Polarized Fuel for Controlled Thermonuclear Fusion

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An enhancement of nuclear reaction rates in a magnetically confined plasma can be obtained by taking advantage of their dependence on the spin orientation of the reacting nuclei relative to each other and to the local equilibrium magnetic field

Also the direction of fusion products is spin-dependent, allowing one to control the energy transfer from the plasma to the reactor wall or to concentrate the neutron flux to defined wall areas.

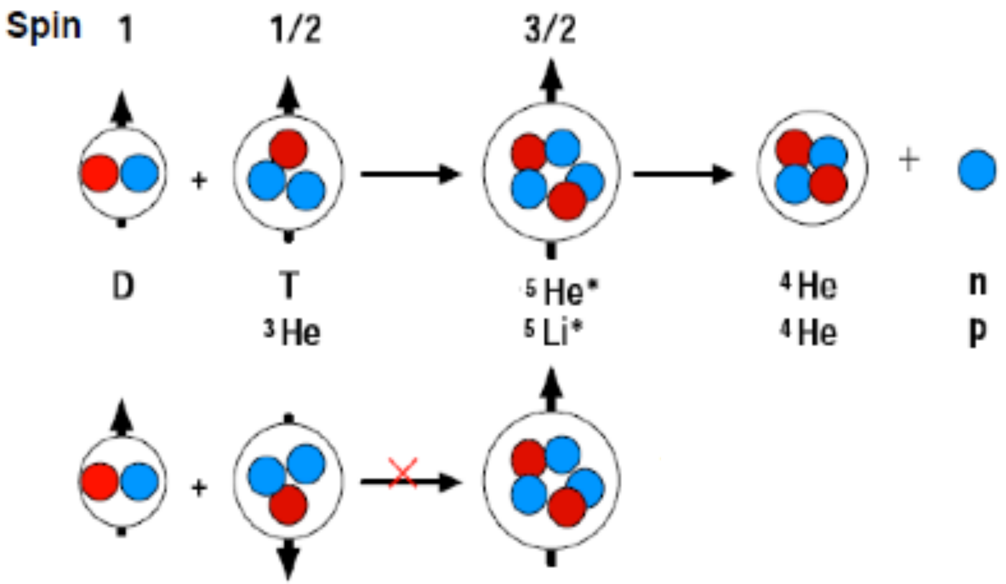
History

Kulsrud R.M. et al., Phys. Rev. Letters **49**, (1982) 1248.
Kulsrud R.M. et al., Nucl. Fus. **26**, (1986) 1443
Cowley S.C. et al., Phys. Fluids **29** (2), (1986) 430.
Coppi B. et al., Phys. Fluids **29** (12), (1986) 4060.

Kulsrud (PPL-Princeton):

“if a reactor is sufficiently marginal in its operation, then the application of polarization could lead to large savings and could even make fusion possible”

Fusion cross section: five nucleons



$^2H + {}^3H \rightarrow {}^4He + n$ + 17.58 MeV
$^2H + {}^3He \rightarrow {}^4He + p$ + 18.34 MeV

S-wave resonance $J^P = 3/2^+$ with $\boldsymbol{\sigma = \sigma_{3/2}}$
Small $J^P = 1/2^+$ component with $\boldsymbol{\sigma_{1/2} \leq 5\ \%\ \sigma_T}$
Total cross-section is:
$\boldsymbol{\sigma = (a + 2/3b + 1/3c)\sigma_{3/2} + (1/3b + 2/3c)\sigma_{1/2}}$
where $a = d_+t_+ + d_-t_-$, $b = d_0$, $c = d_+t_- + d_-t_+$, and $d_\pm$ $t_\pm$ d_0 are the fractions of D, T nuclei aligned parallel, antiparallel or transverse to ext. field ***B***

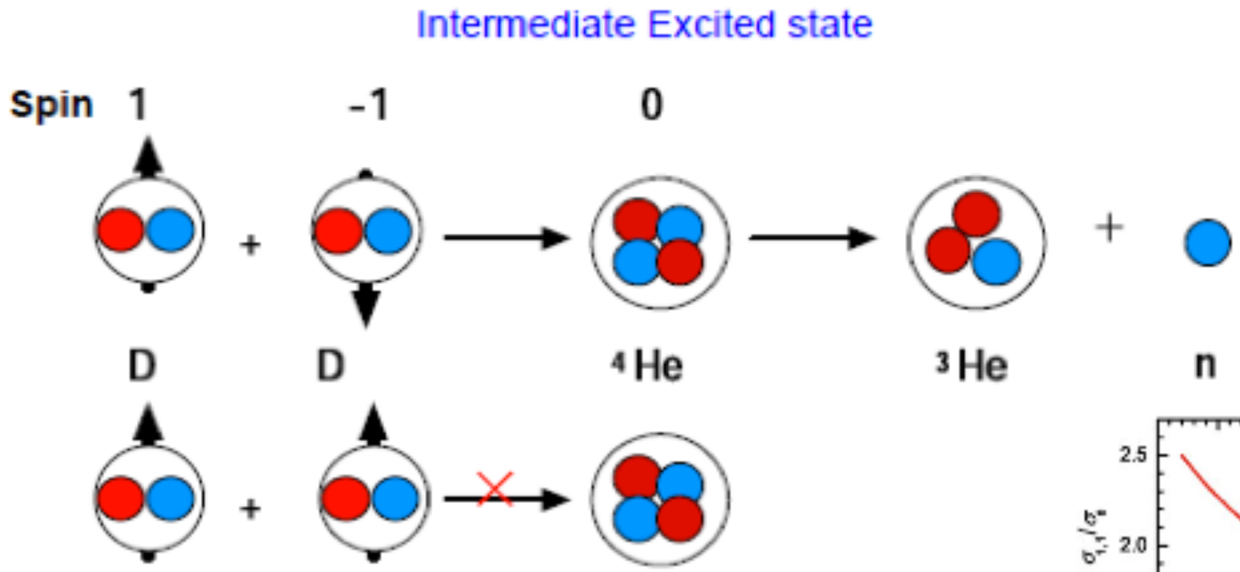
Unpolarized nuclei: a = 1/3 = b = c ➔ $\boldsymbol{\sigma = 2/3\ \sigma_{3/2}}$ *normal mode*

Fully polarized //***B***: a=1, b=c=0 ➔ $\boldsymbol{\sigma = \sigma_{3/2}}$, $\boldsymbol{d\sigma/d\Omega \propto \sin^2\vartheta}$, ***α's and neutrons ≈ ⊥ B*** *enhanced mode*

D polarized ⊥ ***B*** , T unpol.: a=0=c, b=1 ➔ $\boldsymbol{\sigma = 2/3\ \sigma_{3/2}}$, $\boldsymbol{d\sigma/d\Omega \propto k - \cos^2\vartheta}$ ***roughly //B*** *unenhanced mode*

Fully pol. // ***B,*** but antipar.: a=0=b, c=1 ➔ $\boldsymbol{\sigma = 1/3\ \sigma_{3/2}}$ $\boldsymbol{d\sigma/d\Omega \propto k' - \cos^2\vartheta}$ ***//B*** *suppressed mode*

Fusion cross section: four nucleons



***$^2H + {}^2H \rightarrow {}^3He + n$* + 3.268 MeV**

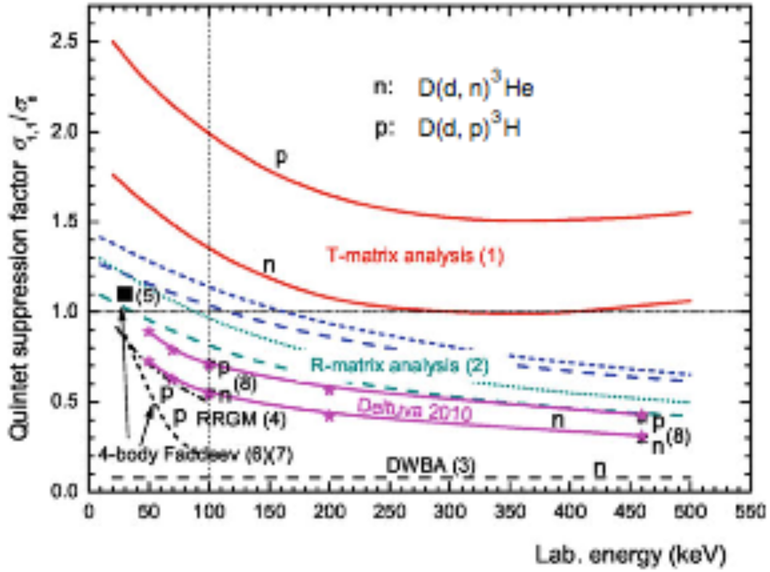
***$^2H + {}^2H \rightarrow {}^3H + p$* + 4.033 MeV**

Reaction complicated and still poorly known!

Possible enhancement by 2-3 for transverse orientation ***⊥ B*** and opposite ***// B***

Suppression of neutron- producing d-d fusions in d-t or d-^{3}He reactors might be possible but lack of exp. data on

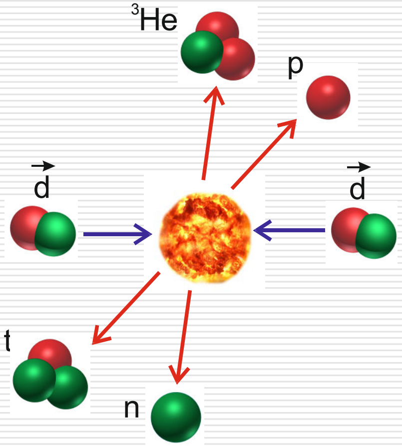
Quintet Suppression Factor = $\boldsymbol{\sigma_{1,1} / \sigma_T}$



Polfusion collaboration at PNPI Gatchina

Investigation of 4-nucleons reaction
with the both initial particles polarization
at the 10-100 keV energy (center of mass) .

$$\vec{d} + \vec{d} \begin{array}{l} \nearrow \; t + p \\ \searrow \; {}^{3}\mathrm{He} + n \end{array}$$



Petersburg Nuclear Physics Institute, Russia
Forschungszentrum Jülich, Germany
Ferrara University, Italy
Cologne University, Germany
KVI, Gronningen, Netherlands

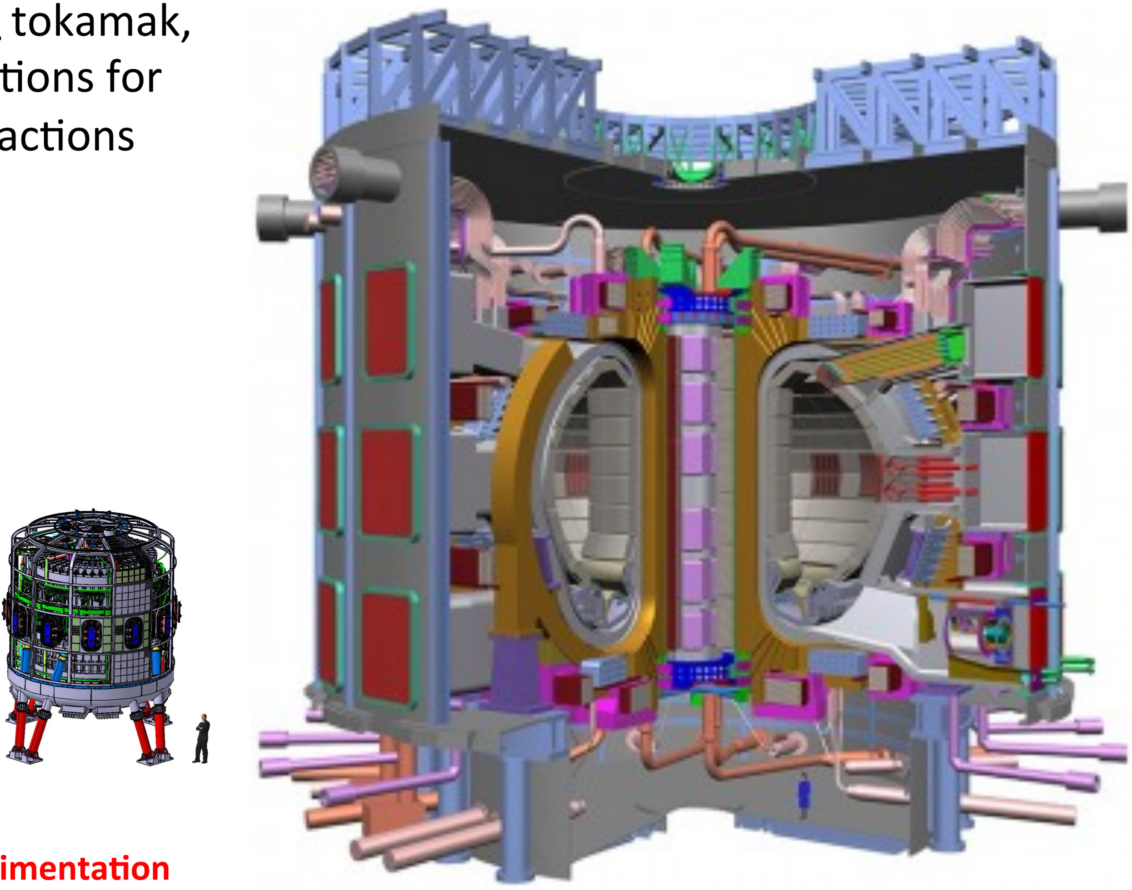
- Measurements of the cross section polarized dd reaction
- Systematic measurements of spin-correlation coefficients
- Measurements of neutrons suppression -
  Quintet suppression factor
- Angular distribution of the reaction products
- Investigation of the principle possibility polarized fuel for Fusion reactors
  Persistence of the Polarization in a Fusion Process

A. Vasilyev et al., in "Nuclear Fusion with polarized Fuel", Springer Proc. in Phys., Vol. 187 p. 35 (2016)

Two ways to thermonuclear fusion: ITER and/or IGNITOR

IGNITOR, high field, high-density, high-Q tokamak, aiming to reach the ohmic heating conditions for allowing self-sustained nuclear fusion reactions

	ITER	IGNITOR
Diam.	29 m	7 m
Alt.	26 m	8 m
PlasmaVol.	840 m^3	10 m^3
Weight	23000 t	770 t
Fusion Power	500 MW	100 MW
El. density	$\sim 10^{20}\ m^{-3}$	$\sim 10^{21}\ m^{-3}$
$Q=P_f/P_{in}$	5 -10	> 50
Toroidal field	5.3 T	13 T
τ_E	3.7 sec	0.6 sec
Est. Cost	> 20 G€	~ 0.35 G€



ITER biggest flaw: Q-value too low, useful experimentation for a realistic, commercial reactor impossible!

Depolarization mechanisms

Unfavorable energy balance: $\Delta E_{pol} \approx 10^{-7} - 10^{-6}$ eV << kT ≈ 10^{4} eV but

"the mechanisms for depolarization of nuclei in a magnetic fusion reactor are surprisingly weak" (Kulsrud)

Polarization survival ~ energy confinement time τ_E = 0.65 sec at B_0 =13 T for IGNITOR, (5 sec for ITER)

Ion+electron recombination: spin exchange hyperfine mixing ∝ $(B_c/B0)^2$ very small ≈ 10^{-6} sec^{-1} for IGNITOR

Binary collisions dominated by spin-orbit coupling: $dP_T/dt \cong 8 \bullet 10^{-6}$, $dP_D/dt \cong 3 \bullet 10^{-7}$ sec^{-1}

Depolarization from wall recycling: difficult to estimate, expected for non-metallic materials < 1 sec^{-1} (^{12}C no unpaired e^-, no μ)

Field inhomogeneities for IGNITOR (B_0=13 T, R=1.32 m, kT=10.5 keV)

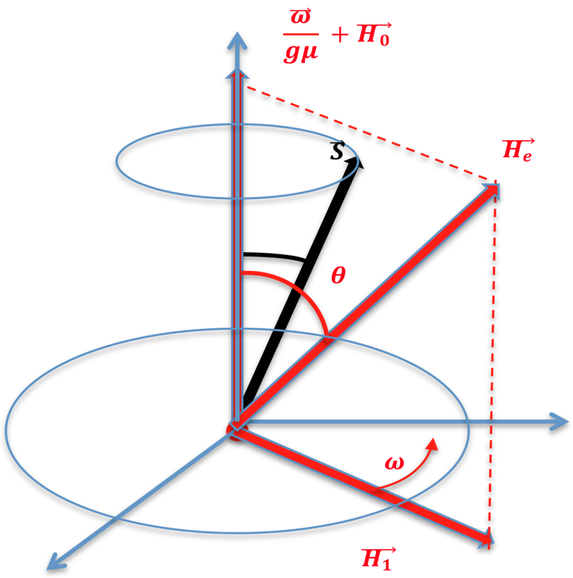
$$\frac{\partial P_D}{\partial t}(sec^{-1}) = -\frac{4.5 \ * 10^{-2}\, n_D \left(\frac{10^{14}}{cm^3}\right)}{R^2\ (m) B^2 (T) \sqrt{kT_D} (keV)} = \ 4.7 \ * 10^{-5}\, n_D \left(\frac{10^{14}}{cm^3}\right)$$

Resonant plasma waves: the spin-flip matrix element for ^3H in a S_z =+1/2 is approximately given by:

$$\frac{(\delta c_{-1/2})^2}{t} \approx \frac{1}{8}\langle\left(\frac{\delta B_\perp}{B}\right)^2\rangle \Omega_p \qquad = 0.027\ sec^{-1} \qquad \text{for } \delta B_\perp \approx 1\ G,\ B=13\ T,\ \Omega_p = 2\pi \bullet 590\ MHz$$

A direct polarization survival measurement is needed before developing options for polarizing Tokamak fuel

Motion of free spin



Spin motion in a magnetic field $\vec{H}$ as seen in a rotating frame ($\vec{\varpi}$)

$$\left.\frac{d\vec{S}}{dt}\right|_{\omega} = g\mu\,\vec{S}\times\vec{H} + \vec{S}\times\vec{\varpi} = g\mu\,\vec{S}\times\left(\frac{\vec{\varpi}}{g\mu} + \vec{H}\right)$$

$$\vec{H} = H_0(t)\hat{z} + H_1[\hat{x}cos(\omega_1 t) + \hat{y}sin(\omega_1 t)] \qquad \gamma = g\mu, \qquad tg\theta = \frac{H_1}{H_0 + \omega/\gamma} = \frac{\omega_1}{\omega_0 - \omega}$$

$$H_e = [(H_0 + \frac{\omega}{\gamma})^2 + H_1^2]^{1/2} = -\frac{a}{\gamma} = -[(\omega_0 - \omega)^2 + \omega_1^2]^{1/2}\frac{1}{|\gamma|}$$

Adiabaticity: in a rotating frame continuously aligned along $\vec{H_e}$, if $|\omega(t)| << |\gamma H_e(t)|$ for any t, then

$$\dot{H}_0 << \frac{\gamma {H_e}^2}{sin\theta}$$

max. at resonance ($\theta = \pi/2, H_e = H_1$), so if the initial magnetic moment is parallel to H_0, when the field varies with time, its component parallel to H_e will remain constant by crossing the resonance and thus end up as antiparallel to H_0. Either $H_0 = H_z$ is kept constant and ω_1 is slowly varied or the inverse is possible

If there's a distribution of precession frequencies (field inhomogenities) of width δ, all the spins are not at resonance simultaneously, so the magnetic moment component along H_e is still an adiabatic invariant, but its transverse value may be reduced by a factor ω_1/δ

Polarization in a reactor’s field

Polarization vector $P = \langle S_z \rangle = 1$ for a single spin, but may average to 0 for an ensemble of spin (pure vs. mixed states).

It precesses around magnetic field in the same way as a classical magnetic dipole

$$\frac{d\vec{\boldsymbol{P}}}{dt} = \gamma\, \vec{\boldsymbol{P}} \times \vec{\boldsymbol{H}}$$

If H homogeneous the parallel component of P will be conserved.

In a typical Tokamak the space dependence of toroidal and poloidal field give rise to a transverse field (to both) H_1 with components $H_{1p} \approx r_{ci} H_t / R$ and $H_{1t} \approx a H_{1p} / R$.

This is seen by the particle as an oscillating field at $\omega_1 = eH_1/m = \omega_{ci}\,(g_i/2)(m_i/m_p)/Z_i\, H_1/H_t$. (Lodder, PL **98A**, 179(1983))

Hence the total equation for polarization in rotating coordinates is

$$\left.\frac{d\vec{\boldsymbol{P}}}{dt}\right|_{rot} = (\vec{\boldsymbol{\varpi}}_1 + \vec{\boldsymbol{\varpi}}_{ci} - \vec{\boldsymbol{\varpi}}_0) \times \vec{\boldsymbol{P}} = \vec{\boldsymbol{\varpi}}_T \times \vec{\boldsymbol{P}}$$

So the direction of ω_1 gives the displacement of the nutation centre from the average field direction and the spin motion is a precession in a narrow cone about it.
This random process leads to spin diffusion by classical mixing of their directions.
Mixing by random perturbations (collision, plasma waves) is not reversible, unlike collisionless mixing.
The perturbation need not to be at the precession frequency, but just at the difference frequency ω_{ci}- ω_0.

Ion Cyclotron Resonant Heating (ICRH) in a tokamak

ICRH is a potential source of depolarization.
Typical RF parameters

frequency **10 – 100 MHz** power **2-12 MW** electric field **E ≈ 20kV/m** magnetic induction B ≈$\mathbf{10^{-3}}$ **T << $\mathbf{H_0}$≈10 T**

The use of ICRH may harm polarization, if $\omega = \boldsymbol{\omega_{pi} \pm n\omega_{ci} + k_B v_B}$ Doppler-shifted to couple with spin

RF Bandwidth required ≥ $\mathbf{[d\omega_{pi}/dt]^{1/2}}$ to stay on resonance, Depolarization rate ≈

$$\frac{\left(\delta c_{-\frac{1}{2}}\right)^2}{t} \approx \frac{1}{8}\left\langle\left(\frac{\delta B_\perp}{B}\right)^2\right\rangle \Omega_p \cdot \frac{\Omega_p}{\sqrt{d\Omega_p/dt}}$$

Fusion fuels ($\boldsymbol{\gamma_i=\omega_{pi}/2\pi}$, $\boldsymbol{vi=\omega_{ci}/2\pi}$):

g_D = 0.86 ; γ_D =6.54 MHz/; ν_D = 7.60 MHz/T; $|\underline{S}|$ = **1** for deuterium

g_T = 5.96 ; γ_T = 45.40 MHz/T; ν_T = 5.08 MHz/T; $|\underline{S}|$ = **1/2** for tritium

g_{He3} = - 4.26 ; γ_{He} = 32.43 MHz/T; ν_{He} = 10.12 MHz/T; $|\underline{S}|$ = **1/2** for ^{3}He

IGNITOR: Two proposed RF frequencies 95 MhZ for 9<B_0<11 T , 115 MHz for 11<B_0<13 T (Cardinali, ENEA)

Deuterium: giration and precession frequencies quite near due to the **g_D = 0.86**

Position of resonant layer (norm. plasma radius units): x=-0.29 1st harmonic

$$x = A \times \left[15.2 \times \frac{N_{harm} Z_i m_p B_0}{m_i f_{RF}} - 1\right]$$

Critical range 59 – 85 MHz for n=0, 127 – 184 MHz for n=1

Tritium: $\gamma_T/\nu_T \approx 9$ ➔ RF frequency = 590 MHz at 13 T**,** coupling $\propto J_n^2(k_\perp v_\perp/\omega_c) \approx z^n/(2^n n!)$,

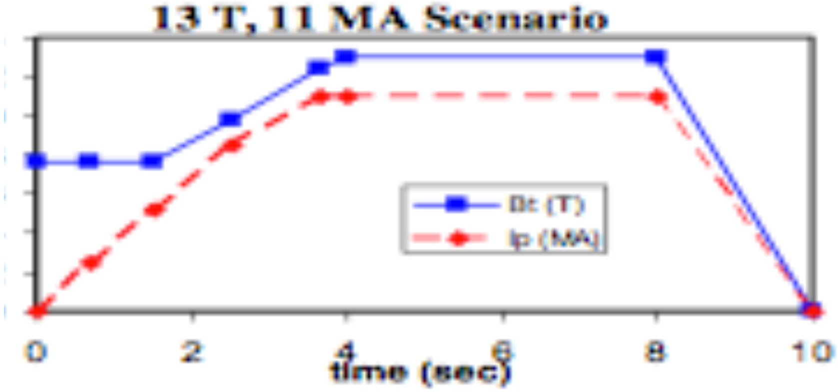
higher harmonics suppressed for small z

Helium-3: $\gamma_{He}/\nu_{He} \approx 3.2$ ➔RF frequency = 421 MHz and critical range 72 – 105 MHz for n =-4

For neither D-T nor D-^{3}He plasma polarization is likely to interact with ICRH

External RF fields to interact with polarization

Injecting unpolarized atoms in high magnetic field: ineffective at high temperature! fraction of nuclei contributing to NMR ≈μB/kT ≈ 3•10^{-11} for D at H_0= 13T and E=10 keV.



Injecting two-states electron-polarized atomic beams and polarizing nuclei via hyperfine transitions:
adiabaticity requires $dH_0/dt \ll \gamma H_1^2$
field ramping-up≈2T/s
$H_1 \gg 5$ G for D, $H_1 \gg 2$ G for T
but injection available rate still insufficient!

Compensation of resonant depolarization by plasma stray waves: possible with special RF field with a proper bandwidth and H-component parallel to the H_0 field? Unable to cope with random perturbations.
RF specialists at ENEA are presently upgrading simulation codes to include polarization

Experimental issues

Polarized Atomic Beam Sources: max. ≈ 10^{17} a/s, polarization > 90%, largely insufficient for Tokamak operation: few moles with 10^8 sec lifetimes; here Kmoles with 10 sec lifetimes required! ITER-scale reactor would require 2000 moles of D and T with 100% polarization per day!

Polarization survival must be demonstrated first, then polarized Tritium technology need development (optical pumping method, like polarized ^{3}He for NMR) ➔ long-term R&D goal

Polarization survival observed for H_2 molecules after recombination on a inert surface like frozen Fomblin oil at 100 °K: does it work also for deuterium? Possibility of polarized D_2 molecules, frozen and stored for several hours to be injected into a Tokamak.

Present US (DIII-D, JLAB) Proposal: Use of Inertial Confinement Fusion pellets to be filled

1) with solid HD molecules and then frozen to m°K temperatures in high magnetic fields (> 15 T) to get high > 90% polarization
2) with polarized ^{3}He from ABS to study the polarized $^2H + ^3He \rightarrow ^4He + p$ reaction

But: existing cryo-injection guns need upgrade for high magnetic field (15-17 T), low temperature (2°K) operation and polarization monitoring (inline-SQUID) ➔ short-term R&D goal

IGNITOR recent history

Long and controversial history, dating back from the late 70's: somehow similar to ITER, but in this case the international support was missing and UE bureaucracies were adverse

1994-2000: big funding for R&D on IGNITOR assigned to ENEA by italian Parliament but no take off of the project (ENEA, MIUR, EURATOM unfavourable)

2008: investigative reporting by italian Senate, ➔ consultations Italy – Russia ➔ in2010 a MoU between Ministries ➔ cooperation for IGNITOR project and NP, ➔ agreement for IGNITOR project on the territory of the Russian Federation.

2011: IGNITOR is a 'Flagship' project in the italian PNR with a 80 M€ budget

2012: INFN is entrusted the machine construction, NRC "Kurchatov Institute" for the upgrading of the existing equipment and the host infrastructure

2013: INFN and NRC Kurchatov agree on a standard evoluting path for IGNITOR

2014: joint italian-russian working group built to produce a CDR

2015 (july): CDR eventually ready and submitted to the respective political authorities

And now? One more year is over: are INFN and MIUR really committed to IGNITOR? And Russia?