Neutron beta decay with pulsed cold neutron beams: PERKEO III and PERC

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Topics:

V_{ud} and neutron decay

More on the precision of PERKEO III: pulsed beam!

How does PERC improve?

Prospects beyond PERC: ESS

$\mathrm{V_{ud}}$ from Neutron Decay

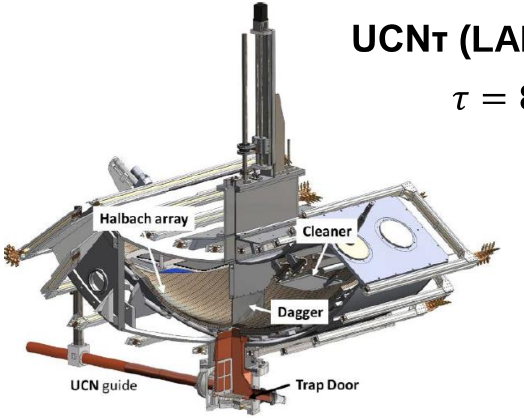
With a factor of two improvement, the most precise determination will come from neutron decay!

Requires only two experimental inputs and radiative corrections. No nuclear corrections.

talk by M. Gorshteyn

Neutron Lifetime τ_n

UCNτ (LANL), Gravitrap (ILL), PENeLOPE (TUM), τSpect (Mainz), J-PARC, BNL-2 (NIST), ...



UCNτ (LANL)

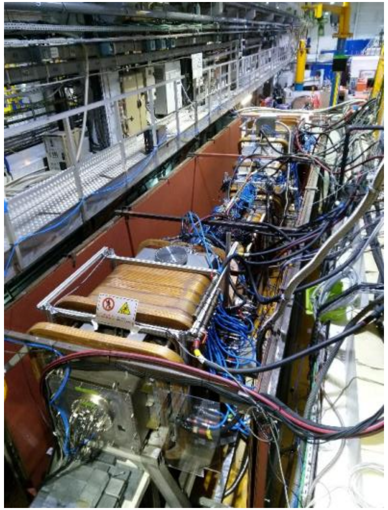
$$\tau = 877.75 \pm 0.33\ \mathrm{s}$$

$$\frac{\Delta\tau}{\tau} = 3.8 \times 10^{-4}$$

Gonzalez *et al.*, Phys. Rev. Lett. 127, 162501 (2021)

Nucleon Axial-Coupling: $\lambda = g_A/g_V$

PERKEO III (ILL), UCNA (LANL), *a*Spect (ILL), aCorn (NIST) Nab (SNS), PERC (MLZ), …



PERKEO III (ILL)

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

Märkisch *et al.*, Phys. Rev. Lett. 122, 222503 (2019)

Goal of PERC (MLZ)

$$\frac{\Delta\lambda}{\lambda} \leq 1 \times 10^{-4}$$

$$V_{ud}^{n,best} = 0.97402(13)_{\mathrm{theory}}(20)_{\tau}(35)_{\lambda} = 0.97402(42)$$

Cirigliano *et al.*, Phys. Rev. D 108, 053003 (2023)

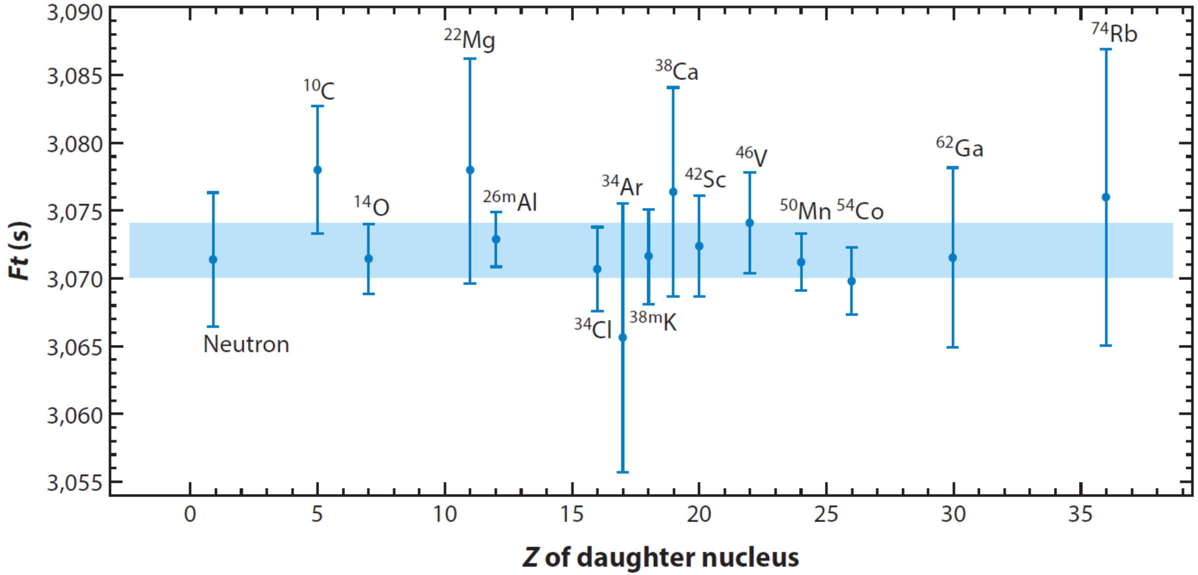
aSpect: talk by U. Schmidt

talk by W. Dekens

Comparison to Superallowed Decays

Neutron: vector part of neutron *Ft*

$$Ft_{nV} \equiv f\,t_{nV}(1+\delta_R') = \tfrac{1}{2}\ln 2\, f\tau_n\,(1+3\lambda^2)(1+\delta_R')$$



Neutron data point does not yet include UCNτ 2021 result.

λ_{avg} = -1.2754(11), ***S* = 2.2** includes all measurements

Dubbers & BM, Ann. Rev. Nucl. Part. Sci. 71, 139-163 (2021)
Ft values from Hardy & Towner, Phys. Rev. C 102:045501 (2020)

See N. Severijns *et al.*, Phys. Rev. C 107, 015502 (2023) for a review of nuclear *mirror* decays

Status of $\lambda = g_A/g_V$ from Neutron Decay Correlations

New beta asymmetry A results **consistent** – but disagree with older measurements and new *a*Spect electron-neutrino correlation a result.

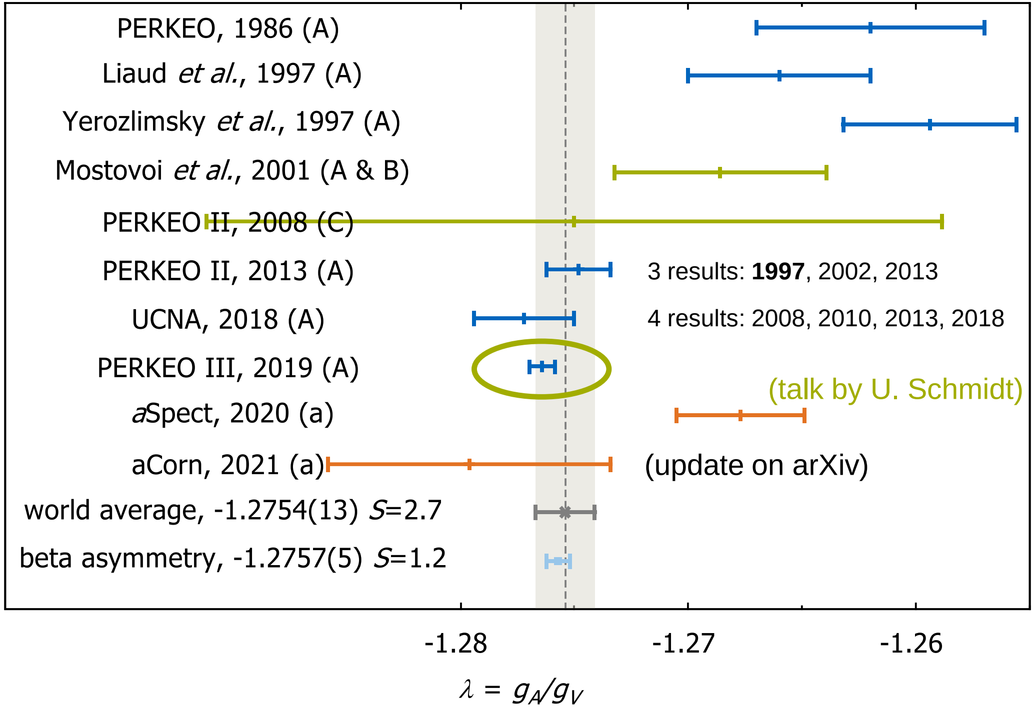
$$A_{avg} = -0.11958(21), \qquad S = 1.2$$

Newer measurements of A have order of magnitude **smaller corrections**.

UCNA, PERKEO III, aCorn, *a*Spect:
blinded analysis to avoid potential bias.

(Newer results of UCNA & PERKEO II include older results)

Aim of PERC is five-fold improvement.

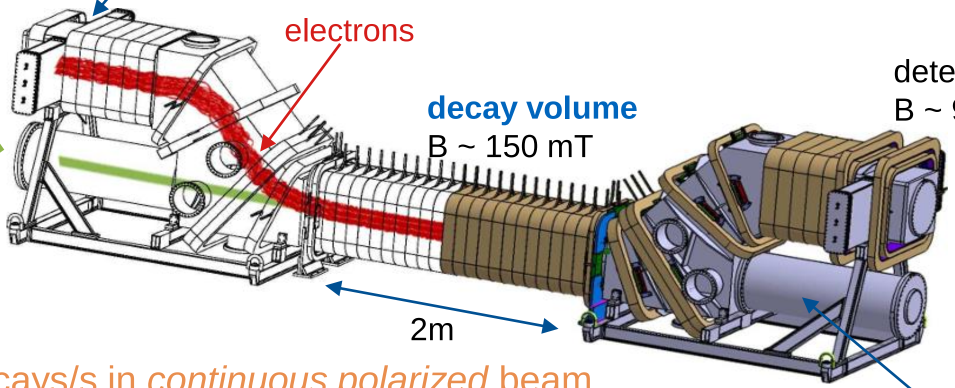


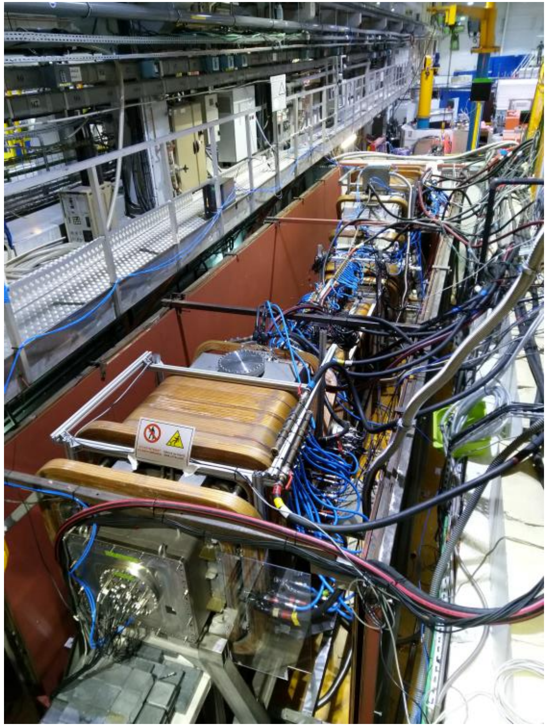
Experimental observables are ***not*** identical to correlation parameters: radiative corrections change

Neutron Decay Spectrometer PERKEO III at ILL, Grenoble

Designed to use a *pulsed beam* to control or eliminate leading systematic errors.

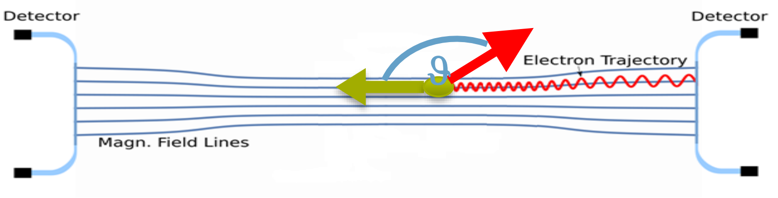
Originally built by Uni. Heidelberg, now operated by TUM, TU Vienna, HD & ILL.





~50.000 decays/s in *continuous polarized* beam

time avg. ~200 s^{-1} in **pulsed**, polarized mode, P ~ 99.1%



Symmetric setup, two detectors (see U. Schmidt‘s talk)

PERKEO III: Pulsed Neutron Beam and Background Control

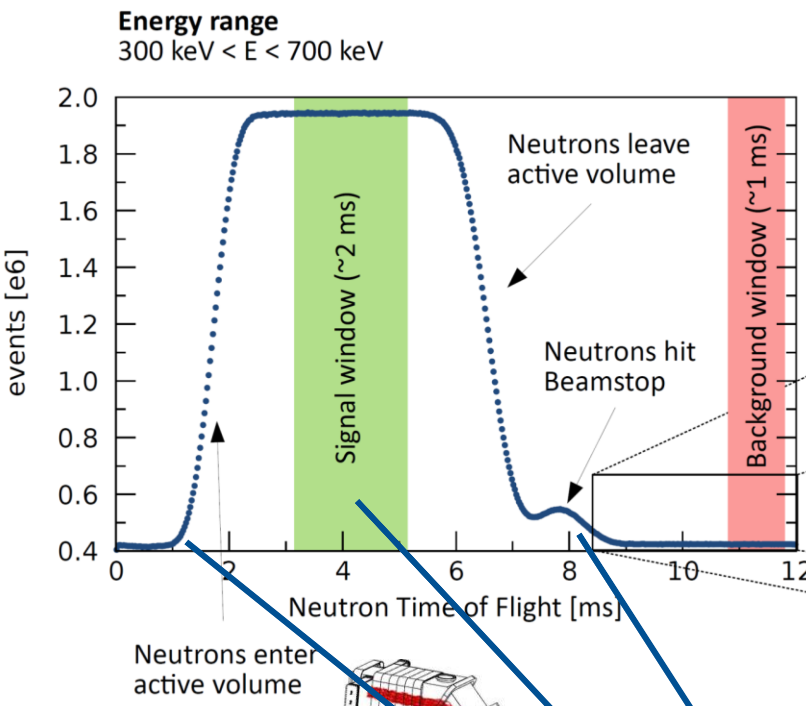
Pulsed beam allows nearly perfect background subtraction

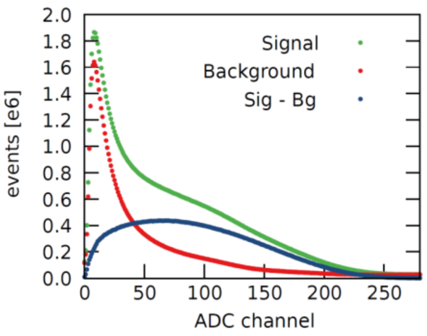
Free neutron pulse does not interact with matter during measurement.
Same background condition in *signal and background time window.*

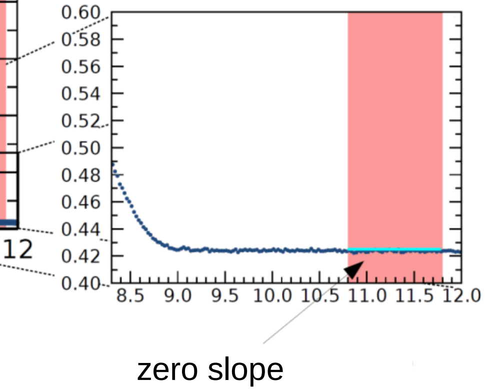
Related Uncertainties $\Delta A/A$
Time dependence 0.8×10^{-4}
Chopper disc uniformity 0.7×10^{-4}

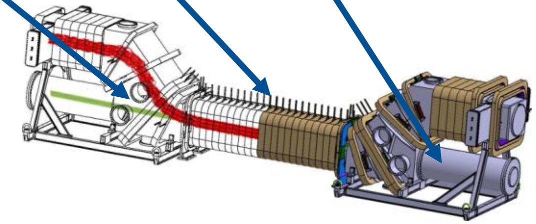
(PERKEO II: 10×10^{-4})

… also eliminates or controls more systematic effects: edge *and* magnetic mirror effects

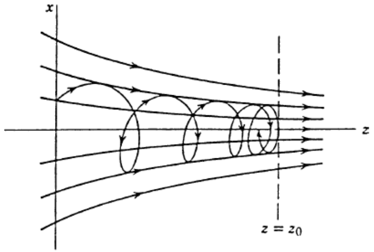








PERKEO III: Magnetic Mirror Effect



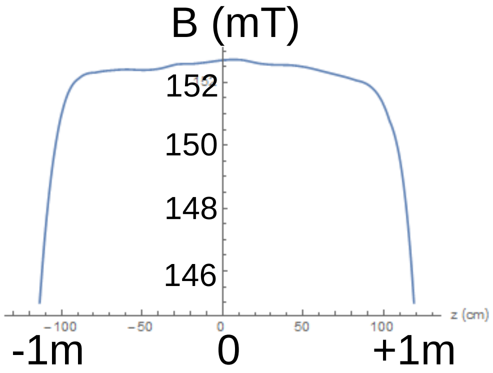
Flux through cross section of gyration is *adiabatic invariant*

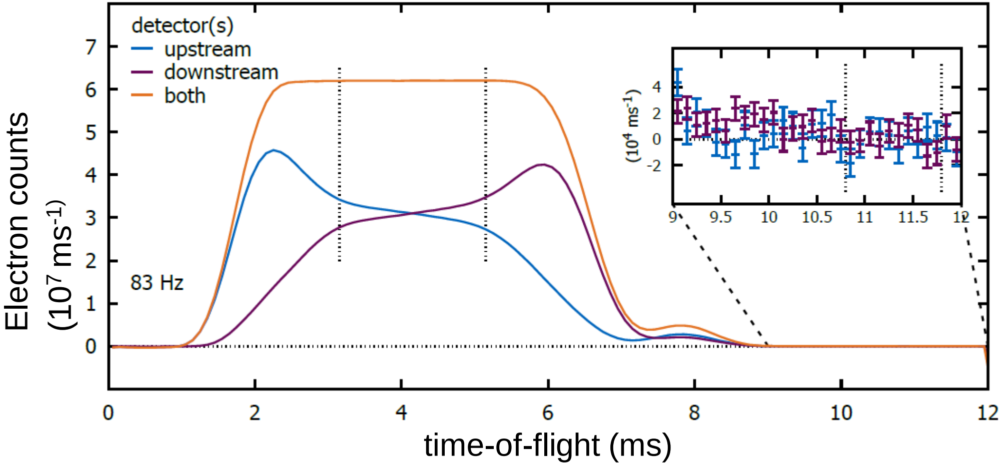
$$B_0 r_0^2 = B_1 r_1^2$$

Critical angle for reflection

$$\Theta_c = \arcsin\sqrt{\frac{B_1}{B_0}}$$

Non-uniformity of magnetic field modifies solid angle coverage of detectors: significant rate change on **single** detector:



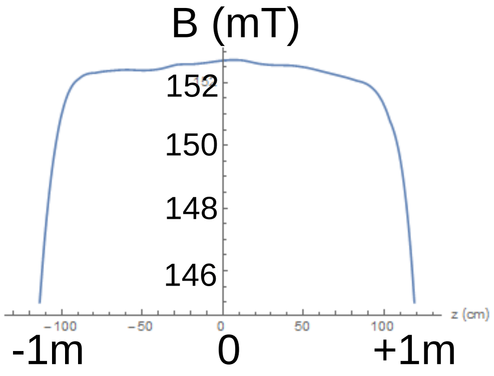


PERKEO III: Mirror Effect Controlled with Pulsed Beam

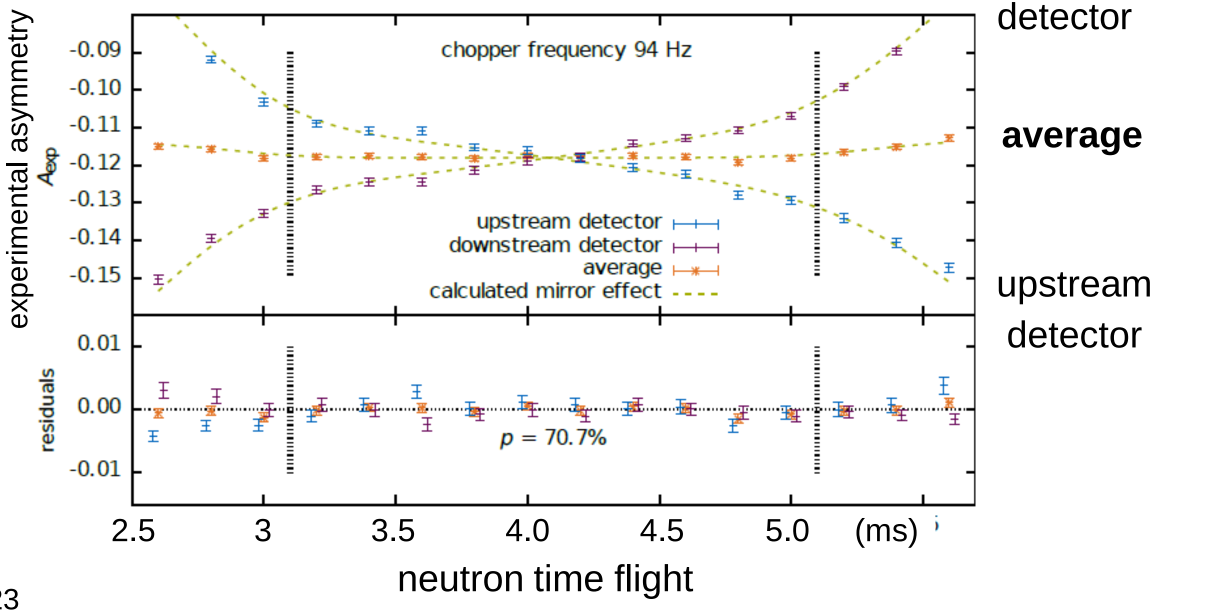
Non-uniformity of magnetic field modifies solid angle coverage of detectors.

Correction calculated based on *measurements* of the magnetic field and neutron pulse.
Result reproduces time-of-flight behavior of asymmetry. **No fit!**

Most of the effect cancels by **averaging** detectors.

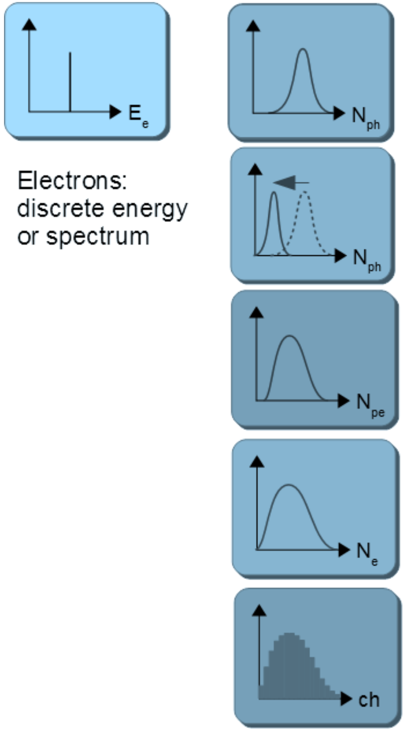


Correction:
$\Delta A/A = 46.1(4.5) \times 10^{-4}$



PERKEO III: Detector Model

Major improvements to the description of the detector response enable consistent energy-dependent analysis. Calibration only based on electron conversion sources.



Electrons:
discrete energy
or spectrum

Scintillation:
$N_{ph} = f(E_e)$
poisson statistics

Non-linearity of scintillation light production (measured)

Photon transport:
$N'_{ph} = f(E_e, x, y)$
binomial statistics

Non-uniformity of detector response (measured)

Photon to photoelectron conversion:
$N_{pe} = f(N_{ph})$
binomial statistics

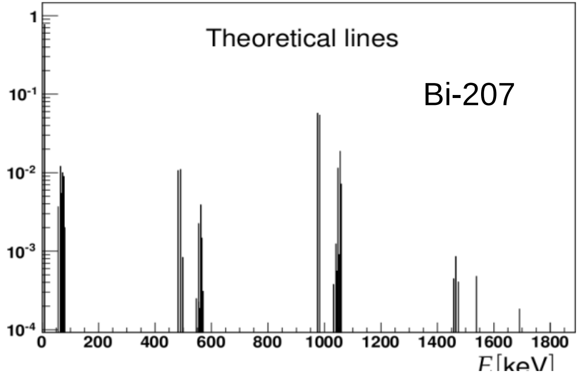
Electron multiplication (PMT):
$N_e = f(N_{pe})$
poisson statitisics at N=19 stages

Higher moments of the distribution

Signal processing + charge integration:
$A_{QDC} = f(N_e)$
gaussian noise

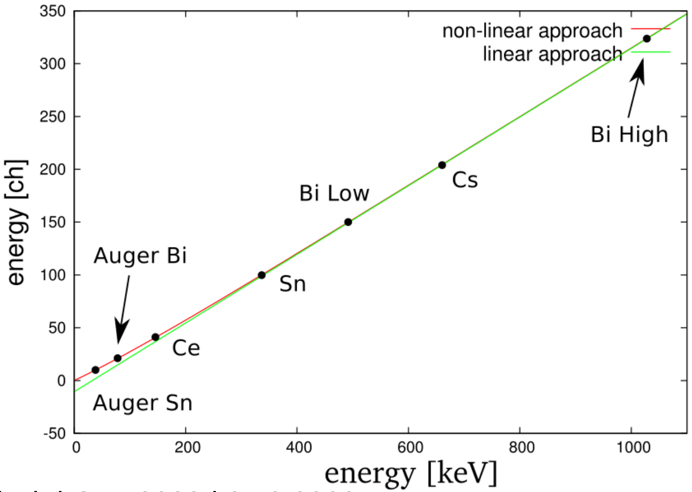
Non-linearity of electronics (partly measured)

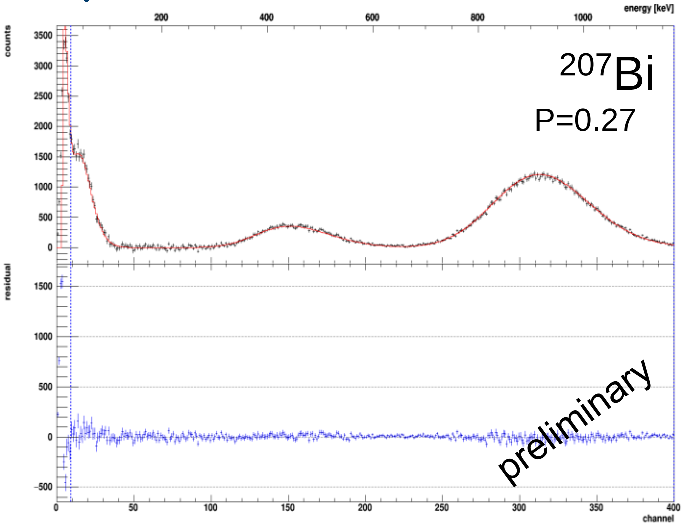
PERKEO III: Detector Response



Theoretical spectrum (>200 combinations: electron conversion + electrons from deexcitation of the atom) (Uncertainties in fluorescence problematic for future 10^{-4} accuracy at low energies)

Model of detector properties (non-linearity of photon production PMT statistics, electronic noise, …)

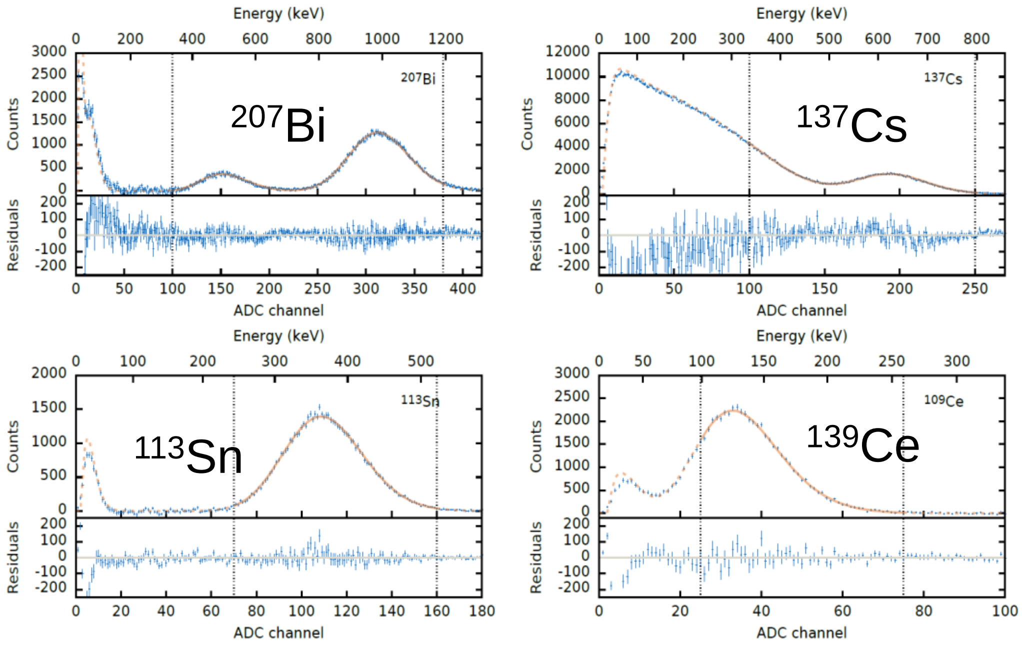




PERKEO III: Detector Calibration Fit

Major improvements to the description of the detector response and electron-conversion sources enable consistent *energy-dependent analysis*.

Nearly identical angular distribution on detector.



(2x per day calibration + hourly drift measurements + weekly uniformity scans)

Apply detector model to theoretical data. **Free fit parameters:**

non-linearity, gain, photo-electrons (widths), norms

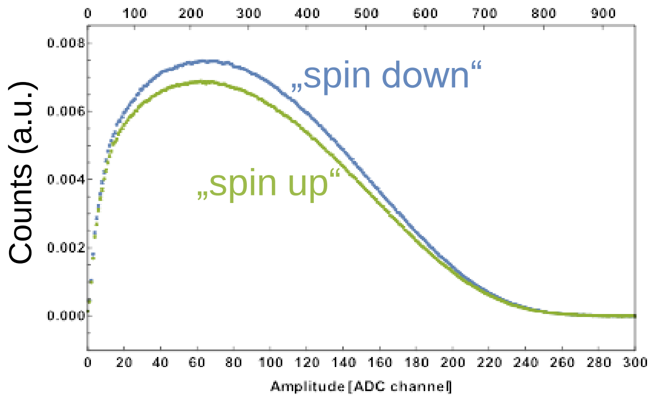
X^2/NDF = 1.0 – 1.3 (for all 96 data sets)

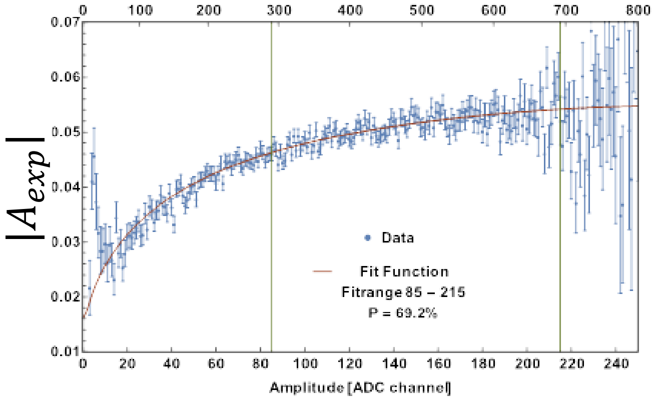
Related Uncertainties ΔA/A	
Sources:	1×10^{-4}
Statistics:	0.1×10^{-4}
Non-linearity:	4×10^{-4}
Stability:	3.7×10^{-4}

(PERKEO II: 25×10^{-4})

H. Saul, C. Roick, H. Mest

PERKEO III: Asymmetry Extraction





Asymmetry $A \sim -12\%$ already visible in electron spectra from "spin up" and "spin down" neutrons.

Largest data set from polarized neutron decay by one order of magnitude: 6×10^8 events in analysis

Single parameter fit to experimental asymmetry:

$$A_{exp}(E_e) = \frac{N^{\uparrow}(E_e) - N^{\downarrow}(E_e)}{N^{\uparrow}(E_e) + N^{\downarrow}(E_e)} = \frac{1}{2} P_n \frac{v}{c} A$$

Most corrections to the „raw“ fit result on the 10^{-3} – 10^{-4} level only.

Analysis blinded by separate analysis of largest corrections.

$$\begin{aligned} \lambda &= -1.27641(45)_{\text{stat}}(33)_{\text{sys}} \\ &= -1.27641(56) \\ A &= -0.11985(17)_{\text{stat}}(12)_{\text{sys}} \\ &= -0.11985(21). \end{aligned}$$

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

Märkisch *et al.*, PRL 122, 222503 (2019)

PERKEO III: Summary of Corrections and Uncertainties

Corrections to the „raw“ fit result on the 10^{-3} – 10^{-4} level only.

Analysis blinded by separate analysis
by independent teams *to avoid potential bias*:

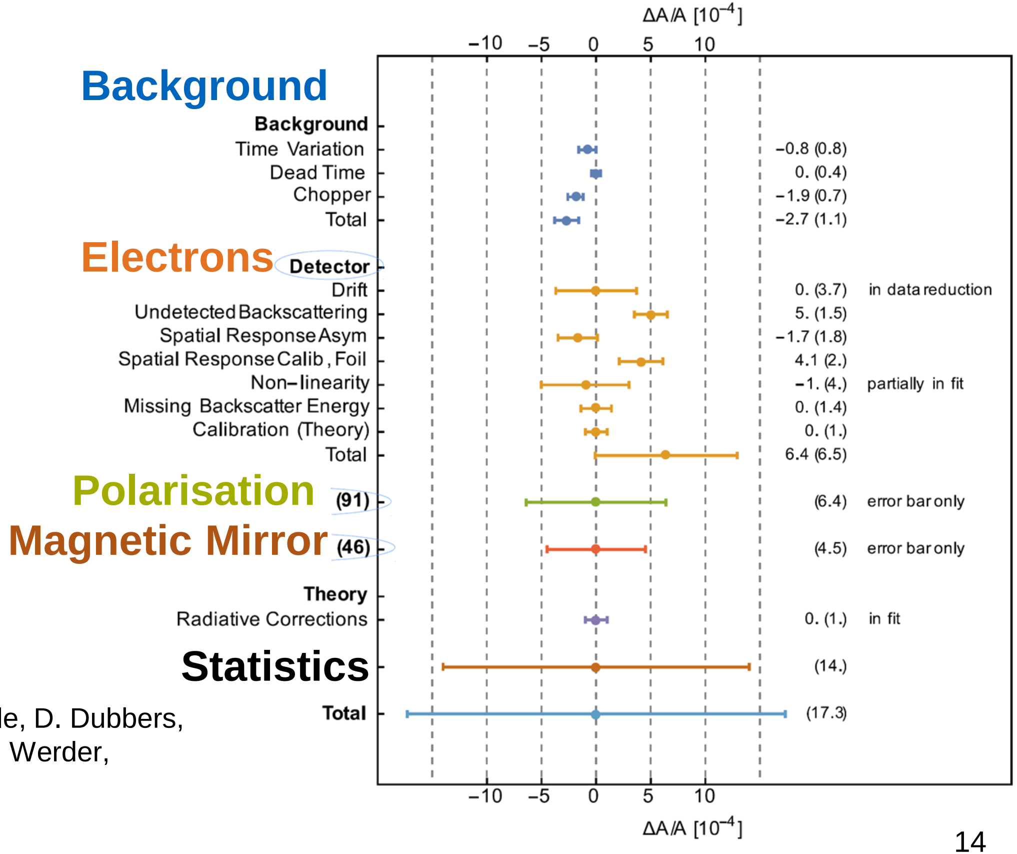
- electron and background measurements,
- neutron polarization: opaque ^{3}He spin filters,
- magnetic mirror effect correction

Result:

$$\lambda = -1.27641(45)_{\mathrm{stat}}(33)_{\mathrm{sys}}$$
$$= -1.27641(56)$$
$$A = -0.11985(17)_{\mathrm{stat}}(12)_{\mathrm{sys}}$$
$$= -0.11985(21).$$

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

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

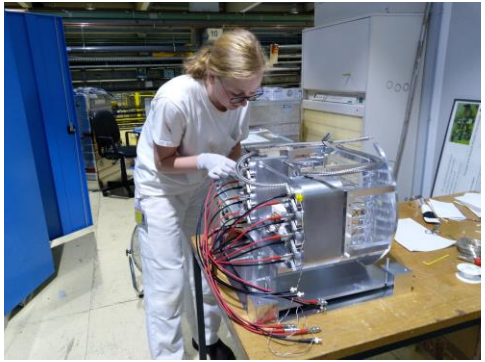


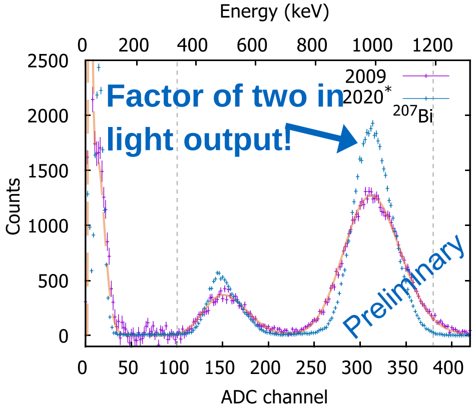
B. Märkisch, H. Mest, H. Saul, X. Wang, H. Abele, D. Dubbers, M. Klopf, A. Petoukhov, C. Roick, T. Soldner, D. Werder, Phys. Rev. Lett. 122, 222503 (2019)

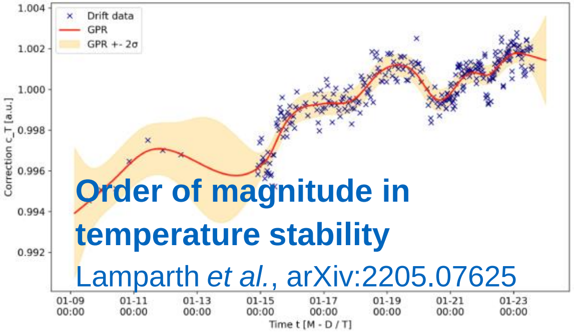
PERKEO III: Beta Spectrum Measurement at ILL `19/`20

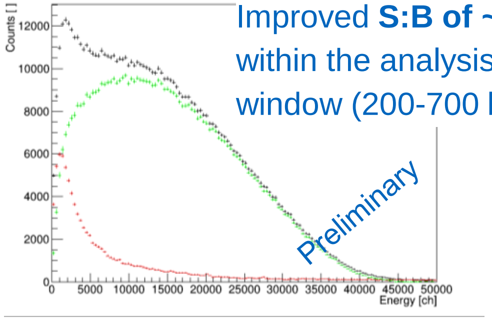
Dedicated run with the *aim* to measure Fierz term $\Delta b \sim 5 \times 10^{-3}$. 5×10^{8} events.

Strongly improved detectors. Blinded analysis ongoing. Systematics limited.

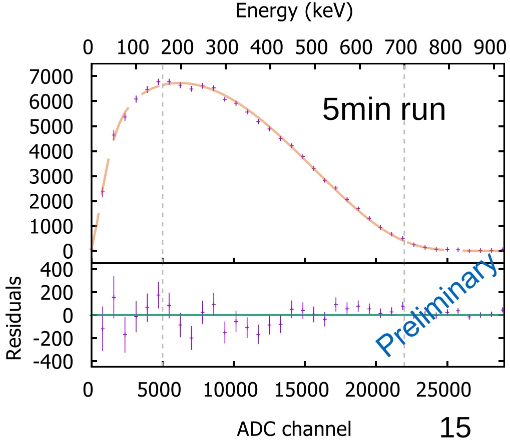








Improved **S:B of ~10:1** within the analysis window (200-700 keV)



The next generation:
PERC (Proton Electron Radiation Channel) at MLZ / FRM, Garching

Goal: Order of magnitude improvement.

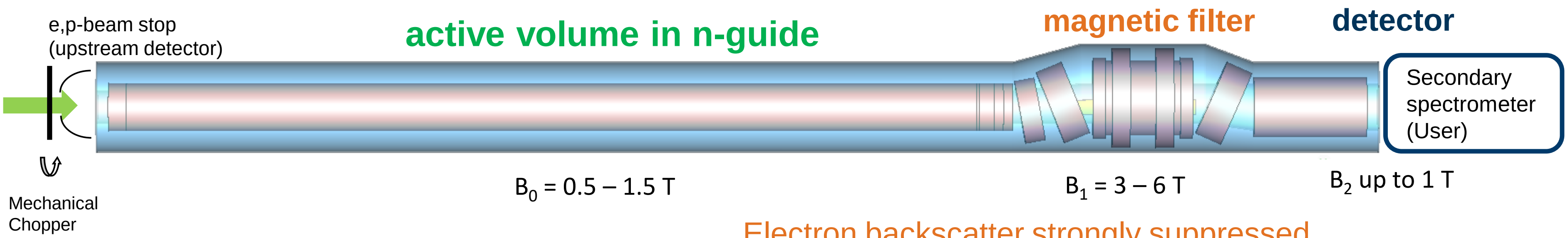
New observables.

Priority Programme SPP1491 of the German Research Foundation (DFG)

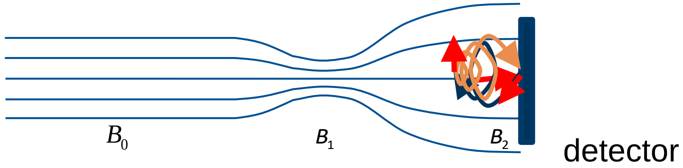
PERC Concept and Systematics

PERC´s asymmetric layout with magnetic filter improves systematics

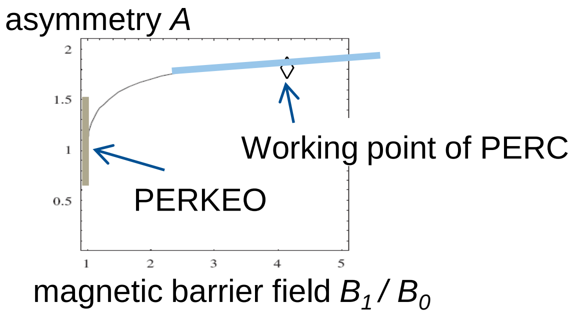
Strong field ensures high phase space density, small detectors, excellent S/B and only a *single* detector!.



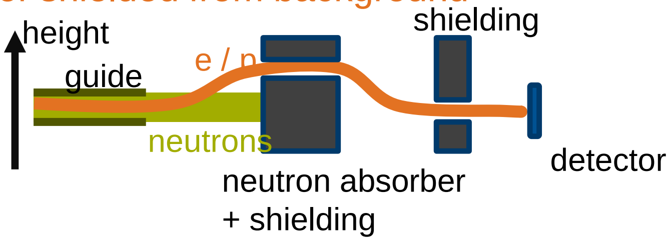
Electron backscatter strongly suppressed



Phase space cut: magnetic field influence



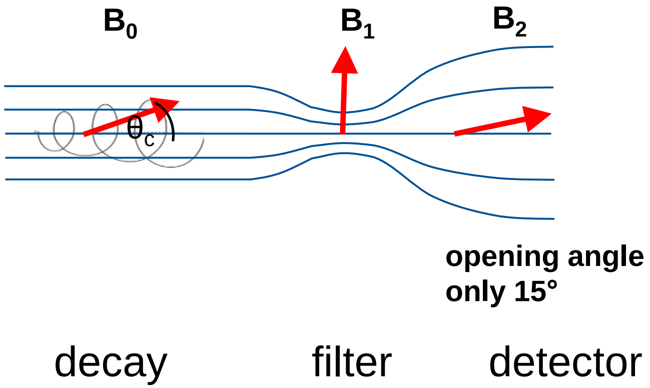
Main detector shielded from background

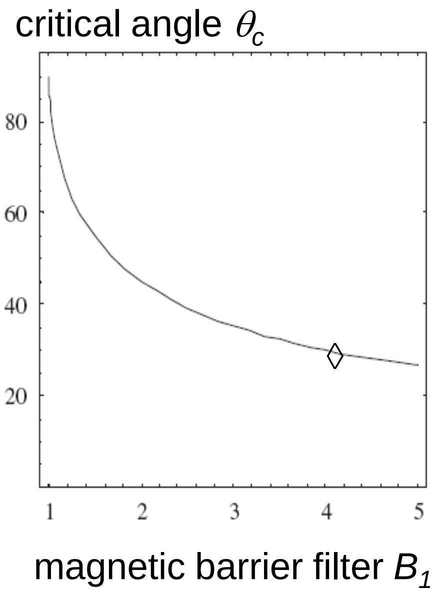


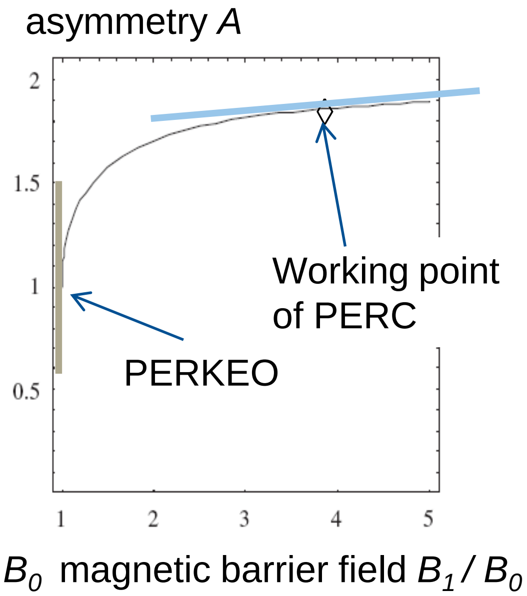
PERC: Magnetic Barrier Field

Errors due to non-uniform magnetic field are strongly suppressed

Still need to know magnetic field on the 10^{-4} level





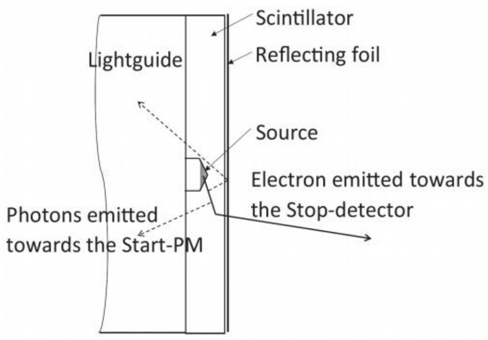


D. Dubbers *et al.*, *Nucl. Instr. Meth. A* **596** (2008) 238 and arXiv:0709.4440

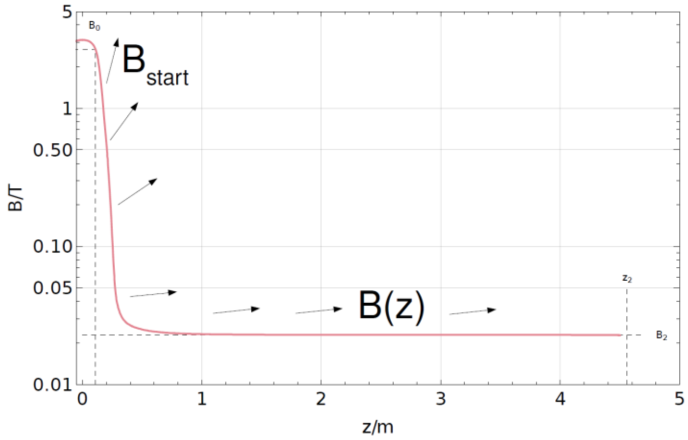
Electron Time-of-Flight for Detector Calibration

New concept to overcome calibration uncertainties at low energies
Identify backscatter events via time difference in upstream/downstream detector.

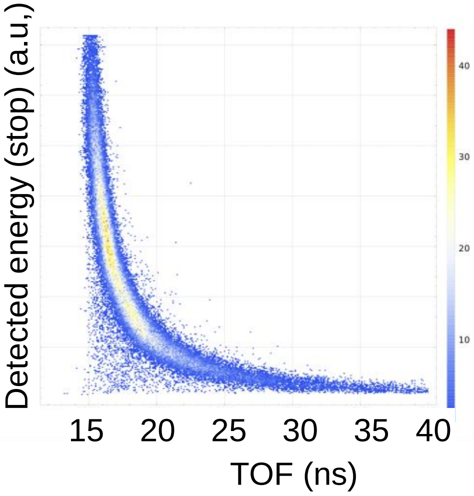
Active source:
Start signal



Adiabatic reduction of magnetic field in flight path reduces opening angle of gyration



Target detector: relate **time-of-flight** to electron energy



C. Roick, D. Dubbers, B. Märkisch, H. Saul, U. Schmidt, Phys. Rev. C 97 (2018)

PERC: Systematic Corrections and Uncertainties on Correlations

All systematic uncertainties O(10^{-4}) or smaller: goal $\frac{\Delta\lambda}{\lambda} \leq 1 \times 10^{-4}$

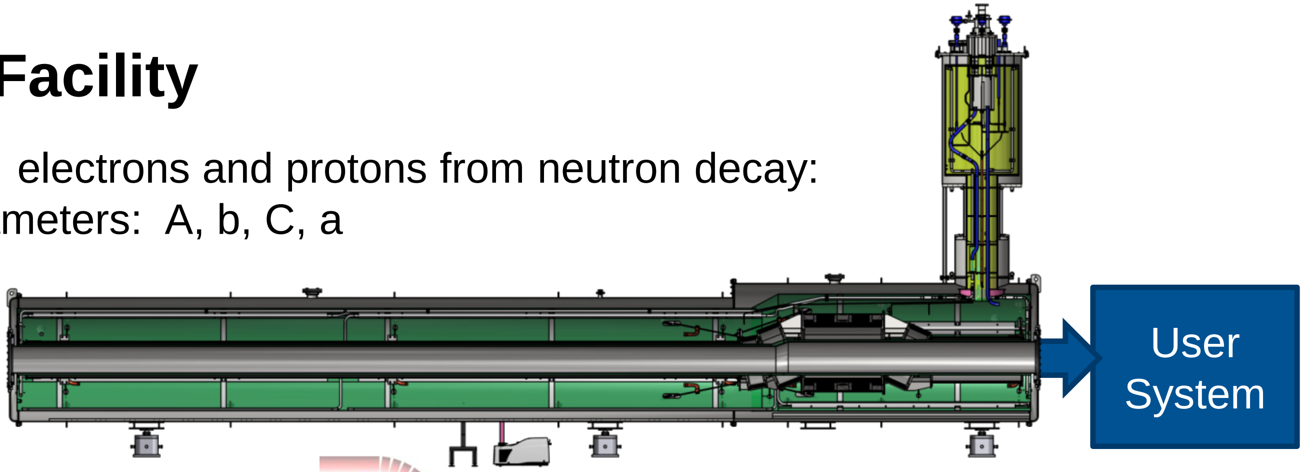
Nucl. Instr. Meth. A **596** (2008) 238 and arXiv:0709.4440

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 Magn. mirror effect for pulsed n-beam	2×10^{-2} 5×10^{-5}	4×10^{-4} $< 10^{-5}$	 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 ... with active e/p-beam dump	2×10^{-3} -	4×10^{-4} 1×10^{-4}	worst case worst case
Neutron polarisation	3×10^{-3}	$\mathbf{1 \times 10^{-4}}$	C. Klauser, T. Soldner et al. A. Petoukhov et al. (ILL)

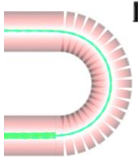
Note: not every error source contributes to all measurements

PERC is a **Facility**

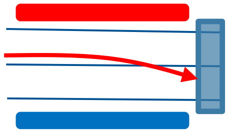
Clean source of electrons and protons from neutron decay:
Correlation parameters: A, b, C, a



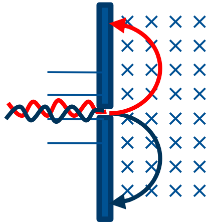
R×B spectrometer



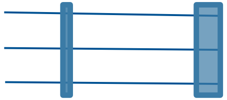
Wien filter for protons



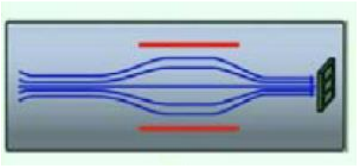
Magnetic spectrometer



Electrostatic chopper & p detector



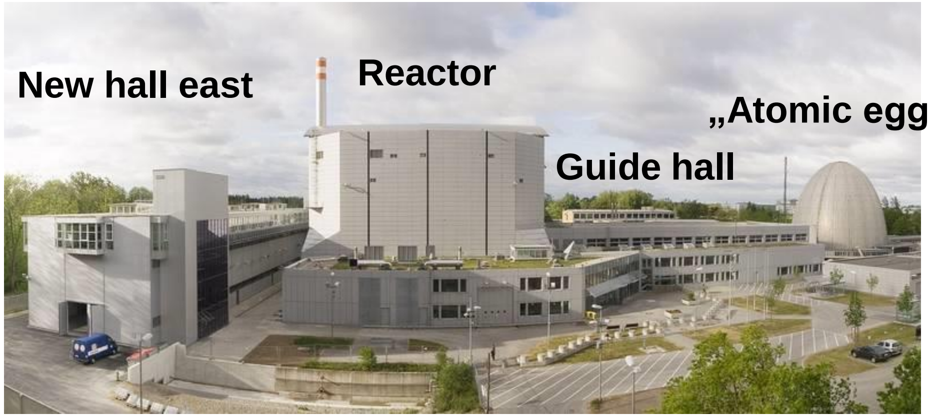
MAC-E filter (“aSPECT”)

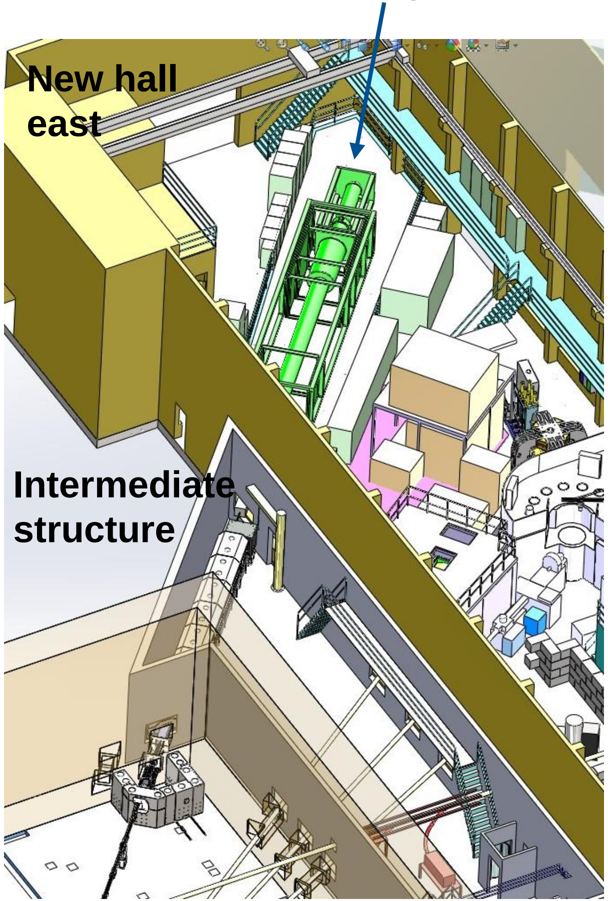


Electron or proton detector

Scintillator, Silicon, …

Beam Site Mephisto, MLZ/FRM II, Garching





Neutron guide:

length 40 m, R = 3000 m, *m* = 2.5

Expected intensity equal to PF1b at ILL, $2\times10^{10}\ s^{-1}cm^{-2}$

Only very few neighbours:

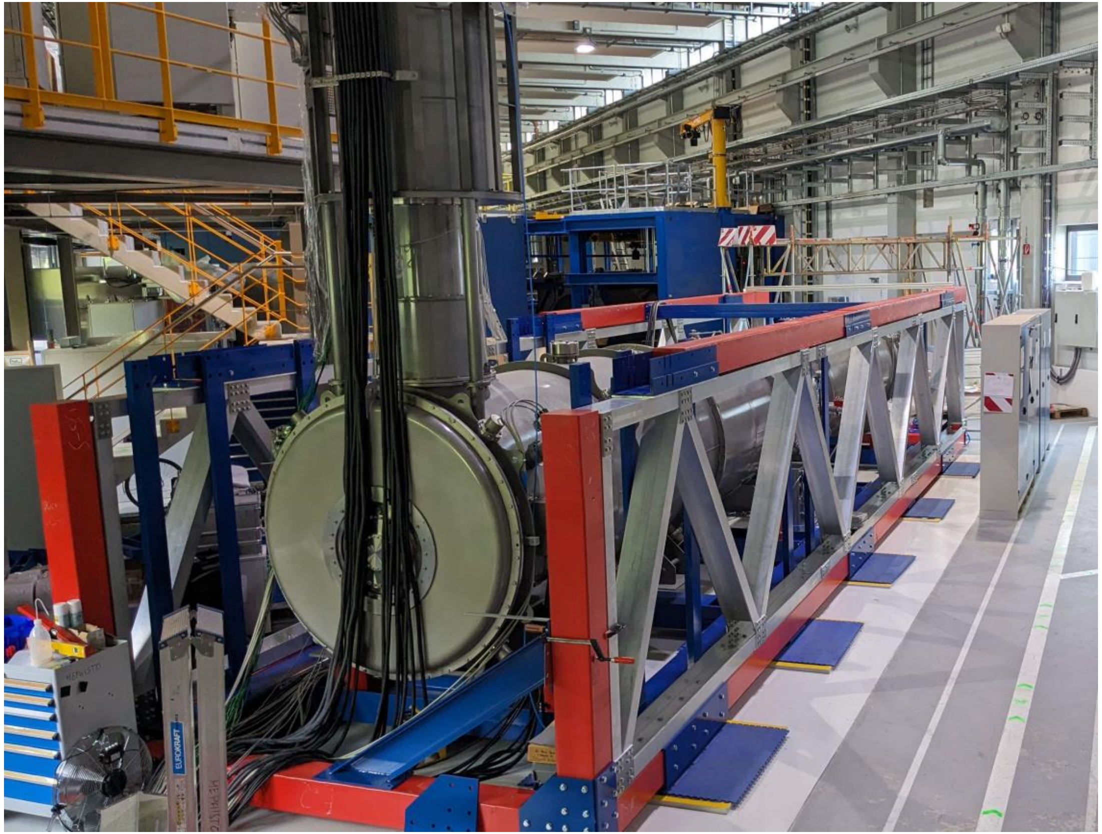
low ambient background

All guide components ready to be installed.

Status of PERC Magnet Installation

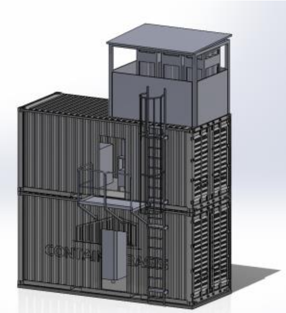
Status 9/2023:
PERC magnet installed,
yoke frame nearly completed.

Ongoing electrical installation.
Next: cooling



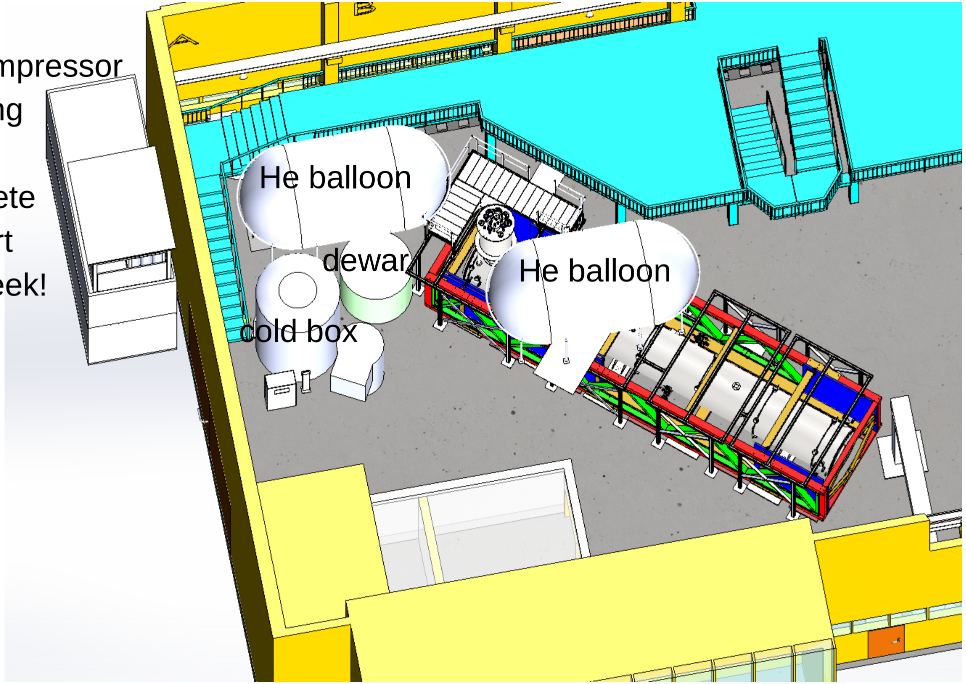
PERC Temporary He Infrastructure

Dedicated He liquefier and recovery system: closed circuit
complete and ready to be installed



He compressor
Housing

Concrete
support
this week!

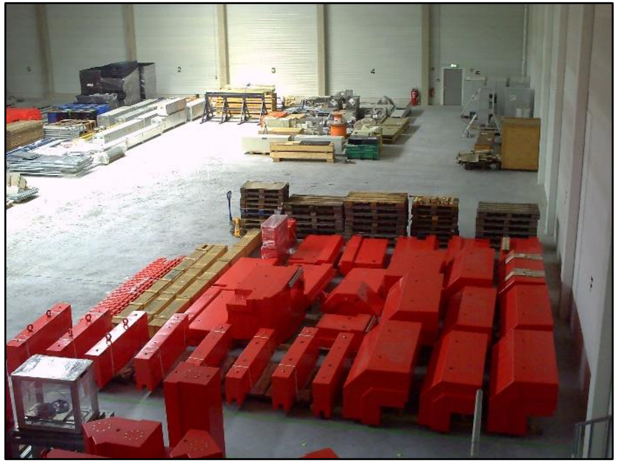


Up to 70l/h

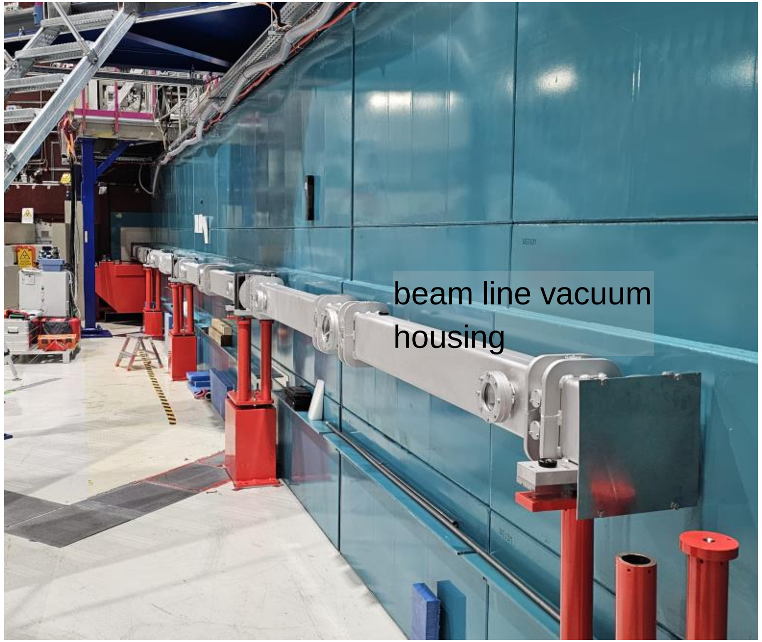
PERC: Installation of beam line

Removal of previous installations completed
Successfull mechanical test installation.

All beam-line components available:
40m (conventional) neutron guides,
40m vacuum tubes, 200t of radiological shielding, …



reactor core
with „new“ insert



Installation test (no shielding yet)

Non-depolarizing Internal Neutron Guide for PERC

PERC's goal of 10^{-4} measurement accuracy requires neutron spin control on same level

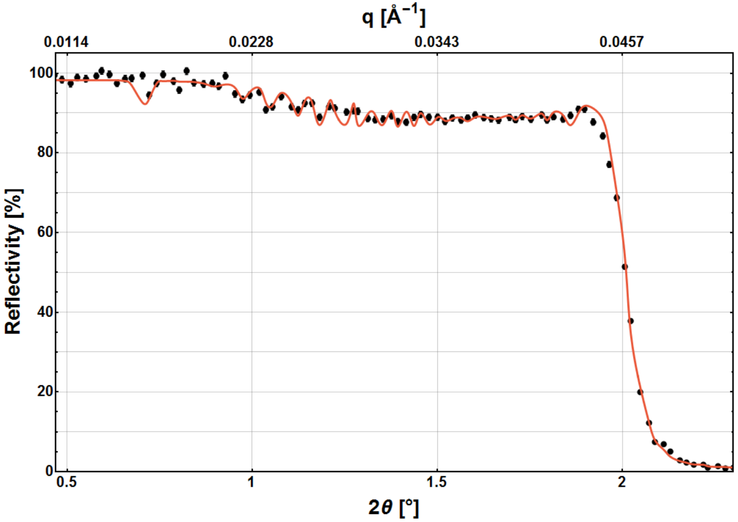
Polarization measurement at 10^{-4} level using polarized ^{3}He gas cells: C. Klauser, T. Soldner *et al.* (ILL)

Neutron guide inside PERC magnet at 1.5T (decay volume): only polarization change of 10^{-4} per bounce allowed:

Solution: CuTi m=2 supermirror

Multi-layer system with 190 layers

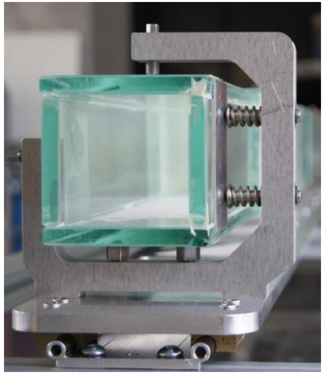
Challenge is to control interdiffusion of Cu while maintaining neutron optical contrast.



A. Hollering *et al.*, Nucl. Instrum. Meth. A 1032, 166634 (2022)

Performance **verified** in dedicated campaign at ILL in 8/2023.

K. Bernert, J.M. Gomez, C. Klauser, B. M., U. Schmidt, T. Soldner



Internal Guide support (HD) (glass only)

Proposed Cold Beamline for Particle Physics at ESS

Particle Physics Beamline at the European Spallation Source

ESS design goal is same time average neutron flux as ILL. Peak brightness in pulse: 30 × ILL

Using pulsed beam for particle physics already at reactor sources!

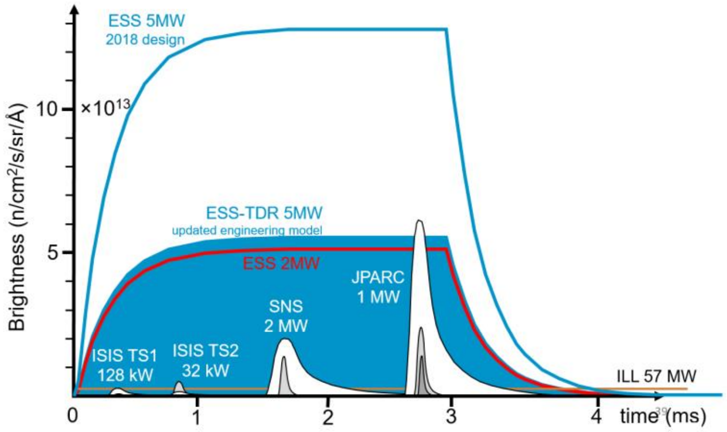
Statistics gain factor for a PERC-like system: x 15 !

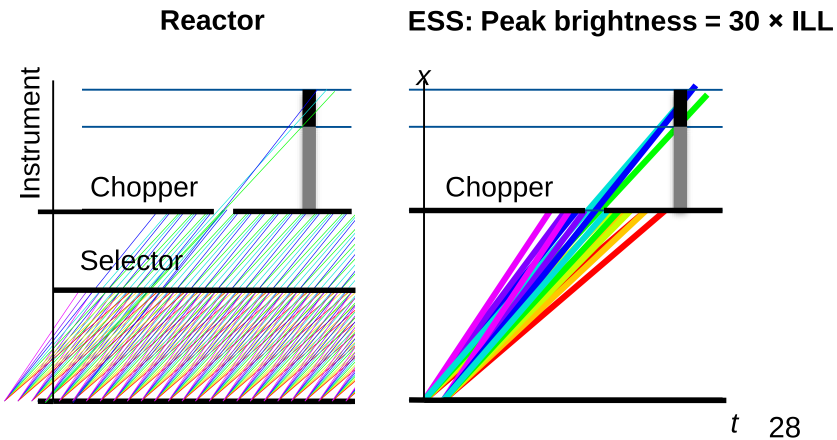
ANNI – A pulsed cold neutron beam facility for particle physics at the ESS
T. Soldner, *et al.*, EPJ Web Conf. 219, 10003 (2019)

Particle Physics at the European Spallation Source
H. Abele, *et al.*, Physics Reports 1023, 1-84 (2023)

General purpose particle physics beam line:

Neutron beta decay, EDM, hadronic weak interaction, Baryon number violation, …





Summary and Outlook

PERKEO III Leading beta asymmetry and Fierz term results. Analysis of proton asymmetry and beta spectrum campaigns ongoing, Establishes *pulsed cold beam* technique.

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

PERC Aims at improved measurements of Parameters A, (B), C, a, b. Commissioning!

$$\frac{\Delta\lambda}{\lambda} \leq 1 \times 10^{-4}$$

ANNI at ESS Proposed beam line at the ESS. Statistics gain factor for a PERC-like system: ×15 !

T. Soldner, *et al.*, EPJ Web Conf. 219, 10003 (2019)

DFG Schwerpunktprogramm SPP1491

SLOW NEUTRONS DFG SPP 1491

Particle Physics with Cold and Ultra-Cold Neutrons