A research program to measure the lifetime of spin polarized nuclei in magnetically confined fusion plasmas

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[9]*Jefferson Lab*

UCIRVINE

The DIII-D Tokamak in San Diego

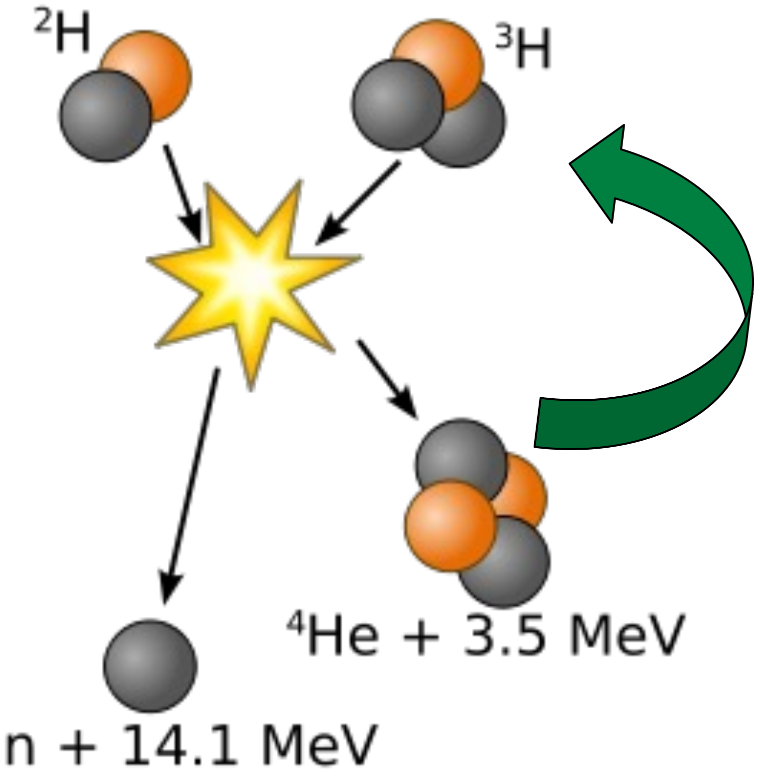
Spin polarized fuel relaxes the requirements for fusion energy

- **D-T fusion cross-section is increased by 50% when the spins of both nuclei are polarized along the magnetic field[1]**

- **Due to self-heating, >50% increase in fusion power with no additional requirement on plasma confinement[2]**

- **Depolarization mechanisms are theoretically weak in the core,[1] but the polarization lifetime has never been measured**

- **Polarized fuel is now available in sufficient quantities for experimental tests[2]**



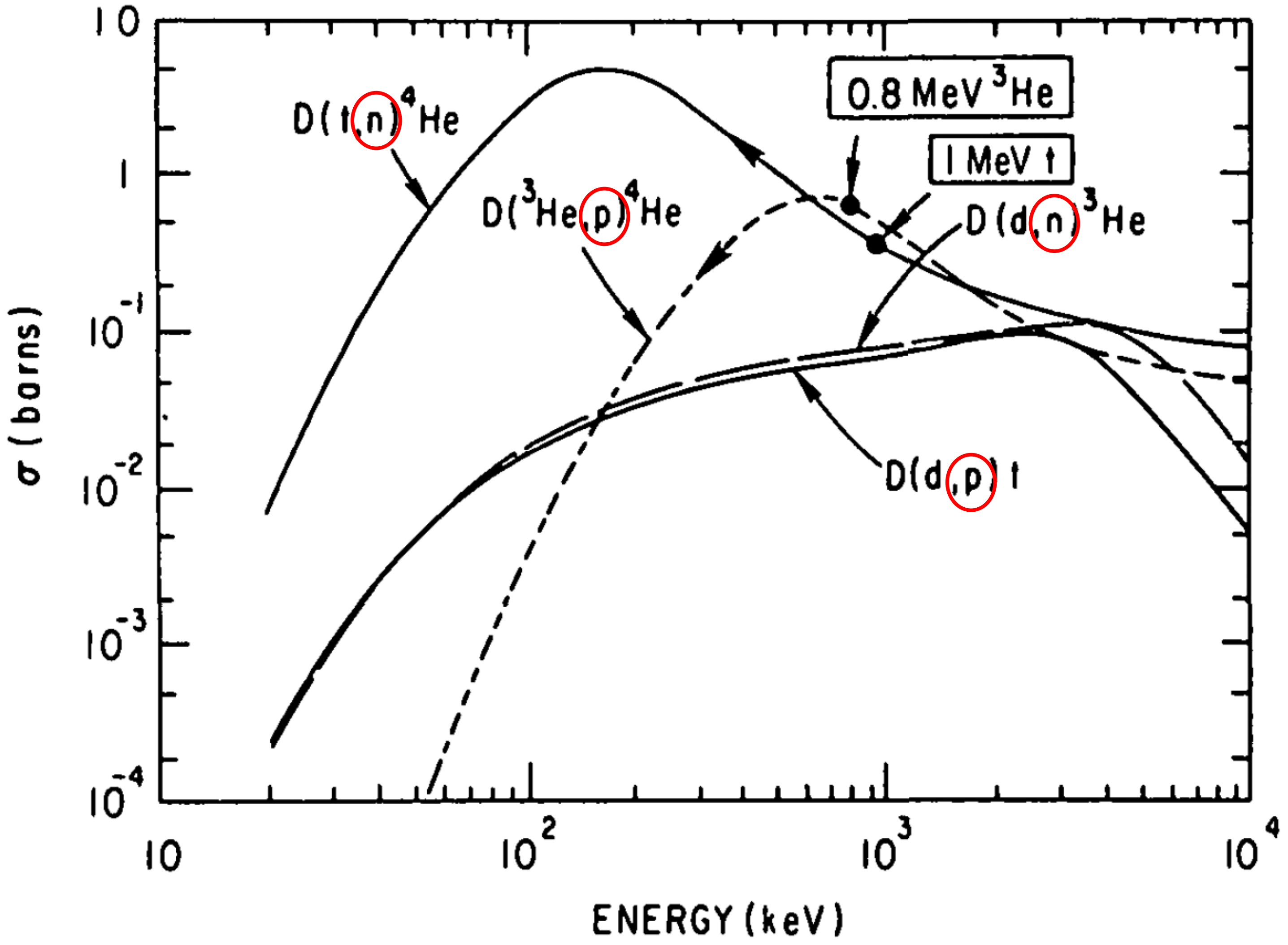
[1] R.M. Kulsrud et al., Nucl. Fusion **26** (1986) 1443.
[2] L. Baylor et al., Nucl. Fusion **63** (2023) 076009

Outline

1. **Fusion in contemporary magnetic fusion experiments**
2. **Spin polarized fuel**
3. **Depolarization mechanisms**
4. **Planned & desired experiments**

Three fusion reactions are often measured in fusion experiments

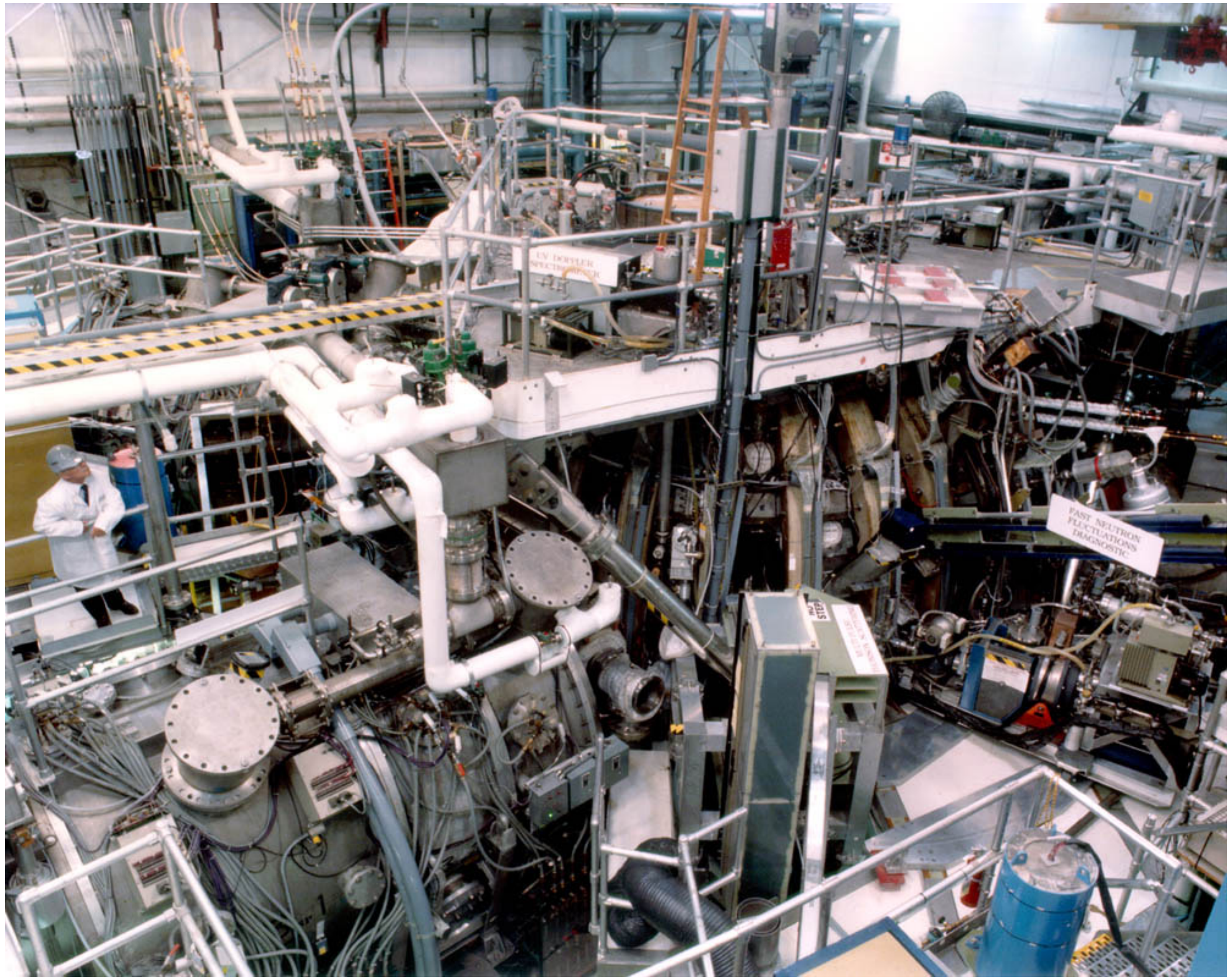
- **Deuterium is usually the main ion species**
- **Many fusion reaction products are unconfined in a moderate-size tokamak**

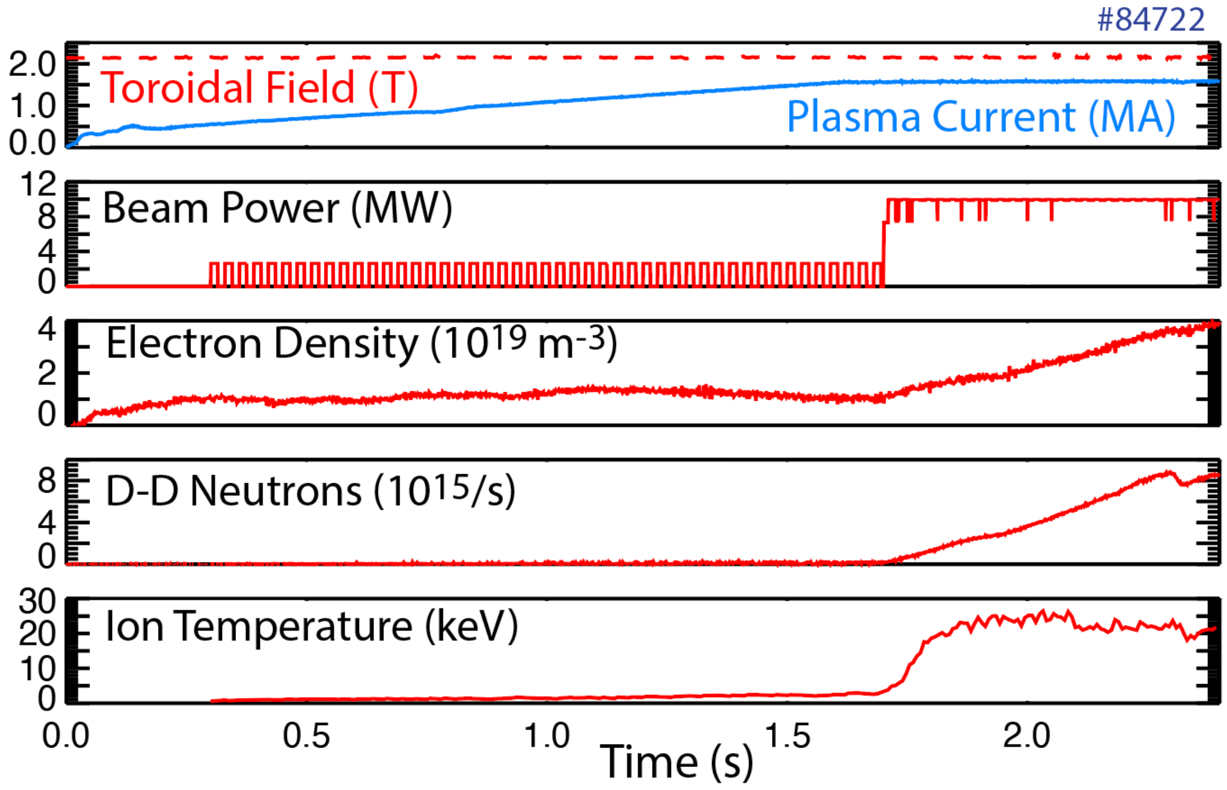


Heidbrink et al., Nucl. Fusion **23** (1983) 917

Many experiments are heated by neutral beams

- Inject ~ 80 keV D neutrals
- Beam ions take *O(0.1 s)* to thermalize
- Routinely measure 2.45 MeV neutrons from d(d,n)^{3}He





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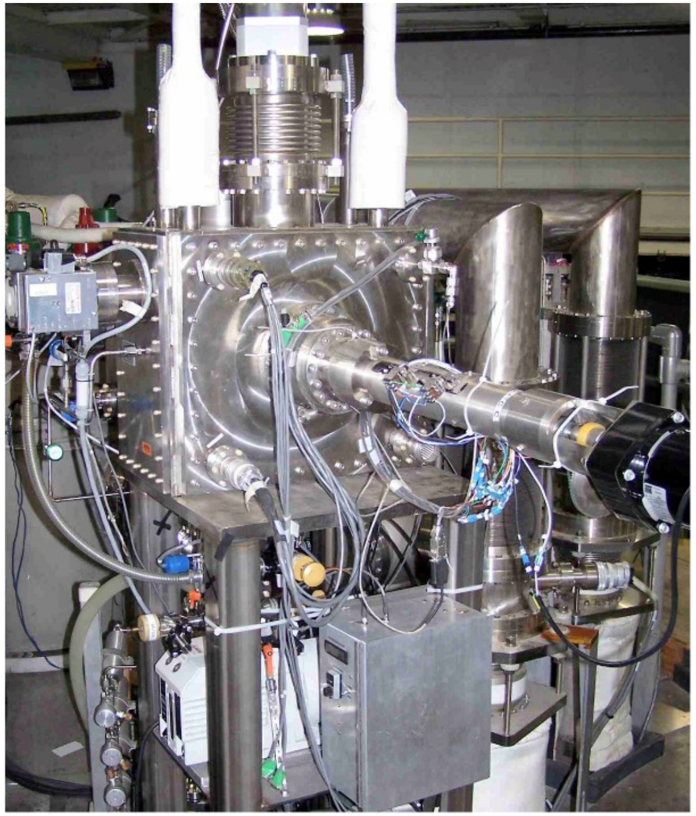
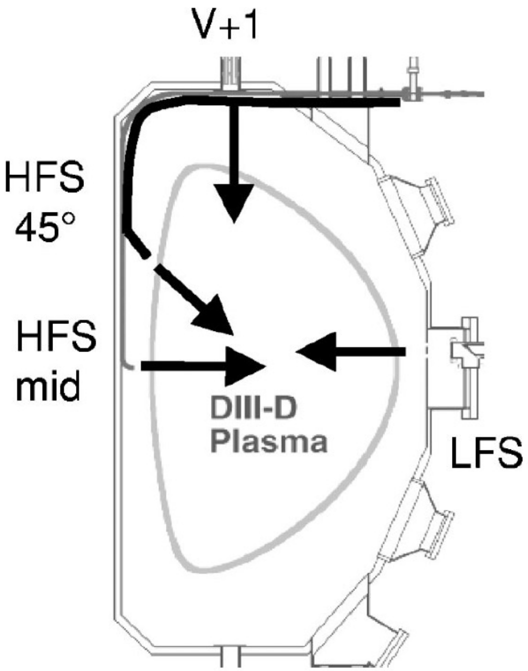
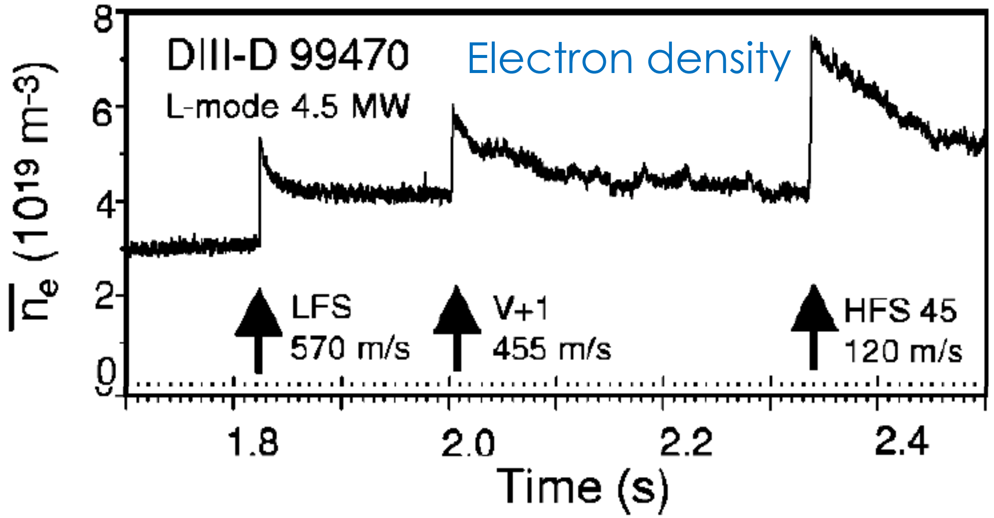
Some experiments are fueled by pellets that ablate & ionize in the plasma

- **Inject frozen D pellets**
- **Inject "shell pellets" with gas inside**
- **Typical "particle confinement time" is *O(0.1 s)***

Pellet injector above DIII-D







L. Baylor et al., Phys. Plasmas **7** (2000) 1878

OAK RIDGE National Laboratory

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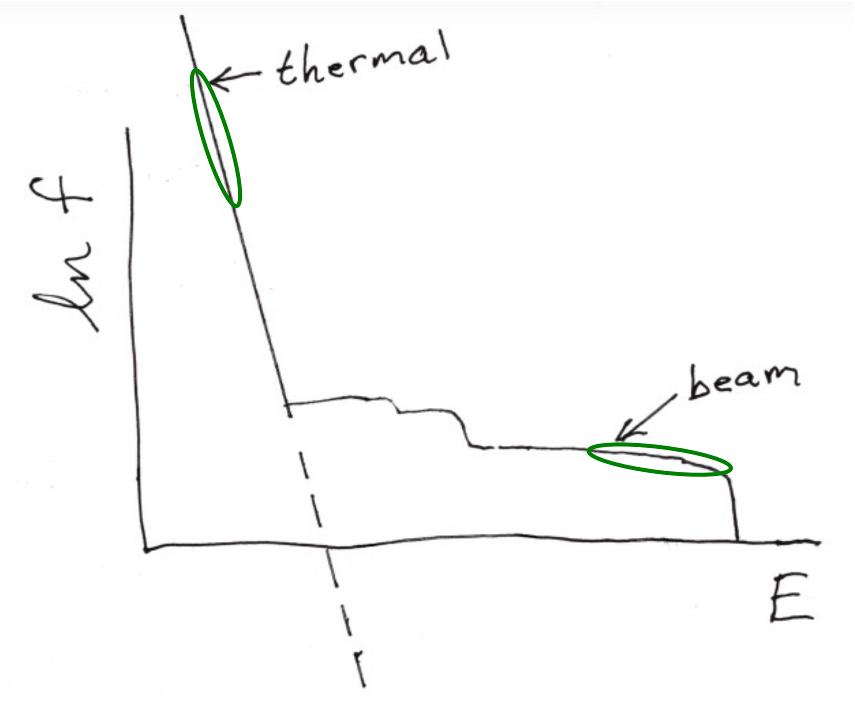
Distinguish between thermal & super-thermal distribution functions

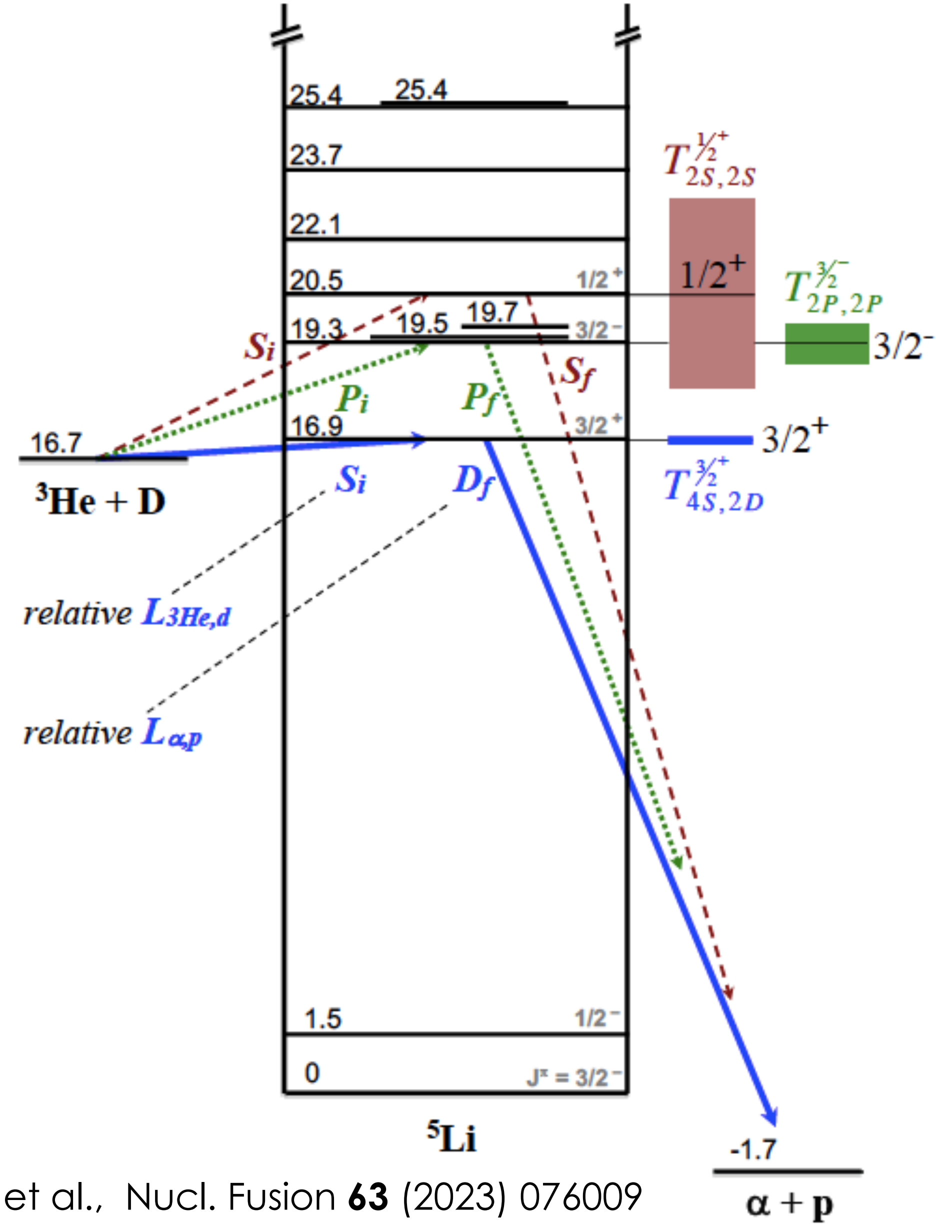
- **Most of the plasma is thermal with ion temperatures T_i of a few keV**
- **Neutral beams produce non-thermal, anisotropic populations with *O(100 keV)* energies**

Typical D distribution function *f*



Use D-^{3}He as a proxy for D-T

- **Mirror reaction virtually identical at *O(100 keV)* energies**

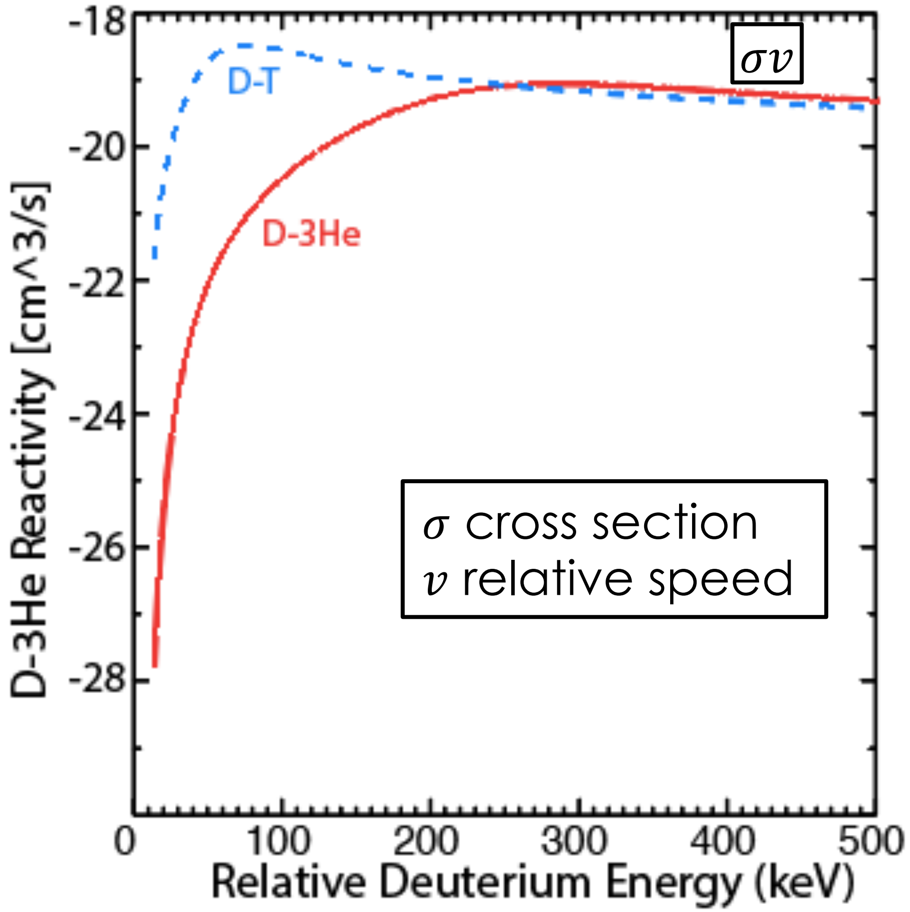


L. Baylor et al., Nucl. Fusion **63** (2023) 076009

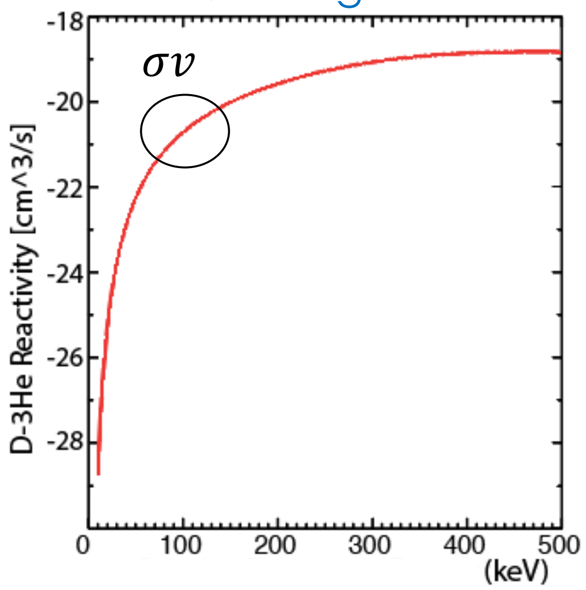
Fusion products:
- **14.7 MeV proton**
- **3.6 MeV alpha**

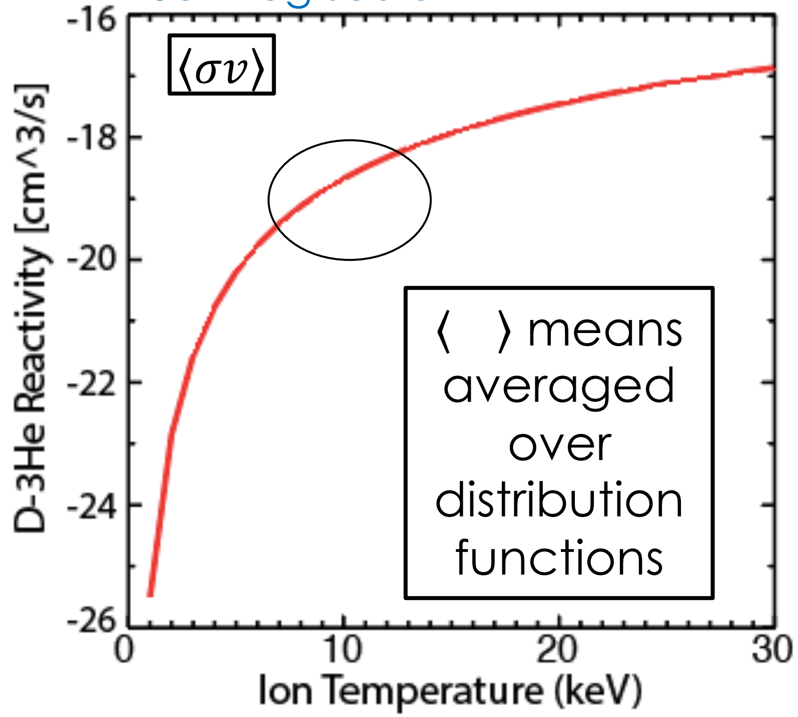
Relative reactant energies of ~100 keV are needed for a D-^{3}He experiment

Semilog scale

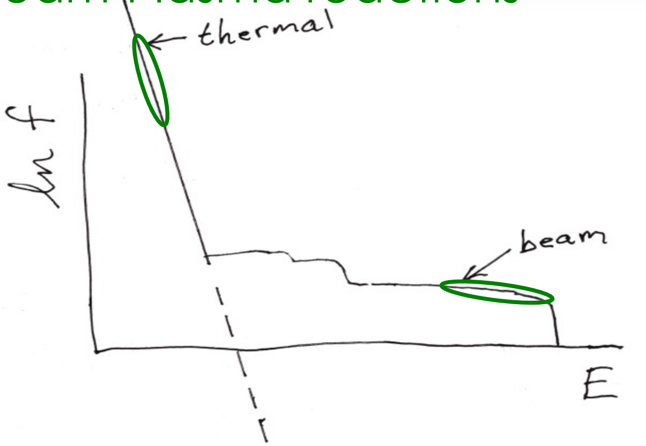


For adequate count rate, require either 100 keV fast ions or T_i > 10 keV

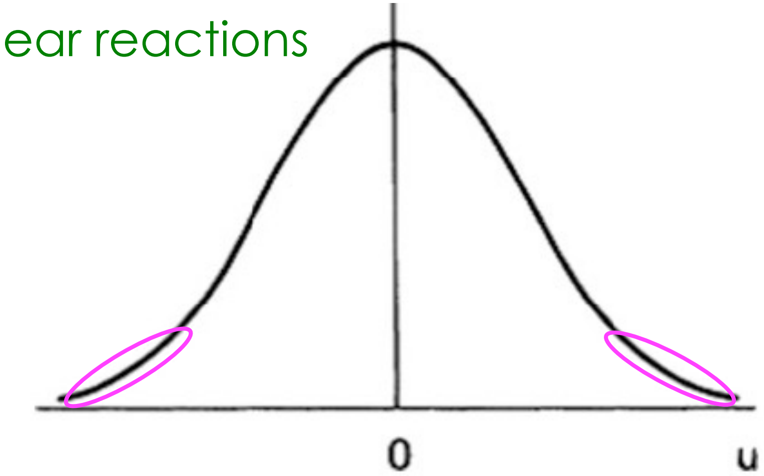




Beam-Plasma reactions



Thermonuclear reactions

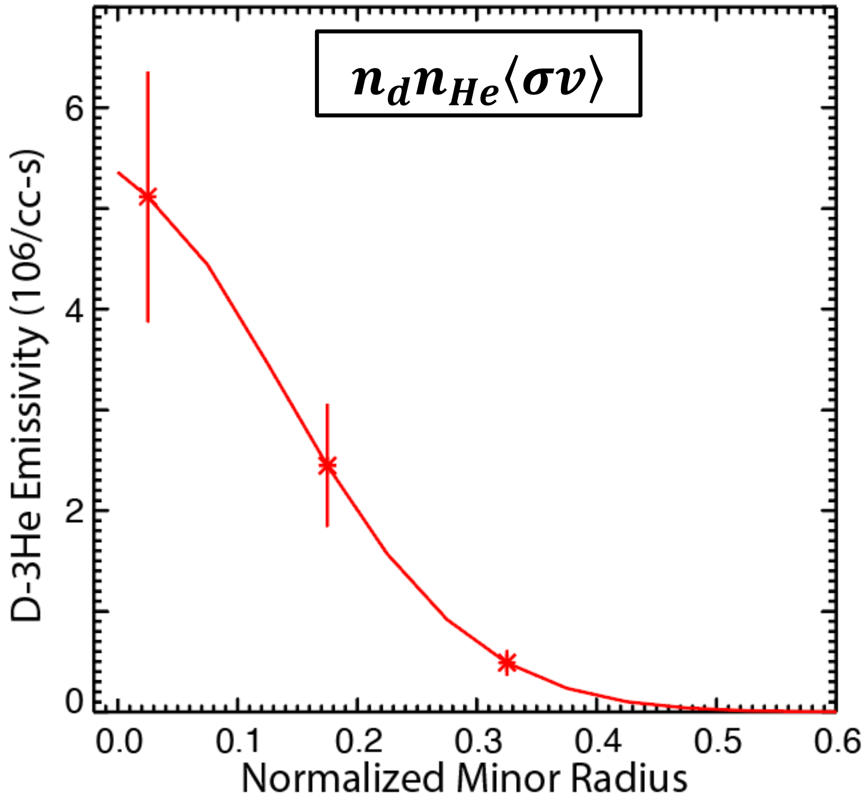


Must use relative measurements of the differential cross section to measure the polarization accurately*

D-^{3}He "emissivity" is $n_d n_{He} \langle \sigma v \rangle$
(the "reaction rate" is the integral of the emissivity over the volume)

- **Magnetic fusion plasmas are not very reproducible**
- **The deuterium density n_d is known to ~ 10% accuracy**
- **The helium density n_{He} is known to ~10% accuracy**
- **The ion temperature T_i is known to 5-10% accuracy → large uncertainty in $\langle \sigma v \rangle$**

→ Uncertainty in reaction rate > effect of polarization



*A.V. Garcia et al., Nucl. Fusion **63** (2023) 026030

Use relative measurements of the differential cross section to measure polarization

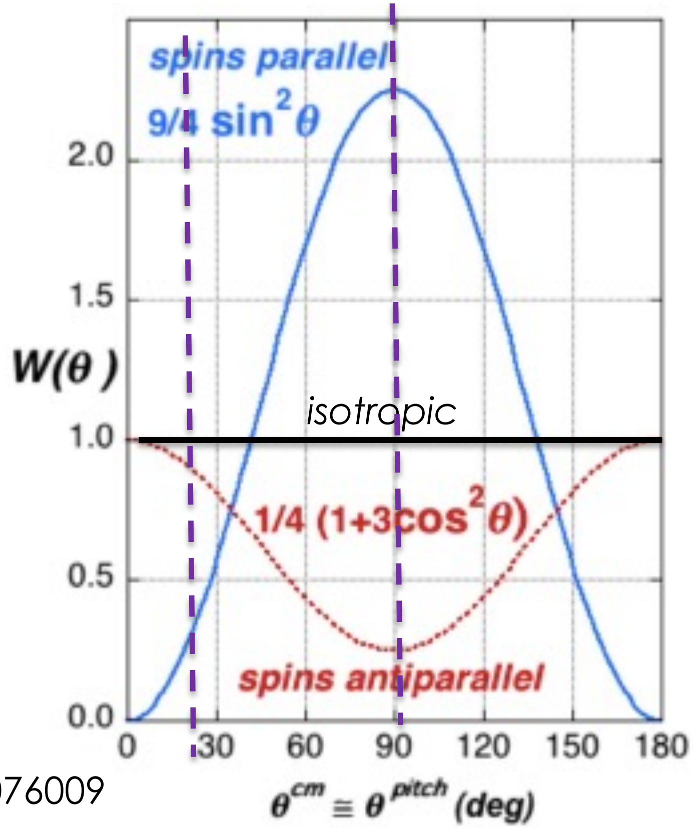
- **Differential cross section depends upon the tritium (or ^3He) polarization P_T & the vector and tensor D polarizations, P_D^V and P_D^T**

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi}\left\{1 - \frac{1}{2}P_D^V P_T + \frac{1}{2}\left[3P_D^V P_T \sin^2\theta + \frac{1}{2}P_D^T\left(1 - 3\cos^2\theta\right)\right]\right\}$$

θ: angle of emitted fusion product relative to $\vec{B}$

$$P_T = t_+ - t_-$$
$$P_D^V = d_+ - d_-$$
$$P_D^T = d_+ + d_- - 2d_0 = 1 - 3d_0$$

- **50% increase in σ if <u>both</u> maximally polarized ($P_T = P_D^v = 1$)**
- **No change in <u>total</u> cross section if only one is polarized**
- **[If only one polarized] must be P_D^T**



The <u>relative</u> change in emitted perp/parallel fusion-product signal is sensitive to polarization

Persistence of polarized signal → lifetime measurement

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Outline

1. Fusion: Use D-^{3}He differential cross section to test 50% enhancement in D-T cross section
2. Spin Polarized Fuel
3. Depolarization Mechanisms
4. Possible experiments

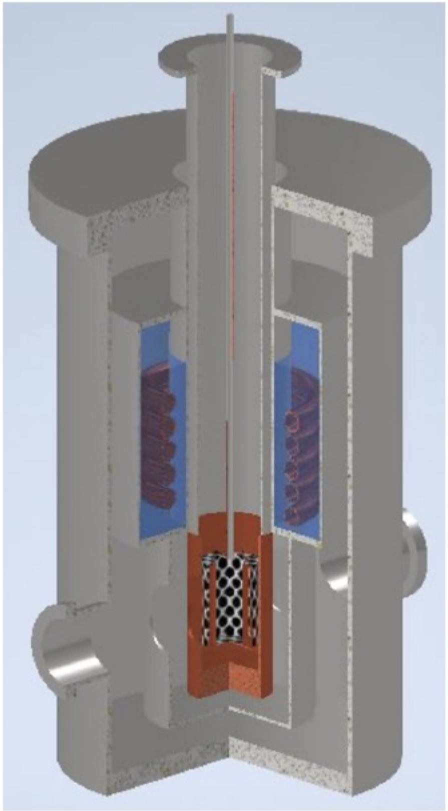
Deliver deuterium as a solid ^{7}Li-D pellet*

Use dynamic nuclear polarization to transfer spin polarization from electrons to nuclei to align the D spins.

- **Electrons are aligned in a strong B field at low temperature**
- **Microwaves drive a hyperfine transition that transfers spins to D nuclei.**
- **Use lithium to avoid high Z contamination of the plasma**
- **Use ^{7}Li to avoid background fusion reactions**
- **Spin transfer occurs on multi-hour timescale**
- **Need cryogenic (<4K) pellet gas gun to interface with polarizer**

Target: $P_D^V \approx 70\%$ & $P_D^T \approx 41\%$
~ 10^{20} D nuclei

Cryostat for e-beam bombardment of LiD pellets



Xiangdong Wei, Wed. 11:30

Jefferson Lab

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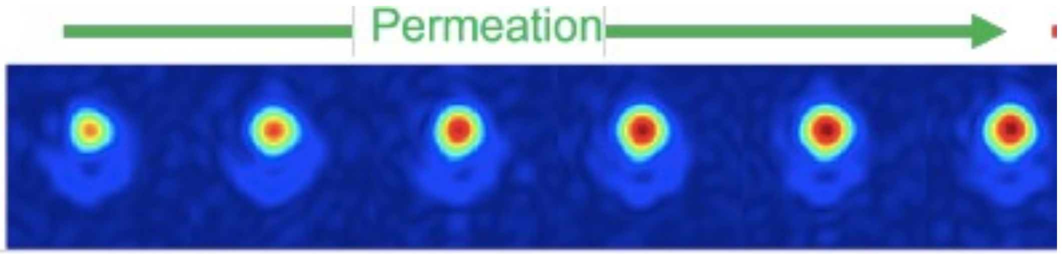
Deliver ^3He as a shell pellet*

- **Hybrid spin-exchange optical pumping polarizes the ^3He at high temperature**
- **Polarized fuel is transferred to a glow-discharge polymer (GDP) capsule**
- **Relaxation time is 3 days at 77K**

Photograph of amber GDP pellet

Target: $P^V_{3He} \approx 80\%$ @ 25 atm
~10^{19} ^3He nuclei

MRI images of ^3He permeating a GDP capsule



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UNIVERSITY of VIRGINIA

An intense polarized neutral beam is desirable

- **Sona-like transition**
- **In neutral frame, rapidly changing $\nabla\vec{B}$ is an RF wave at precession frequency that provides radio-wave pumping within the Zeeman splitting**
- **Hope to test at Tokamak Energy**

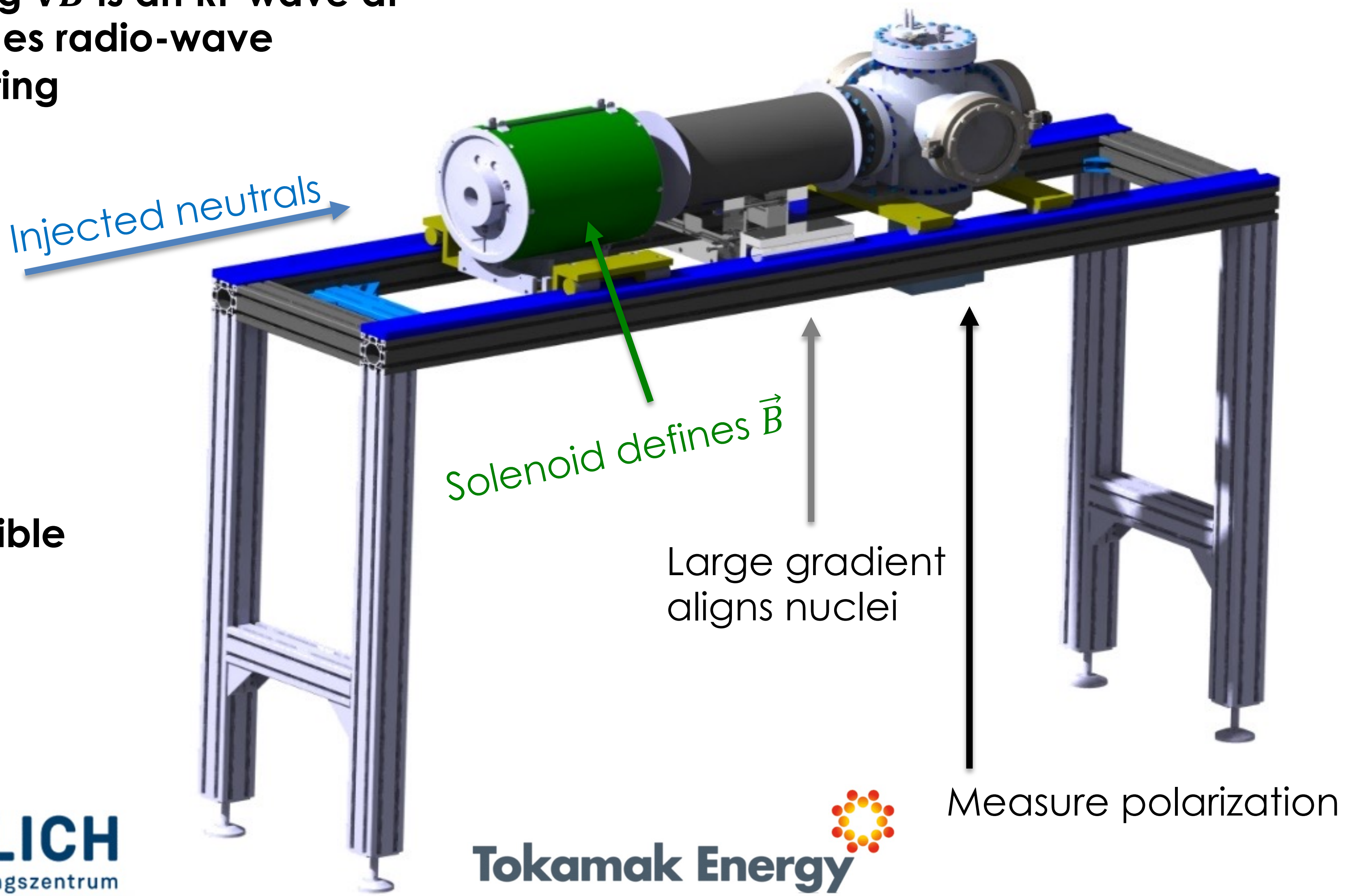
Target: *O(10^19)* polarized D or ^{3}He nuclei per second

Polarized beams would:

- **simplify DIII-D experiments**
- **enable experiments on small flexible devices**

Faatz, Today 15:00
Kannis, Tuesday 9:00
Ciullo, Tuesday 12:00

<u>Schematic of test apparatus</u>



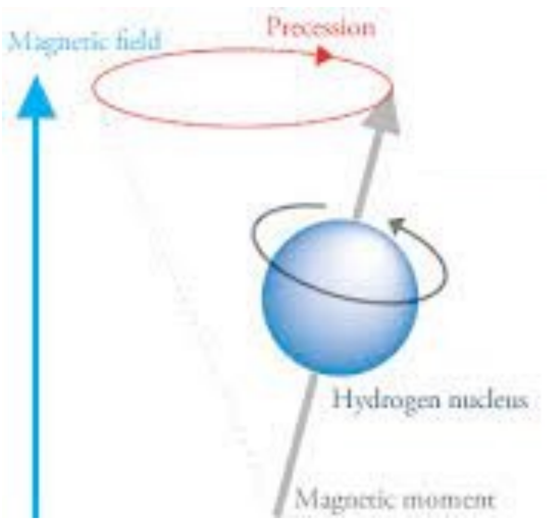
Outline

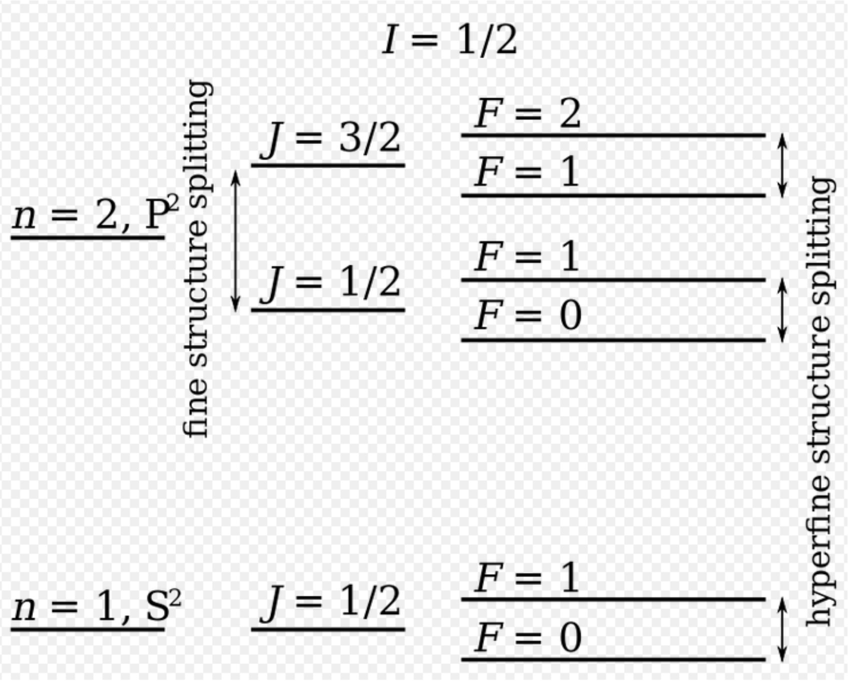
1. Fusion
2. Spin Polarized Fuel: Exists in quantities sufficient for a DIII-D experiment
3. **Depolarization Mechanisms**
4. **Possible experiments**

Two mechanisms can cause depolarization: resonances at the precession frequency & hyperfine interactions

- **Deuterium precession frequency is 0.43 $\boldsymbol{\omega_{ci}}$**
- **^{3}He precession frequency is 2.13 $\boldsymbol{\omega_{ci}}$**

$\boldsymbol{\omega_{ci}} = eB/m$ proton cyclotron frequency



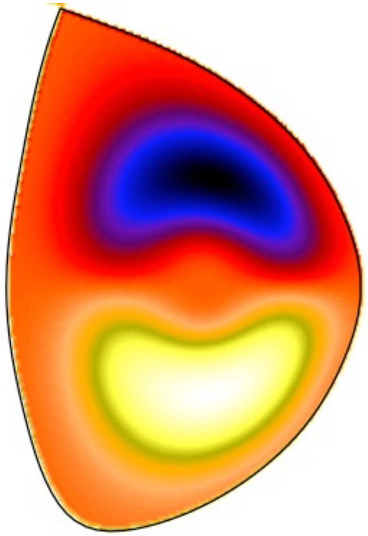


Hyperfine interactions with bound electrons also a depolarization mechanism.

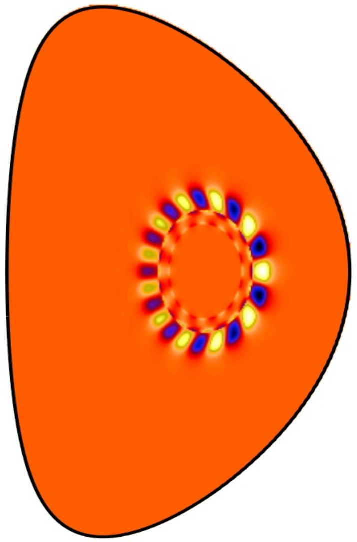
Nuclei in a hot plasma are fully ionized, so this mechanism is irrelevant

A fusion plasma is filled with waves—won't they depolarize the nuclei?

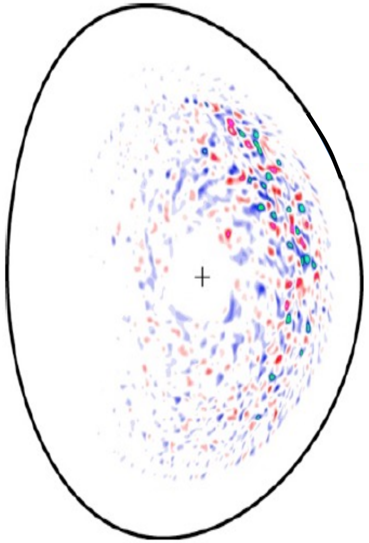
Decreasing Spatial Scale; increasing frequency →



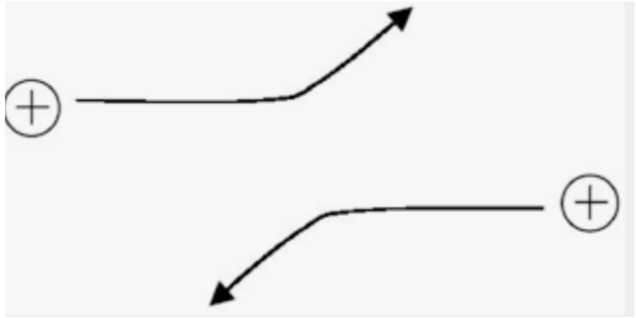
Fluid (MHD) instabilities



Fast-ion driven instabilities



Thermal-gradient driven instabilities



Coulomb collisions

In detailed calculations*, Kulsrud *et al* argue that depolarization lifetimes are long but are they right?

*R.M. Kulsrud et al., Nucl. Fusion **26** (1986) 1443.

Magnetic moment μ conservation is a cornerstone of plasma theory

The adiabatic invariant $\mu = W_\perp / B$ is conserved as long as:

- $\omega \ll \omega_{ci}$
- $r_L \nabla B / B \ll 1$ $\quad r_L = v_\perp / \omega_{ci}$ gyroradius

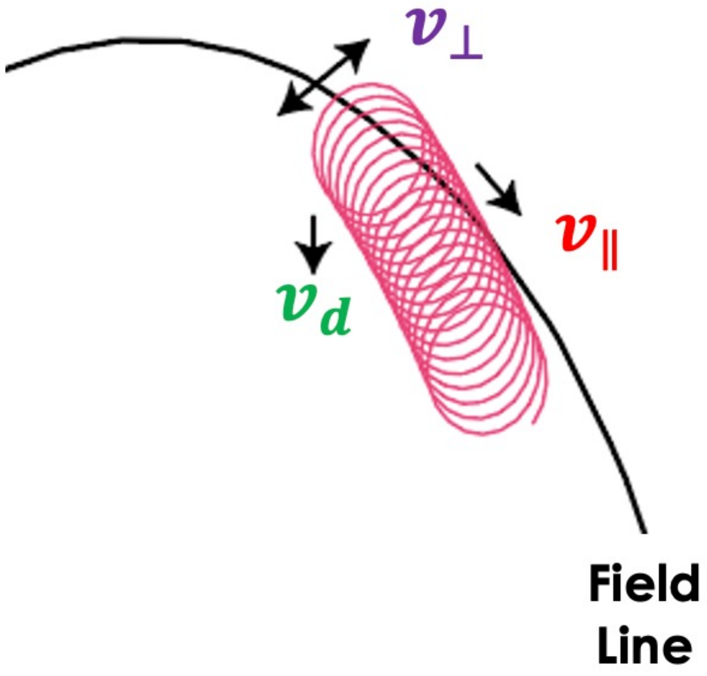
A very successful plasma theory, "gyrokinetics," assumes μ conservation

The particle orbit and polarization (Bloch) equations are nearly identical:

$$\frac{d\mathbf{v}}{dt} = \omega_{ci}(\mathbf{v} \times \hat{b})$$

$$\frac{d\mathbf{P}}{dt} = g\omega_{ci}(\mathbf{P} \times \hat{b})$$

$\mathbf{v}$ particle velocity
$\mathbf{P}$ polarization vector
$\hat{b} = \mathbf{B}/B$ magnetic field unit vector
g gyromagnetic ratio



→ if μ is conserved, the polarization should be too!

Experiments can assess most depolarization mechanisms

- **Inhomogeneous static magnetic fields during injection** ✓
  - Immerse flight tube in a $O(0.1)$ T field to preserve polarization [1]
  - Gradients too long to cause depolarization [1]
- **Hyperfine interactions during ionization** ✓
  - Neutral ground state has no interaction
  - Few % loss for ^{3}He [1]
- **Binary Coulomb collisions** ✓
  - Spin-spin, spin-orbit and quadrupole moment interactions predicted negligible [2]
- **Electromagnetic waves** ✓
  - Most instabilities too low in frequency
  - Waves near ω_{ci} problematic
- **Wall interactions**
  - High depolarization rates at metal walls [3]

Limited by particle confinement time

[1] L. Baylor et al., Nucl. Fusion **63** (2023) 076009.
[2] R.M. Kulsrud et al., Nucl. Fusion **26** (1986) 1443.
[3] Greenside, Journal of Vacuum Science & Technology A 2, 619 (1984).

Outline

1. Fusion
2. Spin Polarized Fuel:
3. Depolarization Mechanisms can be tested in existing facilities
4. **Possible experiments**

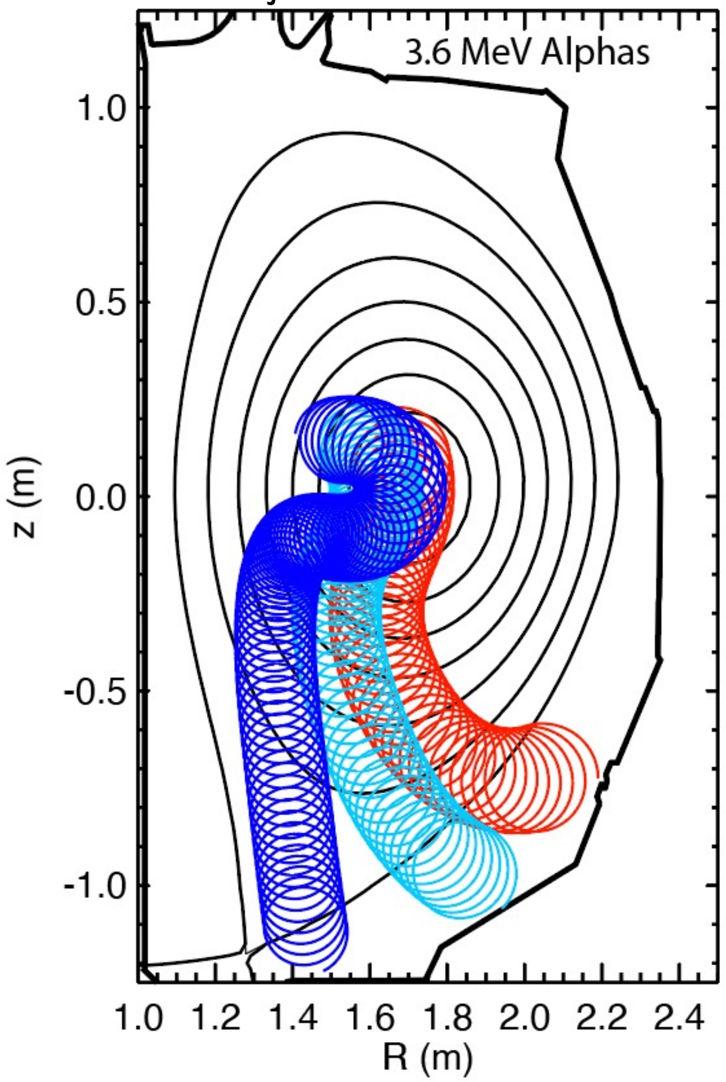
Use relative measurements of emitted 3.6 MeV alphas & 14.7 MeV protons to infer polarization*

- **Complication: $v_\parallel / v$ changes along escaping orbit**

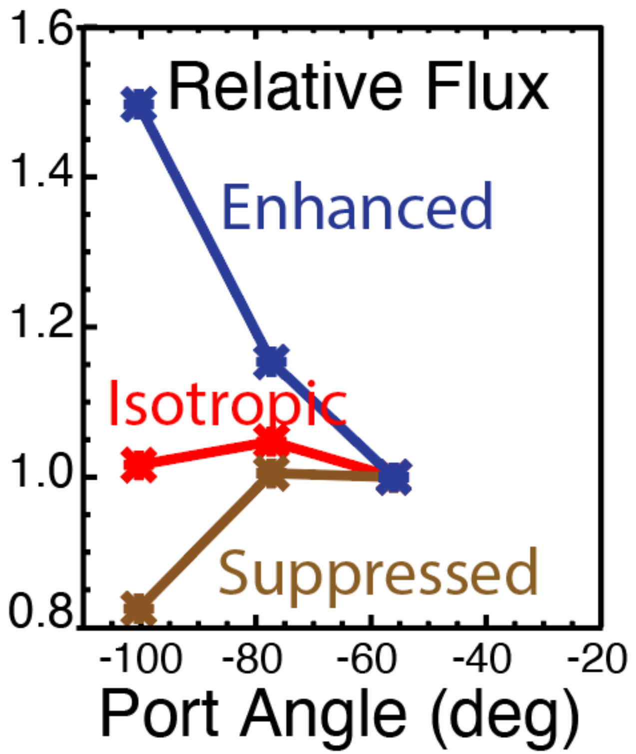
Adequate accuracy despite:

- **counting statistics**
- **realistic polarization fractions**
- **orbit uncertainties**
- **uncertainty in emissivity profile**

Projected orbits



Ideal thermonuclear case



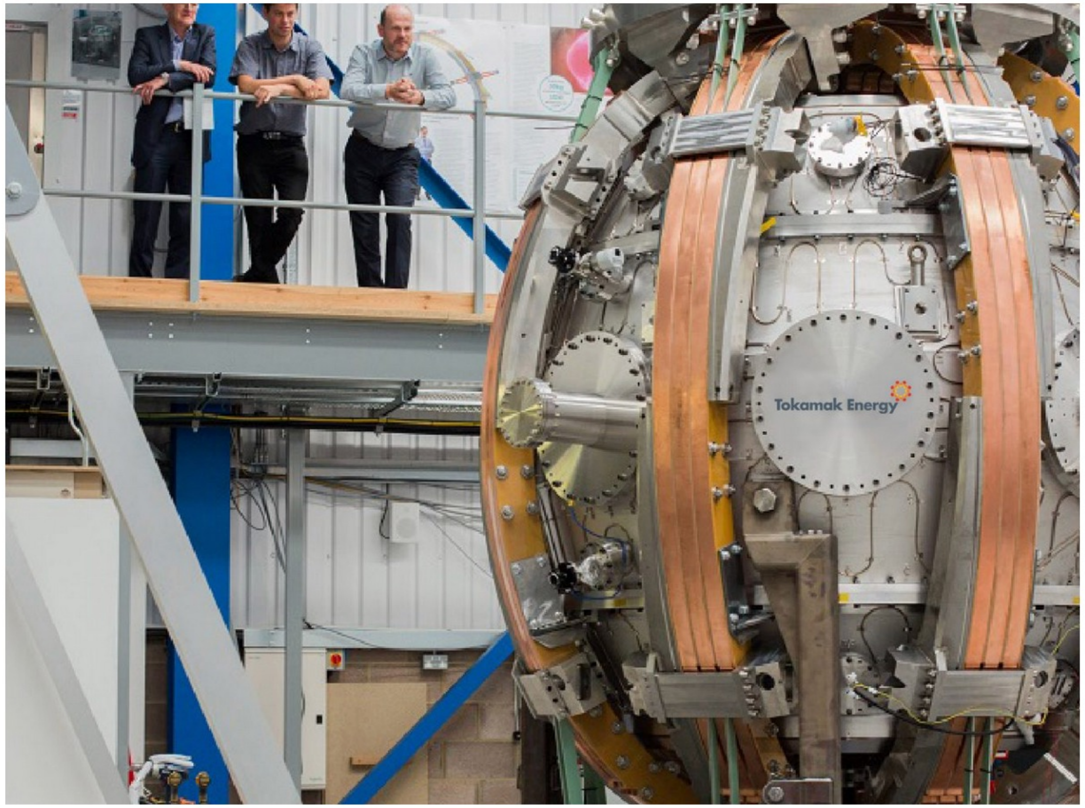
*A.V. Garcia et al., Nucl. Fusion **63** (2023) 026030

Planned experimental scenarios on DIII-D

Scenario	$d\sigma/d\Omega$	Operational challenge
1) T_i > 10 keV thermonuclear with H beams and LiD & ^{3}He pellets.	Large sensitivity	Special operating conditions; very hard plasma to make
2) Beam-plasma with unpolarized ^{3}He neutral beam and LiD pellets.	Weaker sensitivity	Special operating condition; adequate count rate easy
3) Beam-plasma with unpolarized D neutral beam and LiD pellets.	D-D Sensitivity unknown	D beam injection routine; adequate count rate easy
4) Thermonuclear with LiD pellets.	D-D Sensitivity unknown	Easy operational regime; adequate count rate

With intense polarized beams and/or D-D differential cross sections experiments on many other facilities become feasible

Polarized D injection w/ polarized ^{3}He pellet in Tokamak Energy's ST40



Polarized D and ^{3}He injection into WHAM

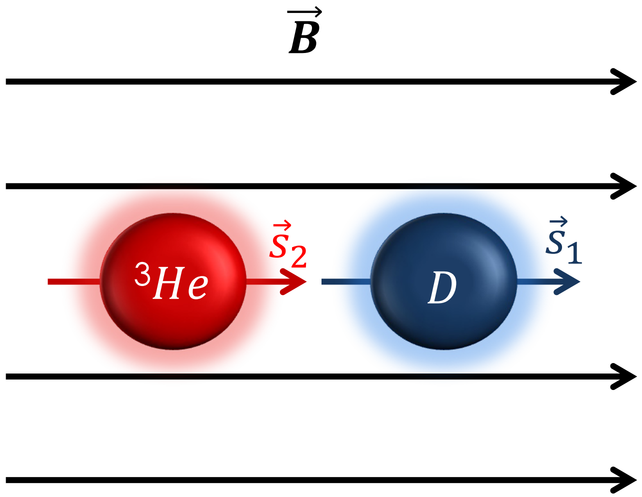
WHAM

Wisconsin HTS Axisymmetric Mirror

D-D experiment on the Madison Symmetric Torus

Conclusions & Opportunities

1. **Fusion: Use D-^{3}He differential cross section to test 50% enhancement in D-T cross section**
2. **Spin Polarized Fuel: JLab and UVa are preparing LiD and ^{3}He pellets for injection into DIII-D**
3. **Depolarization Mechanisms can be tested in existing devices**
4. **DIII-D polarization lifetime measurements are anticipated in ~ 5 years**



Opportunities

- **Provide ~ 1 Amp polarized neutral beam**
- **Polarization dependence of D-D differential cross sections at "low" energy**

1) **"Polarized Fusion and Potential *in situ* Tests of Fuel Polarization Survival in a Tokamak Plasma,"** L. Baylor, A. Deur, N. Eidietis, W.W. Heidbrink, G.L. Jackson, J. Liu, M.M. Lowry, G.W. Miller, D. Pace, A.M. Sandorfi, S.P. Smith, S. Tafti, K. Wei, X. Wei and X. Zheng, Nucl. Fusion **63** (2023) 076009.

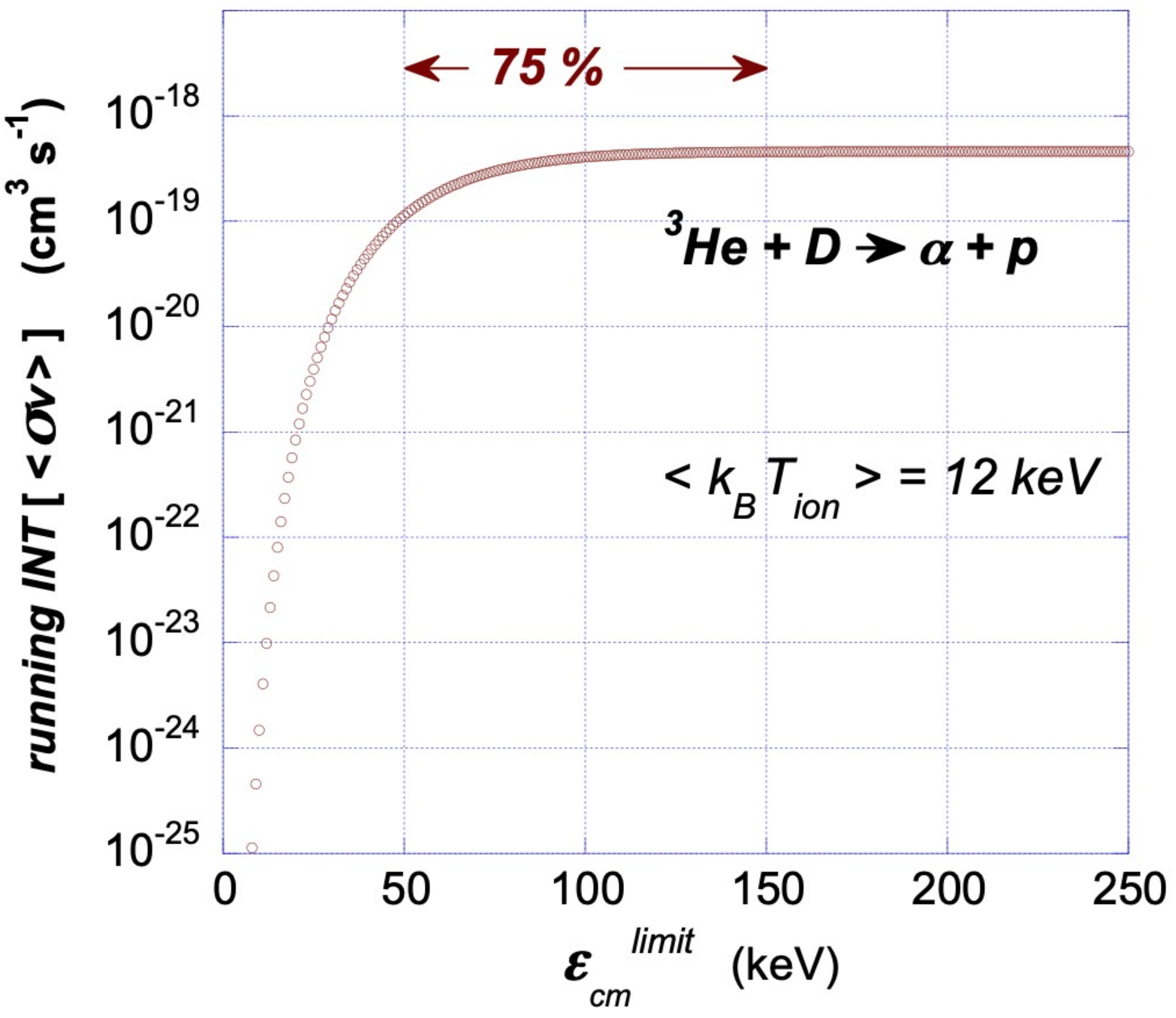
2) **"Conceptual design of DIII-D experiments to diagnose the lifetime of spin polarized fuel"** A.V. Garcia, W.W. Heidbrink and A.M. Sandorfi, Nucl. Fusion **63** (2023) 026030.

Backup

The fusion rate in a thermonuclear plasma is the cross section averaged over a Maxwell-Boltzmann velocity distribution:

$$\langle\sigma v\rangle = \frac{4c}{\sqrt{2\pi M_r}(k_B T)^{3/2}} \int e^{-\varepsilon/k_B T} \varepsilon \sigma(\varepsilon) d\varepsilon.$$

- J.N. Bahcall, *Astrophys. J.* **143**, 259 (1966)



- A.M. Sandorfi and A. D'Angelo, *Springer Proc. Phys.* **187**, 115 (2016)

With the mean plasma temperature ~ 12 keV,

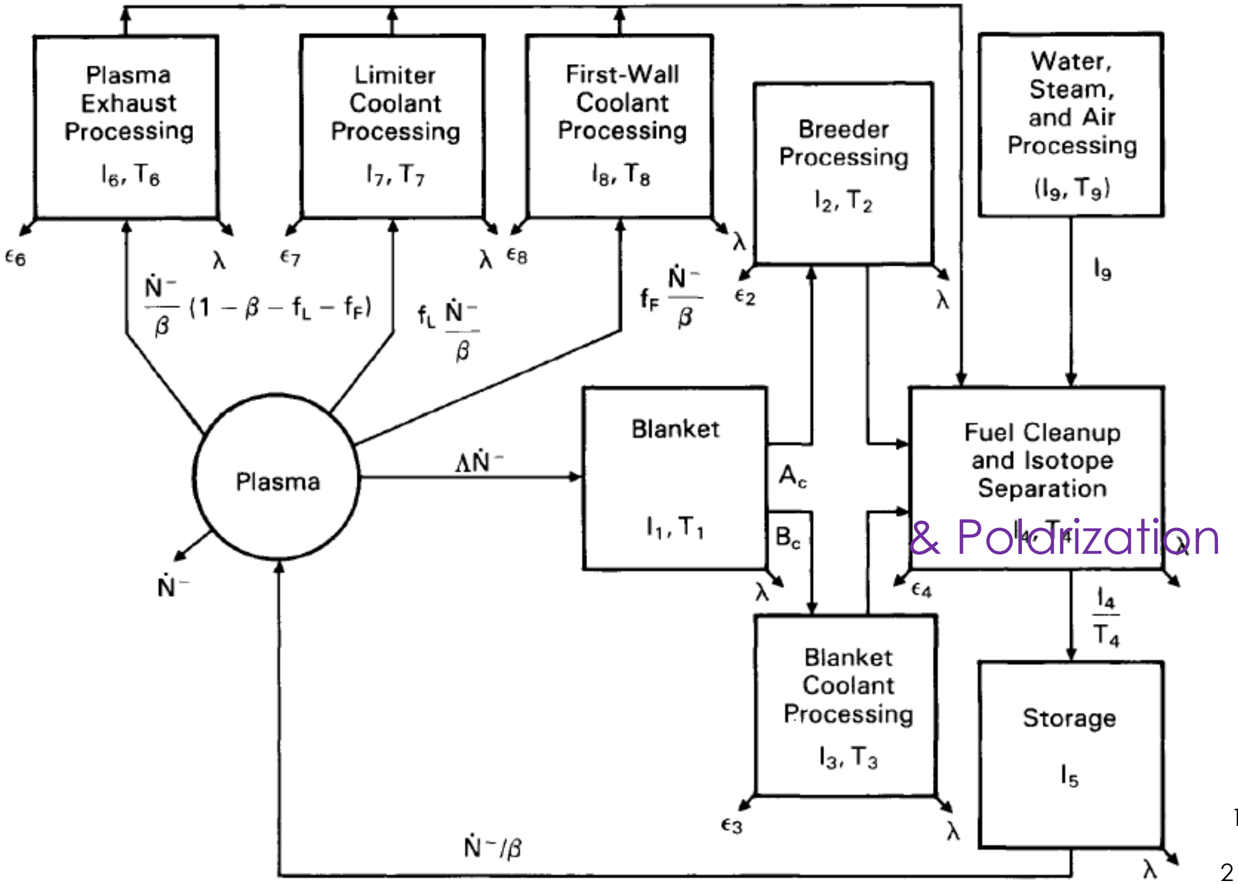
most fusion reactions come from the high energy tail

What about a reactor?

Q: (70% D) * (65% ^3He) only increases the cross section by 23%. Is it worth it?

A: High flux laser driven polarization techniques[1] should achieve 100% D and T polarization

Q: Is the added complexity of polarization practical?



[1] Kannis (2021) Chem. Phys. Lett.
[2] Abdou (1986) Fusion Technology.

A beam-target D-D experiment is attractive but …

- Use unpolarized D beam; tensor polarized D pellet
- Cross section is larger at low energy than for D-^{3}He
- 3.0 MeV protons have nearly the same orbits as 3.6 MeV alphas
- Can also measure energy shift in silicon detectors
- No theoretical expression available for the effect of polarization!

- However, there probably is some effect--the unpolarized cross section is anisotropic
- If we measure an effect of polarization, we can measure how long it persists!

ANDREYANOV et al.

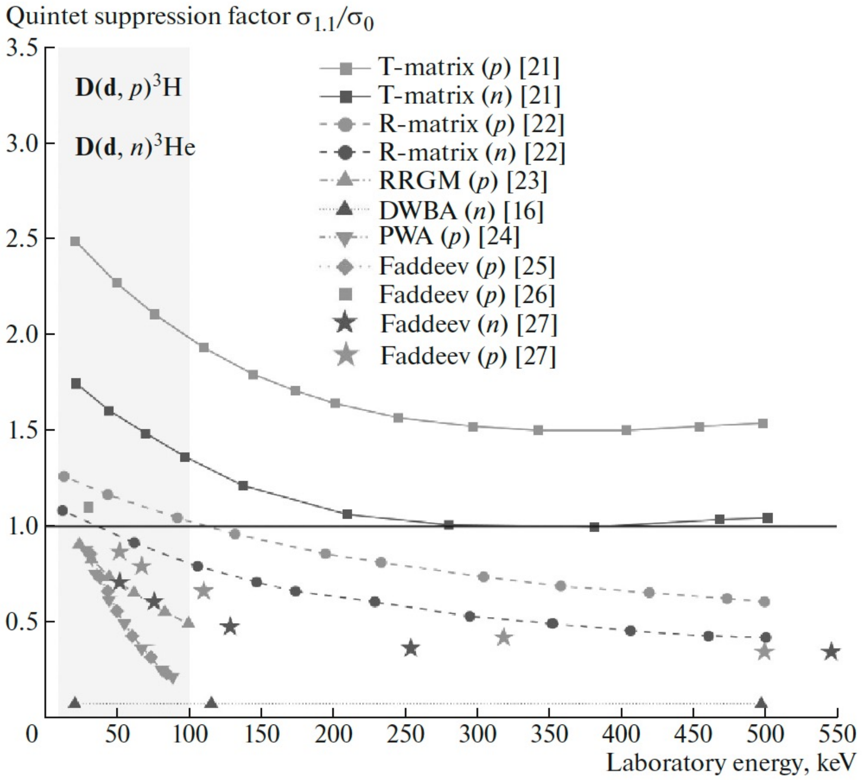
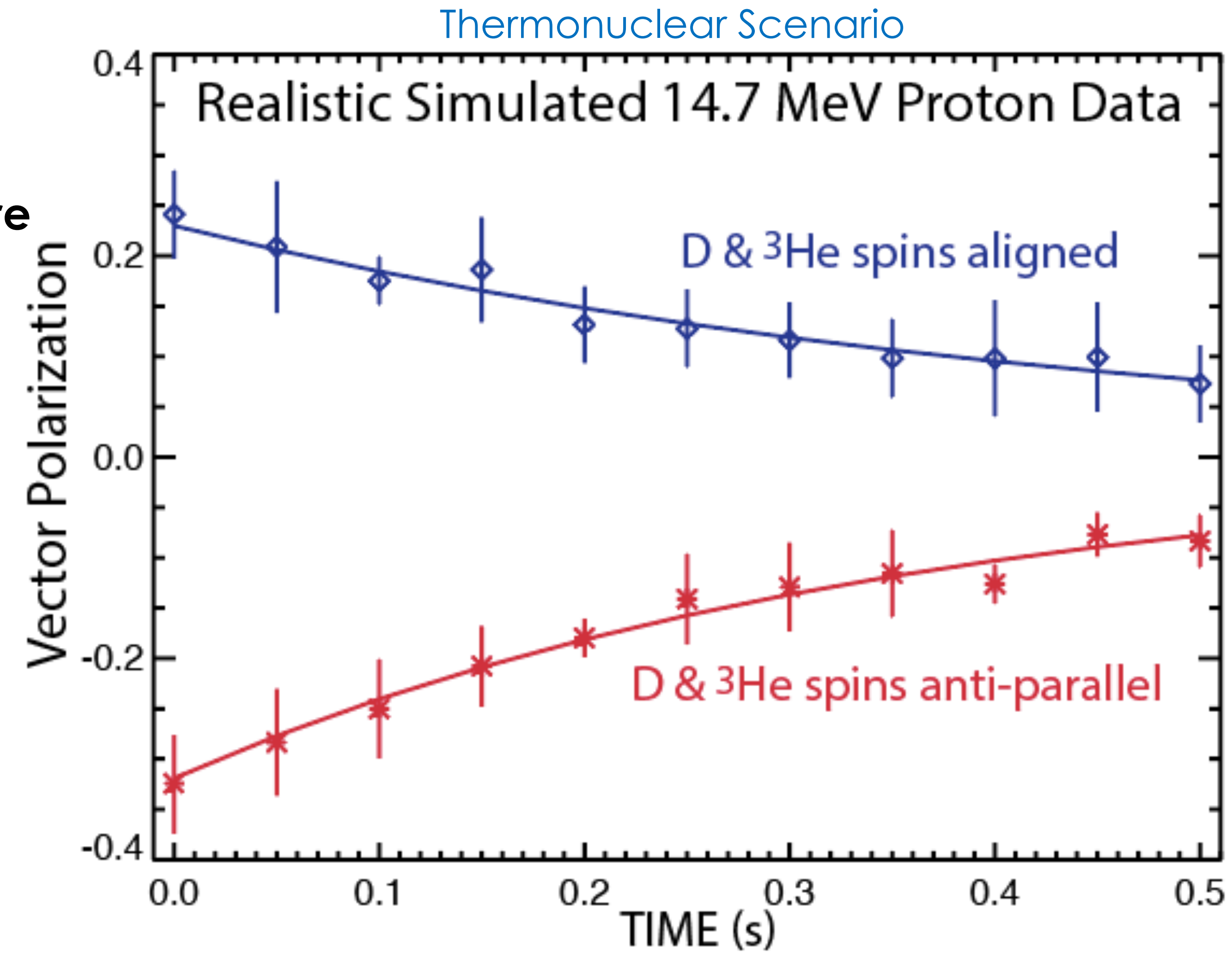


Fig. 2. Calculation of the quintet suppression factor in different theoretical models.

The polarization lifetime can be accurately determined*

- **Simulated data assume 0.40 s lifetime**
- **Inferred lifetimes are $\mathbf{0.45 \pm 0.04}\ s$ & $\mathbf{0.35 \pm 0.04}\ s$**



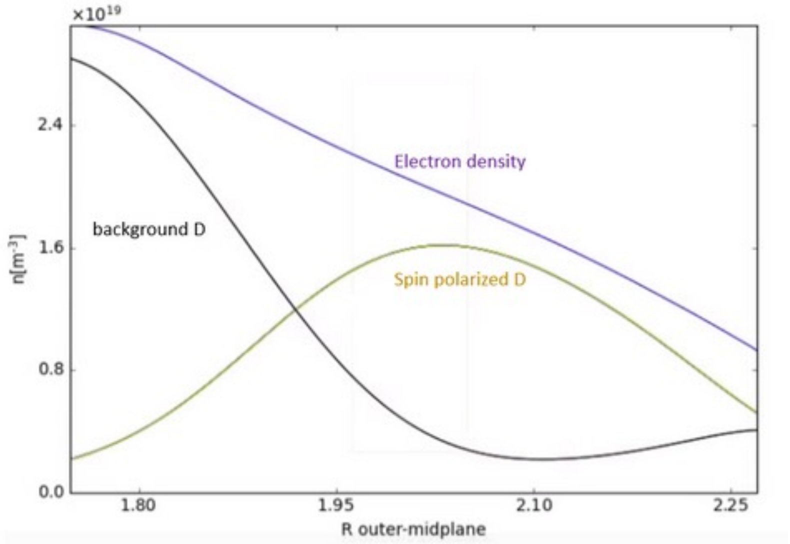
*Garcia (2022).

Complication #2: Pellets not deposited in core

- **Use shell pellet with ^{3}He payload**
- **^{3}He deposited around $\rho = 0.5$**

[1] Hollmann AIP Conference (2009).

- **Deuterium ice pellet mostly deposits at $\rho > 0.5$**

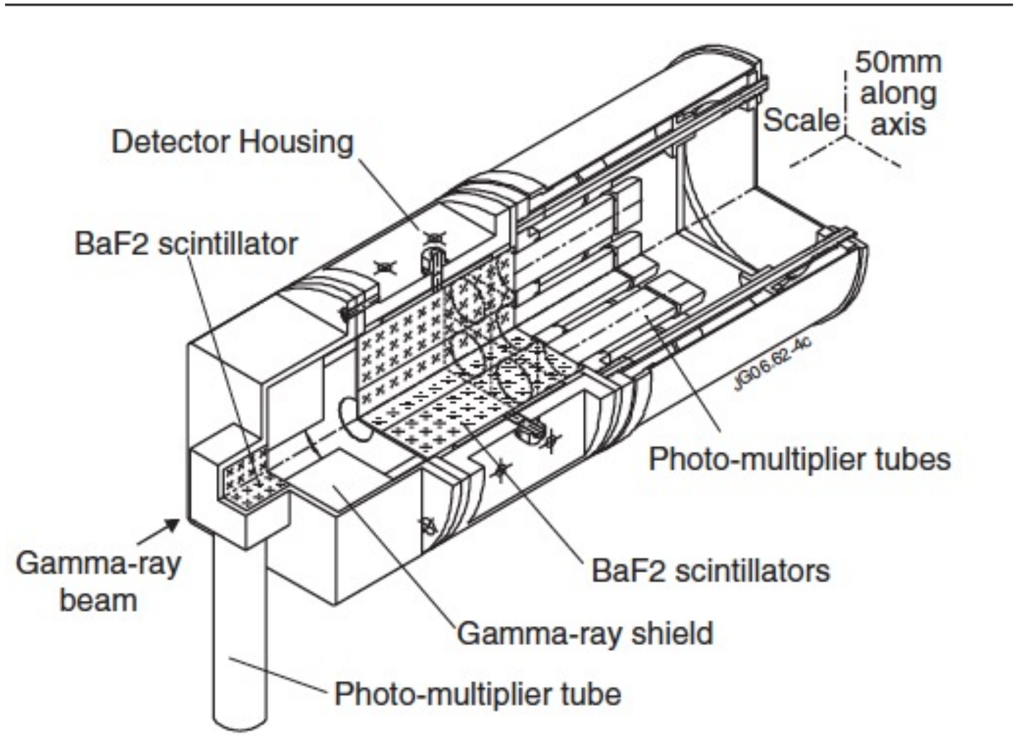


Izzo

Must rely on inward transport to take fuel to core

Use gamma-ray detector for an independent measurement of the total reaction rate

- **The D-^{3}He reaction produces gammas at 16.9 MeV and 15.4 MeV with a branching ratio of approximately 4.5 x 10^{-5}**
- **Different polarization dependence than main branch***
- **Wide solid angle detector needed for adequate counting rate**



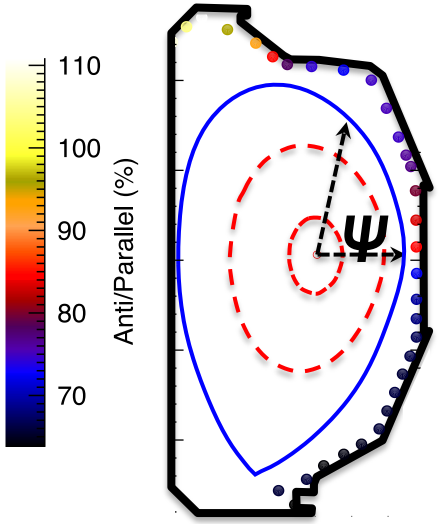
Kiptily, PPCF (2006)

*Garcia (2022)

Measure the pitch, energy & poloidal distribution to diagnose reaction anisotropy

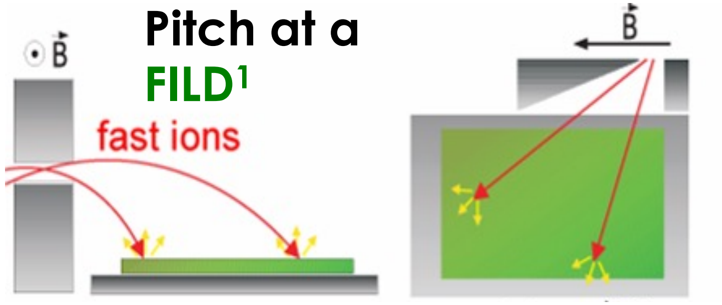
- **Relative changes in escaping CFP pitch, poloidal/axial position, and energy all sensitive to changes in $d\sigma/d\Omega$**

Pitch = $v_{\parallel}/v$

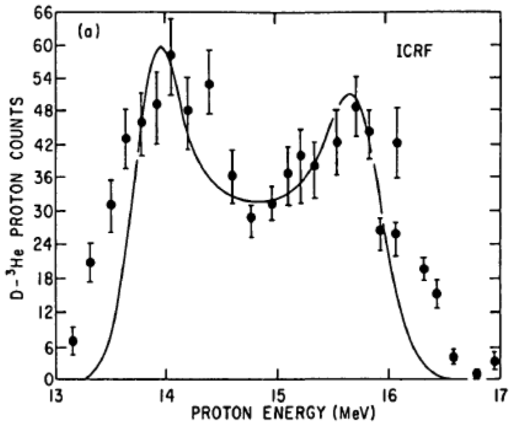


Multiple poloidal locations

Pitch at a FILD[1]



Energy at a silicon diode[2]



[1] Zweben, Nucl. Fusion (1989)

[2] Heidbrink, Nucl. Fusion (1984)

Inject pellets with spin polarized nuclei

			$^{3}\vec{He}$		$\vec{D}$			extraneous material			
carrier	pellet Ø (mm)	shell	# $^{3}\vec{He}$ (x10^{19})	P(^{3}He) (%)	# $\vec{D}$ (x10^{19})	$P_V(D)$ (%)	$P_T(D)$ (%)	# ^{4}He (x10^{19})	# H (x10^{19})	# C (x10^{19})	# ^{7}Li (x10^{19})
^{7}Li D	1.0	—			3.2	70	41				3.2
^{7}Li D	1.5	—			10.7	70	41				10.7
^{3}He	1.8	GDP	0.18	65					1.0	0.9	
^{3}He	3.0	GDP	0.85	65					2.8	2.4	

If using only one pellet: use D pellet and ^{3}He fast ions

Two pellets requires a hot thermonuclear plasma

1. Prepare polarized D pellet
2. Prepare polarized ^{3}He pellet (for thermonuclear experiment)
3. How long will the fuel stay polarized?
4. Preserve polarization during injection

[1]L. Baylor et al.

Direct detection of polarization (like in NMR) is attractive but seems very challenging

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Evaluation of possible nuclear magnetic resonance diagnostic techniques for tokamak experiments

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Potential applications of nuclear magnetic resonance (NMR) diagnostic techniques to tokamak experiments are evaluated. NMR frequencies for hydrogen isotopes and low-Z nuclei in such experiments are in the frequency range ≈20–200 MHz, so existing rf antennas could be used to rotate the spin polarization and to make the NMR measurements. Our tentative conclusion is that such measurements are possible if highly spin polarized H or ^{3}He gas sources (which exist) are used to fuel these plasmas. In addition, NMR measurements of the surface layers of the first wall (without plasma) may also be possible, e.g., to evaluate the inventory of tritium inside the vessel. [DOI: 10.1063/1.1530388]