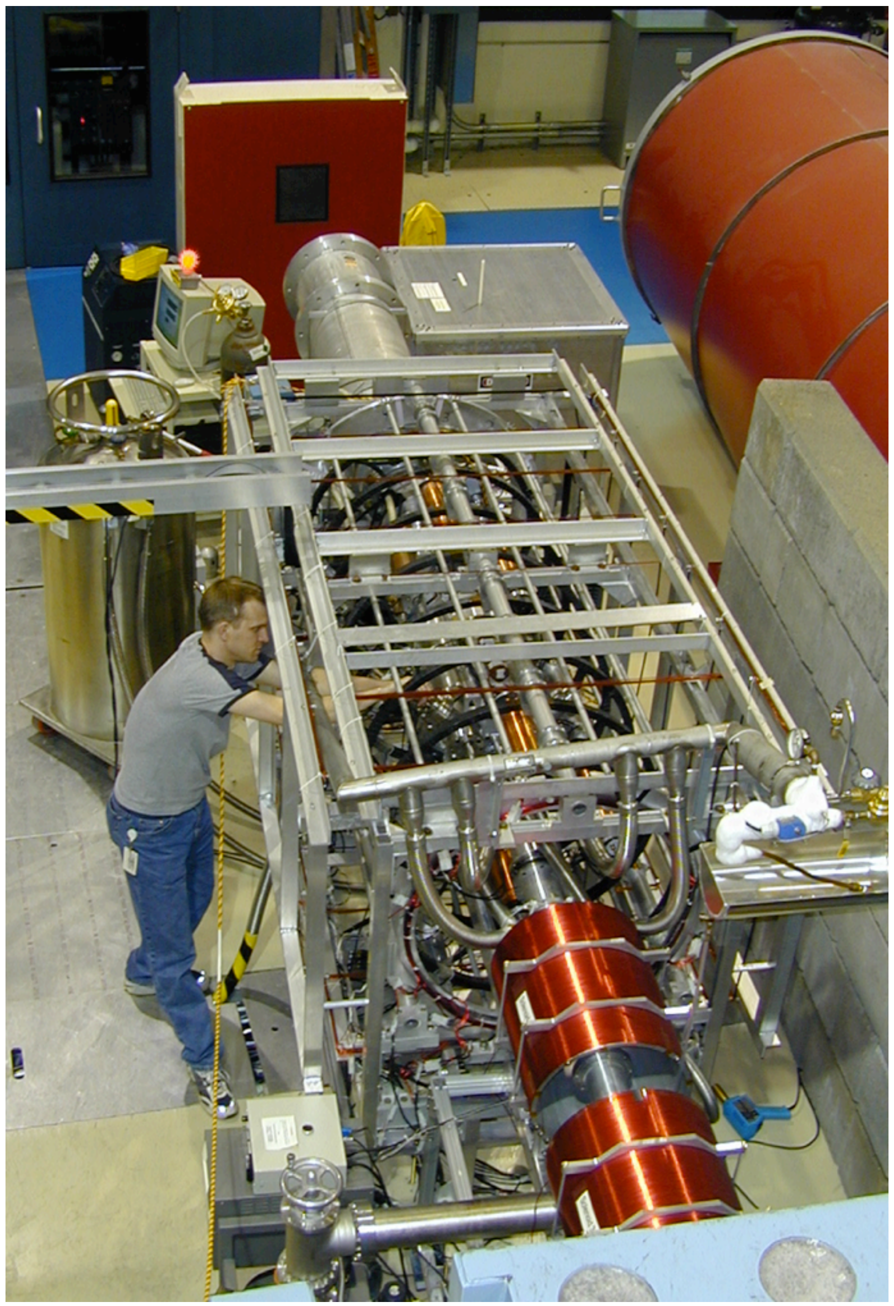
The emiT Experiment: A Search for Time-reversal Violation in Polarized Neutron Beta Decay



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Time Reversal Violation in Nuclear Beta Decay

- The observed matter - antimatter asymmetry indicates the existence of CP violation (and corresponding T-violation) perhaps arising from non-SM interactions.
  - Left-Right Symmetric
  - Exotic Fermion
  - Leptoquark

- Yet In the Standard Model the size of measured CP and T violating effects imply extremely tiny (non-observable) T violating effects in nuclear beta decay.

- T violating contributions to beta decay can arise from
  - Parity violating, Time reversal violating N-N interactions
  - Parity conserving, Time reversal violating N-N interactions
  - Time reversal violating charged current quark-lepton interactions

Hence searches for T violation in nuclear beta decay have the potential to be sensitive to interactions beyond the SM.

Generalized Beta Decay

We can write out a general Hamiltonian:

$$H_{\text{int}} = \sum_{i=V,A,S,P,T} (\overline{\psi}_p O_i \psi_n)(C_i \overline{\psi}_e O_i \psi_\nu + C_i' \overline{\psi}_e \gamma_5 O_i \psi_\nu)$$

In the Standard Model, $C_V' = C_V$, $C_A' = C_A$, and others are zero,

and the C_i are real if T is a good symmetry.

$$\frac{d\omega}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + \sigma_n \cdot \left(A\frac{p_e}{E_e} + B\frac{p_\nu}{E_\nu} + D\frac{p_e \times p_\nu}{E_e E_\nu}\right)\right)$$

$$\lambda \equiv \left|\frac{g_A}{g_V}\right| e^{-i\phi} \approx 1.2670 \pm 0.0035$$

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

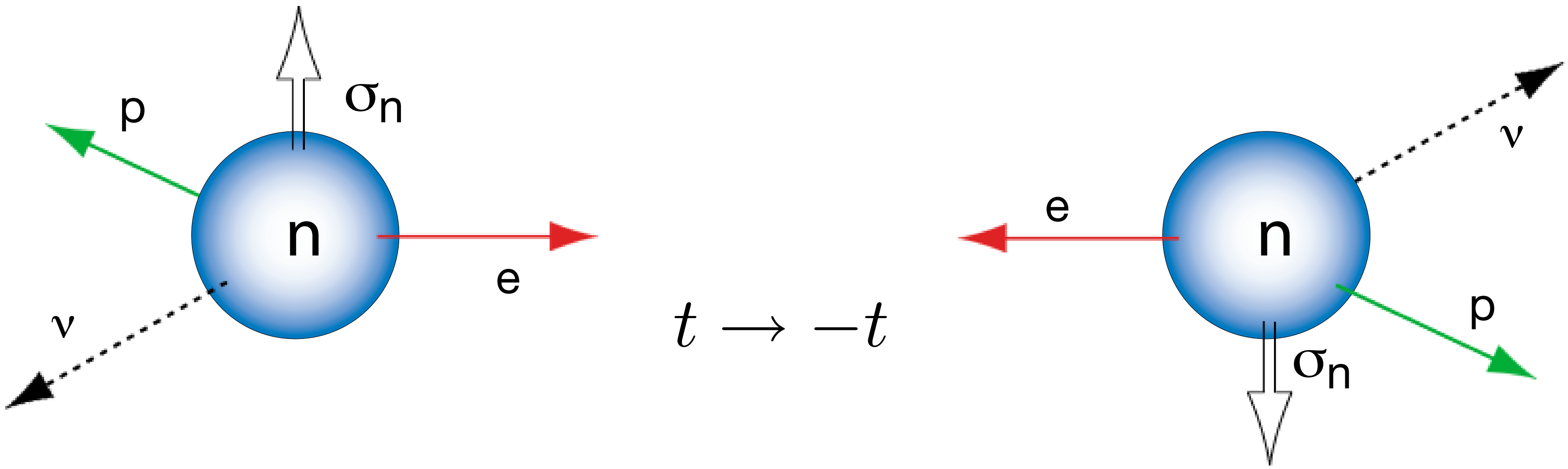
T-odd (P-even)
triple correlation:

$$D = 2\frac{|\lambda|\sin\phi}{1 + 3|\lambda|^2}$$

$$D \approx -\frac{|\lambda|}{1+3|\lambda|^2}\{2\frac{\text{Im}(C_V C_A^*)}{C_V C_A^*} + \frac{\alpha m}{p_e}\text{Re}(\frac{C_s + C_S'}{C_V} - \frac{C_T + C_T'}{C_A^*})\}$$

< 0.02

Polarized Neutron Decay (Time Reversal-Motion Reversal)



~ -0.1 ~ -0.1 ~1.0

$$\frac{d\omega}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + \sigma_n \cdot \left(A\frac{p_e}{E_e} + B\frac{p_\nu}{E_\nu} + D\frac{p_e \times p_\nu}{E_e E_\nu}\right)\right)$$

Measurable & non-zero

T-odd, P-even

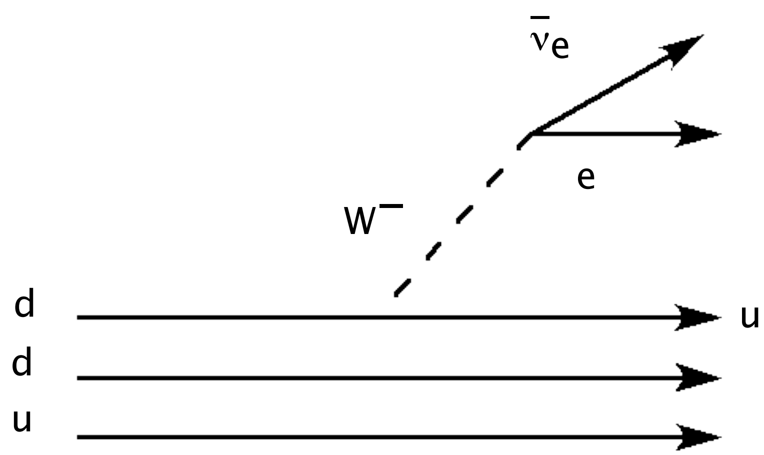
Not quite T reversal; Initial and final states are not reversed: final state interactions

- $|D_{f.s.}| \sim 2 \times 10^{-5}$ $^{19}Ne \sim 2.6 \times 10^{-4}\ p/p_{max}$

Possible Sources of T Violation

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

$$D \approx -\frac{|\lambda|}{1+3|\lambda|^2}\{2\frac{\mathrm{Im}(C_V C_A^*)}{C_V C_A^*} + \frac{\alpha m}{p_e}\mathrm{Re}(\frac{C_s + C_S'}{C_V} - \frac{C_T + C_T'}{C_A^*})\}$$



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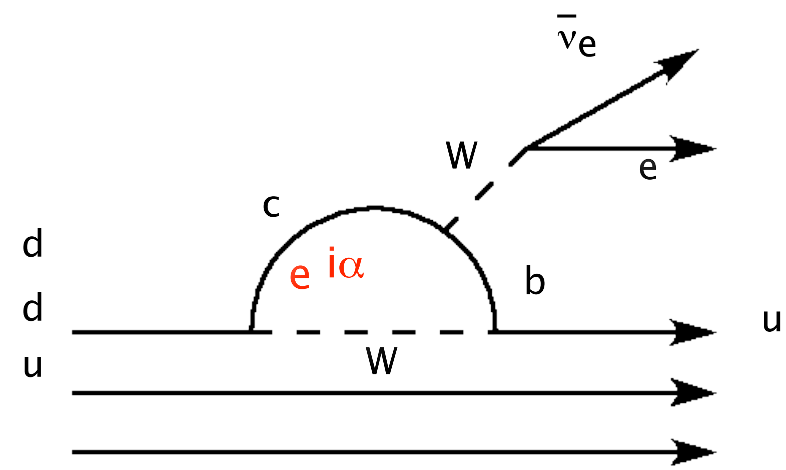
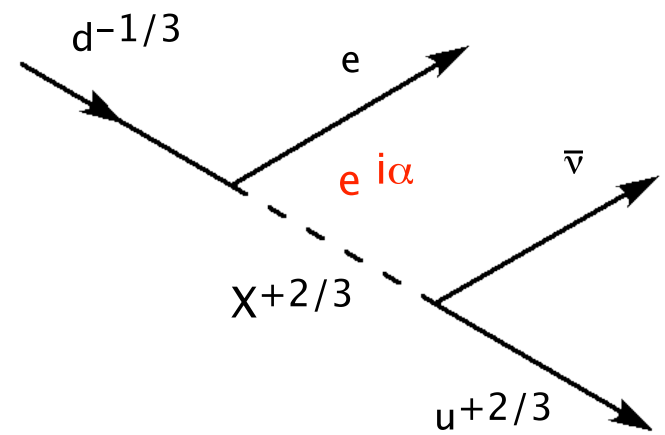


Standard Model



Super-symmetry

L-R symmetric

Lepto-quarks

Theory	D
1. Kobayashi-Maskawa Phase	$< 10^{-12}$
2. Theta-QCD	$< 10^{-14}$
3. Supersymmetry	$\leq 10^{-7} - 10^{-6}$
4. Left-Right Symmetry	$\leq 10^{-5} - 10^{-4}$
5. Exotic Fermion	$\leq 10^{-5} - 10^{-4}$
6. Leptoquark	present limit

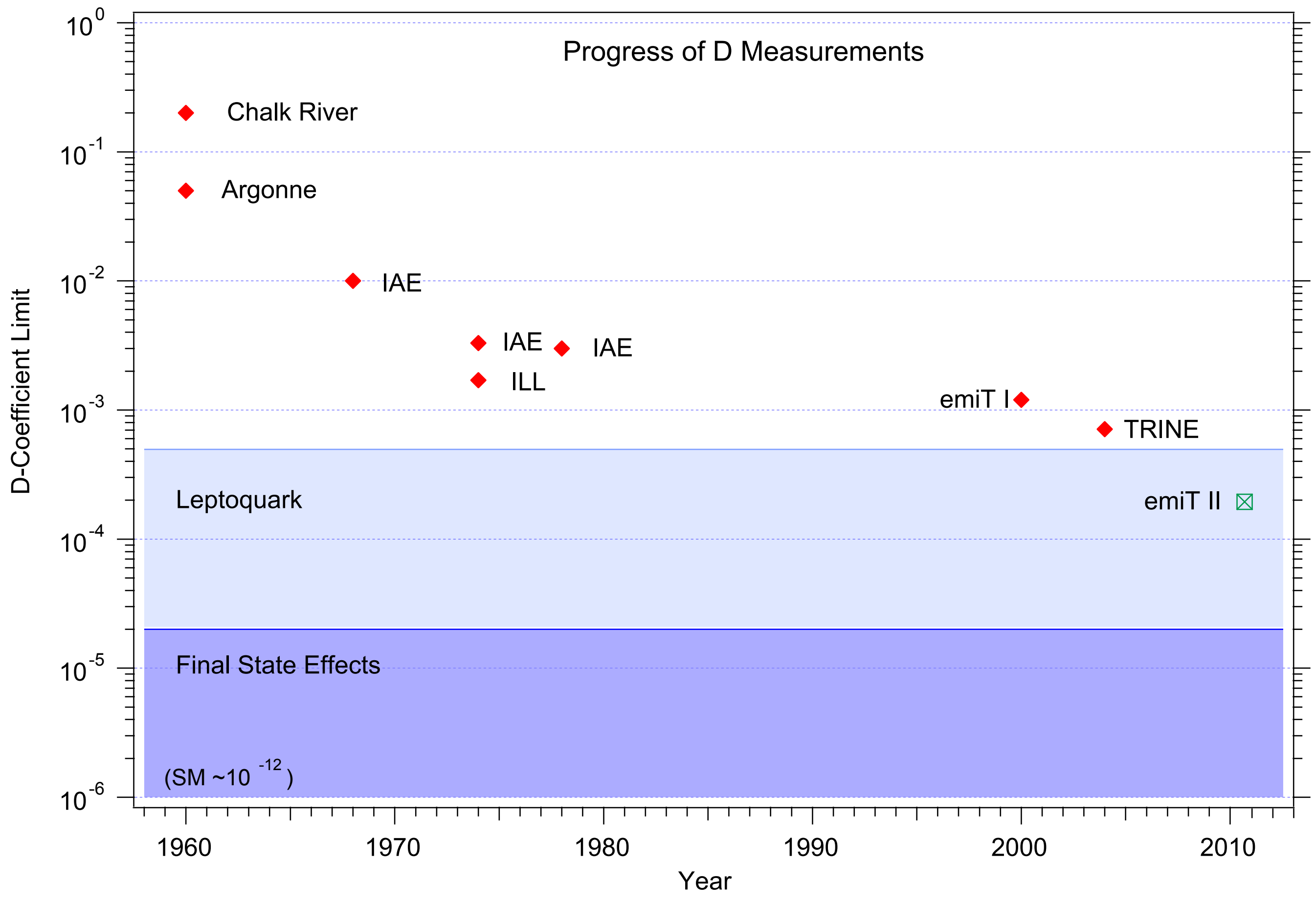
Constraints on D based on other T-odd observables

Beta Decay Tests of T-Invariance

- Combine T-odd combinations of three kinematic variables

$$D\sigma_n \bullet (p_e \times p_\nu) \qquad R\sigma_n \bullet (\sigma_e \times p_e)$$

- Require competing amplitudes with a relative phase
- Must account for final state effects



^{8}Li

R = (0.9 ± 2.2) × 10^{-3} J. Sromicki et al. Phys Rev. Lett. **82** 57 (1999)

^{19}Ne

D = (1 ± 6) × 10^{-4} F. Calaprice, in Hyperfine Interactions (Springer, Netherlands,1985), Vol. 22

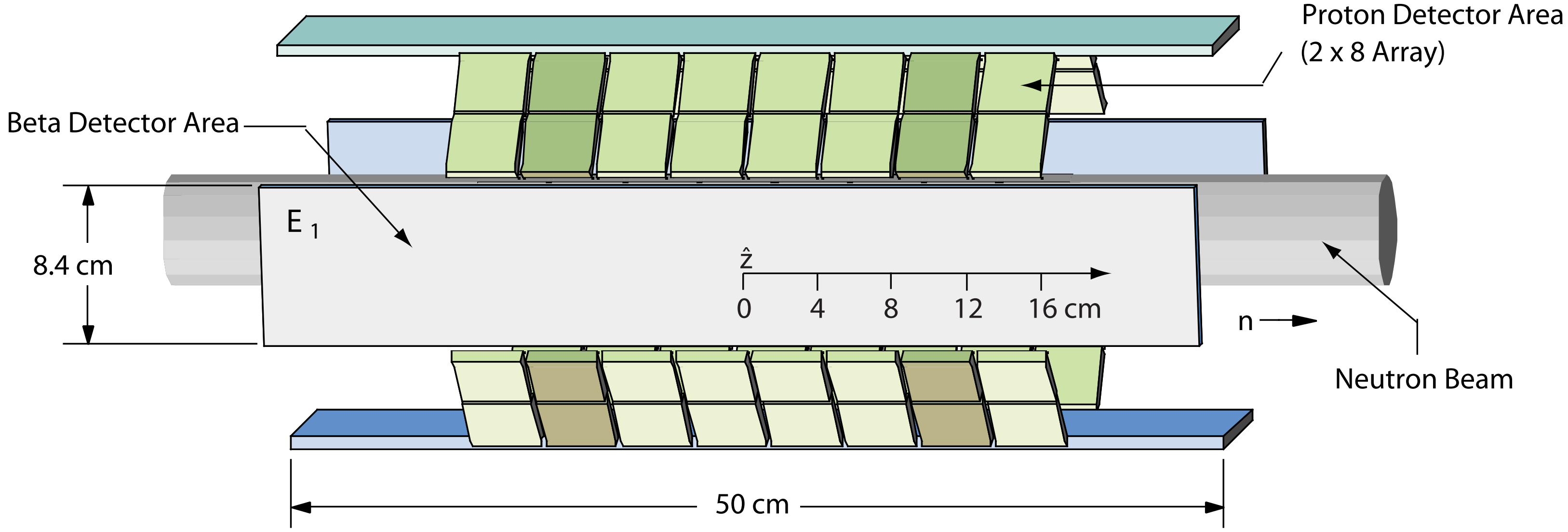
neutron

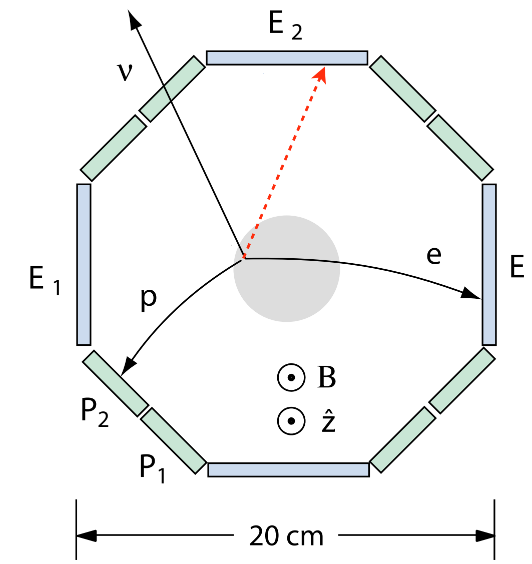
R = (8 ± 15(stat.) ± 5(syst.)) x 10^{-3} Kozela et al. Phys. Rev. Lett. **102** 172301 (2009)

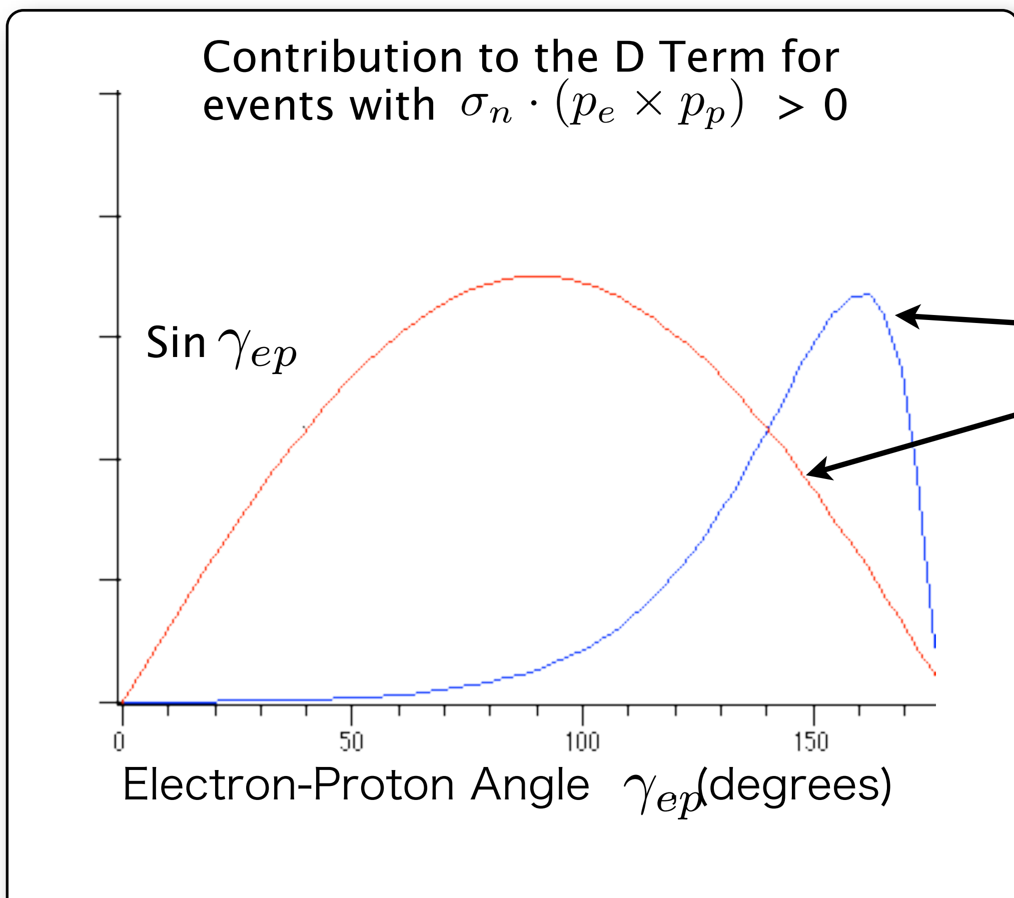
D = (-2.8 ± 7.1) × 10^{-4} T. Soldner et al. Phys. Lett. B **581** (2004)

D = (-6 ± 12(stat.) ± 5(syst.)) x 10^{-4} emiT I *Phys. Rev. C **62** 055501 (2000)*

Experimental Technique







- Symmetrical, segmented detector to minimize sensitivity to A and B, investigate nonuniformities & systematic effects

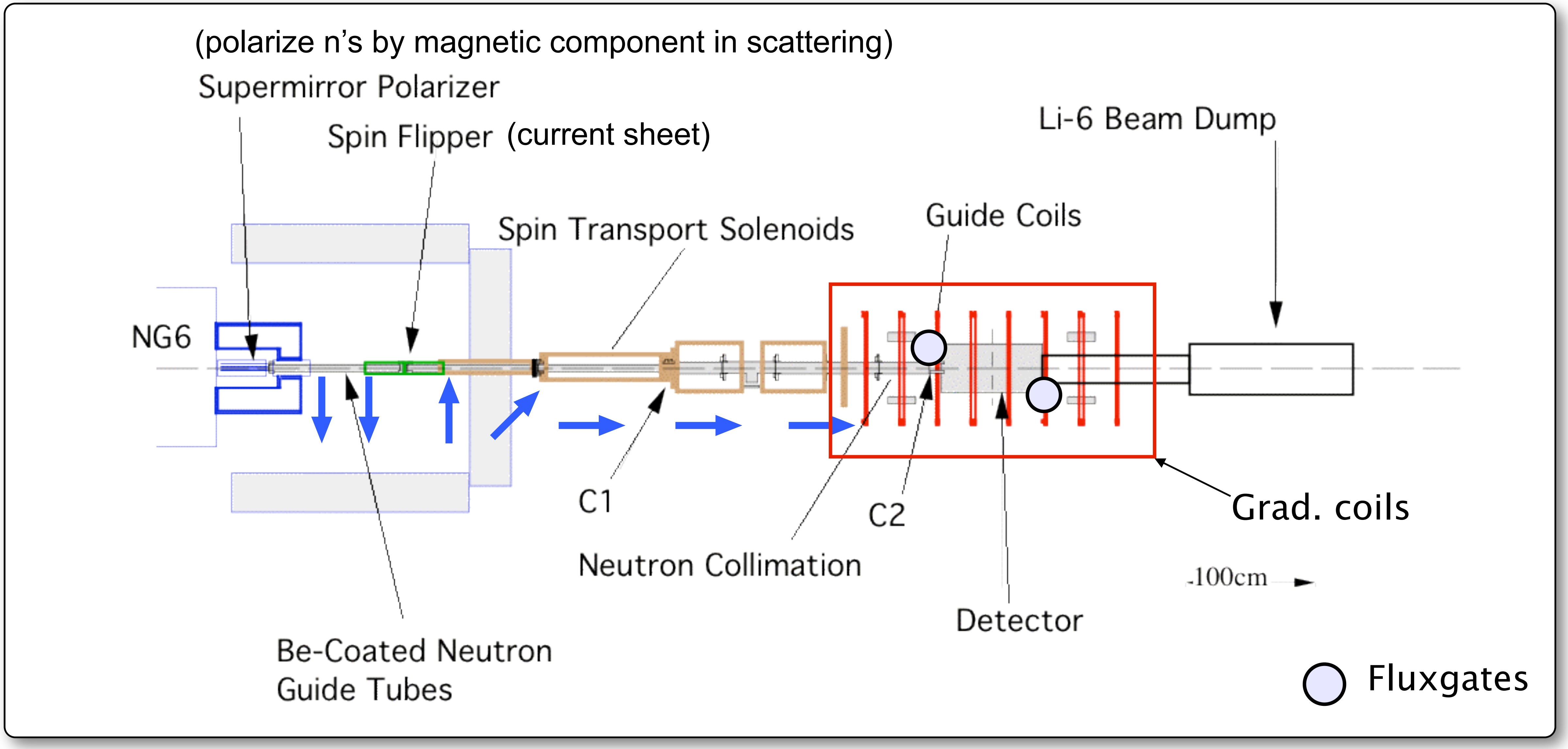
- Detector geometry to maximize sensitivity to $D\sigma_n \cdot (p_e \times p_\nu)$ Proton and electron momenta anti-correlated, Sin γ_{ep} maximized at 180.

emiT gained a factor of three increase in "effective" beam flux over previous "right angle" geometry beam experiments

Difficulties

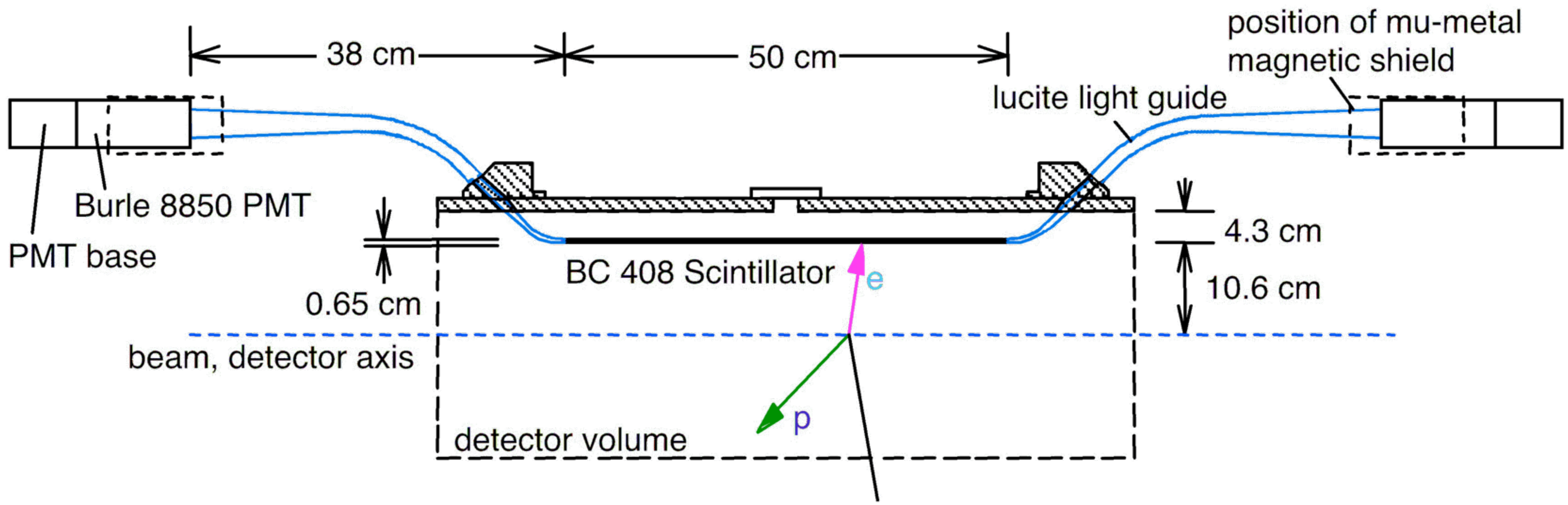
- proton endpoint 750 eV (requires acceleration)
- Neutron lifetime (requires intense source)
- Uniform magnetic guide fields

Neutron Spin Transport



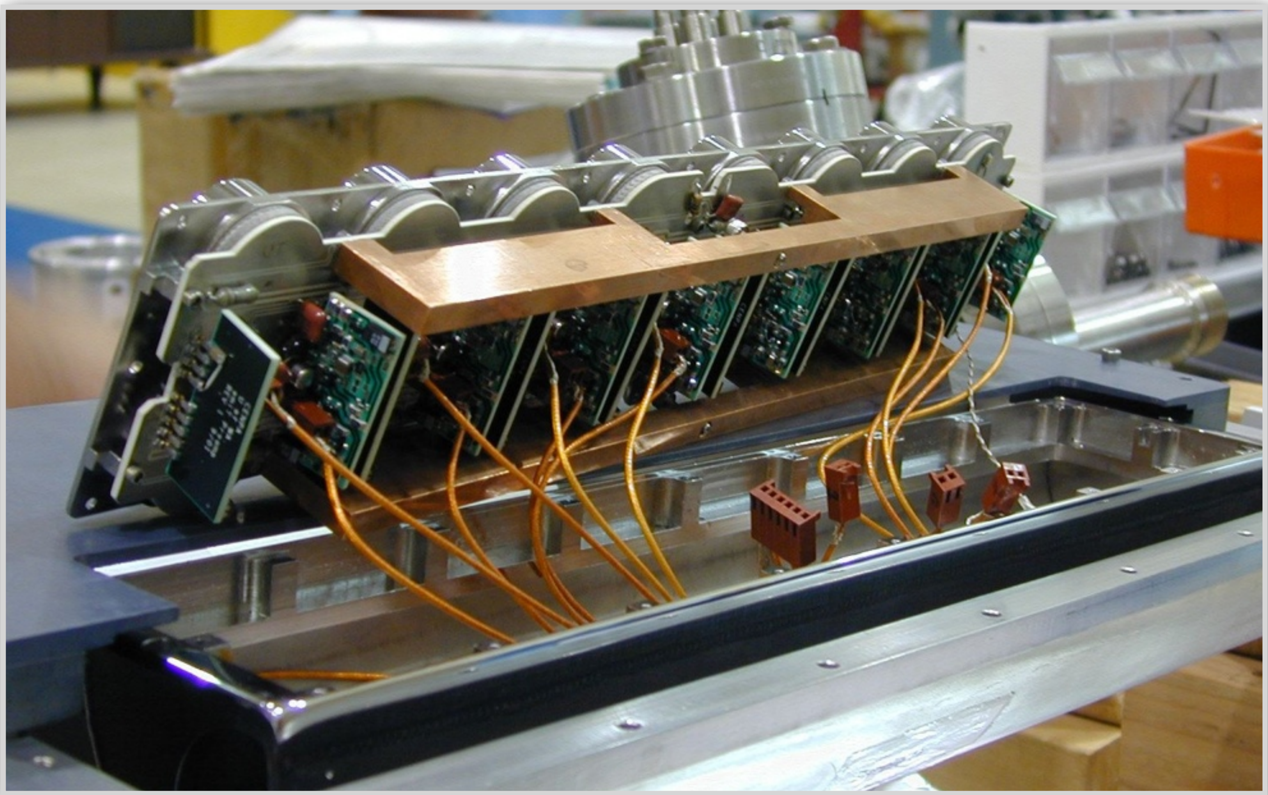
- High continuous neutron flux (1.7×10^8 cm^{-2} s^{-1} at "C2") fission chamber measurement
- 560 μT guide field, monitored during run
- Beam profile at 3 positions via Dysprosium foil activation
- Polarization measured with supermirror analyzer flipping ratio measurement

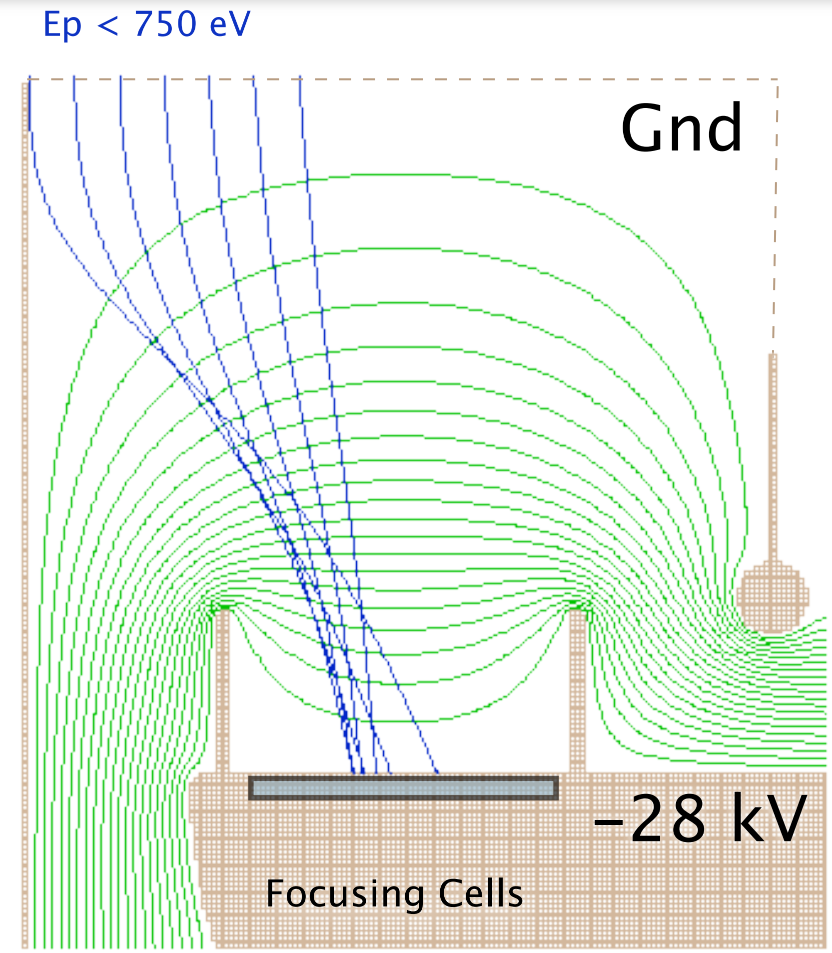
emiT Detector: Beta Detectors (4 panels and support hardware)



- 0.1 ns timing resolution (Pulse arrival time may be used to determine position)
- Thresholds (35-50 keV) (Software cut on geometric mean)
- Resolution ~18% at 1 MeV
- Cosmic ray muons deposit ~ 1.42 MeV (well separated)
- Overall rate 300 s^{-1} per paddle (Signal to accidental ~ 1 to 1)

emiT Detector: Proton Paddle Assembly





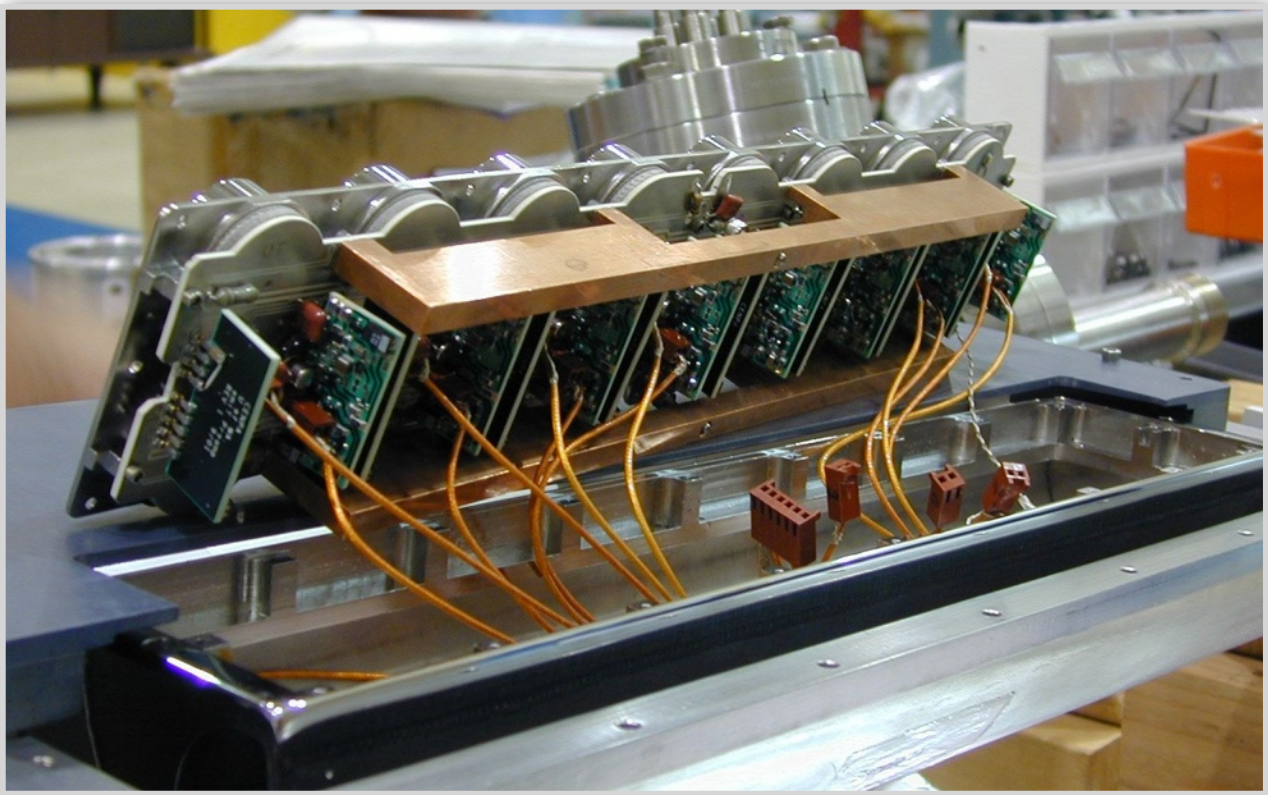
Focusing efficiency reaches 90%
(Voltage Dependent)

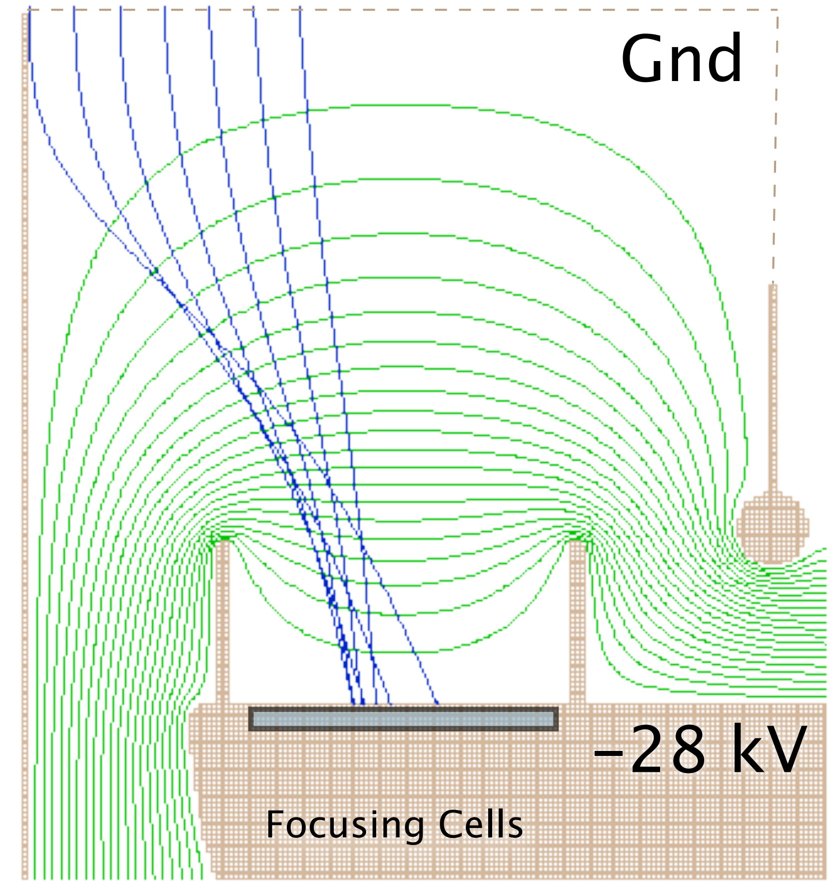
Required detector area reduced by ~ 80%

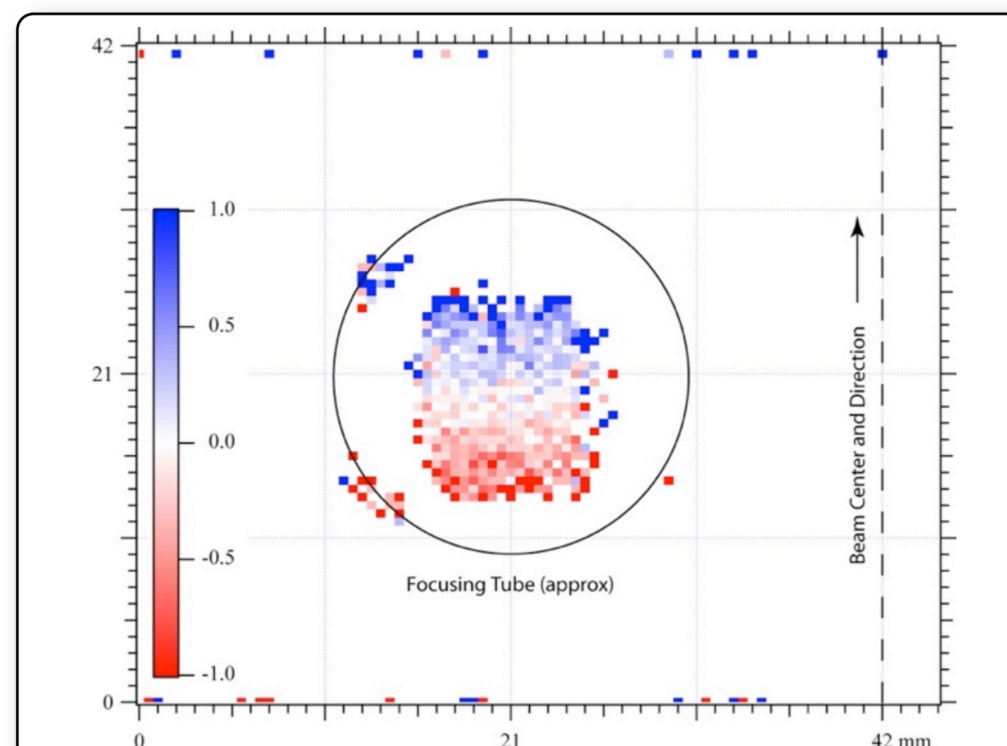
Surface barrier detectors

- 20 μg Au (less energy loss)
- 300 mm^2 active area
- 300 μm depletion depth
- Room temperature leakage current ~ μA

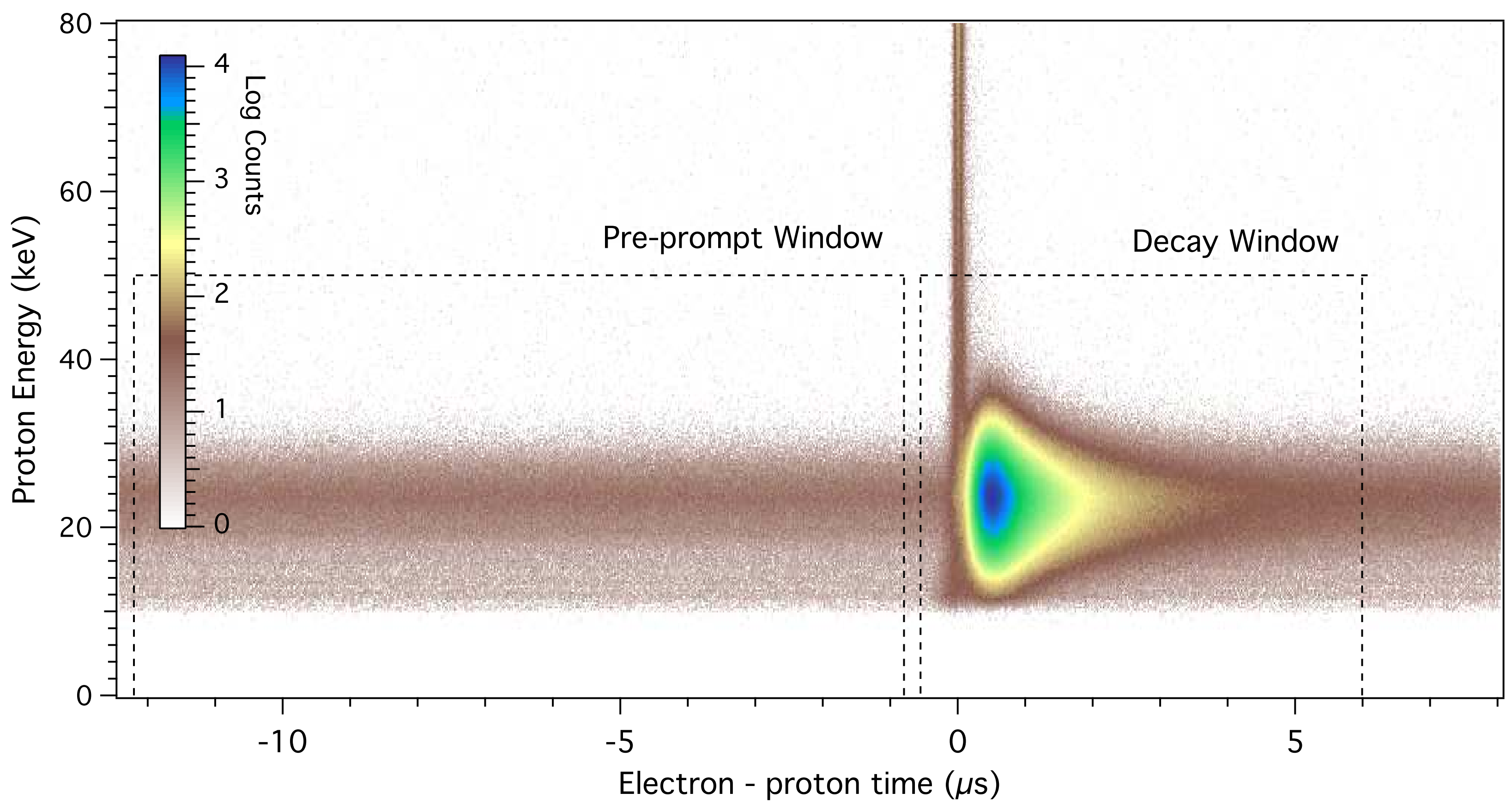
emiT Detector: Proton Paddle Assembly







Coincidence Events & Filtering



- 3 Hz singles per proton Surface Barrier detector
- 0.55 Average coincidence rate per pair
- 25 Hz average coincidence rate
- S:B = 30:1 (after filter)

Filtering and cuts:

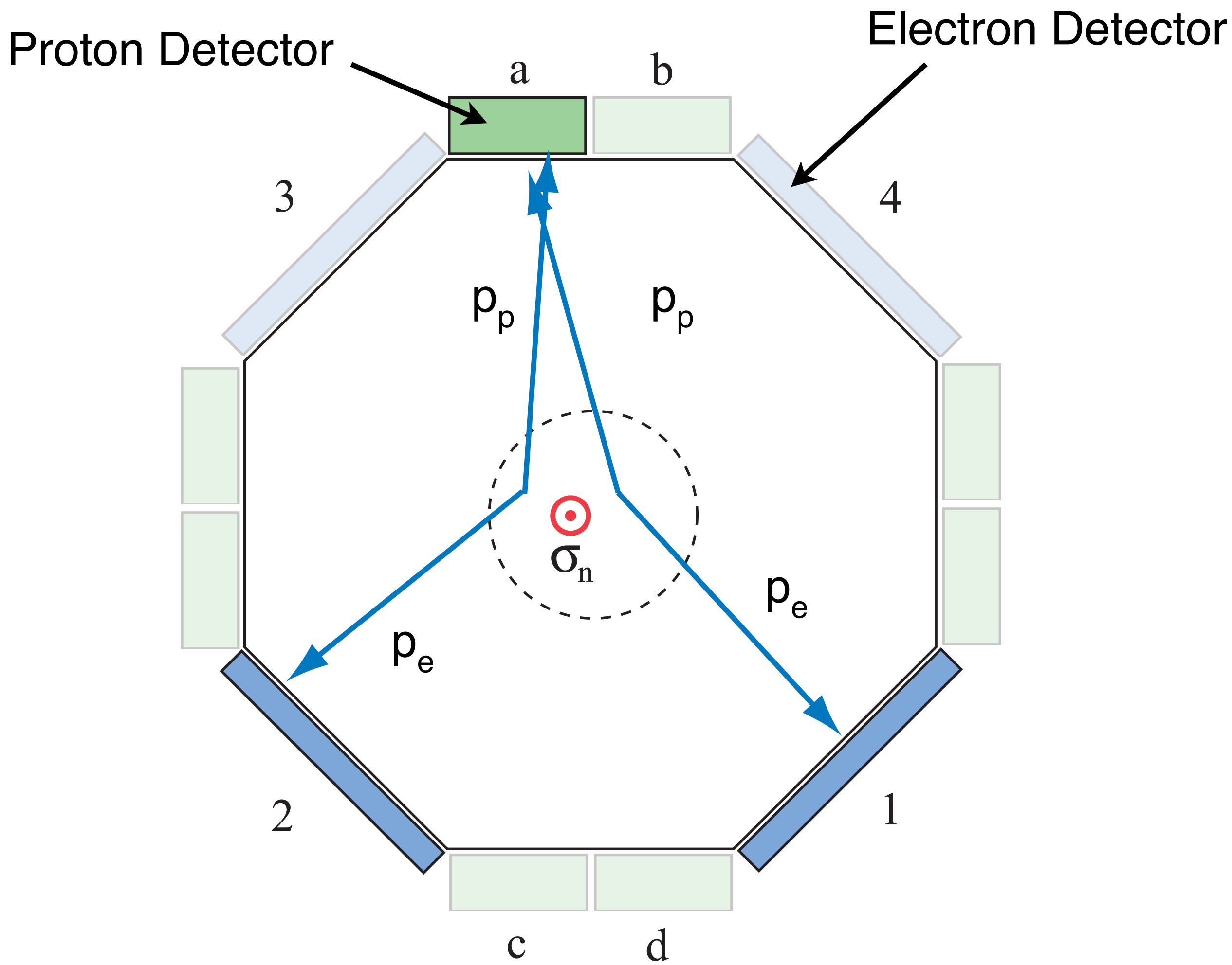
12% - Data collected with acceptable operational parameters (magnetic fields, currents, spin state, ...)

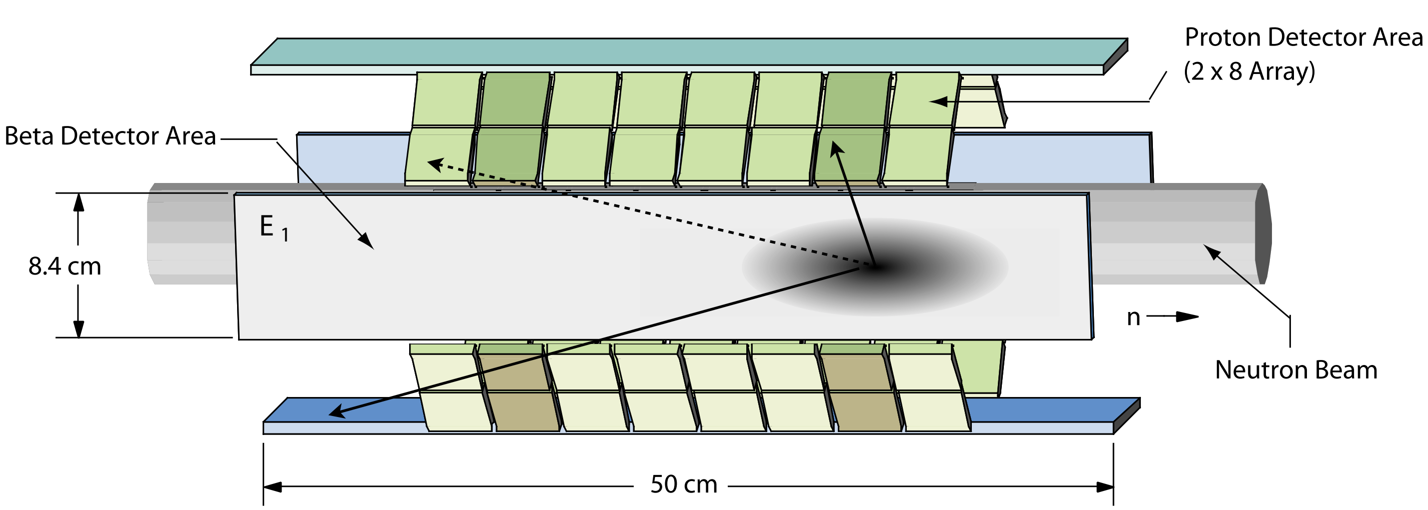
14% - β-energy threshold set to 90 keV, to minimize detection efficiency drifts arising from PMT gain drifts

7% - Require single β detector in coincidence with single proton event

Final data set ~ 300 million accepted coincidence events.

emiT "Blind" Extraction of D





Efficiency independent ratio,

$$w^{p_i e_j} = \frac{N_+^{p_i e_j} - N_-^{p_i e_j}}{N_+^{p_i e_j} + N_-^{p_i e_j}} + \mathcal{B}\hat{z} \cdot \tilde{\mathbf{K}}_D^{p_i e_j}$$

Blind

w is sensitive to *D*, but also to *A*, *B*

Define a parameter,

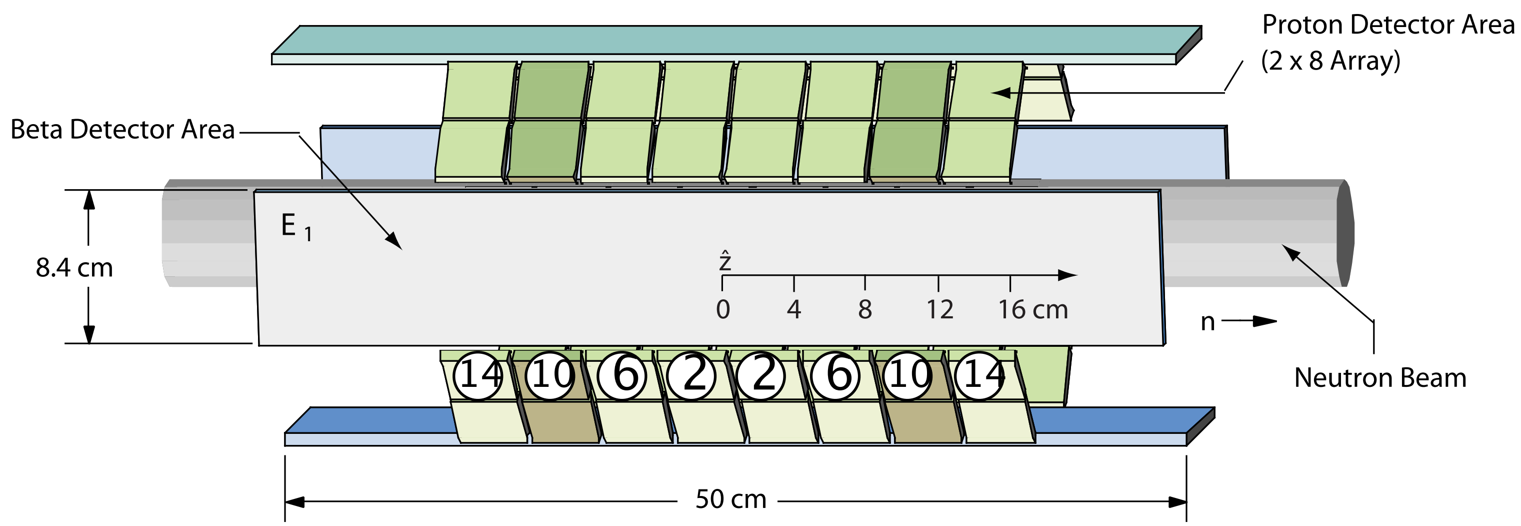
$$v^{p_i} = \frac{1}{2}\left(w^{p_i R} - w^{p_i L}\right)$$

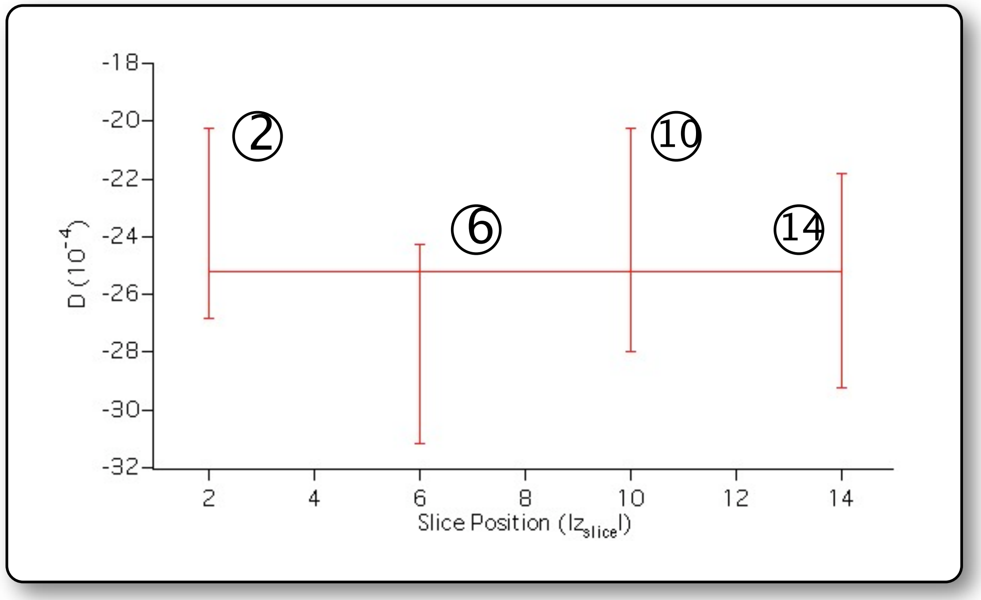
For a symmetric uniform detector,

$$v^{p_i} = PD\hat{z} \cdot \left(\tilde{\mathbf{K}}_D^{p_i e_R} - \tilde{\mathbf{K}}_D^{p_i e_L}\right)$$

Instrumental constant

$$\propto \int \frac{p_e \times p_p}{E_e E_p} d\Omega_a d\Omega_2 dV_{beam}$$





Calculate v for "paired rings" : the average of the values of v from the sixteen proton-cells at the same |z|, i.e. ±2, ±6, ±10, ±14 cm

$$\tilde{D} = \frac{\bar{v}}{P\bar{K}_D} \qquad \bar{K}_D = 0.378 = \hat{z} \cdot \tilde{\mathbf{K}}_D^{p_i e_R} - \tilde{\mathbf{K}}_D^{p_i e_L}$$

The weighted average of the 4 paired rings, $D_{uncor} = 0.72 \pm 1.89$ $\chi 2 = 0.73$ (3 DOF)
Apply corrections yielding the final result;

$$D = (-0.96 \pm 1.89(stat) \pm 1.01(sys)) \times 10^{-4}$$

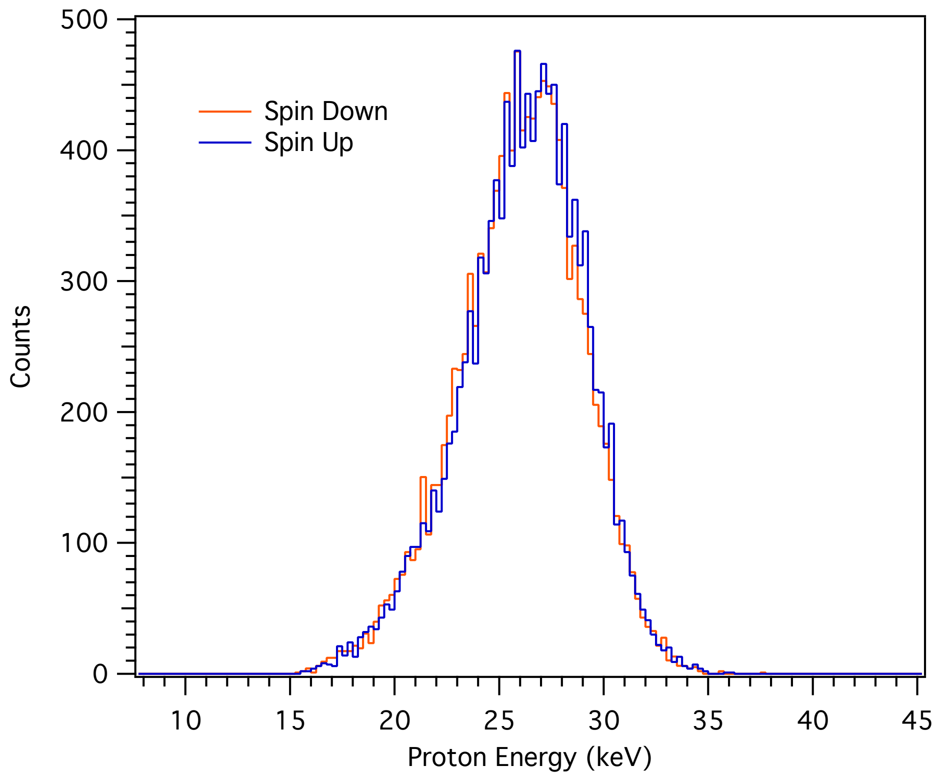
$$\varphi_{AV} = 180.013° \pm 0.028°$$

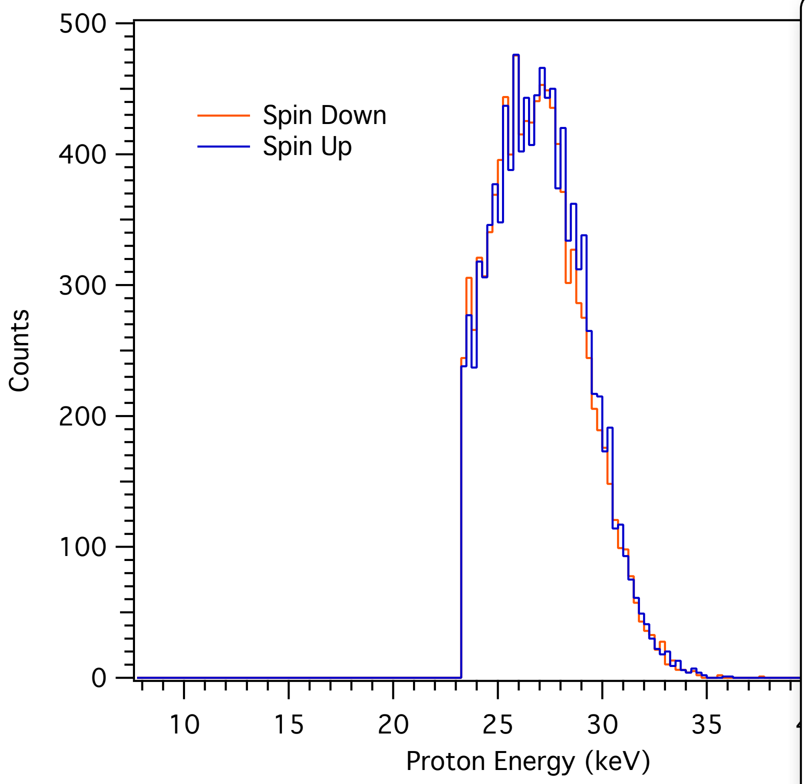
emiT II: Summary of Systematic Effects

Source	Correction	Uncertainty
Background asymmetry	0[a]	0.30
Background subtraction	0.03	0.003
Electron backscattering	0.11	0.03
Proton backscattering	0[a]	0.03
Beta threshold	0.04	0.10
→ Proton threshold	−0.29	0.41
→ Beam expansion, magnetic field	−1.50	0.40
Polarization non-uniformity	0[a]	0.10
ATP - misalignment	−0.07	0.72
ATP - Twist	0[a]	0.24
Spin-correlated flux[b]	0[a]	3×10^{-6}
Spin-correlated pol.	0[a]	5×10^{-4}
Polarization[c]		0.04[d]
$\bar{K}_D$[c]		0.03
Total systematic corrections	−1.68	1.01

[a] Zero indicates no correction applied.
[b] Includes spin–flip time, cycle asymmetry, and flux variation.

[c] Included in the definition of ~D.
[d] Assumed polarization uncertainty of 5%



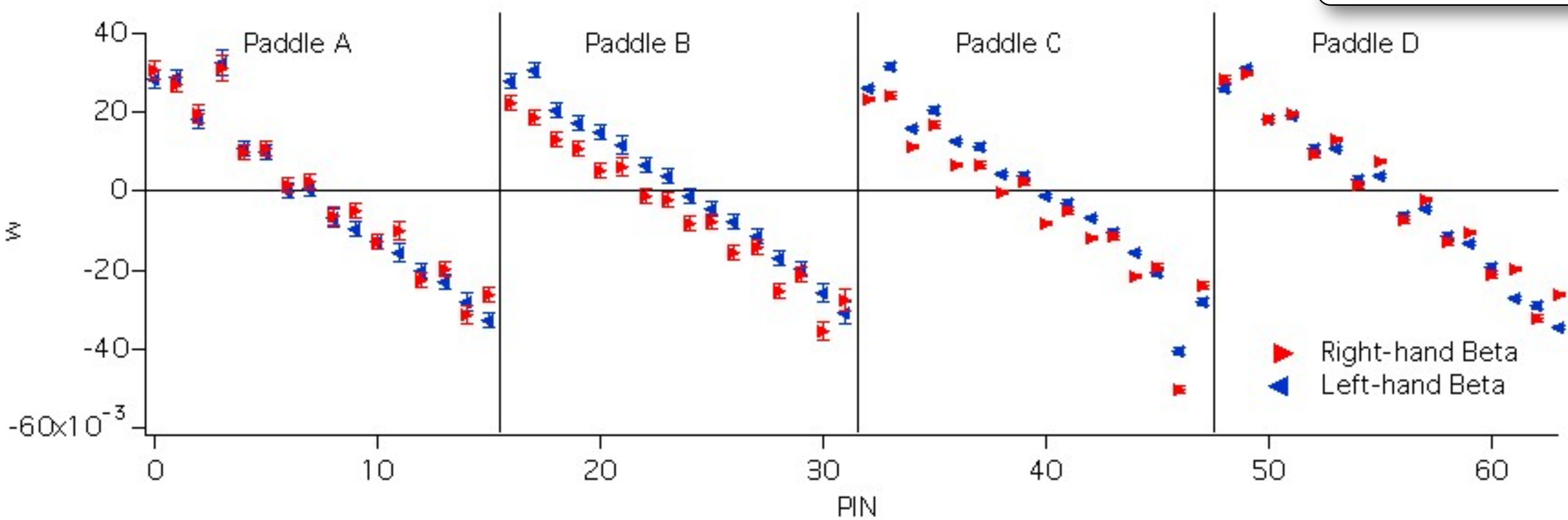


Shift of 159 eV

With a threshold of 23 keV
$w_{false} = 0.008$

$$v^{a2,b1} = \frac{1}{2}(w^{a2} - w^{b1})$$

$$v^{a2,b1} = PD\tilde{\mathbf{K}}_D^{a2} \cdot \hat{z}$$



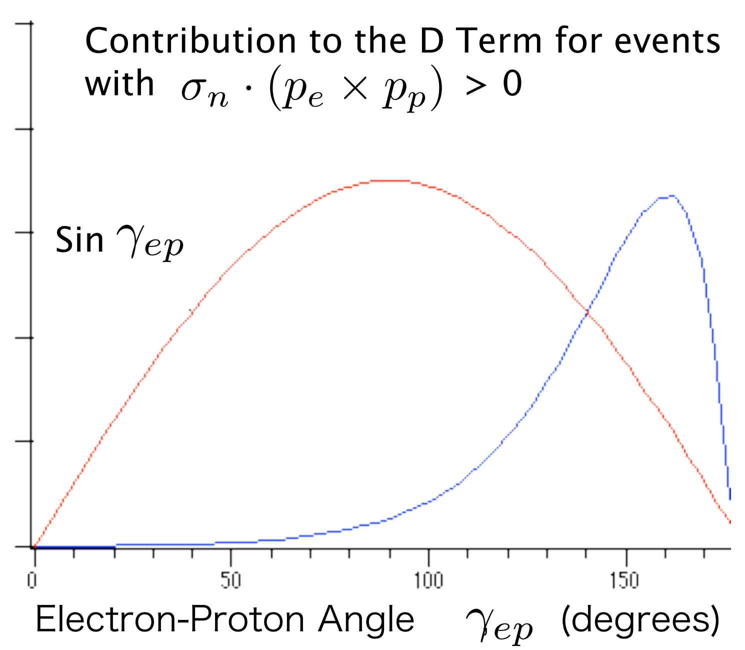
Largely Cancels in *v* - correction: $(-0.29 \pm 0.41) \times 10^{-4}$ (MC and fits to spectra)

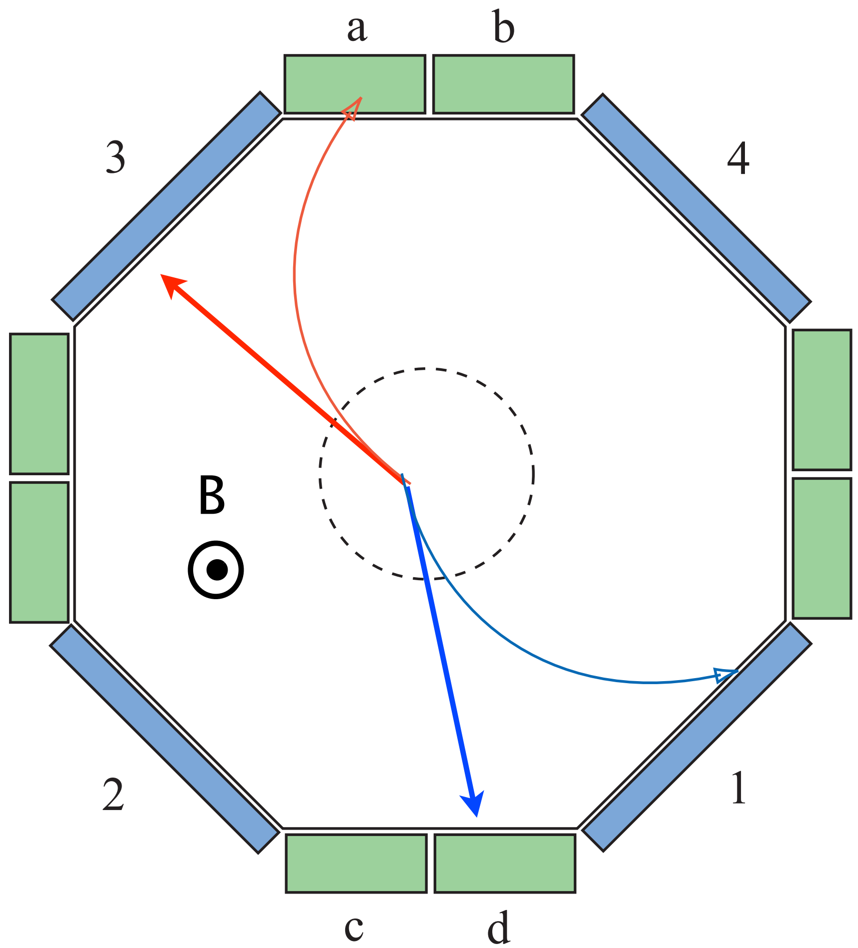
Systematics: Effect of Guide Field

Magnetic field changes e-p angular acceptance.
Expansion changes average.

$$A\sigma_n \cdot \frac{p_e}{E_e}$$

Solution: Detailed Monte Carlo.





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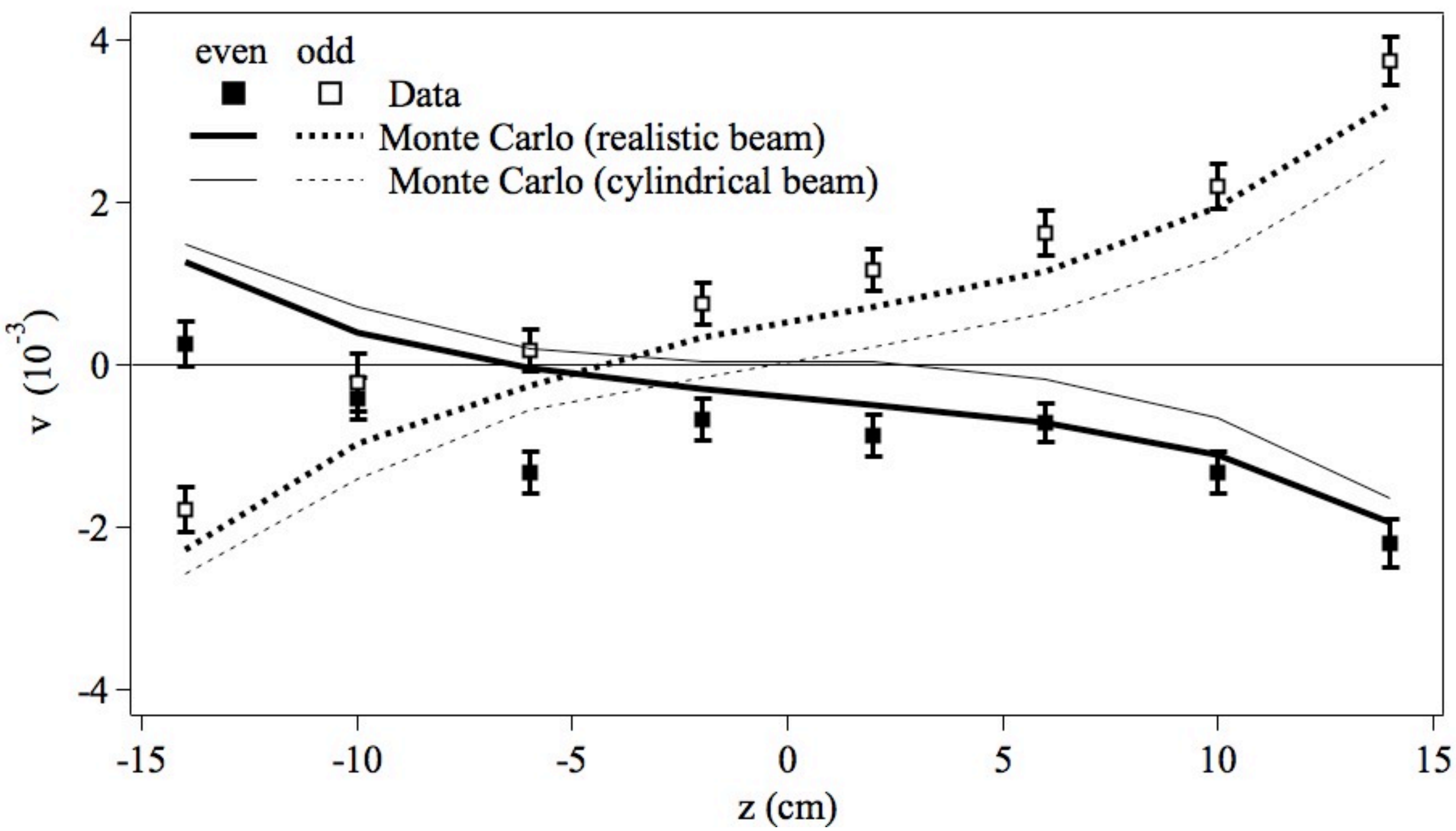
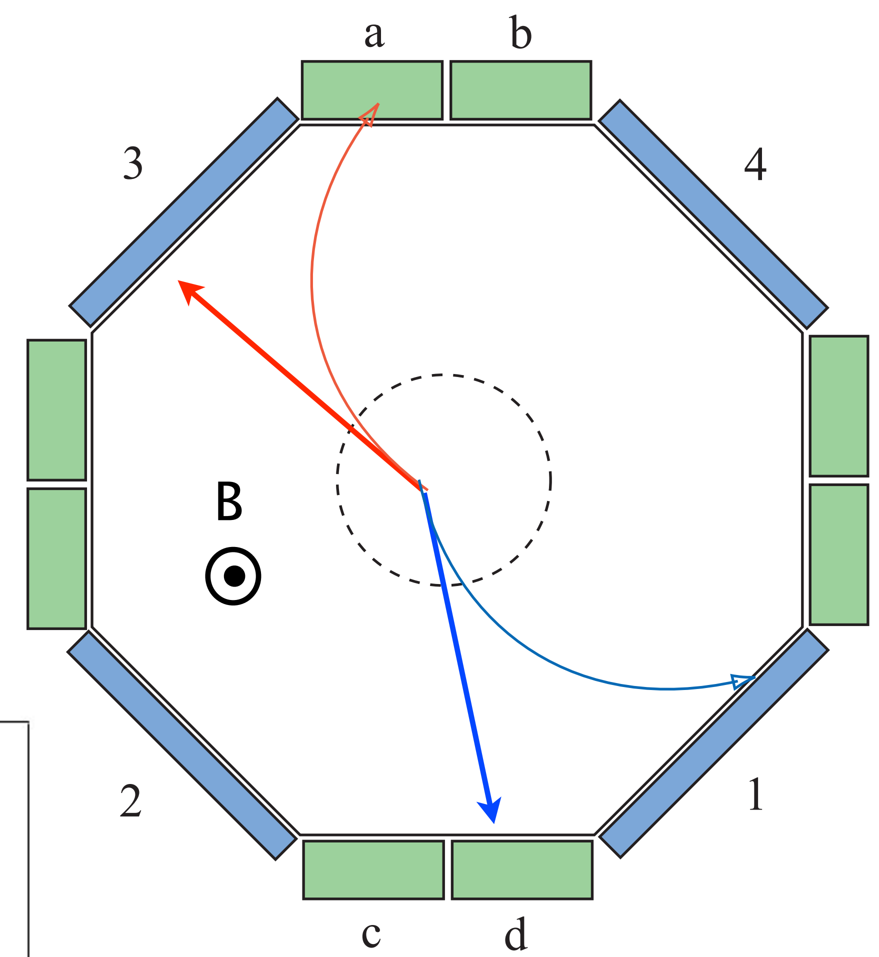
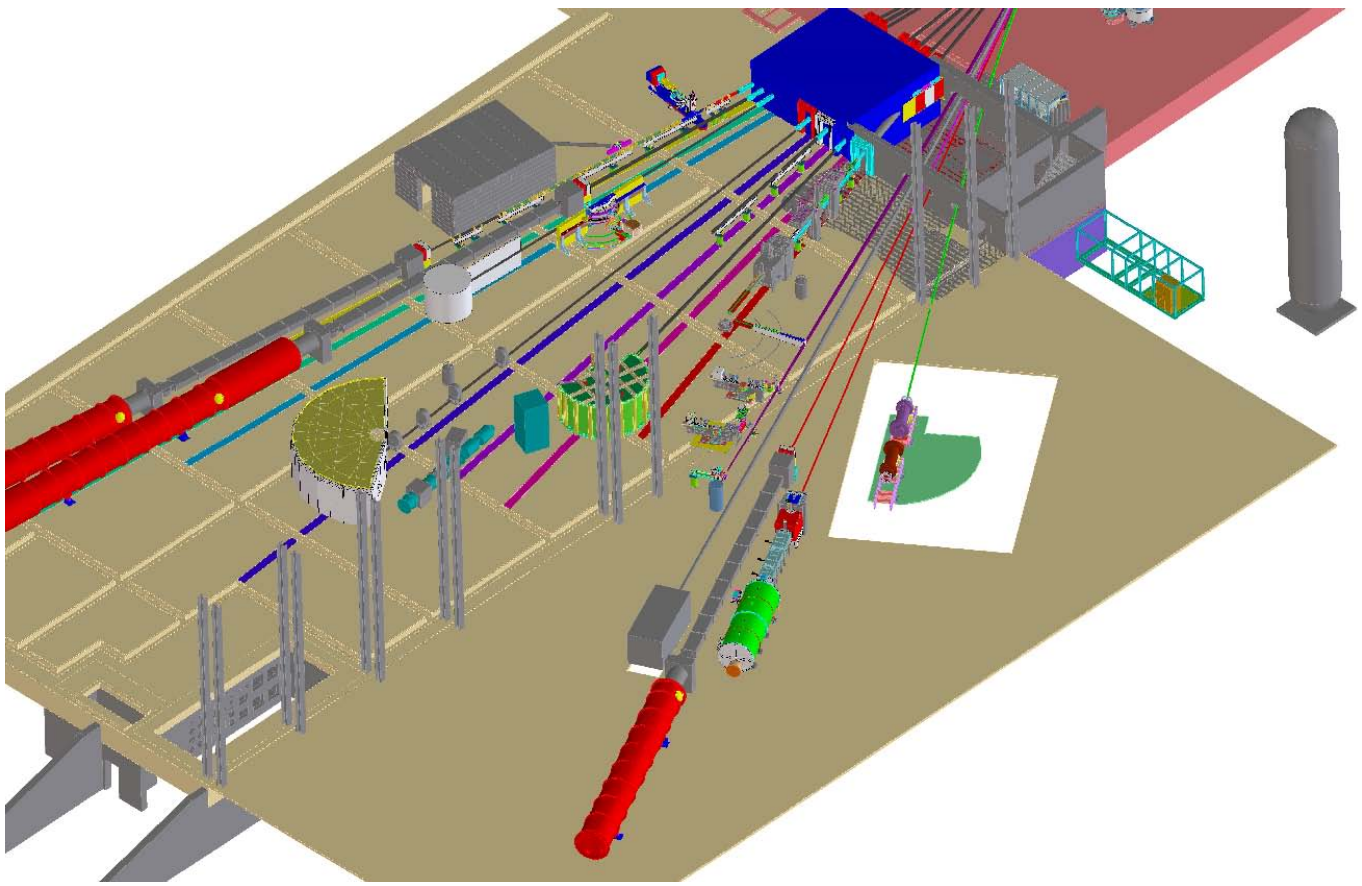


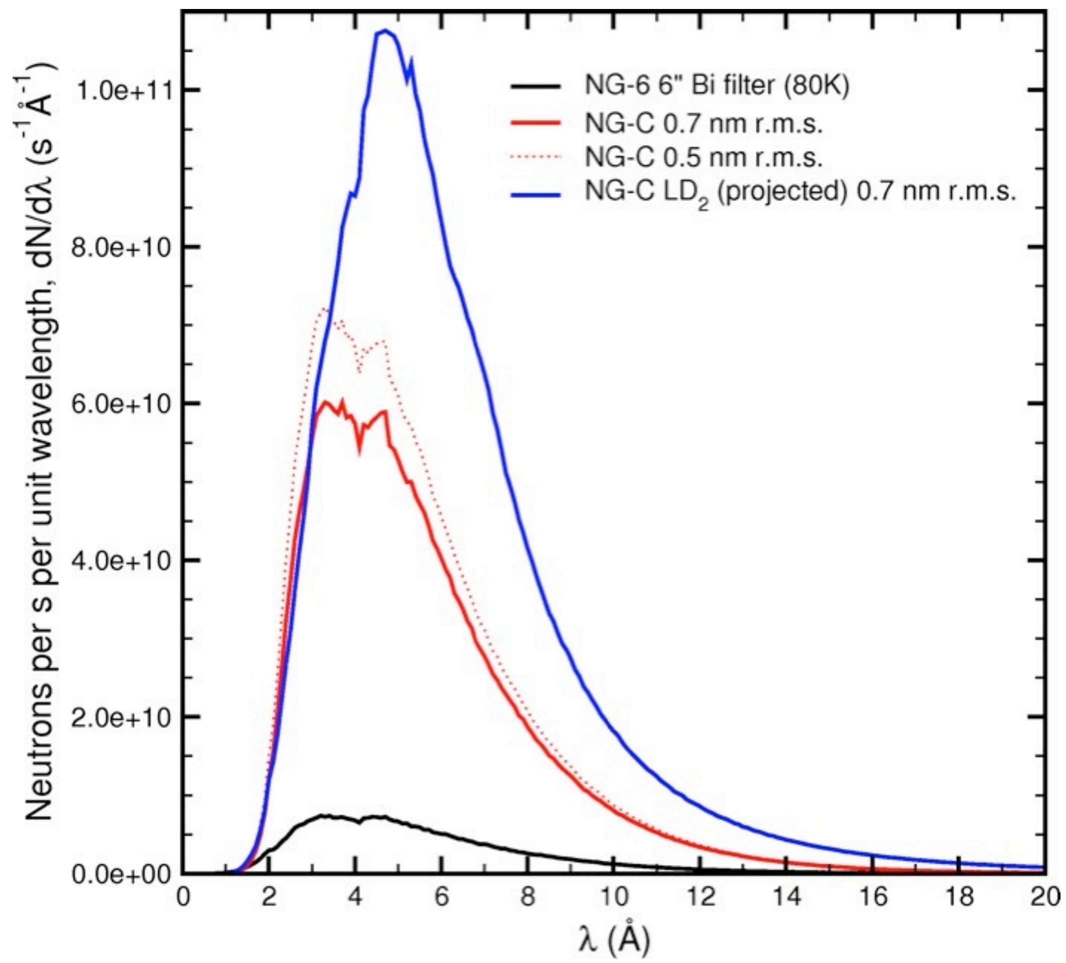


Beam shape, etc...

Correction from Monte Carlo: $(-1.5\pm0.4)\times10^{-4}$

NCNR Expansion

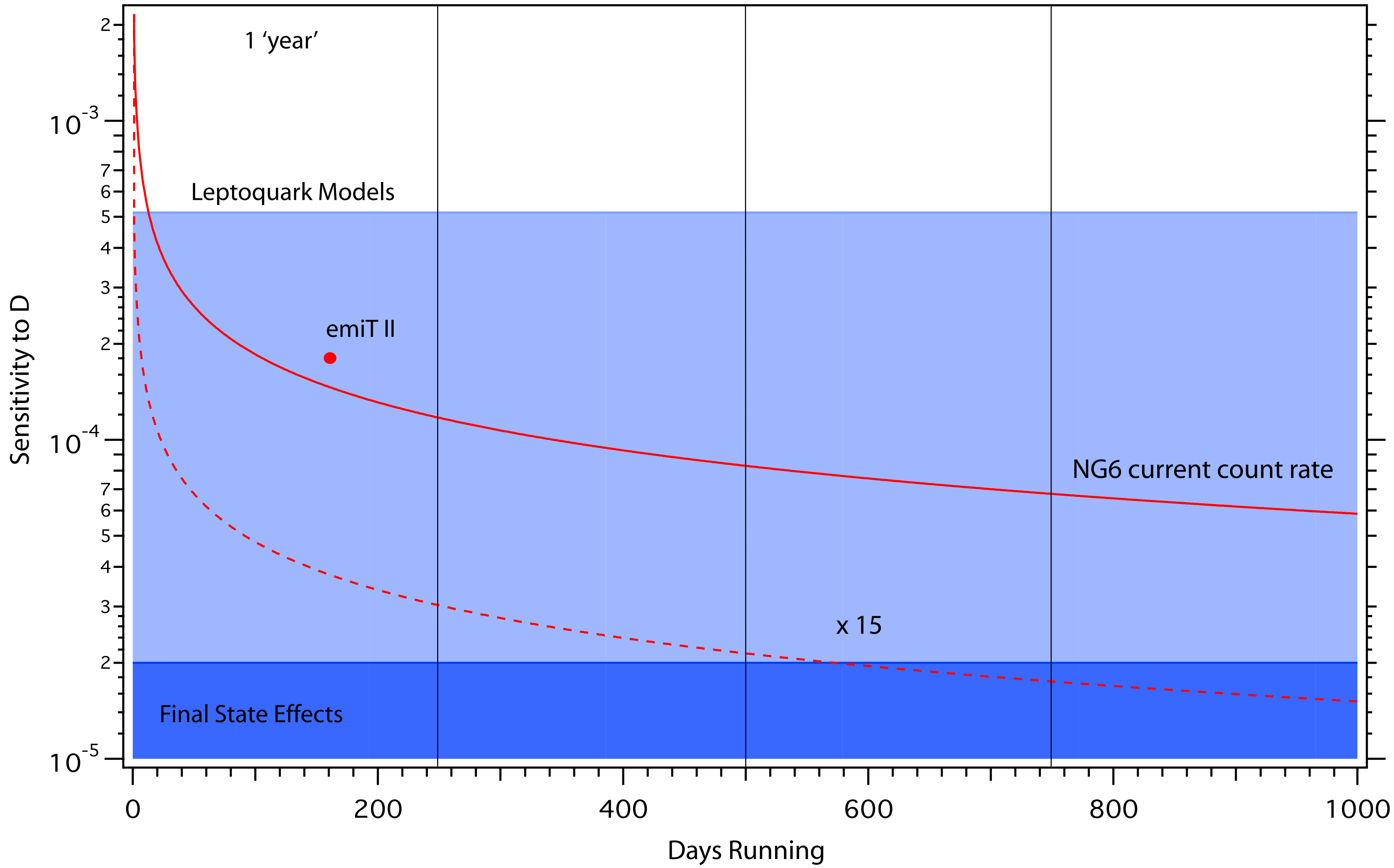




- The new NGC beam line could provide a factor of ~10 increase in neutron flux

- Major systematics
  - Beam expansion/mangetic field: reduce field
  - ATP error also limited by beam shape
    - AFP spin flipper
    - ^{3}He Polarizer
  - Proton threshold requires detetector/electronics improvement

Time Reversal Invariance: emiT III ?



Current apparatus could reach 2-3 x 10^{-5} with simple upgrades

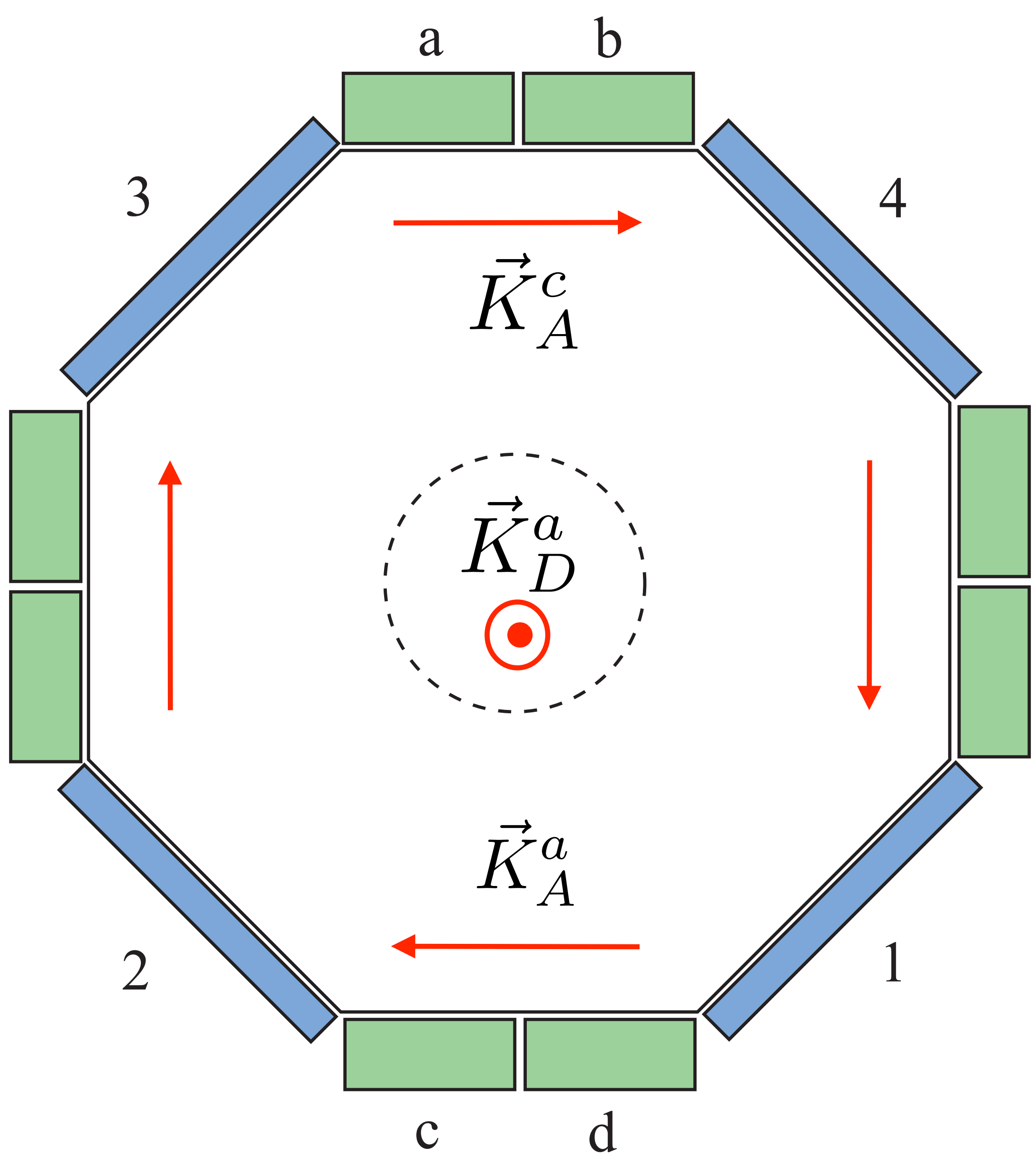
❶ Leptoquarks (Exotic Fermions/L-R symmetry?)

In principle one could *measure* the FSE

❷ Leptoquarks/Exotic Fermions/L-R symmetry + Scalar and Tensor Currents

Systematics: Measured Intensity Distribution (Tilt ATP)

$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A\tilde{\mathbf{K}}_A^{p_i e_j} + B\tilde{\mathbf{K}}_B^{p_i e_j} + D\tilde{\mathbf{K}}_D^{p_i e_j} \right)$$



$D_{false} = 0$

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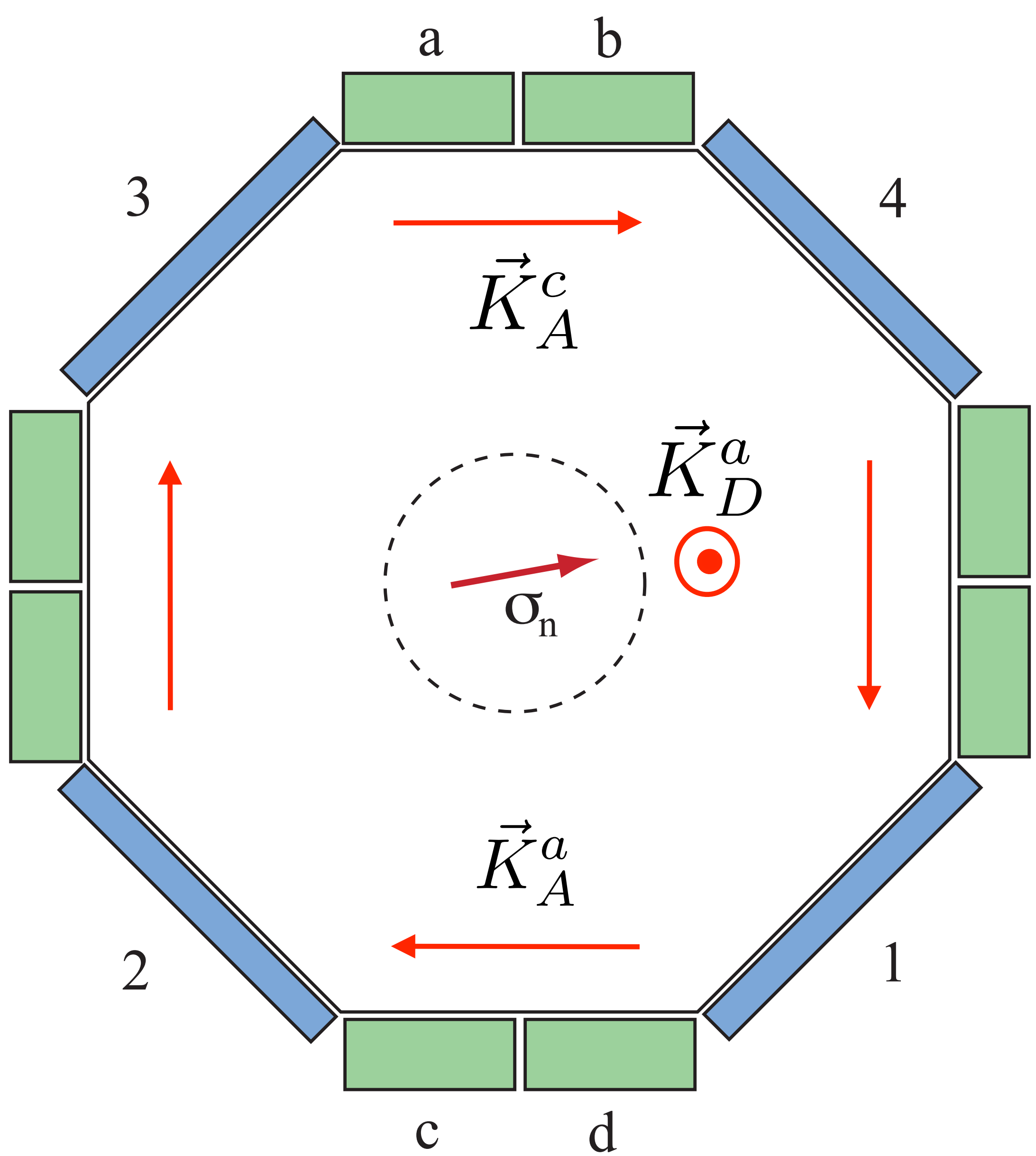

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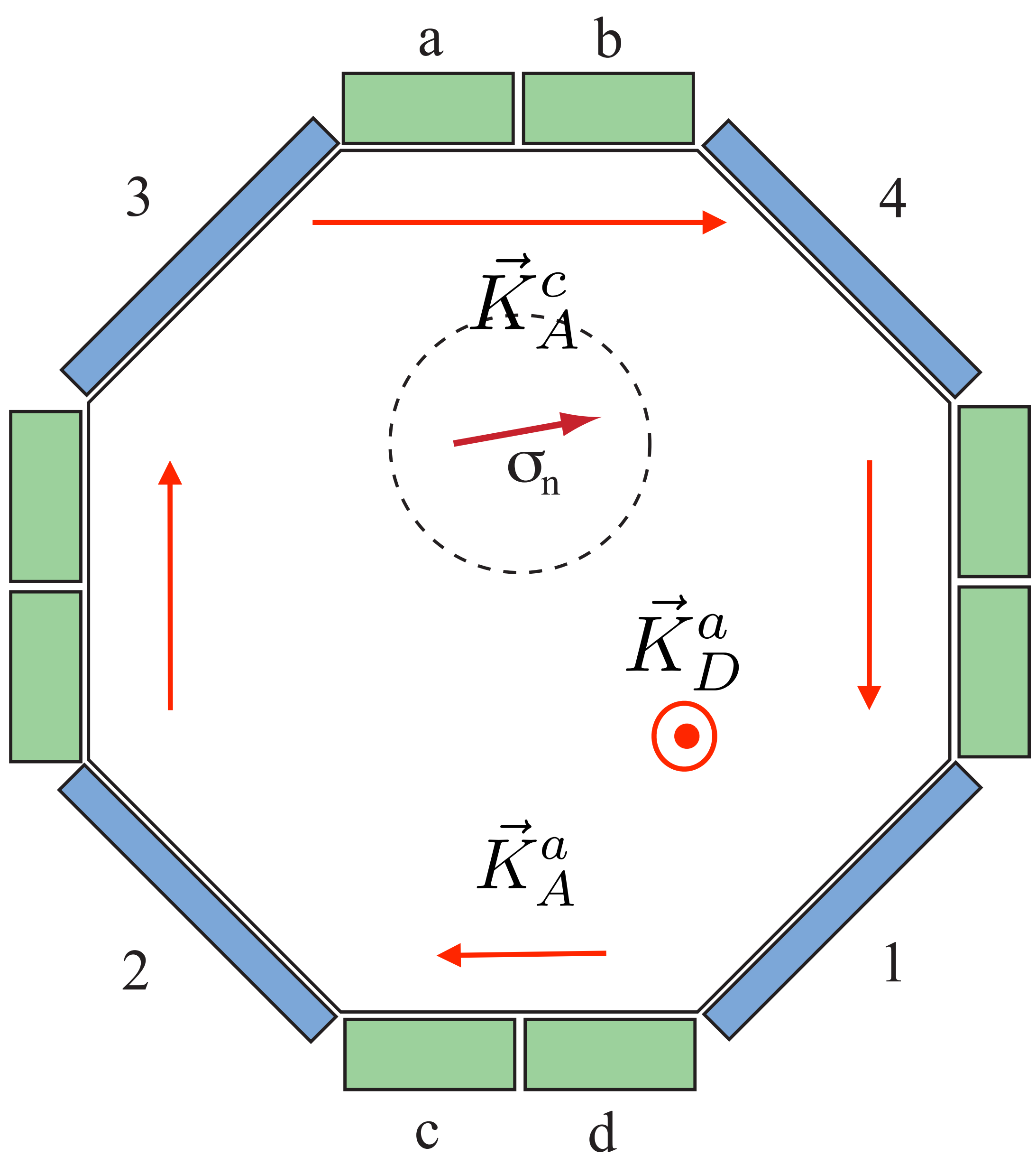
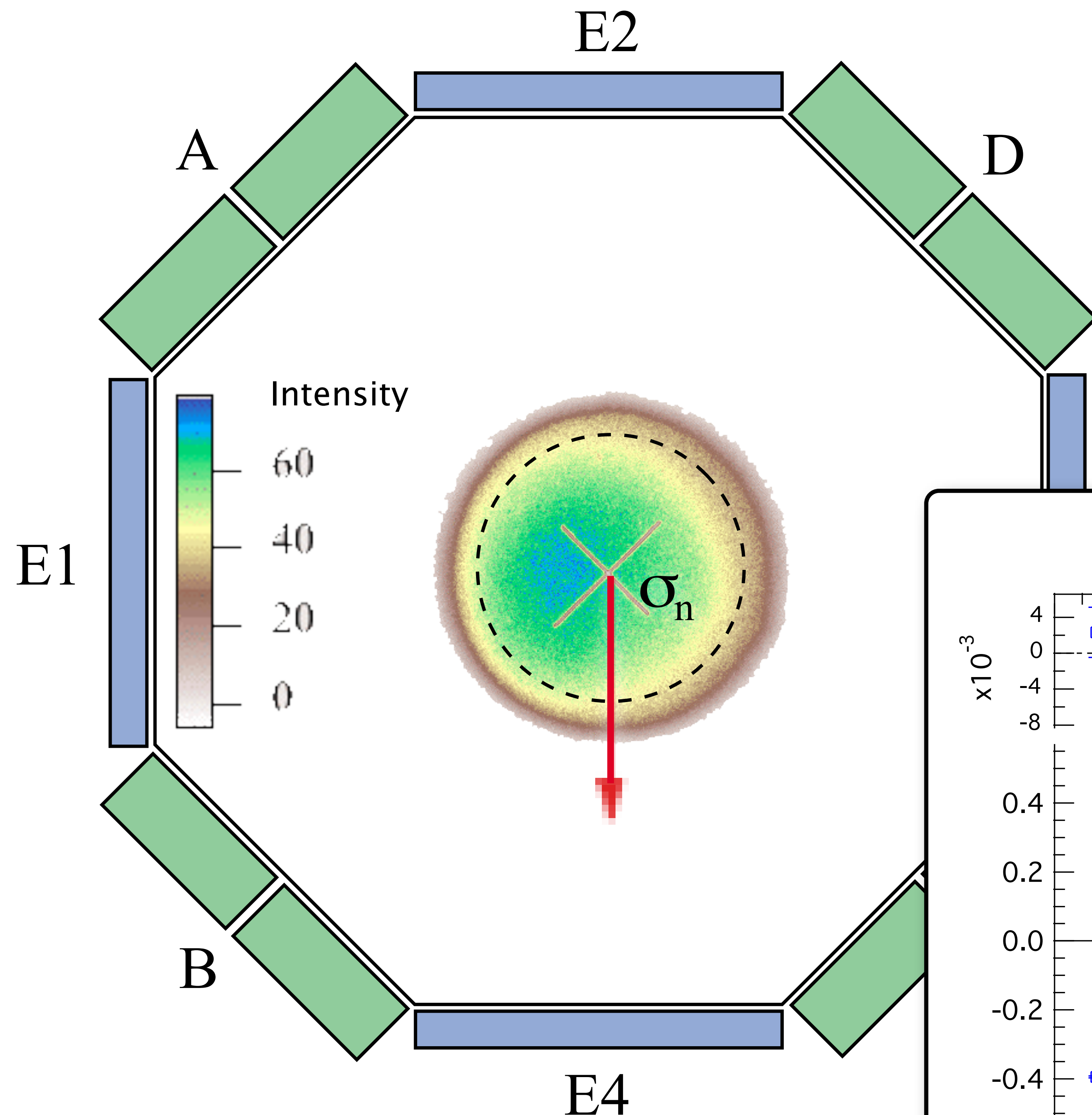


Monte Carlo
15 mrad polarization tilt,
beam displacement 5mm:
$D_{false} \sim 1{\times}10^{-4}$

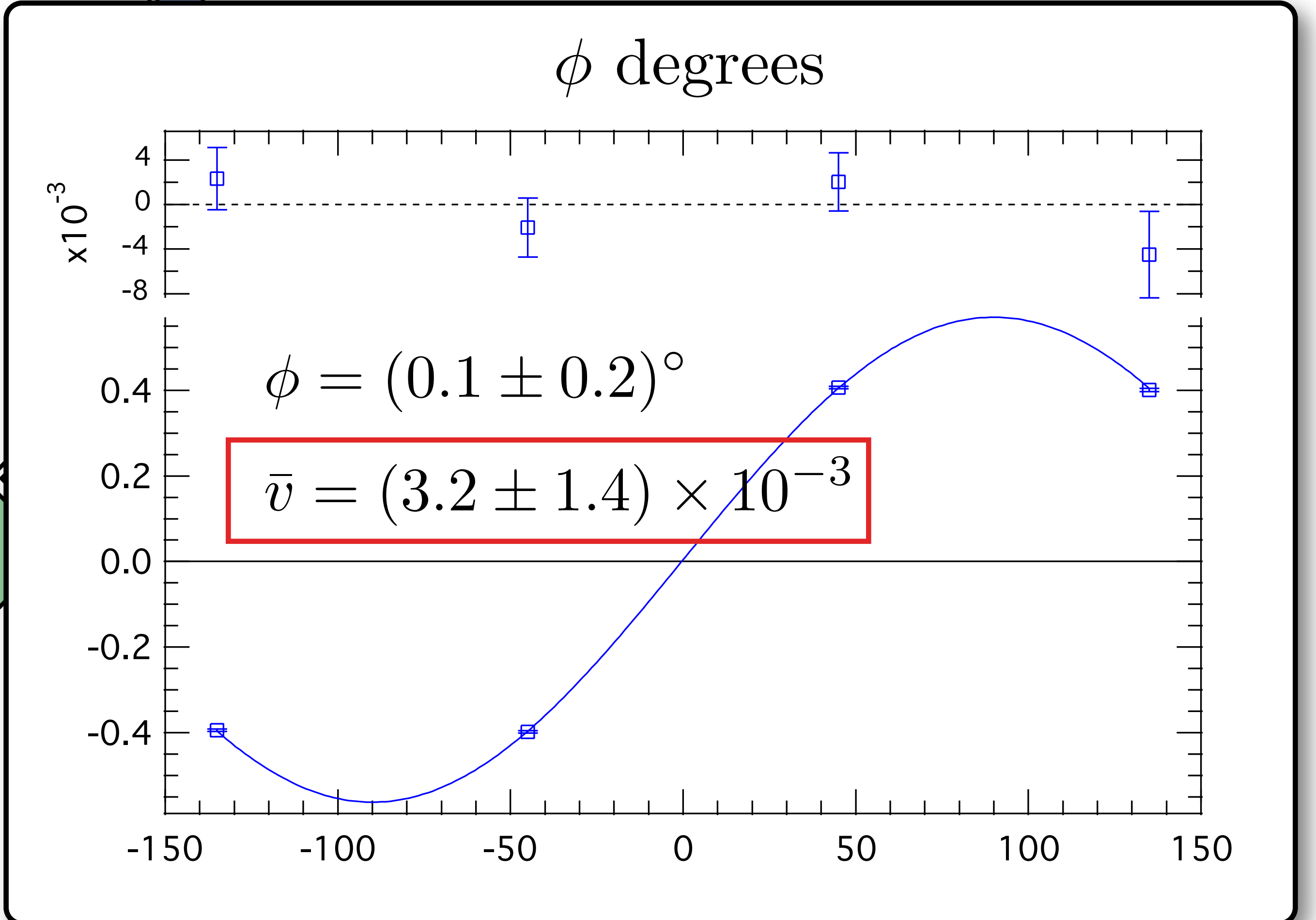
$D_{false} \neq 0$

Two perpendicular asymmetries do *not* cancel

Systematics: Measured Intensity Distribution (Tilt ATP)

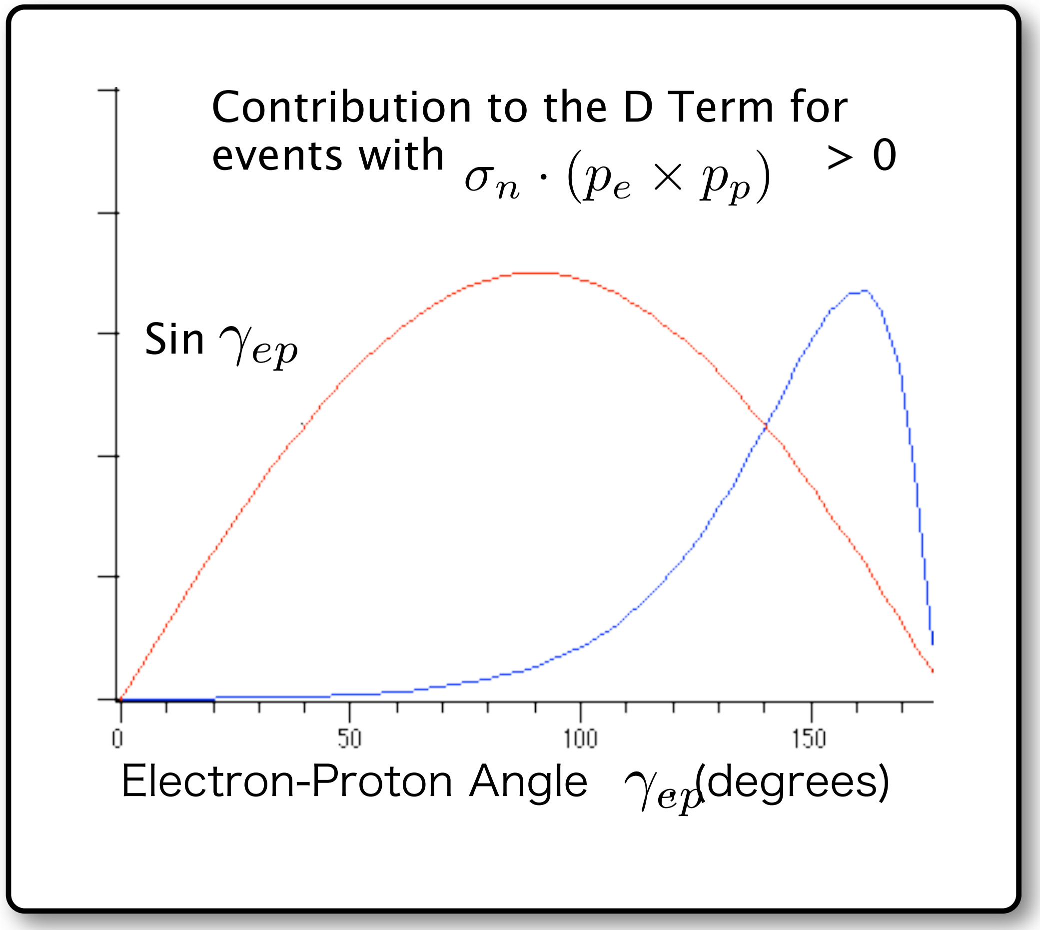


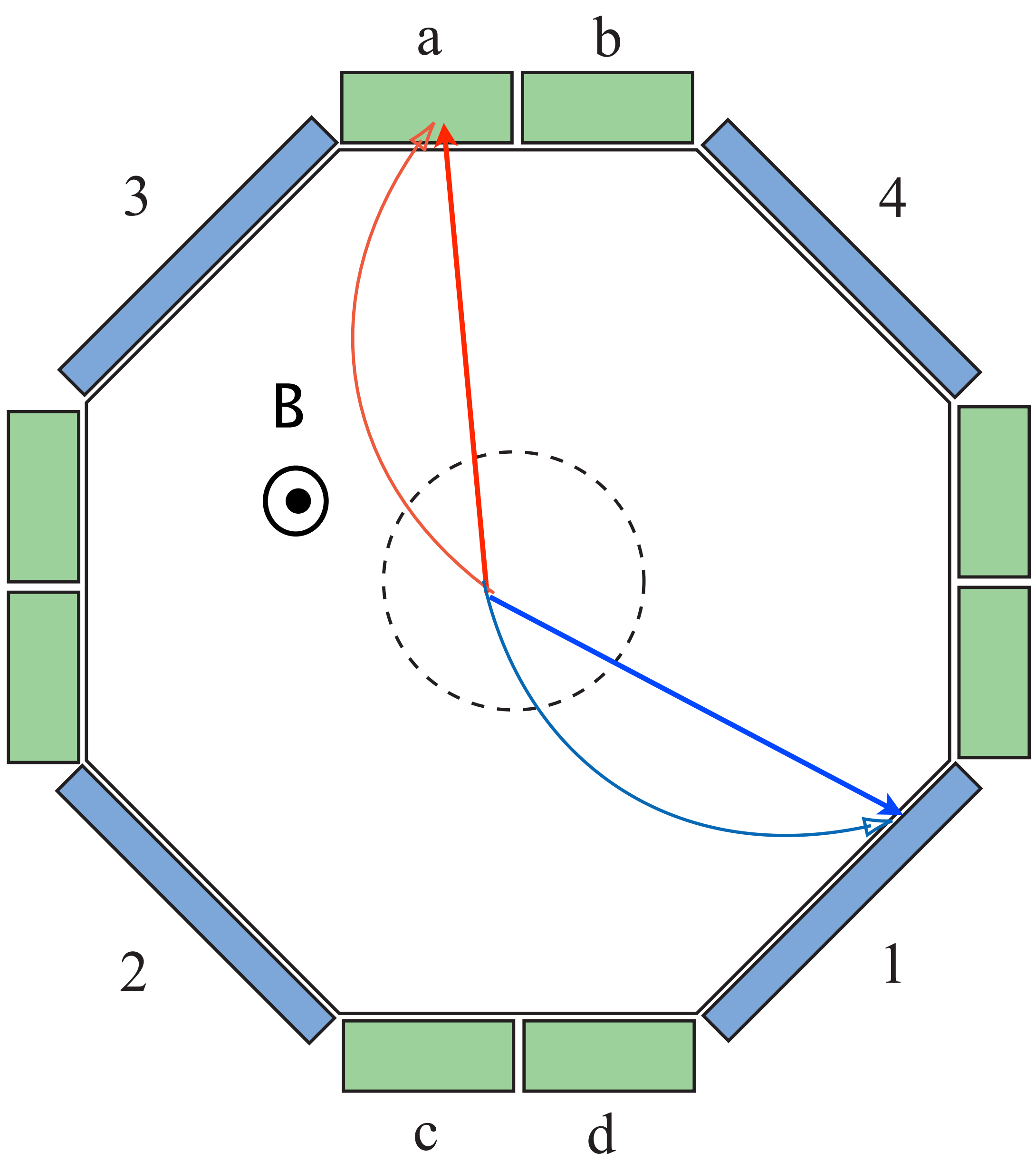
Dysprosium foil activated by the beam
- Cross hair (Cadmium wire) is chamber axis
- Intensity plot linear over 4 orders of magnitude.



Systematics: effect of guide field

But we still have problems.....





Solution: Detailed Monte Carlo.