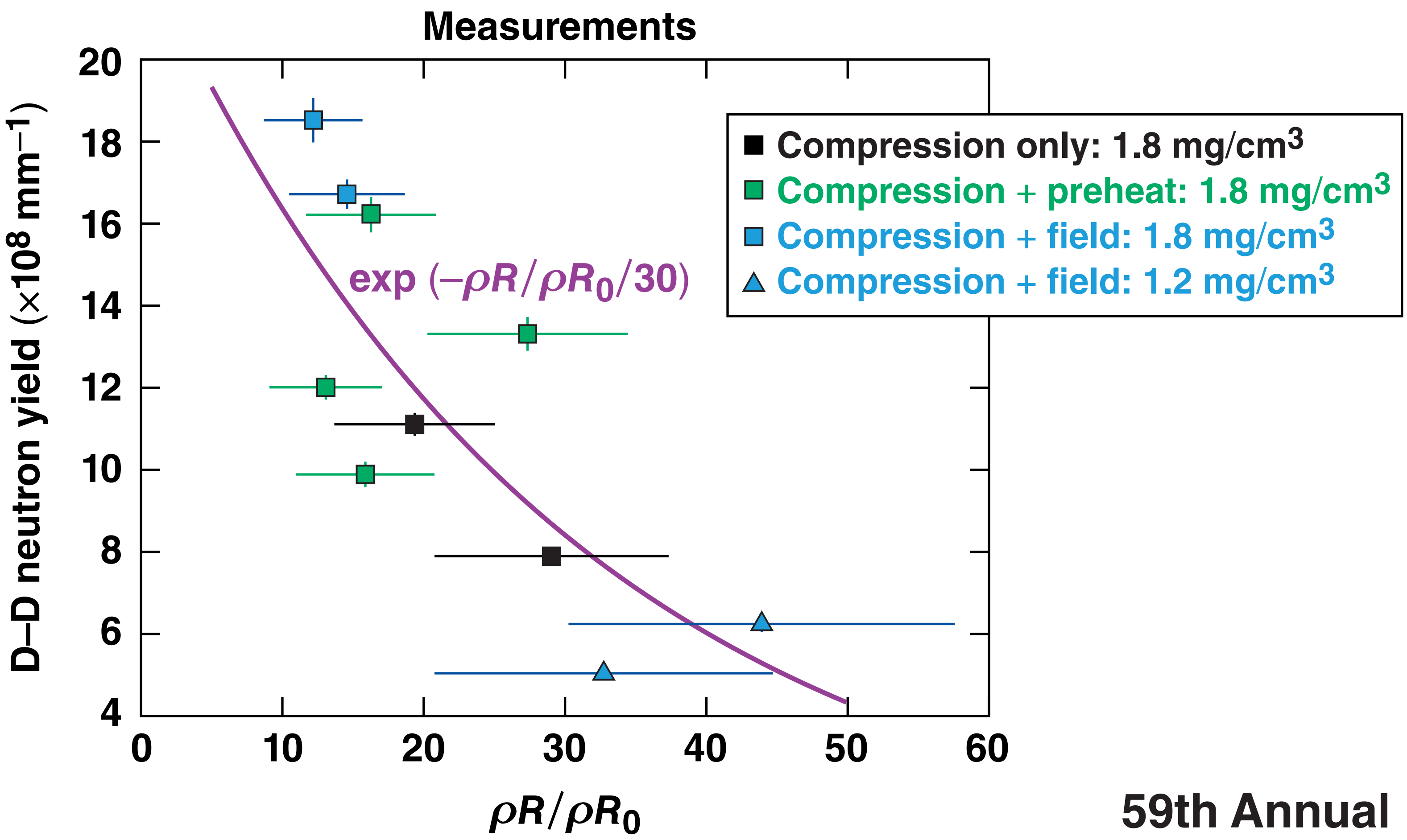
Fuel Areal-Density Measurements in Laser-Driven MagLIF from Secondary Neutrons



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59th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Milwaukee, WI
23–27 October 2017

Summary

The yield ratio of DT to DD neutrons in laser-driven MagLIF* is proportional to the fuel areal density ρR

- Laser-driven MagLIF is being developed on OMEGA to study scaling; ~1000× less drive energy than Z, ~10× smaller in linear dimensions
- Inferred areal densities confirm that preheating, magnetization, and increasing fuel density reduce fuel convergence
- The neutron yield falls with increasing convergence, in disagreement with simulations

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*MAGLIF: magnetized liner inertial fusion

Collaborators

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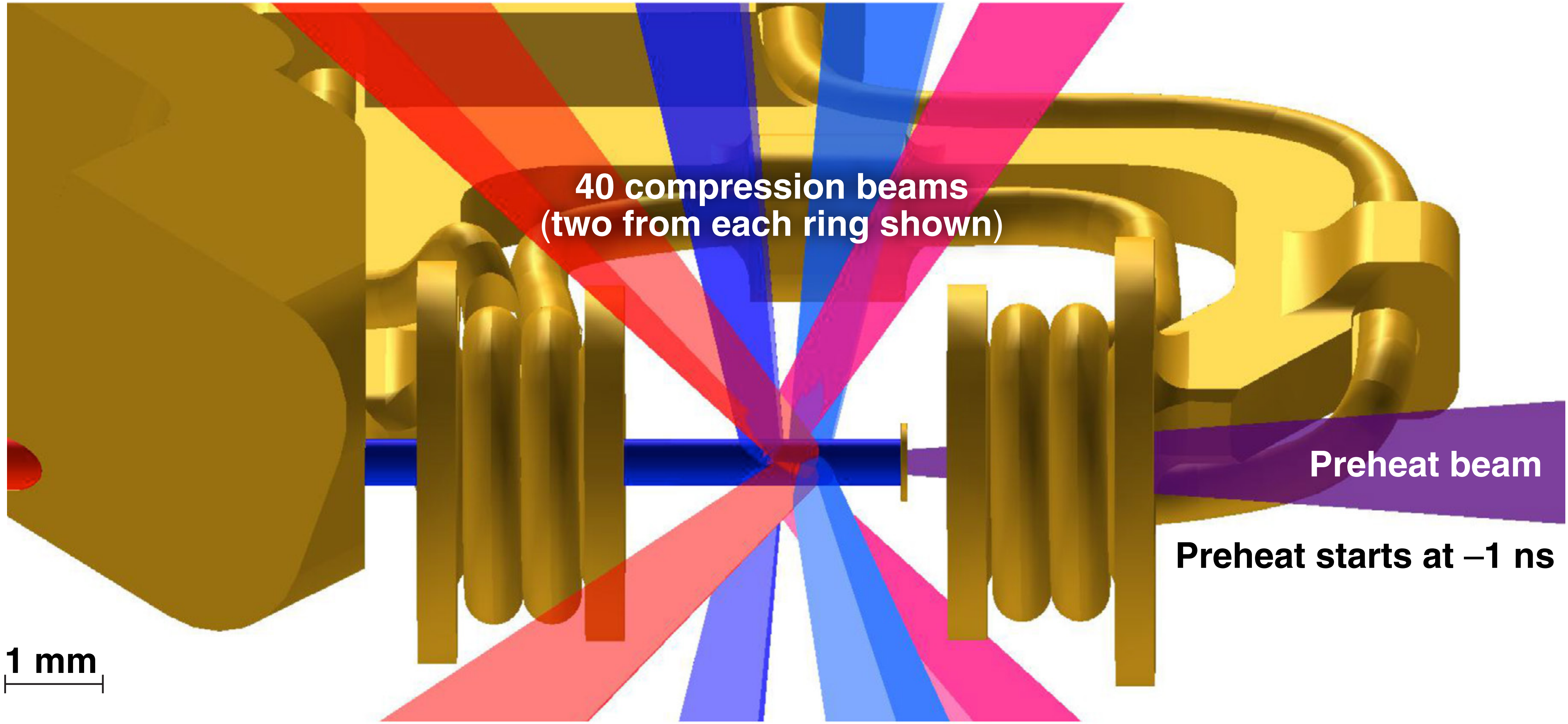
This project is funded by the Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) and the U.S. Department of Energy, under Award Number DE-AR0000568, the Department of Energy National Nuclear Security Administration under Award Number DE-NA0001944.

The laser-driven baseline is a 580-μm-outer-diam, 20-μm-thick CH shell, 1.8-mg/cm^3 D_2 fuel, 10-T axial magnetic field, 180 J for preheat, and 14 kJ for compression in 1.5-ns square-shaped pulses*



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*D. H. Barnak *et al.*, Phys. Plasmas 24, 056310 (2017).

Neutron emission from the hot, compressed DD fuel is one of the primary diagnostics giving yields and ion temperatures

- D–D fusion produces 2.45-MeV neutrons and an equal quantity of 1.01-MeV tritium (in center-of-momentum frames)

  $$\mathrm{D} + \mathrm{D} \rightarrow \begin{cases} {}^{3}\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}\ (2.45\ \mathrm{MeV}) & (50\%) \\ \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.02\ \mathrm{MeV}) & (50\%) \end{cases}$$

  - compression-only shots have a mean yield of 1.0×10^{9} and shots with preheat and/or magnetic field have reached a mean yield of 1.6×10^{9}

- The 1.01-MeV tritium can produce 14.1-MeV neutrons if it fuses with D before leaving the fuel

  $$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}\ (3.5\ \mathrm{MeV}) + \mathrm{n}\ (14.1\ \mathrm{MeV})$$

  - up to 3.5×10^{5} DT neutrons have been detected (threshold $\sim 10^{5}$)

The ratio of DT to DD neutrons can be used to infer the areal density of the DD fuel and, therefore, the fuel convergence ratio

- **Unlike MagLIF experiments on Z,* tritium is not magnetized because the fuel radius is much less than the Larmor radius**
  - **with ideal field compression $r_L \sim 250\ \mu\text{m}$ and $r_{\text{fuel}} \sim 10\ \mu\text{m}$**
- **If tritium energy loss is negligible, then the DT to DD yield ratio is** $\dfrac{Y_{DT}}{Y_{DD}} = \dfrac{\langle \rho s \rangle}{m_D}\sigma_0$
  - **$\langle \rho s \rangle$: fuel areal density averaged along the path length s of the tritium**
  - **m_D: deuterium mass**
  - **σ_0: fusion cross section for 1-MeV T on D at rest ($T_i < 3\ \text{keV} \ll 1\ \text{MeV}$)**
  - **Bosch and Hale** $\sigma_0 = 4.13 \times 10^{-29}\ \text{m}^2$ (assume ±20% uncertainty)**

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*P. F. Schmit *et al.*, Phys. Rev. Lett. 113, 155004 (2014).

**H. S. Bosch and G. M. Hale, Nucl. Fusion 32, 611 (1992); 33, 1919(E) (1993).

The neglect of tritium slowing in the fuel can be quantified by calculating the change in cross section for a small energy loss

- $\sigma \approx \sigma_0 + \left.\frac{d\sigma}{dE}\right|_{E_0} \left.\frac{dE}{ds}\right|_{E_0} s$ for small energy loss dE over path length s

  $\frac{Y_{DT}}{Y_{DD}} \approx \frac{\rho s}{m_D} \sigma_0 \left(1 + \frac{1}{\sigma_0} \left.\frac{d\sigma}{dE}\right|_{E_0} \left.\frac{dE}{ds}\right|_{E_0} \frac{s}{2}\right)$ for constant density ρ

- Slowing caused by tritium–electron collisions ($dE/ds \propto \rho / T_e^{3/2}$) and Bosch and Hale's* fit to the DT fusion cross section give

  $$\frac{Y_{DT}}{Y_{DD}} \approx 0.123\, \rho s_{g/cm^2} \left(1 + 86.1 \frac{\rho s_{g/cm^2}}{T_{keV}^{3/2}}\right)$$

  - the second term is negligible for $Y_{DT}/Y_{DD} \ll 1.42 \times 10^{-3}\ T_{keV}^{3/2}$
  - if slowing is negligible, then so is angular scattering; therefore, a straight-line propagation will be an adequate approximation

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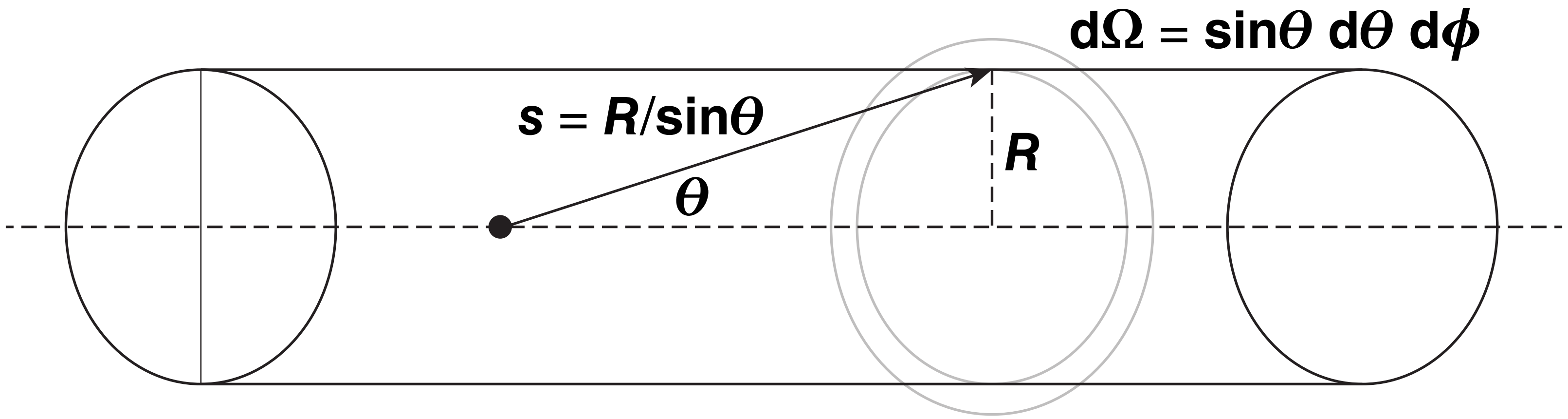
*H. S. Bosch and G. M. Hale, Nucl. Fusion 32, 611 (1992); 33, 1919(E) (1993).

The mean path length of an isotropic source of particles moving in straight lines in an infinitely long cylinder is approximately equal to the radius *R*, allowing ρR to be inferred

Source at $r = 0$



$$\langle s \rangle = \frac{1}{2\pi} \int_{\varphi=0}^{\varphi=2\pi} \int_{\theta=0}^{\theta=\pi/2} \frac{R}{\sin\theta} \sin\theta \, d\theta \, d\varphi = \frac{\pi}{2} R \approx 1.571 R$$

Regardless of the axial distribution

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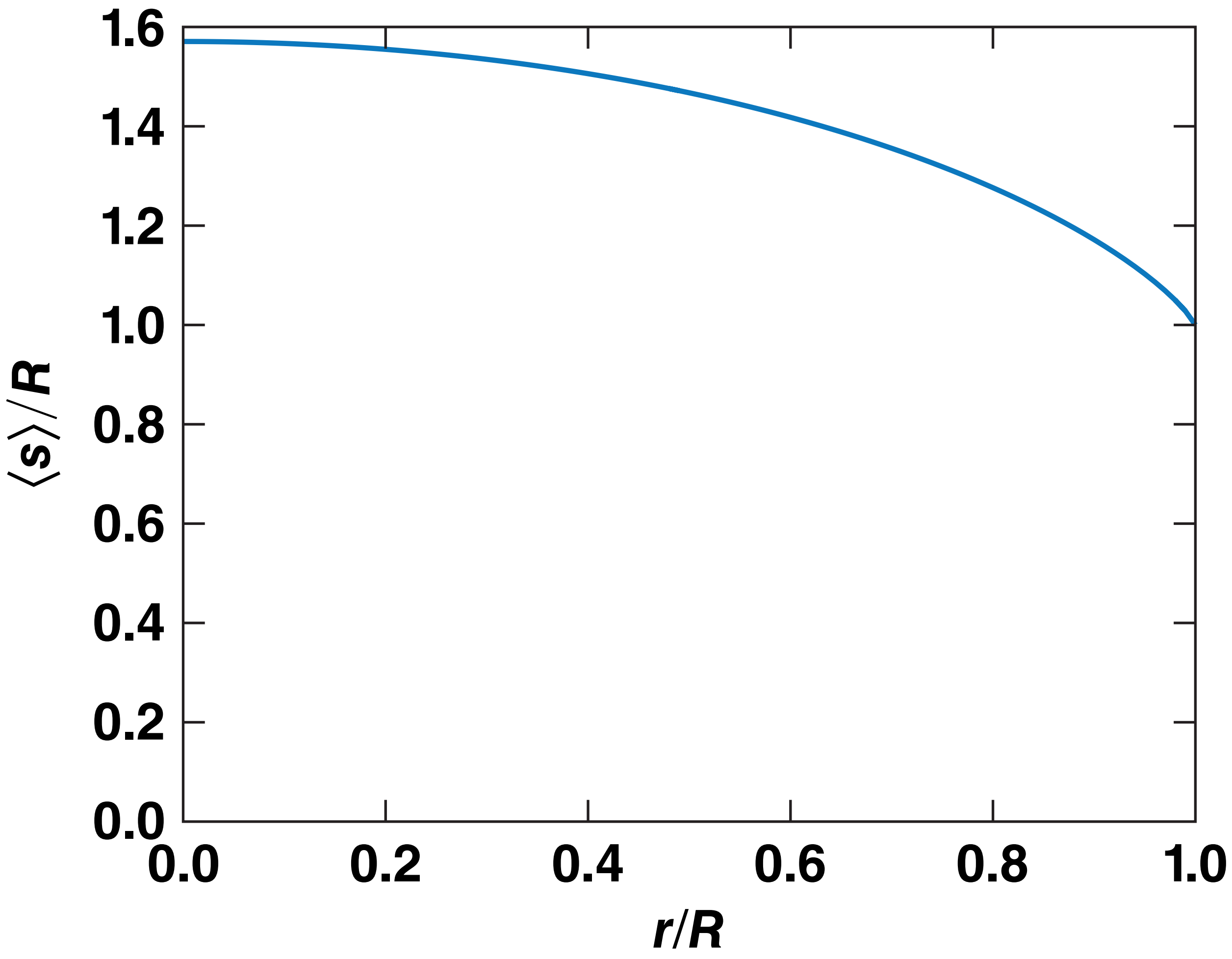
The mean path length of an isotropic source of particles moving in straight lines in an infinitely long cylinder is approximately equal to the radius R, allowing ρR to be inferred



- **General solution for source at r**
  $\langle s \rangle = R\ \mathrm{E}(r/R)$
- **Uniform radial distribution**
  $\langle s \rangle = 1.416\ R$
- **End losses negligible for length $L \gg R$**
  $L > 60\ R$ in compressed targets

Use $\langle s \rangle = (\pi/2)\ R$, which will underestimate ρR by < 10%.

Measurements show that preheat, magnetization, and increasing fuel density reduce fuel convergence in line with 1-D simulations

Type (number of shots)	ρR (mg/cm^2)	ρR 1-D (mg/cm^2)	$\rho R/\rho R_0$	$\rho R/\rho R_0$ 1-D	CR* 1-D
Compression only: 1.8 mg/cm^3 (2)	1.2±0.2	3.8	23±5	77	78
Compression + preheat: 1.8 mg/cm^3 (1)	0.82±0.23	2.2	16±5	46	46
Compression + field: 1.8 mg/cm^3 (2)	0.68±0.14	1.7	13±3	34	52
Integrated: 1.8 mg/cm^3 (1)	<0.68	1.6	<13	32	34
Compression only: 1.2 mg/cm^3 (2)	<3.0	2.2	<95	70	70
Compression + field: 1.2 mg/cm^3 (2)	1.2±0.3	1.2	38±9	37	59

- Upper limits are given where the DT yield was below the detection threshold
- Simple estimates and preliminary 2-D modeling indicate that 1-D will overestimate ρR by a factor of ~2 because of end loss, but give similar convergence ratios**
- $\rho R/\rho R_0$ is less than the convergence ratio for edge-peaked density profiles

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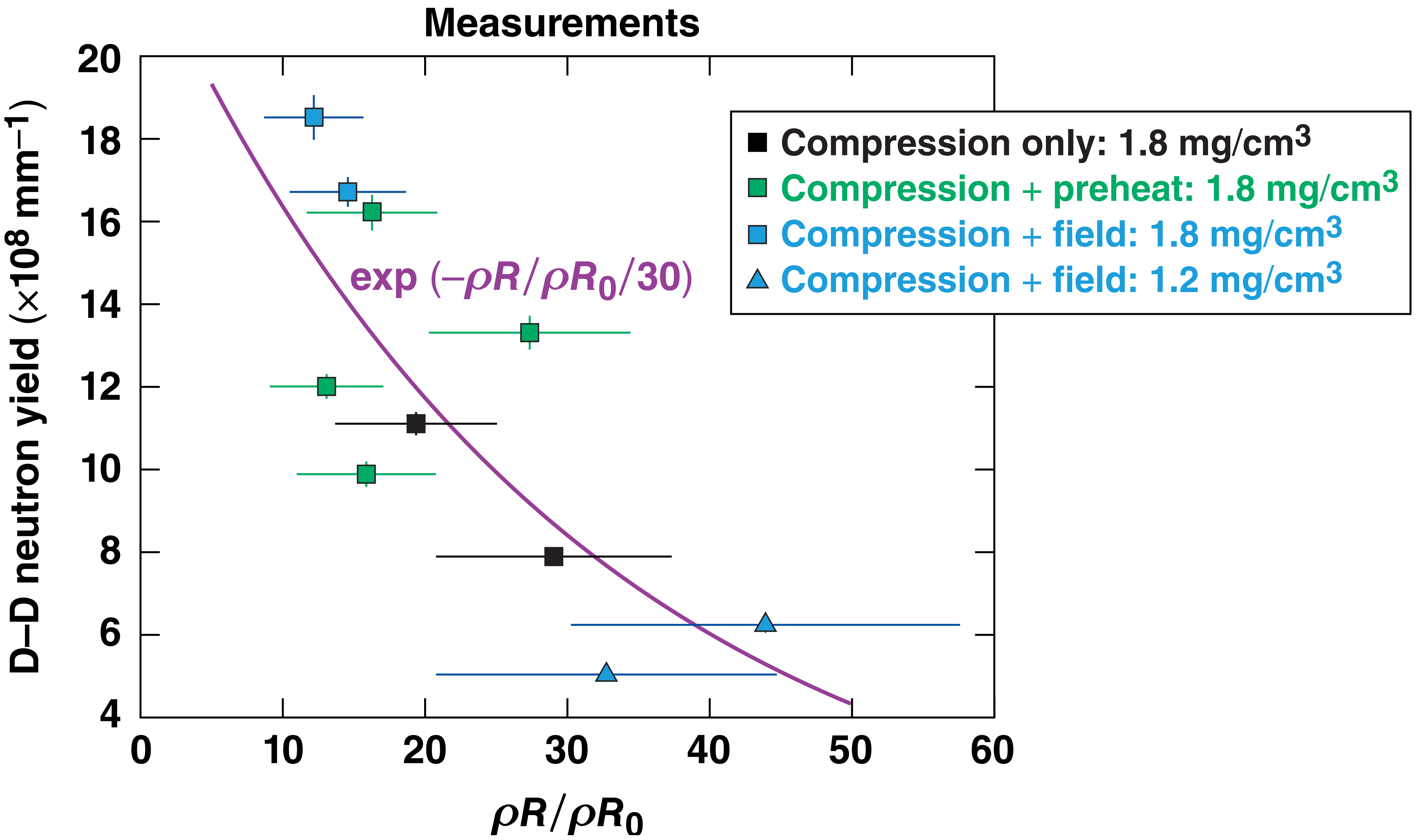
*CR: convergence ratio

**J. R. Davies *et al.*, Phys. Plasmas 24, 062701 (2017).

Measurements show that increasing convergence decreases neutron yield in disagreement with 1-D simulations



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Summary/Conclusions

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Summary of shots with D–T neutron yields above the detection threshold

Shot	OD (μm)	ρ (mg/cm^3)	B_z (T)	E_{pre} (J)	T_i (±0.5) (keV)	Y_{DD} ($\times10^8$)	Y_{DT}/Y_{DD} ($\times10^{-4}$)	ρR (mg/cm^2)	$\rho R/\rho R_0$
82955	581	1.93	0	0	2.77	7.89±0.16	2.94±0.60	1.52±0.43	29.1±8.3
84315	587	1.83	0	173	2.11	13.3±0.41	2.65±0.44	1.37±0.36	27.4±7.1
84318	584	1.85	0	174	2.38	16.2±0.43	1.59±0.31	0.82±0.23	16.3±4.6
85561	584	1.86	10	0	2.59	18.5±0.54	1.20±0.25	0.62±0.18	12.2±3.5
85562	585	1.88	10	0	2.75	16.7±0.36	1.44±0.29	0.75±0.21	14.6±4.1
85563	585	1.86	0	0	2.06	11.1±0.28	1.90±0.41	0.98±0.29	19.4±5.7
85564	583	1.21	10	0	2.44	5.04±0.16	2.08±0.64	1.07±0.39	32.8±12.0
85567	582	1.20	10	0	2.38	6.24±0.19	2.77±0.66	1.44±0.45	44.0±13.7
86429	579	1.83	0	161	1.95	9.88±0.31	1.52±0.36	0.79±0.24	15.9±4.9
86435	579	1.83	0	180	2.08	12.0±0.30	1.25±0.29	0.65±0.20	13.1±4.0