# Measurement of $G_{En}$ in $D(\vec{e}, e'\vec{n})p$

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- Motivation
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- The $D(\vec{e}, e', \vec{n})p$ experiment in A1
- Preliminary results
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# Motivation

Measurement of $G_{En}$ – two main problems:

- No free neutron target
- $(G_{En})^2 \ll (G_{Mn})^2$

Measurements of the charge radius $\langle r^2_{En} \rangle$ by scattering of neutrons at atoms

- $\langle r^2_{En} \rangle = (-0.115 \pm 0.002 \pm 0.003)\,\mathrm{fm}^2$ for $^{208}Pb$
  [Kopecky et al., PRC **56** (1997) 2229]
- $\langle r^2_{En} \rangle = (-0.137 \pm 0.003)\,\mathrm{fm}^2$ for $^{186}W$, $^{209}Bi$
  ("Dubna compilation")

Determines slope of $G_{En}$ at $Q^2 = 0$.

Rosenbluth separation for quasifree $D(e, e')$ scattering at DESY and SLAC:

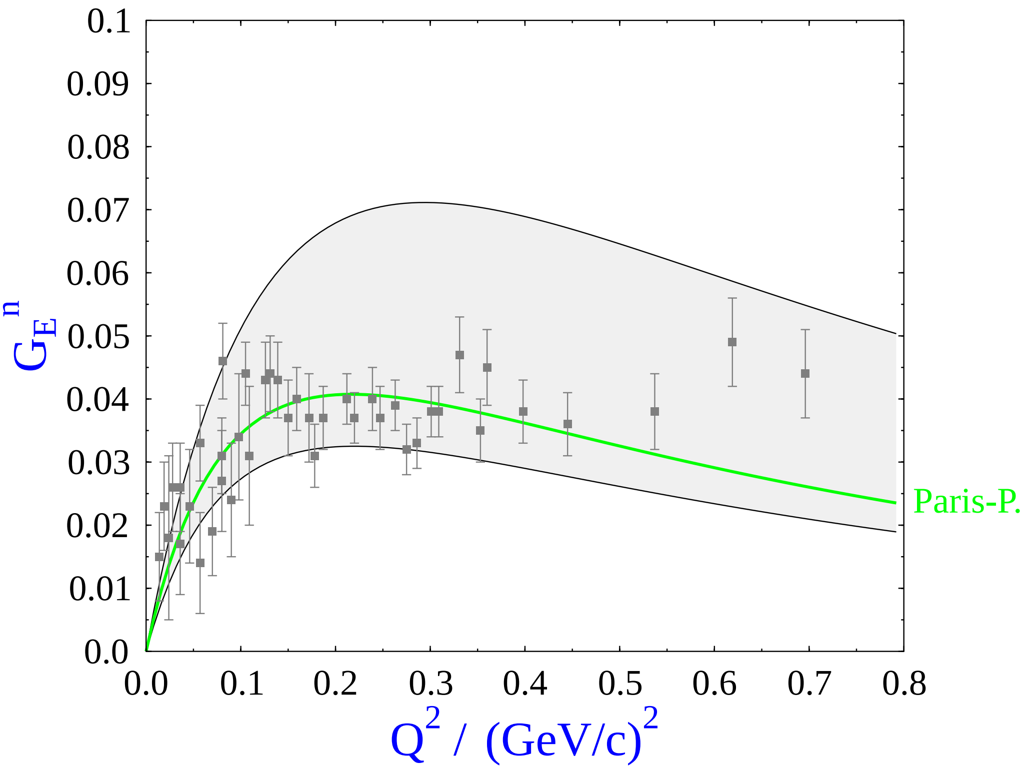
$G_{En}$ compatible with zero. [Lung et al., PRL **70** (1993) 718]

# Elastic scattering $D(e, e')D$

- Measurement of deuteron structure function $A(Q^2)$:

$$\frac{d\sigma}{d\Omega}(D(e, e')) \sim A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

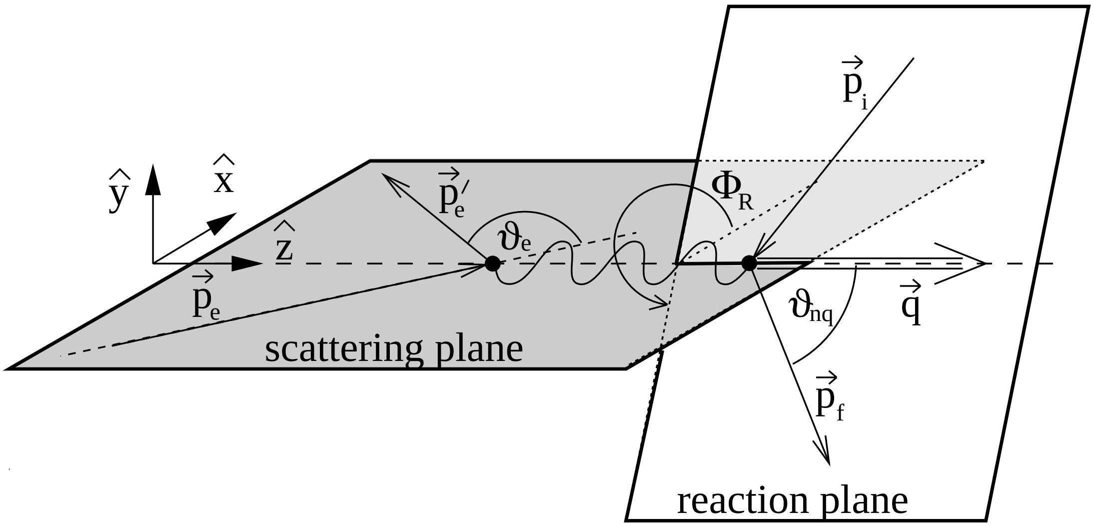
- Sensitive to interference term in $(G_{Ep} + G_{En})^2$
- Results are model dependent and vary with the NN potential used.




[Platchkov et al., NPA **510** (1990) 740]

# Double polarisation experiments

Kinematics of the $n(\vec{e}, e'\vec{n})$ reaction:




Polarisation transfer to the recoil neutron:
[Arnold, Carlson, Gross, PRC **23** (1981) 363]

$$P_x = -P_e \frac{2\sqrt{\tau(1+\tau)}\tan(\theta/2) G_E G_M}{G_E^2 + \tau G_M^2 (1 + 2(1+\tau)\tan^2(\theta/2))}$$

$$P_y = 0$$

$$P_z = P_e \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2) G_M^2}{G_E^2 + \tau G_M^2 (1 + 2(1+\tau)\tan^2(\theta/2))}$$

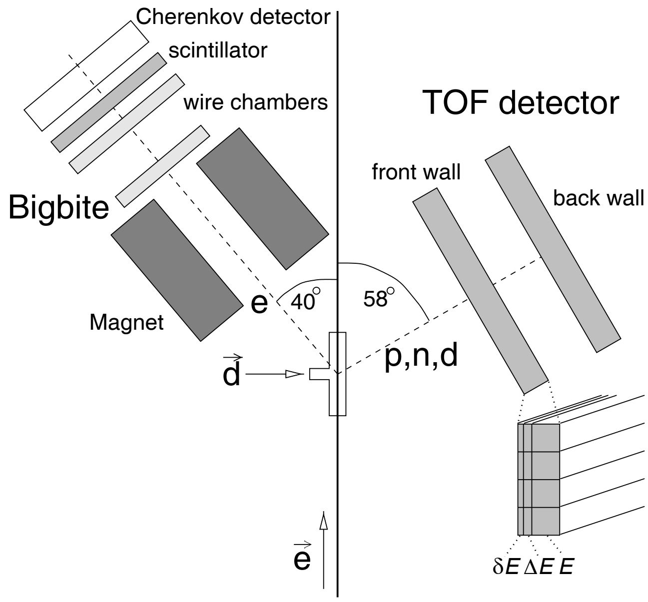
$P_x$ contains interference term $G_{En} G_{Mn}$.

Equivalent terms appear for the asymmetry in $\vec{n}(\vec{e}, e'n)$ scattering.

# Polarised target experiments

Types of double polarisation experiments:

- Measurement of neutron recoil polarisation $D(\vec{e}, e'\vec{n})p$
- Polarised target $\vec{D}(\vec{e}, e'n)p$
- $^3\vec{He}(\vec{e}, e'n)pp$




## AmPS experiment

- Internal gas target
- Vector polarised Deuterium

[Passchier et al., PRL **82** (1999) 4988]

## TJNAF Hall C experiment

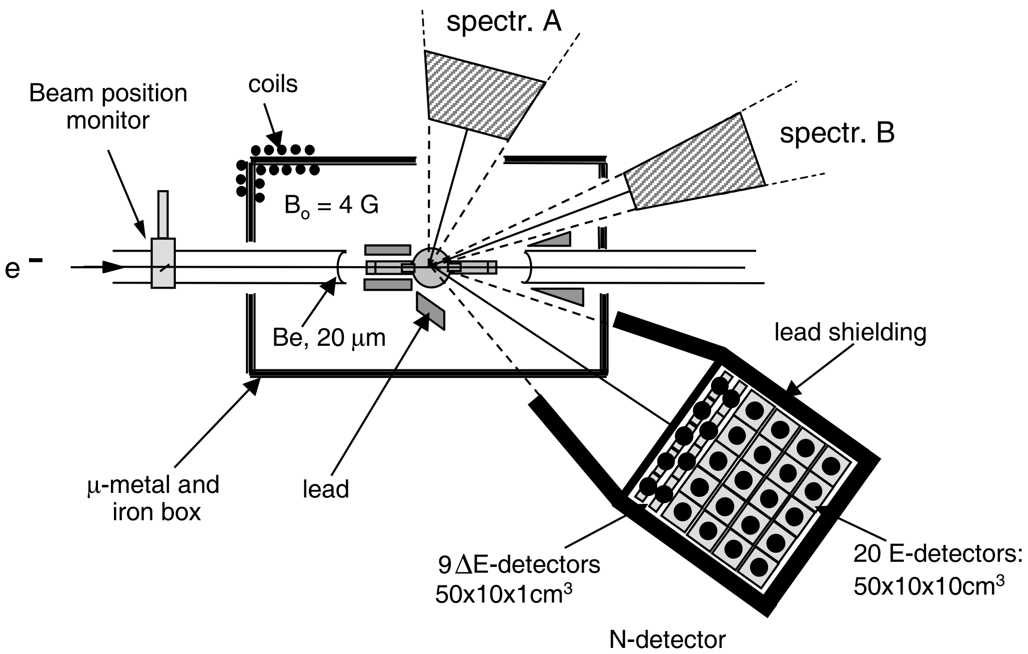
- Target: solid ammonia $^{15}ND_3$ at 1 K
- Dynamic nuclear polarisation
- 20 % target polarisation
- 100 nA beam current

[Zhu et al., PRL **87** (2001) 081801]

# Experiment $^3\vec{He}(\vec{e}, e'n)pp$ at MAMI

- $^3$He structure is dominated by $^4S_{1/2}$ state.
- Magnetic moment $\mu = -2.13\,\mu_N \approx \mu_n = -1.91\,\mu_N$
- Good polarised neutron target for moderate momenta $p_{miss}$

## Setup of the $^3\vec{He}(\vec{e}, e'n)pp$ experiment in the A1 hall:

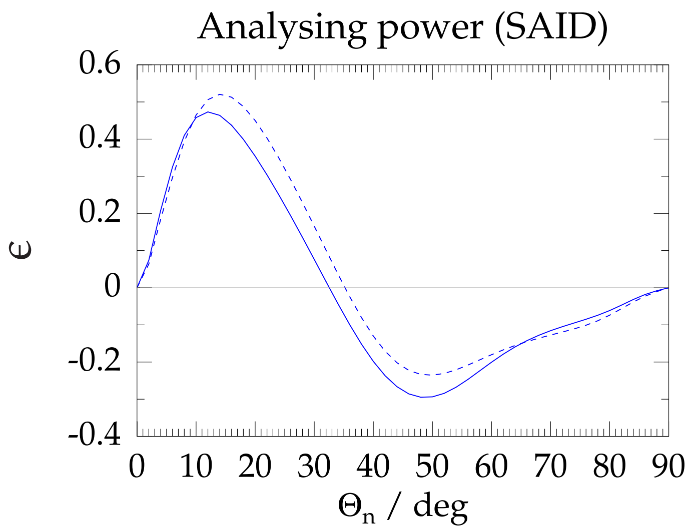



- Measurement of $A_{\|}/A_{\perp} \sim G_{En}/G_{Mn}$
- Electron beam, 10 μA current, $P_e = 80\,\%$
- Target: $^3\vec{He}$, $P_0 = 50\,\%$, relaxation time 33 hours

[Rohe et al., PRL **83** (1999) 4257]

# Neutron polarimetry

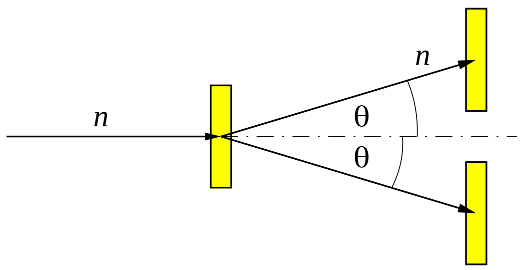
Elastic scattering of polarised neutrons at unpolarised protons has analysing power $\epsilon(\theta_n)$ due to spin-orbit term $V_{LS}$ in NN interaction:




This leads to a $\phi$ asymmetry for the outgoing neutron:

$$I(\theta_n) = I_0 \cdot [1 + \epsilon(\theta_n)(P_x \cos\phi_n + \underbrace{P_y \sin\phi_n}_{=0})]$$

- Analysing reaction $p(n, n'p)$ in scintillation detector
- Detection of outgoing neutron (or proton) in second scintillator

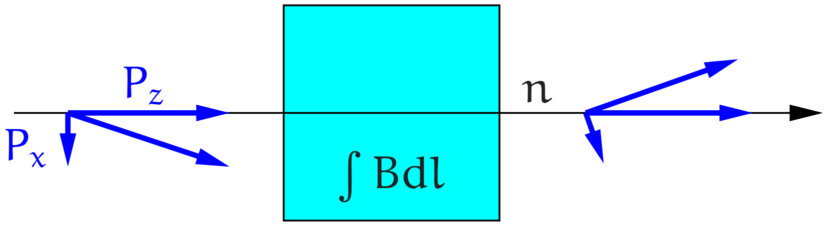



Problem: Also reactions $^{12}C(n, n'p)$ in scintillator with unknown analysing power.

Effective analysing power has to be calibrated!

# Spin precession method

Calibration of the analysing power can be avoided by rotating the neutron spin direction in the $xz$ plane:




Precession angle (from BMT equation):

$$\chi = \frac{2\mu_n}{\hbar c} \cdot \beta_n^{-1} \int Bdl = \frac{-35.02^\circ}{\text{Tm}} \cdot \beta_n^{-1} \int Bdl$$

Transverse polarisation (and therefore asymmetry) after the magnet:

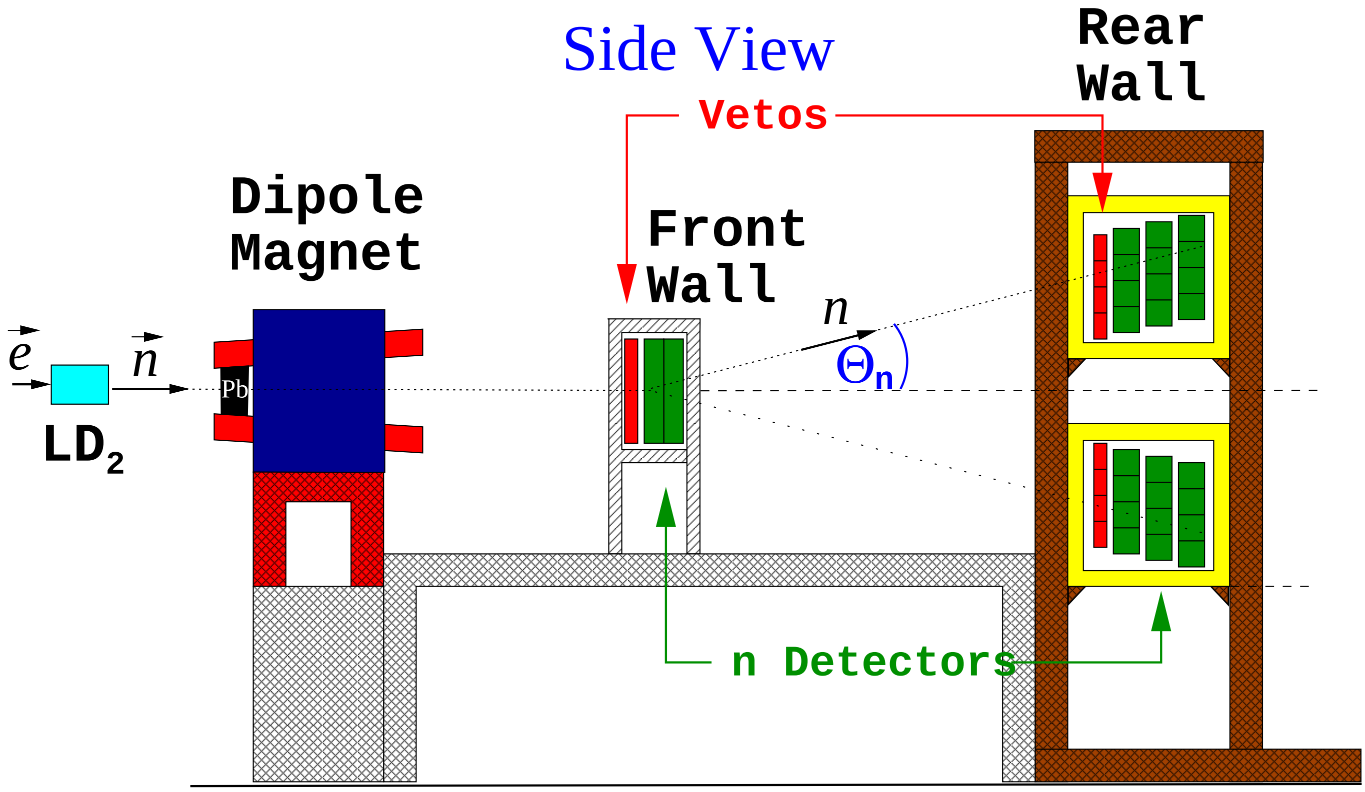
$$P_\perp = P_x \cos\chi - P_z \sin\chi$$

The zero crossing angle $\chi_0$ with asymmetry $A_\perp(\chi_0) = 0$ is determined by the ratio $A_x/A_z$:

$$\tan\chi_0 = \frac{A_x}{A_z} = \frac{P_e \epsilon_{\text{eff}}}{P_e \epsilon_{\text{eff}}} \cdot \frac{-1}{\sqrt{\tau + \tau(1+\tau)\tan^2(\theta/2)}} \cdot \frac{G_{En}}{G_{Mn}}$$

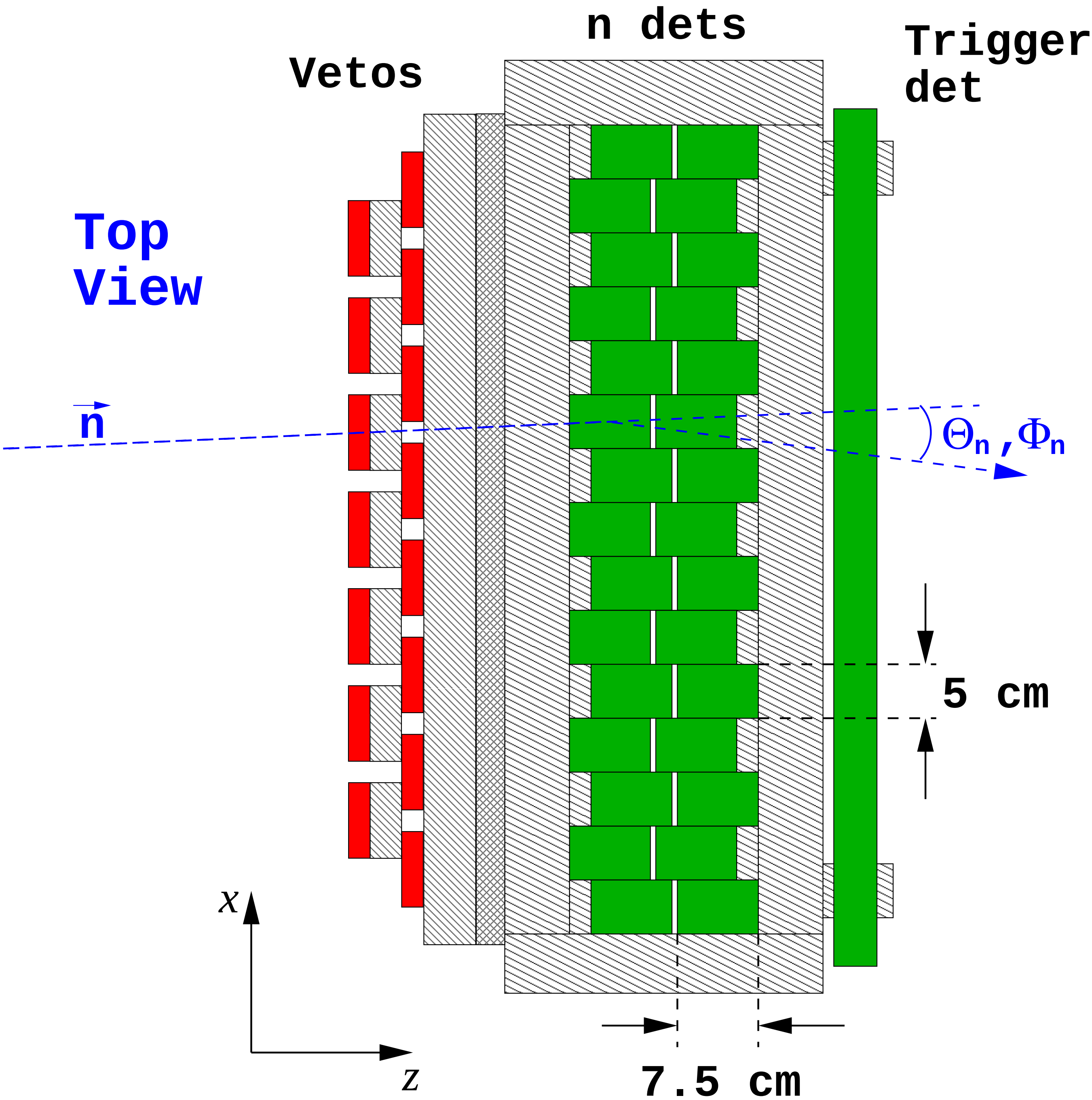
independent of the effective analysing power $\epsilon_{\text{eff}}$.

# Setup of the A1 neutron polarimeter

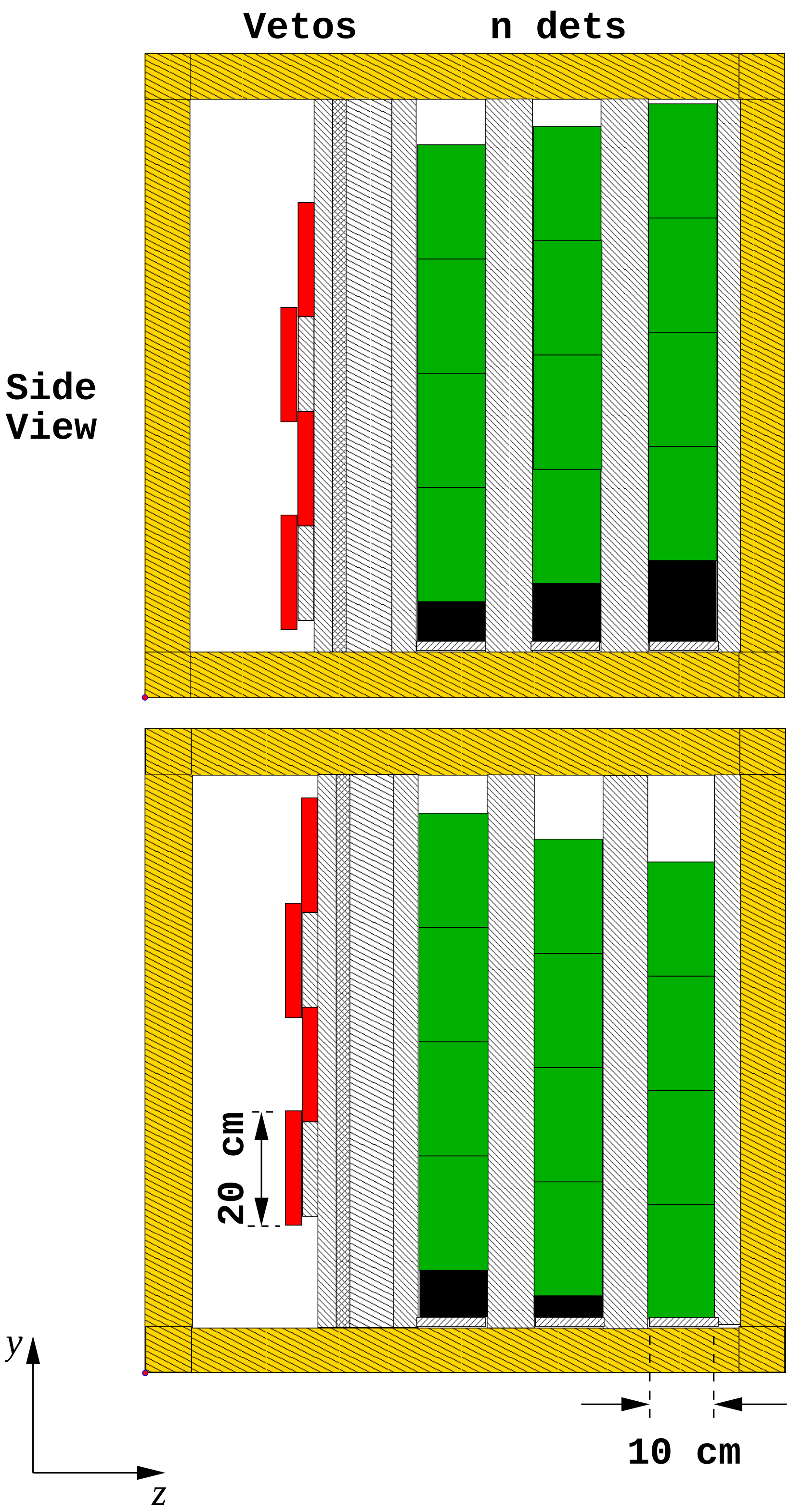



- Front wall: 30 scintillators $80 \times 5 \times 7.5\,\mathrm{cm}^3$
- Rear wall: 24 scintillators $180 \times 20 \times 10\,\mathrm{cm}^3$ (with gap at height of beam)
- 5 cm lead shielding in magnet gap
- Veto scintillators and Al shielding in front of each wall

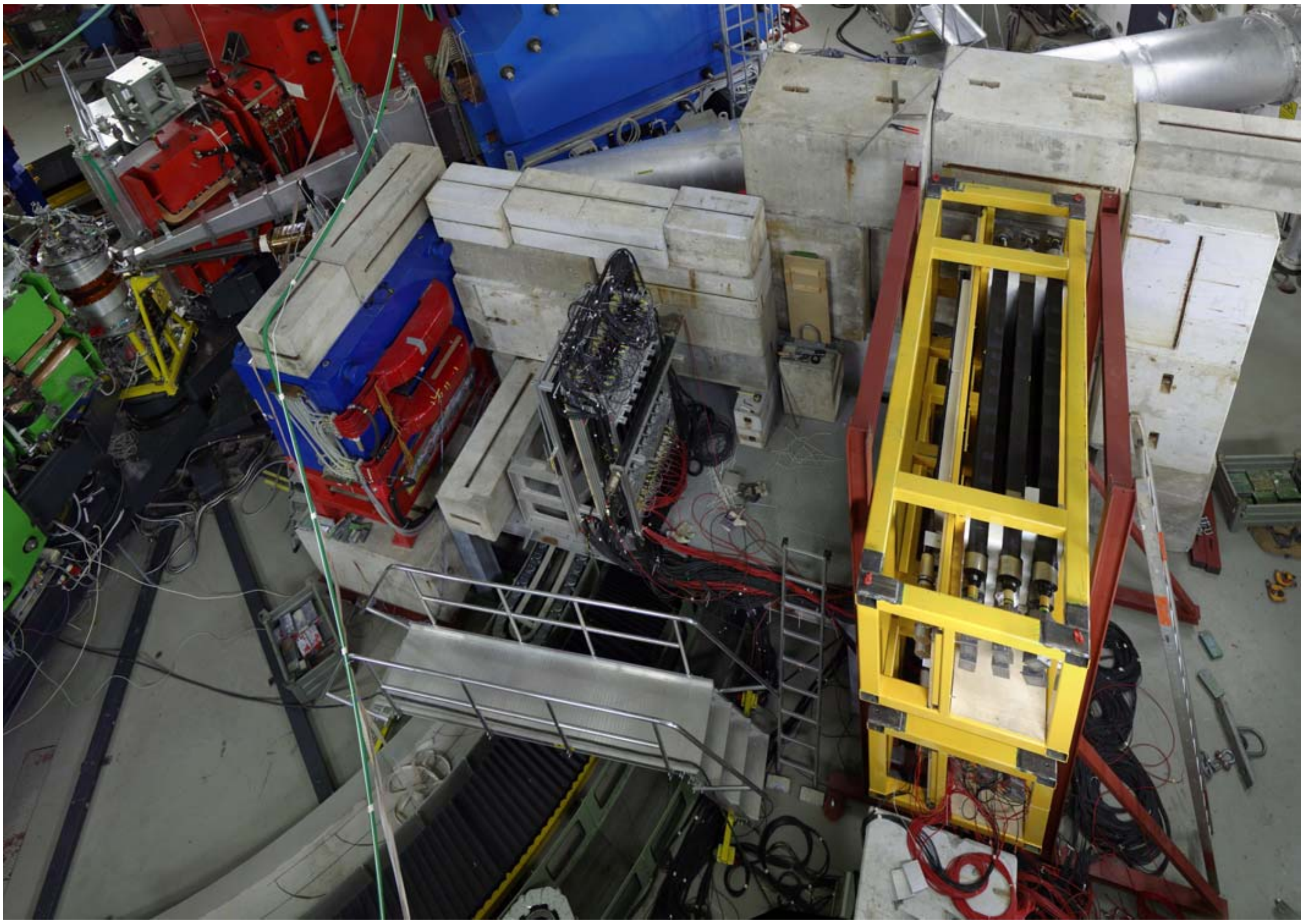
# Setup of first detector wall



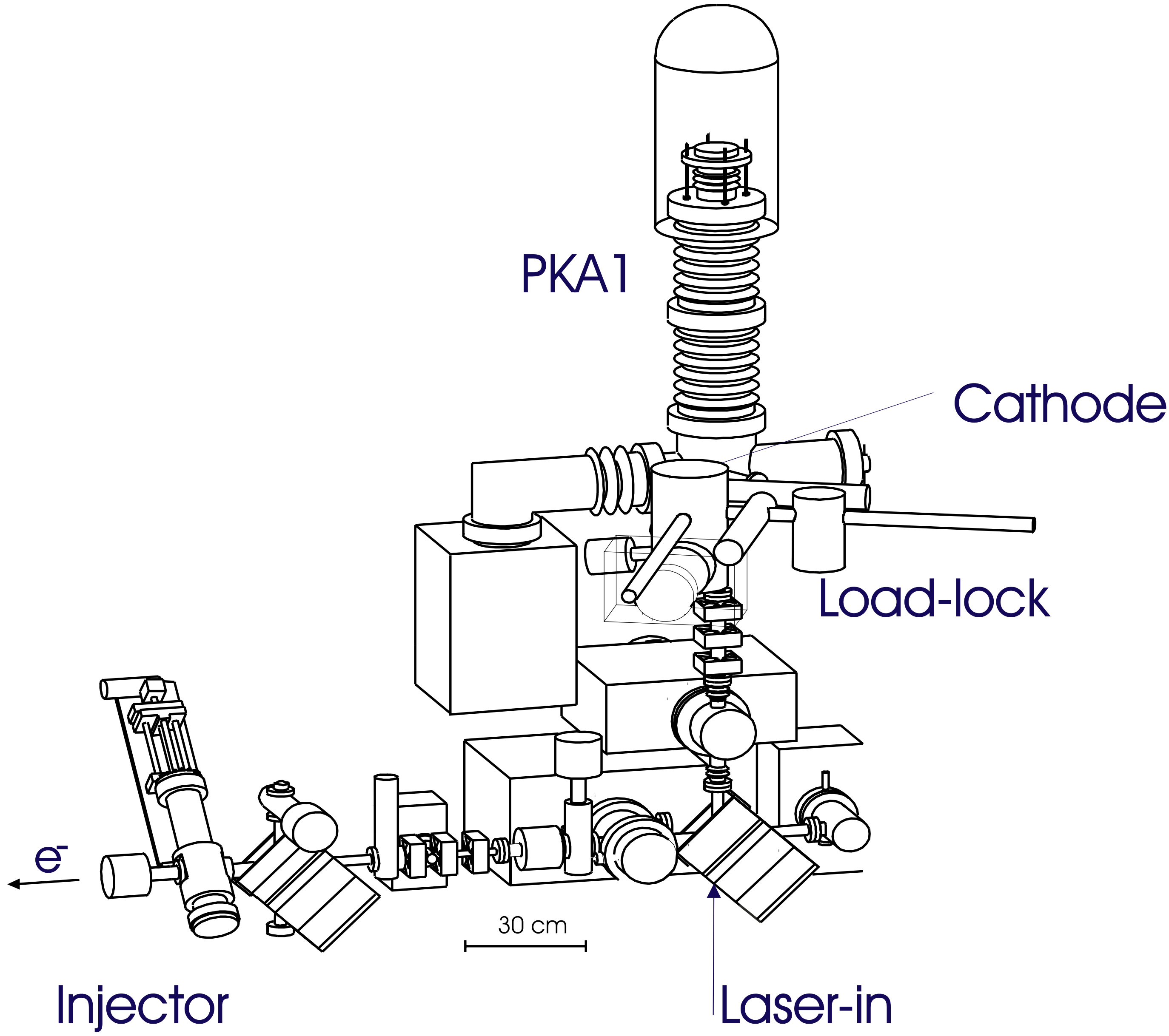
# Setup of second detector wall



# Setup in the A1 spectrometer hall



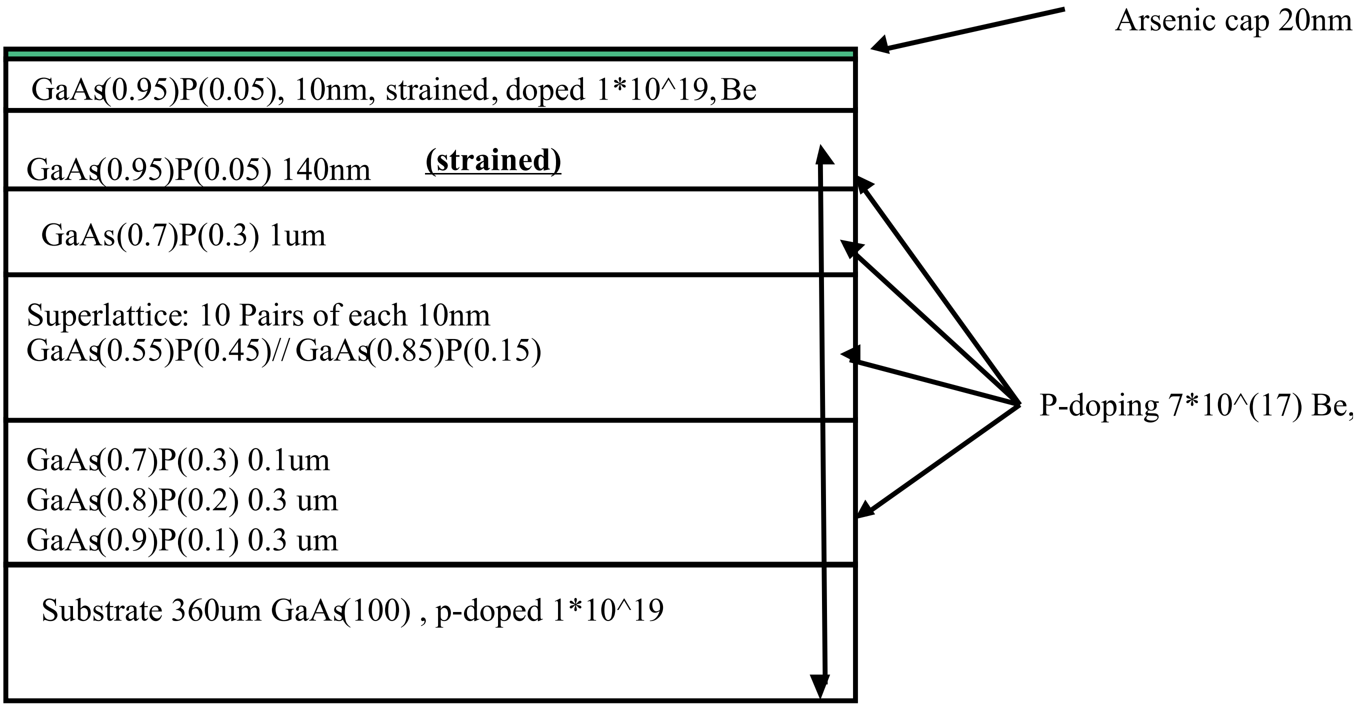
# Polarised electron source




Polarized electron source Installation
at the injector of MAMI

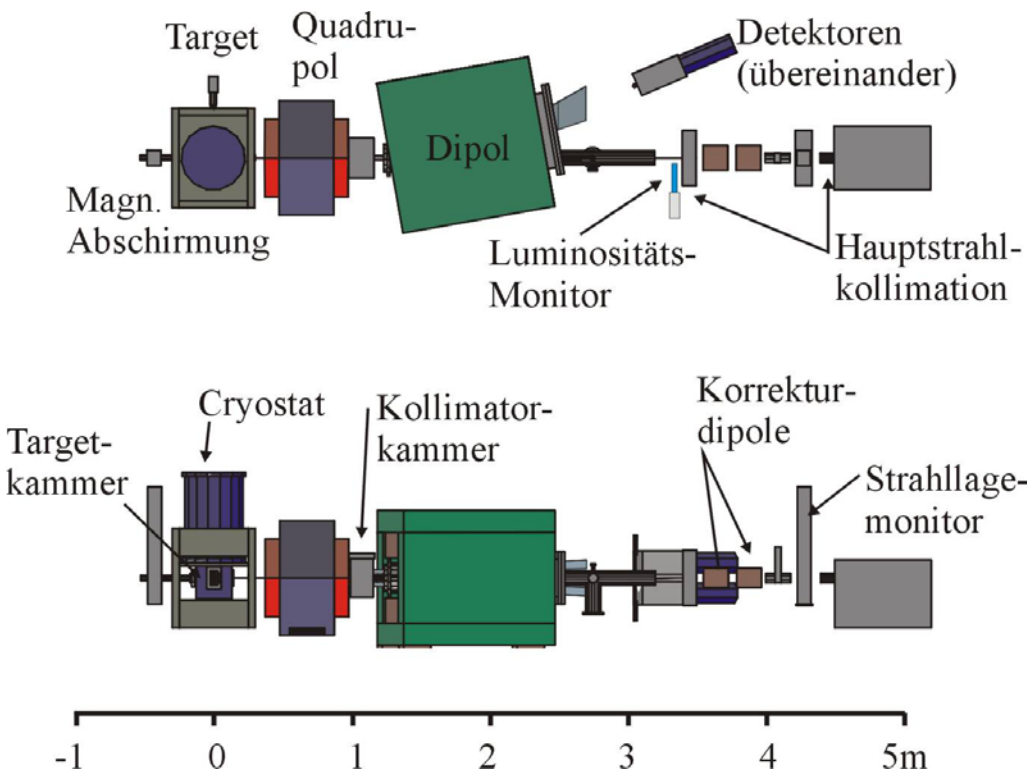
# Polarised electron source

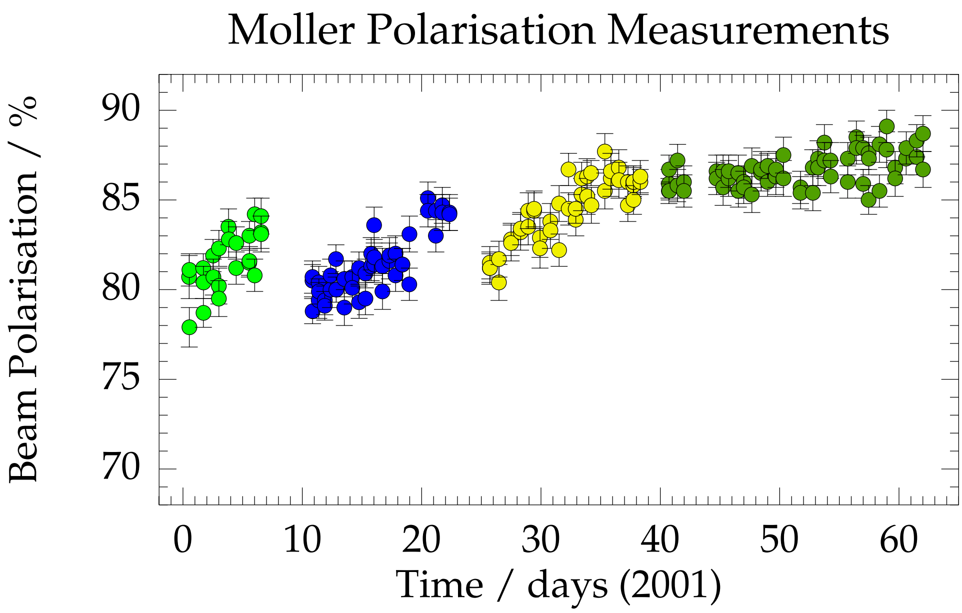
Modulation doped strained layer cathode, developed for KPH Mainz at Joffe Institute St. Petersburg




- Continuous improvement since 1996
- $P = 78\text{–}85\,\%$ (measured with Møller polarimeter), Q. E. dependent
- Quantum efficiency max. 0.7 %
- Operation testet up to 250 µA (0.5 A/cm$^2$) DC
- Different operating wavelengths available, presently 825 nm
- Continuous emission of 40 Coulomb of highly polarised electrons possible, e. g. 3 weeks at 15 µA

# Møller polarimeter



# Kinematics and data taking

## Kinematics

| $Q^2$ | $E$ | $E'$ | $\theta_{e'}$ | $T_n$ | $\theta_n$ |
|---|---|---|---|---|---|
| $(GeV/c)^2$ | MeV | MeV | | MeV | |
| 0.3 | 660 | 497 | 57° | 159 | 47° |
| 0.6 | 855 | 533 | 70° | 319 | 37° |
| 0.8 | 883 | 454 | 90° | 427 | 27° |

## Data taking periods

| | | |
|---|---|---|
| 0.6 $(GeV/c)^2$ | 16 days | Febr. – March 2001 |
| 0.8 $(GeV/c)^2$ | 45 days | April – June 2001 |
| | | and May – June 2002 |
| 0.3 $(GeV/c)^2$ | 19 days | June – Aug. 2002 |

Number of good events $\geq$ 400000 for each $Q^2$ setting

Additional periods for setup, calibration, elastic $p(e, e'p)$

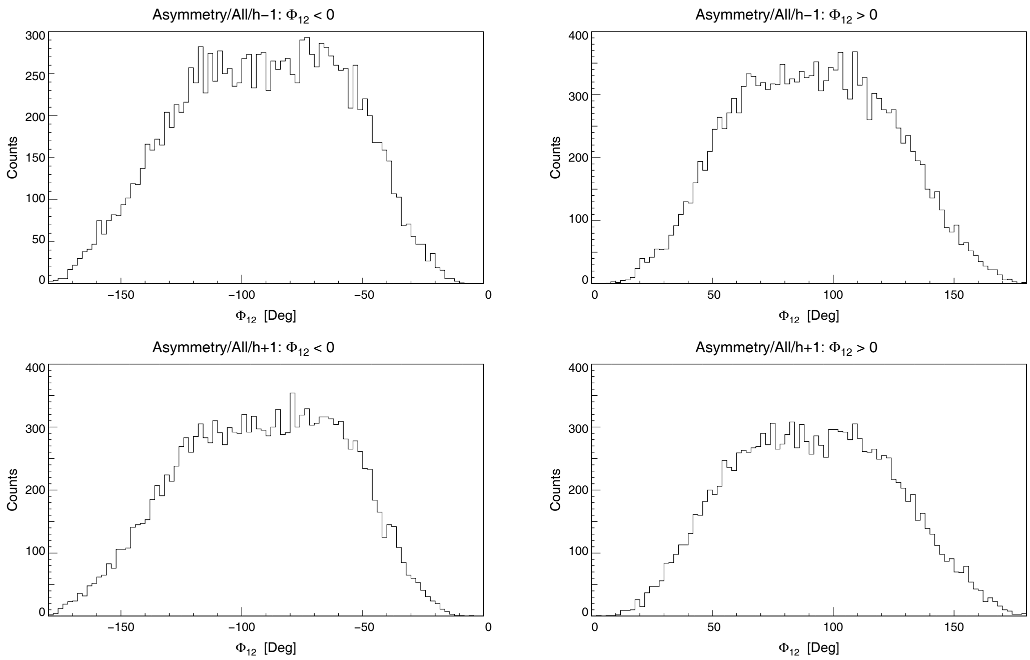
# Data analysis

Analysis proceeds through the following main steps:

- Identification and momentum reconstruction of electron in Spectrometer A
- Scintillator hit pattern and veto information in polarimeter
- Measurement of pulse height and time of flight
- Identification of quasielastic $D(\vec{e}, e'\vec{n})p$ events

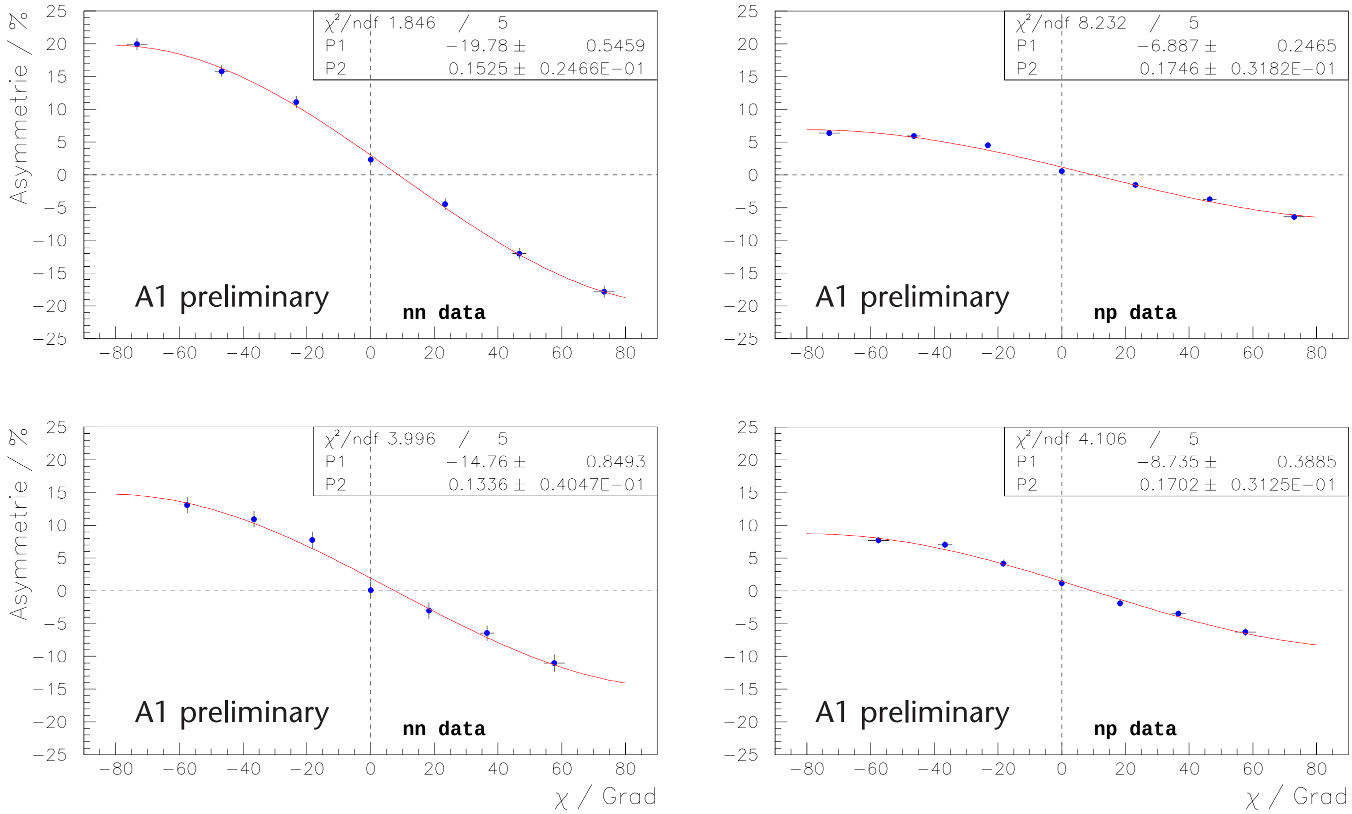
Two statistically independent samples of events:

- "$nn$ events": neutron detected in rear wall
- "$np$ events": proton detected in rear wall



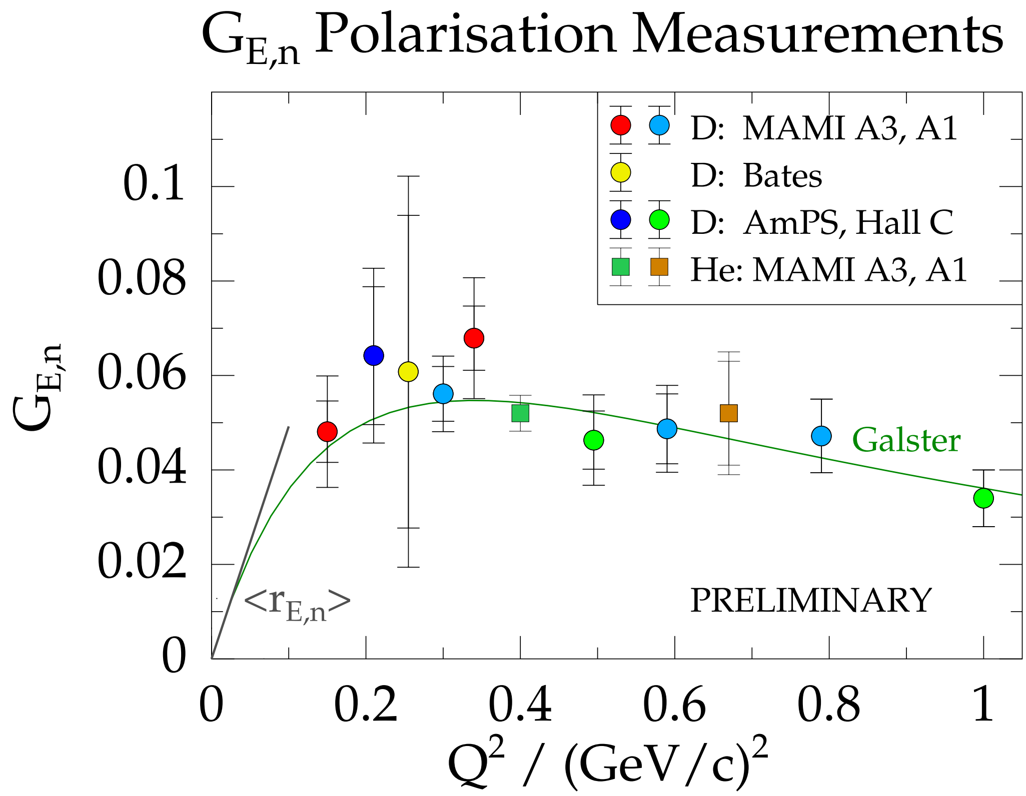
# Measured asymmetries

$Q^2 = 0.3\,(\mathrm{GeV}/c)^2$ $\qquad$ $Q^2 = 0.6\,(\mathrm{GeV}/c)^2$




$$A = \frac{\sqrt{N^+(\phi_n)\cdot N^-(\phi_n+\pi)} - \sqrt{N^+(\phi_n+\pi)\cdot N^-(\phi_n)}}{\sqrt{N^+(\phi_n)\cdot N^-(\phi_n+\pi)} + \sqrt{N^+(\phi_n+\pi)\cdot N^-(\phi_n)}}$$

# World data on $G_{En}$




All data up to $Q^2 = 0.5\,(\mathrm{GeV}/c)^2$ have been corrected for final state interaction.

$D(\vec{e}, e'\vec{n})p$

Bates: [Eden et al., PRC **50** (1994) R1749]

MAMI A3: [Herberg et al., EPJA **5** (1999) 131]

MAMI A1: preliminary

$\vec{D}(\vec{e}, e'n)p$

AmPS: [Passchier et al., PRL **82** (1999) 4988]

Hall C: [Zhu et al., PRL **87** (2001) 081801]

$^3\vec{He}(\vec{e}, e'n)pp$

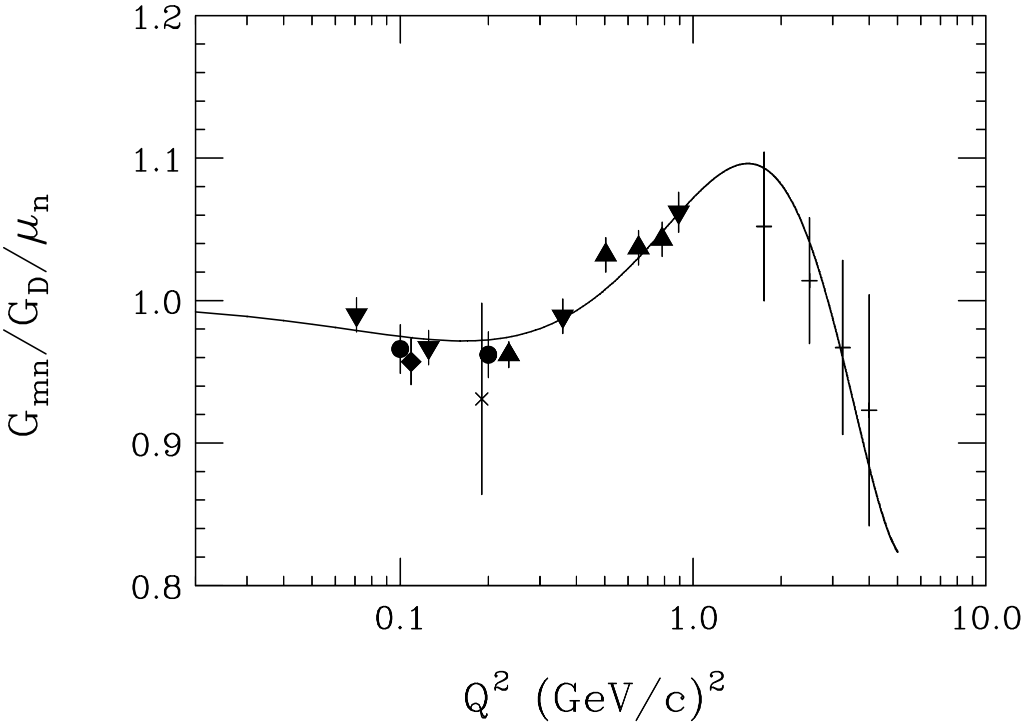
MAMI A3: [Becker et al., EPJA **6** (1999) 329]

MAMI A1: [Rohe et al., PRL **83** (1999) 4257]

# Normalisation of $G_{En}$ data

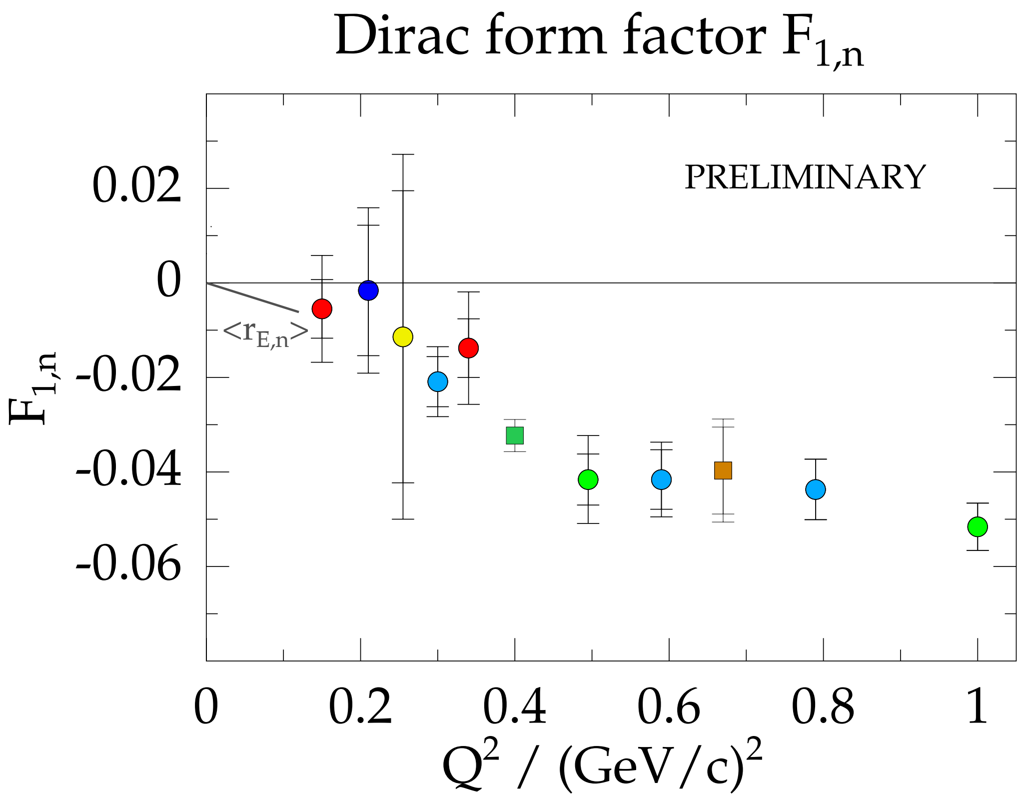
All $G_{En}$ data have been consistently normalised to the $G_{Mn}$ parameterisation by the A1 (Mainz/Basel) experiment.

[Kubon et al., PLB **524** (2002) 26]



# Dirac form factor $F_1^n$

$$F_1(Q^2) = \frac{G_E(Q^2) + \tau G_M(Q^2)}{1 + \tau}$$




Data points as on previous page

Errors are dominated by errors of $G_{En}$ measurements

# Summary

Measurement of the neutron electric form factor is an experimental challenge:

- $G_E^n \ll G_M^n$
- No neutron target

Double polarization experiments provide a model-independent way to measure $G_E^n$ and are sensitive to the $G_E^n \cdot G_M^n$ interference term.

- Polarized target experiments
  $\vec{D}(\vec{e}, e'n)p$ and $^3\vec{He}(\vec{e}, e'n)pp$
- Measurement of recoil polarization $D(\vec{e}, e'\vec{n})p$

Measurement of $G_E^n$ in A1 collaboration at $Q^2 = 0.3 \ldots 0.8\ (GeV/c)^2$ with recoil polarimetry.

- Preliminary results for 0.3, 0.6, and 0.8 $(GeV/c)^2$