Overview of Spin-Polarized-Fusion (SPF)

(ie. Spin in a Fusion Power Plant)

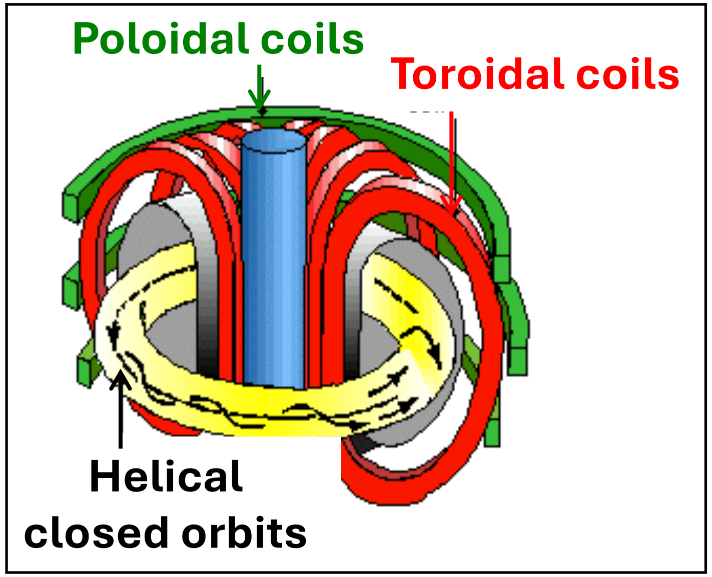
Andrew M. Sandorfi
University of Virginia
Mar 10, 2025

- Preliminaries – the Road to Fusion Power through Magnetic Confinement
- Potential Gains from Spin
- New potential for Large-Scale Fueling of a Power Reactor with Polarized Fuel
- The DIII-D Polarization Survival Demonstration Experiment
- Summary

Preliminaries - the road to fusion power through magnetic confinement

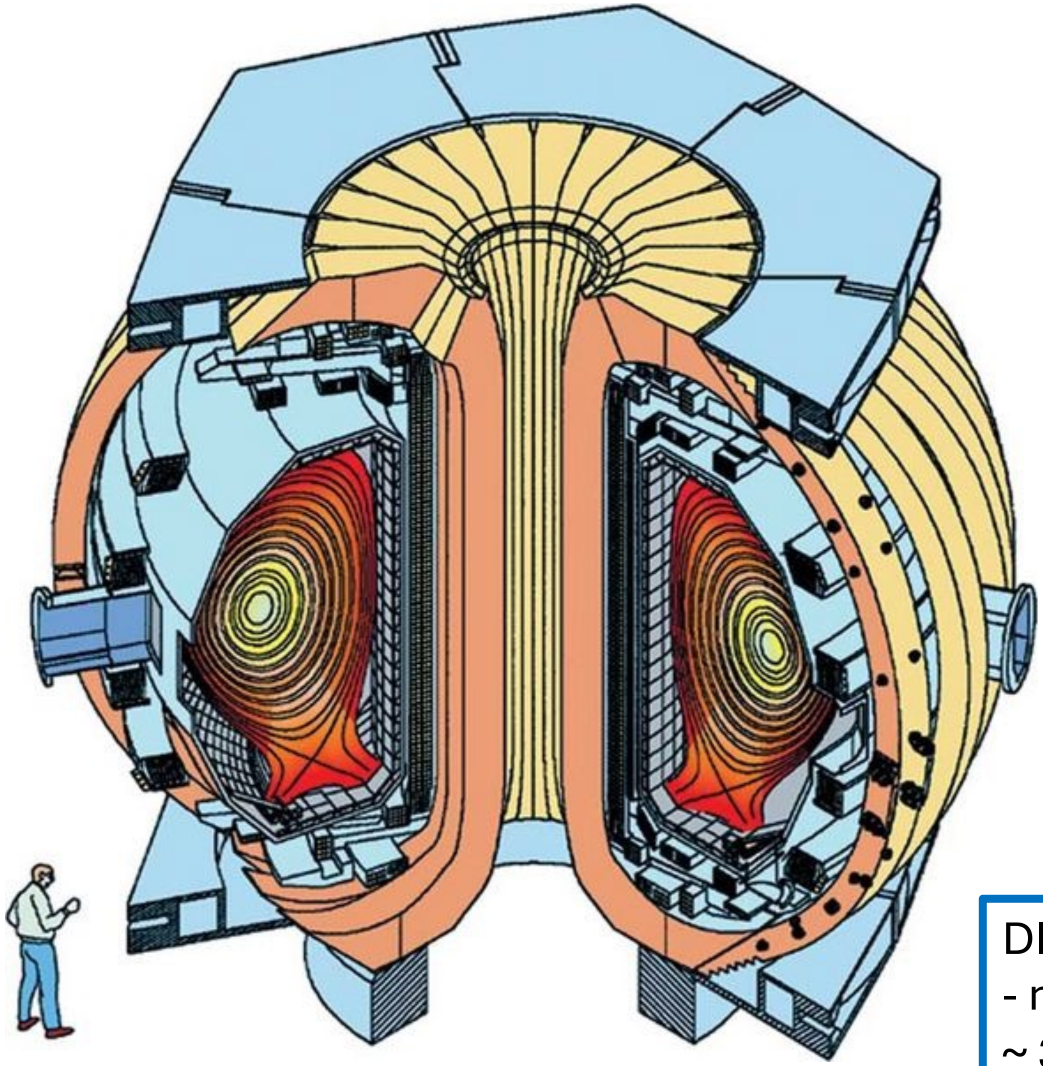
D + T → α + n ,   Q = 17.6 MeV

⇔ though the low-energy tail of a *J* =3/2 resonance in ^{5}He



- combination of Toroidal and Poloidal fields produces confined helical orbits

⇔ multiple chances for fusion



DIII-D tokamak (San Diego / USA)

DIII-D
- most diagnostics of ~ 30 research-scale tokamaks

the next MAJOR step

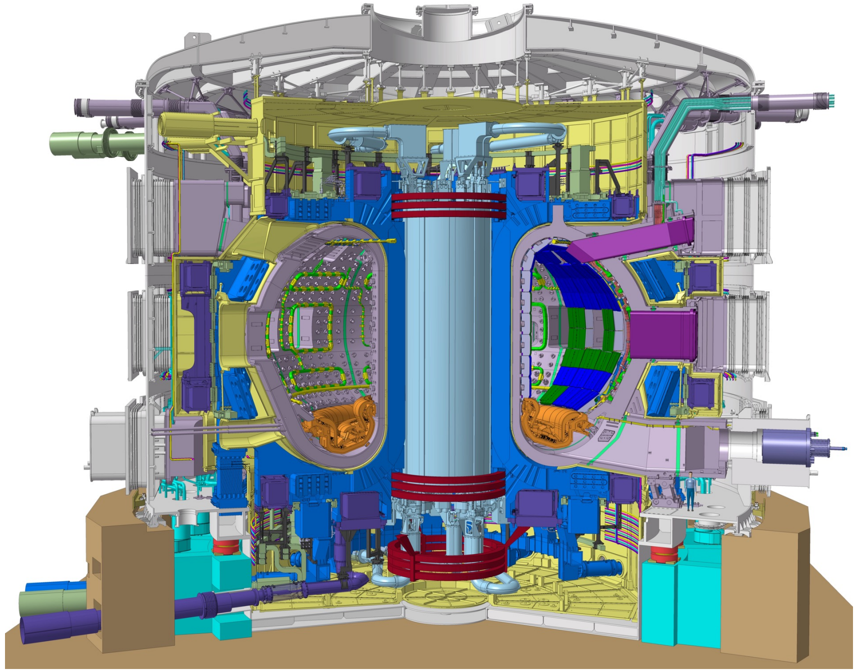
- **ITER**: 1st large-scale plasma science machine

  goals: burning plasma with Q = fusion-power / power-in > 10

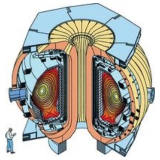
  – 1/2 GW in fusion power, from externally supplied *T*

  – under construction

ITER
(Cadarache / France)

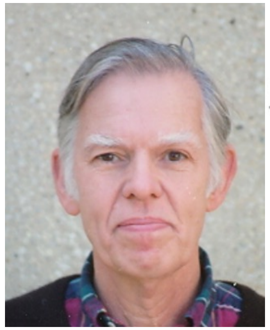


DIII-D
(San Diego / USA)



VOLUME 49, NUMBER 17 PHYSICAL REVIEW LETTERS 25 OCTOBER 1982

Potential gains from Spin



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)

- ***fusion fuels:* $D + T \Rightarrow \alpha + n$, (and $D + {}^3He \Rightarrow \alpha + p$)**
  - ↔ *dominated by J=3/2 resonance just above reaction threshold ⇨ s-waves dominate*
  - ↔ *D (s=1) and T (s=½) preferentially fuse when spins are aligned*

⇨ $$\sigma_{cm} = \sigma_0 \left\{ 1 + \tfrac{1}{2} \vec{P}_D^V \cdot \vec{P}_T \right\}$$

- *polarized fuels ⇔ up to **50%** enhancement in the cross section*
- ***polarization expected to survive in 10^8 K plasma for times longer than fuel burnup***

Running up the low-energy tail: alpha heating ⇔ non-linear enhancements

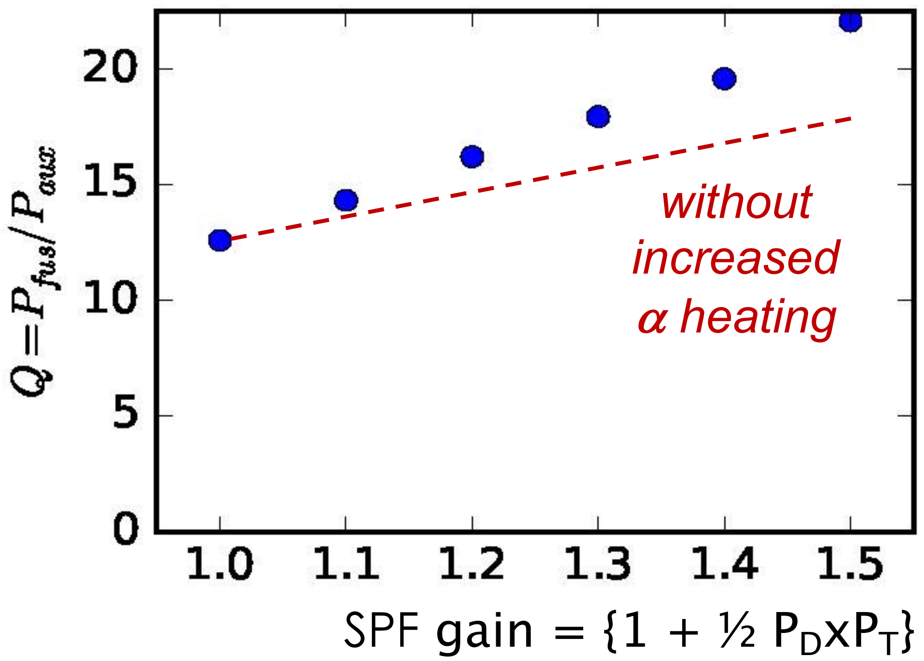
- polarization increases the reaction cross section

  ⇔ increases alpha production, which is mostly confined

  ⇔ alpha collisions heat the plasma ⇔ higher temperature runs σ further up the resonance

- ITER Power simulations with polarized fuel: [Baylor *et al.*, Nucl. Fusion **63,** (2023) 076009]

  ⇔ net 75% gain in power and $Q = P(fusion)/P(in)$



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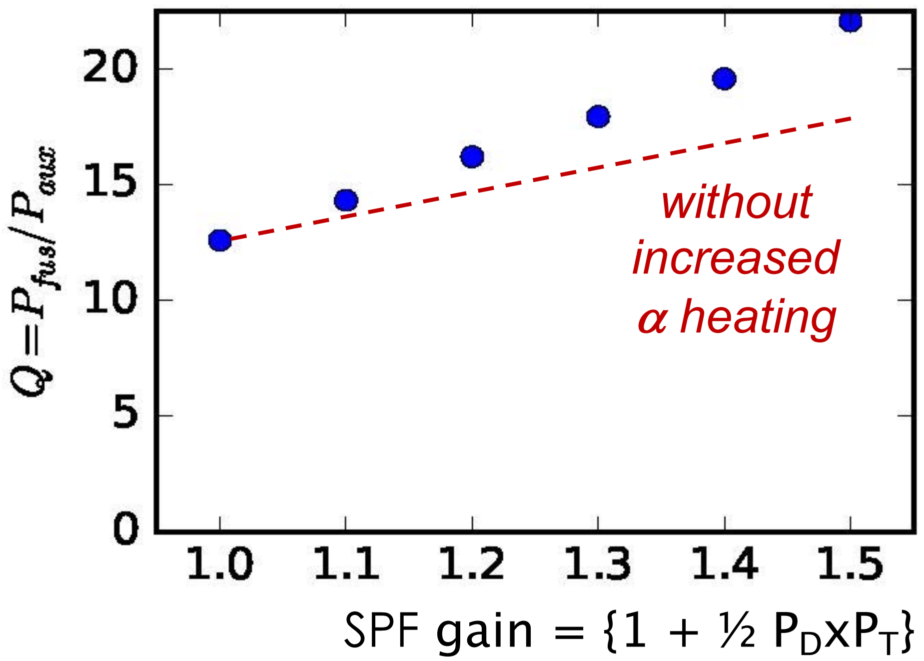

Long term – Fusion Power reactors:

- establish a controlled plasma in a 500 MW reactor
- switch to polarized fuel:

  ⇔ get 900 MW <u>for the same plasma parameters</u>

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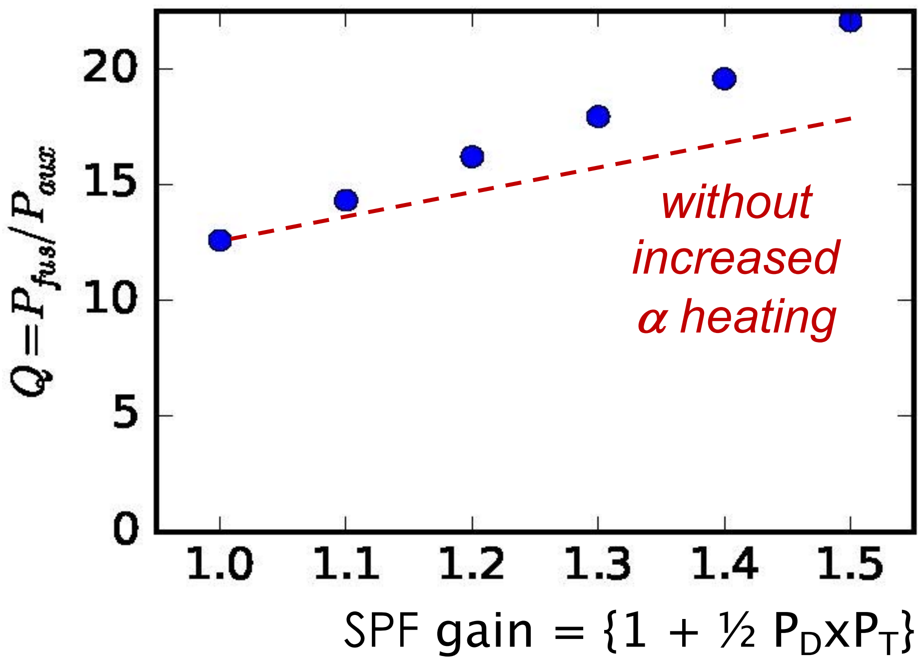
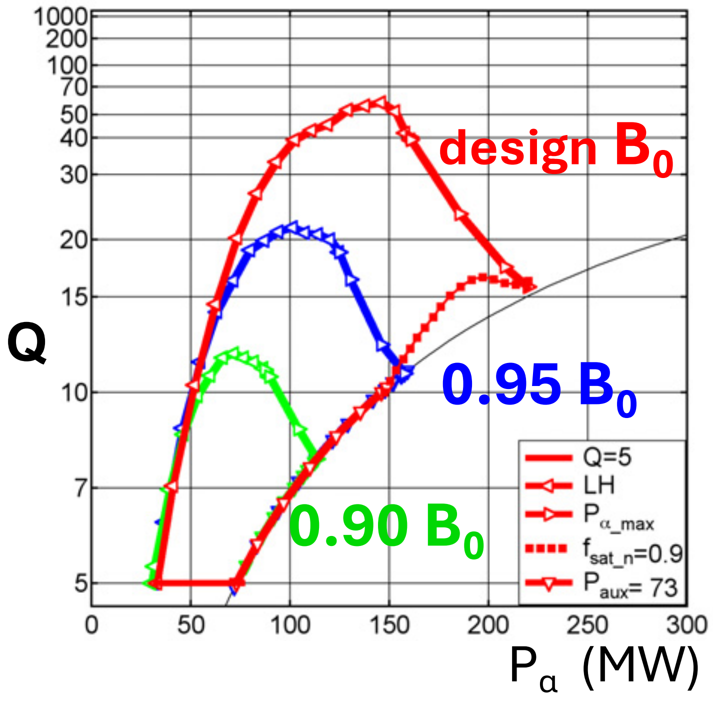


Prototype machines:

- ***eg. field degradation would severely limit ITER parameter space***
- ***polarization gain is independent of B***

⇔ SPF can compensate for field degradation

[Pacher et al, NF**48** (08)105003]



SPF implications for Tritium Breeding

- $\tau_{1/2}$ (Tritium) = 12 yr ⬄ difficult to buildup and maintain large stocks (global inventory ~ 20 kg)

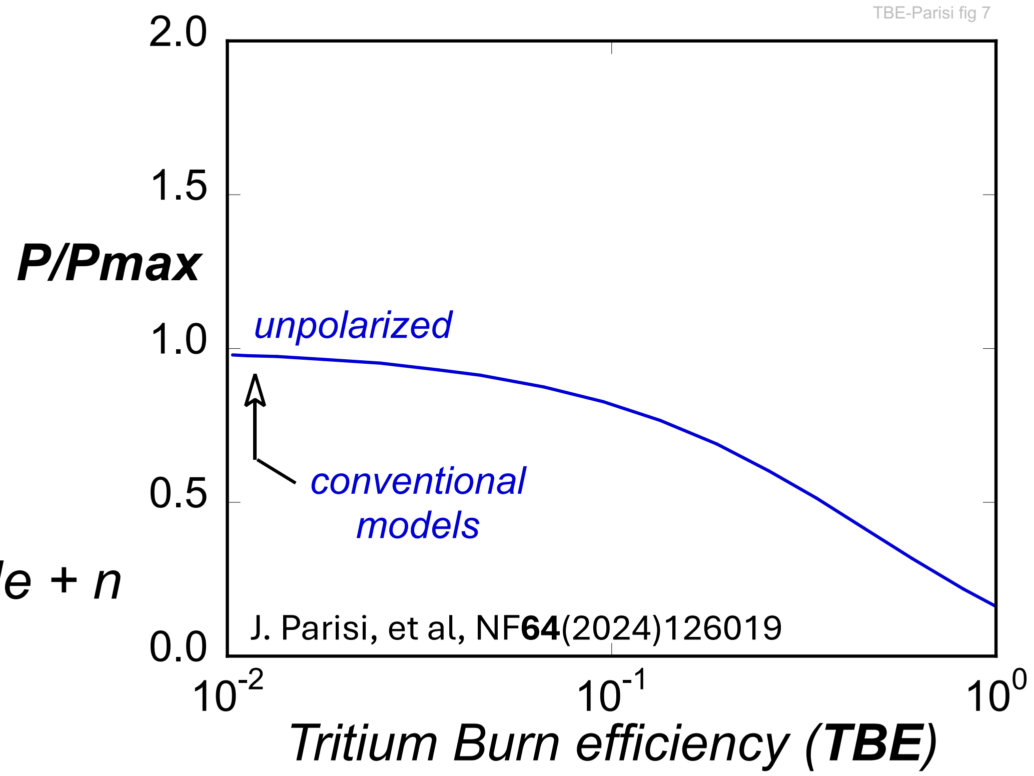
  ⬄ D+T fusion power plants are designed to be tritium self-sustaining, in steady-state OPS by breeding: $D+T \rightarrow {}^4He + n$ (*in* plasma) ⬄ $\boldsymbol{n + {}^6Li \rightarrow {}^4He + T}$ (*in blanket at outer wall*)

- ***BUT***, breeding takes time ⬄ initial tritium inventory required for startup
  - *eg.* 1– 3 kg for *ITER*, ~ 5–14 kg for *DEMO* , …

  ⬄ difficult to start/restart multiple machines

- *Tritium Burn Efficiency* (*TBE*):

  = *T burn-rate / T injection-rate*
  - higher *TBE* would require less *T inventory*
  - BUT, as *TBE* increases, ${}^4He$ *"ash"* from $D+T \rightarrow {}^4He + n$ accumulates in core and the **Power drops**



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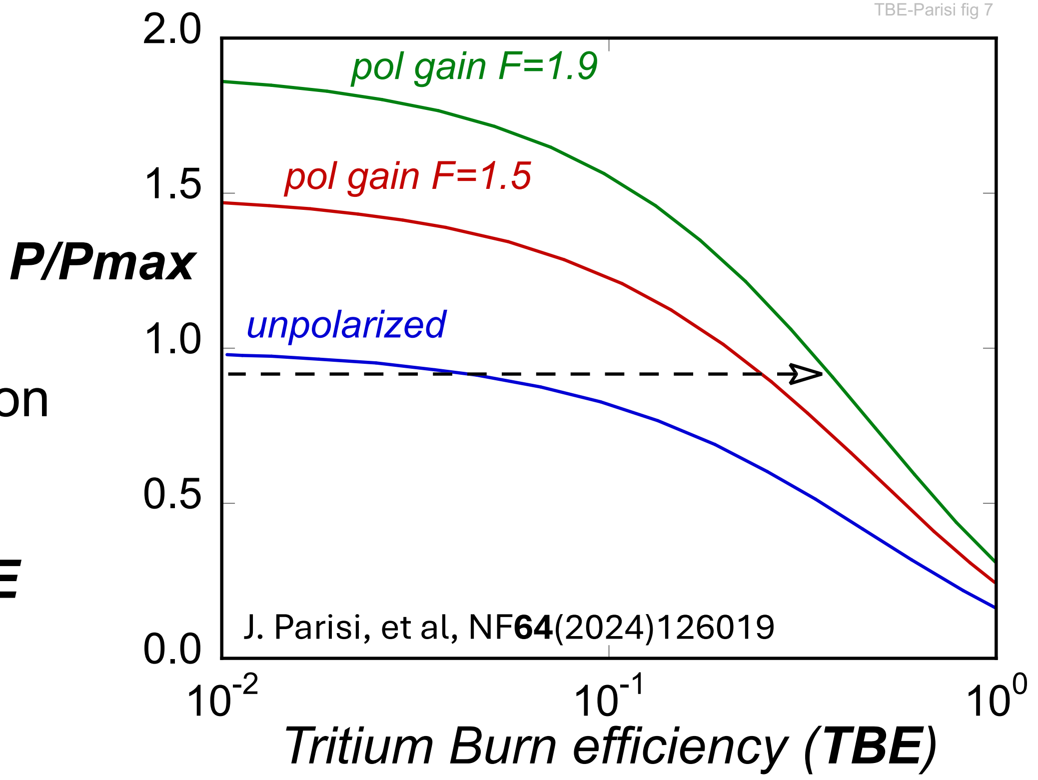
- *with* $\boldsymbol{\sigma}$ *boost from SPF :*
  - drop the T-fuel fraction & increase the D-fuel fraction
  - tolerate increased *^{4}He "ash"*

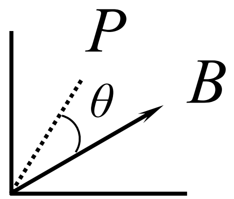
  ⬄ maintain ~ design **Power,** but with x 10 higher ***TBE***

  ⬄ **requires much smaller Tritium inventory** !



Anisotropic spin-dependence in polarized T+D ➔ α + n or ^{3}He+D ➔ α + p

- *polar (pitch) angles measured relative to the local magnetic field direction*



$$\frac{d\sigma}{d\Omega_{cm}} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{1 - \tfrac{1}{2} P_D^V P_{^3He} + \tfrac{1}{2}\left[3 P_D^V P_{^3He} \sin^2\theta + \tfrac{1}{2} P_D^T \left(1 - 3\cos^2\theta\right)\right]\right\}$$

$$\updownarrow$$

$(isotropic)$

- $P_D^V = n_D^{+1} - n_D^{-1} \in [-1,\ +1]$
- $P_D^T = n_D^{+1} + n_D^{-1} - 2n_D^0 \in [-2,\ +1]$
- $P_{^3He} = n_{He}^{+1/2} - n_{He}^{-1/2} \in [-1,\ +1]$

Assumptions:

- *angular-momentum* and *parity* conservation
- reactions dominated by single compound nuclear state (in ^{5}Li or ^{5}He)
  - interference terms contribute ~ 2-3 % at most

[Sandorfi, D'Angelo, Springer Proc Phys **187** (2016) 115]

[Baylor *et al*, NF **63** (2023) 076009]

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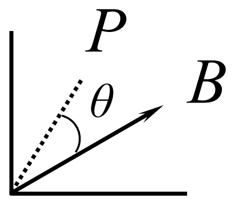

↕

(*isotropic*)

- $P_D^V = n_D^{+1} - n_D^{-1} \quad \in [-1,\ +1]$
- $P_D^T = n_D^{+1} + n_D^{-1} - 2n_D^{0} \quad \in [-2,\ +1]$
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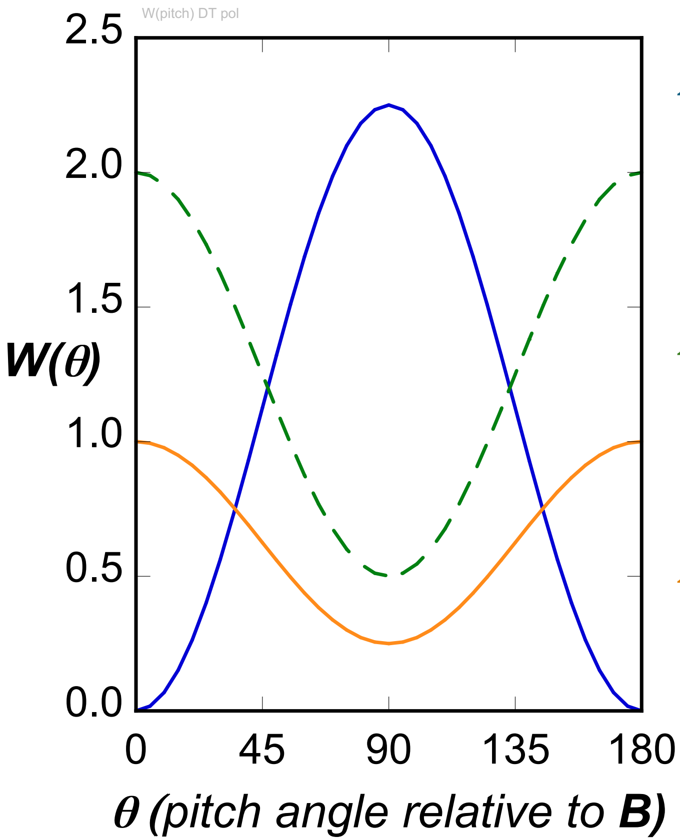


$P_D^V = +1;\ P_{T/^3He} = +1$

$\sigma = \sigma_0\{1 + 1/2\}$

$P_D^T = -2$

$\sigma = \sigma_0$

$P_D^V = +1;\ P_{T/^3He} = -1$

$\sigma = \sigma_0\{1 - 1/2\}$

[Sandorfi, D'Angelo, Springer Proc Phys **187** (2016) 115]

[Baylor *et al,* NF **63** (2023) 076009]

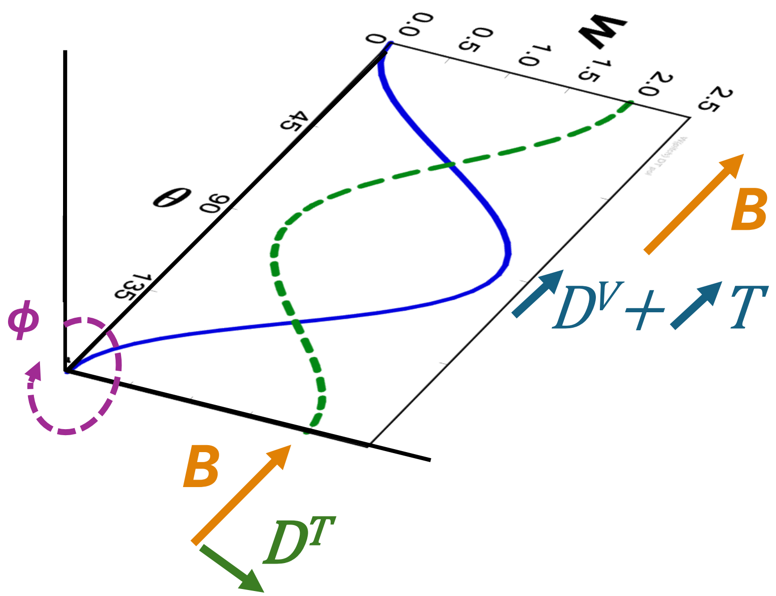
Implications of SPF anisotropy on magnet design

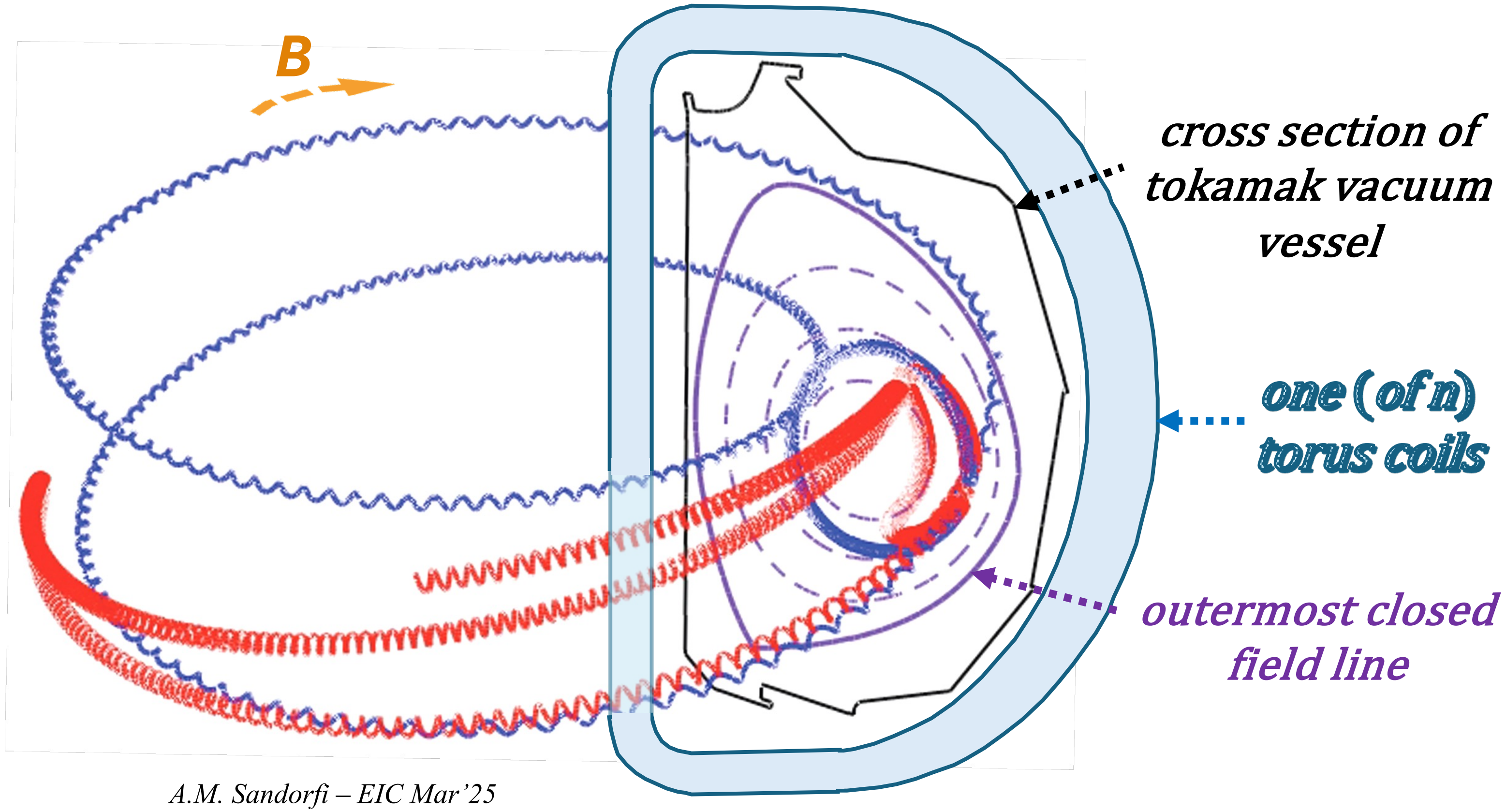
Neutron load on the toroidal magnet ⇔ reactor-design dependent

- analysis for spherical FPP-STAR tokamak: [K. Borowiec, et al., APRA-E SPF workshop, Dec 9-10'2024]
- ***Tensor-polarized D*** ⇔ *neutron production peaked along the local field*

⇔ fast-n (> 100 keV) flux on inboard toroidal coil: 31% lower than with unpolarized fuel

⇔ *projected to increase lifetime of a STAR-magnet (most expensive component) by* ***~ 45%*** !





Potential for large-scale fueling of a power reactor with fully polarized fuel

- **Conventional polarized atomic-beam sources**
  - produces a *stream* of polarized particles by magnetically selecting *(ie. Stern-Gerlach)* the spin alignment of interest. Limited by multiple scattering to ~ 10^{17} s^{-1} (record @ RHIC)

- **New high-flux laser-driven molecular sources** (⇔ *Peter Rakitzis et al.*)
  - polarize molecules by laser excitation into rotational-vibration (*rovibrational*) states
  - Hyperfine interaction (HFI) splits molecular m_J levels and moves polarization to the nuclei

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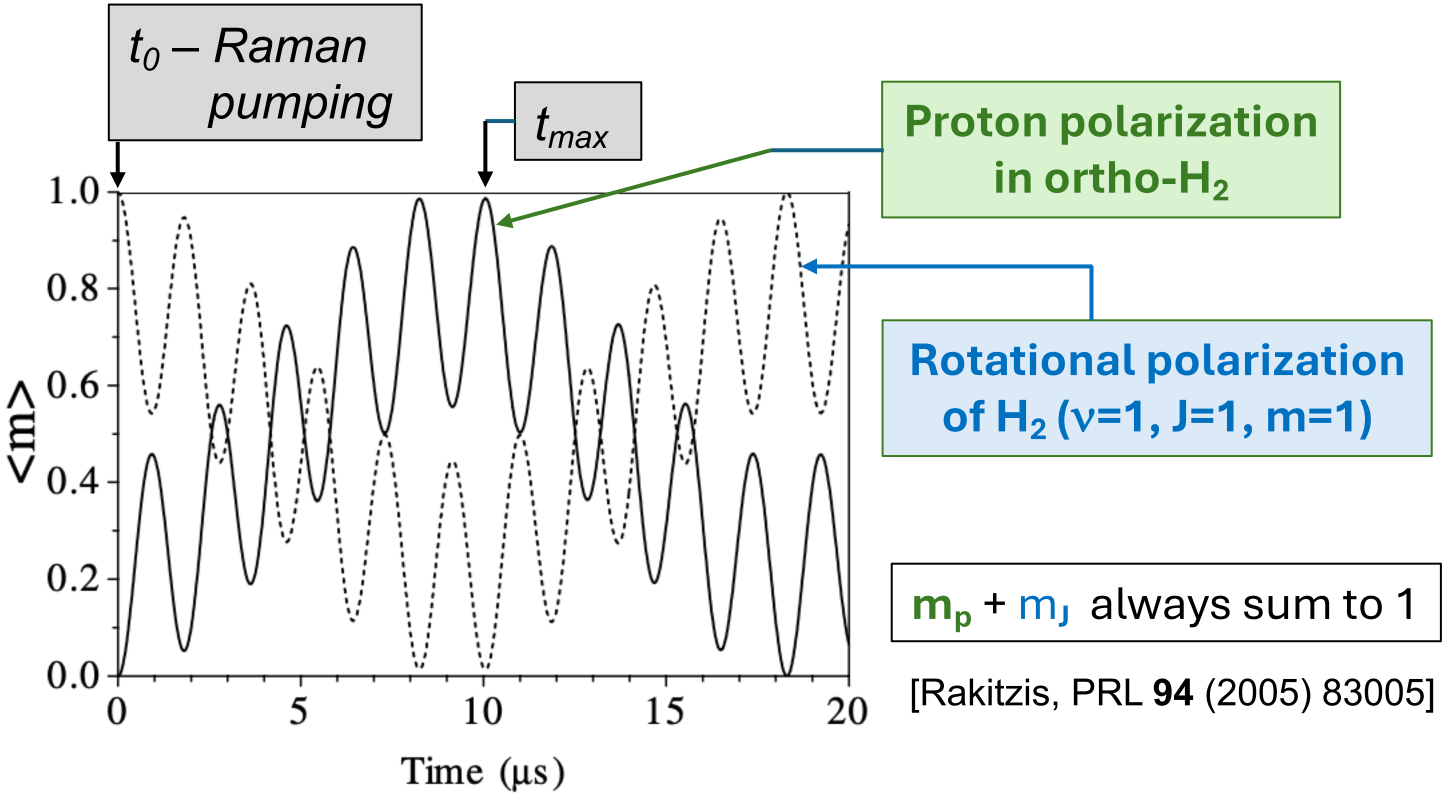


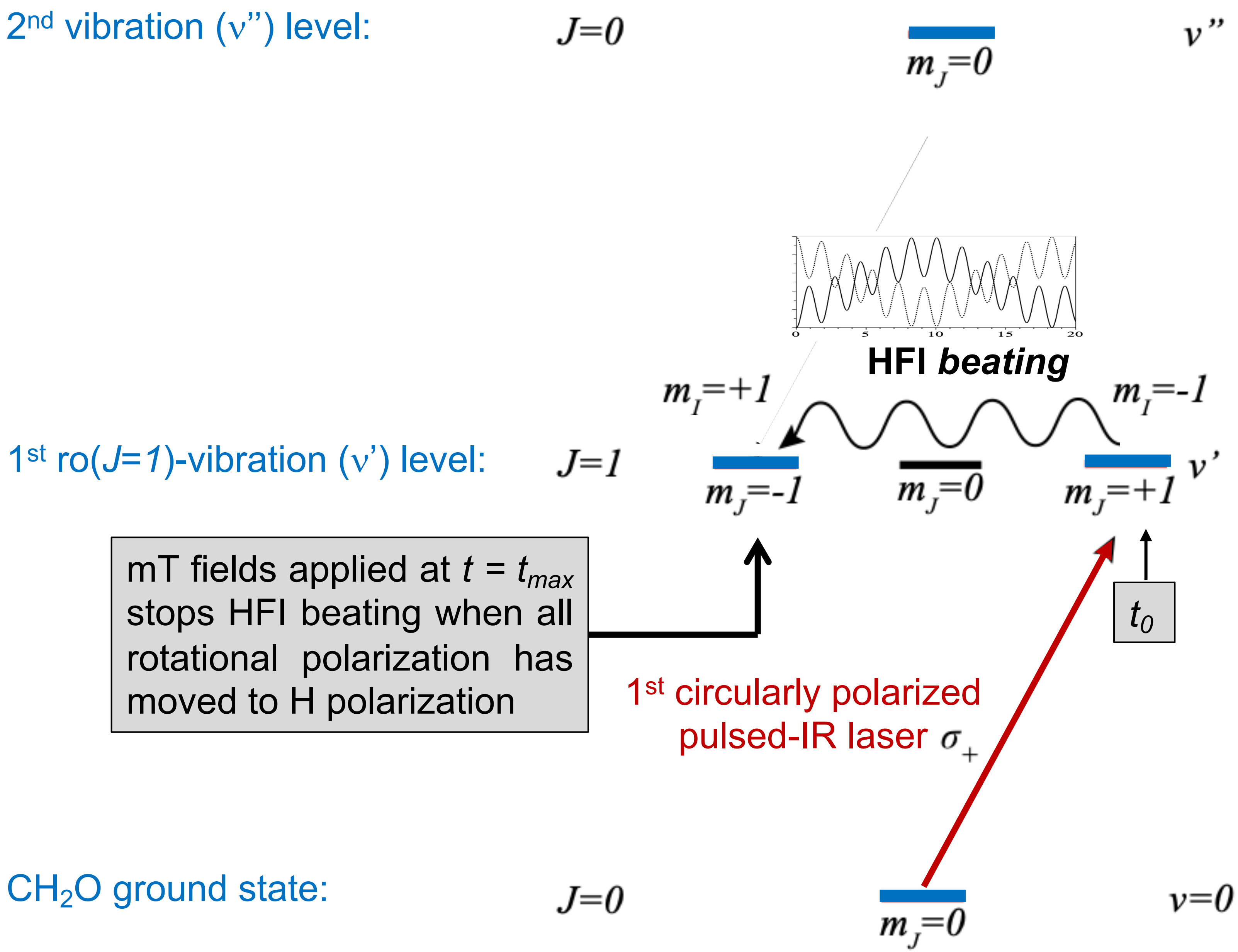
[Rakitzis, PRL **94** (2005) 83005]

eg. $\mathbf{H_2}$:

⬄ HFI beating transfers spin between molecular rotation and nuclear spin as system drifts

Laser-driven molecular polarized H_2 (T_2)

[Kannis, Rakitzis, Chem Phys Lett **784** (2021) 139092]



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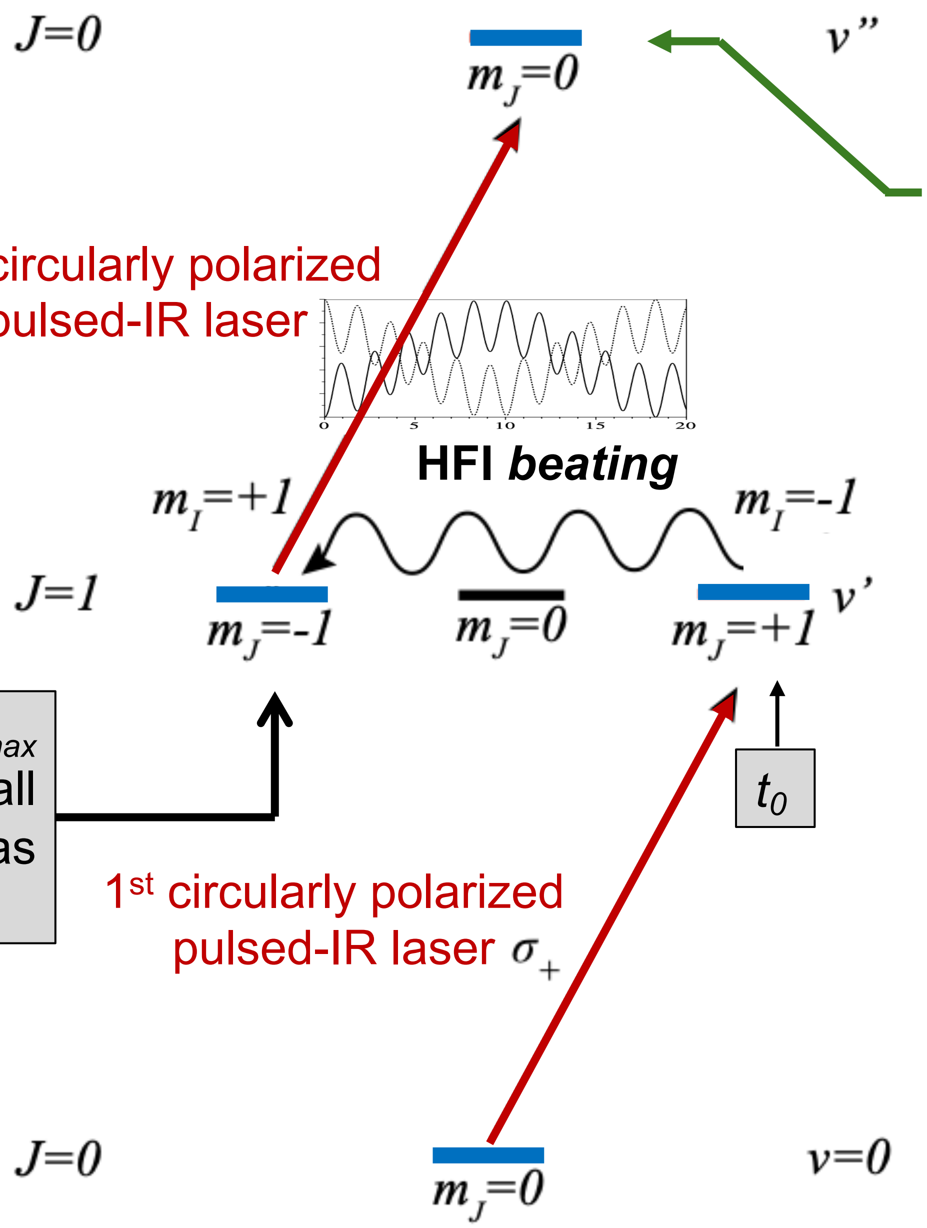
2nd vibration (ν") level:

↑

only molecules with 100% nuclear polarization reach ν"

1st ro(*J=1*)-vibration (ν') level:

CH_2O ground state:



mT fields applied at $t = t_{max}$ stops HFI beating when all rotational polarization has moved to H polarization

visible laser breaks the CO-H_2 bond and photo-dissociates ν" molecules into CO + $\vec{H_2}$

(H_2 carries ~all kinetic energy

⇔ beams naturally separated)

⇔ in static field region to prevent HFI beating within H_2

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1st ro(J=1)-vibration (ν') level:

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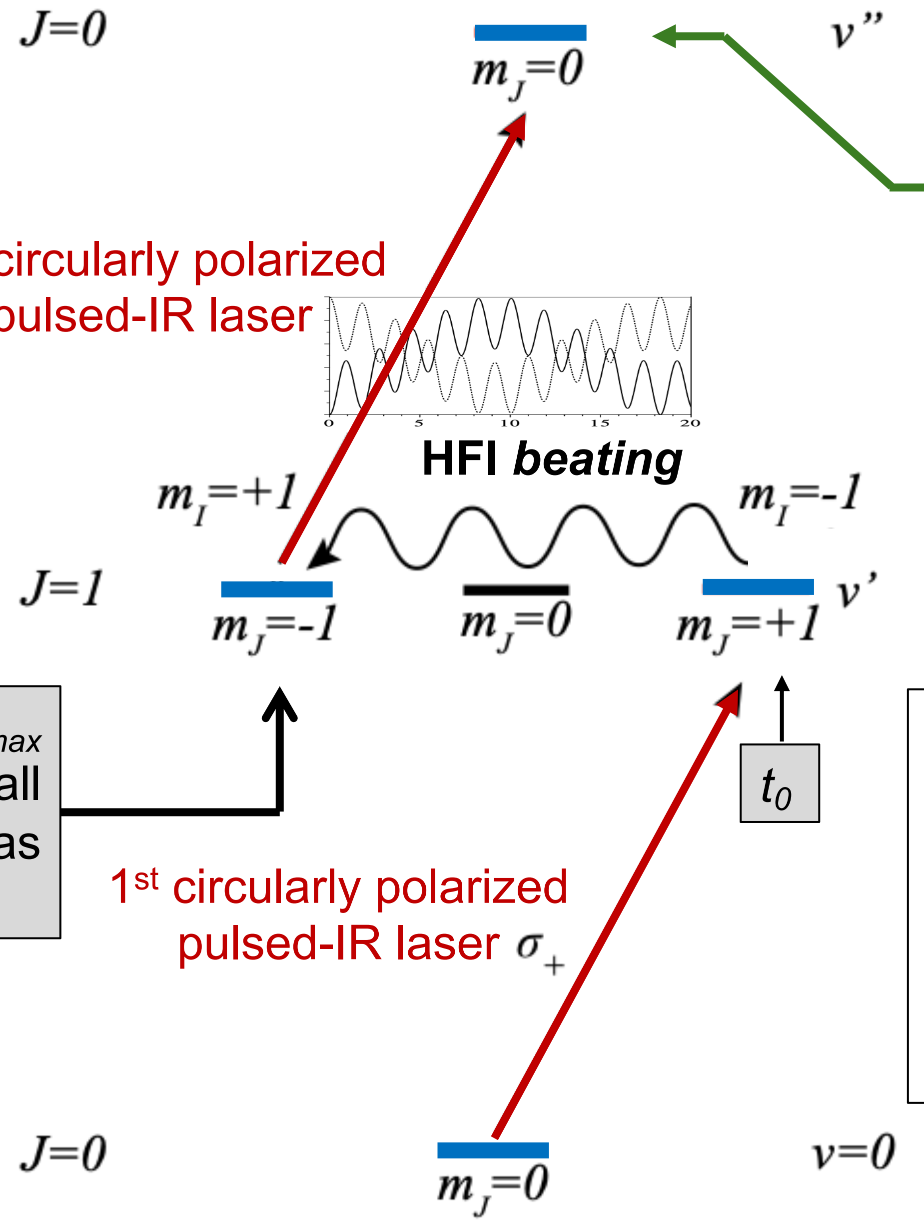

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- each step has been demonstrated (separately) at low power

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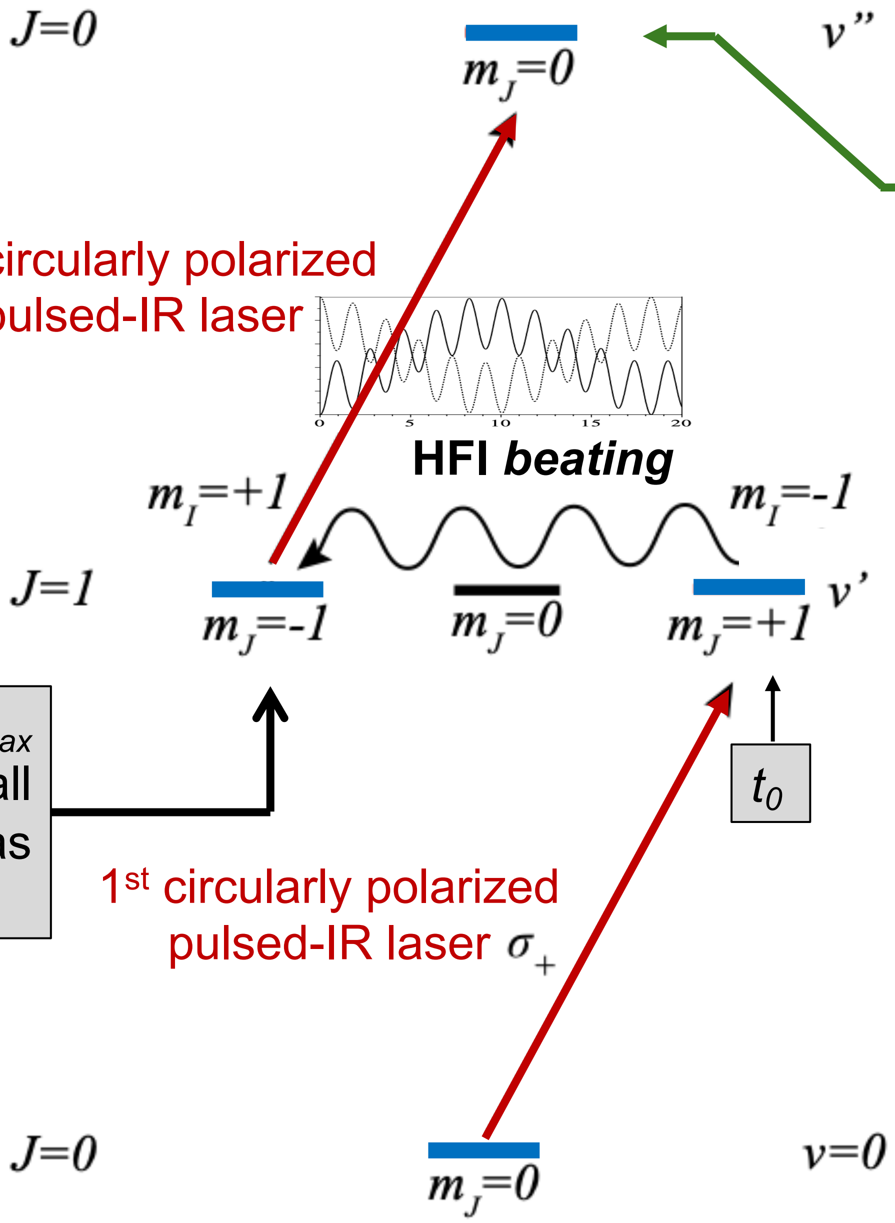

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- each step has been demonstrated (separately) at low power
- new revolution in high-power and high-resolution lasers project

fluxes of 10^{22} s^{-1}

Potential for large-scale fluxes of fully polarized $D^{V}T$ (or tensor D_2^{T} $|m = 0\rangle$)

Requirements:

- **Molecules**:
  - contain hydrogen isotopes
  - dipole moment
  - strong IR (or μw) absorption lines

- **Lasers:**
  - intense, pulsed photon source
  - tunable frequency range
  - narrow spectral line width

- *polarizing **DT** in CDTO (one of many options)* ⇔ *more complex since total spin = 3/2:*
  - *1st **2** circularly polarized IR lasers pump molecules into a $|\boldsymbol{j} = \mathbf{2}; \nu'\rangle$ ro-vibrational state*
  - *HFI beating moves angular momentum to D and T*
  - *2nd **2** circularly polarized IR lasers pump molecules into a higher **j =0** vibrational state*
  - *high-resolution visible laser photo-dissociates the molecule into CO + polarized DT*

- new high-power lasers could yield fluxes of **~10^{22} s^{-1}** ⇔ <u>need significant R&D to verify scaling</u>

- *tensor polarized D_2* ⇔ under study! Will be more complex, but would not need to polarized T ! !

Testing Polarization Survival in a hot plasma – the SPF Experiment in DIII-D

D + ^{3}He as a test-bed for Spin-Polarized-Fusion:

In nuclear reactions, isospin is a very good quantum number, particularly at low energies

⬄ ^{5}He and ^{5}Li are *mirror* nuclei with virtually identical low-energy structure

⬄ D + T ➔ ^{5}He ➔ α + n *and* D + ^{3}He ➔ ^{5}Li ➔ α + p

are mirror reactions, with the same spins, incorporating the same nuclear physics

⬄ Polarization survival can be tested with D + ^{3}He ➔ α + p (avoiding complications of tritium)

Overview of the SPF Demonstration Experiment in DIII-D:

- 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, NF **63** (2023) 076009

  ⬄ *experimental design, simulated polarization signal from change in yields*

- A.V. Garcia, W.W. Heidbrink, A.M. Sandorfi, NF **63** (2023) 026030

  ⬄ *simulated polarization signal from change in angular distributions*

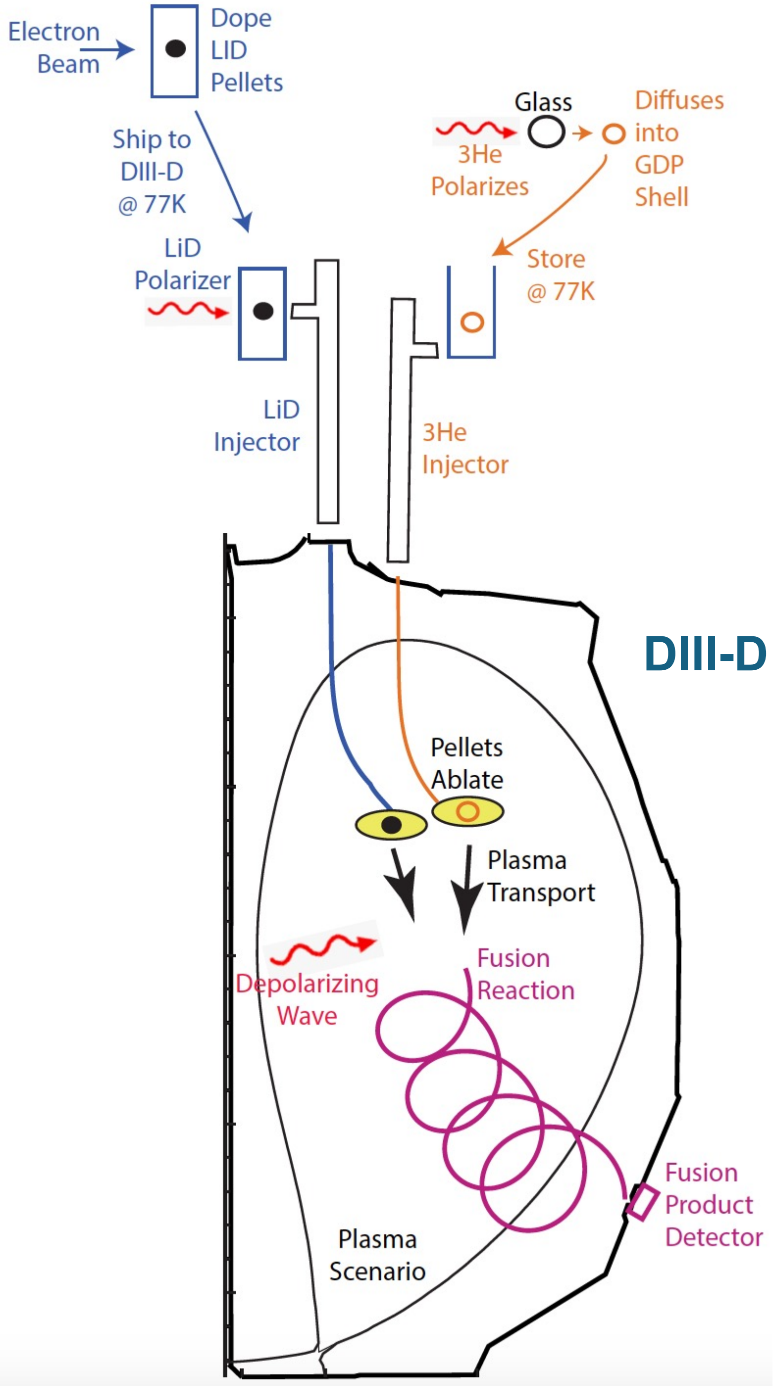
Spin-Polarized-Fusion Collaboration

Jefferson Lab
(Polarized D Fuel)
X. Wei, P. Dobrenz, D. Williams

University of Virginia
(Polarized ^{3}He Fuel)
G. W. Miller, A. M. Sandorfi, X. Zheng, A. Nelsen, S. Patel, E. Gunasekara, G. Cates, H. Nguyen

Oak Ridge National Lab
(Polarized Fuel injectors)
L. Baylor, S. Meitner, …

University of California, Irvine
(Fusion product detection and Diagnostics)
W. Heidbrink, …



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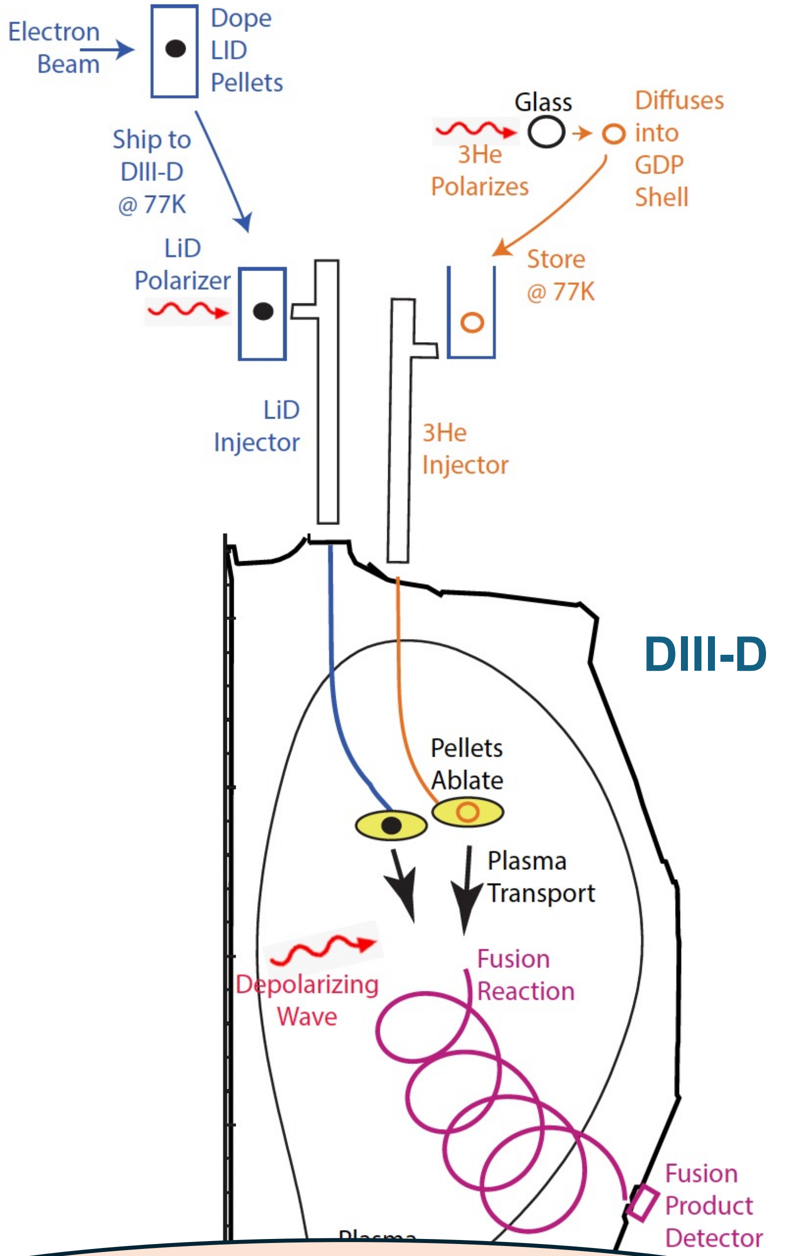


DOE-FES FUNDING – start Sept/2023

General Strategy:

- **use existing NP and Imaging techniques to create polarized fuels with sufficient life-times for a direct *in-situ* test of SPF in a high-T_{ion} plasma within the DIII-D tokamak**

  ⇔ not the fuel for a power reactor, but it mitigates costs in a life-time demonstration exp

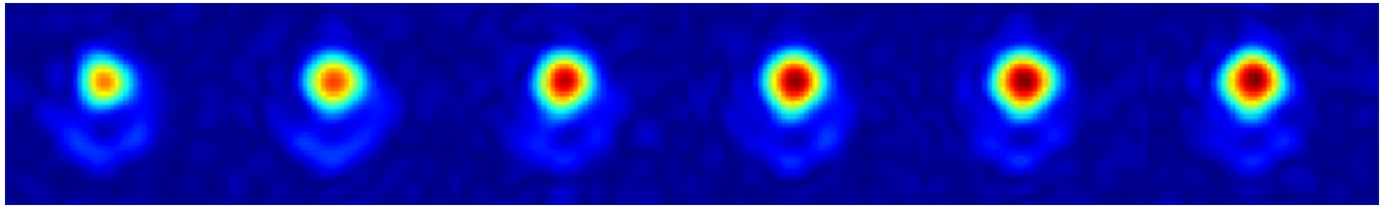
- polarized D (*small DNP Nuclear targets*)

  solid **LiD** cylinders: - 3.0 mm X 1.5 mm OD ; n(D) ~ 3×10^{20}
  - DNP ⇔ P^V(D) = **70%**, P^T(D) = 41%; injected at 4K ⇔ T_1 ~ 6 min

- polarized ^{3}**He**

  pressurized gas: - encapsulated in 3.0 mm OD x ~20 μm wall polymer shells at 25 atm
  - SEOP ⇔ P(^{3}He) = **65%** ; n(^{3}He) ~ 0.1×10^{20}
  - injected at 77 K ⇔ T_1 ~ 3 days

Time-sequenced MRI of polarized ^{3}He filling a GDP pellet



⇔ $\sigma\uparrow\uparrow / \sigma\uparrow\downarrow$ (**Li D + ^{3}He**) = 1.6 [Baylor *et al,* NF **63** (2023) 076009]

Summary

- Polarized fusion fuels increase reaction cross sections by 1.5,
  and could increase Q/power in an ITER-scale MCF reactor by 1.8 due to alpha heating
  ⇔ options: boosts power; BIG decrease in tritium inventory; BIG increase in magnet life

- gains come for the same plasma parameters ⇔ no R&D to change operating conditions
  ⇔ immediate increase in power ⇔ can compensate for complications in prototype machines

- new laser-pumped molecular sources have the potential for large-scale fueling of a power reactor with 100% polarized fuel, but appreciable R&D is required

- Polarization lifetime measurements in realistic MCF conditions are crucial
  ⇔ leverage polarized materials developed for Nuclear/Particle Physics and Medical-Imaging

- Major project underway to measure SPF in the DIII-D tokamak with $D+^3He \rightarrow \alpha+p$, the mirror reaction to $D+T \rightarrow \alpha+n$, using separate pellet injectors for polarized D and ^3He

  ⇔ **start of SPF experiments ~ 2027 - 2028**

extras

the next MAJOR steps

- **ITER**: 1st large-scale plasma science machine

  goals: burning plasma with Q = fusion-power / power-in **>** 10

  – 1/2 GW in fusion power, from externally supplied *T*

  – under construction

- **F**usion **P**ilot **P**lant to generate Electric power

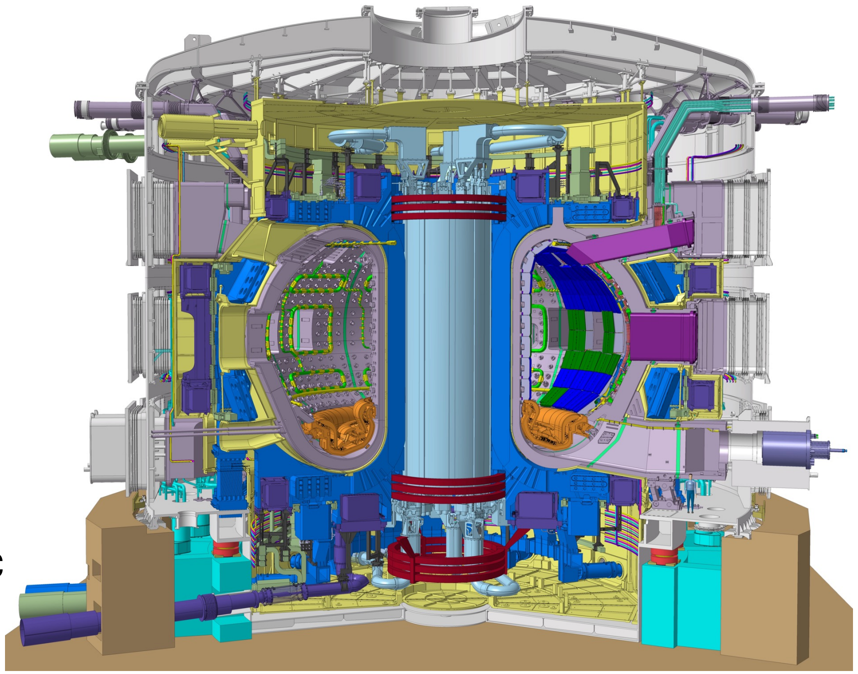
  goals: demonstrate large-scale breeding of tritium

  – **DEMO** -***EU***: 2 GW in fusion ⇔ ¾ GW electric, with Q > 25

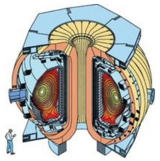
  – **FPP** -***Tokamak Energy***: 0.8 GW in fusion ⇔ 0.085 GW electric

  – **FPP** -***General Atomics***: ~ 1 GW in fusion ⇔ ~ 0.1 GW electric

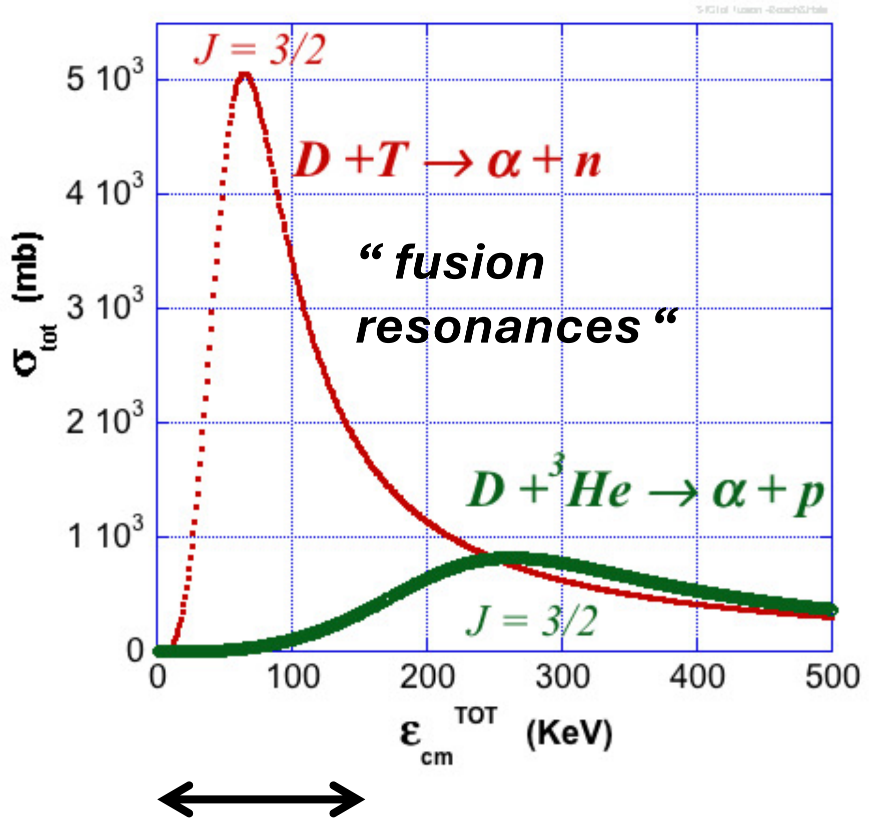
ITER
(Cadarache / France)



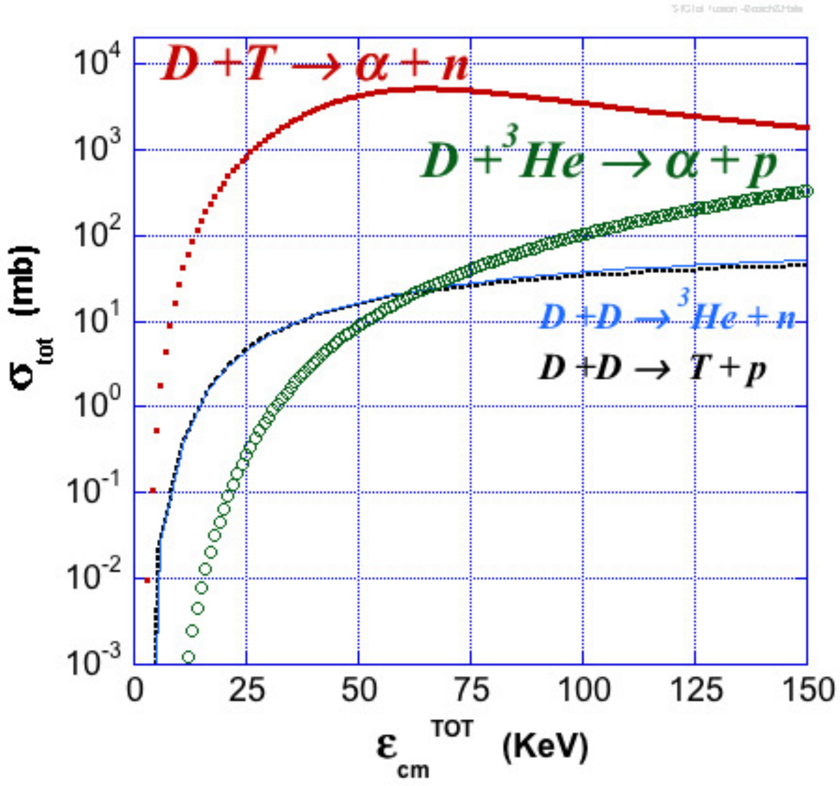
DIII-D
(San Diego / USA)



Reactions through the low energy tails of fusion resonances (in the Sun or in a tokamak)



- Sun's core peaks at 1.3 keV
- ITER plasma will peak at ~ 18 keV



Can Polarization really survive (*long enough*) at 10^8 K ??

- **depolarization immediately following injection**:

  from hyperfine mixing between a bound electron and aligned nucleus

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

$$\frac{\Delta P}{P} = \tfrac{1}{2}\left[1 + \frac{4(\mu_e - \mu_{ion})^2}{A_{HFI}^2} B^2\right]^{-1} \quad < \quad 1\% \text{ for DIII-D}$$

- **polarization loss during particle confinement period**:

  - Kulsrud, Valeo and Cowley,
    Physics of spin-polarized plasmas, 1986, Nucl. Fusion **26,** 1443

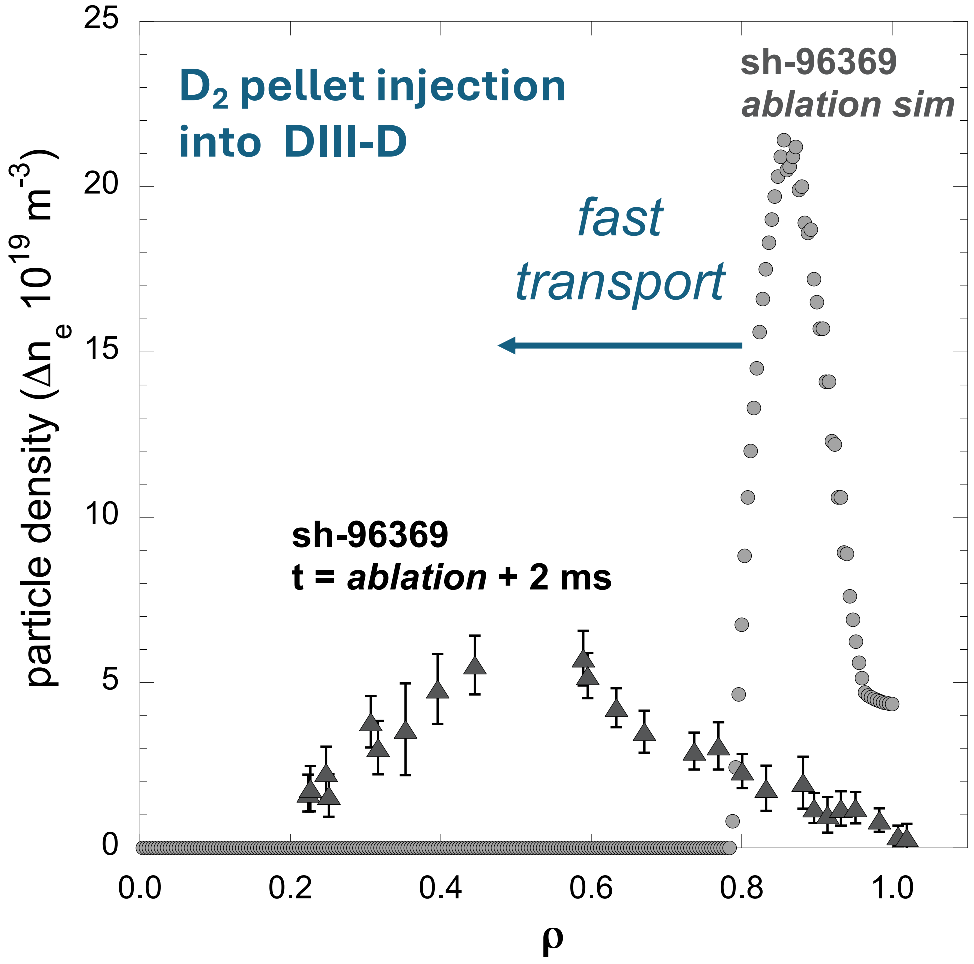
  - Gatto, *Depolarization of Magnetically Confined Plasmas*
    Nuclear Fusion with Polarized Fuel, 2016 Springer Proc. Phys. vol **187**, 79

⇔ two mechanisms survive scrutiny:

- wall recycling
- resonant interactions with plasma waves

Wall recycling (MCF):

- Modern tokamaks fueled by pellet injection
  ⬄ particles reach the core ~immediately
- small fraction react within confinement time τ_p
  (0.1 - 0.2 s in DIII-D; 4 - 8 s projected for ITER)
- most leave the plasma; can depolarize at walls
  ⬄ dilutes polarization if they re-entering plasma



• Mid-Scale Research machines (*eg. DIII-D*)
  - depolarization low for carbon walls (present DIII-D)
  - treating wall surface with a *getter* (Li, B) reduces recycling significantly. (BIG impact on confinement)
  - recycling will limit measurable Pol life-time range

• High-power ITER-scale machines
  - Outer plasma edge (*Scrape-Off-Layer*) essentially opaque to neutrals
  - THERE WILL BE ~ NO WALL RECYCLING IN A POWER REACTOR

[2012 Garzotti *et al*, NF**52**, 013002]

Plasma waves

- spins precess around the magnetic field at the Larmor angular frequency, $\omega_L = \left(\frac{\gamma}{2\pi}\right) B$

  ⬄ there is a potential for depolarization if the frequency of a plasma wave matches ω_L

- ions orbit at cyclotron angular frequency, $\omega_c = \frac{Ze}{2\pi M}\ B$

	D	T	^{3}He
ω_L / ω_c	0.86	8.92	–3.18

  - Lodder, Phys Lett A98 (83) 179 ⬄ big issue
  - Kulsrud, Valeo, Cowley, NF26 (86) 1442 ⬄ small issue

  - Heidbrink *et al*, Frontiers Phys (2024) 1355212 ⬄ *ion-cyclotron* RF (*ICRF*)

  - externally-launched *ICRF* for plasma heating:
    - in tokamaks such as DIII-D, B falls as 1/R,
      ICRF can be configured to match precession frequencies near the wall or outside plasma

  - instabilities in the ICRF are of greater concern, These might propagate to regions where their frequencies match ω_L, potentially driving depolarization.

⬄ Polarization lifetime experiments are needed to explore useful operating regimes.

Secondary Reactions

- consider He(H) -plasma heated with He(H) neutral beams

- simulations follow secondary reactions to estimate background yields:

  $^3He + D \Rightarrow \alpha + p\,(Q = +18.3\ MeV)$ **E(p) ~ 15 MeV**

  ↳ $D + D \Rightarrow {}^3He + n\ (Q = +\ 3.3\ MeV)$

  ↳ $D + D \Rightarrow T + p\ (Q = +\ 4.0\ MeV)$ **E(p) ~ 3 MeV**

  ↳ $D + T \Rightarrow \alpha + n\ (Q = +17.6\ MeV)$

- 15 MeV protons from $^3He + D \Rightarrow \alpha + p$ provide a unique signature that is easily separated

- 2-step ($D + D \Rightarrow {}^3He$) + D wrt primary $^3He + D$ is suppressed by $n(D) / [n(D)^2 x n(D)]$, which is negligible

Polarized Materials used in Nuclear/Particle Physics & Medical Imaging

- Polarized Solids: material brought to high-B and low temp where equilibrium polarization is large
  - three-step process: "*Dynamic Nuclear Polarization*" (DNP) [Goertz…, Prog Part Nucl Phys **49** (2002) 403]

    (*i*) create paramagnetic centers (free electrons) by chemical doping (~ 1%) or by irradiation;

    (*ii*) polarize free electrons at high-*B*/*low-T* ;

    (*iii*) transfer spin alignment from e^{-} to H/D/(T) with μ-waves

eg: *material*	B(tesla) / T(K)	P(H/D)
$La_2(Mg)_3(NO)_3(\mathbf{H}_2O)_{24}$	2.0 / 1.5	70 %
$C_2\mathbf{H}_4(O\mathbf{H})_2$, $C_2\mathbf{H}_6(O\mathbf{H})_2$,	2.5 / 0.5	99 %
H-Butanol $C_4\mathbf{H}_9O\mathbf{H}$	2.5 / 0.3	93 %
D-Butanol $C_4\mathbf{D}_9O\mathbf{D}$	5.0 / 0.2	70 %
H-Ammonia $N\mathbf{H}_3$	5.0 / 1.0	98 %
D-Ammonia $N\mathbf{D}_3$	3.5 / 0.3	50 %
Lithium-Deuteride Li**D**	6.5 / 0.2	70 %

Ionizing the heavier elements that accompany polarized H / D will absorb energy and tend to quench a plasma

⇔ ***Lithium regularly used in tokamaks to suppress ELMs***

Polarized Materials used in Nuclear/Particle Physics & Medical Imaging

- Polarized Solids: material brought to high-B and low temp where equilibrium polarization is large

  - two-step process: *Frozen-Spin HD* [Bass *et al, NIM A* **737** *(2014) 107; Baylor et al, NF* **63** *(2023) 076009*]

    (*i*) polarize *deuterium-hydride* at high-*B / low-T*

    (*ii*) wait (~ weeks to months) for a frozen-spin state to set in for handling at low-B / high-T

eg: *material*		B(tesla) / T(K)	P(H/D)
H **D**	(*i*)	15.0 / 0.01	60 % H & 20% **D**
	(*ii*)	0.1 / ~ 3.0	20 % H & 40% **D** *after RF spin transfer*

- Polarized gases:

  - *Stern-Gerlach* atomic beams: H, D, HD, … P(H,**D**) ~ 90% [Ralf Engels …, PRL **124** (2020) 113003]

    - intensities limited to ~10^{17} s^{-1} ⇔ would require a long collection time to accumulate enough material

  - Polarized ^{3}He:

    - *Spin Exchange Optical pumping* (SEOP): P(^{3}**He**) = 85% [Chen …Gentile … J. Appl Phys **116** (2014) 014903]
      [Mooney, Wilson Miller,… Proc Soc Magn Reson Med **17** (2009) 2166]

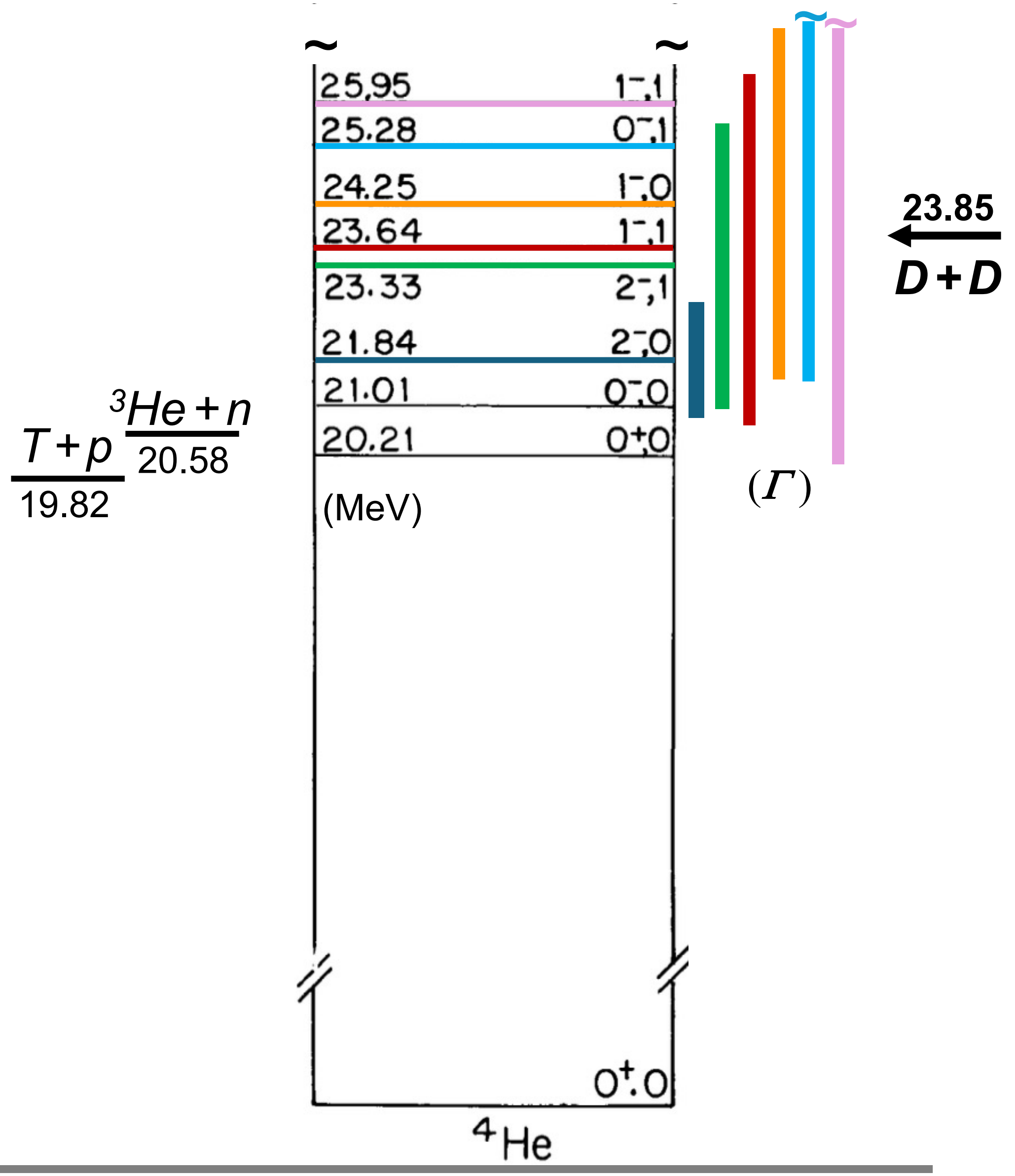
    - *Metastable Exchange Optical pumping* (MEOP): P(^{3}**He**) = 70% [Hussey …Gentile… RSI **76** (2005) 053503]

Other options for testing polarization survival

- *most MCF & ICF run with D plasmas*

$$? \ \vec{D} + \vec{D} \ \Rightarrow \ {}^4He \rightarrow {}^3He + n \ \ or \ \ T + p \ \ ?$$

- D+D feeds a large number of broad (Γ) overlapping levels in ^{4}He ⇔ large interference effects, further complicated by the deuteron *D-state*



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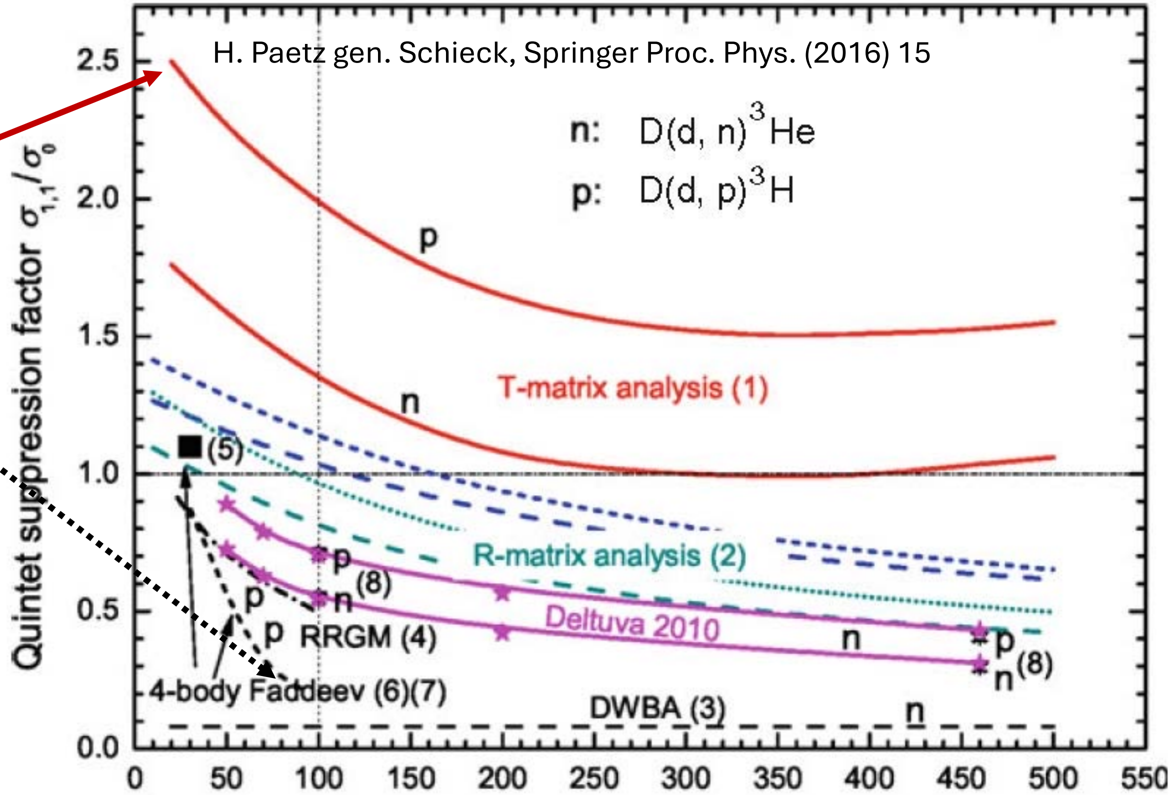
- NP theory predictions for $\sigma(\uparrow\uparrow)/\sigma_0$ range from enhancement by 2.5 to suppression by 10

- 1st direct measurement with polarized beams and targets in preparation at PNPI-Gatchina (*St Petersburg)* with Ferrara and Juelich

$\sigma(\uparrow\uparrow)/\sigma_0$



Other options for testing polarization survival

- *what about $\vec{D}$ +D*

  - polarization asymmetry data *(NP "Analyzing powers")* available down to thermal plasma temperatures

  - However, combining polarized $\vec{D}$ with unpolarized D at the same plasma temperature just dilutes the deuteron polarization ⬄ small signal

  - *option for MCF*:
    ⬄ inject polarized (a) $\vec{D}$ pellets into a ^{4}He or H plasma,
    and (b) 80 keV neutral D beam ⬄ higher energy ⬄ higher cross section

    - A.V. Garcia, W.W. Heidbrink, A.M. Sandorfi, NF (*in press - 2025*)