A Possible $\vec{H}\vec{D}$ Target for Electro-production Experiments

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- *motivating factors for transversely polarized targets*
- *frozen-spin $\vec{H}\vec{D}$ and performance with photon beams*
- *factors limiting depolarization with electrons*
- *advantages for transversely polarized $\vec{H}$ and $\vec{D}$*

Electron experiments with transversely polarized $\vec{H}$ and $\vec{D}$

- ***DVCS, DVMP :***
  $\Rightarrow$ $\tilde{E}$ GPD → ***2+1 dimensional tomography***
  → ***quark orbital angular momentum***

- ***Semi-inclusive-DIS :***
  $\Rightarrow$ Collins function → ***transverse $\vec{q}q$ → Asy in hadron fragmentation***
  → ***transverse quark orbital angular momentum***

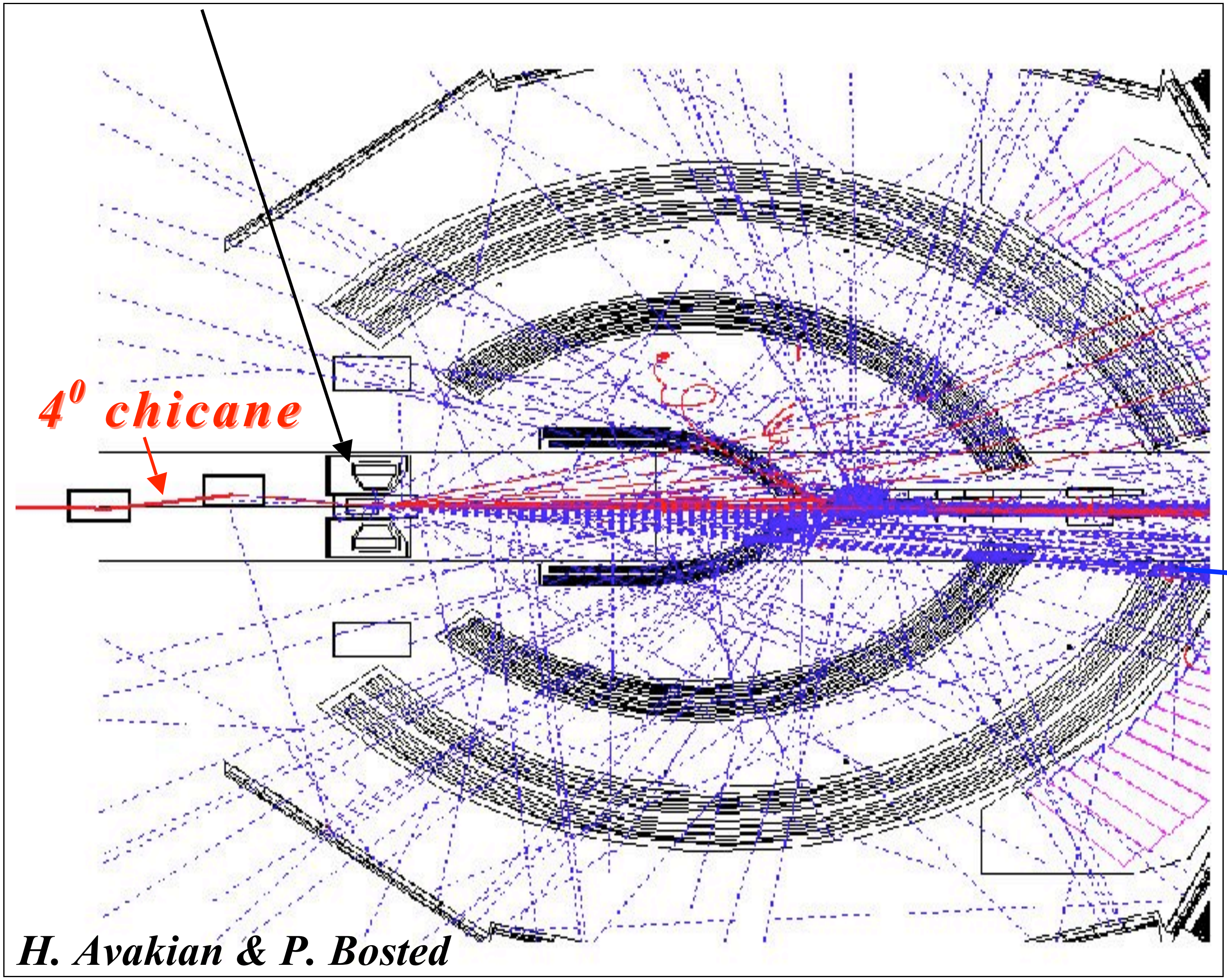
  $\Rightarrow$ Sivers function → ***u-d separation in $\vec{N}^{\perp}$ → single-spin Asy***

- ***Inclusive-DIS :***
  $\Rightarrow$ g_2, A_2 PDF → ***color-polarizability of the gluon field***

- ***N* transition form factors :***
  → ***constraining structure of baryons***

UVa (Oxford) Transverse $N\vec{H}_3$ / $N\vec{D}_3$ target with CLAS

BdL ≈ 4.2 T × 0.3 m



H. Avakian & P. Bosted

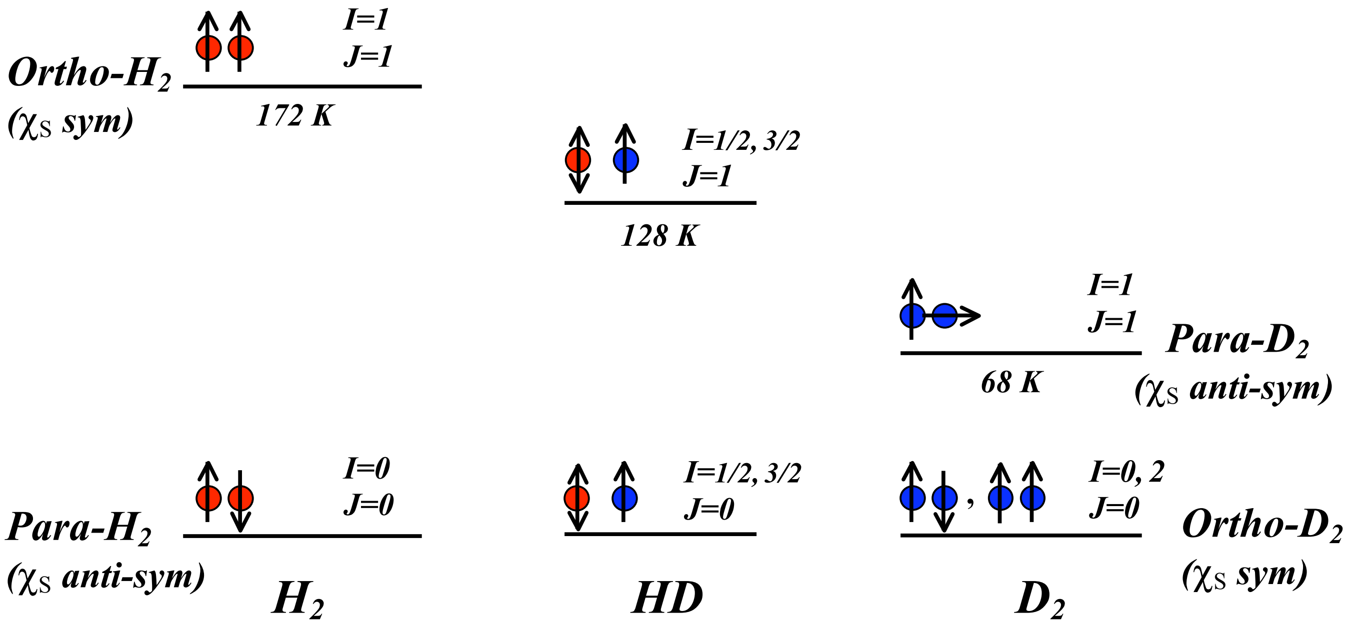
- ***large transverse field compensated by chicane***
- ***brem γ's peaked along incoming e at ~4^0***

⇒"Sheet of flame"
4^0

⇒large background

- ***limited acceptance in θ and Q^2***

Polarizing HD: *the rotational levels of the solid hydrogens*



Ortho-H_2
(χ_S sym)
I=1
J=1
172 K

I=1/2, 3/2
J=1
128 K

I=1
J=1
Para-D_2
68 K
(χ_S anti-sym)

I=0
J=0
Para-H_2
(χ_S anti-sym)
H_2

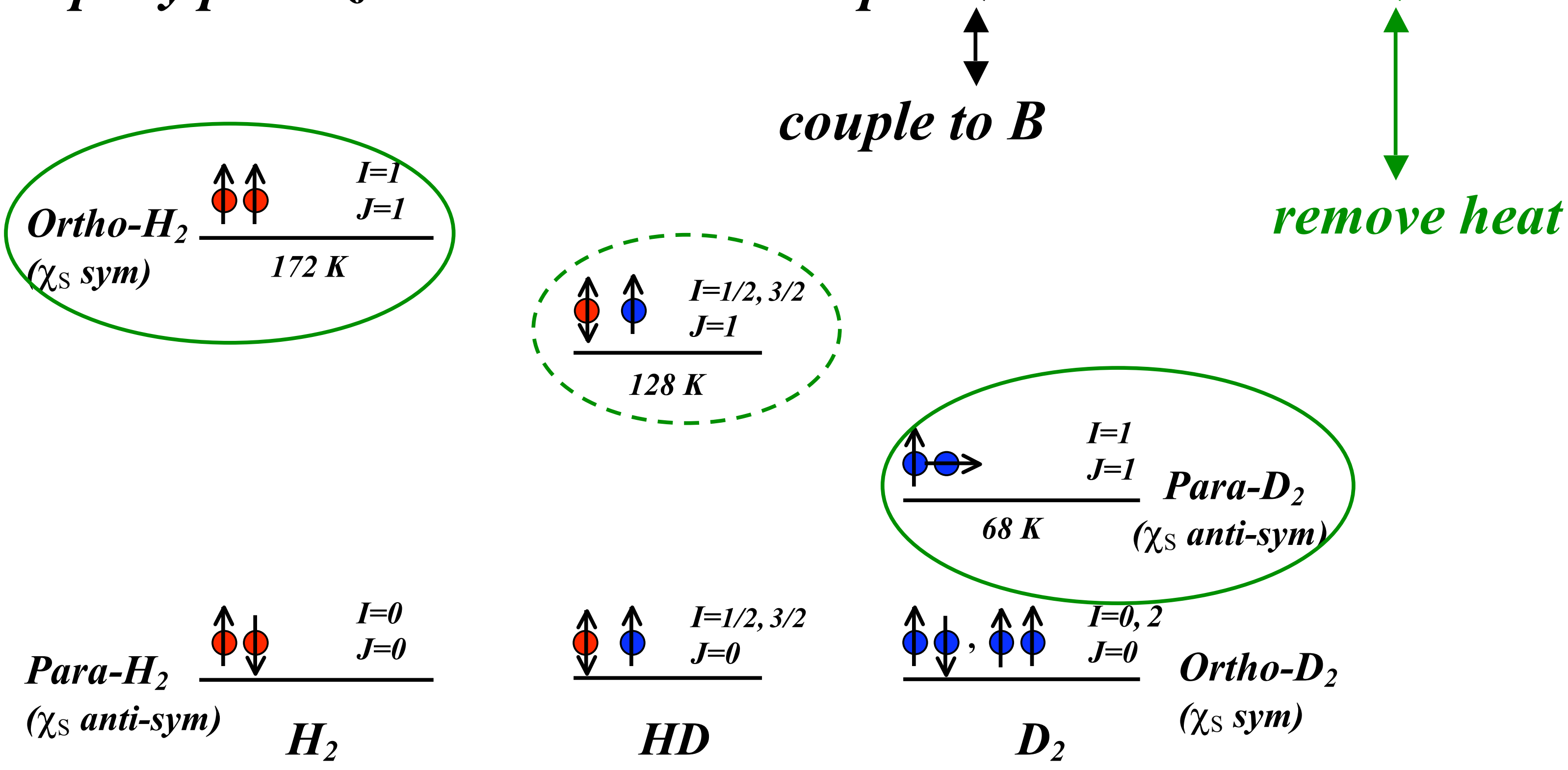
I=1/2, 3/2
J=0
HD

I=0, 2
J=0
Ortho-D_2
(χ_S sym)
D_2

Figure. The relative energy spacing of the low-lying nuclear spin (*I*) and molecular orbital angular momentum (*J*) levels in H_2, HD and D_2. The symmetries of the nuclear spin wavefunction (χ_S) are indicated.

Polarizing HD: the rotational levels of the solid hydrogens

- ***Rapidly polarizable levels: nuclear spin $I\neq0$ AND orbital $J\neq0$***



couple to B

remove heat

Ortho-H_2
(χ_S sym)
$I=1$
$J=1$
172 K

$I=1/2, 3/2$
$J=1$
128 K

$I=1$
$J=1$
Para-D_2
68 K
(χ_S anti-sym)

Para-H_2
(χ_S anti-sym)
$I=0$
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H_2

$I=1/2, 3/2$
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HD

$I=0, 2$
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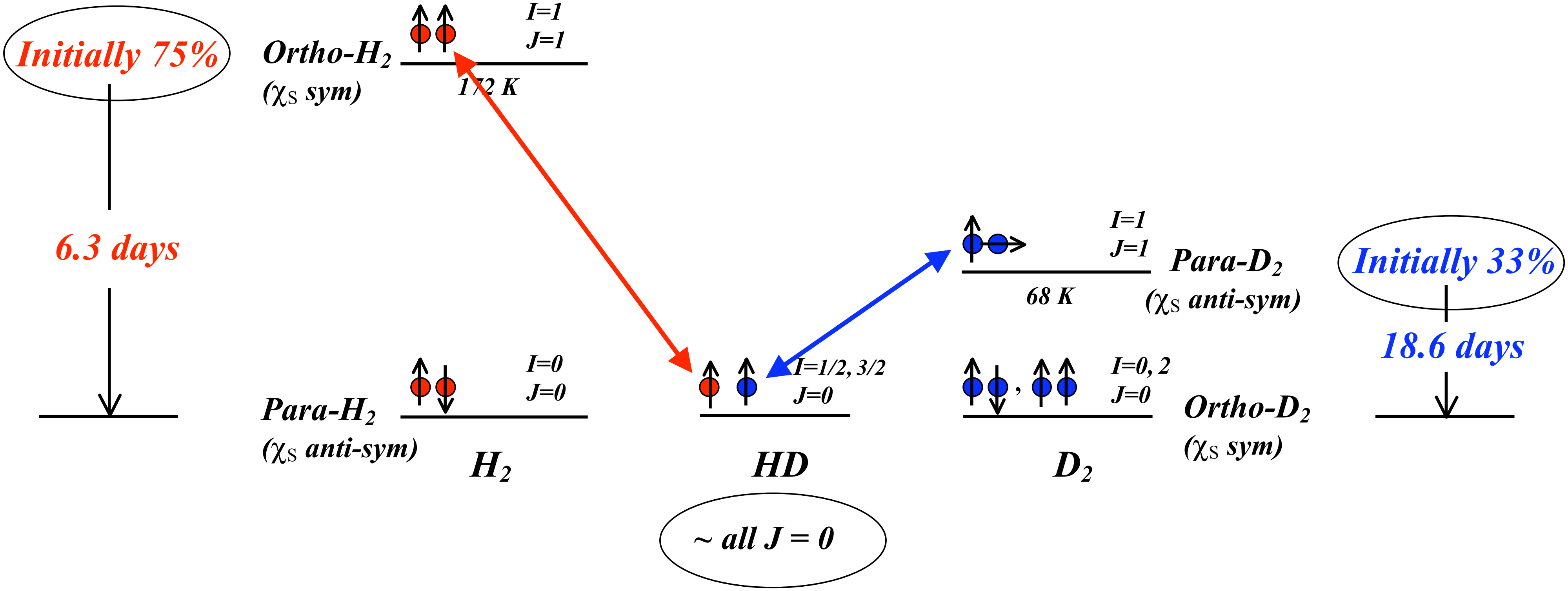
Ortho-D_2
(χ_S sym)
D_2

Figure. The relative energy spacing of the low-lying nuclear spin (*I*) and molecular orbital angular momentum (*J*) levels in H_2, HD and D_2. The symmetries of the nuclear spin wavefunction (χ_S) are indicated.

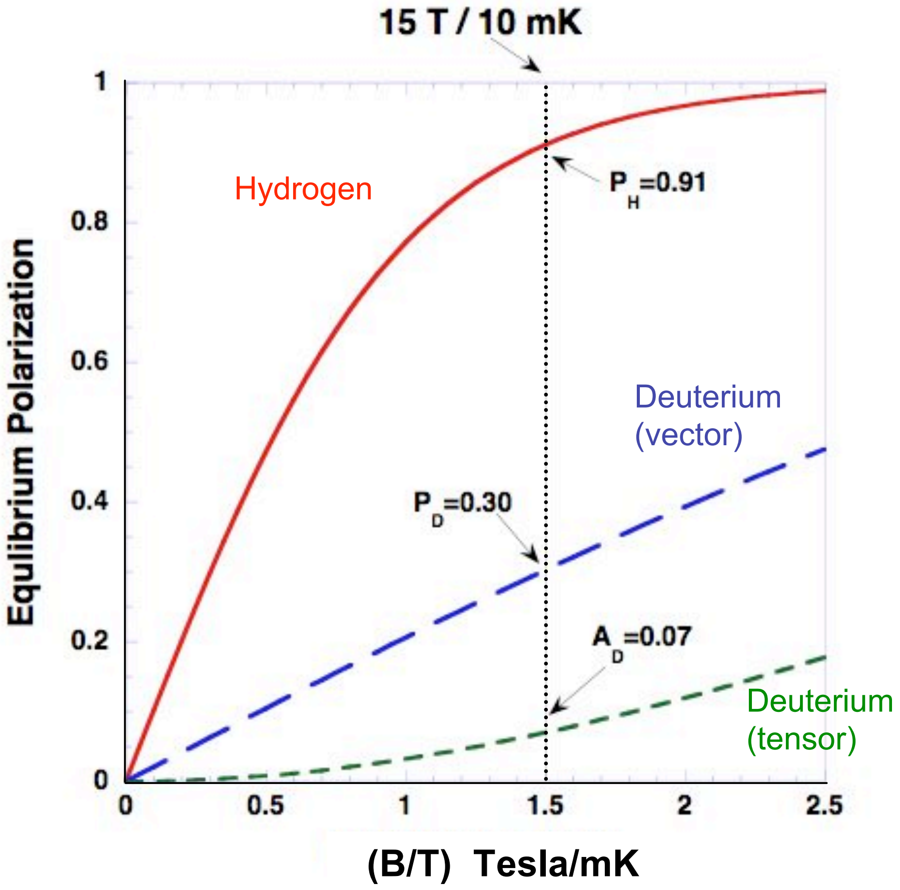
External Magnetic field rapidly aligns Ortho-H_2 and Para-D_2 then spin-exchanges with H and D in HD



- *relaxation switch – A. Honig, Phys. Rev. Lett.* ***19*** *(1967).*

HD field/low-temp Polarization

- align spins with high B (15 Tesla) and low T (~12 mK)
- polarize small concentrations of J=1 H_2 and D_2
- o-H_2 and p-D_2 spin-exchanges and polarizes HD
- wait for J=1 H_2 and D_2 to decay



HD polarize/run sequence:

- condense HD gas → liquid → solid in 2-4 ^{o}K dewar ; *calibrate NMR*

- transfer to dilution refrigerator

  - polarize at 15 tesla and 12-16 mK

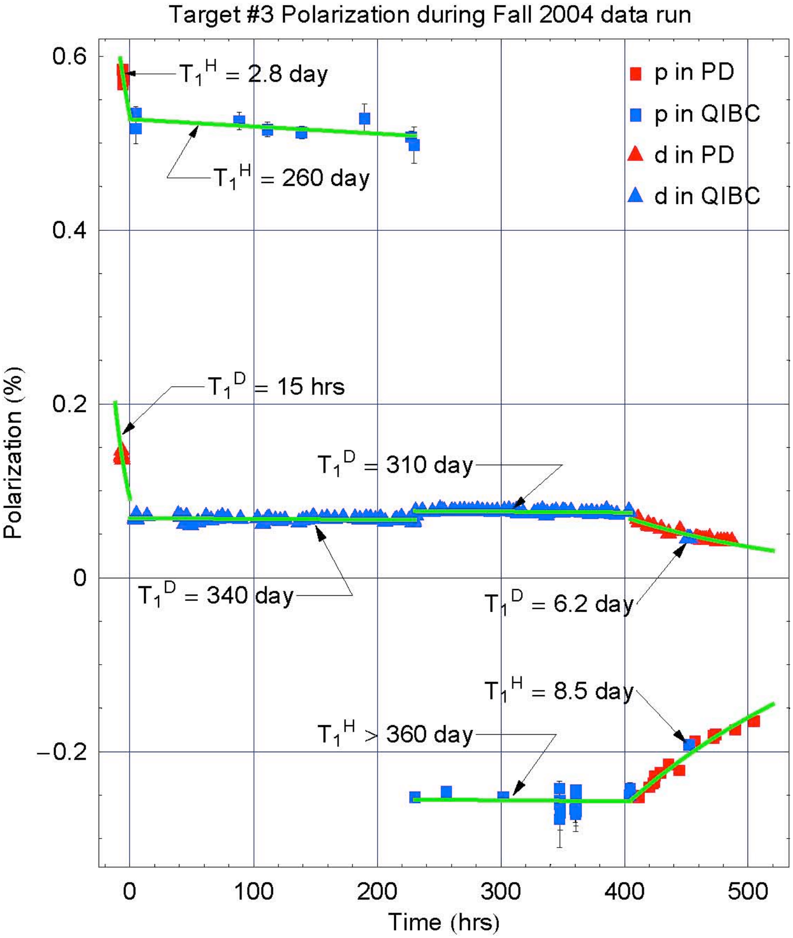
  - hold for 2-6 months, waiting for ortho-H_2 and para-D_2 to decay away

- transfer to 2-4 K dewar for polarization measurement

- transfer to In-Beam-Cryostat

  - hold target for experiment at 0.2 – 0.7 ^{o}K and ~0.1 to 0.9 tesla

  ⇒ Spin-relaxation (T_1) decay times ~ a year


Target #3 Polarization during Fall 2004 data run
Polarization (%)
Time (hrs)
0.6
0.4
0.2
0
−0.2
0
100
200
300
400
500
■ p in PD
■ p in QIBC
▲ d in PD
▲ d in QIBC
T1H = 2.8 day
T1H = 260 day
T1D = 15 hrs
T1D = 310 day
T1D = 340 day
T1D = 6.2 day
T1H = 8.5 day
T1H > 360 day

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  $\Rightarrow$ *Spin-relaxation (T_1) decay times ~ a year*

  - RF transfer $P_H \rightarrow P_D$ at 0.2 ^{o}K and 0.05 tesla

  - RF flip spins as needed

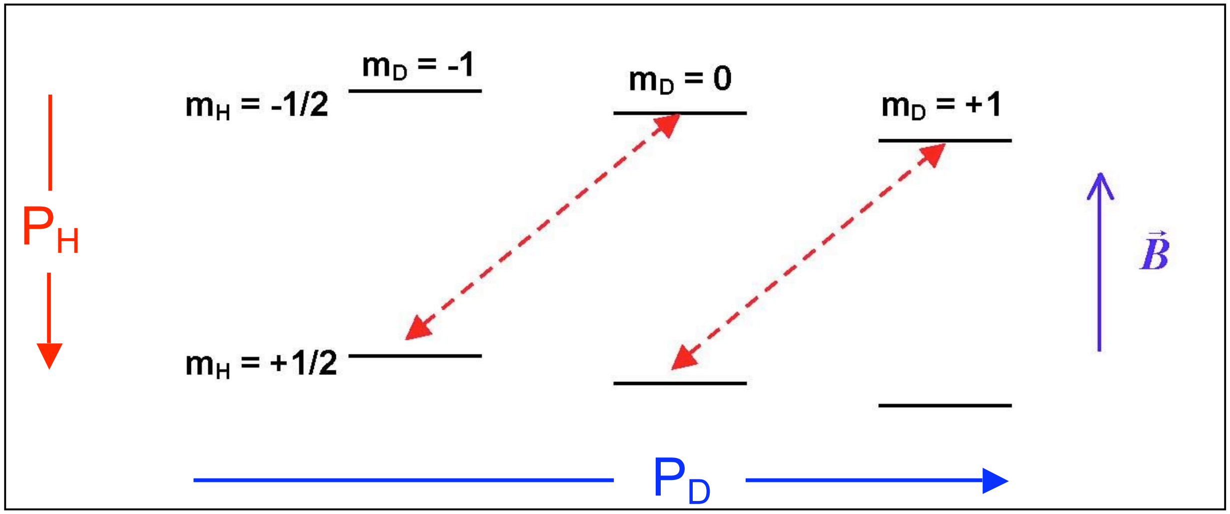
Increasing D polarization:

- *Brute force* (high B/low T) ⇒ $P_D \sim 15\% - 25\%$ ($\mu_D / \mu_H \sim 1/3$)
- *1st forbidden adiabatic fast passage* (FAFP) to invert state polulations;

Zeeman levels of HD

- polarize H

- RF transfer
P(H) → P(D)

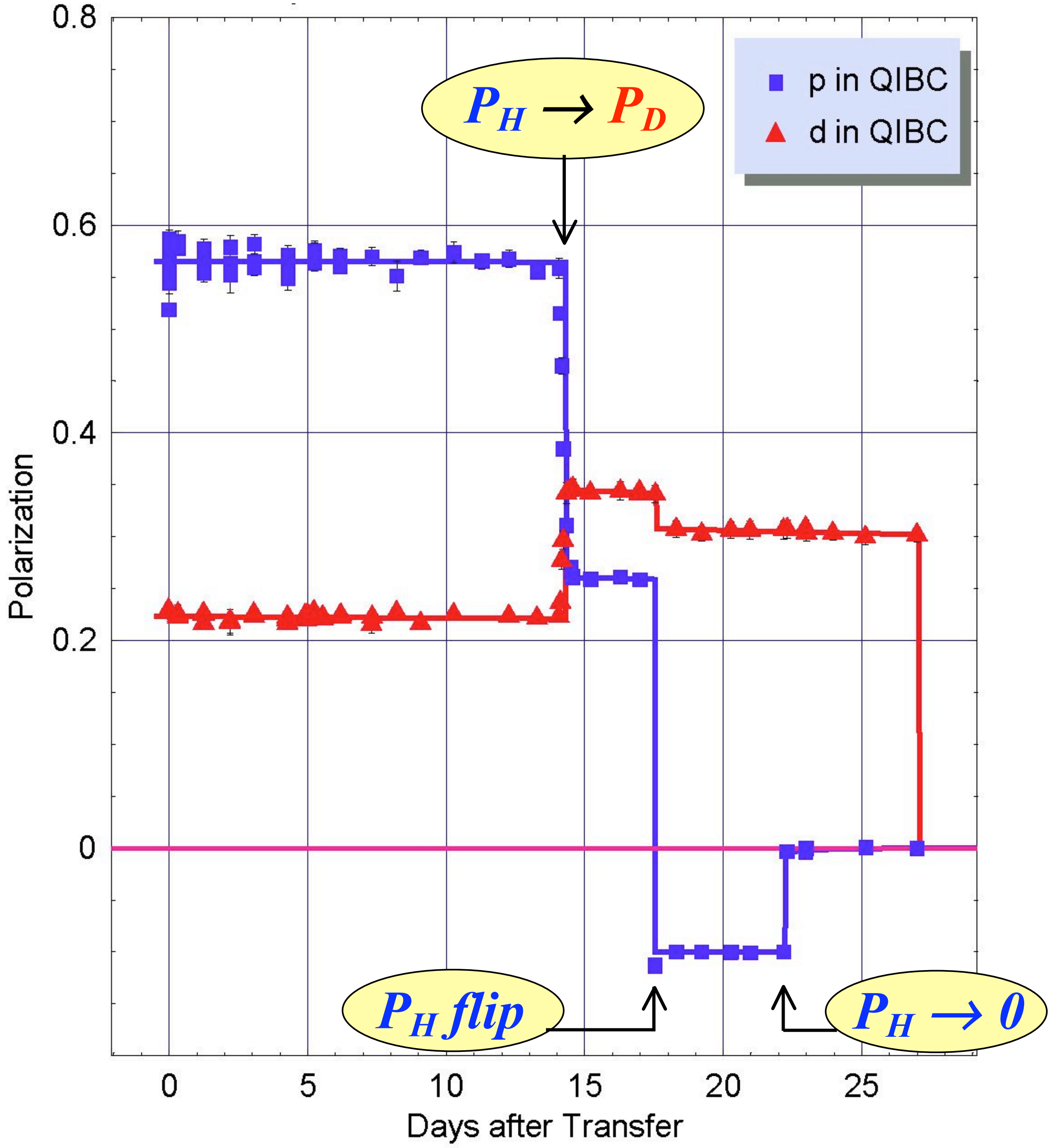


- P_D should reach 50% (limited by NMR field uniformity) ← *requires R&D*

- ***saturating FAFP transition***
  → equalize { $m_H = +1/2; m_D = -1, 0$ } ⇔ { $m_H = -1/2; m_D = 0, +1$ }

  ⇒ P_D = 37% ← ***today***

BNL – Fall'2006



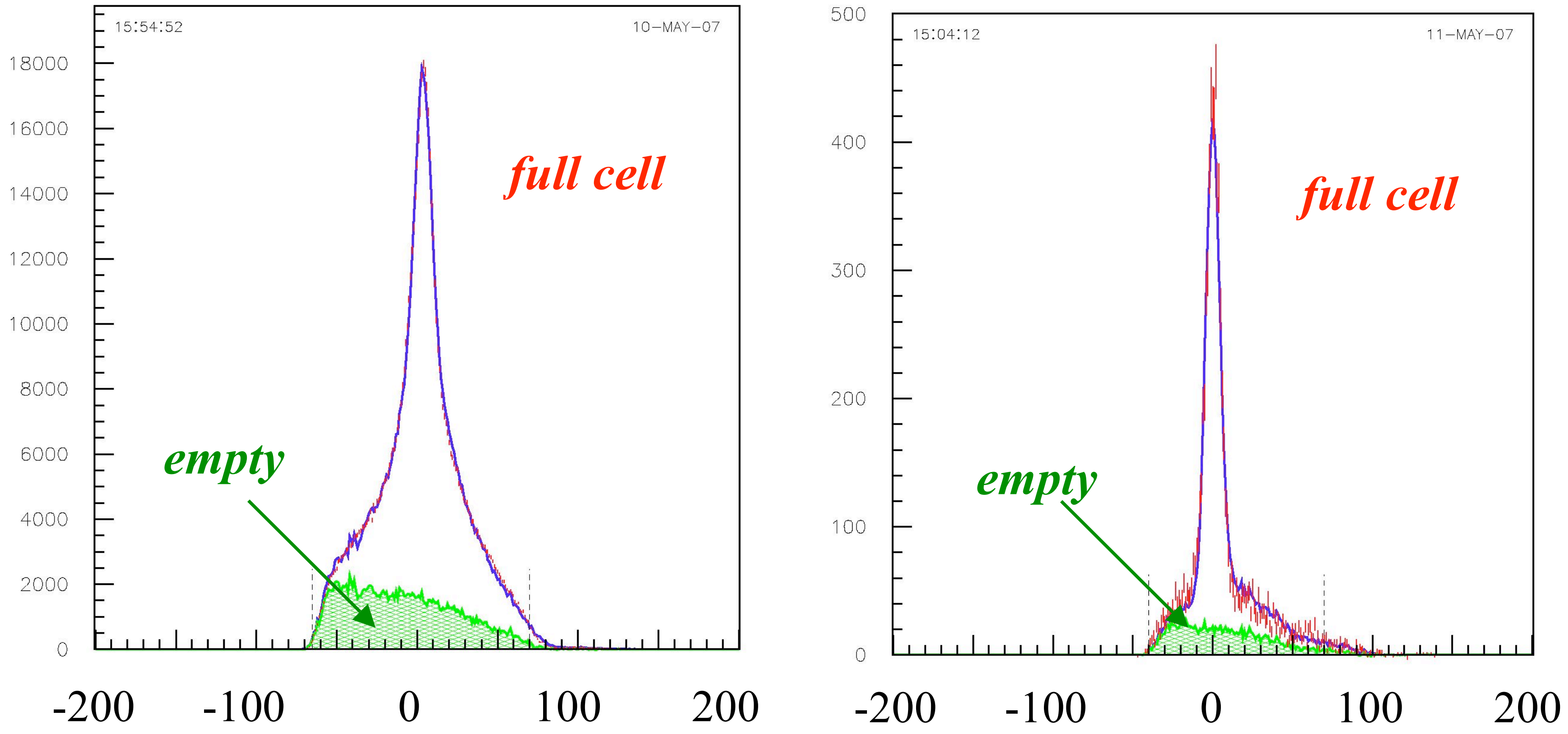
T6 P & D pol in QIBC

- *target cell contribution can be measured and subtracted*

$E_{\gamma} = 300\ MeV$

$\gamma + HD \rightarrow \pi^{\pm}\ X$

$\gamma + H_2 \rightarrow \pi^{+}\ n$



missing 2 - body energy (MeV)

Expected spin-relaxation times for appropriately prepared targets

	measured (γ)		*projected*	
B	*0.89 tesla*	*0.01 tesla*	*0.40 tesla*	*0.04 tesla*
$B \times dL$ *(for L=0.12m)*	*0.108 tesla-m*	*0.001 tesla-m*	*0.048 tesla-m*	*0.005 tesla-m*
orientation	*solenoid*	*solenoid*	*saddle*	*saddle*
$T_1(H)$	*> 300 d*	*8 d*	*>200 d*	*~ 30 d*
$T_1(D)$	*> 500 d*	*55 d*	*>300d*	*~200 d*

Expected T1 w saddle

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compare to 1.4 T-m
with NH_3/ND_3

Expected T1 w saddle

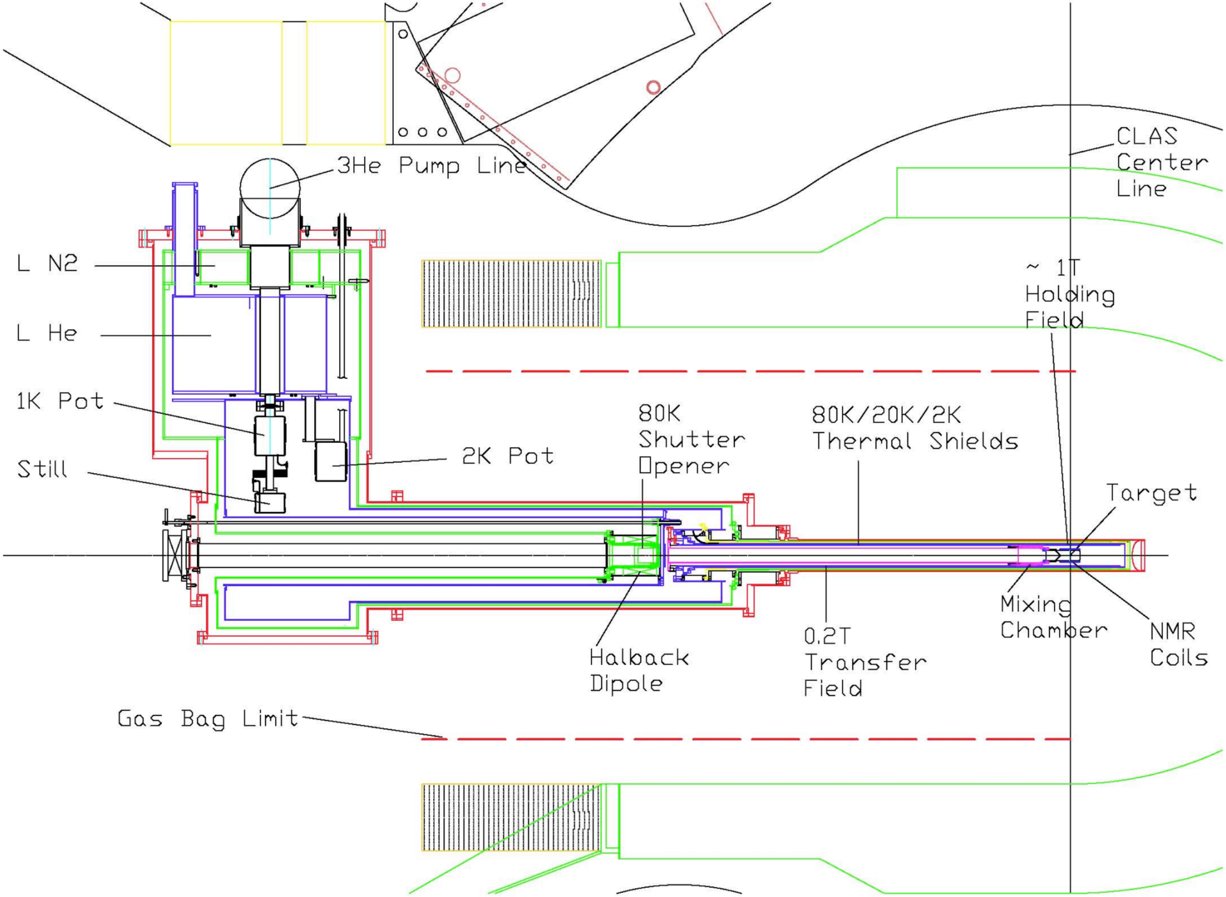


Figure A8. Conceptual design of modified version of the BNL IBC for use in the CLAS.

Depolarization of frozen-spin $\vec{H}\,\vec{D}$ with electrons

- ***beam heating***

  - 5 nA of 10 GeV electrons ⇒ 5 mW heat in 2 cm of HD (GEANT)
  ≈ cooling power of BNL In-Beam Cryostat at 0.5 K (can be increased)

  - 4 times lower heating than FROST(Butanol), due to lower Z
  - spin-relaxation time (T_1) for HD ~ a year at these temperatures

- ***spin-diffusion of paramagnetic centers***

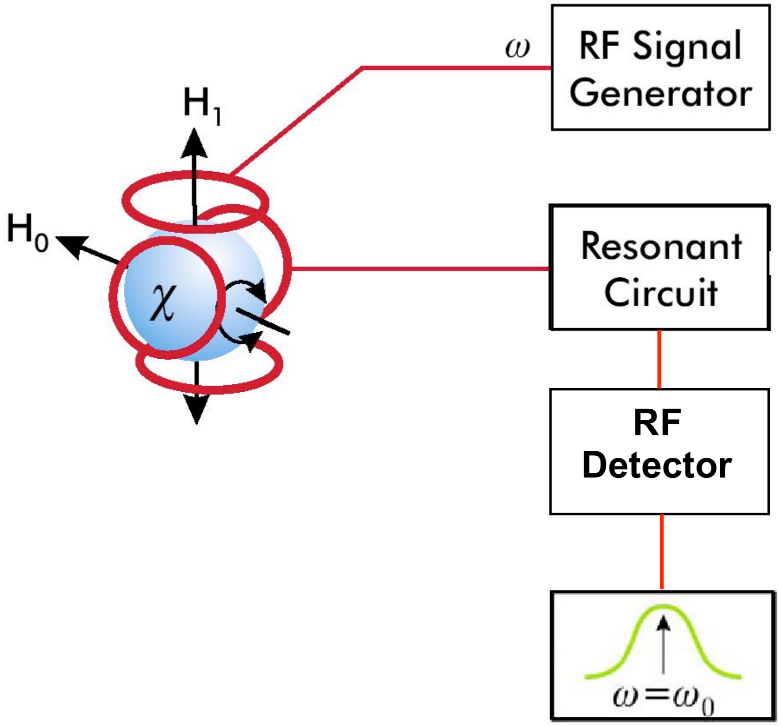
  - *e brem* creates free radicals with randomly oriented nuclear spin;
  absolute number are small, but these can be *sinks* for polarization

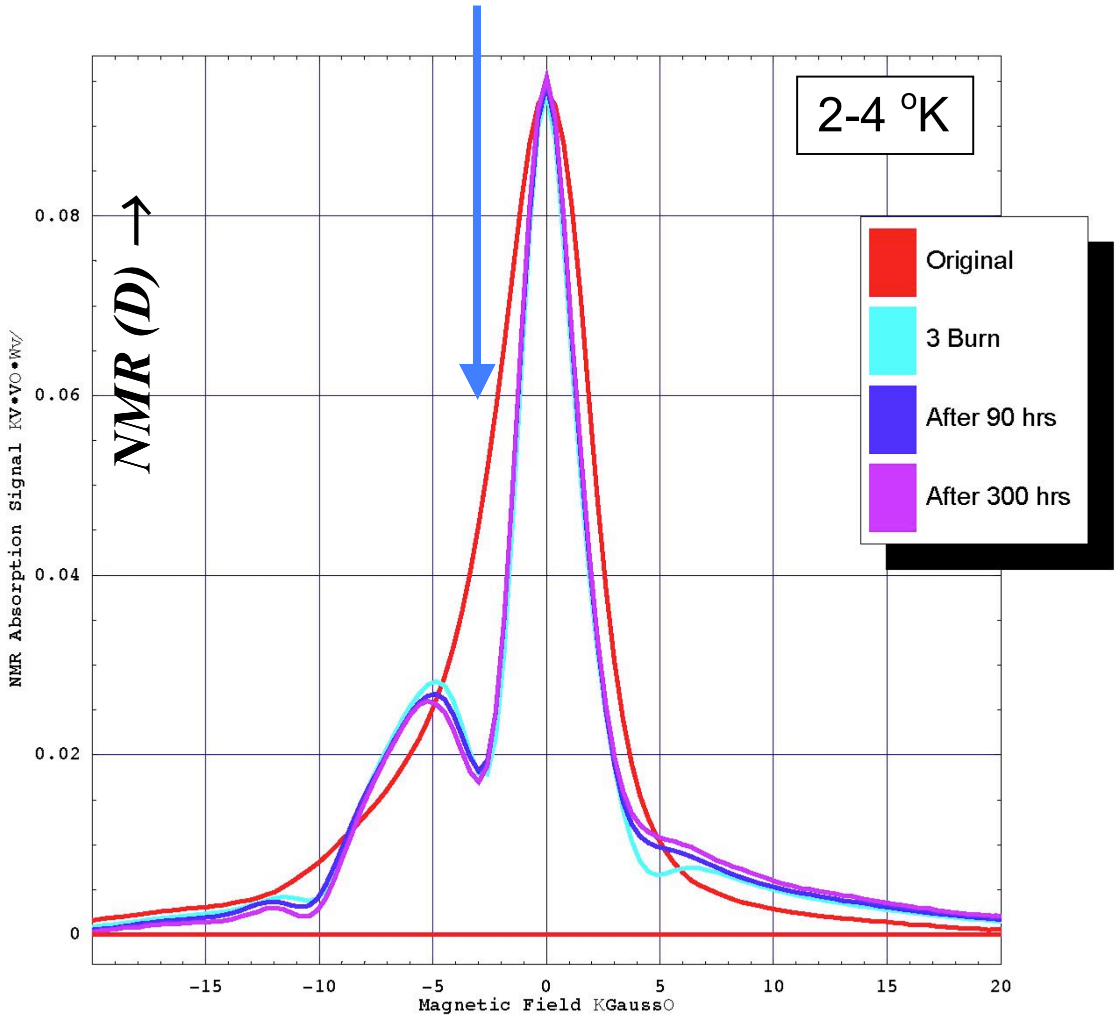
  - *spin-diffusion* time measured at 2 K: ~ 1 day for $\vec{H}$
  ~ ∞ for $\vec{D}$ (unmeasurable in 2 weaks)

  (*spin-diffusion* times could increase at lower T ?)

Burning an RF polarization hole

- *cross-coil NMR*
- *field scan at fixed frequency*





H_o (∝ position) →

- *H_o inhomogeneity ⇒ D-line width*
- *field and position are correlated*
- *no change in the D-polarization hole after 2 weeks ⇒ D spin diffusion extremely slow*

Potential advantages with frozen-spin transverse $\vec{H}\,\vec{D}$

- *very low BdL (almost none for $\vec{D}$)*
  ⇒ no "sheet of flame"

- *better figure of merit*
  → almost no dilution
  → small nuclear background (sampled with empty cell)
  → long Radiation Length (625 cm) ⇒ few brem γ's

- *wide acceptance in θ and Q^2*
  → open geometry cryostat centered in CLAS(6/12)
  (but, will have to deal with low-momentum Møller electrons)

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caveat:

$e+\vec{H}\,\vec{D}$ test is necessary to verify polarization retention with electrons

Extras

Ortho ⇔ para decays generate heat, which must be removed to polarize

- ***HD condensed into target cell with ~ 2000 50 μm Al cooling wires soldered into 60 holes in copper cooling ring***

- ***Composition of a standard target cell with 4 cm of HD (0.9 moles):***

Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

Frozen-Spin $\vec{H}\,\vec{D}$ - summary

- *pure target, high nucleon polarizations*

- *very low-background - cell contains only unpolarizable nucleons (20%)*
  ⇔ *conventional empty-cell subtractions*

  ⇒ *E06-101 HD figure of merit > 20 × FROST(C_4H_9OH)*

- *in-γ-beam life-times* **>** *year*

- *RF moves spins* $\vec{H} \Leftrightarrow \vec{D}$ *as needed*

- *In-Beam Cryostat centered in CLAS; open acceptance at back angles*

- *developed at BNL/LEGS; migrating to JLab*

Table A2. Factors contributing to the systematic error on target polarization.

Source	**δP(H)**	**δP(D)**
thermal equilibrium calibration		
- noise, temperature, bkg, …	0.9%	1.0%
frozen-spin measurement		
- white noise	0.4%	2.0%
- holding field noise	0.5%	0.5%
- non-linearities, homogeneity,…	1.0%	1.0%
calibration transfer		
- circuit drift, differential ramp	1.6%	1.6%
- Lock-in gain differential error	2.8%	2.8%
- cold-transfer loss	1.0%	1.0%

Total fractional error:	3.7%	4.2%