Spin game fresco (Game hall) in the Estense Castle of Ferrara
Sebastiano Filippi (Bastianino) XVI sec.

Polarized Fuel for Fusion

INFN and Unife Of Ferrara

2ND and 3RD October, 2017

Why is it so hard to polarize Nuclear Spin of solid Hydrogen Isotopes?

- **The Hydrogen Family**
- **Static Polarization (brute force)**
- **Dynamic Nuclear Polarization (DNP)**
- **Other Approaches**
- **Conclusions**

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The Hydrogen Family

	Stable	Radioactive
Homonuclear	H_2; D_2	T_2
Heteronuclear	HD	HT; DT

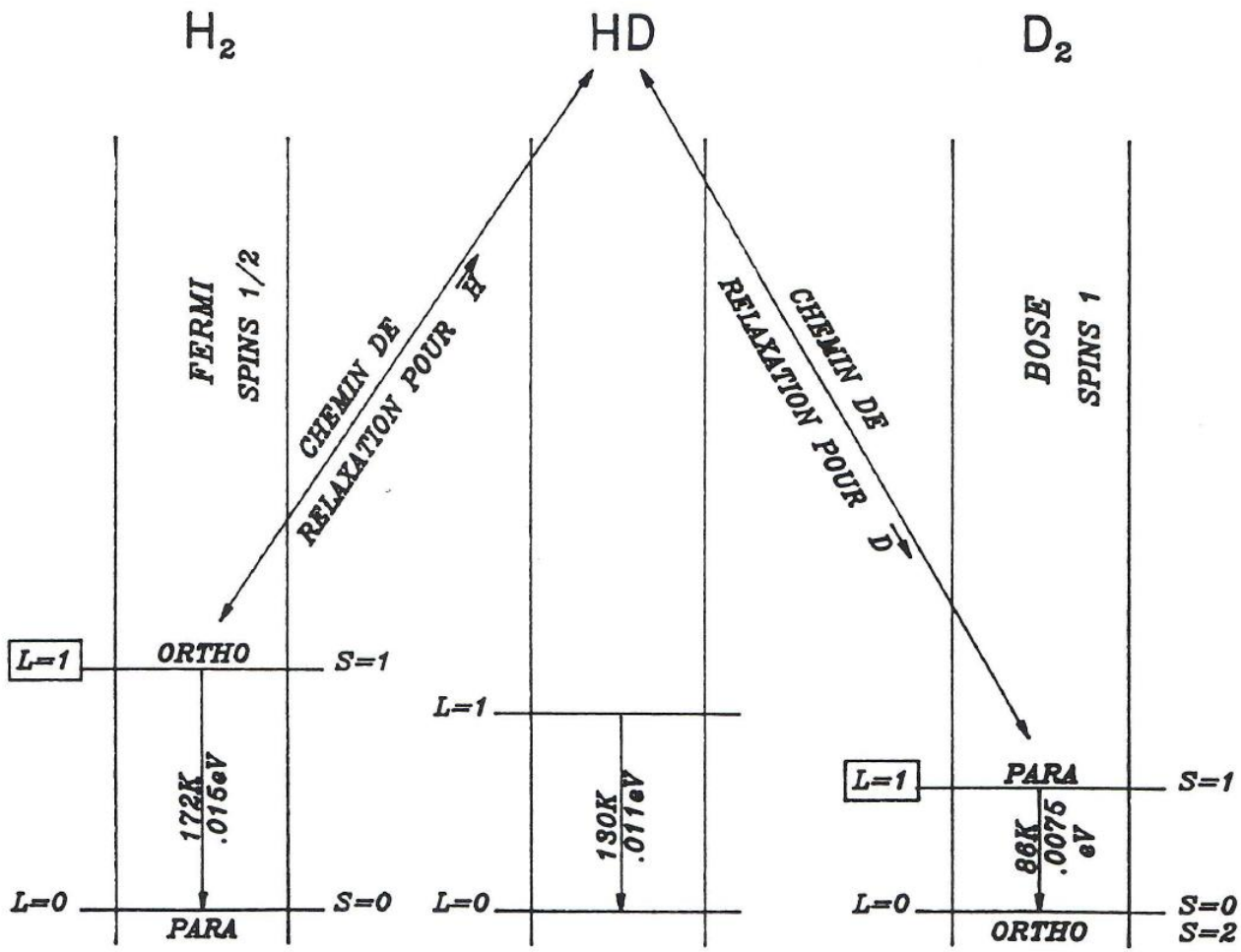
- Homo have symmetry requirements
- Useful for polarized fusion: D_2; $T_2 \rightarrow (H_2)$; DT $\rightarrow$ (HD)

$$D + T \rightarrow {}^4He + n + 17.6\ MeV\ (1.7\ TJ / mol)$$
$$D + D \rightarrow {}^3He + n + 3.267\ MeV\ (0.214\ TJ / mol)$$
$$D + D \rightarrow T + H + 3.98\ MeV\ (0.384\ TJ / mol)$$

$$T \rightarrow {}^3He + \beta^- + \nu + 18.6\ keV;\quad (\bar{E}_\beta = 5.69\ keV);\ \text{half-live} = 12.3\ \text{years}$$

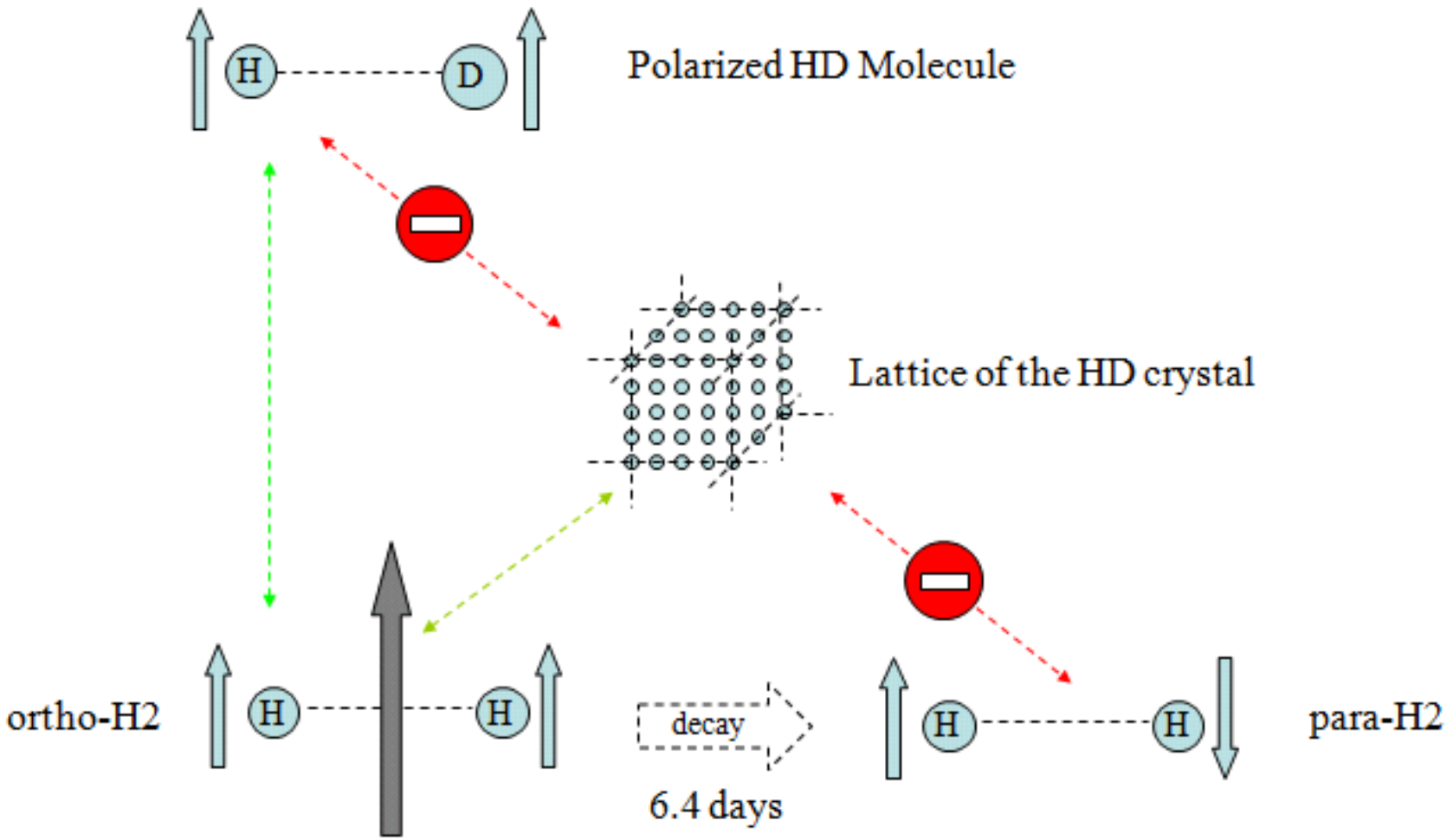
ITER (500 MW) $\rightarrow$ DT consumption = 1 mol / hour

Rotational Molecular States of Hydrogen Molecules



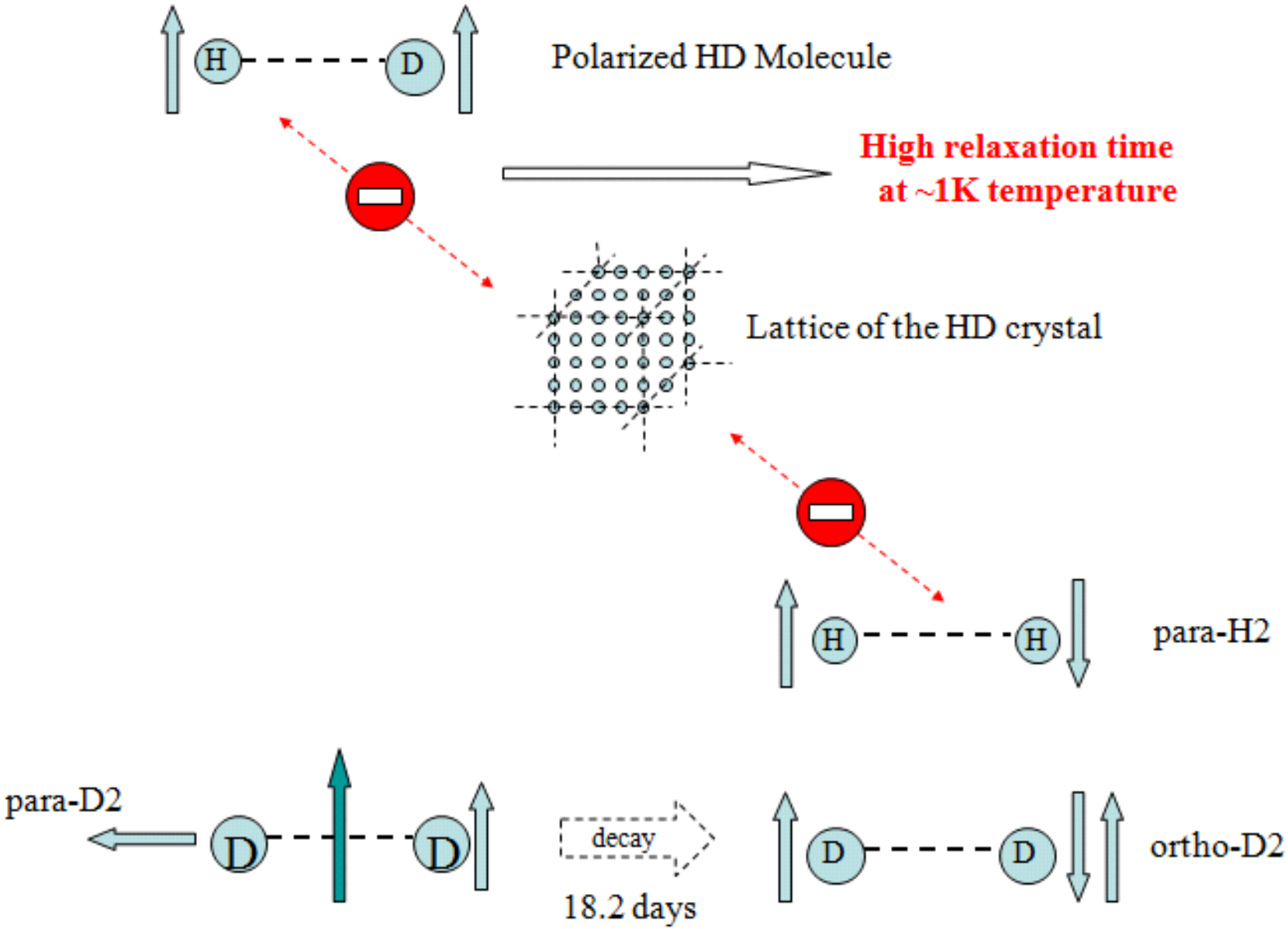
Polarization of protons in HD targets

(Honig, 1967)



Polarization of deuterons in HD targets

(Honig, 1967)



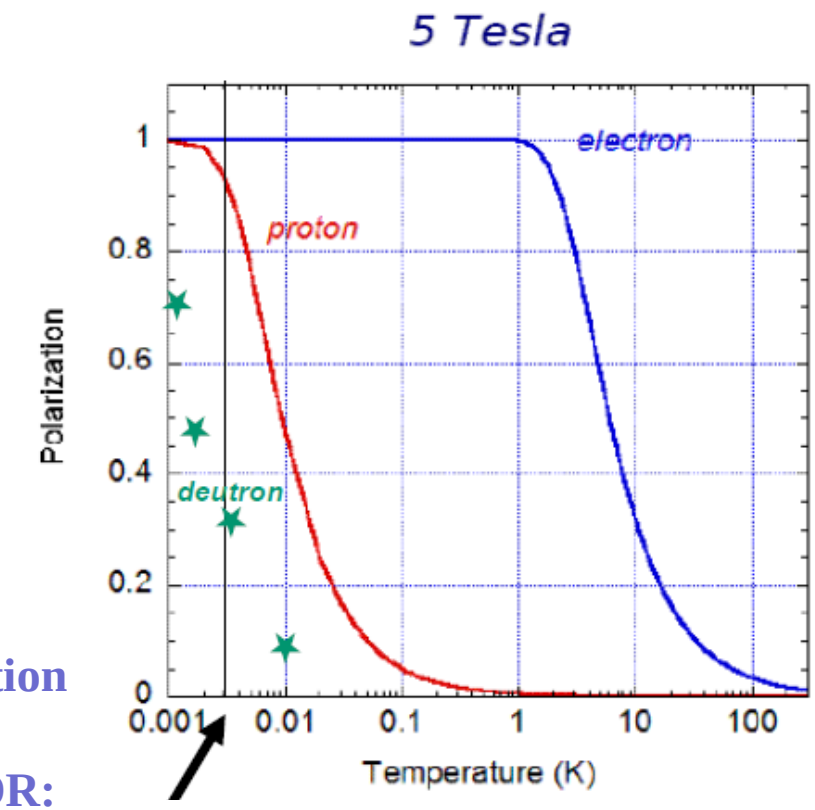
Static Polarization of HD

Brute Force Polarization

$$P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right) \longrightarrow \text{maximize } B, \text{ minimize } T$$

Disadvantages:

1. Requires very large magnet
2. Low temperatures mean low luminosity
3. Polarization can take a very long time
4. Low polarization of deuterons
5. Possibble transfer of the proton polarization to the deuteron by adiabatique fast passage, at the expense of proton polarization
6. Does not work for radioactive species, because heating of the DR: ~ 1 Watt heating → μWatt DR power

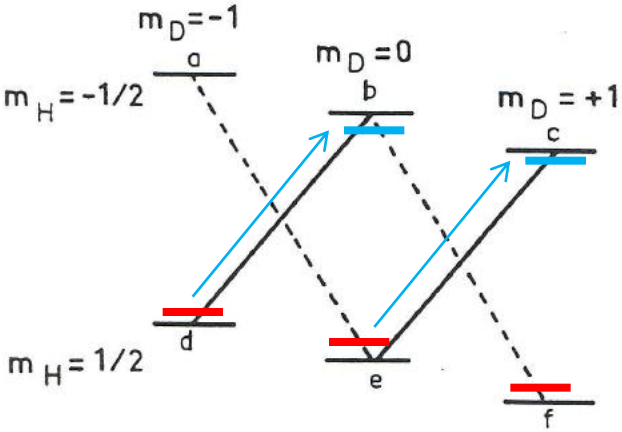


B/T > 1500

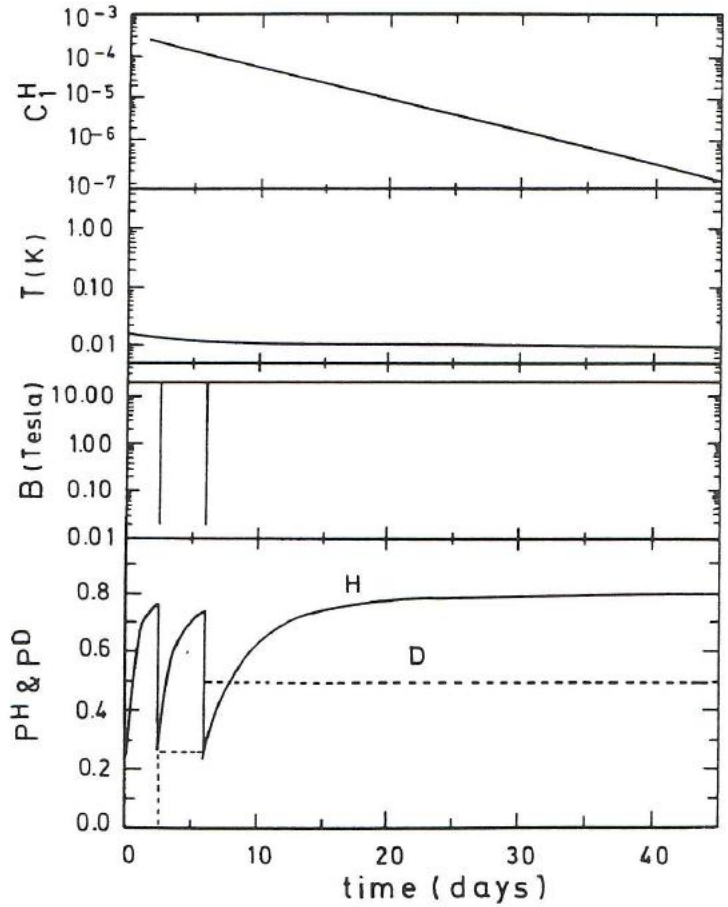
Dilution Refrigerator 10 mK and 17 T (B/T = 1700)

Deuteron Polarization by Adiabatic Fast Passage

$P_H = +1$, $P_D = 0$
after AFP
$P_H = -2/3$; $P_D = +2/3$

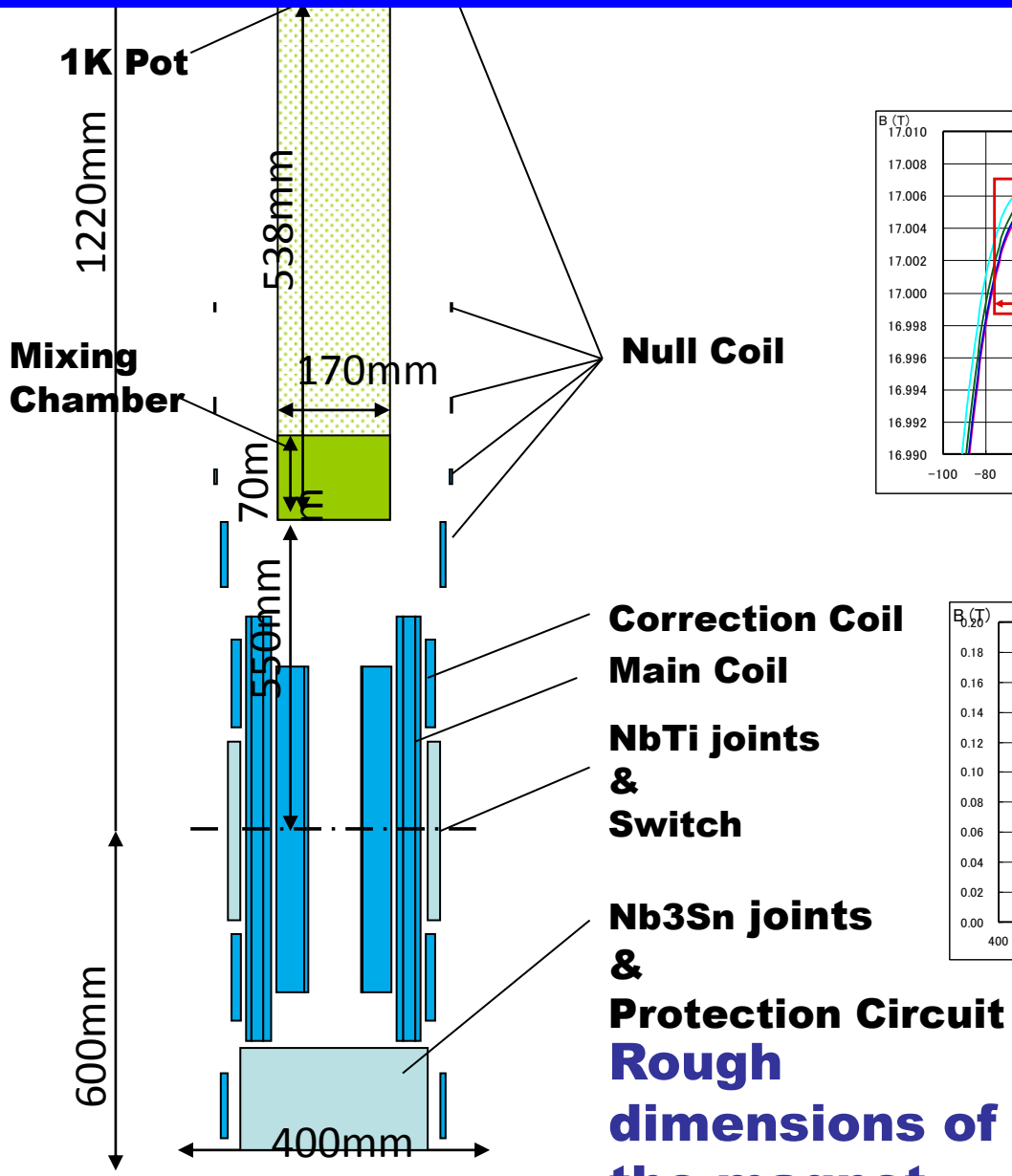


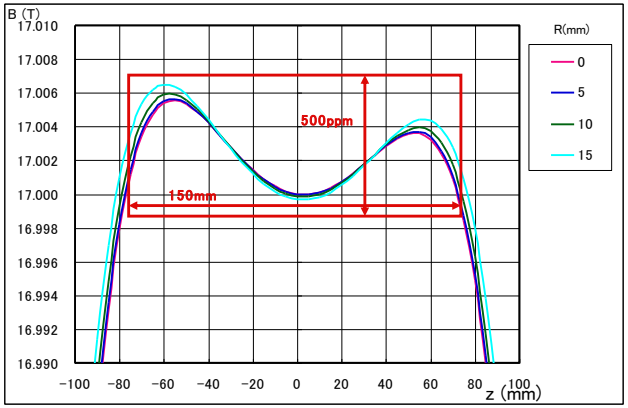
Submagnetic states of H and D nuclei in HD.

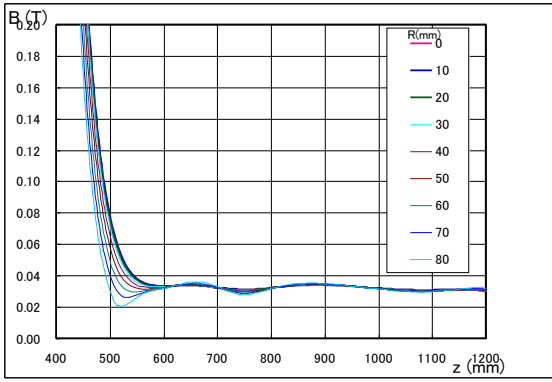


Timing of an AFP

Static Polarization of HD : DR 10 mK, 17 T solenoid







Rough dimensions of the magnet

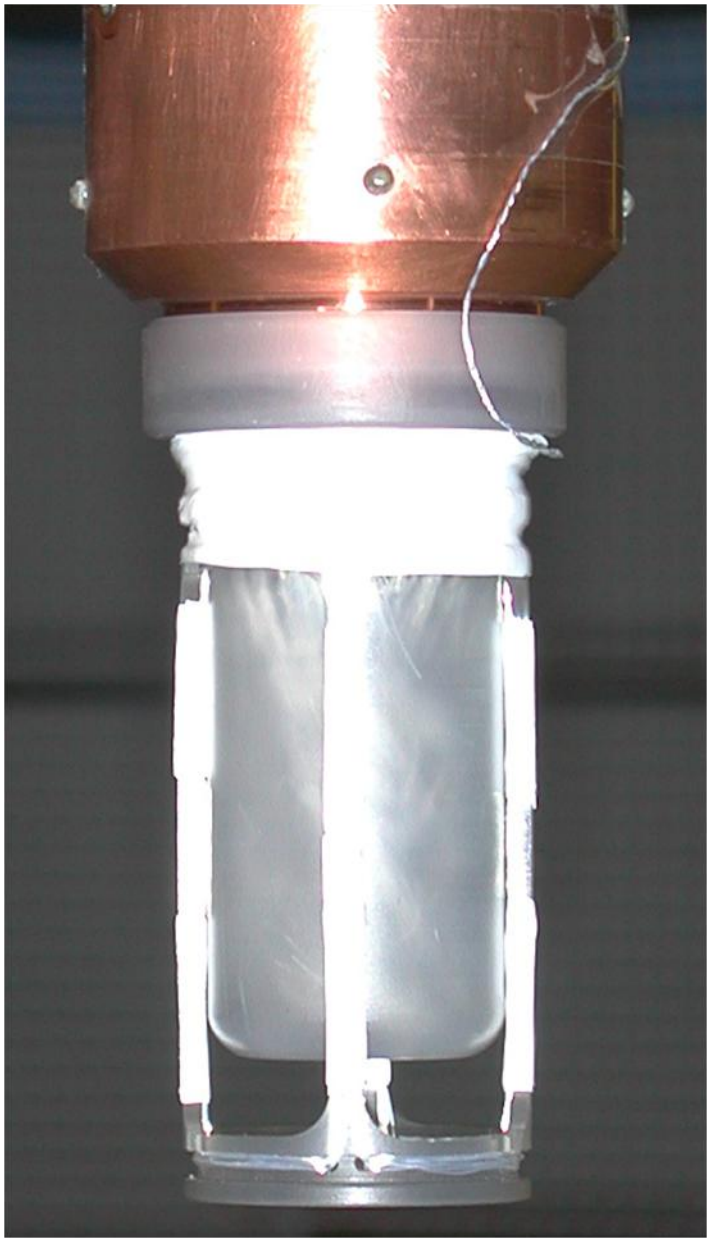
Polarized HD Target
25 cm^3
H (p) polarization > 60%
D (d) vect. polar. > 14%

Nice tool for Nuclear Physics Experiments

it takes **1 MONTH** to make it !

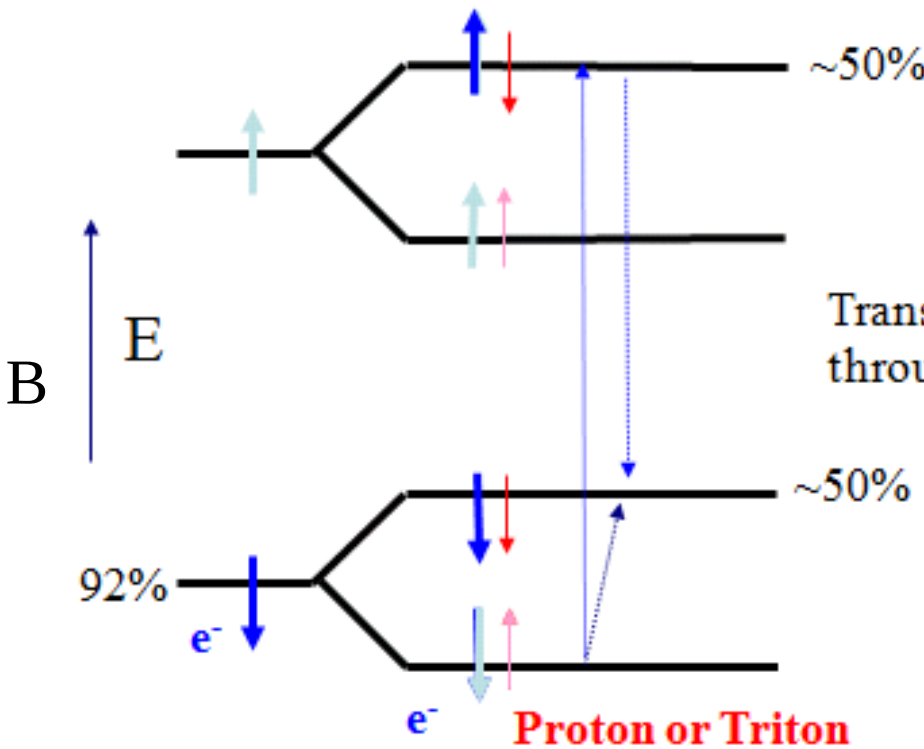
Same volume of polarized DT

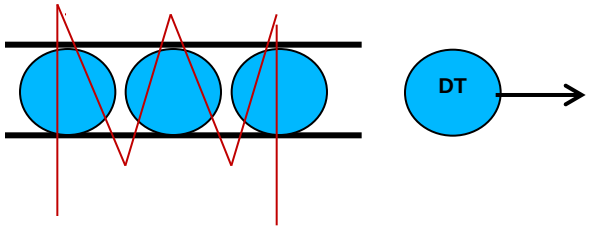
could feed ITER for **1 HOUR !**



Dynamic Polarization of HD or DT

Adding **free electrons**. For B=2.5 T and T = 1 K, e^- polarization = 92%





Transitions made possible through microwave excitation: ~70GHz

Solem et al. in 1974
reach 4% H polarization
with HD containing 4 - 5 % H_2 D_2

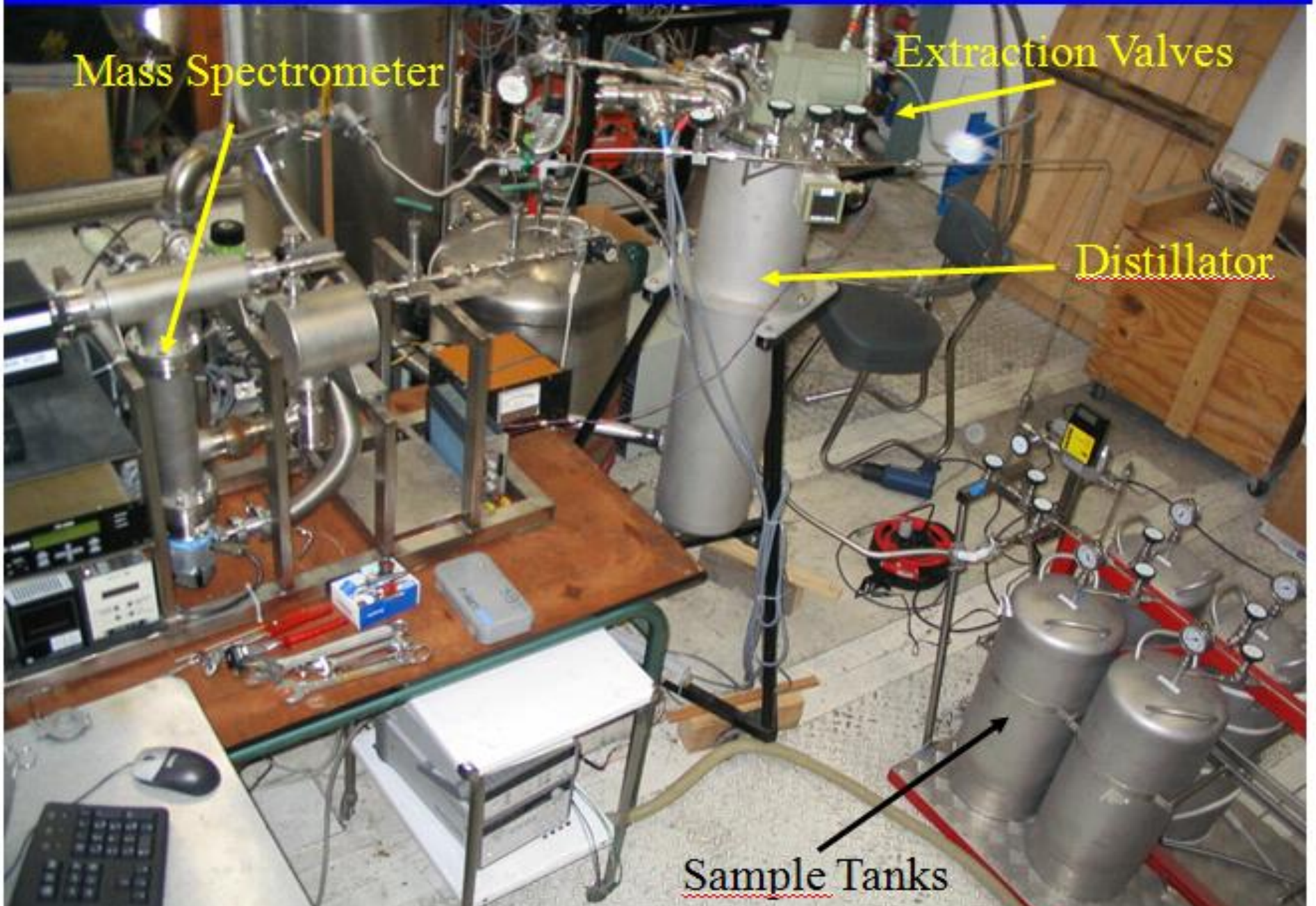
Initial concentration Needed

o-H2: < 0.02 %
p-D2: < 0.1%

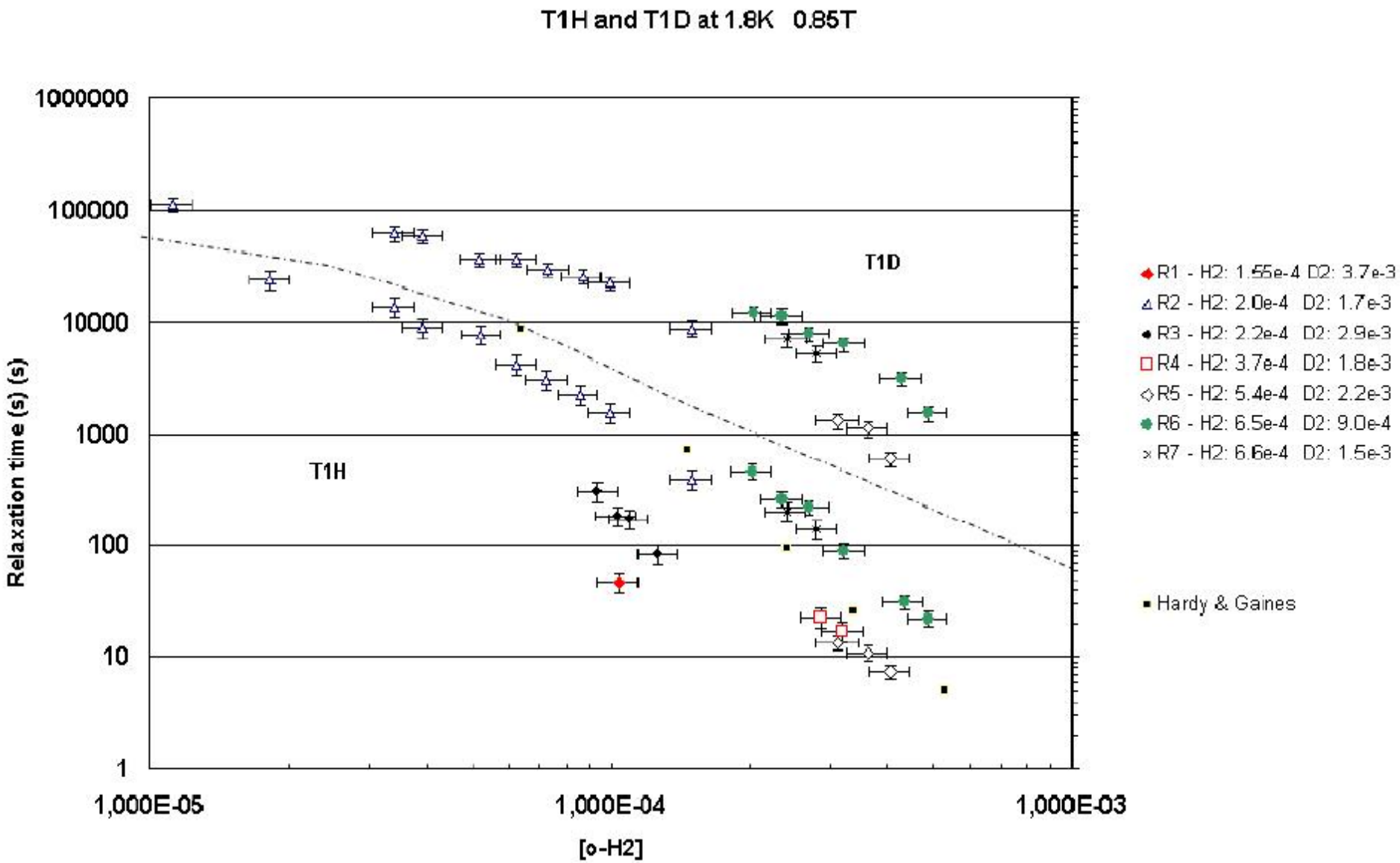
Proton relaxation time >> electron

For DT → $N_\beta \sim 10^{15}$ / mol . s

HD distillation (IPN-Orsay, RCNP-Osaka)



Relaxation Times T1H and T1D in function of ortho-H2 concentrations in HD



S. Bouchigny *et al.,* Nucl. Inst. Meth. A 607, 271–278 (2009).

Other Approaches

Polarization of atoms or molecules → solidification

- *Production of polarized HD molecules in different spin states* Ralf Engels

- *Spin-polarise hydrogen isotopes from UV molecular photodissociation* Peter Rakitzis

- *Experience with polarized hydrogen molecular source* *Dimitrii Toporkov*

We could learn a lot on the polarized solid Hydrogen Isotopes: Relaxation times, configuration of the recombined isotopes, polarization rates of different isotopes, handling of Tritium, etc.

Conclusions

Time needed to prepare one mol of Polarized Solid HD :

- ***Static polarization*** ***One Month***
- ***Dynamique polarization*** ***One Day – One Week***
- ***Atomic Beam Source*** ***Two Years (10^{16} at / s)***

Revival of the HD DNP should be initiated « good HD »

If succesful, extended to DT (necessary for ICF)

A lot of work

We have to find the good people and a good place to do it !