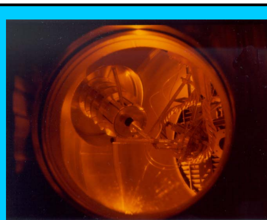

Polarized Jets and Storage Cell Targets for Storage Rings

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I. Introduction

- **What kind of gas target are we interested in for scattering experiments on Nucleon Structure?**

  - Nucleons are represented by the proton (^{1}H) and the weakly bound deuteron (D = ^{2}H)

  - Hydrogen gas is polarized in the atomic state by employing its magnetic moment (of the electron shell)

  - Atomic hydrogen gas recombines at densities above the molecular flow regime

⟶ **No high-pressure gas target like for ^{3}He feasible!**

Only possible combination for hydrogen is

Gas Target and **Storage Ring**

thin, windowless ~ 100mA

Why To Use Polarized Gas Targets?

- **Polarized gas targets:** in conjunction with storage rings luminosities in excess of $10^{31}/cm^2s$ available
- Low background of unwanted reactions due to their purity
  No dilution like in solid pol. targets e.g. NH_3 with dilution factor f < 1/7 ; enters quality factor as $f^2 \sim 1/50$!
- Detection of low-energy recoils possible
- High P_z and P_{zz} of both signs available which can be switched on a msec time scale: high precision!
  See plenary by B.v.Przewoski on Tuesday about PINTEX results.
- Ideal for the measurement of small cross sections which would be completely dominated by background from heavy contaminations, e.g. pion production in pp scattering at threshold, exclusive DIS reactions like DVCS on the nucleon at HERMES

II. Methods for Polarized Gas Targets

(A) Ballistic flow of polarized gas, crossing the fast (electron/ion) beam: Jet Target

Pioneering experiments:

Stanford ≈1978 Glavish, Mavis et al.
Tandem beam on H atomic beam from Atomic Beam Source; few cts /h.
Novosibirsk ≈1985 Estigniev et al, NIMA238 (1985) p.12. Atomic Beam Source (ABS) target with **$t_D = 2 \times 10^{11}/cm^2$** at the VEPP-3 2GeV electron storage ring.

Jet targets presently employed at the EDDA experiment (COSY), and in future at the RHIC polarimeter based on a H atomic beam target of well known polarization

Under study: Ultracold Source **UCS** (Michigan, Dubna) **t prop. to 1/velocity !**
•Hydrogen cooled to 300mK using accomodator chamber covered with superfluid He
•Separated and polarized in the fringe field of superconducting solenoid ($W_{th} < W_{magn}$)

(B) Polarized Atoms injected into Storage Cell

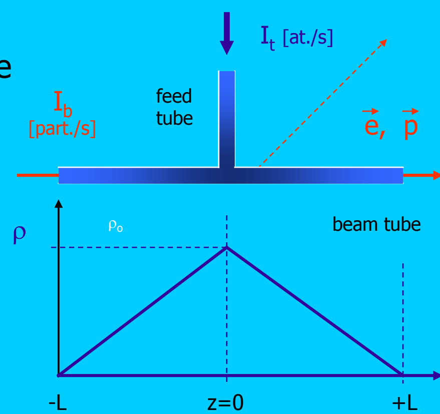
- **Ballistic flow**
  from Atomic Beam Source H, D
- **Flow driven by pressure gradient**
  Laser Driven Sources H, D, ^{3}He

Storage Cell proposed by W. Haeberli

- Proc. Karlsruhe 1965, p. 64
- Proc. Workshop IUCF 1984, AIP Conf. Proc.#128, p.251

Density gain compared to Jet of same intensity can be up to several hundred!

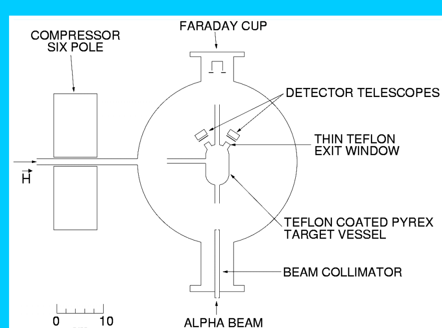
Polarized atoms from source



$\mathbf{t = L\,\rho_o}$ with $\rho_o = I_t / C_{tot}$ and $C_{tot} = \Sigma\, C_i$

First Test of a Storage Cell at Wisconsin

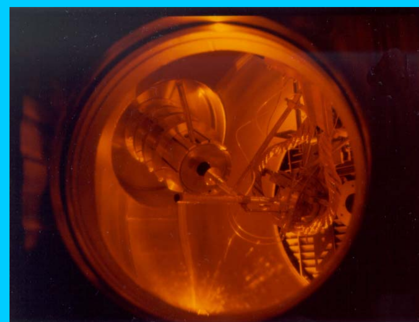
- Atomic beam from an ABS fed into Teflon-coated target vessel similar to Maser storage bulb
- Polarization detected via H(α,p)-scattering
- Polarization was found after subtraction of 50% background to be $P_z = 0.43 \pm 0.07$
- Result is compatible with no depolarization after in average about 900 wall collisions
- The areal density of the fiducial volume viewed by the Si detector system was $t = 1.1\cdot10^{12}/cm^2$



M.D. Barker et al, Proc. Santa Fe 1980. AIP Conf. Proc. 80 (1981) p.931

Storage Cell Design: Requirements

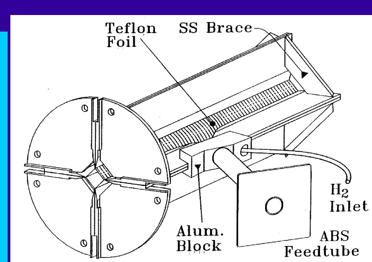
- Minimum aperture allowed by machine optics for high density: $t \sim 1/r^3$
  e.g. $x,y = 15\sigma_{x,y} + 1\text{mm}$
- Maximum length compatible with tracking detector
  e.g. 2L = 400mm (HERMES)
- Thin walls with coating for minimum recombination and depolarization
  e.g. Teflon, Drifilm
- Cooling of cell wall?
  - density enhancement
  - comp. of cell heating

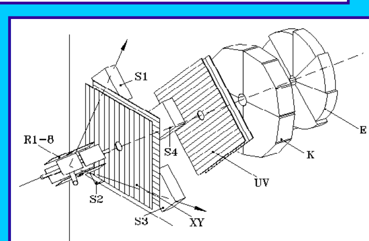


FILTEX target for TSR test experiment (1992)

Storage Cell Design: PINTEX

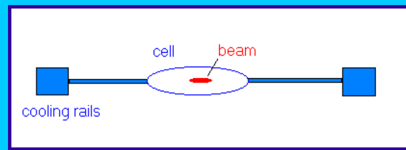
- Optimized for detection of low energy recoil particles - Si strip detectors close to cell
- Walls consist of ~ 450µg/cm² Teflon foil suspended by 4 fins and forming a quadratic channel of 10x10mm², 250mm long
- Cell at room temperature in weak magnetic guide field. The direction of the B-field can be rapidly switched between x, y, z in order to vary the target polarization

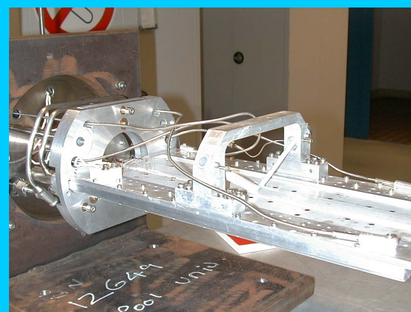




Storage Cell Design: HERMES Target

- Cell optimized for operation in an electron storage ring
- Conducting surface with smooth variation of cross section excitation of wake fields!
- System of W collimators for protection against beam and SR
- Cooled via cooling rails by cold He gas to 60-100K
- 75μm Al walls with Drifilm coating - Radiation damage visible!
- But: Very effective wall coating due to ice layer maintained by small fraction of water in the atomic beam





III. Sources of Polarized Gas for PGTs

Jet targets: high density at interaction point

- low velocity Jet by **ABS** (separation by focusing via 6-poles) or
- by **U**ltra **C**old **S**ource (sep. by magnetic potential well)

Storage cell targets: high flow rate into cell

- ballistic injection: **ABS**, optimized for high intensity
- injection via gas pipe: **LDS** (H, D) or **OPS** for ^{3}He = optically pumped sources at elevated pressure

Operating targets

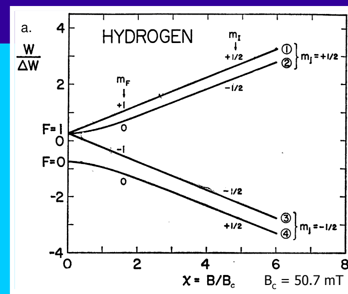
PINTEX/IUCF	H, D	ABS-SC	p
EDDA/COSY	H	ABS-J	p
DEUT./Vepp-3	D	ABS-SC	e
HERMES/HERA	H, D	ABS-SC	e

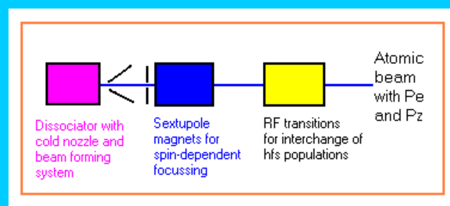
Under design or construction

ANKE/COSY	D, H	ABS-SC	p
RHIC Polarimeter	H	ABS-J	p
BLAST/Bates	H, D	ABS-SC	e
	H	LDS-SC	e
	^{3}He	OPS-SC	e

Principle of Atomic Beam Sources

- Collimated cold atomic beams produced by dissociator with cold nozzle (100K) and differential pumping system ($\Sigma S_i \sim 10^4$ l/s)
- Spin-dependent focussing of H and D atomic beams by 6-pole magnets: $m_J = +1/2$
- Nuclear polarization P_z, P_{zz} produced by means of rf transitions with ~100% efficieny; rapid switching enabled





achievements

frustrations

Atomic Beam Development

Production of a cold atomic beam (i.e. low T_{beam}, e.g. < 20K) studied by many groups, among those were:

- ZGS PIS group (1st nozzle cooling)
- Univ. of Bonn (magnet optics)
- ETH Zürich (30K nozzle, frozen N_2)
- CERN group (1st µW dissociator)
- Dubna, Novosibirsk (cryogenic source)
- Heidelberg-Marburg-Munich-Wisconsin (perm. magnets, velocity meas.)

......and many more....

<u>Achievements over the last 15 years</u>

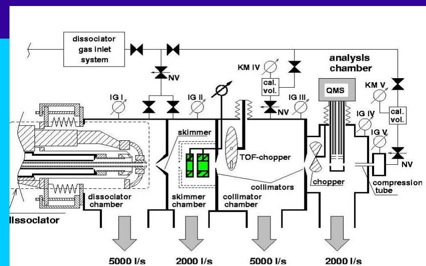
- H intensity in 2 substates up by ~ **<u>3x</u>**
- System of rf transitions able to generate any substate population and provide rapid switching
- Sources extremely reliable over months
- Very low contamination in atomic beams; important for cryogenic cells

<u>Frustrations</u>: - Forward intensity ($\theta \sim 0^o$) saturates with increasing flow rate
- No quantitative understanding of AB sources obtained (yet)

Atomic Beam Studies at HERMES

HERMES test bench

- clean diff. pumping system with 14 000l/s
- nozzle position adjustable within large range
- calibrated C.T. and gas inlets to all stages
- ToF system for velocity measurements
- fast QMS for mass-resolved ToF measurem.
- precise gas flow measurements with spinning ball gauge



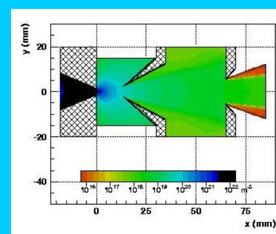
N. Koch & E. St., Rev. Sci. Instr. 70 (1999) 1631

A. Nass et al, Proc. PST 2001, p. 42, and Diss. Univ. Erlangen-N. (2002)

New: Simulations for realistic geometry performed with DSMC program of G.A. Bird and compared with measurements (see PST01 and talk A.Nass this afternoon).

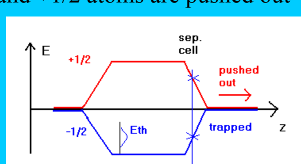
Right: Result of DSMC calculation, showing density distribution during expansion and collimation. Measured and calculated velocities agree on the few% level.

Found unsuccessful: Carrier Jet method

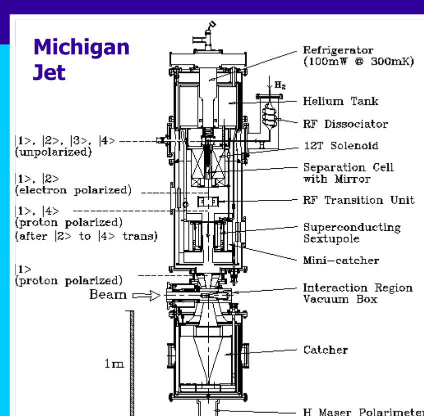


Status Ultra-Cold Source (UCS)

- Ultracold separation cell,covered with superfluid ^{4}He, located in the fringe field of a SC solenoid
- After thermalization to 300mK atoms with $m_J = -1/2$ are trapped, and +1/2 atoms are pushed out



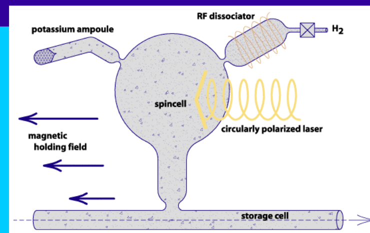
- Further focussing by parabolic mirror and 6-pole magnet and 2-4 rf-transition gives beam in single substate into area 11.0 x 1.4 mm² of **2.2 x 10^{15} H/s**, corresponding to t = 1.1 x 10^{12} H/cm².



V.G. Luppov et al: Status of the Michigan Ultra-Cold Polarized Hydrogen Jet Target. Proc. PST01, Nashville, IN 2001, World Scient. p. 32

Status of the Laser-Driven Source

- Basic idea: employ the high number of circular photons, carrying angular momentum, to polarize hydrogen ($P_{electr.}$)
- Problem: Hydrogen can not be pumped directly due to lack of suitable lasers
- Way out (?): Apply OP on small alkali admixture (e.g. K) with IR lasers and transfer P_e to the H atoms by spin exchange collisions!
- In order to avoid condensation of K the (Drifilm coated) glass cell has to be kept at 150-200C.
- Anticipated flow rates and target densities are well beyond ABS figures, but <u>feasibility has not been demonstrated yet.</u>



Taken from MIT group working on LDS target

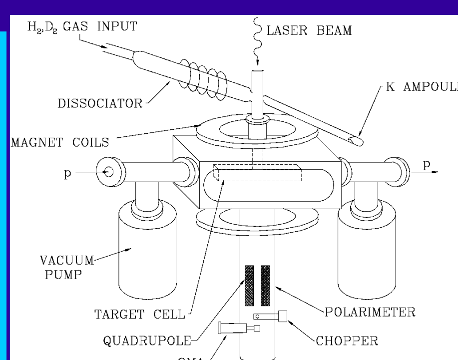
Main difficulty: to keep a high dissociation fraction at the exit of the pumping cell and within the target cell (long-term stability). The presence of molecules dilutes the atom polarization.

Quality factor: (α = dissociation fraction)

$$QF = t \cdot P_{av}^2 = t \cdot P_{at}^2 \cdot \alpha^2$$

LDS History and Current Status

- Proposed in 1984 for internal target use, e.g. at the Aladin storage ring
- Development started at ANL and was continued at Illinois, Erlangen and Bates
- Applications at VEPP-3, HERMES and ANKE-COSY have been considered
- A test experiment at the IUCF Cooler has been performed by the CE66 Argonne-Erlangen-Illinois-Colorado Collaboration in 1996-1999



- Average target polarization measured with polarized proton scattering was

  P_{av} (H) = 0.09 - 0.14

  P_{av} (D) = 0.08 - 0.12

M.A. Miller et al, PST97, p.148 - C. Jones et al, PST99, p.204

- Target thickness was $4 \cdot 10^{14}/cm^2$

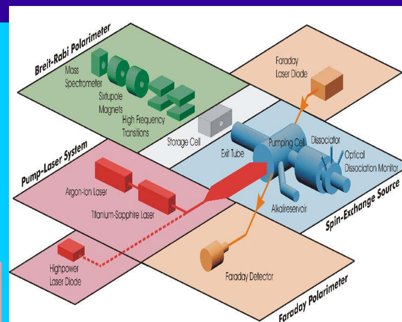
$QF(CE66) = 0.12^2 \cdot 4 \cdot 10^{14}/cm^2 \sim 6 \cdot 10^{12}$

$QF(HERMES) = 0.85^2 \cdot 1 \cdot 10^{14}/cm^2 \sim 75 \cdot 10^{12}$ (x12)

LDS Status: Current Results (Erlangen)

Emphasis on Diagnostics

- **BR polarimeter** for measurement of P_e and P_z
- **Faraday monitor** for detection of ρ_K and P_K
- **Optical monitor** measures dissociation fraction α at the dissociator by comparing Balmer with molecule lines
- **BRP intensity changes** with dissoc. on/off allows for measurement of α in the beam



Achievements and Status

- First exp. verification of **spin-temperature equilibrium** in an LDS: transfer of P_e to P_z (J. Stenger et al, PRL 78, 1997, p.4177)
- **Current status:** strong increase of molecule fraction with increasing K density (doct. thesis F. Schmidt, confirmed by J. Wilbert), measured by Faraday monitor. Long-term LDS performance limited by present surfaces - innovation needed

Target Polarimetry

Two scenarios:

- Measurement of absolute target polarization by scattering of beam particles with known analyzing power -> P_e monitor sufficient for setting up

- No calibrated reaction of beam and target particles with enough statistics like in electron DIS: absolute target polarimetry required!

- Task is to detect the polarization of the target atoms
- Easy: to measure electron polarization of the atomic beam from the source enough for setting up rf transitions
- Difficult: To measure P_e and P_z and the molecule fraction $(1-\alpha)$ for an effusive sample beam from a target cell to 1% accuracy...
- Ambitious: To calculate from these parameters the average polarization seen by the beam! Only for low recombination and depolarization possible

HERMES Target Polarimeter

- Breit-Rabi Polarimeter (BRP) for measurement of substate population n_i in sample beam to 0.01 in precision ($\Sigma\, n_i = 1$)
- Target Gas Analyzer (TGA) measures atomic fraction α of the sample beam to 1%

$$P_{z,av} = \alpha_o\,[\alpha_r + (1-\alpha_r)\beta]\,P_z$$

α_o from source and target chamber

α_r from recombination in cell:

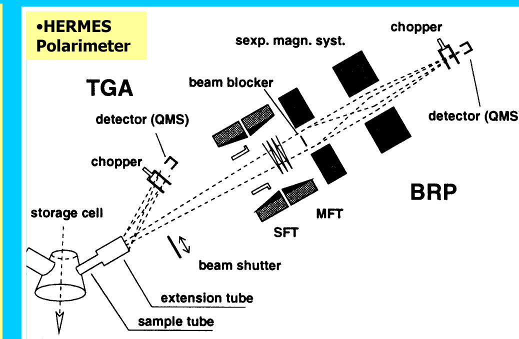
$$\alpha_r = \alpha^{TGA} \cdot C_\alpha$$

β is the relative nucl. pol. of molecules from recombination of pol. atoms

P_z is the atom polarization seen by the beam:

$$P_z = P_z^{BRP}\, C_P$$

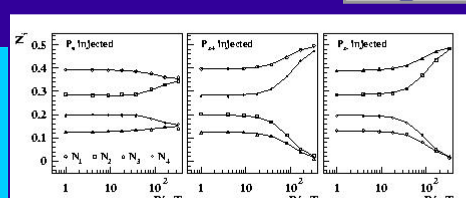
C_α and C_P are correction factors calculated by MC simulations (no assumptions)



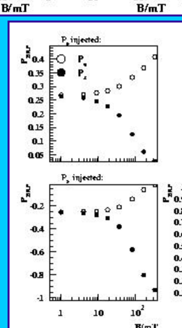
HERMES Target Polarimeter

- Continuous effort needed to meet the requirement of $\delta P/P \sim 3\%$ of the experiment
- Frequent temperature and B-field scans allow for a sensitive monitoring of the target properties
- For close-to-ideal conditions like in 2000 the required precision can be provided

see talk by P.Lenisa this afternoon in session 8



Result of a B-field scan: sensitive to density due to spin-exchange. Used to determine the absolute density



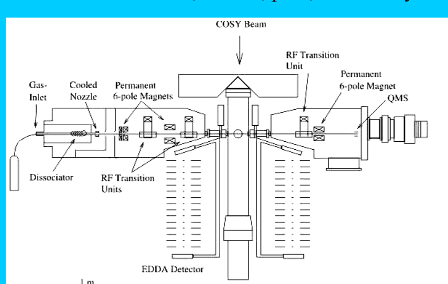
Population numbers N_i (top) and el. and nucl. pol. for different injections as function of B

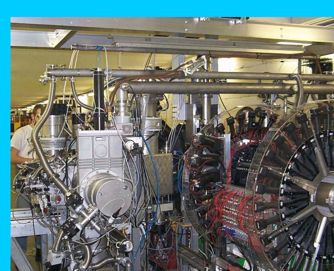
IV: Performance of Operational Targets

• **EDDA/COSY**	H	ABS-J (SC)	p (2.5GeV)
• **PINTEX/IUCF**	H, D	ABS-SC	p (0.45GeV)
• **DEUT./Vepp-3**	D	ABS-SC	e (2.0GeV)
• **HERMES/HERA**	H, D	ABS-SC	e (27.5GeV)

EDDA Target at COSY-Jülich

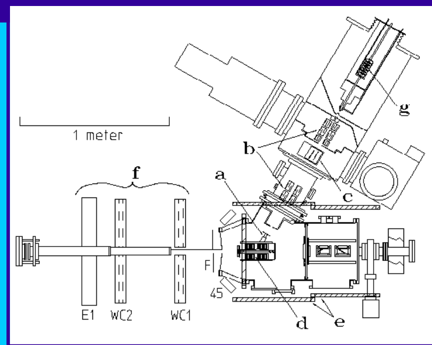
- Detector optimized for the study of pp elastic
- Target built as ABS Jet target (single substate)
- $I_{ABS} \sim 3 \cdot 10^{16}$/s and density $t = 2 \cdot 10^{11}/cm^2$
- Addition of a cell in progress in order to enhance the density to $\sim 10^{13}/cm^2$ for Time Reversal Invariance experiment
  see O.Felden et al, PST01, p.73, and talk by D. Eversheim in session 1





PINTEX Target at the IUCF-Cooler

- Operational since 1993, first for H, and recently also for D atoms
- For H the upper state |1> is injected. By a variable weak B-field (x,y,z) the polarization can be rapidly switched without disturbing the circulating beam
- Room temperature cell with walls from thin Teflon foil
- Surrounded by Si strip detector
- PINTEX has, in conjunction with the flexible IUCF Cooler (polarized protons with T_p = 130 - 450 MeV) produced a wealth of new data



a = feed tube with cell, b = 6-poles, c = rf transition, d = recoil detector, e = flip and correction coils, f = detector, g = dissociator

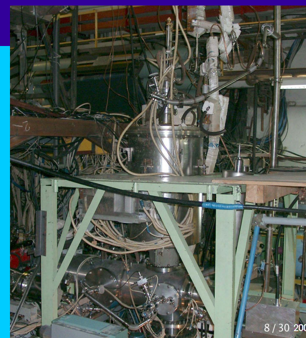
PINTEX Target at the IUCF-Cooler

- Target has been upgraded in 2000 to also produce vector and tensor polarized deuterium targets
- Source provides $+P_z$ and P_{zz} of both signs by a system of two medium field transitions (MFTs)
- Direction of the polarization (and sign for P_z) is provided by the set of Helmholtz coils previously used
- Tensor polarization significantly reduced due to spin exchange in low field

see B. v. Przewoski et al, Proceed. PST01, p.57, and talk this afternoon

DEUTERON Target at VEPP-3, BINP

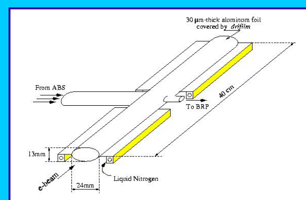
- Experiment working since mid-80s: electron scattering up to 2.0 GeV on tensor polarized deuterium targets, starting with Jet target
- 1st storage cell in a (electron) ring tried in 87/88 by ANL-BINP collaboration
- Attempt in the early 90s to install and commission a LDS provided by ANL with little success, terminated (P_{zz} low, not switchable)
- Cryogenic ABS completed with superconducting 6-poles: up to $8 \cdot 10^{16}$/s H/D achieved



•Measured target polarization of P_{zz} = 0.40 seems affected by recombination, improv. in progress

•Future plans include study of π^o electro product. and to use a deuterium Jet as pol. electron target for measuring the electron beam polarization

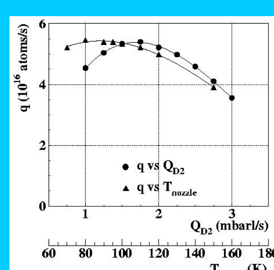
Status of the DEUTERON target: see Proceed. PST01, p.62



HERMES Target at HERA-DESY

- In 1995 successfully operated with ^{3}He target, since then as ABS-SC target for H and D:
  - 1996-97 longitud. H
  - 1998-00 longitud. D
  - since 2001 transverse H
- Operational continuously about 8 months /year, plus setting up
- Large data sets for DIS on polarized and unpolarized gases collected

Transverse target magnet, see talk by D.Reggiani this afternoon, session 8



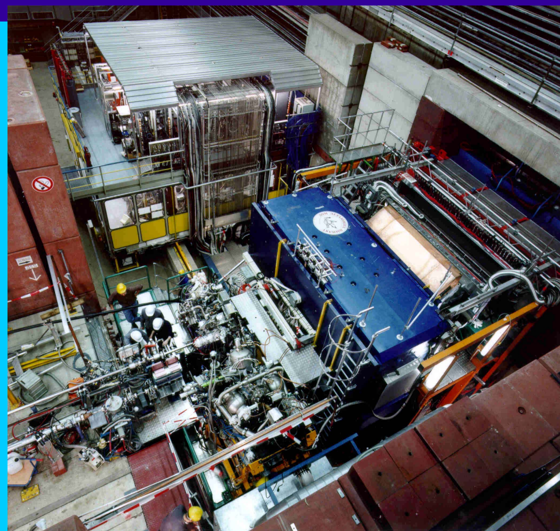
HERMES ABS: dependance on flow rate and nozzle temp.

Interesting finding: there is a considerable ballistic molecule fraction in the beam! See talk by A.Nass this afternoon

HERMES Experiment

Top view of the HERMES experiment

- left: target and forward detectors
- right: spectrometer magnet and backward detectors
- background: electronic hut



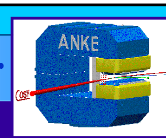
V. Status of Future Facilities

Under construction or in design

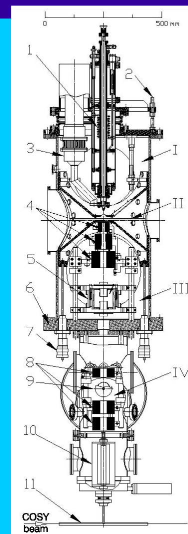
• **ANKE/COSY**	D, H	ABS-SC	**p** (2.5GeV)
• **RHIC polarimeter**	H	ABS-J	**p** (250GeV)
• **BLAST/Bates**	H, D	ABS-SC*	**e** (1GeV)
	H	LDS-SC	**e** "
	^{3}He	OPS-SC	**e** "

*) commissioning in progress

Target of the ANKE-Spectrometer



- H and D storage cell target, working at ‚high' (D) or ‚low' (H) guide field
- State-of-the-art ABS with excellent magnet system and flexible rf transitions for maximum P_z and P_{zz}
- More than $7 \cdot 10^{16}$ H/s accepted by compression tube
- Beam polarization measured by Lamb Shift polarimeter (P ~ 0.9)
  see Proc. PST01, p.47, and talks R.Engels (Tue.) and F.Rathmann (this afternoon)
- Chamber for storage cell target and Si-strip detector under construction



Jet Polarimeter for RHIC

- No polarization standard available for RHIC proton beams
- High statistics polarimeters based on the CNI effect are relative only
- Idea is to relate pp scattering of unpolarized RHIC protons off a Jet of well known polarization to that of polarized protons off an unpolarized (spin-averaged) Jet in the same kinematics
- The required Jet will be produced by an ABS and its polarization measured by a Breit-Rabi type polarimeter
- For the required 3% precision the molecular background at the IP needs to be measured

  see talks this afternoon by T.Wise and A.Zelenski in session 8

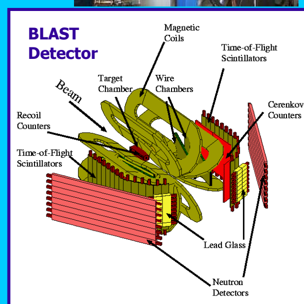
ABS Target for BLAST-Bates

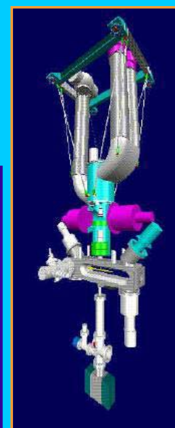
- Target based on former AmPS target(NIKHEF)
- Located within the toroid spectrometer field coils

• Turbopumps placed outside the field region

• Other sensitive components are shielded or also placed out-side the coil system

• The target is being commissioned
see H.Kolster et al, Proc. PST01, p.37, and talk this afternoon





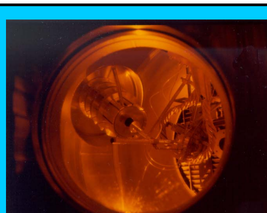
VI. Conclusions and Outlook

Status of Gas Targets for Storage Rings

- Mature technology, well understood
- Have enabled new types of Spin experiments:
  - single user in medium energy storage rings IUCF cooler, COSY, VEPP-3, Bates south hall ring
  - parallel user in high energy colliders HERA-e
- Extremely low background
  - study of reactions with very low cross section
  - open detectors
  ......full angular coverage in one run PINTEX
  ......exploratory experiments HERMES
- New experiments based on state-of-the-art gas target should lead to much improved performance!
  .....e..g. Toroid @ COSY

Outlook: Higher Luminosities?

- Presently available technology for H/D gas targets:
  Atomic Beam Source plus Storage Cell
- ABS intensity seems limited to ~ 10^{17} at./s (2 substates)
- Density enhancement by having a longer cell!
  - partly moves the problem to accelerator and detector design
- Example (HERA-e: here luminosity is crucial)
  - 1m long cell with C_{tot} = 5 l/s gives t = 10^{15}/cm^2
  - One year dedicated HERA-e running (10^7s @ 30mA) results in an integrated luminosity of 3 fb^{-1}: 20x HERMES „Golden Year" 2000!
  ....plus extra gain from improved electron polarization
- Big improvements on (10 y old) HERMES design possible if detector and machine optics tailored to new cell



Polarized Jets and Storage Cell Targets for Storage Rings

- **have done a fantastic job in the past**
- **some new experiments based on these targets are coming up soon**
- **technology ready for future challenges**