Preparations at JLab for a Spin Polarized Fusion Program

The Polarized ^{7}LiD Program for Polarized Fusion Experiments at the DIII-D Tokamak

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9/26/2024

PSTP 2024

20TH INTERNATIONAL WORKSHOP ON POLARIZED SOURCES, TARGETS, AND POLARIMETRY

SEPTEMBER 22-27 JEFFERSON LAB NEWPORT NEWS, VA

Jefferson Lab · DIII-D National Fusion Facility San Diego · University of Virginia · University of California Irvine · Oak Ridge National Laboratory · U.S. Department of Energy Office of Science · JSA

Power!

Clean Power!!

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

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

Fusion!!!

DOE core mission objectives:

… to promote innovative research in clean energy sources, …

Ignition Approaches:

ICF (inertial), MCF (magnetic)…

Channels and Facilities

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

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

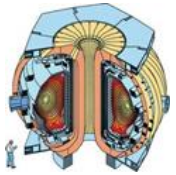
- Most research Tokamaks ever built (~30 in operation today) have focused on D+D reactions.

- *Jump in scale towards a fusion power reactor: the* ***I****nternational* ***T****hermonuclear* ***E****xperimental* ***R****eactor* (***ITER***) will pave the way to fusion power.

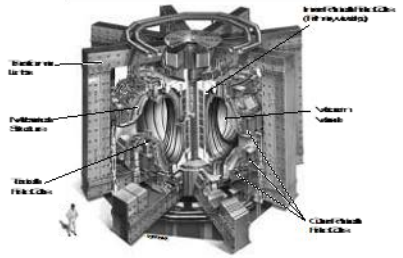
- Polarized fuels could enhance the cross section by up to 50%, & the power and Q by 75%, *without changing the plasma conditions*.

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

DIII-D (USA)
Best instrumented
→most diagnostics
20m³, 2.1T, Q<<1

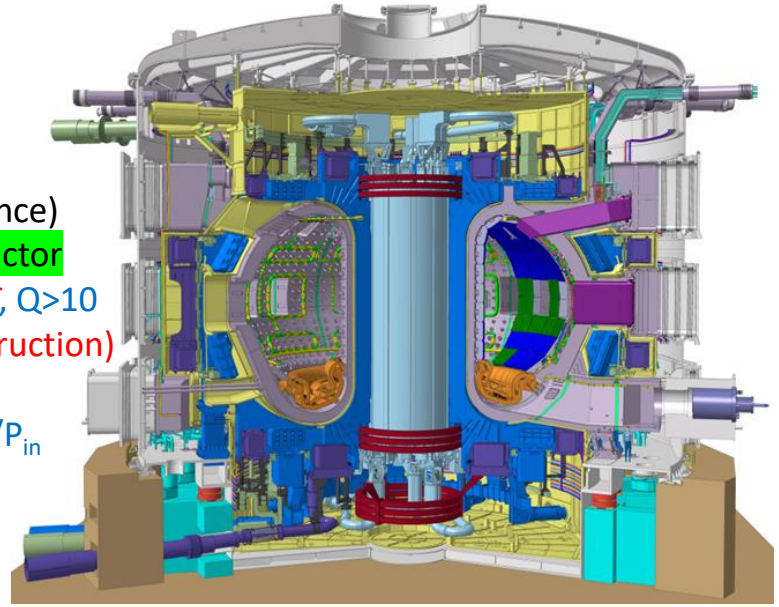


JET (UK)
Only one runs tritium
90m³, 3.8T, Q~2/3



ITER (France)
½ GW reactor
700m³, 5.3T, Q>10
(under construction)

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



Jefferson Lab Fusion Program

SPF Collaboration

Jefferson Lab
(Polarized D Fuel)
X. Wei, P. Dobrenz, D. Williams,…
plus 2 incoming postdocs from UVA

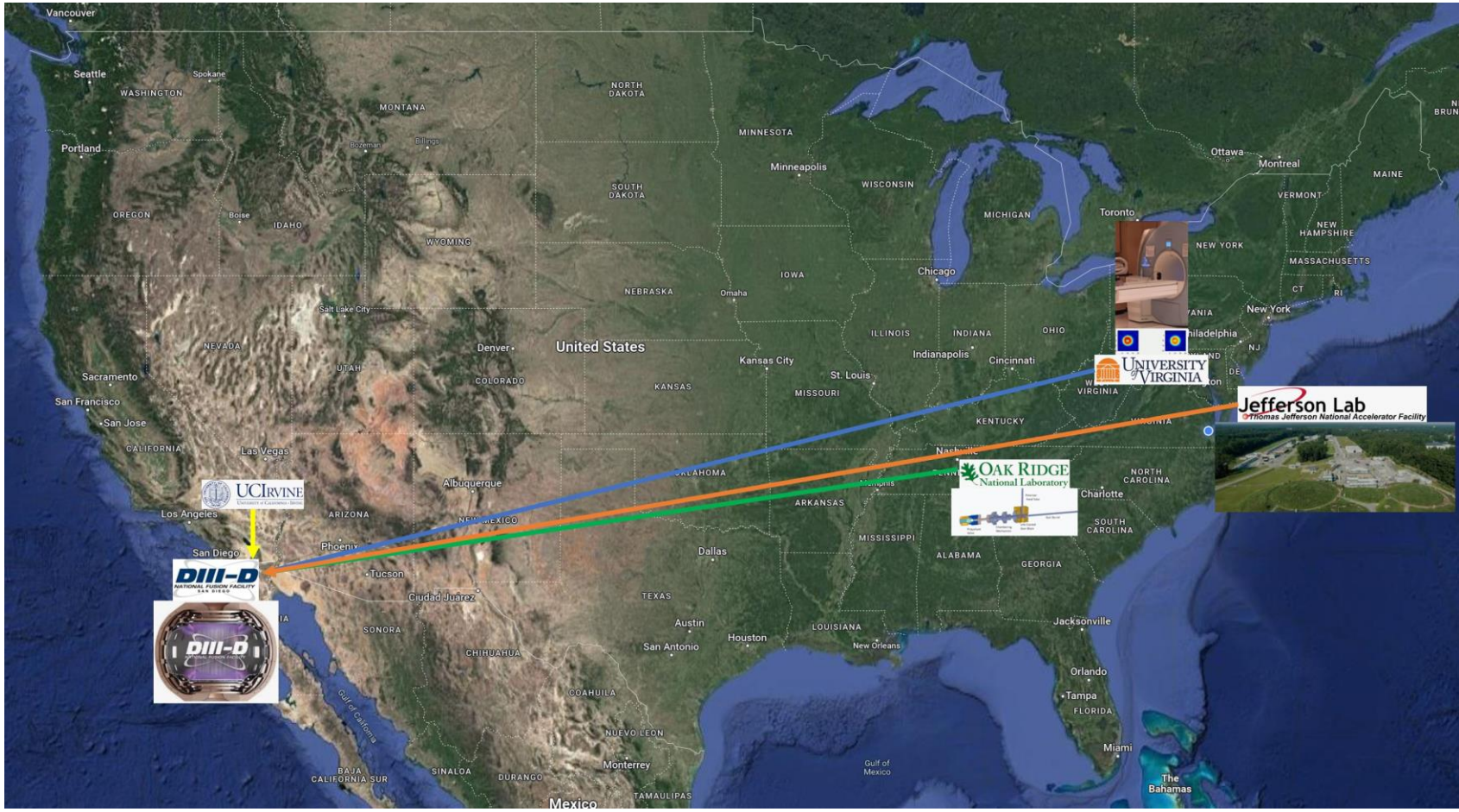
University of Virginia
(Polarized ^{3}He Fuel)
G. W. Miller, A. M. Sandorfi, X. Zheng,…

Oak Ridge National Lab
(Polarized Fuels Delivery)
L. Baylor, S. Meitner, …

University of California, Irvine
(Run Preparations and Diagnostics)
W. Heidbrink, …

Ultimate Goal:

Run $D + {}^3He \rightarrow \alpha + p$ at ***DIII-D*** in FY28-29



First phase, ***Spin Polarized Nuclei for Injection into DIII-D***, has been funded by DOE FES.

Polarized D Fuel at JLab

The life cycle of a polarized ^{7}LiD pellet

Fabrication

Shape, size, density…

Irradiation

beamline, cryostat

Storage

LN2 cryostat

Funded for FY24 & FY25

Polarization

DF, pol chamber, pellet loader, µWave & NMR

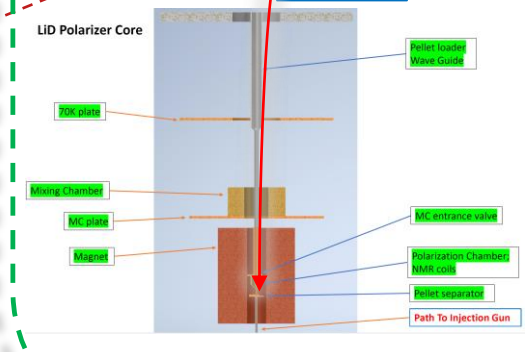
Extraction

Pellet extractor, (integrated with DF and injection gun)

Integration

Integrate pellet polarizer with (ORNL built) injection gun)

µWave



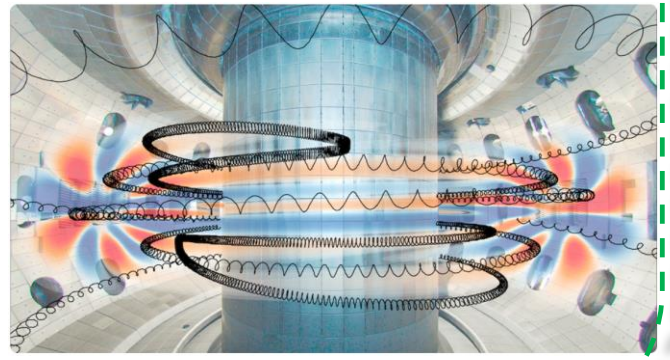
Subsequent renewals (for FY26-29)

Commission

Final installation at *DIII-D* tokamak

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

DIII-D, Particles detection, Data analysis



Ultimate Goal:

Running $D + {}^3He \rightarrow \alpha + p$ in DIII-D tokamak with polarized fuels to test polarization survivability.

Approach:

FY24-25 Equipment preparation, Fuel pellet production, ^{7}LiD Polarizer designs, Prototype, …
FY26-27 Equipment production, System integration, Polarized fuel production, …
FY28-29 Commissioning, Running spin-polarized fusion at DIII-D.

JLab's Short Term focus:

- Preparing ^{7}LiD pellets.
- Irradiating ^{7}LiD pellets with eBeams to create paramagnetic centers for DNP process.
- Preparing μWave and NMR systems for polarization production and monitoring.
- Designing a (commercial dilution refrigerator based) DNP polarizer.
- Building a prototype Polarization Chamber with pellet handling system.

The advantages:

- JLab Target Group operates DNP polarized targets routinely.
- Polarized **LiD** targets have been used successfully – eg. CERN COMPASS exp.
- JLab PAC approved experiments require polarized **^{7}LiD** targets.

The challenges:

- Precision engineering----Uniform shape and ρ to deliver ~10^{20} deuterons/pellet.
- Cold transporting----Pellet dispensed into 4K tokamak injector with holding field.
- Impact resistance----Survives ~20m subsonic injection journey.

Requirements for the polarizer--High cooling-power commercial DF with ~7T magnet.

- A pellet manipulation mechanism for loading/dispensing.
- A polarizing chamber with **NMR** coils (V~0.06cc) and **tuned waveguide**.
- Properly anchor components to achieve low operating temp (~100mK with μWave ON).
- A 77K entrance interface and a 4K exit interface.

To consistently deliver ~10^{20} deuterons/shot, the shape, density and edges of the pellet must be well controlled and smoothly fit inside injection gun, for achieving high injection speed.

^{7}LiD is chemically unstable, and caustic; must be handled in an inert gas environment.

- ^{7}LiD pellets can be:
  1. fused from powder;
  2. casted;
  3. machined from a solid chunk;
  4. purchased from a vender – preferred; discussions in progress

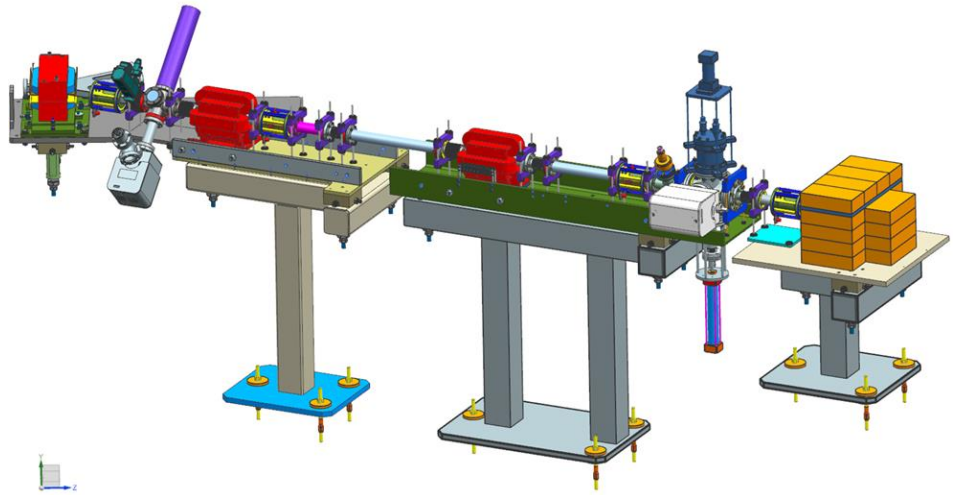
- ^{7}LiD Pellet size: cylindrical, ϕ=1.5mm, L=3.0mm.

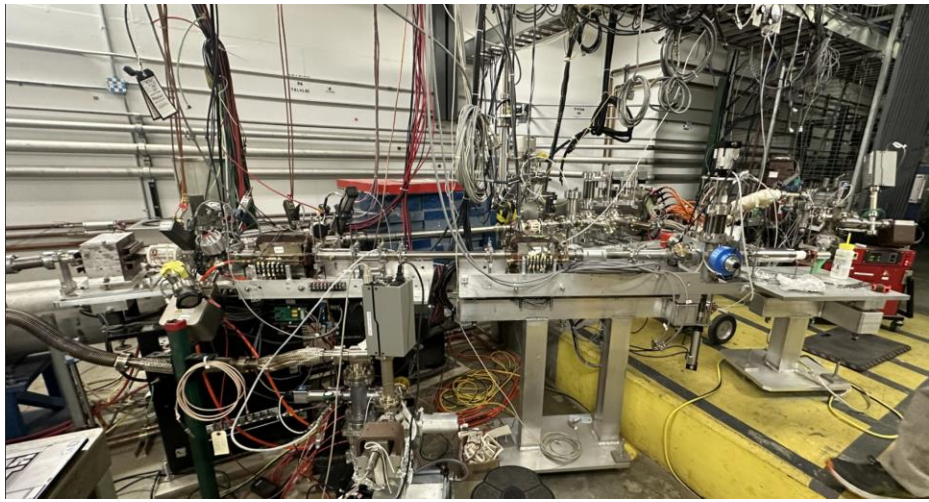
- Totally ~200 ^{7}LiD pellets will be used for developing, testing and running the SPF experiment.

Doping ^{7}LiD Pellets

Beamline

- The ^{7}LiD pellets must be irradiated with electron beams to create *paramagnetic centers* for the DNP process.
- The pellets will be irradiated at ~185K with ~10μA electron beams (~9MeV) for several hours and stored/transported under 77K.
- CEBAF Injector will be used for the irradiations.
- The irradiation beamline has been built by Injector Group and is currently under vacuum.





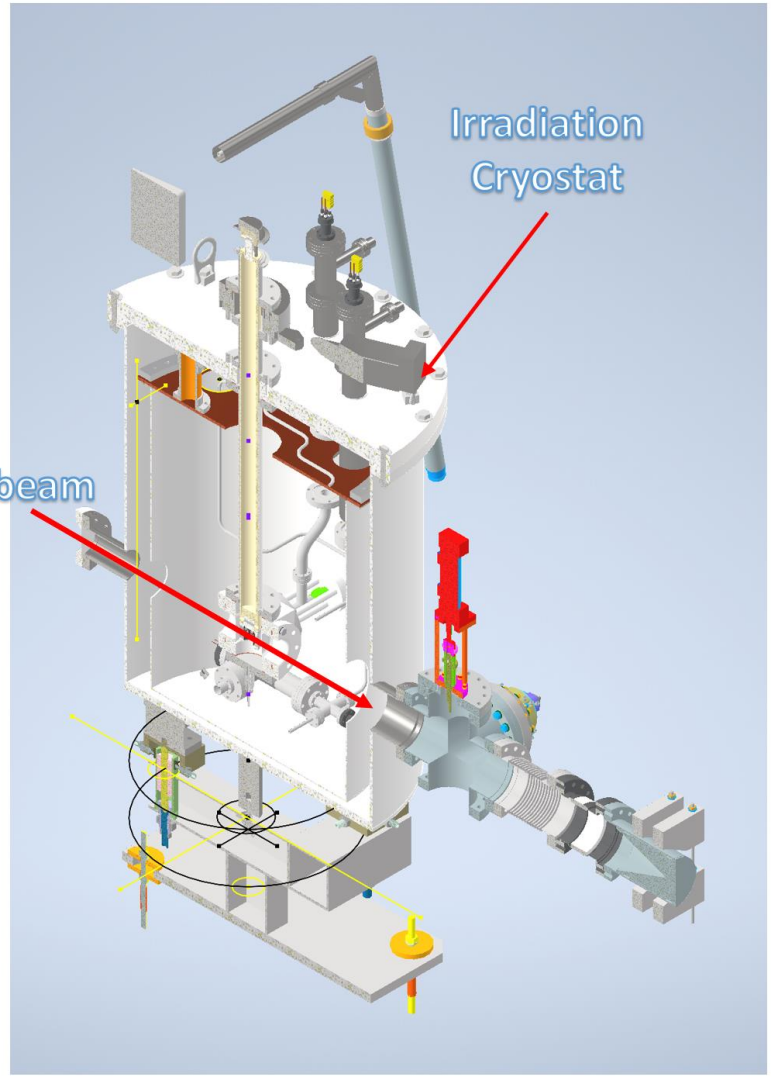
Dosing ^{7}LiD Pellets

Irradiation Cryostat

- The ^{7}LiD pellets will be irradiated at ~185K with ~10μA electron beams (~9MeV) for several hours to create ~2x10^{17} e- /cm^{2} for the DNP process and stored/transported under 77K. (*See Kageya's talk tomorrow*)

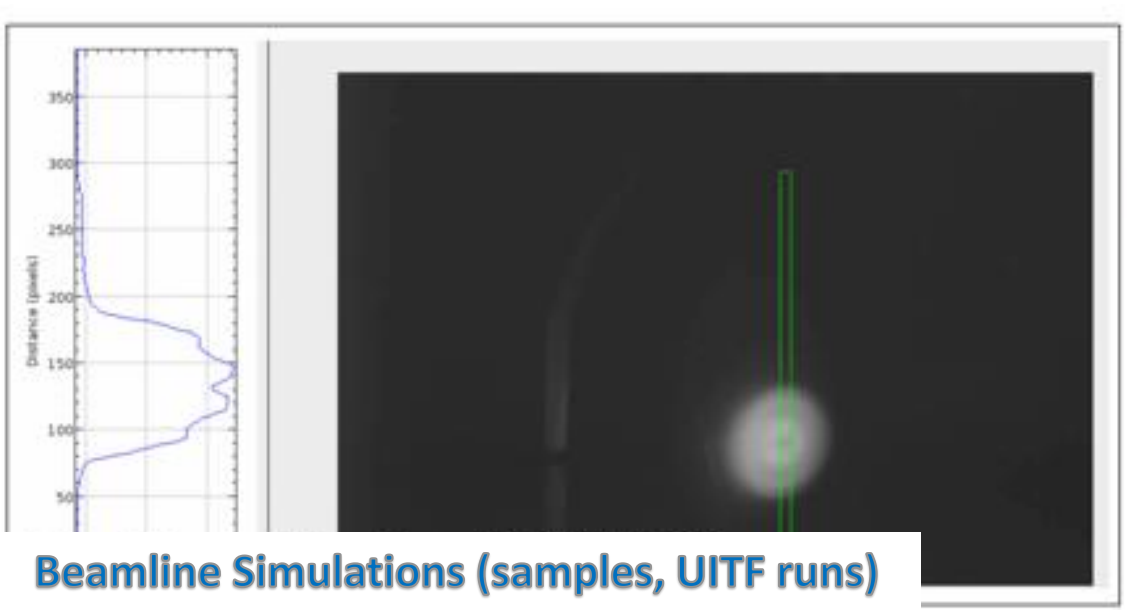
- The Irradiation Cryostat has been designed by the Target Group and the Fusion Group. Together, we will build it in FY25.

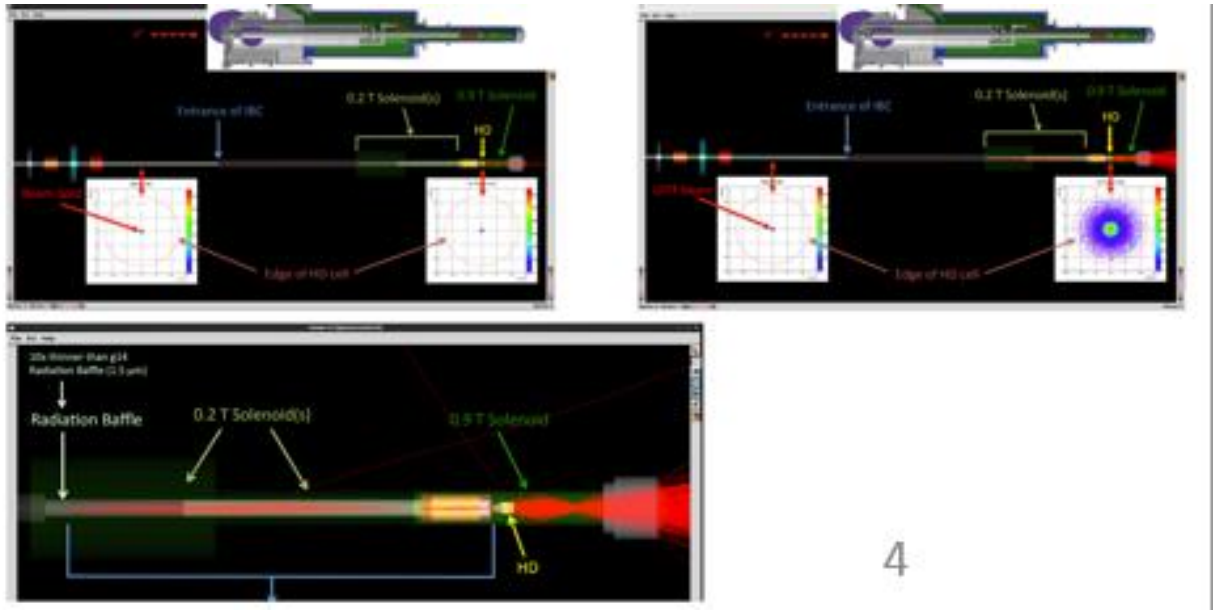
- The irradiation results will be validated by measuring achievable polarization with DNP at the onsite Polarized Target Development Lab. (*See Brock's talk on Tuesday*)



Goals of the Beamline Simulation:

1. Guide the beamline commissioning;
2. Guide the target material irradiation runs by predicting the missing electrons with the dump current and viewers data.



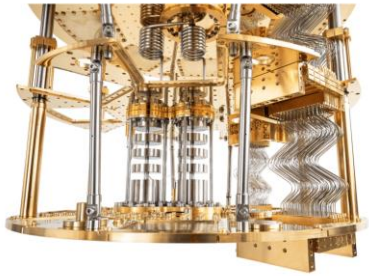


Beamline Simulations (samples, UITF runs)

NMR coils & Polarizing Chamber

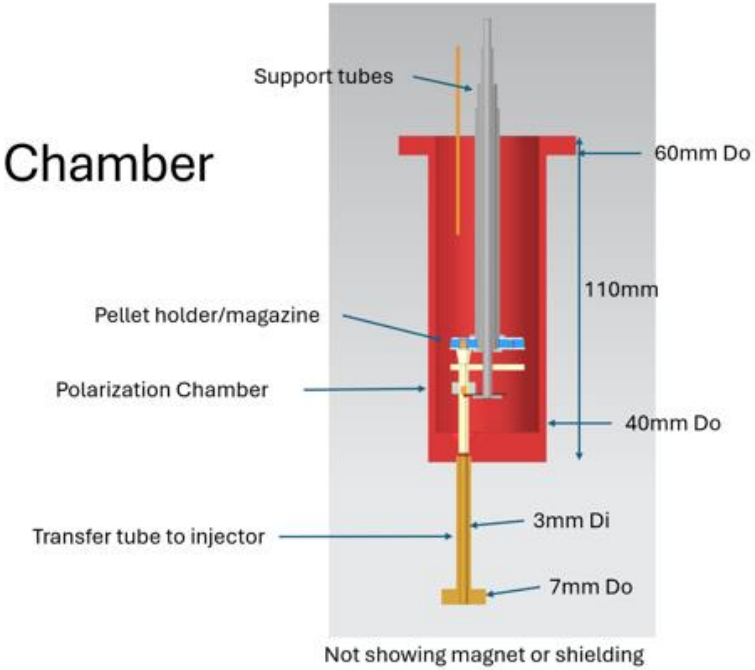
Designing the Polarization Chamber to fit in a commercial DF
(for phase-II funding)

As an example, a standard Commercial Dilution Refrigerator with a 7.5T Magnet can be purchased.
Credit: Bluefors



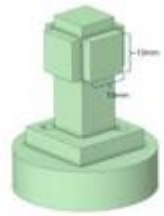
XLD1000sl	Guaranteed	Expected
Base temperature	10 mK	8 mK
Cooling power at 20 mK	>30 µW	34 µW
Cooling power at 100 mK	>1000 µW	1100 µW
Cooling power at 120 mK	>1400 µW	1600 µW
MXC Flange Diameter	500 mm	

Polarization Chamber

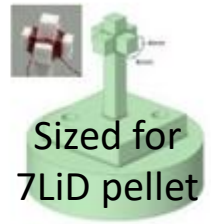


Not showing magnet or shielding

2 Large Coils, V_c=60 cc, n=6



2 Medium Coils, V_c=2.2 cc, n=10



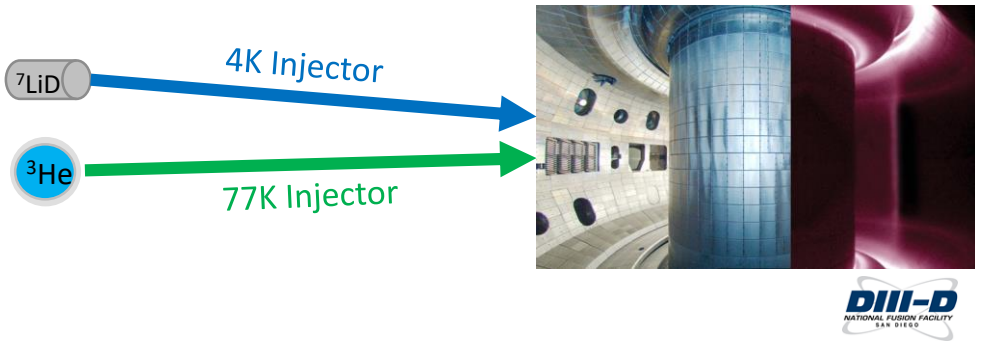
2 Small Coils, V_c=0.064 cc, n=20

Sized for 7LiD pellet

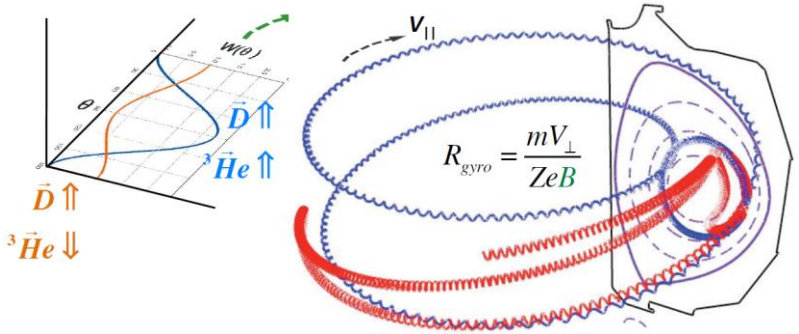
Sized for NP target

While JLab is preparing the polarized D fuel:

- UVA will build the ^{3}He polarizer.
- ORNL will design/build the cold pellet injection gun with continuous magnetic field.
- UC-I will study fusion product detection and plasma diagnostics.
- All components will be shipped to DIII-D in 2027.



- parallel spins ⇒ large $V_\perp$
- anti-parallel spins ⇒ large $V_{||}$



- 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)

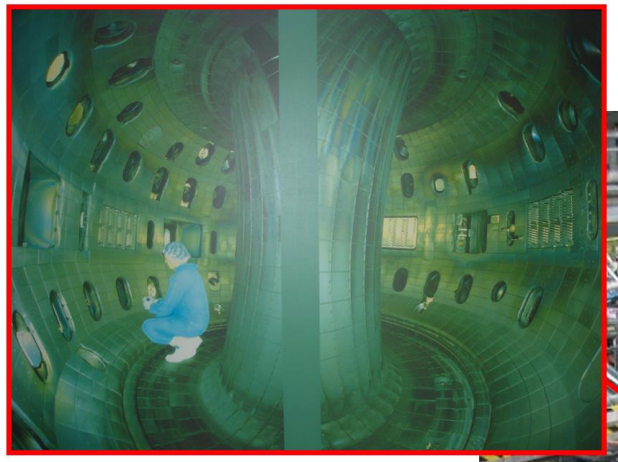
↳ D + D ⇨ T + **p** (Q = + 4.0 MeV) **E(p) ~ 3 MeV**

↳ D + T ⇨ α + n (Q = +17.6 MeV)

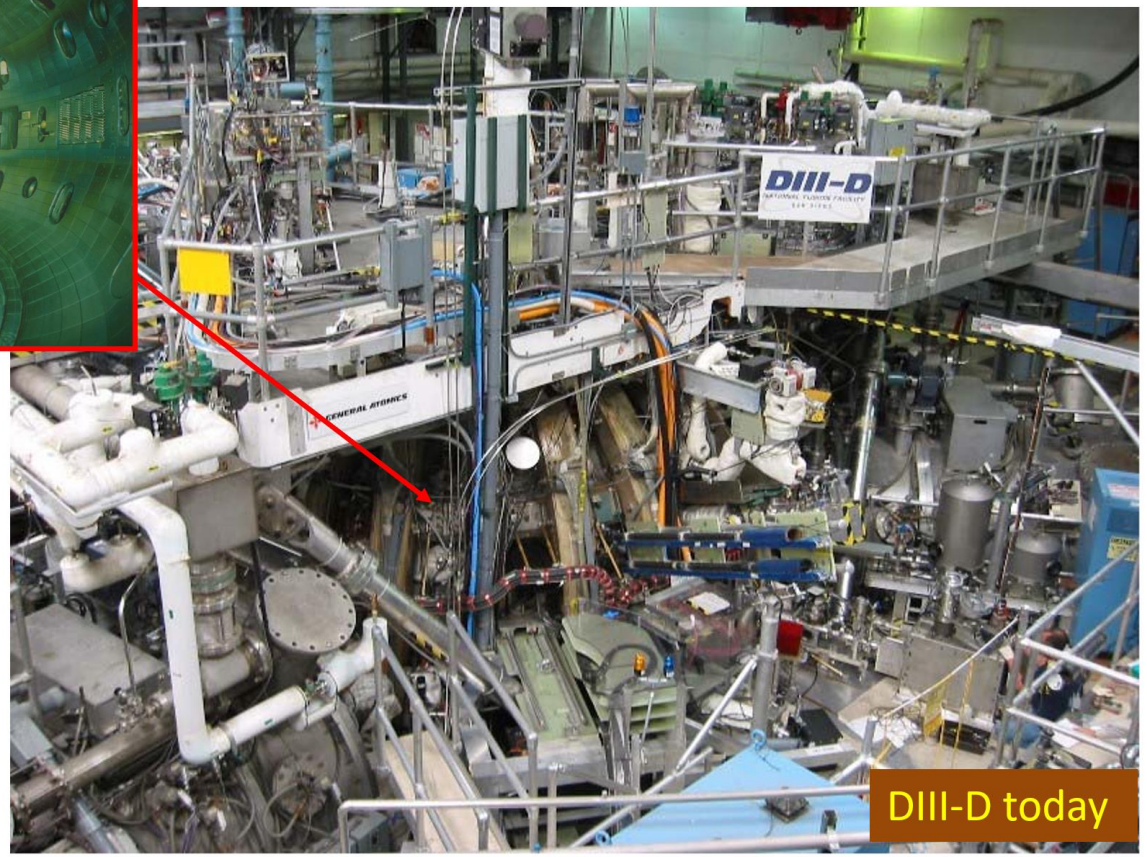
- 15 MeV proton orbits are unconfined
  ⇒Measure $V_\perp/V_{||}$ at wall to infer polarization.

The Ultimate Goal

Run **D + ^{3}He** --> α + ***p*** in FY28



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

Expecting to run the *D + ^{3}He* test within 5-6 years.

Work at JLab for the current funding cycle:

- **FY24: Preparing ^{7}LiD pellets, designing/Building Irradiation Cryostat and Beamline.**
- **FY25: Testing Irradiation Cryostat, Producing Irradiated ^{7}LiD pellets.**

In subsequent funding cycles:

- **FY26-27: Finishing subsystem constructions and then production test.**
- **FY28-29: System integration and final assembly.**

Polarized *D + ^{3}He* fusion at DIII-D!!!