Disposition

H. Seyfarth, IKP, FZ Jülich

# Spin effects in hydrogen and deuterium recombination

[A. Vassiliev: Polarization in $H_2$ and $D_2$ Molecules (ISTC project)] *

## I. Introduction

The H and D atom
The $H_2$ and $D_2$ molecule

## II. Polarized H or D storage-cell gas targets

## III. The ISTC project

Activities in Gatchina, status
Combined set-up in Jülich

## IV. Outlook

**Participating institutions**

**Forschungszentrum Jülich,** Institut für Kernphysik, Exp-II:
R. Engels, K. Girgoriev, B. Lorentz, F. Rathmann, H. Seyfarth
+ infrastructure IKP, COSY group, infrastructure FZJ (ZAT, ZEL)

**(St.) Petersburg Nuclear Physics Institute** (Gatchina),
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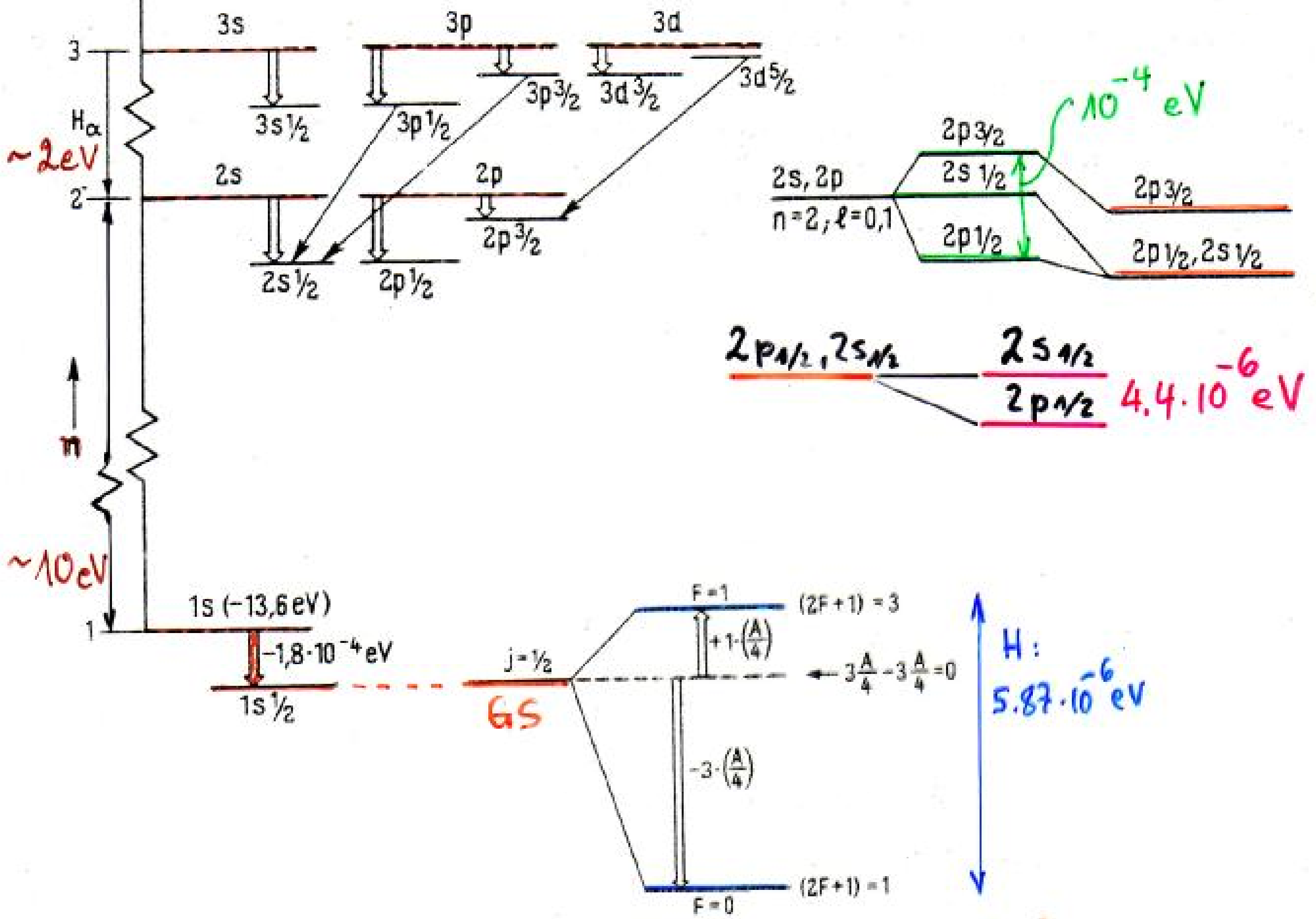
N. Chernov, L. Kochenda, A. Kovalev, P. Kravtsov, M. Mikirtytchiants,
M. Polavtsev, S. Sherman, V. Trofimov, A. Vassiliev
+ infrastructure Department of Cryogenics and Superconductive Techniques

**Universität zu Köln**, Institut für Kernphysik:
H. Paetz gen. Schieck

* Topics of this talk, which had been announced, are included in the present talk

# The H and D atom

**H**



- $E_n = \frac{m_p}{m_p + m_0} R_\infty \cdot \frac{1}{n^2}$ ; $R_\infty[eV] = hc \cdot \frac{m_0 Z e^2 \alpha}{4\pi\hbar^2}$
- Spin-orbit ($\vec{s}\cdot\vec{\ell}$) coupling ⇒ $j = \ell \pm 1/2$ } FS
- Relativistic corrections ⇒ $E = f(j)$ } ($10^{-5}$)
- QED effects $g_{el} = 2.00231....$

  degeneracy $2(3)\,p_{1/2}$, $2(3)\,s_{1/2}$ removed
  (Lamb shift)
- Hyperfine structure (HFS) $V_{HFS} = -\vec{\mu}_p \cdot \vec{B}_0$

  $\mu_p/\mu_{el} = 1/658 \rightsquigarrow 10^{-7}$

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**D** : $m_d = 2 \cdot m_H$ ; $\mu_d/\mu_p = 0.86/2.79$

$I_d = 1$ (boson!) ; $F = 3/2, 1/2$

# The $H_2$ molecule

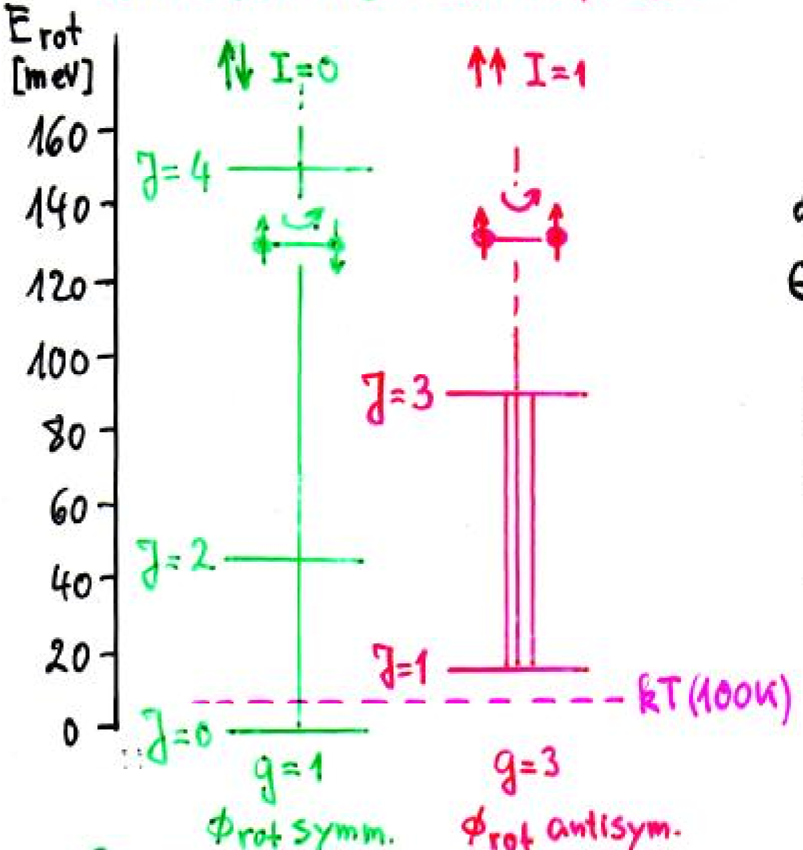
$H_2$ ("homonuclear diatomic molecule")

2 protons with $I = 1/2$ (fermions)

$\psi_{tot} = \psi_r \, \phi_{rot} \cdot \chi_{spin}$ antisymmetric

| para-$H_2$ ($p$-$H_2$) | ortho-$H_2$ ($o$-$H_2$) |
|---|---|
| singlet states | triplet states |
| spin w.f. antisym. | spin w.f. sym. |

| | | $m_I$ |
|---|---|---|
| $p$-$H_2$: | $\frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$ | 0 |
| $o$-$H_2$ | $\uparrow\uparrow$ | 1 |
| | $\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow)$ | 0 |
| | $\downarrow\downarrow$ | −1 |



G.S. $\psi_r$ symm. , ${}^1\Sigma^+$

$d = 0.74144$ Å

$\Theta = 3.07 \cdot 10^{-29}$ eV·s²

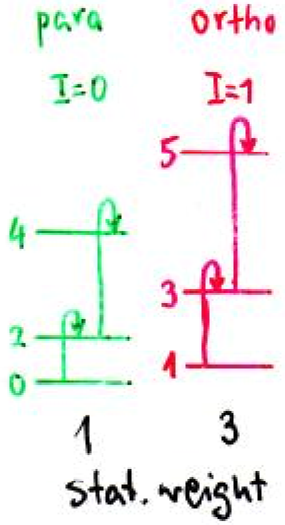
$(J=1) \to (J=0)_{g.s.}$

spin flip transition

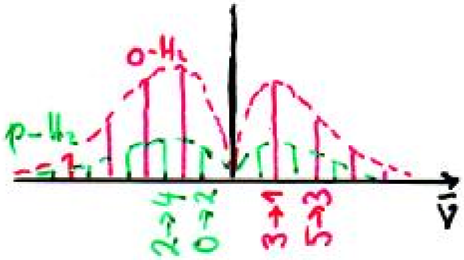
$\tau = \mathcal{O}\{a\}$

Enhancement by, e.g., paramagnetic material

g.s.: stable, "for some time" even after warming or evaporation



Stronger lines from "ortho-$H_2$ ($D_2$)



$T \approx 300$ K

$$\frac{\text{Int.}(1\to3)}{\text{Int.}(0\to2)} \approx \frac{3}{1}$$

No $\Delta I = 1$ transitions

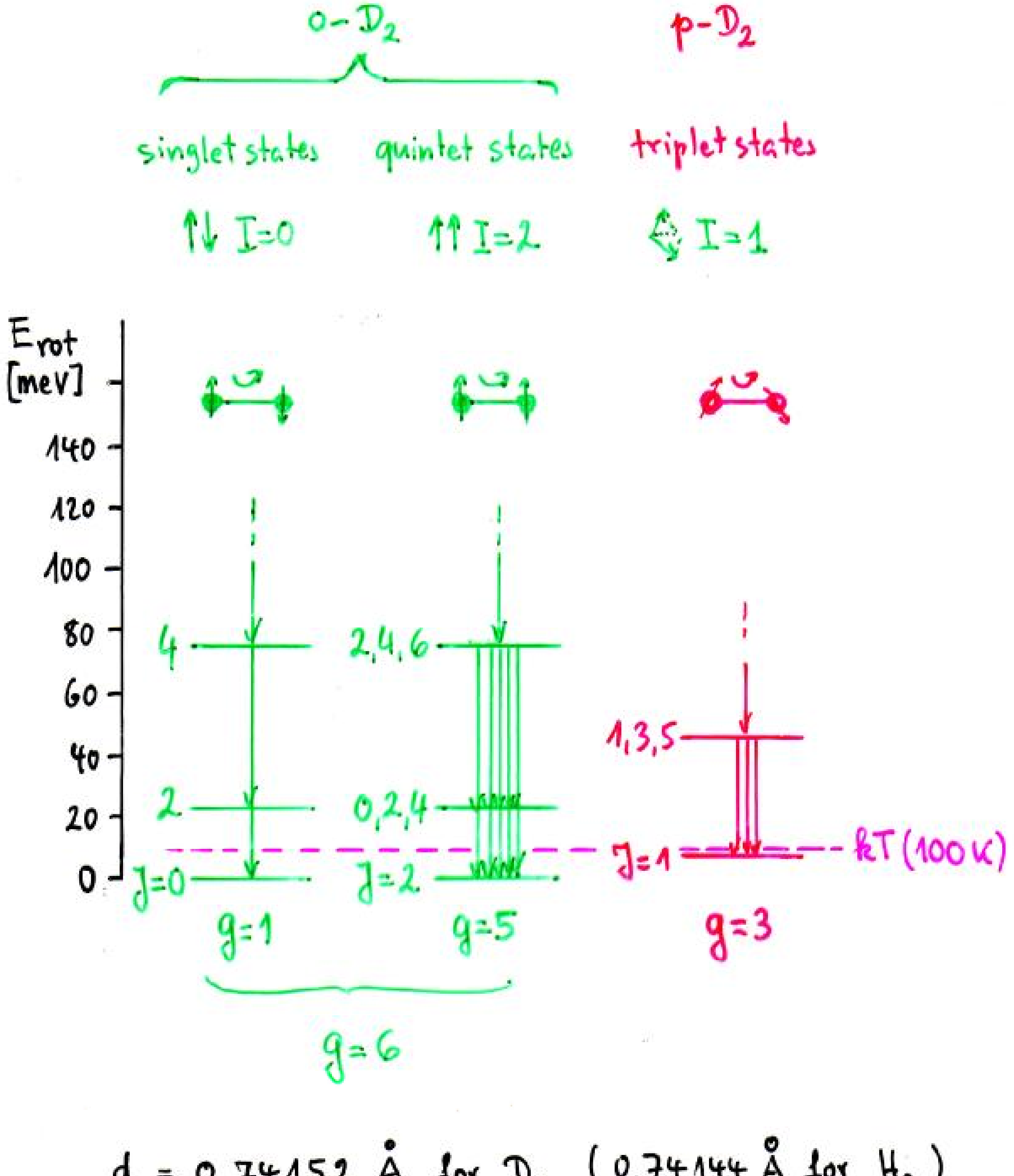
$\Delta I = \pm 2$ rotational Raman transitions

# The $D_2$ molecule

$D_2$

2 deuterons with $I = 1$ (bosons)

$\psi_{tot} = \psi_r \cdot \phi_{rot} \cdot \chi_{spin}$ symmetric



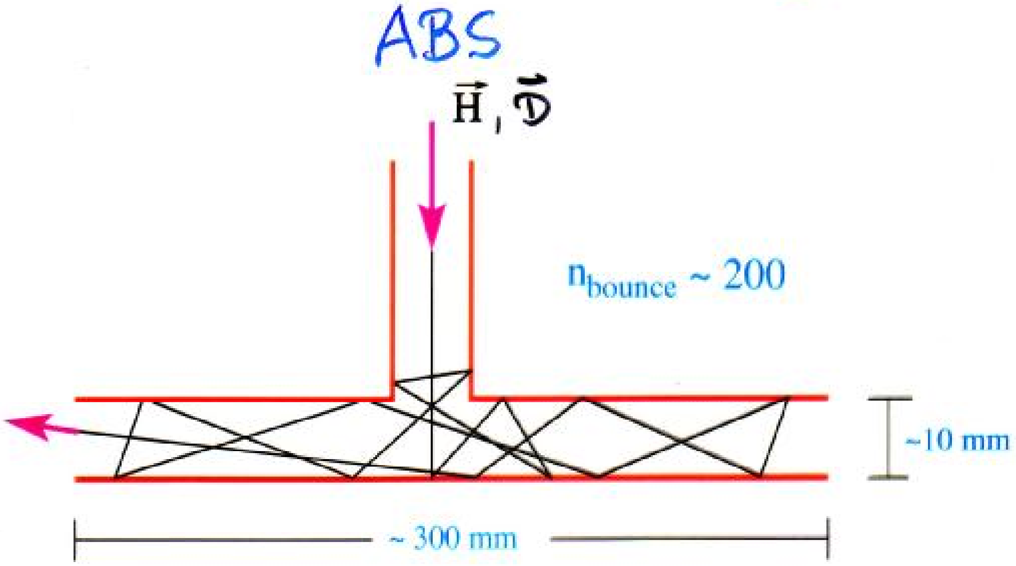
$d = 0.74152$ Å for $D_2$ ($0.74144$ Å for $H_2$)

$$\rightarrow \Theta_{D_2} = 2 \cdot \Theta_{H_2} = 6.14 \cdot 10^{-29} \text{ eV} \cdot \text{s}^2$$

$$E_{rot} \sim \frac{1}{\Theta} \rightarrow E_{rot}^{D_2} = \frac{1}{2} E_{rot}^{H_2}$$

The storage cell
(transparency: F. Rathmann)

# Recombination in a Storage Cell

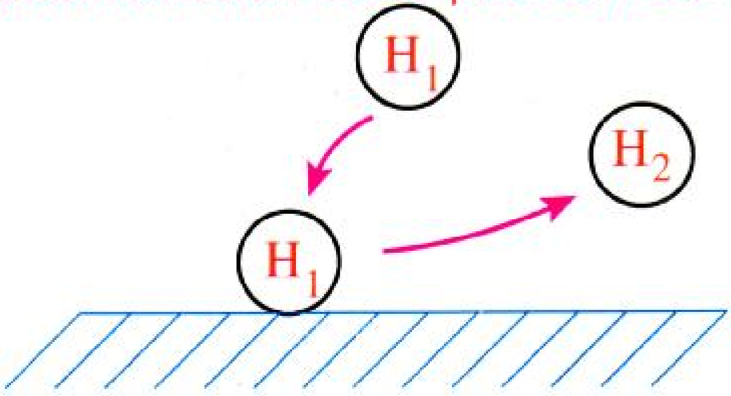


**Reduction of Nuclear Polarization** in cell by:

- Spin Relaxation

  ⇒ Suitable coatings: Ice, Teflon, Fomblin, Drifilm

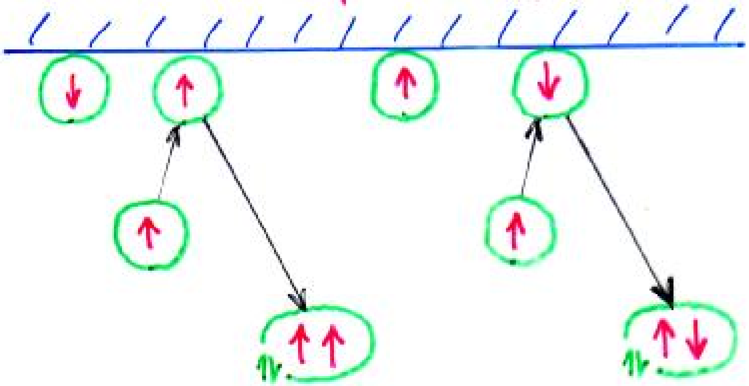
  $\vec{D}_1 + \vec{D}_1 \to D_2, \vec{D}_2$?
- Recombination $\vec{H}_1 + \vec{H}_1 \to H_2, \vec{H}_2$?
  - Note: No volume recombination in a storage cell
    typical: $P \approx 10^{-4}$ mbar $\approx \lambda = 0.5$ m
  - $\Longrightarrow$ Recombination takes place on surface!



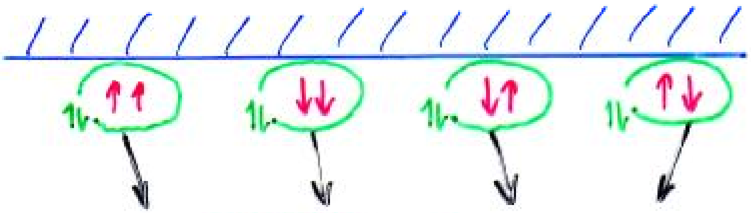
# Maintenance of nuclear polarization in recombination

$$\vec{H}_1 + \vec{H}_1 \to H_2, \vec{H}_2$$

$$n_{surf}^{\uparrow} = n_{surf}^{\downarrow} \, ?$$



$$P_{mol} = \frac{n_p^{\uparrow} - n_p^{\downarrow}}{n_p^{\uparrow} + n_p^{\downarrow}} = \frac{3-1}{4} = \frac{1}{2} \quad \left(< \frac{1}{2} ?\right)$$



$$P_{mol}^{migr} = 0 \quad (?)$$

$$P_{mol} = f(\text{surf.mat.}, T, B)$$

H $(I = 1/2)$

D $(I = 1,\ \mu_d/\mu_p = 0.86/2.79)$

The NIKHEF experiment
(transparency F. Rathmann)

# Evidence for Nuclear Polarized $\mathrm{D}_2$

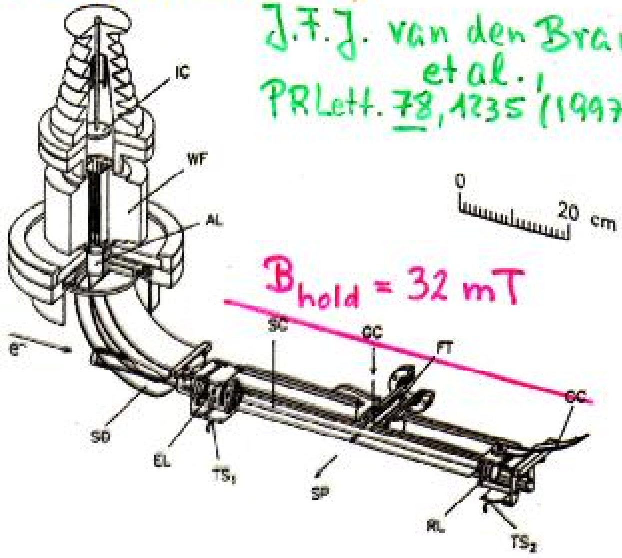
## PIT at AmPS (NIKHEF)

Beam: $e^-$ 704 MeV

Target: tensor-Pol. D

Extraction: $\mathrm{D}^-$ and $\mathrm{D}_2^-$

Dissociation: $\alpha = \frac{m_{D_1}}{m_{D_1} + 2 \cdot m_{D_2}}$



J.F.J. van den Brand et al., PRLett. 78, 1235 (1997)

$B_{hold} = 32$ mT

| | | |
|---|---|---|
| variable $\alpha$ (different cells) | $\Longrightarrow$ On Teflon: | $\alpha = 0.71 \pm 0.02$ |
| | On Copper: | $\alpha = 0.26 \pm 0.03$ |

Atomic Pol. $^3\mathrm{H}(\vec{\mathrm{d}}, \mathrm{n})\alpha$ [SP & WH, NIM **A349**,321 **A326**,416]

[Zhou *et al.*, NIM **A379**, 212]

Total Target Pol. $T_{20}$ *ed* scattering

**Result:** $$Q_{zz}(\mathrm{D}_2) = (0.81 \pm 0.32) \cdot \mathrm{Q}_{\mathrm{zz}}(\mathrm{D})$$

[van den Brandt *et al.*, PRL **78**, 1235 (1997)]

**But:**

Result based upon the assumption that $P_{zz}(D)/P_{zz}(D_2)$, $A_{ed}(D)/A_{ed}(D_2)$ are the same for Cu and Teflon

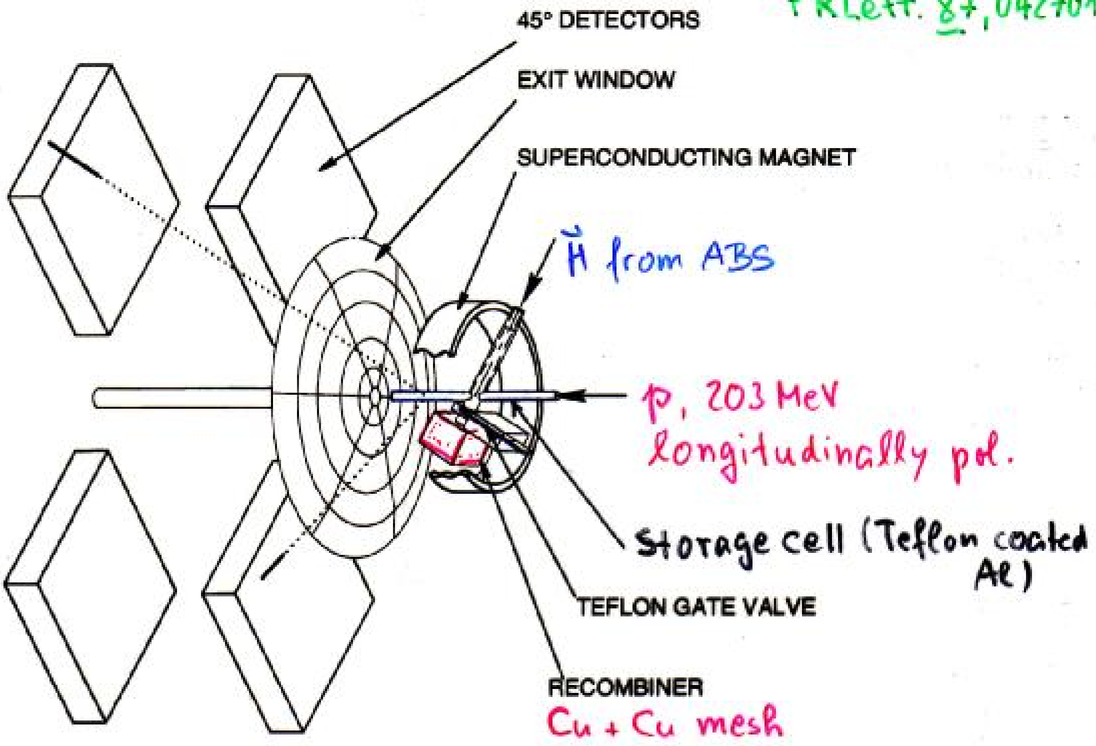
- Is this really true?
- Does it also hold for $\vec{\mathrm{H}}$–targets?
- How does effect depend on T, B . . . ?

$\Longrightarrow$ Need Experimental Verification and more detailed Study!

The IUCF experiment
(with use of a transparency
of F. Rathmann)

# Setup at IUCF

T. Wise et al.,
PRLett. 87, 042701 (2001)



- Elastically scattered proton are detected in coincidence around $\theta_{\mathrm{lab}} \approx 45°$.
- Magnetic Field at Target: Strong field to decouple electron and nucleon spin $\Rightarrow \mathrm{B} > \mathrm{B}_c^{\mathrm{H}} = 50.7$ mT. Closed–orbit distortions of the stored beam avoided, cell surrounded by a **single Superconducting Coil:**

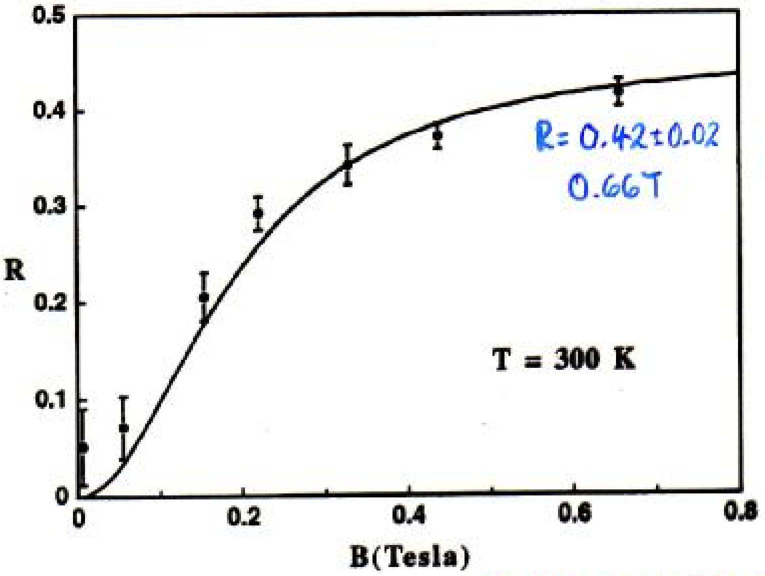
$\vec{B}$ *longitudinal* at Target: $B_{\max} = 0.66$ T

- Recoombiner–Volume with gate–valve
  - **Open:** Atoms exposed to Copper (low $\alpha$).
  - **Closed:** Atoms exposed to Teflon (high $\alpha$).

The IUCF experiment
(with use of a transparency
of F. Rathmann)

# Dependence on magnetic Field

$R = \frac{P_{H_2}}{P_H}$



R = 0.42±0.02
0.66T

[T. Wise *et al.*, PRL **87**, 042701 (2001)]

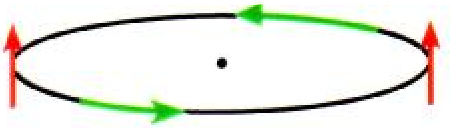
$R = 0.46 \cdot e^{-10^3 \cdot \left(\frac{6.1}{B[mT]}\right)^2}$

n = 1000 (±30%)

Measured: $\frac{d_t(o)}{d_t(c)} = 1.364 \pm 0.004$, ideally $\sqrt{2}$, (−3.7%!)

| | $\alpha$(open) | $\alpha$(closed) |
|---|---|---|
| Measured $\alpha$: | $0.089 \pm 0.007$ | 1 |
| | 0 | $0.879 \pm 0.010$ |

Ortho-$H_2$



Spin–Rotation $B' = 2.7$ mT $\quad B_c = 1.19\left[\frac{4}{3}B'^2 + \frac{24}{25}B''^2\right]^{\frac{1}{2}}$

Dipole–Dipole $B'' = 3.4$ mT $\quad B_c = 5.4$ mT $(J = 1)$

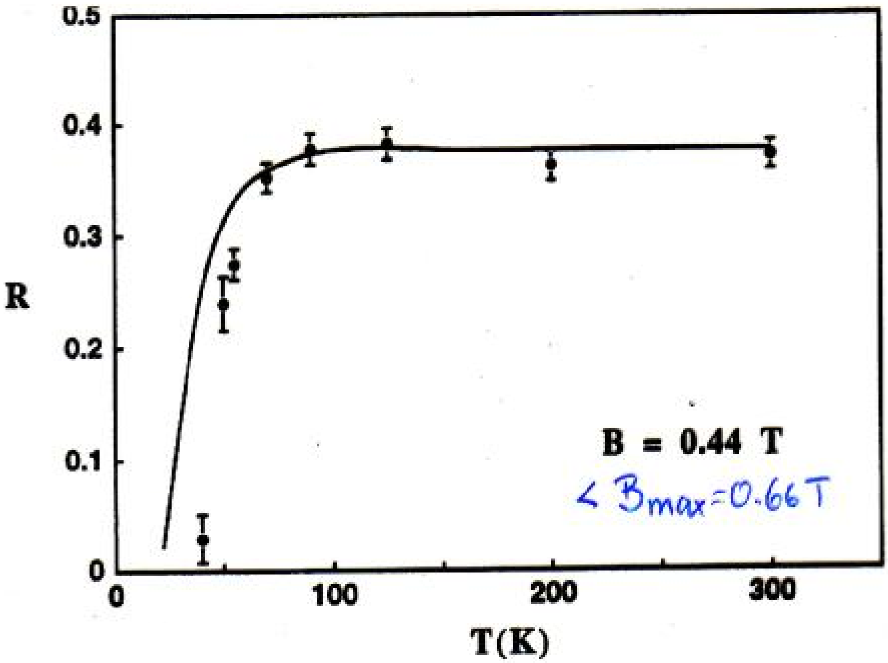
adding $J = 3$ (12%) → $B_c = 6.1$ mT

$$\boxed{R = R_0 \exp\left[-n\left(\frac{B_c}{B}\right)^2\right]}$$

(using $n = 1000$ and $R_0 = 0.46$)

# Temperature Dependence

$R = \frac{P_{H_2}}{P_H}$



Curve: Nuclear Polarization of H–Atoms in a copper cell with 80 wall collisions, where about 65% of the atoms recombined to molecules.

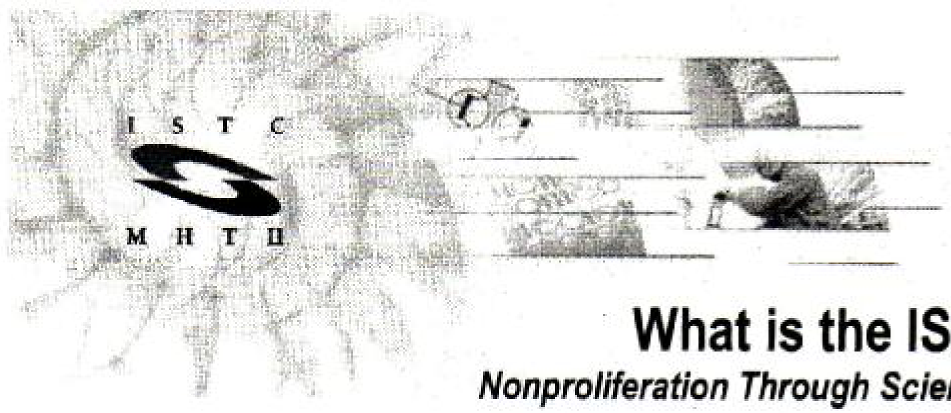
$$R = R_0 \cdot e^{-n (B_c/B)^2}$$

$n = 80, B = 440$ mT

$$B_c = f(n_{J=3}/n_{J=1}) = f(T)$$

| $T$ | 300 K | 100 K |
|---|---|---|
| $n_{J=3}/n_{J=1}$ | 0.13 | $2 \cdot 10^{-4}$ |
| $B_c$ | 6.1 mT | 5.4 mT |
| $R/R_0$ | 0.9847 | 0.9880 |

ISTC - an international organisation



# What is the ISTC?

## *Nonproliferation Through Science Cooperation*

### A Decade of Service - History of the ISTC

The International Science and Technology Center (ISTC) is an intergovernmental organization dedicated to the nonproliferation of weapons and technologies of mass destruction. Founded in 1992 by International Agreement by the European Union, Japan, Russian Federation, and the United States of America, the ISTC coordinates the efforts of numerous governments, international organizations, and private sector industries, providing weapons scientists from Russia and the Commonwealth of Independent States new opportunities to redirect their talents towards peaceful scientific research.

### Structure of the ISTC

The ISTC Governing Board is comprised of representatives from Canada, European Union, Japan, Russian Federation, the United States, plus a CIS country rotating member. Scientific Advisory experts guide proposal evaluation and identify new priorities for project and program development.

The Secretariat, headed by the Executive Director and Deputies from each of the Governing members, includes nearly 200 scientific, financial, and administrative staff. The ISTC maintains its Secretariat headquarters in Moscow, with branch offices in Armenia, Belarus, Georgia, Kazakhstan, and Kyrgyzstan, and an information office in Tajikistan. The ISTC enjoys support at the highest levels in the capitals of its member countries.

Governing Board, 03 November 2000 (23rd meeting)

Approval of:

1861 Creation of the Universal Gas Polarized Target for the Investigation of the Nuclear Polarization in the Molecules of Hydrogen (Deuterium) at the Different Interactions with the Target's Walls
Project Manager: Chernov N N; Leading Institution: Nuclear Physics Institute (Gatchina, Leningrad reg.); Collaborator: Universitat zu Koln / Institut fur Kernphysik (Köln, Germany); Duration: 36 months; Funding parties: EU+Other

The ISTC project
(scientific aims)

# Conclusion and Outlook

- One can produce nuclear–polarized Ortho-Hydrogen
  - In a field of $B = 0.66$ T

$$\boxed{\frac{Q(\text{open})}{Q(\text{closed})} \approx \frac{Q(\text{Molecule})}{Q(\text{Atom})} = 0.42 \pm 0.02}$$

- **Interesting New Object!**

- Further Investigations should address
  - $\begin{matrix}\vec{H}_2\\ \vec{D}_2\end{matrix}\left(\overset{\text{magnetic field strength}}{B}, \underset{\text{cell-wall temperature}}{T}, HFS^{1}, n^{2}, A^{3}\right)$

- Research in the near Future in the framework of an International Science and Technology Center Project (Jülich, Gatchina, Cologne)

[Poster HK14.29]

1 dependence of hyperfine-state population

2 dependence of number of wall collisions (variation of cell dimensions)

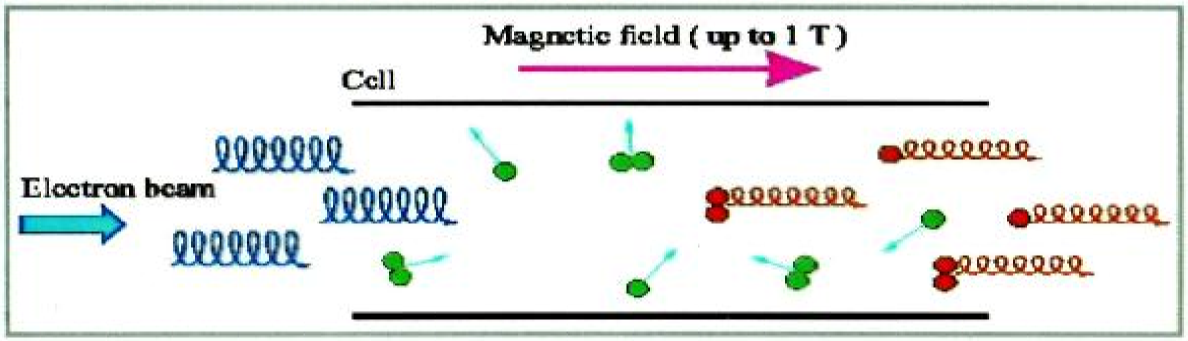
3 dependence of cell-surface material

The ISTC project
(principles)
Transparency of
F. Rathmann

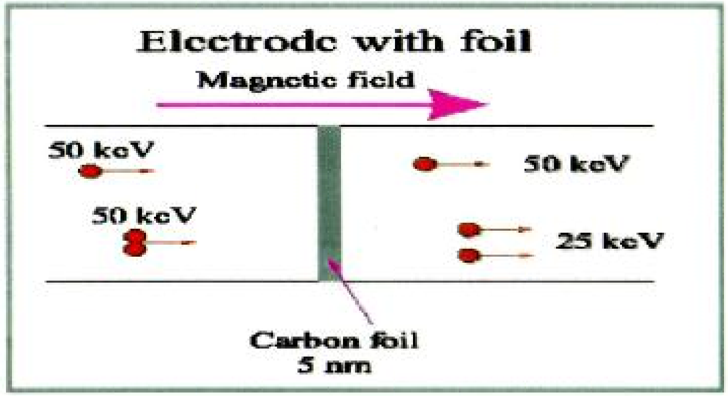
Electron-impact ionization - acceleration - dissociation

# Experimental Concept

1. Conversion of polarized atoms and molecules into ions



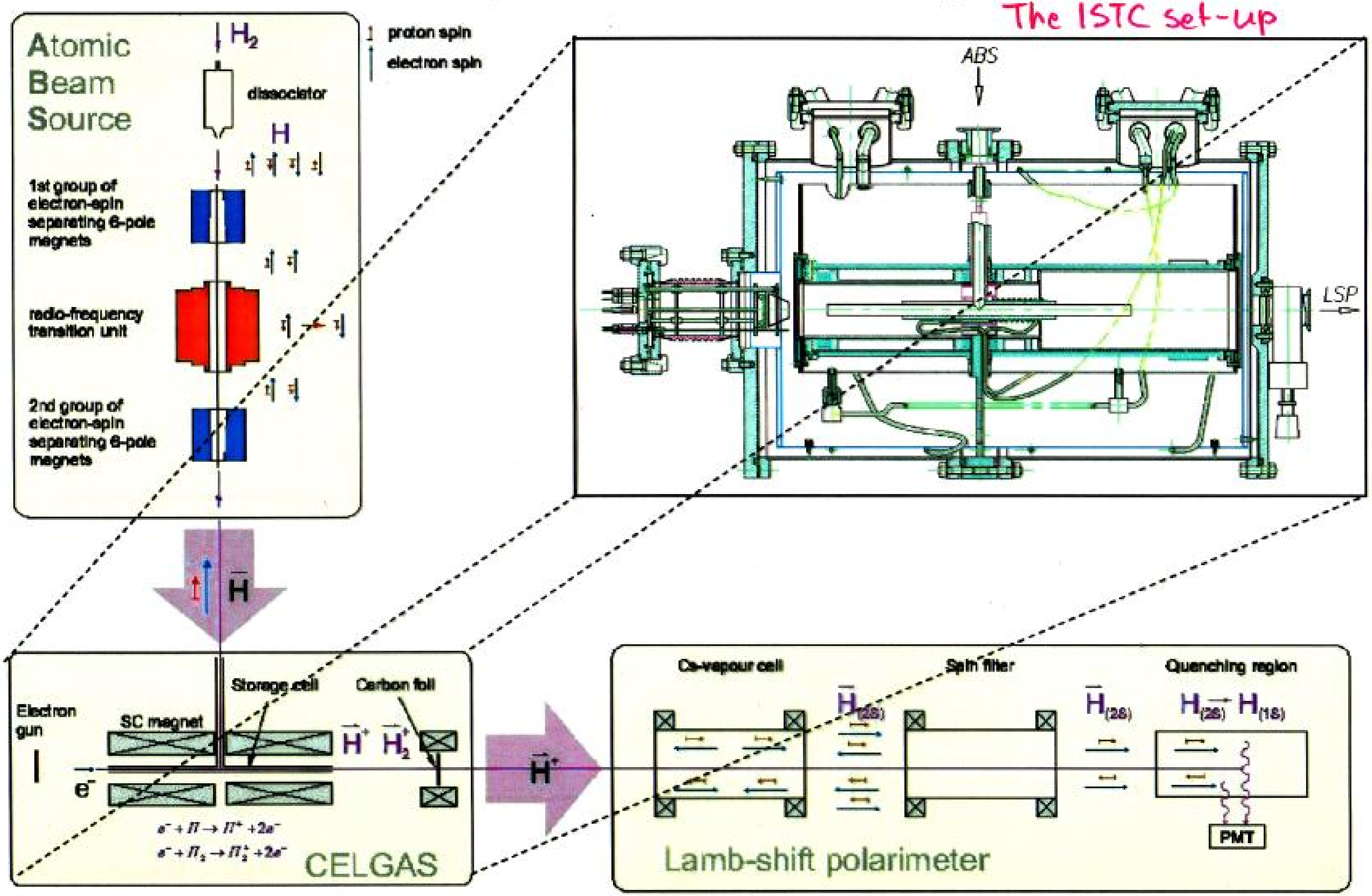
2. Conversion of $H_2$+ and H+ ions into protons with different energy



3. Separation of ions by energy
4. Measurement of proton polarization in Lamb-Shift polarimeter

# Experimental setup

The ISTC set-up



The ISTC project
(set-up development)
Transparency of
F. Rathmann

The ISTC project
(principles)
Transparency of
F. Rathmann

Electric potentials to adapt the proton energy behind the foil to that needed by the Lamb-shift polarimeter (≤ 1 keV) (a) for protons from H and (b) for protons from $H_2$

# Separation of ions

## Atomic polarization measurement

(a)

| Cathode | Cell | Electrode with foil | Polarimeter |
|---|---|---|---|
| +0.4 kV | +0.5 kV | -50 kV | 0 kV |

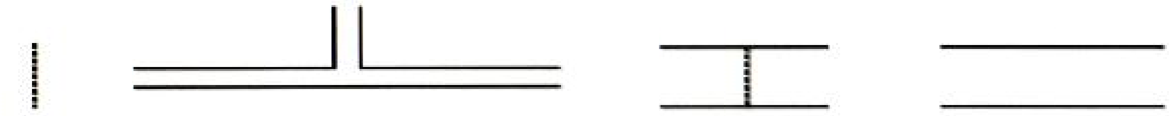
| | | | | | | |
|---|---|---|---|---|---|---|
| $H^+$ | – | $10^{-5}$ | | 50.5 | 50.5 | 0.5 |
| $H_2^+$ | – | $10^{-5}$ | | 50.5 | 2*25.25 | – |
| $e^-$ | 0.1 | 0.1 | | – | – | – |

Energy, keV

## Molecular polarization measurement

(b)

| Cathode | Cell | Electrode with foil | Polarimeter |
|---|---|---|---|
| +25.9 kV | +26 kV | -25 kV | 0 kV |

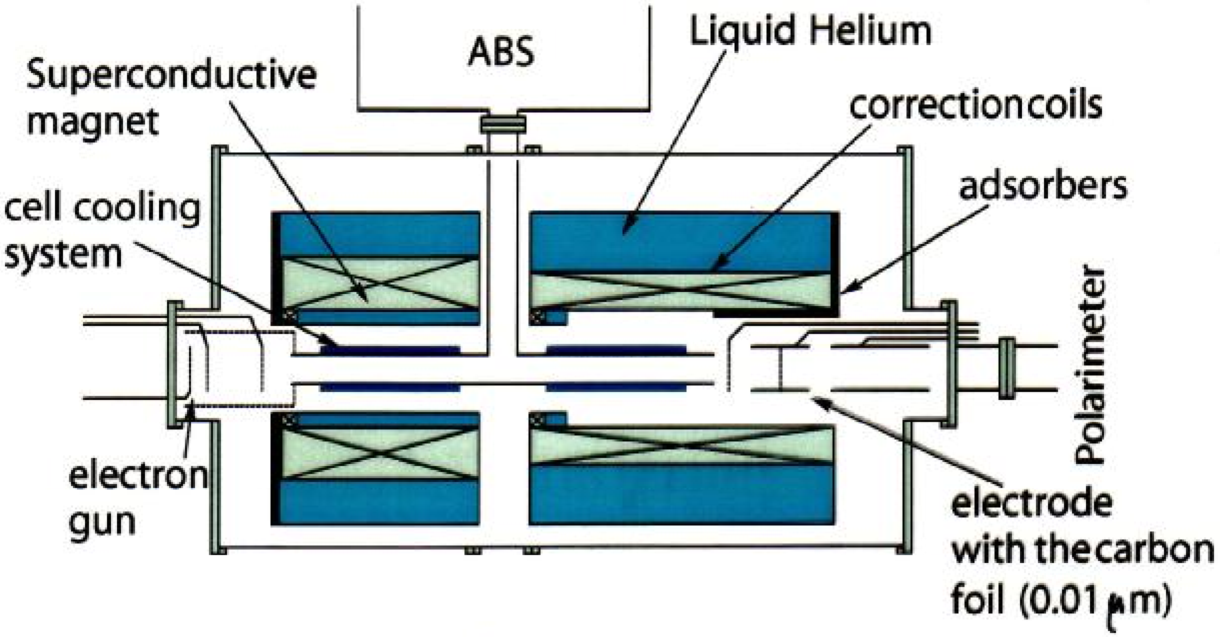


| | | | | | | |
|---|---|---|---|---|---|---|
| $H^+$ | – | $10^{-5}$ | | 51 | 51 | 26 |
| $H_2^+$ | – | $10^{-5}$ | | 51 | 2*25.5 | 0.5 |
| $e^-$ | 0.1 | 0.1 | | – | – | – |

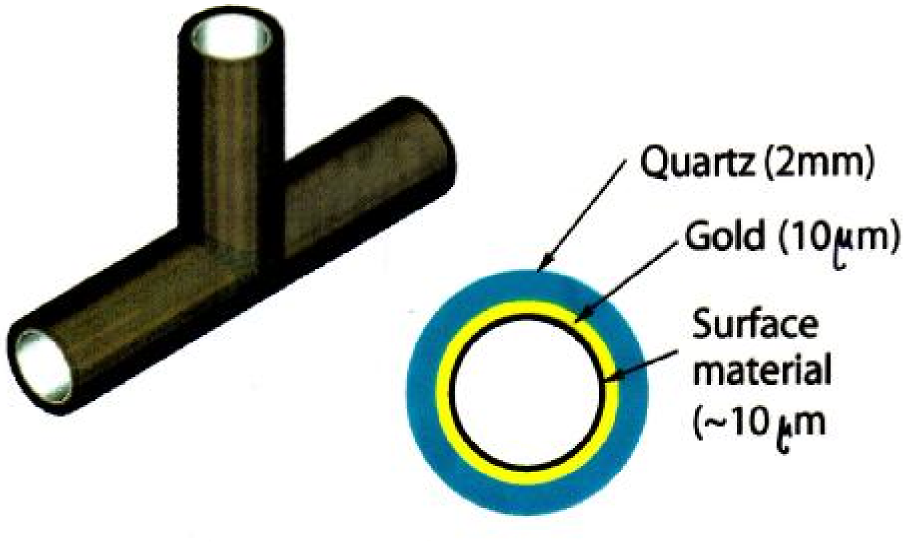
Energy, keV

The ISTC project
(Layout)
Transparency from PNPI

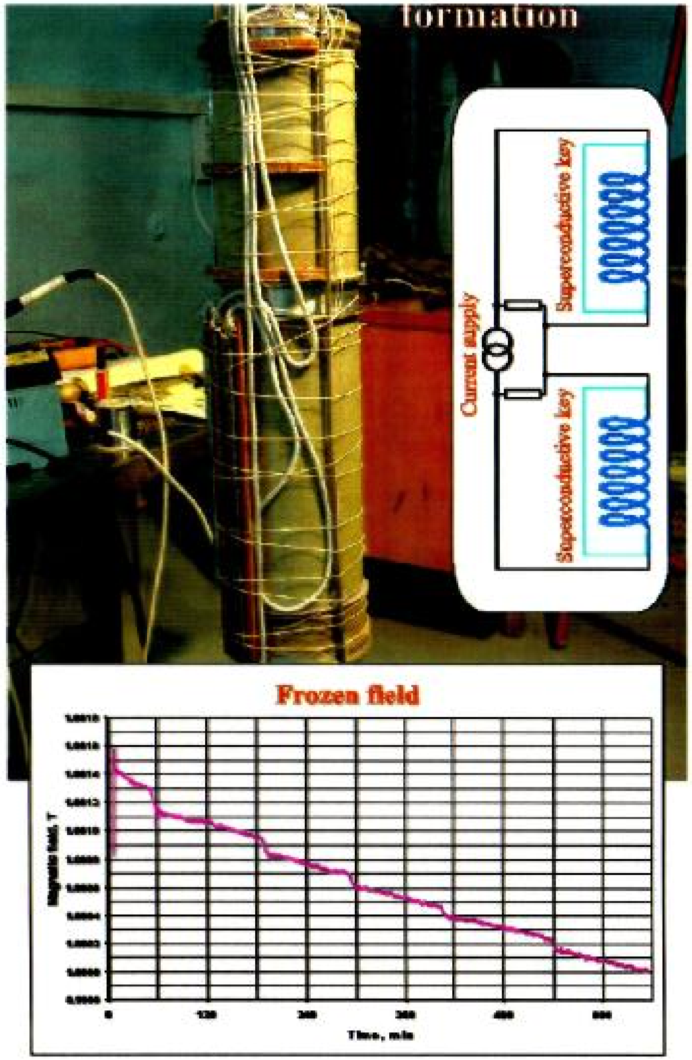
# General layout



# Quartz cell



# Superconducting Solenoid Magnet



- Magnet and powersupply assembled and tested
- Assembly of the complete experimental setup during first half of 2004 in Jülich

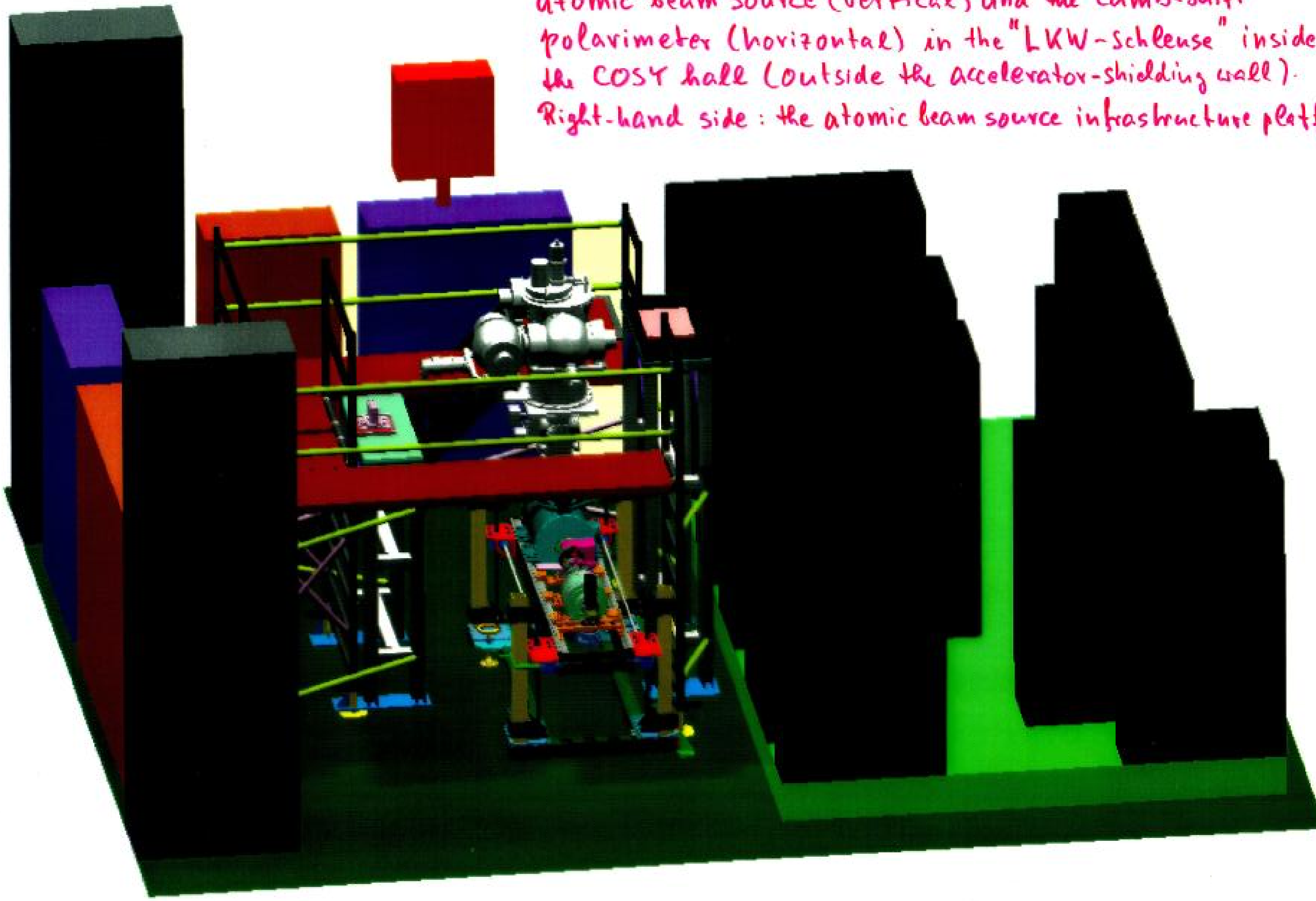
The ISTC project
(the SC magnets)
Figures from PNPI

The ISTC project
(the chamber)

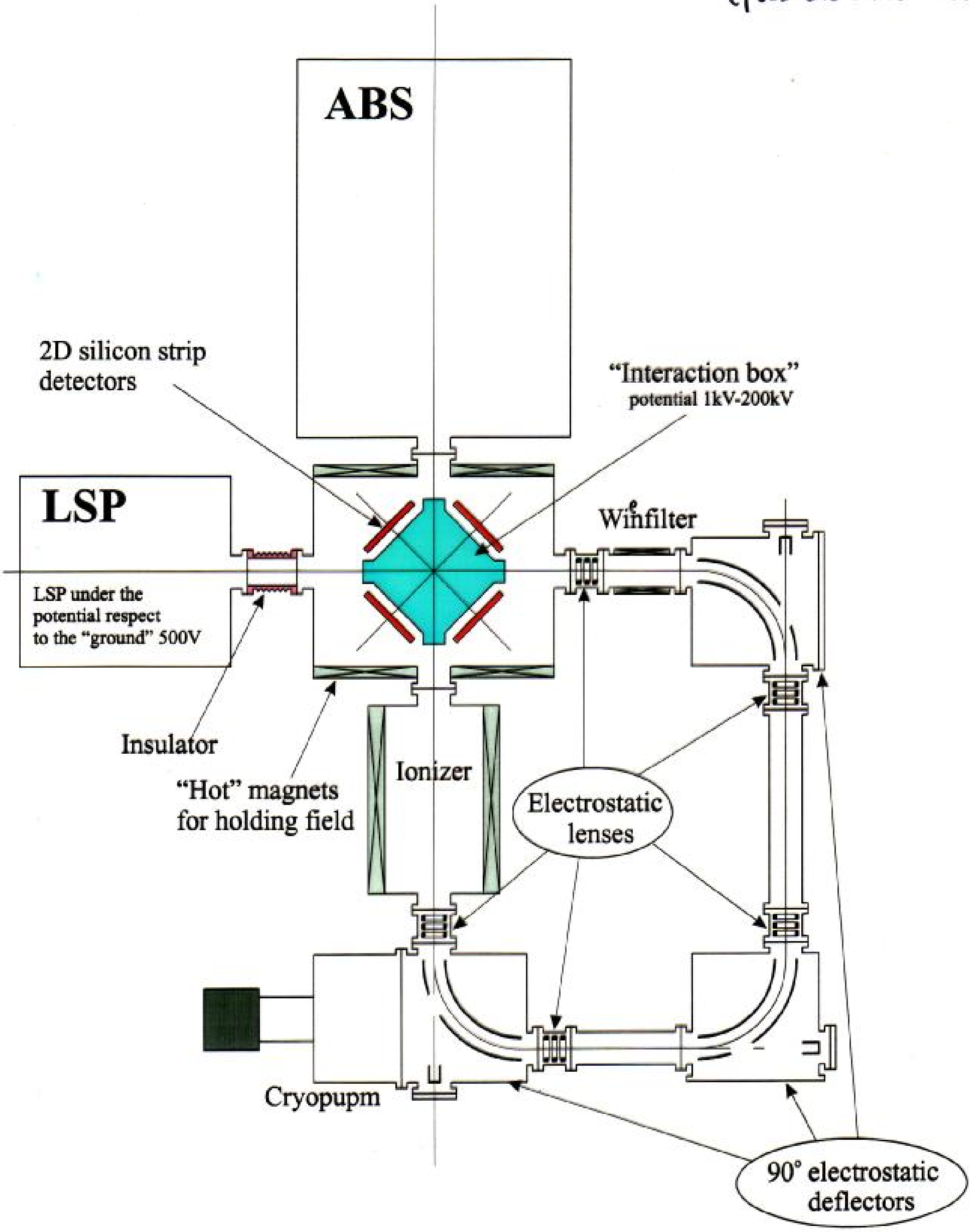
Two members of the PNPI team at the
chamber with magnet coils cooled down
(Viktor Trofimov, left, and Leonid Kochenda, right), May 2004

The ISTC project

3D drawing : the ISTC chamber between the polarized
atomic beam source (vertical) and the Lamb-shift
polarimeter (horizontal) in the "LKW-schleuse" inside
the COSY hall (outside the accelerator-shielding wall).
Right-hand side : the atomic beam source infrastructure platform



Outlook
(possible extension)



Measurement of low-energy $\vec{H}$-$\vec{H}$ and $\vec{D}$-$\vec{D}$ cross sections in a crossed beam set-up