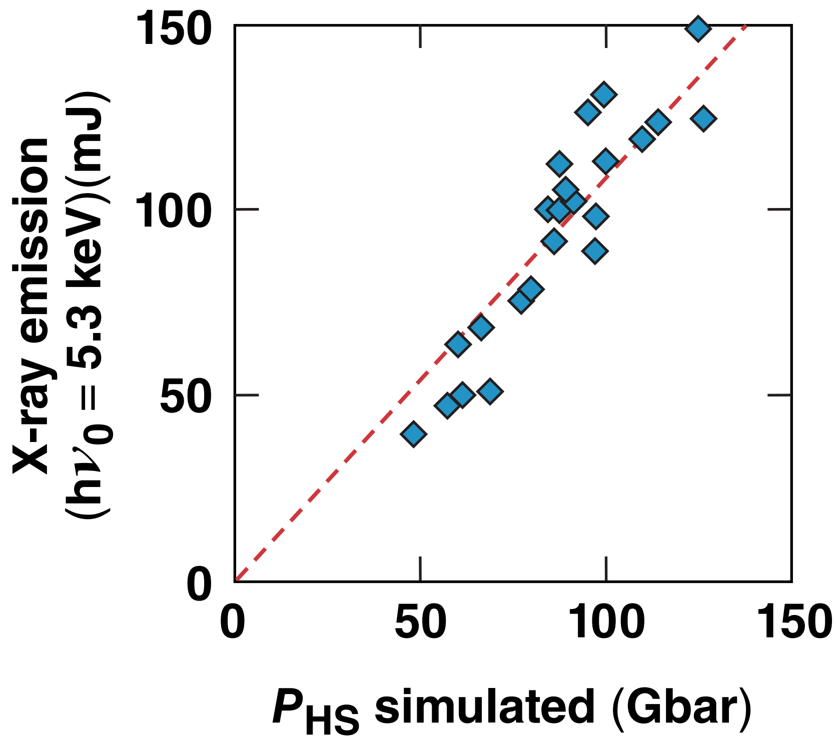
A Pressure Diagnostic Based on X-Ray Continuum Images of Compressed Isobaric Hydrogen Implosion Cores

Simulations of OMEGA cryo implosions



- Simulations represent the ranges $1.5 < \alpha_{shell} < 3.5$ and $1.3 \times 10^{13} < Y_n < 1.3 \times 10^{14}$

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Summary

The x-ray emission of imploded cryogenic hot spots provides a diagnostic of the hot-spot pressure

- The x-ray emissivity of an imploded hydrogen hot spot, measured with an appropriate spectral response, scales as the square of the pressure and is nearly independent of temperature
- The hot-spot pressure profiles are directly related to the hot-spot emissivity profiles obtained from time-resolved implosion images
- The hot-spot stagnation pressure can be inferred from the total photon yield, image size, and neutron yield/rate measurements

Collaborators

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Prism Computational Sciences

*V. N. Goncharov, GI3.00001, this conference (invited).
**R. Nora, GI3.00002, this conference (invited).

Measurements of x-ray emission from emissivity that is a function of pressure alone is potentially very important

- The hot-spot pressure, through the Lawson criterion,* is a key measure of near-ignition implosion performance
- Pressures inferred from x-ray emission depend weakly on prior assumptions, such as temperature profiles, normalization to simulations, etc.
- Photon yield measurements of electron thermal parameters complement existing neutron yield diagnostics of ion thermal parameters
- The required spectral responses have been implemented on an existing instrument

*J. D. Lawson, Proc. Phys. Soc. Lond. B 70, 6 (1957); R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

Hydrogen free-free (FF) emission is described accurately by simple pressure and temperature scaling

- The Kramers "free-free" emissivity expression

$$\varepsilon_{\nu}^{FF} = \frac{32}{3}\sqrt{\frac{\pi}{3}}\chi_H (\alpha a_0)^3 \langle Z^2 \rangle n_e n_i \left(\frac{\chi_H}{kT}\right)^{1/2} g_{FF} e^{-h\nu/kT}$$

- The Kulsrud* approximation for the Gaunt factor applies at high energy and high temperature

$$g_{FF} \approx \frac{2\sqrt{3}}{\pi}\beta\left(\frac{kT}{h\nu}\right)^{1/2}, \qquad \beta = 0.87, \qquad h\nu > kT, \qquad kT \gg \chi_H$$

- For ideal gas: $P = (n_e + n_i)kT$

$$\varepsilon_{\nu}^{FF} = \text{const} \times P^2 (h\nu)^{-1/2} \times \frac{e^{-h\nu/kT}}{T^2}$$

*R. M. Kulsrud, Astrophys. J. 119, 386 (1954).
**W. J. Karzas and R. Latter, Astrophys. J. Suppl. Ser. 6, 167 (1961).

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The emissivity is almost entirely a function of pressure when measured with an appropriate spectral response

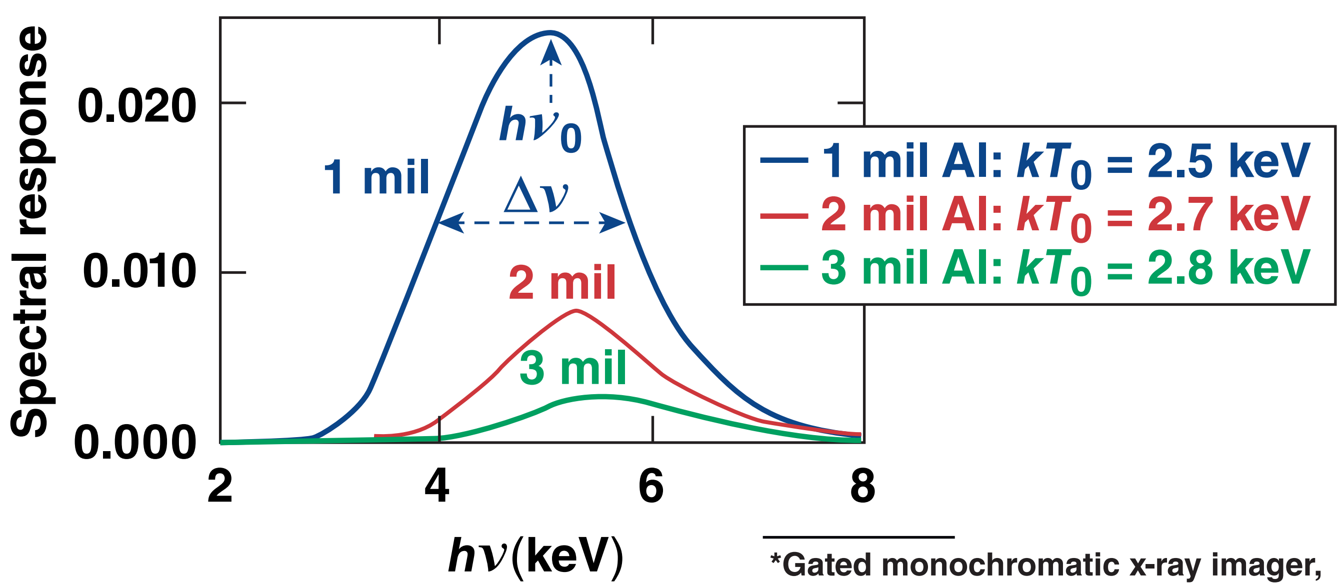
- Integrate the FF emissivity over a width $\Delta\nu$ at $\nu = \nu_0$

$$E_{\nu_0} = \int \varepsilon_\nu^{FF} F(\nu) d\nu = \text{const} \times P^2 \times (h\nu_0)^{-1/2} \Delta\nu \times \frac{e^{-h\nu_0/kT}}{T^2}$$

- The criterion for temperature independence is $\frac{d}{dT}\left(\frac{e^{-h\nu_0/kT}}{T^2}\right) = 0$

or $h\nu_0 = 2kT$

GMXI* filtered responses $F(\nu)$



*Gated monochromatic x-ray imager,
F. J. Marshall and J. A. Oertel, Rev. Sci. Instrum. 68, 735 (1997);
F. J. Marshall *et al*., Phys. Rev. E 49, 4381 (1994).

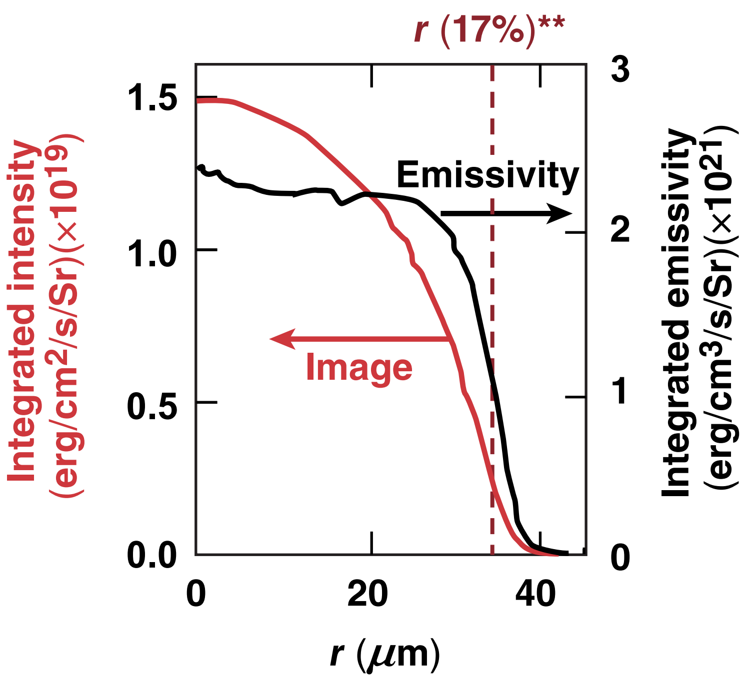
A simulated time-resolved image provides an emissivity profile that accurately measures the hot-spot pressure

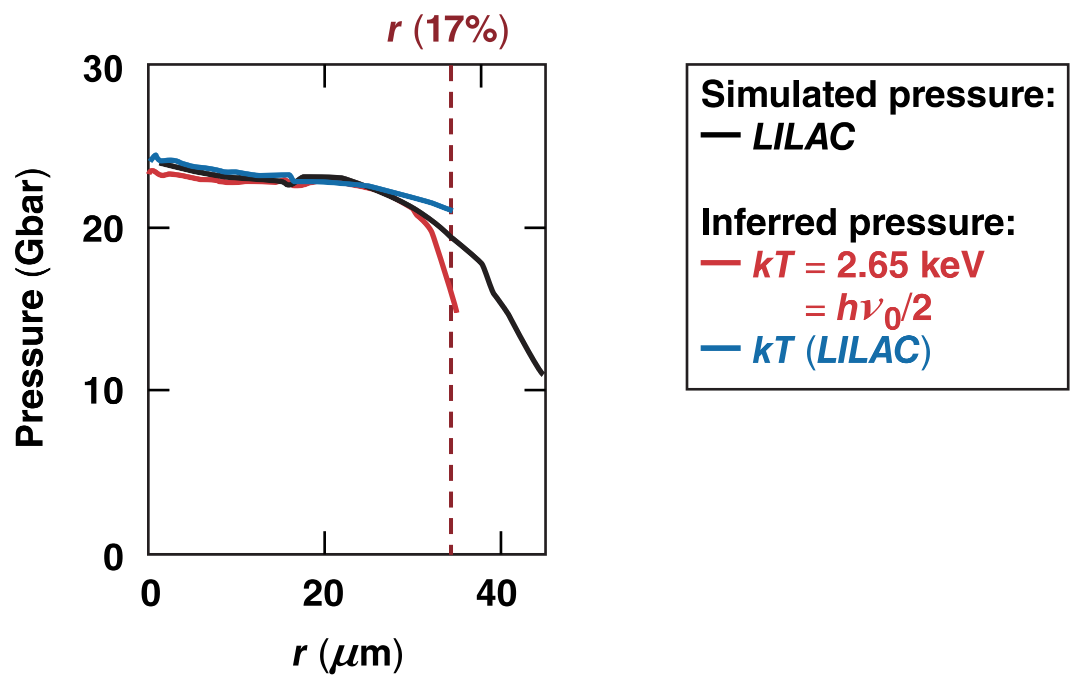
- Emissivity profile from an Abel-inverted *LILAC/Spect3D** image at 5.3 keV

- Pressure profiles obtained from the emissivity profile

$$E_{\nu_0} = \text{const} \times P^2$$

Shot 68791 at stagnation





*Prism Computational Sciences, Inc., Madison, WI 53711.
**G. A. Kyrala *et al*., Rev. Sci. Instrum. 81, 10E316 (2010); M. A. Barrios *et al*., Phys. Plasmas 20, 072706 (2013).

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A simulated time-resolved image provides an emissivity profile that accurately measures the hot-spot pressure

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- Pressure profiles obtained from the emissivity profile

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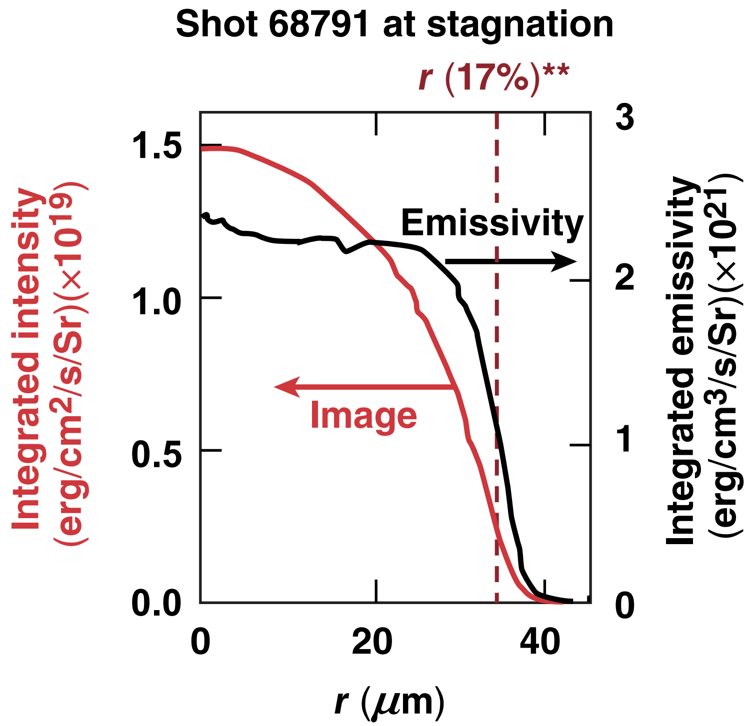

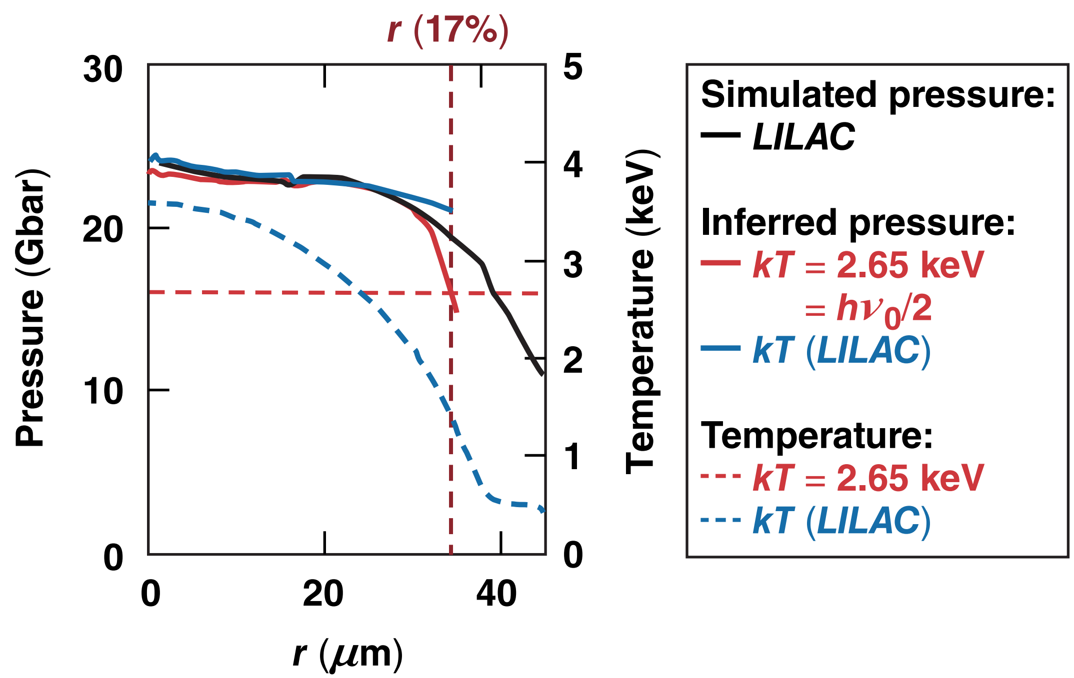

*Prism Computational Sciences, Inc., Madison, WI 53711.
**G. A. Kyrala *et al*., Rev. Sci. Instrum. 81, 10E316 (2010); M. A. Barrios *et al*., Phys. Plasmas 20, 072706 (2013).

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The time-integrated x-ray yield can be used to infer the hot-spot pressure

- Photon yield infers a hot-spot pressure P using

$$Y_{\nu_0} = \iint E_{\nu_0}(r)\,dVdt = \text{const} \times \langle P^2 \rangle_t \times Vt$$

- The inertial force of shell deceleration balanced by core pressure at the time of stagnation gives* $M_{SH} R/t^2 = 4\pi R^2 P$

- Postulate a hot-spot adiabat** $P \propto \alpha_{HS} V^{-5/3}$

- Obtain $Vt \propto (\alpha_{HS} M_{SH})^{1/2} P^{-1}$

- Obtain the scaling expression $Y_{\nu_0} \propto (\alpha_{HS} M_{SH})^{1/2} P$

*R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).
**R. Betti *et al*., Phys. Plasmas 9, 2277 (2002).

In a large sample of simulated cryo implosions, hot-spot pressure is correctly inferred from the simulated integrated x-ray emission

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Using: $P \propto Y_{\nu_0}$, $\nu_0 = 5.3$ keV

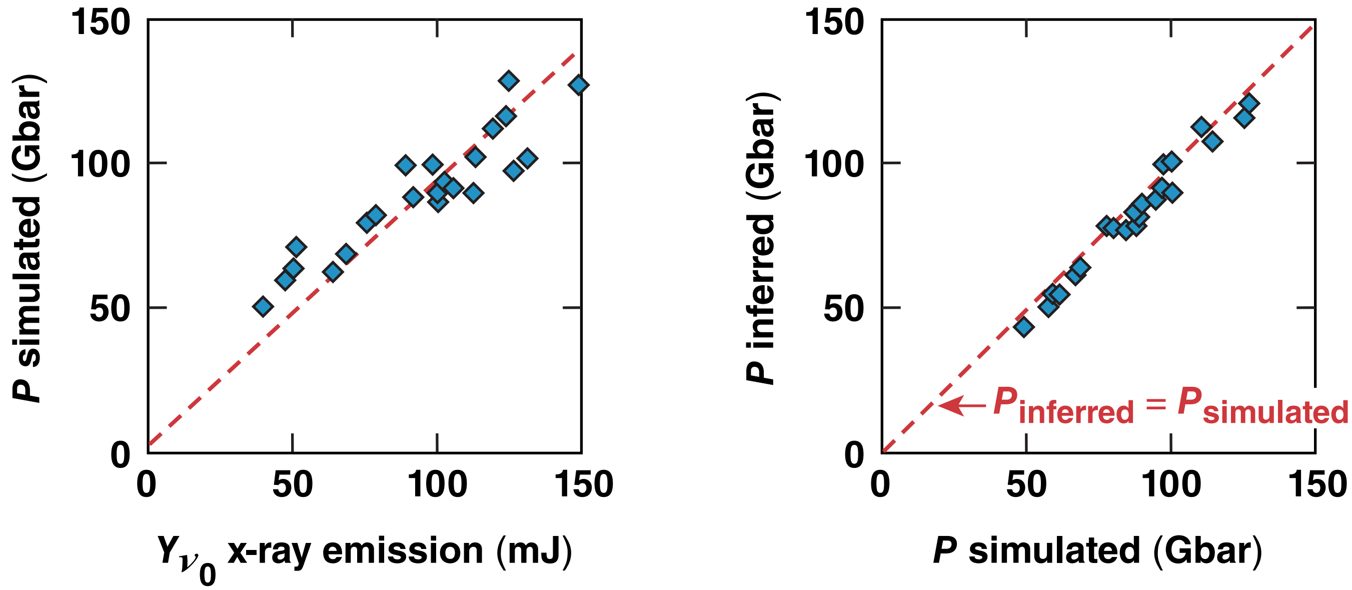
Y_{ν_0} from *LILAC*/*Spect3D*

P from *LILAC*

Using: $Y_{\nu_0} = \text{const} \times P^2 \times Vt$

V from 17% image contour radius

t from (neutron yield)/(neutron rate)



- Simulations represent the ranges $1.5 < \alpha_{\text{shell}} < 3.5$, $1.3 \times 10^{13} < Y_n < 1.3 \times 10^{14}$
- Excess x-ray emission would indicate ablator mix into the hot spot*

*T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013);
T. C. Sangster *et al.*, Phys. Plasmas 20, 056317 (2013).

TC11048

Summary/Conclusions

The x-ray emission of imploded cryogenic hot spots provides a diagnostic of the hot-spot pressure

- The x-ray emissivity of an imploded hydrogen hot spot, measured with an appropriate spectral response, scales as the square of the pressure and is nearly independent of temperature
- The hot-spot pressure profiles are directly related to the hot-spot emissivity profiles obtained from time-resolved implosion images
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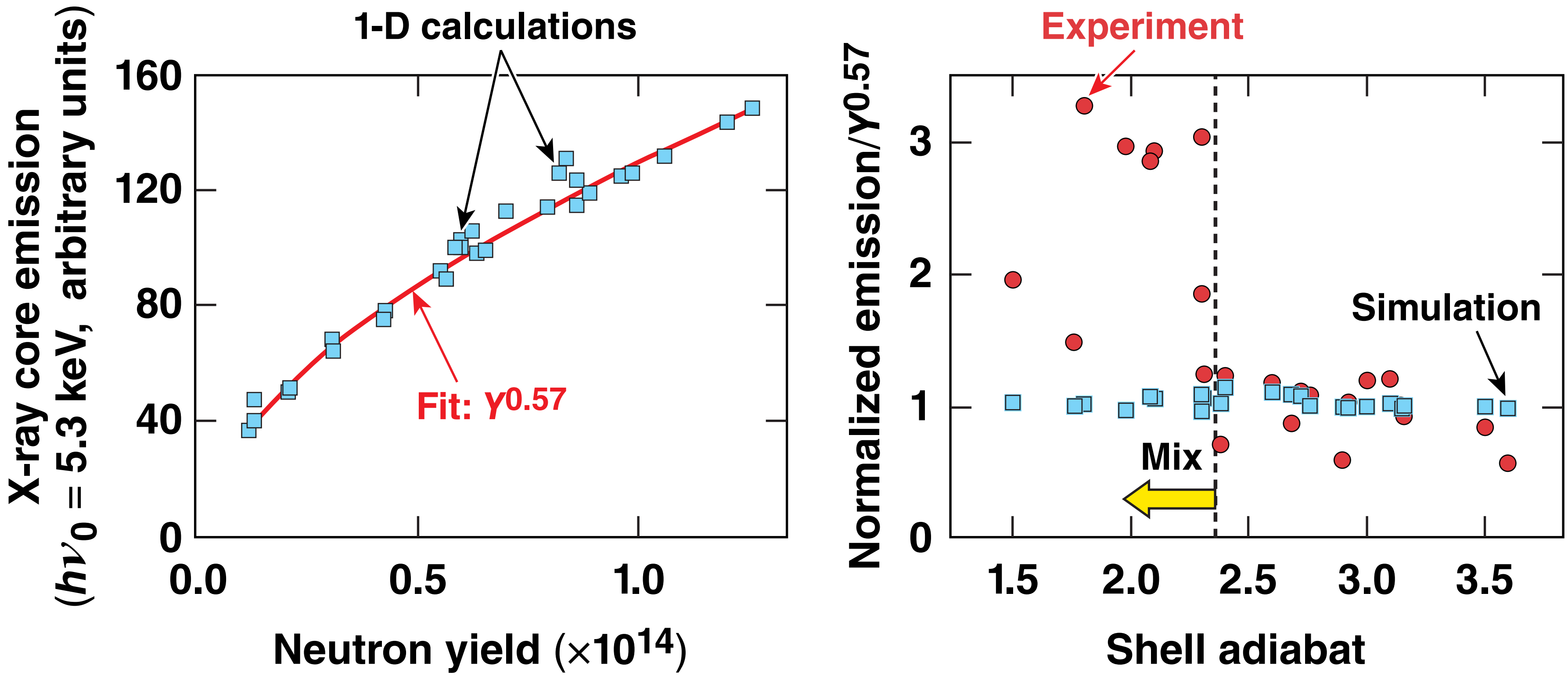
Core x-ray emission exhibits simple scaling with neutron yield in cryogenic implosion simulations*



- Excess x-ray emission for low adiabats suggests ablator mix into the hot spot
- Measured yields are consistent with $Y_\nu \propto Y_n^{0.57}$ scaling for higher adiabats

*T. C. Sangster *et al.*, Phys. Plasmas 20, 056317 (2013).

TC10254b

The neutron yield scaling of photon yield is obtained for the isentropic compression of isobaric hot spots

- Neutron yield from the Bosch–Hale* reaction rate:

$$Y_n = \iint n_D n_T \langle \sigma v \rangle dVdt \propto P^2 T^{2+\varepsilon} Vt \qquad \langle \sigma v \rangle \propto T^{4+\varepsilon}$$

- Photon yield

$$Y_{\nu_0} = \iint E_{\nu_0}^{FF}(r) dVdT \propto P^2 T^{\eta} Vt \qquad e^{-h\nu_0/kT} / T^2 \propto T^{\eta}$$

- The inertial force of shell deceleration is balanced by core pressure at the time of stagnation gives**

$$Vt \propto \alpha_{HS}{}^{1/2} M_{SH} P^{-1}$$

- Postulate a hot-spot adiabat $P \propto \alpha_{HS} V^{5/3}$

- Obtain scaling $Y_{\nu_0} \propto (Y_n)^q$, where $q = \dfrac{5+2\eta}{9+2\varepsilon} \approx 0.56$

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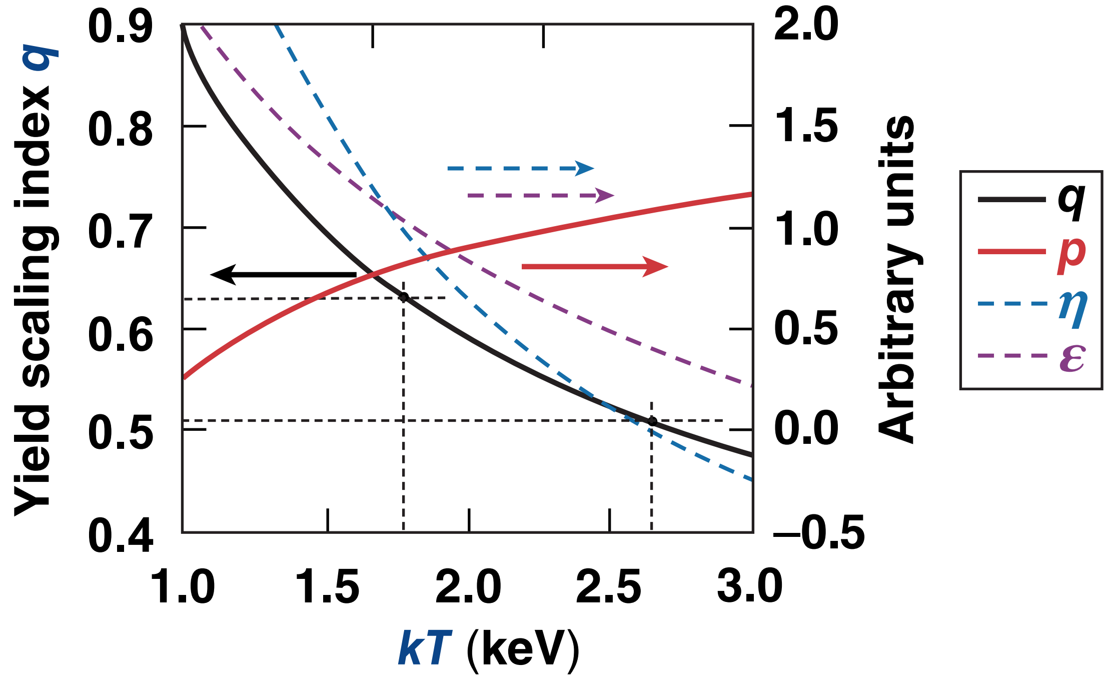
*H.-S. Bosch and G. M. Hale, Nucl. Fusion 32, 611 (1992).
**R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

The yield scaling index obtained from scaling arguments agrees with 1-D *LILAC* results over a broad temperature range

$$Y_{\nu_0} \propto \left[\frac{(M_{SH})^{2/9} (M_{HS})^{10/9}}{(\alpha_{HS})^{4/9}} \right]^p (Y_n)^q$$

$$q = \frac{5 + 2\eta}{9 + 2\varepsilon} \approx 0.56$$

$$p = \frac{1 + (\varepsilon - \eta)/2}{1 + 2\varepsilon/9} \approx 1.0$$



- The scaling $q = 0.57 \pm 0.06$ is obtained for $kT = 2.21 \pm 0.43$ keV and is to be compared with $q = 0.57$ from *LILAC* results

Hot-spot photon and neutron yields scale with parameters specific to the particular implosions

- Neutron and photon yields

$$Y_n \propto PT^{2+\varepsilon}(\alpha_{HS})^{1/2}(M_{SH})^{1/2}$$

$$Y_{\nu_0} \propto PT^{\eta}(\alpha_{HS})^{1/2}(M_{SH})^{1/2}$$

- Postulate a hot-spot adiabat $P \propto \alpha_{HS} V^{-5/3}$

- Obtain scaling $Y_{\nu_0} \propto \left[\frac{(M_{SH})^{2/9}(M_{HS})^{10/9}}{(\alpha_{HS})^{4/9}}\right]^p (Y_n)^q$, where

$$p = \frac{1+(\varepsilon-\eta)/2}{1+2\varepsilon/9} \approx 1.0$$

$$q = \frac{5+2\eta}{9+2\varepsilon} \cong 0.56$$

Shell mass, hot-spot mass, and adiabat variations obscure the hot-spot neutron and photon yield scaling.

Excess hot-spot x-ray emission above the expected clean DT level gives the mix fraction of shell C in the hot spot[1]

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- Free-free (FF) plus bound-free (BF) x-ray "yield"

$$Y_\nu \propto n_\mathrm{i} n_\mathrm{e} \left[\langle Z^2 \rangle_I \left(\frac{\chi_\mathrm{H}}{kT} \right)^{1/2} + 2 \langle Z^4 e^{\chi/kT} \rangle_I \left(\frac{\chi_\mathrm{H}}{kT} \right)^{3/2} \right] \langle e^{-h\nu/kT} \rangle_\mathrm{det} Vt$$

- The composition is DT, $n_\mathrm{D} = n_\mathrm{T}$ with a trace $x = n_Z/(n_\mathrm{D} + n_\mathrm{T})$ of a contaminant, e.g., C ($Z = 6$)

Using $n_\mathrm{e} = (n_\mathrm{D} + n_\mathrm{T})(1 + xZ)$ $\quad n_\mathrm{i} \langle Z^n \rangle = (n_\mathrm{D} + n_\mathrm{T})(1 + xZ^n)$
and the neutron yield:

$$Y_\mathrm{n} \approx n_\mathrm{D} n_\mathrm{T} \langle \sigma \nu \rangle Vt$$

Obtain

$$Y_\nu / Y_\mathrm{n} \approx f(T)(1 + xZ)(1 + x\, j_z / j_\mathrm{DT})$$

The shell-mix fraction x is obtained[1] from Y_ν / Y_n ratio measurements and emissivity j_Z, j_DT values from OPAL[2] and DCA[3] tables.

[1] T. Ma *et al*., Phys. Rev. Lett. 111, 085004 (2013).
[2] F. J. Rogers, F. J. Swenson, and C. A. Iglesias, Astrophys. J. 456, 902 (1996).
[3] H. A. Scott and S. B. Hansen, High Energy Density Phys. 6, 39 (2010).