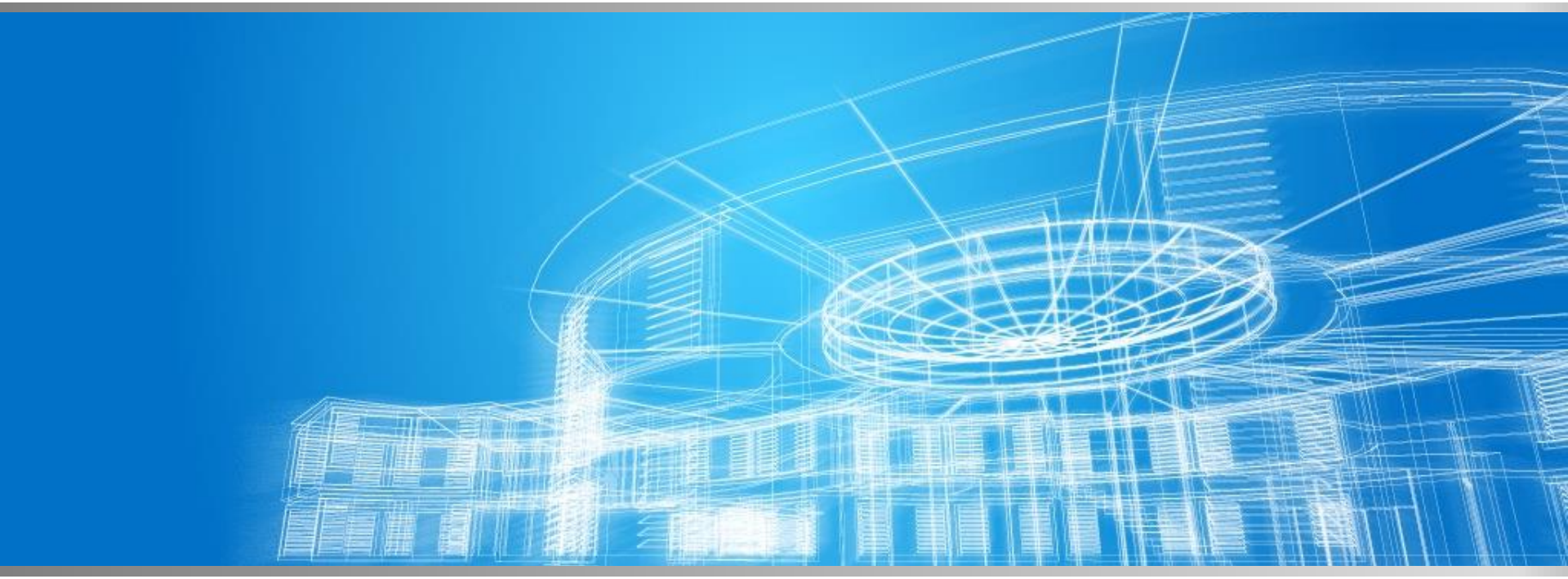
Free neutron β-decay: Searching New Physics Beyond Standard Model

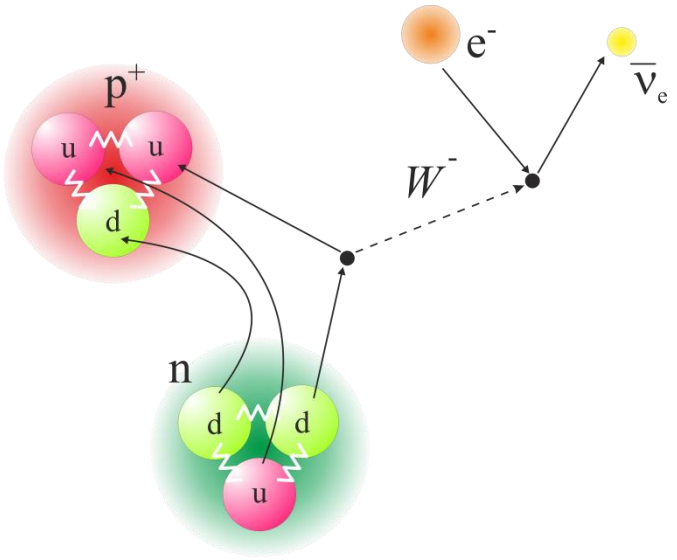
Dr. Xiangzun Wang 王相尊 博士



Outline

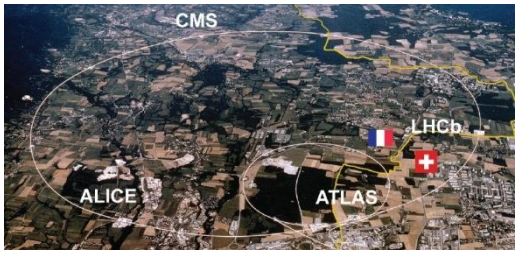
- Introduction to the free neutron decay.
- PERKEO III experiment of β-asymmetry at ILL.
- Design of the PERC beam station.
- R×B drift momentum spectrometer.
- Design of electron cyclotron frequency spectrometer.

Introduction to Neutron β-Decay

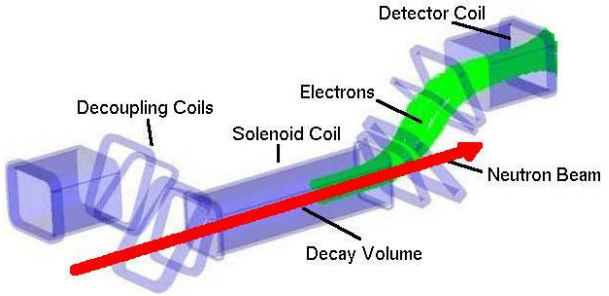


Standard Model And New Physics Beyond

- **Standard Model**
  - Neutrino mass, neutrino oscillation.
  - Dark energy, dark matter.
  - 19 free individual parameters.
  - Gravitation.
  - Origin of P-violation, right handed neutrino & week current.
  - ……
- **Test SM and search physics beyond:**



High energetic experiment
Requires more and more energy.



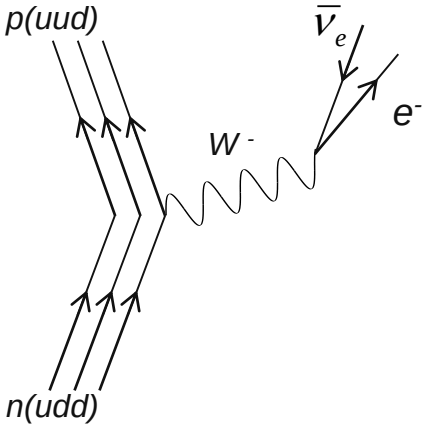
Low energy scale experiments.
Depends on model, low E exp. can be better to search BSM.

β-decay of Free Neutron

- Free neutron decay: Semi-leptonic process,

$$n(udd) \rightarrow p^{+}(uud) + e^{-} + \bar{\nu}_e + 782.3\,\mathrm{keV} \qquad \tau_n = 880.1\,\mathrm{s}$$

- All quarks and leptons in the 1st generation are included.
- Simple and low energetic process, can be precisely characterized in theory.



- Low energy process: high precision can be achieved in Exp.
- No nuclear structure influences: clean environment.
- Most accurate check of BSM in weak charge interaction.

Measurable Quantities in Free n-decay

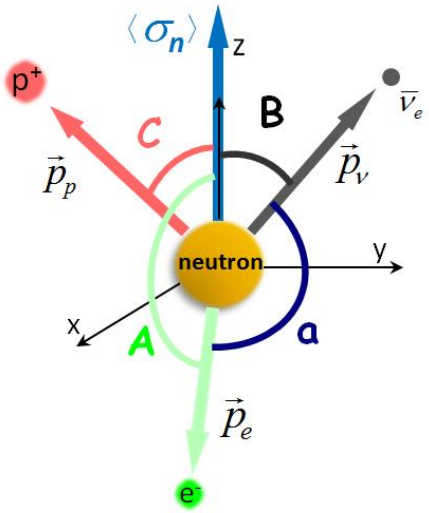
- Probability of n-decay:

$$W \propto G_F^2 \,|V_{ud}|^2\,(1+3|\lambda|^2)F(E_e)\left\{1+a\frac{\boldsymbol{p}_e\boldsymbol{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}}+b\frac{m_e}{E_e}+\langle\boldsymbol{\sigma}_n\rangle\cdot\left(A\frac{\boldsymbol{p}_e}{E_e}+B\frac{\boldsymbol{p}_{\bar{\nu}}}{E_{\bar{\nu}}}+D\frac{\boldsymbol{p}_e\times\boldsymbol{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}}+R\frac{\boldsymbol{p}_e\times\hat{\boldsymbol{\sigma}}_e}{E_e}\cdots\right)\right\}$$

Decay rate

Angular distribution of e^-, p^+, ν

- Decay rate:
  - Neutron life time τ.
- Spectra of e^-, p^+, $F(E_{e,p})$.
- Angular Correlation Coefficients:
  - Discribe the distribution of e^-, p^+, ν momentum and spins.



Measurable Quantities in Free n-decay

- Neutron decay in Standard Model: only 4 parameters:

Fermi Coupling:	G_F	Ratio of Vector, Axial Vector coupling:	λ
ud element of CKM matrix:	$\lvert V_{ud} \rvert$	CP-violation phase angle:	Φ

- Ample room to test and check the Standard Model, and the extensions of Standard Model in n-decay.
  - Other T-violation origins.
  - Unitarity of CKM matrix.
  - Tensor and Scalor contribution in weak interaction.
  - .....

Theory Developments

Motivation from models:

High mass scale physics connected to neutrino mass (seesaw models), and warm dark matter motivate possible contributions from **L/R symmetric models and leptoquarks** at EW scale

Discovery of Higgs particle motivates contributions from a **charged Higgs sector** (new scalar interactions)

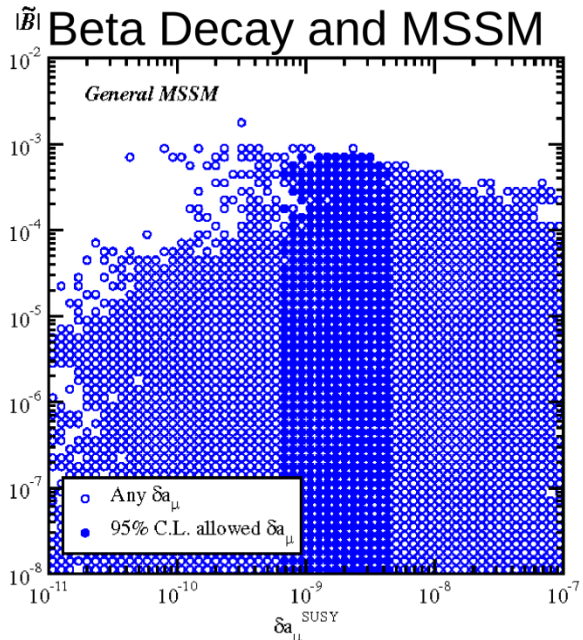
Baryogensis, dark matter, etc… motivate **supersymmetry** at EW scale

Beta Decay is Sensitive to these models!

Recent Developments:

Model Independent (MI) analysis through Effective Field Theory (EFT) provides generic framework for comparing constraints from LHC measurements with beta decay

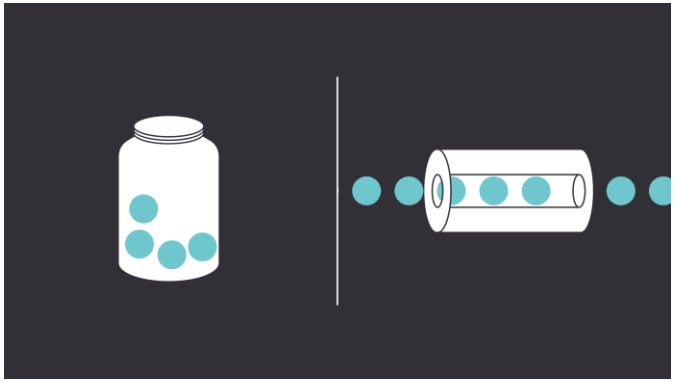
High precision lattice results for form factors in nucleon couplings constants now available and Improving continuously!



Tulin and Ramsey-Musolf, Phys. Rev. D **75**, 075017 (2007)

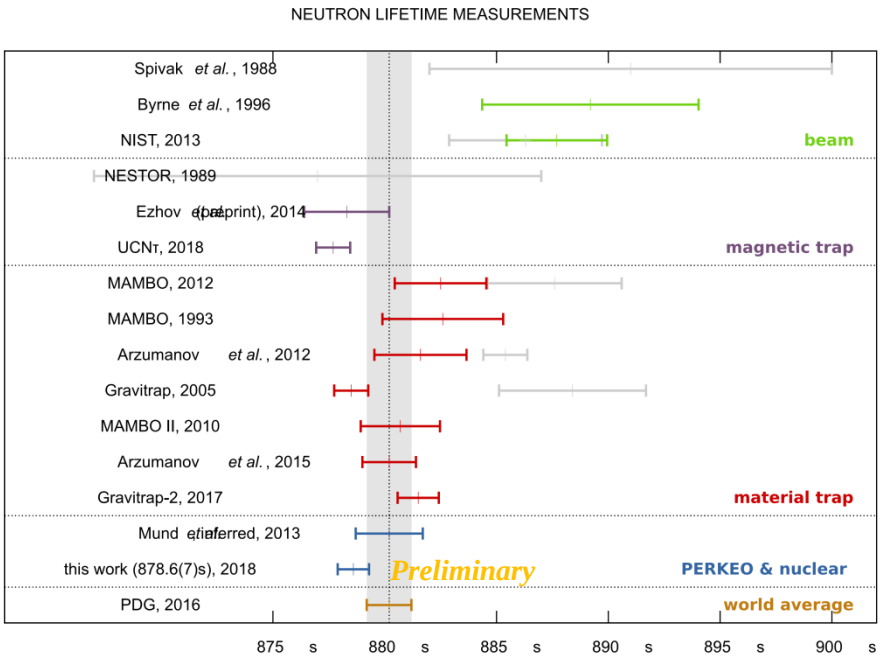
Puzzle of Free Neutron Lifetime

- **Two methods of n lifetime measurement:**



- **Bottle mode**
  - Measure Number of neutron
- **Beam mode**
  - Measure decay e-/p+

- **Difference : ~ 5σ**
  - Beam: τ = 888.0±2.0 s
  - Bottle: τ = 878.1±0.5 s



Dark Matter?

- **A new guess: dark matter.**
  - Possible neutron dark decay channels:
    - Dark matter + photon

$$n \rightarrow \chi + \gamma$$ ✗ (LANL UCN facility)

    - Dark matter + electron-positron pair

$$n \rightarrow \chi + e^{+} + e^{-}$$ ✗ ? (PERKEO II old data)

    - Dark matter + Dark matter

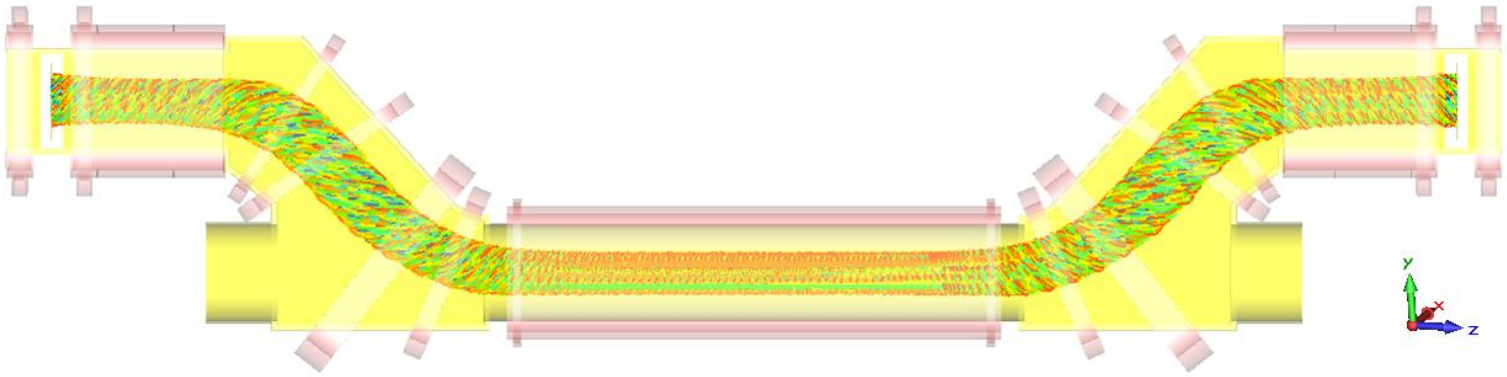
$$n \rightarrow \chi + \phi$$?

    - ……

More possibilities?

More precise experiments are needed.

Experiment of PERKEO III



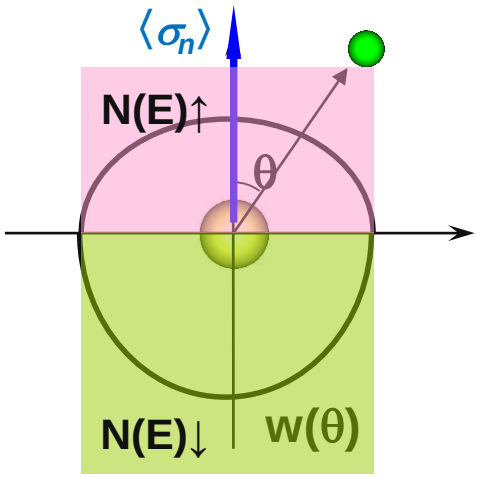
Principle of PERKEO III Spectrometer at ILL

- PERKEO III experiment at ILL in 2008~2009:
  - β-asymmetry in n-decay: Correlation Coefficient A
  - e^- distribution:

$$w(\theta) \propto 1 + A \cdot \frac{v_e}{c} \cos(\theta)$$

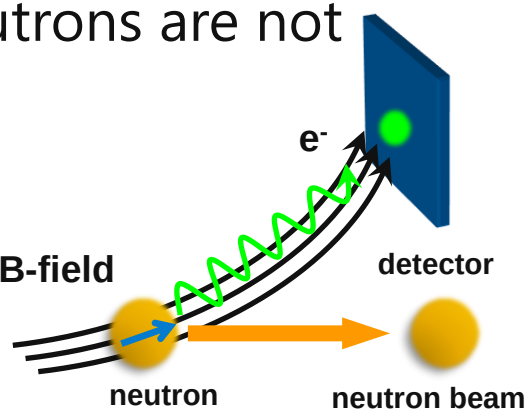
  - θ: emission angle.
- Integrate over θ, spectra in two hemispheres, $N^{\uparrow}(E)$ and $N^{\downarrow}(E)$.
- Compare the $N^{\uparrow}(E)$ and $N^{\downarrow}(E)$:

$$A_{\exp}(E) = \frac{N^{\uparrow}(E) - N^{\downarrow}(E)}{N^{\uparrow}(E) + N^{\downarrow}(E)} = \frac{1}{2} A \cdot \frac{v_e}{c}$$



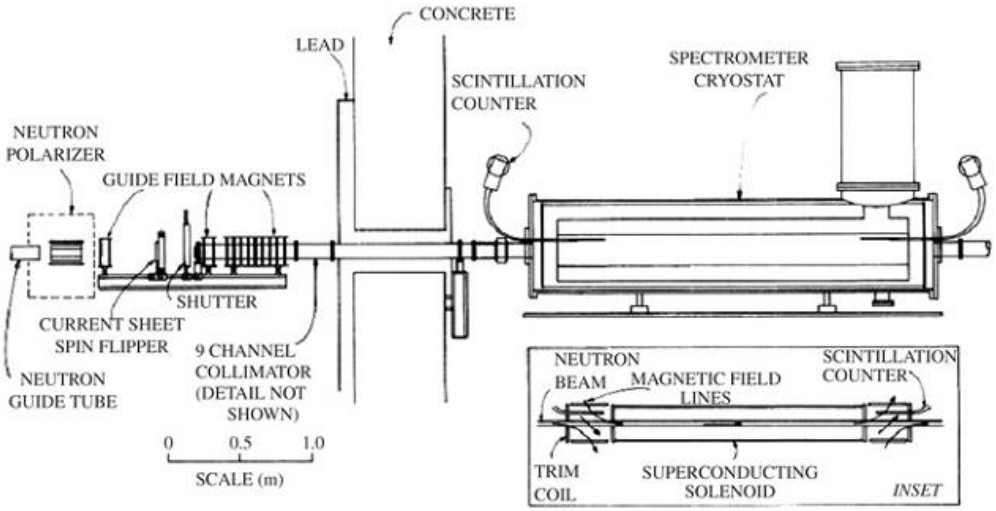
Principle of PERKEO III Spectrometer

- Applying a magnetic field:
  - $\boldsymbol{B}$-field holds the neutron spin. Emission angle θ is converted to e^- pitch angle, $\boldsymbol{B}$ and $\boldsymbol{p_e}$.
  - Helical motion: e^- are automatically collected, integrated over θ.
  - Curved $\boldsymbol{B}$-line guides e^- to detectors. Neutrons are not influenced.
- Applying a polarizer and spin-flipper, to alternate neutron spin.
  - Detector can measure the e^- spectra $N^{\uparrow}(E)$ & $N^{\downarrow}(E)$.

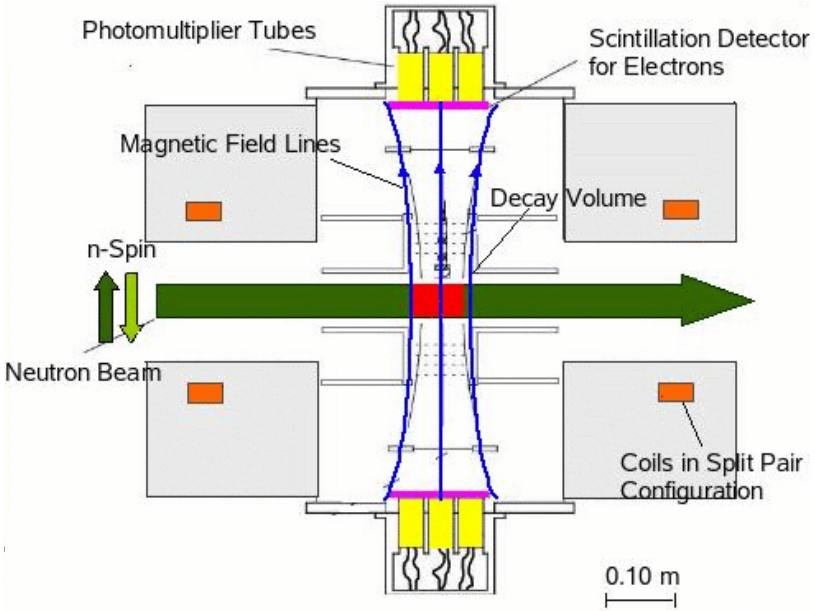


PERKEO Series Experiments

- **PERKEO I & II of Heidelberg University.**



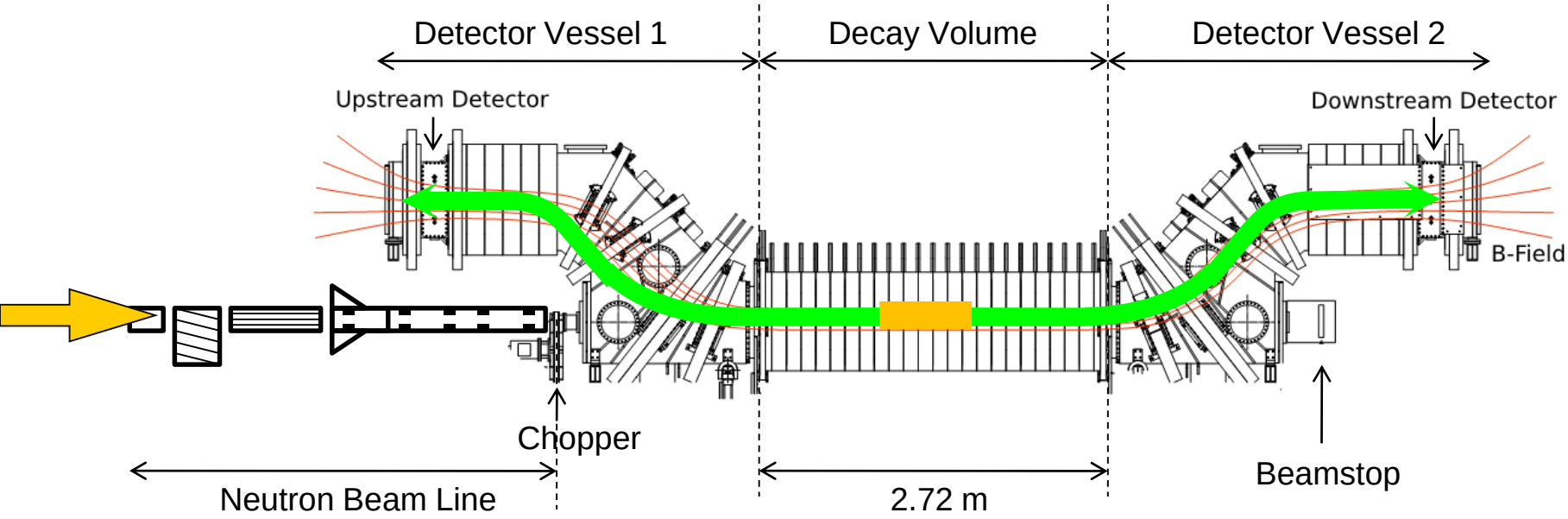
Perkeo I
(1986)



Perkeo II & IIB
(2000-2006)

PERKEO III Experiment at ILL

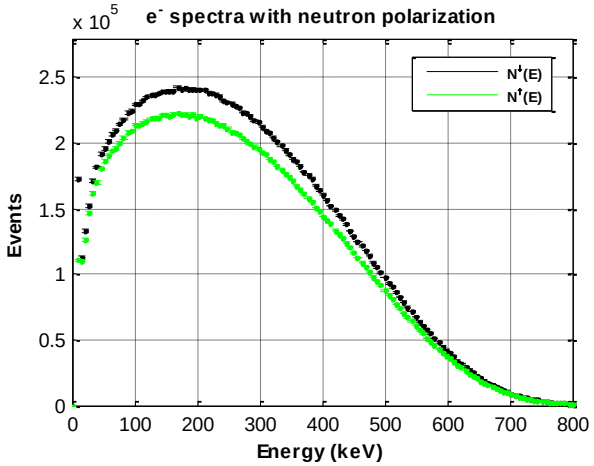
- Instrument of PERKEO III (2006-2014):



- Beam Line: polarized, pulsed, chromatic neutron beam.
- Copper Coils: curved magnetic field.
- Neutron in Decay Volume: e^- measurements (p^+).
- 2 Detector Systems, 4π detection.

Data Analyses and Preliminary Results

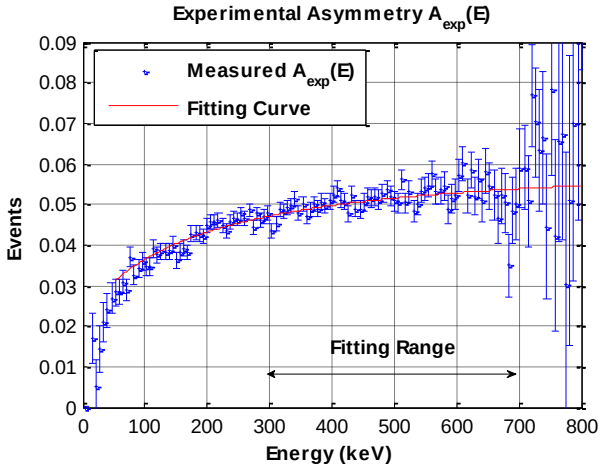
- **Data analyses: Measured e^- spectra $N^{\uparrow}(E)$ and $N^{\downarrow}(E)$:**



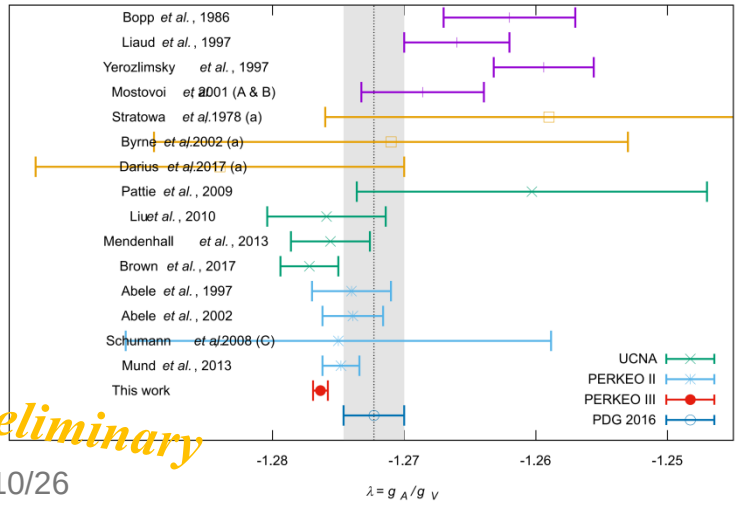
Fitting A to

$$A_{\exp}(E) = \frac{N^{\uparrow}(E) - N^{\downarrow}(E)}{N^{\uparrow}(E) + N^{\downarrow}(E)}$$

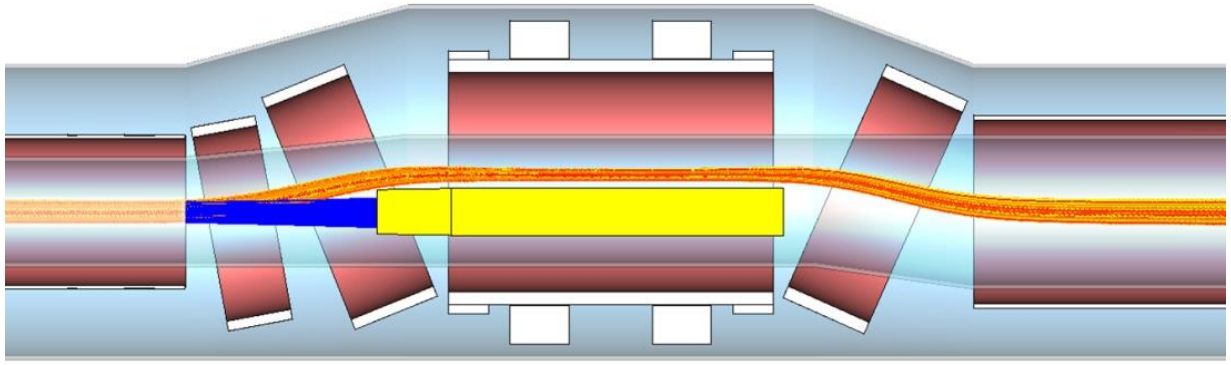
$$= \frac{1}{2} A \cdot \frac{v_e}{c}$$



- **Result: Most precise *A* and λ.**

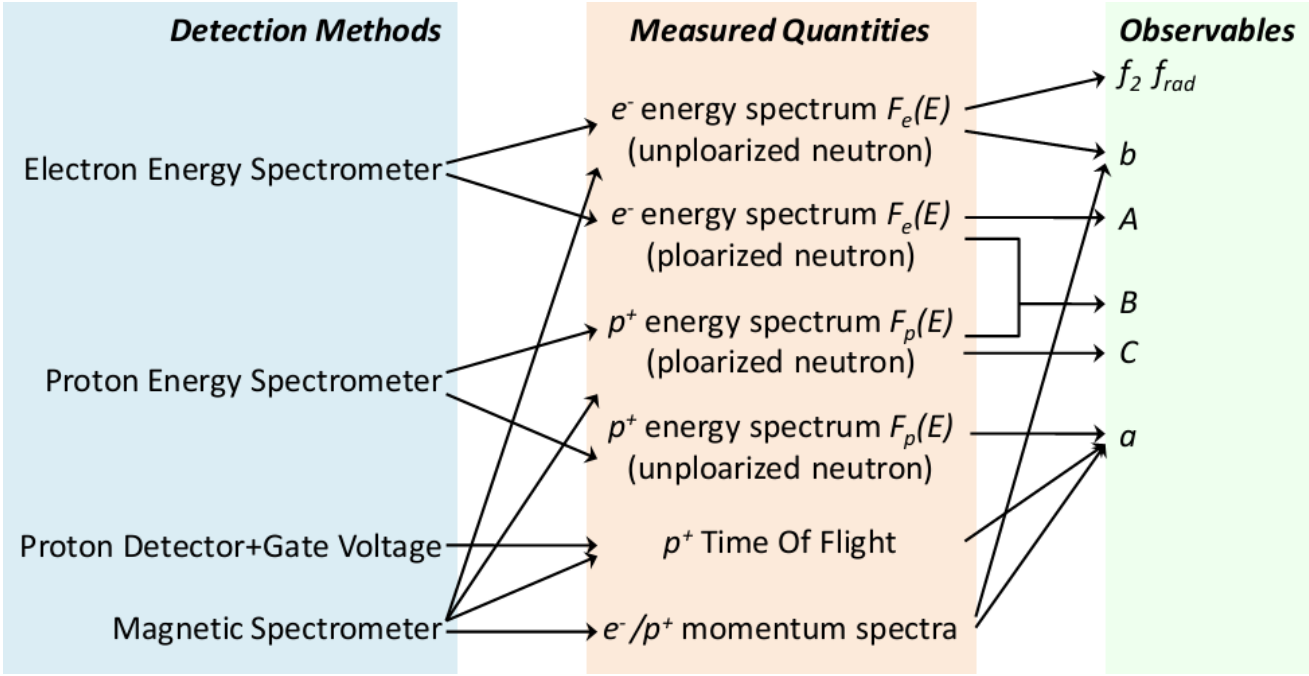


Design of PERC Beam Station



Next Generation: PERC Beam Station

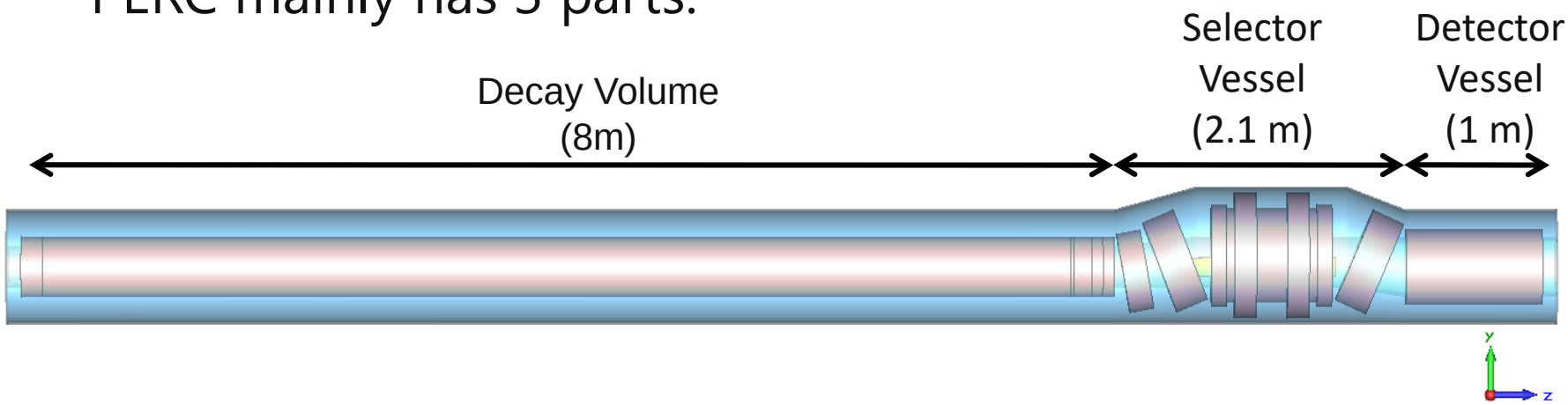
- PERC (Proton and Electron Radiation Channel) motivation:
  - Versatile for measurements of various parameters.

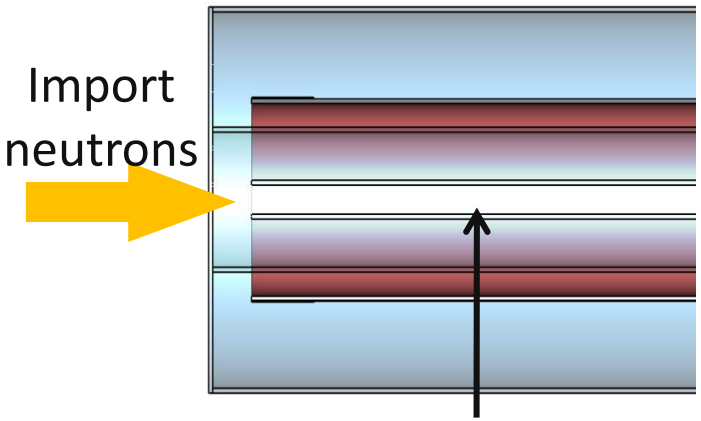


  - e^-/p^+ spectra distortion-free on 10^{-4}.
  - Coefficients can be measued 1 order of magnitude more precise.

Principle of PERC

- PERC mainly has 3 parts:

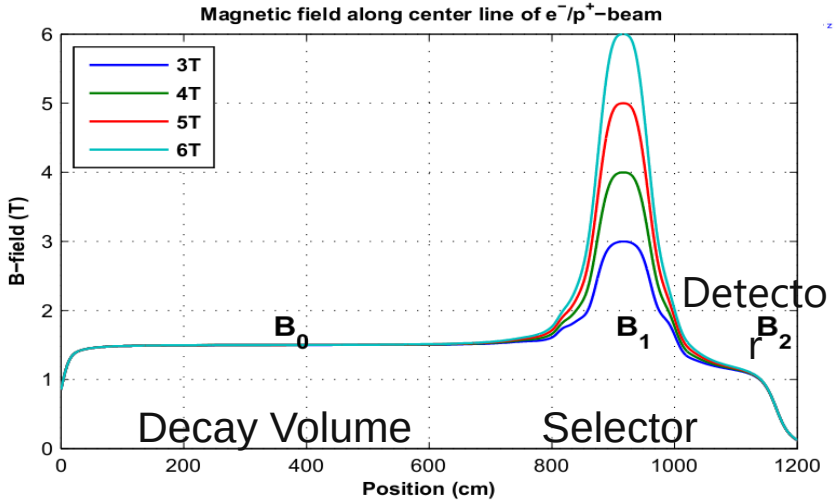




Decay volume in the neutron guide

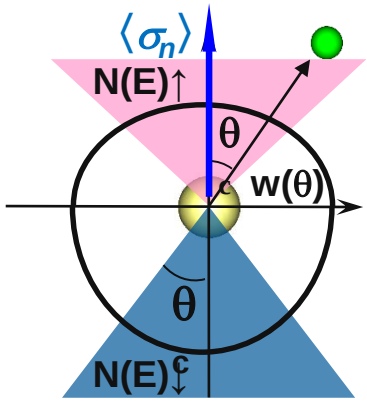
- Decay Volume in a neutron guide.
  - n-beam size is confined.
  - Decay Volume can be long.
  - Decay events: 10^6 /s.
- Superconducting coil.
  - Homogeneous B_0 field.

Functional B-Field Distribution:



- Specified *B*-field strength distribution:
  - *Decay volume*: B_0=1.5 T
  - *Selector*: B_1 = 3 T~6 T
  - *Detector*: B_2 = 0.5 T

- Magnetic mirror defines pitch angle: $\frac{\sin\theta_0}{\sin\theta_1} = \sqrt{\frac{B_0}{B_1}}$

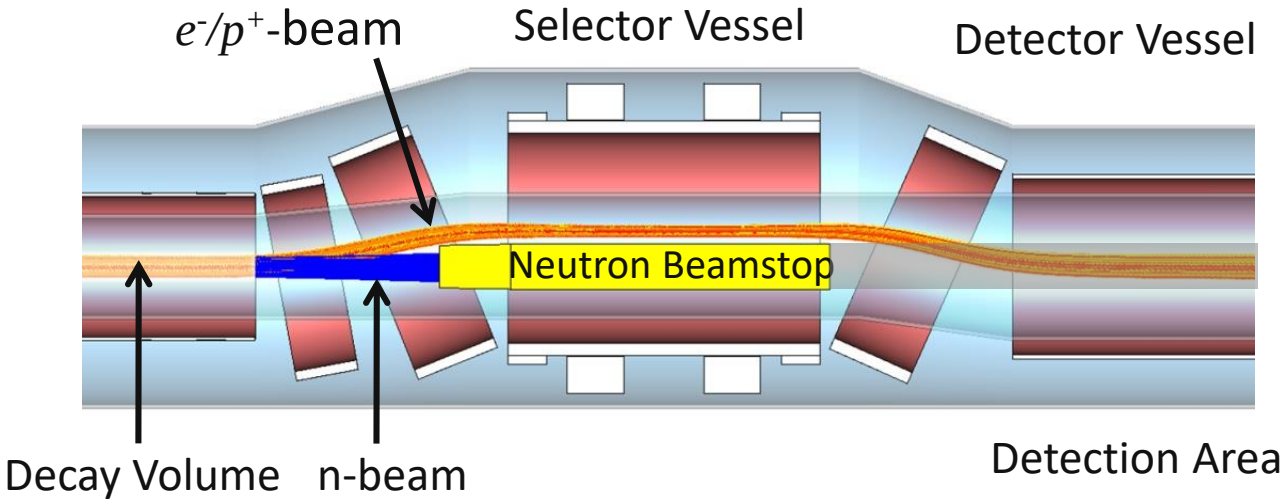


- Further the measured observable. e.g., electron correlation coefficient A:

$$A_{exp} = A \cdot \frac{1}{2}\beta(E)\left(1+\sqrt{1-\frac{B_0}{B_1}}\right), \text{ with } \beta = \frac{v_e}{c}$$

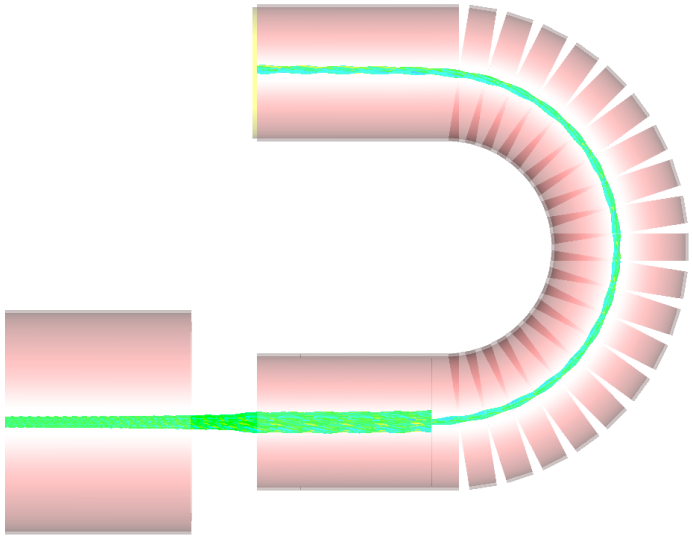
Selector of PERC

- Selector of PERC:



- A series of tilted coils generate a curved B-field.
- e^-/p^+ are separated from the n-beam, filtered by B_1 field, then guided back coaxial to n-beam, to the detector.
- Neutron beamstop shields the γ-background from decay volume. Detection obtains clean enviroment.

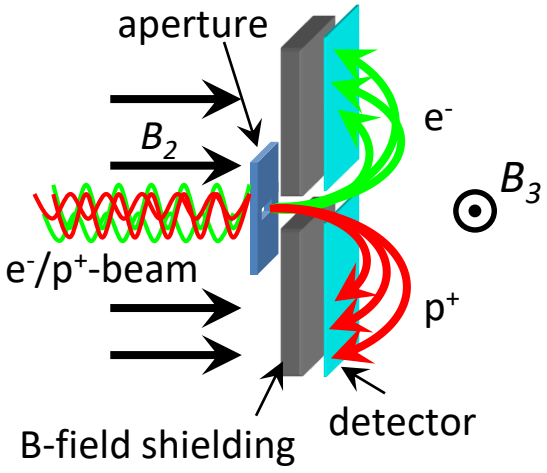
R×B Drift Momentum Spectrometer

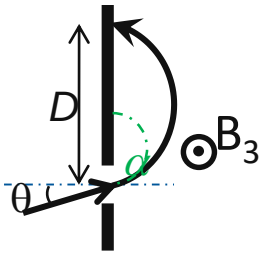


R×B Drift Momentum Spectrometer

- In PERC experiment, momentum spectrometer is desired.
  - Momentum spectrum: low energy scale, ideal for Fierz term b.
  - e^-/p^+ can be measured simultaneously.
  - Pixel detector: less sensitive to background & backscatter.

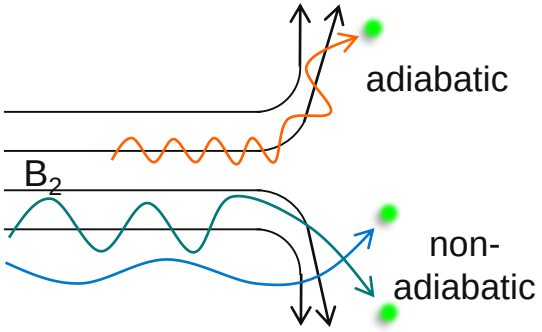
- Magnetic spectrometer:





$$D = \frac{p}{qB} \cdot \alpha \cdot \frac{2}{\pi} \cdot \cos\theta$$

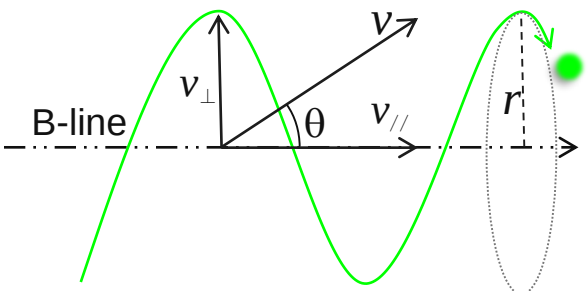
- Problem at PERC:

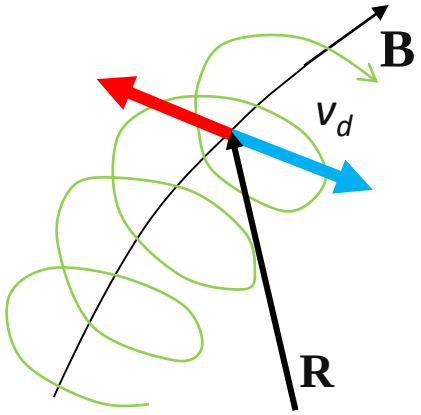


  - e^-/p^+ incident angles are highly distorted.
  - Dispersion cannot represent the momenta.

Principle of R×B Drift Spectrometer

- When a particle propagates in a curved magnetic field, it has a drift effect perpendicular to the ***B***-field and the curvature ***R***: **R×B** drift



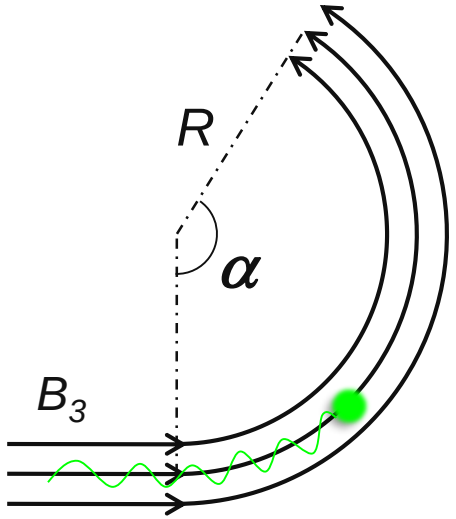


- To the 2nd order:

$$\mathbf{v}_d = \underbrace{\frac{m}{qBR}\left(v_{//}^2 + \frac{1}{2}v_{\perp}^2\right)\frac{\mathbf{R}\times\mathbf{B}}{RB}}_{1^{st}\text{ order}} - \underbrace{\frac{m}{B^2}\left(\frac{\mathrm{d}v_d}{\mathrm{d}t}\times\mathbf{B}\right)}_{2^{nd}\text{ order}}$$

Principle of R×B Drift Spectrometer

- If we apply a uniformly curved ***B***-field:
  - ***B*** and ***R*** are constants, ***B***-lines are parallel and coaxial.
  - $\boldsymbol{v_d}$ is constant. 2nd order $dv_d/dt=0$.
  - Pitch angle θ of a particle is constant.



- Integrating over T, the Drift Distance is:

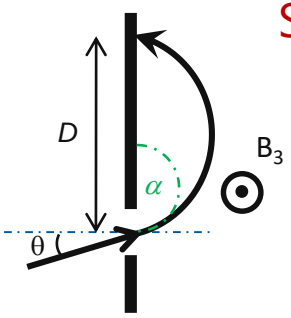
$$D = \int v_d \mathrm{d}t = \boxed{\frac{p}{qB}} \cdot \alpha \cdot \frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

- α : the bending angle during time T, $\quad \alpha = \dfrac{v_{//} \cdot T}{R}$

Momentum analyses with R×B *drift.*

R×B Spectrometer: Large Acceptance

- Compare the **R×B** with dispersive magnetic spectrometer:



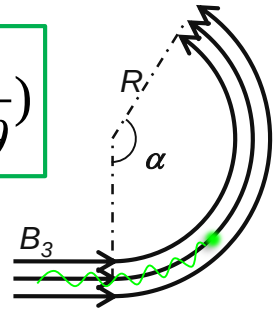
Dispersion in Mag. Spec.

$$D = \frac{p}{qB} \cdot \alpha \cdot \frac{2}{\pi} \cdot \cos\theta \qquad f(\theta)$$

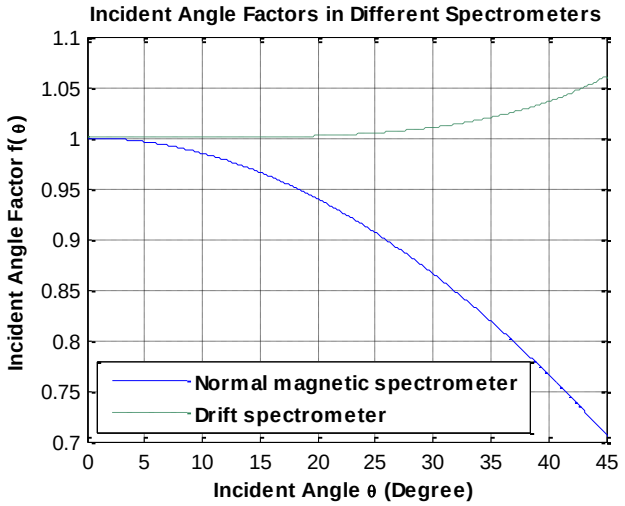
$$\Longleftrightarrow$$

RxB Drift

$$D = \frac{p}{qB} \cdot \alpha \cdot \frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right) \qquad f(\theta)$$

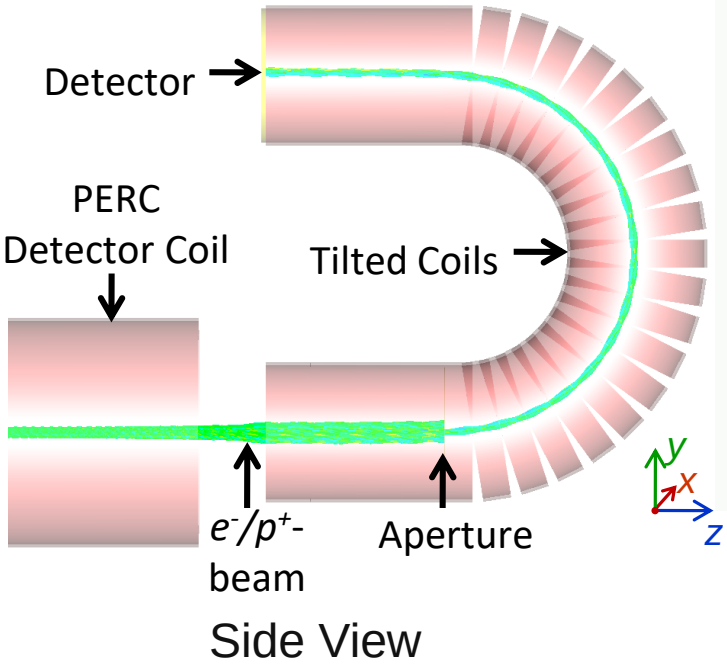


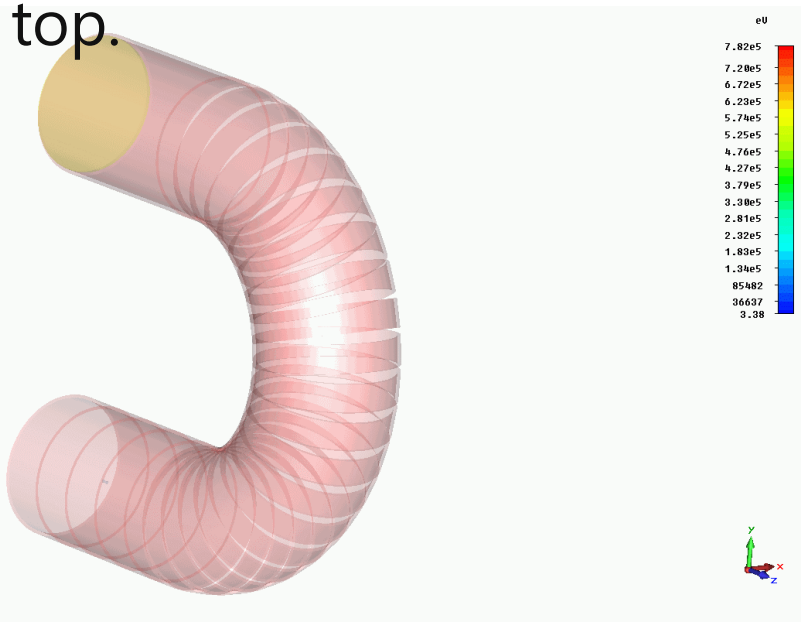
- Compare the incident (pitch) angle corrections $f(\theta)$:
  - **R×B**: For θ < 9.6°, solid angle Ω < 88 msr, the direct aberration $f(\theta)$ < 10^{-4}.
  - Mag. Spec. : $f(\theta) \sim 10^{-2}$.
  - Large acceptance of pitch angle.



Design of R×B Spectrometer

- A series of tilted coils after PERC, uniformly curved ***B***-field.
- e^-/p^+ particles from PERC pass through the aperture, follow the ***B***-field, reach the detector on top.



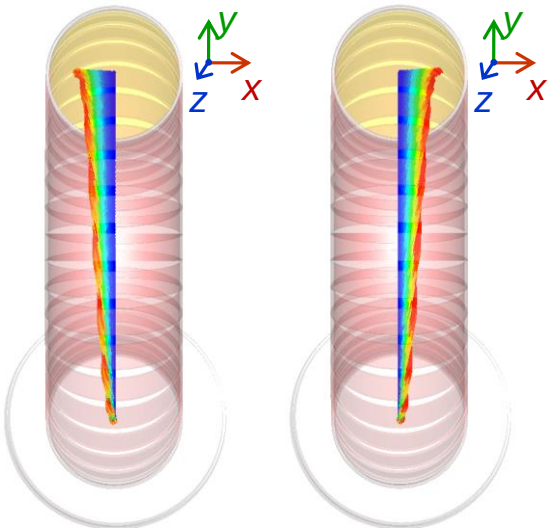


The guiding field is gradually evolved, particles are transported adiabatically,

Precise measurement is possible.

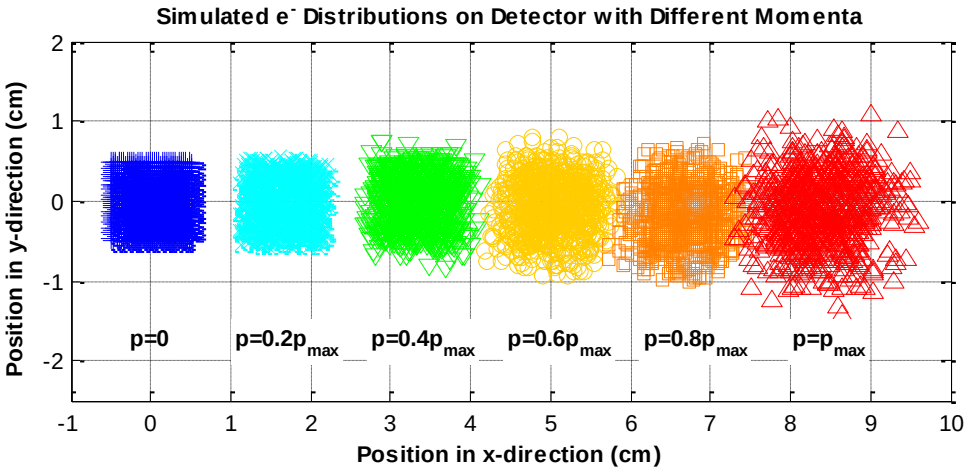
Simulation of Particles in R×B Spectrometer

- In the curved B-field, particles drift along x-axis, according to their ***p,*** *q* and $\boldsymbol{B_3}$.
- The effect can be observed in simulation.



p^+ e^-

Front View

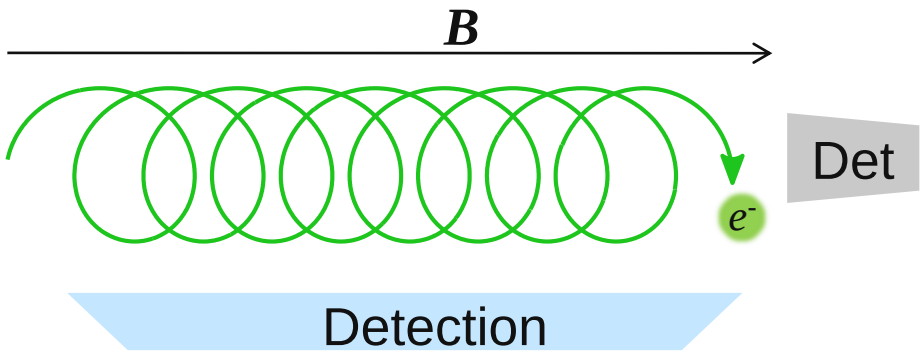


Max. e^-/p^+ momentum in n-decay: p_{max} = 1.19 MeV/c^2,

Max. drift: D_{max} = 8.29 cm.

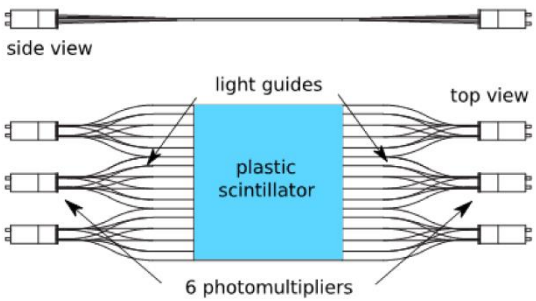
Project NoMoS is under construction.

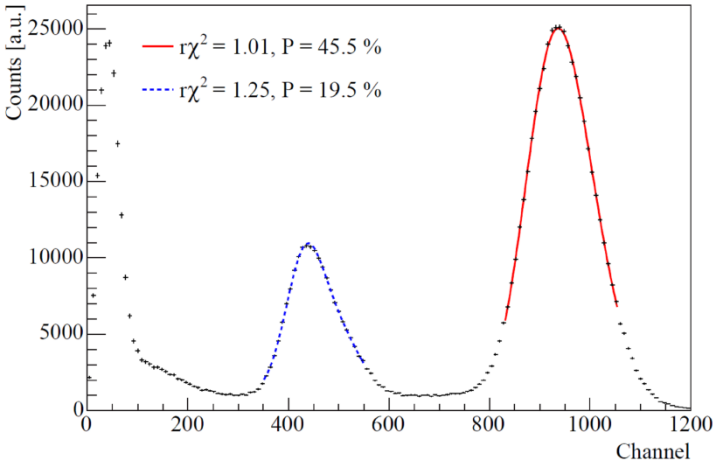
Electron Energy Measurement Method



Present e^- Detection Methods

- **Plastic scintillator + photomultiplier.**
  - Wide distribution of energy
  - Aging of plastic scintillator
  - Non-linearity of energy, complex plastic property
  - Scale drift, inhomogeneity, etc.





(e) ^{207}Bi. 2 Peaks at 504.7 keV and 997.9 keV.

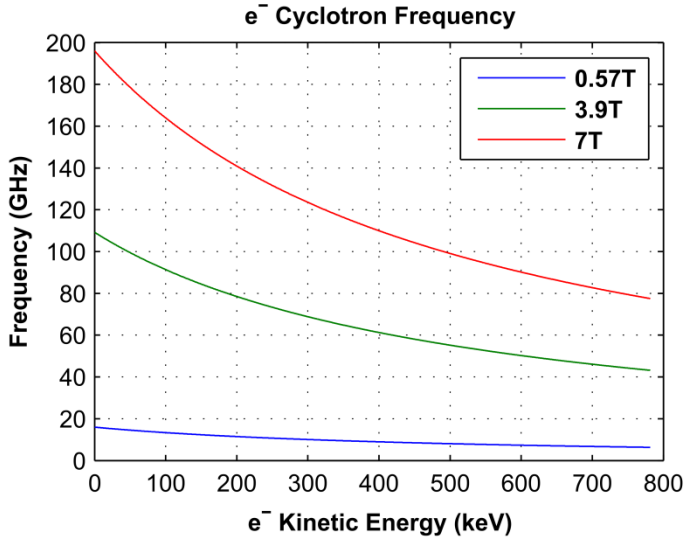
- **Silicon semiconductor detector.**
  - Backscatter effect 20%~40%

New Methods of e⁻ Energy Measurement

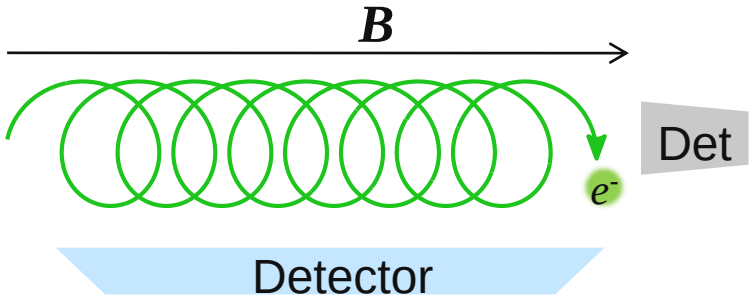
- **Relativistic electrons: relation between kinetic energy E_k & gyo-frequency f in a magnetic field.**

$$f = \frac{eB}{2\pi\gamma m_0} \qquad \text{with} \qquad \gamma = 1 + \frac{E_k}{m_0 c^2}$$

- **e.g.: e⁻ from free neutron decay: 0~800 keV.**

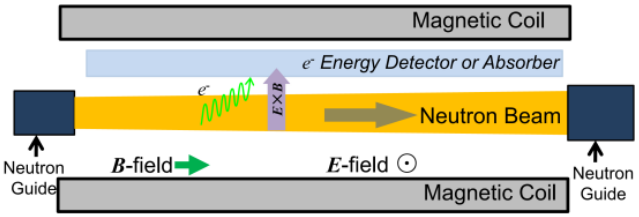


- **Measurement of e⁻ cyclotron frequency in a homogeneous magnetic field.**

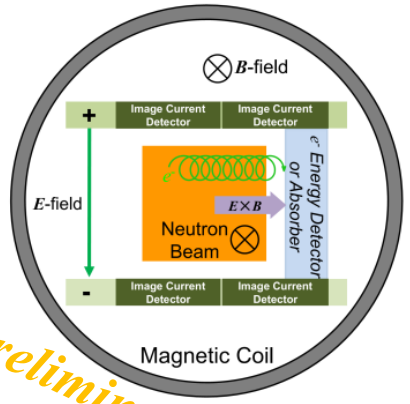


e^- Cyclotron Frequency Measurement

- **Possible methods:**
  - Microwave radiation (Project 8)
  - Surface current
- **Advantages:**
  - Precise and accurate.
  - Frequency measurement is mature.
  - No broadening, no drift, no calibration.
  - Basically no damage on electron energy.
- **Application:**
  - Neutrino mass measurement (Project 8).
  - Precise measurement of e^- spectra, search new physics.
  - Some special coefficients, e.g. R.



(a) Side View



(b) Front View

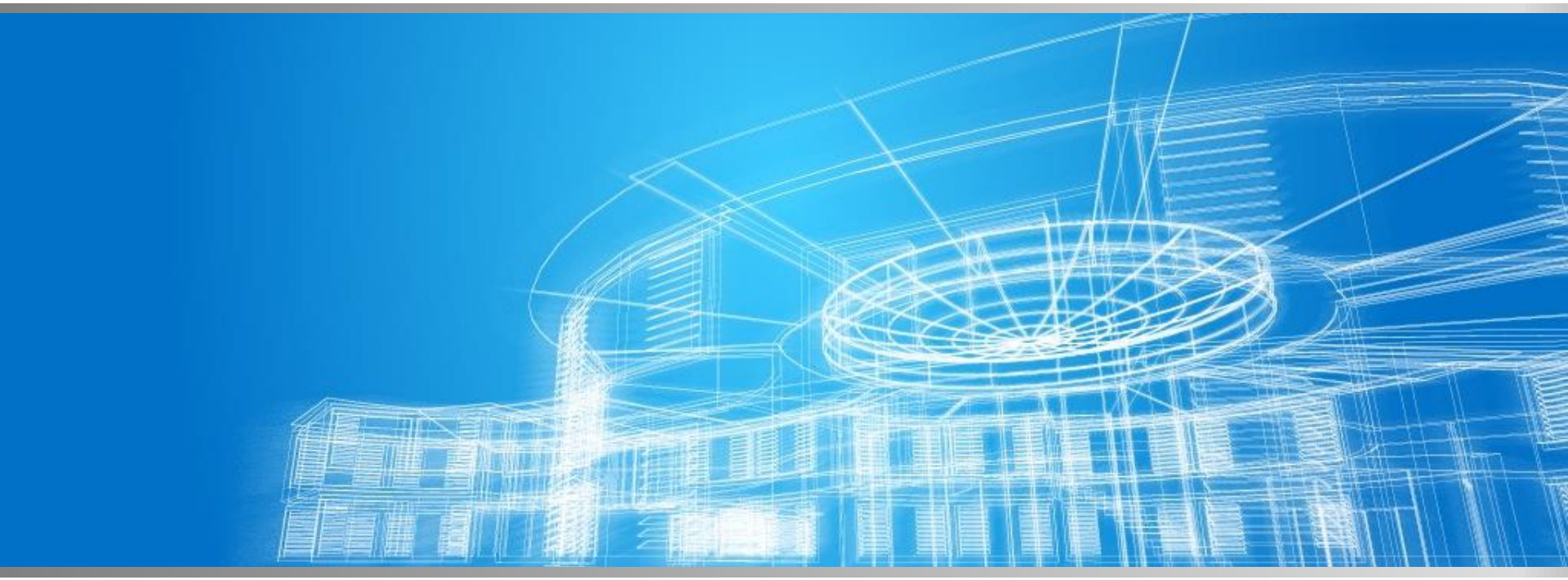
Preliminary

Project in progress

Summary & Outlook

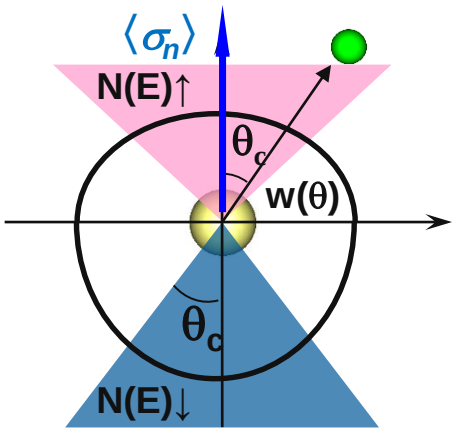
- Precise measurements of neutron decay is to test the limit of new physics beyond Standard Model.
- β-asymmetry experiment with PERKEOIII at ILL has achieved 5 times more precise results.
- The PERC beam station is delicately designed, will be performed at FRM, measured distorsion-free on 10^{-4} level,
- R×B drift, cyclotron frequency etc. new detection methods can improve experiments.

Thank you for your attention!



More Efficient Measurements with PERC

- More efficient measurements:
  - Coefficients *A, B, D, R…* are more obvious near the neutron spin.
  - Select specific emission angle range: more efficient measurement.

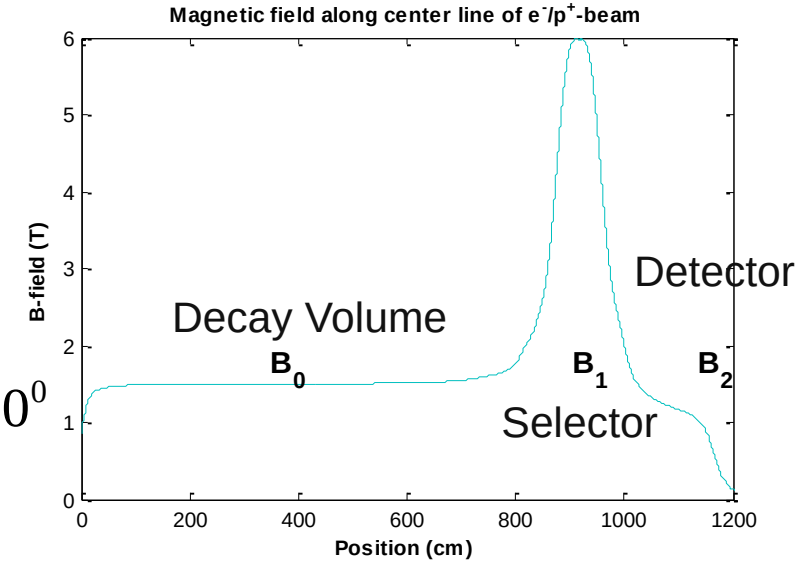


- Emission angle selection: magnetic mirror effect.
  - Specific *B*-field distribution.

— *Decay* : B_0=1.5 T

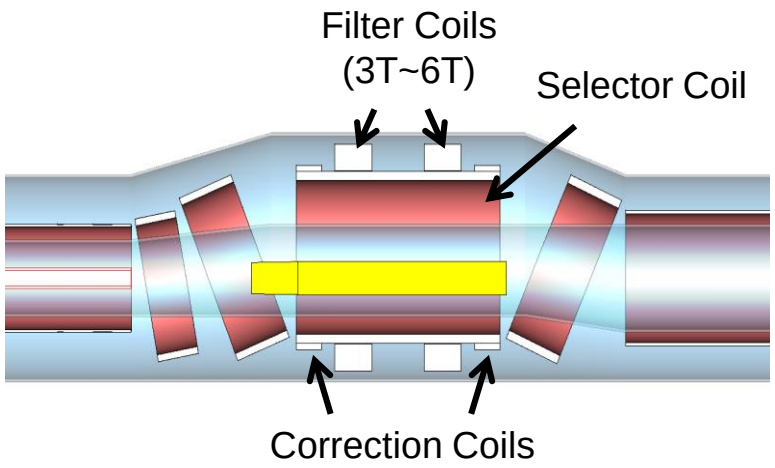
— *Selector* : B_1 = 6 T

Critical emission angle: $\sin\theta_{cri.} = \sqrt{\frac{B_0}{B_1}} = 30^0$



Selector Field Optimization

- Selector field: B_1 field variation
  - A pair of Filter Coils vary B_1 field between 3T~6T.
  - Observables as function of critical pitch angle $\theta_{cri.}$
- Pairs of Filter anc Correction coils.
  - Homogenize the B_1 field.
  - Induced A_{exp} deviation $<10^{-4}$.



B_1	Max. $\Delta B_1/B_1$	Max. $\Delta A_{exp}/A_{exp}$
3 T	1.6×10^{-4}	3.3×10^{-5}
4 T	1.6×10^{-4}	2.1×10^{-5}
5 T	8.1×10^{-5}	7.9×10^{-6}
6 T	8.0×10^{-5}	6.2×10^{-6}

B-field deviation: ~10^{-4}
$A_{\exp}$ deviation: < 10^{-4}

Advantages of R×B Spectrometer

- Adiabatic transports of e^-/p^+ particles.
  - Angular distribution of particles can be kept and measured.
- Very low momenta measurements.
  - Especially ideal for Fierz term estimation.
- Large acceptance of incident angle.
  - When $\theta < 9.6^{o}$, (corresponding to solid angle $\Omega < 88$ msr), the direct aberration is $< 10^{-4}$.
- Low backscatter effect.
  - Backscattered particles can hardly reach the detector.

$$\Delta A / A = 1.7 \times 10^{-3}$$

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