The 21st International Symposium on Spin Physics (Spin2014)

Polarized Fusion and its Implications:

the Potential for Direct in situ Measurements of Fuel Polarization Survival in a Tokamak Plasma

A.M. Sandorfi
Thomas Jefferson National Accelerator Facility

(for the Jlab-GA SPF Collaboration)

(Peking University, Beijing – October 21, 2014)

potential for running a Tokamak with polarized fuel

- ***fusion fuels:*** ***D + t ⇨ α + n ;*** *D + ^{3}He ⇨ α + p*
  - ↔ *both dominated by J=3/2 resonance just above threshold*
  - ↔ *ion temperatures < 100 KeV ⇨ s-waves dominate*
  - ↔ *D (s=1) and t (s=½) preferentially fuse when spins are aligned*
- ***polarized fuels:*** *up to 50% enhancement in the cross section*
  - ↔ *obvious benefits: boost to "ignition"; increased power, Q(eff)*
  - ↔ *iff polarizations survive in the plasma (for ~ few sec) ???*
- **History**
  - Kulsrud, Furth, Valeo & Goldhaber, Phys Rev Lett **49** (82) 1248
  - Lodder, Phys. Lett. A98 (83) 179
  - Greenside, Budny & Post, J Vac Sci & Technology A2 (84)
  - 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
  - …

JLab-GA SPF (Spin-Polarized-Fusion) Collaboration

- **Jefferson Lab**

  HDice:

  A.M. Sandorfi, A. Deur, T. Kageya, M. Lowry, X. Wei — $H\vec{D}$

- University of Virginia:

  X. Zheng, W.A. Tobias — $^3\vec{He}$

- **General Atomics/Fusion Energy Research**

  GA-DIII-D:

  G. Jackson, N. Eidietis, A. Hyatt, M. Lanctot, D. Pace, S. Smith, H. St-John

  plasma, orbit & transport simulation

  GA-ICF Pellet Division:

  M. Farrell, M. Hoppe, A. Nikroo — *ICF pellets for HD, ^3He*

- Oak Ridge National Lab:

  L. Baylor — *cryo-injection guns*

- UC-Irvine:

  W.W. Heidbrink — *fast particle detection*

Potential Power gain from polarization in a large Tokamak

- $d+t \rightarrow \alpha+n$ transport Modeling – Sterling Smith, GA

- Transport equation:

$$\frac{d(Temp)}{d(time)} + \nabla \cdot \Gamma(heat\ flux) = S(source)$$

$$= reaction\ rate \times \alpha\ heating \times spin\ enhancement$$

$$= N_D N_t \langle \sigma V(T) \rangle \times \left(E_\alpha = 3.5\ MeV\right) \times \boldsymbol{F}$$

$$\Uparrow$$

- Flux: $\Gamma = \Gamma_{neoClassical} + \Gamma_{turbulent}$, $polarization\ factor \in [1,\ 1.5]$

$\uparrow$ $\uparrow$

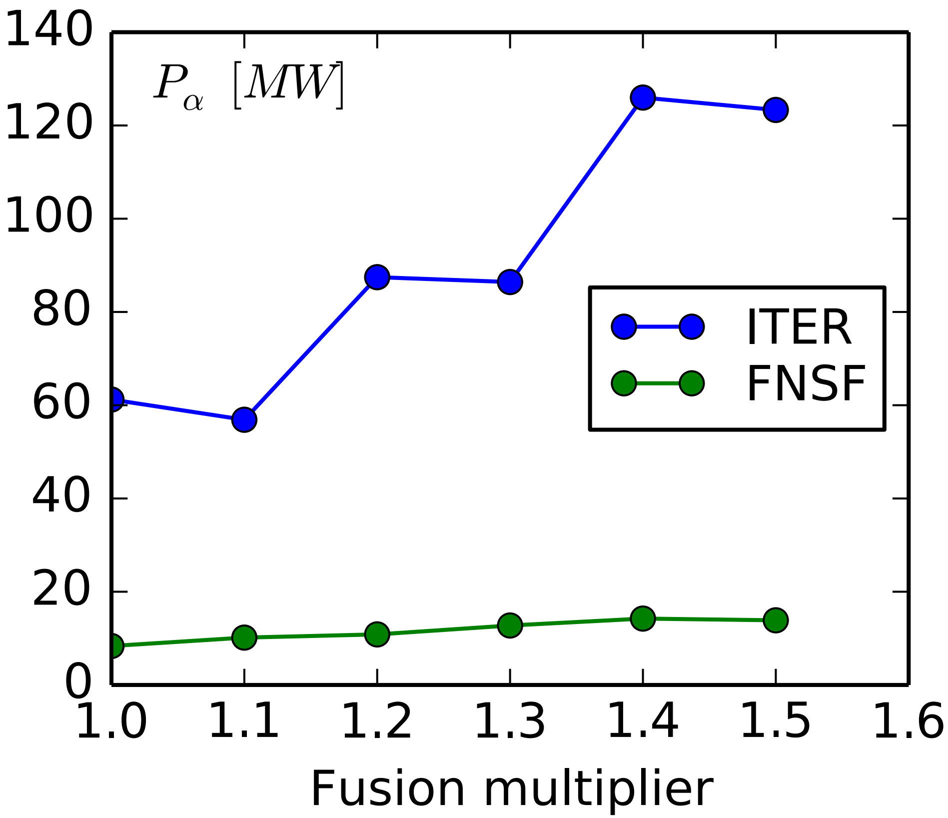
- simulation codes: NEO TGLF TGYRO

$\downarrow$

- steady-state flux matched to source: $\Gamma_{neoC} + \Gamma_{turb} = \int S\,dV$

$f(N, \partial N,\ T, \partial T)$

ITER and FNSF total fusion power output increases with fusion multiplier



Alpha heating vs fusion multiplier; multiply by 5 to get total fusion power

- **The ITER gain is greater than the fusion factor**
  - 60 MW to 120 MW for 50% increase in fusion factor
- **FNSF gain is also greater, but not by as much**
  - 8 MW to 14 MW

- net ITER gain is a factor of 2 in power

the path to polarized fuelling

- over past ~3 decades NP and HEP have developed polarized materials, but with very different goals: $10^6 - 10^8$ s lifetimes in few mole samples

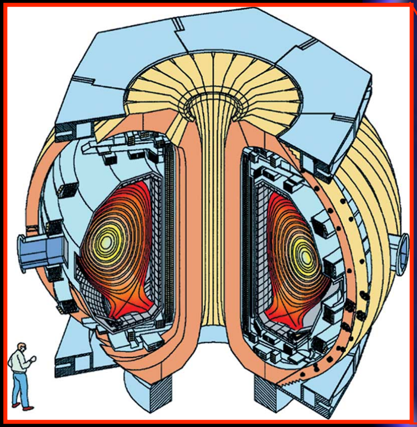
- Fusion energy would need only 1 - 10 s lifetimes, but K-moles/day

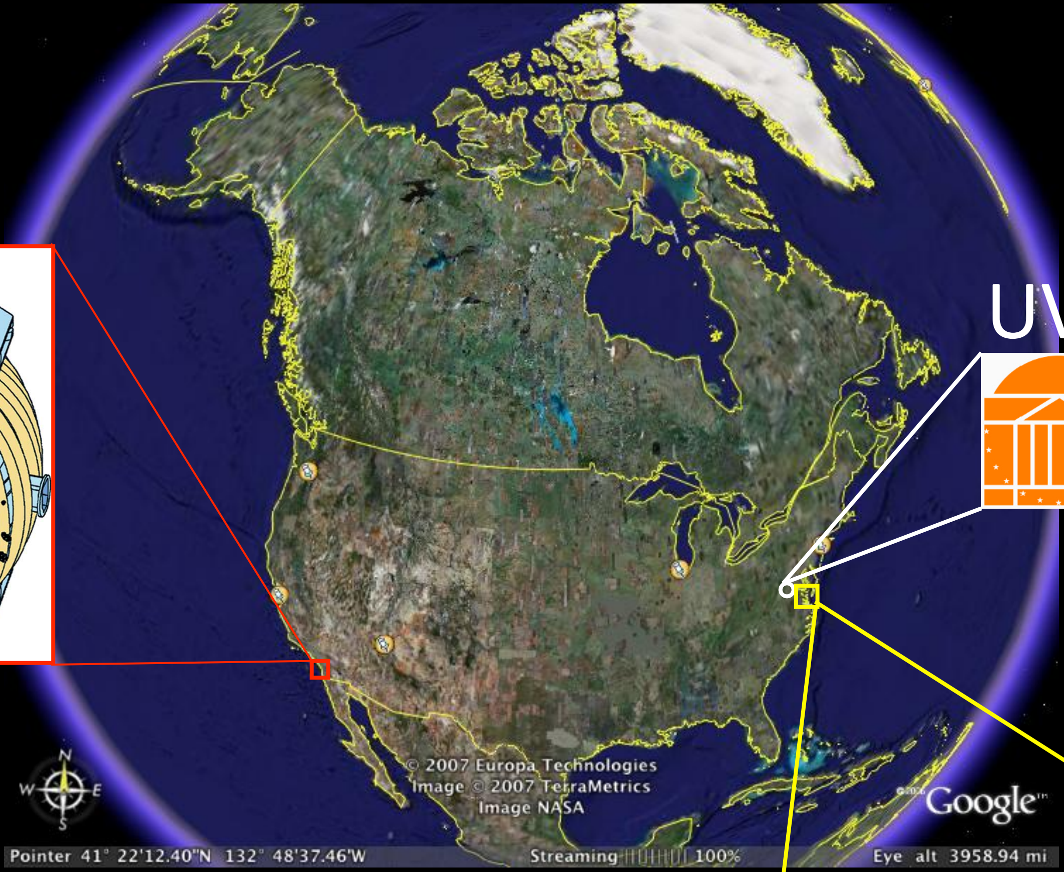
⇨ *simply scaling up NP/HEP production techniques is **not** appropriate*
⇨ *new R&D would be required*

⇨ *MUST demonstrate polarization survival before such an investment*

Polarization survival test in the DIII-D Tokamak

DIII-D





UVa

Strategy: use existing NP techniques and equipment to create polarization life-times sufficient to produce fuel for a test at DIII-D, which mitigates costs.

Jefferson Lab

Measurement strategy - overview

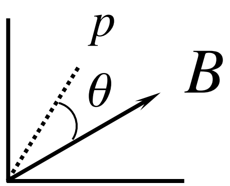
- test reaction: $\vec{D} + {}^3\vec{He} \rightarrow \alpha + p$ {mirror reaction to $D + t \rightarrow \alpha + n$}
- use existing JLab facilities to create solid $H\vec{D}$; ship to Tokamak
  - ➔ diffuse 200-400 atm HD into ICF shells; cool to solid; polarize H and D; H ⇨ D spin transfer to maximize D spin; transport to DIII-D Tokamak; load into cryo-gun
- use existing UVa facilities to polarize ${}^3\vec{He}$ gas (~ 10-30 atm)
  - ➔ remove polarizing agents, diffuse into ICF shells; cool to seal; load into DIII-D cryo-gun
- generate H (or ${}^4He$) plasma in the DIII-D Tokamak
  - ➔ inject polarized fuel into plasma, alternating alignment:

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

A look at the experiment in a little detail

- polarization-dependent angular distributions
- preparation of polarized HD and polarized ^{3}He
- ICF pellets and permeation of fuel material
- the DIII-D Tokamak and pellet injection
- Tokamak geometry and simulations of expected orbits in DIII-D
- expected reaction rates in a DIII-D test experiment
- secondary reactions
- particle detection: eg. Fast-Ion-Loss Detectors
- approximate time scale

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



- *angles relative to the magnetic field direction*
- *neglecting interference terms (good to ~ 2-3 %)*

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

➔ *angle integrated cross section :*

$$\sigma_{cm} = \sigma_0 \left\{1 + \tfrac{1}{2} \vec{P}_D^V \cdot \vec{P}_{^3He}\right\} \quad , \quad \sigma_0 = \frac{4\pi}{\left(k_D^{cm}\right)^2} \sum \frac{\left(2J_{^5Li} + 1\right)}{\left(2I_D + 1\right)\left(2I_{^3He} + 1\right)} \left| {}^{J^\pi}T_{(2S_i+1)L_i,\,(2S_f+1)L_f} \right|^2$$

⇧

50% cross section gain for 100% parallel spin alignment

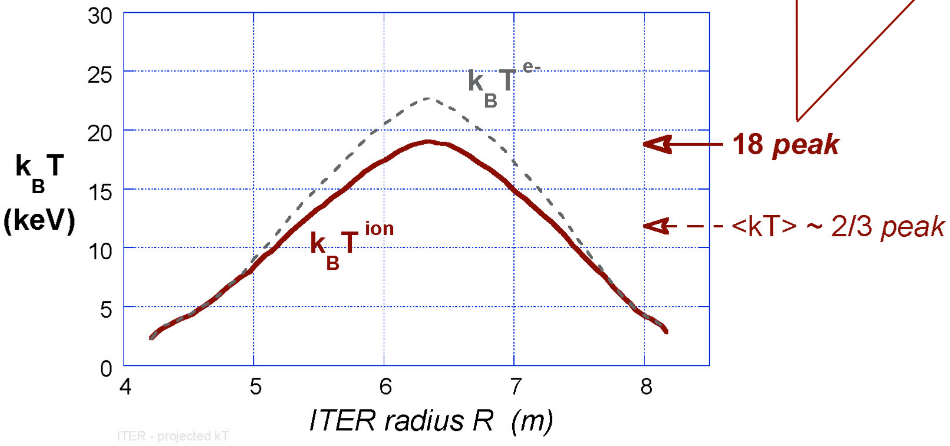
reaction rate in a heated plasma

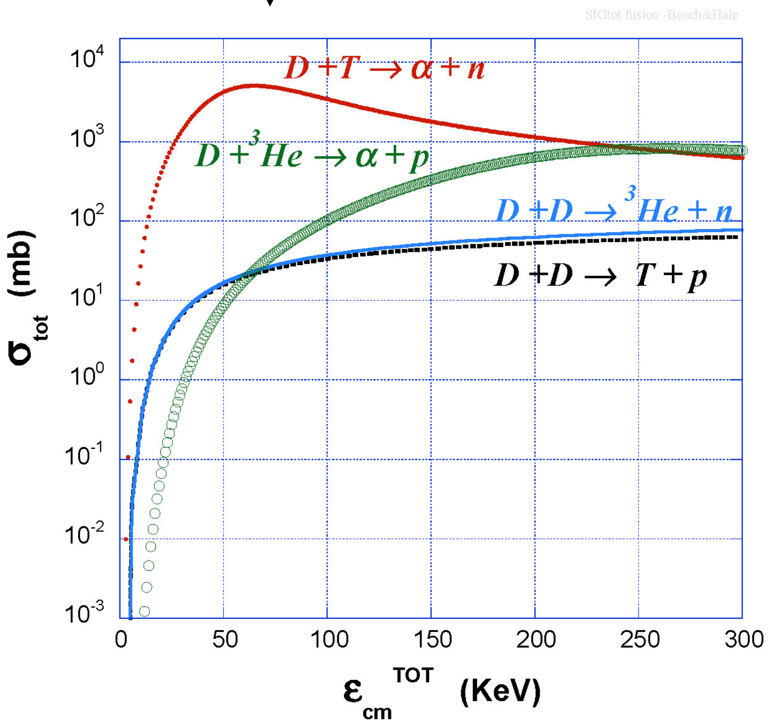
Cross sections are averaged over a Maxwellian Velocity distribution

$$\langle \sigma V \rangle = \frac{4c}{\sqrt{2\pi M_r}\,(k_B T)^{3/2}} \int e^{-\varepsilon/k_B T}\,\varepsilon\,\sigma(\varepsilon)\,d\varepsilon$$

eg: ITER

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

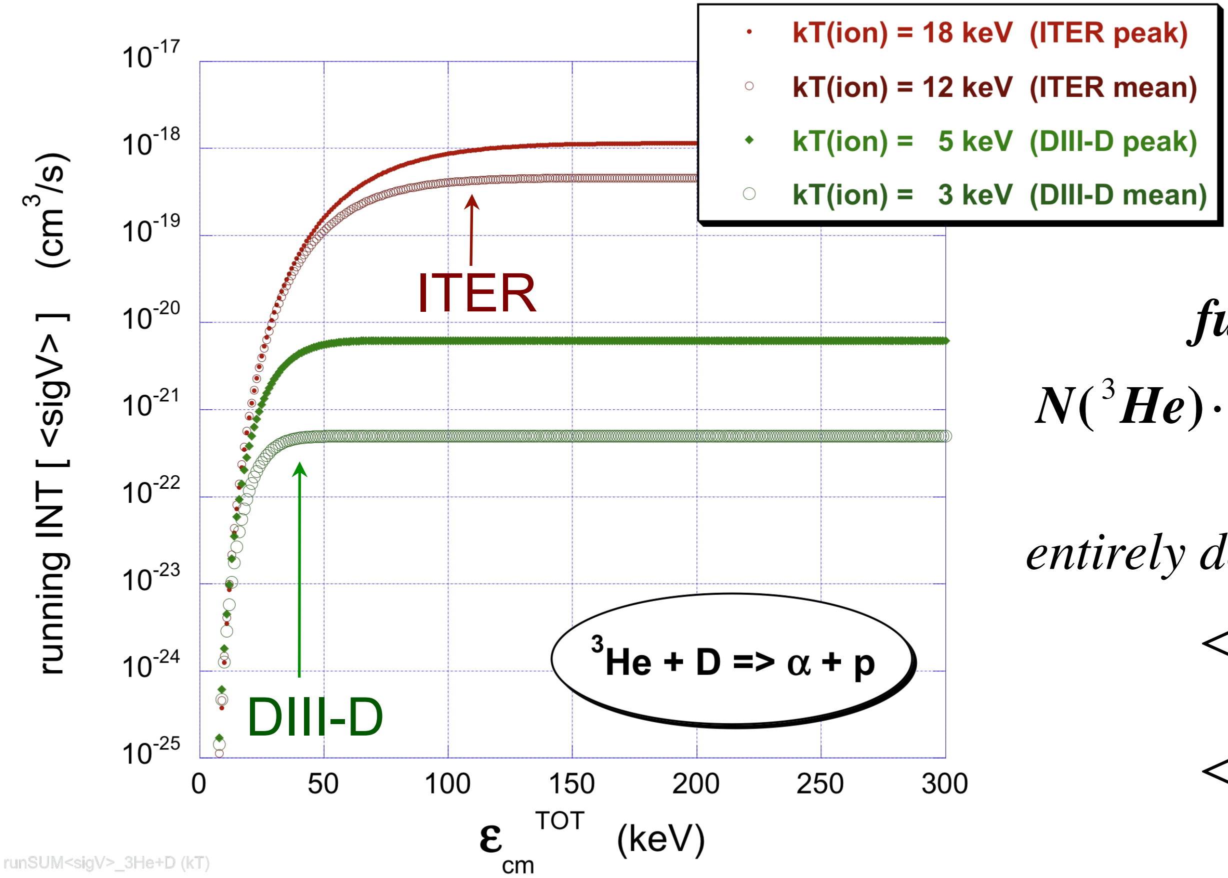




eg: DIII-D,	nominal	reduced density
kT(peak)	~ 5 keV	(9-13 keV)
kT(mean)	~ 3 keV	(6-8 keV)

relevant energy range

$$\text{running int}\langle\sigma V\rangle = \frac{4c}{\sqrt{2\pi M_r}\,(k_B T)^{3/2}} \int^{\varepsilon_{cm}^{tot}} e^{-\varepsilon/k_B T}\,\varepsilon\,\sigma(\varepsilon)\,d\varepsilon$$



fusion rate(s^{-1}):

$$N(^3He)\cdot N(D)\cdot\langle\sigma V\rangle\cdot Vol(m^3)$$

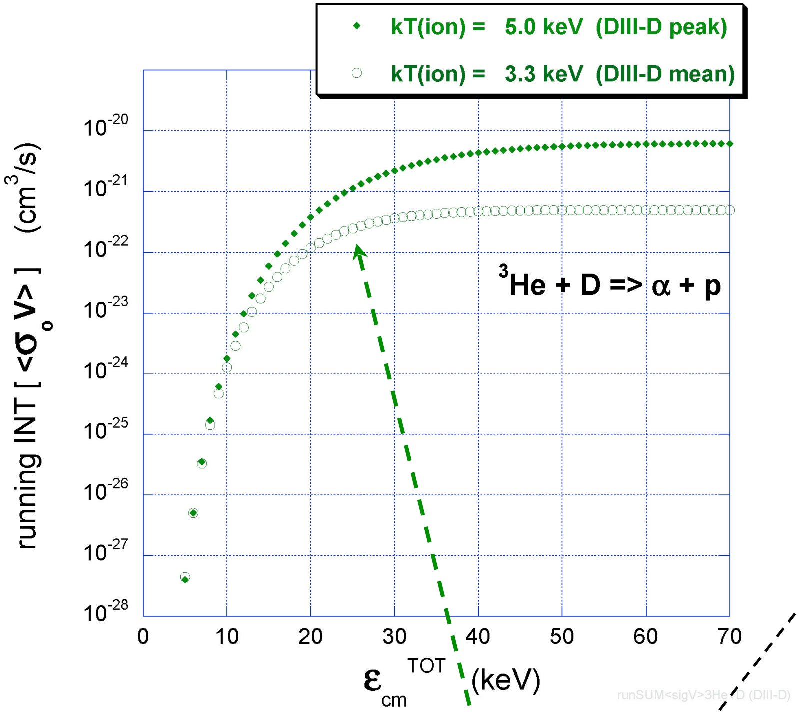
entirely determined by energies

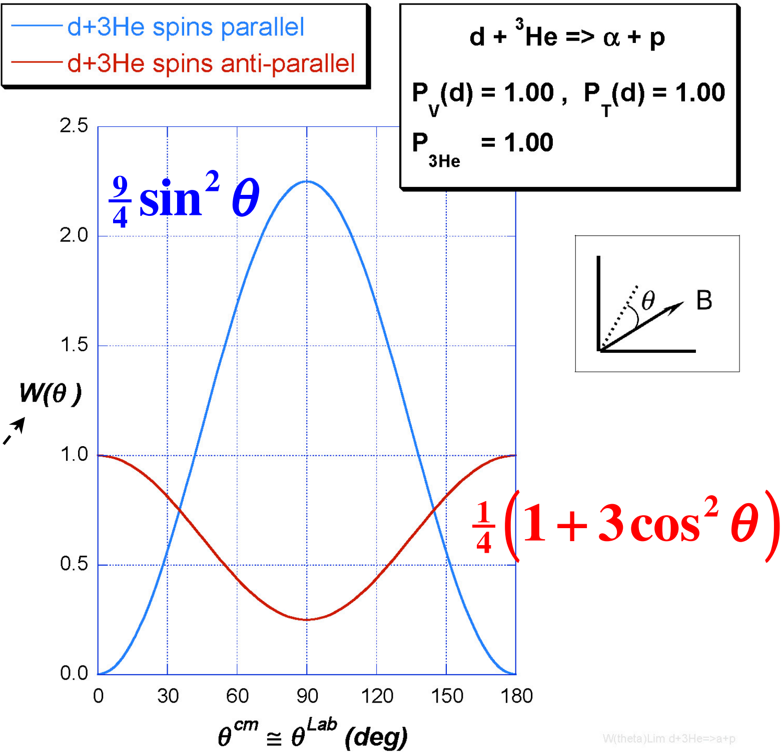
< *120 keV (ITER)*

< *40 keV (DIII-D)*

d+^{3}He ➔ α +p distributions wrt torus field

$$\frac{4c}{\sqrt{2\pi M_r}\,(k_BT)^{3/2}} \int^{\varepsilon_{cm}^{tot}} e^{-\varepsilon/k_BT}\,\varepsilon\,\sigma_o(\varepsilon)\,d\varepsilon$$





$$\left\langle d\sigma(\theta)V\right\rangle = \tfrac{1}{4\pi}\left\langle\sigma_o V\right\rangle\cdot W(\theta)$$

$$= \tfrac{1}{4\pi}\left\langle\sigma_o V\right\rangle\cdot\left\{1-\tfrac12 P_d^V P_{^3He} + \tfrac12\left[3P_d^V P_{^3He}\sin^2\theta + \tfrac12 P_d^T\left(1-3\cos^2\theta\right)\right]\right\}$$

expected d+^{3}He ➔ α+p distributions in a DIII-D test experiment

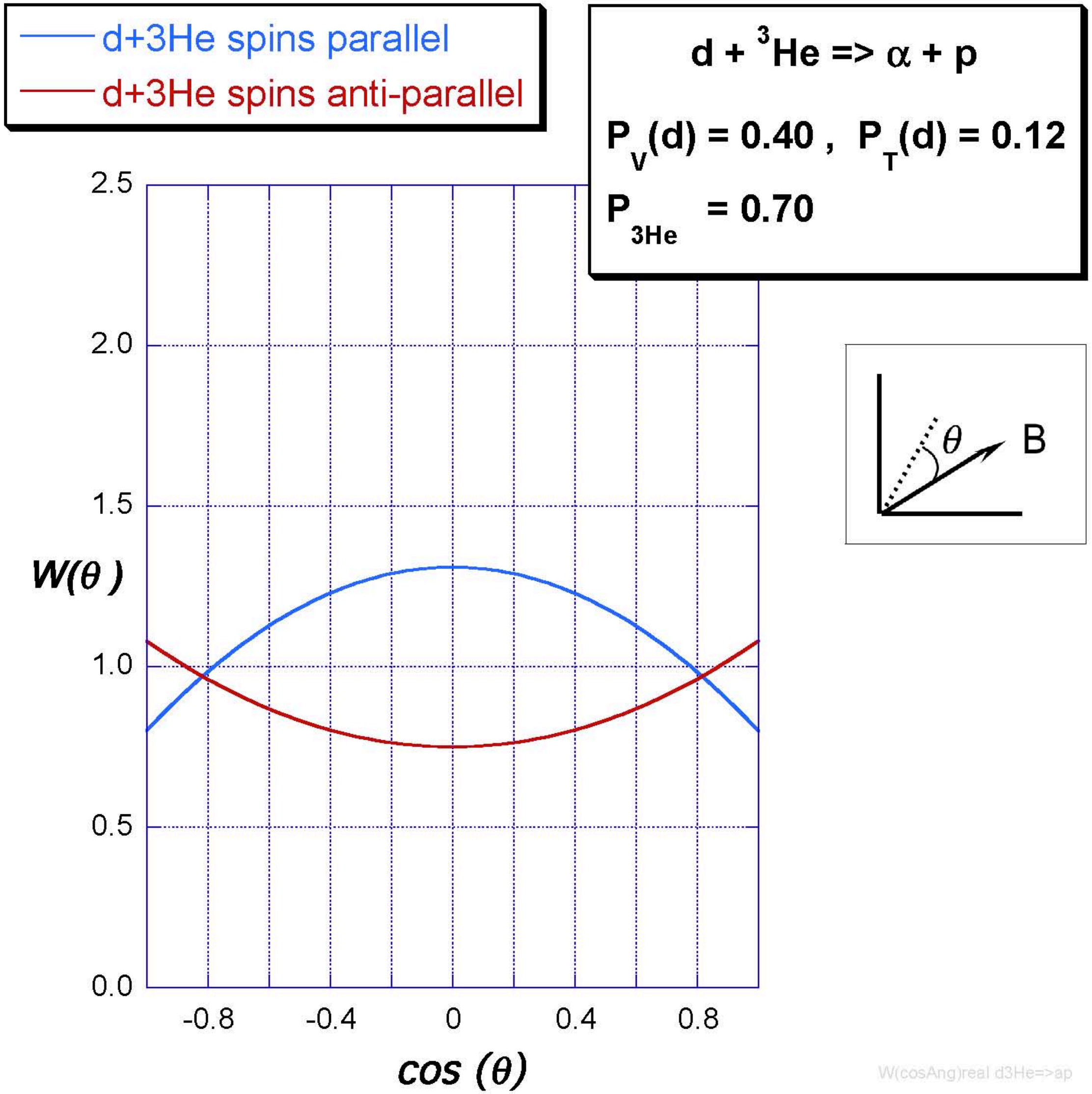
$$P_V\left(\vec{D}\right)=0.40,\ P_T\left(\vec{D}\right)=0.12$$

$$P\left({}^3\vec{H}e\right)=0.70$$

$$\left\langle\sigma^{par}V\right\rangle=\left\langle\sigma_o V\right\rangle\left\{1+\tfrac{1}{2}(0.28)\right\}$$

$$\left\langle\sigma^{anti}V\right\rangle=\left\langle\sigma_o V\right\rangle\left\{1-\tfrac{1}{2}(0.28)\right\}$$

$$\boxed{\Rightarrow\ \frac{\left\langle\sigma^{par}V\right\rangle-\left\langle\sigma^{anti}V\right\rangle}{\left\langle\sigma_o V\right\rangle}\ =\ 0.28}$$



d + ^{3}He => α + p

P_V(d) = 0.40 , P_T(d) = 0.12

P_{3He} = 0.70

Preparing $\vec{HD}$ fuel

⇨ talk by X. Wei
Friday, Parallel-VII: S10

- **process**: HD, with impurities (10^{-4}) of H_2 and D_2 condensed to solid
  ➔ transferred to high field (15 tesla) and low temp (10-15 mK)
  ➔ H_2 & D_2 impurities metastable, polarize rapidly, transfer spin to HD
  ➔ H_2 & D_2 catalysts decay, leaving HD in frozen-spin state (T_1~10^8 s)

- typical frozen-spin polarizations: $P(\vec{H}) = 60\%,\ P_V(\vec{D}) = 20\%$
- RF transitions are used to move spin from H to D $\Rightarrow\ P_V(\vec{D}) = 40\%$

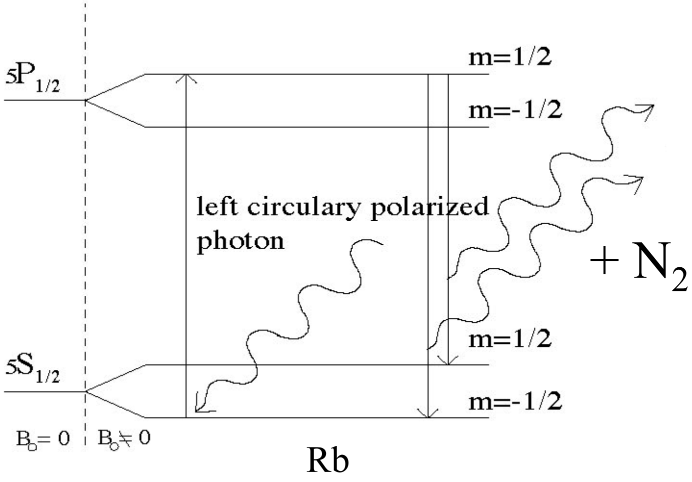
- large targets used in Nuclear Physics experiments at JLab and BNL
  - these polarizations are ~ ⅔ of theoretical maximum
  ➔ there maybe some further gain in small ICF pellet sizes

Preparing $^3\vec{He}$ fuel

eg. talk by J.P. Chen
Friday, Parallel-VIII: S10

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

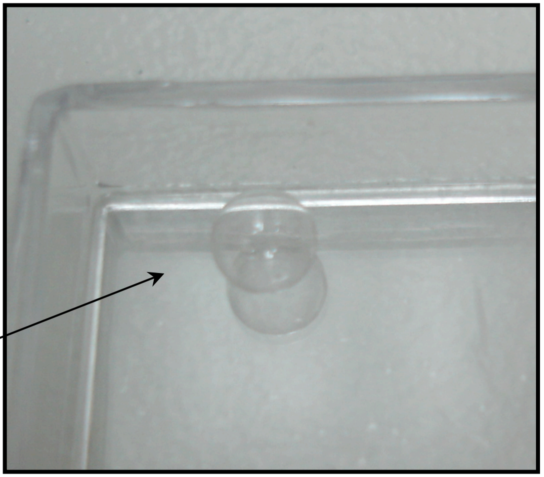
- Rb vapor pumped with 795 nm laser -100W (in oven > 200 C; with ~1 % N_2; uniform B)
- Rb transfers polarization to K by collisions
- K transfers spin to ^{3}He by collisions



- 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,
  ➔ remove alkalis (~few ppm of ^{3}He)
  ➔ then diffuse into ICF shell

filling ICF shells

- ICF shells:
  - fabricated by GA-ICF Pellet division
  - PAM (Poly-Alcohol repeating Monomer, C_9H_{10}) mandrel is coated with a glow discharge polymer (GDP, $CH_{1.3}$); heating to 600 K (326 C) dissociates PAM which diffuses out through GDP, leaving a shell behind.



- GDP shells filled in high-pressure chamber; pressure increased in steps to maintain small pressure differential across shell walls.
- Filling rate adjusted to remain below the shell buckling pressure:

  eg. typically $\Delta P = 2/3 \times P_{buckle}$
- HD shells: 4 mm OD x 20 µm wall
- ^{3}He shells: 4 mm (possibly 8 mm) OD x 20 µm wall

eg. HD Shell filling times

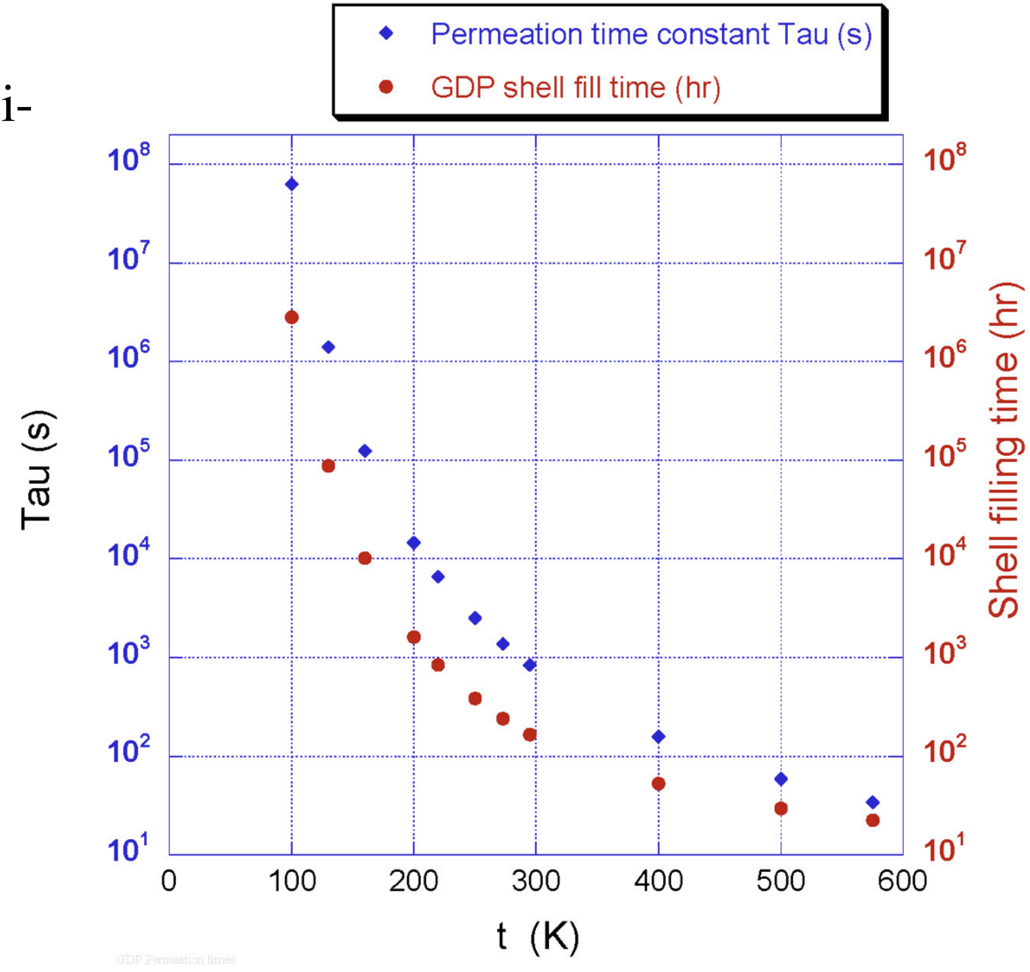
- eg. 4 mm OD x 20 μm wall GDP shells require **23 hr** to fill to 0.3 milli-moles with HD at 575 K

- pressure drops as chamber is cooled cryogenically:

  - at 100 K, pressure = 73 atm, permeation time ~ 1 year

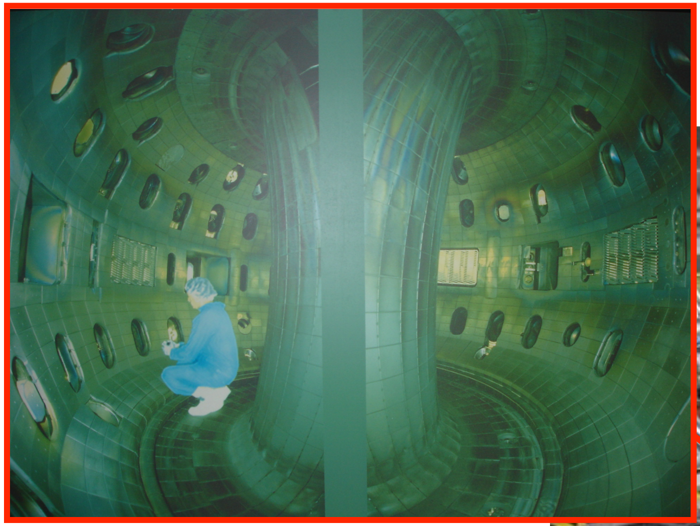
  ➔ **pellet is sealed** !!!

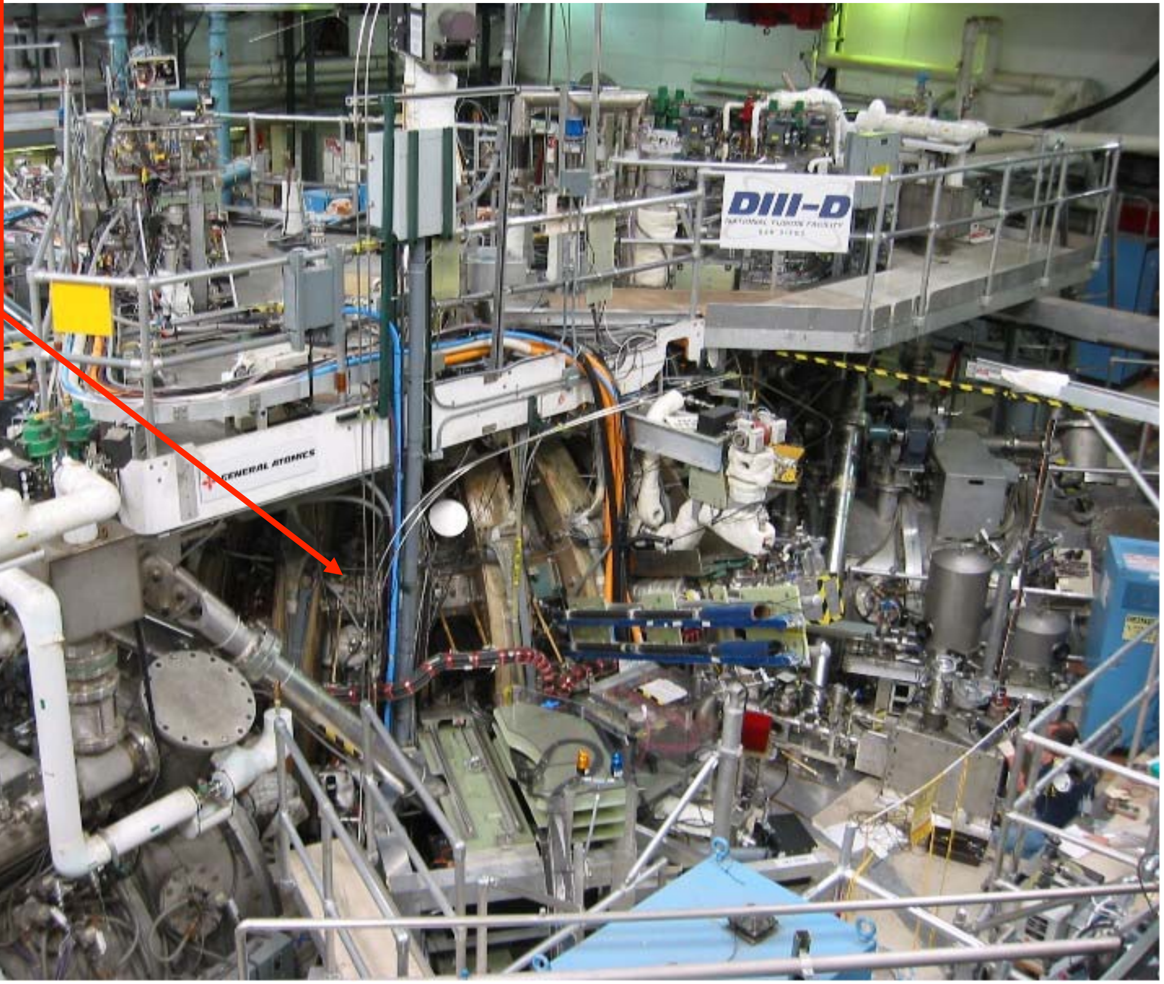
  - at 18 K, pressure = ¼ atm, exterior gas pumped away & replaced with He for cooling



DIII-D Tokamak at GA, San Diego

2.1 tesla torus (normal-conducting coils)



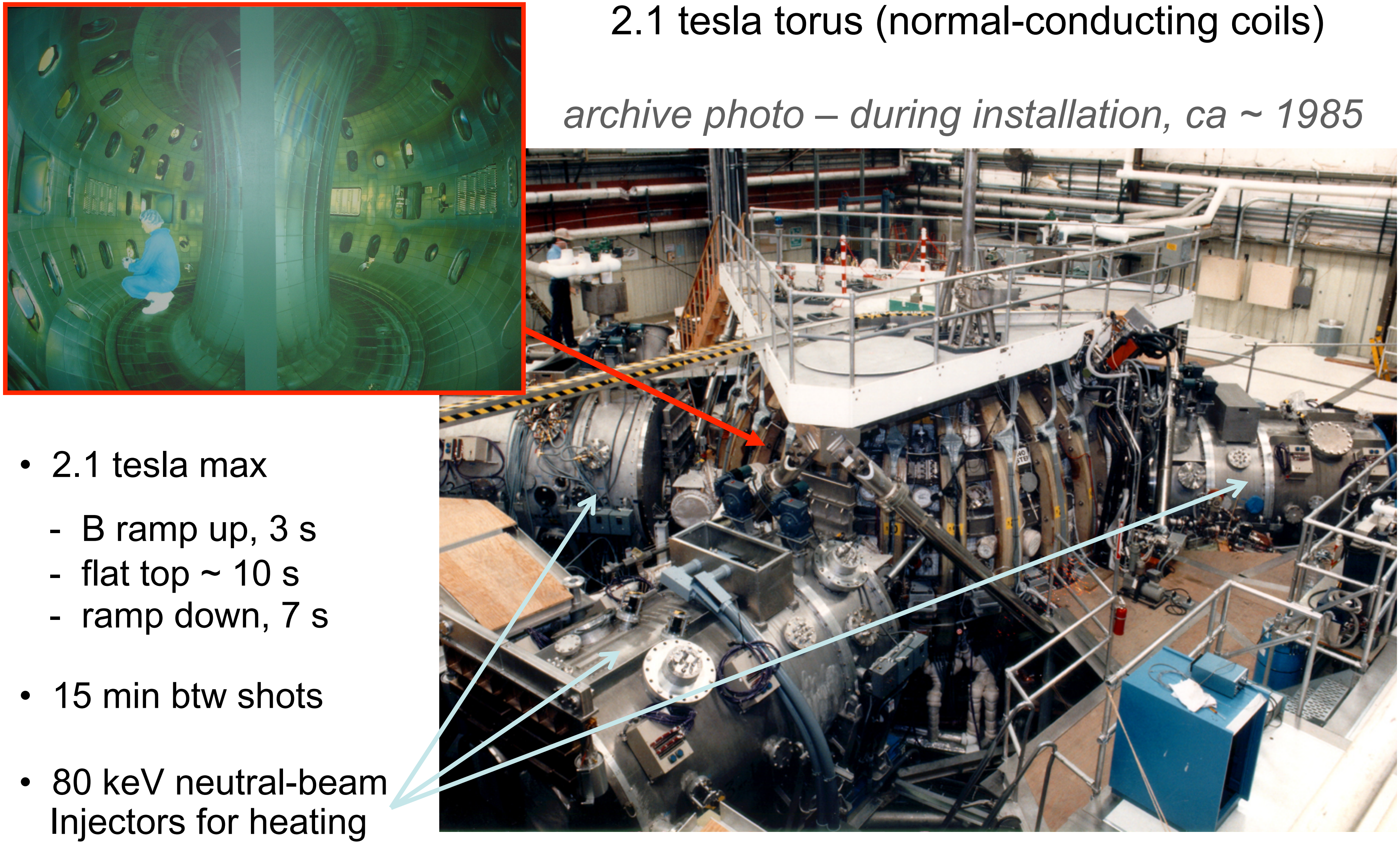


- 2.1 tesla max
  - B ramp up, 3 s
  - flat top ~ 10 s
  - ramp down, 7 s
- 15 min btw shots
- 80 keV neutral-beam Injectors for heating

DIII-D Tokamak at GA, San Diego

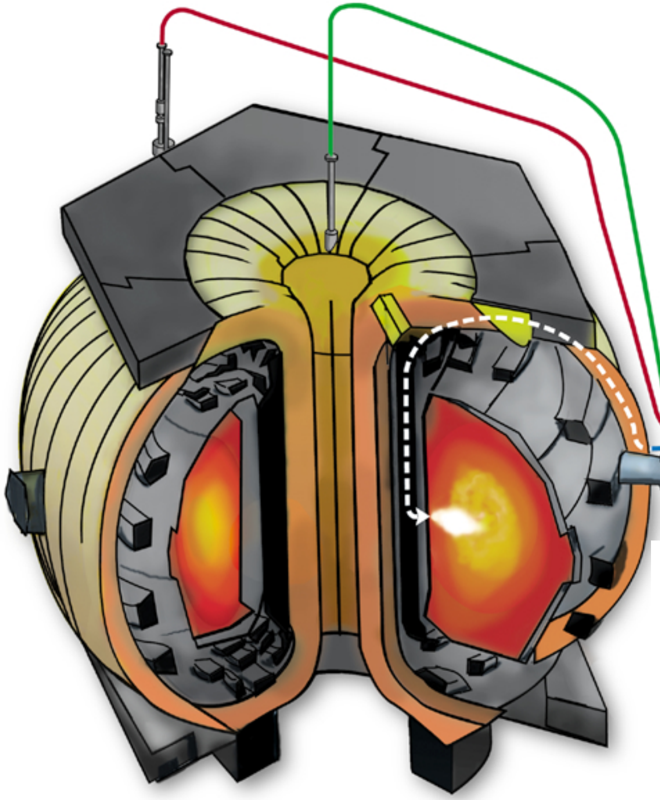
2.1 tesla torus (normal-conducting coils)

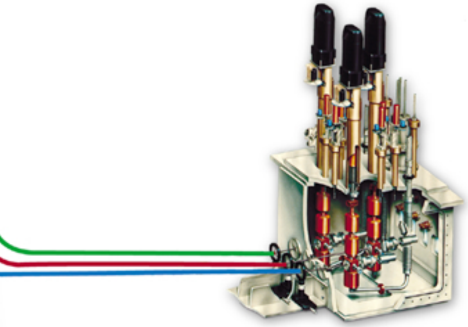
archive photo – during installation, ca ~ 1985



- 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

pellet injection into DIII-D

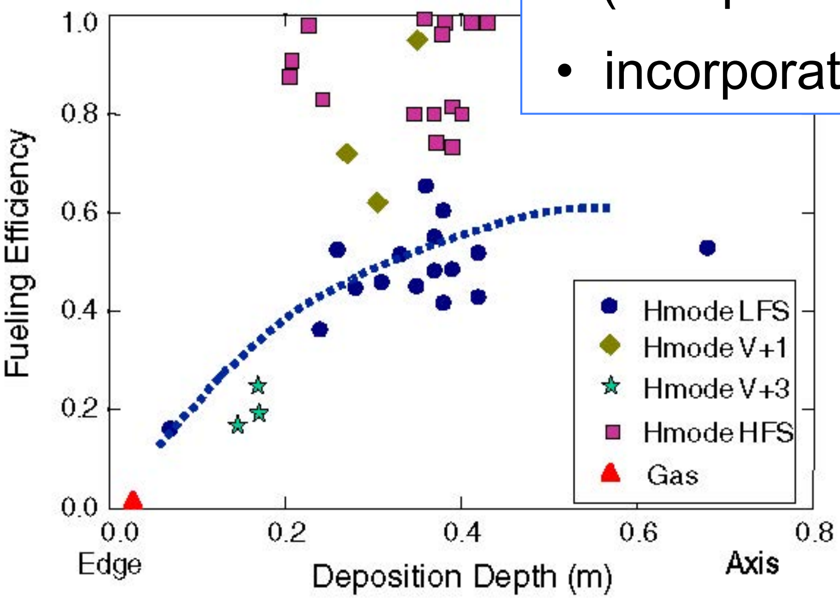




- ORNL cryp-pellet injectors operating at 4 K
  - pellets propelled by H_2 gas ~1000 m/s

Modifications:

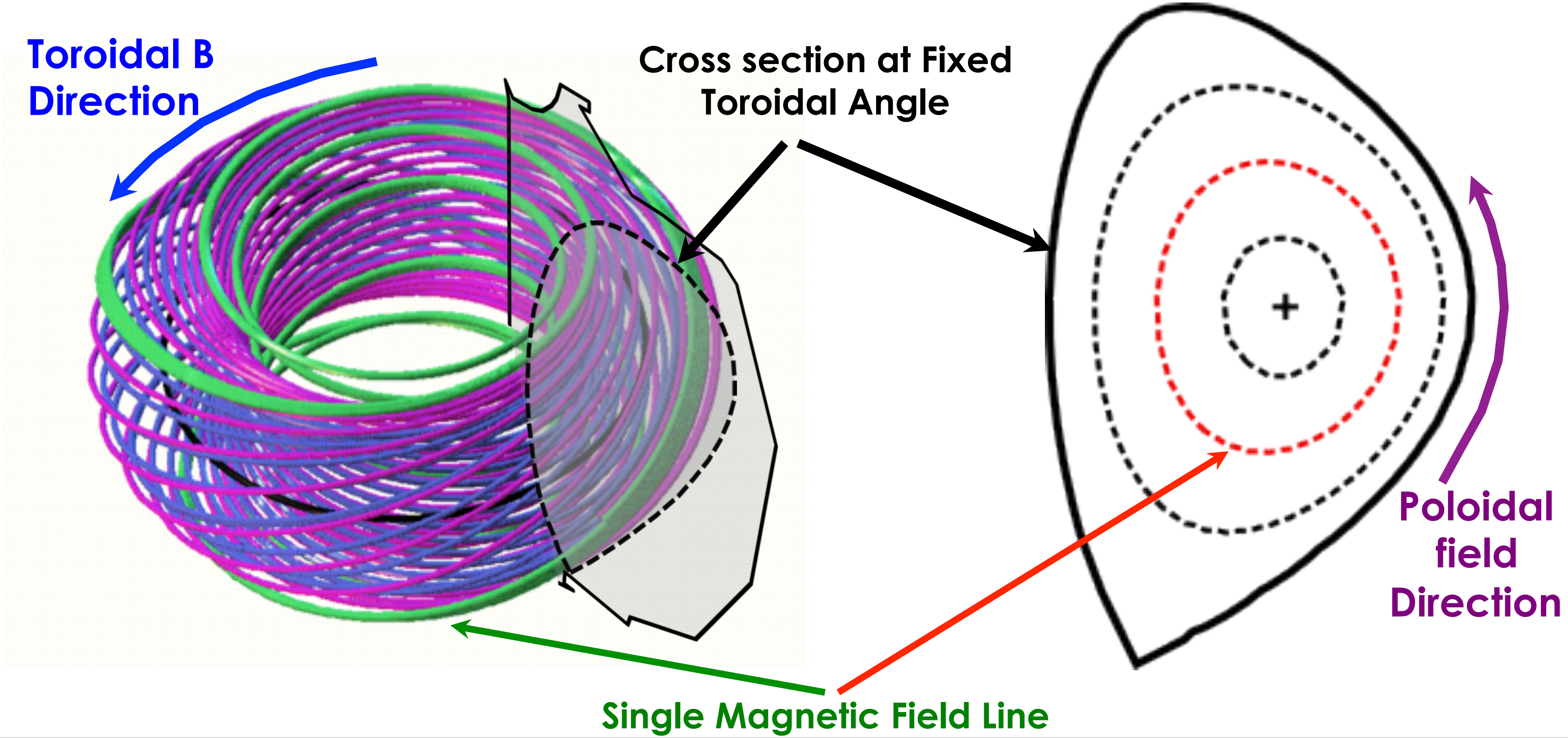
- provide B field along full length of guide tubes
- adapt to HD cartridges (and possibly ^{3}He)
- incorporate SQUIDS



Baylor *et al*, Nucl Fus 47 (07) 1598

Magnetic Geometry of a Tokamak –a Series of Nested Flux Surfaces

- confinement via gyrotron oscillation around closed magnetic field lines
- Axis-symmetry: equivalent cross-sections at different toroidal positions
- Flux surfaces represent the region of closed magnetic field lines



Toroidal B Direction

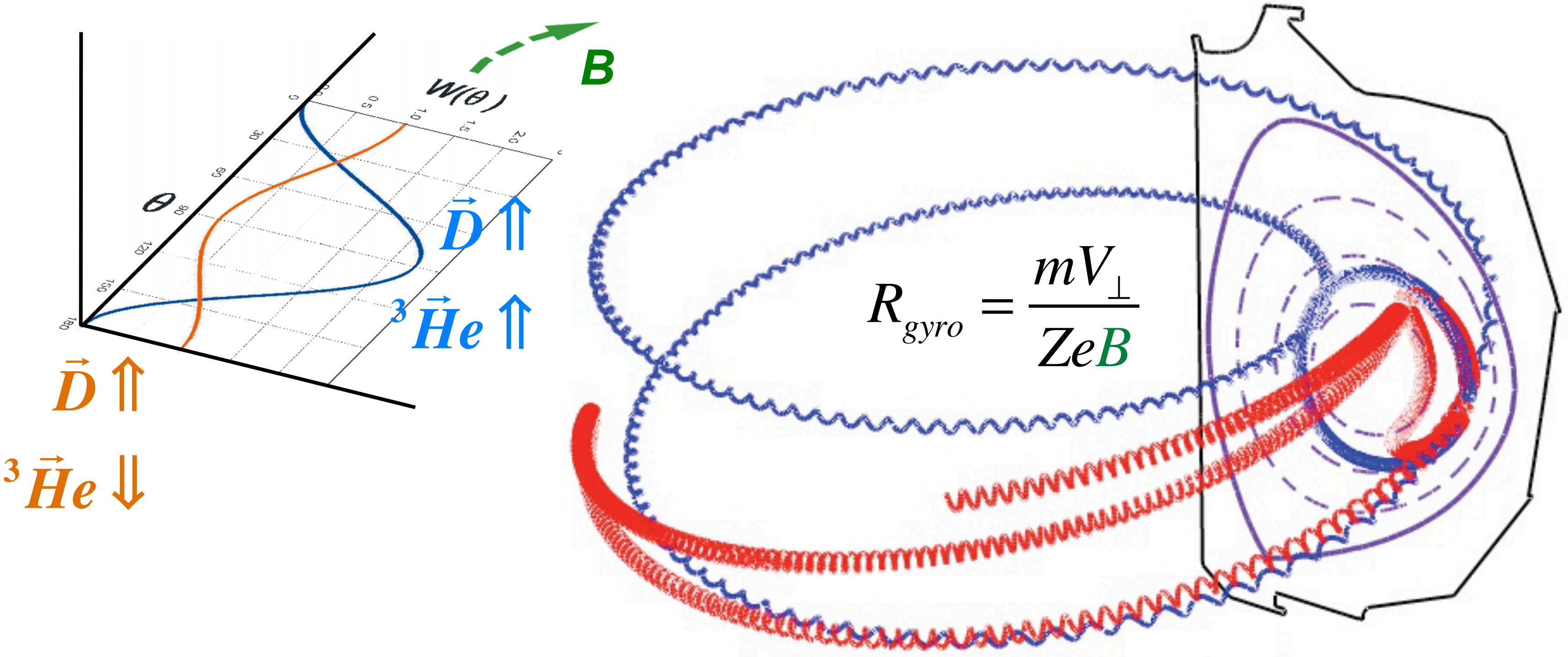
Cross section at Fixed Toroidal Angle

Poloidal field Direction

Single Magnetic Field Line

Spin-Alignment and Orbit Losses

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

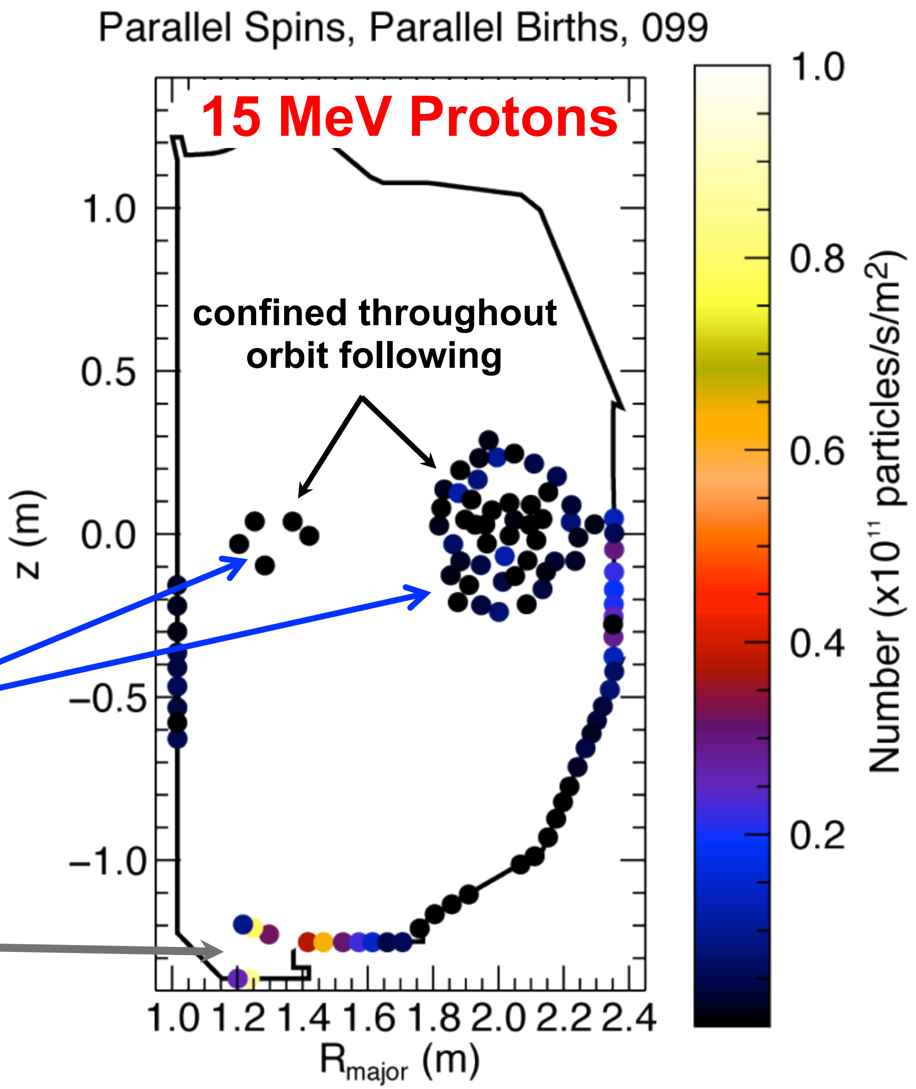


$$R_{gyro} = \frac{mV_\perp}{ZeB}$$

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

tracking fusion products through DIII-D

- Orbit calculation follows a large (but limited) number of physical steps along the ion trajectory, until a wall strike is detected
- Most trajectories intersect the Tokamak wall wiithin a few orbits
- For α+p born parallel to the local field ($\theta_{cm} \approx 0$), some are confined, depending on origin within the plasma
- Divertor region is location of largest loss population for parallel birth

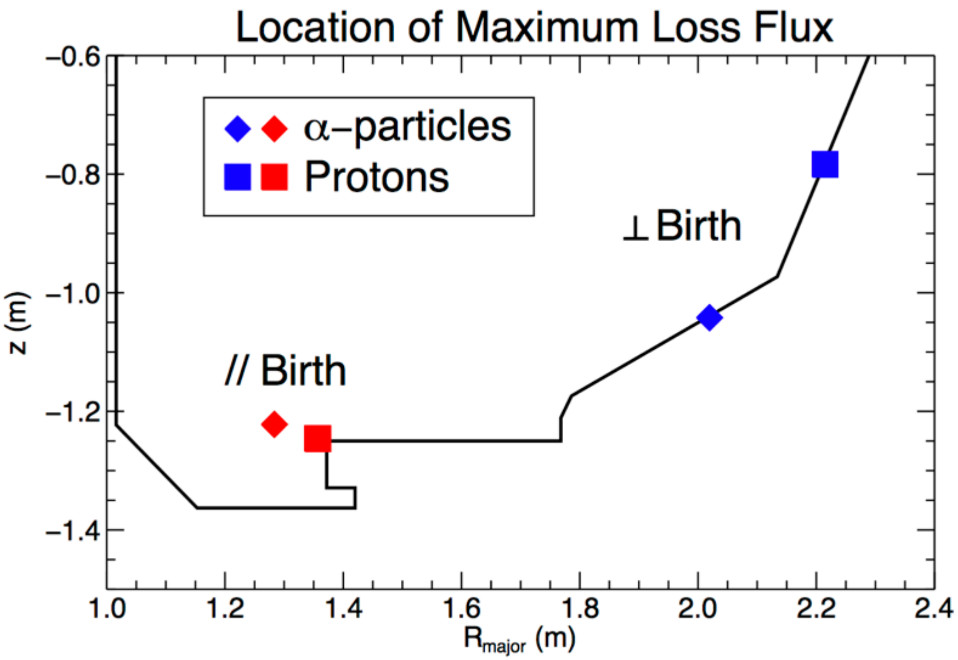


Peak Loss Fluxes Occur at Different wall locations for || ($\theta_{cm}\approx 0$) birth and ⊥($\theta_{cm}\approx 90$) birth fusion products

- Typical detector area ≈ 4×4 cm^2
- Expected fluxes from tracking: ~ 10^9 particles reach detector

eg. flux (in units of 10 pA):

⊥ Birth	Anti-parallel Spin	Parallel Spin
α-particles	**1.6**	**2.6**
Protons	**1.6**	**2.5**

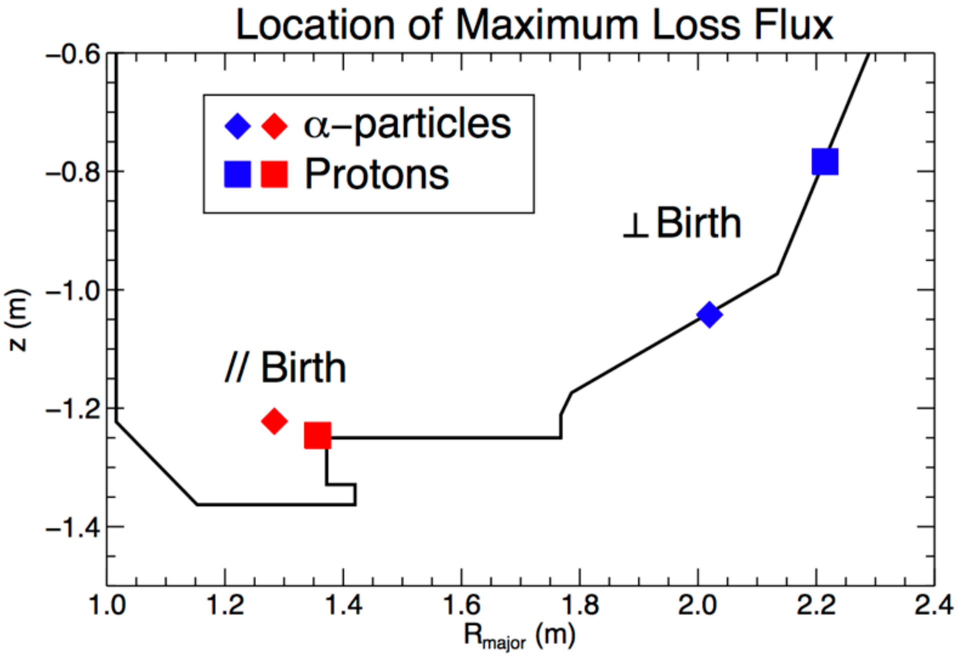


Peak Loss Fluxes Occur at Different wall locations for || ($\theta_{cm}\approx0$) birth and ⊥($\theta_{cm}\approx90$) birth fusion products

- Typical detector area ≈ 4 x 4 cm^2
- Expected fluxes from tracking: ~ 10^9 particles reach detector

eg. flux (in units of 10 pA):

⊥ Birth	**Anti-parallel Spin**	**Parallel Spin**
α-particles	**1.6**	**2.6**
Protons	**1.6**	**2.5**



- 28% difference $(\sigma_{\uparrow\uparrow}-\sigma_{\uparrow\downarrow})/\sigma_0$ in polarized cross sections ⇨ 44% difference in proton signals, due to polarized angular distributions and how products propagate in B_{Torus}
- tracking studies are underway to optimize signal and detector locations

secondary reactions

- use H-plasma heated with H neutral beams

- simulations follow secondary reactions to estimate background yields:

  $^{3}\text{He} + \text{D} \Rightarrow \alpha + \text{p}$ (Q = +18.3 MeV) ⟷ **E(p) ~ 15 MeV**

  ↳ $\text{D} + \text{D} \Rightarrow {}^{3}\text{He} + \text{n}$ (Q = + 3.3 MeV)

  ↳ $\text{D} + \text{D} \Rightarrow \text{t} + \text{p}$ (Q = + 4.0 MeV) ⟷ **E(p) ~ 3 MeV**

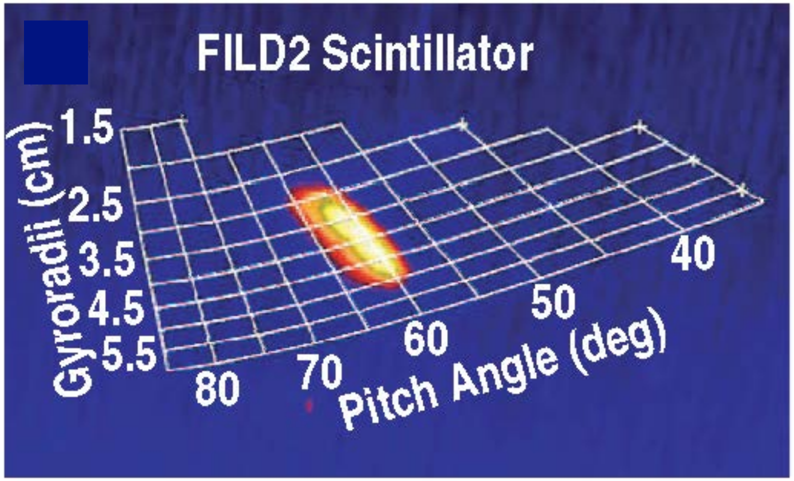
  ↳ $\text{D} + \text{t} \Rightarrow \alpha + \text{n}$ (Q = +17.6 MeV)

- 15 MeV protons from $^{3}\text{He} + \text{D} \Rightarrow \alpha + \text{p}$ provide a unique signature that is easily separated

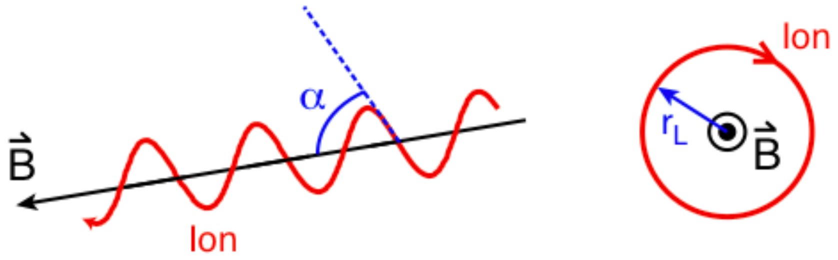
Fast Ion Loss Detector (FILD) Measures the Energy and Pitch Angle of Energetic Ions that Reach its Position on the Outer Wall

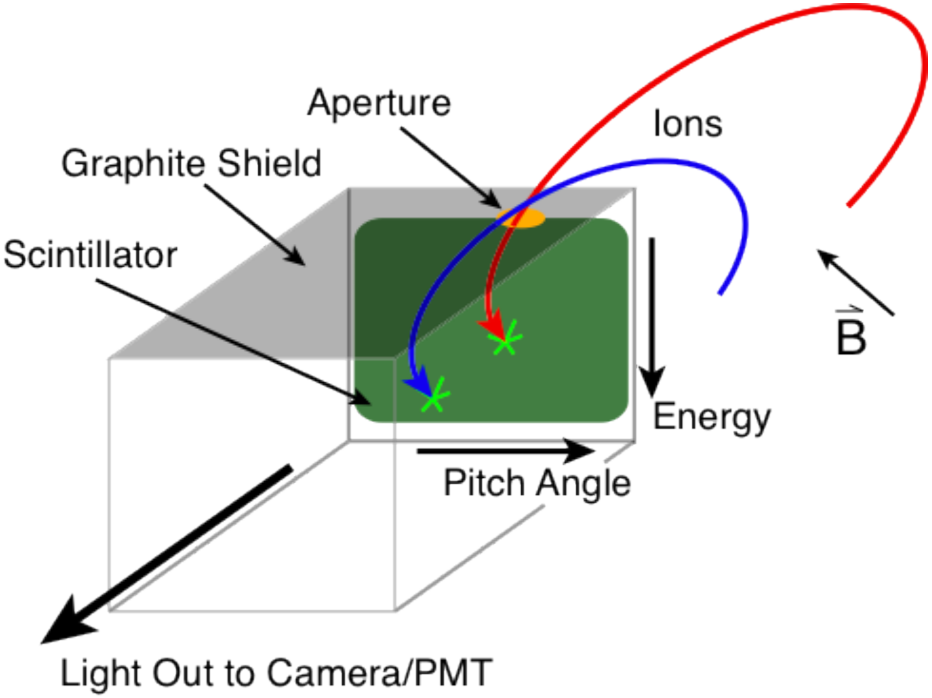
light emission pattern :

- ↳ Gyro-radius ⇨ ion energy
- ↳ pitch (polar) angle



Chen *et al*, Rev Sci Inst **83** (2012) 10D707





Possible approximate Timeline

I. R&D (internally funded) to address open issues in preparation for a proposal to US DOE

- plasma requirements, injection, fusion product detection
  - **2013-2014 (2015) IR&D from General Atomics - funded** ✔

- HD: effects of ICF shell diffusion; max D polarization
  (largely riding on the tail of ongoing NP target development)
- ^{3}He: polarization after diffusion; max pressure
  - **some R&D required –** tbd

↓

II. Possible Funding request for a full experiment

- **eg. 2015-2016, proposal to US DOE (FES + NP)**

➔ experiments at DIII-D ~ 2019