Polarized Fusion, its implications and plans for Direct Measurements in a Tokamak Plasma

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for

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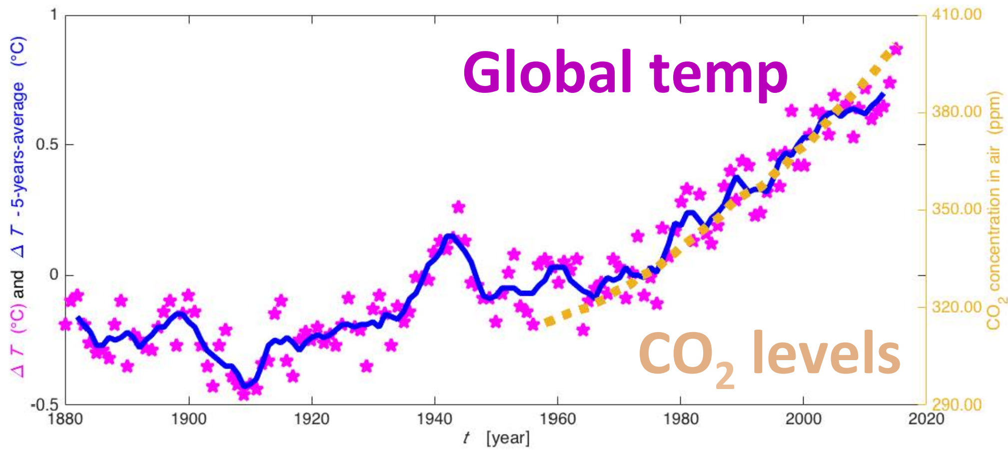
The world is burning !

• dramatic consequences cannot be avoided

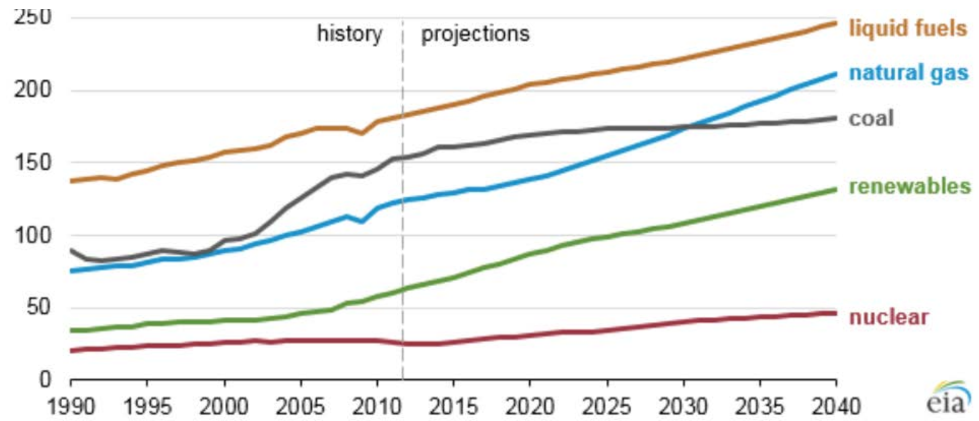
• Q: is there anything that we have learned from spin which could mitigate them ?

• A: not in the short term, but in the longer term, yes quite possibly, in the push towards fusion power



G. Ciullo, *Nuclear Fusion with Polarized Fuel*, Springer Proc. Phys., Springer-Verlag (2016)

Projected world energy consumption

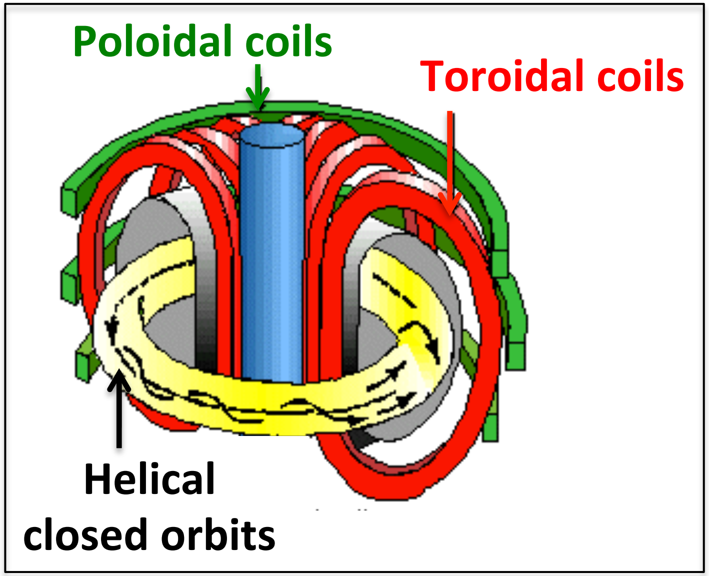


US Energy Information Administration

The road to fusion through magnetic confinement - preliminaries

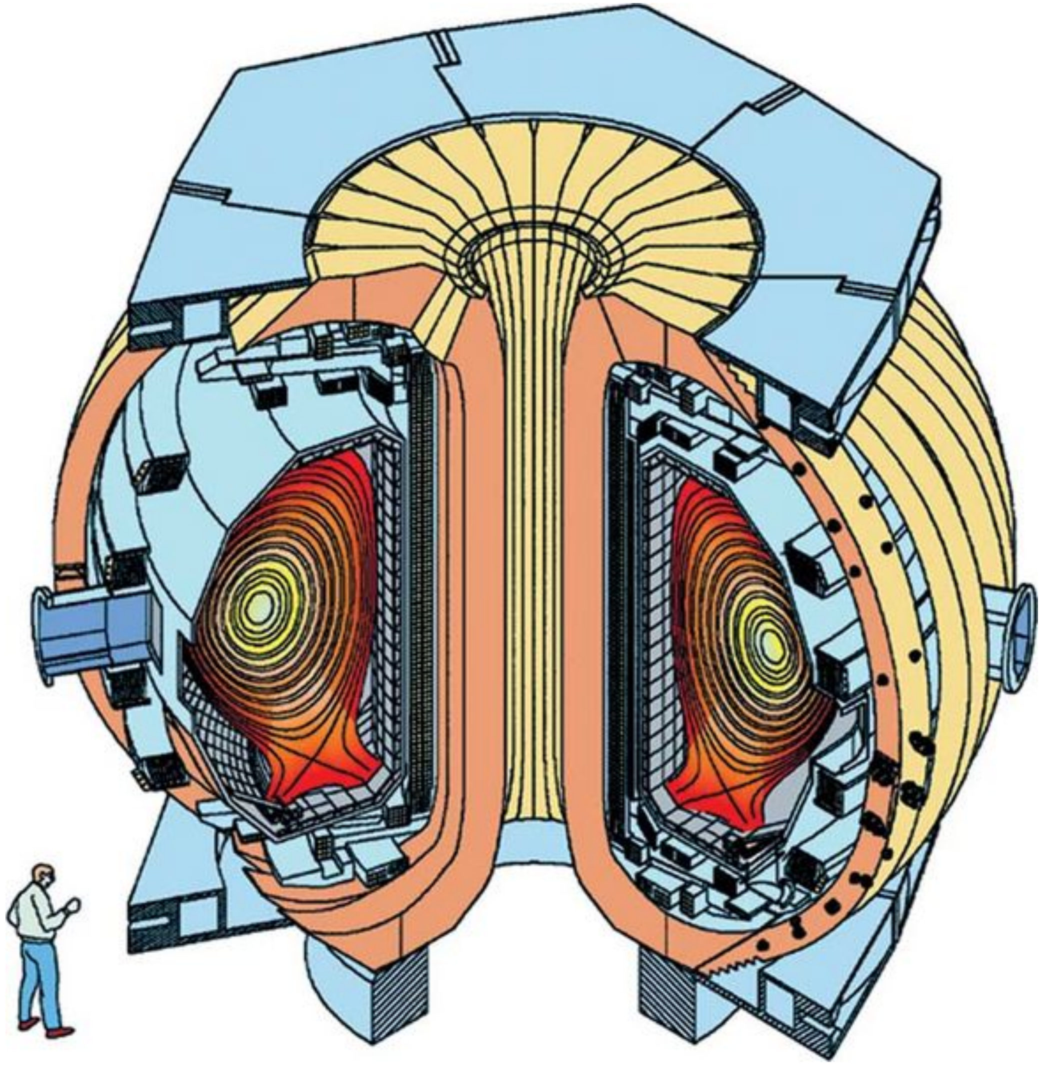
D + t → α + n ,   Q = 17.6 MeV

⇔ 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)

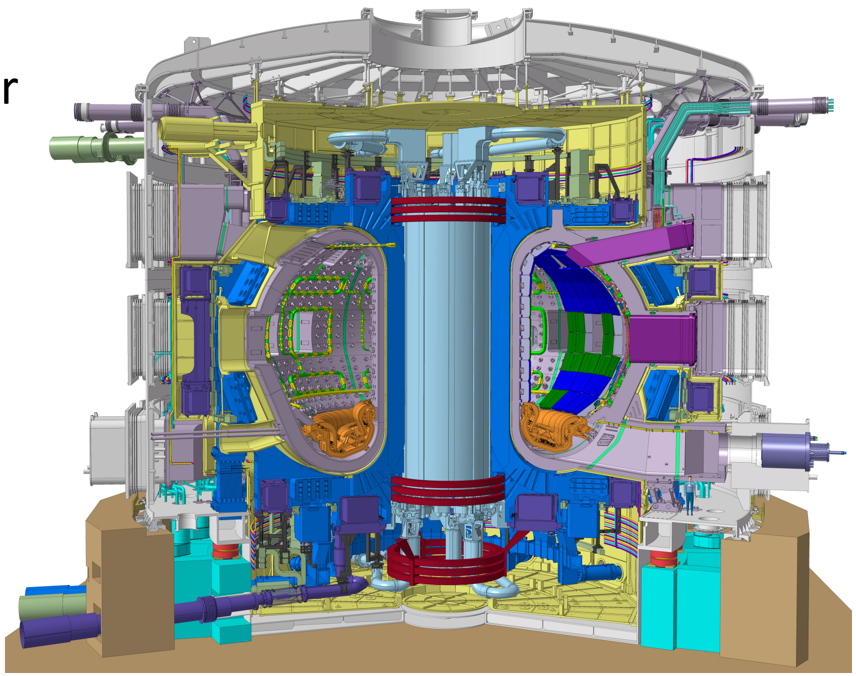
The road to fusion through magnetic confinement - preliminaries

- about 180 research tokamaks have been built; there are currently about 30 in operation

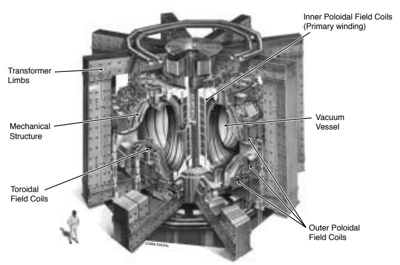
⇔ mostly studying ***D+D*** reactions

- quantum leap towards fusion power: **I**nt. **T**hermonuclear **E**xperimental **R**eactor

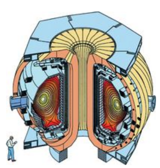
ITER
(Cadarache / France)



JET
(Oxfordshire / UK)



DIII-D
(San Diego / USA)



best instrumented -most diagnostics

only machine that can run with tritium

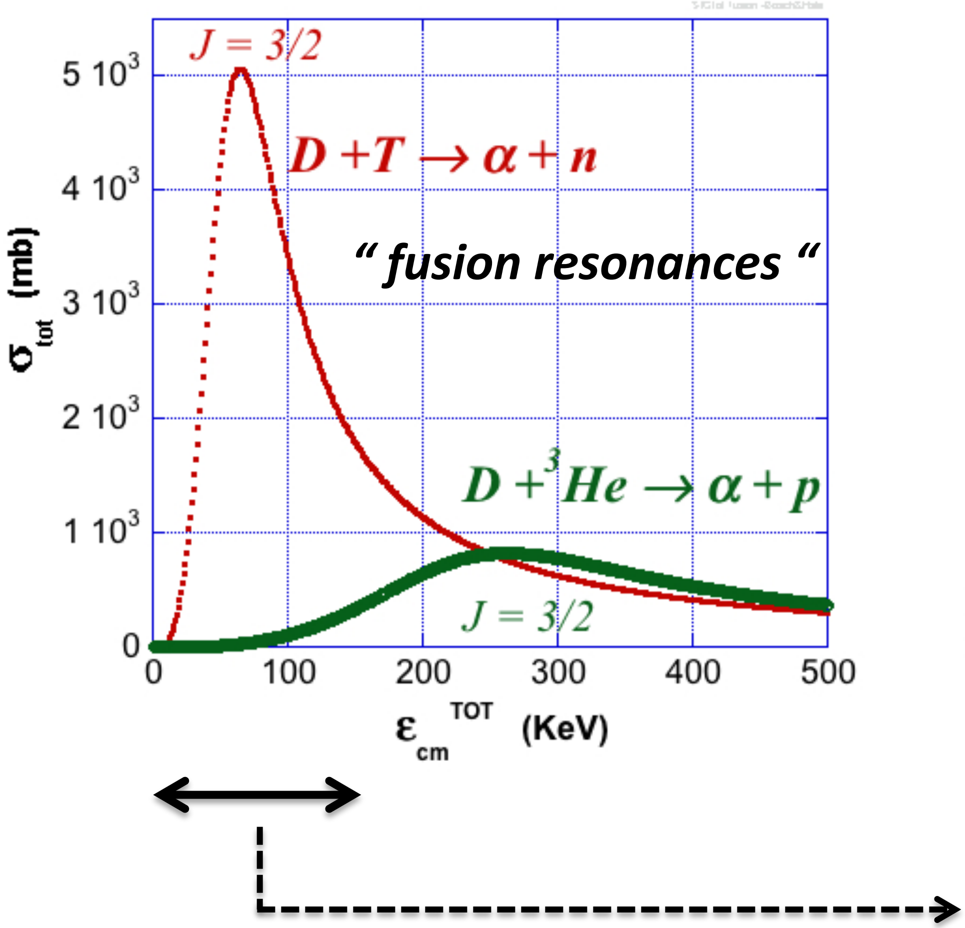
½ GW reactor - under construction

The road to fusion through magnetic confinement

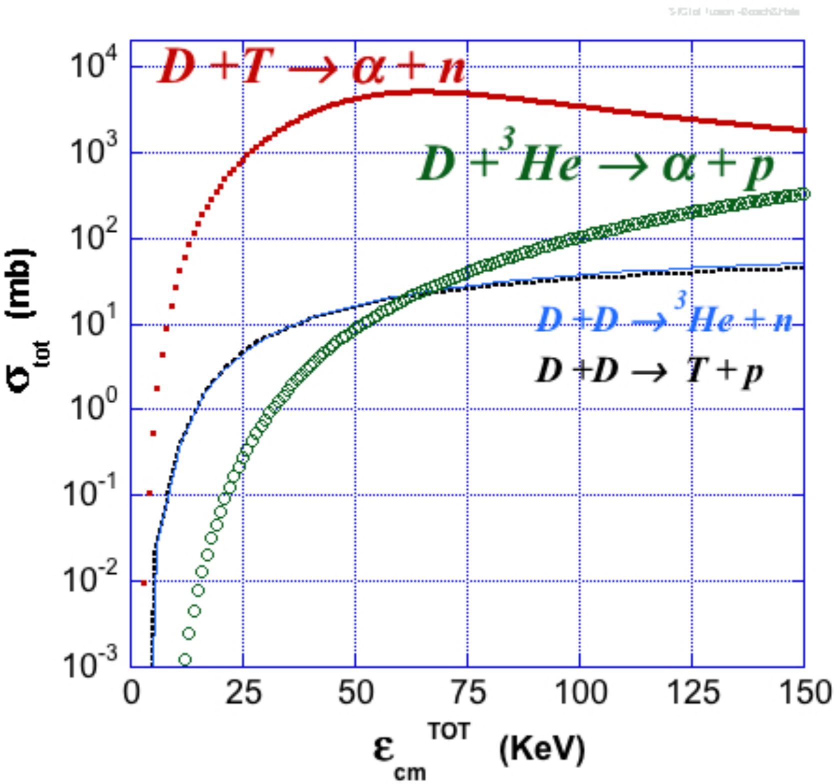
	V(plasma)	B_c (tesla)	P(MW)	Q = P(fus)/P(in)	coils
DIII-D	20 m^3	2.1	—	<<1	normal
JET	90 m^3	3.8	16	~ ⅔	normal
ITER	700 m^3	5.3	500	~ 10	superconducting

- **superconducting coils are needed to reach high field over a large volume**
  ⇔ concerns over potential field degradation from neutron flux
- **ITER is to be a stepping-stone, requiring at least one more iteration to reach a viable fusion power plant**
- **Plant costs ~ V(plasma) x $(B_c)^2$** ⇔ *eg*. **20 – 40 B$ for ITER**

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



The potential of SPIN

- ***fusion fuels:*** ***D + T ⇨ α + n*** ; (and *D +* ^{3}*He ⇨ α + p*)
  - ↔ *dominated by J=3/2 resonance just above reaction threshold*
  - ↔ *ion temperatures < 10s of KeV ⇨ s-waves dominate*
  - ↔ *D (s=1) and T (s=½) preferentially fuse when spins are aligned*

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

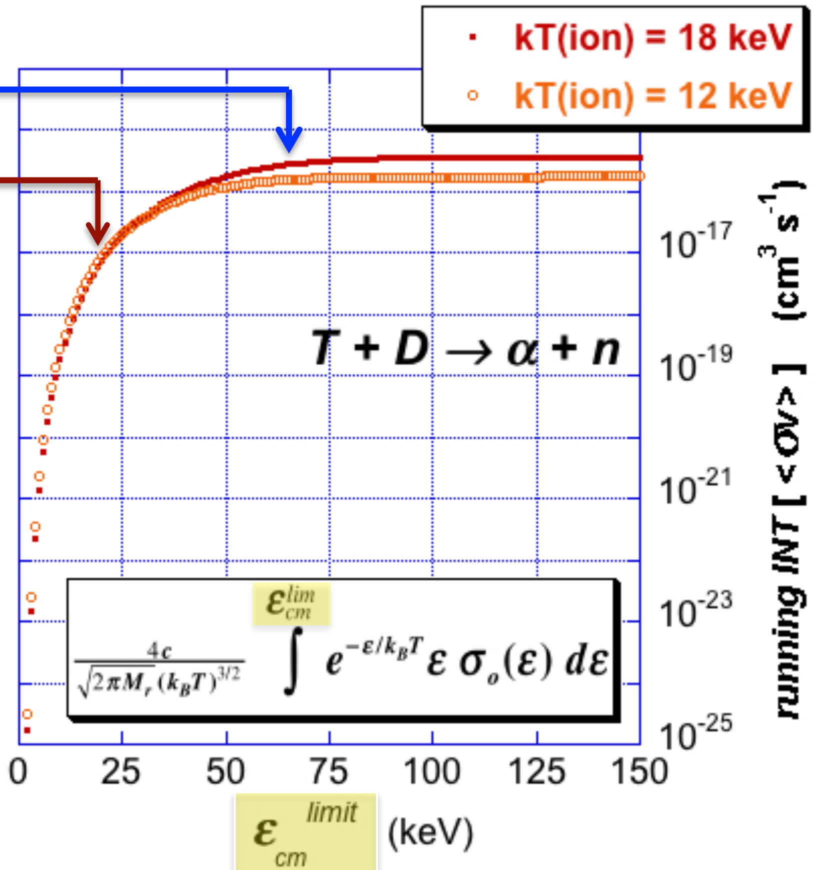
- ***polarized fuels*** ⇔ *up to **50%** enhancement in the cross section*

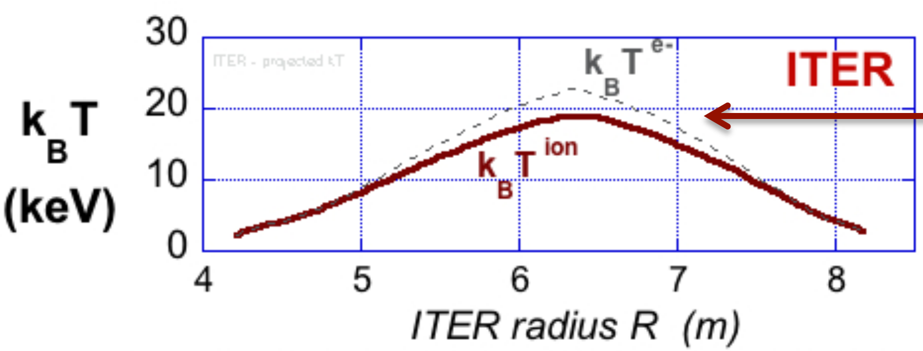
Reaction rates in a heated plasma
~ cross sections averaged over a Maxwellian velocity distribution

$$R = n_D\, n_T\, V_{pl} \times \left\{ \langle \sigma v \rangle = \frac{4c}{\sqrt{2\pi M_r}\,(k_B T)^{3/2}} \int e^{-\varepsilon/k_B T}\, \varepsilon\, \sigma(\varepsilon)\, d\varepsilon \right\}$$

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

- **D+T resonance peaks at 65 keV**
- **ITER plasma expected to peak at 18 keV**
- most of the yield from low energies
- <σv> integral extends to higher energies but saturates by ~ 50 keV





ITER Design Report, Plasma Physics and Controlled Fusion **44** (2002) 519

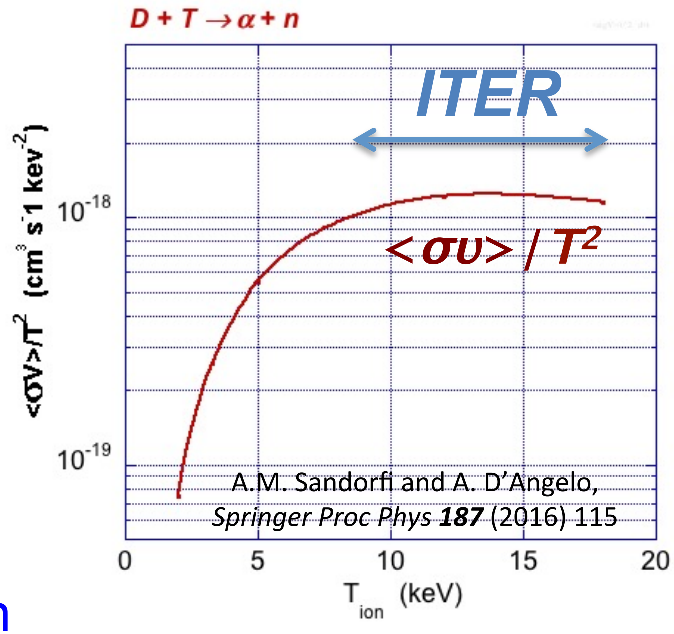
alpha heating ⇔ non-linear enhancements from the resonance tails

Recast the fusion rate:

$$R = n_D n_T V \cdot \langle \sigma \upsilon \rangle \;=\; \frac{\beta^2}{4\mu_0^2} V \cdot \frac{\langle \sigma \upsilon \rangle}{T^2} \cdot B^4$$

plasma pressure ~ constant

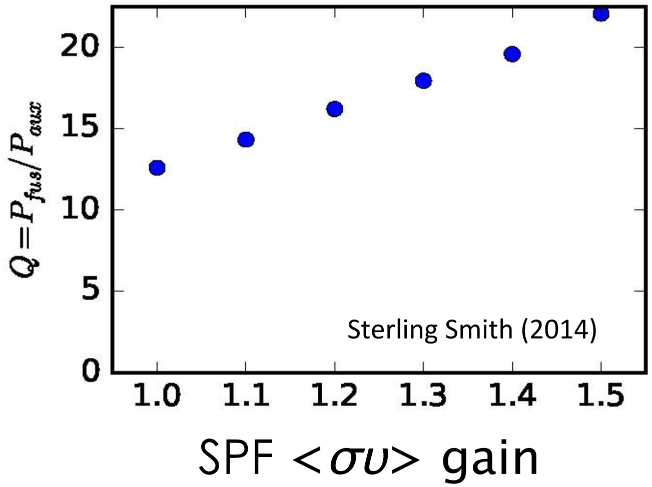
~ constant for ITER



⇔ new simulations for ITER show net 75% gain in power and Q = P(fusion)/P(in) with spin polarized fuel, from increased alpha heating

⇔ polarization equivalent to 15% change in B

⇔ on the ITER scale, Q = 10 could be reached even with toroidal field degradation



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- ***polarized fuels*** ⇔ *up to **50% enhancement** in the cross section*

  ⇔ ***up to 75% enhancement in power and Q***

  ⇔ *could compensate for 15% magnetic field degradation on the ITER scale, and maintain high Q*

  ⇔ *costs savings of future fusion reactor plants (~ B^2) as much as 30% ⇔ a potentially huge factor !*

Polarization survival - history

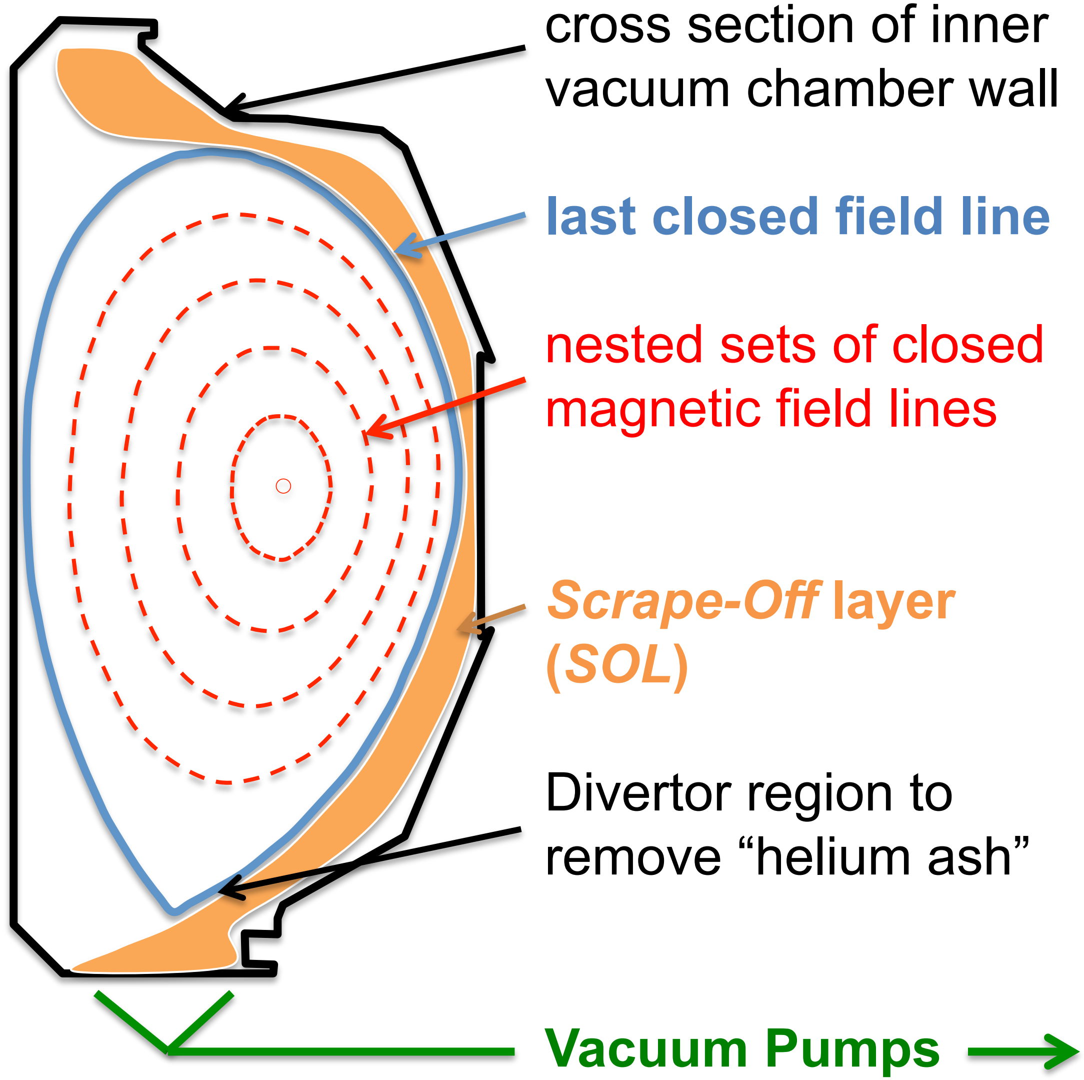
- Potentially large benefits require fuel polarization to survive a 10^8 K plasma for the energy containment time ~ a few sec

- **History**
  - Kulsrud, Furth, Valeo & Goldhaber, Phys Rev Lett **49** (82) 1248
  - Lodder, Phys. Lett. A98 (83) 179
  - Greenside, Budny and Post, *J. Vac. Sci Technol.* A **2**(2), (84) 619
  - Coppi, Cowley, Kulsrud, Detragiache & Pegoraro, Phys Fluids **29** (86) 4060
  - Kulsrud, Valeo & Cowley, Nucl Fusion **26** (86) 1443
  - Cowley, Kulsrud, Valeo, E.J. Phys. Fluids 29 (86) 1443

    …

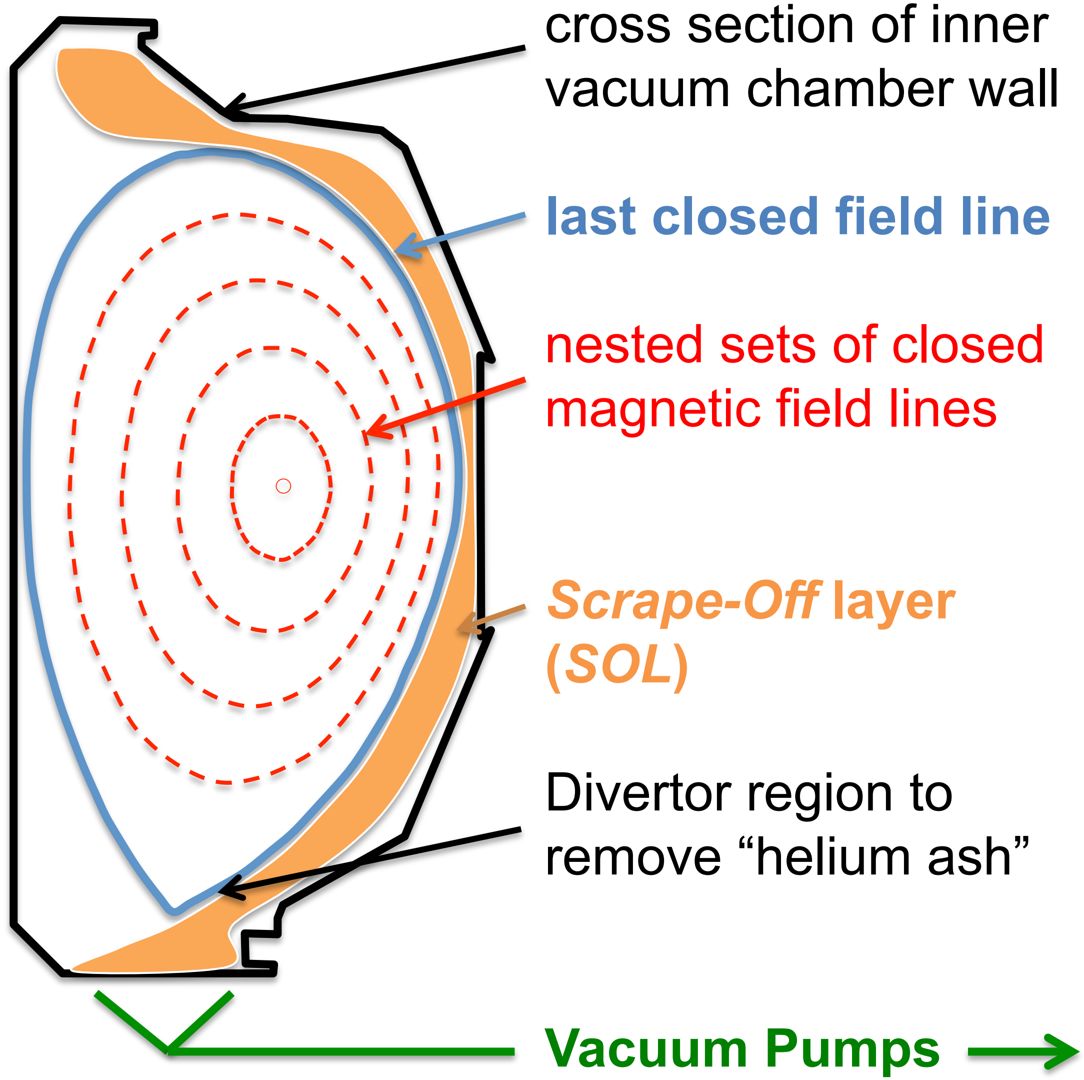
- **Depolarization mechanisms**
  - a great <u>many</u> mechanisms were investigated in the '80s; two survive scrutiny
  - both hinge on **wall recycling**

Wall Recycling through the scrape-off layer



Wall Recycling through the scrape-off layer

- after injection, some few % of the fuel undergoes fusion; the rest escapes the plasma
- escaping ions strike outer walls and are neutralized
- depending on wall conditions, ions could depolarize
- if these reenter the plasma, they could dilute polarization of the core
- fuel leaving the plasma will eventually diffuse through the SOL and be pumped away



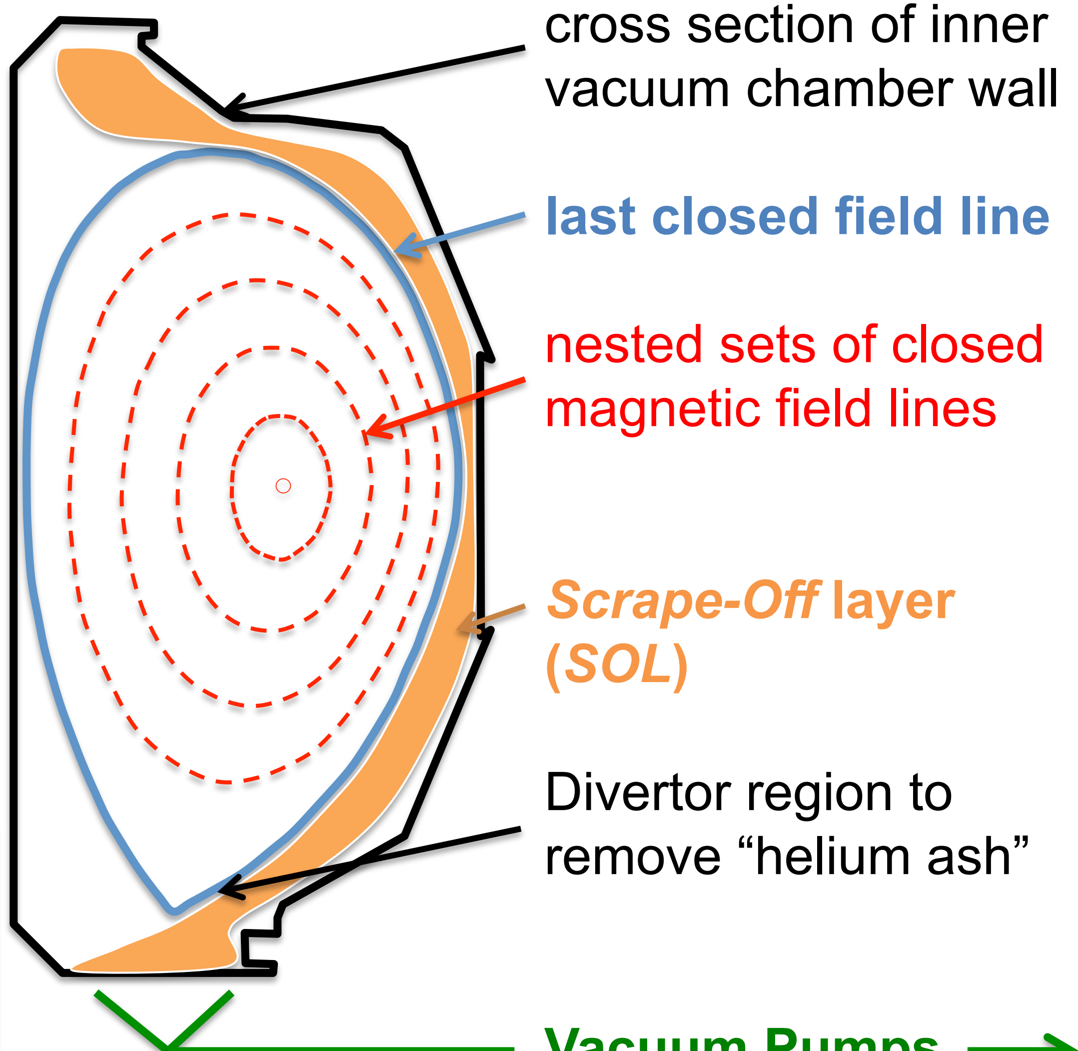
the ITER scrape-off layer

What's new ?

- Plasma Simulations for ITER:

- Pacher *et al.*, *Nucl. Fus*. **48** (2008) 105003
- Garzotti et al., *Nucl. Fus*. **52** (12) 013002

⇔ at ½ GW, the SOL is opaque to neutrals, which are swept to the divertor by convection



⇔ Wall recycling will be insignificant in ITER scale reactors

Q: how to produce polarized fuel for a ~ GW reactor ?

- every characteristic of polarized material comes at a cost;

  eg. NP techniques have emphasized lifetime (T_1) of 10^6 –to- 10^8 sec,
  (which is useless for fusion where ~ 10 sec would be more than adequate)

- ITER will require 2000 moles/day, much more than consumed in NP exps

⇔ **significant R&D, tailored to fusion requirements, will be required**

eg. 0th order speculation:
- spin-exchange optical pumping (SEOP) of molecular DT gas with 2 lasers;
  alternate: separate SEOP of HD and HT (since H is benign in a plasma)
- condense polarized gas to solid pellets for injection with *Pellet Injectors*, modified to maintain continuous magnetic holding fields

- **Crucial to first verify expectation of polarization survival in plasma**

next challenge: demonstrate polarization survival in a plasma

Focused efforts by two groups:

I. SPF (Spin-Polarized-Fusion) Collaboration:

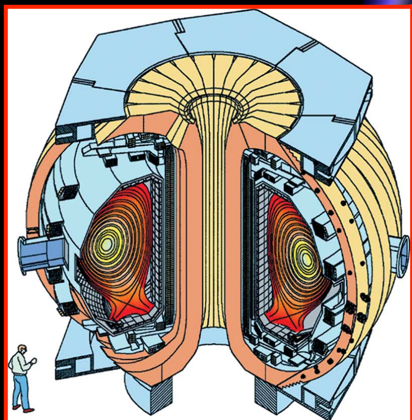
- Jefferson Lab
- DIII-D National Fusion Facility:
  - General Atomics, **(parallel VIII, Applications)**
  - ORNL,
  - UC-Irvine
- University of Virginia **(parallel VIII, Applications)**
- University of Connecticut

II. PolFusion Collaboration:

- Forschungszentrum Jülich
- University Düsseldorf
- TU Darmstadt
- Università di Ferrara **(parallel VIII, Applications)**
- PNPI Gatchina
- Budker Institute Novosibirsk **(parallel VIII, Applications)**

SPF collaboration: Polarization survival test in the DIII-D Tokamak

DIII-D



UVa

General Strategy: use existing NP techniques and equipment to create polarization life-times sufficient to produce fuel for a test at DIII-D, thus mitigating costs for a demonstration exp.

Jefferson Lab

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 and lessons learned can be directly applied to D + T ➔ α + n

Strategy for testing polarization survival in DIII-D

- test reaction: $\vec{D} + {}^3\vec{He} \rightarrow \alpha + p$ {mirror reaction to $D + t \rightarrow \alpha + n$ }
- use existing JLab facilities to create solid $H\vec{D}$; ship to DIII-D
  - ➔ diffuse 200-400 atm HD into ICF shells; cool to solid; polarize H and D; $H \Rightarrow D$ spin transfer to maximize D spin; transport polarized pellets to DIII-D; load into 2 K cryo-gun

- use existing UVa facilities to develop polarized ${}^3\vec{He}$ gas-filled ICF shells
  - ➔ diffuse ~20 atm polarized ${}^3\vec{He}$ into ICF shells; cool to seal; move polarizer to DIII-D; fill shells; load into 77 K cryo-gun
- generate H plasma in the DIII-D Tokamak
  - ➔ inject polarized fuel into plasma, alternating spin alignment:

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

anti-parallel: $H\vec{D} \Downarrow + {}^3\vec{He} \Uparrow$

$\Bigg\} \Leftrightarrow$ *compare proton yields*

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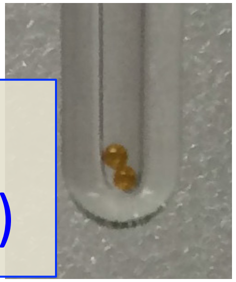
- test reaction: $\vec{D} + {}^3\vec{He} \rightarrow \alpha + p$ {mirror reaction to $D + t \rightarrow \alpha + n$ }
- use existing JLab facilities to create solid $\vec{HD}$; ship to DIII-D



➔ diffuse 200-400 atm HD into ICF shells; cool to solid; polarize H and D; H ⇨ D spin transfer to maximize D spin; transport polarized pellets to DIII-D; load into 2 K cryo-gun

Standard technology – just a small NP target
(eg. parallel IV, Low-Energy)

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$$\left.\begin{array}{ll} \text{parallel:} & \vec{HD}\Uparrow + {}^3\vec{He}\Uparrow \\ \text{anti-parallel:} & \vec{HD}\Downarrow + {}^3\vec{He}\Uparrow \end{array}\right\} \Leftrightarrow \textit{compare proton yields}$$

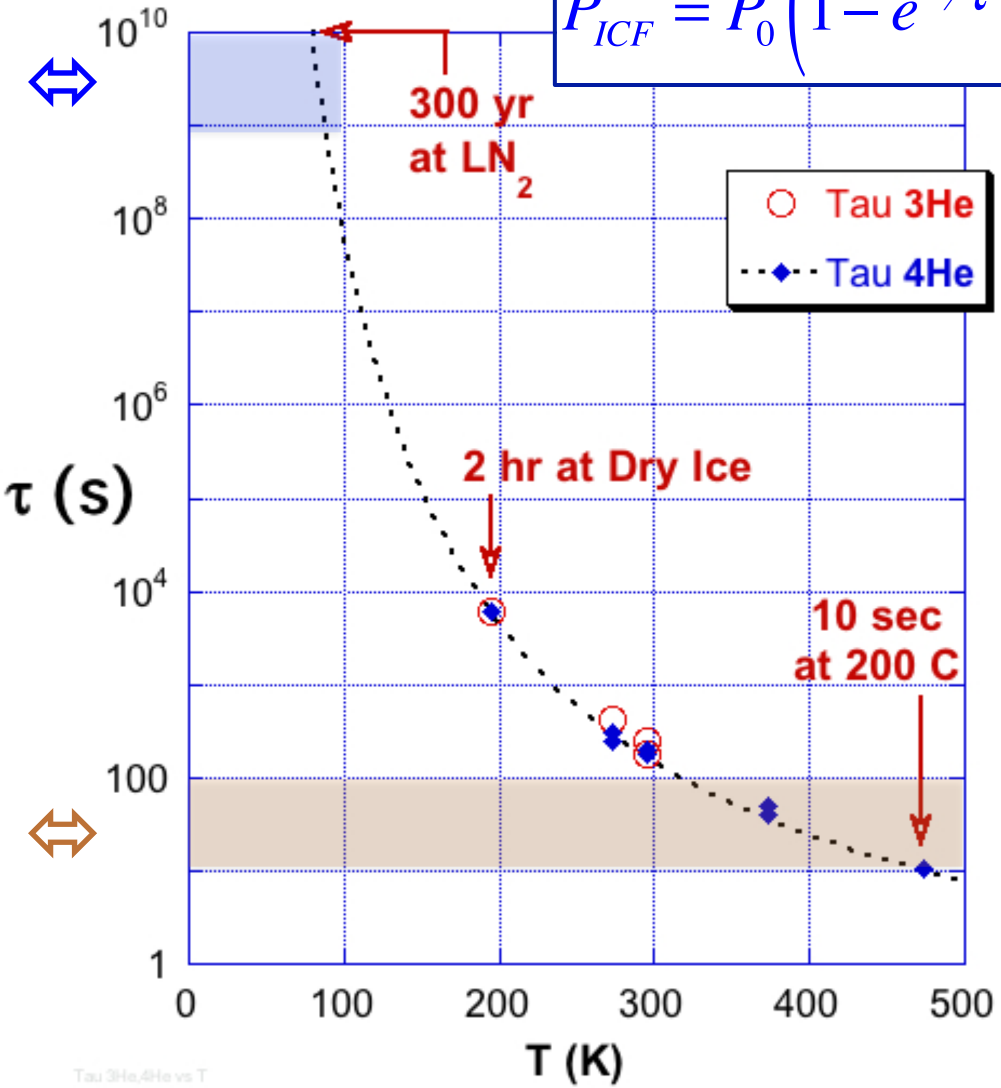
fuel delivery via Inertial-Confinement (ICF) polymer shells

2 mm Ø
ICF shells

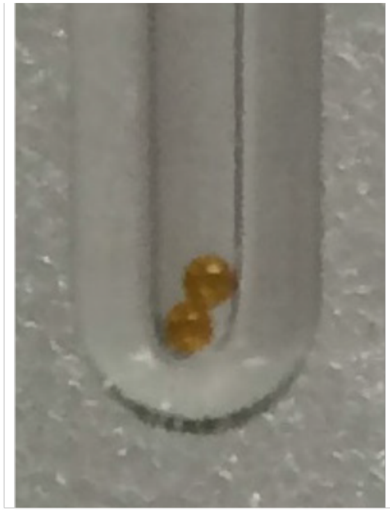
cool to ~ LN_2
to seal shell

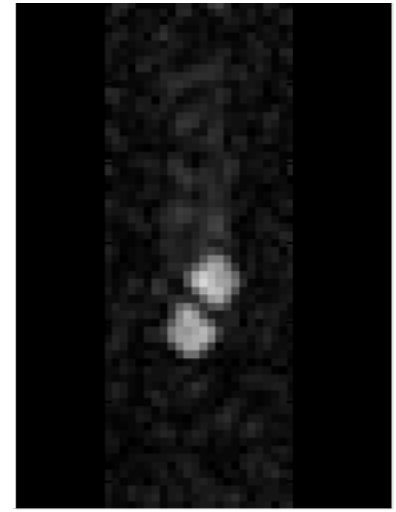
permeate gas through
shell wall, 20 - 200 C

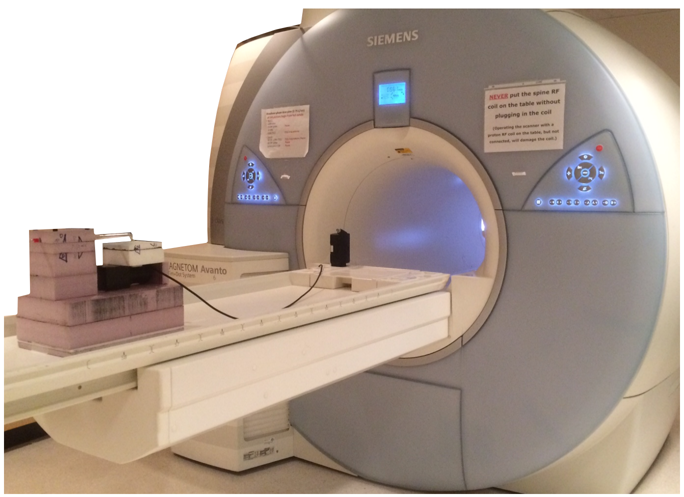
$$P_{ICF} = P_0\left(1 - e^{-t/\tau}\right)$$



Imaging ICF pellets filled with polarized $^{3}\vec{He}$ at UVa





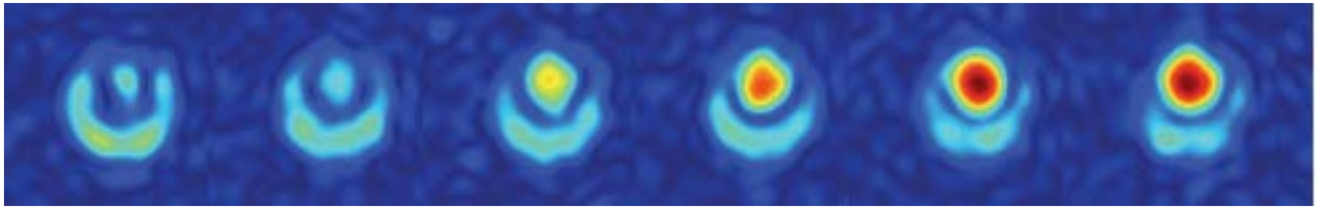


- 2 mm Ø ICF shells in a glass tube

- MRI scan of ICF shells filled with polarized ^{3}He, cooled to 77K to seal, ^{3}He outside removed

^{3}He polarization inside ICF shells can be maintained for ~ 10 hr at 77 K

Options for ICF shells – polarization loss during permeation



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

ICF shell material	Known issues	Fractional loss of ^3He polarization during permeation
GDP (glow discharge polymer)	**free radicals**	~ **0.3** at 295K (*)
PAMS (Poly-alpha-methylstyrene)	no free radicals	tbd
Polystyrene	no free radicals	tbd

* **G.W. Miller, Parallel VIII - Applications**

Likely options to reduce loss:

- Permeate at higher temperature where time spent in polymer wall is less
- Different materials, which have no free radicals

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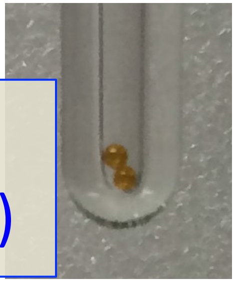

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^{3}He must be polarized 1st, then diffused into shell

(parallel VIII, Applications)

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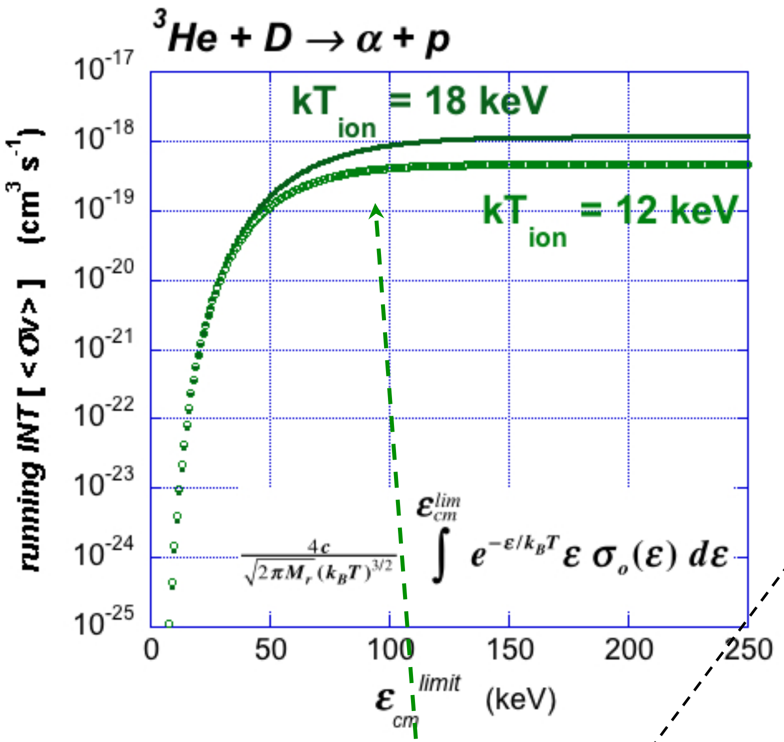
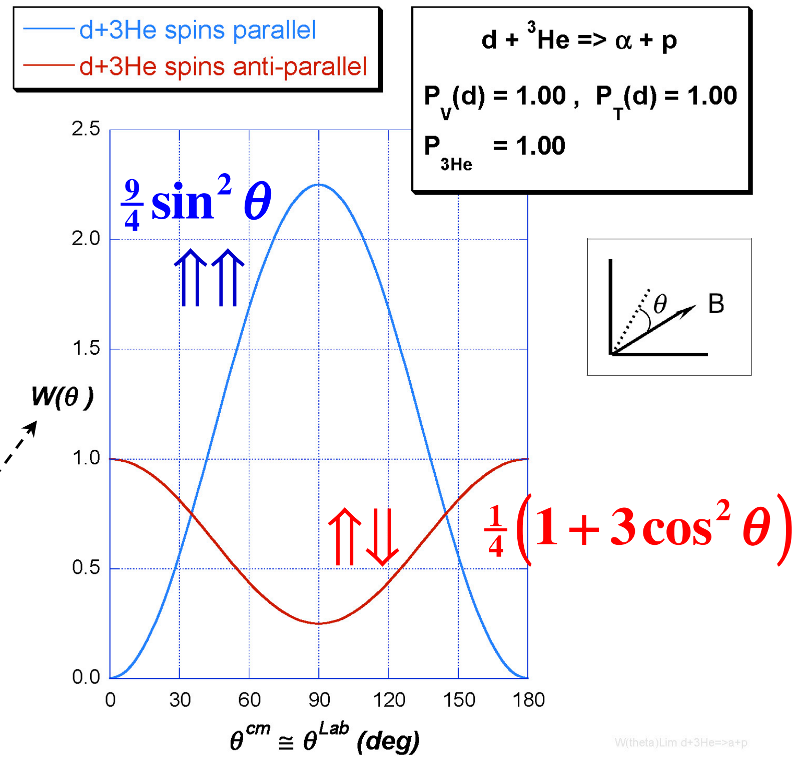
$\Leftrightarrow$ *compare proton yields*

$D + {}^3He \rightarrow \alpha + p$ distributions wrt torus field





$$\langle d\sigma(\theta)\,\upsilon\rangle = \tfrac{1}{4\pi}\langle\sigma_o\,\upsilon\rangle\cdot W(\theta)$$

$$= \tfrac{1}{4\pi}\langle\sigma_o\,\upsilon\rangle\cdot\left\{1-\tfrac{1}{2}P_d^V P_{{}^3He}+\tfrac{1}{2}\left[3P_d^V P_{{}^3He}\sin^2\theta+\tfrac{1}{2}P_d^T\left(1-3\cos^2\theta\right)\right]\right\}$$

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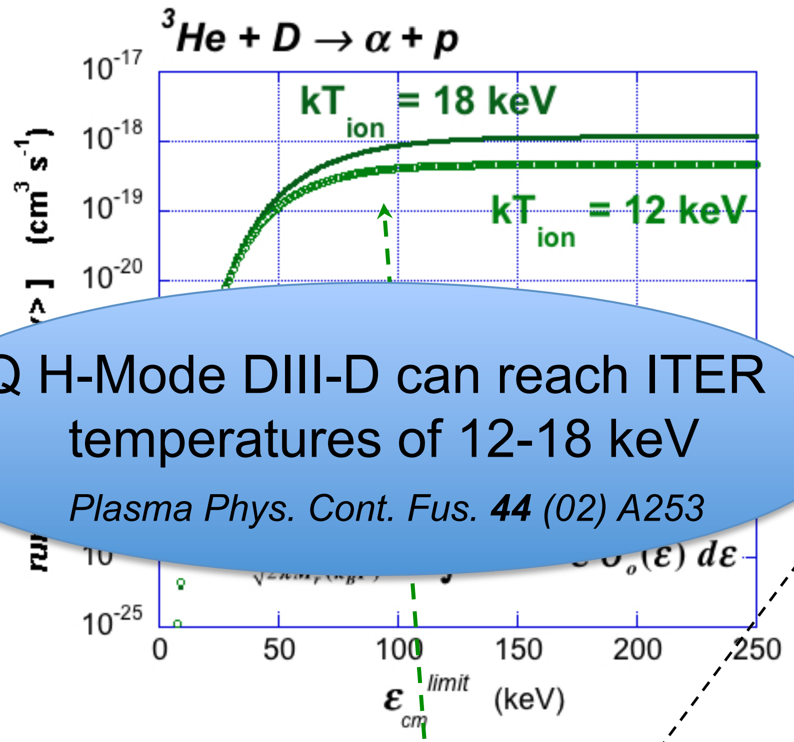
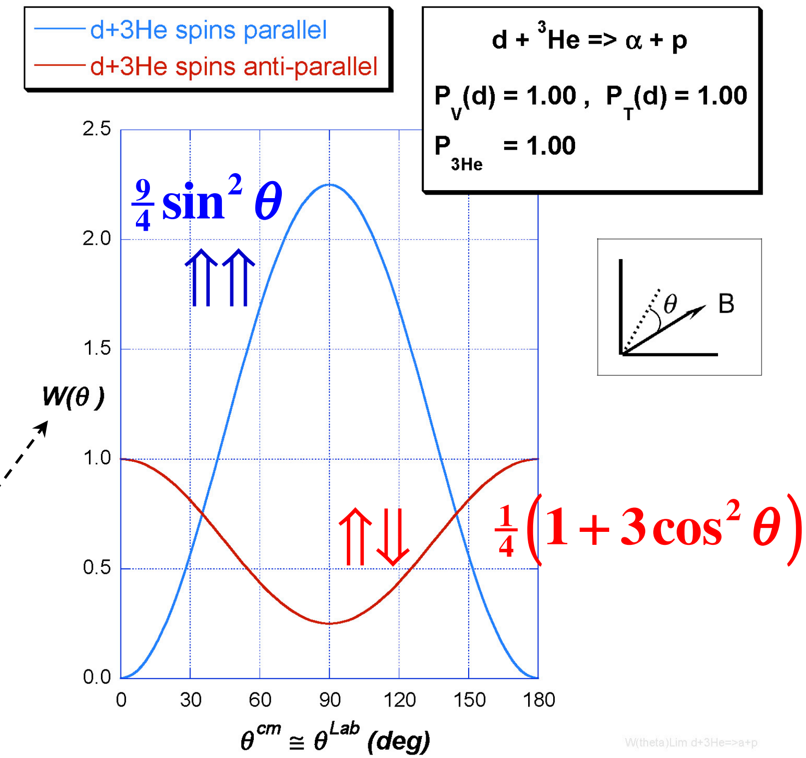


Q H-Mode DIII-D can reach ITER temperatures of 12-18 keV

Plasma Phys. Cont. Fus. ***44*** *(02) A253*



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expected d+^{3}He → α +p signal with existing NP material

Jlab: $P_V\left(\vec{D}\right)=0.40$

UVa: $P\left({}^3\vec{H}e\right)=0.65$

→

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

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

***Signal** from comparing shots* ⇔

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

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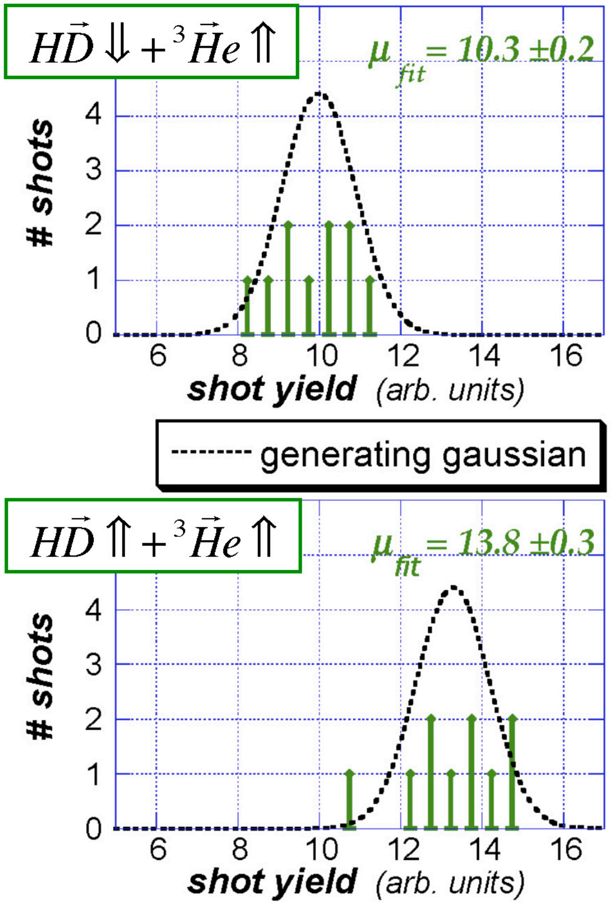
  ➔ ***^{3}He must be polarized 1st, then diffused into shell***
  (parallel VIII, Applications)

- generate H plasma in the DIII-D Tokamak

  ➔ inject polarized fuel into plasma, alternating spin alignment:

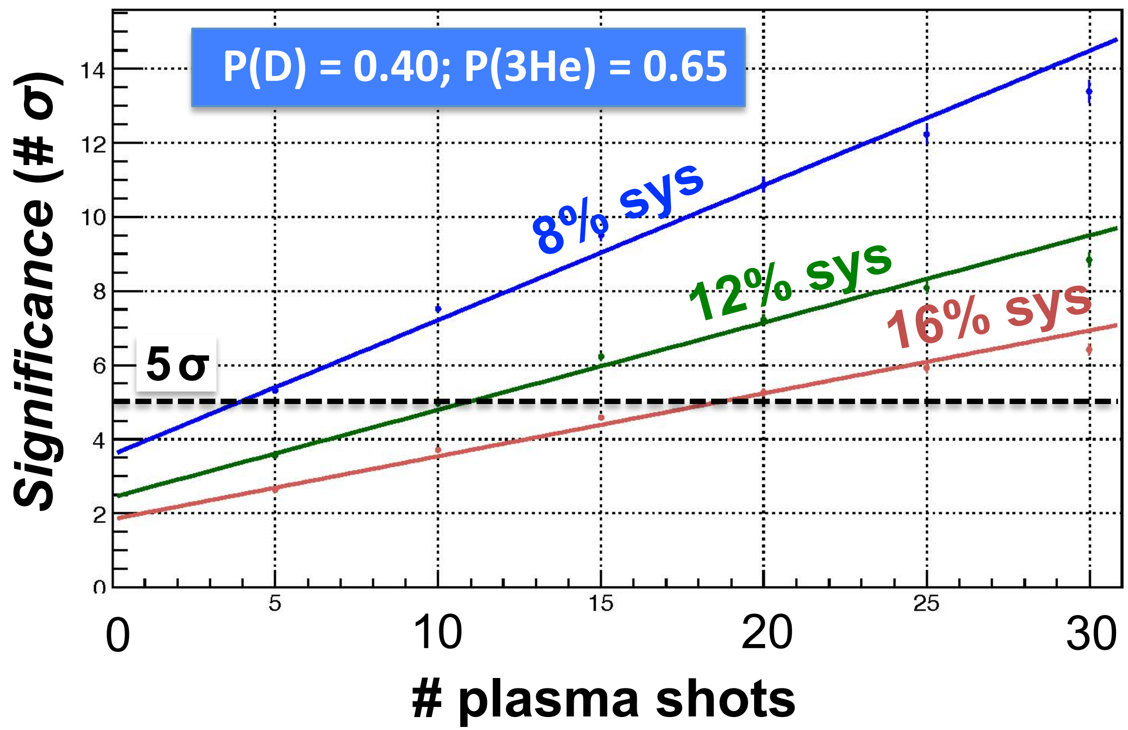
  "signal" comes from comparing different plasma shots ⇔ requires good shot reproducibility

Systematic variations btw plasma shots determines # shots needed for a definitive experiment



How many shots in each spin alignment to reach 5σ confidence ⇔ Monte Carlo

- 8% plasma variation ⇔ 4 shots
- 16% plasma variation ⇔ 18 shots



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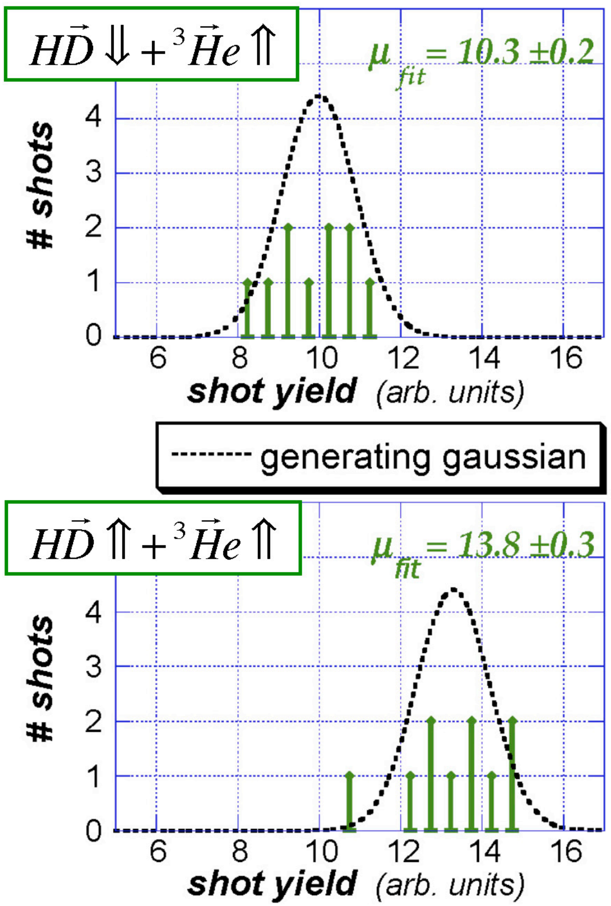
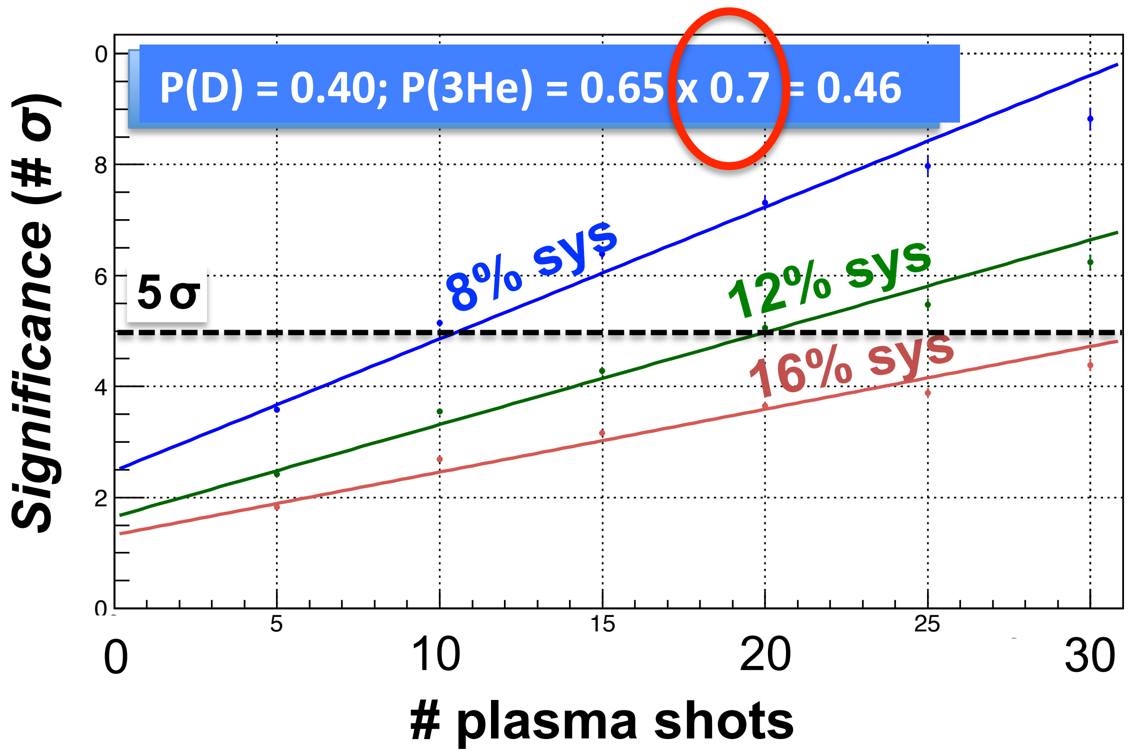


How many shots in each spin alignment to reach 5σ confidence ⇔ Monte Carlo

- 8% plasma variation ⇔ 10 shots
- 16% plasma variation ⇔ 30 shots

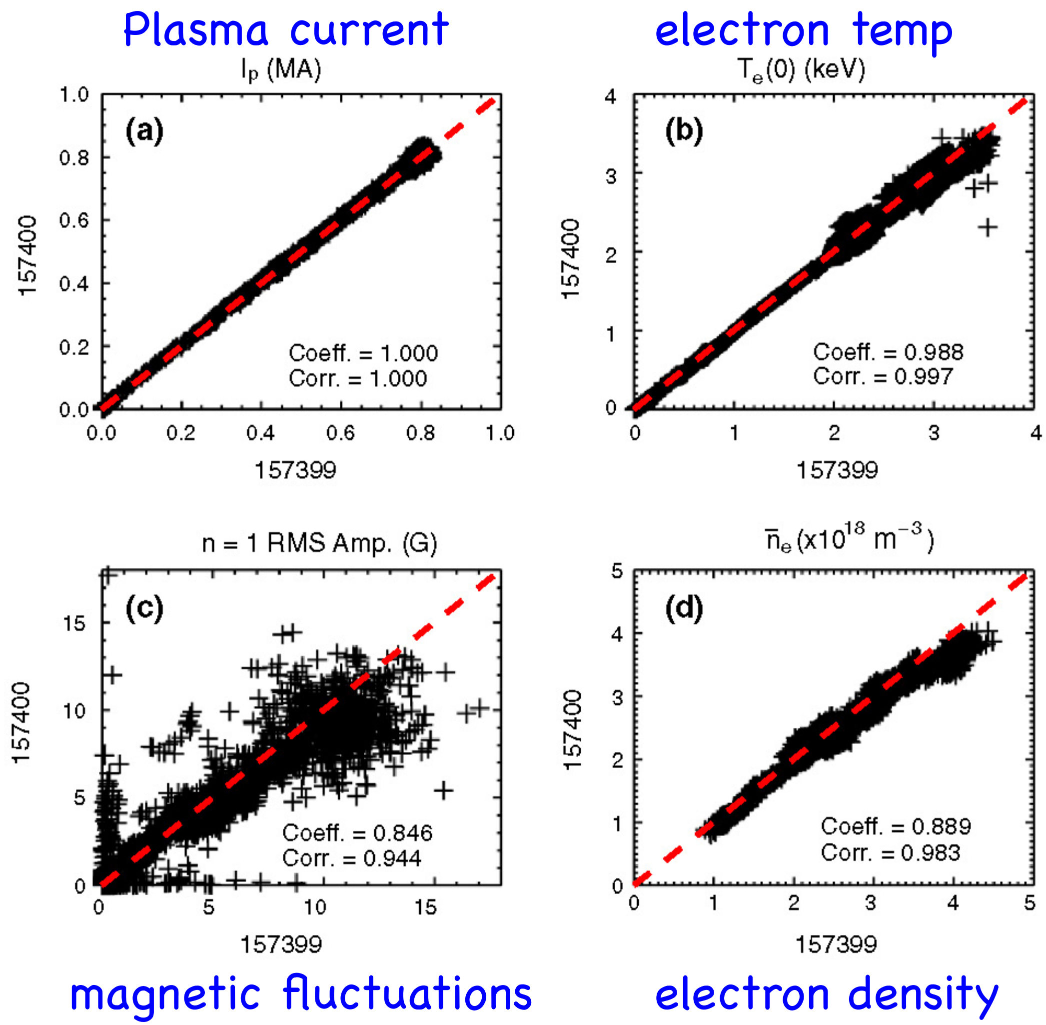


DIII-D shot reproducibility

DIII-D plasma shots:
- 3 s ramp up to 2.1 tesla
- 10 s flat top, with 80 keV neutral-beam heating
- 7 s ramp down
- 15 min btw shots

• parameters of repeated shots are high correlated, to ~ 10% ⬄

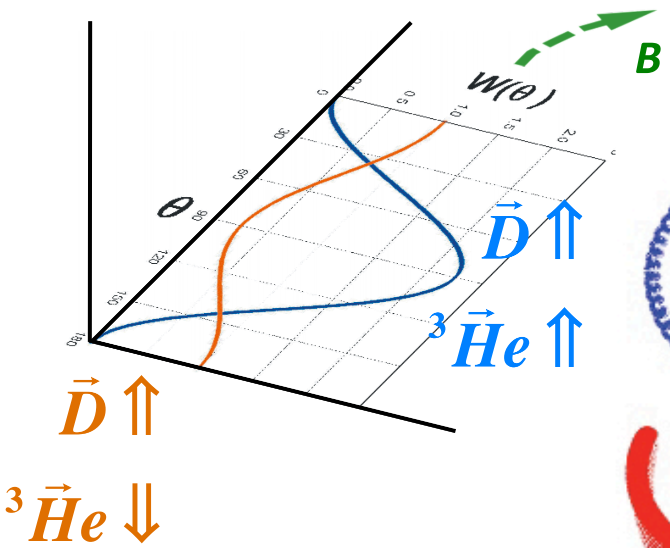
• time requested to study reproducibility of high-performance Quiescent H-mode for polarized fusion

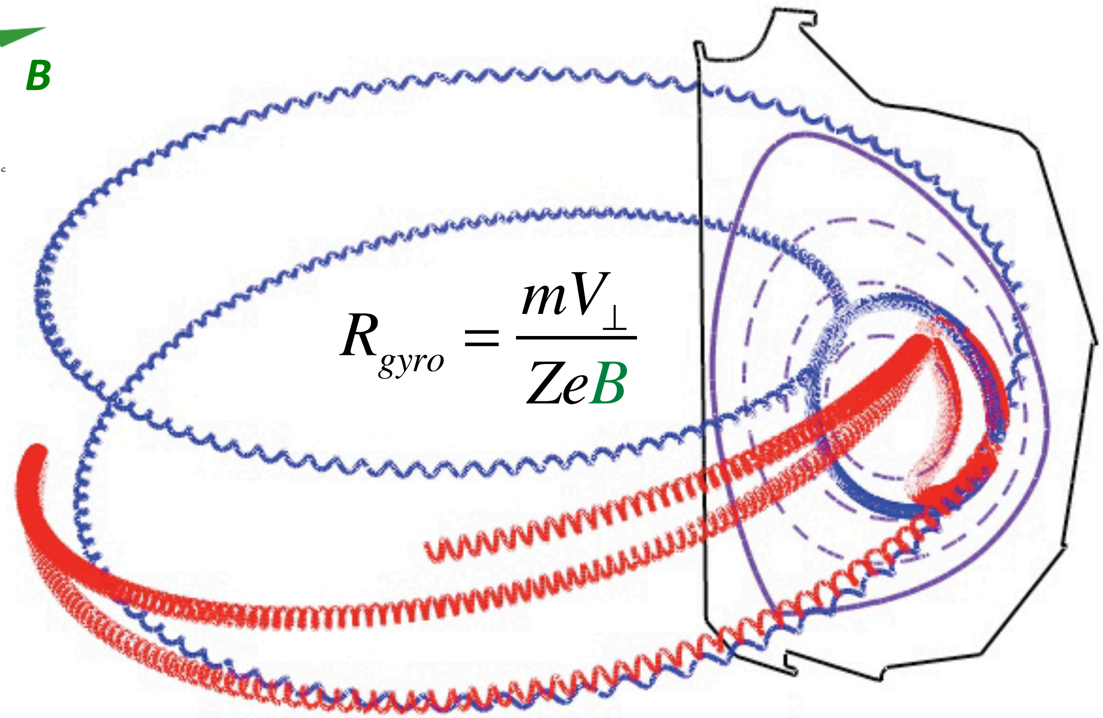


Pace, Lanctot, Jackson, Sandorfi, Smith, Wei, *J. Fus. Energy* **35** (2016) 54

Tracking fusion products in DIII-D: Spin Alignment and Orbit Losses

- parallel spins ➔ large $V_\perp$ ➔ large gyroradii ➔ protons hit the wall in a few orbits
- anti-parallel spins ➔ large $V_{||}$ ➔ small gyroradii ➔ better confined





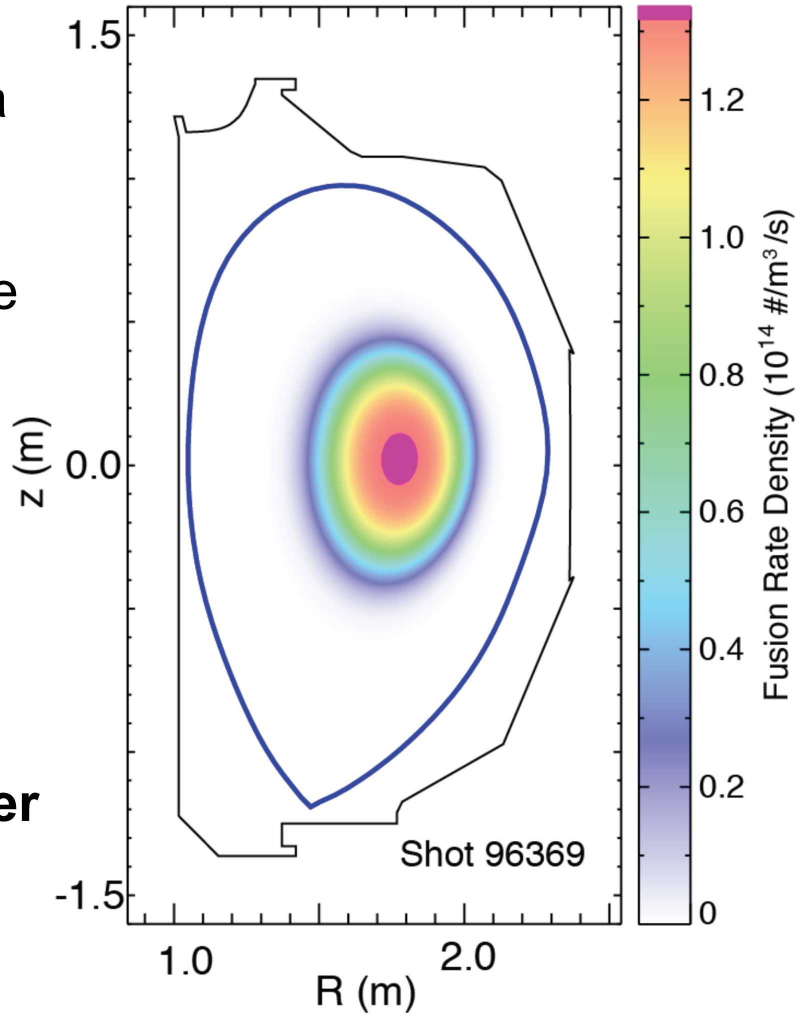
$$R_{gyro} = \frac{mV_\perp}{ZeB}$$

α and p loss-locations on Tokamak wall depend on initial polarizations

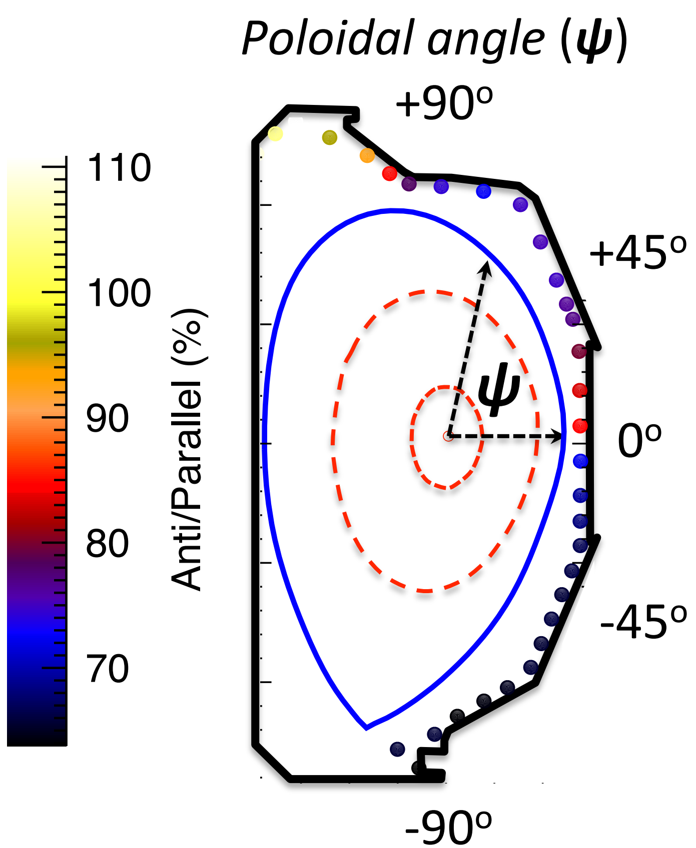
Tracking D + ^{3}He ➔ α + p products in DIII-D

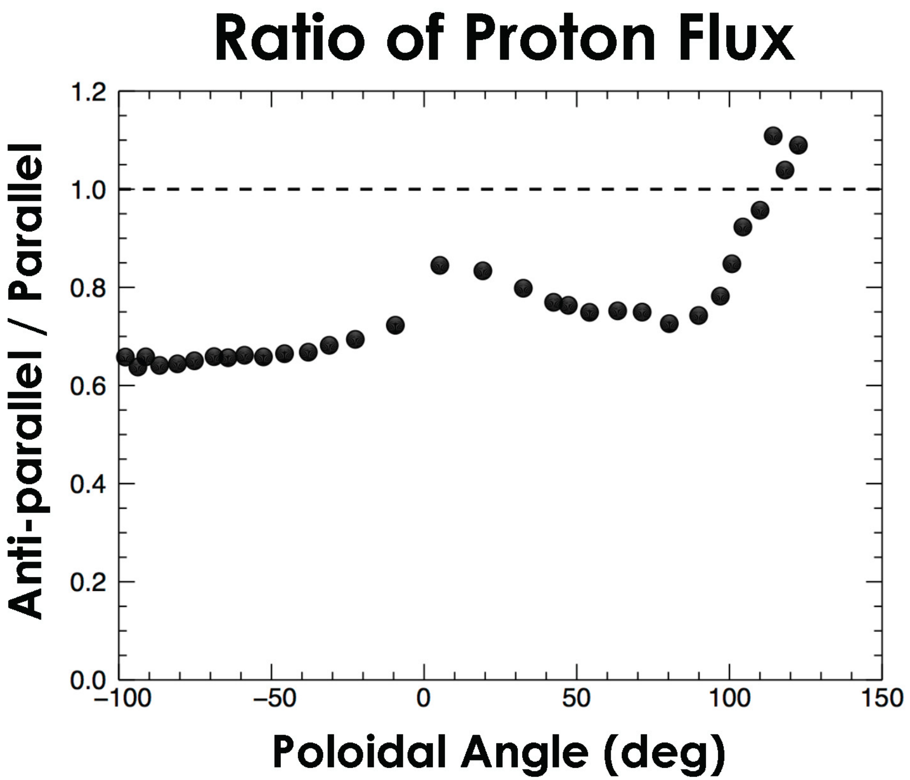
Tracking Simulations:

- fusion rate density taken from data with a solid D_2 pellet (shot 96369)
- cross sections scaled from D+D to D+^{3}He
- T_{ion} energy scaled to 15 keV (as expected for Quiescent H-Mode)
- fusion profile discretized; α + p generated along different polar (pitch) θ and azimuthal (gyrophase) ϕ, relative to the local field, **weighting the relative number by the polarized angular distributions**
- particles are tracked until striking a wall



Predicted ratio of protons from anti-parallel & parallel spins





Definitive Signal:

- ~30% change expected at several wall locations
- distinctive dependence on poloidal angle (ψ)

SPF (Spin-Polarized-Fusion) Collaboration

- **Jefferson Lab** *$H\vec{D}$ & pellet filling*
  A. Deur, C. Hanretty, M. Lowry, A.M. Sandorfi, X. Wei
- **University of Virginia** *$^3\vec{He}$*
  J. Liu, G.W. Miller, X. Zheng
- **University of Connecticut** *$^3\vec{He}$ & pellet filling*
  K. Wei
- **General Atomics/Fusion Energy Research**

  GA-DIII-D: *plasma, orbit & transport simulation*
  N. Eidietis, A. Hyatt, G. Jackson, M. Lanctot, D. Pace, S. Smith, H. St-John

  GA-ICF Pellet Division: *ICF pellets for HD, ^3He*
  M. Farrell, M. Hoppe, M. Schoff, N. Alexander

  Oak Ridge National Lab *cryo-injection guns*
  L.R. Baylor

  UC-Irvine *fast particle detection*
  W.W. Heidbrink

The next steps

- complete study of ICF shell materials to maximize ^3He polarization
  - UVa, JLab, U Conn
- study of variations in high-T_{ion} Quiescent H-mode plasma shots
  - DIII-D/GA, JLab
- preliminary design of polarized pellet injectors (to define costs)
  - ORNL, JLab

next challenge: demonstrate polarization survival in a plasma

Focused efforts by two groups:

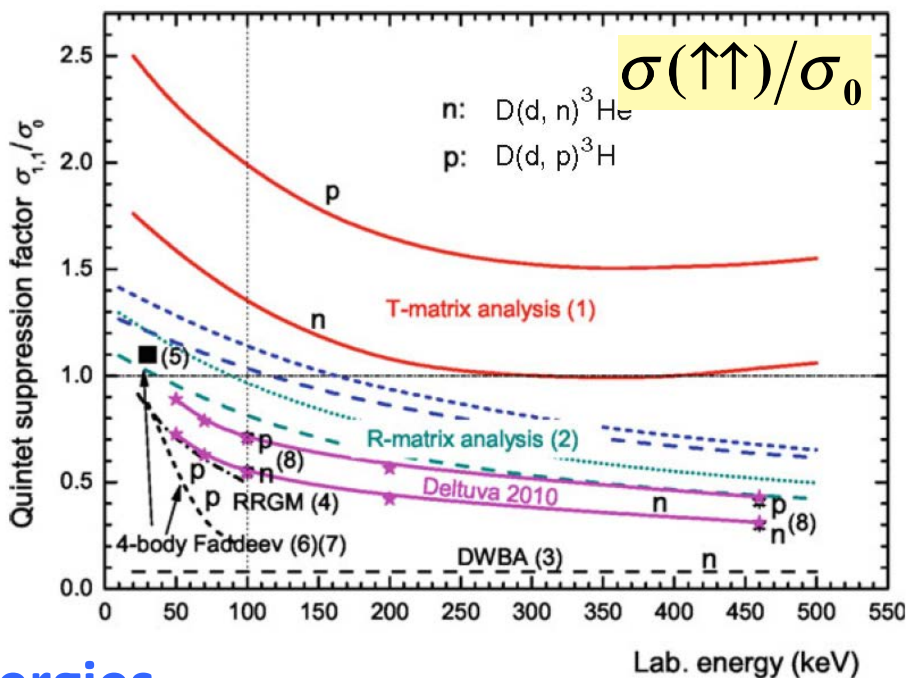
I. SPF (Spin-Polarized-Fusion) Collaboration:
- Jefferson Lab
- DIII-D National Fusion Facility:
  - General Atomics, **(parallel VIII, Applications)**
  - ORNL,
  - UC-Irvine
- University of Virginia **(parallel VIII, Applications)**
- University of Connecticut

II. PolFusion Collaboration: ←
- Forschungszentrum Jülich
- University Düsseldorf
- TU Darmstadt
- Università di Ferrara **(parallel VIII, Applications)**
- PNPI Gatchina
- Budker Institute Novosibirsk **(parallel VIII, Applications)**

Direct measurements of low-energy $\vec{D}+\vec{D}$ asymmetries

- *could* $\vec{D}+\vec{D} \Rightarrow {}^4He \rightarrow {}^3He + n \;\; or \;\; T + p$ *test pol survival ?*
- to 1st order, two parallel spin 1 deuterons cannot form spin 0 ^{4}He
  - but, this is complicated by NP effects (deuteron D-state, …)
- NP theory predictions for $\sigma(\uparrow\uparrow)/\sigma_0$ range from, suppression by 10 to enhancement by 2.5
- 1st direct measurement with polarized beams and targets in preparation at PNPI-Gatchina (St Petersburg, RU)

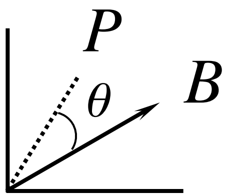
H. Paetz gen. Schieck, Springer Proc. Phys. (2016) 15



⇔ **potentially high impact if they can reach very low energies**

extras

spin-dependent ^{3}He+D ➔ α+p (or T+D ➔ α+n) angular distributions



- polar (pitch) angles relative to local magnetic field direction
- neglecting interference terms (good to ~ 2-3 %)

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

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

➔ angle integrated cross section :

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

Polarization dilution from HFS in partially ionized states at injection

- *g.s*. of all fuels (DT, HD, ^{3}He, …) have 2 electrons paired to *1s* ⇔ *no nuclear int.*
- after injection, a partially-ionized state with 1 electron will exist for ~ 10 ms, during which there will be level mixing and a degree of dilution of nuclear pol
- net fractional polarization loss: $$\frac{\Delta P}{P} = \frac{1}{2}\left[1 + \frac{4(\mu_e - \mu_I)^2 B^2}{A_{HFS}^2}\right]^{-1}$$

⇔ ^{3}He has the largest hyperfine splitting, A_{HFS} = -8.66565 GHz

⇔ **mean *ΔP/P* for ^{3}He, averaged over the DIII-D plasma field region and weighted by particle density = 1 %**

⇔ **HFS ~ 1/B^2 ⇔ irrelevant in ITER, due to higher magnetic fields**

Secondary Reactions

- use H-plasma heated with H neutral beams

- simulations follow secondary reactions to estimate background yields:

  ^{3}He + D ⇨ α + **p** (Q = +18.3 MeV) **E(p) ~ 15 MeV**

  ↳ D + D ⇨ ^{3}He+n (Q = + 3.3 MeV)

  ↳ D + D ⇨ T + **p** (Q = + 4.0 MeV) **E(p) ~ 3 MeV**

  ↳ D + T ⇨ α + n (Q = +17.6 MeV)

- 15 MeV protons from ^{3}He + D ⇨ α + p provide a unique signature that is easily separated

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