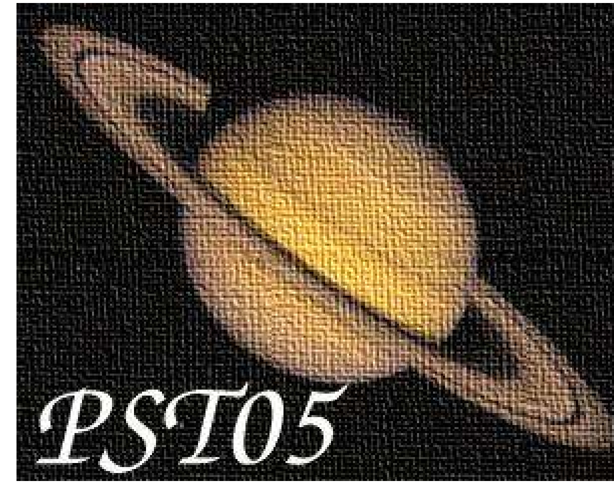
The MIT laser-driven target of nuclear polarized hydrogen gas



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- Introduction
- Original apparatus and results
- Monte Carlo simulation
- Results from an improved design (Large-1)
- Comments and Summary

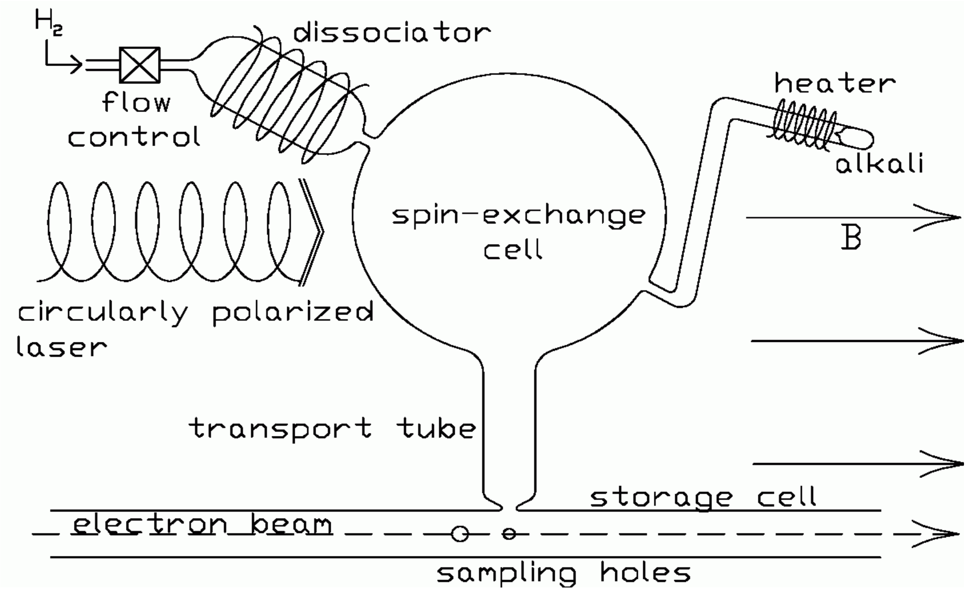
Introduction

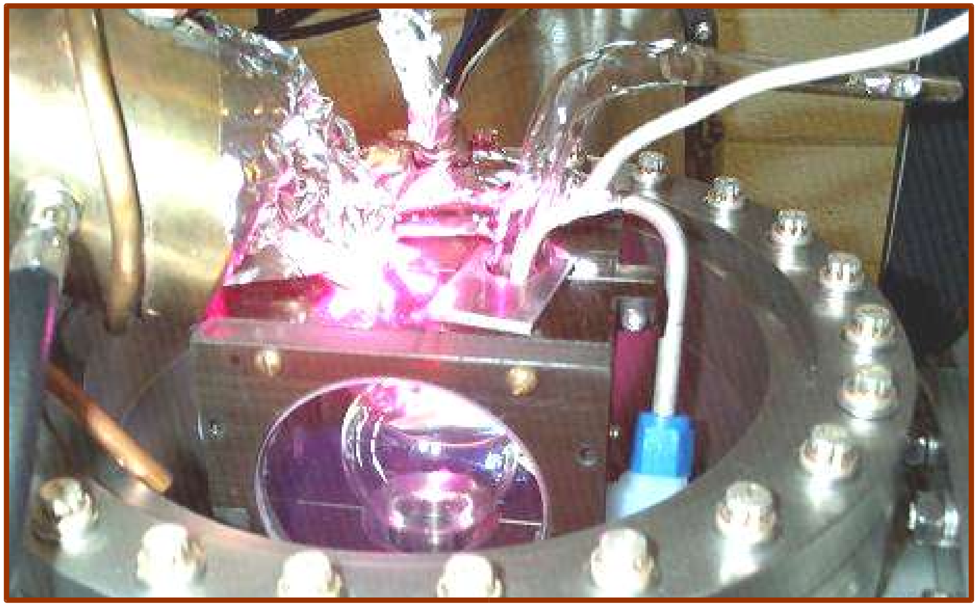
1) A circularly polarized laser is absorbed by potassium vapor, which **polarizes the potassium vapor** (optical pumping)

2) The vapor is mixed with hydrogen (H) and spin is transferred to the H electrons through spin-exchange collisions

$$\mathbf{H + \vec{K} \rightarrow \vec{H} + K}$$

3) The **H nuclei are polarized** through the hyperfine interaction during frequent H-H collisions





Spin-Temperature Equilibrium (STE)

If there are many H-H collisions, the H atom species approach

Spin Temperature Equilibrium (STE):

Spin exchange rate to H nuclei = Spin exchange rate back to H electron

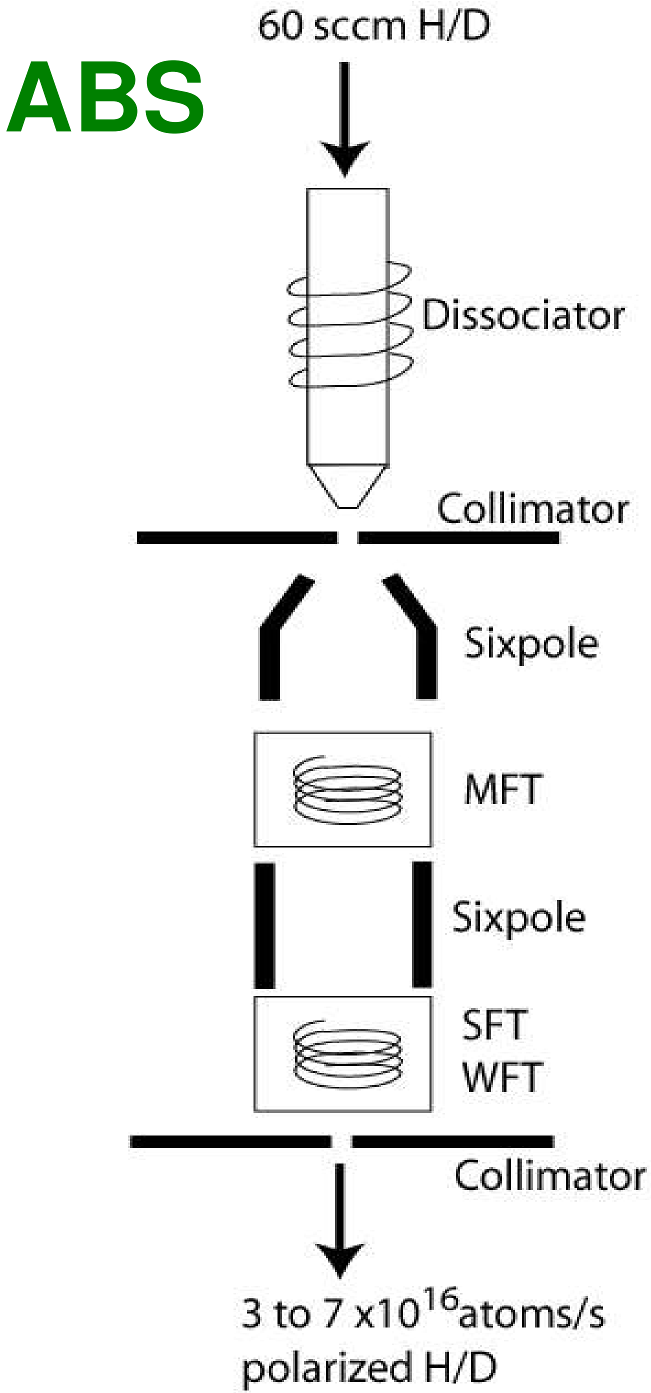
Hydrogen nucleus becomes polarized, $p_z = P_e$

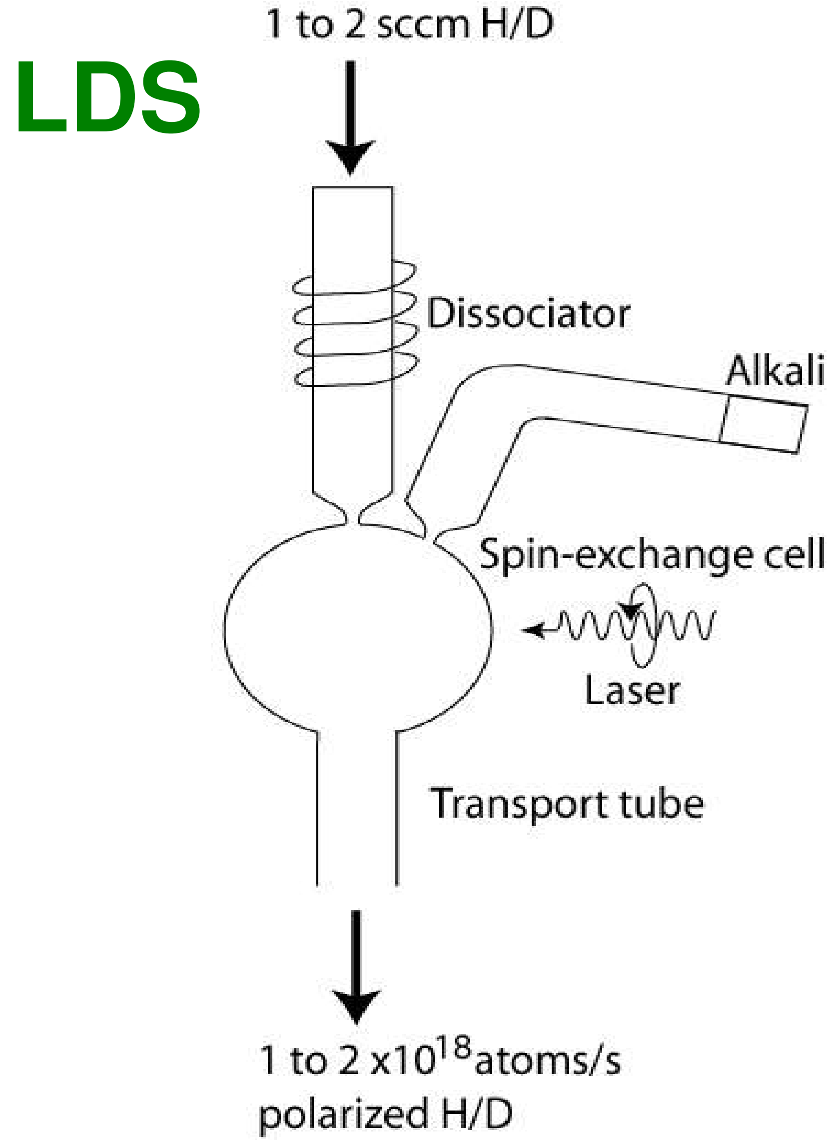
RF transition units are not required to polarize the nucleus

Spin temperature equilibrium has been verified by:

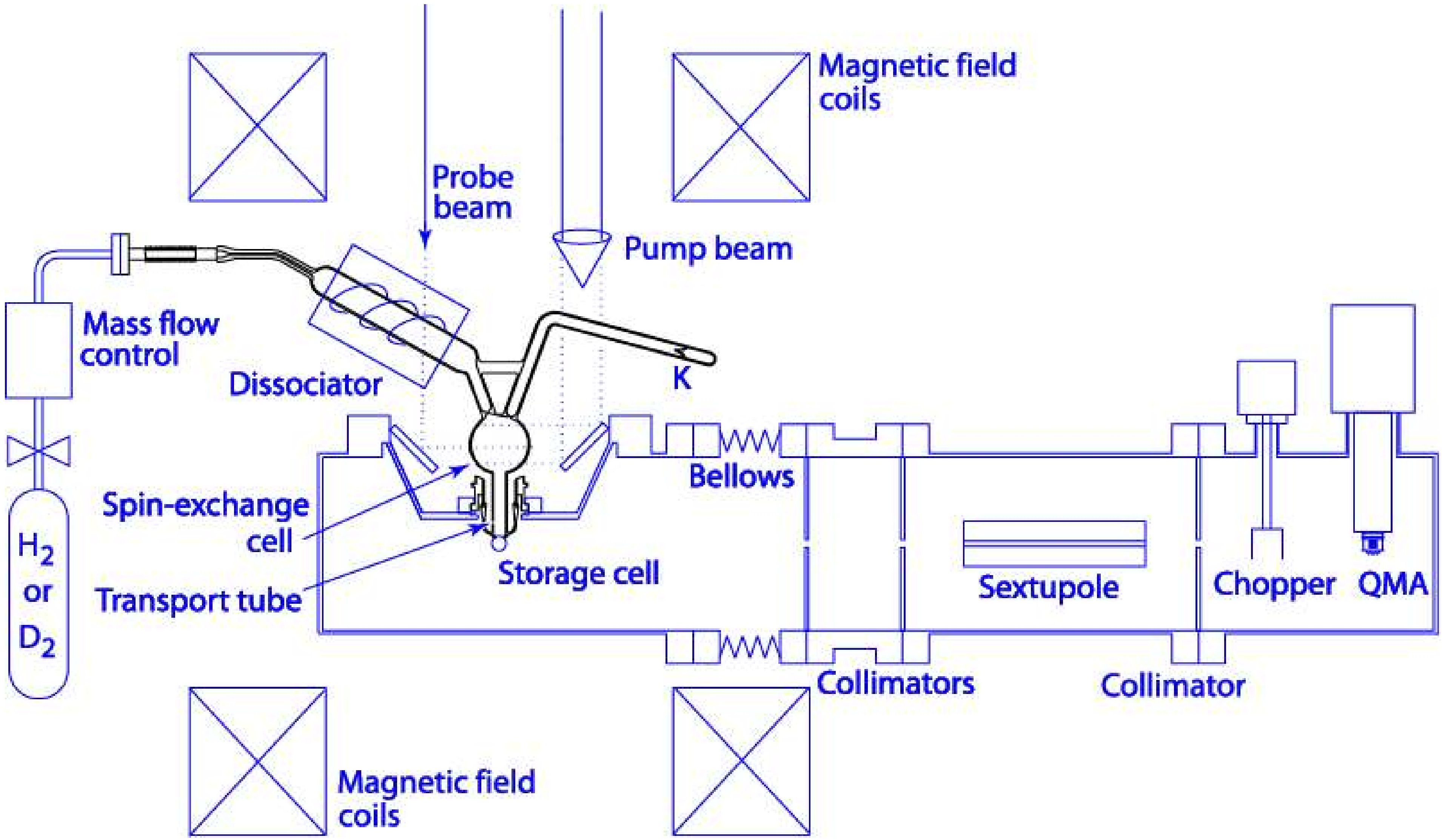
- **Breit-Rabi polarimeter for Hydrogen,Deuterium** *J. Wilbert et al., Proc. PST01, p83*
  J. Stenger et al., Phys. Rev. Lett. ***78,*** *4177 (1997)*
- **p_{zz} polarimeter for Deuterium** *J.A. Fedchak et al., Nucl. Instrum. Methods A* ***417****, 182 (1998)*
- **Proton scattering for Hydrogen** *R. V. Cadman, Ph.D. thesis, Univ. of Illinois at Urbana-Champaign (2001)*

Comparison of ABS and LDS

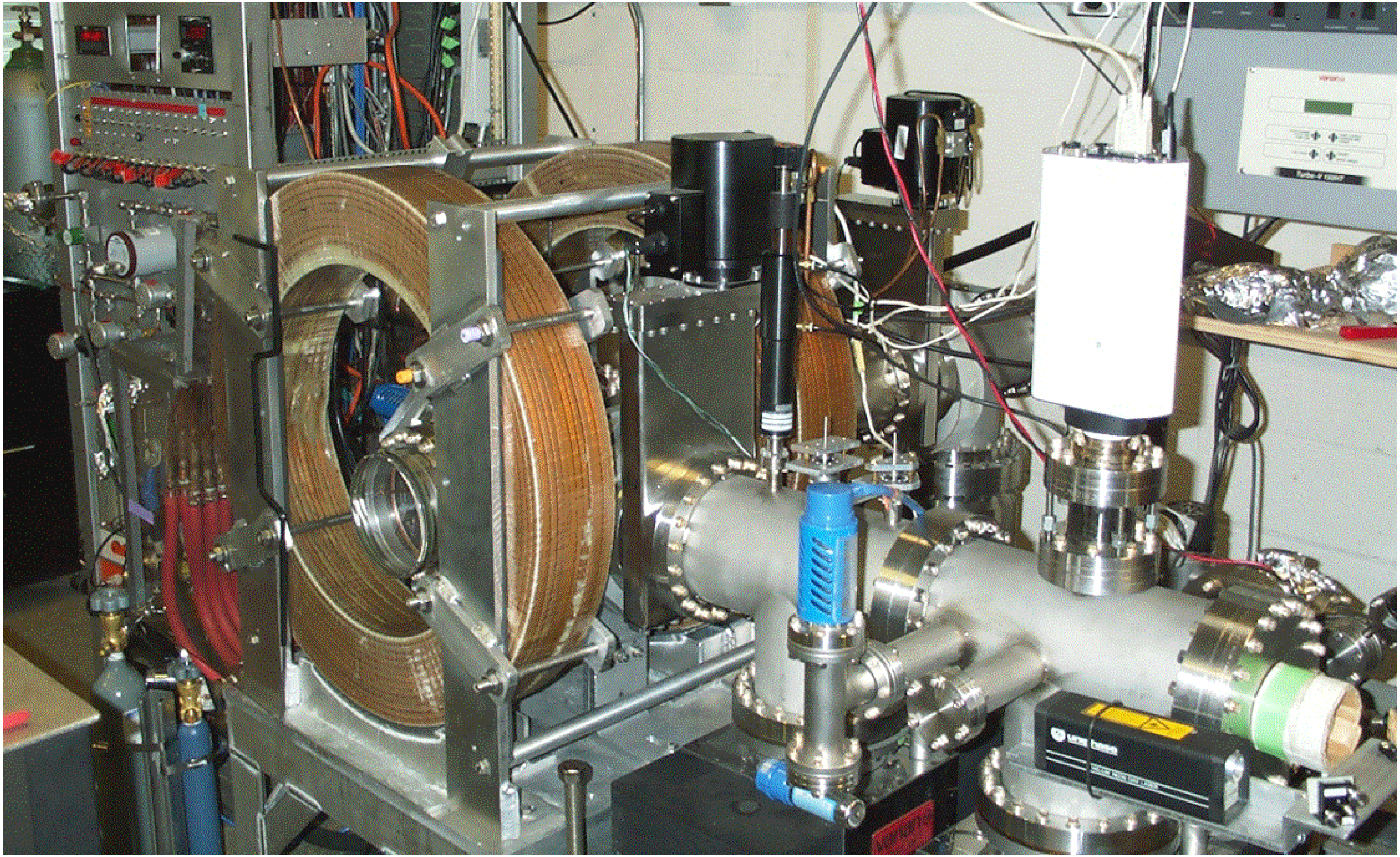




Experimental apparatus and the Original spin-exchange cell design



The MIT Laser-Driven target



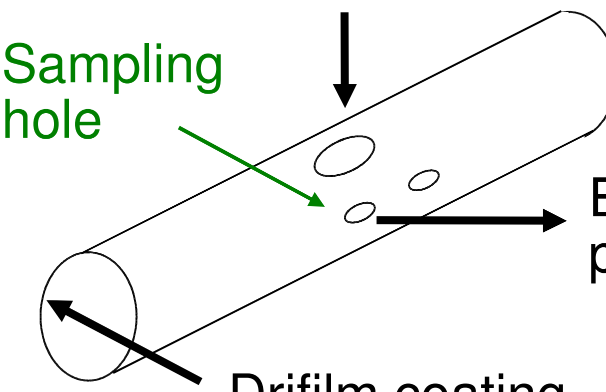
Results from the Original design

- **The storage cell**

  Aluminum cylinder with drifilm coating

  400 mm long and 12.5 mm inner diameter

  Average wall collisions in storage cell = 135



- **Results for hydrogen**

  For gas exiting the sampling hole:

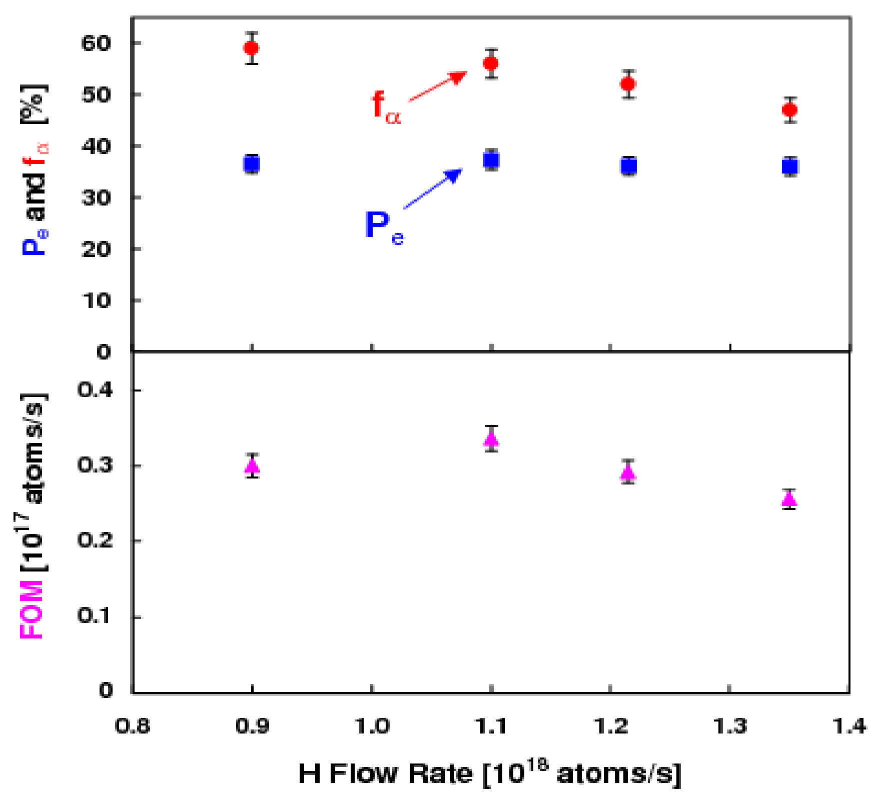
  f_α = Degree of dissociation

  P_e = H electron polarization

  = H nuclear polarization, p_z

$$\langle p_z \rangle = \frac{f_\alpha \times P_e}{f_\alpha + \sqrt{2}(1 - f_\alpha)}$$

FOM = Flow $\times \langle p_z \rangle^2$

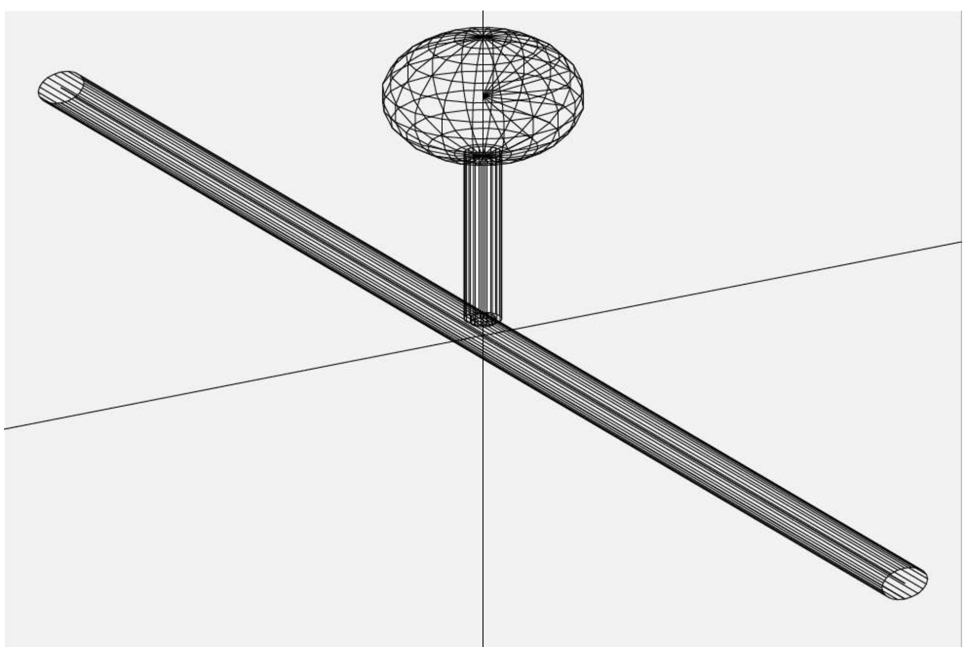


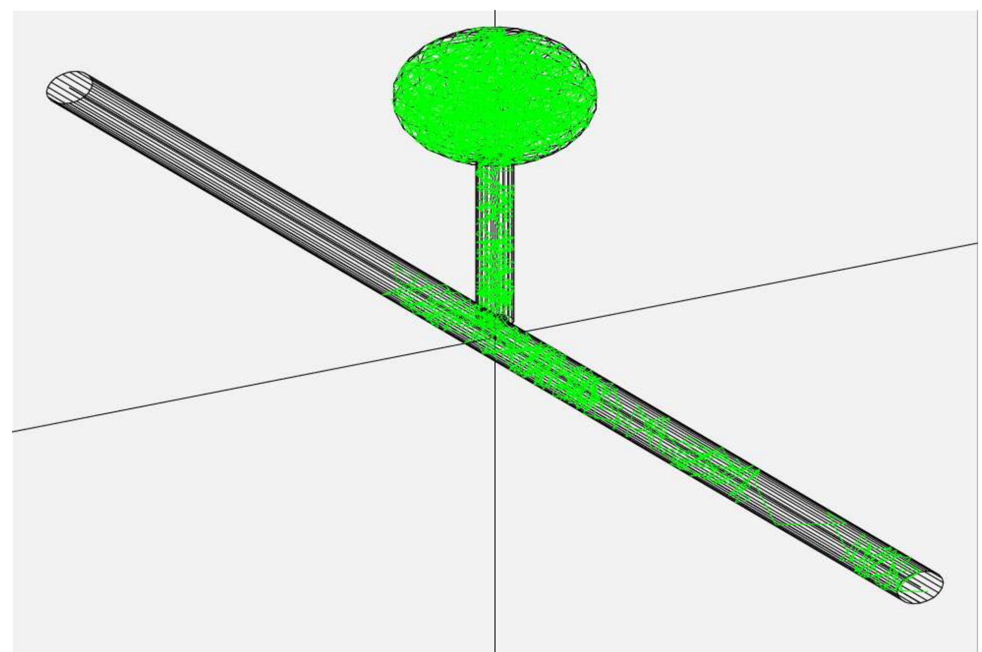
Monte Carlo simulation

- H atoms move in straight lines between wall collisions (molecular flow)
- Fit coefficients to the results from the Original design

Recombination coefficient, $\gamma_{recomb} = (3.33 \times 10^{-18}\ cm^3) \times n_H$

Depolarization coefficient, $\gamma_{depol} = 0.00355$





Monte Carlo simulation

Spin-exchange collisions

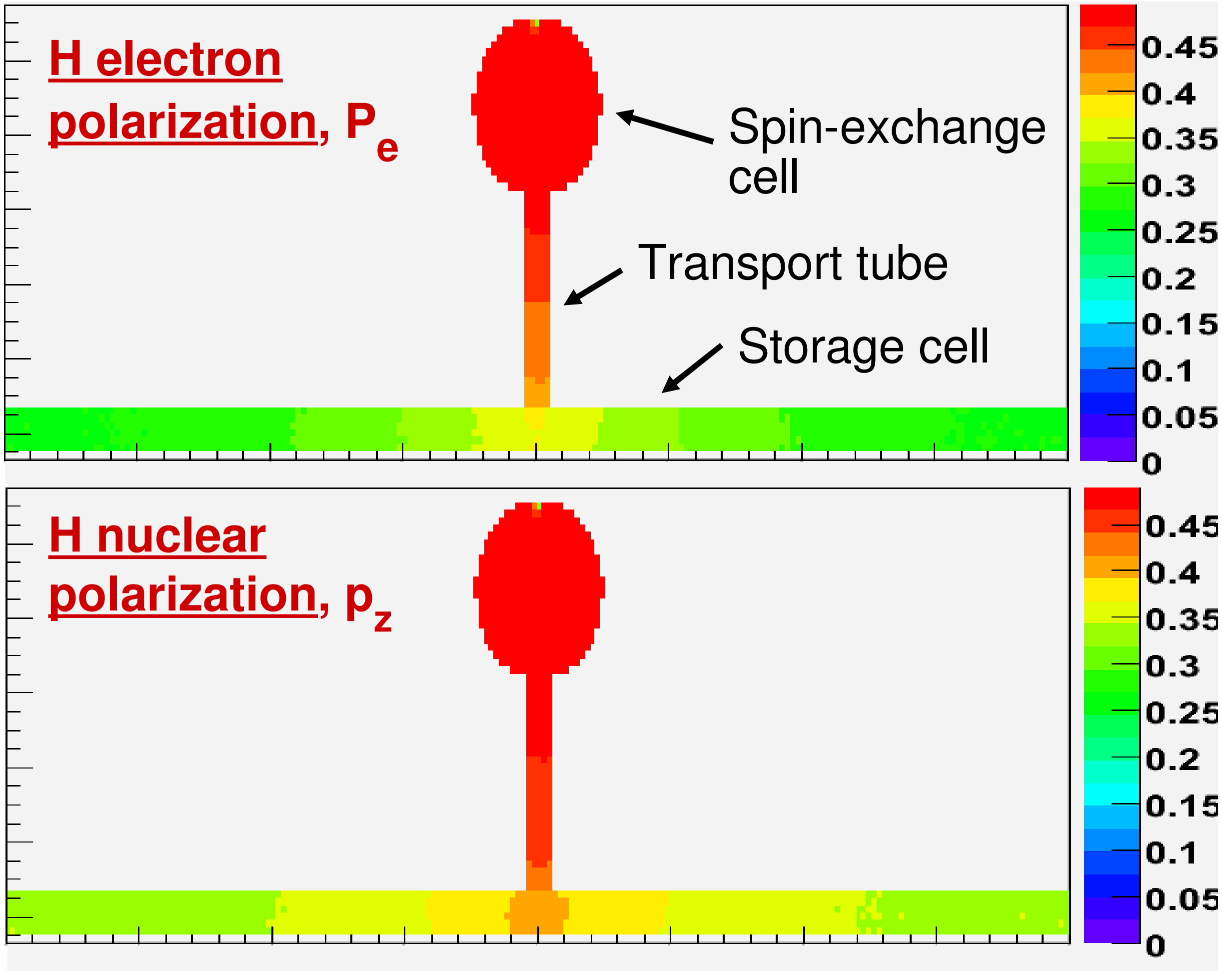
P_K

$$\frac{1}{\tau_{HK}} = \rho_K \langle \sigma_{SE}^{HK} v_{rel}^{HK} \rangle$$

P_e

$$\frac{1}{\tau_{HH}} = \frac{\rho_H \langle \sigma_{SE}^{HH} v_{rel}^{HH} \rangle}{1+(B/B_c)^2}$$

p_z



Optical pumping, KH spin-exchange, HH spin-exchange and radiation trapping was included in the Monte Carlo

Motivation for optimizing the geometry

The polarization increases with pump laser power

However ... saturation seen in the polarization after only 1.5 Watts

Original design

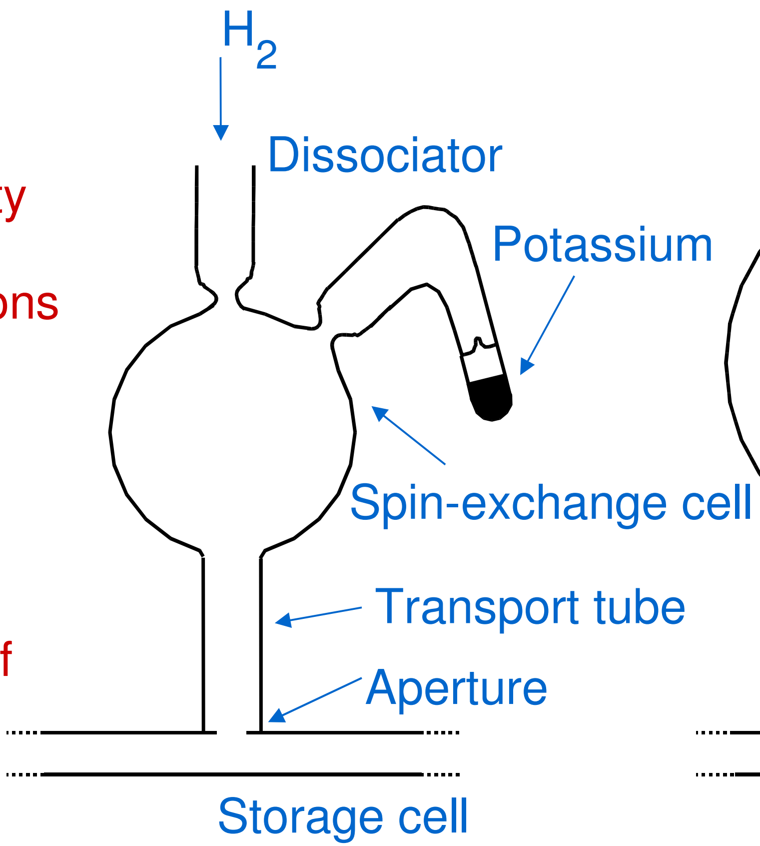
F = H_2 flow rate

n_K = potassium density

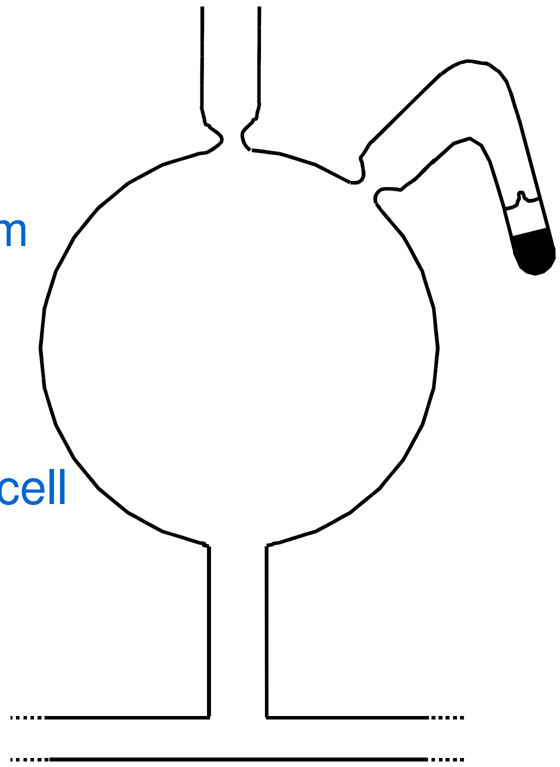
N_{WC} = avg wall collisions per H atom

L = avg path length in the spin-exchange cell

τ_H = avg dwell time of a H atom in the spin-exchange cell



New design



$F' = F$

$n_K' = n_K$

$N_{WC}' = N_{WC}$

$L' > L$

$\tau_H' > \tau_H$

Monte Carlo results

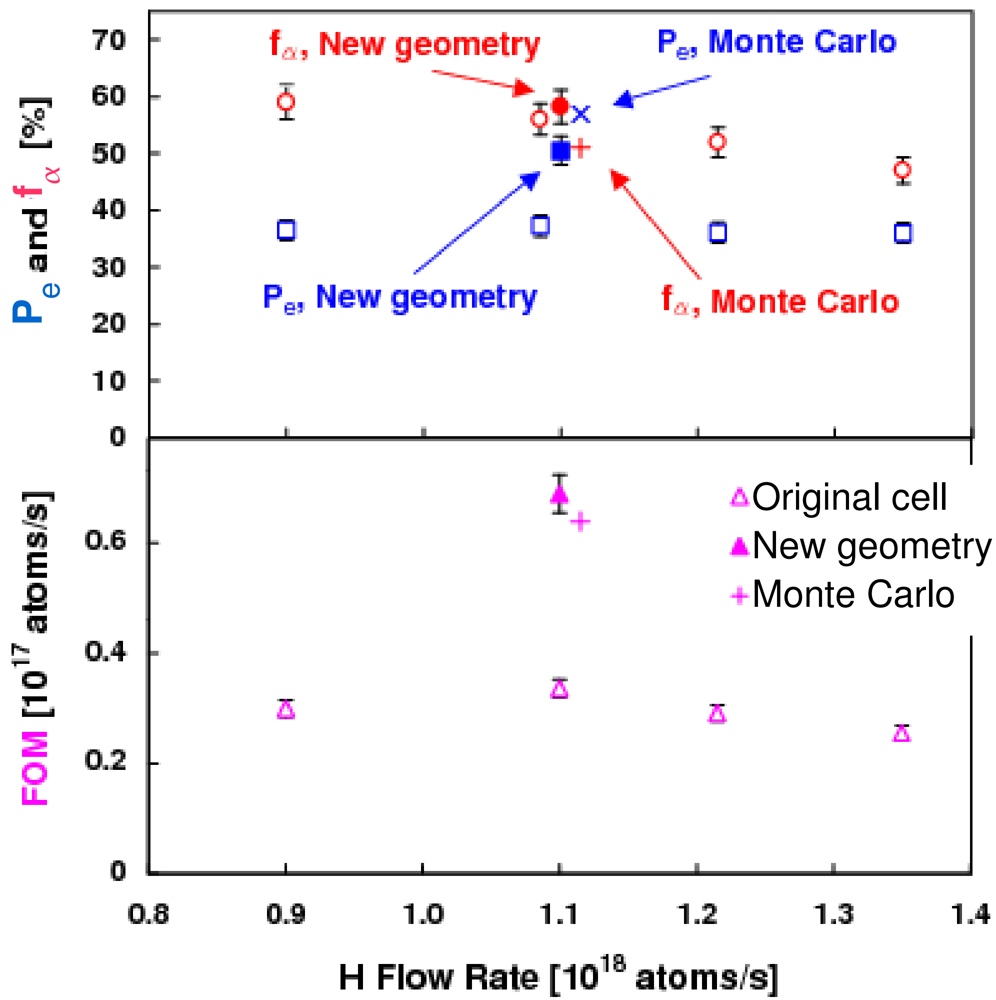
	Original	Large-1	Large-2
Flow (10^{16} atoms/s)	110	110	110
f_α	0.55	0.51	0.50
P_e	0.37	0.57	0.64
$\langle p_z \rangle$	0.17	0.23	0.26
FOM $F \times \langle p_z \rangle^2$ (10^{16} atoms/s)	3.3	6.0	7.3
Dwell time/STE time	185	245	285

Ratio of Volume (Large-1 / Original) = 6.8

Ratio of Volume (Large-2 / Original) = 13.5

Large-2 will not fit on the existing target chamber

Results with the new geometry (Large-1)



	HERMES (ABS)		IUCF (LDT)		MIT LDT Original	MIT LDT Large-1
Gas	H	D	H	D	H	H
F	6.57	5.15	100	72	110	110
t	11	[10.5]	50	50	150	150
f_α			∼0.48	∼0.48	0.56	0.58
P_e			∼0.45	∼0.45	0.37	0.50
$\langle p_z \rangle$	0.78	0.85	0.145	0.102	[0.175]	[0.247]
$F \times \langle p_z \rangle^2$	4.0	3.8	2.1	0.75	3.4	6.7
$t \times \langle p_z \rangle^2$	6.7	7.6	1.1	0.52	4.6	9.2

F = Flow (10^{16} atoms/s)

t = Thickness (10^{13} atoms/cm^2)

$F \times \langle p_z \rangle^2$ = FOM (10^{16} atoms/s)

$t \times \langle p_z \rangle^2$ = FOM (10^{13} atoms/cm^2)

Comments

1) The experimental FOM could be increased further (20%) by using the Large-2 design

   The Large-2 design does not fit on the existing vacuum chamber, a new chamber design is necessary for better and more stable performance

2) Other attempts were made to improve the FOM

   Diamond coating

   Double dissociator

   From our limited studies, these changes did not improve the FOM, however, further studies are necessary to draw more conclusive statements

3) Recently this target has been relocated to Duke University with plans to use it in the future at IMP, Lanzhou, China

Summary

1) The best result achieved with the MIT LDT:

   1.1×10^{18} atoms/s hydrogen flow rate

   50.5% atomic polarization and 58.2% degree of dissociation for atoms exiting the sampling hole in the storage cell

   FOM $(t \times \langle p_z \rangle^2) = 9.2 \times 10^{13}$ atoms/cm^2

2) Laser-driven targets offer a more compact design than atomic beam sources and can provide a larger FOM

3) A Monte Carlo simulation of spin-exchange optical pumping has been used to optimize the geometry, and the predicted results from the new geometry were in good agreement with the experimental results

4) Such a target is planned for future use at the CSR, Inst. of Modern Physics (IMP), Lanzhou, China by a collaboration between Duke University and IMP