Spin polarized fuel in tokamak fusion reactors

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with
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GENERAL ATOMICS

Injecting spin polarized fuel in an existing tokamak would inform the possibility of enhanced future tokamaks

- Spin polarizing the fuel in the most favorable fusion reaction

  $$D + T \rightarrow {}^{5}He \rightarrow \alpha + n \ (+17.6\ \text{MeV})$$

  yields up to a factor of 1.5 greater cross section for this reaction

- In the power balance of a future tokamak reactor, a 50% increase in cross section leads to a 75% increase in fusion power

- The polarization survival should be testable in DIII-D by injecting spin polarized HD and ^{3}He pellets and measuring the quantity and distribution of fusion products on the tokamak wall from

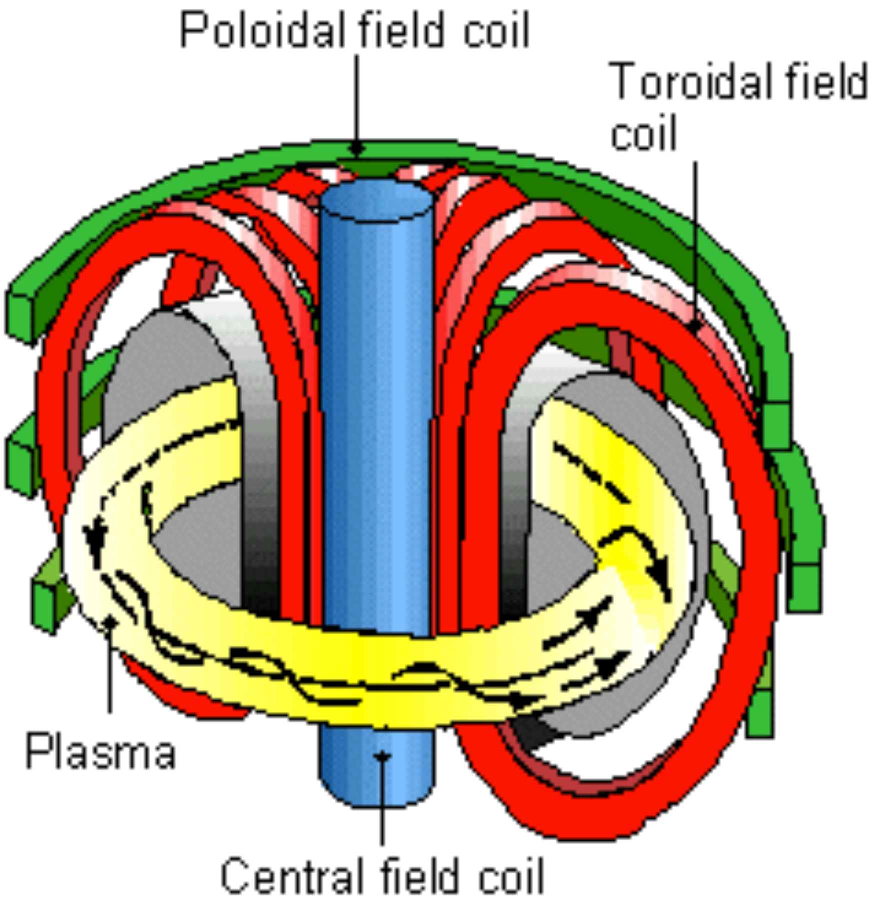
  $$D + {}^{3}He \rightarrow {}^{5}Li \rightarrow \alpha + p$$

Outline

- What is a tokamak?
- Nuclear physics of spin polarized fusion
- Implications for future reactors
- Testing spin polarization survivability in DIII-D

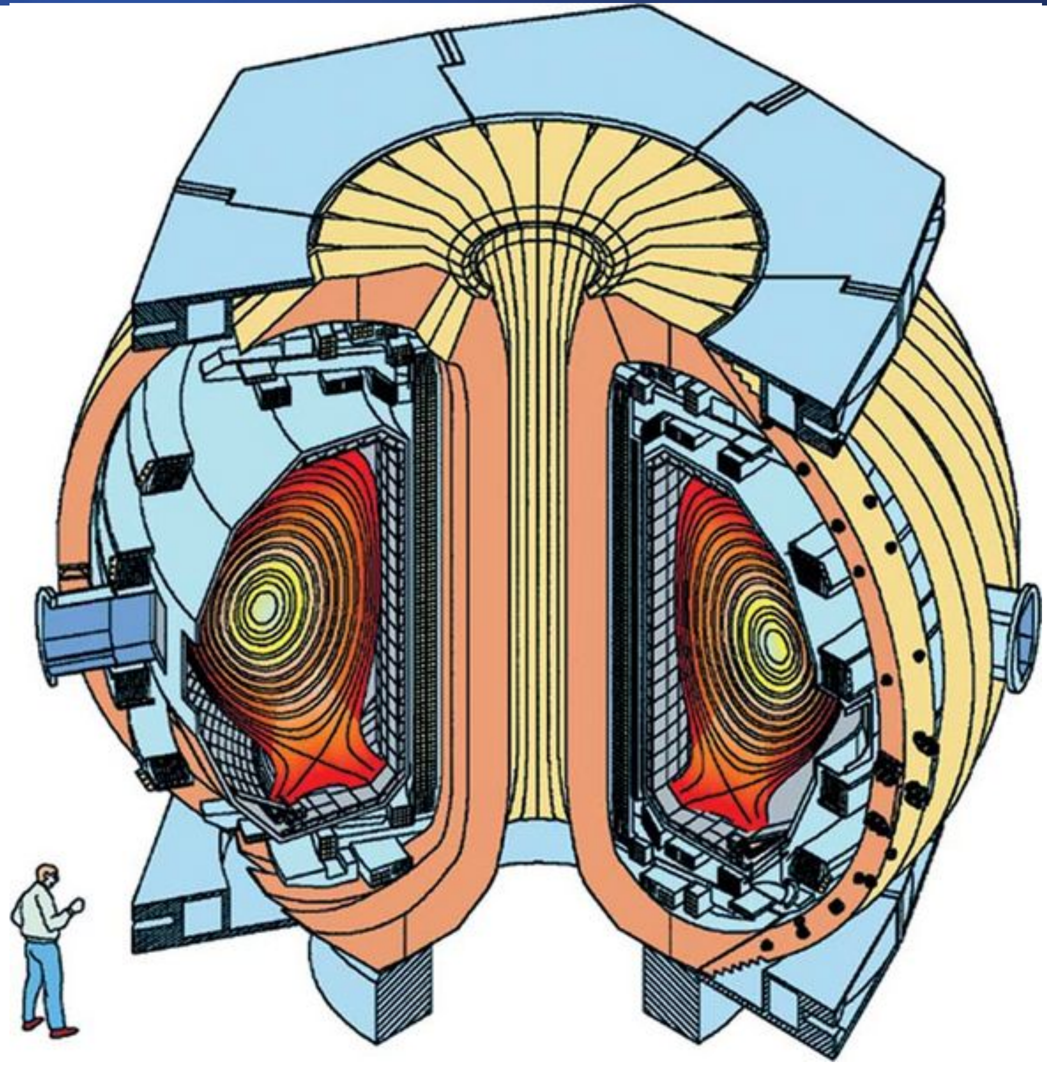
Tokamak = Toroidal Confinement by Magnetic Fields

- The toroidal guide field is produced by external coils
- The poloidal field is produced by driving current toroidally in the plasma
- Helically winding magnetic field lines trace out a flux surface
- The plasma particles are confined long enough to undergo fusion



DIII-D is a medium sized, but well diagnosed tokamak

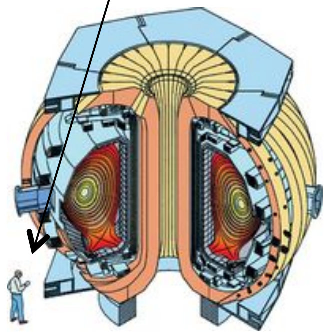
- B_T < 2.1 T, I_p < 1.5 MA
- R = 1.6 m, a = 0.6 m
- H, D, or He Fuel
- Elect. Dens. ~ $5 \times 10^{19}/m^3$
- Elect. Temp. < 12 keV
- Ion Temp. < 18 keV
- 15 MW Neutral Beams
- 3 MW Electron Cyclotron Heating
- Discharge current flat-top 5-10 s
- 1 discharge (shot) per 12-15 minutes



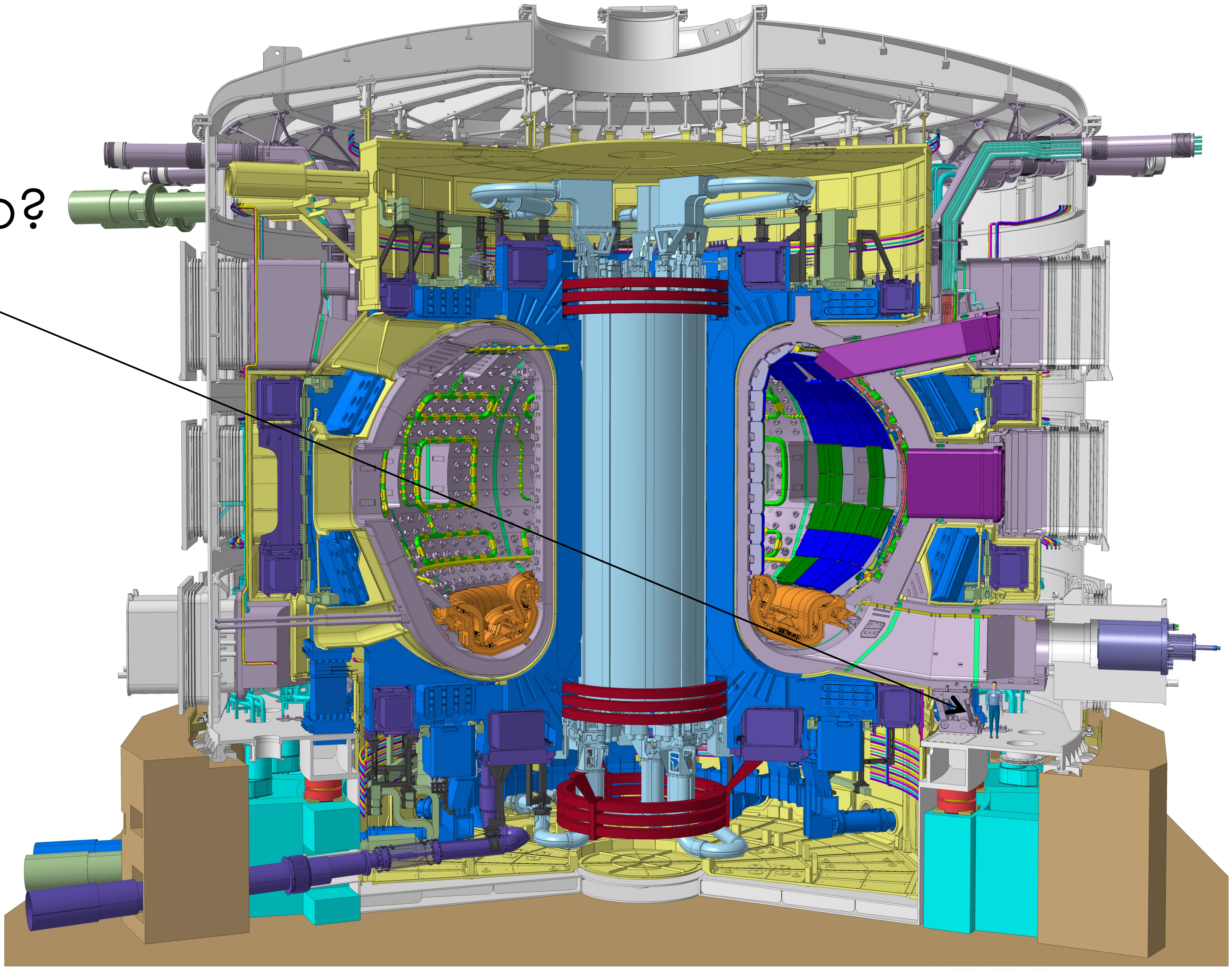
DIII-D tokamak (San Diego / USA)

ITER is the next step device being built in France

Where's Waldo?



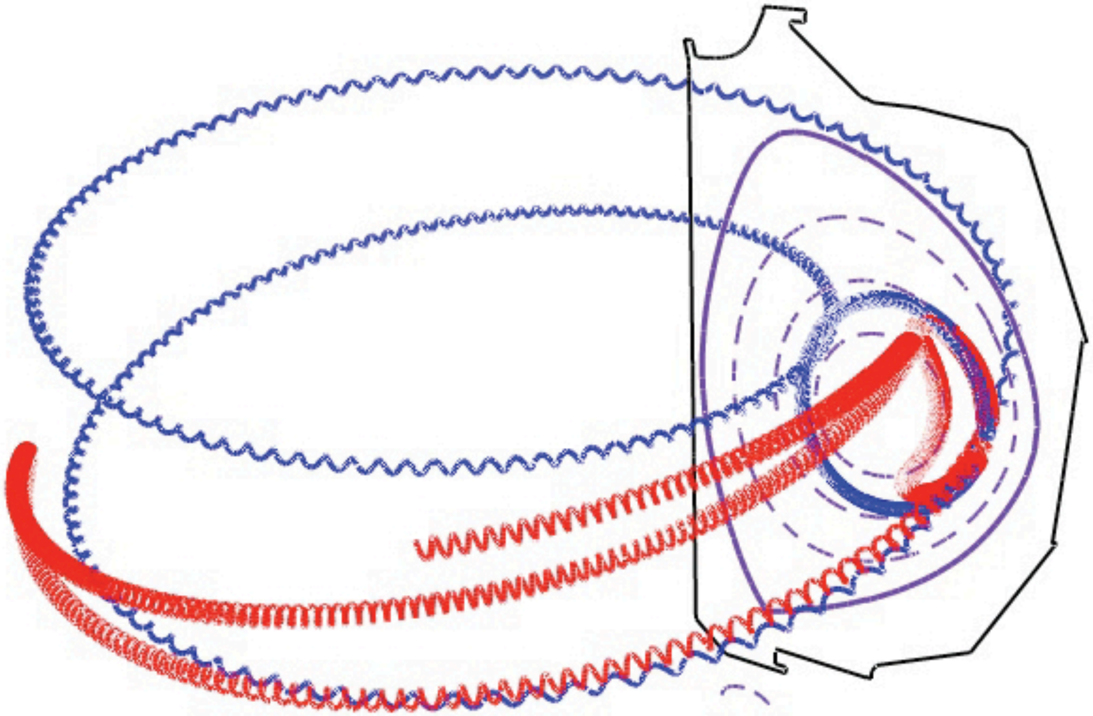
DIII-D



ITER

Pitch (polar) angle of fusion products relative to the magnetic field matters in a tokamak

- **Pitch angle closer to 0 or 180 degrees: <u>passing</u> particle stays closer to magnetic field line and samples all of the flux surface**
  - confined longer to give energy to thermal plasma
- **Pitch angle closer to 90 degrees: <u>trapped</u> particle has large excursions from the flux surface and doesn't sample inboard.**



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- What is a tokamak?
- **Nuclear physics of spin polarized fusion**
- Implications for future reactors
- Testing spin polarization survivability in DIII-D

Reactor Performance can be Improved by Exploiting the Dependence of Fusion Cross-section on Spin Polarization

Fusion Reaction

$$D + T \rightarrow \alpha + n\ (+17.6\ \text{MeV})$$

Reaction Rate, R (s^{-1})

$$R = n_D\, n_T\, V_{plasma} \langle \sigma v \rangle$$

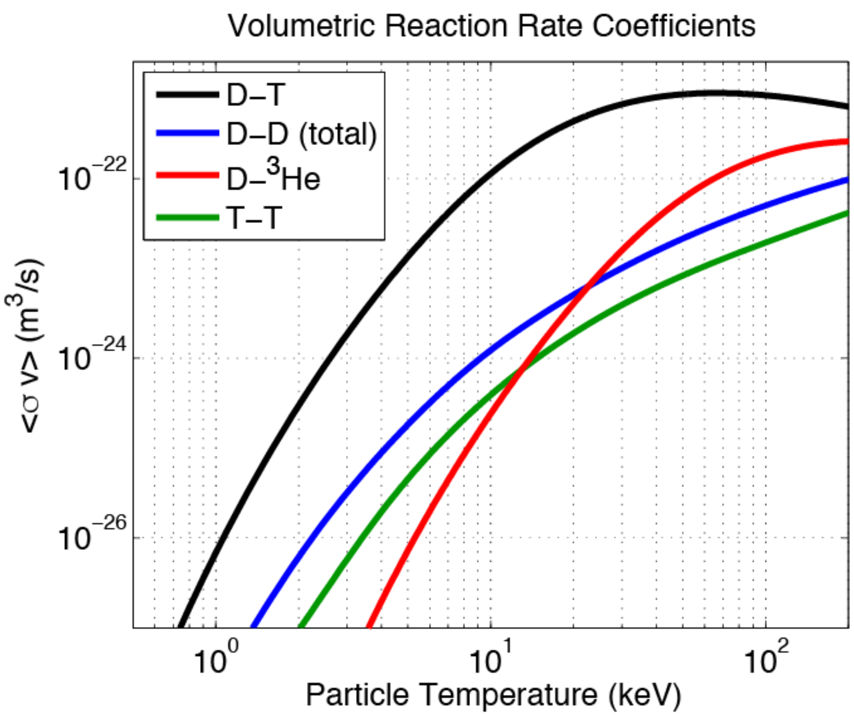
Isotropic Spin Distribution

$$\int \sigma \rightarrow \sigma_0$$

Spin Polarized Distribution: parallel to B

$$\int \sigma \rightarrow 1.5\ \sigma_0$$

50% fusion rate increase for full polarization



Z.S. Hartwig and Y.A. Podpaly, *The Magnetic Fusion Formulary*, PSFC MIT (2012)

Studying the D + ^{3}He Reaction Addresses the Physics Necessary for Application to D + T Reactions

D + T → ^{5}He → α + n   D + ^{3}He → ^{5}Li → α + p

- **Isospin (neutron/proton equivalence) is a very good quantum number, particularly at the low energies of particles in a tokamak**
  - ^{5}He and ^{5}Li are mirror nuclei with nearly identical low-energy structure
  - D+T and D+^{3}He reactions are mirror reactions with same spins and same nuclear physics

Polarization Leads to a Non-isotropic Fusion Cross-section

- **Inject polarized fuel into a tokamak**

D + ^{3}He → ^{5}Li → α + p

$$parallel\ spins\ \vec{D}\Uparrow\ {}^3He\Uparrow:\quad \frac{d\sigma}{d\Omega_{cm}} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{\tfrac{9}{4}\sin^2\theta\right\}$$

$$antiparallel\ spins\ \vec{D}\Uparrow\ {}^3He\Downarrow:\quad \frac{d\sigma}{d\Omega_{cm}} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{\tfrac{1}{4}\left(1+3\cos^2\theta\right)\right\}$$

- **Pitch angle (θ) of the charged fusion products relative to the magnetic field is skewed**
  - parallel spins produce more trapped particles
  - anti-parallel spins produce more passing particles

(Anti-) Aligning Spins Yields (-)+50% Change in Fusion Rate

- **Angle-integrated fusion cross-section:**

$$\sigma_{\rm cm} = \sigma_0 \left\{ 1 + \frac{1}{2} \vec{P}_D^V \cdot \vec{P}_{^3\rm He} \right\}$$

- **Fully polarized fuel:**

$$\left|\vec{P}_D^V\right| = 1 \;,\quad \left|\vec{P}_{^3He}\right| = 1$$

- **Resulting fusion rate is modified**
  - both spins parallel to B: $\sigma_{\rm cm} = \sigma_0 \left\{ 1 + \frac{1}{2} \right\}$
  - one spin parallel, the other anti-parallel to B: $\sigma_{\rm cm} = \sigma_0 \left\{ 1 - \frac{1}{2} \right\}$

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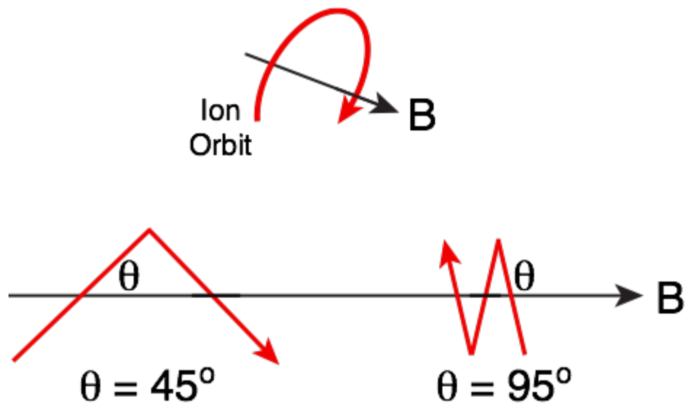
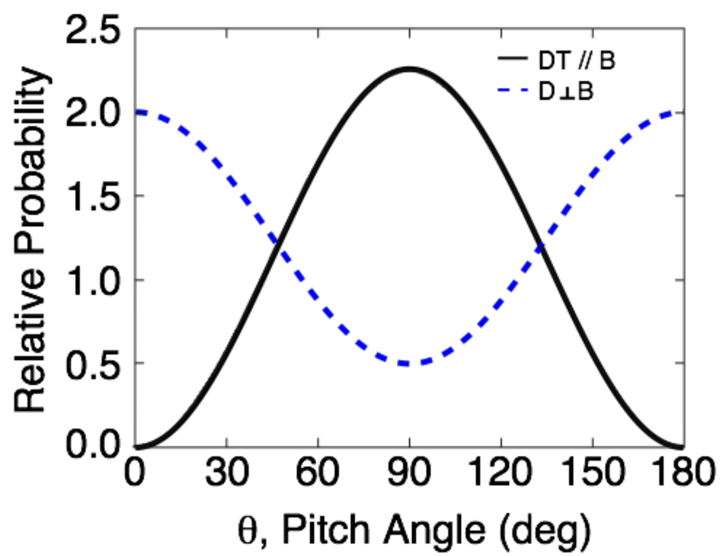
Spin Polarized Fuel can Benefit Fusion Reactors by Improving either Power Generation or α-particle Confinement*

- **Improving power generation**
  - D and T polarized // B
  - 100% polarization produces fusion rate increase of 50%
  - α-particle birth pitch angle $N(\theta_\alpha) \sim \sin^2(\theta_\alpha)$



- **Enhanced α-particle confinement**
  - D polarized ⊥ B
  - $N(\theta_\alpha) \sim 1 + 3\cos^2(\theta_\alpha)$
  - larger passing α-particle population



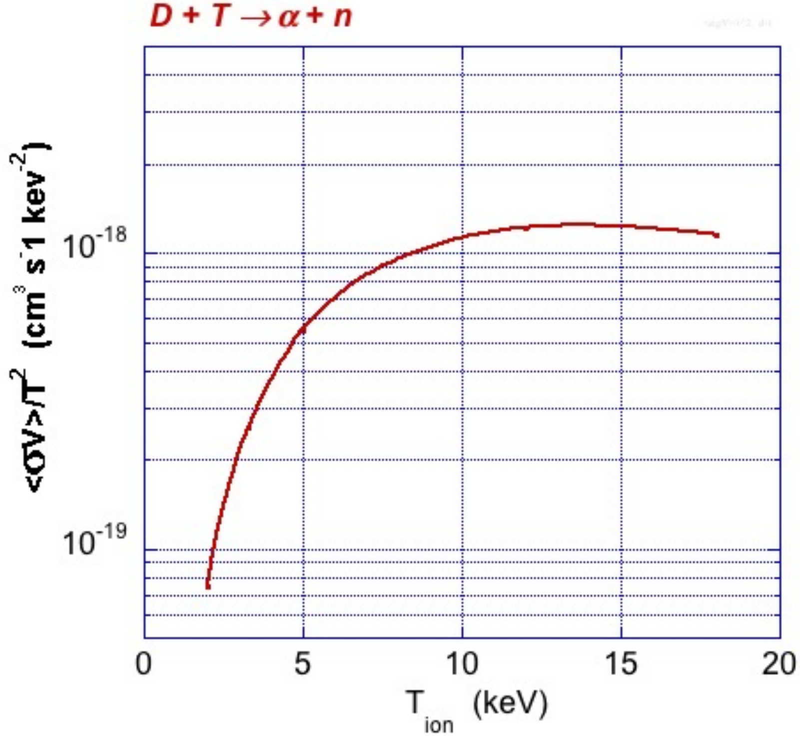
*R.M. Kulsrud, et al., *Phys. Rev. Lett.* **49**, 1248 (1982); R. Kulsrud, E. Valeo, and S. Cowley, *Nucl. Fusion* **26**, 1443 (1986)

D.C. Pace, et al., *J. Fusion Energ.*, DOI 10.1007/s10894-015-0015-4 (2016)

Spin Polarized Fuel can Makeup for Magnetic Field Degradation in Superconducting Tokamaks

- **Recast the fusion rate in terms of magnetic field**

$$R = n_D n_T V_{\text{plasma}} \langle \sigma v \rangle$$
$$= \frac{\beta^2 B^4}{4\mu_o^2 T^2} V_{\text{plasma}} \langle \sigma v \rangle$$

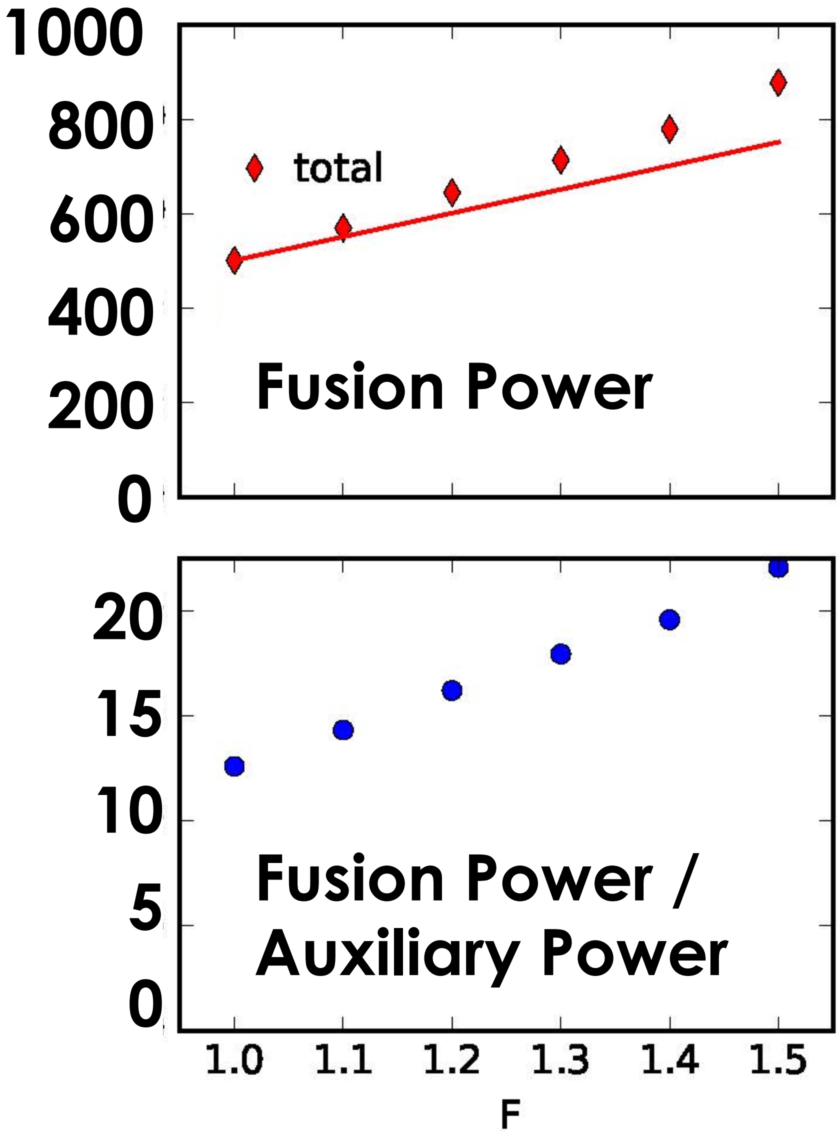


A.M. Sandorfi and A. D'Angelo, Springer Proc. Phys. 187 (2016) 115

- **50% increase in reaction rate is equivalent to as much as a 11% increase in magnetic field for ITER**
  - improve Q at targeted magnetic field
  - **reach Q = 10 even if facing toroidal field degradation**

Increase in Fusion Power Scales Faster than the Reaction Rate

- Fusion alphas heat a reactor through collisional damping on electrons and ions
- Increased fusion alpha heating increases the plasma temperature
- Increased plasma temperature further increases fusion rate until a new power balance is reached
- Fusion rate increase of 1.5 → fusion power increase of 1.75



Polarized Fuel has the Potential to Significantly Reduce Reactor Cost

- **Fuelling a 500 MW plasma in ITER**
  - 5 mm outer diameter pellets of separate D and T injected at 7 Hz
  - 2000 mol/day of each species at 100% polarization
- **If these quantities of polarized fuel are available**
  - equivalent to ~15% magnetic field increase
  - tokamak reactor cost scales as B^2
  - **reactor cost is reduced by ~30%**

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

Next Step in SPF Research is to Demonstrate that the Fuel Remains Polarized Longer than a Confinement Time

- **SPF benefits require that polarization persists in the tokamak long enough for fusion to occur**
  - energy splitting between polarization states is minuscule: 10^{-10} keV << T_{ion}

- **Many depolarization mechanisms have been explored, but survival is expected (collisions and recycling are small depolarization mechanisms)***
  - **Recent ITER modeling predicts that wall recycling will be negligible for its hot plasma conditions**

- **We propose that polarization survival should be tested in current devices with current polarization techniques**

*R.M. Kulsrud, H.P. Furth, E.J. Valeo and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982)
R.M. Kulsrud, E.J. Valeo and S. Cowley, Nucl. Fusion 26, 1443 (1986)

Outline

- What is a tokamak?
- Nuclear physics of spin polarized fusion
- Implications for future reactors
- **Testing spin polarization survivability in DIII-D**

DIII-D Experiments could Confirm Polarization Lifetime by Comparing Fusion Product Yields

- **Prepare polarized deuterium with existing Jefferson Lab facilities: solid $H\vec{D}$ pellets**
  - diffuse 200 - 400 atm HD into shells (Inertial Confinement Fusion ICF type from General Atomics)
  - cool gas to reach solid state
  - polarize both H and D
  - spin transfer H → D for maximum D polarization
  - fired from 2 K pellet launcher at DIII-D

$$H\vec{D} \Uparrow + {}^3\vec{He} \Uparrow$$

$$H\vec{D} \Downarrow + {}^3\vec{He} \Uparrow$$

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  - coo
  - pol
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standard technology well established in nuclear physics experiments

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standard technology well established in nuclear physics experiments

- **Develop polarized ^{3}He with existing U. Virginia facilities: gas-filled ICF-type pellets**
  - build equipment to reproduce procedure at DIII-D
  - fired from 77 K pellet launcher

$$H\vec{D}\Uparrow + {}^{3}\vec{He}\Uparrow$$

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- **Develop polarized ^{3}He with existing U. Virginia facilities: gas-filled ICF-type pellets**
  - buil
  - fire

active research and technique development

$$H\vec{D}\Uparrow + {}^3\vec{He}\Uparrow$$

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DIII-D Experiments could Confirm Polarization Lifetime by Comparing Fusion Product Yields

- **Prepare polarized deuterium with existing Jefferson Lab facilities: solid $H\vec{D}$ pellets**
  - diffu… type…
  - coo…
  - pol…
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standard technology well established in nuclear physics experiments

- **Develop polarized ^{3}He with existing U. Virginia facilities: gas-filled ICF-type pellets**
  - buil…
  - fire…

active research and technique development

- **Fire pellets with alternating spin alignment into appropriately high-T_i plasma at DIII-D**

$$H\vec{D}\Uparrow + {}^3\vec{He}\Uparrow$$

$$H\vec{D}\Downarrow + {}^3\vec{He}\Uparrow$$

Variable Spin-aligned Fuels will Produce Different Fusion Product Distributions

- **Consider realistic polarization fractions**

$$P_V\left(\vec{D}\right)=0.40 \quad \textbf{JLab}$$

$$P\left({}^3\vec{He}\right)=0.65 \quad \textbf{UVa}$$

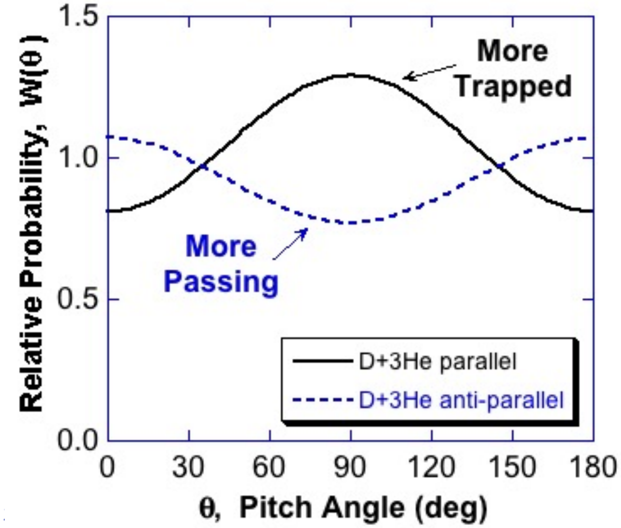
- **Resulting fusion cross-sections produce a 30% difference in fusion rate**

$$\langle\sigma^{par}V\rangle=\langle\sigma_o V\rangle\left\{1+\tfrac{1}{2}(0.26)\right\}$$

$$\langle\sigma^{anti}V\rangle=\langle\sigma_o V\rangle\left\{1-\tfrac{1}{2}(0.26)\right\}$$

$$\frac{\langle\sigma^{par}V\rangle}{\langle\sigma^{anti}V\rangle}=1.30$$

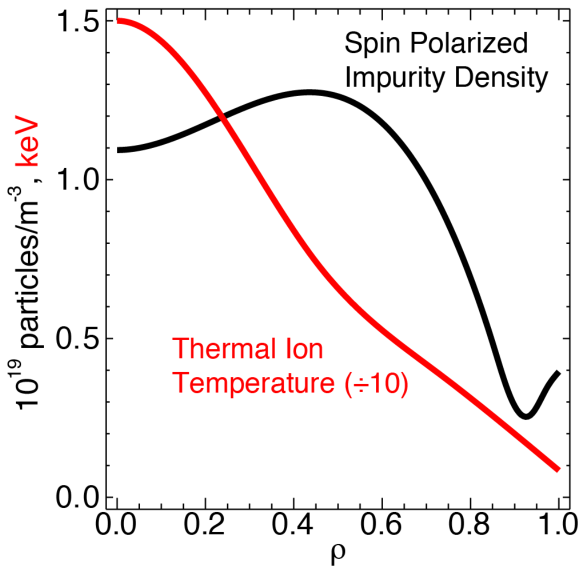
- **Trapped/passing population of the fusion products is also dependent on the spin-alignment**

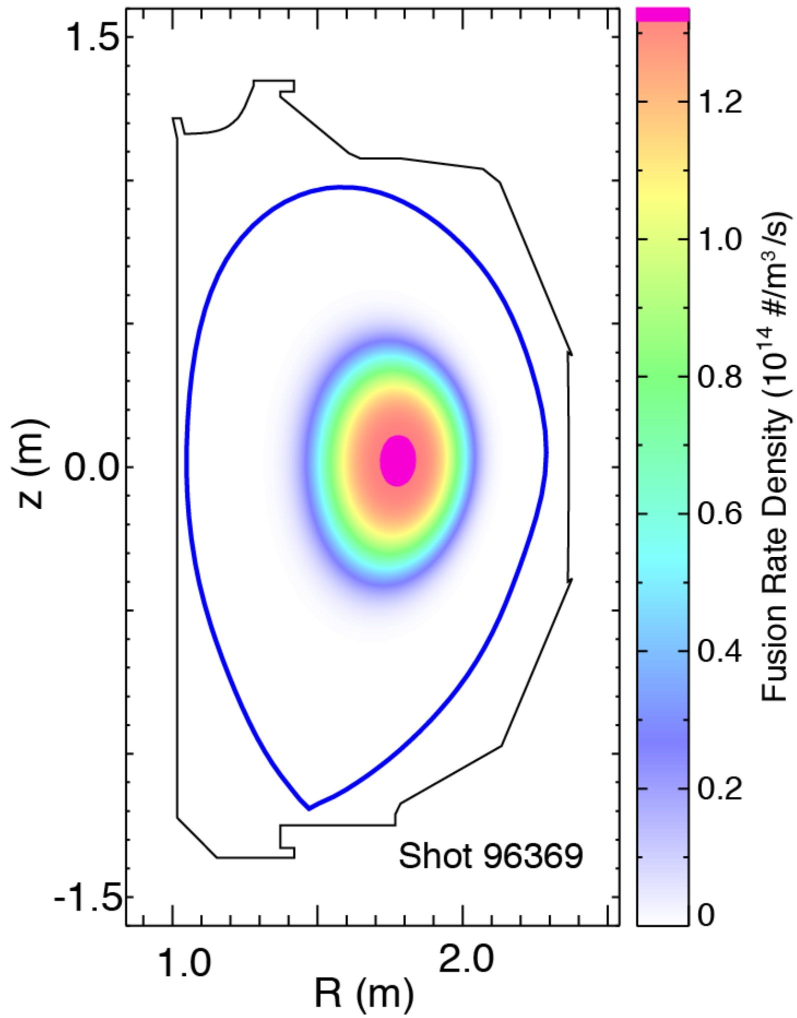


S.P.Smith et al./22nd International Spin Symposium/September

QH-mode Shot with $T_i(0)$ = 15 keV is Modeled to Demonstrate Output Profile of Charged Fusion Products

- Start from ONETWO* calculations of D-D fusion rate for D pellet injected shot
- Convert to equivalent for D-^{3}He
- Scale up to high T_i discharge

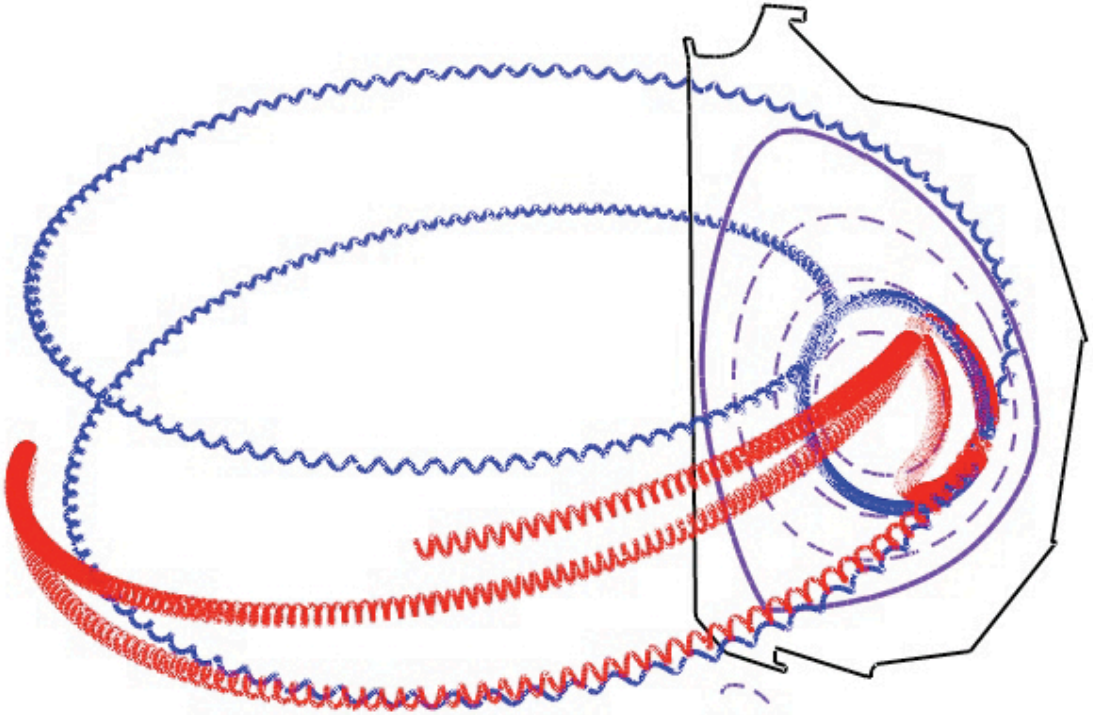




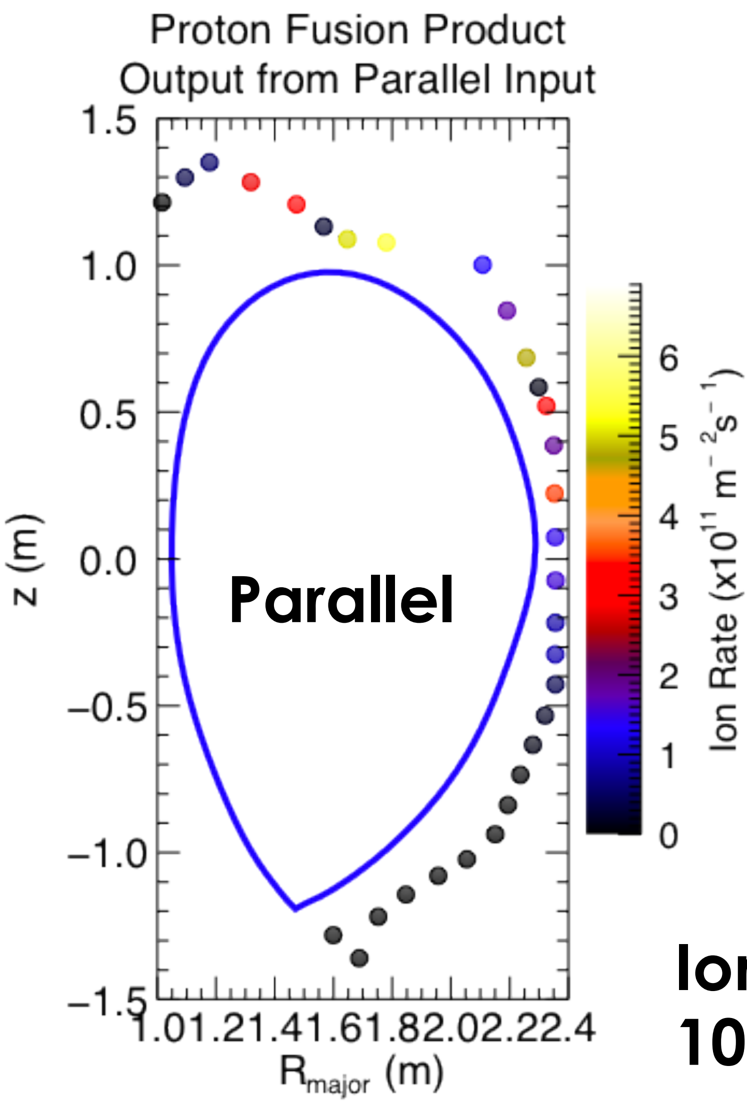
*H.S. John, et al., Proceedings of the 15th IAEA Conference, Seville, Vol. 3, 603 (1994)

Following fusion products of various birth locations and pitch angles reveals final losses to walls in DIII-D

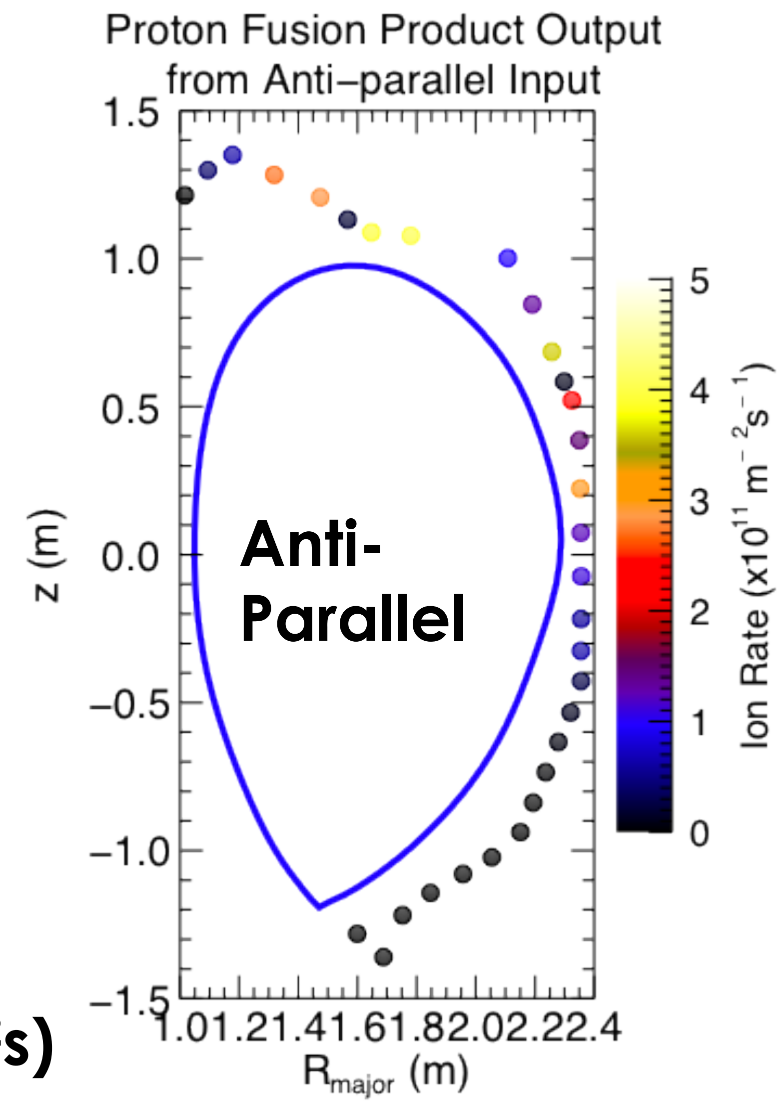
- Trapped particles get preferentially lost to different locations than passing particles



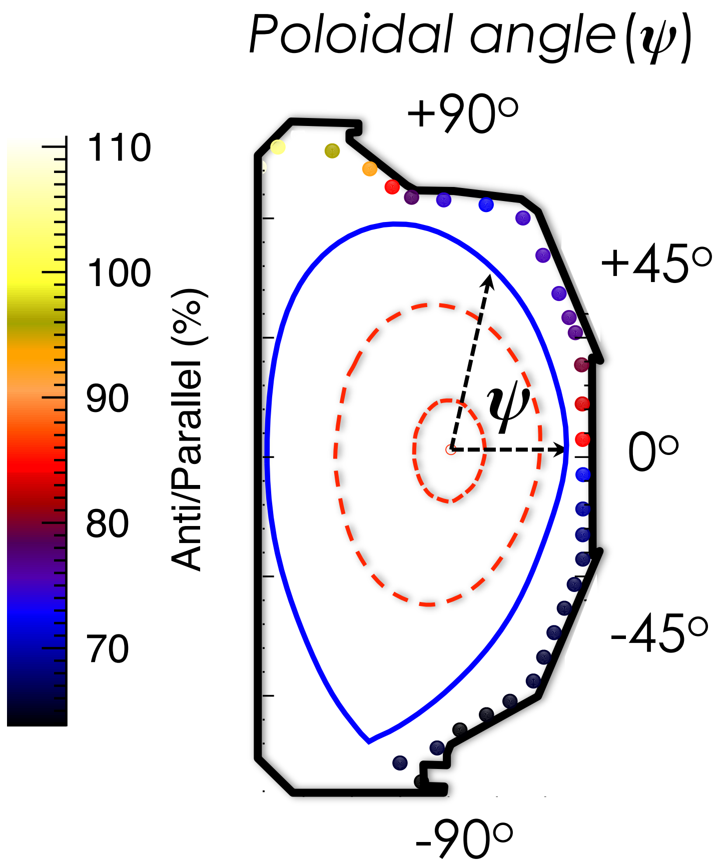
Following protons of various birth locations and pitch angles reveals final losses to walls in DIII-D

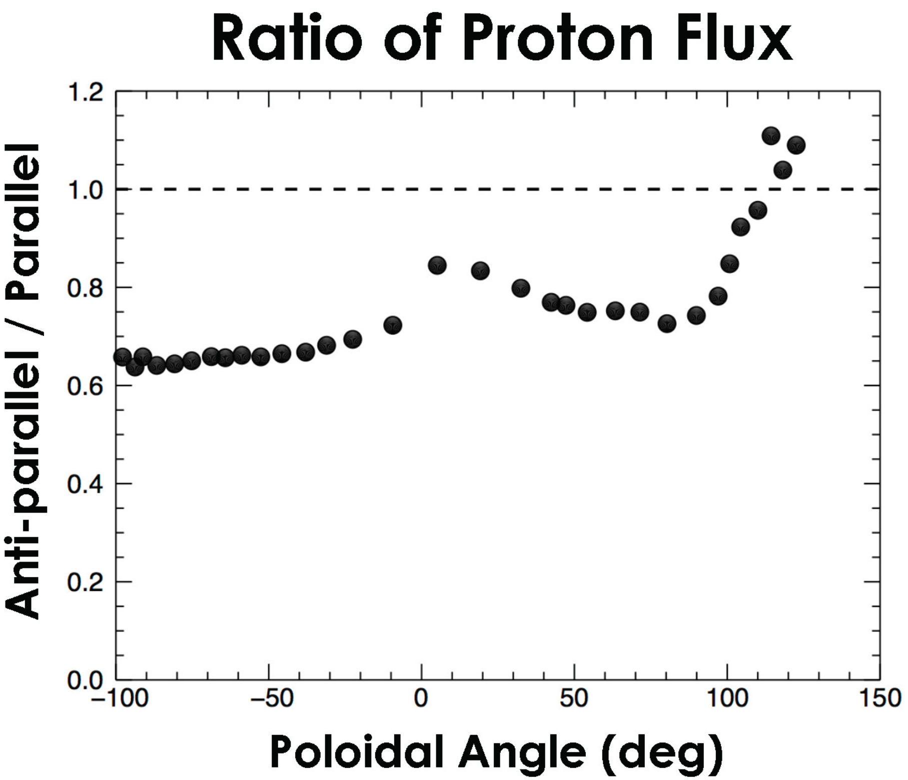


Ion Rate
$10^{11}/(m^2s)$



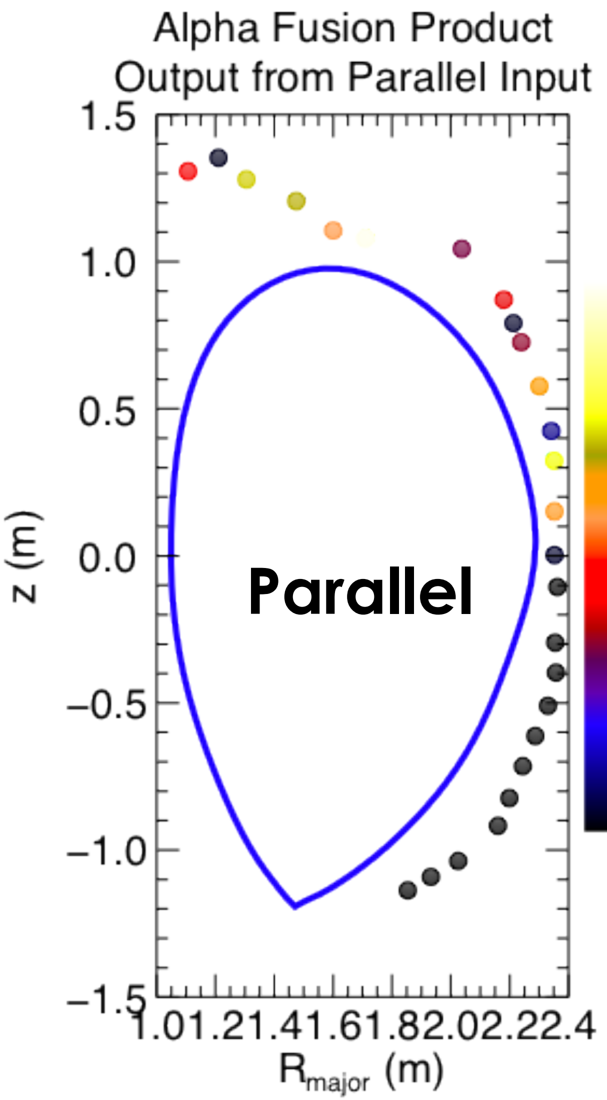
Ratio of parallel to anti-parallel proton fusion product poloidal distribution yields up to 30% change

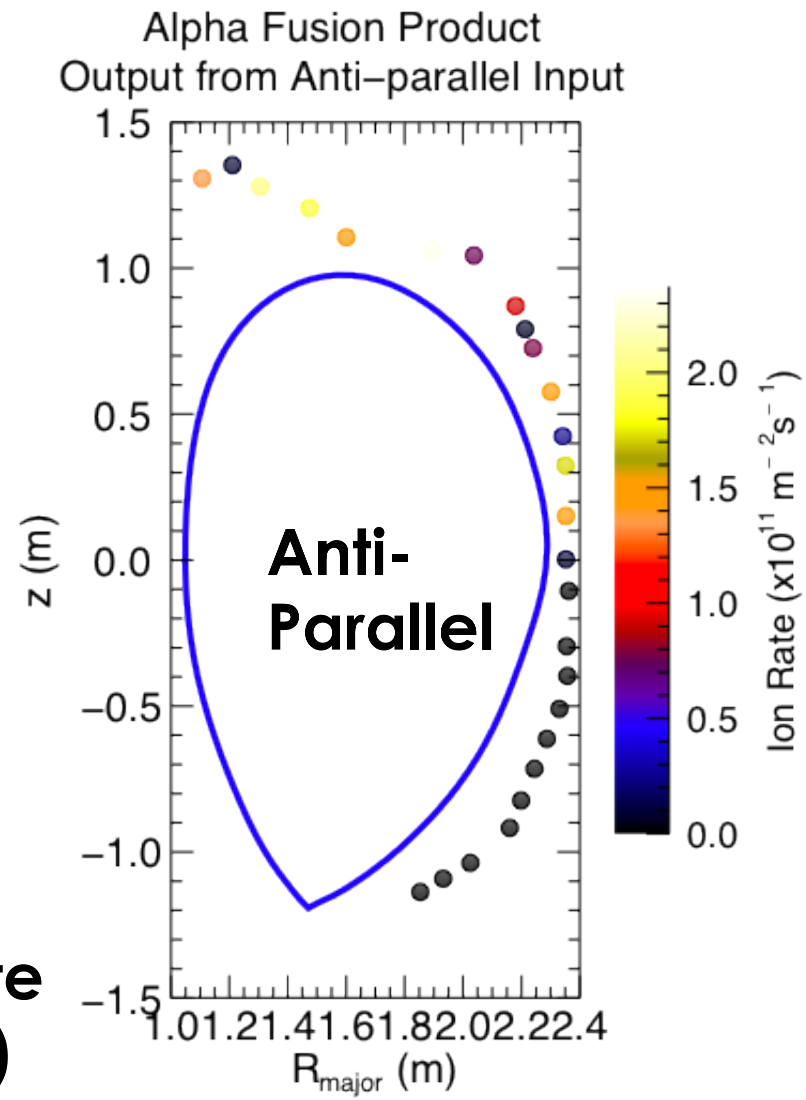




Characteristic signature of SPF is poloidal dependence of Anti/Parallel proton ratio

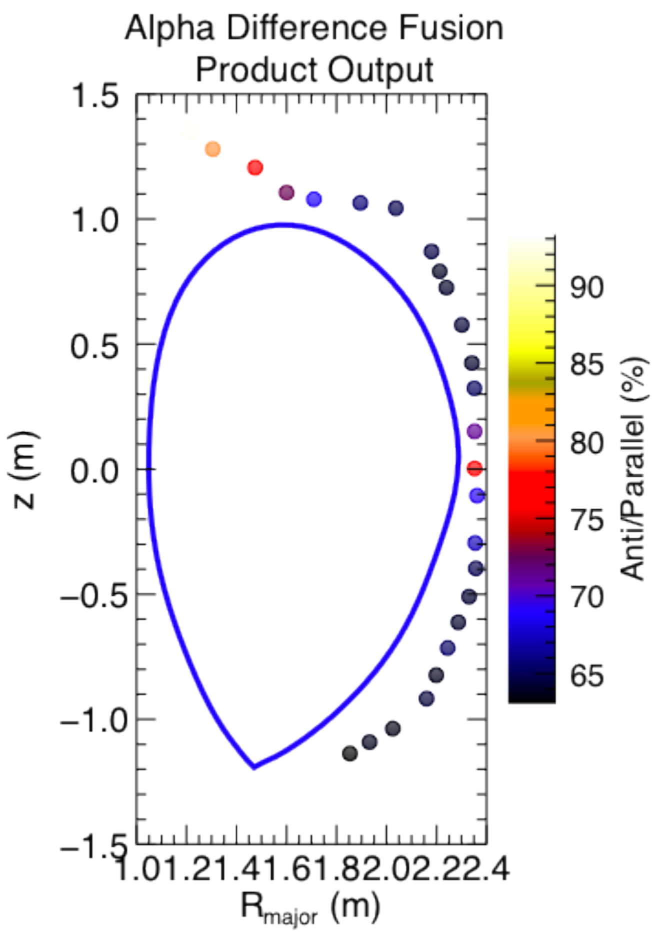
Following alphas of various birth locations and pitch angles reveals final losses to walls in DIII-D

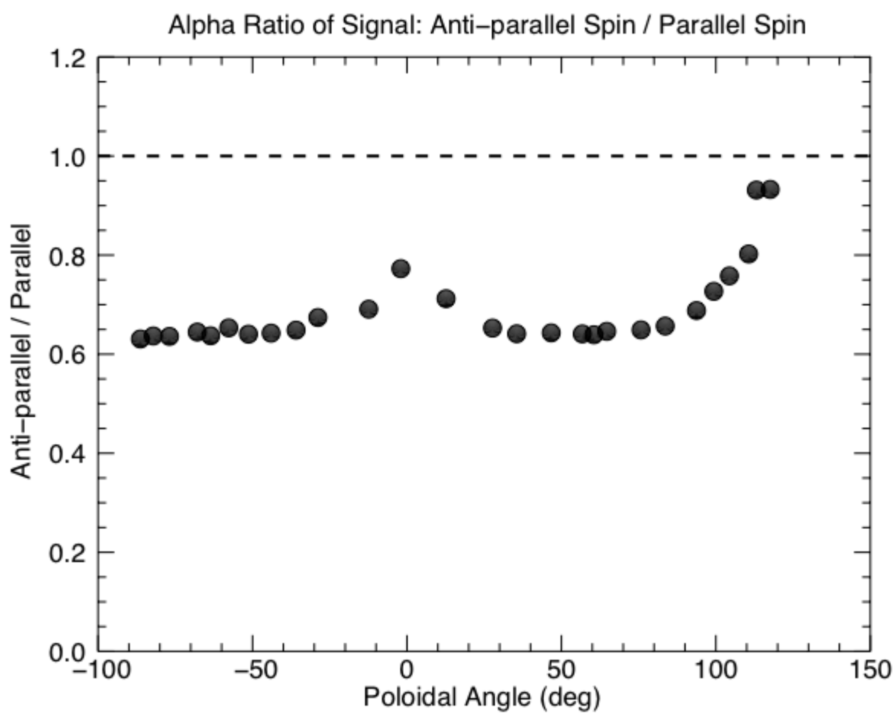




Alpha Rate
$10^{11}/(m^2 s)$

Ratio of parallel to anti-parallel alpha fusion product poloidal distribution yields up to 30% change





Characteristic signature of SPF is poloidal dependence of Anti/Par alpha ratio

DIII-D Experiments will Confirm Polarization Lifetime by Comparing Fusion Product Yields

- **Prepare polarized deuterium with existing Jefferson Lab facilities: solid $H\vec{D}$ pellets**
  - diff
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  - fired from 2 K pellet launcher at DIII-D

standard technology well established in nuclear physics experiments

- **Develop polarized ^{3}He with existing U. Virginia facilities: gas-filled ICF-type pellets**
  - buil
  - fire

active research and technique development

- **Fire pe**
  into ap

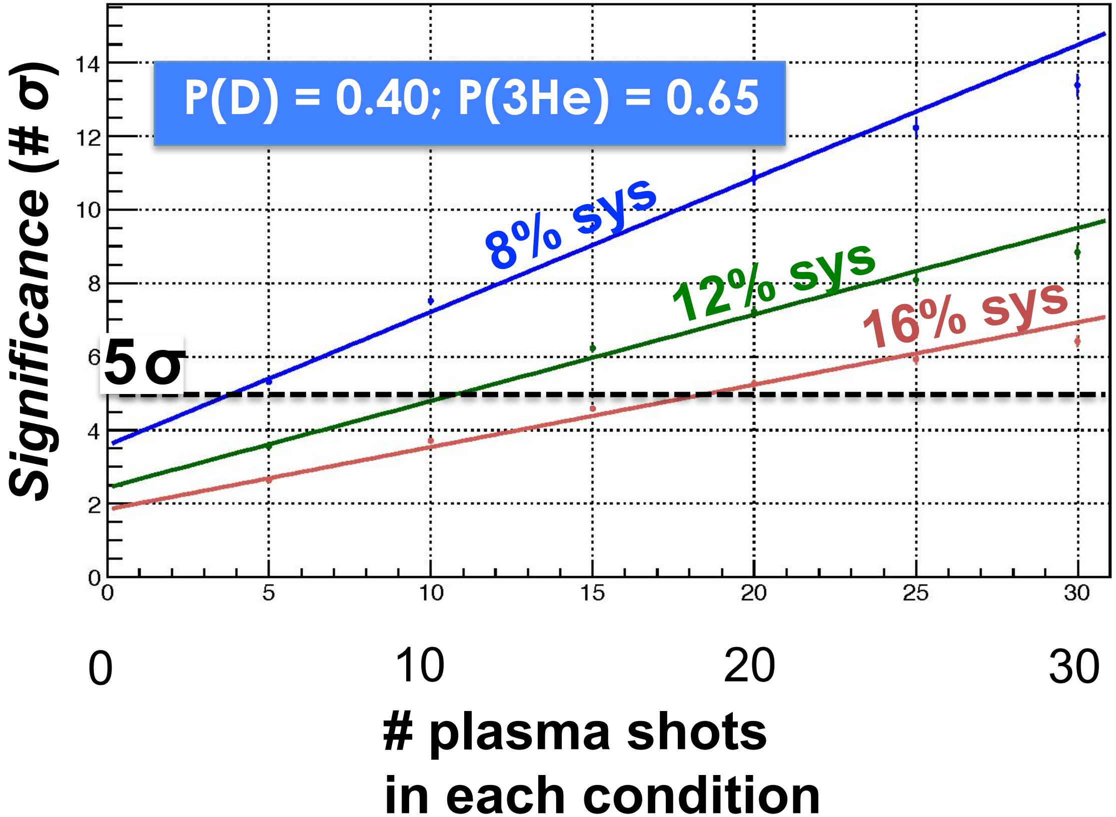
$H\vec{D}\Uparrow + {}^3\vec{He}\Uparrow$

signal-to-noise must satisfy certainty criterion

$H\vec{D}\Downarrow + {}^3\vec{He}\Uparrow$

Scientific Demonstration of an SPF Effect May Require ~40 (Repeated) Plasma Shots

- **Scientific demonstration achieved when effect is measured at 5σ certainty**
- **Expected significance level determined from Monte Carlo calculations**
- **Significance depends strongly on shot repeatability**
  - 8% variation → 4 shots
  - 16% variation → 18 shots

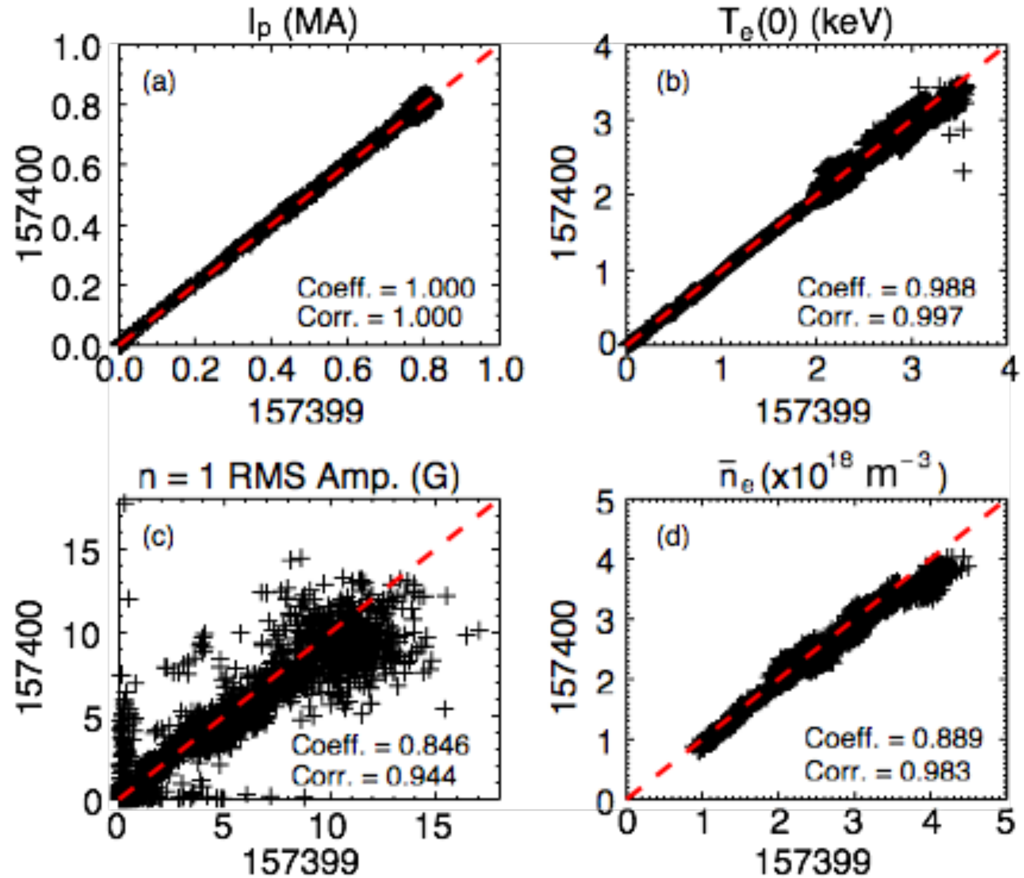


A.M. Sandorfi and A. D'Angelo, Springer Proc. Phys. 187 (2016) 115
A.M. Sandorfi, et al., (to be published)

DIII-D Shots are Generally Reproducible, though it Remains to Demonstrate this for an SPF-relevant Plasma

- **Repeating a shot produces the same result, even when considering instabilities**
- **High-performance discharges exhibit ~10% variability in peak temperatures***
- **Need to determine the profile repeatability in a high ion temperature shot**

$$R \propto n_{He} n_D T_i$$



*G.L. Jackson, "DIII-D shot series with similar shots," *Internal Memo*, December 9, 2014

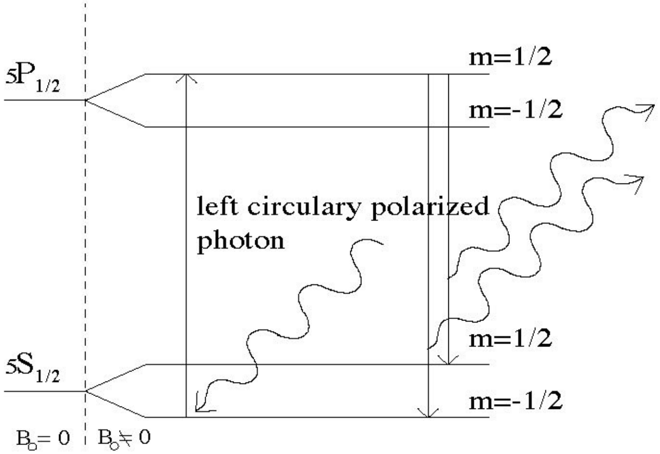
Development of Spin Polarized Fusion (SPF) Could Yield Great Rewards; Further Research Needed

- **SPF can reduce reactor costs through increased fusion rate at given plasma conditions**
- **Test of polarization lifetime can be achieved in DIII-D plasmas**
- **Companion work is leading to improved techniques for fuel preparation**

Supplementary Slides

^{3}He is Regularly Polarized; Newest Results Show that Polarization Survives Permeation through Shell

- **^{3}He is polarized through spin-exchange optical pumping**
  - Rb vapor pumped with 795 nm, 100 W laser in an oven at > 200 C
  - Rb transfers polarization to K by collisions
  - K transfers polarization to ^{3}He by collisions

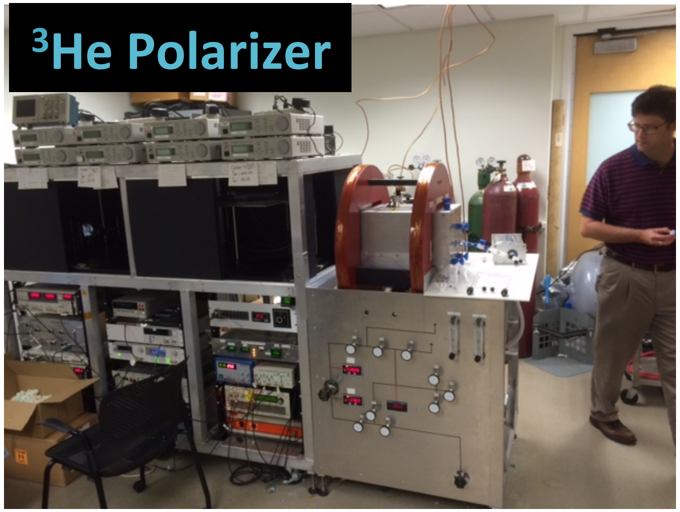


- **Typical polarization is 70% @ 10 amagats (~10 atm)**

- **Large volume targets are used in Nuclear Physics experiments**

- **Challenge for the tokamak fuel**
  - high power laser, polarize materials inside a glass cell
  - remove alkalis (~few ppm)
  - permeate through ICF-type shell

Experiments Confirm ^{3}He Maintains Polarization During Permeation Process



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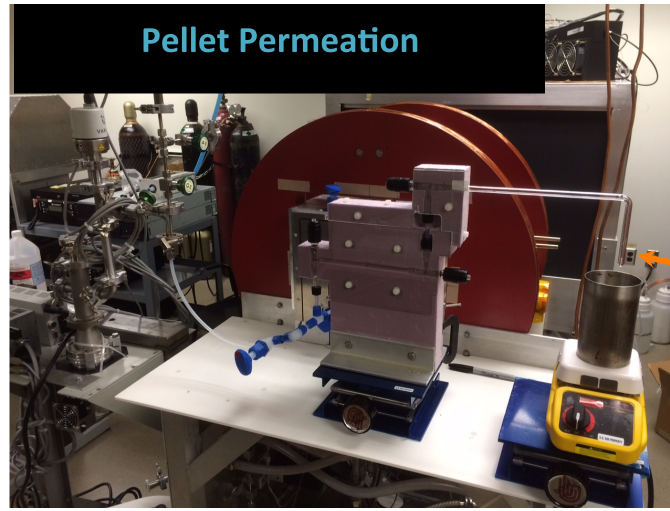
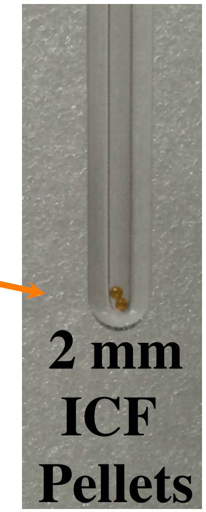
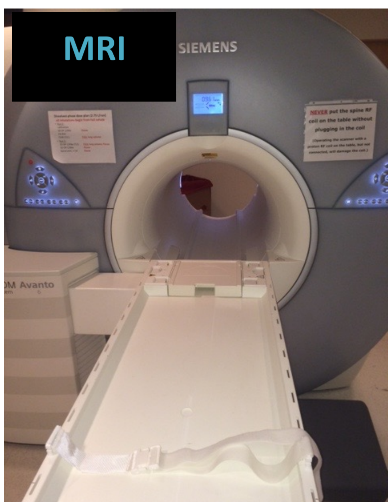


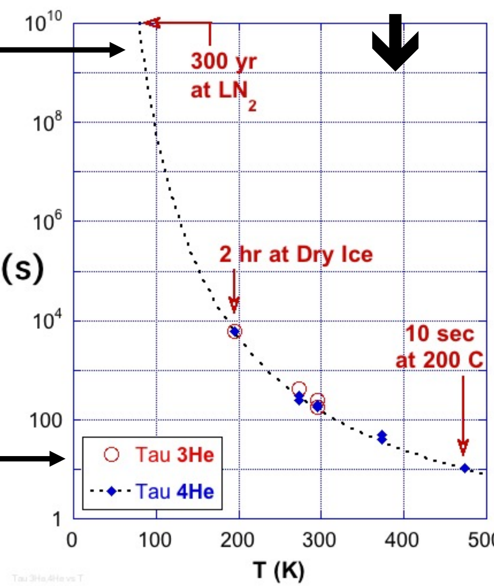




- Cool to LN_2 to seal pellet
- Polarization decay

$$P_{\rm ICF} = P_o\left(1 - e^{\frac{-t}{\tau}}\right)$$

- Permeation at 20 - 200 C



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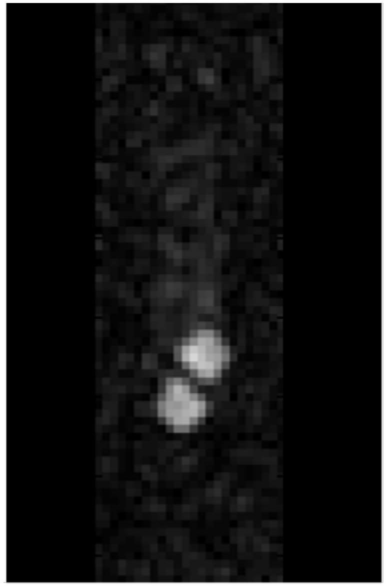
Jefferson Lab

Experiments Confirm ^{3}He Maintains Polarization for Hours Following Permeation through a Shell

- 2 mm Ø GDP pellets in a glass tube



- pellets permeated with polarized ^{3}He, cooled to 77K to seal, ^{3}He outside removed

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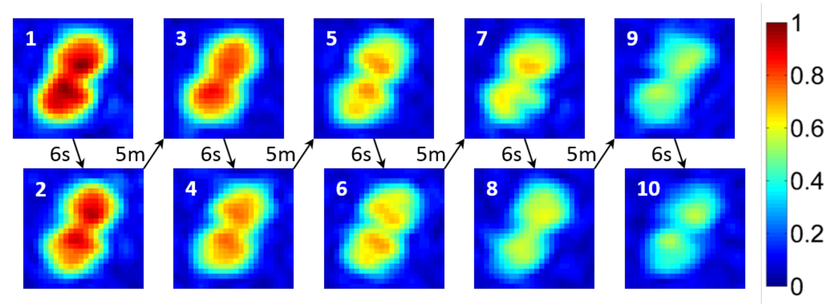
- further R&D is ongoing



- MRI time sequenced images; signal loss dominated by RF loss; ⇔ polarization decay T_1 > 6 hours

ICF pellets can be filled with polarized ^{3}He and maintained for hours at LN_2 (77 K)

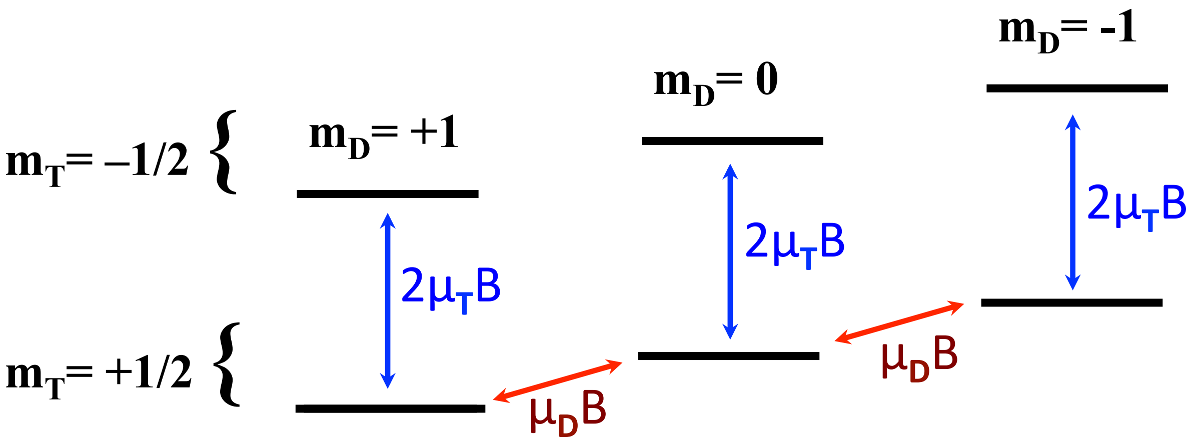
Previous Cost/Benefit Analysis Determined SPF is a Worthwhile Development for Reactor Applications

- **Analysis published in 1985:**
  P. Finn, J. Brooks, D. Ehat, Y. Gohar, C. Baker, R. Mattas, NL/FPP-85-1 Report DE86-007949; Fus. Sci. Tech. 10, 902 (1986)

- **Modeling setup**
  - plant costs are ~1/10 * ITER (STARFIRE design)
  - full polarization of injected fuel
  - no consideration for increased alpha heating
  - result: insignificant increase in reactor cost to implement SPF

- **Modest gains projected**
  - reduced cost for necessary current drive to reach ignition
  - increased lifetime of first wall
  - allows for reduced field and reactor size
  - reduced operating cost per MW

Enhanced D and T Spin Substate Populations do not Arise Naturally in a Tokamak Magnetic Equilibrium



D-T Zeeman levels

$\mu_T = 9.4 \times 10^{-11}$ keV/Tesla

$\mu_D = 2.7 \times 10^{-11}$ keV/Tesla

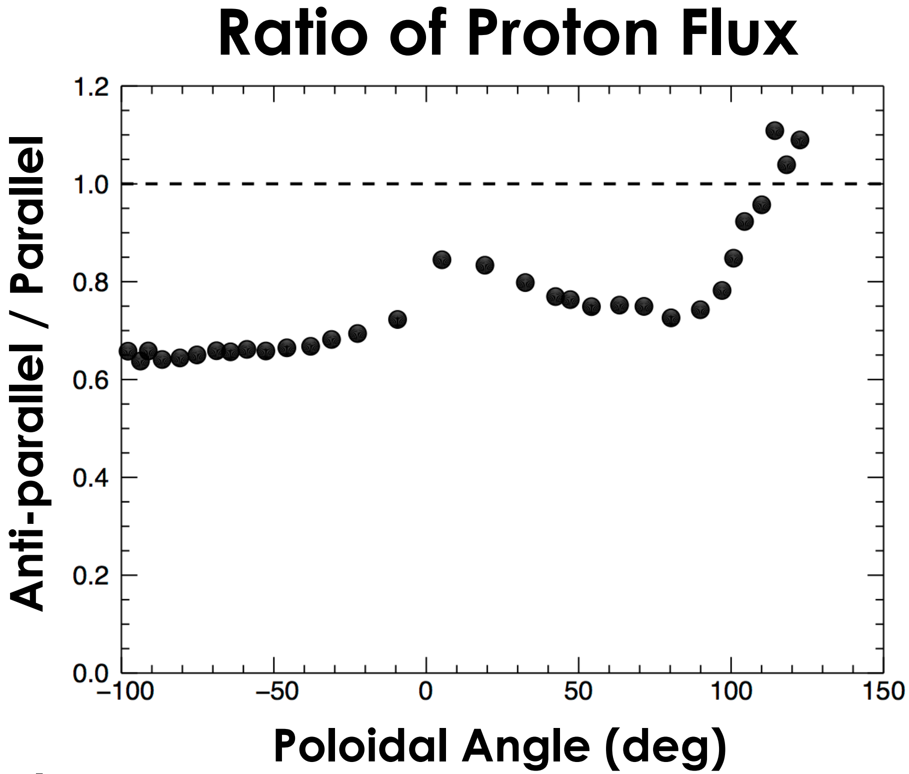
- **Unequal populations → *polarization***
- **Triton polarization: P(t) = N(– ½) – N(+ ½)**
- **Deuteron vector polarization: P^V(D) = N(– 1) – N(+ 1)**
  - spin all parallel to B: P = +1
  - spin all anti-parallel to B: P = -1
- **Negligible polarization from tokamak field ~ 10^{-9}**

Charged Fusion Products Reach the Walls with a Unique Poloidal Profile Conducive to Measurement

- Proton and alpha products from D + ^{3}He reaction are lost due to their large orbit size: 14.7 MeV proton → 25 cm gyroradius at 2.15 T

- Modeled scenario shows the majority of lost protons spread across a 50° poloidal range of the wall

- Large SPF effect manifests as differences in fusion proton flux between anti-parallel and parallel spin alignment cases



Characteristic signature of SPF is poloidal dependence of Anti/Par proton ratio