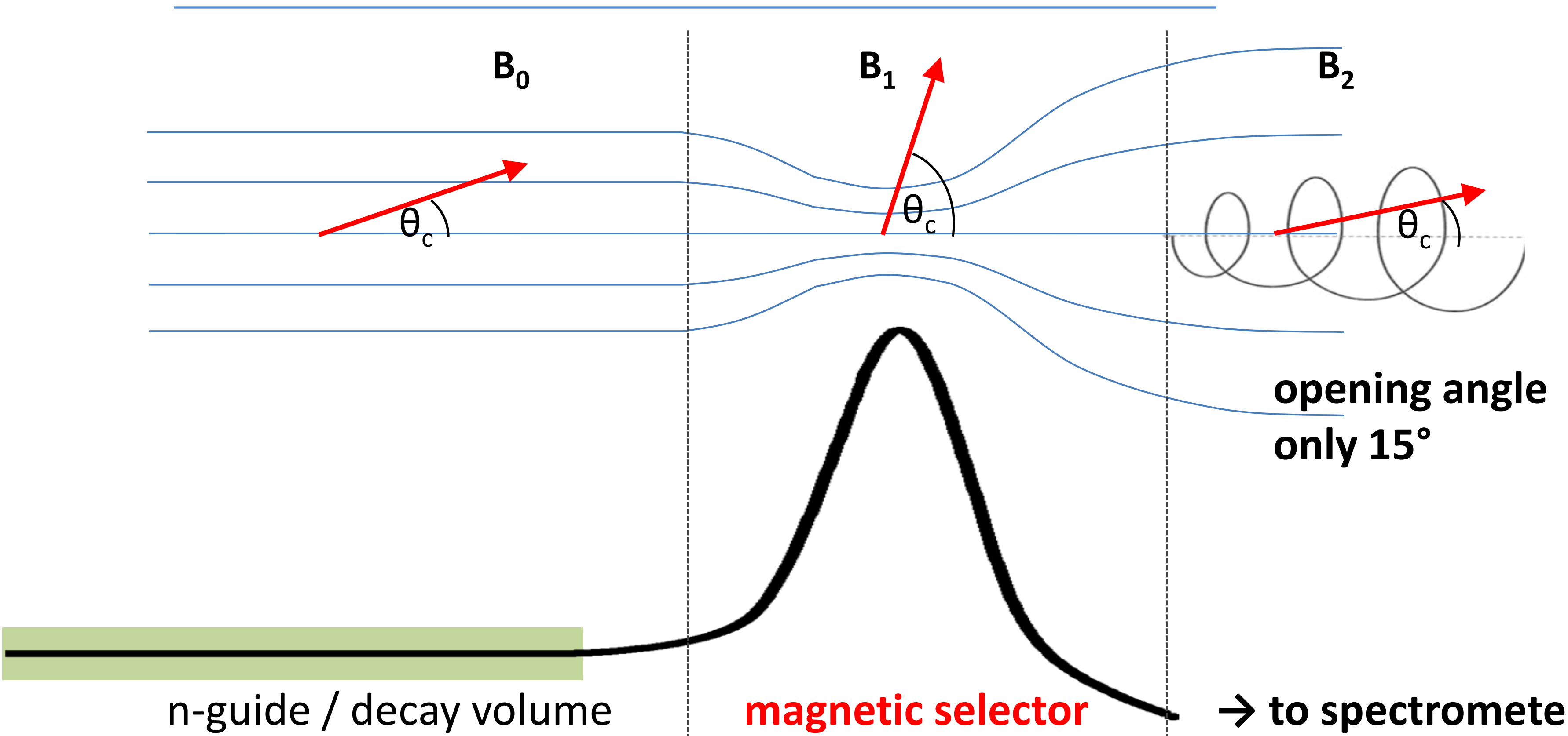
PERC Design



Pulsed Beam:

- Frequency < 70 Hz, λ_{mean}= 5 Å,
  Pulse length 2-3 m, 2.5 – 3.8 ms
- eliminate background from beam stop
- control on background from neutron guide
- control magnetic mirror effect

Magnetic Barrier

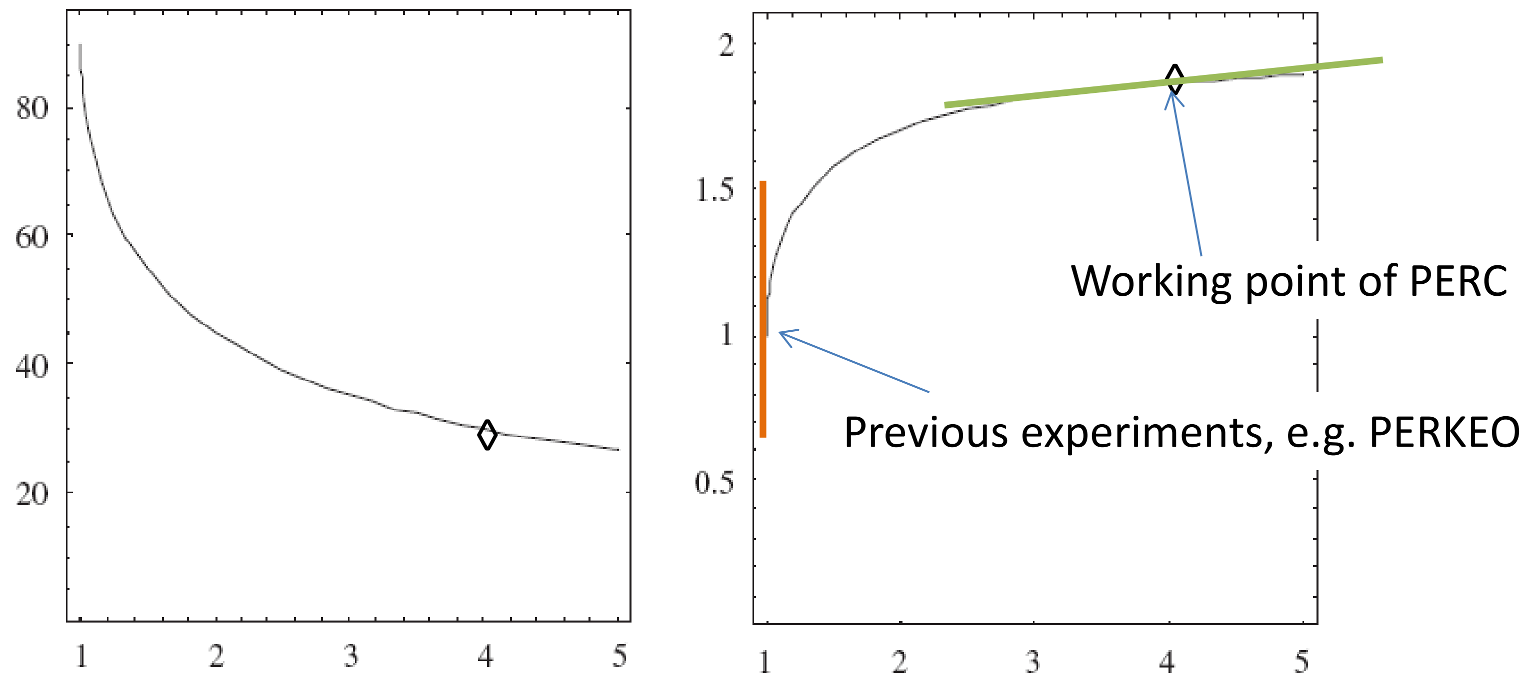


Magnetic field	B_0 = 1.5 T	B_1 = 6 T	B_2 = 0.375 T
Radius of gyration	< 1 mm	< .5 mm	< 2 mm
Opening angle θ_c	30°	90°	15°
Beam size	5 cm	2.5 cm	10 cm

Magnetic Barrier Field

Errors due to non-uniform magnetic field are strongly suppressed

critical angle θ_c asymmetry A

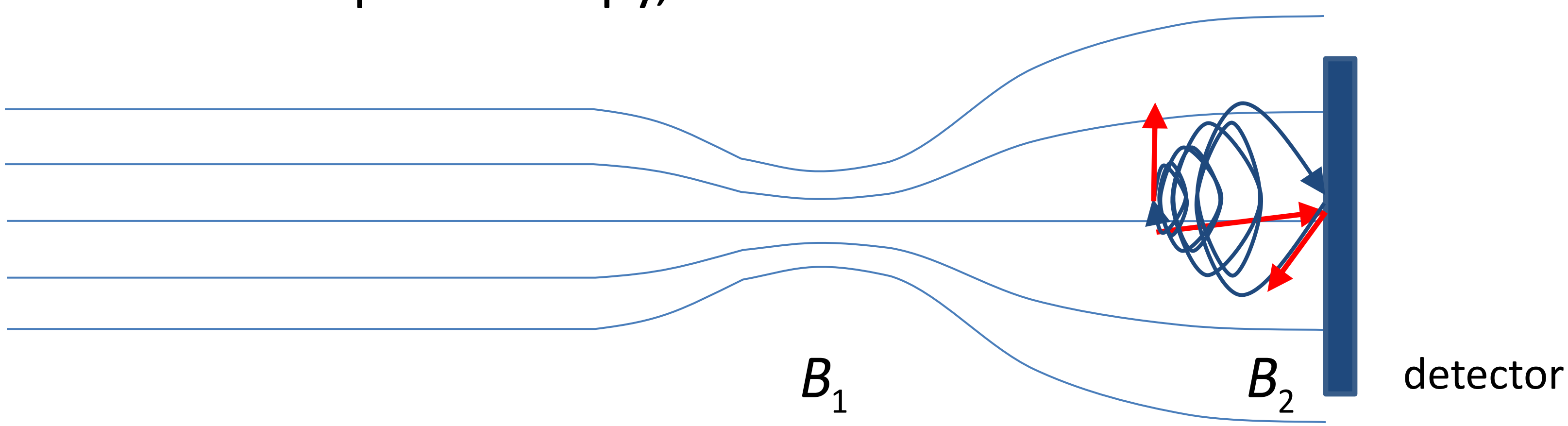


magnetic barrier filter B_1 / B_0 magnetic barrier field B_1 / B_0

D. Dubbers *et al.*, *Nucl. Instr. Meth. A* **596** (2008) 238 and arXiv:0709.4440

Backscattering

Backscattering typically major source of systematic error in electron spectroscopy, but:



- Incident angle on detector $\theta_2 < 15°$
  → backscattering **small**
- Efficient **suppression** by magnetic mirror

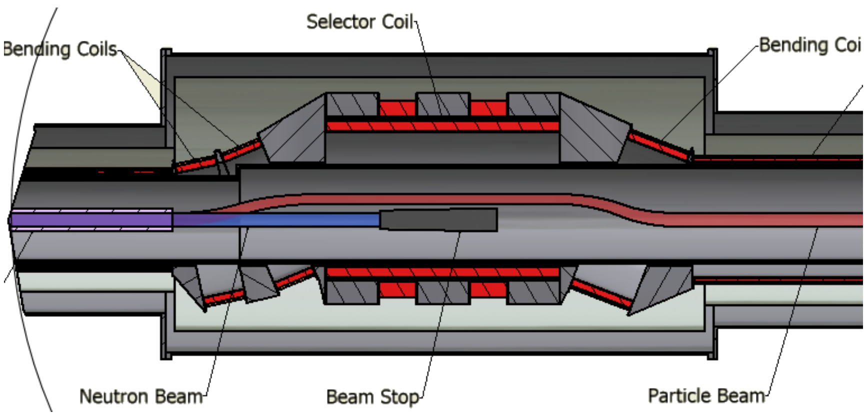
$$\frac{\Omega}{2\pi} = \frac{B_2}{2B_1} = 1/32$$

→ One detector only sufficient!

Background Shielding

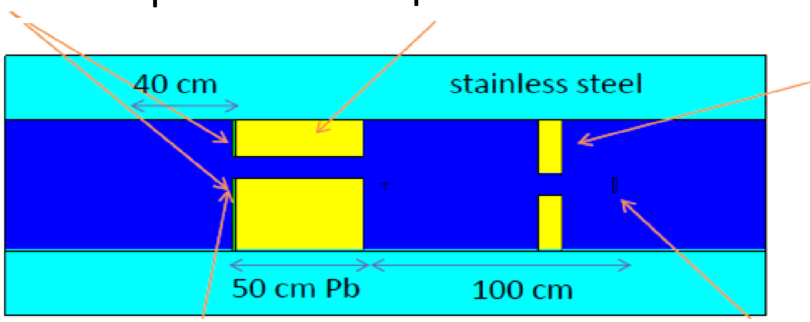
Shielding Concept: 2 Pin-holes - MCNP simulations

C. Gösselsberger,
E. Jericha (ATI)



$^{10}B_4C$ beamstop

lead pin-hole



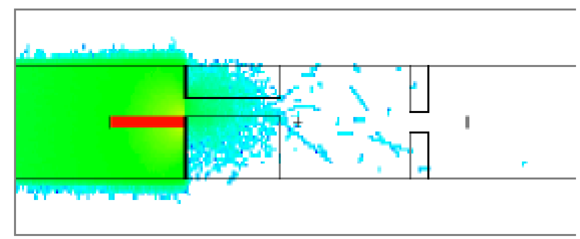
lead pin hole

sources

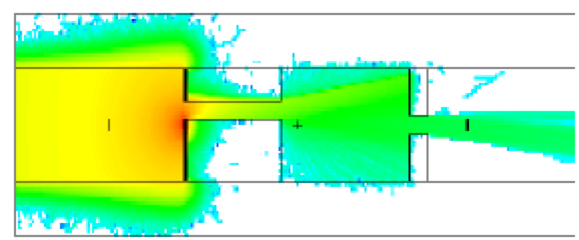
detector

Simulate 10^{10} n/s on beamstop

Fast neutrons: $0\ s^{-1}$



Gamma: $35\ s^{-1}$



Systematic Error Budget

Source of error	Correction	Error	Comment
Non-uniform n-flux Φ	2.5×10^{-4}	5×10^{-5}	For $\Delta\Phi/\Phi$=10% over 1cm width
Other edge effects on e/p-window	4×10^{-4}	1×10^{-4}	For max. gyration radius = worst case
Magn. mirror effect for cont's n-beam	2×10^{-2}	4×10^{-4}	
Magn. mirror effect for pulsed n-beam	5×10^{-5}	$< 10^{-5}$	For $\Delta B/B$=10% over 7m length
Non-adiabatic e/p-transport	5×10^{-5}	5×10^{-5}	
Background from n-guide	2×10^{-3}	1×10^{-4}	is separately measurable
Background from n-beam stop	2×10^{-4}	1×10^{-5}	is separately measurable
Backscattering off e/p-beam dump	5×10^{-5}	1×10^{-5}	
Backscattering off e/p-window	2×10^{-5}	1×10^{-5}	
Backscattering off organic scintillator	2×10^{-3}	4×10^{-4}	worst case
... with active e/p-beam dump	-	1×10^{-4}	worst case
Neutron polarisation	3×10^{-3}	$\mathbf{1 \times 10^{-4}}$	**state of the art - ILL**

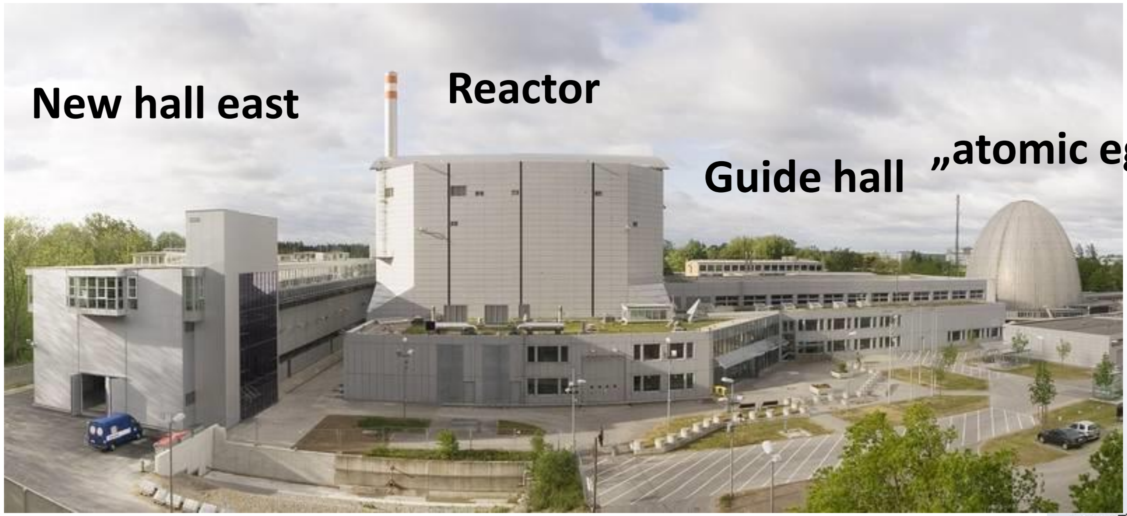
Note: not every error source contributes to all measurements

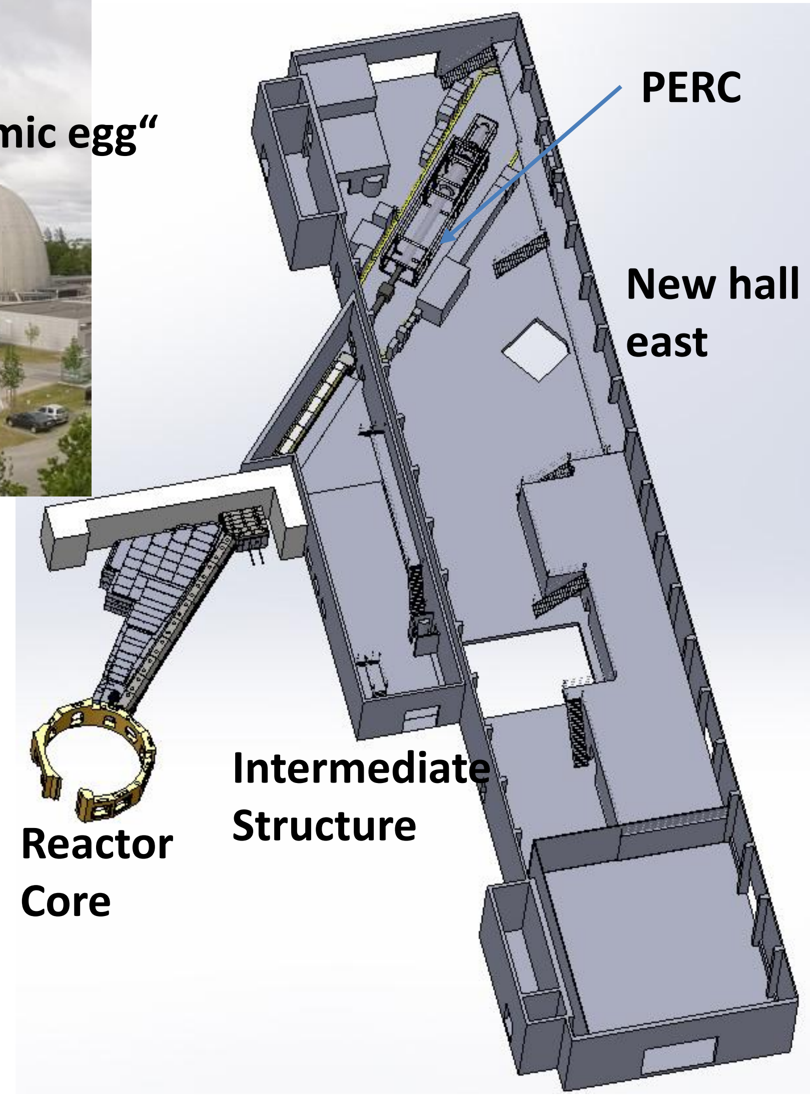
Nucl. Instr. Meth. A **596** (2008) 238 and arXiv:0709.4440

All errors $O(10^{-4})$ or smaller

More than one order of magnitude improvement

Beam Site Mephisto, FRM II



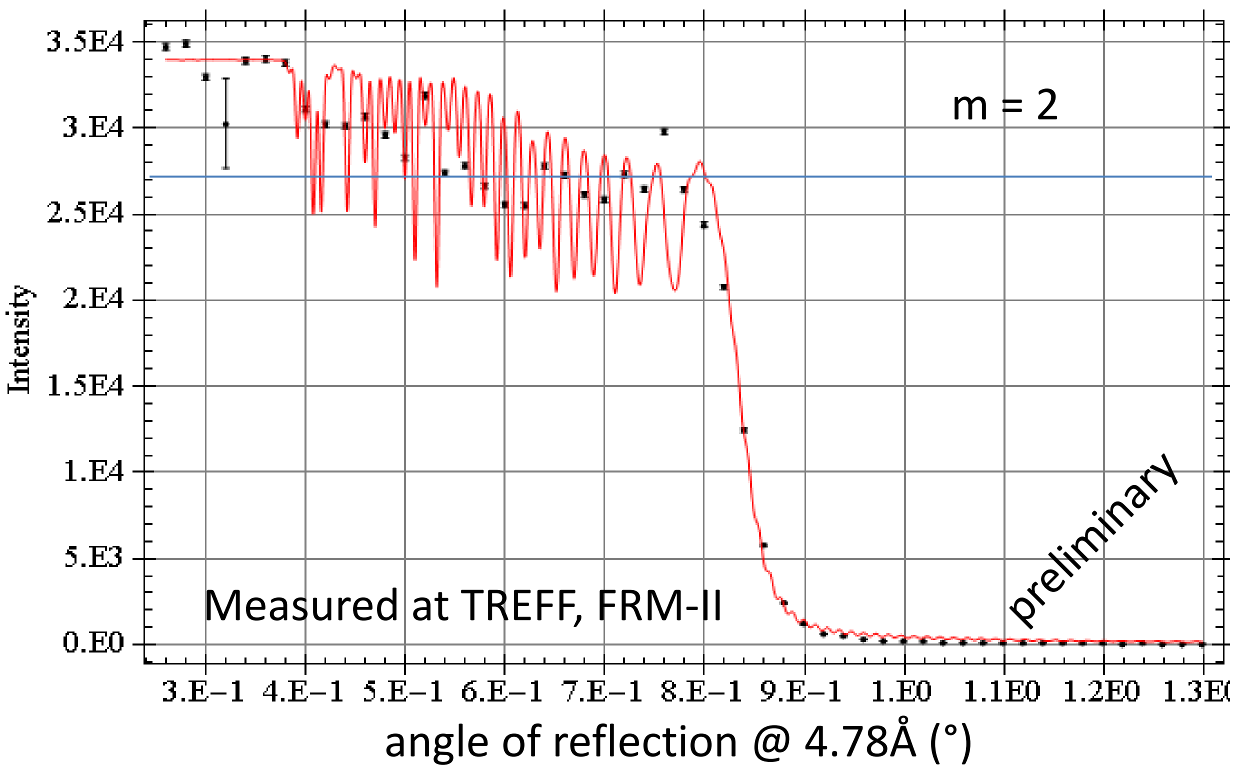


- “Empty” new hall
- State of the art neutron guide, length 40 m, R = 3000 m, *m* = 2.5
- Expected intensity equal to PF1B at ILL
- Only very few neighbours: low background
- Easy ground level access
- **Length 25 m, Width 5 m**

Non-depolarising n-guide

Challenge: Guide inside PERC needs to preserve neutron polarization,
Max. depolarisation 10^{-4} per bounce at B = 1.5 T

Cu/Ti Supermirrors, 119 layers, m = 1.8



Reflectivity > 80%

N. Rebrova,
U. Schmidt, UHD

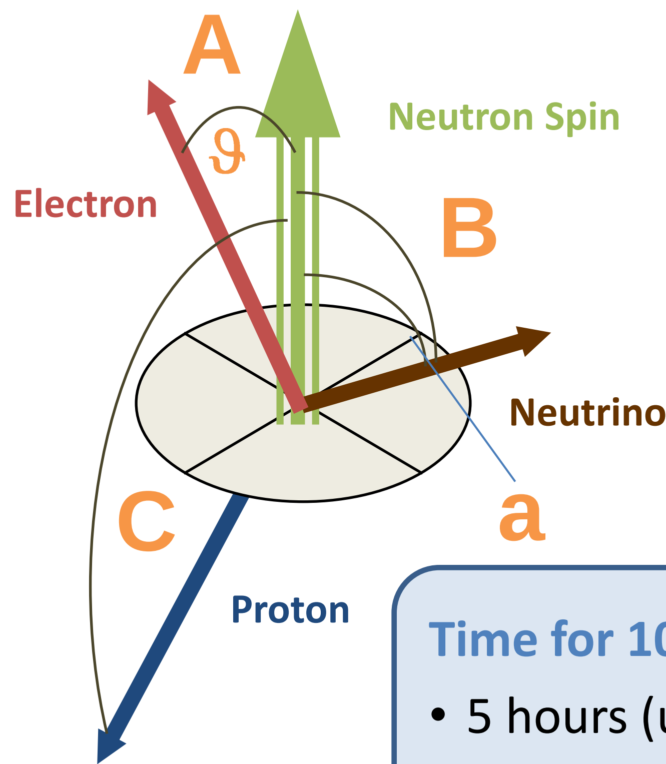
Test experiments with Cu/Ti and Ni-Mo/Ti (m = 2) running at Mephisto, FRM II

Observables and Statistics

Focus on non-coincident measurements due to high count rates:

Polarised neutrons

- β-asymmetry ***A***
- Proton asymmetry ***C***
  Neutrino asymmetry ***B***
- Weak magnetism f_{WM}
  from β-asymmetry or
  polarised spectra



Unpolarised neutrons

- Correlation ***a***
  from proton spectrum
- Fierz coefficient ***b***
  from electron spectrum or
  β-asymmetry
- Electron helicity ***h***

Time for 10^9 events

- 5 hours (unpolarised)
- 1 day polarised 98%
- 2 days polarised 99.7%
- ×25 for pulsed mode

Summary

- Pulsed beams provide effective means to suppress major systematic sources of error:
  Background, Magnetic Mirror Effect, Edge Effects, Neutron Polarisation
- PERC and PERKEO III have been designed to exploit the power of pulsed beams
- Pulse length of ESS LP reasonable for PERC – see talk by Christine Klauser

Require cold beam station for particle physics

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