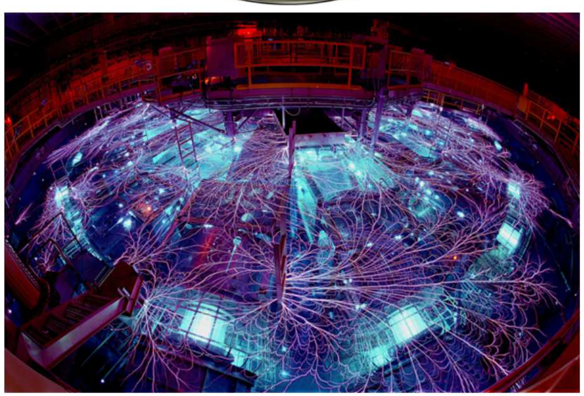
Modeling kinetic processes in magnetized ICF plasmas



Paul F. Schmit

Fundamental Science with Pulsed Power

Breakout session

July 23rd, 2014

SAND-###-####

U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration · LDRD Laboratory Directed Research & Development

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Thanks to many collaborators

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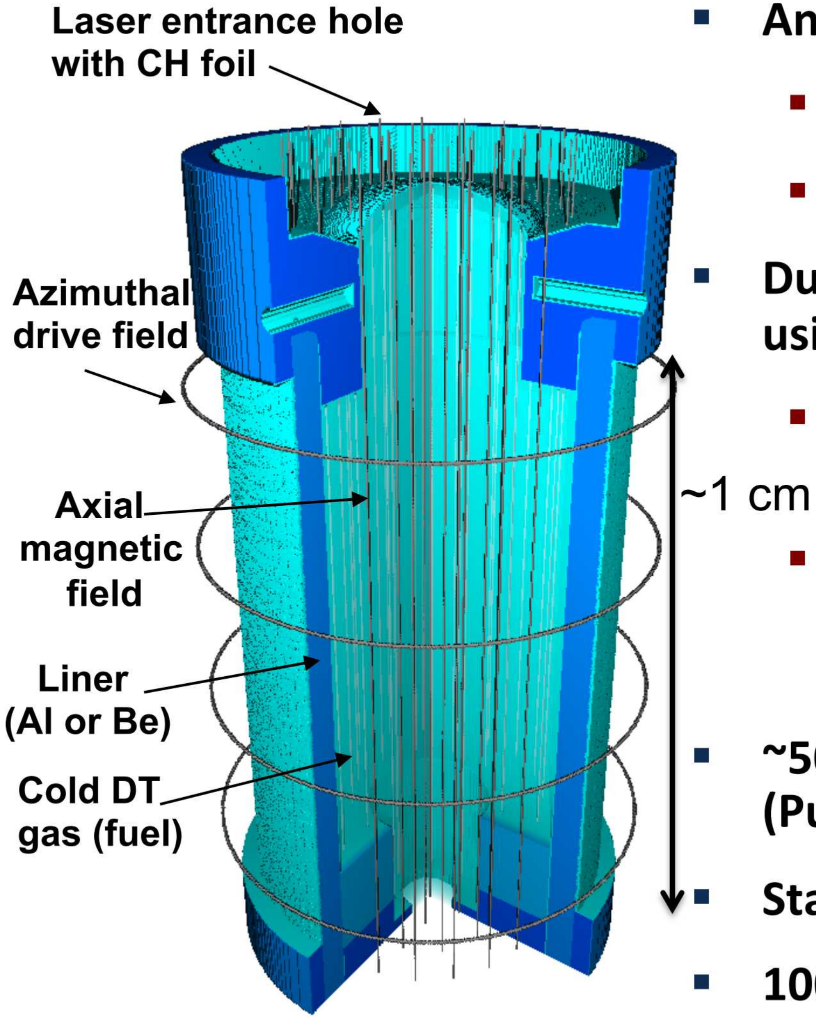
We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that may reduce fusion requirements



- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - May help stabilize implosion at late times
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank (Pulsed power is very energy efficient!)
- Stagnation pressure required is ~5 Gbar
- 100 kJ yield may be possible on Z using DT
  Early experiments would use DD fuel

*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

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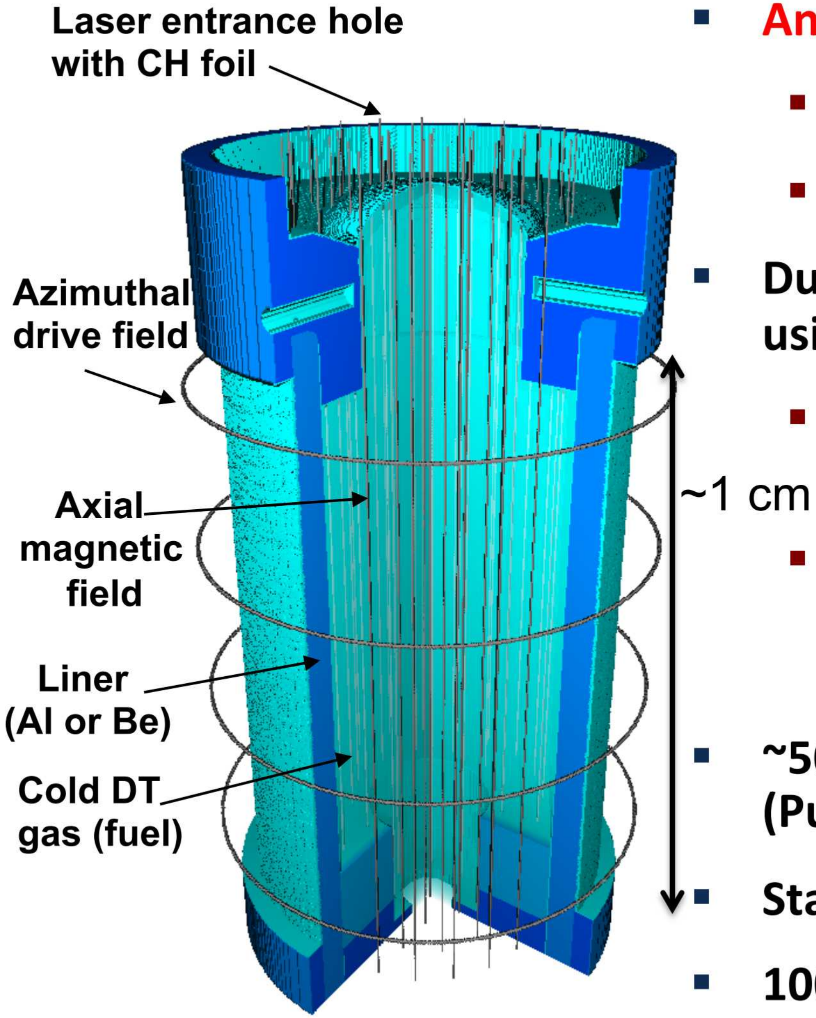

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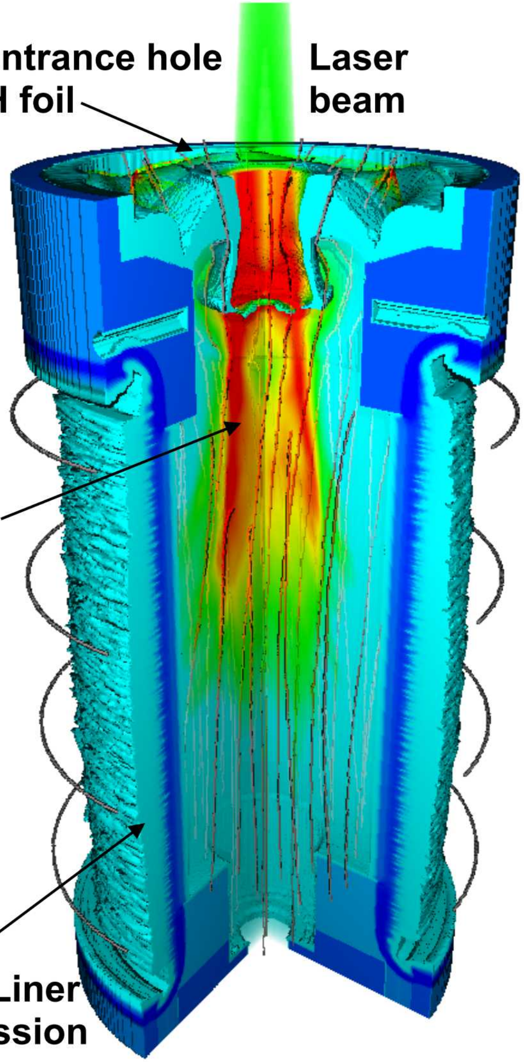

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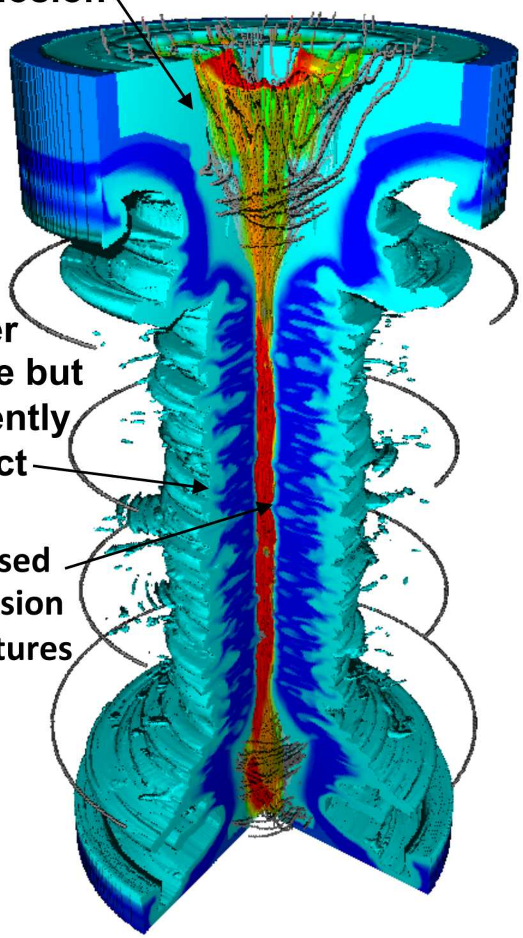

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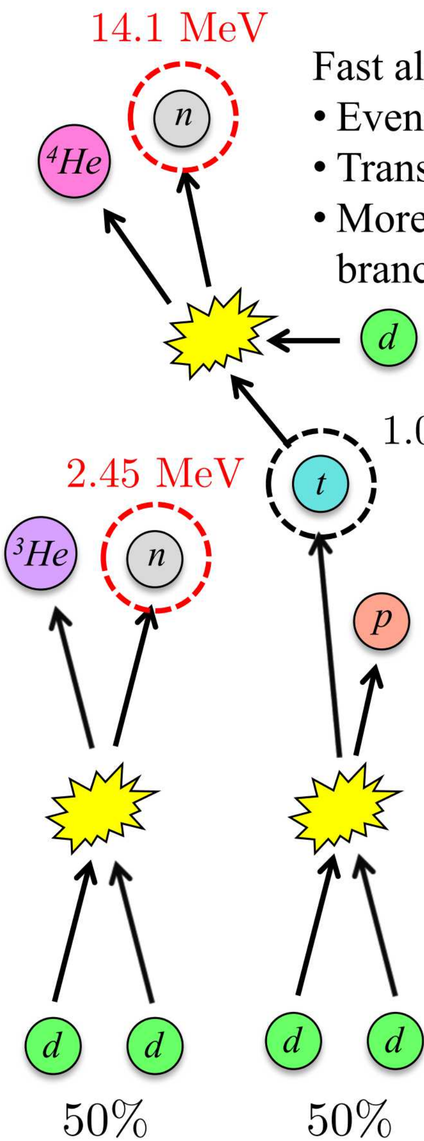
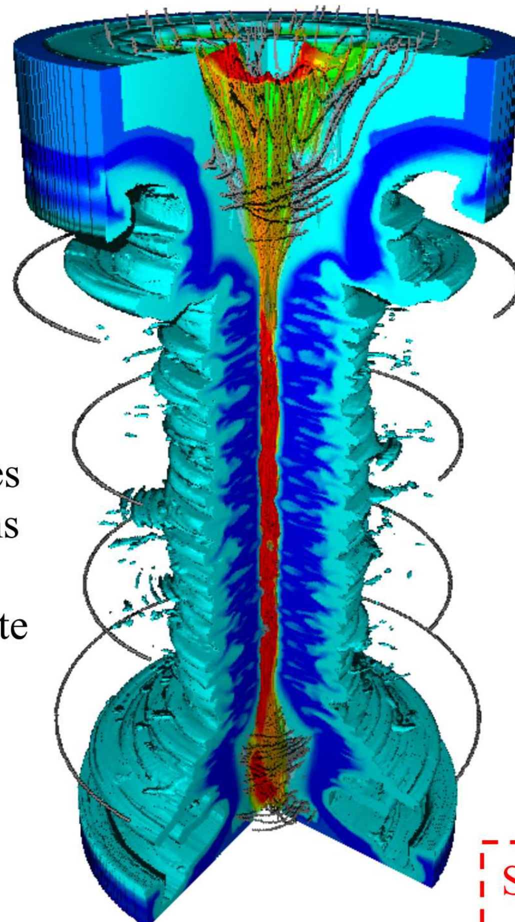
Kinetic processes in magnetized ICF plasma



Fast alphas:
- Eventual DT fuel expts
- Transport/deposition
- More secondary reaction branches→diagnostics?

Fast tritons:
- Transport properties
- Secondary reactions →diagnostics
- 3.5 MeV α surrogate

Fuel deuterons:
- Tail-depletion
- Transport properties
- Fuel-liner interface
- Mix



$\rho_{\text{fuel}} \sim 0.5\ \text{g/cm}^3$
$\rho_{\text{liner}} \sim 10\ \text{g/cm}^3$

$(\rho R)_{\text{fuel}} \sim 2 - 10\ \text{mg/cm}^2$
$(\rho Z)_{\text{fuel}} \sim 0.2 - 1\ \text{g/cm}^2$
$(\rho R)_{\text{liner}} \gtrsim 1\ \text{g/cm}^2$

$T_{\text{fuel}} = 3\ \text{keV}$
$\Rightarrow \ln \Lambda_{ii} \sim \ln \Lambda_{ie} \sim 7.3$
$\Rightarrow \omega_{ci}\tau_{ii} \sim 1$ at 100 MG

$T_{\text{fuel}} = 8\ \text{keV}$
$\Rightarrow \ln \Lambda_{ii} \sim \ln \Lambda_{ie} \sim 8.8$
$\Rightarrow \omega_{ci}\tau_{ii} \sim 3$ at 100 MG

$\omega_{ce}\tau_{ee} = \mathcal{O}(100)$
$R/r_{L,\alpha} = \mathcal{O}(1)$

Strongly magnetized electrons, marginally magnetized fuel ions, magnetized/confined fast ions, weak coupling→LFP

Monte Carlo modeling of minority ion species

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Test-ion kinetic equation, arbitrary number of background fuel species:

$$\frac{\partial F_a}{\partial t} = -\frac{\partial}{\partial \rho}\mathcal{F}_\rho F_a - \frac{\partial}{\partial \phi'}\mathcal{F}_\phi F_a - \frac{\partial}{\partial \mu}\mathcal{F}_\mu F_a - \frac{\partial}{\partial \varepsilon_k}\mathcal{F}_\varepsilon F_a + \frac{1}{2}\frac{\partial^2}{\partial \phi'^2}\mathcal{D}_{\phi\phi}F_a + \frac{1}{2}\frac{\partial^2}{\partial \mu^2}\mathcal{D}_{\mu\mu}F_a + \frac{1}{2}\frac{\partial^2}{\partial \varepsilon_k^2}\mathcal{D}_{\varepsilon\varepsilon}F_a$$

Drag terms

$$\mathcal{F}_\rho = \sigma\varepsilon_k^{1/2}\cos\phi'$$

$$\mathcal{F}_\phi = \frac{Z_a}{2}\frac{\partial \Phi}{\partial \rho}\frac{\sin\phi'}{\sigma\varepsilon_k^{1/2}} - \sigma\varepsilon_k^{1/2}\frac{\sin\phi'}{\rho} + \chi_a$$

$$\mathcal{F}_\mu = \frac{Z_a}{2}\frac{\partial \Phi}{\partial \rho}\frac{\sigma\mu}{\varepsilon_k^{1/2}}\cos\phi' - \frac{\rho_m \Pi_a}{\varepsilon_k^{3/2}}\mu F(\varepsilon_k)$$

$$\mathcal{F}_\varepsilon = -\left(\frac{2\rho_m\Pi_a}{\varepsilon_k^{1/2}}A_a\left\langle\frac{1}{A_b}\right\rangle[D(\varepsilon_k) - T_a D'(\varepsilon_k)] + Z_a\frac{\partial \Phi}{\partial \rho}\sigma\varepsilon_k^{1/2}\cos\phi'\right)$$

Diffusion terms

$$\mathcal{D}_{\phi\phi} = \frac{\rho_m\Pi_a}{\varepsilon_k^{3/2}}F(\varepsilon_k)\frac{1}{1-\mu^2}$$

$$\mathcal{D}_{\mu\mu} = \frac{\rho_m\Pi_a}{\varepsilon_k^{3/2}}F(\varepsilon_k)\left(1-\mu^2\right)$$

$$\mathcal{D}_{\varepsilon\varepsilon} = 4\rho_m\Pi_a T_a A_a\left\langle\frac{1}{A_b}\right\rangle\frac{D(\varepsilon_k)}{\varepsilon_k^{1/2}}$$

$$^*\chi_a \equiv \frac{\omega_{ca}}{\nu_{\mu 0}}$$ (magnetic field **only** shows up in gyrophase drag term)

$$^*\Pi_a \equiv \frac{\langle Z_b^2 \ln\Lambda_{ab}\rangle}{\langle Z_b^2 \ln\Lambda_{ab}\rangle_0}$$

(Transition function, D, includes interactions with electrons and ions, assumed to be at same T locally)

$$\frac{d\rho}{dt} = \mathcal{F}_\rho$$

$$\frac{d\phi'}{dt} = \mathcal{F}_\phi + \mathcal{D}_{\phi\phi}^{1/2}\Gamma_1(t)$$

$$\frac{d\mu}{dt} = \mathcal{F}_\mu + \mathcal{D}_{\mu\mu}^{1/2}\Gamma_2(t)$$

$$\frac{d\varepsilon_k}{dt} = \mathcal{F}_\varepsilon + \mathcal{D}_{\varepsilon\varepsilon}^{1/2}\Gamma_3(t)$$

The formal solution to this equation can be found by solving an equivalent set of single-particle stochastic differential orbital equations for an ensemble of test particles

Overview of Knudsen loss mechanism

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- First work on tail-ion depletion & Knudsen layers in ICF by Petschek and Henderson:

VOLUME 33, NUMBER 19 PHYSICAL REVIEW LETTERS 4 NOVEMBER 1974

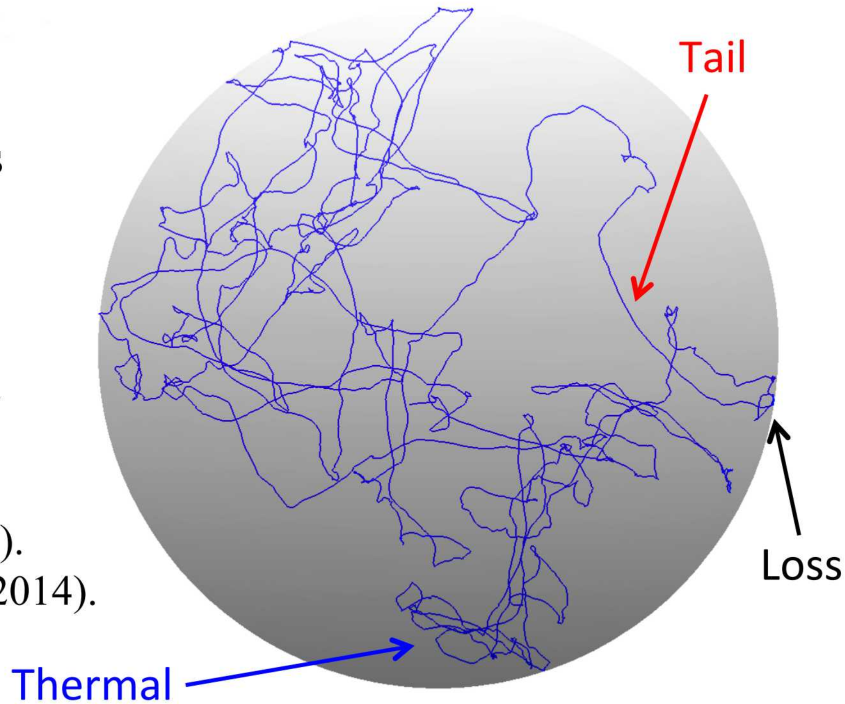
Burn Characteristics of Marginal Deuterium-Tritium Microspheres

Dale B. Henderson
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544
(Received 5 August 1974)

Long mean free paths for ions in the tail of the distribution may allow escape, quenching the burn of marginal ($\rho R < 10^{-2}$ g/cm^2) deuterium-tritium microspheres, possibly explaining the lack of success in experiments to date.

$$\text{Hydro}: \quad \frac{\lambda_{\text{mfp}}}{L} \ll 1$$

$$\text{Fuel ions}: \quad \lambda_{\text{mfp}} \sim v^4$$

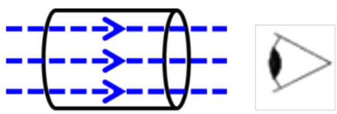


- Knudsen layer research in the ICF community has regained significant attention recently
  - K. Molvig *et al.*, Phys. Rev. Lett. **109**, 095001 (2012).
  - P. F. Schmit *et al.*, Phys. Plasmas **20**, 112705 (2013).
  - B. J. Albright *et al.*, Phys. Plasmas **20**, 122705 (2013).
  - X. Z. Tang *et al.*, Phys. Plasmas **21**, 032706 (2014).
  - X. Z. Tang *et al.*, Phys. Plasmas **21**, 032707 (2014).
  - C. J. McDevitt *et al.*, Phys. Plasmas **21**, 032708 (2014).
  - M. J. Rosenberg *et al.*, Phys. Rev. Lett. **112**, 185001 (2014).

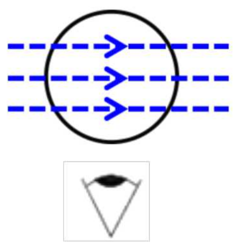
Tail-depletion and reactivity reduction with B-fields*

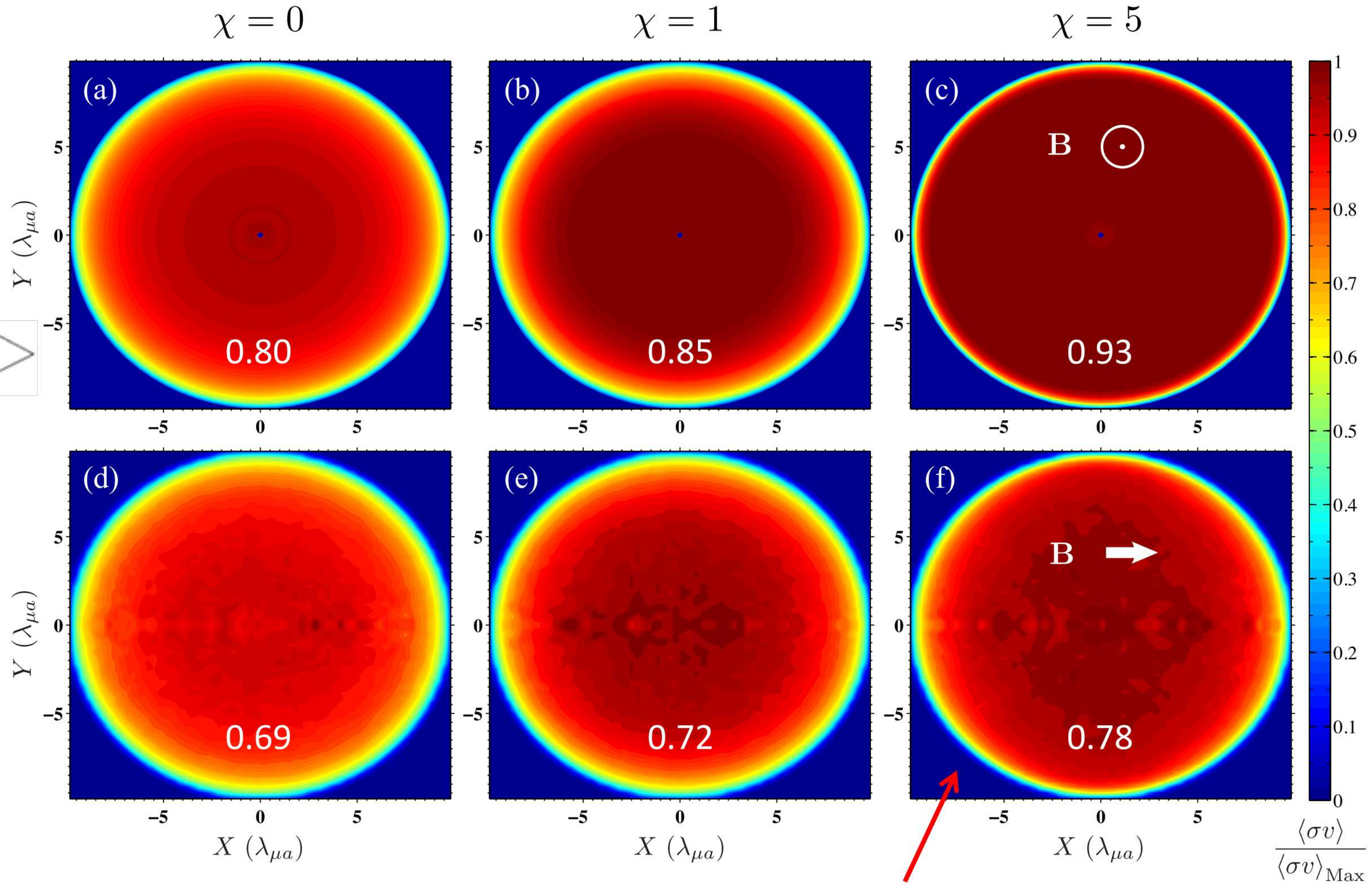
Cylindrical and spherical systems: 5 keV, 1 g/cc, DD plasma, $N_K = 0.1$

Cylinder: depletion suppressed *completely* by B-field



Sphere: depletion suppressed only *partially* by B-field





Spherical symmetry-breaking of reactivity contours (3D→1D)

*χ defined alternatively as : $\chi \equiv \dfrac{\omega_{ca}}{\nu_{\mu a}} \approx \dfrac{N_K}{N_B}$

* P. F. Schmit, Kim Molving, and C. W. Nakhleh, *Physics of Plasmas* **20**, 112705 (2013).

Exploring the dimensionless parameter landscape

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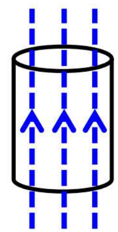
Cylindrical system: 8 keV, 1 g/cc, DD plasma: volume-averaged reactivity reduction

Relevant MagLIF timescales:

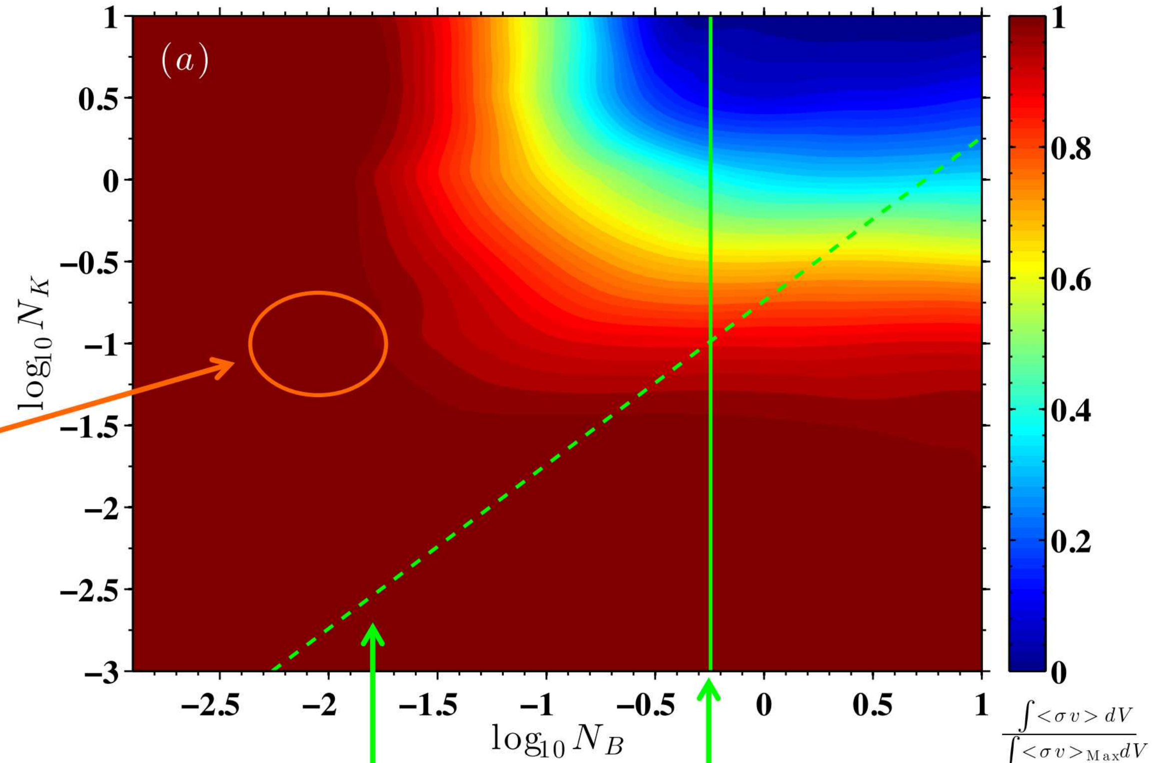
$\tau_{dd}^{\mu} \sim \mathcal{O}(10 \text{ ps})$

$\tau_{eq} \sim \mathcal{O}(100 \text{ ps})$

$\tau_{burn} \sim \mathcal{O}(1 \text{ ns})$



(Knudsen numbers for thermal D ions)



MagLIF point design is well within the plateau regime for fully restored Maxwellian reactivities.

MagLIF operating regime*

Magnetization threshold $N_B/N_K = \xi^{3/2}$

Confinement threshold $N_B = \xi^{-1/2}$

$(\xi \approx 3.1)$

$$N_K \sim \frac{\lambda_{mfp}}{L} \sim \frac{T^2}{nL}$$

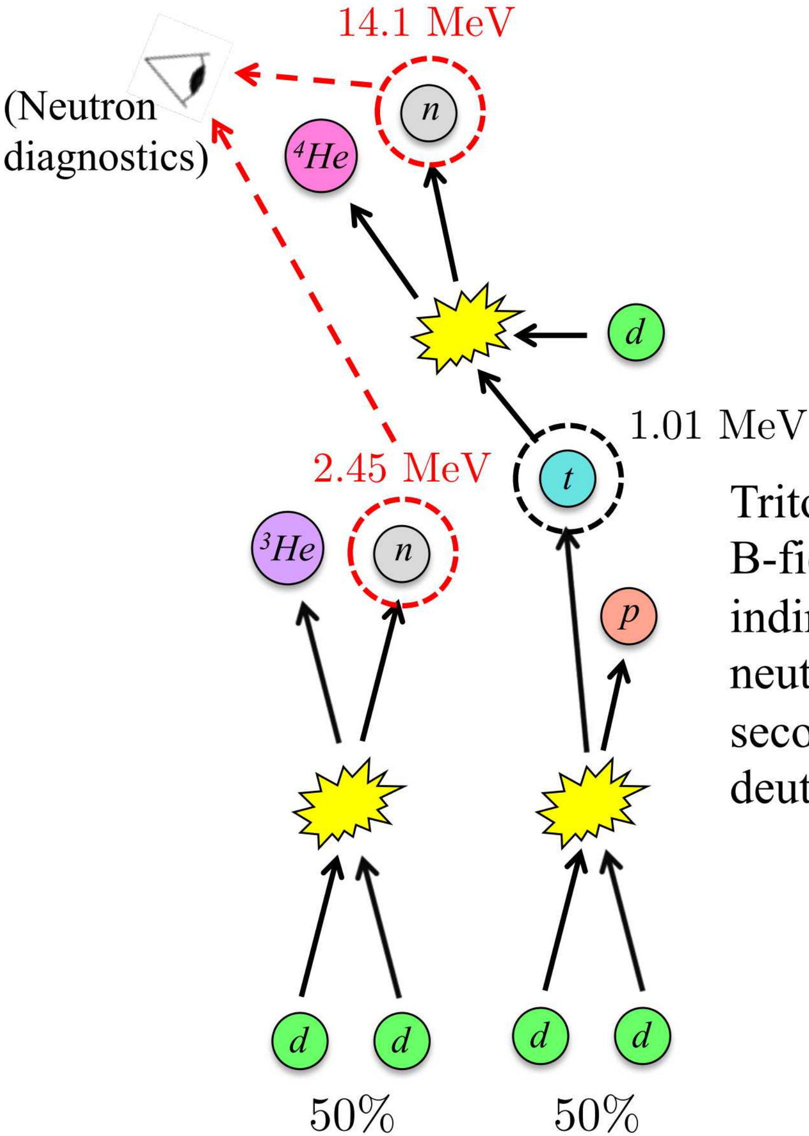
$$N_B \sim \frac{\rho_L}{L} \sim \frac{T^{1/2}}{BL}$$

$\Longrightarrow$ Scan (N_K, N_B)-space at fixed T, n by varying B, L.

*Hot spot parameters: 8 keV, 0.5 g/cc, 100 MG B-field, 100 micron radius

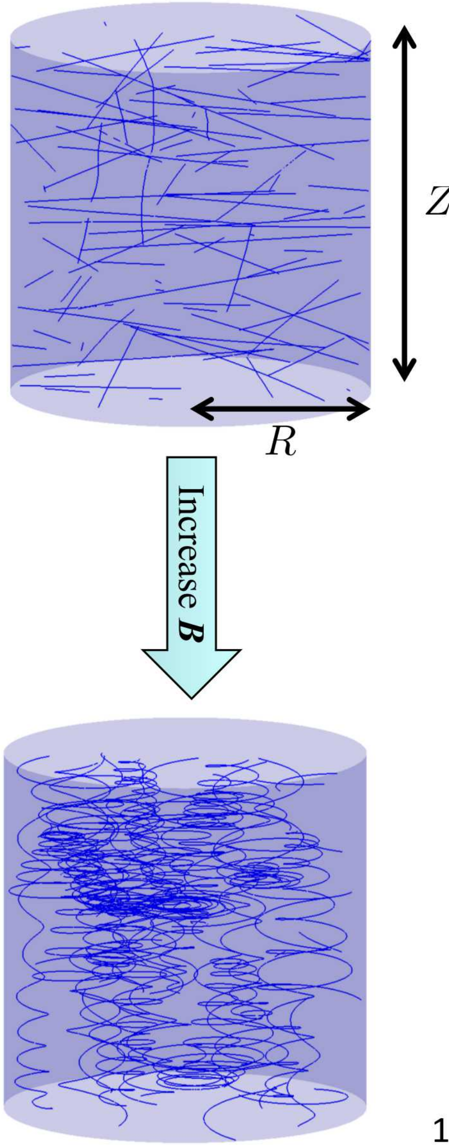
* S. A. Slutz *et al.*, PoP 17, 056303 (2010). A. B. Sefkow *et al.*, SAND 2012-0876C (2012).

Kinetic modeling of secondary reaction physics



We model ensembles of triton "test particles" and calculate their reactivities

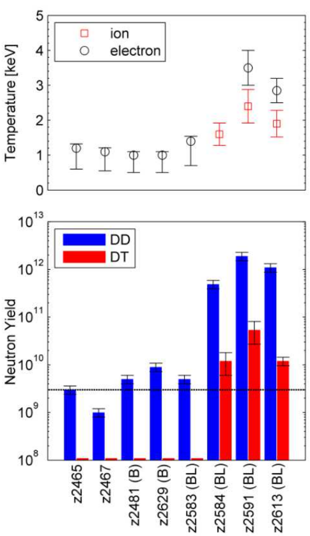
Tritons carry info about the B-field, which we extract indirectly via observation of neutrons produced by their secondary reactions with the deuterium fuel



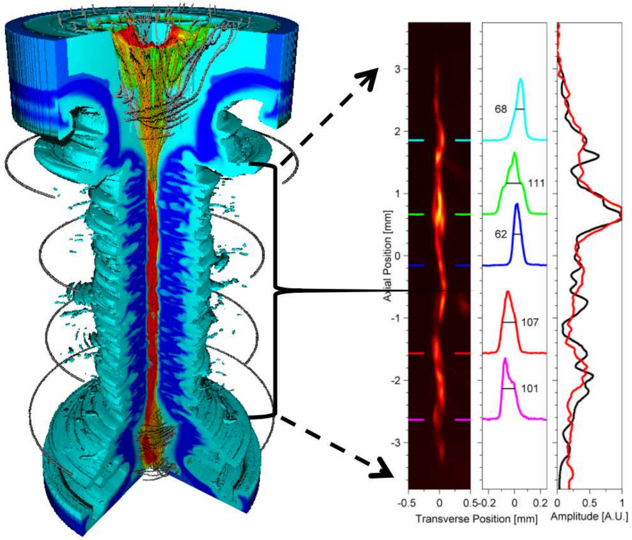
A strong magnetic field causes triton path lengths to scale with Z instead of R, where $Z >> R$

Probing magnetization and mix with secondary nuclear reactions

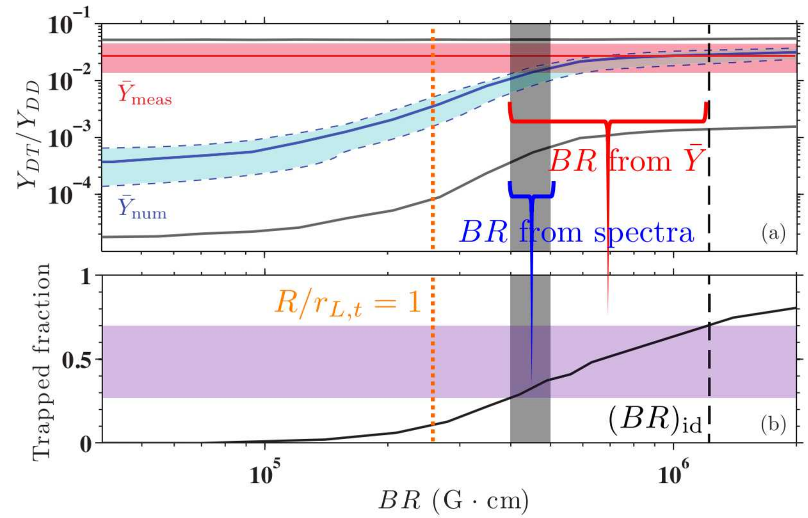
Roosevelt experimental temperature/yield data**



Roosevelt experimental fuel self-emission data**



Kinetic calculations of DT/DD vs. *BR**



Experimental DT/DD | Numerical DT/DD & confidence interval

BR from neutron spectra | Estimated trapped triton fraction

First integrated tests of MagLIF:

- multi-keV T_e and T_i
- $O(10^{12})$ primary DD neutron yields
- *Remarkable*, $O(10^{10})$ secondary DT neutron yields

Self-emission data constrains stagnation radius: $R \gtrsim 30 - 60\ \mu\text{m}$

Kinetic ions + Monte Carlo nuclear reactions:

- Inputs determined by expt data & uncertainty
- DT/DD yield scales strongly with *BR*
- Triton gyroradius: $R/r_{L,t} \propto BR$
- For $R \approx 50\ \mu\text{m}$, indicates $B \gtrsim 80$ MG
- Models assume homogeneous fuel conditions, effects of inhomogeneities being studied

*P. F. Schmit, P. F. Knapp *et al.*, submitted to Phys. Rev. Lett., **M. R. Gomez *et al.*, submitted to Phys. Rev. Lett.

Probing magnetization and mix with secondary nuclear reactions

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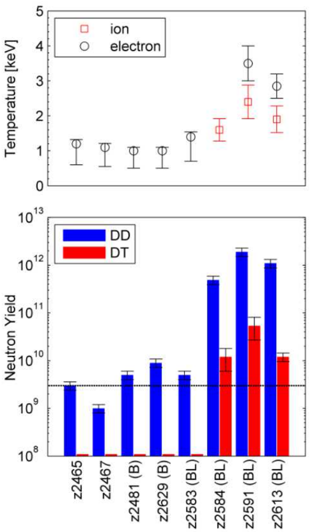

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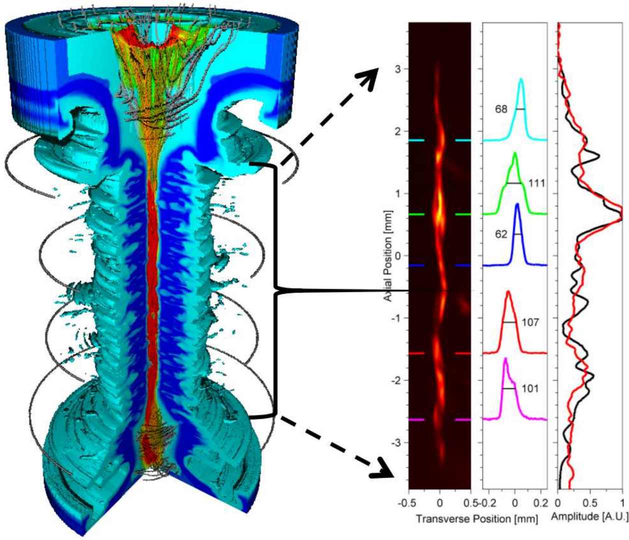
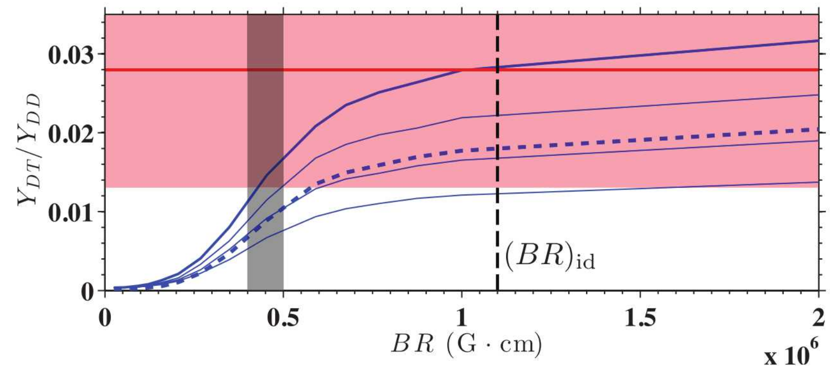


DT/DD vs. BR vs. beryllium mix*



dashed : $\rho_d R = 1$ mg/cm^2, $n_{\rm Be}/n_{\rm tot} \equiv c_{\rm Be}$: 0.1

solid : $\rho_d R = 2$ mg/cm^2, $c_{\rm Be}$ (ascending order) : 0.3, 0.2, 0.1, 0

Experimental DT/DD Numerical DT/DD

BR from neutron spectra

First integrated tests of MagLIF:

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Self-emission data constrains stagnation radius: $R \gtrsim 30 - 60\ \mu$m

DT/DD also constrains fuel-pusher mix:

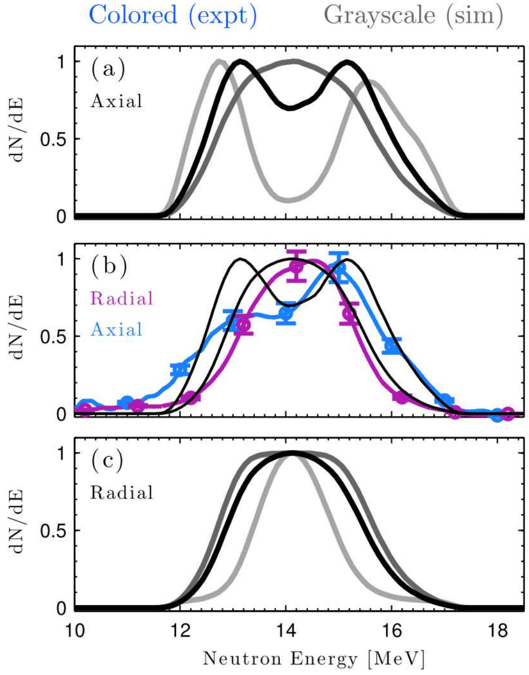
- Assumed uniform mix (worst-case scenario)
- Mix lowers DT/DD in magnetized limit (enhanced stopping→shorter triton ranges)
- $(BR)_{\rm id}$ assumes no flux losses and R = 50um
- Mix likely <10%, emission analysis agrees**
- Reducing measurement uncertainty important

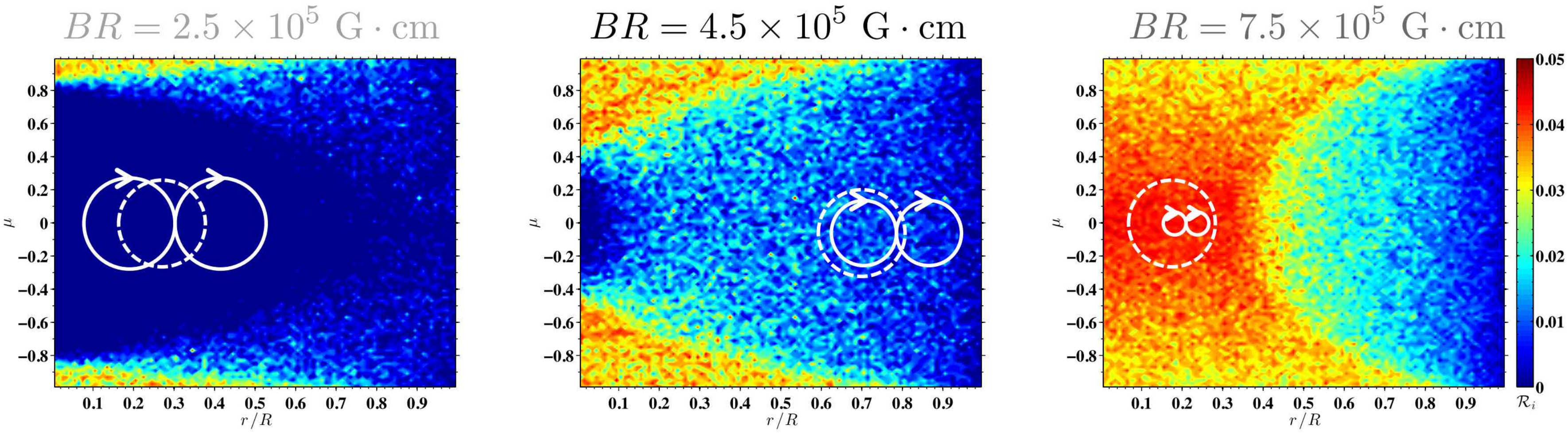
*P. F. Schmit, P. F. Knapp *et al.*, submitted to Phys. Rev. Lett., **M. R. Gomez *et al.*, submitted to Phys. Rev. Lett.

Probing magnetization and mix with secondary nuclear reactions

- Measured DT neutron energy spectra anisotropic
- Calculated spectra match data well, suggesting narrower range: $BR \approx 4-5 \times 10^5$ G · cm
- Axial view shows double-peak, due to Doppler shift from most reactive tritons
- Radial view shows single peak
- *Spectra features highly sensitive to BR!*

- Figures below show triton reaction probability ($\mathcal{R}_i$) based on initial radial position and pitch-angle relative to magnetic field ($\mu = \cos\theta$)





HYDRA (fluid) and LSP (particle) simulations are used to generate synthetic neutron spectra*

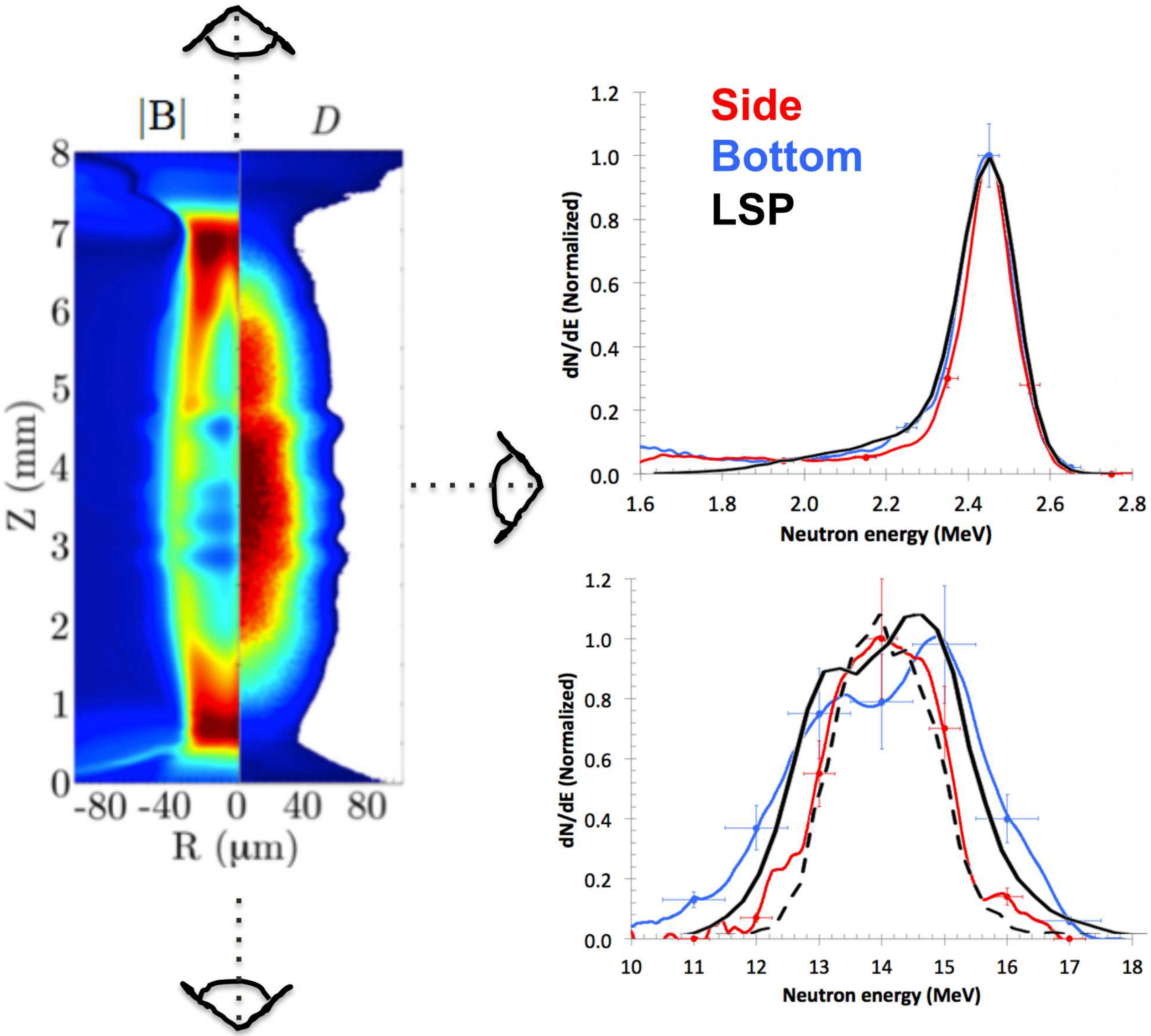
PIC simulations are initialized with HYDRA output (n, T, B) just before stagnation, and then run through burn.

All ions are evolved kinetically.

Binary scattering between all species is treated.

Binary fusion events are treated.

Synthetic neutron detectors are located to the side, top, and bottom of the stagnation column.



*Slide provided by Adam Sefkow

Other interesting kinetic topics in ICF with possible consequences/departures in MagLIF

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- Kinetic transport effects at the plasma-liner (plasma-metal) interface
  - Recent developments in theory and modeling of *unmagnetized* plasma-metal interfaces:
    - "Non-linear structure of the diffusing gas-metal interface in a thermonuclear plasma," K. Molvig *et al.*, 2014 Anomalous Absorption Conference. **Transport theory in lo-Z/hi-Z plasma.**
    - "Kinetic effects at material interfaces in ICF implosions," S. C. Wilks *et al.*, 2014 Anomalous Absorption Conference. **Lsp modeling of lo-Z/hi-Z plasma.**
    - "A new theory of mix in Omega capsule implosions," D. A. Knoll *et al.*, 2014 Anomalous Absorption Conference. **Transient double-layer effects.**
  - Differences in MagLIF:
    - Axial magnetic field marginally to moderately magnetizes fuel ions and strongly magnetizes electrons near stagnation, but liner plasma far more collisional. Different local transport modes?
    - Does ***B*** suppress double-layers/ambipolar fields? If not completely, and radial E-field exists near density gradient, possible azimuthal ExB rotation
    - Extra D.o.F to account for. Velocity shear transport barrier?