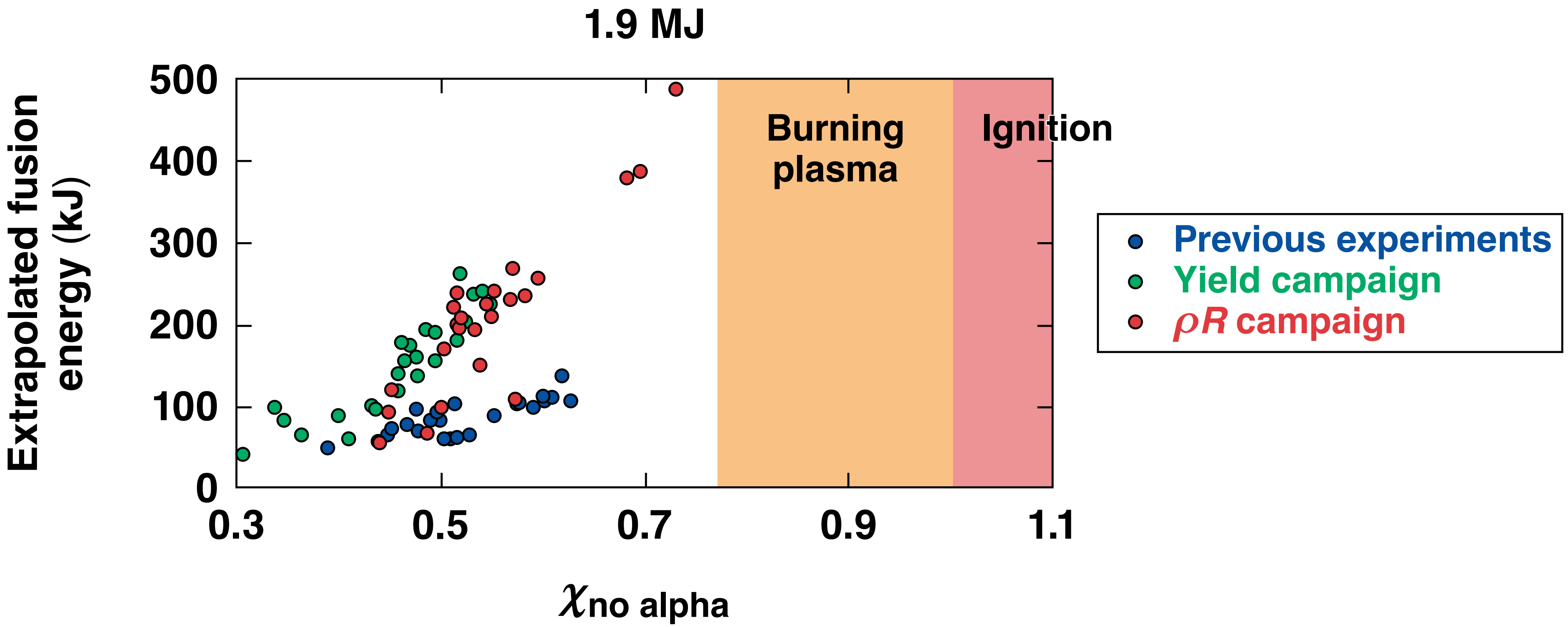
Optimization of Direct-Drive Inertial Fusion Implosions Through Predictive Statistical Modeling



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Summary

Recent results from the yield and optimization campaigns show predictable improvements in performance leading to about 500 kJ of extrapolated yield

- The OMEGA implosion performance can be predicted pre-shot using statistical mapping
- This new predictive capability led to improvements in yields and areal density (1.6×10^{14} with 160 mg/cm^2 of average areal density)
- The extrapolated no-alpha ignition parameter $\chi_{\text{no alpha}} = 0.74$ leads to a yield amplification of 3.0× and extrapolated yield of ~500 kJ at 1.9 MJ of symmetric illumination
- Further improvements are expected from the optimization campaign and from the upcoming facility upgrades (new phase plates, advanced ablators, fill-tube capability, and possible CBET* mitigation**)

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*CBET: cross-beam energy transfer

**R. Follett, NI2.00005, this conference.

Collaborators

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Plasma Science and Fusion Center
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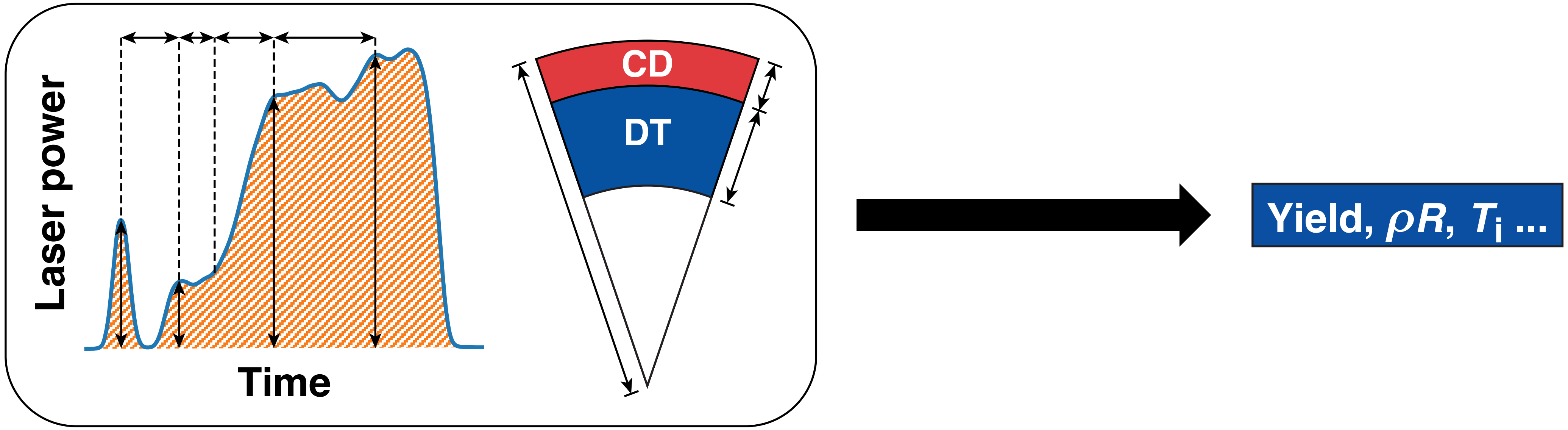
Optimization of an ICF* target requires a search through an $n > 10$ dimensional space



- Predictive tools are needed to efficiently search through this space
- Relative to the experimental frequency, these tools need to be
  1) accurate when evaluated
  2) quick to evaluate
  3) easily updated with experimental feedback

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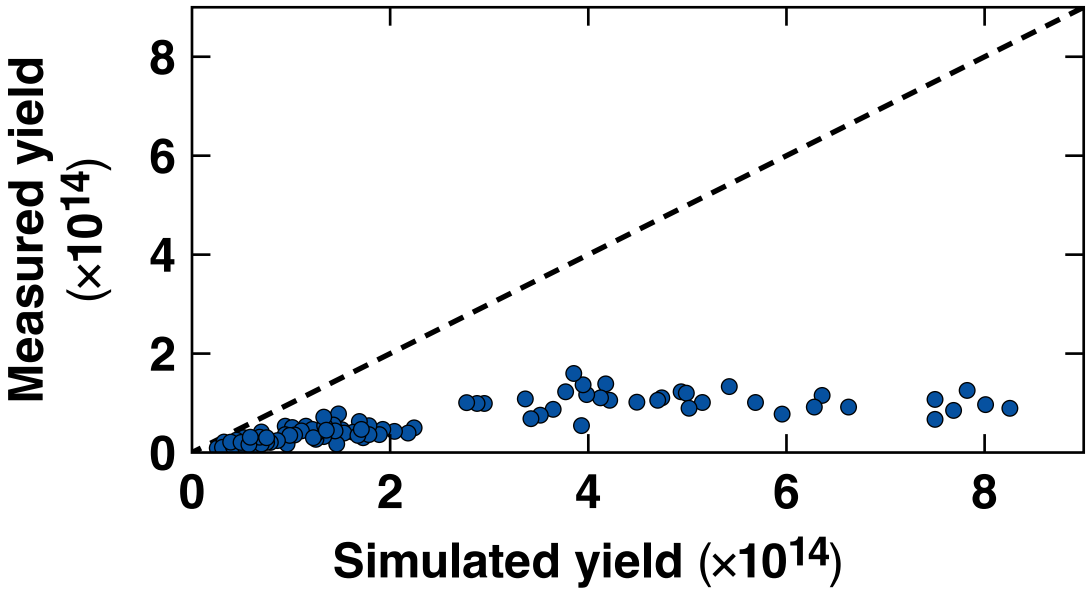
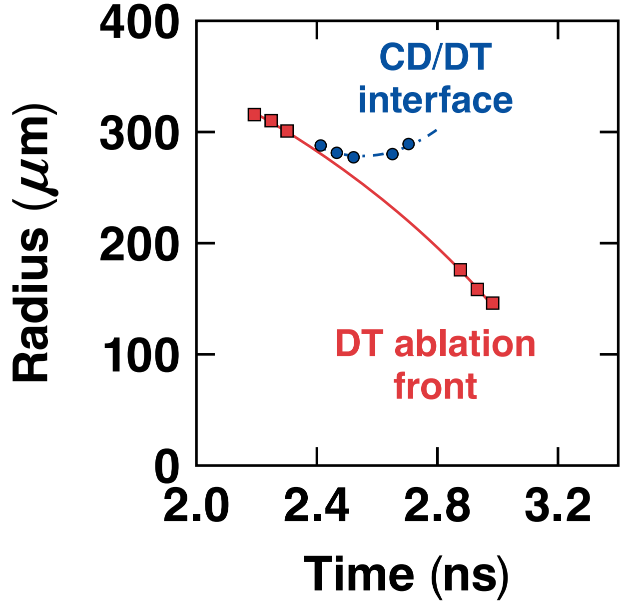
*ICF: inertial confinement fusion

Simulations have traditionally been the primary predictive tool in ICF, but are not accurate enough to efficiently guide experimental design

- 1-D simulations are computationally inexpensive, and are often used for target design
- These simulations overestimate the yield and areal density, but correctly model the energy coupling and implosion velocity
- 2-D and 3-D simulations are slow, unsuitable for parameter scans, and generally not predictive



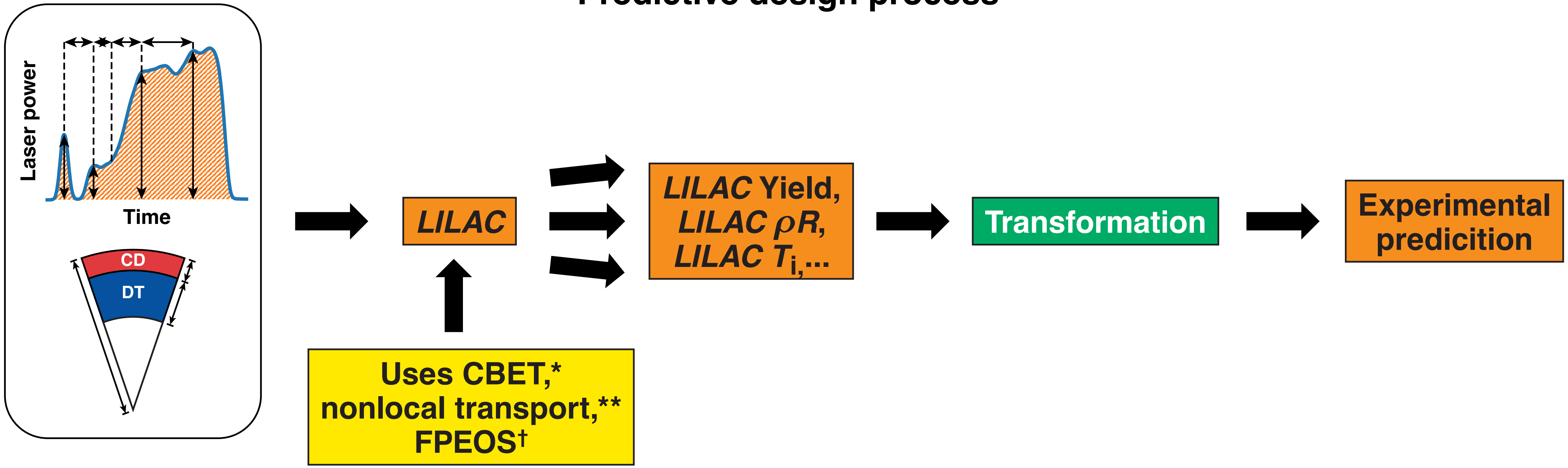


D. T. Michel *et al.*, Phys. Rev. Lett. 114, 155002 (2015).

TC14567

Using the experimental and 1-D simulation database of OMEGA implosions, we construct a function that transforms the code outputs into experimental predictions

Predictive design process



LILAC

Uses CBET,* nonlocal transport,** FPEOS†

LILAC Yield, *LILAC* ρR, *LILAC* T_i,...

Transformation

Experimental predicition

V. Gopalaswamy *et al.*, “Tripling the Yield in Direct-Drive Laser Fusion via Statistical Modeling,” submitted to Nature.

[*] I. V. Igumenshchev *et al.*, Phys. Plasmas 17, 122708 (2010).

[**] V. N. Goncharov *et al.*, Phys. Plasmas 13, 012702 (2006).

[†] FPEOS: first-principle equation of state; S. X. Hu *et al.*, Phys. Rev. E 92, 043104 (2015).

The transformation is derived from statistical mapping relations between experimental observables and 1-D simulation outputs

Pulse shape + target specs

Systematic and random nonuniformity seeds

Experimental observables → $O^{\text{exp}} = F_{\text{exp}}\left[I_{\text{1-D}}, S^{\text{sys}}_{\text{3-D}}, S^{\text{ran}}_{\text{3-D}}\right]$

Simulated observables → $O^{\text{sim}}_{\text{1-D}} = F_{\text{sim}}\left[I_{\text{1-D}}, 0, 0\right]$ ➡ $I_{\text{1-D}} = F^{-1}_{\text{sim}}\left[O^{\text{sim}}_{\text{1-D}}\right]$

Constant if systematic

Neglect if experiments are repeatable

$$O^{\text{exp}} = \underbrace{F_{\text{exp}}\big[F^{-1}_{\text{sim}}}\big(O^{\text{sim}}_{\text{1-D}}\big), S^{\text{sys}}_{\text{3-D}}, S^{\text{ran}}_{\text{3-D}}\big]$$

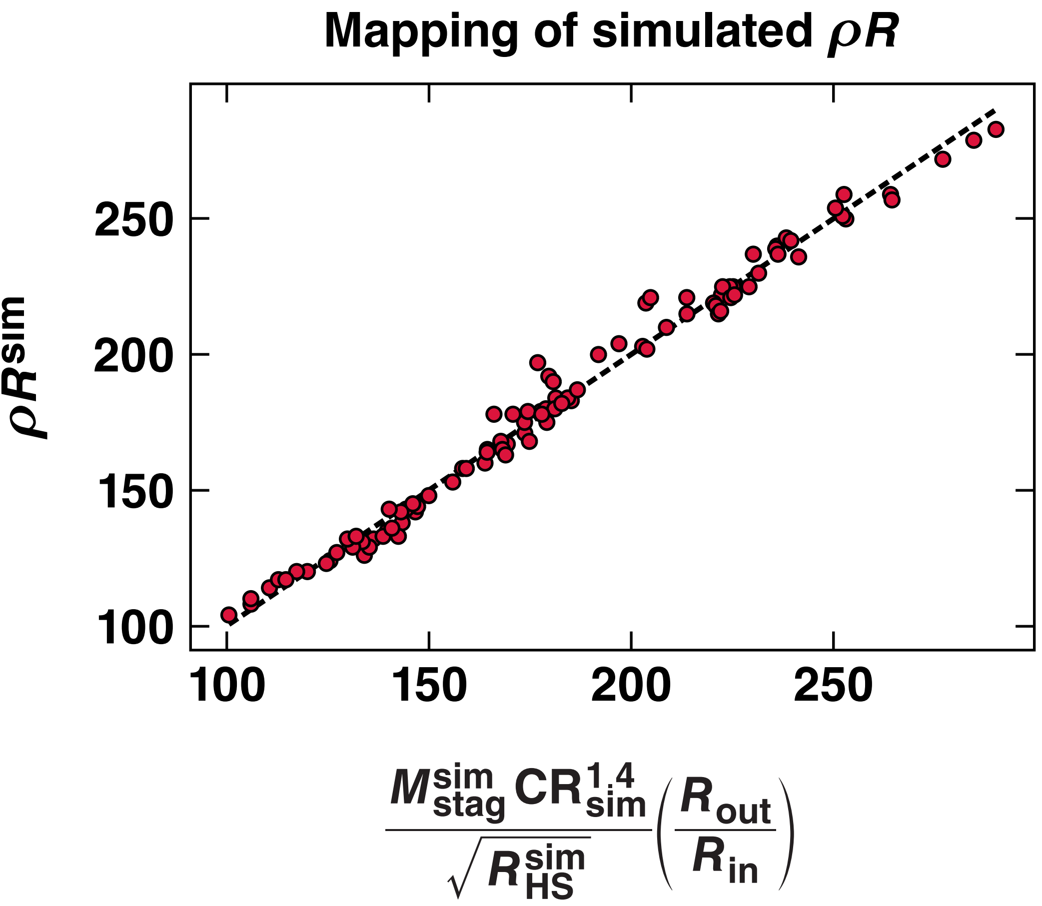
$$\boxed{O^{\text{exp}} \approx F_{\text{map}}\left[O^{\text{sim}}_{\text{1-D}}\right]}$$ ⬅ **Predict experiment from 1-D simulation**

Existence of mapping relation requires repeatable experiments → only systematic nonuniformities.

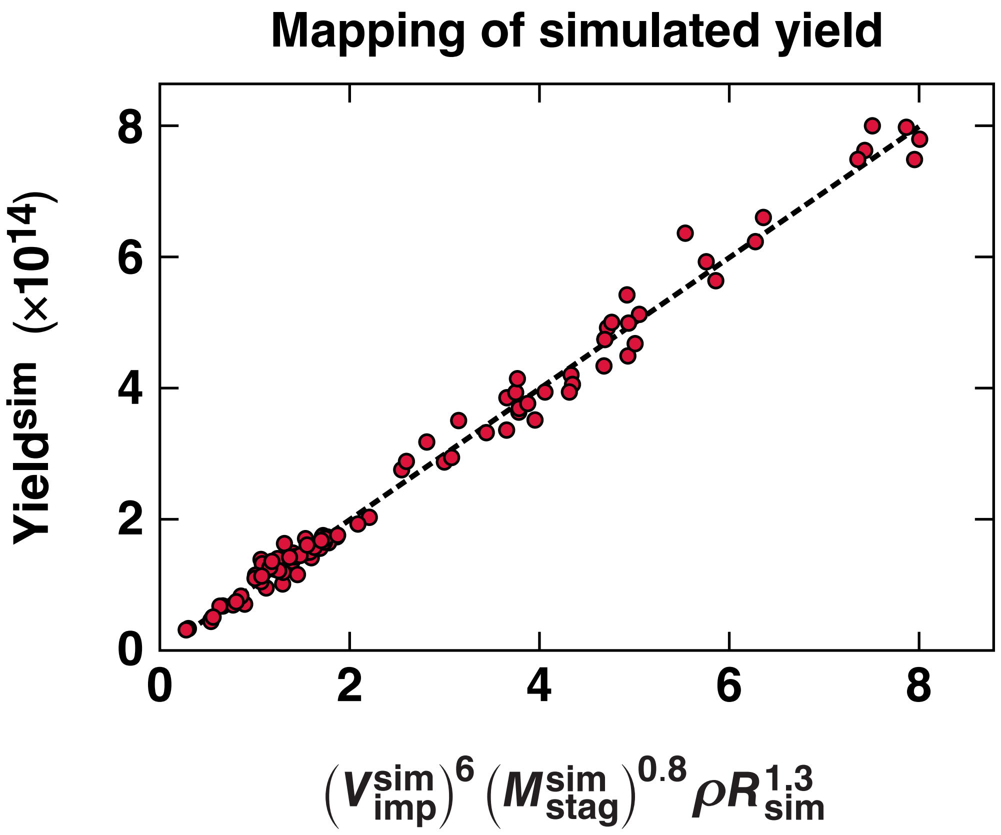
Test on Basis Functions

Power laws are used as basis functions to expand the mapping relation

$$O_{\text{exp}} \approx F_{\text{map}}\left(O_{\text{1-D}}^{\text{sim}}\right) \sim \prod_{i=1}^{N}\left(O_{\text{1-D, i}}^{\text{sim}}\right)^{\mu_i}$$



Test on *LILAC* simulations with CBET, nonlocal transport, FPEOS



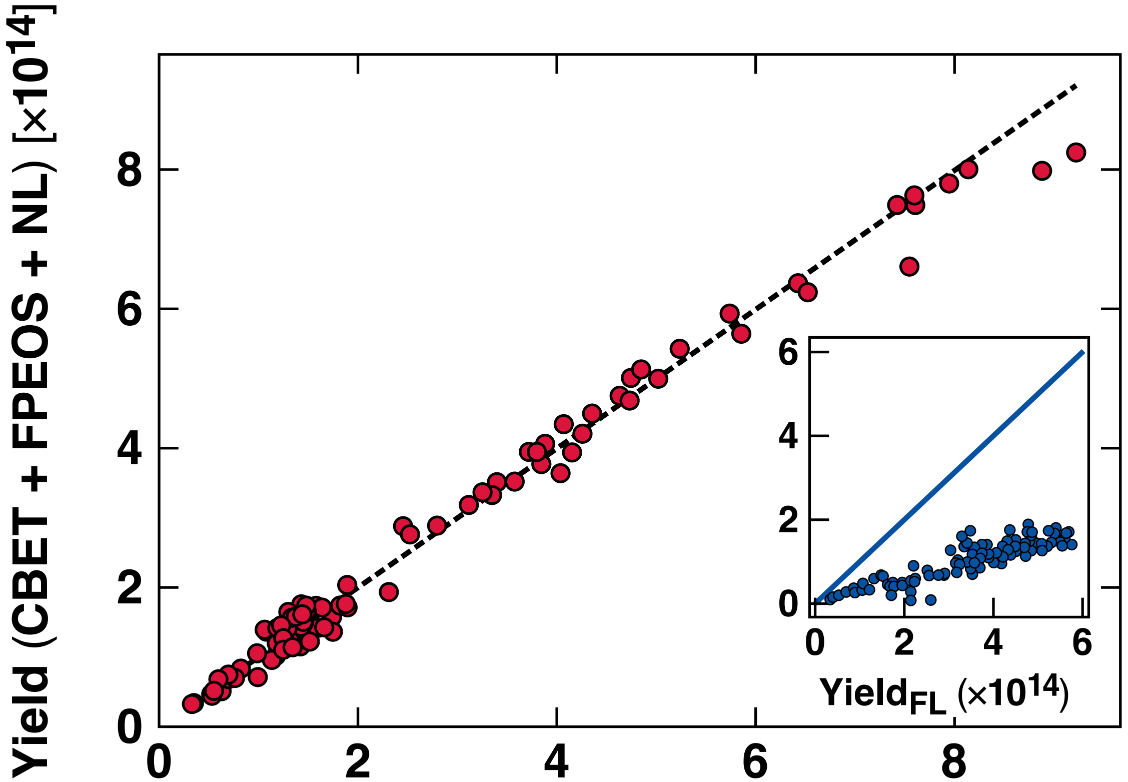
Many choices of variables are suitable for accurate mapping.

TC14570

Test on Missing Physics

Deficiencies in the code physics models can be partially remedied through statistical relations

Test: recover *LILAC* with nonlocal + CBET + FPEOS from *LILAC* flux limiter without CBET



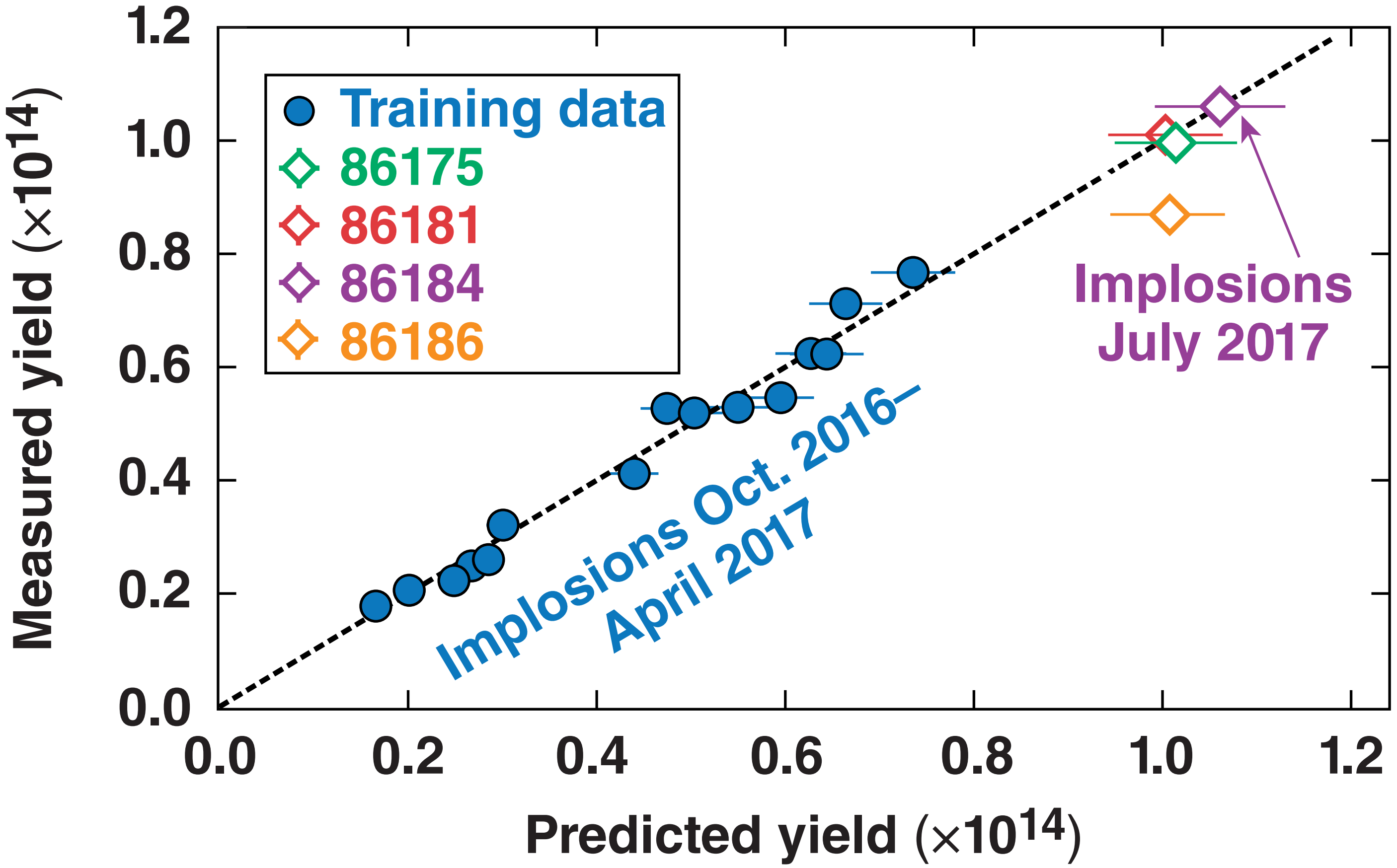
$$\sim \frac{M_{FL}\langle P_{FL}\rangle^{2.5} R_0^{6.5}\langle T_{FL}\rangle^{2.4}}{\rho R_{FL}^3 V_{FL}^4}$$

NL: nonlocal thermal transport
FL: flux-limited simulations

TC14571

Application to OMEGA implosions to increase the fusion yield

The mapping relation correctly predicted a higher yield when the target size was increased



$$\text{Yield}_{\text{pred}} = 4.2 \times 10^{13} \left(\frac{V_{\text{imp}}^{\text{sim}}}{400}\right)^{4.2} \left(\frac{M_{\text{stag}}^{\text{sim}}}{0.01}\right)^{0.6}$$

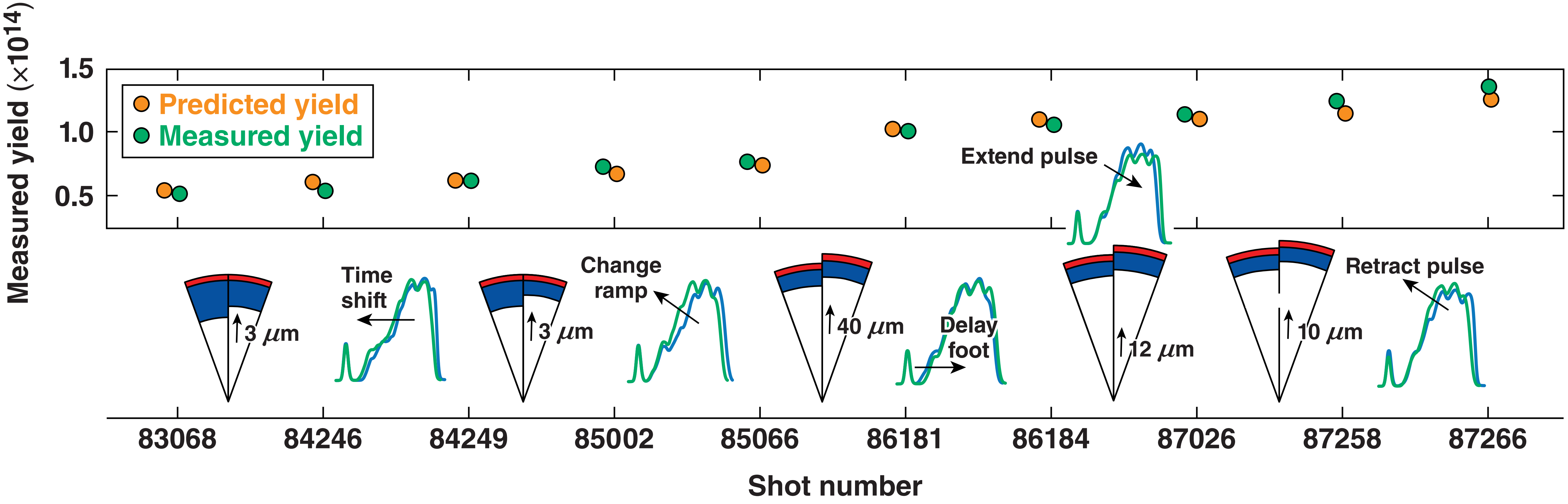
TC14353a

Larger targets, thinner ice, and changes to the pulse shapes led to higher yields as predicted by the mapping relations

- The mapping relation evolves as more shots are added

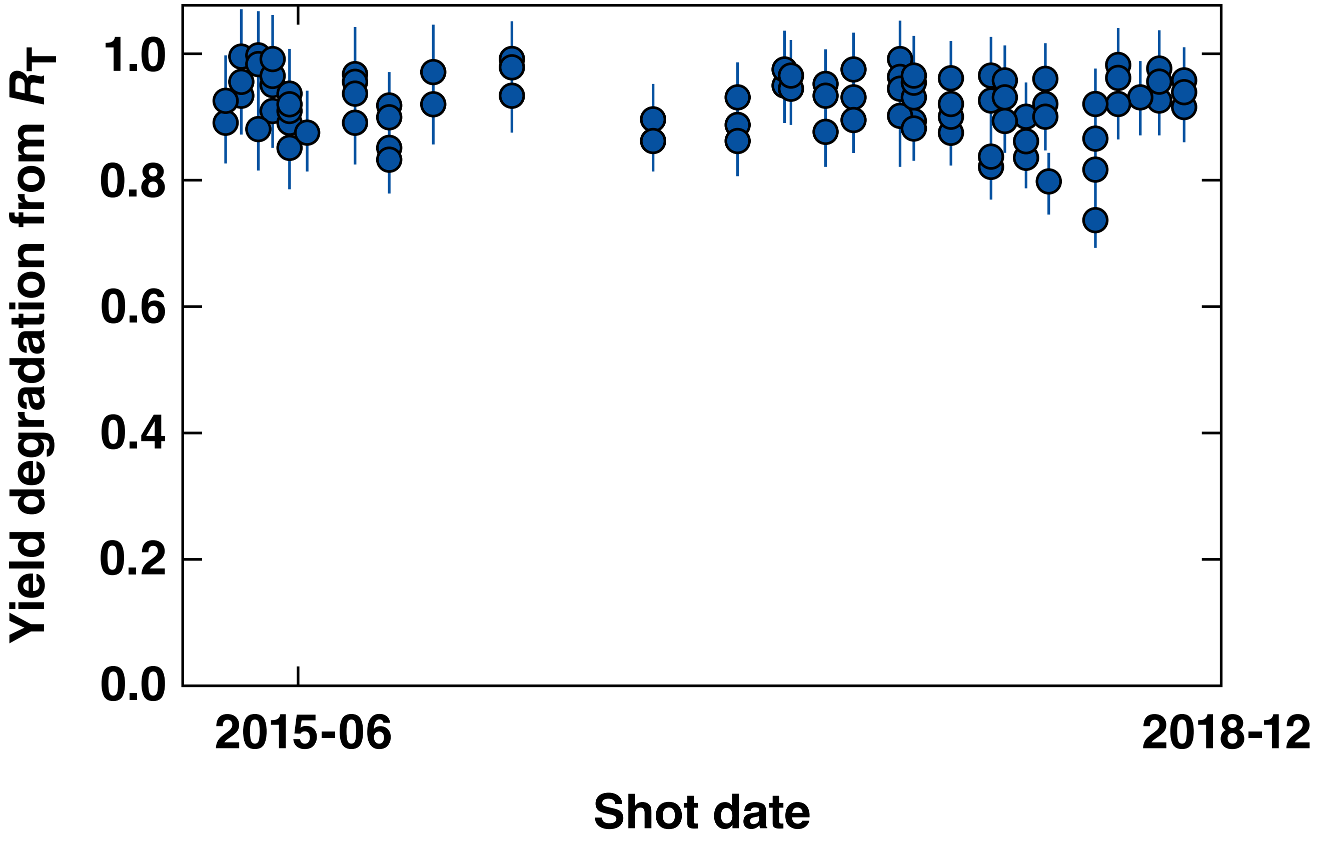
$$\text{Yield}_{\text{pred}} = 4.2 \times 10^{13} \left(\frac{V_{\text{imp}}^{\text{sim}}}{400}\right)^{4.2} \left(\frac{M_{\text{stag}}^{\text{sim}}}{0.01}\right)^{0.6}$$

$$\text{Yield}_{\text{pred}} = \frac{4.4 \times 10^{13}}{R_T^{0.6}} \left(\frac{V_{\text{sim}}}{400}\right)^{4} \left(\frac{M_{\text{sim}}}{0.01}\right)^{0.6} \left(\frac{\rho R_{\text{sim}}}{110}\right)^{0.3} \left(\frac{415}{R_0}\right)^{0.6}$$



TC14354b

"Random" effects lead to ~10% yield variation and are accounted for post-shot through the measured ion temperature asymmetries



- Random variations in yield are caused by target offsets, power imbalance, and surface roughness
- nTOF* detectors measure the ion temperature along six lines of sight
- The ion temperature asymmetry metric, $R_T = \frac{T_{max}}{T_{min}}$ acts as a proxy for this effect
- The yield is degraded by $\approx R_T^{-0.6}$

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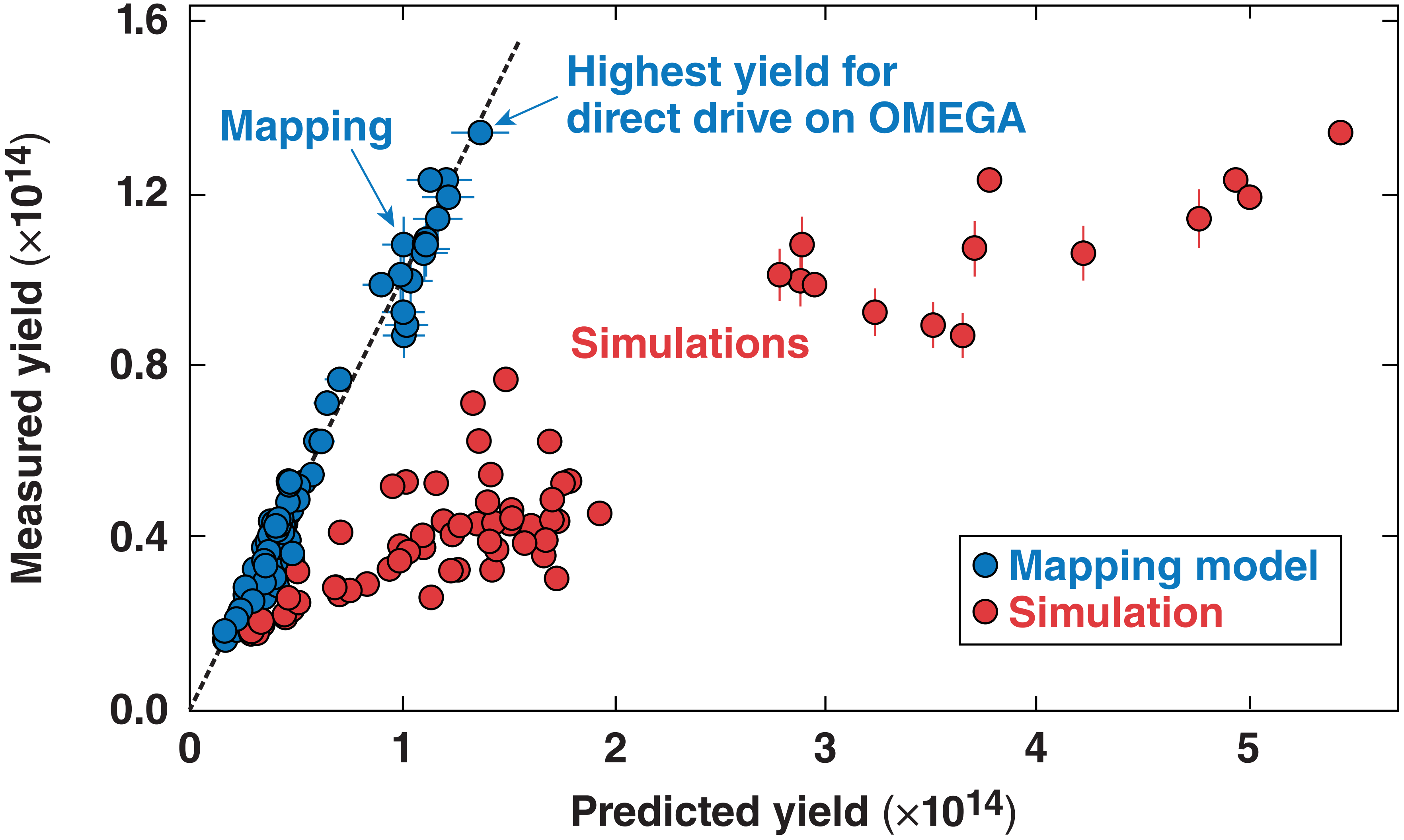
*nTOF: neutron time-of-flight

TC14572

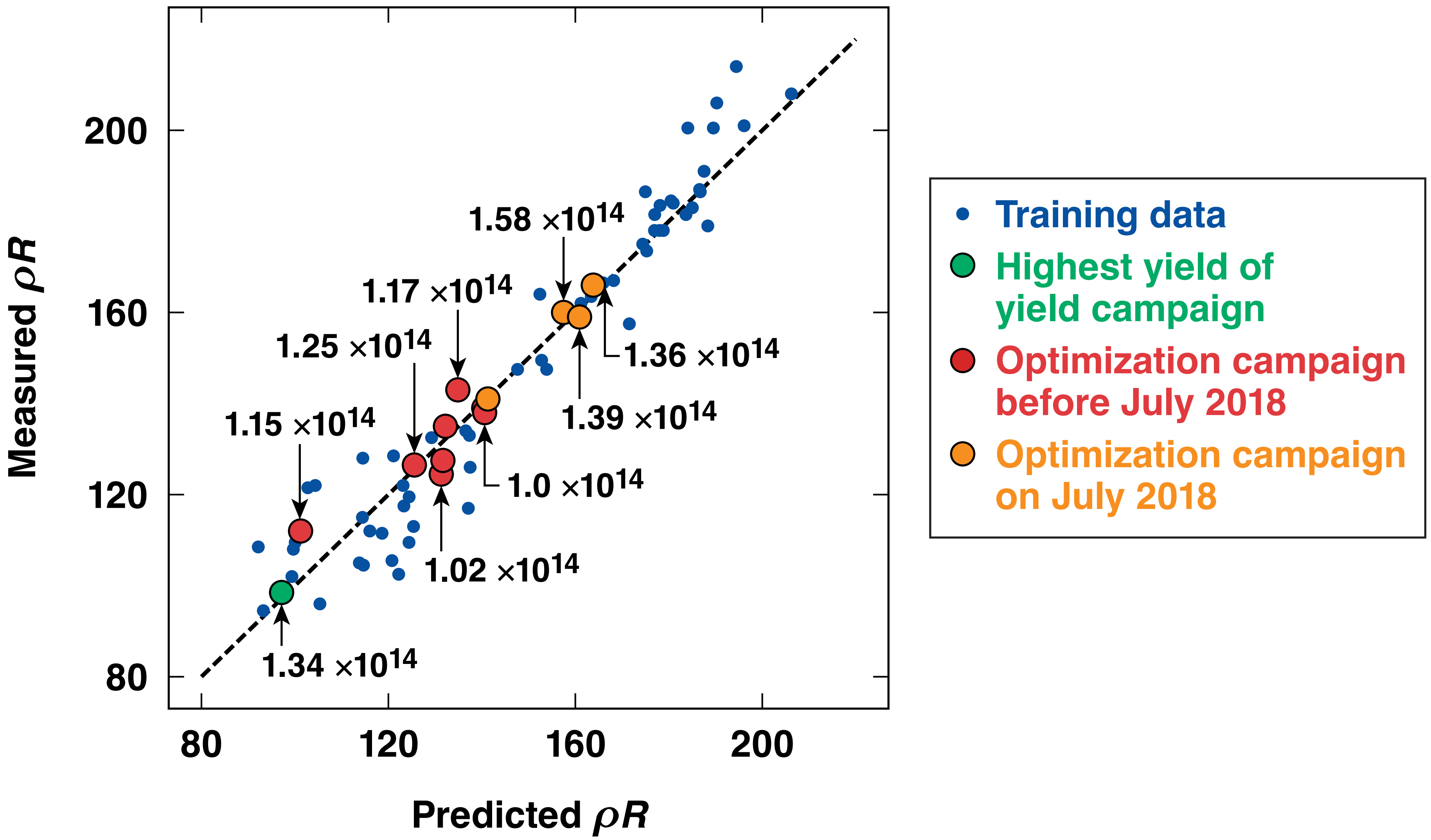
Tripling of the fusion yield was achieved in seven shot days using statistical mapping predictions



TC14355b

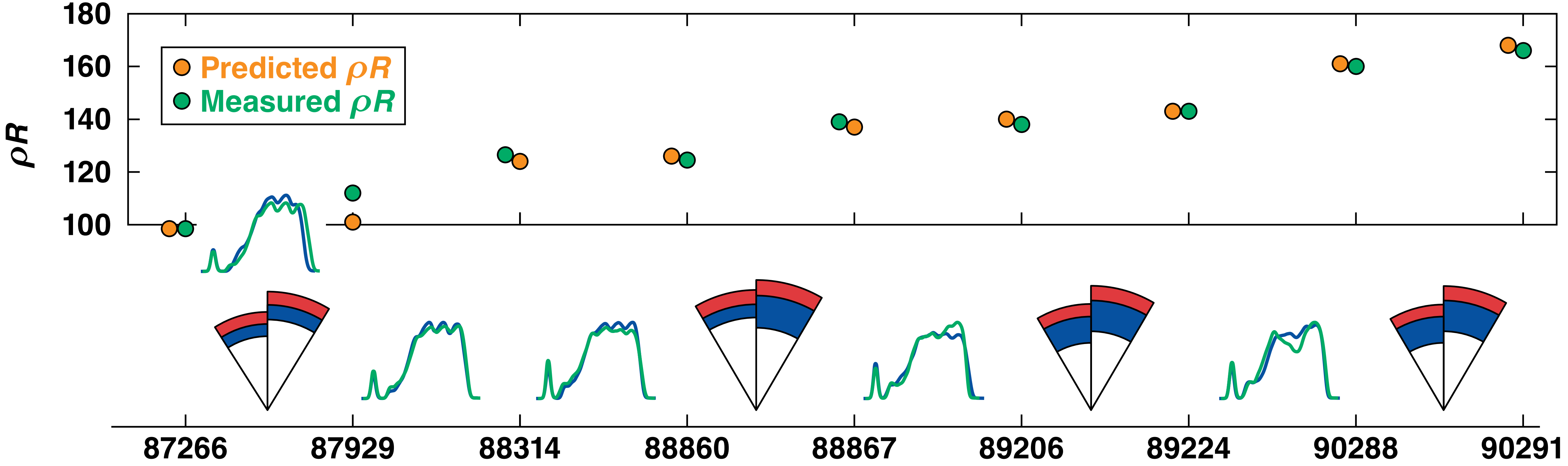
Application to OMEGA implosions to increase the areal density at high yields

The areal density was increased by ~65%, keeping the yield above 10^{14} using the model predictions



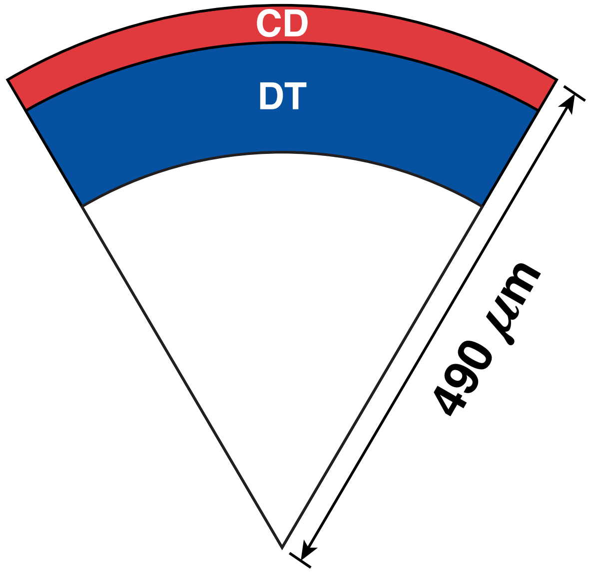
TC14573

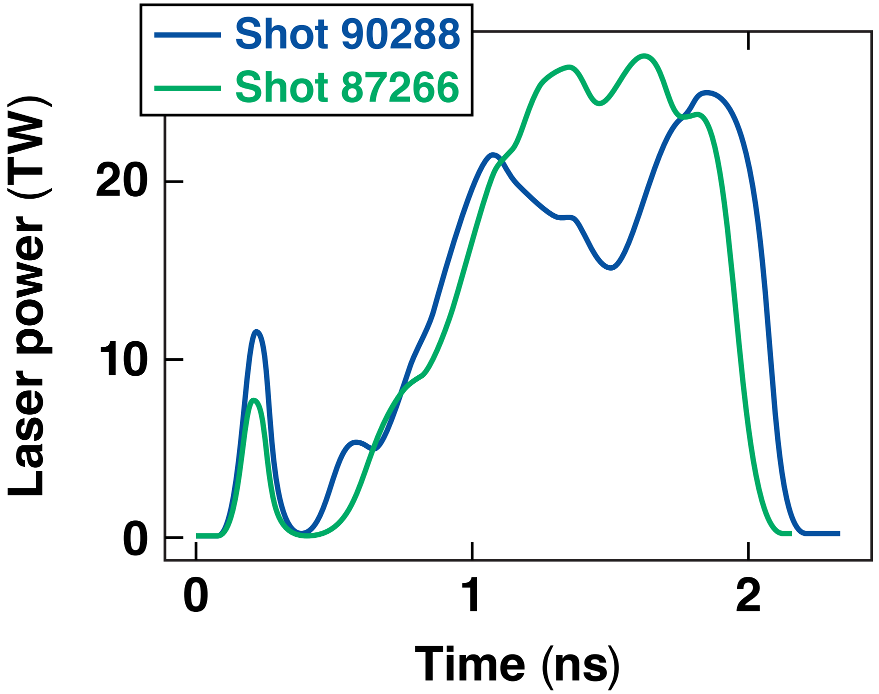
The increase in areal density was obtained through adjustments to the pulse shape and target specifications



TC14574

The best performing implosions used a new pulse shape and exhibited both high yields and areal density





	87266	90288
Yield	1.4×10^{14}	1.56×10^{14}
ρR (mg/cm^2)	100	160
Radius (GMXI-c, μm)	33	28

GMXI: gated monochromatic x-ray imager
D. Patel *et al.*, GO6.00006, this conference.

Performance degradation mechanisms for OMEGA implosions

The in-flight-aspect-ratio (IFAR) appears as a key figure of merit in the statistical predictions of both yield and ρR

- Mixing front from imprint travels distance $h \sim \beta g t^2 \sim \beta R_0$, and fraction of shell comprised

$$= \frac{h}{\Delta} \sim \frac{\beta R_0}{\Delta} = \beta \mathrm{IFAR}$$

- $\beta \sim 0.03$ to 0.07

Statistical models

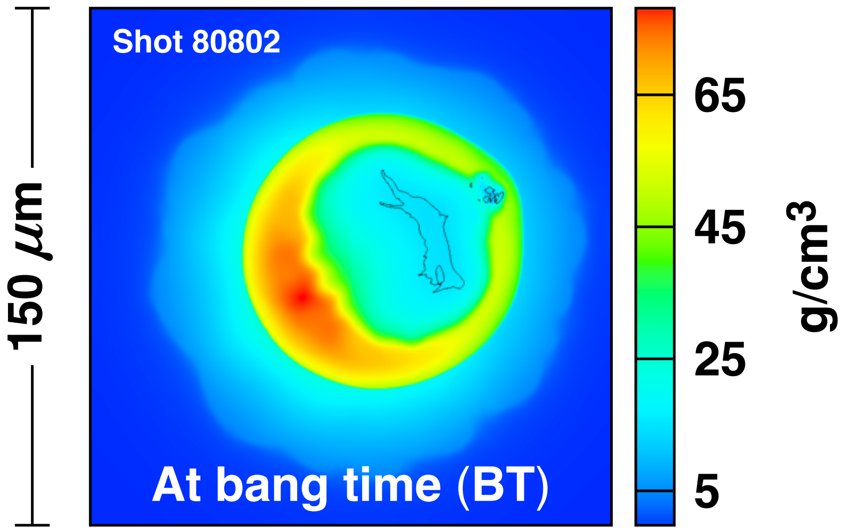
$$Y_{\mathrm{exp}} \sim \frac{1}{\mathrm{IFAR}^{1.2}}$$

$$\rho R_{\mathrm{exp}} \sim \frac{1}{\mathrm{IFAR}^{0.5}}$$

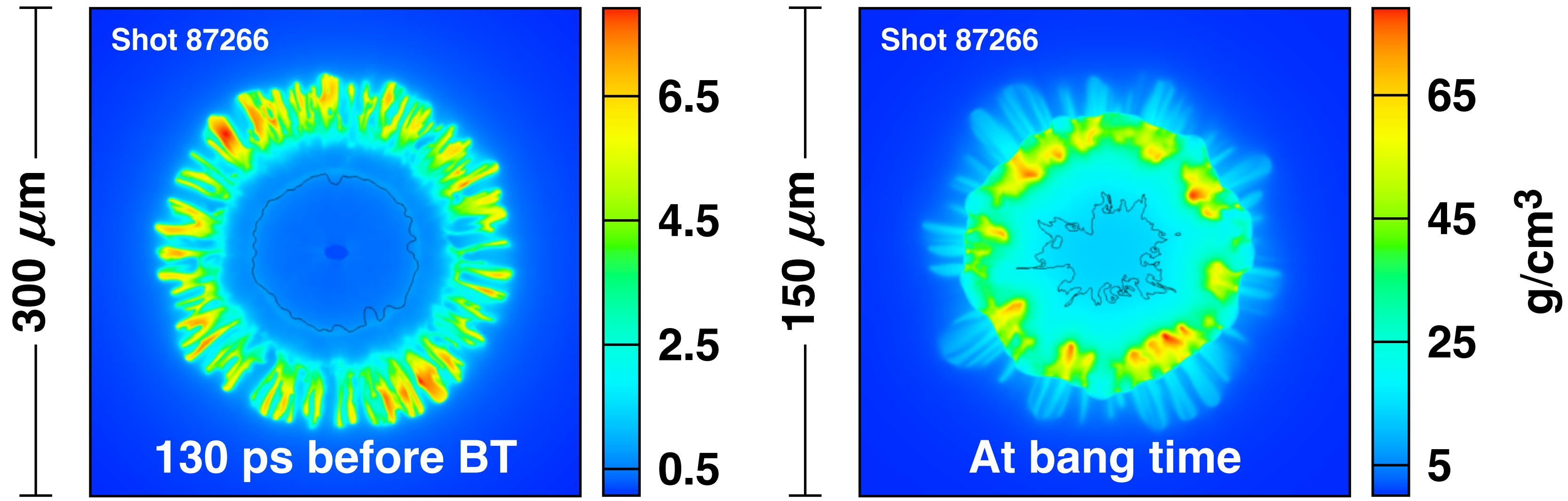
TC14576

Three-dimensional *ASTER** simulations indicate that high modes from laser imprinting ($\ell > 100$) are limiting the performance at high IFAR's

Lowest IFAR = 17



Highest IFAR = 44



TC14577

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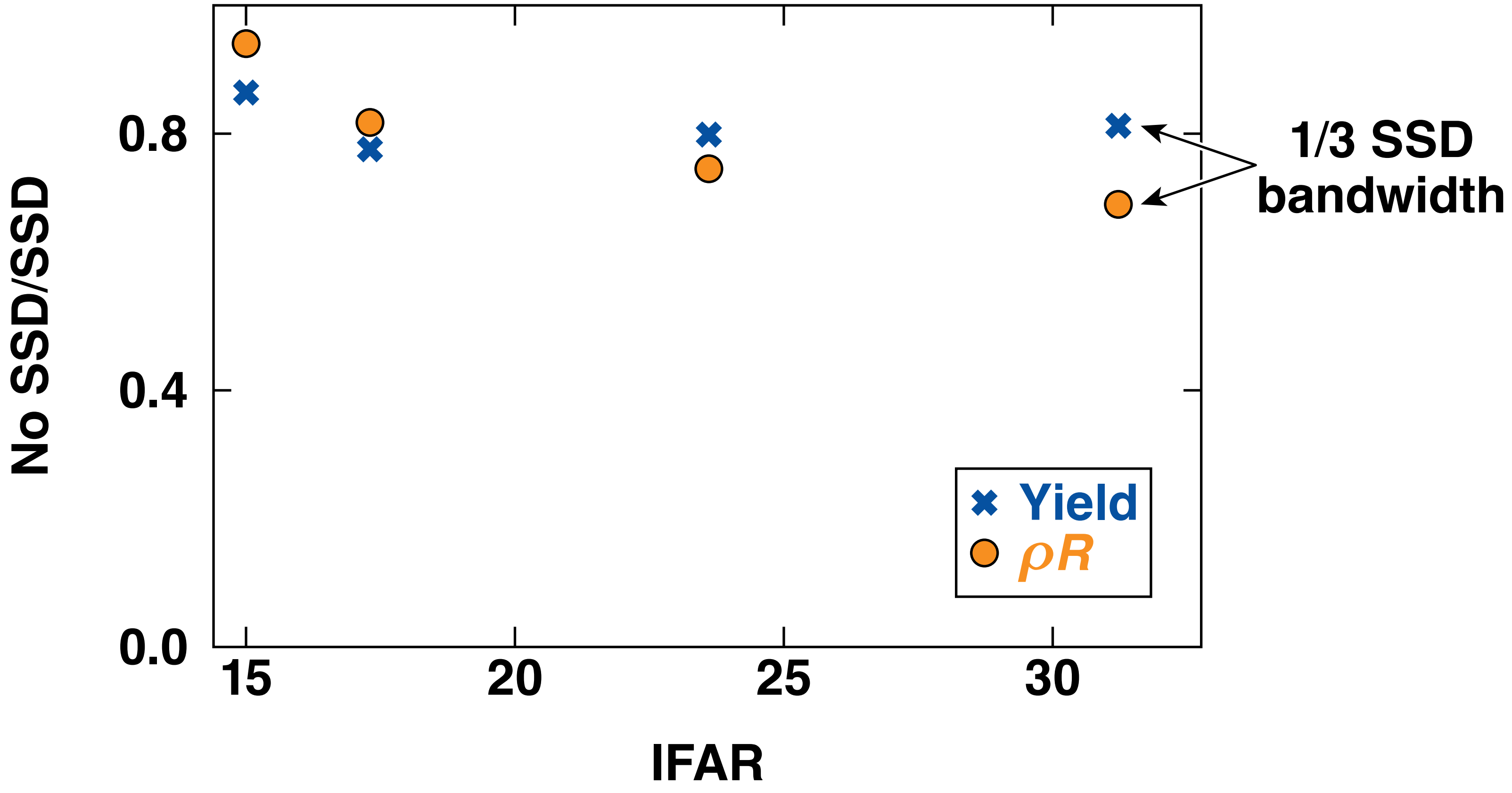
*I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).

SSD* on/off experiments show that laser imprinting causes 30% degradation of areal density at higher IFAR's



High-performance implosions are degraded by imprint.

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*SSD: smoothing by spectral dispersion

The role of high modes will be clarified through mitigation techniques that are under development

- New ablator designs, such as the recently tested polystyrene ablators, show lower levels of surface imperfections than the CD ablators currently in use[*]
- Foam-coated ablators have the potential to reduce the effects of laser imprint[**]
- Future experiments will investigate whether increasing the SSD bandwidth can further mitigate laser imprint
- Fill-tube–based target fills can create a more-uniform ice layer and reduce the amount of tritium damage to the targets[†]
- New, smaller DPP's[‡] (R75[‡*]) may enable high-velocity implosions at lower IFAR's

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[*] S. P. Regan *et al.*, "The National Direct-Drive Inertial Confinement Fusion Program," submitted to Nuclear Fusion.

[**] S. X. Hu *et al.*, Phys. Plasmas 25, 082710 (2018).

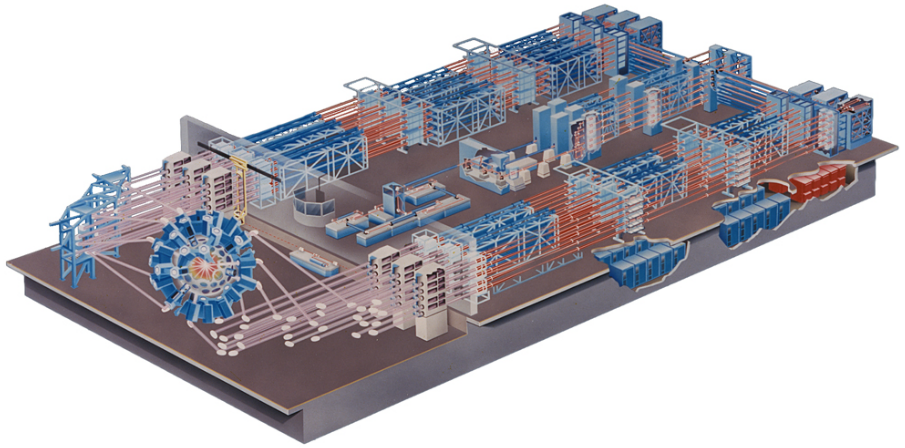
[†] D. R. Harding *et al.*, Fusion Sci. Technol. 73, 324 (2018).

[‡] DPP: distributed phase plates

[‡*] I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).

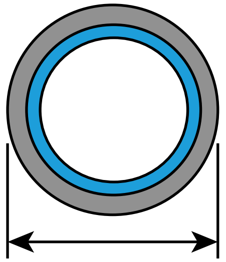
Hydrodynamic scaling of OMEGA implosions to NIF energies

The performance metric is the generalized Lawson criterion scaled to NIF energies



Scale 1:70 in energy

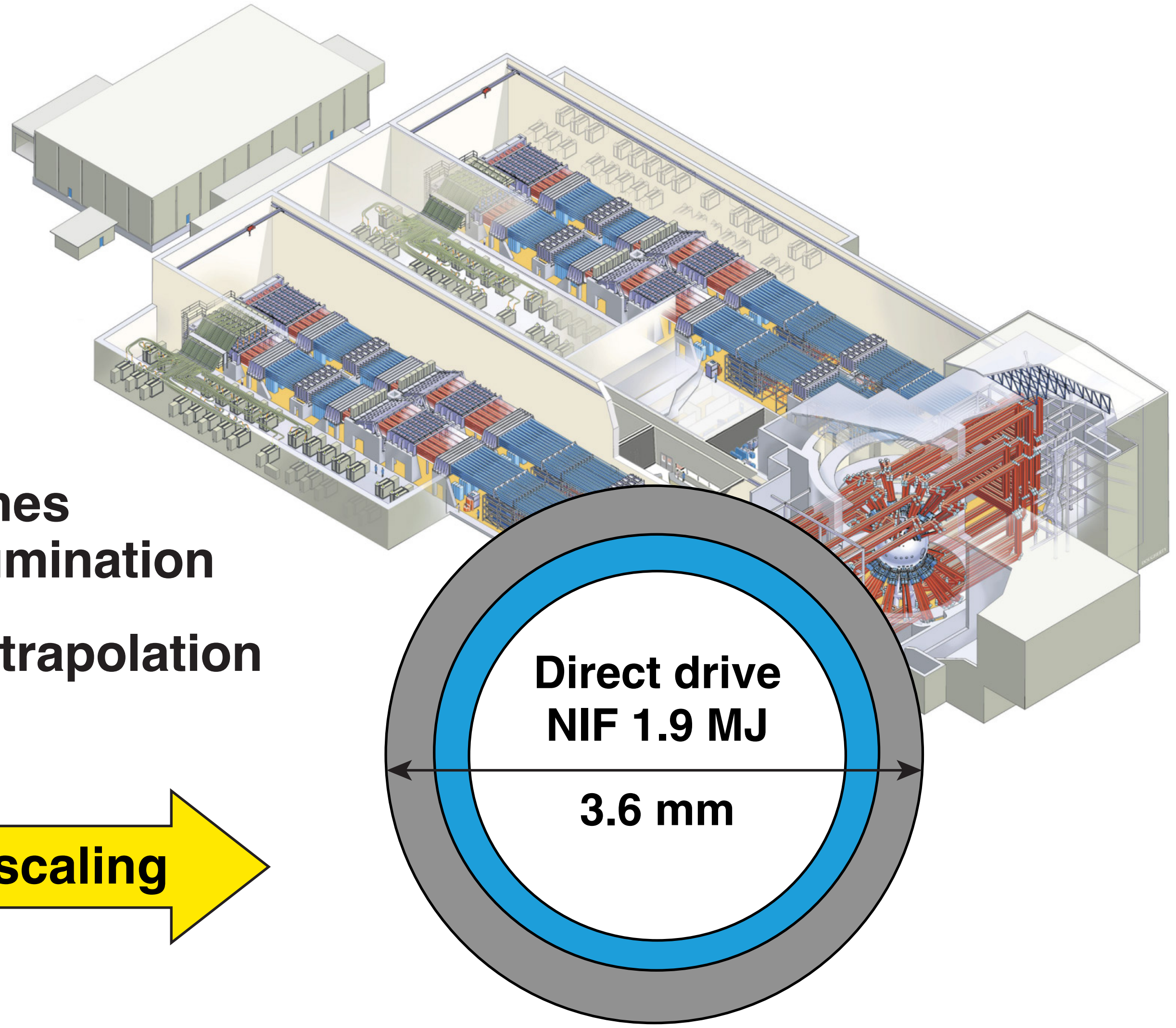
OMEGA 26 kJ



0.86 mm

- Initially assumes symmetric illumination
- Polar-drive extrapolation will follow

Hydrodynamic scaling



Direct drive NIF 1.9 MJ

3.6 mm

R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014);
R. Nora, Ph.D. thesis, University of Rochester, 2015.

TC13889I

Hydro scaling provides a simple and robust tool to scale OMEGA performance to NIF energies

Same hydro for OMEGA and NIF

- Same implosion velocity and adiabat
- Same final hot-spot pressure and shell density
- Mass and volume scale with laser energy
- Same energy coupling to target
- All nonuniformities scale with size (conservative for NIF since ice roughness/target –radius is less and impact of fill tube is less)

LPI* not included in hydro scaling

- Hydro scaling does not account for differences in LPI
- LPI depends on size and is different for OMEGA and the NIF
- Assessing the impact of LPI on the NIF requires dedicated experiments on the NIF (DD MJ campaign on NIF)
- Results from planar and sub-scale spherical experiments on NIF suggest that hot electron levels will be manageable in direct-drive ignition designs

OMEGA will validate the hydrodynamics (that scales), while the NIF will assess the LPI (that does not scale).

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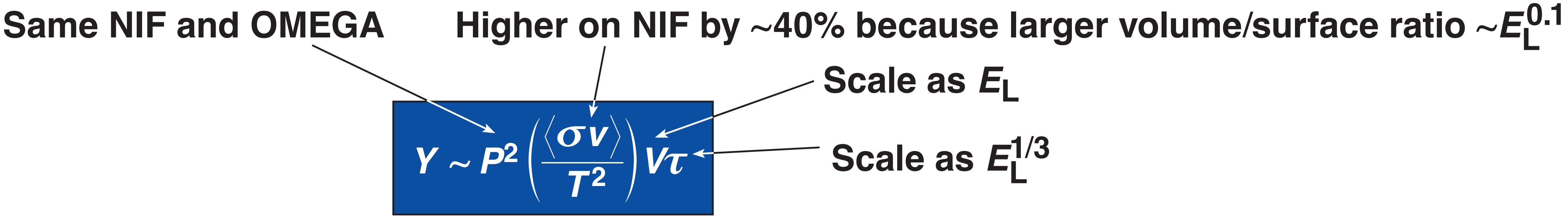
*LPI: laser–plasma interaction

M. Rosenberg *et al.*, CO4.00005, this conference.

A. A. Solodov *et al.*, JO6.00010, this conference.

The no-alpha hydro scaling can be explained with simple physics

- **No-alpha scaling, pure hydrodynamics, and thermal transport**



Same NIF and OMEGA

Higher on NIF by ~40% because larger volume/surface ratio $\sim E_L^{0.1}$

Scale as E_L

Scale as $E_L^{1/3}$

$$Y \sim P^2 \left(\frac{\langle\sigma v\rangle}{T^2}\right) V\tau$$

$$Y^{NIF}_{\text{no }\alpha} \approx \left(\frac{E_{NIF}}{E_{OMEGA}}\right)^{1.43} \times Y^{OMEGA}_{\text{no }\alpha}$$

$$Y^{NIF}_{\text{no }\alpha} \approx 400 \times Y^{OMEGA}_{\text{no }\alpha}$$ ← at 1.9 MJ

$1.6 \times 10^{14} \rightarrow 6 \times 10^{16}$

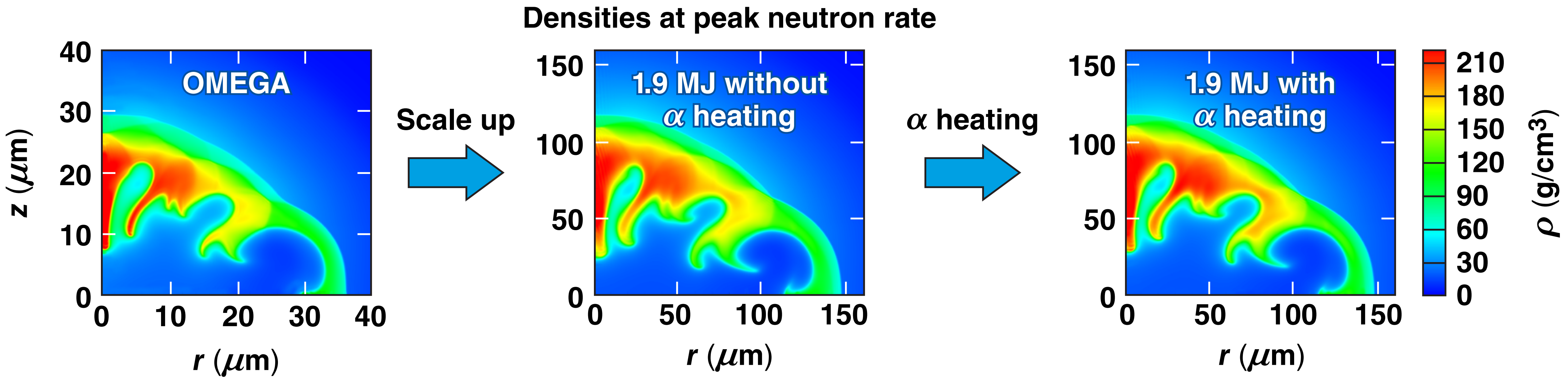
$$Y^{NIF}_{\text{no }\alpha} \approx 540 \times Y^{OMEGA}_{\text{no }\alpha}$$ ← at 2.5 MJ

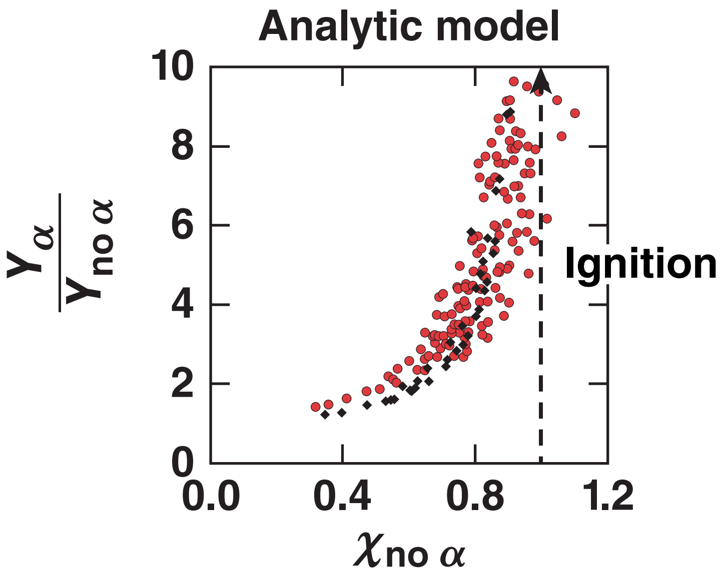
$1.6 \times 10^{14} \rightarrow 8.7 \times 10^{16}$

R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

The effect of alpha heating is assessed through simple theory or simulations of hydro-equivalent targets

Hydroscaled simulations


Densities at peak neutron rate

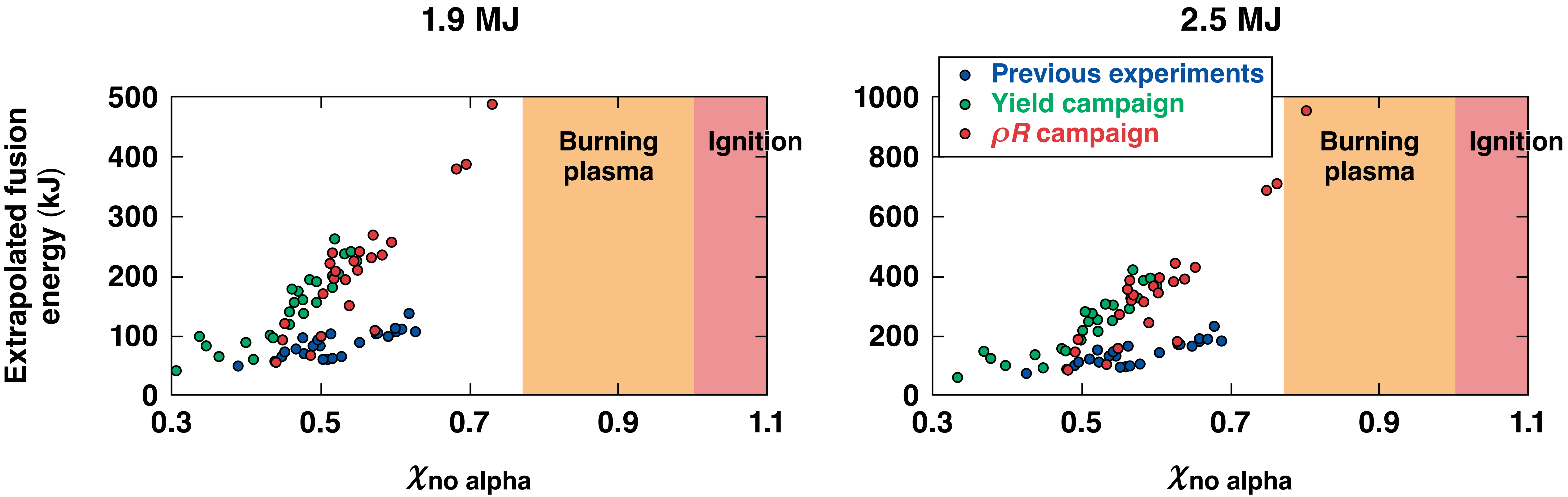

Analytic model

$$\chi_{\text{no}\,\alpha} = \rho R^{0.61}_{\text{g/cm}^2} \left(\frac{0.12\,Y_{16}}{M^{\text{mg}}_{\text{stag}}}\right)^{0.34} \left(\frac{E_{\text{NIF}}}{E_{\text{OMEGA}}}\right)^{0.34}$$

$$\boxed{\hat{Y}^{\text{amp}}_{\alpha} \approx \left(1 - \chi^{\text{NIF}}_{\text{no}\,\alpha}\right)^{-3/4}}$$

A. Bose, Ph.D. thesis, University of Rochester, 2017;
A. Bose *et al.*, Phys. Rev. E 94, 011201(R) (2016).

The highest-yield OMEGA implosions from the Optimization Campaign scale to 500 kJ of fusion energy at 1.9 MJ of symmetric drive (to 1 MJ for a 2.5-MJ drive)



TC14582

Summary/Conclusions

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- The OMEGA implosion performance can be predicted pre-shot using statistical mapping
- This new predictive capability led to improvements in yields and areal density (1.6×10^{14} with 160 mg/cm^2 of average areal density)
- The extrapolated no-alpha ignition parameter $\chi_{\text{no alpha}} = 0.74$ leads to a yield amplification of 3.0× and extrapolated yield of ~500 kJ at 1.9 MJ of symmetric illumination
- Further improvements are expected from the optimization campaign and from the upcoming facility upgrades (new phase plates, advanced ablators, fill-tube capability, and possible CBET* mitigation**)

TC14565

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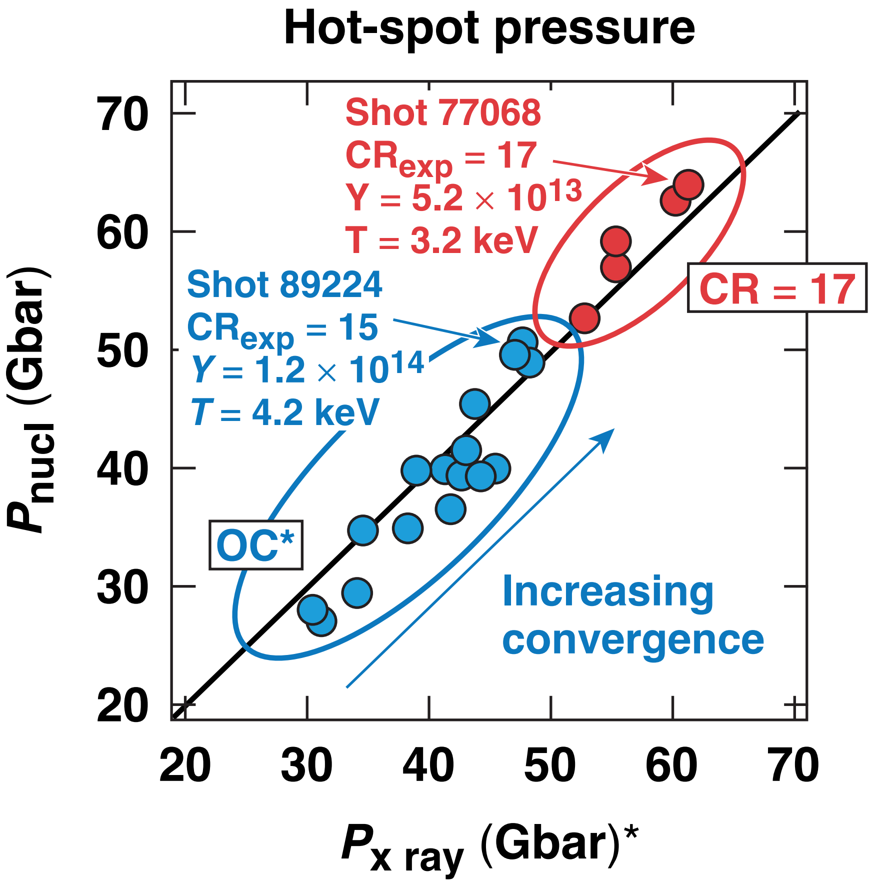
*CBET: cross-beam energy transfer

**R. Follett, NI2.00005, this conference.

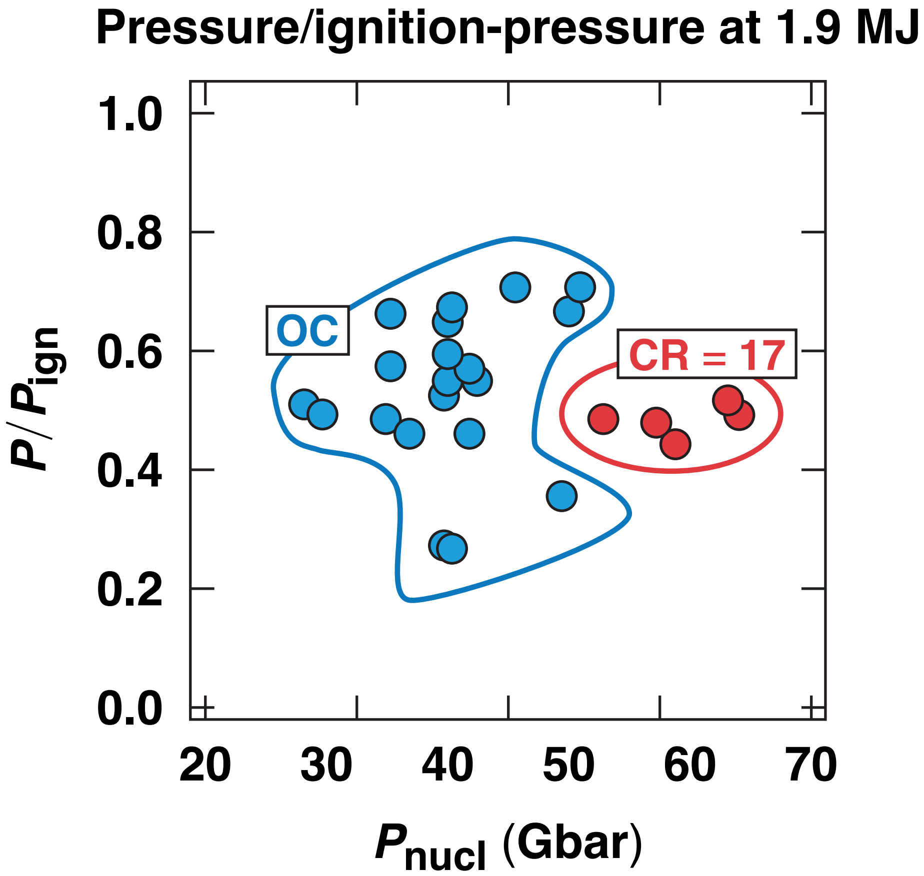
Backup

Because of higher temperatures, recent implosions require lower pressures and lower convergence to achieve hydro-equivalent ignition conditions



Minimum pressure required for ignition

$$P_{ign} \sim \frac{T^2}{\tau \langle \sigma v \rangle}$$



P_{nucl} = pressure from nuclear measurement
$P_{x\ ray}$ = pressure from x ray measurement

Ignition is defined as 1 MJ of fusion yield.

The x-ray pressure uses one reference nuclear measurement for absolute value
*OC: optimization campaign

Interpreting the mapping relations provides physical insight in the target design

Mapping relation (less accurate) for average measured areal density

$$\rho R_{\mathrm{nTOF+MRS}} \sim \left(\frac{\langle \rho \rangle_{\mathrm{n}}}{\langle T \rangle_{\mathrm{n}}}\right)^{0.7} \frac{1}{F_{\mathrm{coast}}^{2}} \frac{1}{F_{\mathrm{laser}}^{5}} \left(\frac{R_{\mathrm{out}}}{R_{\mathrm{in}}}\right)^{4} R_{\mathrm{out}}$$

$\langle \rho \rangle_{\mathrm{n}}$ → High simulated convergence is good

$\langle T \rangle_{\mathrm{n}}$ → Will pay a price by increasing T_{i} but mitigated if one uses higher R_{out}

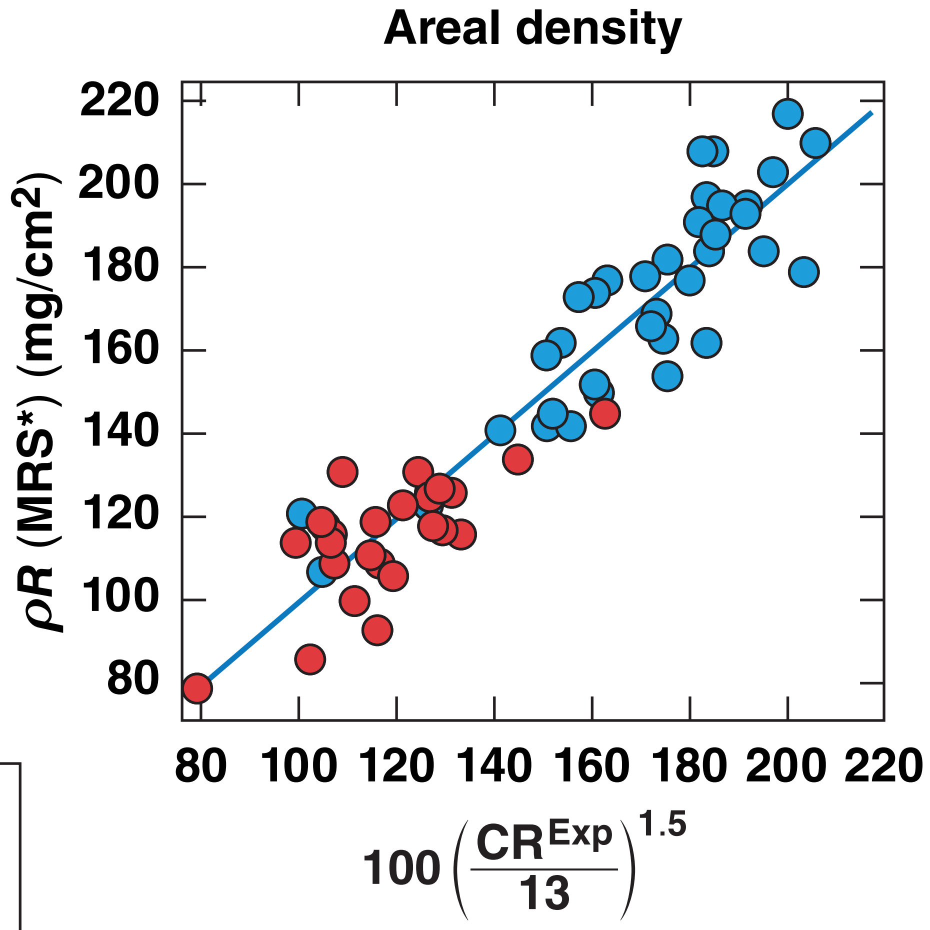
$\left(\frac{R_{\mathrm{out}}}{R_{\mathrm{in}}}\right)$ → Thicker ice helps

$F_{\mathrm{coast}} \sim 1 + t_{\mathrm{coast}}/t_{\mathrm{imp}}$ → No coasters give higher ρR

$F_{\mathrm{laser}} \sim 1 + t_{\mathrm{laser}}/t_{\mathrm{imp}}$ → Get high ρR with shortest possible laser pulses

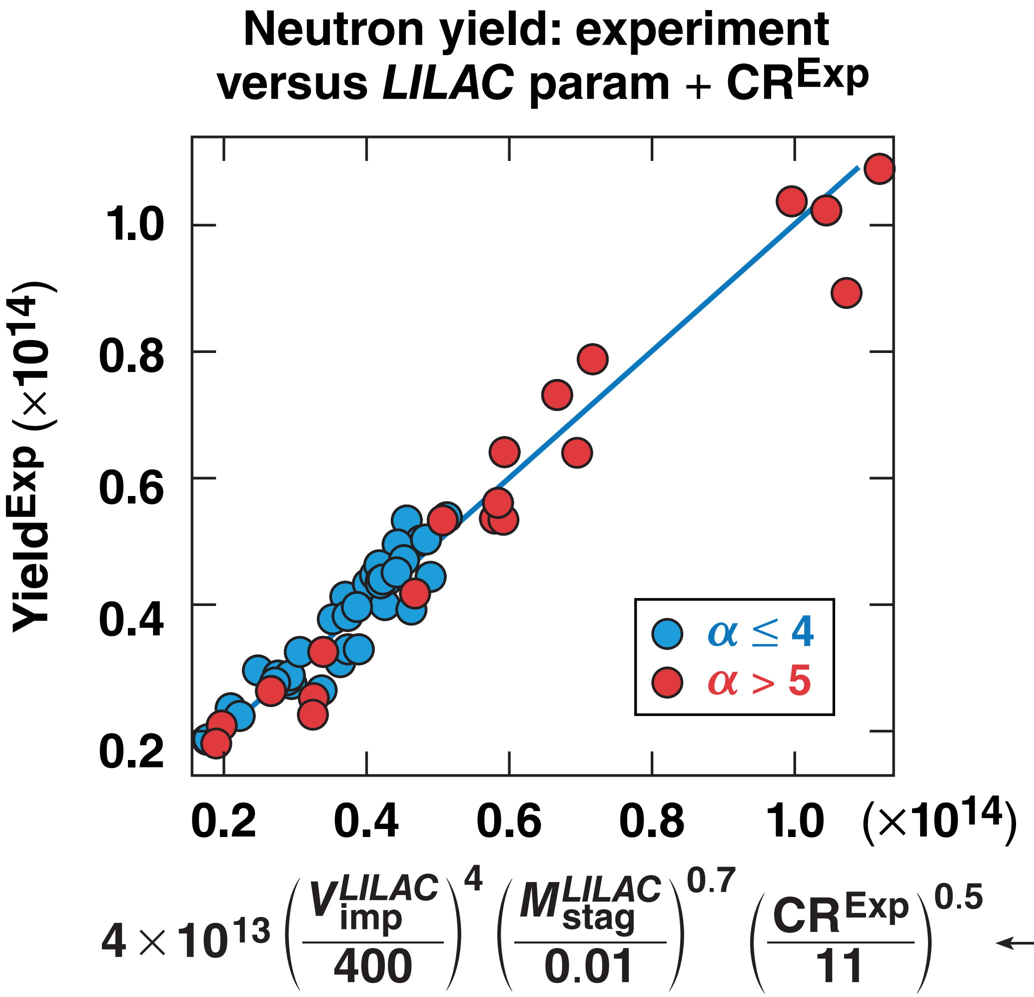
TC14584

Including lower-adiabat implosions shows the yield increase from convergence is less than 1-D predictions while the areal density scales as 1-D



1-D theory

$$100\left(\frac{CR}{13}\right)^{1.7}$$



1-D theory CR^2

In experiments, a higher convergence ratio (CR) leads to a very modest increase in yield.

TC13739b

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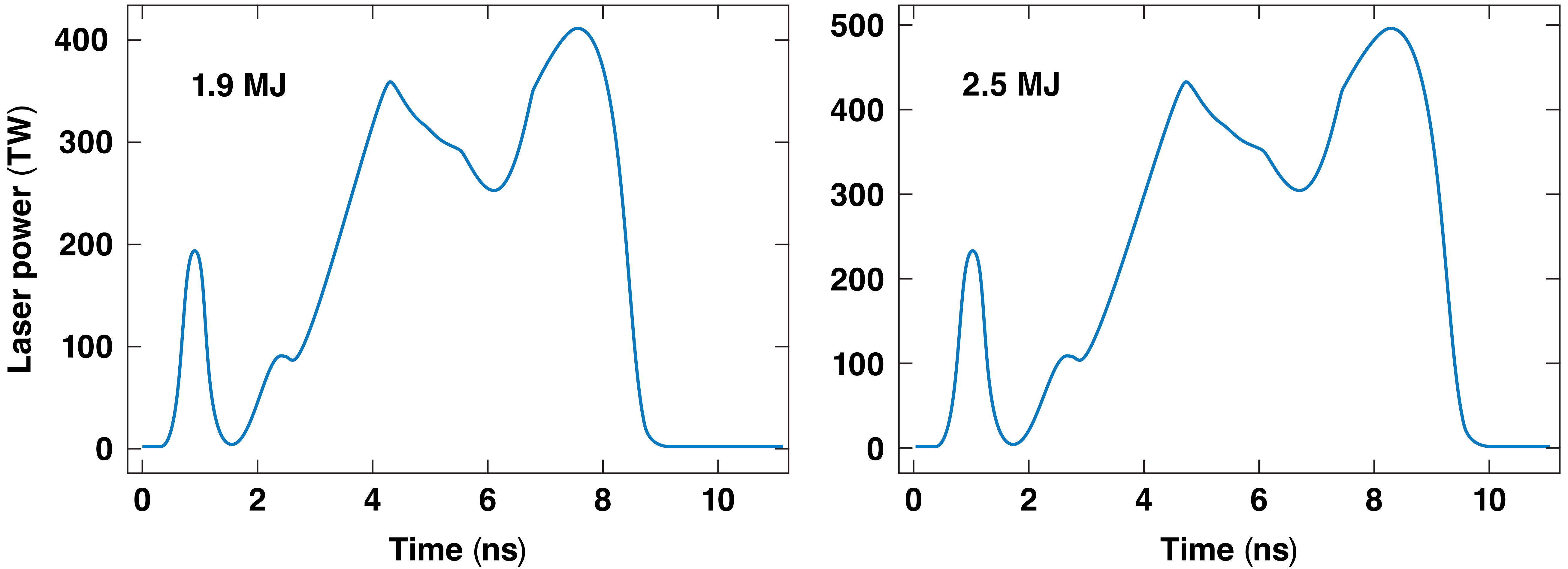
*MRS: magnetic recoil spectrometer

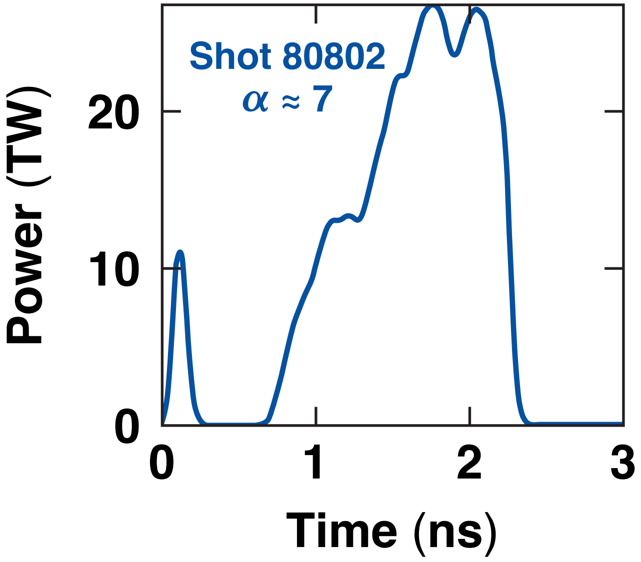
The hydro-scaled laser pulses do not exceed 500 TW



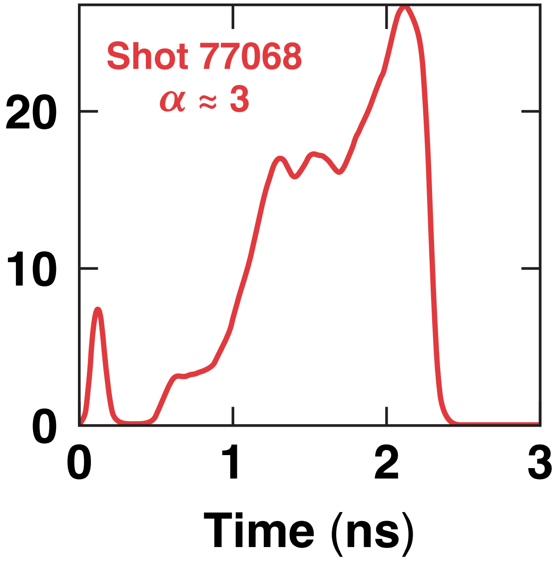
TC14585

The sensitivity of the areal density to the details of the laser pulse shape (i.e., shock timing) and the large measurement errors (~±10%) complicate the predictions

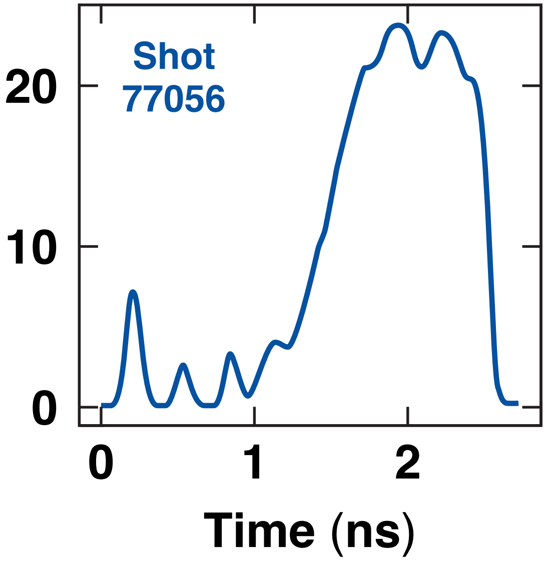
- Mapping of the full ρR database provides a less accurate but more general prediction
- Using a subset of ρR data improves accuracy by limiting the parameter space of laser pulse shapes and target specs



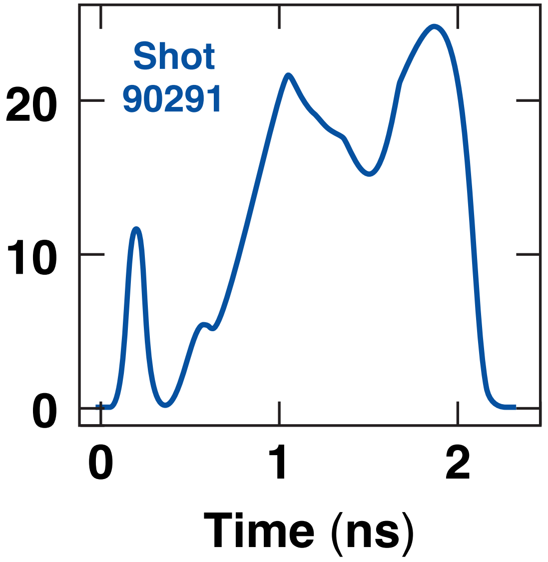
**Single picket,
“flat top”**



**Single picket,
single spike**



**Triple picket,
“flat top”**



**Single picket,
double spike**

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