Study of the ignition conditions of polarized DT fuel for Inertial Confinement Fusion

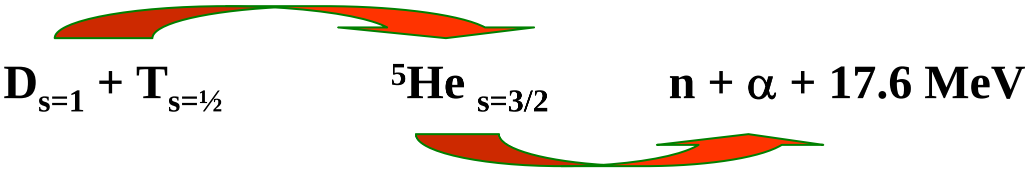
M. Temporal[1], V. Brandon[2], B. Canaud[2], J. P. Didelez[3], R. Fedosejevs[4], R. Ramis[1]

1) Universidad Politécnica de Madrid, Spain

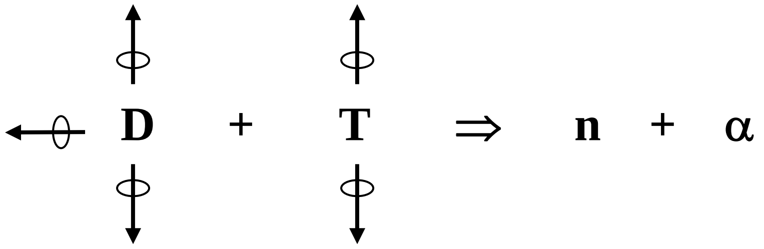
2) CEA, DAM, DIF, F-91297 Arpajon, France

3) Institut de Physique Nucléaire, CNRS/IN2P3 et Université Paris XI 91406 Orsay, France

4) University of Alberta, Department of Electrical & Computer Engineering, Edmonton, Canada



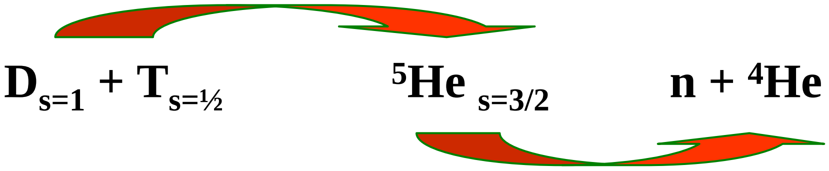
$D_{s=1} + T_{s=½}$ $^{5}He_{s=3/2}$ $n + \alpha + 17.6$ MeV



$D + T \Rightarrow n + \alpha$

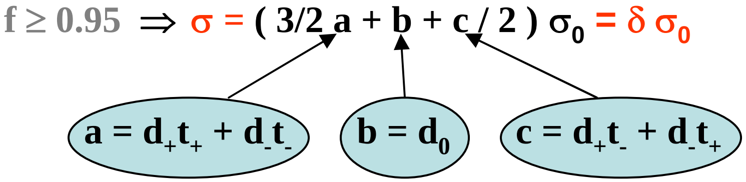
Direct Drive and Fast Ignition Workshop
Prague, May 27-30, 2012

Nuclear cross section depends on the polarization of the Deuterium and Tritium



$D_{s=1} + T_{s=½}$ $\quad {}^5He_{\,s=3/2}$ $\quad n + {}^4He$

$$\sigma = (3/2\, a + b + c / 2)\, f\, 2/3\, \sigma' + (b + 2 c) (1 - f)\, 2/3\, \sigma' = \delta\, 2/3\, \sigma' = \delta\, \sigma_0$$



$f \geq 0.95 \Rightarrow \sigma = (3/2\, a + b + c / 2)\, \sigma_0 = \delta\, \sigma_0$

$a = d_+t_+ + d_-t_-$

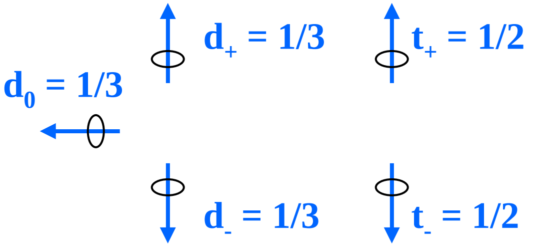
$b = d_0$

$c = d_+t_- + d_-t_+$

Unpolarized DT : $a = b = c = 1 / 3 \Rightarrow \sigma = \sigma_0$

Fully polarized DT: $a = 1$; $b = c = 0 \Rightarrow \sigma = 3/2\, \sigma_0$

Unpolarized DT

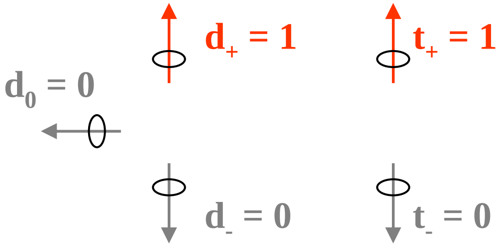


$d_+ = 1/3$ $\quad t_+ = 1/2$

$d_0 = 1/3$

$d_- = 1/3$ $\quad t_- = 1/2$

Fully polarized DT



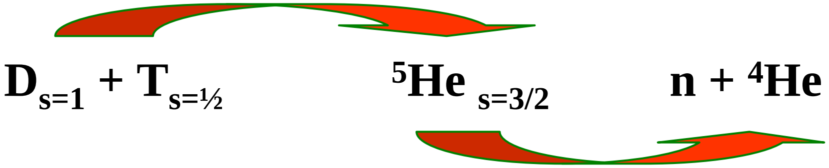
$d_+ = 1$ $\quad t_+ = 1$

$d_0 = 0$

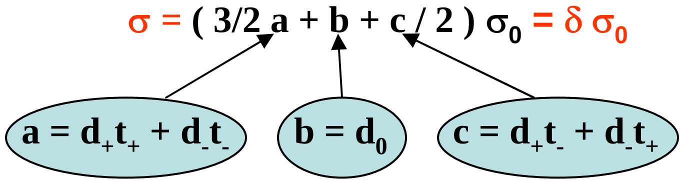
$d_- = 0$ $\quad t_- = 0$

R.M. Kulsrud, E.J. Valeo and S.C. Coweley *Nucl. Fus.* **26** 335 (1986)

DT cross section increases by 50% for fully polarized nuclei



$D_{s=1} + T_{s=½}$ $^{5}He_{s=3/2}$ $n + {}^{4}He$

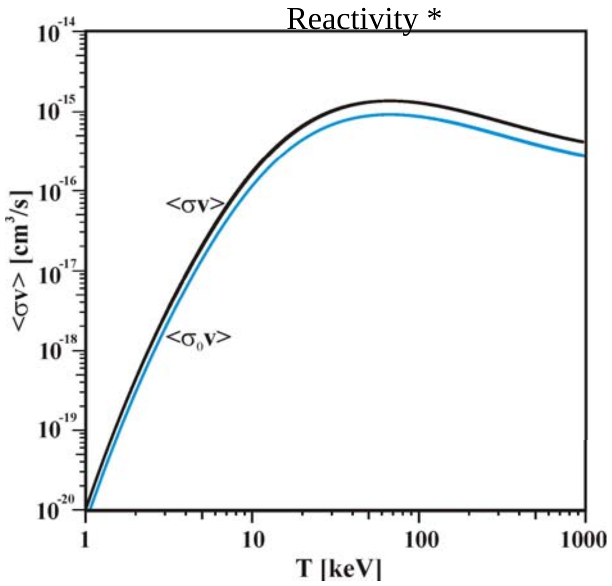


$\sigma = (3/2\, a + b + c / 2)\, \sigma_0 = \delta\, \sigma_0$

$a = d_+t_+ + d_-t_-$

$b = d_0$

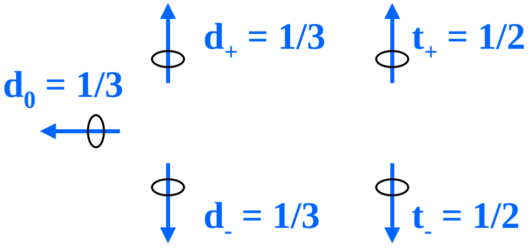
$c = d_+t_- + d_-t_+$



Unpolarized DT : $a = b = c = 1 / 3 \Rightarrow \sigma = \sigma_0$

Fully polarized DT: $a = 1; b = c = 0 \Rightarrow \sigma = 3/2\, \sigma_0$

Unpolarized DT

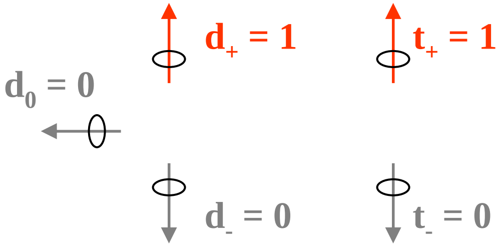


$d_+ = 1/3$ $t_+ = 1/2$

$d_0 = 1/3$

$d_- = 1/3$ $t_- = 1/2$

Fully polarized DT



$d_+ = 1$ $t_+ = 1$

$d_0 = 0$

$d_- = 0$ $t_- = 0$

* HS Bosch and GM Hale *Nucl. Fusion* **32** 611 (1992)

The burn parameter H_B decreases as the reactivity increases

$D_{s=1} + T_{s=½}$ $^5He_{s=3/2}$ $n + {}^4He$

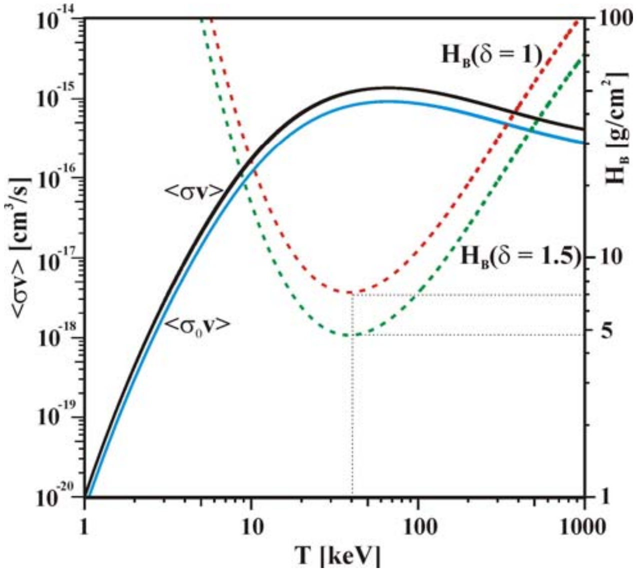
$\Rightarrow \sigma = \delta\,\sigma_0$; fully polarized DT $\Rightarrow \delta = 1.5$

$\sigma = (3/2\, a + b + c/2)\,\sigma_0 = \delta\,\sigma_0$

$a = d_+t_+ + d_-t_-$ $b = d_0$ $c = d_+t_- + d_-t_+$

Unpolarized DT : $a = b = c = 1/3 \Rightarrow \sigma = \sigma_0$

Fully polarized DT: $a = 1;\ b = c = 0 \Rightarrow \sigma = 3/2\,\sigma_0$



ICF energy gain: $G = E_{TN} / E$

$E_{TN} = q_{DT}\, M_{DT}\, \phi$

Burn fraction:

$\phi \cong \rho_h R_h / (\rho_h R_h + H_B)$

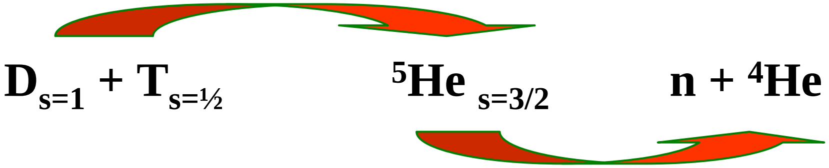
burn parameter * :

$H_B \cong 9\, T^{½} / \langle\sigma_0 v\rangle \cong 7$

$H_B \cong 9\, T^{½} / \langle\sigma\, v\rangle \cong 5$

* S Atzeni & J Meyer-ter-Vehn *The Physics of Inertial Fusion* (2004)

Ignition conditions for an isobaric hot-spot configuration (Multi-1D simulations)



$D_{s=1} + T_{s=½}$ $\quad {}^5He_{\,s=3/2}$ $\quad n + {}^4He$

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$\sigma = (\,3/2\,a + b + c\,/\,2\,)\,\sigma_0 = \delta\,\sigma_0$

$a = d_+t_+ + d_-t_-$

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Unpolarized DT $: a = b = c = 1\,/\,3 \Rightarrow \sigma = \sigma_0$

Fully polarized DT: $a = 1;\ b = c = 0 \Rightarrow \sigma = 3/2\,\sigma_0$

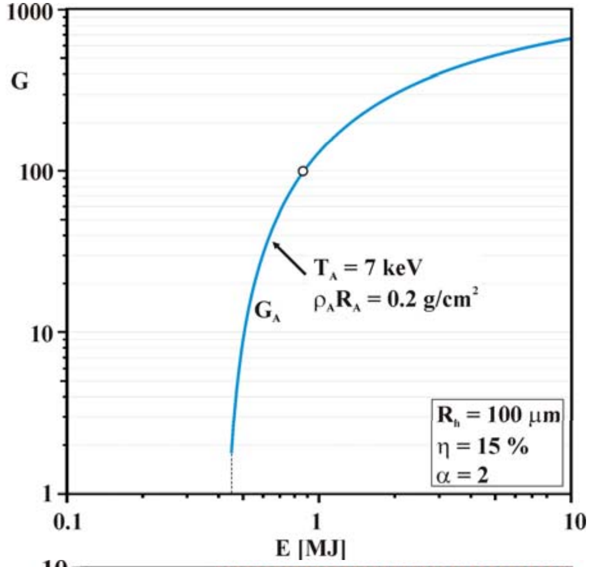
Burn fraction:

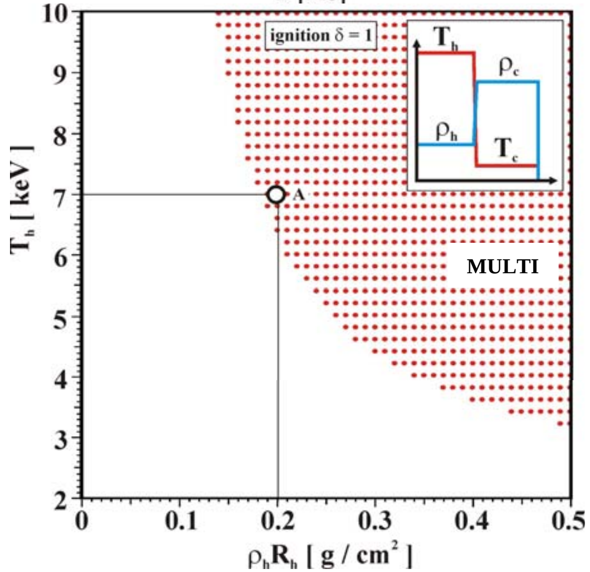
$\phi \cong \rho_h R_h\,/\,(\,\rho_h R_h + H_B\,)$

$E_{TN} = q_{DT}\,M_{DT}\,\phi$

ICF energy gain: $G = E_{TN}\,/\,E$

Isobaric model *





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* J. Meyer-ter-Vehn *Nucl. Fusion* **22** 562 (1982)

Polarized nuclei implies an extension of the ignition region in the $\rho_h R_h$ - T_h space

$D_{s=1} + T_{s=½}$ $^5He_{s=3/2}$ $n + {}^4He$

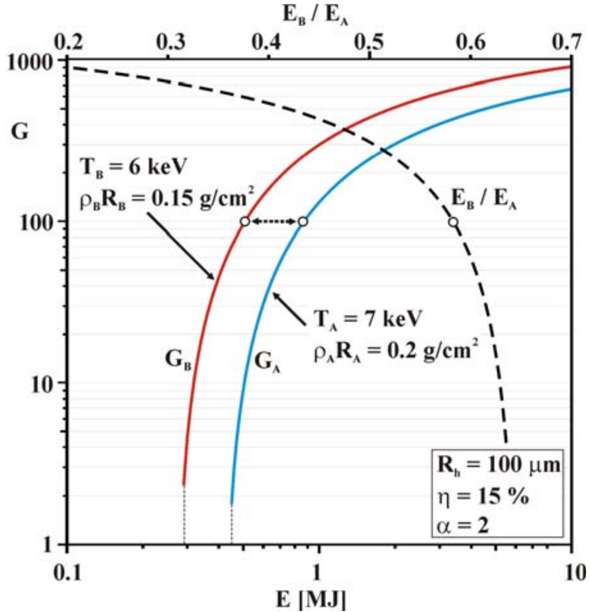
$\Rightarrow \sigma = \delta\, \sigma_0$; fully polarized DT $\Rightarrow \delta = 1.5$

$\sigma = (3/2\, a + b + c / 2)\, \sigma_0 = \delta\, \sigma_0$

$a = d_+t_+ + d_-t_-$

$b = d_0$

$c = d_+t_- + d_-t_+$



Unpolarized DT : $a = b = c = 1 / 3 \Rightarrow \sigma = \sigma_0$

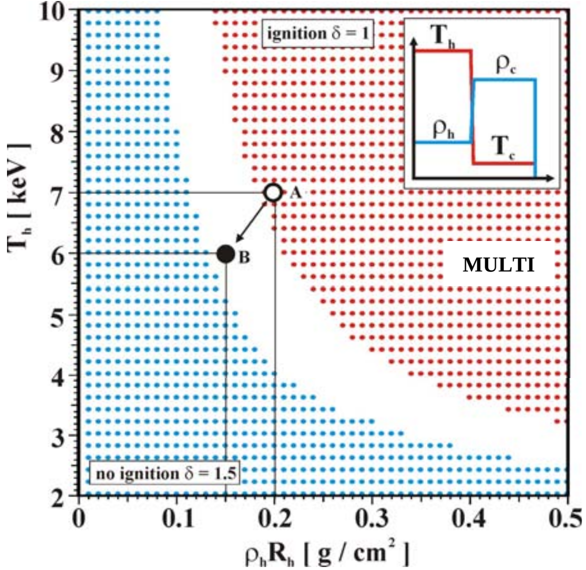
Fully polarized DT: $a = 1$; $b = c = 0 \Rightarrow \sigma = 3/2\, \sigma_0$

Burn fraction:

$E_{TN} = q_{DT}\, M_{DT}\, \phi$

$\phi \cong \rho_h R_h / (\rho_h R_h + H_B)$

ICF energy gain: $G = E_{TN} / E \downarrow$



The reduction of the hot-spot ignition conditions e.g. from [0.2 g/cm², 7 keV] to [0.15 g/cm², 6 keV] implies a reduction of the driver energy E which in turn increases the gain G

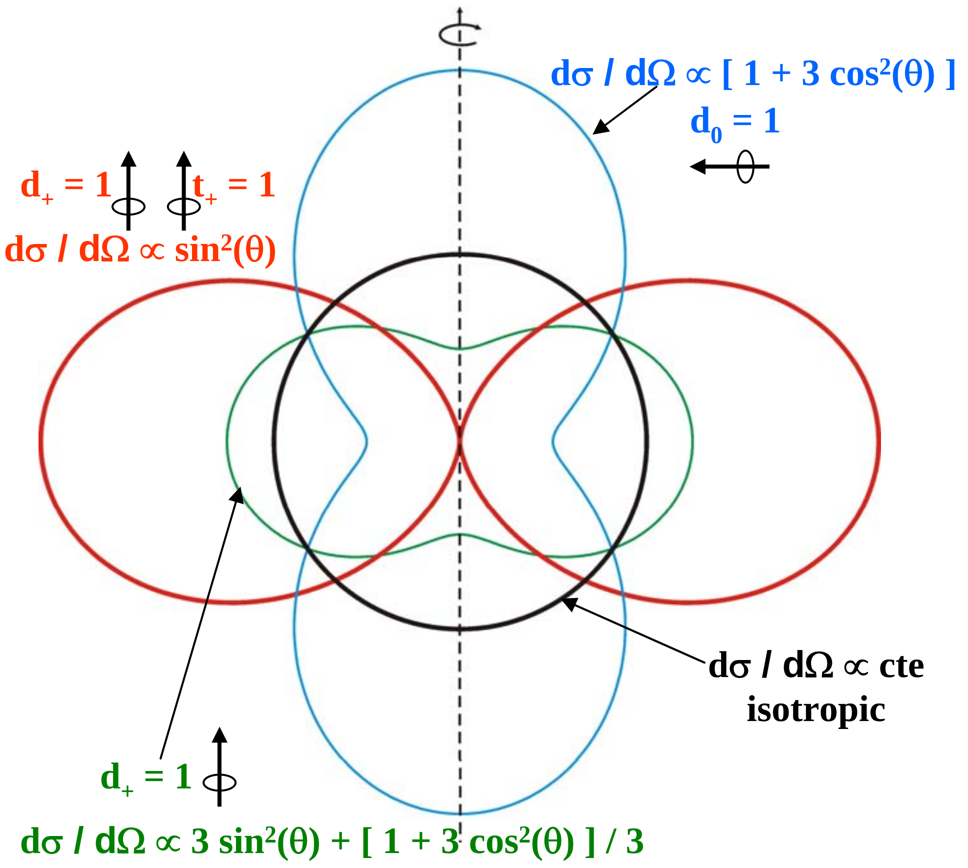
The angular distribution of the fusion products also depends on the polarization

$D_{s=1} + T_{s=½}$ $^{5}He_{s=3/2}$ $n + {}^{4}He$

$$d\sigma / d\Omega \propto 3\,a \sin^2(\theta) + (2\,b / 3 + c / 3)\,[\,1 + 3\cos^2(\theta)\,]$$

$a = d_+t_+ + d_-t_-$ $b = d_0$ $c = d_+t_- + d_-t_+$

$$\sigma = (\,3/2\,a + b + c / 2\,)\,\sigma_0 = \delta\,\sigma_0$$



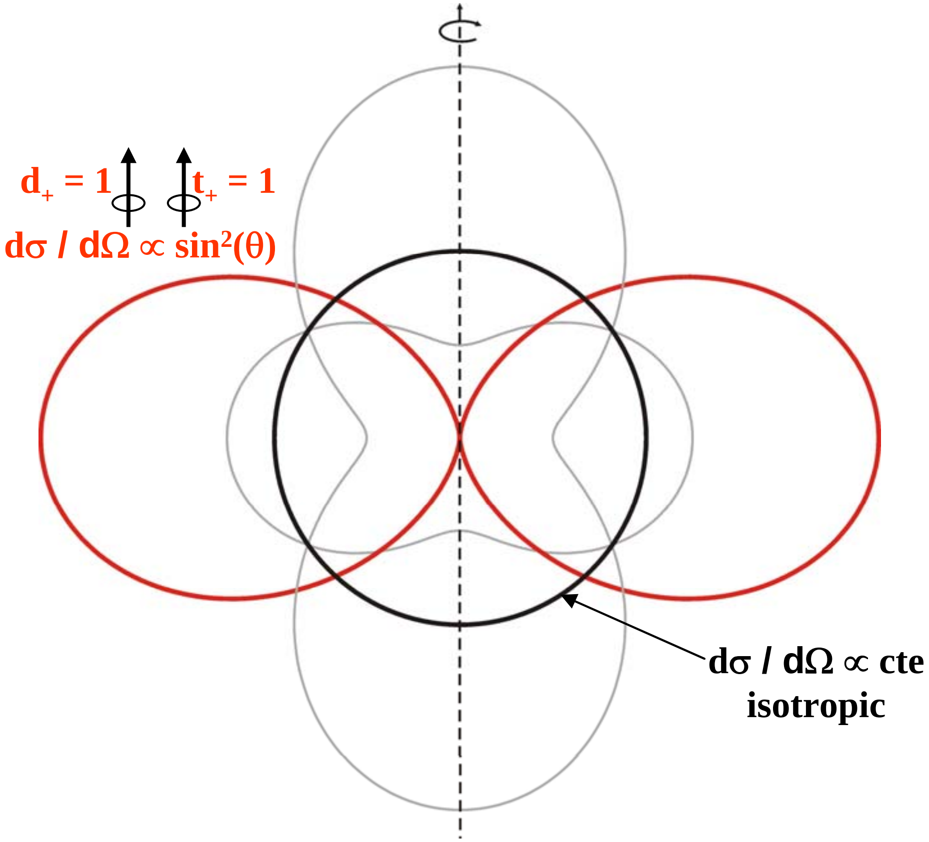
R.M. Kulsrud, H.P. Furth, E.J. Valeo and M. Goldhaber *Phys. Rev. Lett.* **49** 1248 (1982)

Non-isotropic angular distribution does not modify the ignition condition by itself

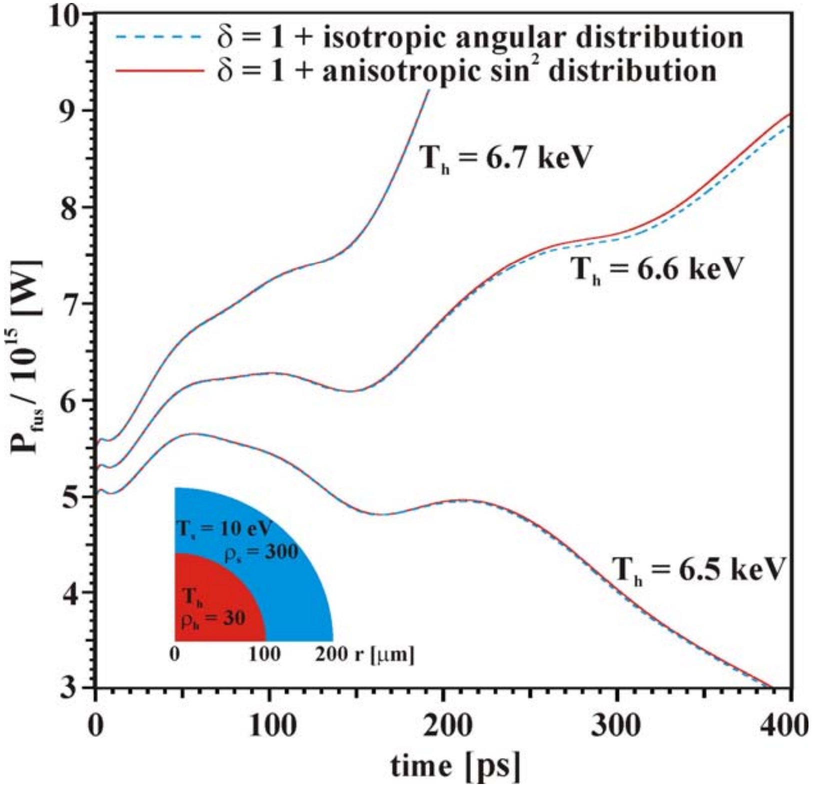
$\mathrm{D}_{s=1} + \mathrm{T}_{s=\frac{1}{2}} \rightarrow {}^{5}\mathrm{He}_{\,s=3/2} \rightarrow \mathrm{n} + {}^{4}\mathrm{He}$

$d\sigma / d\Omega \propto 3\,a \sin^2(\theta) + (2\,b/3 + c/3)\,[\,1 + 3\cos^2(\theta)\,]$

The effect of the non-uniform [$\sin^2(\theta)$] angular distribution has been analyzed neglecting the increased cross section (always $\delta = 1$)

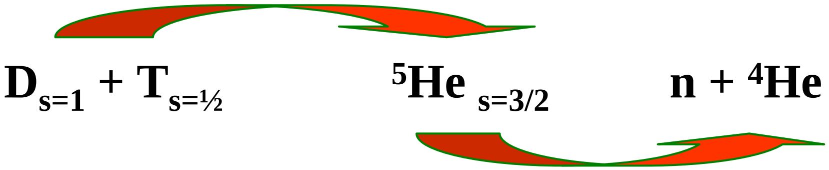


2D-DUED code with a 3D Monte-Carlo alpha particle package accounting for the angular distribution has been used to analyze if the anisotropic angular distribution could affect the ignition condition.



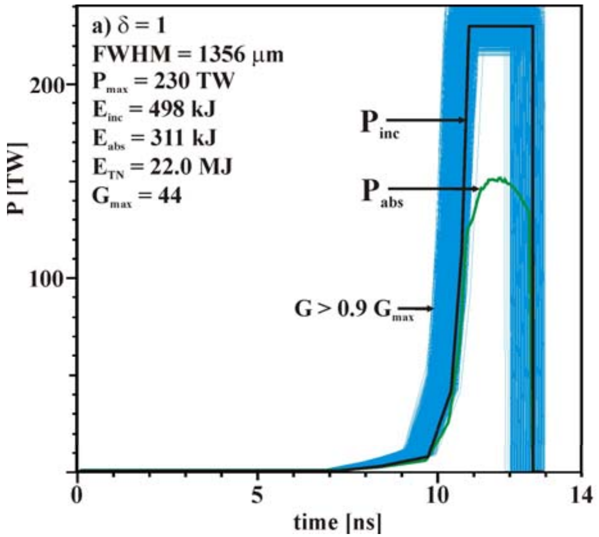
No significant modification of the thermonuclear power and ignition energy threshold when the non-isotropic $\sin^2(\theta)$ angular distribution is used by itself.

1D numerical simulation of a direct-driven target

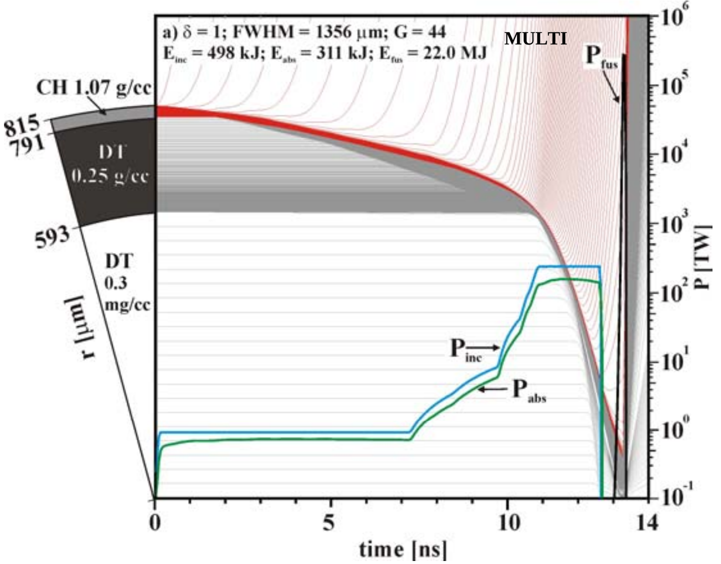


$D_{s=1}$ + $T_{s=½}$ $^{5}He_{s=3/2}$ n + ^{4}He

$\Rightarrow \sigma = \delta\, \sigma_0$; unpolarized DT $\Rightarrow \delta = 1$



A Direct Drive capsule [*] has been considered



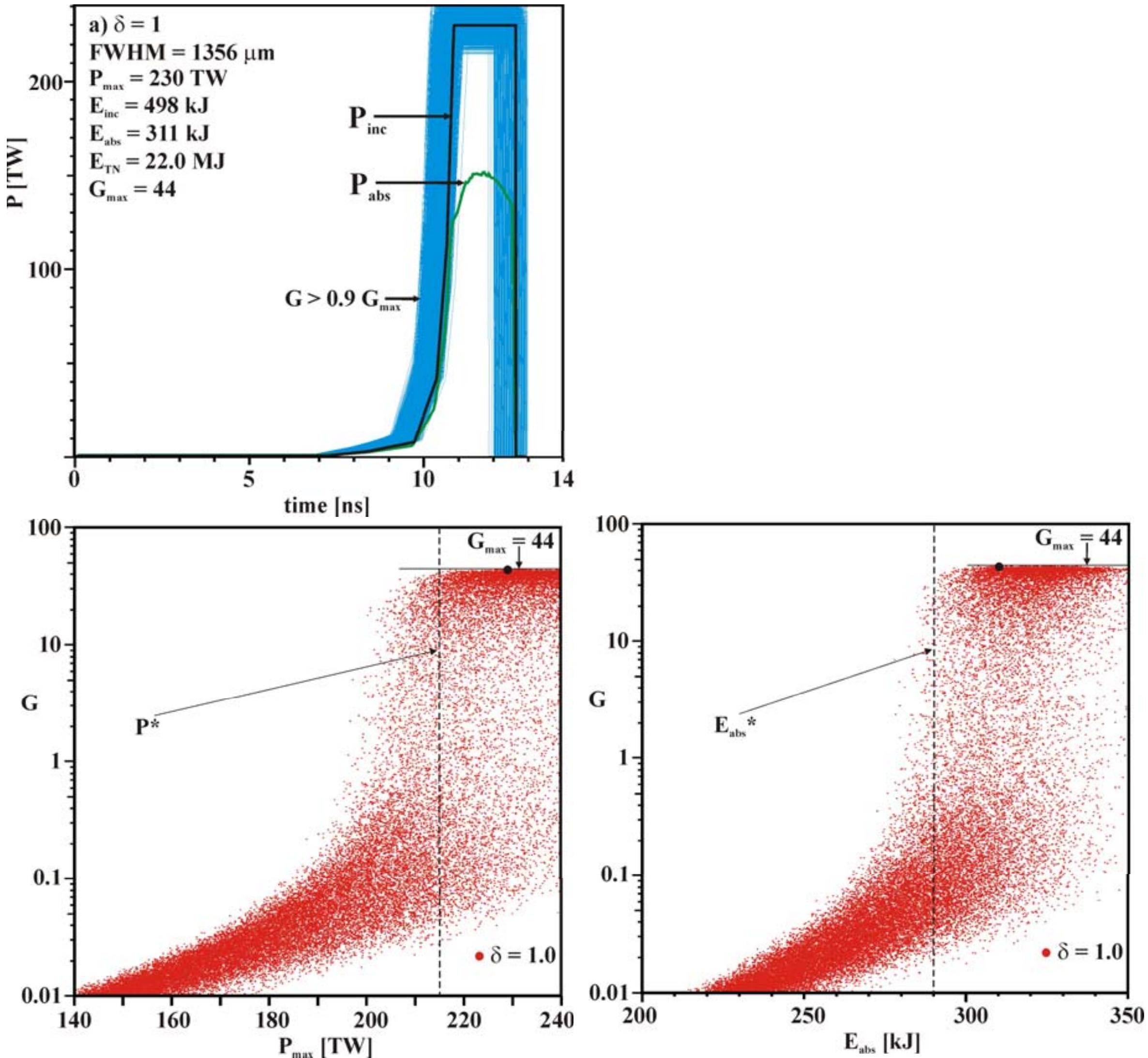
* See talk of Vincent Brandon, Tuesday $10^{\underline{00}}$: 1D baseline target design for direct drive shock ignition

Gain versus peak laser power and absorbed energy

$D_{s=1} + T_{s=½}$ $^5He_{\ s=3/2}$ $n + {}^4He$

$\Rightarrow \sigma = \delta\, \sigma_0$; unpolarized DT $\Rightarrow \delta = 1$

$\delta = 1 \Rightarrow G_{max} = 44$;
$P^* = 215$ TW; $E^* = 290$ kJ

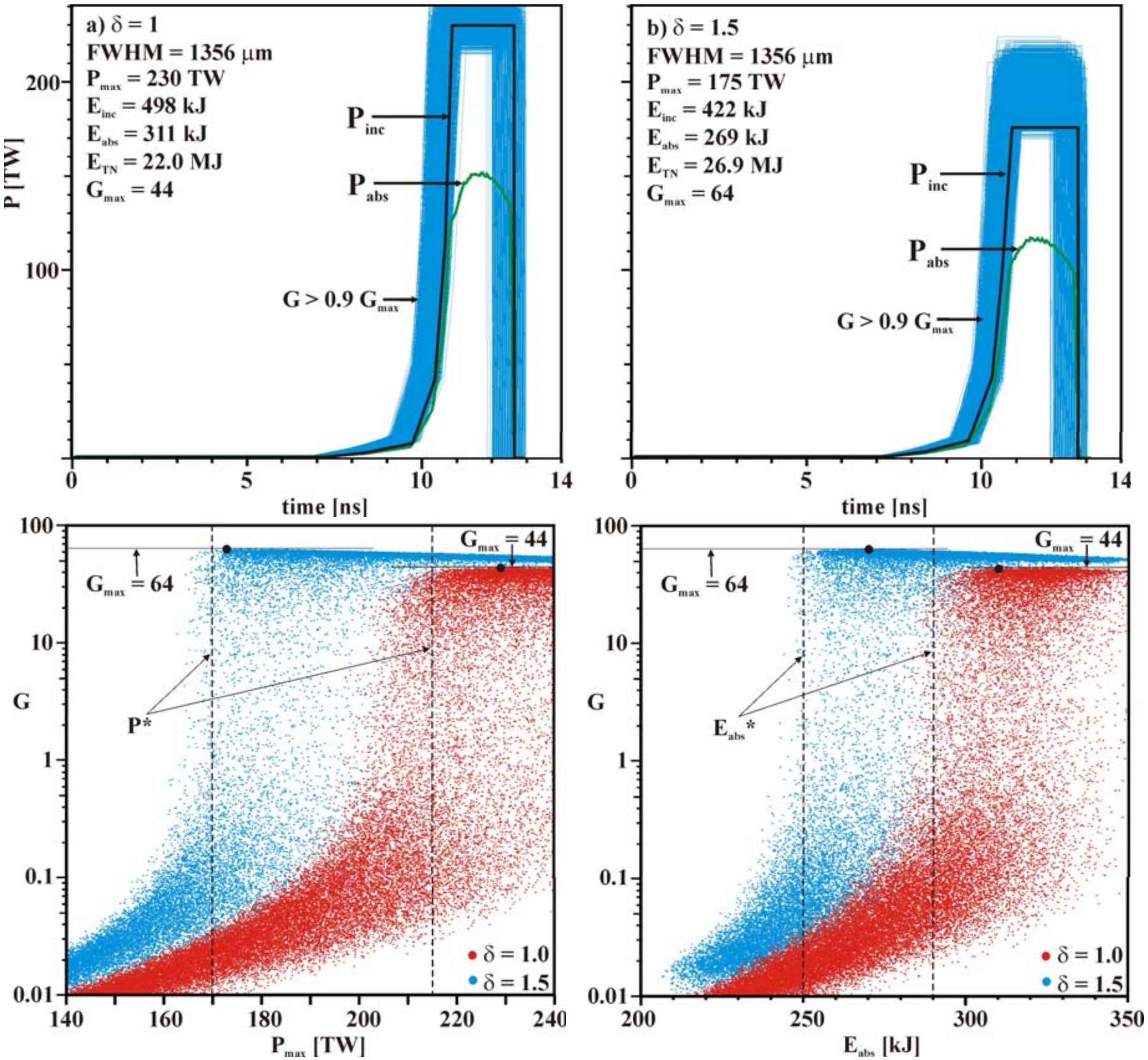


Gain versus peak laser power and absorbed energy

$D_{s=1} + T_{s=½}$ $^5He_{s=3/2}$ $n + {}^4He$

$\Rightarrow \sigma = \delta\,\sigma_0$; unpolarized DT $\Rightarrow \delta = 1$

fully polarized DT $\Rightarrow \delta = 1.5$



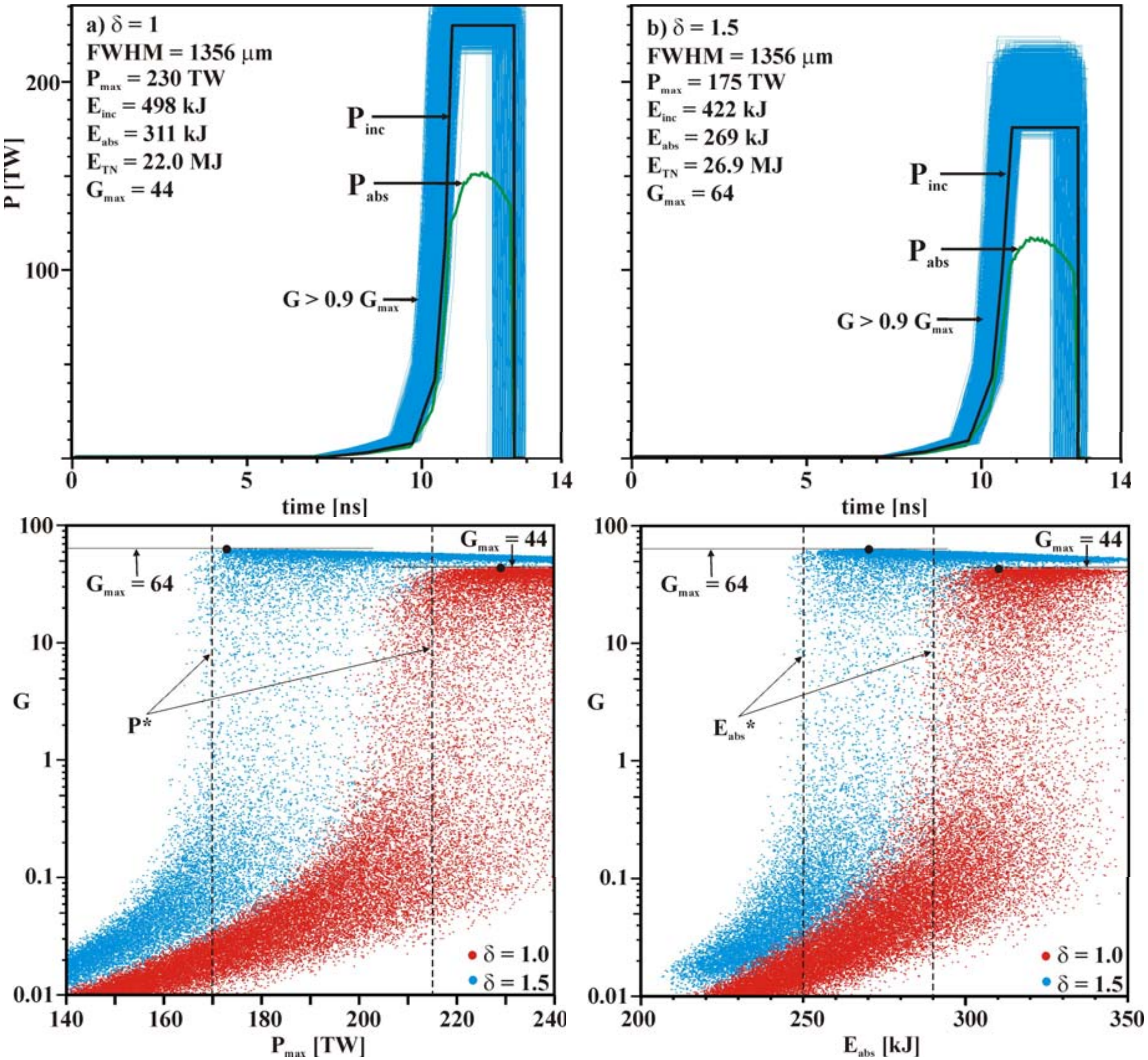
δ= 1 $\Rightarrow$ G_{max} = 44;
P* = 215 TW; E* = 290 kJ

δ= 1.5 $\Rightarrow$ G_{max} = 64;
P* = 170 TW; E* = 250 kJ

The gain G increases nearly linearly ($\propto \delta^{0.9}$) with the polarization factor δ

$D_{s=1} + T_{s=½}$ $^5He_{s=3/2}$ $n + {}^4He$

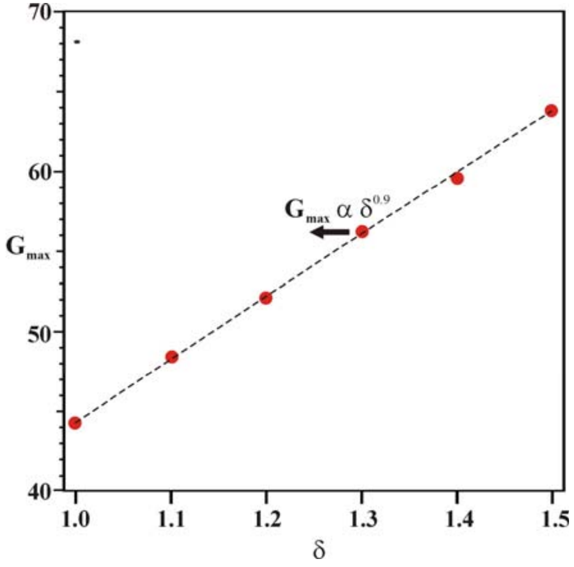
$\Rightarrow \sigma = \delta\, \sigma_0$; fully polarized DT $\Rightarrow \delta = 1.5$



δ= 1 ⇒ G_{max} = 44;
P* = 215 TW; E* = 290 kJ

δ= 1.5 ⇒ G_{max} = 64;
P* = 170 TW; E* = 250 kJ

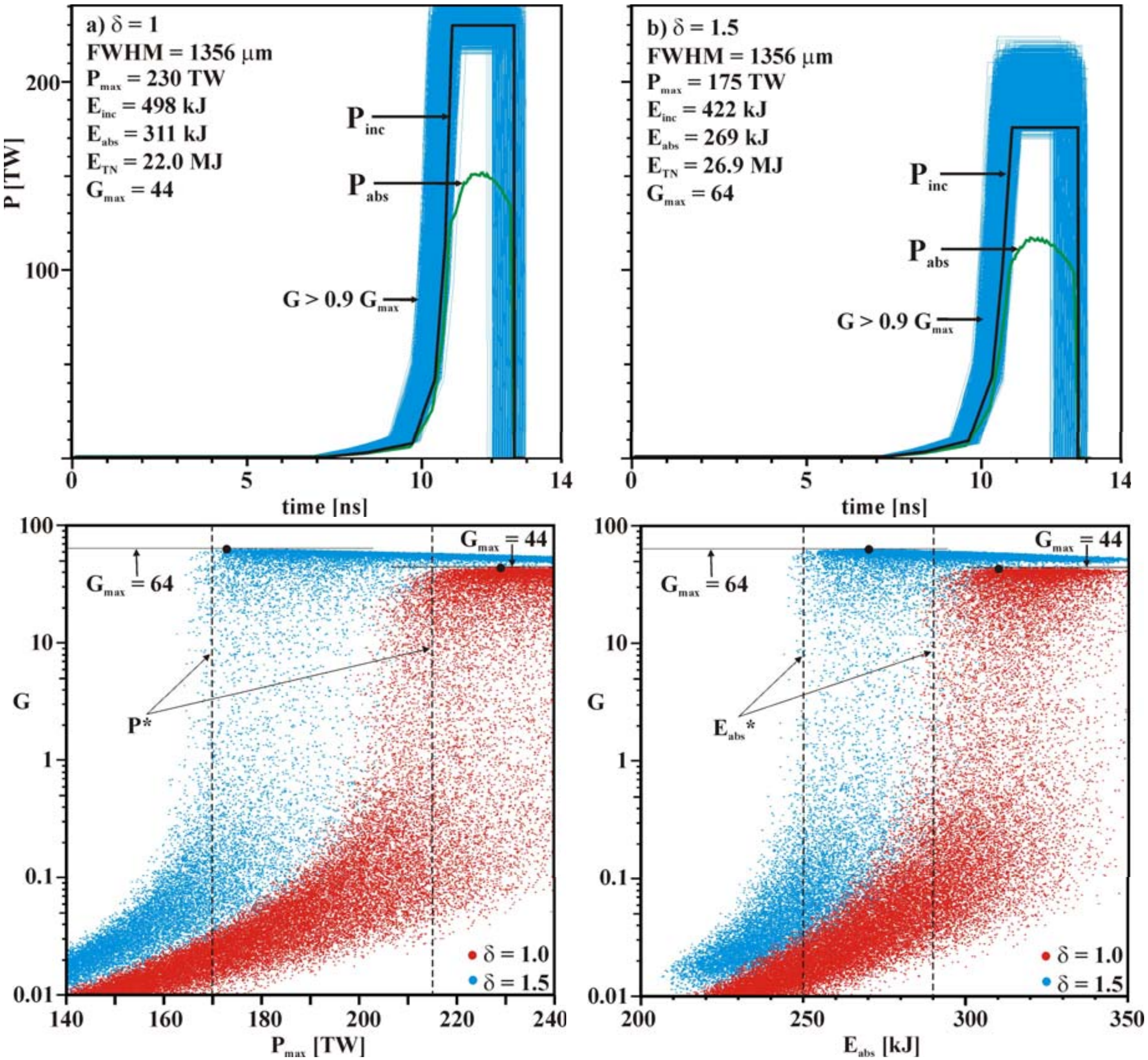
The maximum gain $G_{max} \propto \delta^{0.9}$ as found by
M. D. Rosen, J. D. Lindl and A. R. Thiessen
Laser Program Annual Report UCRL-50021-83
Lawrence Livermore National Laboratory



Absorbed energy ($\propto \delta^{-0.4}$) and peak power ($\propto \delta^{-0.6}$) thresholds reduce by about 15% and 20%

$D_{s=1} + T_{s=½}$ $\quad$ $^5He_{s=3/2}$ $\quad$ $n + ^4He$

$\Rightarrow \sigma = \delta\, \sigma_0$; fully polarized DT $\Rightarrow \delta = 1.5$



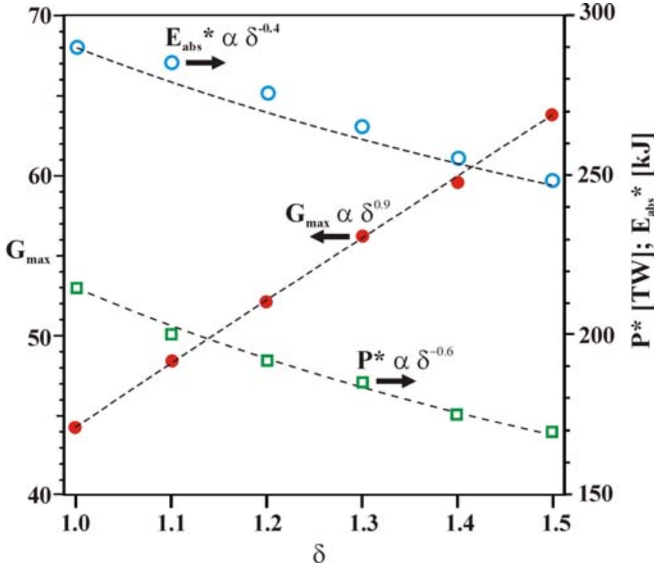
δ= 1 $\Rightarrow$ G_{max} = 44;
P* = 215 TW; E* = 290 kJ

* * *

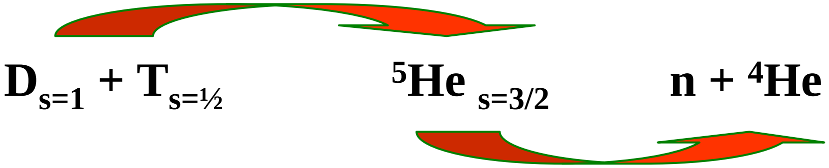
δ= 1.5 $\Rightarrow$ G_{max} = 64;
P* = 170 TW; E* = 250 kJ

* * *

$G_{max} \propto \delta^{0.9}$; $P^* \propto \delta^{-0.6}$; $E^* \propto \delta^{-0.4}$



Summary



$D_{s=1} + T_{s=\frac{1}{2}}$ $\quad {}^5He_{\,s=3/2}$ $\quad n + {}^4He$ $\Rightarrow \sigma = \delta\, \sigma_0$; fully polarized DT $\Rightarrow \delta = 1.5$ $\quad \Uparrow d_+ = 1 \; \Uparrow t_+ = 1$

⇒ DT cross section increases by 50% for fully polarized nuclei

⇒ The burn fraction depends inversely with the burn parameter H_B $\quad \phi \cong \rho_h R_h / (\rho_h R_h + H_B) \uparrow$

⇒ The burn parameter H_B decreases as the reactivity increases $\quad$ ⇒ The energy gain increases $G = q_{DT} M_{DT}\, \phi / E$

⇒ Polarization implies an extension of the ignition region in the $\rho_h R_h$ - T_h space: [0.2 g/cm², 7 keV] [0.15 g/cm², 6 keV]

⇒ No significant modification of the thermonuclear power and ignition energy threshold when the non-isotropic $\sin^2(\theta)$ angular distribution is used by itself.

1D numerical simulation of a direct-driven target

⇒ The gain G increases ($\propto \delta^{0.9}$) with the polarization factor δ

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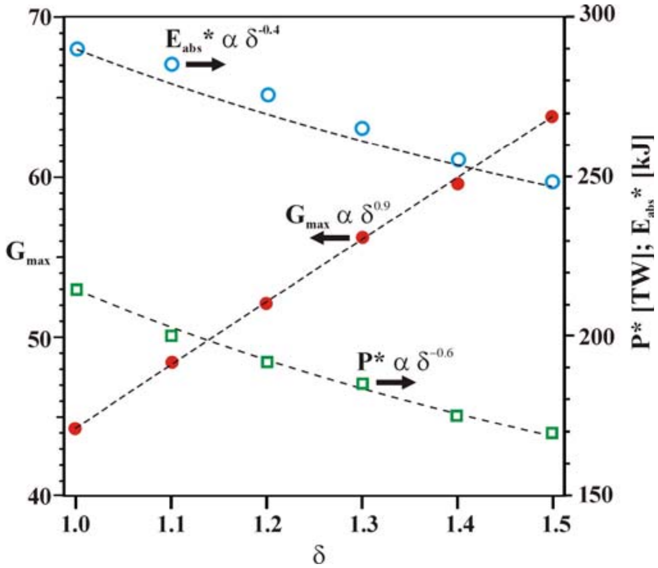
$\delta = 1 \quad \Rightarrow G_{max} = 44$; $P^* = 215$ TW; $E^* = 290$ kJ

$\delta = 1.5 \Rightarrow G_{max} = 64$; $P^* = 170$ TW; $E^* = 250$ kJ

$G_{max} \propto \delta^{0.9}$; $P^* \propto \delta^{-0.6}$; $E^* \propto \delta^{-0.4}$



Summary

$D_{s=1} + T_{s=½}$ $^5He_{s=3/2}$ $n + {}^4He$ $\Rightarrow \sigma = \delta\, \sigma_0$; fully polarized DT $\Rightarrow \delta = 1.5$ ↑ $d_+ = 1$ ↑ $t_+ = 1$

$\Rightarrow$ DT cross section increases by 50% for fully polarized nuclei

$\Rightarrow$ The burn fraction depends inversely with the burn parameter H_B $\phi \cong \rho_h R_h / (\rho_h R_h + H_B)$ ↑

$\Rightarrow$ The burn parameter H_B decreases as the reactivity increases $\Rightarrow$ The energy gain increases $G = q_{DT} M_{DT} \phi / E$

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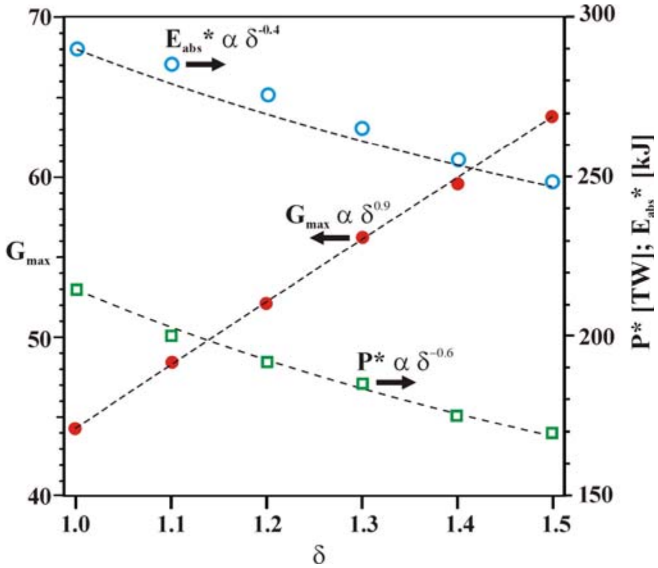
Thank you



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Fusion Reactor Plasmas with Polarized Nuclei

R. M. Kulsrud, H. P. Furth, and E. J. Valeo
Princeton Plasma Physics Laboratory, Princeton, New Jersey 08544

and

M. Goldhaber
Brookhaven National Laboratory, Upton, New York 11973

(Received 25 May 1982)

Nuclear fusion rates can be enhanced or suppressed by polarization of the reacting nuclei. In a magnetic fusion reactor, the depolarization time is estimated to be longer than the reaction time.

PACS numbers: 52.50.Gj, 25.50.-s, 28.50.Re, 52.55.-s

Recent technological developments[1,2] have made possible the generation of polarized gases in quantities of practical interest for the production of polarized fusion plasmas. The dependence of nuclear fusion reactions on nuclear spin[3] suggests that polarization of the reacting particles may be advantageous in providing control of the reaction rates and the angular distribution of the reaction products.

The large cross section for the reaction $D(T, n)^4He$ at low energy arises primarily from a $J = \frac{3}{2}^+$ resonant level of ^5He at 107 keV above the energy of the free D and T nuclei.[4] At low energies, the reaction occurs only in the $l = 0$ state, so that the angular momentum must be supplied by the spin of the D and T nuclei. Since D has spin 1 and T spin $\frac{1}{2}$, their possible combined spin states are $S = \frac{3}{2}$ and $\frac{1}{2}$. The reaction is due almost entirely to interacting pairs of D and T nuclei with $S = \frac{3}{2}$. The statistical weight of this state is 4 while that of the $S = \frac{1}{2}$ state is 2. Thus, for a plasma of unpolarized nuclei, effectively only $\frac{2}{3}$ of the interactions contribute to the reaction rate.

We consider now the case of a magnetic D-T reactor where the fractions of D nuclei polarized parallel, transverse, and antiparallel to $\vec{B}$ are d_+, d_0, and d_-, respectively, while the corresponding fractions of the T nuclei are t_+ and t_-. Then the total cross section is

$$\sigma = (a + \tfrac{2}{3}b + \tfrac{1}{3}c) f\sigma_0 + (\tfrac{2}{3}b + \tfrac{4}{3}c)(1 - f)\sigma_0, \qquad (1)$$

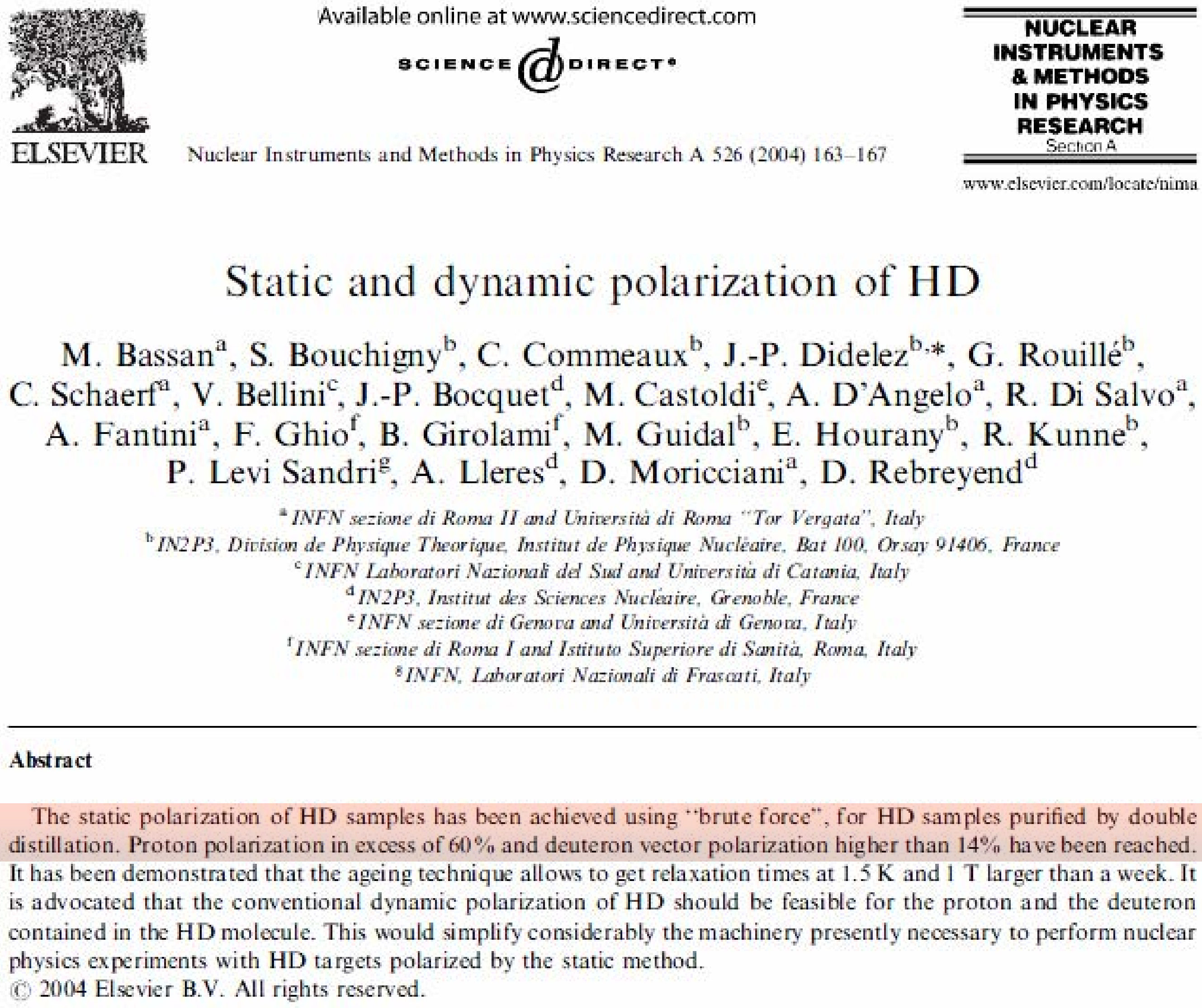
where $a = d_+t_+ + d_-t_-$, $b = d_0$, $c = d_+t_- + d_-t_+$, and $f\sigma_0$ is the cross section for the $\frac{3}{2}^+$ state. The magnitude of f has been estimated at about 0.95,[4] but may be greater than 0.99.[5] (The remainder of the cross section is ascribed to a $\frac{1}{2}^+$ state that lies 3 MeV about the $\frac{3}{2}^+$ state.) For an unpolarized plasma, $a = b = c = \frac{1}{3}$ so that $\sigma = \frac{2}{3}\sigma_0$. On the other hand, if all the nuclei are polarized along $\vec{B}$, then $a = 1$, $b = c = 0$, and $\sigma = f\sigma_0$, so that the enhancement of reactivity is $\frac{3}{2}f$.

The resultant angular distributions of the neutrons and α particles are

$$\frac{d\sigma}{d\Omega} = \frac{f\sigma_0}{2\pi}\left[\tfrac{3}{4}a \sin^2\theta + (\tfrac{2}{3}b + \tfrac{1}{3}c)\left(\frac{(4/f) - 3 + 3\cos^2\theta}{4}\right)\right], \qquad (2)$$

where θ is the pitch angle relative to $\vec{B}$. If all the nuclei are polarized parallel to $\vec{B}$, the angular distribution of the neutrons and α particles is $\sin^2\theta$; if the D nuclei are polarized transverse to $\vec{B}$, then

The statistical weight of the J = 3/2 state is four and that of the J = 1/2 state is two, so if the D and T nuclei are both randomly polarized, the probability for the colliding system to be in the J = 3/2 state is two-thirds. An immediate consequence of this is that if it is ensured that the nuclei come together with J = 3/2, the effective cross-section is 3/2 times the unpolarized cross-section. One way to accomplish this is to align all spins of both the D and T nuclei



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
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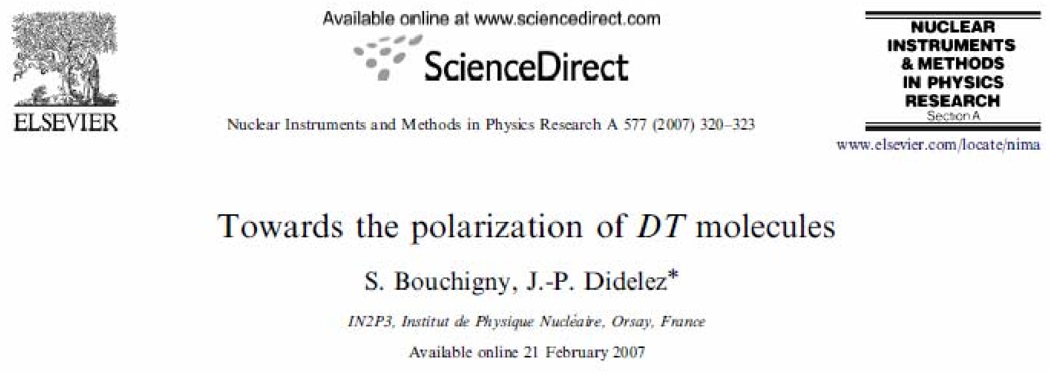
Static and dynamic polarization of HD

M. Bassan[a], S. Bouchigny[b], C. Commeaux[b], J.-P. Didelez[b,*], G. Rouillé[b], C. Schaerf[a], V. Bellini[c], J.-P. Bocquet[d], M. Castoldi[e], A. D'Angelo[a], R. Di Salvo[a], A. Fantini[a], F. Ghio[f], B. Girolami[f], M. Guidal[b], E. Hourany[b], R. Kunne[b], P. Levi Sandri[g], A. Lleres[d], D. Moricciani[a], D. Rebreyend[d]

[a] *INFN sezione di Roma II and Università di Roma "Tor Vergata", Italy*
[b] *IN2P3, Division de Physique Theorique, Institut de Physique Nucléaire, Bat 100, Orsay 91406, France*
[c] *INFN Laboratori Nazionali del Sud and Università di Catania, Italy*
[d] *IN2P3, Institut des Sciences Nucléaire, Grenoble, France*
[e] *INFN sezione di Genova and Università di Genova, Italy*
[f] *INFN sezione di Roma I and Istituto Superiore di Sanità, Roma, Italy*
[g] *INFN, Laboratori Nazionali di Frascati, Italy*

Abstract

The static polarization of HD samples has been achieved using "brute force", for HD samples purified by double distillation. Proton polarization in excess of 60% and deuteron vector polarization higher than 14% have been reached. It has been demonstrated that the ageing technique allows to get relaxation times at 1.5 K and 1 T larger than a week. It is advocated that the conventional dynamic polarization of HD should be feasible for the proton and the deuteron contained in the HD molecule. This would simplify considerably the machinery presently necessary to perform nuclear physics experiments with HD targets polarized by the static method.



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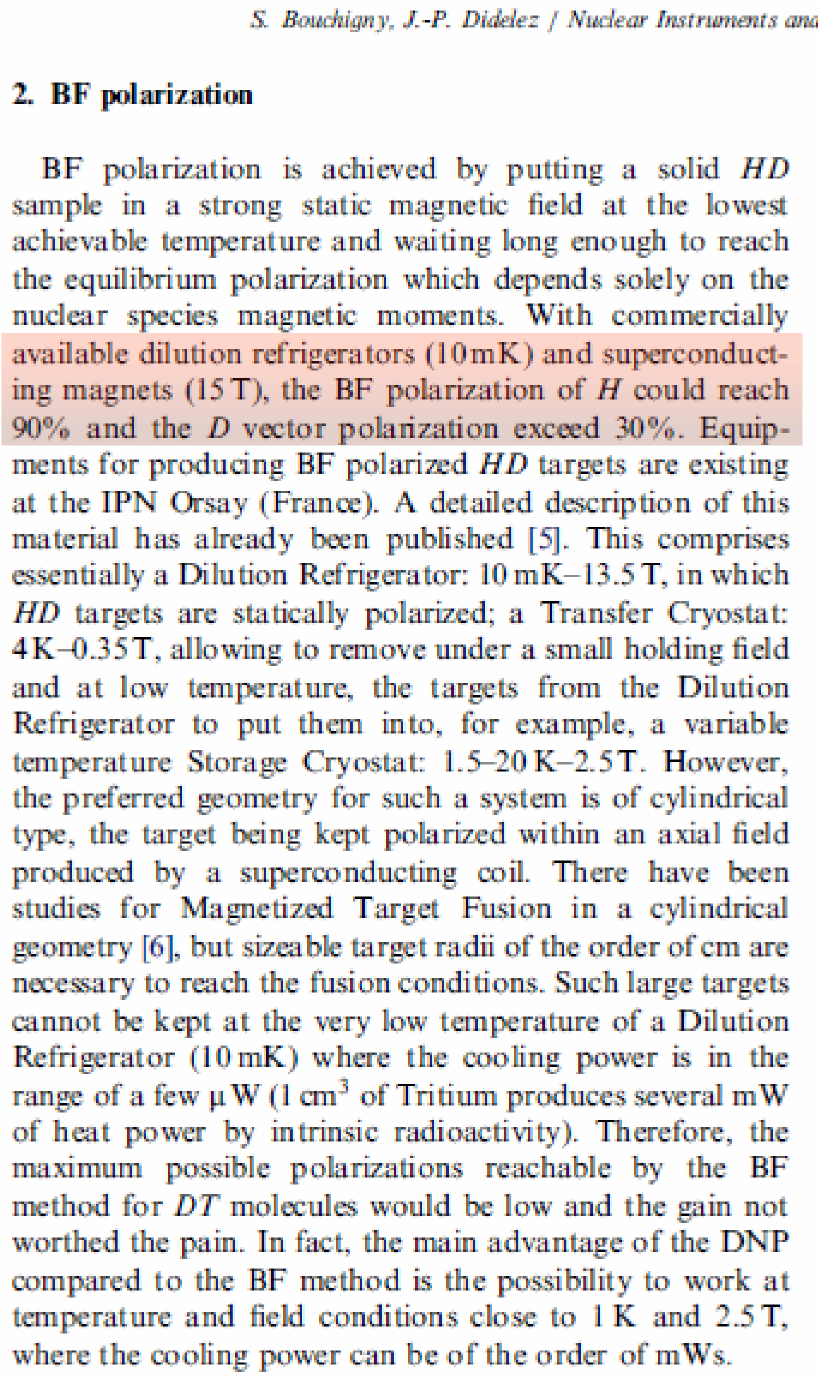
Towards the polarization of *DT* molecules

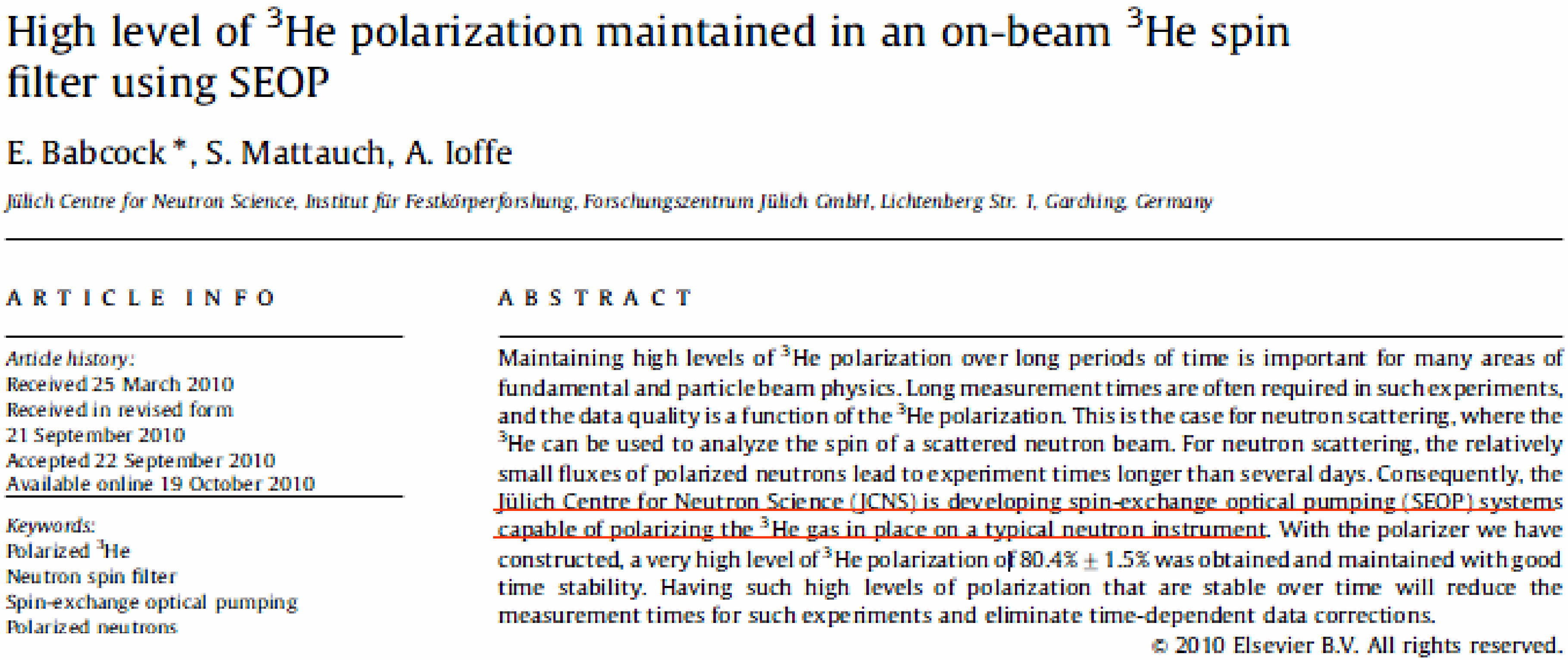
S. Bouchigny, J.-P. Didelez*

IN2P3, Institut de Physique Nucléaire, Orsay, France



2. BF polarization

BF polarization is achieved by putting a solid *HD* sample in a strong static magnetic field at the lowest achievable temperature and waiting long enough to reach the equilibrium polarization which depends solely on the nuclear species magnetic moments. With commercially available dilution refrigerators (10 mK) and superconducting magnets (15 T), the BF polarization of *H* could reach 90% and the *D* vector polarization exceed 30%. Equipments for producing BF polarized *HD* targets are existing at the IPN Orsay (France). A detailed description of this material has already been published [5]. This comprises essentially a Dilution Refrigerator: 10 mK–13.5 T, in which *HD* targets are statically polarized; a Transfer Cryostat: 4 K–0.35 T, allowing to remove under a small holding field and at low temperature, the targets from the Dilution Refrigerator to put them into, for example, a variable temperature Storage Cryostat: 1.5–20 K–2.5 T. However, the preferred geometry for such a system is of cylindrical type, the target being kept polarized within an axial field produced by a superconducting coil. There have been studies for Magnetized Target Fusion in a cylindrical geometry [6], but sizeable target radii of the order of cm are necessary to reach the fusion conditions. Such large targets cannot be kept at the very low temperature of a Dilution Refrigerator (10 mK) where the cooling power is in the range of a few μW (1 cm^3 of Tritium produces several mW of heat power by intrinsic radioactivity). Therefore, the maximum possible polarizations reachable by the BF method for *DT* molecules would be low and the gain not worthed the pain. In fact, the main advantage of the DNP compared to the BF method is the possibility to work at temperature and field conditions close to 1 K and 2.5 T, where the cooling power can be of the order of mWs.



High level of ^{3}He polarization maintained in an on-beam ^{3}He spin filter using SEOP

E. Babcock *, S. Mattauch, A. Ioffe

Jülich Centre for Neutron Science, Institut für Festkörperforshung, Forschungszentrum Jülich GmbH, Lichtenberg Str. 1, Garching, Germany

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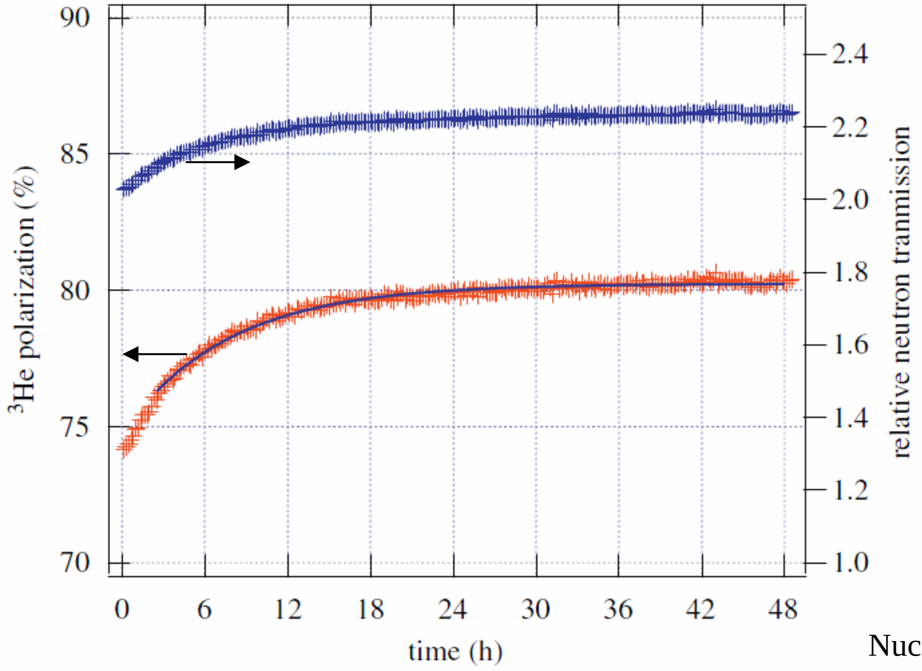
ABSTRACT

Maintaining high levels of ^{3}He polarization over long periods of time is important for many areas of fundamental and particle beam physics. Long measurement times are often required in such experiments, and the data quality is a function of the ^{3}He polarization. This is the case for neutron scattering, where the ^{3}He can be used to analyze the spin of a scattered neutron beam. For neutron scattering, the relatively small fluxes of polarized neutrons lead to experiment times longer than several days. Consequently, the Jülich Centre for Neutron Science (JCNS) is developing spin-exchange optical pumping (SEOP) systems capable of polarizing the ^{3}He gas in place on a typical neutron instrument. With the polarizer we have constructed, a very high level of ^{3}He polarization of 80.4% ± 1.5% was obtained and maintained with good time stability. Having such high levels of polarization that are stable over time will reduce the measurement times for such experiments and eliminate time-dependent data corrections.



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Nuclear Spin-Polarized Fuel in Inertial Fusion

Richard M. More
Lawrence Livermore National Laboratory, Livermore, California 94550

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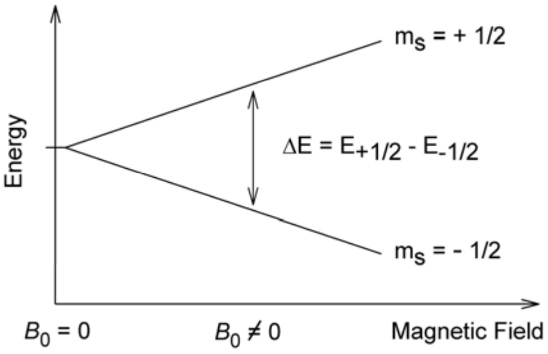
This Letter examines the possibility of using spin-polarized DT fuel for inertial-confinement fusion. Analytic models and estimates are developed to determine whether an initial spin-polarized state would survive target irradiation and implosion. It is found that collisional depolarization cross sections are not large enough to give significant depolarization, and that the short duration of inertial-fusion implosions precludes spin resonance for magnetic fields that can be reasonably expected in the target fuel.

Dynamic Nuclear Polarization

Dynamic nuclear polarization (DNP) results from transferring spin polarization from electrons to nuclei, thereby aligning the nuclear spins to the extent that electron spins are aligned. Alignment of electron spins at a given magnetic field and temperature is described by the Boltzmann distribution under the thermal equilibrium.

When electron spin polarization deviates from its thermal equilibrium value, polarization transfers between electrons and nuclei can occur spontaneously through electron-nuclear cross relaxation and/or spin-state mixing among electrons and nuclei. On the other hand, when the electron spin system is in a thermal equilibrium, the polarization transfer requires continuous microwave irradiation at a frequency close to the corresponding electron paramagnetic resonance (EPR) frequency



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Deuteron polarization of solid DT

P. C. Souers
Chemistry and Materials Science, Lawrence Livermore National Laboratory, Livermore, California 94550

P. A. Fedders
Department of Physics, Washington University, St. Louis, Missouri 63130

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Various possible means of attaining a large nuclear polarization of deuterons in solid deuterium tritide (DT) for use as a hydrogen-fusion fuel are considered. It is noted that dynamically polarized nuclear targets have reached only 40% polarization for deuterons despite there being no theoretical limit. In contrast, protons have been polarized to almost 100%. We consider dynamic nuclear polarization using both electrons as the pumping source (EDNP) and nuclei (NDNP). Most polarized targets have worked by EDNP thermal mixing. If protons are present, they bleed off part of the polarization intended for the deuterons. In a pure deuterated material, the smaller deuteron magnetic moment has so far prevented adequate nuclear cooling. The method most likely to work is the EDNP solid-state effect, which requires a narrow ESR spectrum for the atoms in solid DT. Should the tritons be polarized, their polarization can be transferred to the deuterons. Using NDNP thermal mixing, again, only 40% deuteron polarization is obtained. Using the NDNP solid-state effect and many polarization cycles, over 90% is achieved. The calculations offer optimism regarding deuteron polarization as far as the state of present knowledge of the properties of solid DT is concerned.