Caucasian-German School and Workshop
on Hadron Physics

Polarisation Experiments in Storage Rings

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Introduction

Past ~15 years, tremendous progress in spin-physics experiments with polarized beams on internal targets

Near future exploitation at COSY

Experimental and theoretical developments pave the way to **Future Hadron Physics** programs at FAIR

- Hadronic Probes:
  - –IUCF-PINTEX:
    - Proton-Proton Elastic
    - NN → NNπ
    - Proton-Deuteron Elastic
  - –COSY
    - – EDDA:
      - •Proton-Proton Elastic
      - •Time-Reversal Invariance
    - – ANKE:
      - •Proton-Deuteron Breakup
      - •Proton-Neutron Elastic
    - – WASA:
      - -Parity of Θ+
  - –RHIC-SPIN
- Electromagnetic Probes:
  - –Bates-BLAST
  - –Novosibirsk-VEPP-3
  - –HERA-HERMES

Outline

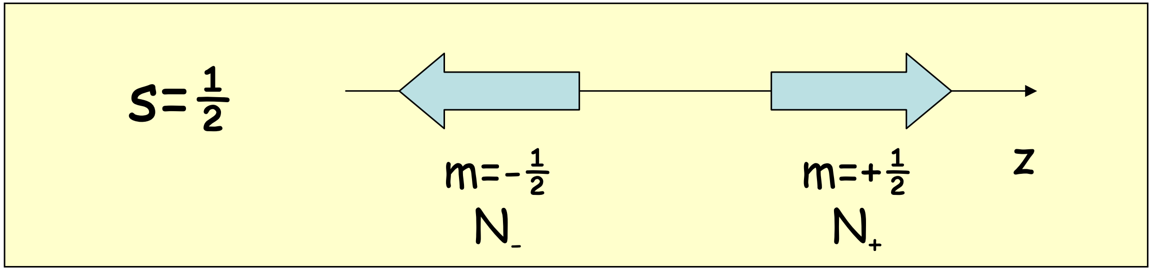
- Basics
- Medieval Warfare
  - Storage Rings and Internal Targets
- Polarimetry
  - Selected Experimental Results
- Production of Polarized Antiprotons
- Medical Application of Polarized Targets

Basics: Polarization

Spin $\vec{s}$: 2s+1 possible orientations along quantization axis z

- spin ½ → 2 orientations
- spin 1 → 3 orientations

magnetic quantum number $m=s_z$ (z-component in units of hbar)



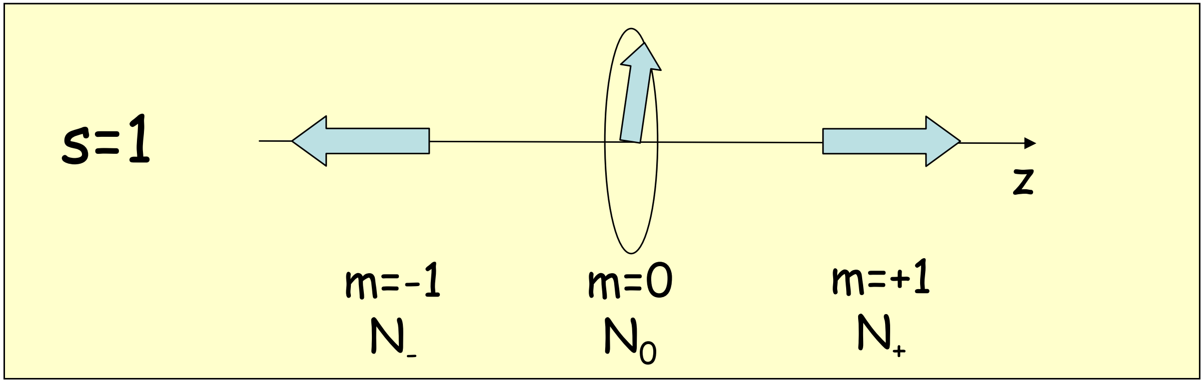
Two numbers N_- and N_+ fully characterize the beam.
Usually linear combinations are used:

Intensity $I = N_- + N_+$

Polarization $P_z = (N_+ - N_-)/(N_+ + N_-)$

$-1 \leq P_z \leq +1$

Basics: continued



Three numbers N_-, N_0 and N_+, or linear combinations:

Intensity $I = N_- + N_0 + N_+$

Vector Polarization $P_z = (N_+ - N_-)/(N_+ + N_0 + N_-)$

$-1 \leq P_z \leq +1$

Tensor Polarization $P_{zz} = (N_+ - 2 \cdot N_0 + N_-)/(N_+ + N_0 + N_-)$

$-2 \leq P_{zz} \leq +1$

Q: What is P_z if $P_{zz}=0$? A: $-2/3 \leq P_z \leq +2/3$

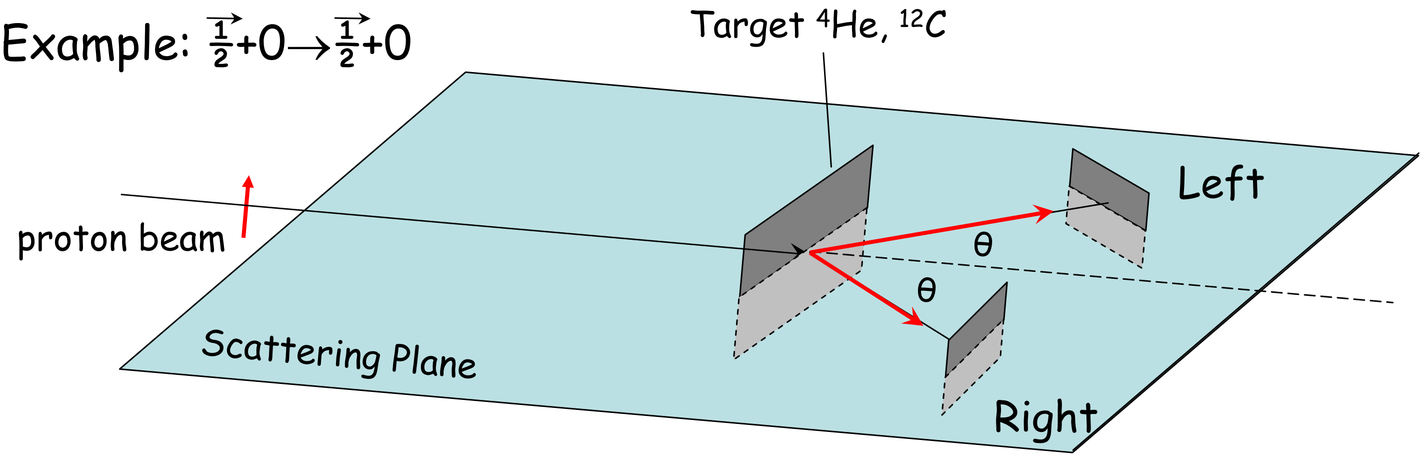
Basics: continued

$$P_{zz} = 0 \rightarrow N_+ - 2 \cdot N_0 = 0$$
$$\rightarrow N_+ = 2 \cdot N_0$$
$$\rightarrow P_z = (N_+ - N_-)/(N_+ + N_0 + N_-)$$
$$= 2 \cdot N_0/(2N_0 + N_0)$$
$$= +2/3$$

(other case analog)

Basics: A Polarization Experiment

Example: $\vec{\tfrac{1}{2}}+0 \rightarrow \vec{\tfrac{1}{2}}+0$



Experiment measures "asymmetry"

$$\varepsilon = P_y \cdot A_y = \frac{N_L - N_R}{N_L + N_R}$$

Analyzing Power $A_y(\theta,E)$

Beam Polarization

Approximation $N_L \sim N_R \sim N$

$$\Delta A_y = \frac{1}{P \cdot \sqrt{2 \cdot N}} \sim \frac{1}{P \cdot \sqrt{I}}$$

ΔA_y=0.1	N(~t)
P=1	50
P=½	200

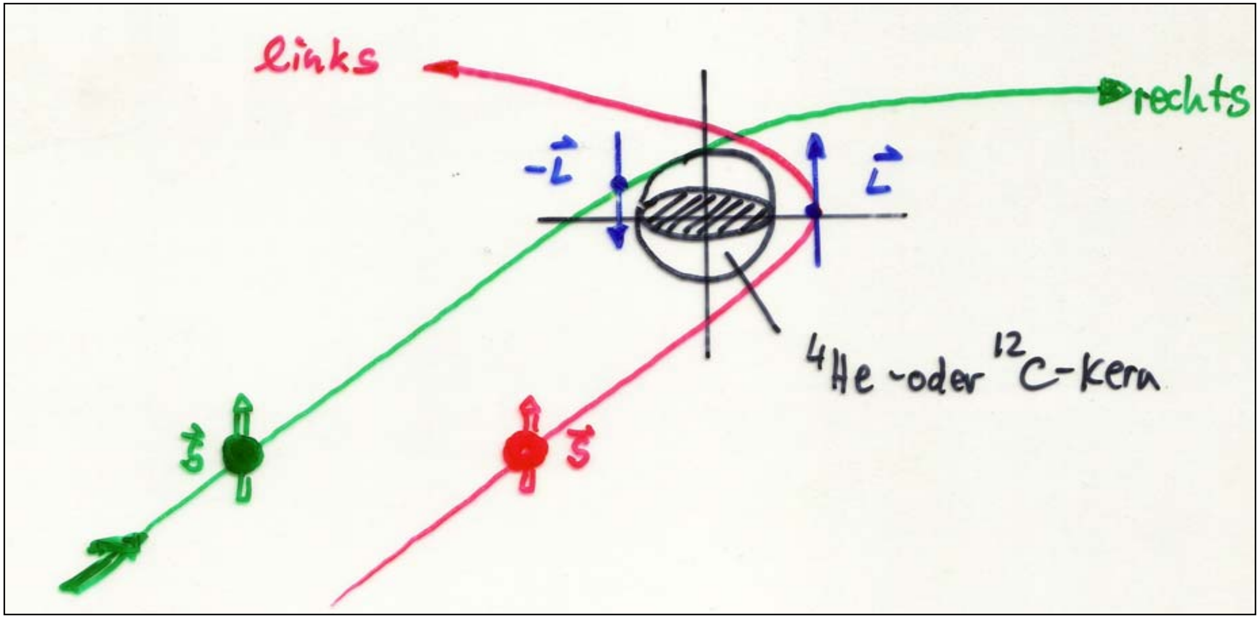
$\rightarrow$ FOM=$P^2 \cdot I$

Basics: Spin-dependence of NN interaction

Description of Interaction between Nucleons requires spin-orbit term in the NN potential

$V_{LS}(r)(\vec{L}\cdot\vec{S})$

$\vec{L} = \vec{r} \times \vec{p}$



→ Left-Right Asymmetry ⊥ to scattering plane

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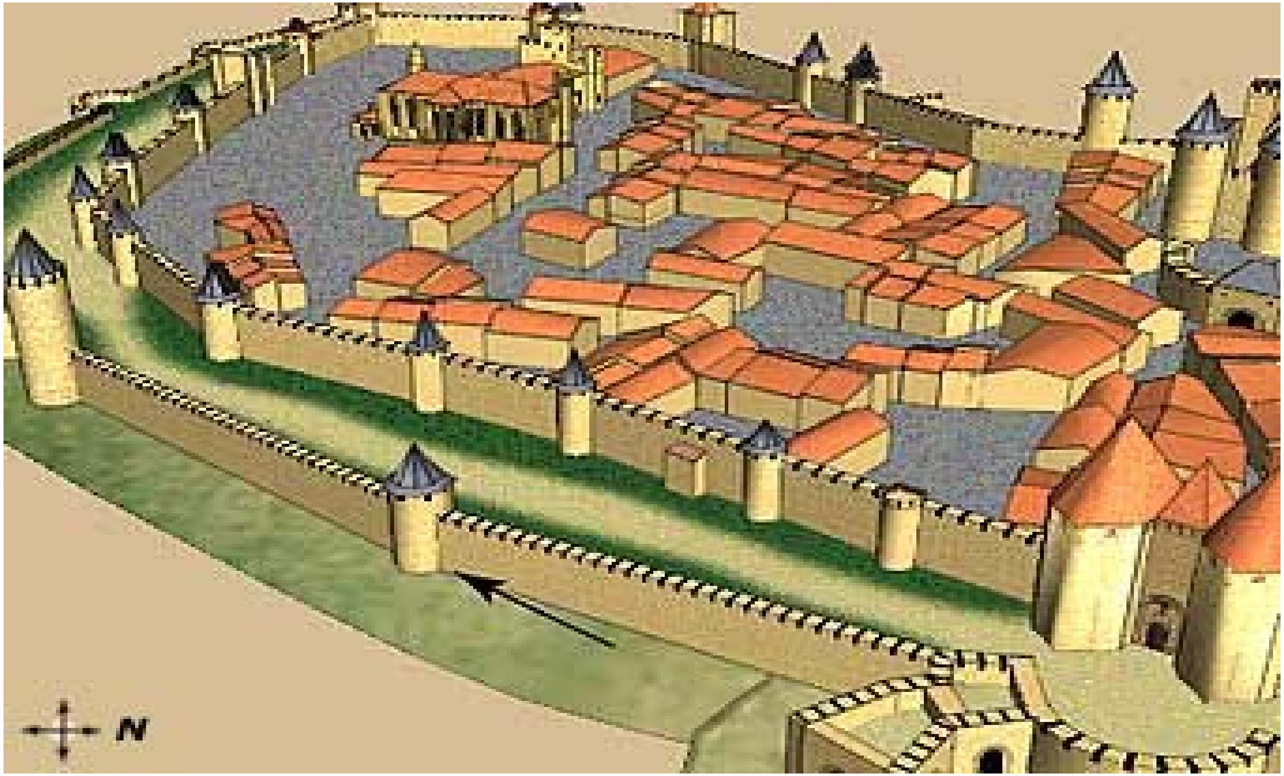
Carcassonne

South of France, between Toulouse and the Mediteranian

Carcassonne

Philippe III (the Strong) built the fortress (1270-1285).



Medieval Warfare

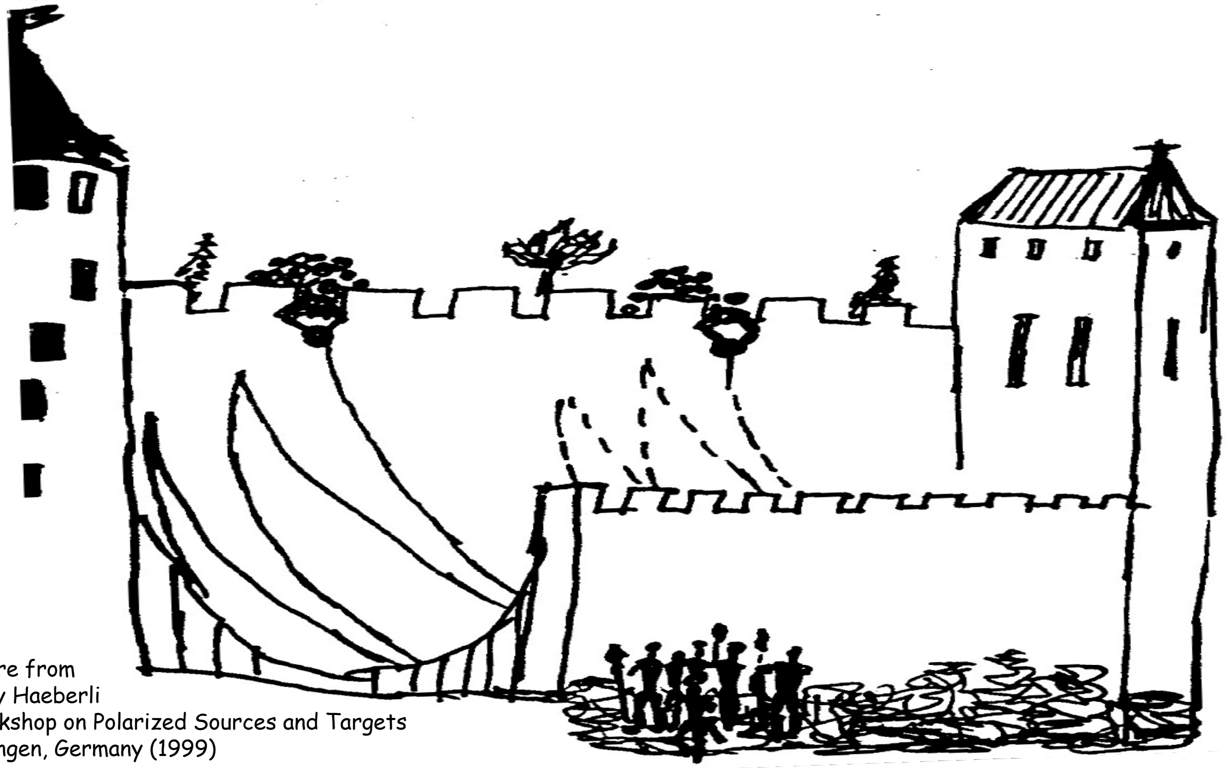
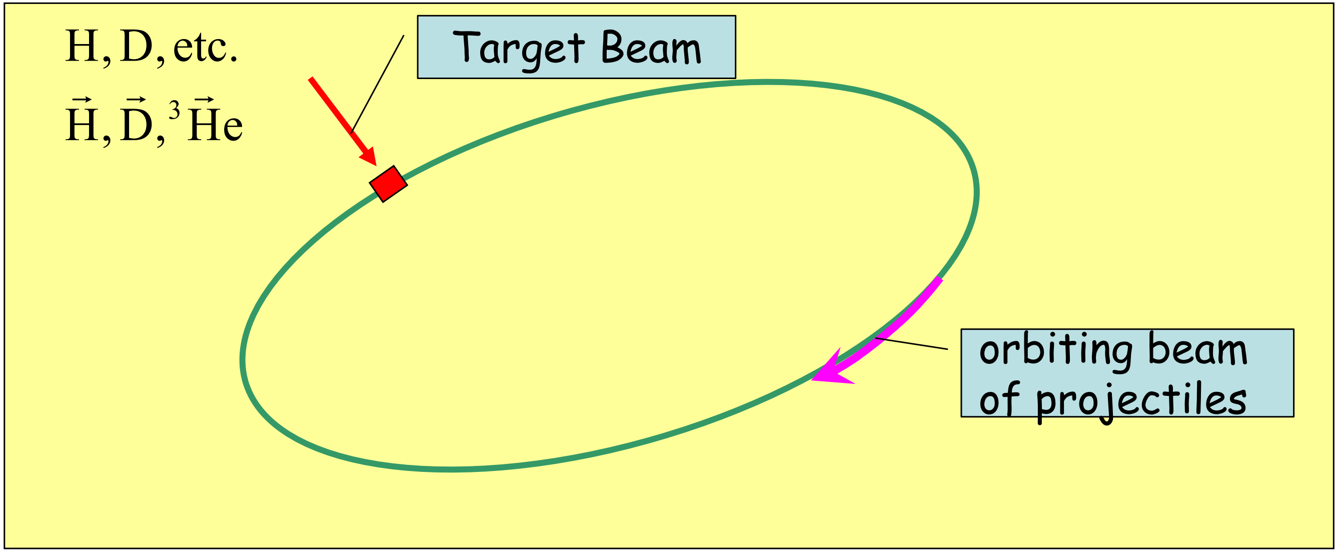


Figure from
Willy Haeberli
Workshop on Polarized Sources and Targets
Erlangen, Germany (1999)

Multiple use of a projectile oscillating in a potential well.

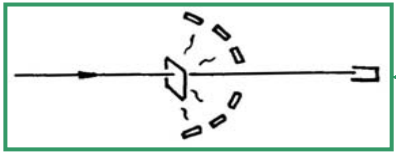
Internal Target in a Storage Ring



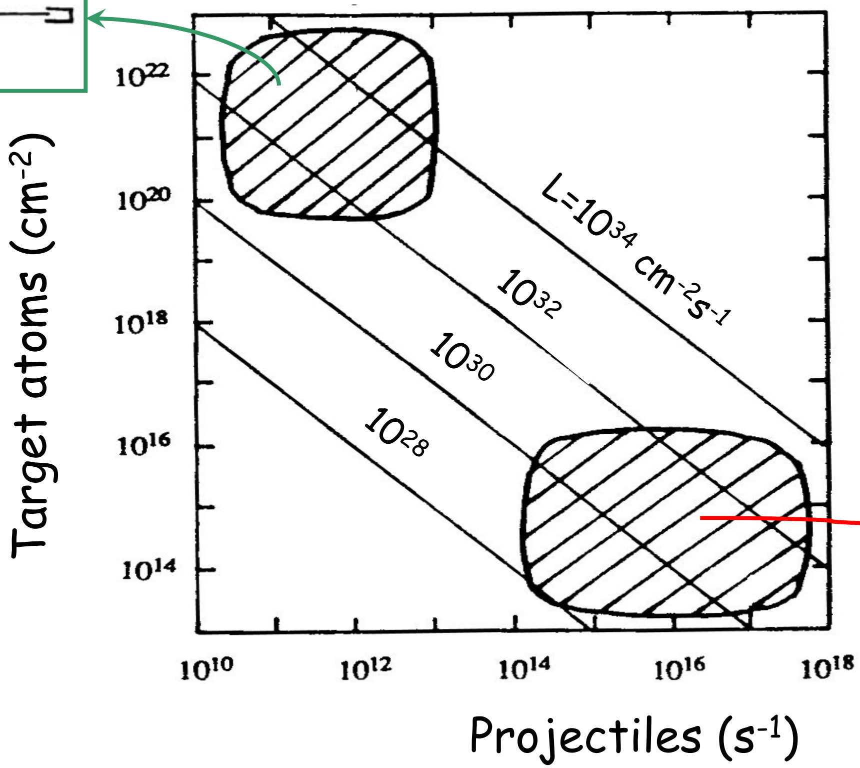
Storage Ring: Re-usable Projectiles
Carcassonne application (type 1)

External vs Internal

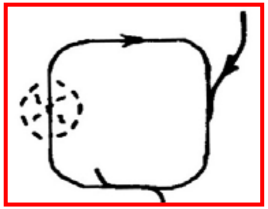
New approach (~15 years) to scattering experiments



$L = I_{beam} \cdot d_t$



$L = N_{stored} \cdot f_{rev} \cdot d_t$



Example: Parity of Θ^+ Pentaquark

Double polarization experiment fixes parity of Θ^+ free of any model!

Spin-correlation coefficient A_{xx} in $\vec{p}\vec{p} \rightarrow \Theta^+\Sigma^+$

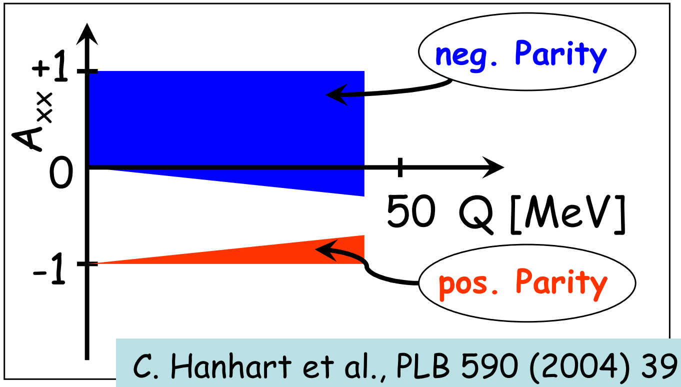
TOF-COSY with a NH_3 polarized target

d_t=0.93g/cm³·0.8cm =0.74g/cm² =3.7·10²³nucl./cm²

$d_t = 0.93\,g/cm^3 \cdot 0.8\,cm = 0.74\,g/cm^2 = 3.7\cdot10^{23}\,nucl./cm^2$

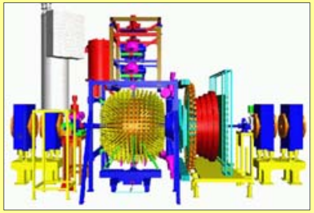
$I = 5\cdot10^6\,s^{-1}$

$FOM = (3/17\cdot0.6)^2\cdot d_t\cdot I = 2.1\cdot10^{28}\,cm^{-2}s^{-1}$



C. Hanhart et al., PLB 590 (2004) 39

WASA-COSY with a polarized gas target



$d_{t,Jet} = 10^{12}\,nucl./cm^2$

$d_{t,Cell} = 5\cdot10^{13}\,nucl./cm^2$

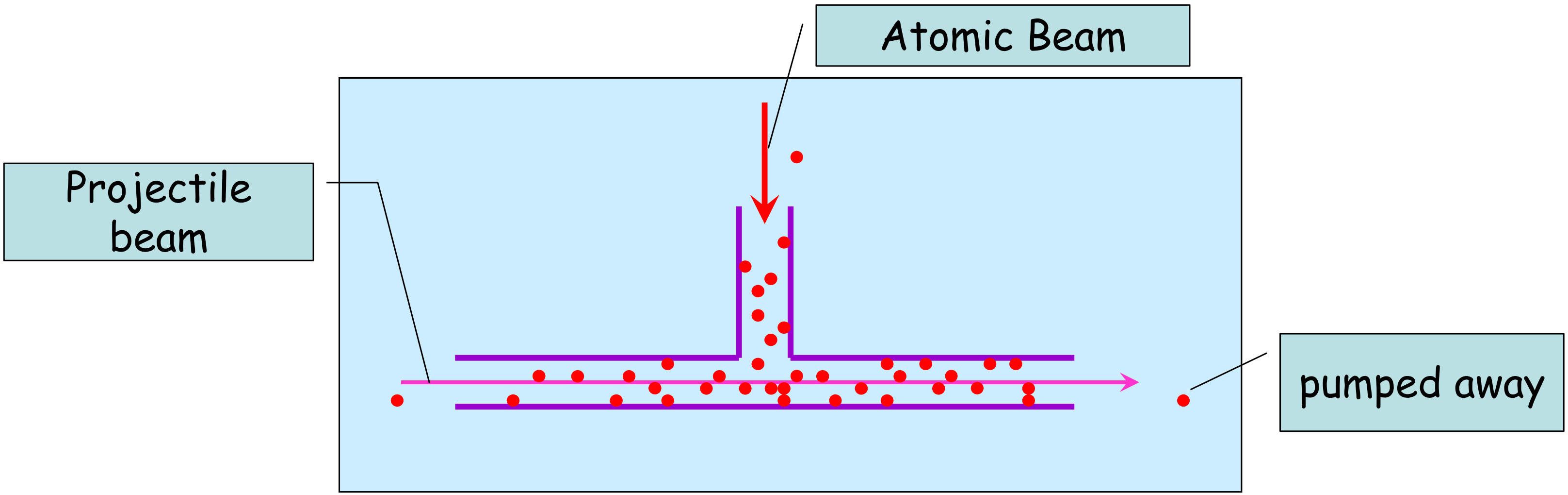
$I = 5\cdot10^{10}\cdot1.6\cdot10^6\,s^{-1}$

$FOM_{Jet} = (0.8)^2\cdot d_{t,Jet}\cdot I = 5\cdot10^{28}\,cm^{-2}s^{-1}$

$FOM_{Cell} = 2.5\cdot10^{30}\,cm^{-2}s^{-1}$

3-120 x shorter measurement time

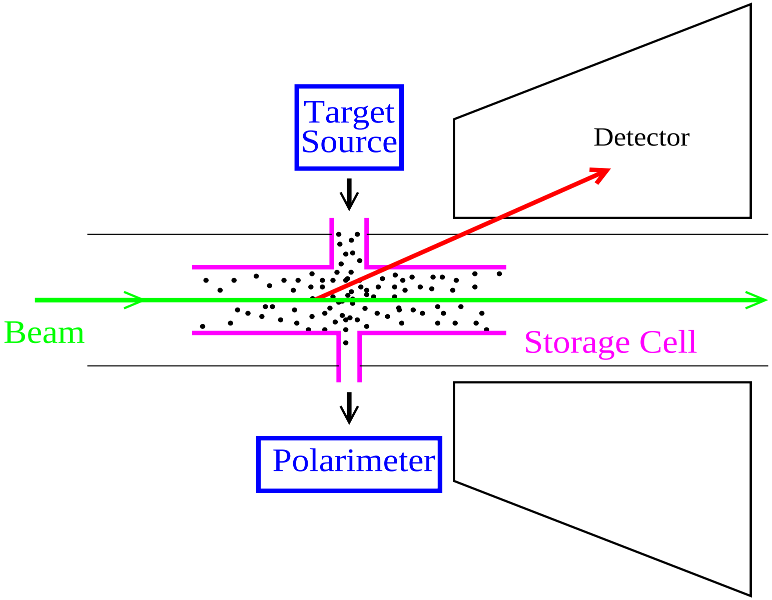
Polarized Storage Cell Target



After wall collisions, atoms can intercept beam again.

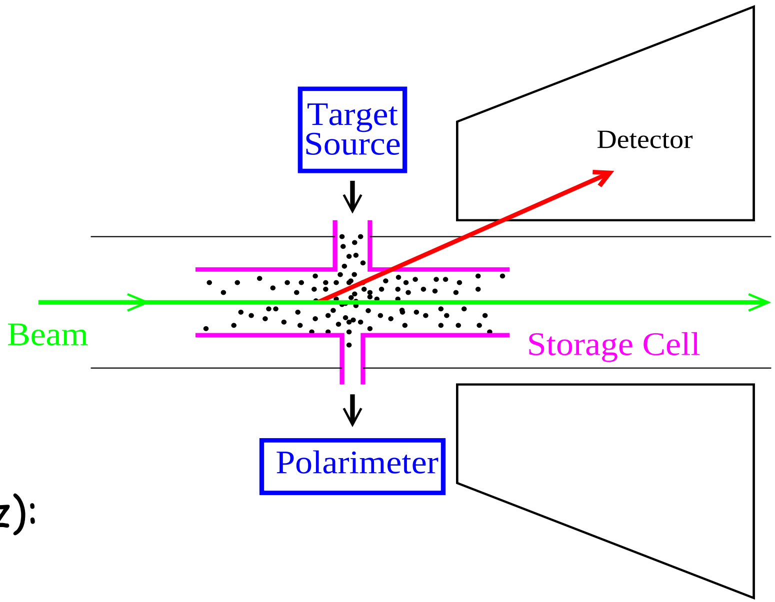
Cell Target: Re-usable target atoms
Carcassonne application (type 2)

Principle of a polarized internal target



Interaction Region				
point-like	5-10 mm	free jet	low density	10^{12} cm^{-2}
extended	200-500 mm	storage cell	high density	10^{14} cm^{-2}

Principle of a polarized internal target



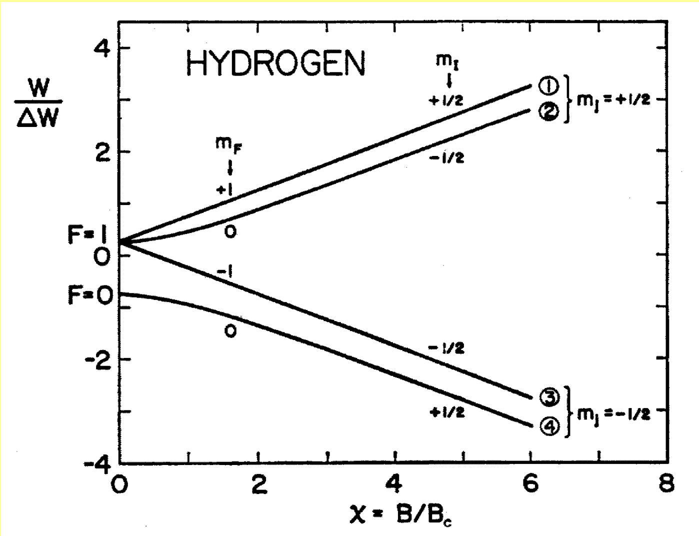
Distinct advantages over solid or high pressure targets:

- rapid reversal of target spin (x,y,z):
  In H/D up to 100 Hz achieved
- isotopically pure, no contamination by unpolarized components in the target
- low background due to absence of container walls
- no radiation damage, target gas replenished every few ms

$\Rightarrow$ **Ideally suited for high precision experiments**

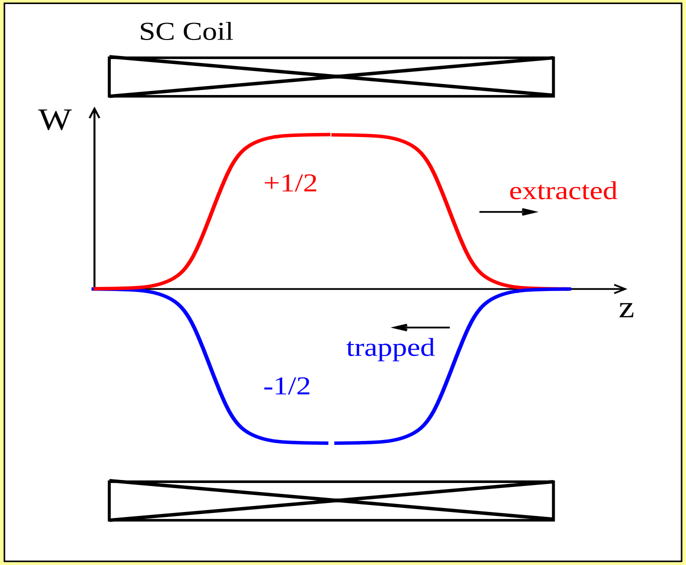
Four main types of sources for PIT's

① Atomic beam source



Atoms with $m_j=+\frac{1}{2}$ focused in sextupole magnets. RF transitions select HFS.

② Ultra-cold source

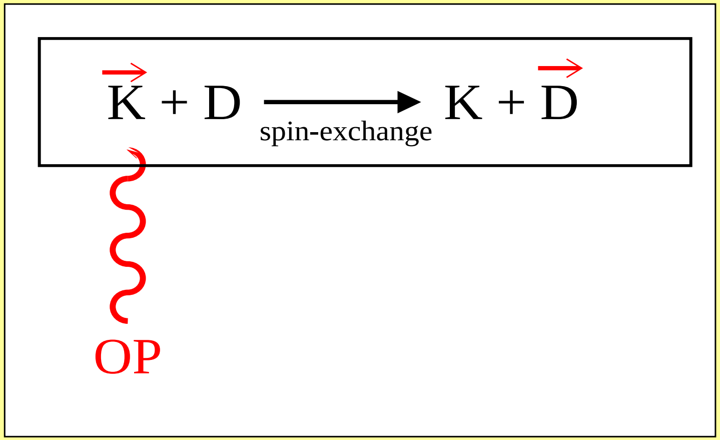


$W_{thermal} << W_{magnetic}$

One electron spin state $m_j=\frac{1}{2}$ extracted from strong solenoid field and focused

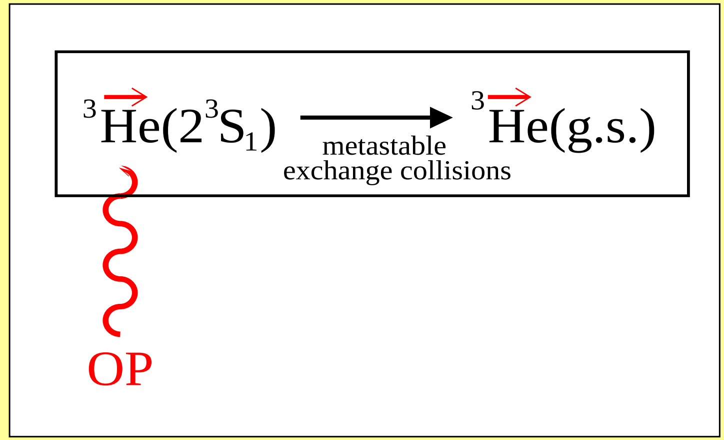
Main types of sources (cont'd)

③ Spin-Exchange source



Deuterium or Hydrogen atoms polarized by spin-exchange with optically pumped potassium vapor

④ ^{3}He source



Small fraction of metastable ^{3}He ($2^{3}S_{1}$) atoms pumped with laser optical pumping. Ground state atoms polarized via exchange collisions

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- **Polarimetry**
  - Selected Experimental Results
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Polarimetry of PIT's

Three different approaches are distinguished:

I. Calibration by a known reaction

- FILTEX test (αp scattering)
- pp elastic scattering (PINTEX at IUCF)

II. Ion extraction

- NIKHEF Ion extraction polarimeter

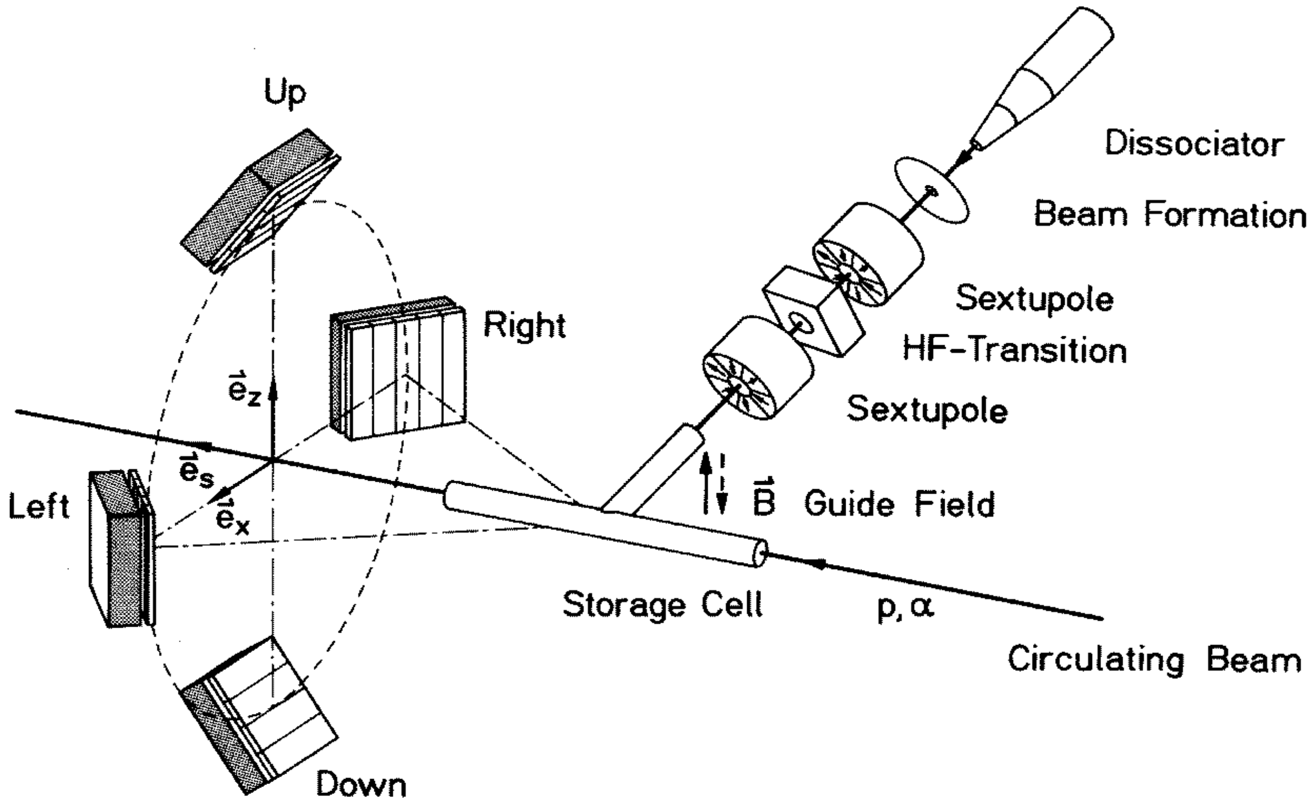
III. Neutral gas extraction

- Breit-Rabi Polarimeter for HERMES
- Lamb-shift Polarimeter for ANKE

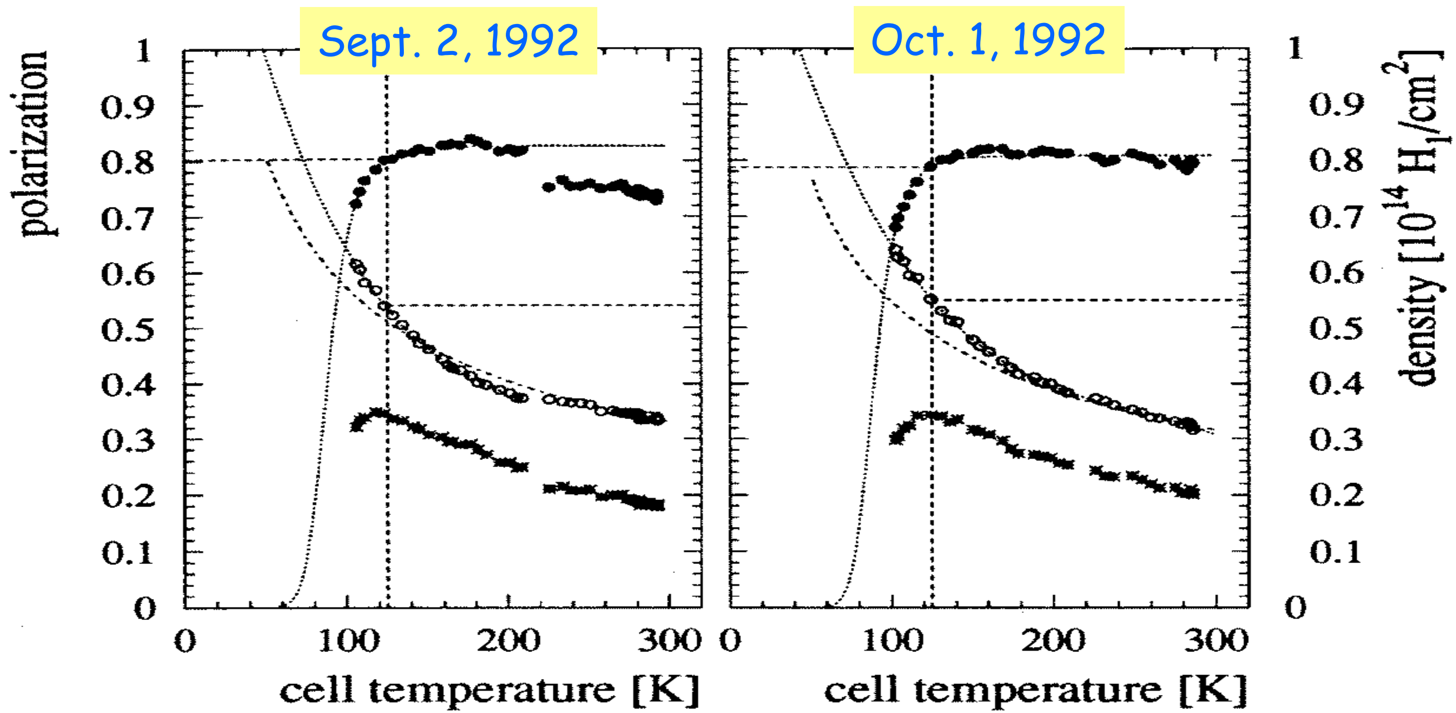
Method I does not distinguish atoms from molecules or any other material in the target ⇒ **1st choice** where applicable

Methods II and III measure the polarization of atoms in the target, with additional instrumentation also the degree of dissociation in the target
but: Molecules dilute the polarization!
and: What is the polarization of the molecules? (→ Talk by H. Seyfarth)

Ex. 1: αp scattering at 27 MeV



FILTEX Results



T_{opt} = 125 K

P = 0.80 ± 0.02

d_t = (5.4 ± 0.3)·10^{13} 1/cm²

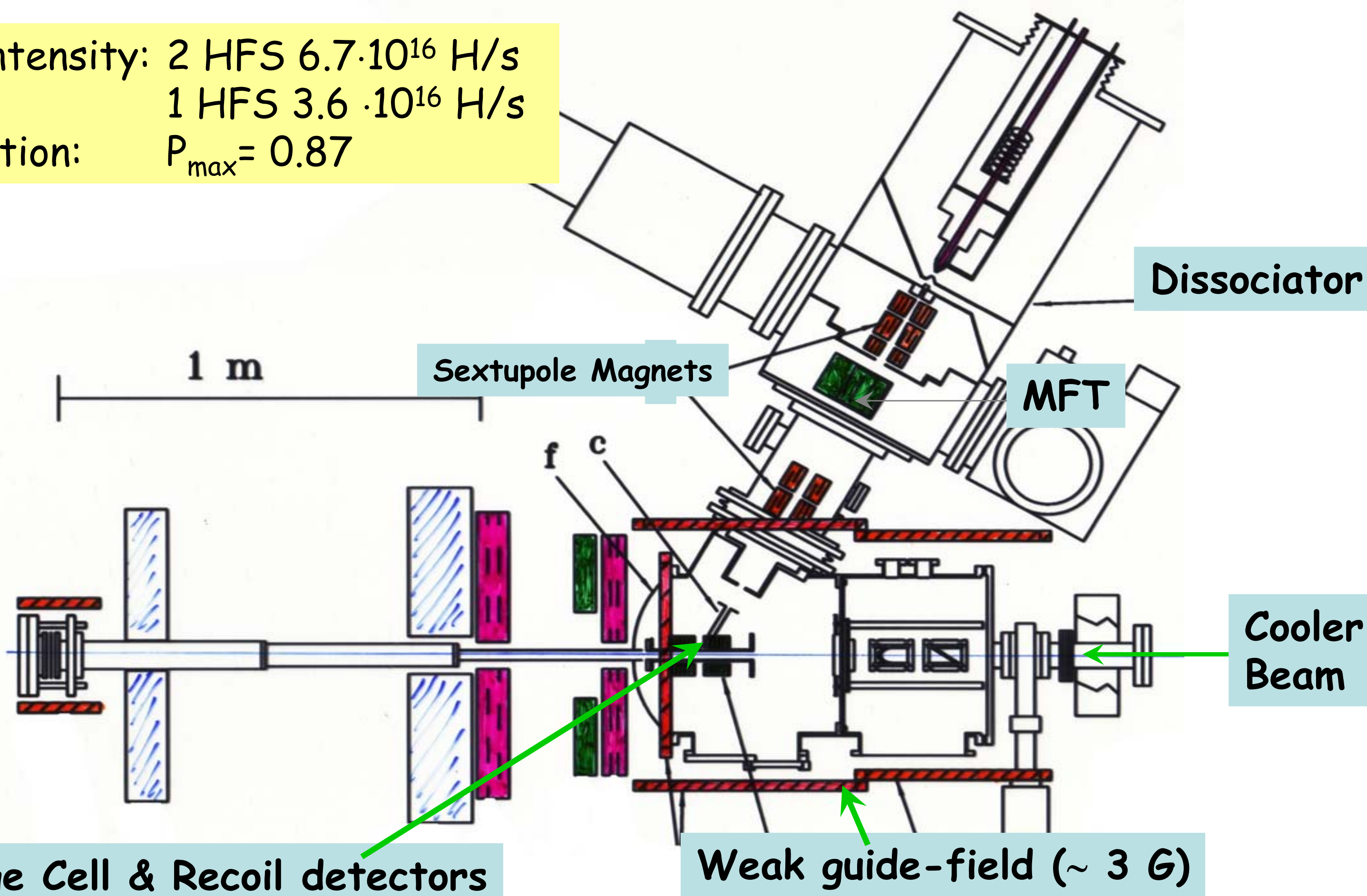
P = 0.79 ± 0.02

d_t = (5.4 ± 0.3)·10^{13} 1/cm²

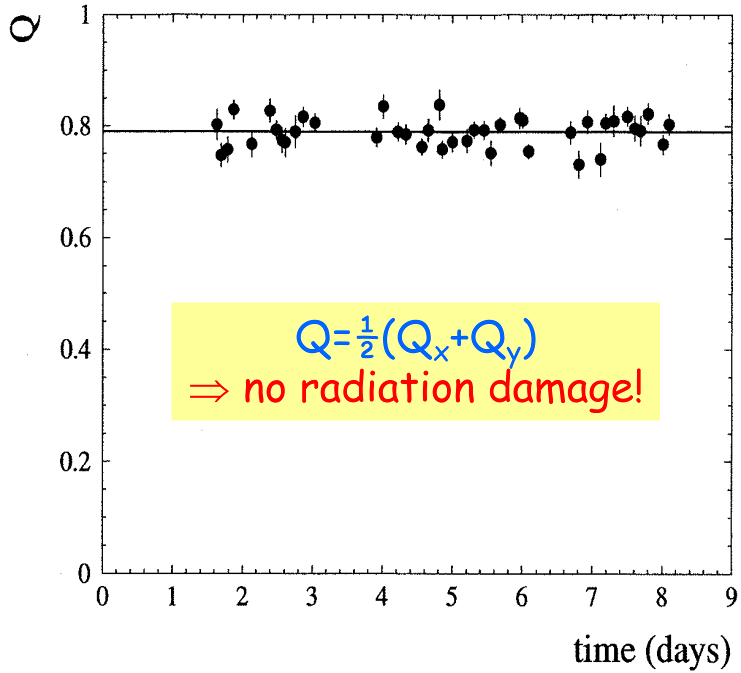
No radiation damage of the wall coating

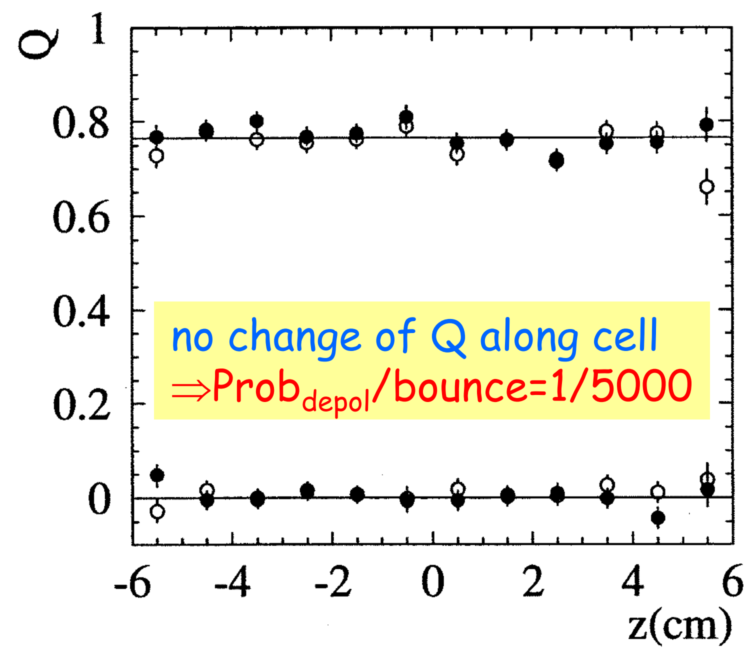
Ex. 2: PINTEX pp elastic scattering (IUCF)

Beam Intensity:	2 HFS $6.7 \cdot 10^{16}$ H/s
	1 HFS $3.6 \cdot 10^{16}$ H/s
Polarization:	$P_{max} = 0.87$



Polarization vs time and vs z





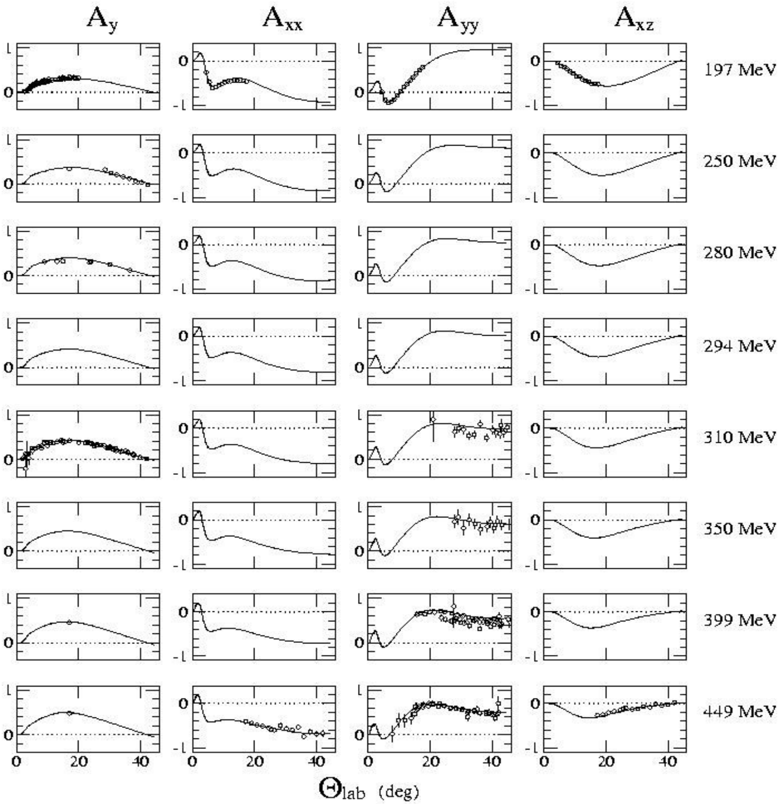
with I_{beam} = 100 – 400 μA ⇒ L = $5{\cdot}10^{28}$ $cm^{-2}s^{-1}$

Spincorrelation Parameters

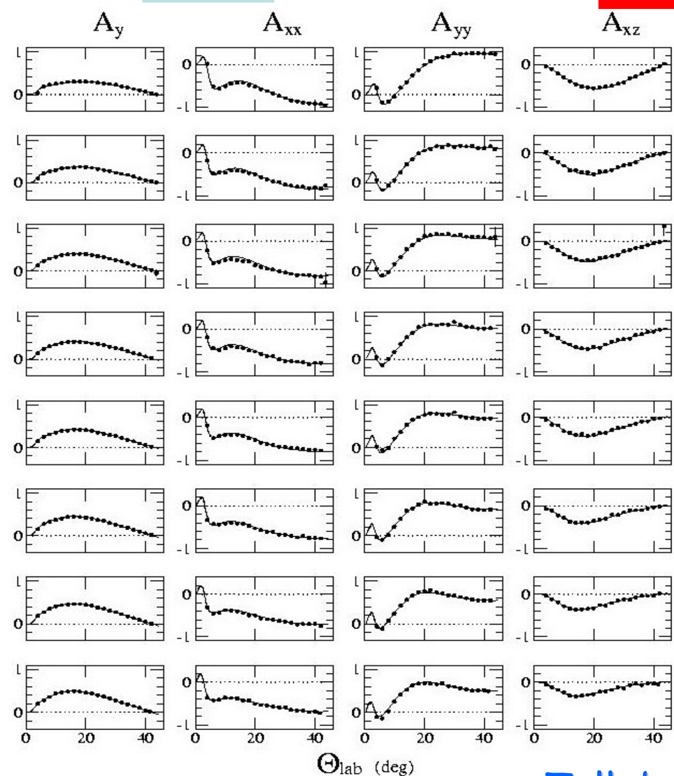
W. Haeberli et al., PRC 55, 597 (1997)
F. Rathmann et al., PRC 58, 658 (1998)
B.v. Przewoski et al., PRC 58, 1897 (1998)
B. Lorentz et al., PRC 61, 054002 (2000)

Relativ statistical error of the normalization

Before



After



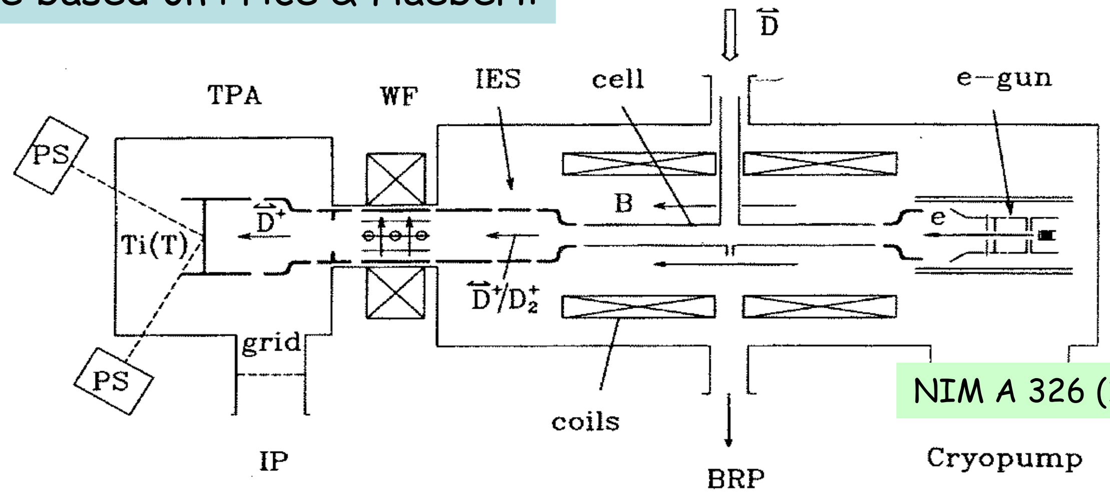
δk/k (%)

- 0.31
- 1.08
- 0.89
- 1.17
- 1.01
- 1.03
- 0.86
- 1.00

→ Talk by Pia

Ex. 3: NIKHEF Ion-extraction polarimeter

Principle based on Price & Haeberli



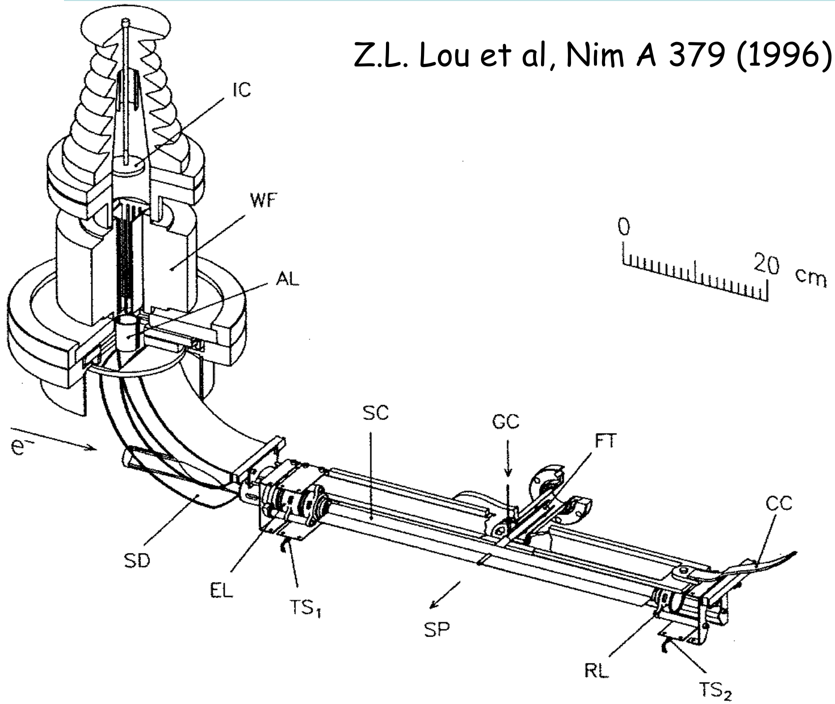
NIM A 326 (1993)

Measurement of Tensorpolarization via $^{3}\mathrm{H}(\vec{\mathrm{d}},\mathrm{n})^{4}\mathrm{He}$

Ex. 3: NIKHEF Ion-extraction polarimeter

Ionization in AmPS via stored e$^-$: σ(1 keV)/ σ(565 keV) ~1/50

Z.L. Lou et al, Nim A 379 (1996)

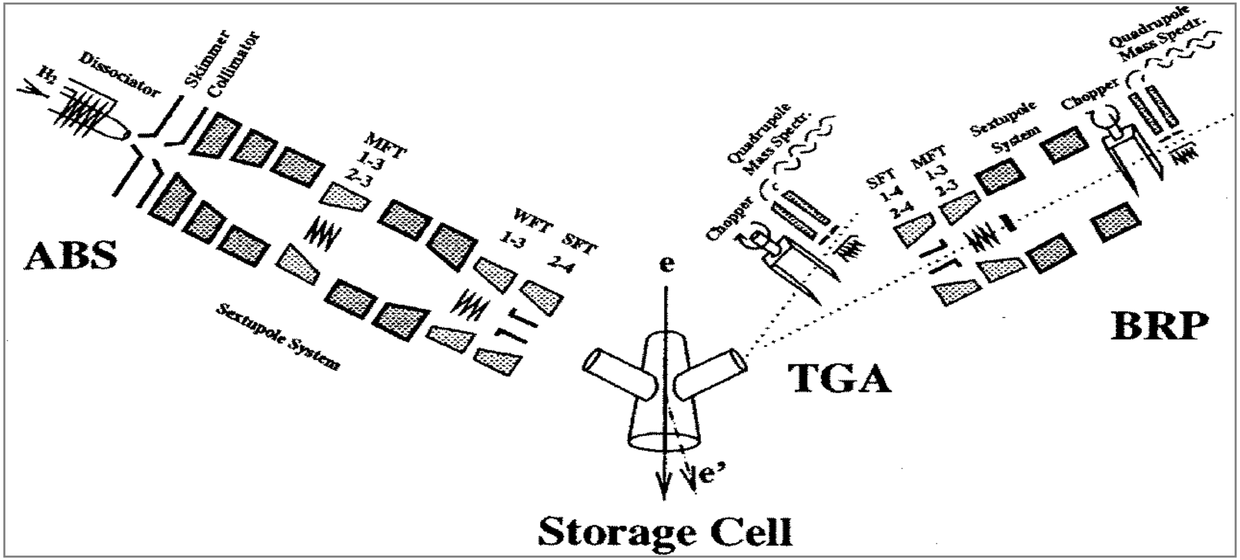


Polarized Ion Measurement with a prototype

$$-0.89^{\pm 0.03\,\text{stat.}}_{\pm 0.05\,\text{syst.}} < P_{zz} < 0.49^{\pm 0.01\,\text{stat.}}_{\pm 0.03\,\text{syst.}}$$

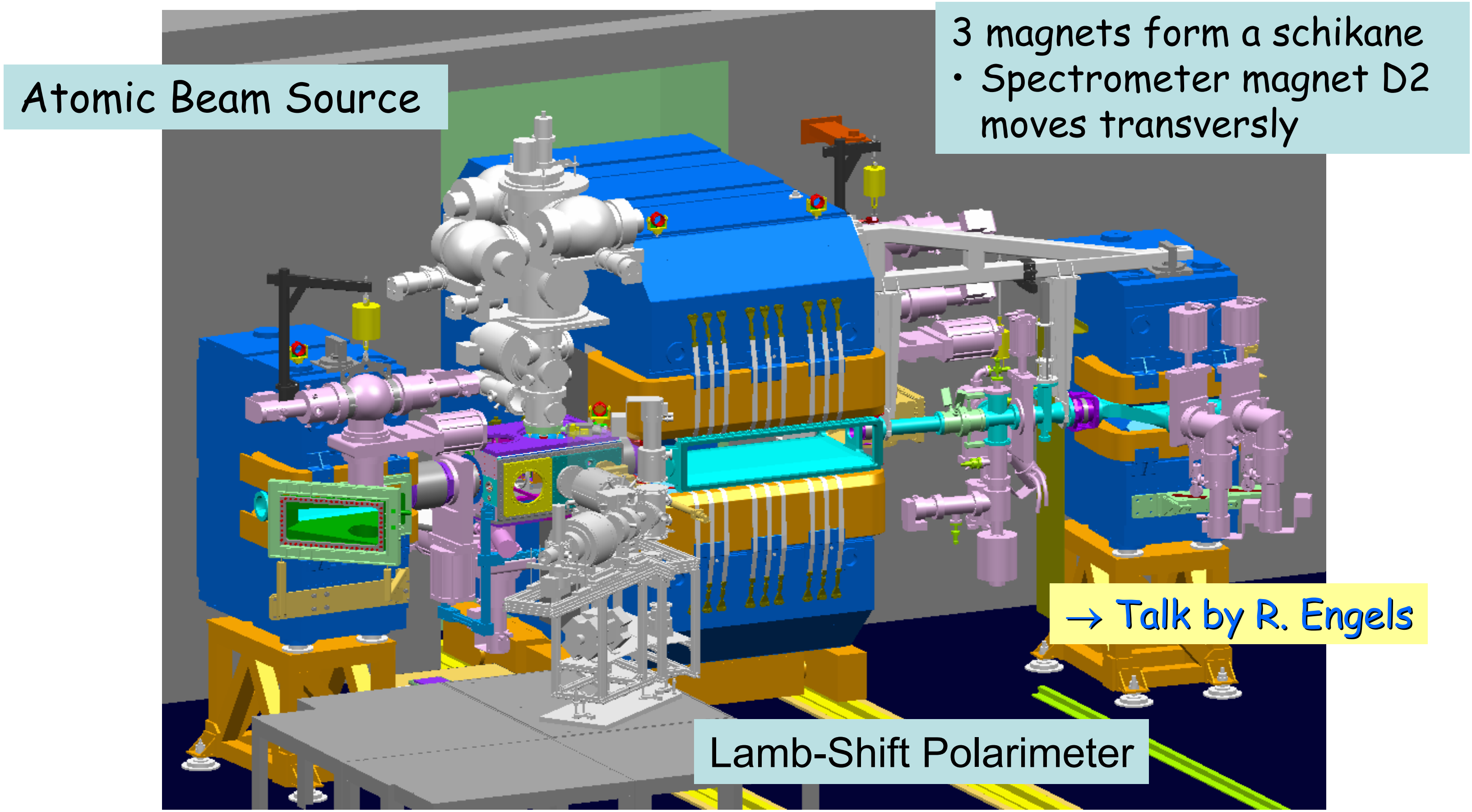
Ex. 4: HERMES Breit-Rabi Polarimeter

Determination of Hyperfine state population numbers by
- RF transitions
- sextupole magnet system



→ Talk by Paolo Lenisa

Polarized Internal Target for ANKE



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Polarization Buildup: General Features I

$$\sigma_{tot} = \sigma_0 + \sigma_\perp \cdot \vec{P} \cdot \vec{Q} + \sigma_{||} \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k})$$

P beam polarization
Q target polarization
k || beam direction

For initially equally populated spin states: ↑ (m=+½) and ↓ (m=-½)

transverse case:

$$\sigma_{tot\pm} = \sigma_0 \pm \sigma_\perp \cdot Q$$

longitudinal case:

$$\sigma_{tot\pm} = \sigma_0 \pm (\sigma_\perp + \sigma_{||}) \cdot Q$$

$$\tau_{beam} = \frac{1}{(\sigma_0 + \Delta\sigma_c) \cdot d_t \cdot f_{rev}}$$

$$\tau_{pol} = \frac{1}{\sigma_{pol} \cdot Q \cdot d_t \cdot f_{rev}}$$

$$I_+(t) = \frac{I_0}{2} \cdot e^{-\frac{t}{\tau_{beam}}} \cdot e^{-\frac{t}{\tau_{pol}}}$$

$$I_-(t) = \frac{I_0}{2} \cdot e^{-\frac{t}{\tau_{beam}}} \cdot e^{+\frac{t}{\tau_{pol}}}$$

Time dependence of P, I, and FOM

$$P(t) = \frac{I_+ - I_-}{I_+ + I_-} = -\tanh\left(\frac{t}{\tau_{pol}}\right)$$

$$I(t) = I_+ + I_- = I_0 \cdot e^{-\frac{t}{\tau_{beam}}} \cdot \cosh\left(\frac{t}{\tau_{pol}}\right)$$

$$FOM(t) = P(t)^2 \cdot I(t)$$

Polarization Buildup: General Features II

statistical error of a double polarization observable (A_{TT})

$$\delta_{A_{TT}} = \frac{1}{P \cdot Q \cdot \sqrt{N}}$$

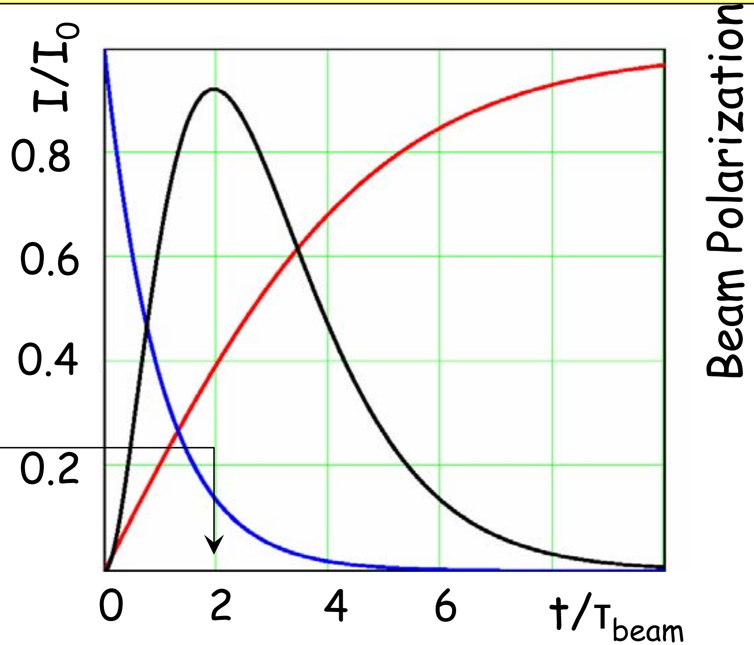
(N ~ I) →

Measuring time t to achieve a certain error δ_{ATT}

$t \sim FOM = P^2 \cdot I$

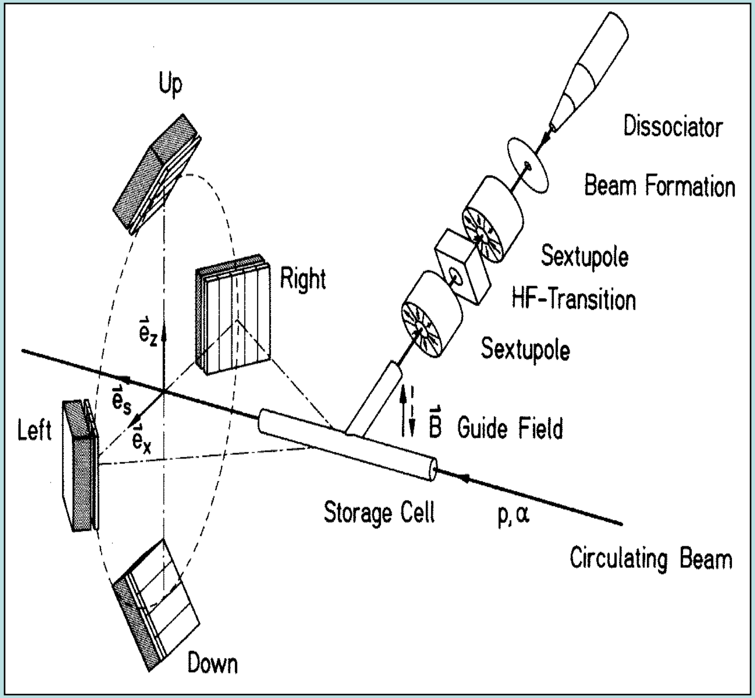
Optimimum time for Polarization Buildup given by maximum of FOM(t)

$t_{filter} = 2 \cdot \tau_{beam}$

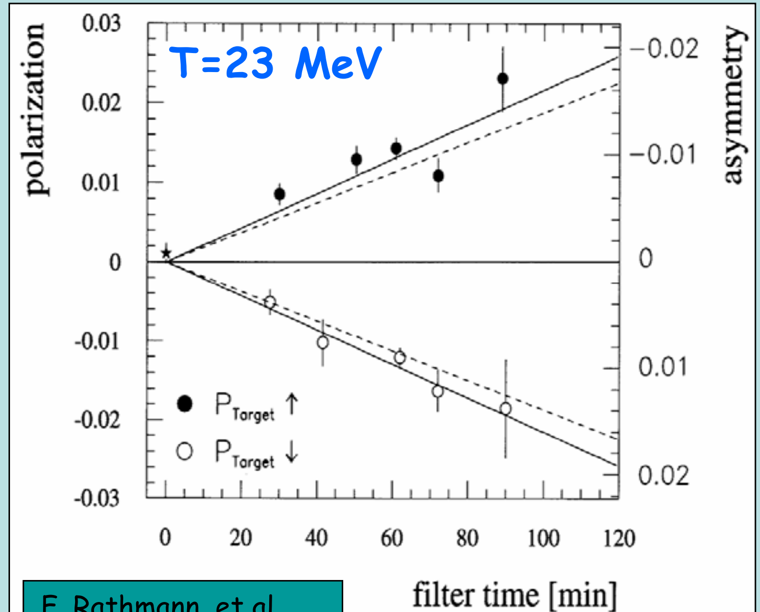


1992 Filter Test at TSR with protons

Experimental Setup



Results



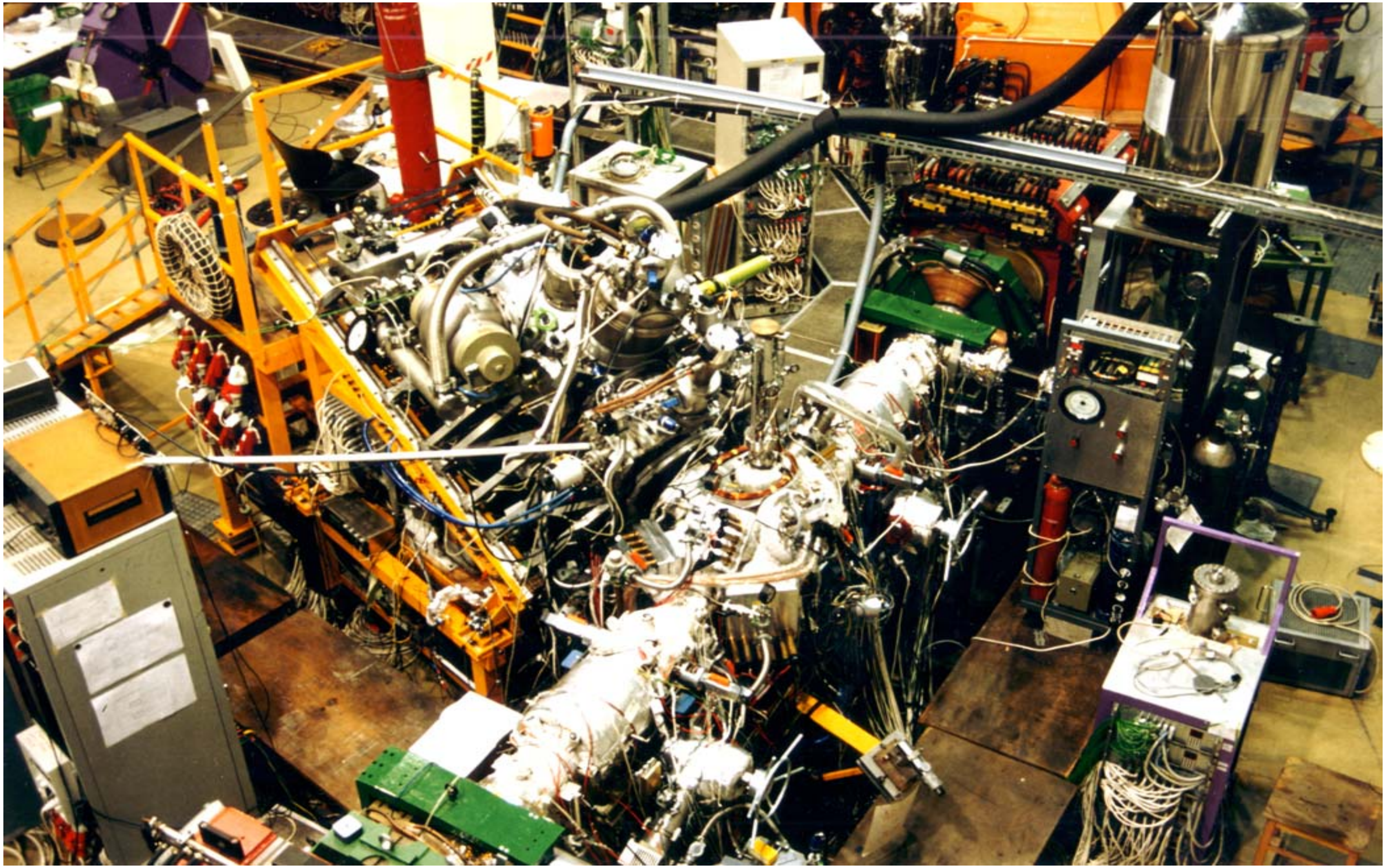
F. Rathmann. et al., PRL 71, 1379 (1993)

Low energy pp scattering

$\sigma_1 < 0 \Rightarrow \sigma_{tot+} < \sigma_{tot-}$

Expectation	
Target	Beam
↑	↑
↓	↓

Experimental Setup at TSR (1992)

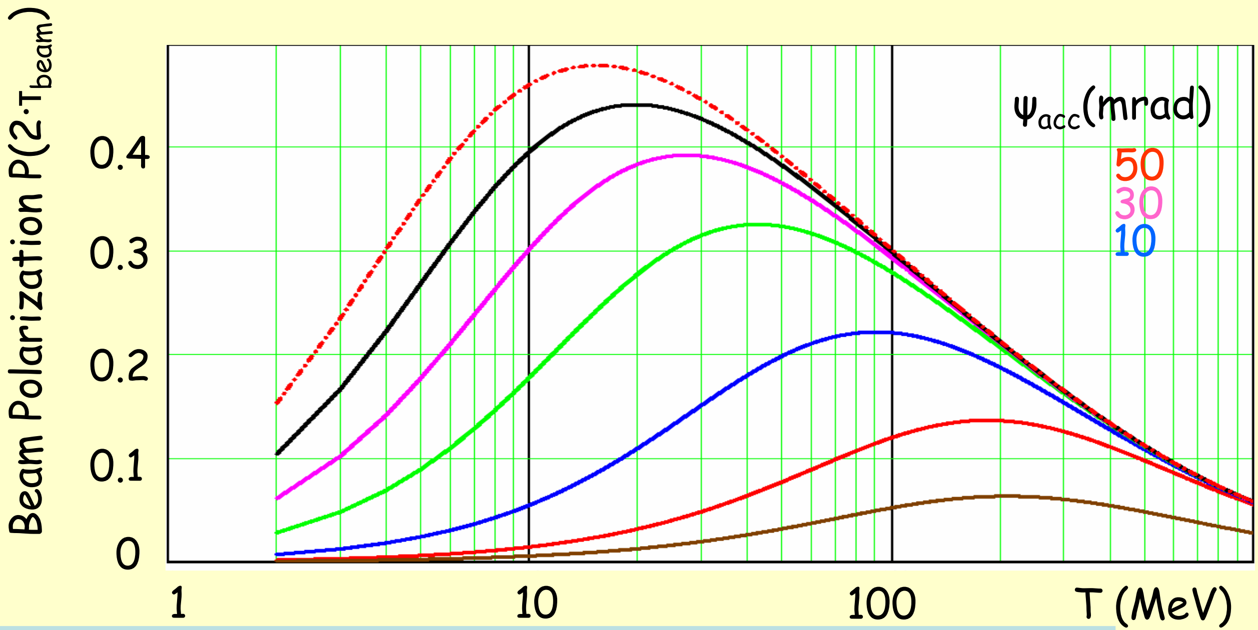


Beam Polarization in a dedicated Antiproton Polarizer

Polarisation buildup through spin transfer

$$\bar{p} + \vec{e} \rightarrow \vec{\bar{p}} + e$$

Horowitz & Meyer, PRL 72, 3981 (1994)
H.O. Meyer, PRE 50, 1485 (1994)



PAX will exploit spin-transfer to polarize antiprotons and to go after transversity

→Talk by Paolo Lenisa

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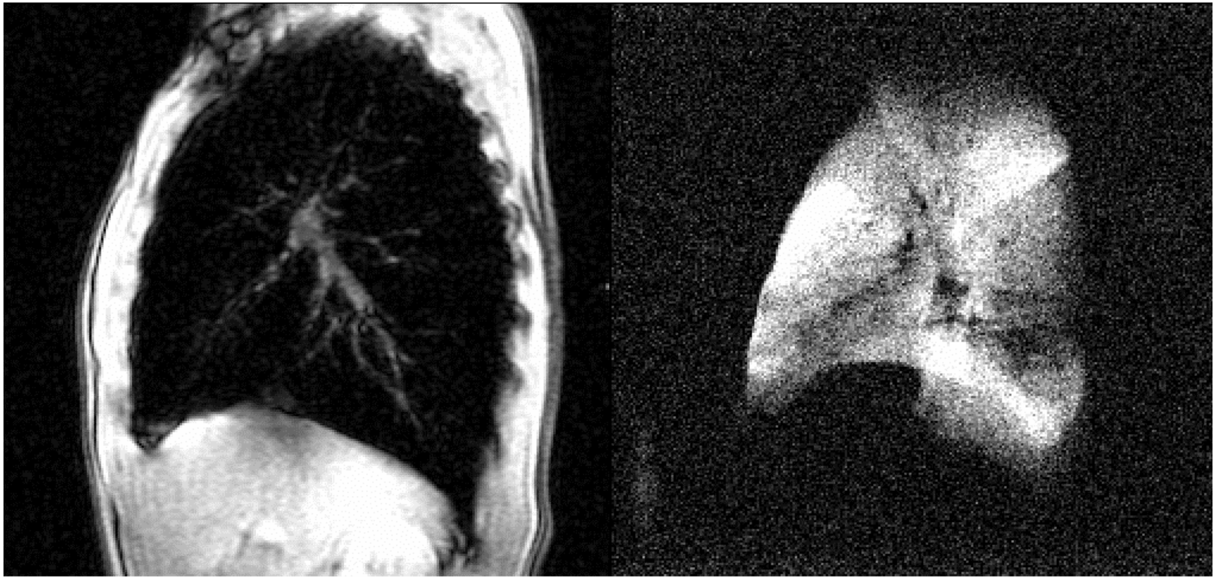
Polarized ^{3}He for NMR's of the human lung (Werner Heil)

Spin-Off of Polarized Gas Target Technology

Human Lung with 0.7 bar×liter of polarized ^{3}He



Proton - MRI (1 H) Helium - MRI (^{3}He)

DKFZ, HD Nov. 1995; Lancet 1996

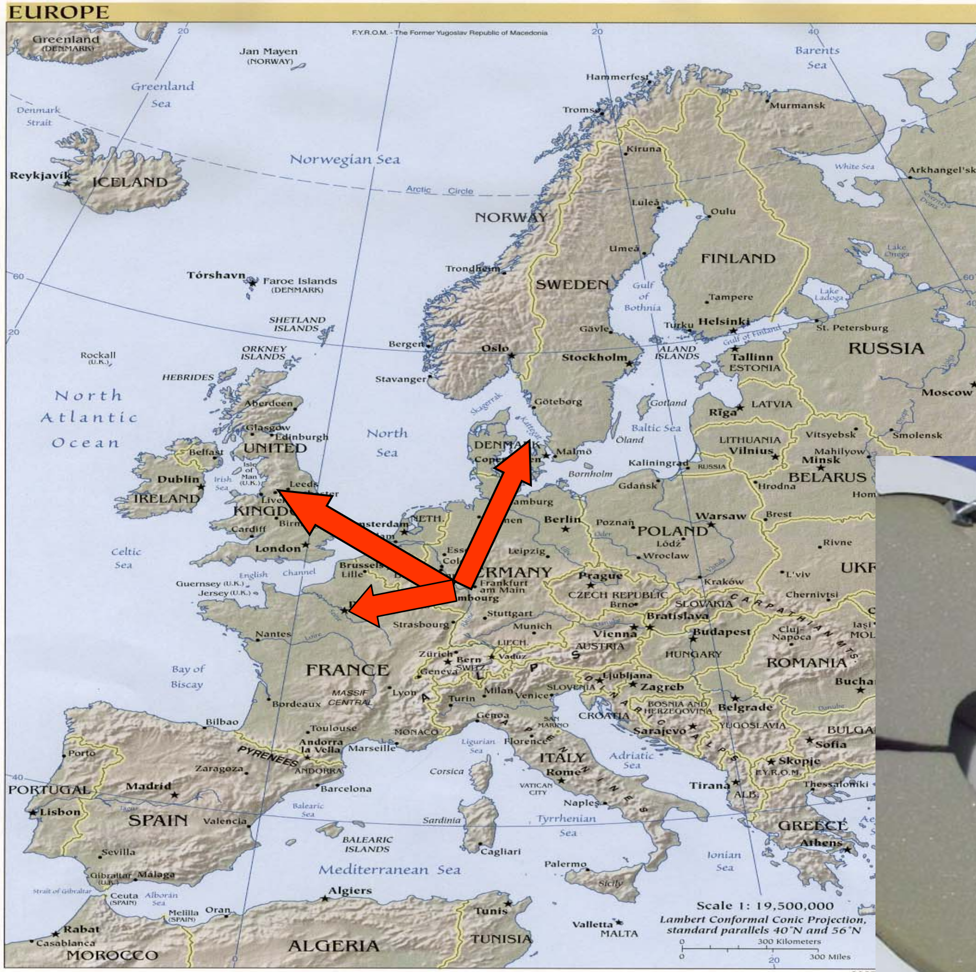
$P_H \sim m \cdot B/kT$
$\sim 5 \cdot 10^{-6}$

$P_{He} \sim 1$

$\rho_H/\rho_{He} \sim 2500$

signal $P \cdot \mu \cdot \rho$
$S/S_H > 10$

amount of gas:
1 bar · liter



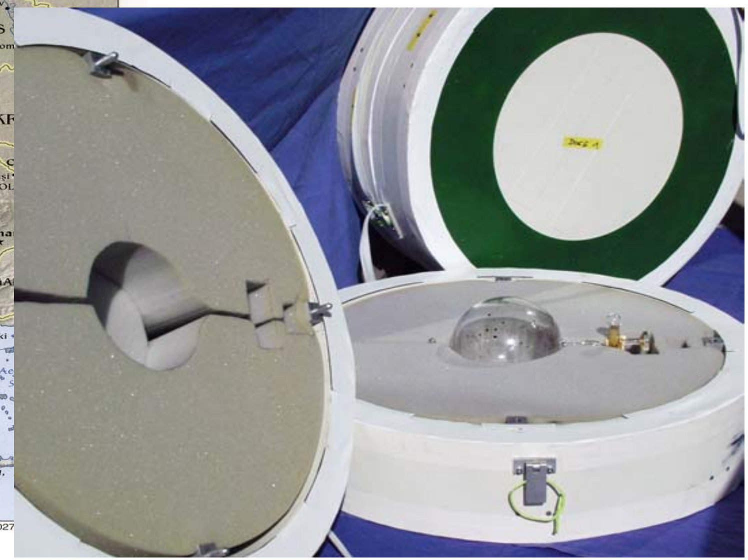
Transport time:

Mainz-Sheffield :10 h

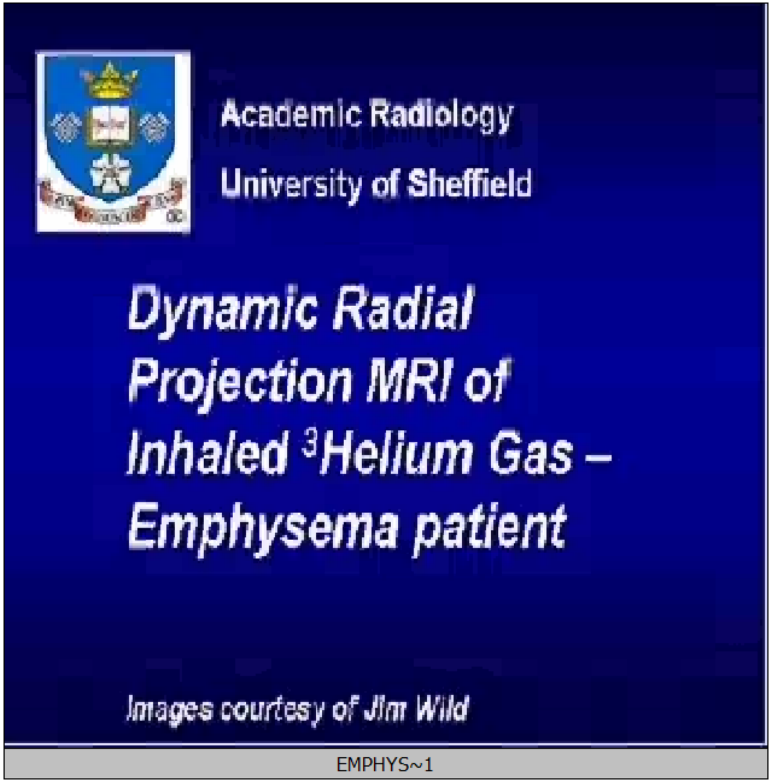
Mainz-Copenhagen : < 7 h

Mainz-Orsay (Paris): 8 h

T_1~160 h



Funktionelle NMR mit ^{3}He



Final Remark

In 1981 Rudolf Fleischmann (1903-2002)

- Professor of Physics in Erlangen
- "originator" of the first polarized atomic beam source (1956)

asked ***himself*** at a conference, why progress in physics sometimes was so slow and took so many roundabouts.

"It seems to me that the main reason is that too much confidence is put in theoretical, and therefore quite hypothetical concepts and models, which are popular during the corresponding period and that it is very difficult to free oneself from them."

from D. Fick, Talk held on 5.5 2003 in the
Physics Colloquium at University of Erlangen