Precision neutron beta-decay experiments for ANNI beamline at ESS

"Workshop on Research & Innovation. Polish contribution to ESS",
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Outline

- Why study the free neutron?
- EFT – "communication protocol" between "***ENERGY***" and "***PRECISION***" frontiers
- Neutron β-decay in SM
- Precision SM parameters V_{ud} and λ
- Search for BSM with neutron β-decay
- ANNI beamline
- Summary

Why study the free neutron?

- Main goal of Particle Physics:
  Establish consistent picture of Nature's fundamental interactions
  - High Energy PP:
    - Operates at TeV scale (10^{12} eV) $\Rightarrow$ study of 2nd (s, c, μ, ν_μ) and 3rd (b, t, τ, ν_τ) particle families

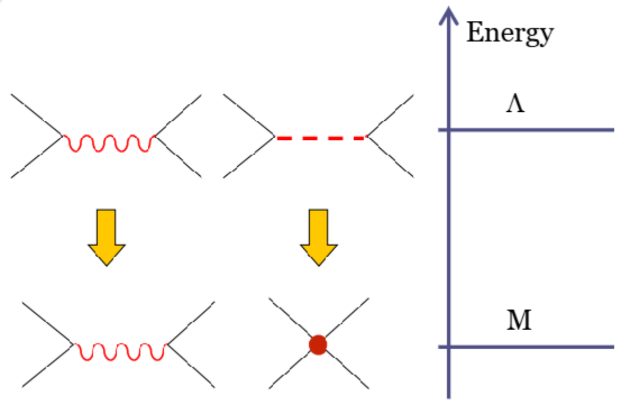
"ENERGY front"

  - Low Energy PP (e.g. with slow neutrons):
    - Operates at neV scale (10^{-9} eV) $\Rightarrow$ study of 1st (u, d, e, ν_e) particle family
    - Reveals respectable sensitivity:
      - Energy: $\Delta E/E \sim 10^{-11} \div 10^{-13}$ ($\Delta E \sim 10^{-23}$ eV)
      - Momentum: $\Delta p/p \sim 10^{-10} \div 10^{-11}$
      - Spin polarization: $\Delta s/s \sim 10^{-7}$

"PRECISION (intensity) front"

  - *Fundamental neutron physics provides more than **20** observables reach in information which is difficult to achieve (or not achievable at all) in other fields of Particle Physics*

EFT approach in β-decay



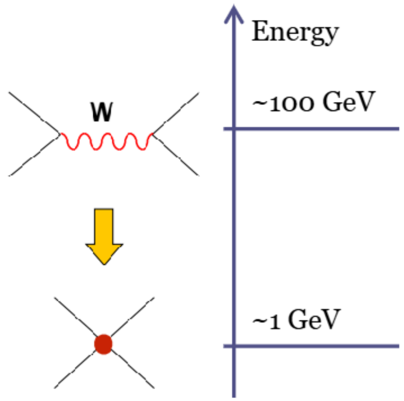
- For experiments at energy significantly lower than BSM scale (Λ_i):

$$\boxed{\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{1}{\Lambda_i^2}\mathcal{L}_i \approx \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum \alpha_i \mathcal{O}_i^{(6)}}$$

$\mathcal{O}_{\text{i}}^{(6)}$ – dimension-6 operators

α_{i} – *Wilson coefficients* $\alpha_i = \Lambda^2 f_i\left(g_{\text{BSM}}, M_{\text{BSM}}\right)$

Observables for $E \ll \Lambda$: $$\mathcal{R} = \mathcal{R}_0\left(1 + \frac{\mathcal{O}(M)}{\Lambda} + \frac{\mathcal{O}\left(M^2, E^2, ME\right)}{\Lambda^2} + \dots\right)$$



- Semi-leptonic processes, partonic level, exchanged W-boson is heavy – SM interaction Lagrangian takes the contact (V-A)×(V-A) form

$$\mathcal{L}_{\text{SM}} = -\frac{G_F V_{ud}}{\sqrt{2}}\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

EFT approach in β-decay (cont.)

- Model independent EFT parameters

V. Cirigliano et al., Nucl. Phys. B 830 (2010)
T. Bhattacharya et al., Phys. Rev. D 85 (2012)
V. Cirigliano et al., JHEP 1302 (2013)
M. Gonzalez-Alonso et al., Ann. Phys. 525 (2013)
M. Gonzalez-Alonso et al., Phys. Rev. Lett. 112 (2014)

$$\begin{aligned}\mathcal{L}_{\rm eff} = & -\frac{G_F V_{ud}}{\sqrt{2}} [\,(1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\ & + \tilde{\epsilon}_L\ \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\ & + \epsilon_R\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\ & + \tilde{\epsilon}_R\ \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\ & + \epsilon_S\ \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d\ +\ \tilde{\epsilon}_S\ \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d \\ & - \epsilon_P\ \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d\ -\ \tilde{\epsilon}_P\ \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \\ & + \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \\ & + \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d] + \text{h.c.}\ .\end{aligned}$$

Wilson coefficients

- Valid also for $\pi^{\pm} \rightarrow \pi^0 e^{\pm}\nu$

- Low-energy simplifications:
  - Neglect RH neutrinos: $\tilde{\epsilon}_{L,R,S,P,T} = 0$
  - Pseudo-scalar contribution (non-relativistic limit): $\epsilon_P = 0$

$$\begin{aligned}\mathcal{L}_{\rm eff} = & -\frac{G_F V_{ud}}{\sqrt{2}} [1 + \text{Re}(\epsilon_L + \epsilon_R)] \times \\ & \times \{\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu [1-(1-2\epsilon_R)\gamma_5]\, d \\ & + \epsilon_S\ \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d \\ & +\ \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\} + \text{h.c.}\end{aligned}$$

Nucleon-level effective couplings

- Recent global fits to constrain Wilson coefficients:

  Falkowski, González-Alonso, Naviliat-Cuncic, *"Comprehensive analysis of beta decays within and beyond the Standard Model"*, *J. High Energ. Phys.* **2021**, 126 (2021), arXiv:2010.13797

- Effective nucleon-level couplings can be expressed in parton-level parameters:

$$
\begin{aligned}
\overline{C}_V &= g_V\,(1+\epsilon_L+\epsilon_R+\tilde{\epsilon}_L+\tilde{\epsilon}_R)\\
\overline{C}'_V &= g_V\,(1+\epsilon_L+\epsilon_R-\tilde{\epsilon}_L-\tilde{\epsilon}_R)\\
\overline{C}_A &= -g_A\,(1+\epsilon_L-\epsilon_R-\tilde{\epsilon}_L+\tilde{\epsilon}_R)\\
\overline{C}'_A &= -g_A\,(1+\epsilon_L-\epsilon_R+\tilde{\epsilon}_L-\tilde{\epsilon}_R)
\end{aligned}
$$

$$
\begin{aligned}
\overline{C}_S &= g_S\,(\epsilon_S+\tilde{\epsilon}_S)\\
\overline{C}'_S &= g_S\,(\epsilon_S-\tilde{\epsilon}_S)\\
\overline{C}_P &= g_P\,(\epsilon_P-\tilde{\epsilon}_P)\\
\overline{C}'_P &= g_P\,(\epsilon_P+\tilde{\epsilon}_P)\\
\overline{C}_T &= 4\,g_T\,(\epsilon_T+\tilde{\epsilon}_T)\\
\overline{C}'_T &= 4\,g_T\,(\epsilon_T-\tilde{\epsilon}_T)
\end{aligned}
$$

- *Form factors are the key ingredients for translation of hadron-level coupling constants to parton-level parameters*

Neutron β-decay in Standard Model

- Neutron β decay can establish only 2 SM parameters:

$$H = \frac{G_F}{\sqrt{2}} V_{ud} \; \bar{p}\left\{\gamma_\mu\left(1+\lambda\gamma_5\right)+\frac{\mu_p-\mu_n}{2m_p}\sigma_{\mu\nu}q^\nu\right\}n \;\; \bar{e}\gamma^\mu\left(1-\gamma_5\right)\nu_e$$

V_{ud} – CKM matrix element

$\lambda \equiv \frac{g_A}{g_V}$ – axial-to-vector coupling constant ratio

- Can be extracted from:
  - Neutron lifetime (total decay rate):

$$\boxed{\tau_n^{-1} = \frac{G_F^2 m_e^2}{2\pi^3}\left|V_{ud}\right|^2 f\left(1+\delta_R\right)\left(1+\Delta_R\right)\left(1+3\lambda^2\right)}$$

f – phase space factor
δ_R – radiative correction (model independent)
Δ_R – radiative correction (model dependent)

  - λ (independently) from ***Correlation coefficients*** (parametrization of the differential decay rate):

$$\boxed{V_{ud} = \left(\frac{5099.34\ \mathrm{s}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}\right)^{1/2}}$$

Neutron β-decay correlations

- For decay of polarized neutrons (polarization $\langle \mathbf{J} \rangle / J$):

$$
\begin{aligned}
\frac{d^2\Gamma}{dE_e d\Omega_e d\Omega_\nu} \sim\; & 1 + a \frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + b\frac{m_e}{E_e} + \frac{\langle \mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}}{E_e} + B\frac{\mathbf{q}}{E_\nu} + D\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right] + \ldots \\
& + \sigma\cdot\left[G\frac{\mathbf{p}}{E_e} + H\frac{\mathbf{q}}{E_\nu} + K\frac{\mathbf{p}}{E_e+m_e}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + L\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu} + N\frac{\langle \mathbf{J}\rangle}{J}\right] \\
& + \sigma\cdot\left[Q\frac{\mathbf{p}}{E_e+m_e}\frac{\langle \mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + R\frac{\langle \mathbf{J}\rangle}{J}\times\frac{\mathbf{p}}{E_e} + S\frac{\langle \mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + T\frac{\mathbf{p}}{E_e}\frac{\langle \mathbf{J}\rangle}{J}\cdot\frac{\mathbf{q}}{E_\nu}\right] \\
& + \sigma\cdot\left[U\frac{\mathbf{q}}{E_\nu}\frac{\langle \mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + V\frac{\mathbf{q}}{E_\nu}\times\frac{\langle \mathbf{J}\rangle}{J} + W\frac{\mathbf{p}}{E_e+m_e}\frac{\langle \mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right]
\end{aligned}
$$

p – electron momentum

q – neutrino momentum

σ – electron spin sensing direction

J.D. Jackson et al., Phys. Rev. 106, 517 (1957); J.D. Jackson et al., Nucl. Phys. 4, 206 (1957); M.E. Ebel et al., Nucl. Phys. 4, 213 (1957)

- Coefficients ***a***, ***b***, …, ***W*** are functions of λ (and not of V_{ud})
- Including proton polarization, there are 51 correlations (C.-Y. Seng, Phys. Rev. D **109**, 073007 (2024))
- Form highly over-constrained system of observables ideal for reliable consistency checks)

CKM Unitarity

- V_{ud} is highly important; departure from the SM value suggest physics BSM

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

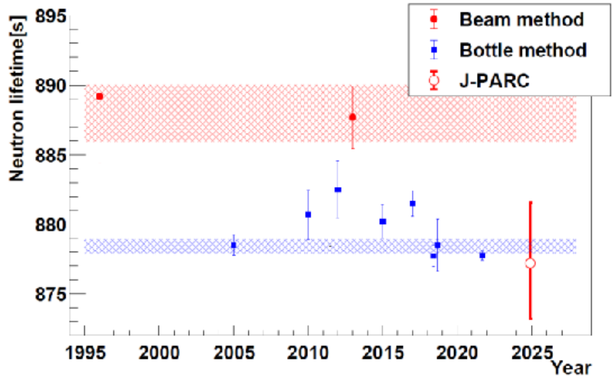
- At precision of 10^{-4} covers the scale of BSM up to 10 TeV. Presently:

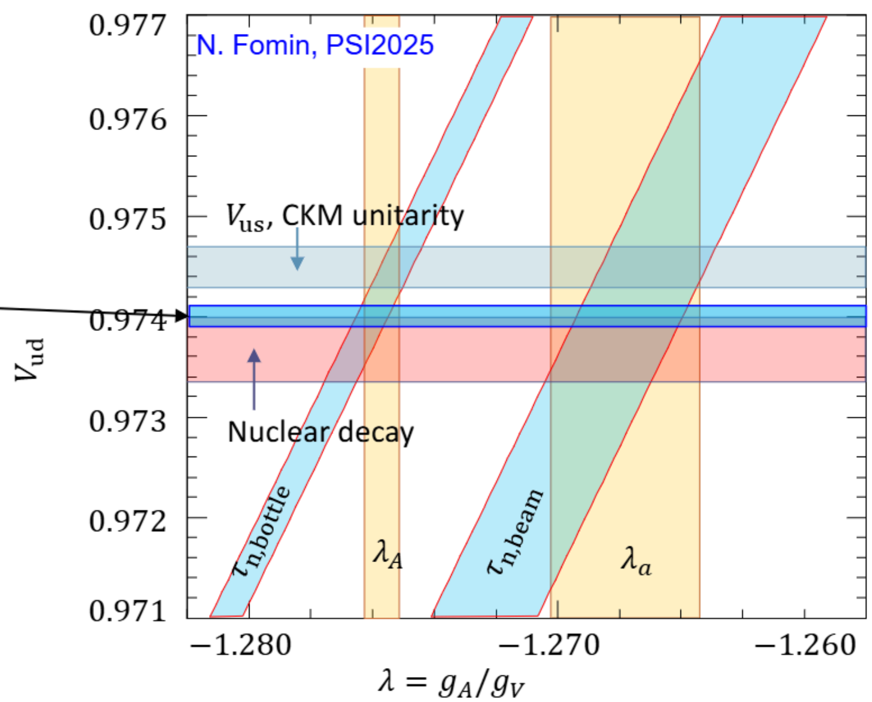
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5) \neq 1$$

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

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

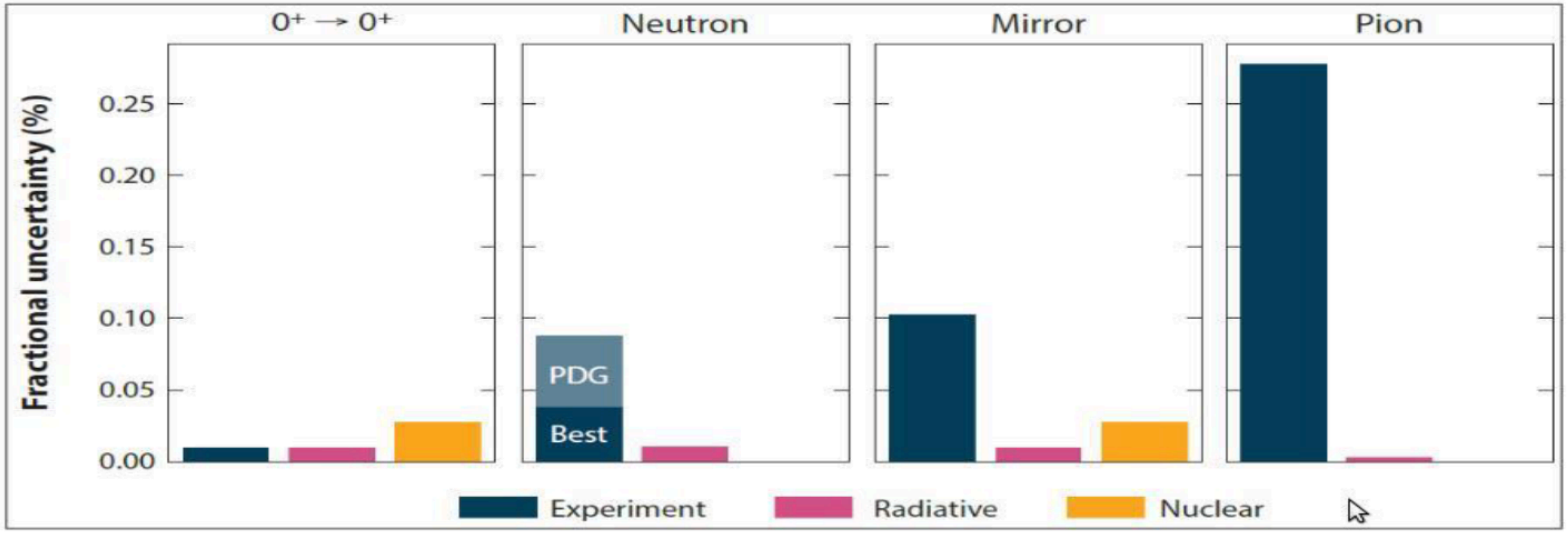
- Why not enter 10^{-5} regime ?
- Presently, correlations are limiting !





E. importance of the neutron

if current **best values** for **lifetime and $\lambda = g_A/g_V$** (from beta asymmetry) are used,
V_{ud} value from neutron has **similar precision as from pure Fermi decays**!



This is within reach in the coming 5 to 10 years !

See the many talks on the neutron half-life and *a*- and *A*-correlation parameters !!
and e.g. D. Dubbers, B. Märkisch, Ann. Rev. Nucl. Part. Sci. 71 (2021) 139

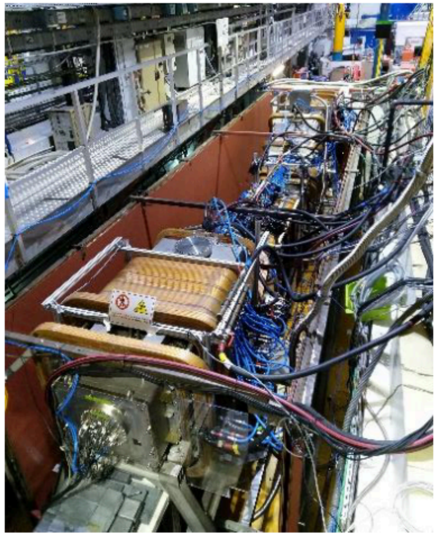
KU LEUVEN

(Courtesy of B. Maerkisch)

Neutron β-decay correlations

- Two approaches:
  - (A) Phase space integrating, electric and magnetic filters (strong magnetic field)
  - (B) Event-by-event decay kinematics reconstruction (very weak magnetic field)
- From class A experiments, for immediate implementation on the ANNI beamline at ESS are:

PERKEO III
Beta-Asymmetry *A*
Fierz-Term *b*
Proton-Asymmetry *C*



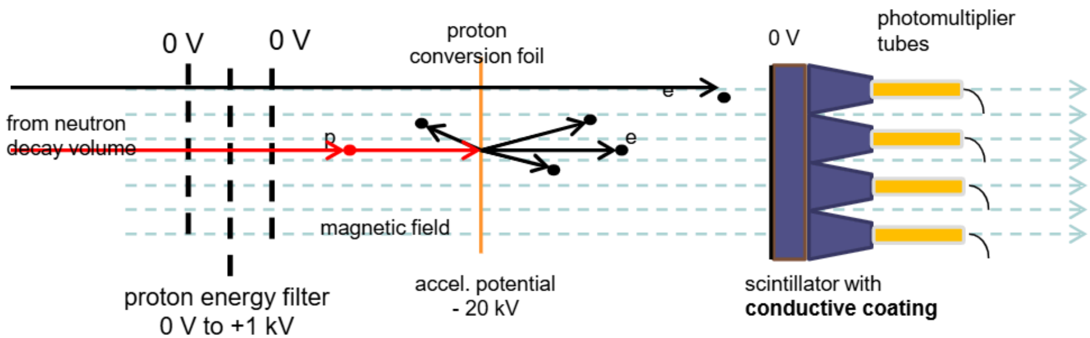
PERC
Beta-Asymmetry *A*
Fierz-Term *b*
(Proton-Asymmetry *C*)

- Evolution of *ongoing* research. Existing instruments.
- Profit from time-structure. Require highest neutron polarization and lowest backgrounds.

(Courtesy of B. Maerkisch)

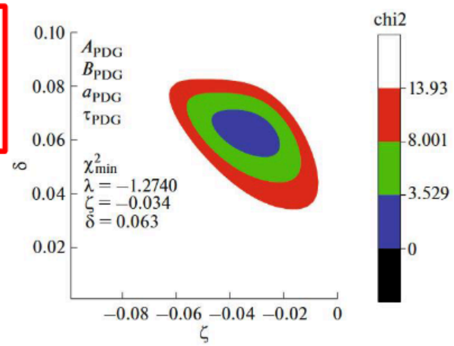
PERKEO III: Proton Asymmetry C

Detection concept: Coincident detection of electron and proton with integrated proton energy determination:



$$C = -4x_C \frac{\lambda}{1+3\lambda^2} = x_C(A+B)$$

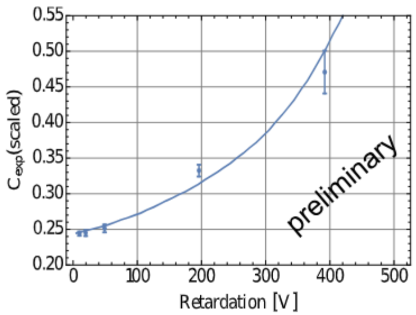
A. Serebrov *et al.*, Phys. Part. Nucl. Lett. 22, 229–235 (2025)

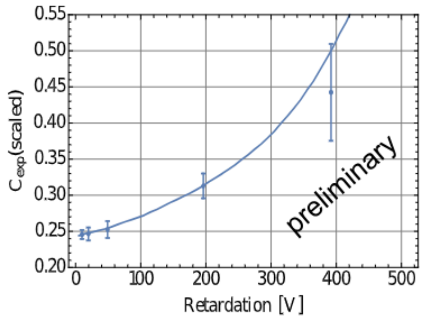


Latest analysis indicates the existence of right-handed currents (and possibly scalar and tensor interactions).

Demonstration of this concept at ILL in 2014/15 with O(1%) precision.

Theses C. Roick (TUM), L. Raffelt (TUM/HD), M. Klopf (TUW), A. Hollering (TUM)





With conversion foils of the required size developed at NCSU, the currently only published result by PERKEO II could be improved at ESS by an *order of magnitude*.

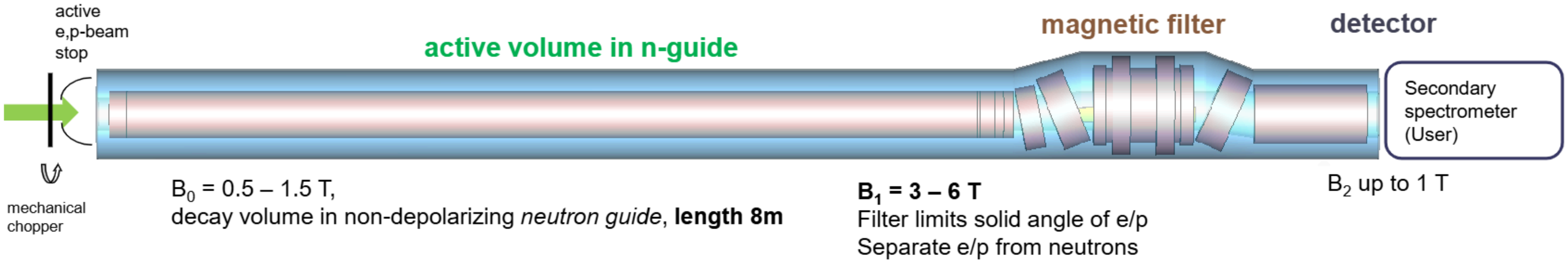
PERC: Phase Space Integration

(Courtesy of B. Maerkisch)

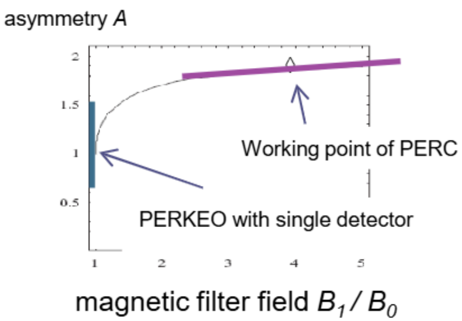
PERC´s asymmetric layout with magnetic filter improves systematics

Strong field ensures high phase space density, small detector size, excellent S/B

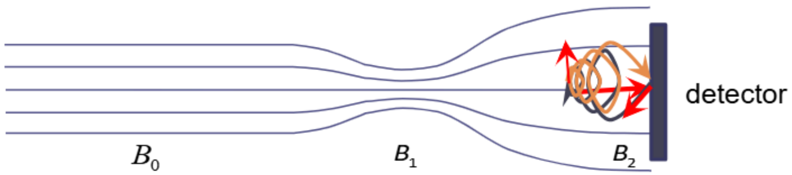
Observable decay rate enhanced by two orders of magnitude: length and decay inside neutron guide



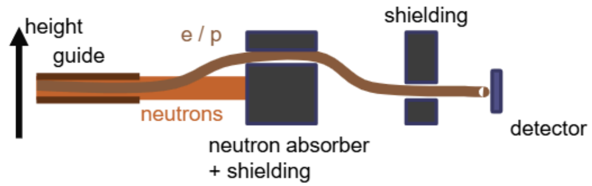
Phase space cut: magnetic field influence



Electron backscatter strongly suppressed



Main detector shielded from background

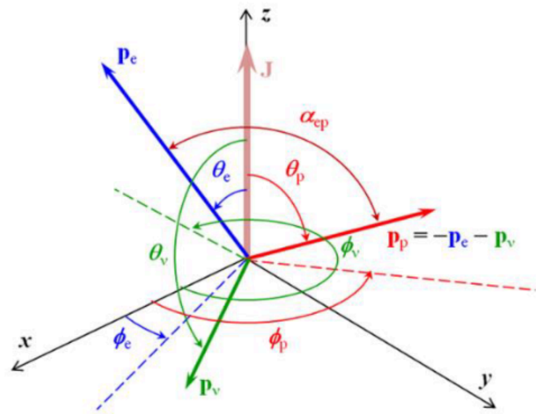


Dubbers *et al.*, Nucl. Instr. Meth. A 596, 238-247 (2008)

BRAND – exploring transverse polarization of electrons

- If only transverse electron polarization can be observed:

$$\frac{d^2\Gamma}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + b\frac{m_e}{E_e} + \frac{\langle \mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}}{E_e} + B\frac{\mathbf{q}}{E_\nu} + D\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right]$$
$$+\ \boldsymbol{\sigma}_\perp\cdot\left[H\frac{\mathbf{q}}{E_\nu} + L\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu} + N\frac{\langle \mathbf{J}\rangle}{J} + R\frac{\langle \mathbf{J}\rangle}{J}\times\frac{\mathbf{p}}{E_e}\right]$$
$$+\ \boldsymbol{\sigma}_\perp\cdot\left[S\frac{\langle \mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + U\frac{\mathbf{q}}{E_\nu}\frac{\langle \mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + V\frac{\mathbf{q}}{E_\nu}\times\frac{\langle \mathbf{J}\rangle}{J}\right]$$



- All correlation coefficients can be expressed as **combinations** of real and imaginary parts of exotic (**scalar** and **tensor**) couplings:

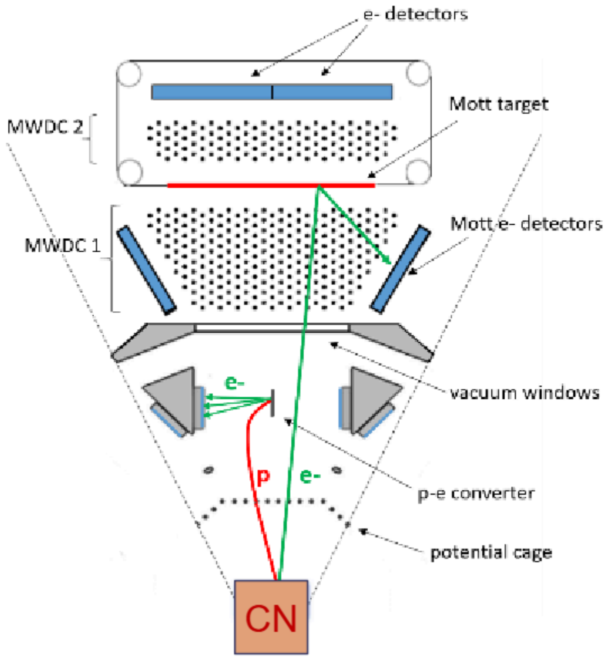
	SM (λ)	FSI (λ)	c(Re*S*)	c(Re*T*)	c(Im*S*)	c(Im*T*)
H	+0.0609	0	-0.1714	+0.2762	0	0
L	0	-0.0004	0	0	+0.1714	-0.2762
N	+0.0681	0	-0.2176	+0.3348	0	0
R	0	+0.0005	0	0	-0.2176	+0.3348
S	0	-0.0018	+0.2176	-0.2176	0	0
U	0	0	-0.2176	+0.2176	0	0
V	0	0	0	0	-0.2176	+0.2172

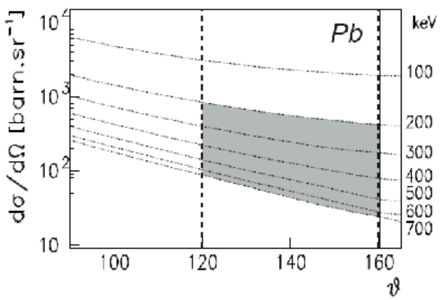
$$X = X_{\mathrm{SM}} + X_{\mathrm{FSI}} + c_{\mathrm{Re}S}\,\mathrm{Re}S + c_{\mathrm{Re}T}\,\mathrm{Re}T + c_{\mathrm{Im}S}\,\mathrm{Im}S + c_{\mathrm{Im}T}\,\mathrm{Im}T$$

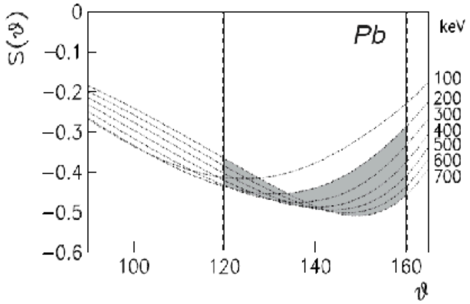
$S = \frac{C_S + C_S'}{C_V}$, $T = \frac{C_T + C_T'}{C_A}$, $c_{\mathrm{Re}S}, c_{\mathrm{Re}T}, c_{\mathrm{Im}S}, c_{\mathrm{Im}T}$ – functions of $\lambda = C_A/C_V$ and kinematical quantities

BRAND – exploring transverse polarization of electrons

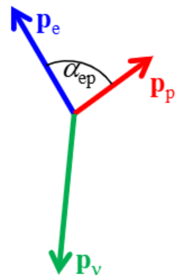
- Class B experiment (Low magnetic field, event-by-event kinematics reconstruction):
  - Complementary to phase space integrating experiments using charged decay product separators (PERKEO, PERC,…)
  - Measure decay electrons, protons and *e-p* coincidences
  - Electron tracking in hexagonal, low *Z*, low pressure MWDC
  - *p-e* conversion followed by secondary *e* detection in plastic scintillator (ToF, position)
  - Reconstruction of electron and proton momenta
  - Decay vertex reconstruction
  - Electron spin analysis by Mott scattering (vertex reconstruction)

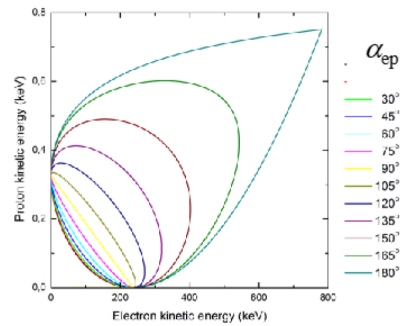






- Analyzing power caused by spin-orbit force
- Parity and time reversal conserving (electromagnetic process)
- Sensitive **exclusively** to the **transverse polarization**





BRAND – exploring transverse polarization of electrons

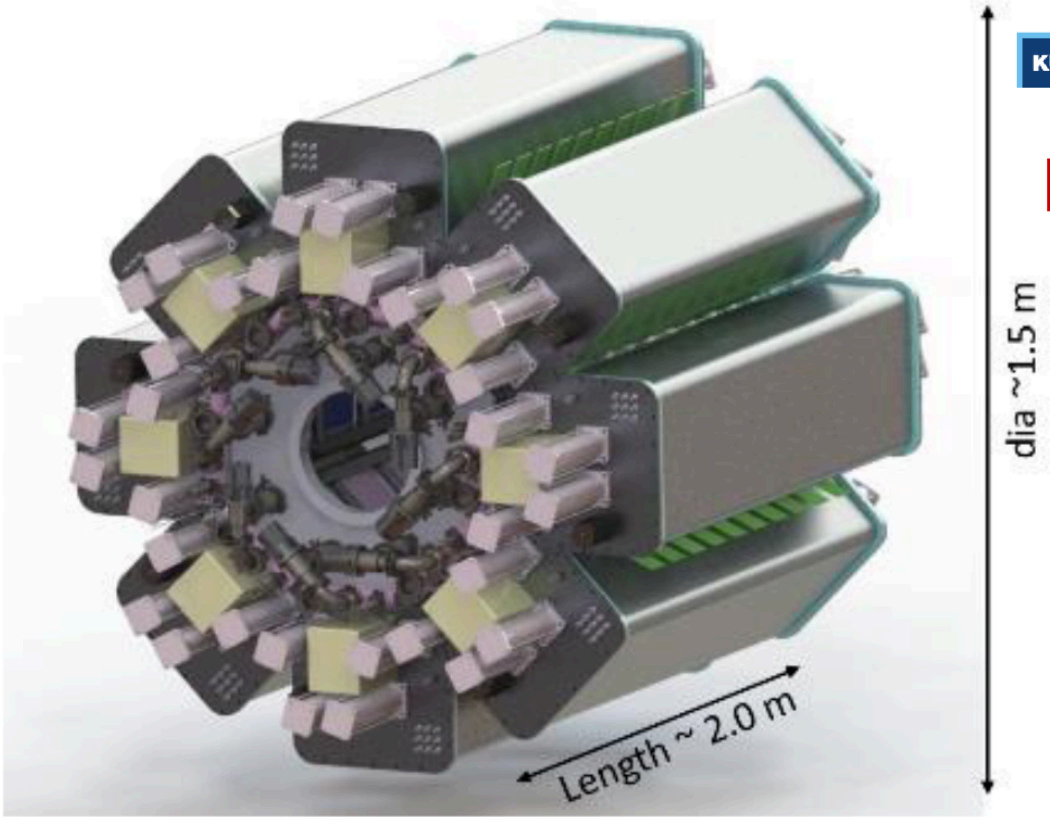
- BRAND will focus on the transverse electron polarization related coefficients ***H***, ***L***, ***N***, ***R***, ***S***, ***U***, ***V***.

- Simultaneously, will measure with high statistics "classical" coefficients ***a***, ***A***, ***B***, ***D*** (Fierz term ***b*** will be accessible, too).

- Gradual improvement of experimental accuracy (statistical & systematic uncertainty):

4×10^{-3}	→	2×10^{-3}	→	1×10^{-3}	→	5×10^{-4}
nTRV (PSI)		BRAND I (ILL)		BRAND II (ILL)		BRAND III (ESS)

- Demonstration phase at ILL – ongoing



BRAND – exploring transverse polarization of electrons

- Cold neutron beam requirements:
  - Intensive (high flux density leading to at least 5×10^4 decays/s/m in fiducial volume)
  - Maximum fiducial volume: $6\times6\times200$ cm^3
  - Highly parallel (low divergence)
  - Highly polarized ($P > 99.5\%$)
  - Pulsed
  - Low background

- Assuming 5×10^4 decays/s in fiducial volume and 2 years of data taking:
  - 10^{12} direct electrons (coefficient ***A***)
  - 3×10^{11} protons in coincidence with direct electrons (coefficients ***a***, ***B***, ***D***)
  - 3×10^8 Mott scattered electrons (coefficient ***N***, ***R***)
  - 10^8 Mott protons in coincidence with Mott-scattered electrons (coefficients ***H***, ***L***, ***S***, ***U***, ***V***)

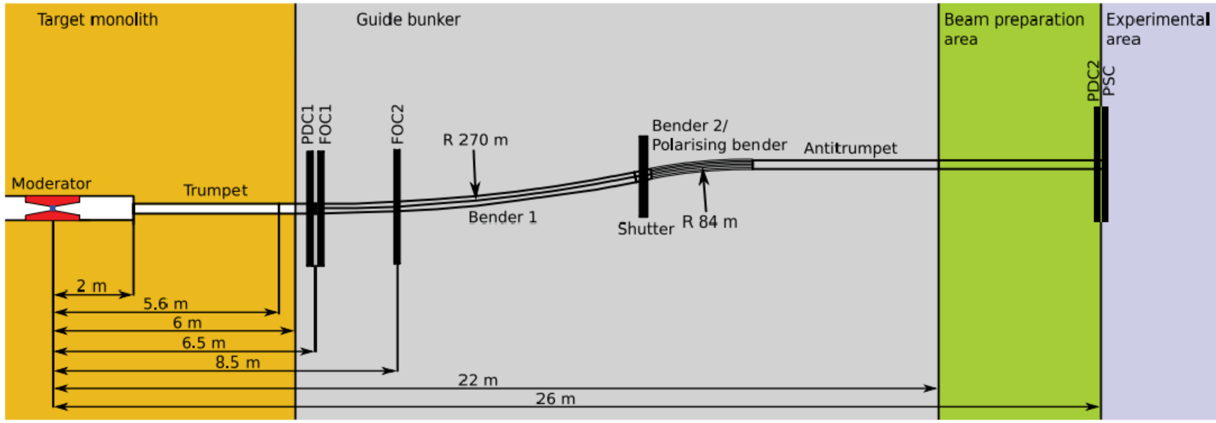
Basic requirements for precision neutron β-decay experiments

- In a cold neutron beam, only about 10^6 neutrons decay per second over 1 m flight path; Specific acceptance of an experiment may **reduce this by 1-2 orders** of magnitude.
- All other beam neutrons are potential source of background.
- Low background beam line design is the must.
- Pulsed beams are essential:
  - In PERKEO III and PERC, the pulsed neutron beam eliminates or controls leading sources of systematic errors like (i) edge effects, (ii) magnetic mirror effect, (iii) separation of signal and background in time.
  - In BRAND, a pulsed beam is vital to exclude the direct gamma-induced background radiation.
- Neutron polarization analysis:
  - Precision β-decay experiments **require highest possible polarization**; at the envisaged precision level of $O(10^{-5})$, a 1% deviation from 1 leads to a $O(10^3)$ σ correction.
  - Polarizer with 99.7% polarization (A. K. Petoukhov, *et al.*, *Rev. Sci. Instrum.* 94 (2): 023304 (2023)).
  - Polarization analysis with $O(10^{-5})$ precision (C. Klauser, *et al.*, *J. Phys.: Conf. Ser.* 340, 012011 (2012)).
  - Neutron guide with $O(10^{-5})$ spin preservation (J. M. Gómez-Guzmán, et al., *Nucl. Instr. Meth. A 1080, 170795 (2025), arXiv:2503.22561*)

(B. Maerkisch & KB)

ANNI – A pulsed cold neutron beam facility for particle physics at the ESS

T. Soldner, H. Abele, G. Konrad, B. Märkisch, F. Piegsa, U. Schmidt, C. Theroine, P. Torres Sánchez: EPJ Web Conf. 219, 10003 (2019)

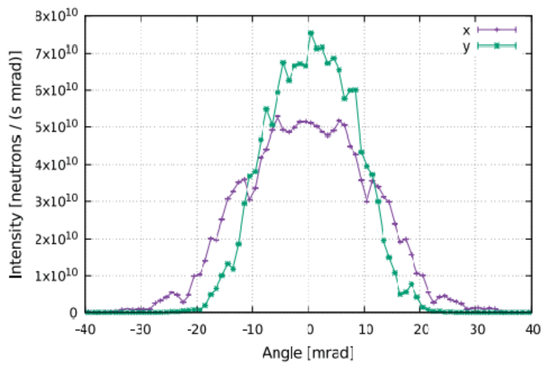


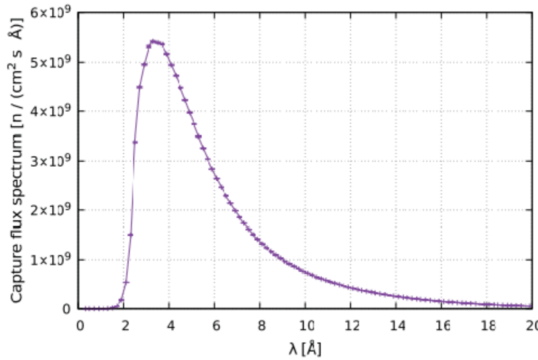
Element	Dist [m]	Rad [m]	Len [m]	X-section [cm²]	NOC	m value	γ* [mrad]	λ* [Å]
Trumpet	2.0	∞	3.6	9 × 6 → 13 × 6	1	LR: 3.5, TB: 3.0		
Straight 1	5.6	∞	0.9	13 × 6	1	3.0		
Bender 1	6.5	270	8.0	13 × 6	2	LRT: 3.0, B: 3.5	14.7	2.44
Straight 2	14.5	∞	0.4	13 × 6	2	3.0		
Bender 2 or Polarizing bender	6.5	-84	2.5	13 × 6	6	LRB: 3.0, T: 3.5	14.7	2.44
Antitrumpet	17.4	∞	4.6	13 × 6 → 11 × 7	1	LR: 3.5, TB: 3.0		

Side view of the ANNI beam line (schematic). The vertical scale is stretched by a factor of 4 for better readability.

- Expected performance (avr. over 11×7 cm²)
  - Full spectrum capture flux density: **2.5×10¹⁰** n/(cm²s)
  - Polarization losses:
    - Moderate polarization: factor 2
    - Highest polarization: factor 4

Simulated





Neutron decay correlation coefficients at ANNI beamline – projected sensitivity

100 days at 5 MW ESS power

Proposed experiment	Measurement	Quantity	Last measured	Current value / limit	Statistical uncertainty (1σ) @ANNI [100 days]
	$n \to p + e + \bar{\nu}_e$				
ep/n	A	Beta asymmetry	PERKEO III@PF1B [276]	$-0.11985 \pm 0.00017 \pm 0.00012$	1×10^{-5}
ep/n	C	Proton asymmetry	PERKEO II@PF1B [316]	$-0.2377 \pm 0.0010 \pm 0.0024$	1×10^{-4}
ep/n	a	e-$\bar{\nu}_e$ correlation from p recoil spectrum	aSPECT@PF1B [278]	-0.10430 ± 0.00084	1×10^{-4}
ep/n	b	Fierz interference from beta asymmetry	PERKEO III@PF1B [277]	$0.017 \pm 0.020 \pm 0.003$	6×10^{-4}
CRES	b	Fierz interference from beta spectrum	UCNA@UCN-LANL [408]	$0.067 \pm 0.005^{+0.090}_{-0.061}$	1×10^{-4}
BRAND	a	e-$\bar{\nu}_e$ correlation from e-p correlation	aCORN@NG-C [322]	$-0.10758 \pm 0.00136 \pm 0.00148$	5×10^{-5}
BRAND	B	Neutrino asymmetry	PERKEO II@PF1B [315]	$0.9802 \pm 0.0034 \pm 0.0036$	5×10^{-5}
BRAND	D	Triple correlation D	emiT@NG-6 [318]	$(-0.94 \pm 1.89 \pm 0.97) \times 10^{-4}$	5×10^{-5}
BRAND	R	Triple correlation R	nTRV@FUNSPIN [299]	$(4 \pm 12 \pm 5) \times 10^{-3}$	1×10^{-3}
BRAND	N	σ_n-$\sigma_{e,\perp}$ Correlation	nTRV@FUNSPIN [299]	$0.067 \pm 0.011 \pm 0.004$	1×10^{-3}
BRAND	H, L, S, U, V	Other correlations with $\sigma_{e,\perp}$	unmeasured	unmeasured	1×10^{-3}

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Summary

- World-leading neutron β-decay program proposed for ESS including:
  - Nucleon axial coupling with a precision entering level 10^{-5}.
  - V_{ud} and CKM unitarity test.
  - New effective BSM couplings (scalar, tensor, RH currents …)
- Evolution of existing and in construction instruments (PERKEO III, PERC, BRAND…).
- No compromise on the dedicated beam line should be undertaken; further optimization of ANNI proposal is possible:
  - World-leading intensity in a pulsed beam with low divergence.
  - Excellent background conditions.
  - Highly polarized beam.

Backup slides

BRAND – exploring transverse polarization of electrons

- Benefits from pulsed cold neutron beam & space requirements:
  - Pulsed operation (time-of-flight) provides additional means for controlling and suppressing backgrounds (mainly upstream gamma)
  - Complete experiment including auxiliary equipment and a distant beam stop (at least 4 m away from detectors) can be accommodated in a 10 m long beam section.

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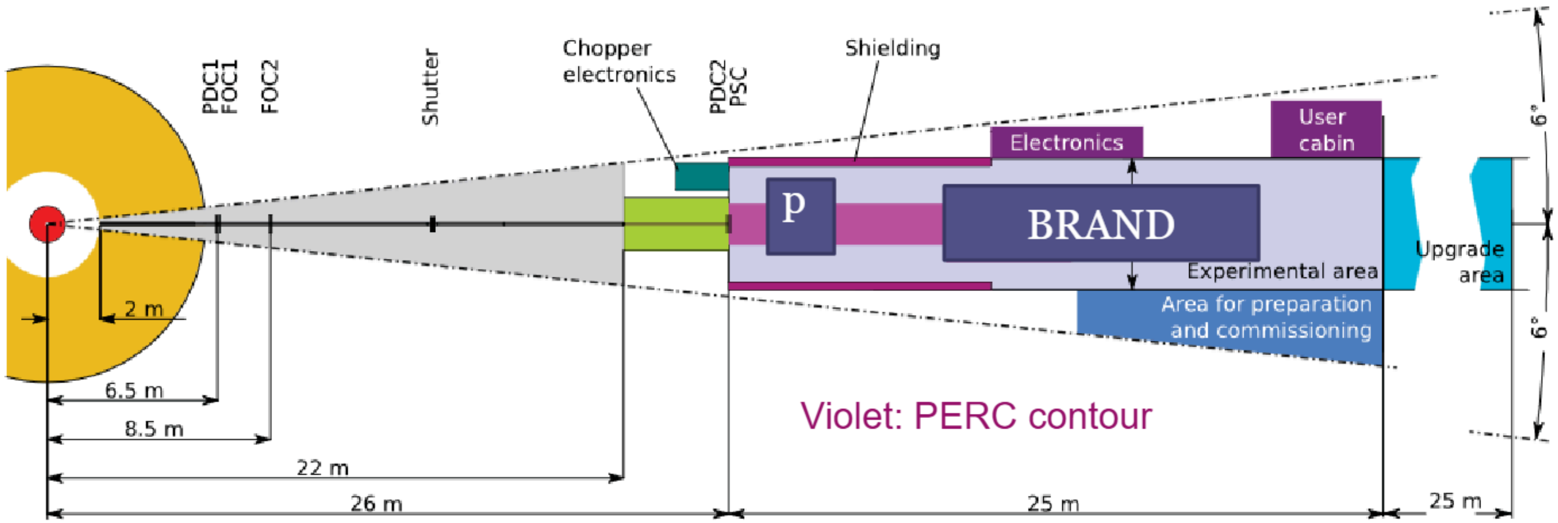

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