

# Nuclear Fusion with Polarized Fuel

## - Some thoughts on the PREFER collaboration -

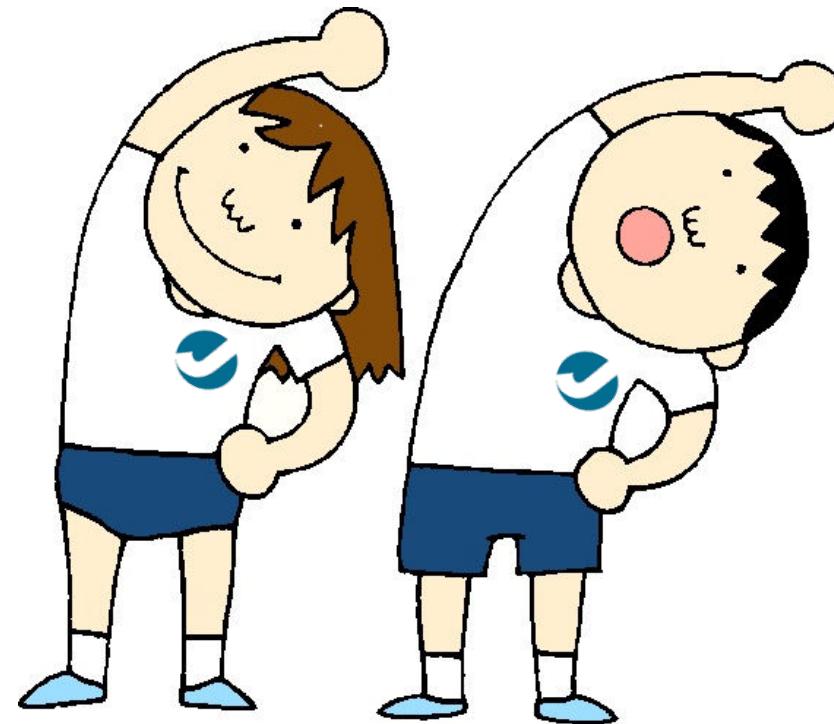
Workshop on Nuclear Fusion with Polarized Fuel

Ferrara | 2/3 October 2017

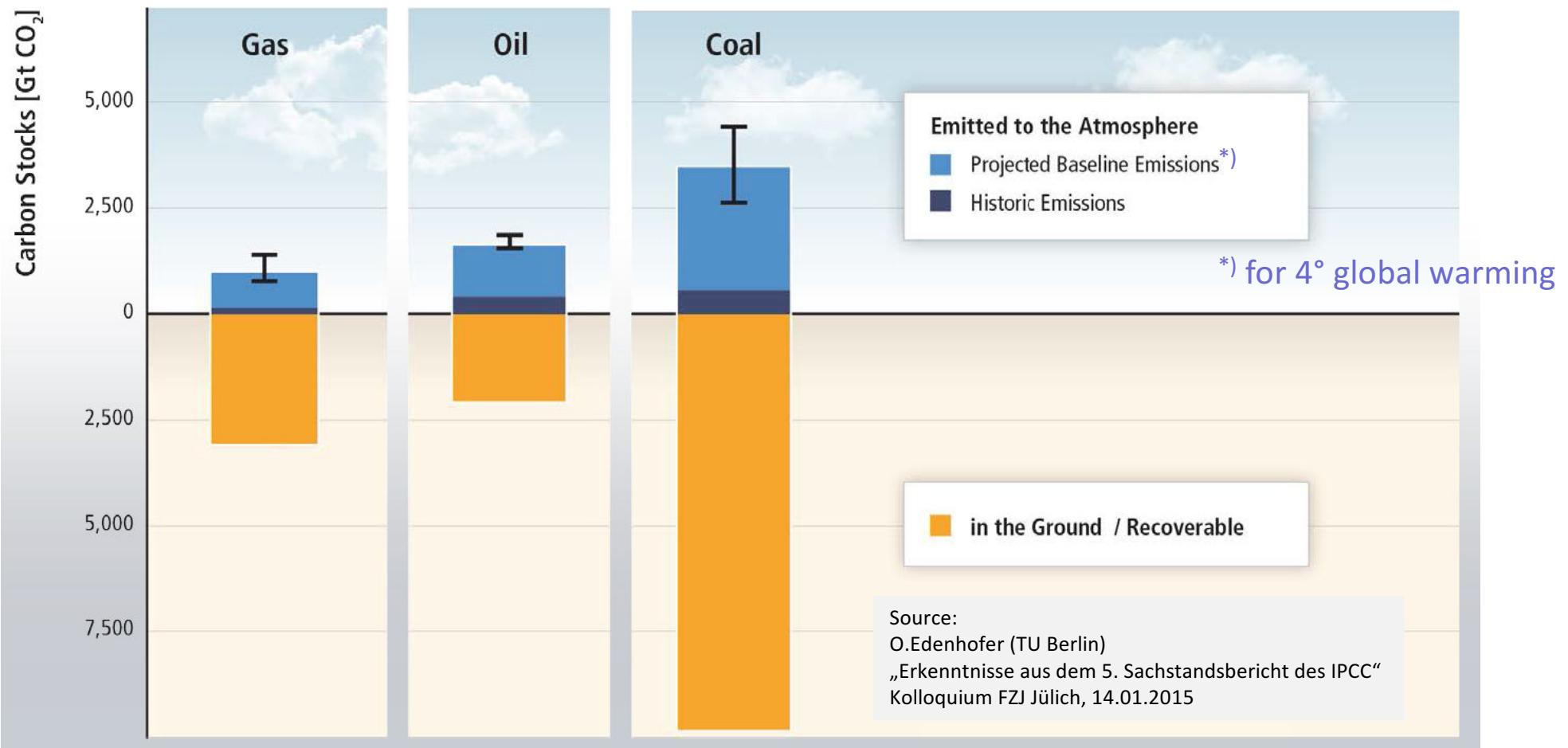
Markus Büscher



# Polarized Fusion Workshop: “Warm-up”



# CO<sub>2</sub> Emissions and Global Warming



👉 Alternative sources of energy (base load) w/o CO<sub>2</sub> emission?



# Fusion Energy: What You Find on Google

“Binds resources that are needed for the fight against climate change”



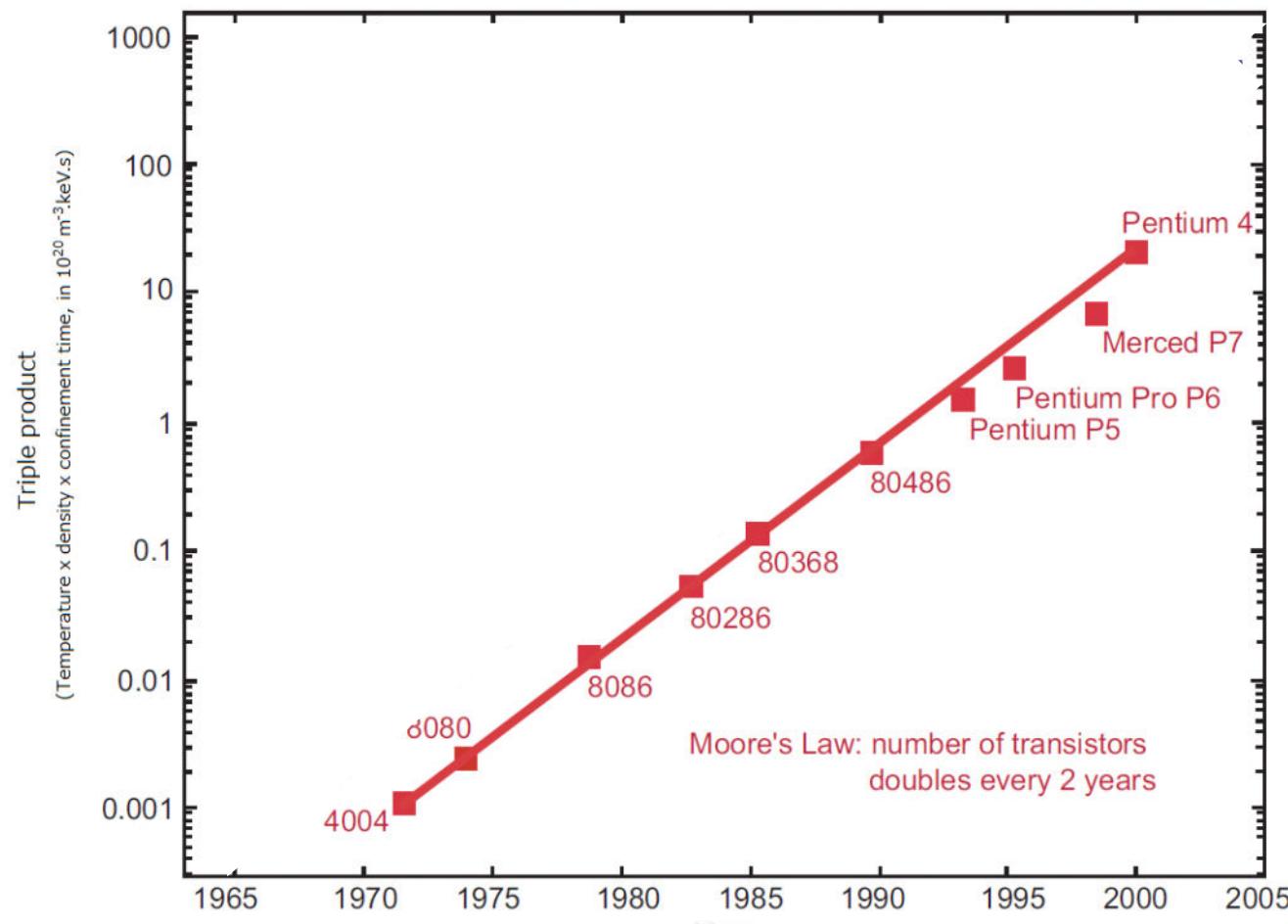
“The material and technical challenges are extreme”

“The return on renewables has been very much higher. Because renewable technologies are newer, there might still be stones unturned in terms of research”

“Nuclear fusion is 30 years away, and always will be. That's the refrain we've heard, again and again for decades.”



# Moore's Law



# The Lawson Criterion

Condition for a fusion reactor:  $E(\text{Fusion}) > E(\text{Heating}, \dots)$

$$n \cdot \tau_c > \frac{12k_B T}{E_f \langle \sigma_f v \rangle}$$

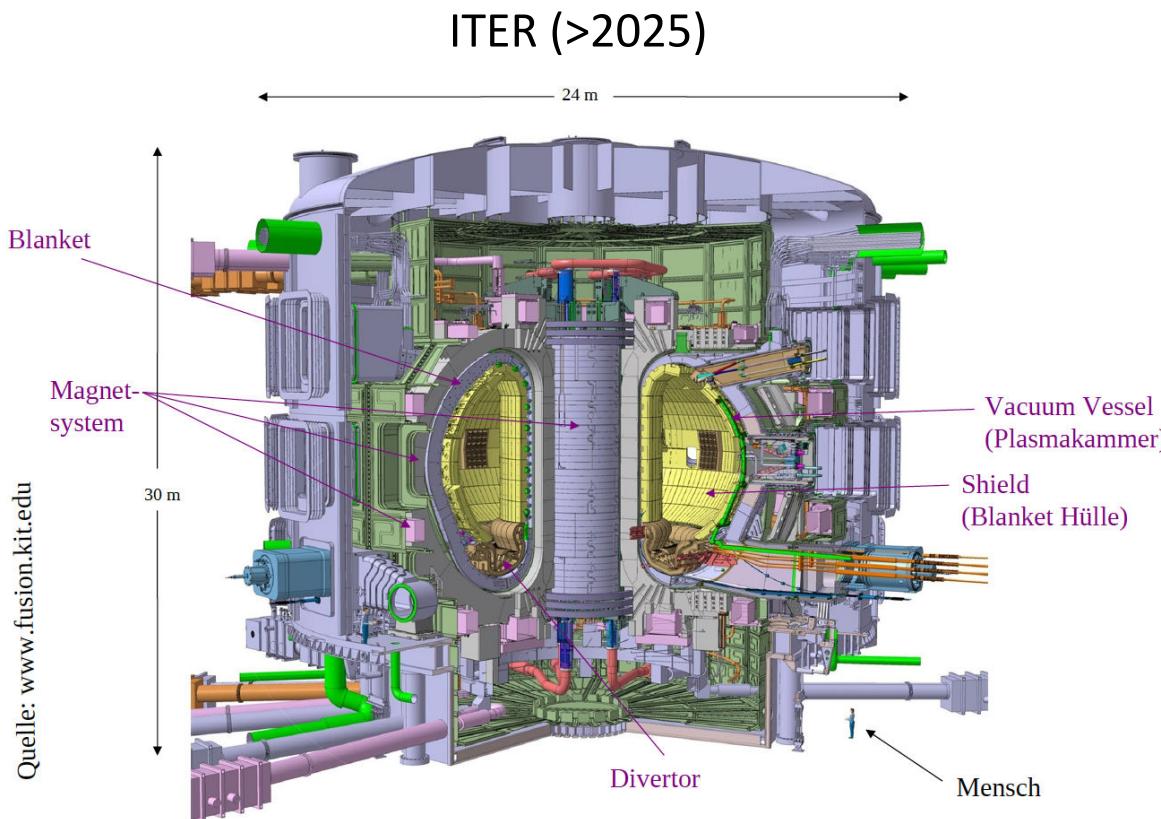
$n$ : ion density  
 $\tau_c$ : confinement time  
 $T$ : ion temperature  
 $E_f$ : Energy per fusion  
 $\sigma_f$ : fusion cross section  
 $v$ : ion velocity



Density and  
confinement time  
large

# Magnetic Confinement Fusion

Plasma density  $n = 10^{14} \text{ cm}^{-3}$ ; confinement time  $\tau_E = 100 \text{ s}$

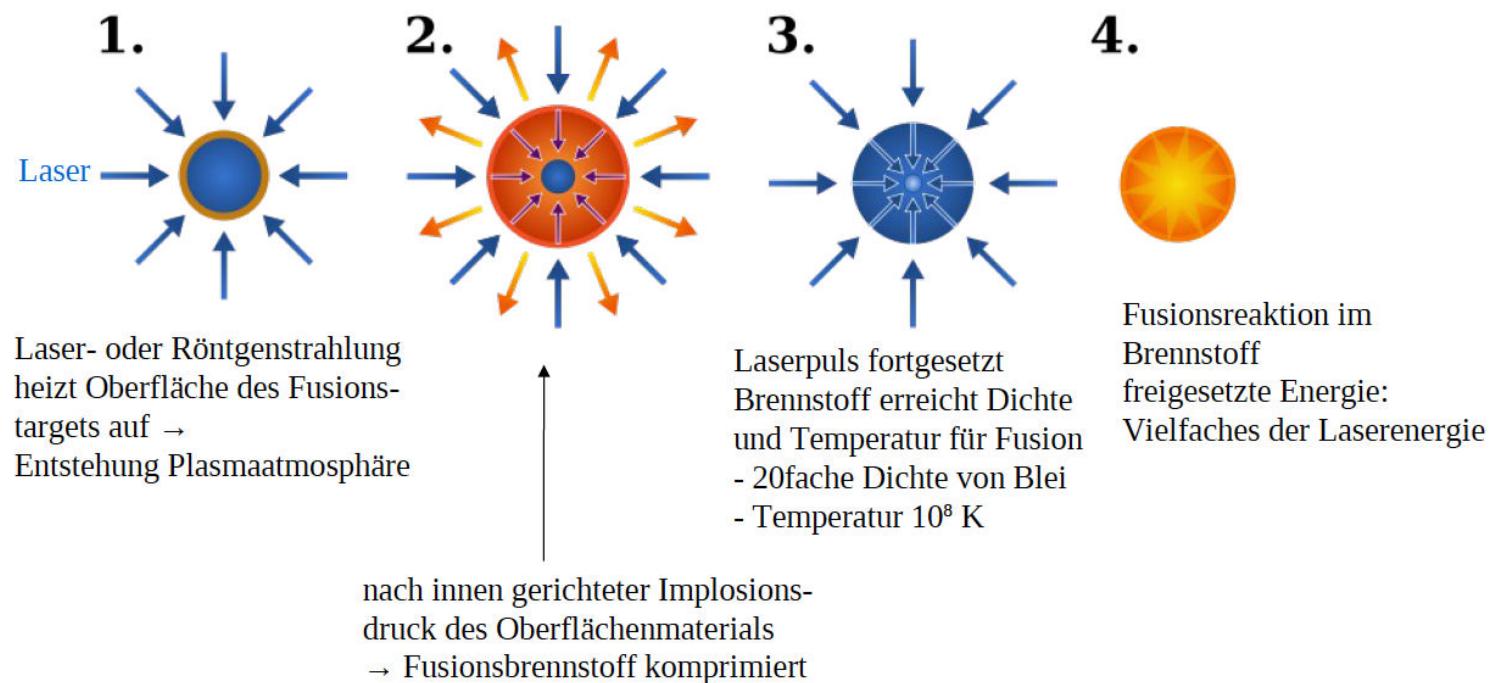


Fusionsleistung	500 MW
Fusionsleistung / Heizleistung (ohne alpha-Heizung)	$Q \geq 10$
Mittlere Neutronenbelastung der Wände	$0,57 \text{ MW/m}^2$
Brenndauer des Plasmas	$\geq 300 \text{ Sekunden}$
Plasmastrom (durch Transformator induziert)	15 MA
Plasmavolumen	$837 \text{ m}^3$
Installierte externe Heizung	73 MW
Toroidales Magnetfeld	5,3 T

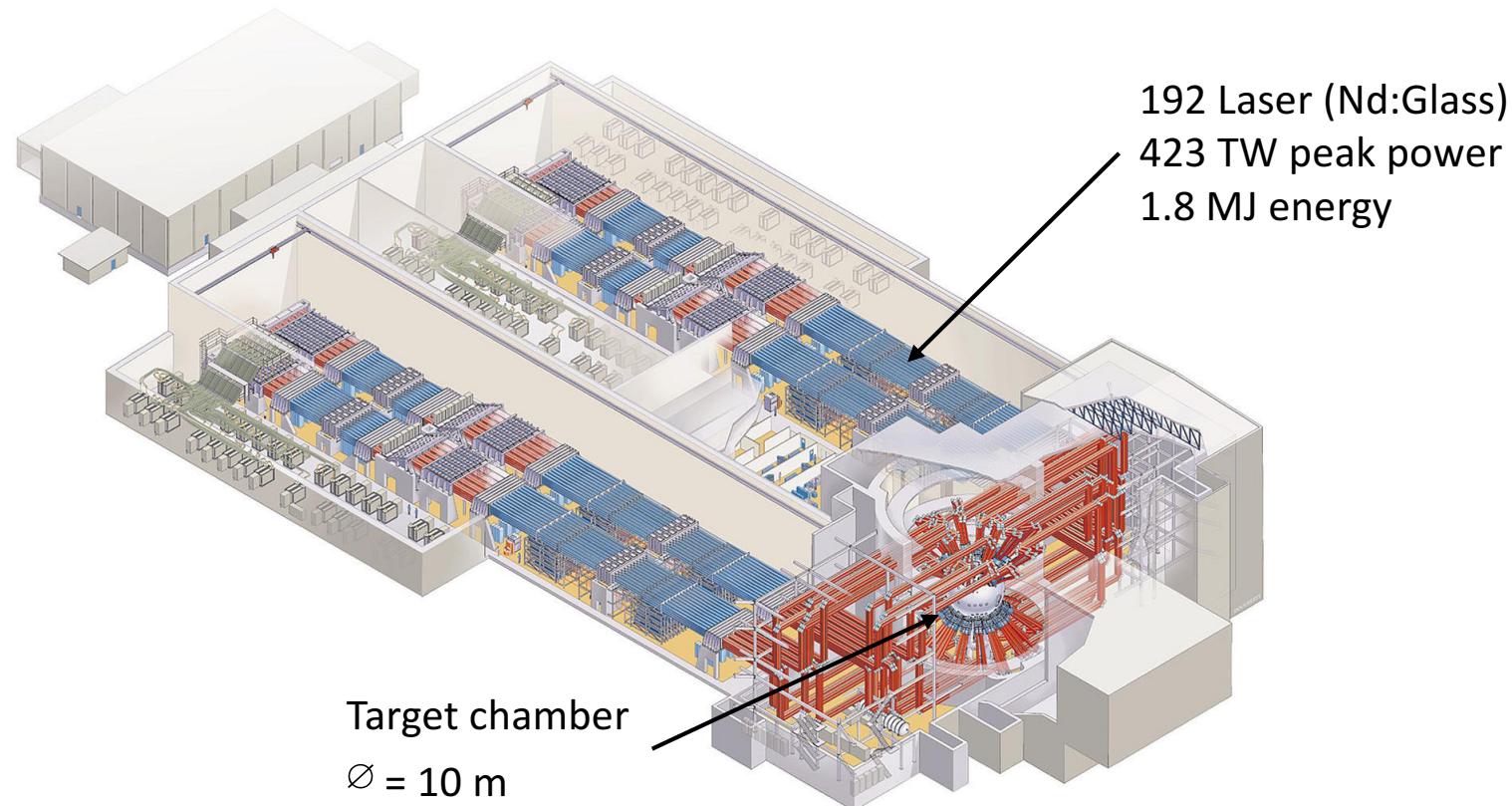
Quelle: www.fusion.kit.edu

# Inertial Confinement Fusion

Plasma density  $n = 10^{26} \text{ cm}^{-3}$ ; confinement time  $\tau_E = 10^{-10} \text{ s}$

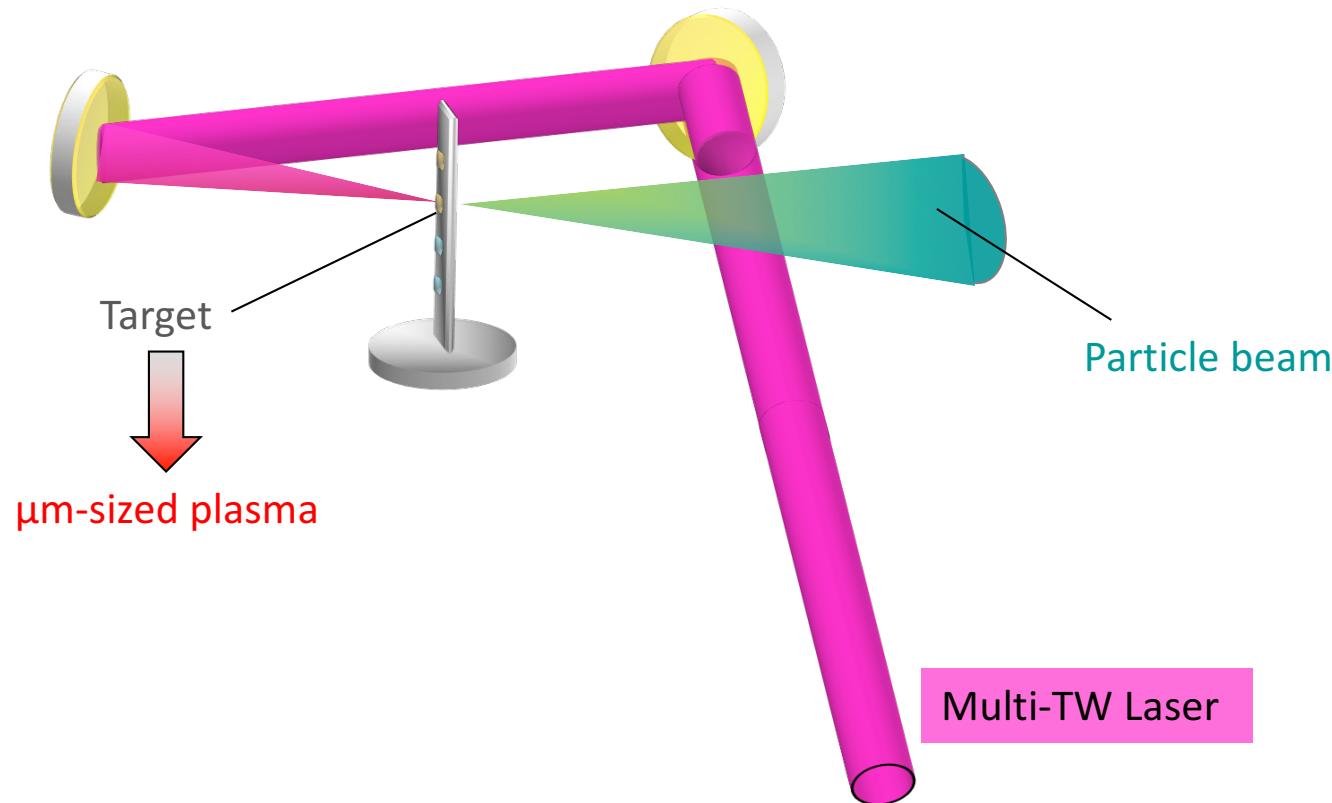


# National Ignition Facility (NIF)



<https://lasers.llnl.gov>

# Laser-induced Production of Fusion-like Plasmas



Düsseldorf  
DARC<sub>turus</sub>  
LASER FACILITY

PHELIX

SIOM

JuSPARC

# Fusion Reactions in Laser-induced Plasmas

Here:  $D + D \rightarrow {}^3\text{He} + n$

Experiment @ Max-Planck-Institut für Quantenoptik (CD<sub>2</sub> foil target)

PHYSICAL REVIEW E

VOLUME 58, NUMBER 1

JULY 1998

## Neutron production by 200 mJ ultrashort laser pulses

G. Pretzler,<sup>1</sup> A. Saemann,<sup>1</sup> A. Pukhov,<sup>1</sup> D. Rudolph,<sup>2</sup> T. Schätz,<sup>2</sup> U. Schramm,<sup>2</sup> P. Thirolf,<sup>2</sup> D. Habs,<sup>2</sup> K. Eidmann,<sup>1</sup> G. D. Tsakiris,<sup>1</sup> J. Meyer-ter-Vehn,<sup>1</sup> and K. J. Witte<sup>1</sup>

<sup>1</sup>*Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*

<sup>2</sup>*Sektion Physik, LMU München, Am Coulombwall 1, D-85748 Garching, Germany*

(Received 27 October 1997; revised manuscript received 30 January 1998)

We report the observation of neutrons released from  $d(d,n){}^3\text{He}$  fusion reactions in the focus of 200 mJ, 160 fs Ti:sapphire laser pulses on a deuterated polyethylene target. Optimizing the fast electron and ion generation by applying a well-defined prepulse led to an average rate of 140 neutrons per shot. Furthermore, the production of a substantial number of MeV  $\gamma$  rays could be observed. The occurrence of neutrons and  $\gamma$  rays is attributed to the formation and explosion of a relativistic plasma channel in the laser focus, which is confirmed by numerical calculations. [S1063-651X(98)08507-9]

# The Lawson Criterion Revisited

$$n \cdot \tau_c > \frac{12k_B T}{E_f \langle \sigma_f v \rangle}$$

$n$ : ion density  
 $\tau_c$ : confinement time  
 $T$ : ion temperature  
 $E_f$ : Energy per fusion  
 $\sigma_f$ : fusion cross section  
 $v$ : ion velocity

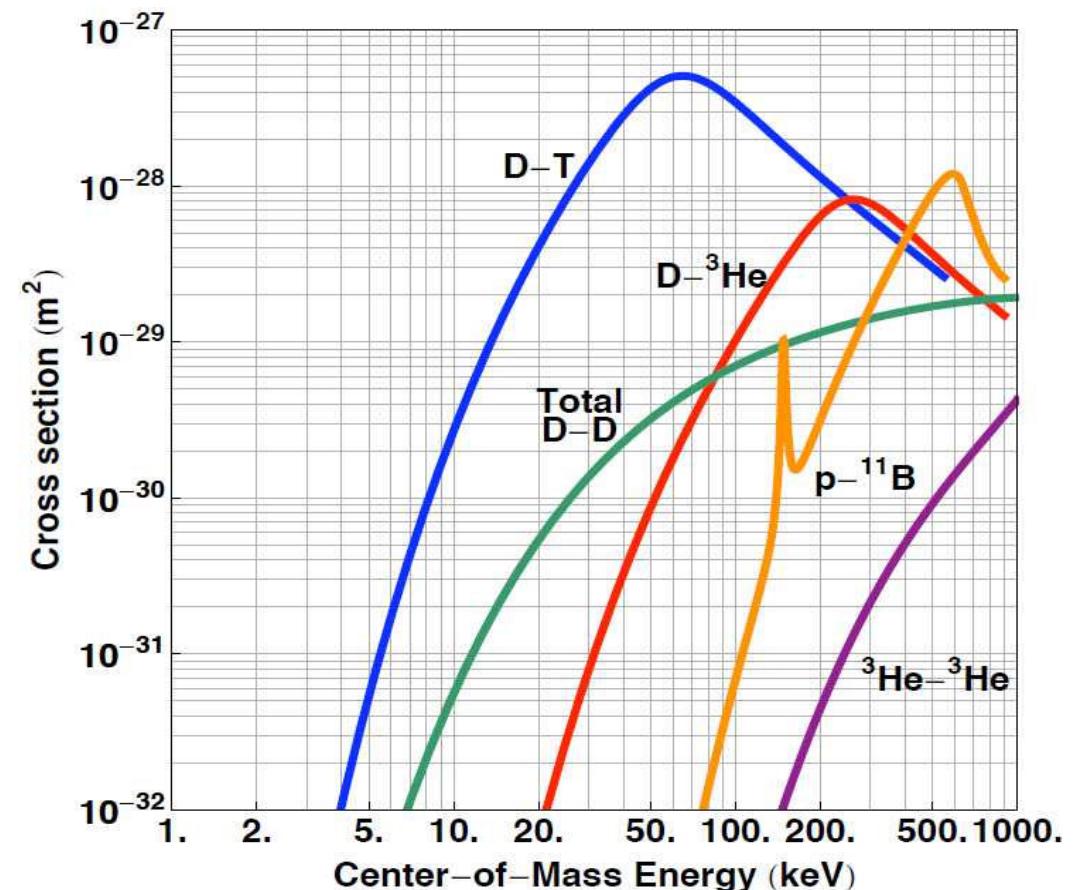
„External parameters“: pressure, temperature, confinement time

„Intrinsic parameter“: fusion cross section  $\sigma_f$



☞ can this be changed “from outside”????

# Fusion Reactions



- most promising candidates for fusion reactors
- no neutrons from a fusion reactor operated with pure  ${}^3\text{He}$  fuel ( ${}^4\text{He}$  and protons only)

# Polarized Fusion: First Ideas ...

VOLUME 49, NUMBER 17

PHYSICAL REVIEW LETTERS

25 OCTOBER 1982

## 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

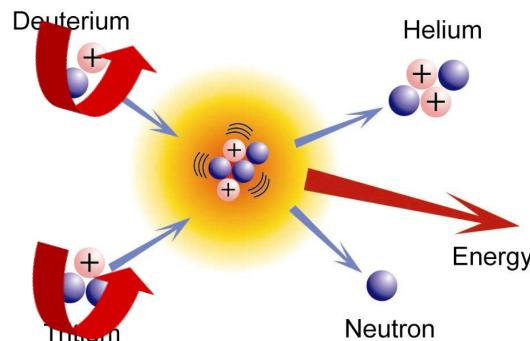
*Brookhaven National Laboratory, Upton, New York 11973*

(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.

See also: *The status of “polarized fusion”*, H. Paetz gen. Schieck, Eur. Phys. J. A **44**, 321–354 (2010)

# Polarized Fusion: Increased Total Cross Section



Die  ${}^3\text{He}(d,p){}^4\text{He}$ -Reaktion mit polarisiertem und unpolarisiertem Target und polarisiertem Deuteronenstrahl bei  $E_d = 430$  keV  
von Ch. Leemann, H. Bürgisser, P. Huber, U. Rohrer, H. Paetz gen. Schieck  
und F. Seiler

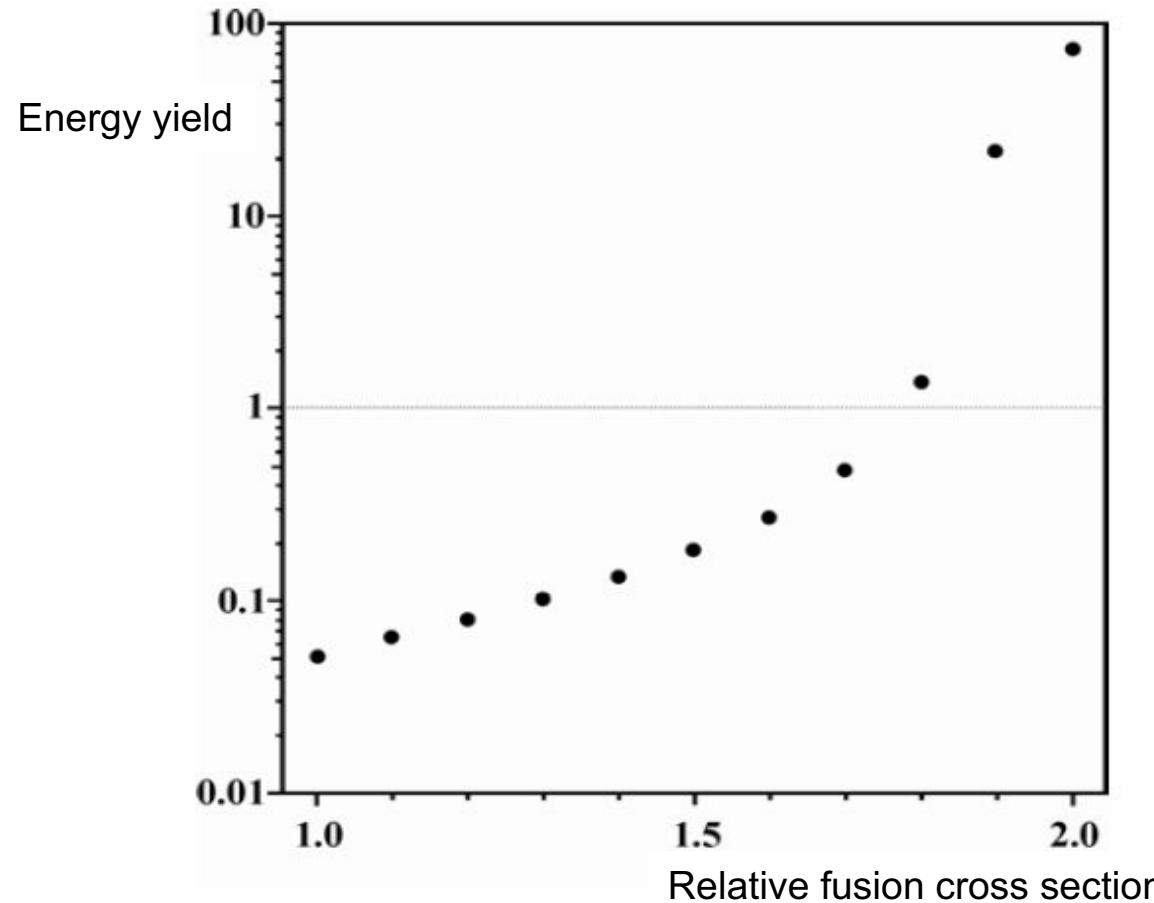
Physikalisches Institut der Universität Basel

Helv. Phys. Acta 44, 141 (1971)

${}^3\overrightarrow{\text{He}} + \overrightarrow{d} \rightarrow {}^4\text{He} + p$  total cross section  
enhanced by factor 1.5 @430 keV

# Polarized Fusion: Increased Energy Yield

Here: inertial fusion

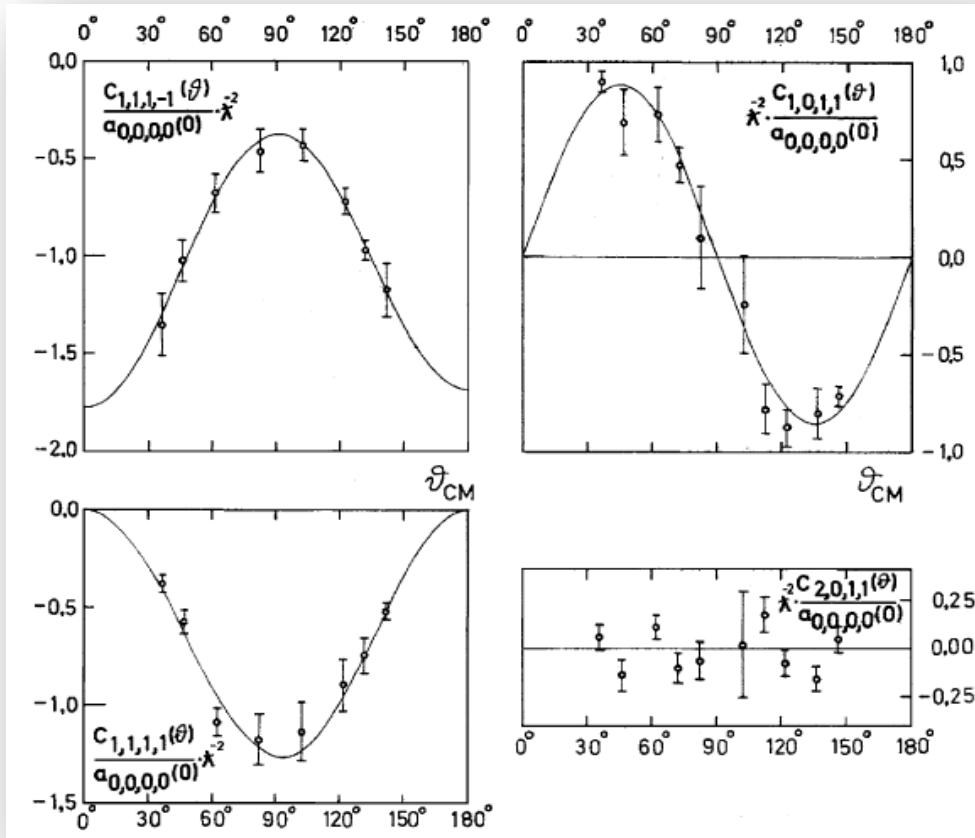


☞ Enhancement by factor 4  
with polarized fuel

From:  
M. Temporal et al.;  
Priv. comm.

# Polarized Fusion: Angular Distributions

Measurements @Basel 1971:  $\overset{\rightarrow}{D} + \overset{\rightarrow}{^3\text{He}} \rightarrow \overset{\rightarrow}{^4\text{He}} + p$



Die  $^3\text{He}(d,p)^4\text{He}$ -Reaktion mit polarisiertem und unpolarisiertem Target und polarisiertem Deuteronenstrahl bei  $E_d = 430$  keV von Ch. Leemann, H. Bürgisser, P. Huber, U. Rohrer, H. Paetz gen. Schieck und F. Seiler

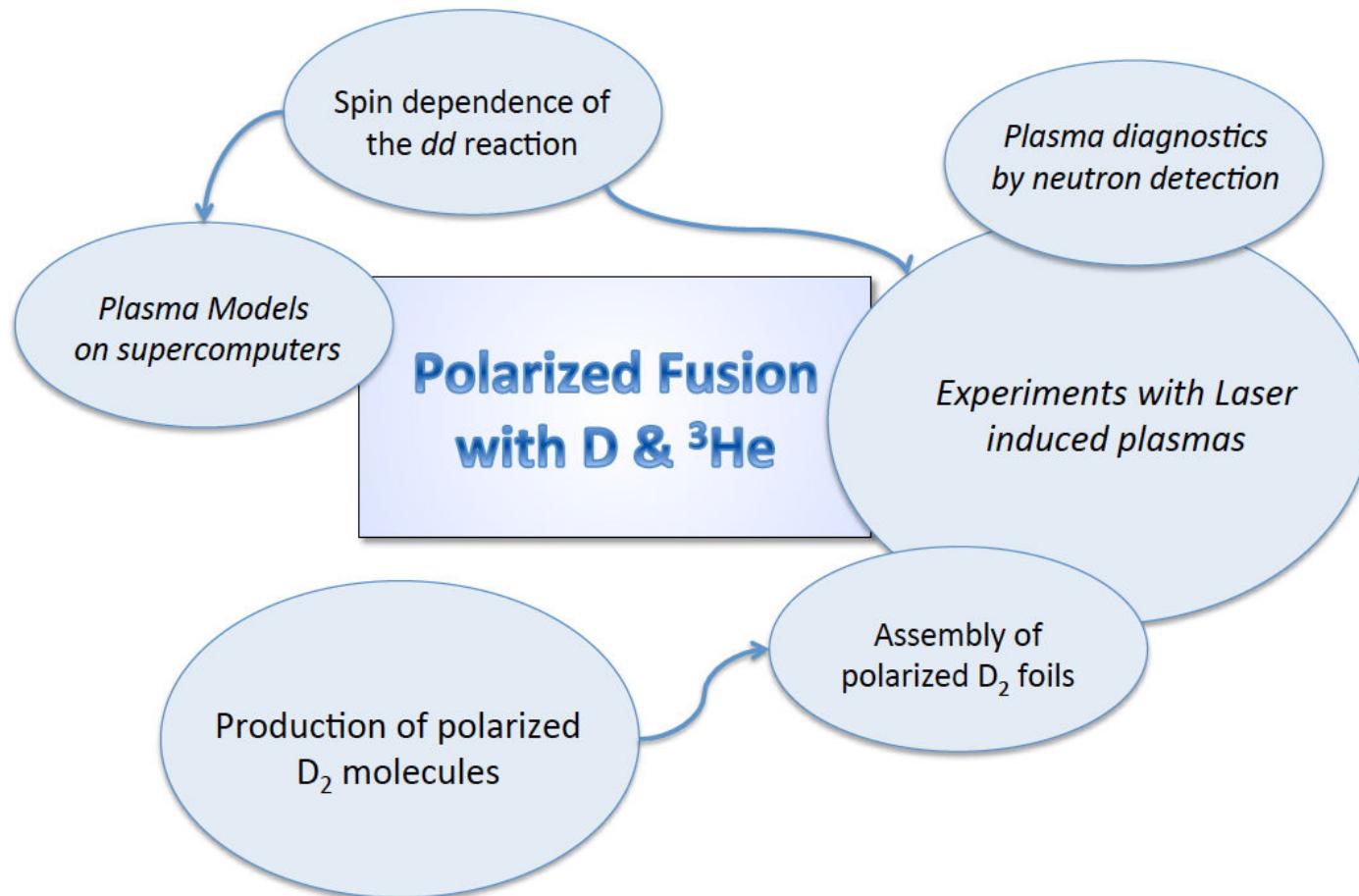
Physikalisches Institut der Universität Basel

Helv. Phys. Acta 44, 141 (1971)

☞ Emitted Protons (Neutrons) can be guided  
(even if only Deuterons are polarized)

# The PolFusion Project (2015 / ERC proposal)

- Measure the polarization dependence of fusion rates in laser-induced relativistic plasmas



# 2016: Approval of a DFG-RSF project

Joint proposal within the DFG-RSF Cooperation:  
“Possibility for Joint German-Russian Project Proposals in Physics and Mathematics”

**Towards a Molecular Source for Polarized Deuterium Fuel in Nuclear Fusion Research and other Applications**



## Applicants

on the German side:

Prof. Dr. Markus Büscher  
Institut für Laser- und Plasmaphysik  
Heinrich-Heine-Universität Düsseldorf  
Universitätsstraße 1  
40225 Düsseldorf

[Markus.Buescher@uni-duesseldorf.de](mailto:Markus.Buescher@uni-duesseldorf.de)

on the Russian side:

Dr. Dmitriy Toporkov  
Budker Institute of Nuclear Physics of  
Siberian Branch Russian Academy of Sciences  
Lavrentiev Avenue 11  
630090, Novosibirsk

[D.K.Toporkov@inp.nsk.su](mailto:D.K.Toporkov@inp.nsk.su)

# 2017: The PREFER Collaboration

Polarization Research for  
Fusion Experiments and Recactors



## *AGREEMENT FOR COOPERATION*

### *BETWEEN*

Forschungszentrum Jülich GmbH  
52425 Jülich  
Federal Republic of GERMANY  
- hereinafter referred to as „JÜLICH“-

### *AND*

Heinrich-Heine Universität Düsseldorf  
Universitätsstraße 1  
40225 Düsseldorf  
Federal Republic of GERMANY  
- hereinafter referred to as „HHUD“-

### *AND*

Budker Institute of Nuclear Physics of  
Siberian Branch Russian Academy of Sciences  
Lavrentiev Avenue 11  
630090, Novosibirsk  
RUSSIA  
- hereinafter referred to as „BINP“-

### *AND*

Università degli Studi di Ferrara  
Via Savonarola, 9  
And  
INFN-sezione di Ferrara  
Via Saragat 1  
44121 - Ferrara  
ITALY  
- hereinafter referred to as „UNIFE/INFN-Fe“-

### *AND*

National Research Center "Kurchatov Institute"  
Petersburg Nuclear Physics Institute,  
188300, Gatchina,  
RUSSIA  
- hereinafter referred to as „PNPI“-

- together hereinafter referred to as „Partners“ -

# PREFER: Work Packages (1)

Measurement of  $\overrightarrow{d}d \rightarrow \overrightarrow{d}d$  cross section / PolFusion experiment (PNPI, Ferrara)



☞ Talk by Peter Kravtsov

# PREFER: Work Packages (2)

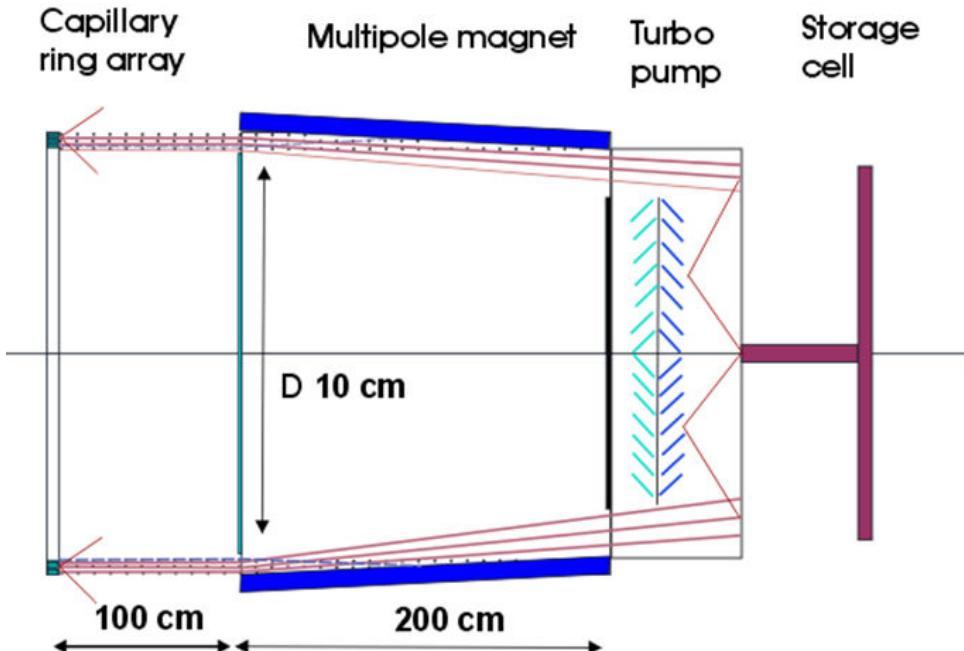
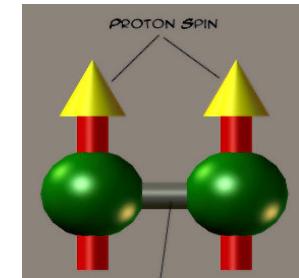
## Theory / Scattering of two spin-1 particles (PNPI)

$$\begin{aligned}
 \sigma(\Theta, \Phi) = \sigma_0(\Theta) \{ & 1 + \frac{3}{2} [A_y^{(b)}(\Theta)p_y + A_y^{(t)}q_y] + \frac{1}{2} [A_{zz}^{(b)}(\Theta)p_{zz} + A_{zz}^{(t)}(\Theta)q_{zz}] \\
 & + \frac{1}{6} [A_{xx-yy}^{(b)}(\Theta)p_{xx-yy} + A_{xx-yy}^{(t)}(\Theta)q_{xx-yy}] \\
 & + \frac{2}{3} [A_{xz}^{(b)}(\Theta)p_{xz} + A_{xz}^{(t)}(\Theta)q_{xz}] \\
 & + \frac{9}{4} [C_{y,y}(\Theta)p_yq_y + C_{x,x}(\Theta)p_xq_x + C_{z,z}(\Theta)p_xq_z \\
 & \quad + C_{z,x}(\Theta)p_zq_x + C_{z,z}(\Theta)p_zq_z] \\
 & + \frac{3}{4} [C_{y,zz}(\Theta)p_yq_{zz} + C_{zz,y}(\Theta)p_{zz}q_y] \\
 & + C_{y,xz}(\Theta)p_yq_{xz} + C_{xz,y}(\Theta)p_{xz}q_y + C_{x,yz}(\Theta)p_xq_{yz} \\
 & + C_{yz,x}(\Theta)p_{yz}q_x + C_{z,yz}(\Theta)p_zq_{yz} + C_{yz,z}(\Theta)p_{yz}q_z \\
 & + \frac{1}{4} [C_{y,xx-yy}(\Theta)p_yq_{xx-yy} + C_{xx-yy,y}(\Theta)p_{xx-yy}q_y \\
 & \quad + C_{zz,zz}(\Theta)p_{zz}q_{zz}] \\
 & + \frac{1}{3} [C_{zz,xz}(\Theta)p_{zz}q_{xz} + C_{xz,zz}(\Theta)p_{xz}q_{zz}] \\
 & + \frac{1}{12} [C_{zz,xx-yy}(\Theta)p_{zz}q_{xx-yy} + C_{xx-yy,zz}(\Theta)p_{xx-yy}q_{zz}] \\
 & + \frac{4}{9} [C_{xz,xz}(\Theta)p_{xz}q_{xz} + C_{yz,yz}(\Theta)p_{yz}q_{yz}] \\
 & + \frac{8}{9} [C_{xy,yz}(\Theta)p_{xy}q_{yz} + C_{yz,xy}(\Theta)p_{yz}q_{xy}] \\
 & + \frac{16}{9} C_{xy,xy}(\Theta)p_{xy}q_{xy} \\
 & + \frac{1}{9} [C_{xz,xx-yy}(\Theta)p_{xz}q_{xx-yy} + C_{xx-yy,xz}(\Theta)p_{xx-yy}q_{xz}] \\
 & + \frac{1}{36} C_{xx-yy,xx-yy}(\Theta)p_{xx-yy}q_{xx-yy} \\
 & + \frac{1}{2} [C_{x,xy}(\Theta)p_xq_{xy} + C_{xy,x}(\Theta)p_{xy}q_x + C_{z,xy}(\Theta)p_zq_{xy} \\
 & \quad + C_{xy,z}(\Theta)p_{xy}q_z] \}
 \end{aligned}$$

 Talk by Polina Kravchenko

## PREFER: Work Packages (3)

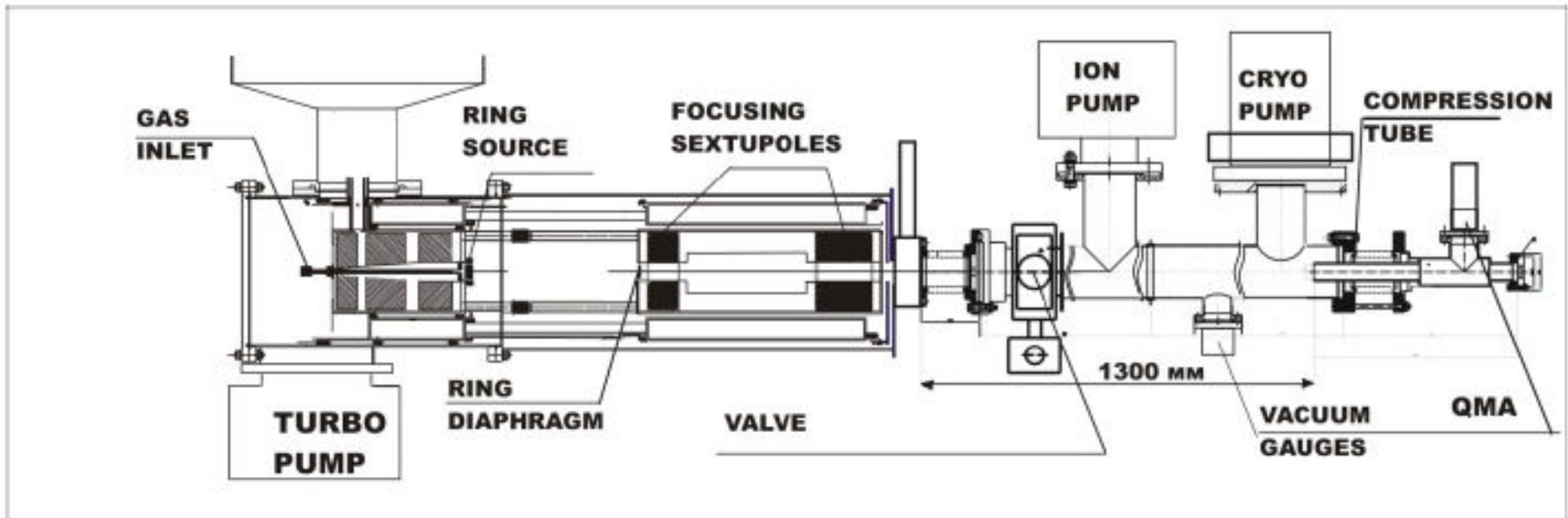
Polarized molecular beam source (BINP)



**DFG** Deutsche  
Forschungsgemeinschaft

## PREFER: Work Packages (4)

Construction & test of a Lamb-shift polarimeter (HHUD, FZJ, Ferrara)

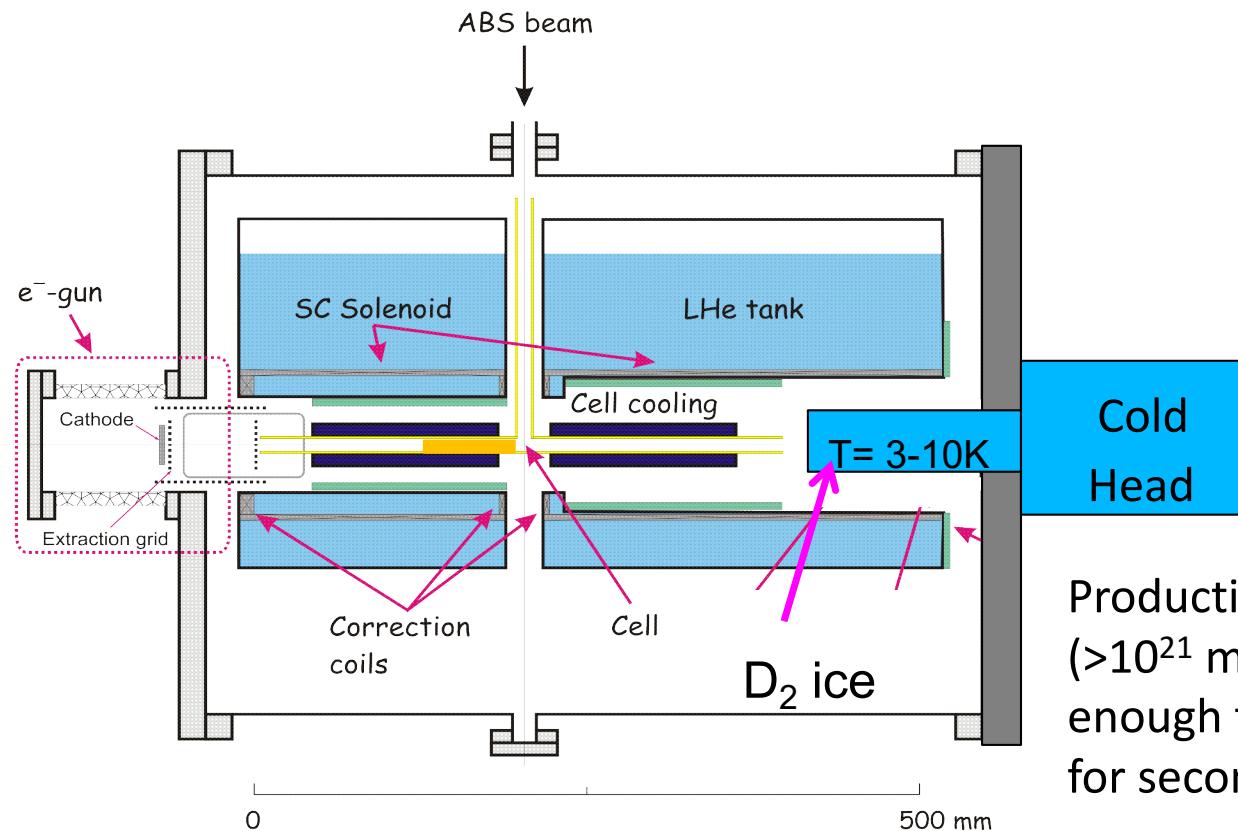


**DFG** Deutsche  
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 *Talk by Ralf Engels*

# PREFER: Work Packages (5)

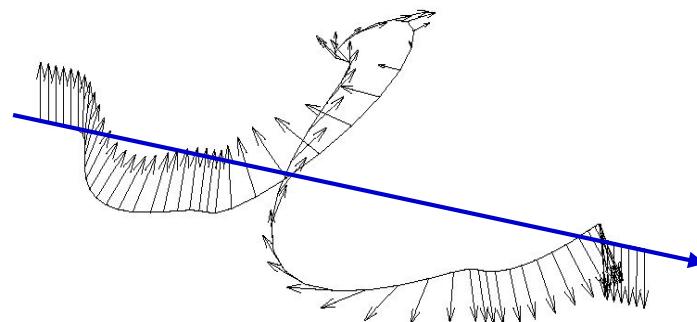
Foils of frozen polarized Hydrogen (HHUD, FZJ, BINP)



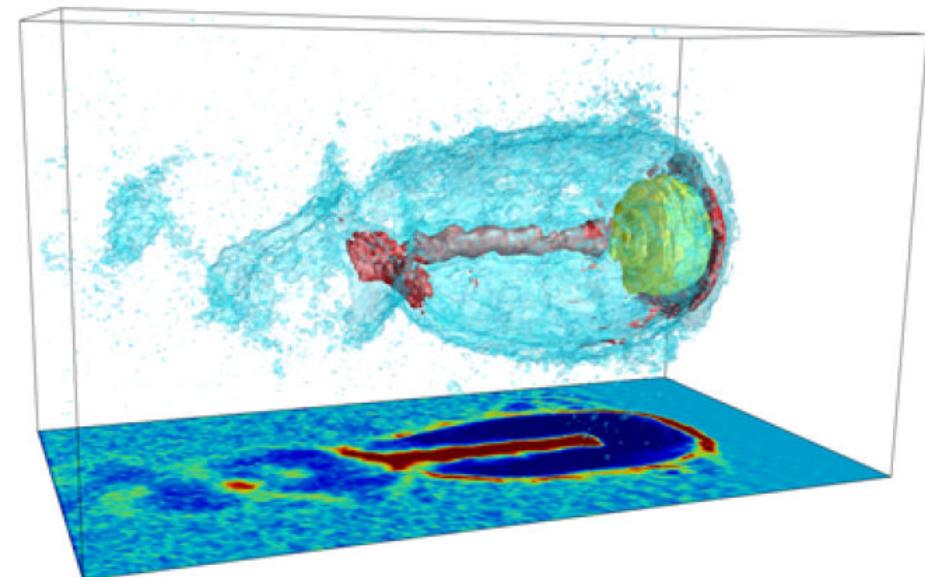
Production of 1 day  
( $>10^{21}$  molecules) is  
enough to feed a Tokamak  
for seconds !!

# PREFER: Work Packages (6)

Theory / Nuclear spins in Laser-induced plasmas (HHUD)



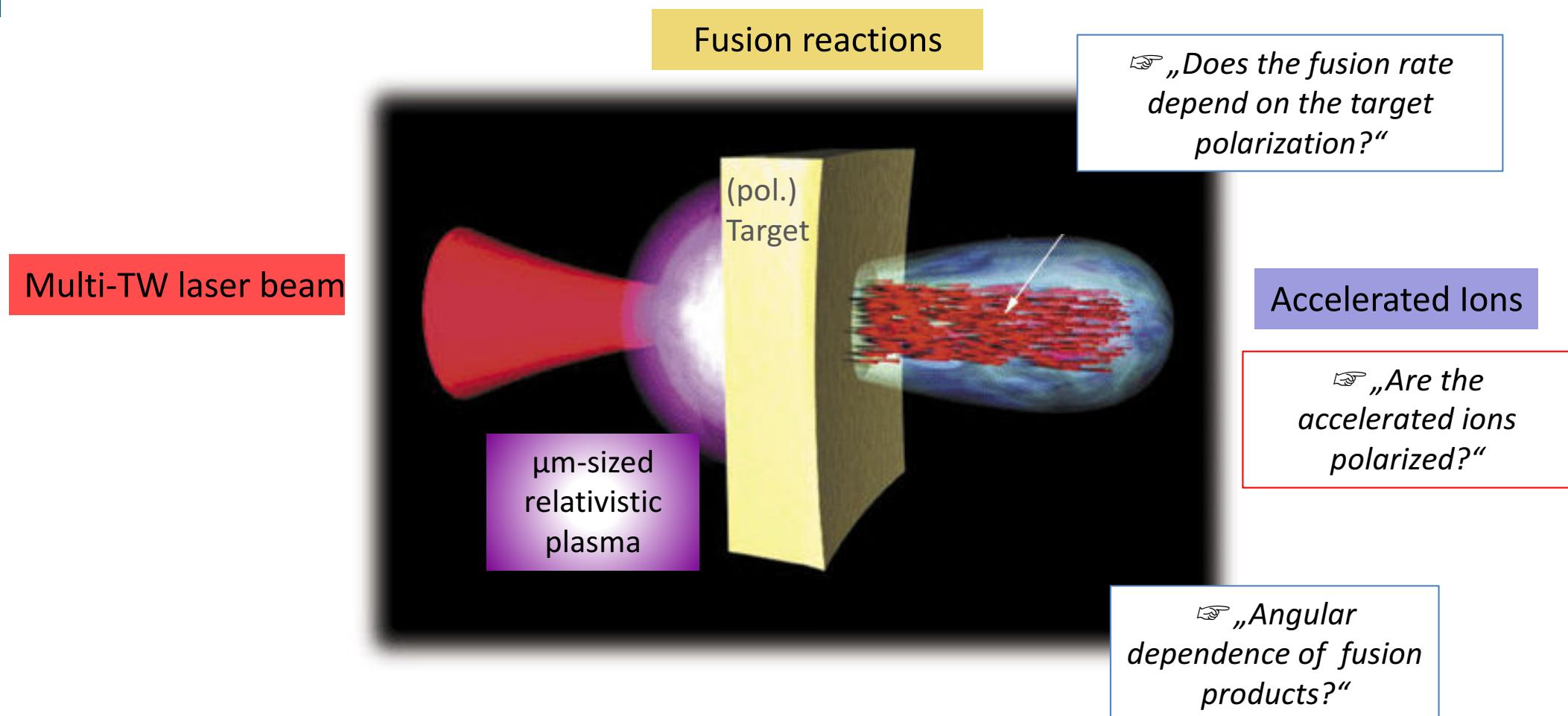
*Thomas-BMT equation  
Sokolov-Ternov effect  
Stern-Gerlach effect*



*PIC codes*

# PREFER: Work Packages (7)

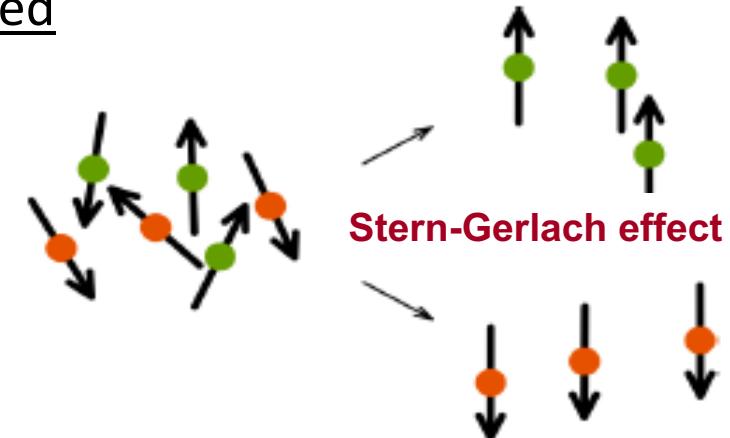
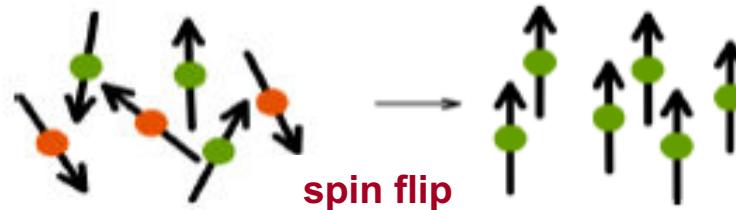
Nuclear Spins in Laser-induced Plasmas / Experiments (HHUD, FZJ)



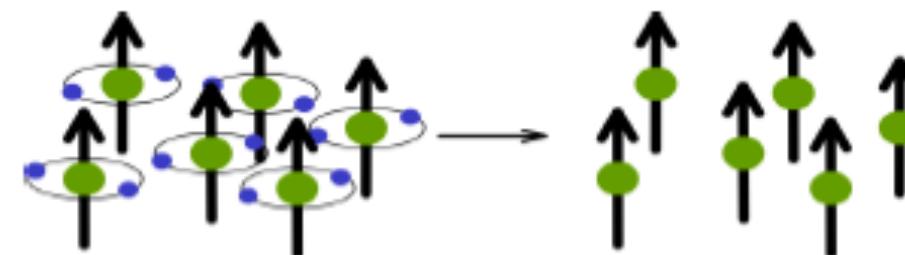
# Generation of Polarized Particle Beams

Possible scenarios:

Polarization is generated



Polarization is preserved



# Polarized $^3\text{He}$ Gas

Glass vessels surrounded by permanent magnets (Univ. Mainz) / max. pressure 3 bar



☞ Talk by İlhan Engin

# PHELIX @ GSI Darmstadt

Petawatt High-Energy Laser for Heavy Ion EXperiments



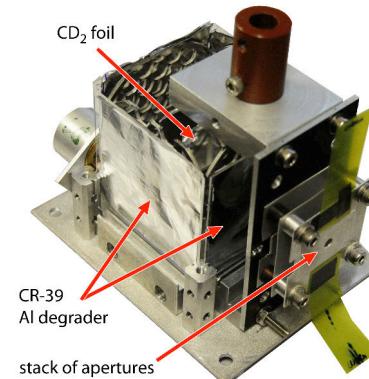
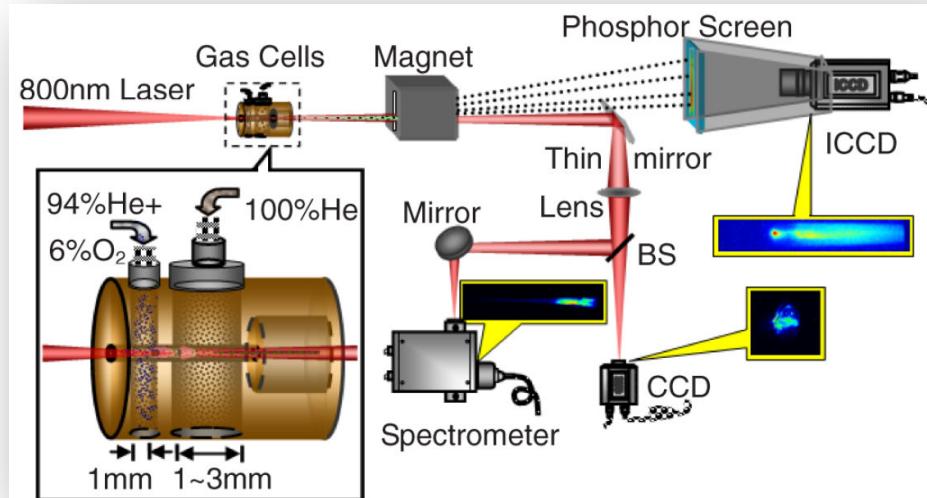
Flashlamp-pumped Nd:glass system

Repetition rate: 1 shot per 1.5 hours

	Long pulse	Short pulse
Pulse duration	0.7 – 20 ns	0.4 – 20 ps
Pulse energy	300 – 1000 J	250 J
Max. intensity	$10^{16}$ W/cm <sup>2</sup>	$2 \cdot 10^{21}$ W/cm <sup>2</sup>

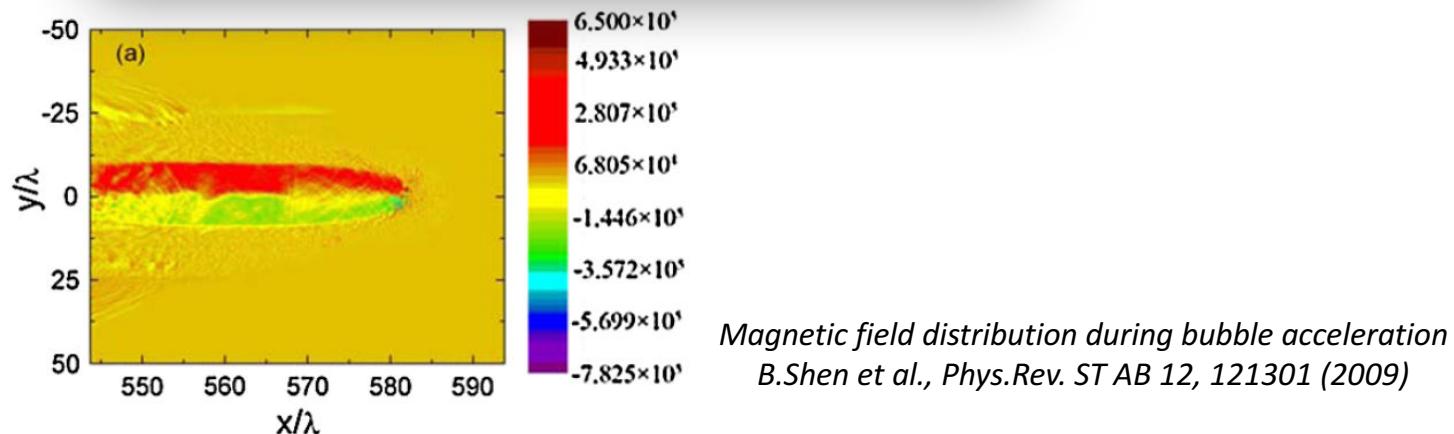
# Polarized Protons from Unpolarized Gas Targets

SIOM/Shanghai: Planned measurements at a 10 PW laser



Polarimeter for  ${}^3\text{He}$  ions

I.Engin et al., DOI: 10.1007/978-3-319-39471-8\_5



# Proton Polarimetry (@3 MeV)

PHYSICS OF PLASMAS 21, 023104 (2014)

## Polarization measurement of laser-accelerated protons

Natascha Raab,<sup>1,a)</sup> Markus Büscher,<sup>1,2,3,b)</sup> Mirela Cerchez,<sup>3</sup> Ralf Engels,<sup>1</sup> İlhan Engin,<sup>1</sup> Paul Gibbon,<sup>4</sup> Patrick Greven,<sup>1</sup> Astrid Holler,<sup>1</sup> Anupam Karmakar,<sup>4,c)</sup> Andreas Lehrach,<sup>1</sup> Rudolf Maier,<sup>1</sup> Marco Swantusch,<sup>3</sup> Monika Toncian,<sup>3</sup> Toma Toncian,<sup>3</sup> and Oswald Willi<sup>3</sup>

<sup>1</sup>Institut für Kernphysik and Jülich Center for Hadron Physics, Forschungszentrum Jülich, 52425 Jülich, Germany

<sup>2</sup>Peter Grünberg Institut (PGI-6), Forschungszentrum Jülich, 52425 Jülich, Germany

<sup>3</sup>Institute for Laser- and Plasma Physics, Heinrich-Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany

<sup>4</sup>Institute for Advanced Simulation, Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany

## MOST READ THIS MONTH

Gyro-induced acceleration of magnetic reconnection

Progress towards ignition on the National Ignition Facility<sup>a)</sup>

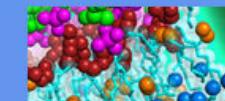
Polarization measurement of laser-accelerated protons

International Journal of High-Energy Physics

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Mar 28, 2014

### New results mark progress towards polarized ion beams in laser-induced acceleration



The Arcturus Laser

The field of laser-induced relativistic plasmas and, in particular, laser-driven particle acceleration, has undergone impressive progress in recent years. Despite many advances in understanding fundamental physical phenomena, one unexplored issue is how the particle spins are influenced by the huge magnetic fields inherently present in the plasmas.

Laser-induced generation of polarized-ion beams would without doubt be important in research at particle accelerators. In this context,  $^3\text{He}^{2+}$  ions have been discussed widely. They can serve as a substitute for polarized neutron beams, because in a  $^3\text{He}$  nucleus the two protons have opposite spin directions, so the spin of the nucleus is carried by the neutron. However, such beams are currently not available owing to a lack of corresponding ion sources. A promising approach for a laser-based ion source would be to use pre-polarized  $^3\text{He}$  gas as the target material. Polarization conservation of  $^3\text{He}$  ions in plasmas is also crucial for the feasibility of proposals aiming at an increase in efficiency of fusion reactors by using polarized fuel, because this efficiency depends strongly on the cross-section of the fusion reactions.

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cooling solutions

**Goodfellow**  
Metals and Materials for Research and Industry

# PREFER: Work Packages

Who else??

