Status of preparations for a polarized-fuel Demonstration experiment in the DIII-D Tokamak

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(for the *Spin-Polarized Fusion (SPF)* collaboration)

The road to fusion through magnetic confinement - preliminaries

- intended fuel: ***D + t → α + n***
- about 180 research tokamaks have been built; there are currently about 30 in operation

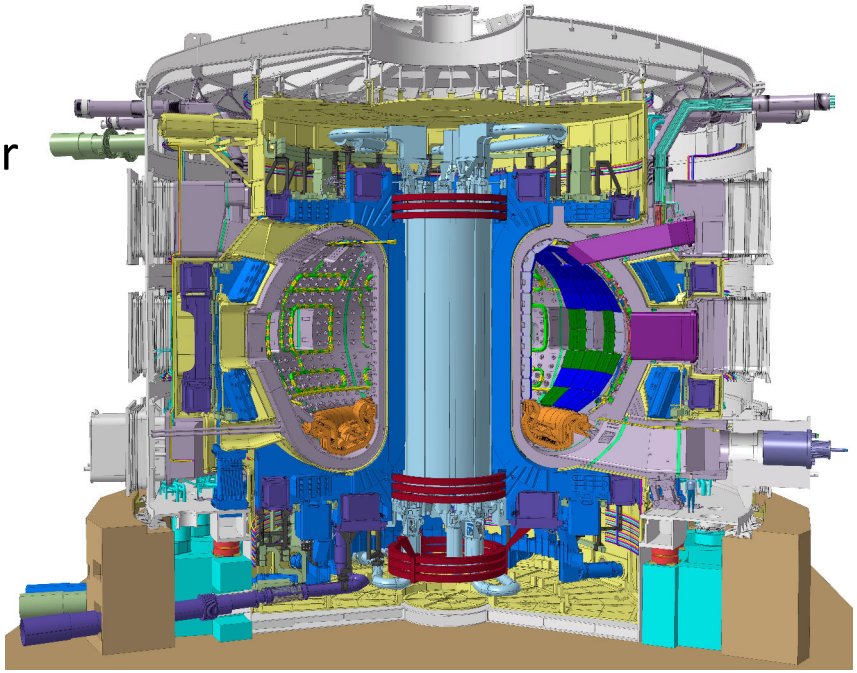
⇔ mostly studying ***D+D*** reactions

- quantum leap towards fusion power:

  Int. **T**hermonuclear **E**xperimental **R**eactor

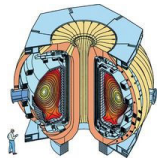
ITER

(Cadarache / France)



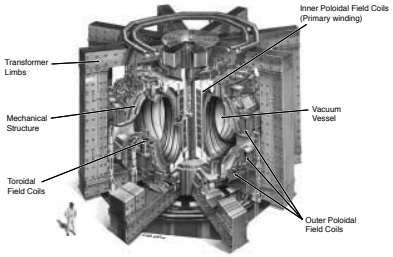
DIII-D

(San Diego / USA)



JET

(Oxfordshire / UK)



best instrumented
-most diagnostics

only machine that
can run with tritium

½ GW reactor
- under construction

The road to fusion through magnetic confinement

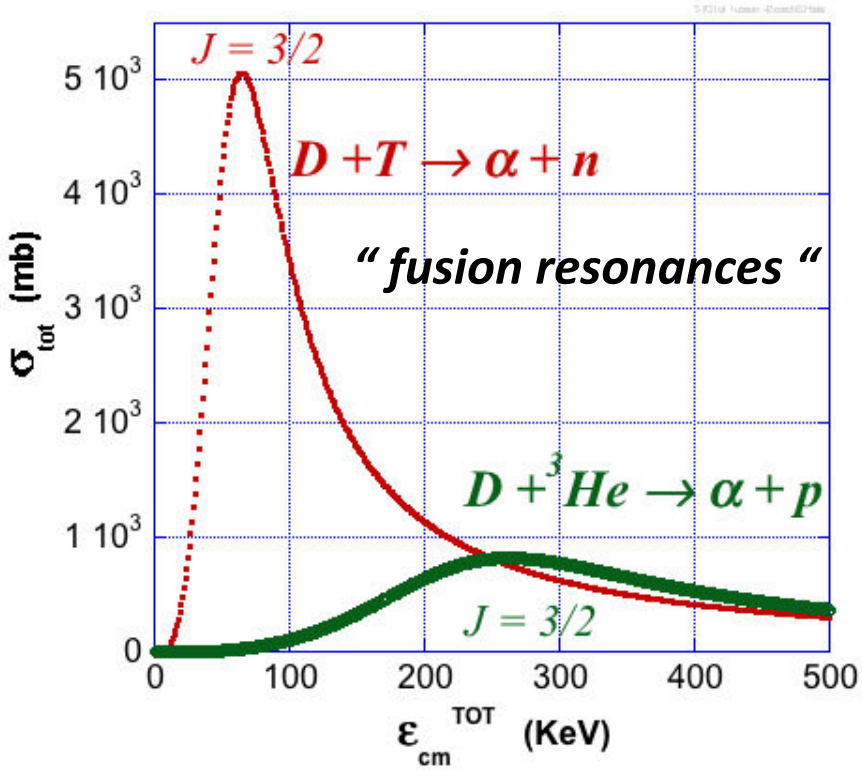
	V(plasma)	B_c (tesla)	P(MW)	Q = P(fus)/P(in)	coils
DIII-D	20 m^3	2.1	—	<<1	normal
JET	90 m^3	3.8	16	~ ⅔	normal
ITER	700 m^3	5.3	500	> 10	superconducting

- **superconducting coils are needed to reach high field over a large volume**
  ⇔ *concerns over potential field degradation from neutron flux*

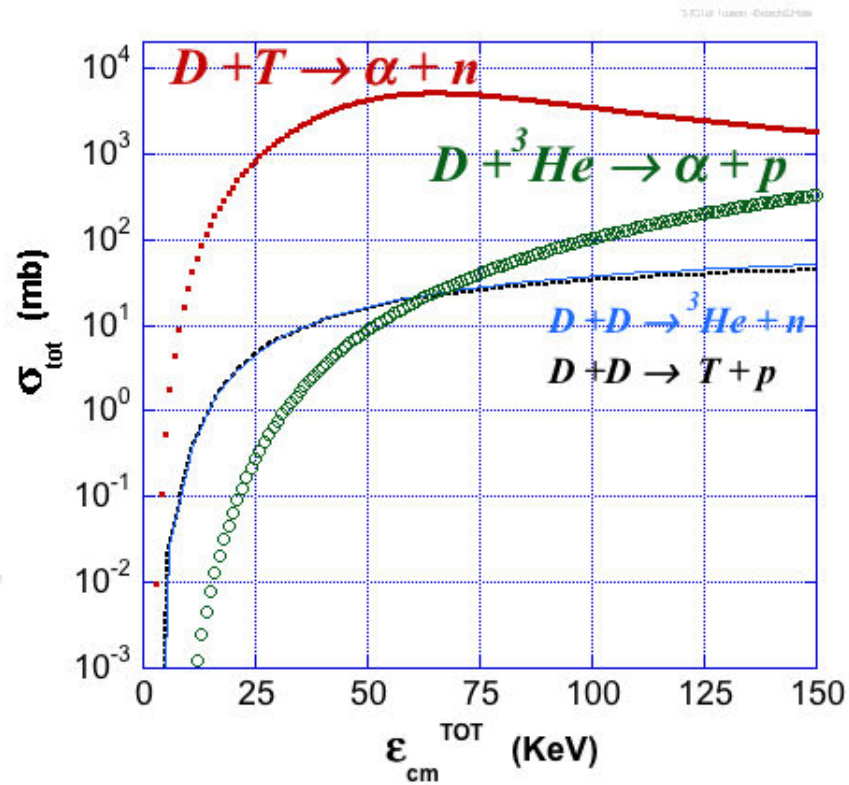
- **ITER is to be a stepping-stone, requiring at least one more iteration to reach a viable fusion power plant**

- **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 $D + {}^3He \Rightarrow \alpha + p$)
  - ↔ *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*

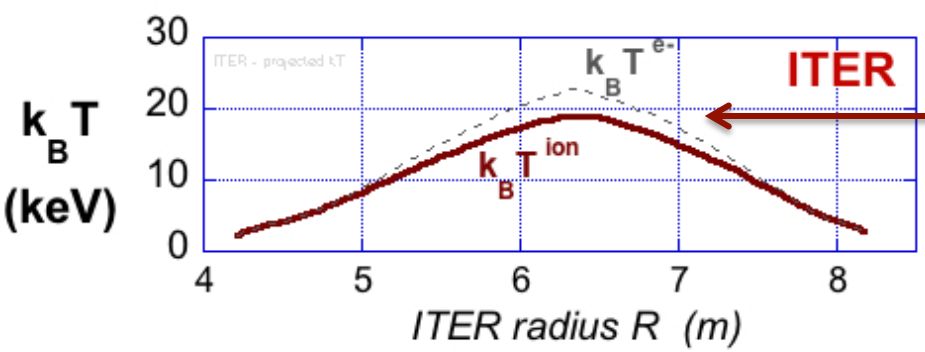
Reaction rates in a heated plasma

~ cross sections averaged over a Maxwellian velocity distribution

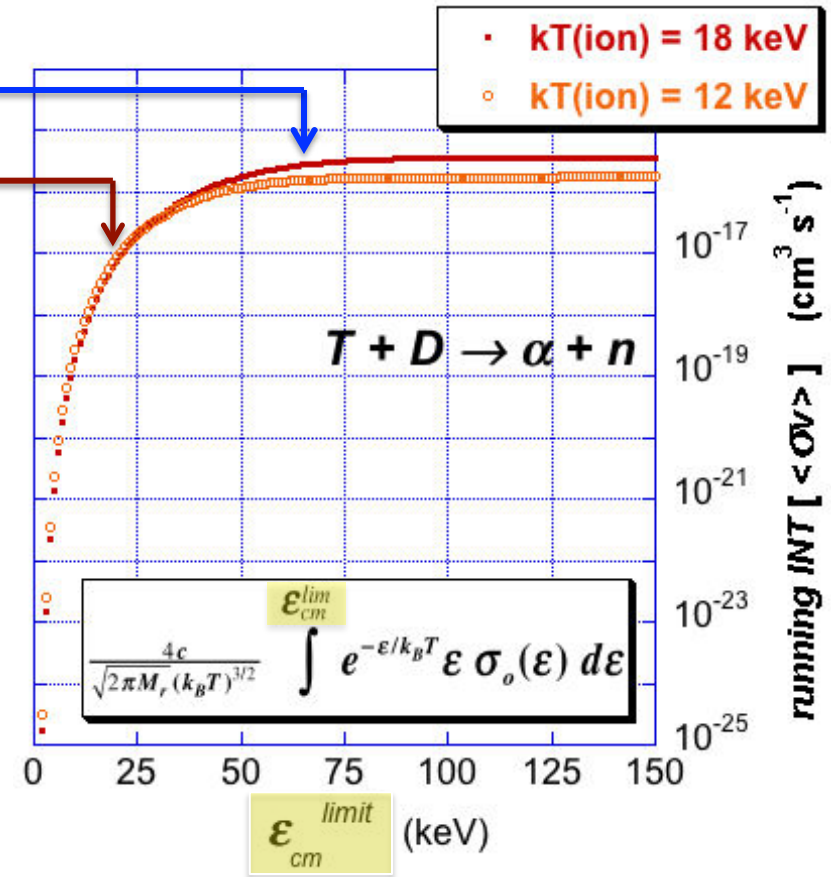
$$R = n_D\, n_T\, V_{pl} \times \left\{ \langle \sigma v \rangle = \frac{4c}{\sqrt{2\pi M_r}\,(k_B T)^{3/2}} \int e^{-\varepsilon/k_B T}\, \varepsilon\, \sigma(\varepsilon)\, d\varepsilon \right\}$$

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



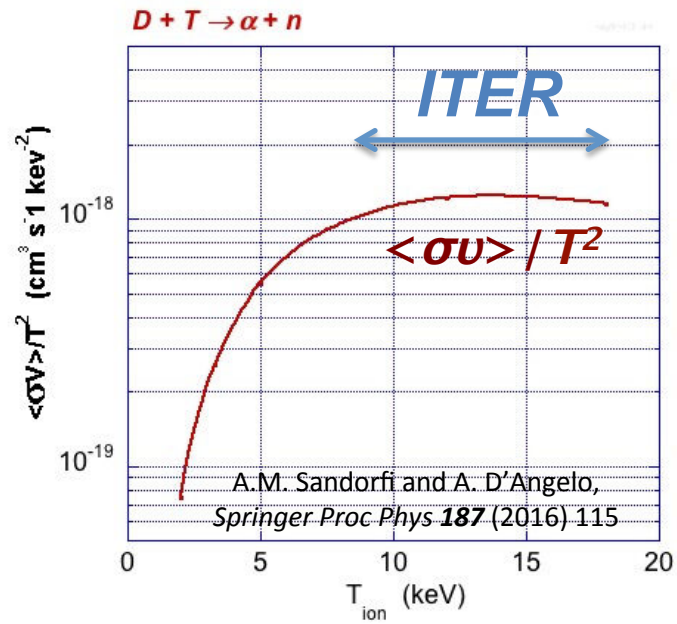
Dependence on toroidal field

Recasting the fusion rate :

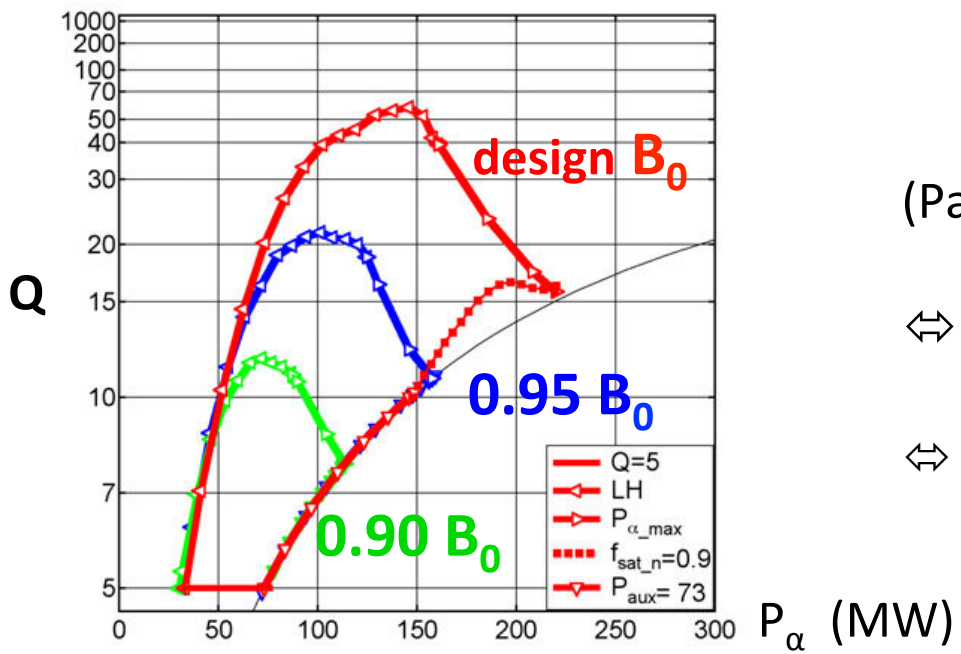
$$R = n_D n_T V \cdot \langle \sigma \upsilon \rangle = \frac{\beta^2}{4\mu_0^2} V \cdot \frac{\langle \sigma \upsilon \rangle}{T^2} \cdot B^4$$

plasma pressure ~ constant

~ constant for ITER



- ITER simulations:



(Pacher et al, NF**48** (08)105003):

⇔ $R \sim B^6$

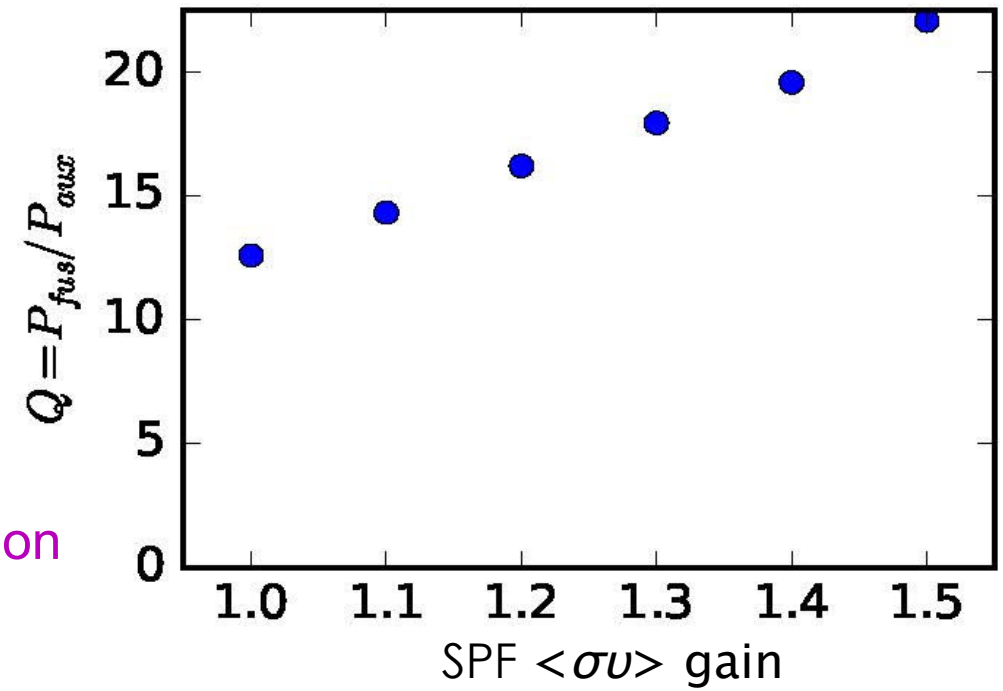
⇔ field degradation would severely reduce parameter space for ITER operations

alpha heating ⇔ non-linear enhancements from the resonance tails

ITER Power simulations with polarized fuel:
(Sterling Smith – GA)

⇔ 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 gain is <u>independent of field</u>,
➔ compensates for a drop in B



⇔ on the ITER scale,
could reach Q > 20,
even with toroidal field degradation

The potential of SPIN

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  - ↔ *dominated by J=3/2 resonance just above reaction threshold*
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$$\sigma_{cm} = \sigma_0 \left\{ 1 + \tfrac{1}{2} \vec{P}_D^V \cdot \vec{P}_T \right\}$$

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

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

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

  ⇔ *costs savings of future fusion reactor plants (~ B^2) as much as 20%* ⇔ *a potentially huge factor !*

Polarization survival - history

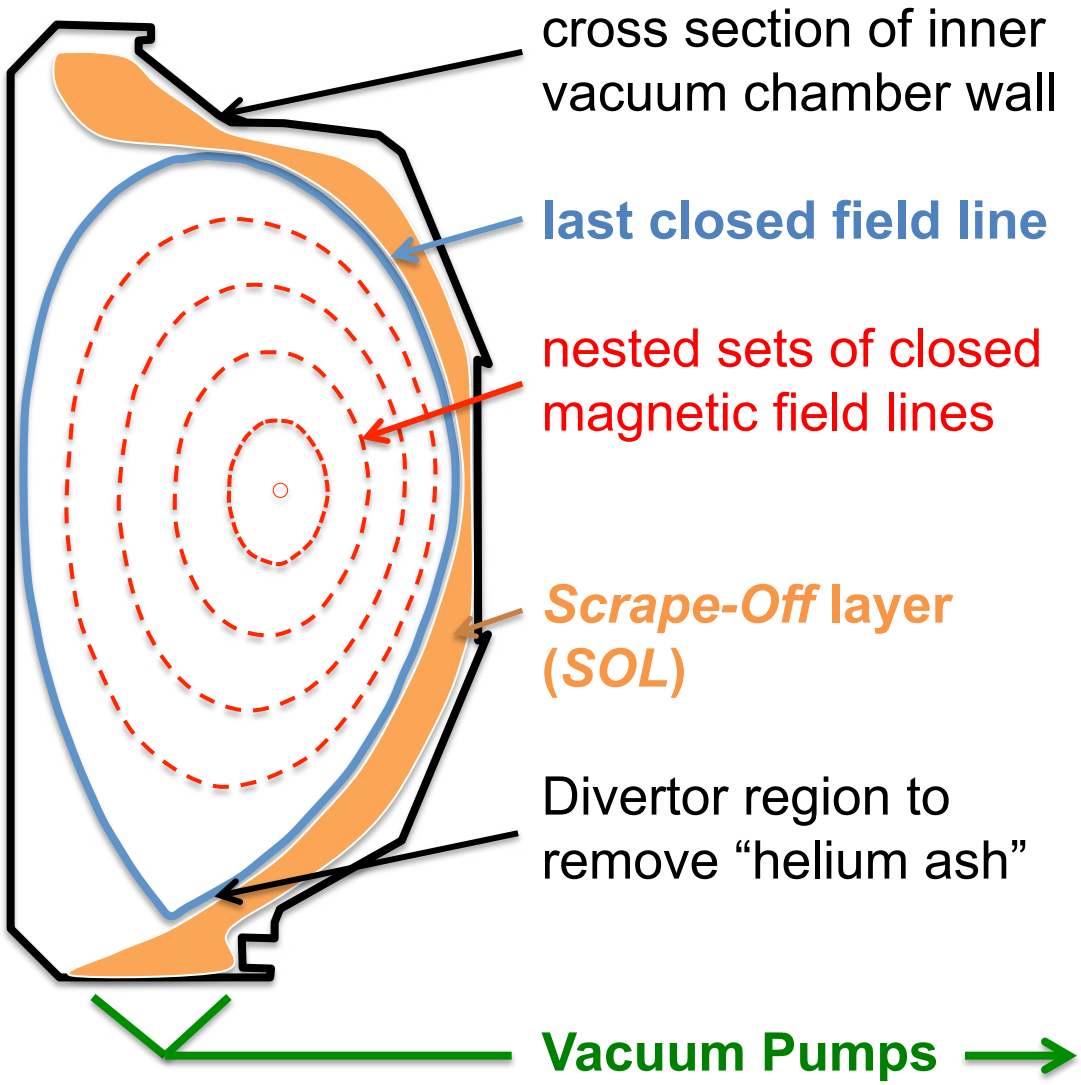
- **Potentially large benefits require fuel polarization to survive a 10^8 K plasma for the energy containment time ~ a few sec**

- **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

    ...

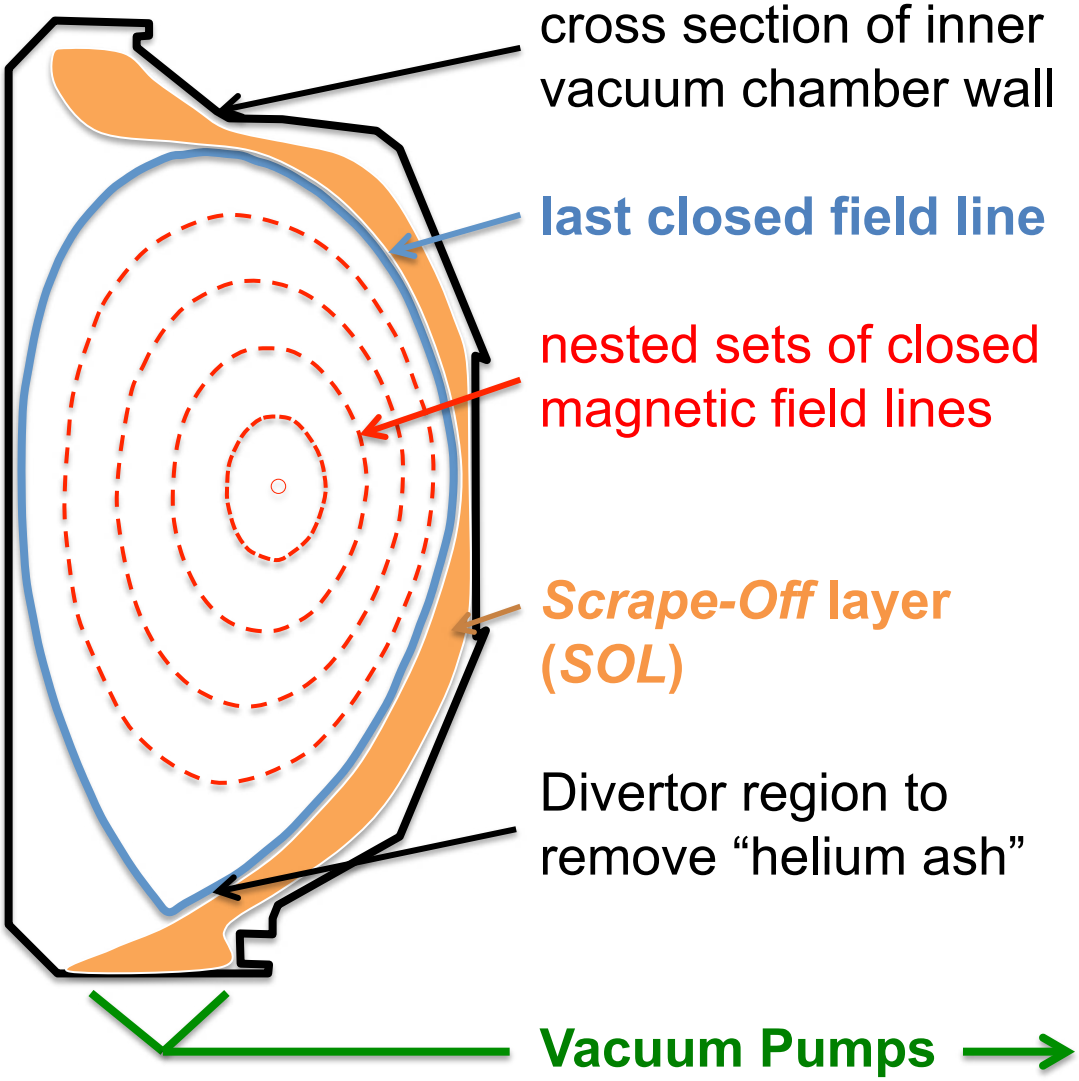
- **Depolarization mechanisms**
  - a great <u>many</u> mechanisms were investigated in the '80s; two survive scrutiny
  - both hinge on **wall recycling**

Fuel Recycling from the walls through the scrape-off layer



Fuel Recycling from the walls 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

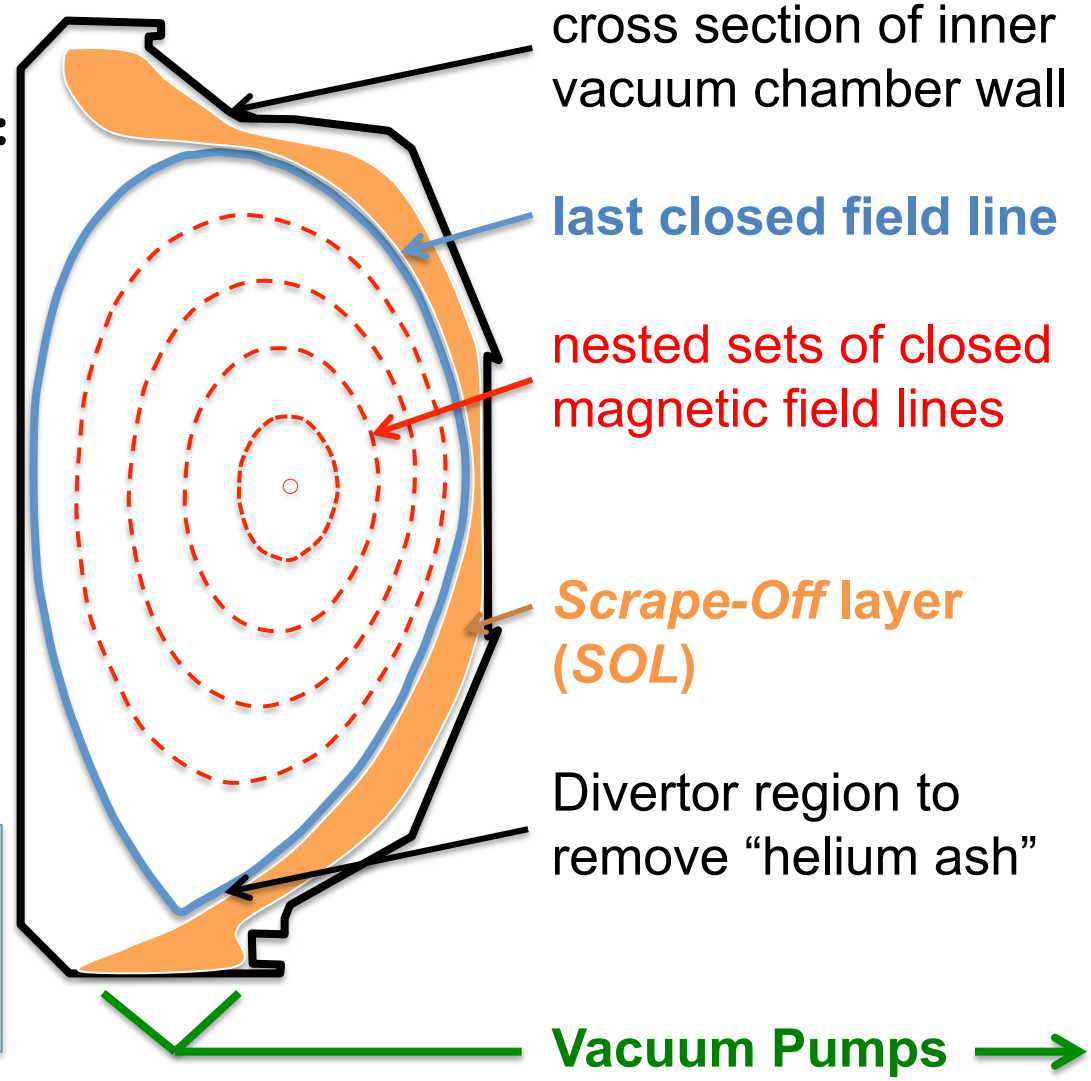
What's new ?

- 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 <u>convection</u>

⇔ **fuel recycling from the walls will be insignificant in ITER scale reactors**



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: $$\frac{\Delta P}{P} = \frac{1}{2}\left[1 + \frac{4\left(\mu_e - \mu_I\right)^2 B^2}{A_{HFS}^2}\right]^{-1}$$

⇔ ^{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**

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 ~ 30 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. <u>1st order speculation</u>:
- spin-exchange optical pumping (SEOP) of molecular DT gas with 2 lasers;
  alternate: separate SEOP of HD and HT
- 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**

SPF (Spin-Polarized-Fusion) Collaboration

- **Jefferson Lab**

  JLab:

  A. Deur, C. Hanretty, M. Lowry, A.M. Sandorfi, X. Wei

  Univ. of Connecticut

  K. Wei

- **University of Virginia**

  J. Liu, G.W. Miller, S. Tafti, X. Zheng

- **General Atomics/Fusion Energy Research**

  GA-DIII-D:

  N. Eidietis, A. Hyatt, G. Jackson, M. Lanctot, D. Pace, S. Smith, M. Wade

  GA-ICF Pellet Division:

  M. Farrell, M. Hoppe, M. Schoff, N. Alexander

  Oak Ridge National Lab

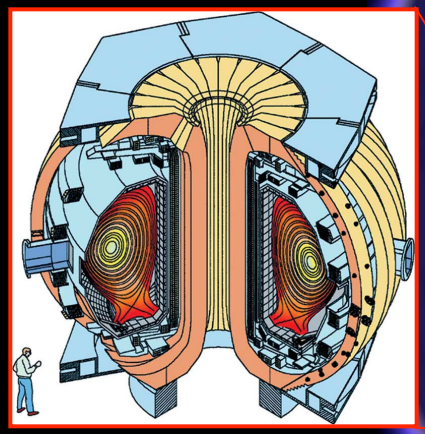
  L.R. Baylor

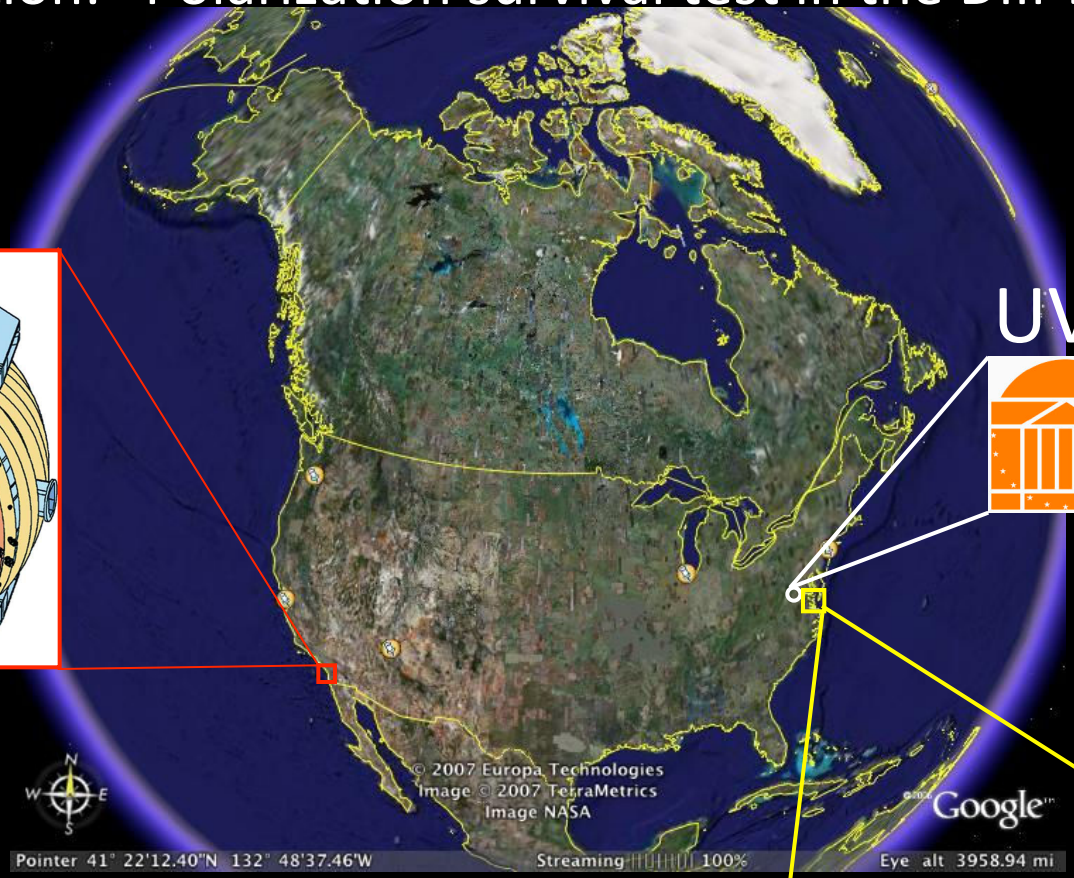
  UC-Irvine

  W.W. Heidbrink

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 in a demonstration exp.

Jefferson Lab

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

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

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

⇔ $D + T \rightarrow {}^5He \rightarrow \alpha + n$ *and* $D + {}^3He \rightarrow {}^5Li \rightarrow \alpha + p$ are mirror reactions, with the same spins, incorporating the same nuclear physics

⇔ Polarization survival can be tested with $D + {}^3He \rightarrow \alpha + p$ and lessons learned can be directly applied to $D + T \rightarrow \alpha + n$

Strategy for testing polarization survival in DIII-D

- test reaction: $\vec{D} + {}^3\vec{He} \rightarrow \alpha + p$ {mirror reaction to $D + t \rightarrow \alpha + n$ }
- ***$\vec{D}$ shells***: use existing JLab facilities to create solid $H\vec{D}$
- ***${}^3\vec{He}$ shells***: develop polarized ${}^3\vec{He}$ gas-filled shells at existing UVa facilities
- ***DIII-D***: generate H plasma in the DIII-D Tokamak

  ➔ inject polarized fuel into plasma, alternating spin alignment:

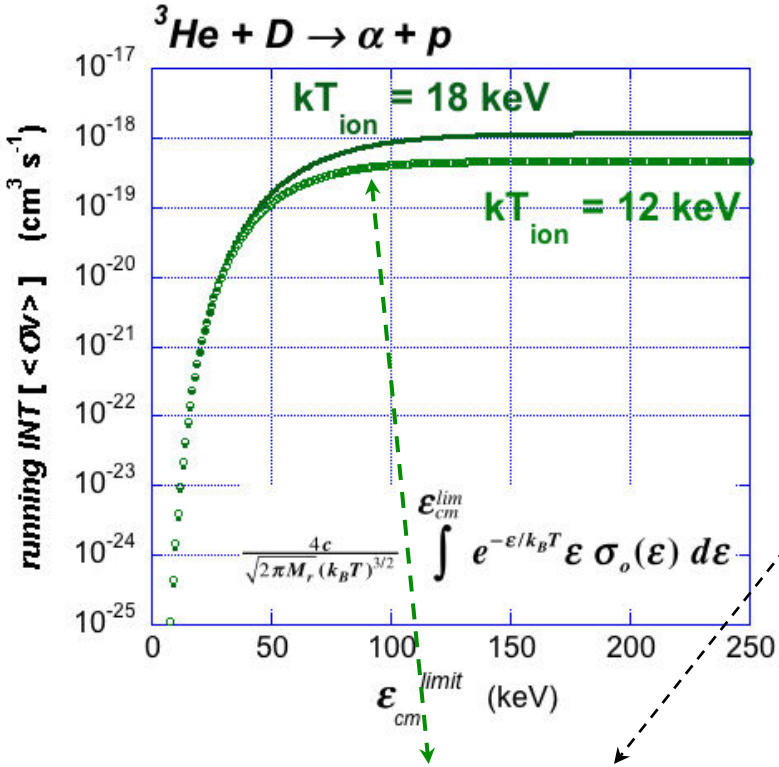
$$\left.\begin{array}{ll} \text{parallel:} & H\vec{D}\Uparrow + {}^3\vec{He}\Uparrow \\ \text{anti-parallel:} & H\vec{D}\Downarrow + {}^3\vec{He}\Uparrow \end{array}\right\} \Leftrightarrow \textit{compare proton yields}$$

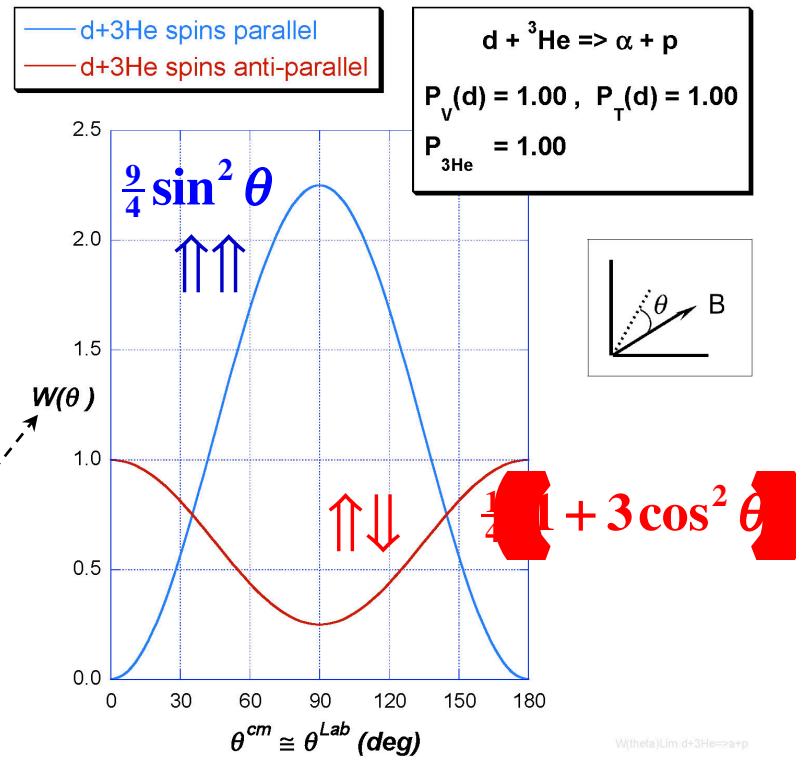
Status of efforts towards a SPF demonstration experiment

- ***White Paper* & presentation to a DOE-FESAC subcommittee** - May 31/17 ✔
  for inclusion in the *Fusion Energy Sciences* long-range R&D plan
  ➔ report due out Jan/2018

⇔ proposed next step:
- funding in FY'19 (Oct'18) for **TR-3** (*Technical Readiness Level 3)*:
  - the beginning of an *official DOE-FES "project"*
    ➔ initial designs and cost analysis of each major subsystem

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





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

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

⇔ neglecting interference terms (~ 2-to-3%)

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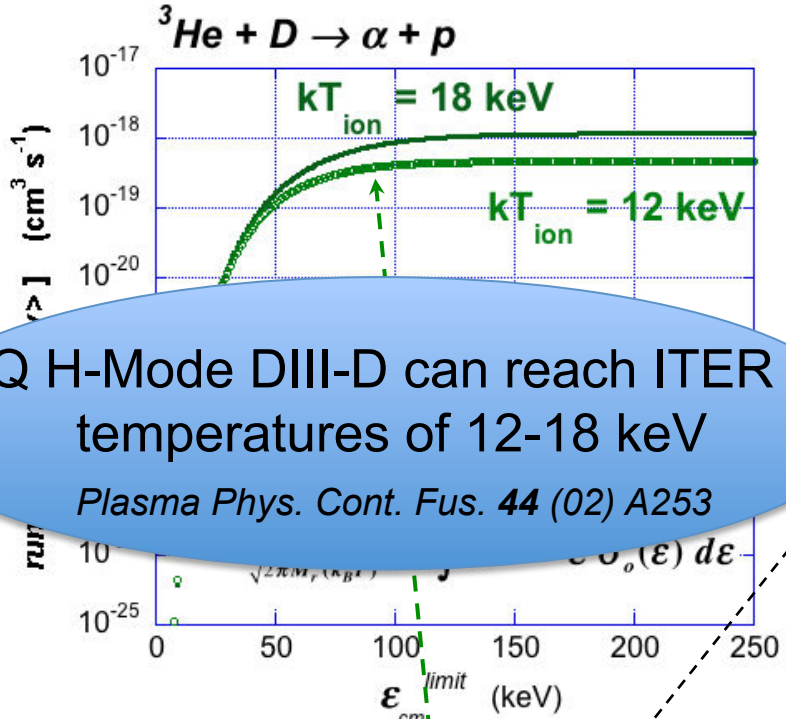
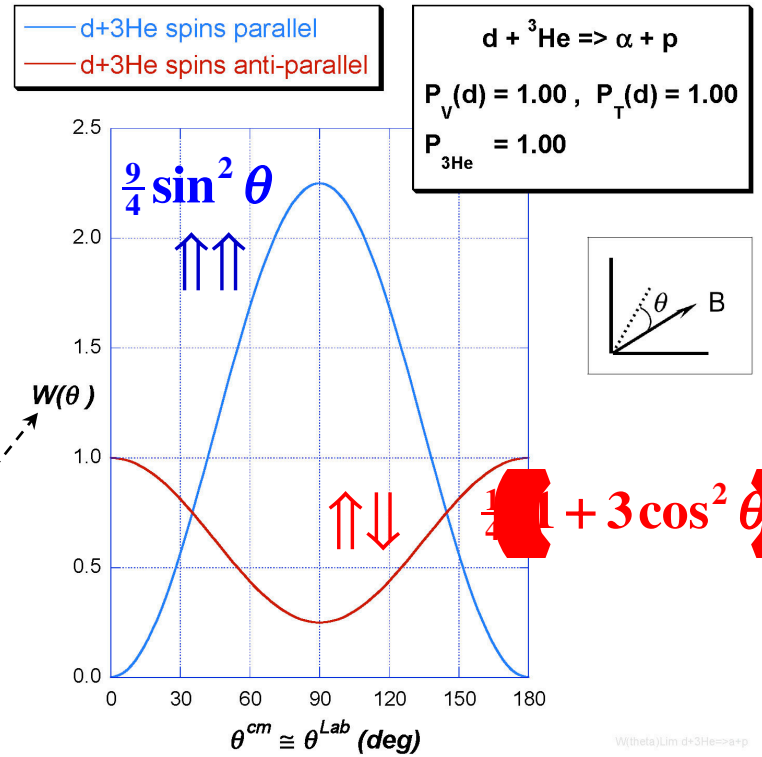


Q H-Mode DIII-D can reach ITER temperatures of 12-18 keV

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



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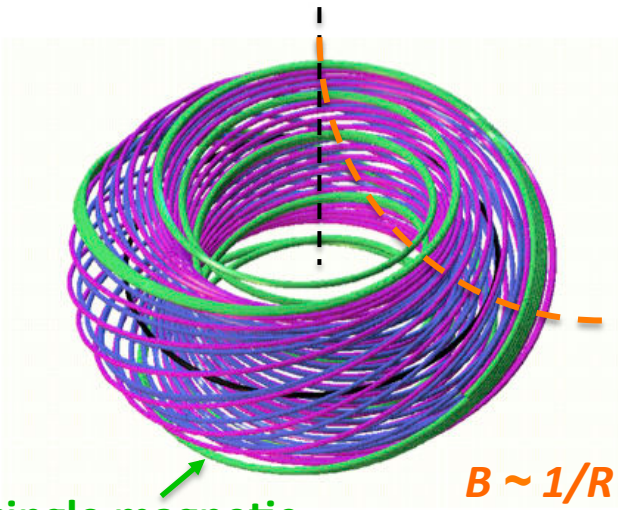
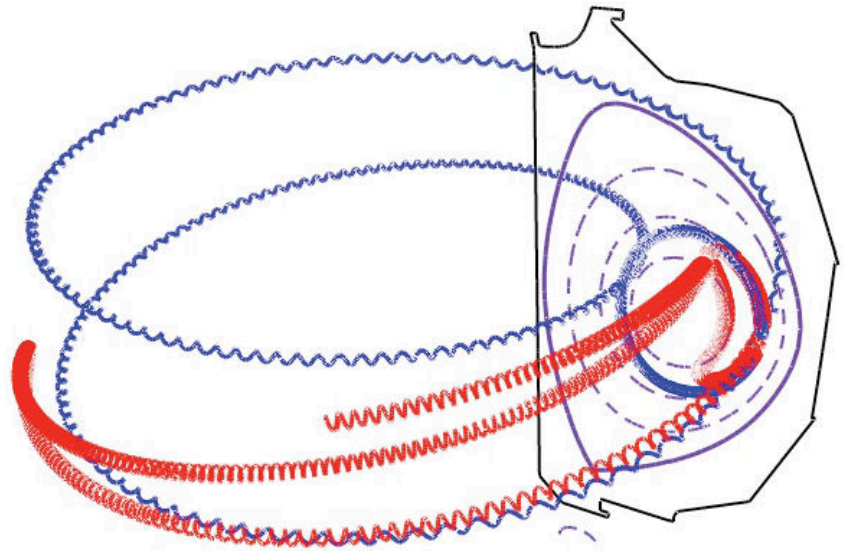
⇔ Neglecting interference terms (~ 2-to-3%)

Magnetic field lines in a tokamak

- e^- and ions follow helical trajectories around nested sets of closed magnetic field lines



single magnetic field line



- ***trapped*** *(mirror)* orbits, with larger ***R*** variations, are confined by local angular momentum conservation

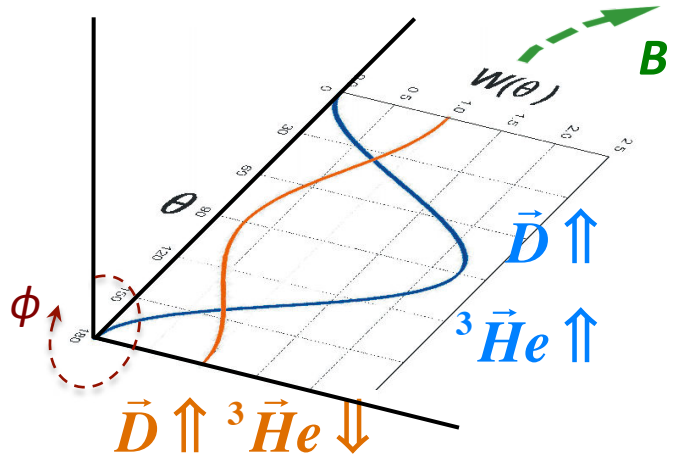
- ***passing*** orbits, confined around the torus

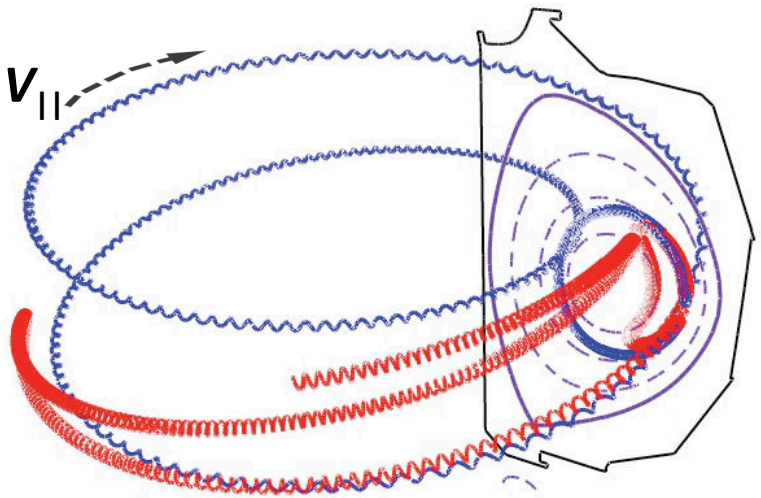
Helical gyro-rotation

$$\Rightarrow \quad L_{Gyro} \propto \frac{V_\perp^2}{B}$$

as R decreases, $V_{par} \rightarrow 0$ and orbit reverses direction

polarized fusion relative to the local field





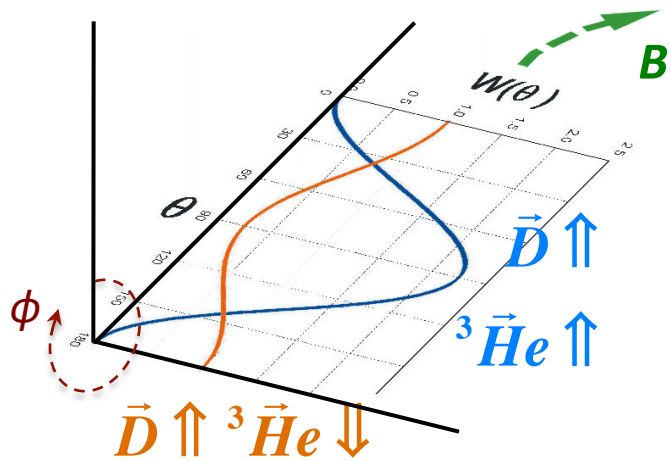
polarized fusion relative to the local field

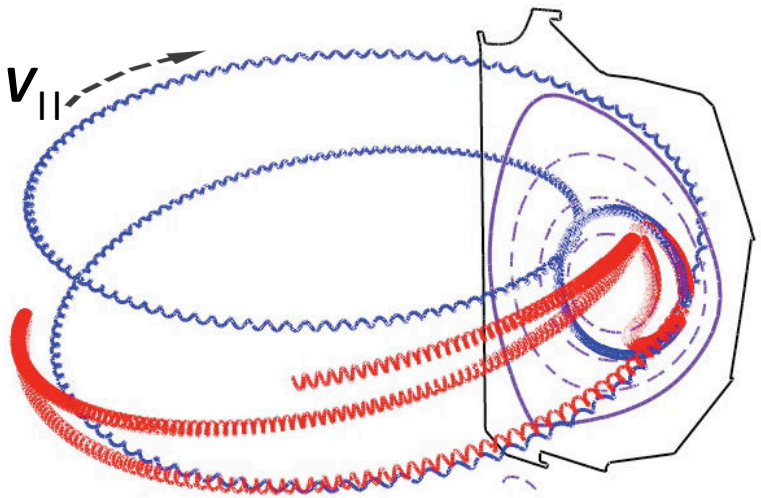
$$f_L = \frac{\gamma}{2\pi} B$$ ⇔ *Spin precession*

D	T	^{3}He	
6.5	45.4	-32.4	(*MHz/T x B*)

$$f_{gyro} = \frac{q}{2\pi}\frac{B}{m}$$ ⇔ *Cyclotron motion*

D	T	^{3}He	
7.6	5.1	5.1	(*MHz/T x B*)





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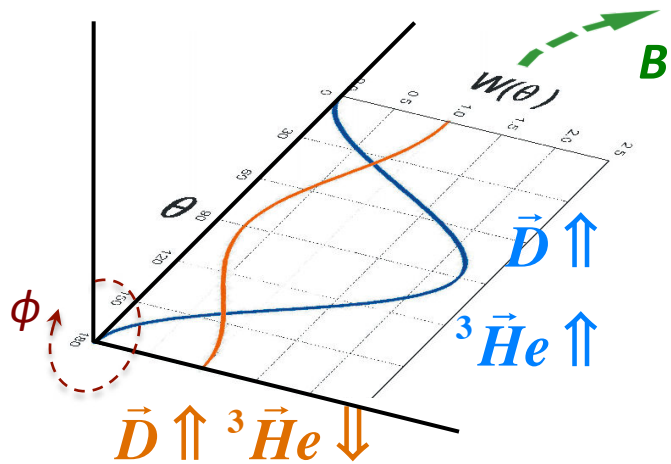

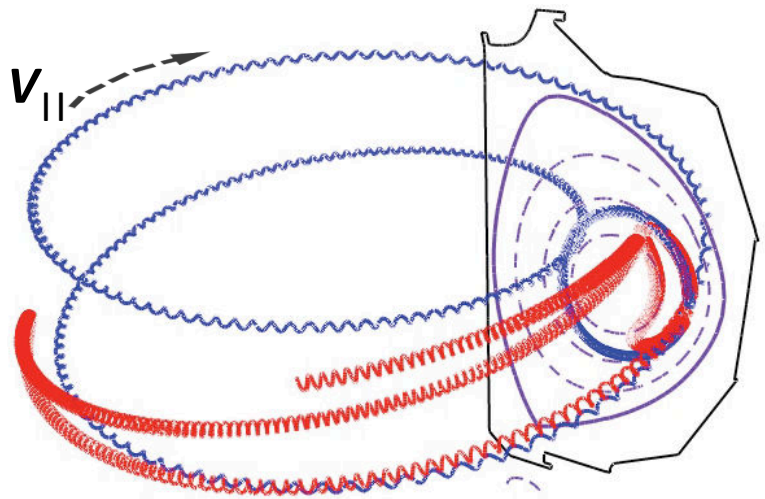

Cowley, Kulsrud, Valeo, Phys Fluids **28** (86) 430 ⇔ Fokker-Planck eqs for B =5 tesla, kT_{ion}=10 keV plasma :

- no ion depolarization without collisions ⇔ spin just follows the field
- collisional depolarization negligible in uniform B, and ~10^{-4} s^{-1} for inhomogeneous B

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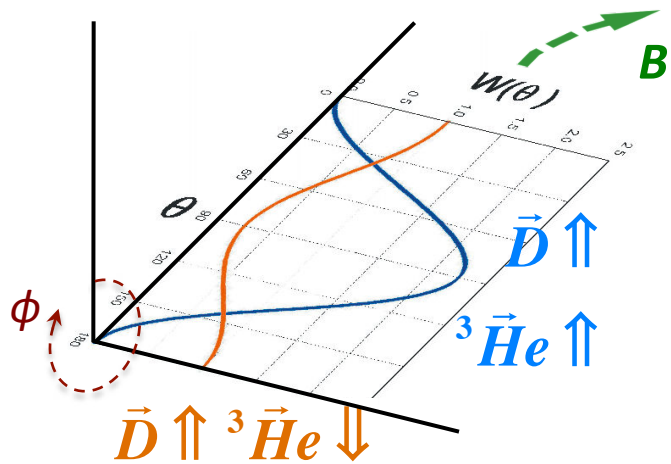

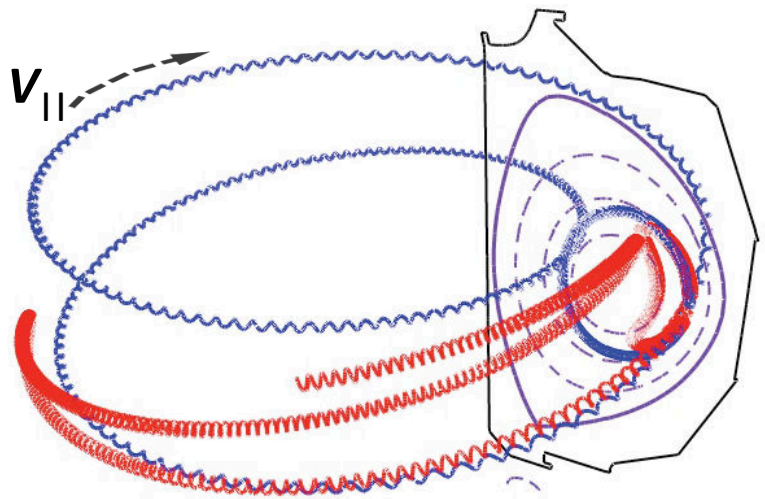

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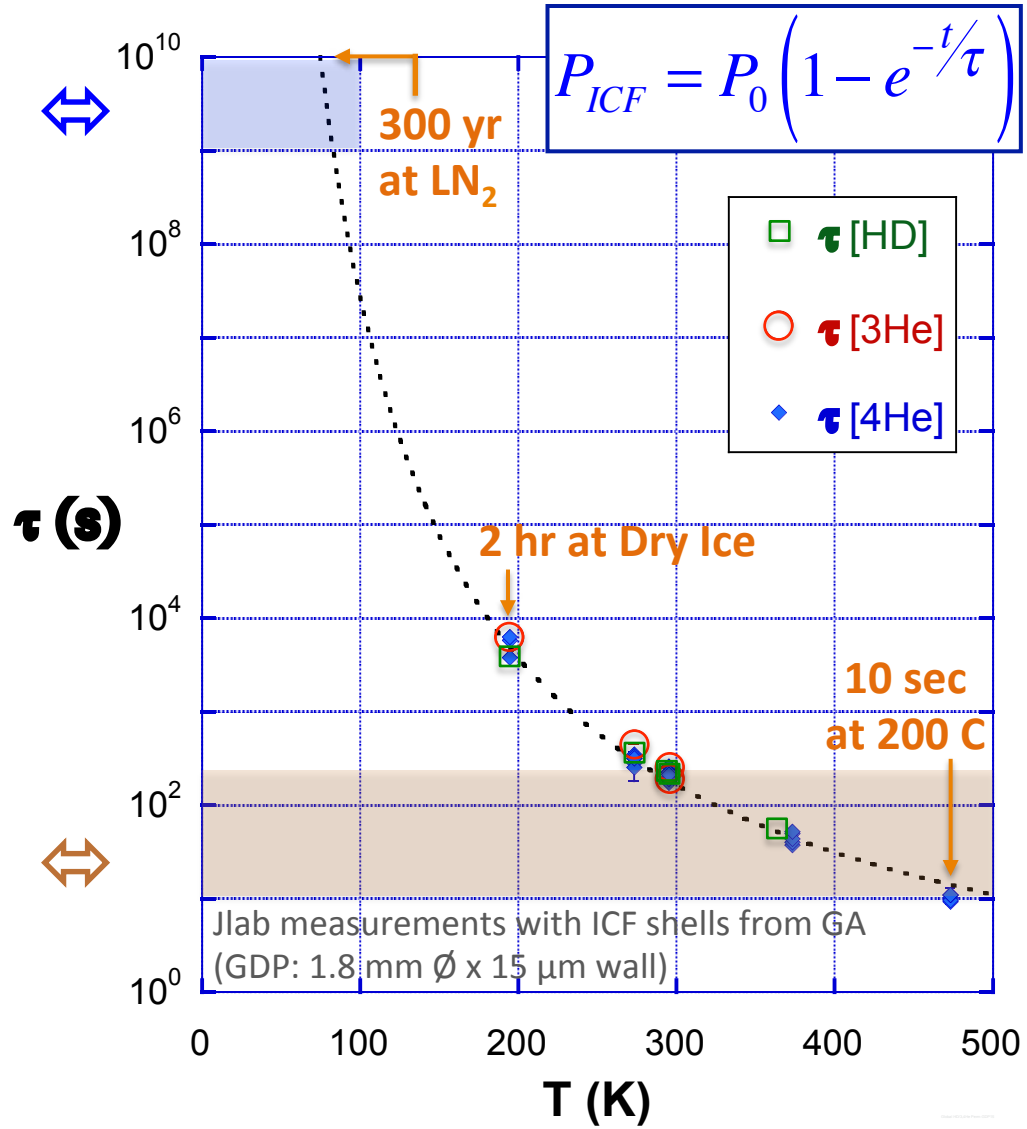
- collisional depolarization negligible in uniform B, and ~10^{-4} s^{-1} for inhomogeneous B
- worst case: $\delta B_\perp$= 1 gauss plasma wave fluctuations at f_L ⇔ depolarization T_1 ~ 10 s (tritons)
  – plasma waves (*eg.* Alfvén eigenmodes) suppressed in asymmetric plasmas, *such as* ITER or DIII-D

Preparing polarized-fuel for injection; 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 ⇔



Strategy for testing polarization survival in DIII-D

- test reaction: $\vec{D} + {}^3\vec{He} \rightarrow \alpha + p$ {mirror reaction to $D + t \rightarrow \alpha + n$ }
- $\vec{D}$ **shells**: use existing JLab facilities to create solid $H\vec{D}$

  ➔ diffuse 200 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

- ${}^3\vec{He}$ **shells**: develop polarized ${}^3\vec{He}$ gas-filled shells at existing UVa facilities
  ➔ 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

- ***DIII-D***: generate *Hydrogen* plasma in the DIII-D Tokamak
  ➔ inject polarized fuel into plasma, alternating spin alignment:

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

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

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

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

➔

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

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

***Signal** from comparing shots* ⇔

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

Strategy for testing polarization survival in DIII-D

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  ➔ diffuse 200-400 atm HD into ICF shells; cool to solid;
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  Adapt known technology – a small NP target

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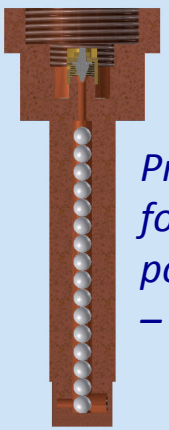
  anti-parallel: $H\vec{D} \Downarrow + {}^3\vec{He} \Uparrow$
  } ⇔ *compare proton yields*

Adapting HD polarized target technology

- use existing JLab facilities to create solid $\vec{HD}$:
  - ➔ diffuse ~ 200 atm HD into ICF shells,
    cool to solid – in NP compatible fixtures ⇔ *eg.*



Prototype chamber for permeation and polarization – all within an NP target envelope

  - ➔ polarization of $\vec{H}$ and $\vec{D}$
    followed by $H \Rightarrow D$ spin transfer:
    typical polarization decay times (T_1) of years;
    typical P($\vec{D}$) ~ 40% in 25 cc NP targets ⇔ assumed for planning
    ⇔ limited by cooling rates and RF uniformity over large NP cells
    ⇔ the maximum of 67% should be approached in 0.03 cc ICF pellets
  - ➔ transport polarized pellets to DIII-D:
    NP targets routinely transported ~1 km to the Jlab experimental hall
    ⇔ need equipment to transport ~ 4000 km to DIII-D
  - ➔ modify 2 K cryo-gun for injection of polarized pellets into DIII-D

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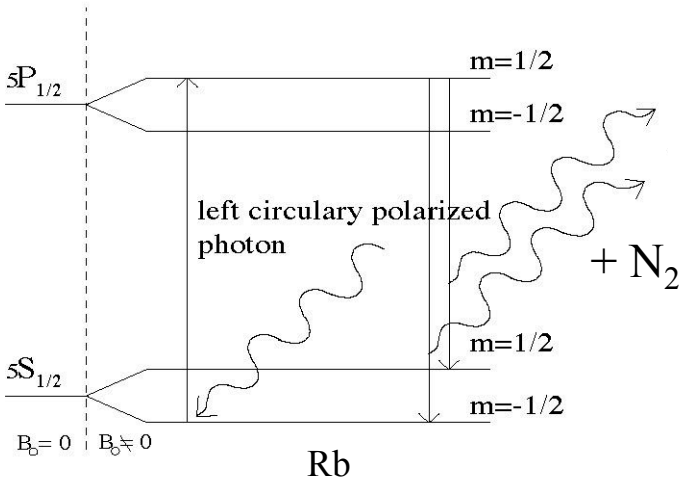
  $\Leftrightarrow$ *compare proton yields*

Polarizing $^3\vec{He}$ fuel

^{3}He process - *spin exchange optical pumping*

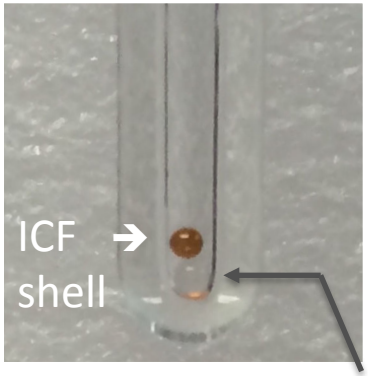
- Rb vapor pumped with 795 nm laser -100W (in oven > 200 C; with ~1 % N_2; uniform B)
- Rb transfers polarization to K by collisions
- K transfers spin to ^{3}He by collisions

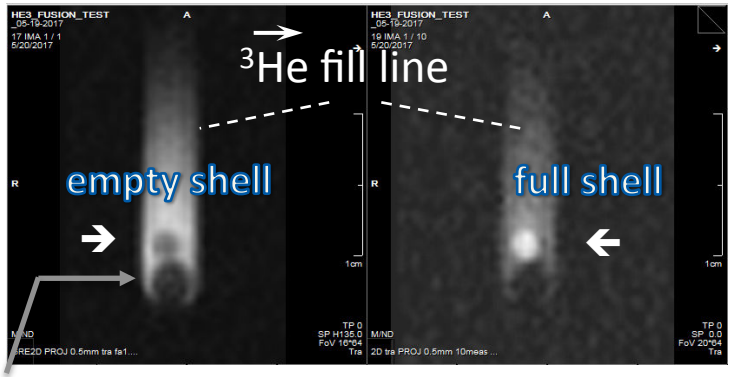


- typical polarizations in pumping chamber: 70% at 10 amagats (~ 10 atm) (some further gain may be possible with the right geometry cell)
- large volume targets used in Nuclear Physics exp at JLab, SLAC,…
- need for high-power laser ➔ must first polarize in glass cell,
  ➔ cool to 20 C to remove alkalis (~few ppm of ^{3}He)
  ➔ then diffuse into ICF shell

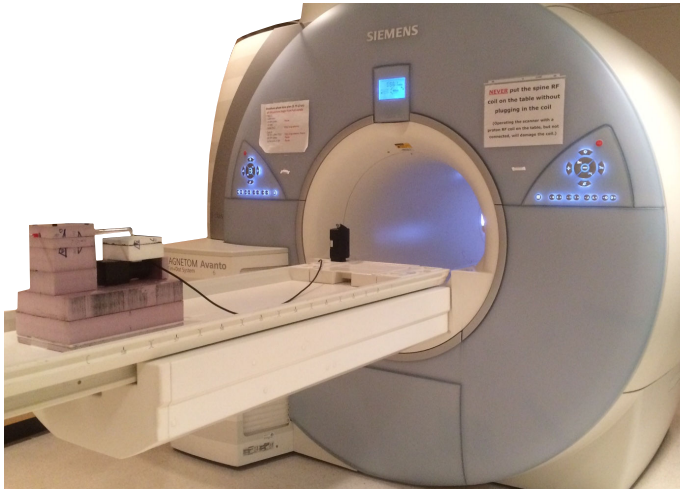
Q: does the polarization survive permeation through the ICF shell wall ?

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

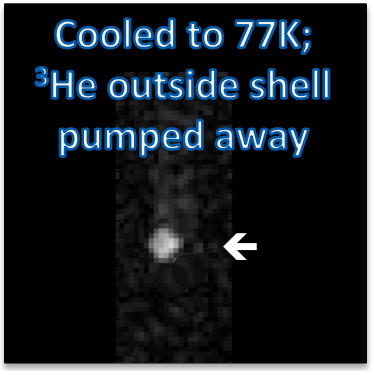




glass bead



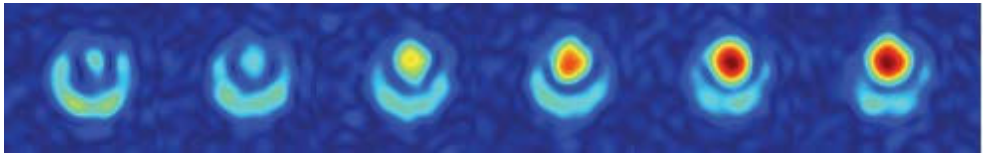
MRI scan of 2 mm OD
ICF shells
filled with polarized ^{3}He



- **^{3}He polarization inside ICF shells can be maintained for ~ 5 hr at 77 K**

➔ will require a ^{3}He polarizer at DIII-D

^{3}He polarization loss during permeation



t(s): 30 90 210 300 540 900

Time sequenced MRI of polarized ^{3}He filling an ICF pellet

Room-temperature permeation of $^3\vec{He}$ into ICF-GDP (Glow Discharge Polymer) pellets:

OD (µm)	wall thickness (µm)	Permeation time constant at 22C (s)	^{3}He P(in pellet)/P_0
1788	15	226	**0.97** ±0.08 ±0.20
1918	26	397	**0.71** ±0.10 ±0.20

preliminary

↑ Sys err

- work continuing to reduce Systematics

- planned ^{3}He pressure = 20 to 25 atm
- Burst pressure of 4 mm Ø x 15 µm wall GDP, cooled to 77 K = 40 atm

➔ **4 mm Ø** x **15 µm wall pellets will work** ✔

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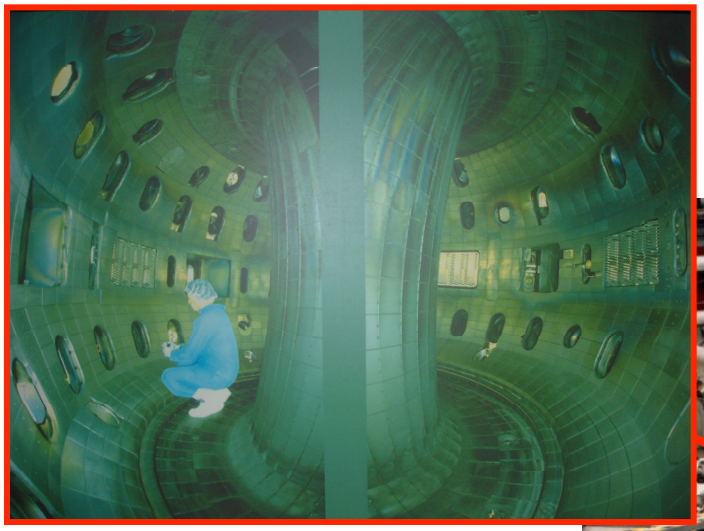
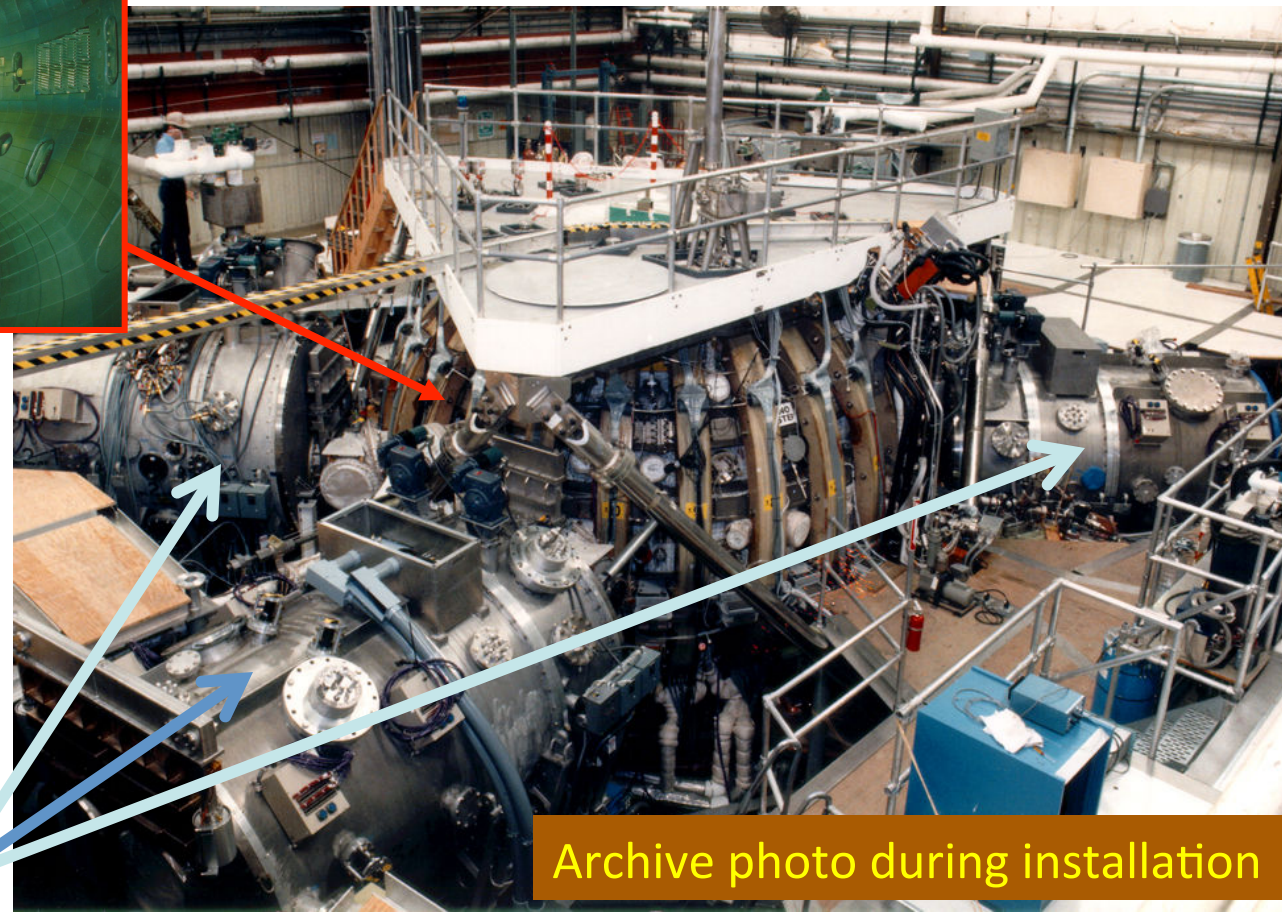
DIII-D Tokamak at General Atomics, San Diego



2.1 tesla torus (normal-conducting coils)



- 2.1 tesla max
  - B ramp up, 3 s
  - flat top ~ 10 s
  - ramp down, 7 s
- 15 min btw shots
- 80 keV neutral-beam Injectors for heating

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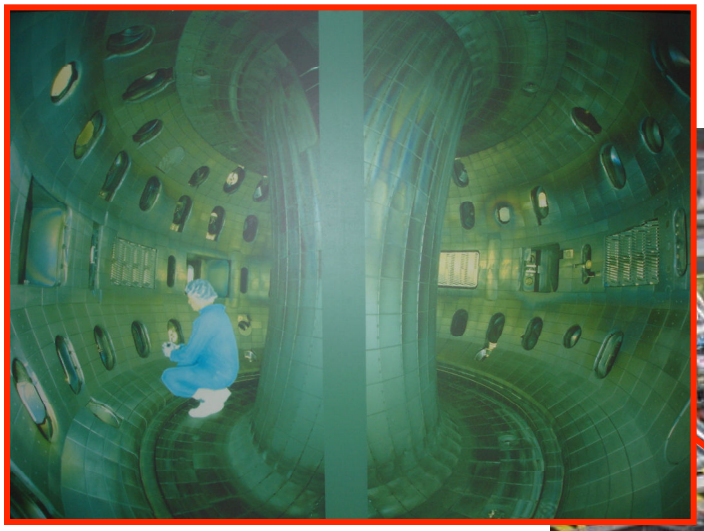

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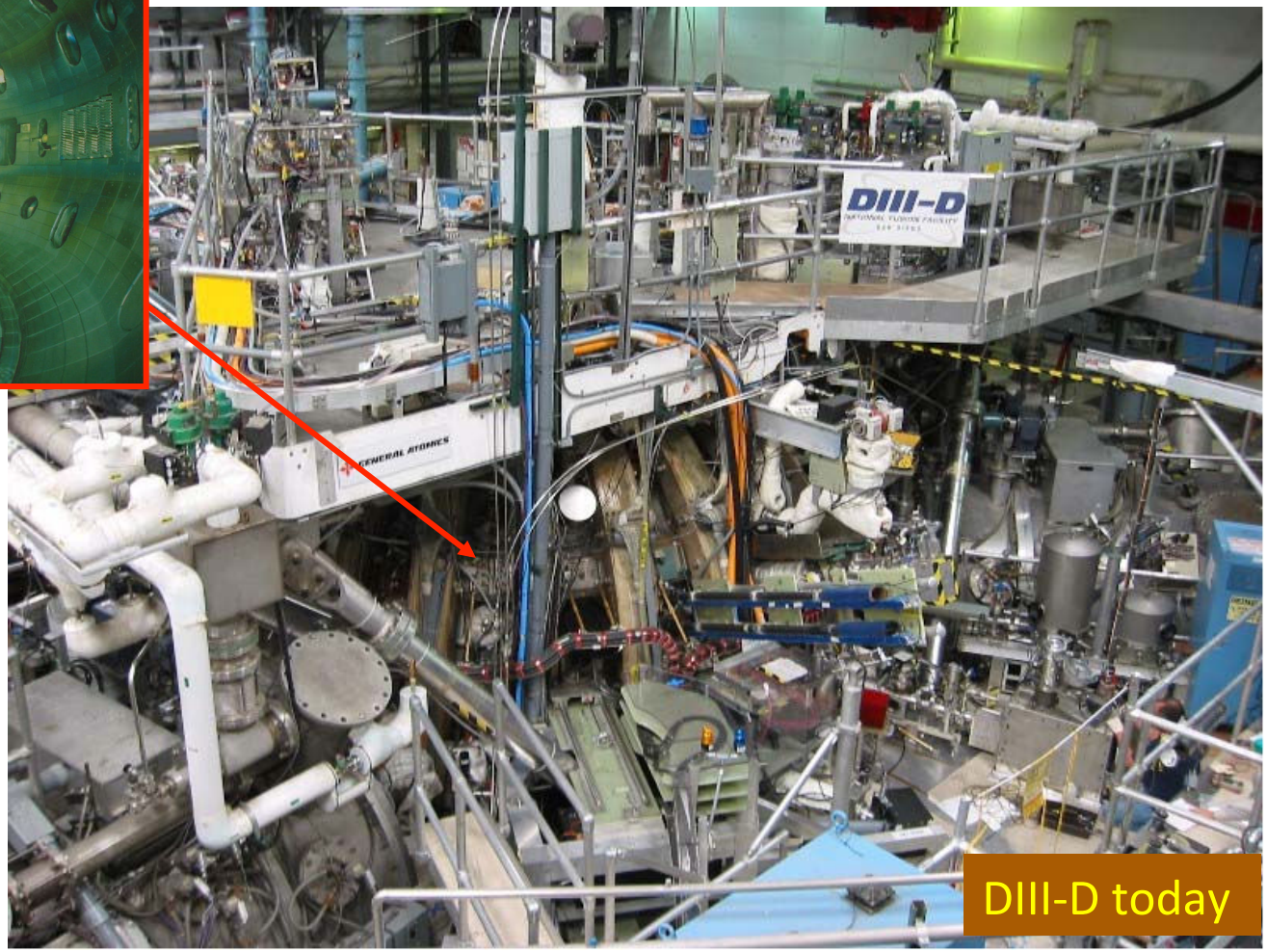

DIII-D today

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$p\,\vec{D}\uparrow + {}^3\vec{He}\uparrow$

$p\,\vec{D}\downarrow + {}^3\vec{He}\downarrow$

$\Leftrightarrow$ *compare proton yields*

"signal" from comparing injections into different plasma shots ⇔ requires good reproducibility

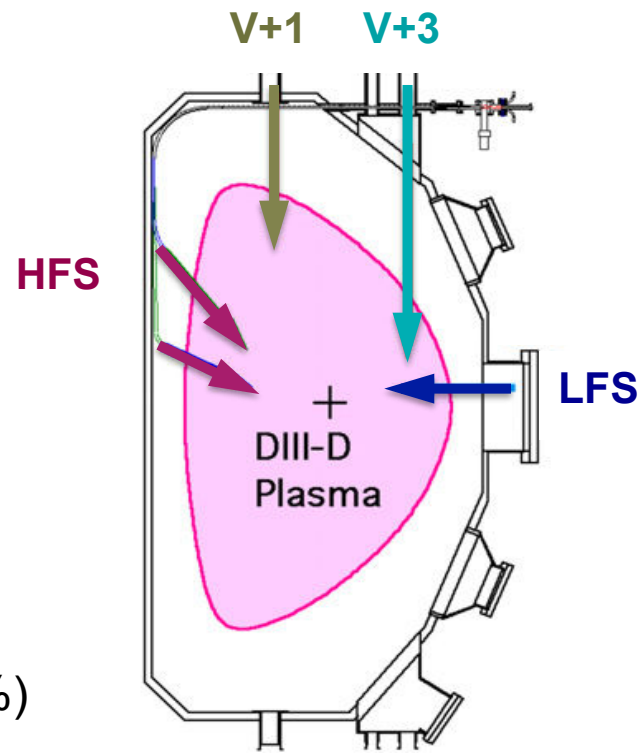
DIII-D Injection reproducibility

- shells propelled by high-pressure H_2 gas
- Balmer-α emissions monitor shell ablation

- laser Thompson-electron scattering:
  - ⇔ deposition profile & extent
  - ⇔ eff = ΔN_e / N_{fuel} = increased e^- density
  - ⇔ **V**ertical (V+1) or **H**igh-**F**ield-**S**ide injection gives deeper penetration of plasma core

- **E**dge-**L**ocalized-**M**odes (ELMs) can be triggered in *H-mode* (high confinement) plasmas
  - ⇔ fraction of shell mass can be ejected
  - ⇔ ε(LFS, V+3) ~ ½ ; ε(HFS, V+1) ~ 0.8 –to–1
  - ⇔ injection efficiencies can be measured (to ~5%)

- V+1 injection for HD & ^{3}He



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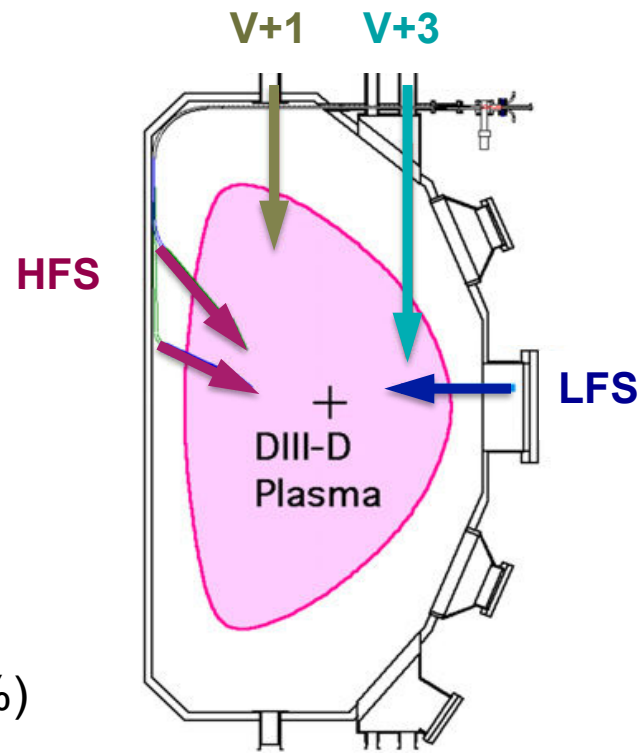


- ***ELMs* are eliminated in *Quiescent H-mode***
  – neutral beams injected against counter-rotating plasma (ion) current
  – Plasma Phys. Cont. Fus. **44** (02) A253

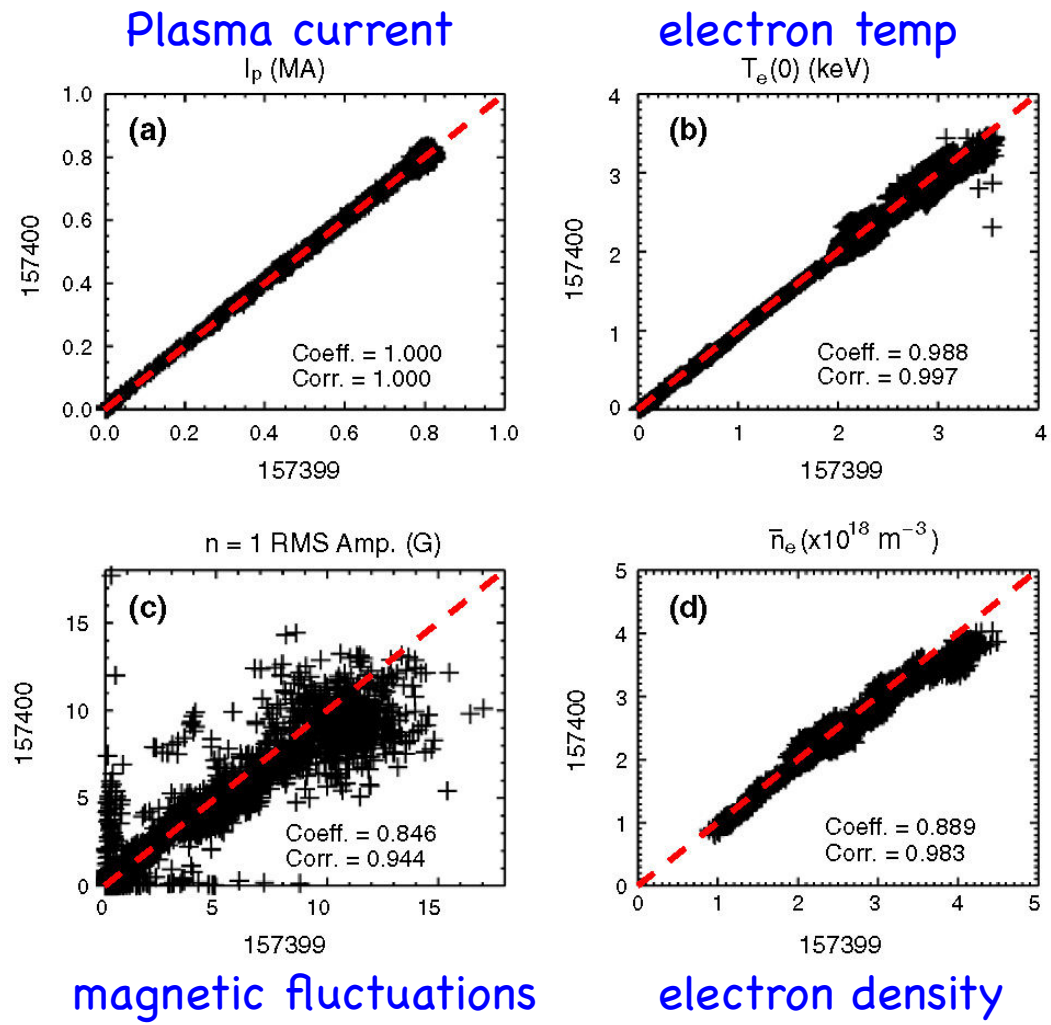
DIII-D plasma shot reproducibility

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%

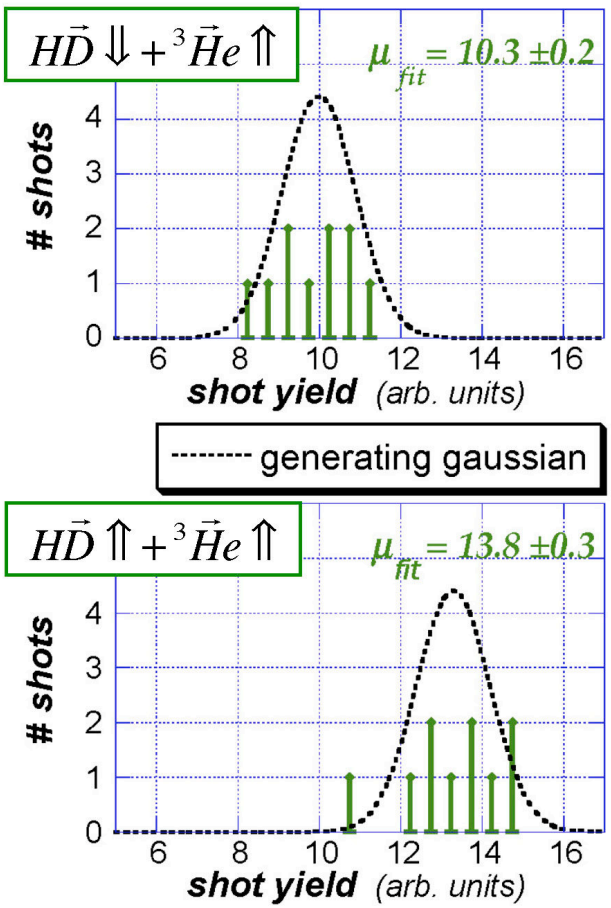
• will need to study reproducibility of high-performance Quiescent H-mode for polarized fusion

⇔



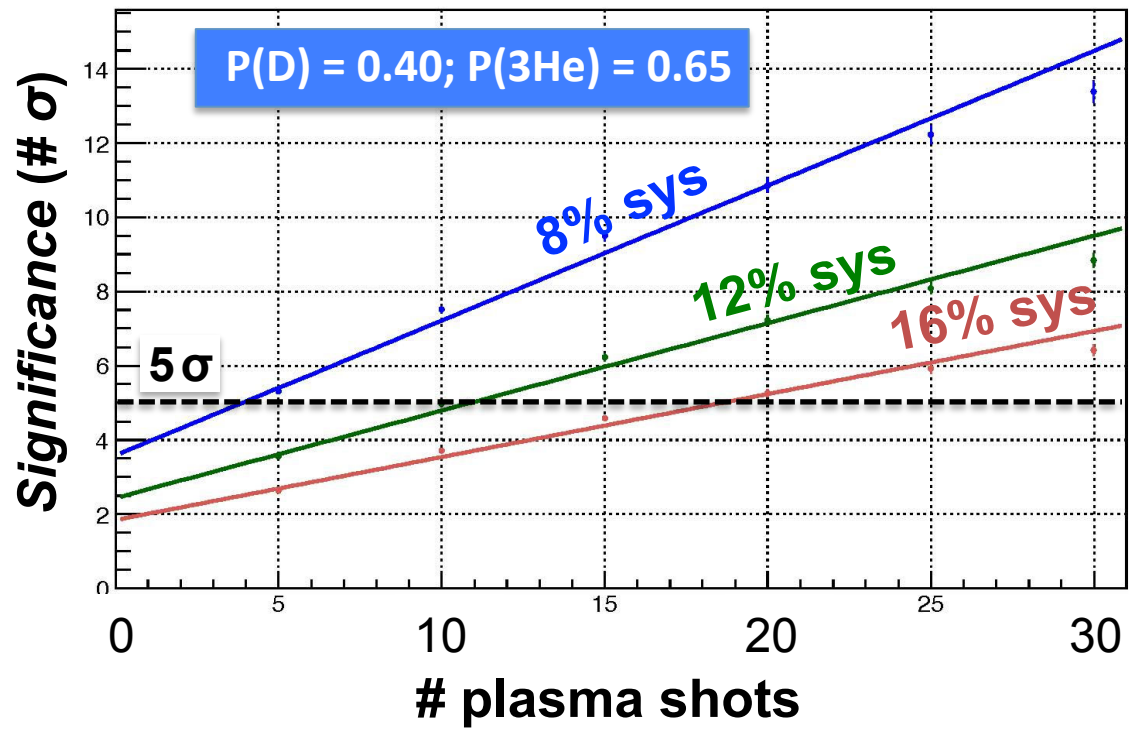
Pace, Lanctot, Jackson, Sandorfi, Smith, Wei, *J. Fus. Energy* **35** (2016) 54

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



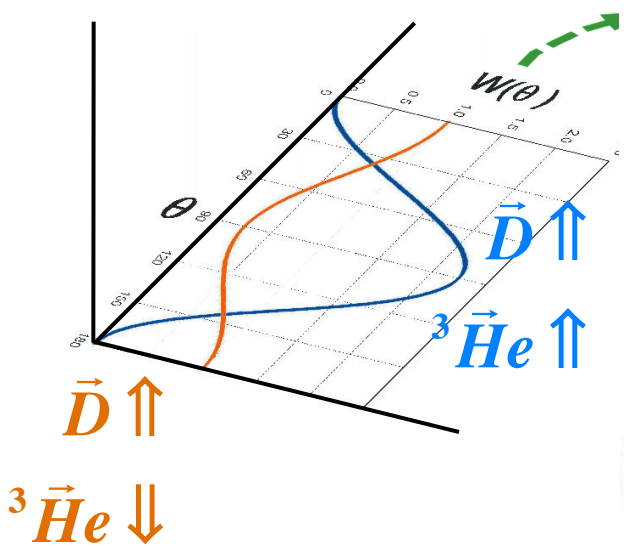
How many shots in each spin alignment to reach 5σ confidence ⇔ Monte Carlo

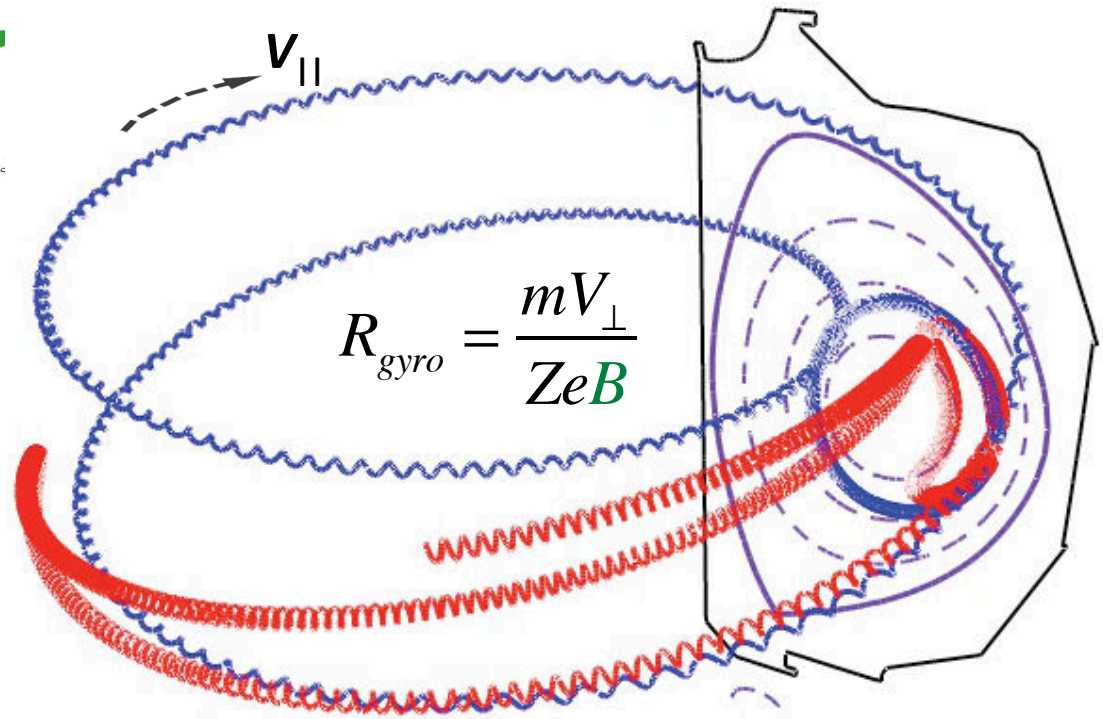
- 8% plasma variation ⇔ 4 shots (P & A)
- 16% plasma variation ⇔ 18 shots (P & A)



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 $V_\parallel$ ➔ small gyroradii ➔ better confined



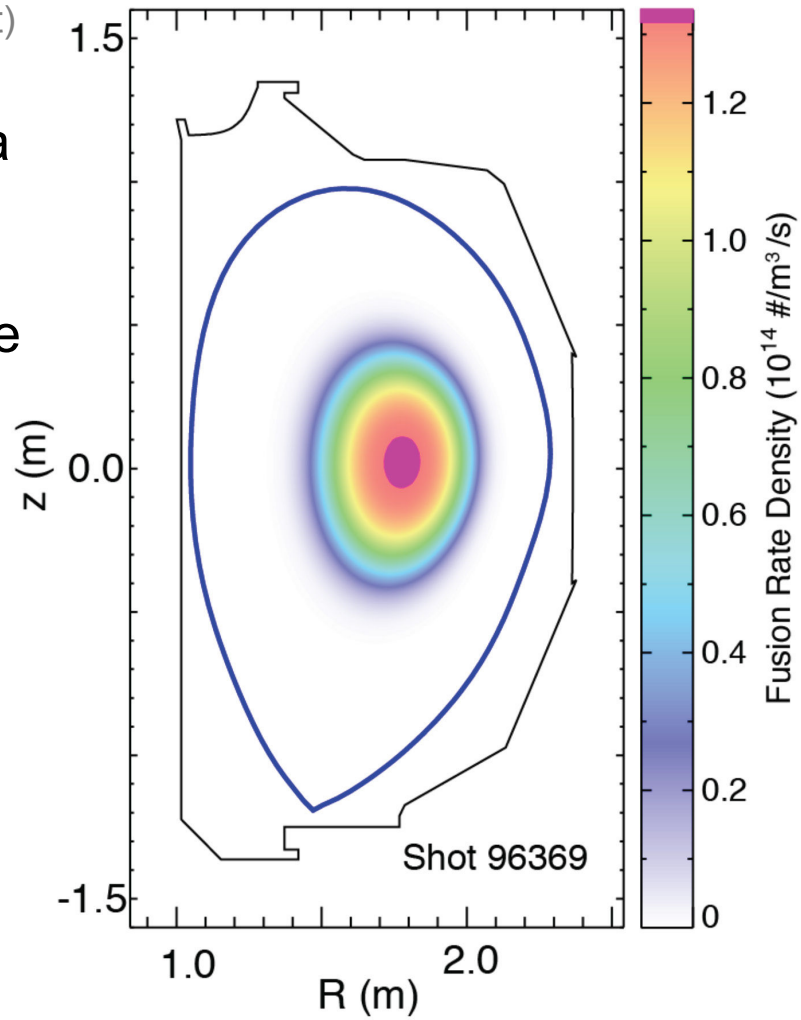


α and p loss-locations on Tokamak wall depend on initial polarizations

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

Tracking Simulations: (GA: D. Pace, M. Lanctot)

- 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)



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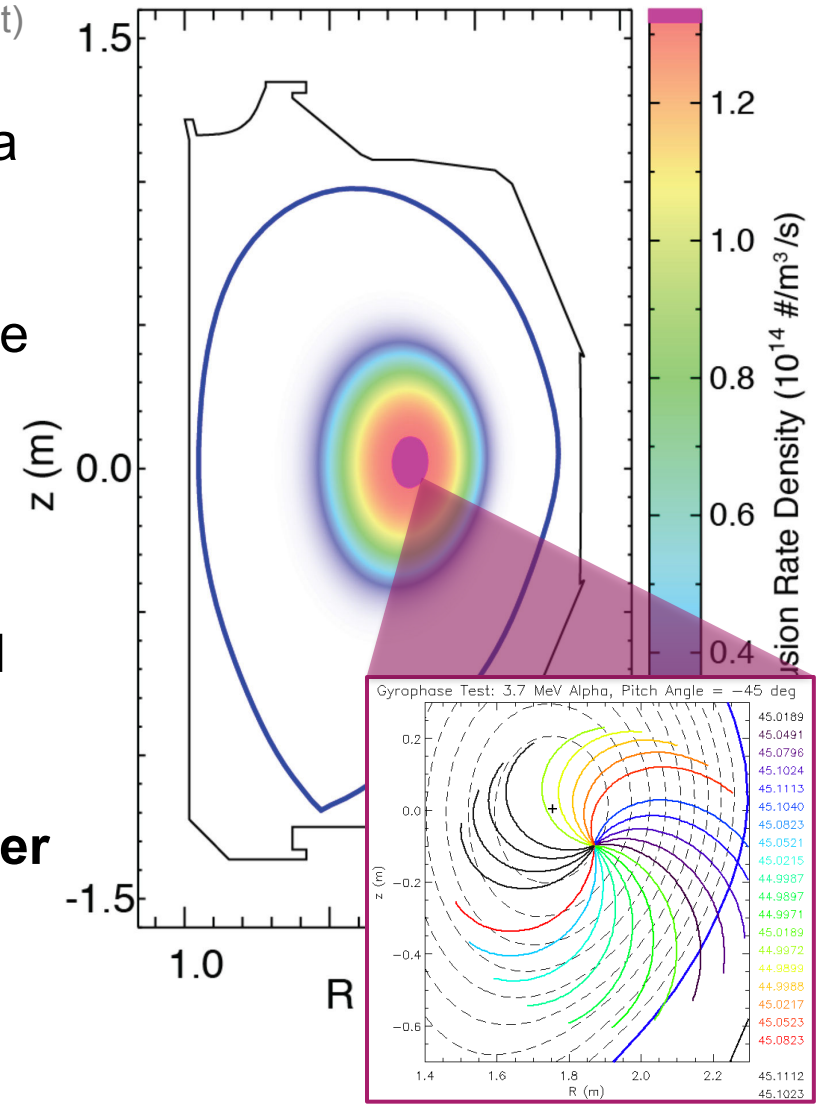
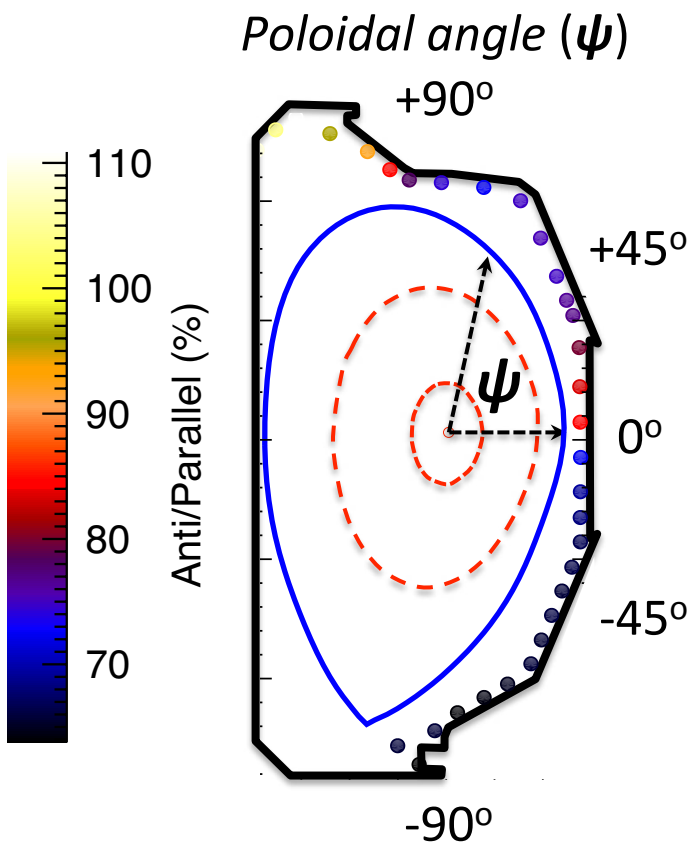
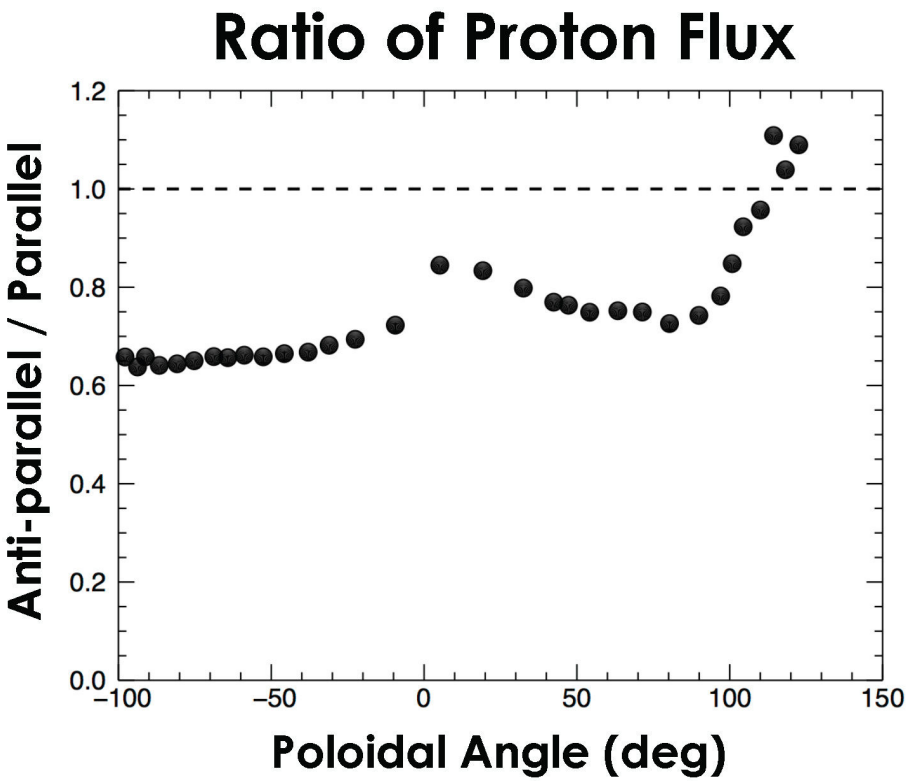
- cross sections scaled from D+D to D+^{3}He
- T_{ion} energy scaled to 15 keV (as expected for Quiescent H-Mode)
- fusion profile discretized; α + p generated along different polar (pitch) θ and azimuthal (gyrophase) φ, relative to the local field, **weighting the relative number by the polarized angular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



Predicted ratio of protons from anti-parallel & parallel spins



P(^{3}He) = 65%; P(D) = 40%



Definitive Signal:

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

Secondary Reactions

- use H-plasma heated with 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

SPF (Spin-Polarized-Fusion) Collaboration

- **Jefferson Lab**

  JLab:

  A. Deur, C. Hanretty, M. Lowry, A.M. Sandorfi, X. Wei

  Univ. of Connecticut

  K. Wei

  $H\vec{D}$ & $^3\vec{He}$ pellet preparation

- **University of Virginia**

  J. Liu, G.W. Miller, S. Tafti, X. Zheng

  $^3\vec{He}$ pellet polarization

- **General Atomics/Fusion Energy Research**

  GA-DIII-D:

  N. Eidietis, A. Hyatt, G. Jackson, M. Lanctot, D. Pace, S. Smith, M. Wade

  plasma, orbit & transport simulation

  GA-ICF Pellet Division:

  M. Farrell, M. Hoppe, M. Schoff, N. Alexander

  ICF pellets for HD, ^{3}He

  Oak Ridge National Lab

  L.R. Baylor

  cryo-injection guns

  UC-Irvine

  W.W. Heidbrink

  fast particle detection

Status of efforts towards a SPF demonstration experiment

- ***White Paper* & presentation to a DOE-FESAC subcommittee** - May 31/17 ✔
  for inclusion in the *Fusion Energy Sciences* long-range R&D plan
  ➔ report due out Jan/2018

⇔ proposed time line:

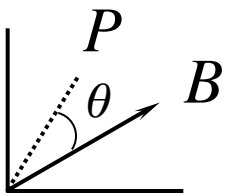
- funding in FY'19 (Oct'18) for **TR-3** (*Technical Readiness Level 3)*:
  - the beginning of an *official DOE-FES "project"*
    ➔ initial designs and cost analysis of each major subsystem

- funding for 3 years beginning in FY'20 (Oct'19) to reach **TR-6**:
  ➔ construction of an optimized ^{3}He polarizer and commissioning at DIII-D
  ➔ construction of (*ICF-like*) systems for rapid pellet permeation
  ➔ development of ancillary equipment to polarize HD and transport to DIII-D
  ➔ retrofit existing cryo-pellet launchers and guide tubes for polarized pellets
  ➔ DIII-D optimization of high-T_{ion} Hydrogen plasmas & vertical fuel injection
  ➔ build and install proton detector array to map poloidal distribution in DIII-D

➔ **1st *in* situ SPF measurements in 2022**

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 :

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