Testing Fuel Polarization Survivability in a Tokamak Plasma

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Jefferson Lab

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

09/26/2022-09/30/2022

Collaborators

Jefferson Lab:
A. Deur, M.M. Lowry, A. M. Sandorfi, and **X. Wei**

General Atomics:
N. Eidietis, A. Hyatt, G. Jackson, D. Pace, S. Smith

Oak Ridge National Lab:
L. Baylor

University of California, Irvine:
A. Garcia, W. Heidbrink

University of Connecticut:
K. Wei

University of Virginia:
J. Liu, G. W. Miller, S. Tafti, X. Zheng

Motivations

Power!

Clean Power!!

Sustainable Clean Power!!!
(with least environmental impact)

Fossil Fuels, Fission, Hydroelectric, Wind Turbine, Solar, Geothermal, Ocean Current, ……

and finally

Fusion

Fusion Channels

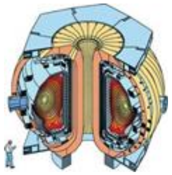
- The intended fuel:
    - $D + T \rightarrow \alpha + n$
    - and $D + {}^{3}He \rightarrow \alpha + p$

- Most of research Tokamaks ever built (~30 in operation today) were for studying D+D reactions.

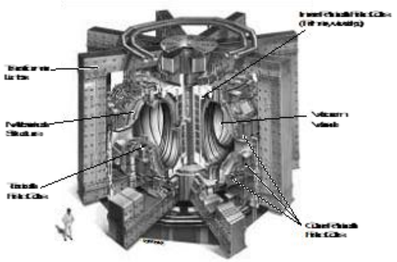
- ***I***nternational ***T***hermonuclear ***E***xperimental ***R***eactor (***ITER***) will make harvesting fusion power possible.

- The cost is ~$V_{\text{-plasma}}$ x B^2.
  $\Rightarrow$20~40 billion dollars

DIII-D (USA)
Best instrumented
→most diagnostics
20m^3, 2.1T, Q<<1

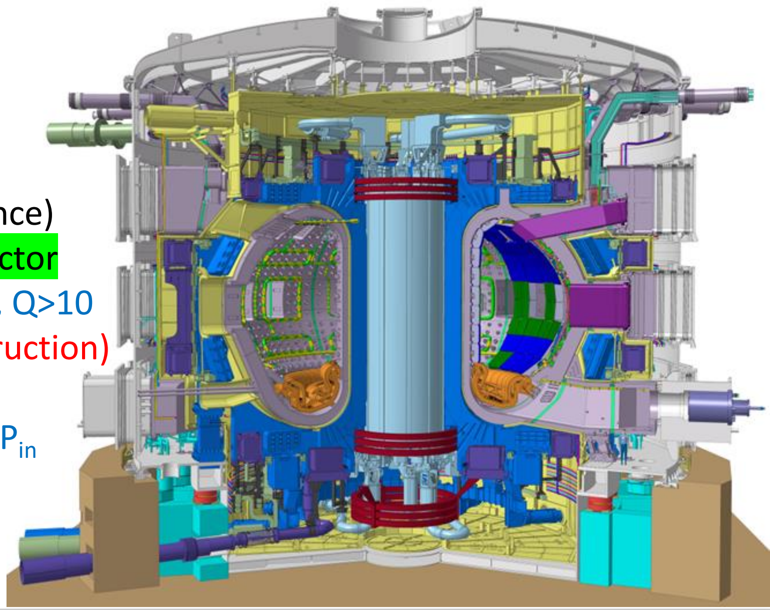


JET (UK)
Only one runs tritium
90m^3, 3.8T, Q~2/3

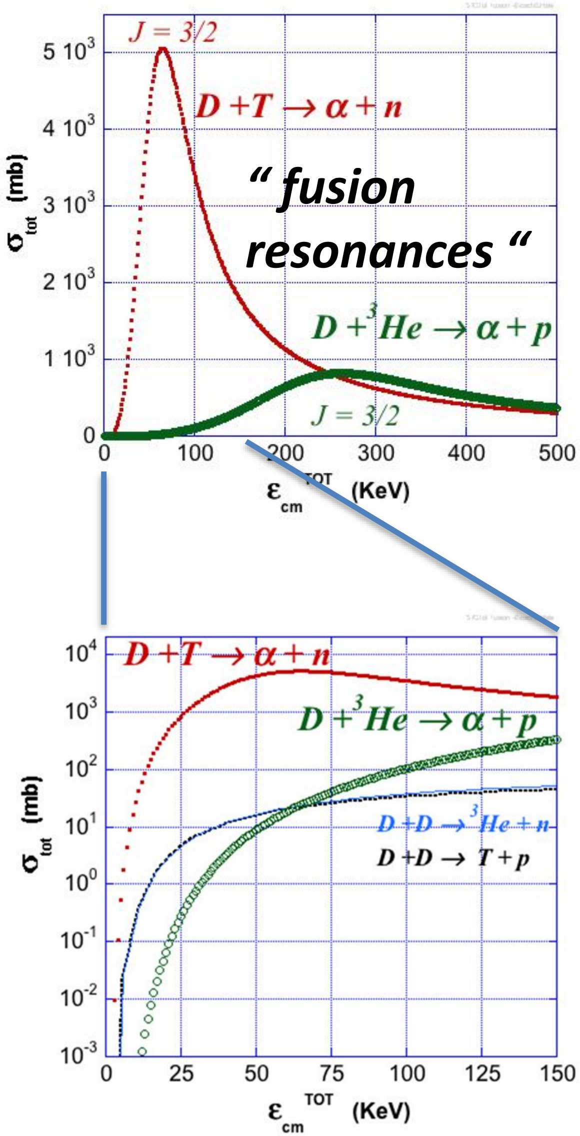


ITER (France)
½ GW reactor
700m^3, 5.3T, Q>10
(under construction)

$Q \equiv P_{out}/P_{in}$



Benefits of Polarized Fuels



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

$$\sigma_{cm} = \sigma_0\{1 + \frac{1}{2}\overrightarrow{P_D^V} \cdot \overrightarrow{P_T}\}$$

Polarized fuels could

- enhance the cross section by up to 50%, power and Q by 75%.
- lower the magnetic field requirement save the cost for future fusion reactors (~B^2) by up to 20%.

Survived Mechanisms

Many mechanisms were invested in late last century and 2 still survived, which hinge on the wall recycling (of the fuels).

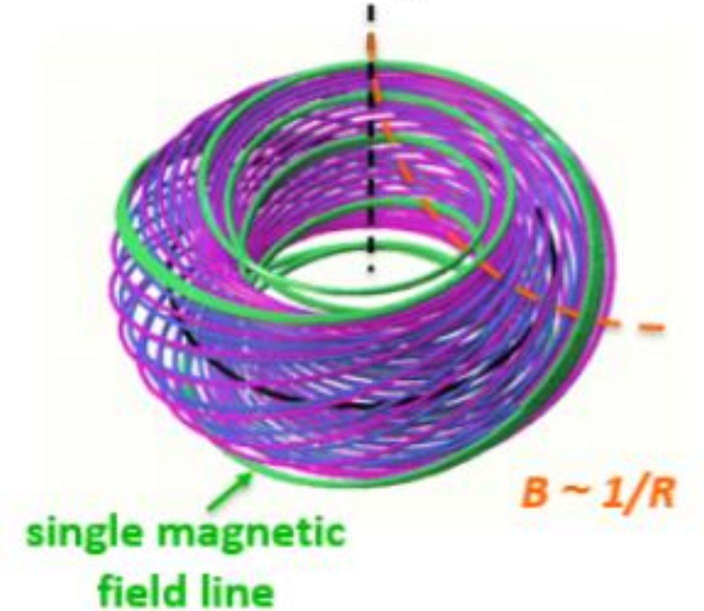
- Kulsrud, Furth, Valeo & Goldhaber, Phys Rev Lett **49** (82) 1248
- Lodder, Phys. Lett. A98 (83) 179
- Greenside, Budny and Post, *J. Vac. Sci Technol*. A **2**(2), (84) 619
- Coppi, Cowley, Kulsrud, Detragiache & Pegoraro, Phys Fluids **29** (86) 4060
- Kulsrud, Valeo & Cowley, Nucl Fusion **26**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

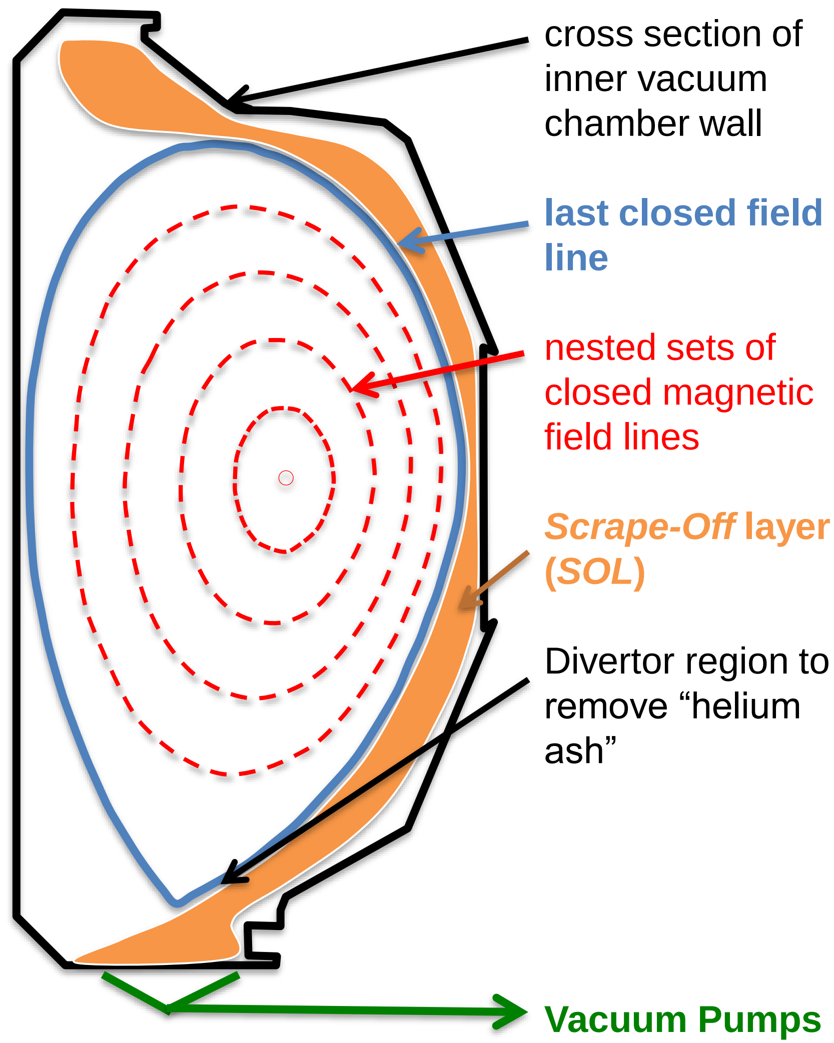
…

A few seconds confinement time in hot plasma is all it needs!

Wall Recycling at the ITER

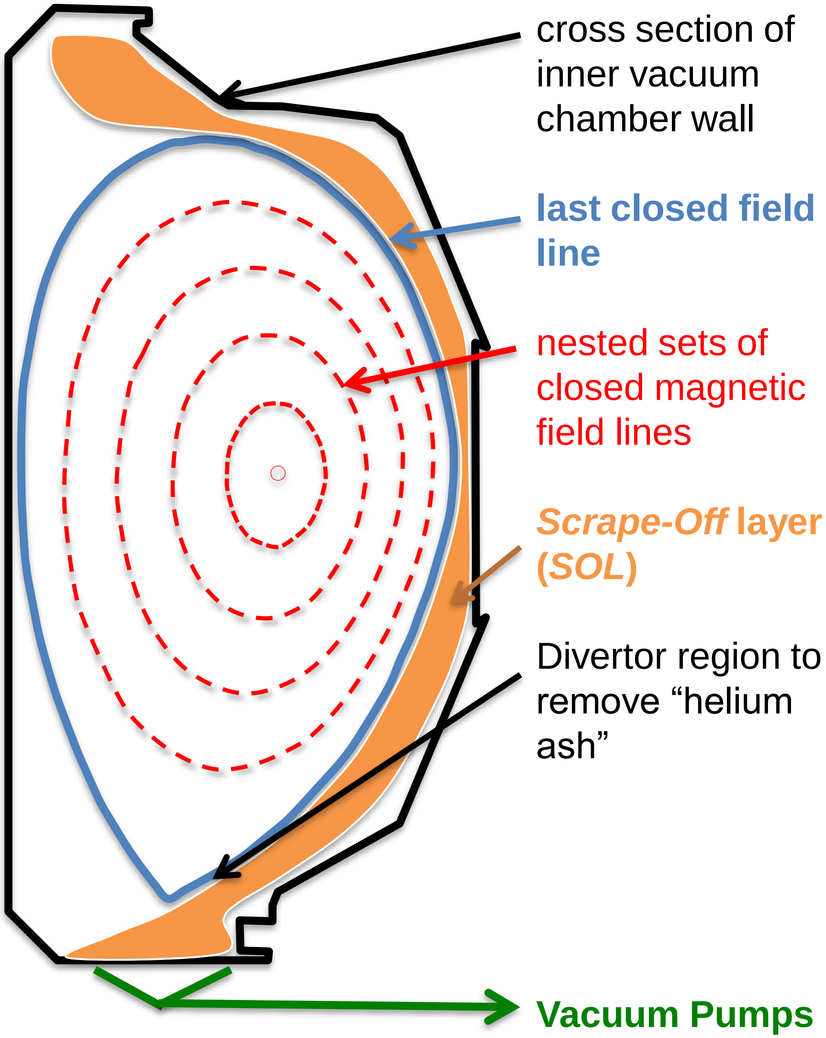
- e^- and ions follow helical trajectories around nested sets of closed magnetic field lines





Wall Recycling at the ITER

- 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 reentering the plasma, they could dilute polarization of the core
- fuel leaving the plasma will eventually diffuse through the SOL and be pumped away



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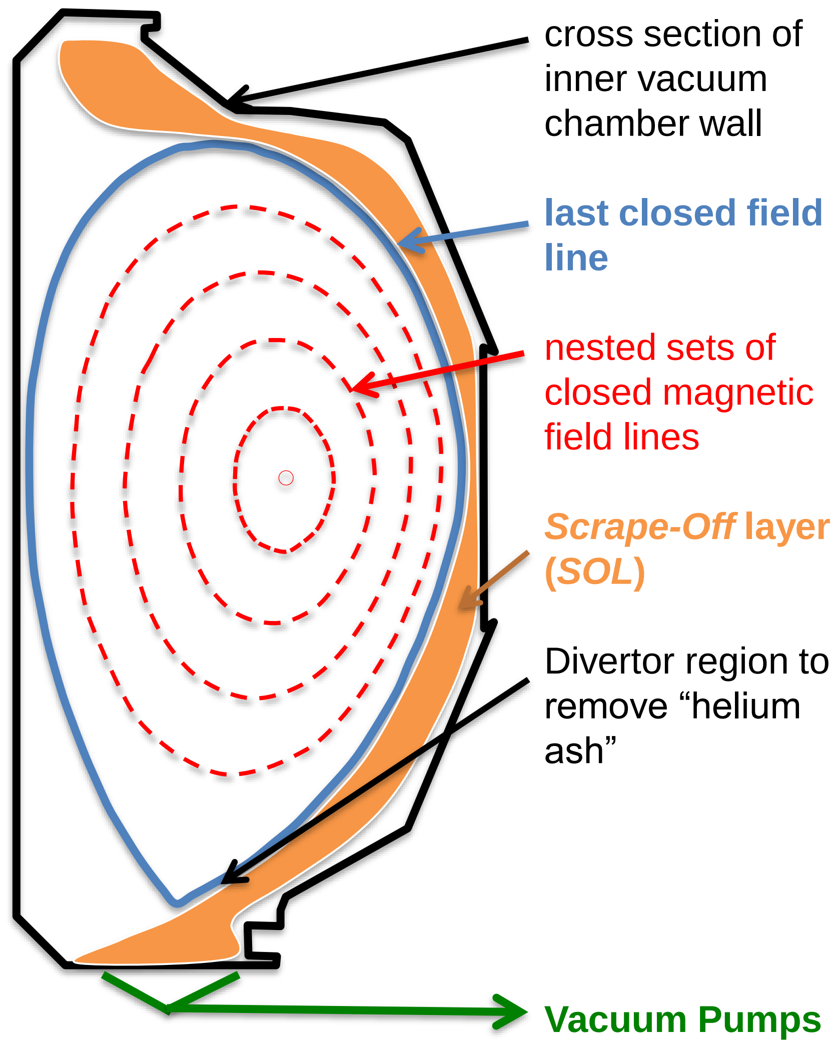
What's new ?

- 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**



SPF Collaboration: Testing Fuel Survivability at DIII-D

Jefferson Lab:
(Polarized Fuel: HD and/or LiD)
A. Deur, M.M. Lowry, A. M. Sandorfi, and **X. Wei**

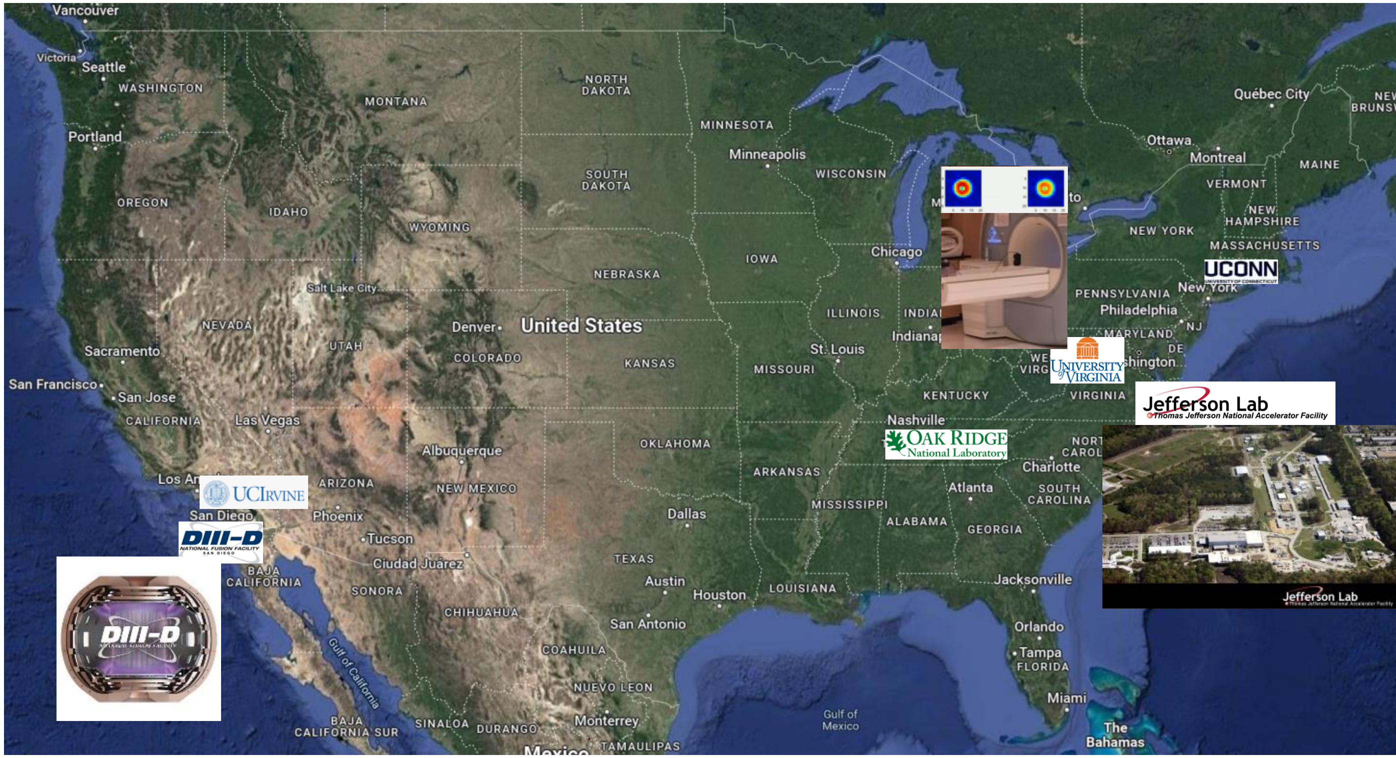
General Atomics (DIII-D):
(Plasma Shots and Simulations)
N. Eidietis, A. Hyatt, G. Jackson, D. Pace, S. Smith

University of California, Irvine:
(Fusion Product Detection)
A. Garcia, W. Heidbrink

Oak Ridge National Lab:
(Fuel Injection Guns)
L. Baylor

University of Connecticut:
(Fuel Pellet Characterization)
K. Wei

University of Virginia:
(Polarized Fuel: ^{3}He, Pellet Imaging)
J. Liu, G. W. Miller, S. Tafti, X. Zheng



Proposed Tests: $D + {}^3He \rightarrow \alpha + n$

- Since the preferred fusion reaction, $\boldsymbol{D + T \rightarrow {}^5He \rightarrow \alpha + n}$, and the mirror reaction, $\boldsymbol{D + {}^3He \rightarrow {}^5Li \rightarrow \alpha + p}$, have the same nuclear physics, we can use the later to test polarization survivability in the fusion plasma.

- The test will be done at the ***DIII-D*** at General Atomic in San Diego, CA. (SPF Collaboration)

- ***D*** (Jlab Team and GA Team) and $\boldsymbol{{}^3He}$ (UVA Team) pellets will be polarized near the DIII-D and delivered into the Tokamak via Cold Injection Guns (ORNL Team) separately.

- Data collected with well designed detectors placed at the most sensitive locations of ***DIII-D*** (GA Team and UC-Irvine Team) for enhancing the output.

(The ***D*** fuel can be polarized either as solid ***HD*** with high ***B*** and low ***T***, or as $\boldsymbol{{}^7LiD}$ ball with DNP method.)

Proposed Tests: D + ^{3}He $\rightarrow \alpha + n$

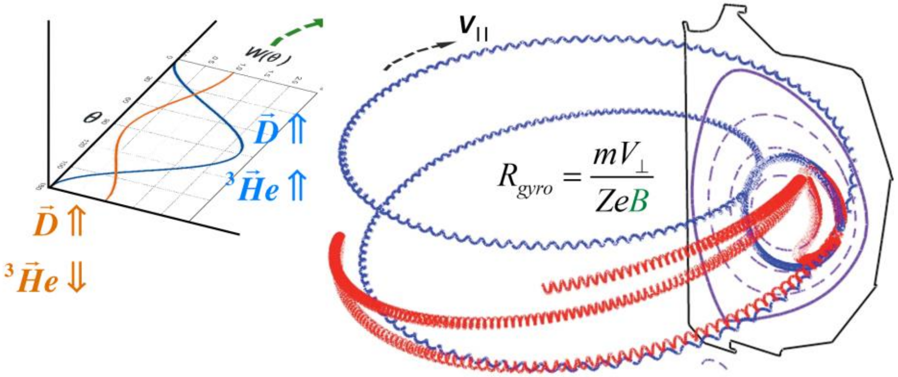
$f_L = \frac{\gamma}{2\pi} B$ ⇔ *Spin precession*

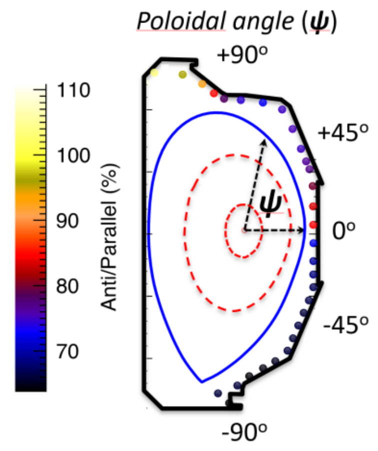
D	T	^{3}He	
6.5	45.4	-32.4	(MHz/T x B)

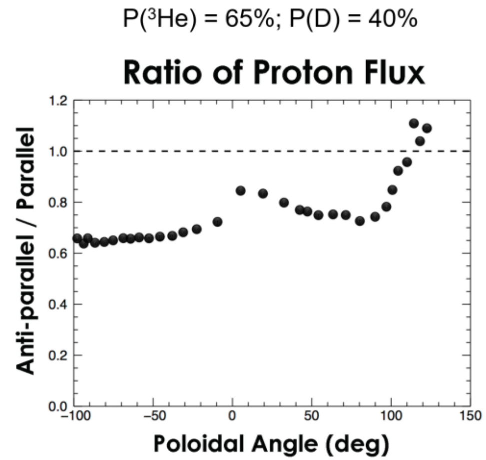
$f_{gyro} = \frac{q}{2\pi} \frac{B}{m}$ ⇔ *Cyclotron motion*

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

- 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







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

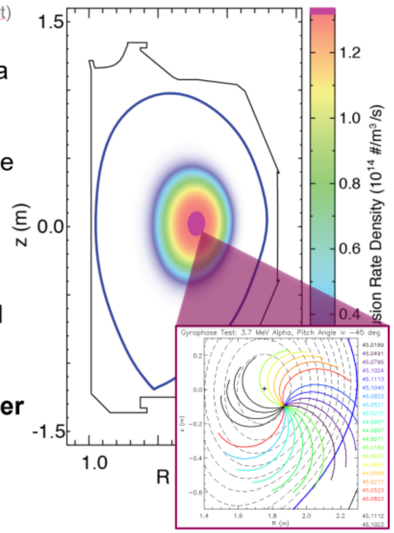
α and p loss-locations on the Tokamak wall depend upon the initial polarizations.

Placing detectors in favored locations will enhance the outcome.

Proposed Tests: D + ^{3}He $\rightarrow \alpha + n$

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)
- 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



- 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)

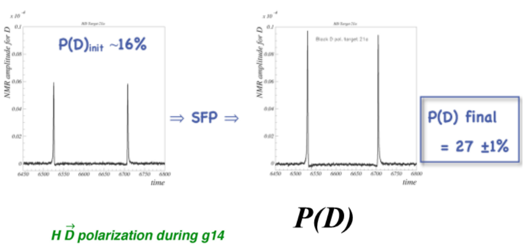
- 15 MeV protons from ^{3}He + D ⇨ α + p provide a unique signature that is easily separated.

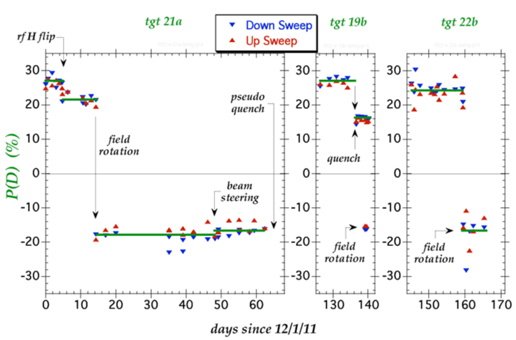
Relevant fusion products' behavior in the DIII-D plasma are well studied.

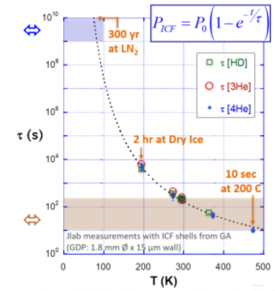
15 MeV protons from the test reaction is a unique signature of fusion.

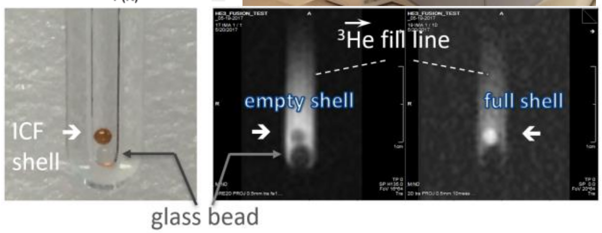
Available Fuels for Spin Survival Test

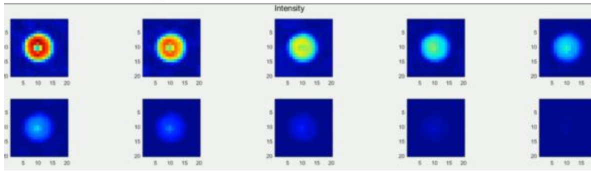
D from HD	D from ^{7}LiD	^{3}He
• Known techniques • Most equipment existing	• Known techniques (DNP) • No container needed	• Known techniques (SEOP)
• Complicated operation	• New equipment needed	• New equipment needed









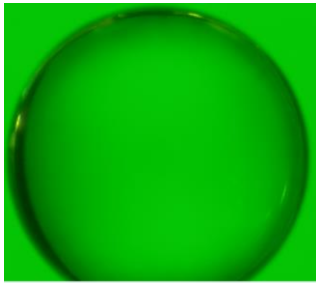


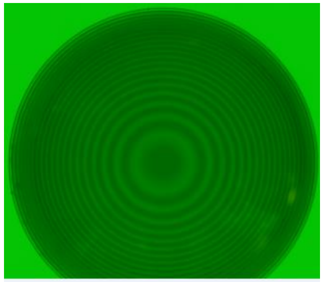
Fuel Developments involved SPF Collaboration

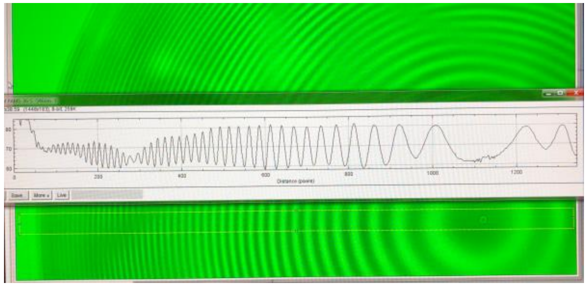
- Polarized ^{3}He gas is routinely used at the Imaging Lab at UVA Medical Center. Characterizing the polarized ^{3}He behaviors inside fusion fuel pellets has been done in Imaging Lab by the teams UVA Imaging, UVA Physics, and Jefferson Lab.
- The concept of using polarized HD as nuclear physics target was developed at Syracuse University, which was realized as SPHICE target at Brookhaven Lab and as HDice target at Jefferson Lab by the same team.
- The polarized HD as the Inertial Confinement Fusion (ICF) fuel was studied at Syracuse. Especially for filling and polarizing the sub-millimeter HD pellet.

Component Readiness: Polarized ^{3}He

- The existing ^{3}He polarizer works. It needs to be optimized to produce 80% polarization, in order to get 65% inside the GDP shells.
- The pellet permeation device and gas handling system is available, some upgrade may needed for better operation.
- The relaxation time of ^{3}He inside fusion pellet was extensive studied at 77K and room temperature. The results are in publishing process.
- Existing pellets (GDP shells) were well characterized.

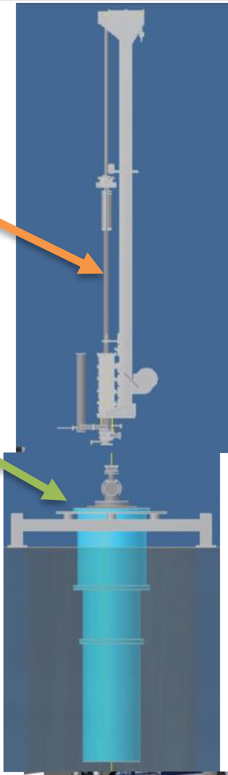






Component Readiness: Polarized HD

- Pellet cartridge transfer cryostat (2K, 0.1T) is operational.
- HD polarizing dilution refrigerator (10mK, 15T) is ready to run.
- Calibration Cryostat (1.4K, 2T) works.
- NMR spectrometers are functional. They need to be modified/upgraded for tiny pellets.
- High pressure HD pellet permeator and gas recycle apparatus need to be built.



Component Readiness: Polarized ^{7}LiD

Another attractive option: ^{7}LiD

1. Can be built elsewhere, and operated by a small group at DIII-D for direct injection.
2. easy to handle.
3. much less equipment involved.

(For a comparison, the HD option requires a larger crew, more cryostats and much longer production cycle.)

But … nothing in hand yet!

- The complete DNP polarizer, including microwave, NMR and ^{7}LiD ball dispensing system, is needed.
- The ^{7}LiD ball production apparatus need to be built. (Literature for the process is available).

LiD was originally studies by Abragam and collaborators:

- *A new polarized target material:* ^{6}LiD, Abragam A., *et al*, 1980 J. de Physique Lett., Edp sciences 41, 309;
- *Dynamic nuclear polarization in* ^{6}LiD, Bouffard V., *et al*, 1980 J. de Physique, 41, 1447.

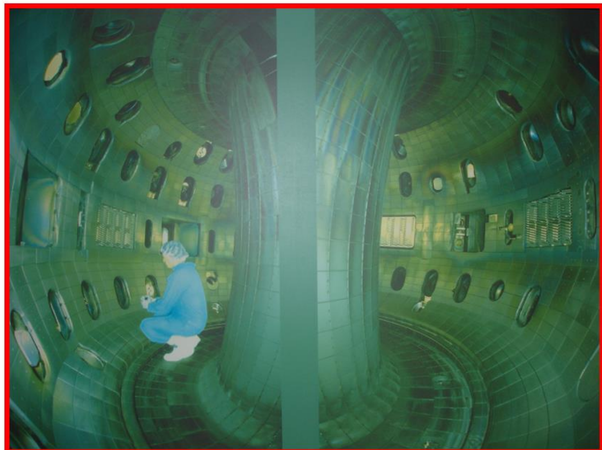
Component Readiness: Cryogenic Injection Gun

- The Oak Ridge National Lab team will design and built
  - (1). the ~2K gun with ~0.1T holding field for polarized HD pellet or polarized *^{7}LiD* ball injections, and
  - (2). the 77K with 0.01T holding field. (The ORNL built the an existing 4K gun without holding field for DIII-D).

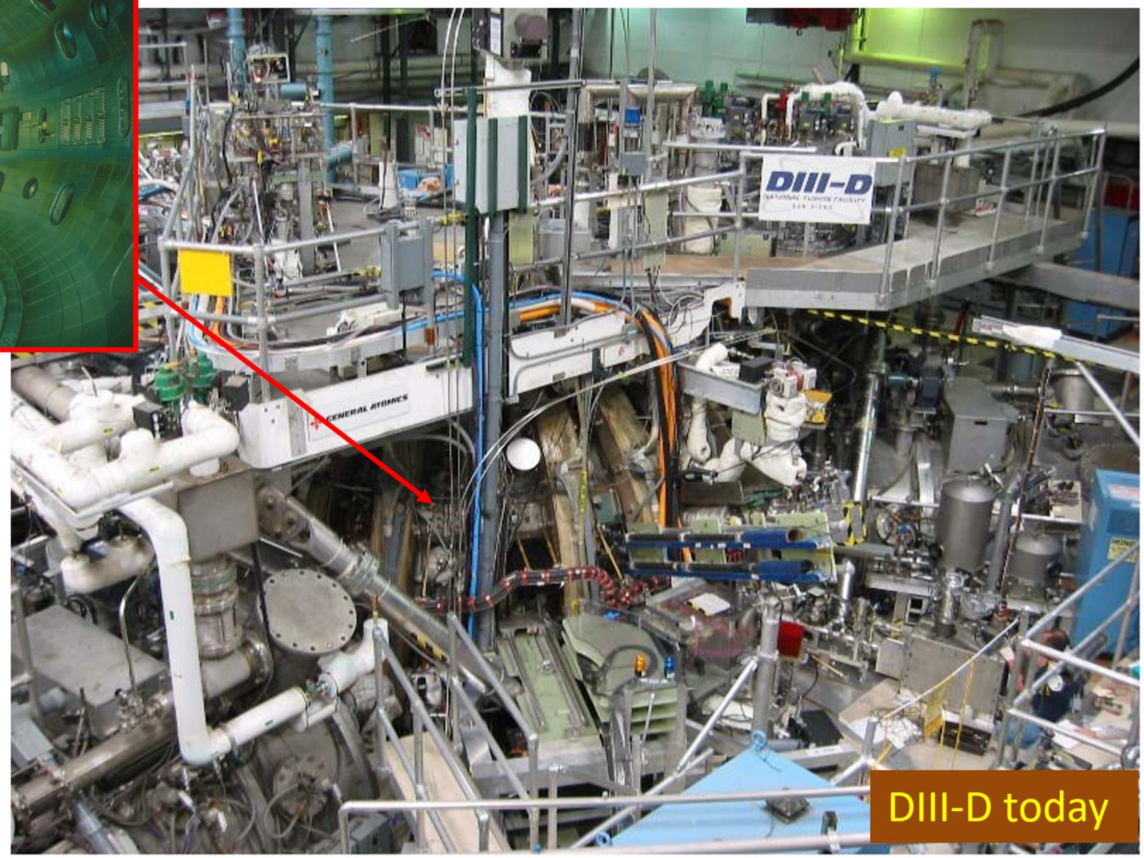
With a careful consideration and team collaboration, the loading port of polarized ^{3}He pellet cartridge can be built to access the 80K stage of the ^{7}LiD polarizer, to allow firing both D and ^{3}He pellets into the Tokamak with a single 2K injection gun.

Component Readiness: DIII-D Tokamak

Ready to be reconfigured for the $D + {}^{3}He \rightarrow \alpha + p$ run



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

SPF Publications Currently Under Review (Sept. 2022)

3 papers from the SPF collaboration currently under peer review:

- "*Encapsulation of Spin-Polarized 3He in Tokamak Fusion Pellets*",
  S. Tafti, J. Liu, A.M. Sandorfi, K. Wei, X. Wei, X. Zheng, and G. W. Miller,
  Nature Physics (2022 – expected)

- "*Polarized Fusion and Potential in situ Tests of Fuel Polarization Survival in a Tokamak Plasma*",
  L. Baylor, A. Deur, N. Eidietis, W.W. Heidbrink, G.L. Jackson, J. Liu, M.M. Lowry, G.W. Miller,
  D. Pace, A.M. Sandorfi, S.P. Smith, S. Tafti, K. Wei, X. Wei and X. Zheng,
  Nuclear Fusion (2022 – expected)

- "*Conceptual design of DIII-D experiments to diagnose spin polarized fuel*",
  A. Garcia, W.W. Heidbrink, and A.M. Sandorfi,
  Nuclear Fusion (2022 – expected)

Timeline

Whence the proposal goes through, we are expecting to run the ***D + ^{3}He*** test within 5 years. *The DOE-FES (Fusion Energy Sciences) has said they are open to a funding request for the next funding cycle (Jan. 2023)*.

- Year 1: Designing cryostats, purchasing electronics for polarizer. Decision for D fuel.
- Year 2: Start building all subsystems.
- Year 3: Finishing subsystem constructions and then production test.
- Year 4: System integration and final assembly.
- Year 5: Run ***D + ^{3}He*** test.