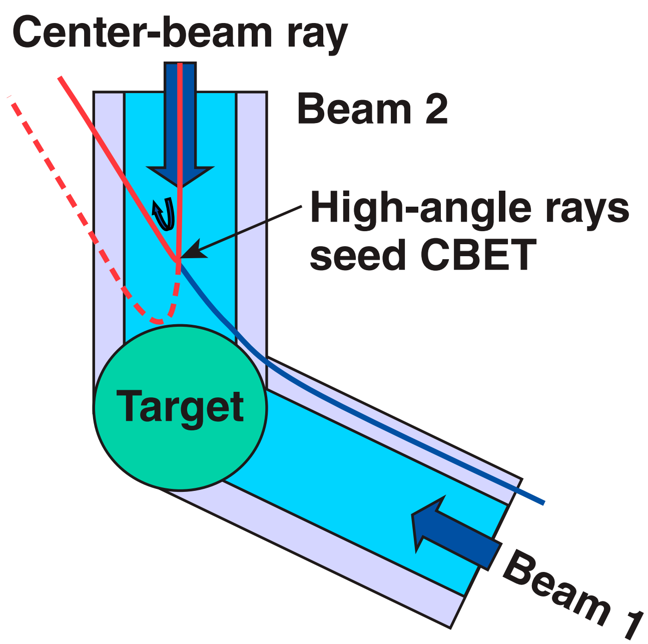
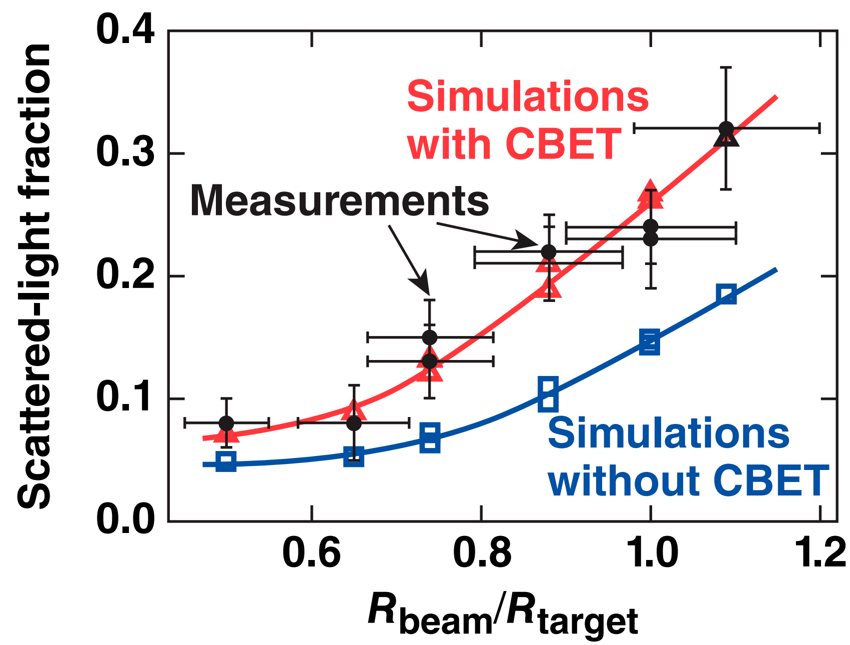
Crossed-Beam Energy Transfer for Direct-Drive Implosions





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Summary

Crossed-beam energy transfer (CBET) can reduce the performance of direct-drive ICF implosions

- CBET is observed in time-resolved reflected-light spectra as a suppression of red-shifted light during the main laser drive
- CBET extracts energy from the center-beam incoming light and transfers it to outgoing light, reducing the laser absorption and hydrodynamic efficiency
- CBET can be reduced
  - using beams smaller than the target diameter
  - using laser beams with two or more colors

Mitigation strategies are being tested on OMEGA.

Collaborators

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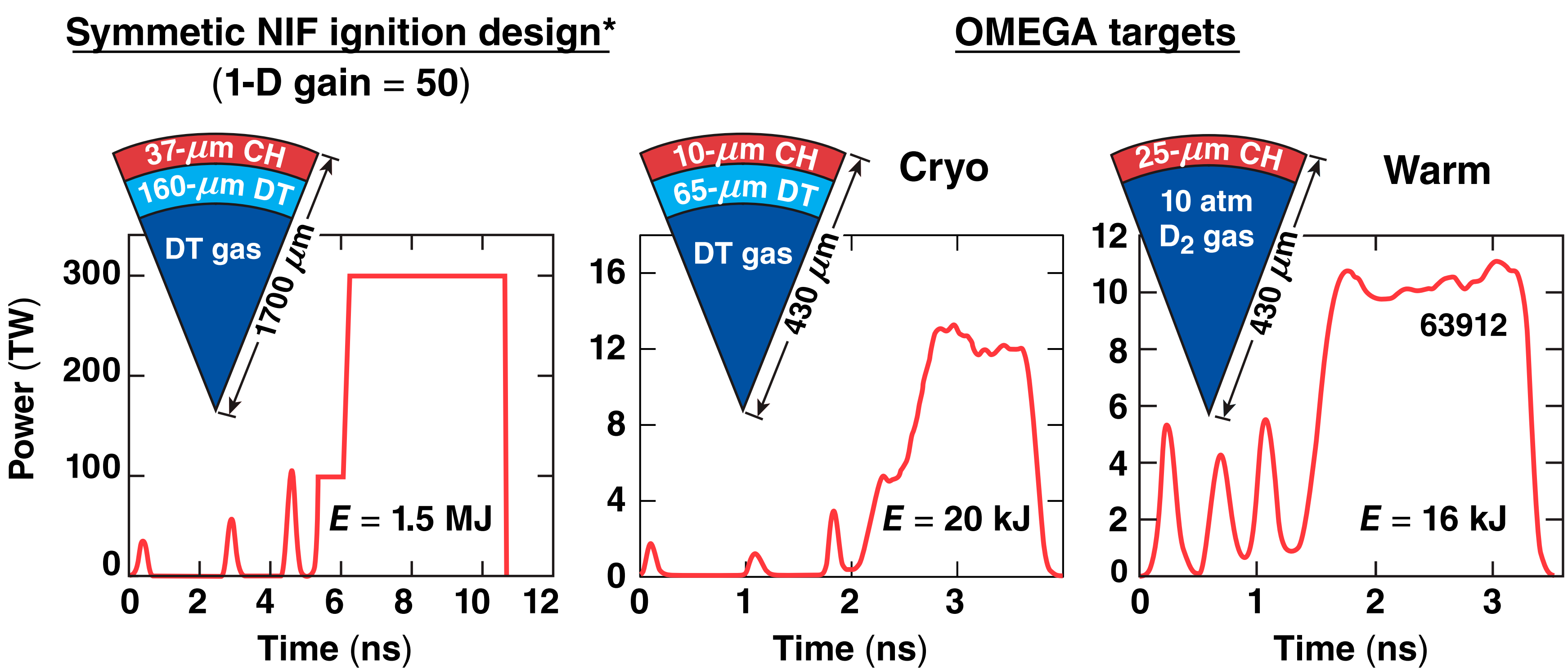
Outline

- Introduction
- Modeling CBET
- CBET in symmetric OMEGA implosions
- Mitigation of CBET: experiments and simulations
- Conclusions

Scaled-down implosion experiments on OMEGA are used to validate direct-drive NIF implosion designs



TC9858

*V. N. Goncharov *et al*., Phys. Rev. Lett. 104, 165001 (2010).

Experiments on OMEGA have been modeled using hydrodynamic codes *LILAC** and *DRACO***

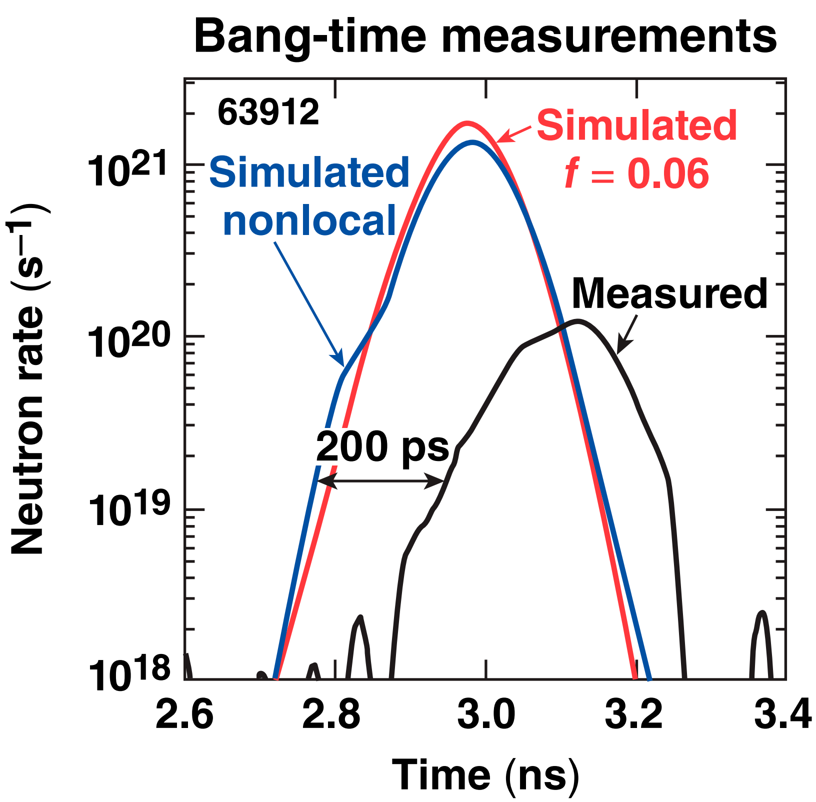
- Radiation transport package
  - multi-group diffusion
- Equation-of-state package
  - *SESAME*
  - QEOS
- Laser absorption package
  - inverse bremsstrahlung
- Thermal transport package
  - flux-limited transport
  - nonlocal transport***

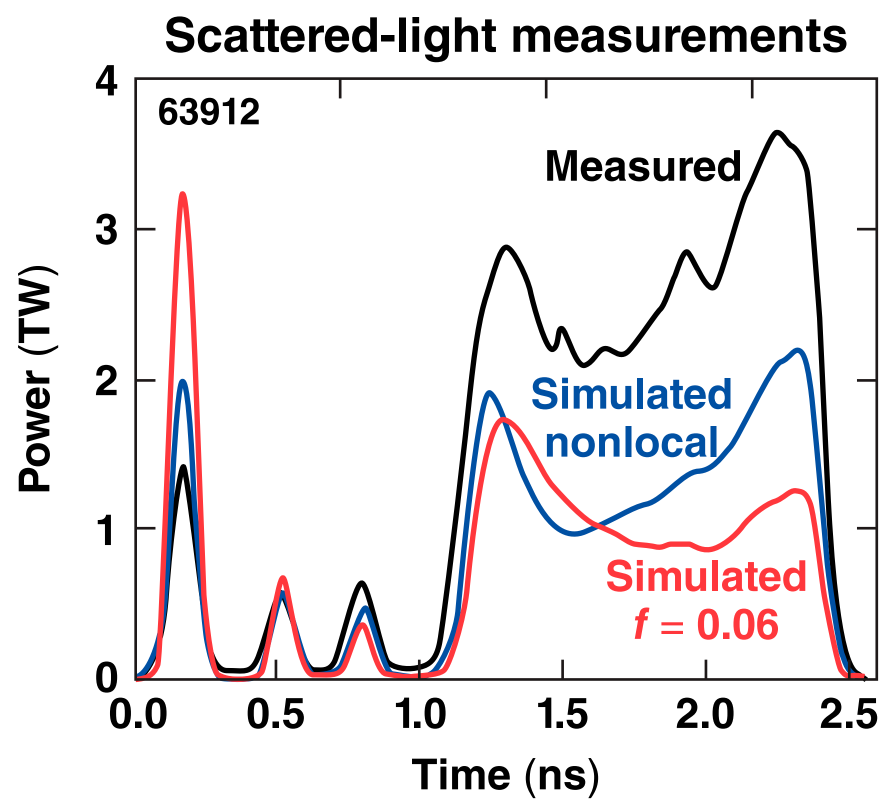
Hydrodynamic efficiency

* J. Delettrez *et al*., Phys. Rev. A 36, 3926 (1987).
** B. Radha *et al*., Phys. Plasmas 12, 032702 (2005).
*** V.N. Goncharov *et al*., Phys. Plasmas 15, 056310 (2008).

TC9881

Measured bang time is late by ~200 ps, indicating reduced laser coupling





TC9859

Simulations overpredict the red-shifted scattered light

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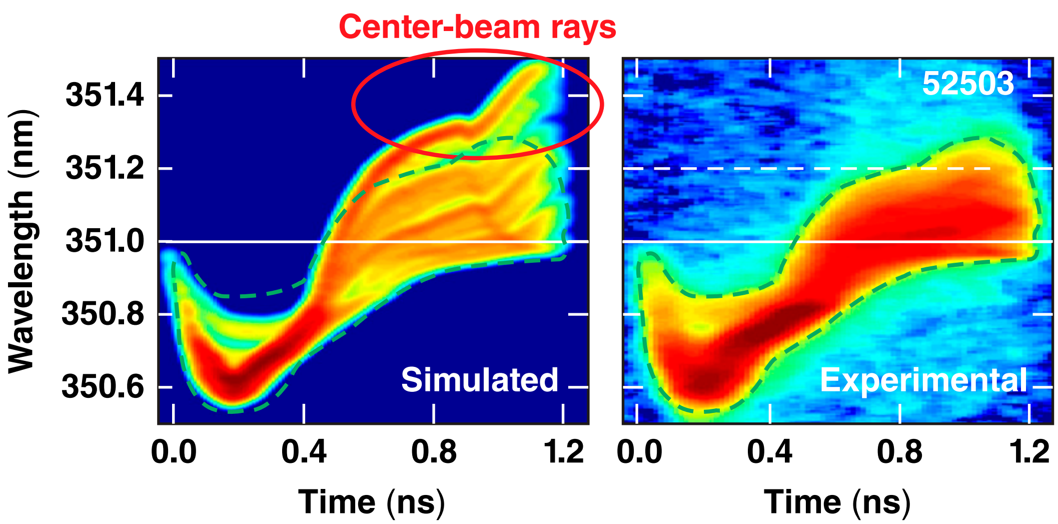
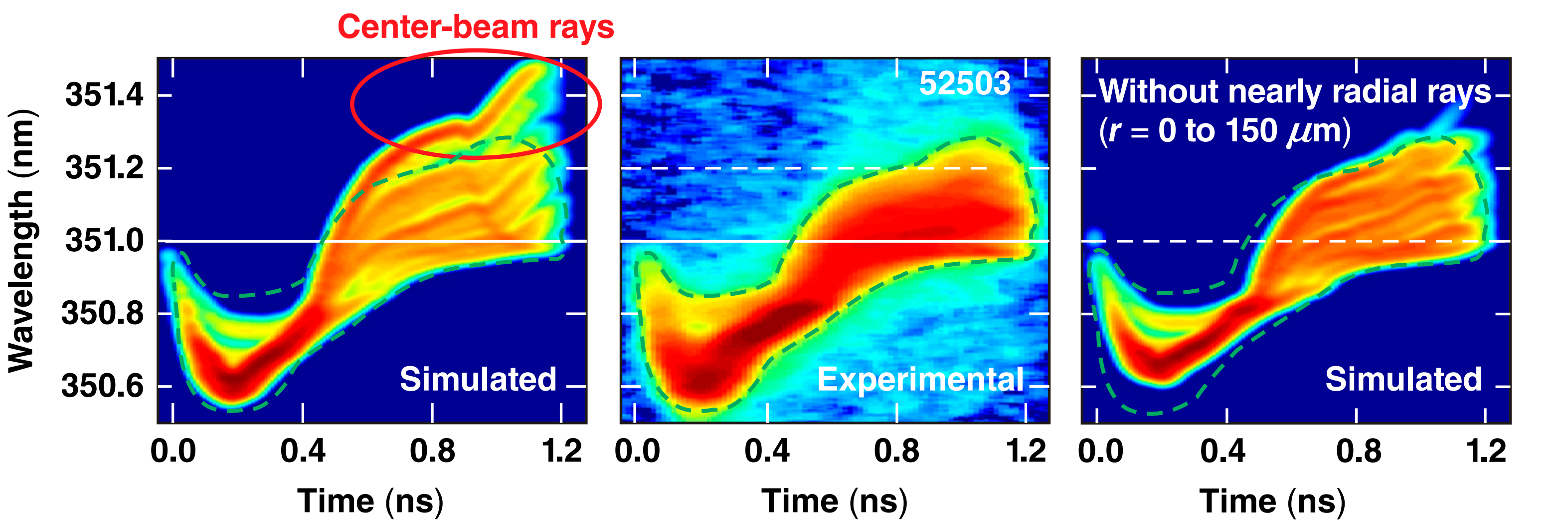
Time-resolved scattered-light spectra from a spherical implosion



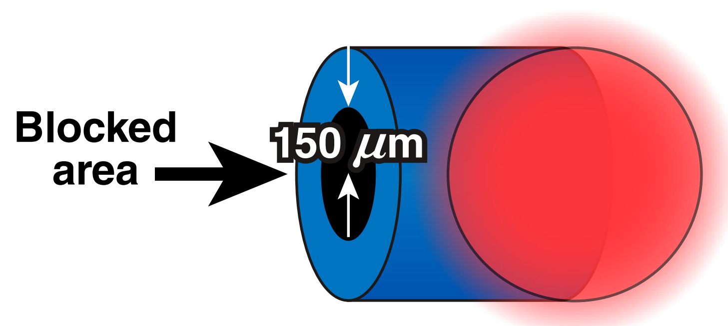
E19908b

Simulations overpredict the red-shifted scattered light

Time-resolved scattered-light spectra from a spherical implosion

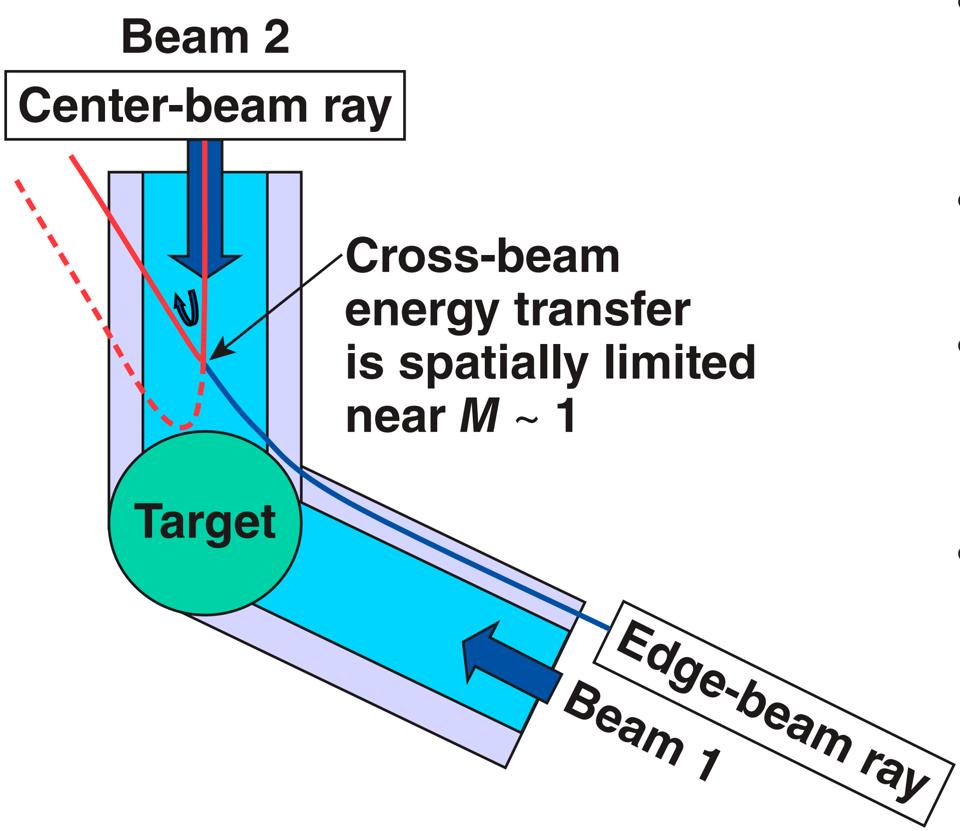


- Blocking the central portion of the beam in the simulations reproduces the observed spectrum



E19908c

CBET can be responsible for the discrepancy between experiments and simulations



- CBET involves electromagnetic (EM)-seeded, low-gain stimulated Brillouin scattering
- EM seed is provided by edge-beam light
- Center-beam light transfers some of its energy to outgoing light*
- The transferred light bypasses the highest absorption region near the critical surface*

CBET reduces laser absorption and hydrodynamic efficiency.**

* D. H. Edgell *et al.*, Bull. Am. Phys. Soc. 52, 195 (2007); 53, 168 (2008); 54, 145 (2009).

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

E19905e

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- **Modeling CBET**
- CBET in symmetric OMEGA implosions
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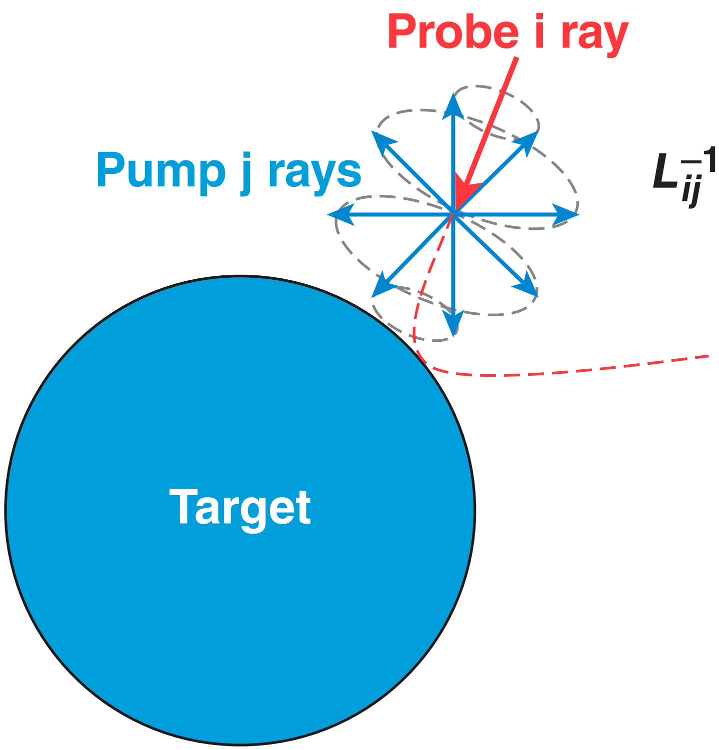
The CBET numerical algorithm considers pairwise interactions of light rays



$$\frac{dI_i}{d\ell} = -\sum_j I_i \times L_{ij}^{-1}$$

$$L_{ij}^{-1} = I_j \times \frac{e^2 \lambda_L}{m^2 c^3} \frac{k_a^2}{\omega_{pe}^2} \frac{n_e/n_{cr}}{\sqrt{1-n_e/n_{cr}}} Im\left[\frac{\chi_e(1+\chi_i)}{1+\chi_e+\chi_i}\right]$$

$$\left.\begin{aligned} \omega_a &= \omega_{probe} - \omega_{pump} \\ \vec{k}_a &= \vec{k}_{probe} - \vec{k}_{pump} \end{aligned}\right\} \text{Three-wave matching condition}$$

- The CBET model*† is implemented in *LILAC* absorption package assuming spherical symmetry**

* C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).
† E. A. Williams *et al*., Phys. Plasmas 11, 231 (2004).
** I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

An ion-acoustic wave saturation model is required to match the scattered-light power for intensities $I \gtrsim 4 \times 10^{14}$ W/cm^2

- The amplitude of ion-acoustic waves is limited by clamping electron- density fluctuations*

$$\frac{dI_i}{d\ell} = \sum_j F\left(\omega_a, \vec{k}_a, n_e, T_e, \ldots\right)\left(\frac{\delta n}{n_e}\right)_{ij} \times \sqrt{I_i I_j}$$

$$\left(\frac{\delta n}{n_e}\right)_{ij} = G\left(\omega_a, \vec{k}_a, n_e, T_e, \ldots\right) \times \sqrt{I_i I_j}$$

$$\boxed{\widetilde{\left(\frac{\delta n}{n_e}\right)}_{ij} = \min\left\{\left(\frac{\delta n}{n_e}\right)_{\text{clamp}}, \left(\frac{\delta n}{n_e}\right)_{ij}\right\}}$$

- The value of the clamping parameter $(\delta n/n_e)_{\text{clamp}}$ is determined by fitting the simulation results with the scattered-light measurements
  - for CH ablators: $(\delta n/n_e)_{\text{clamp}} \approx 0.1\%$

TC9763

*P. Michel *et al*., Phys. Rev. Lett. 102, 025004 (2009).

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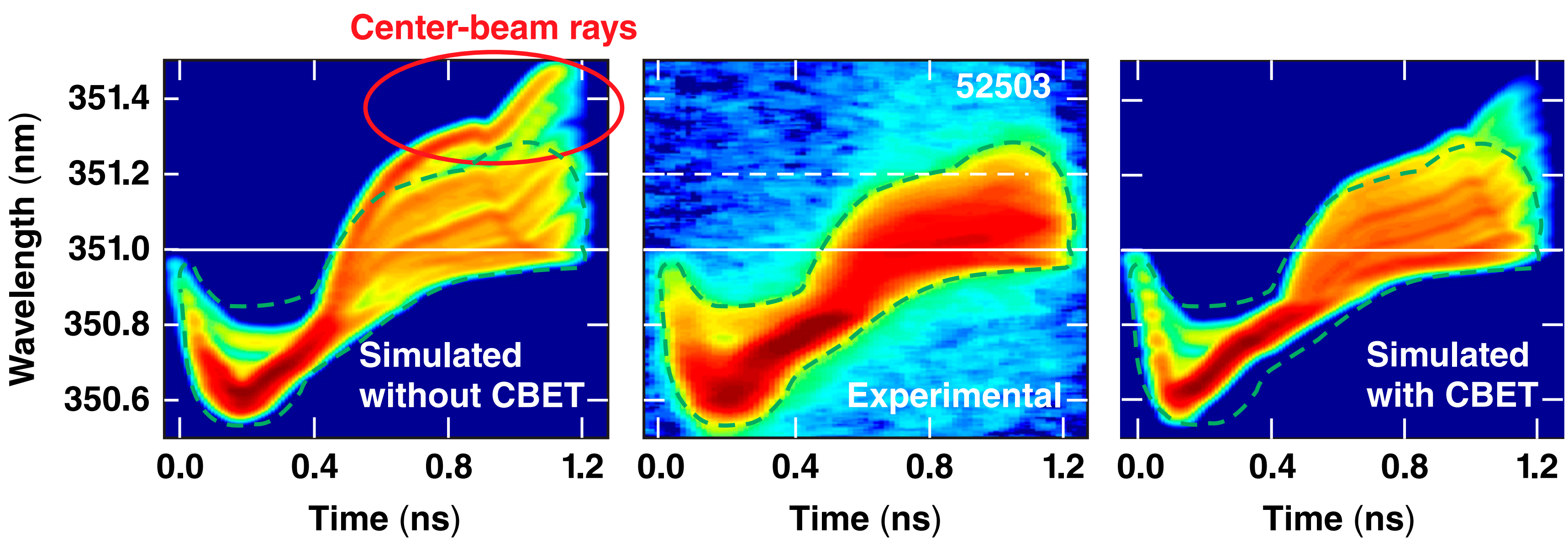
Simulations including CBET agree well with scattered-light spectral measurements

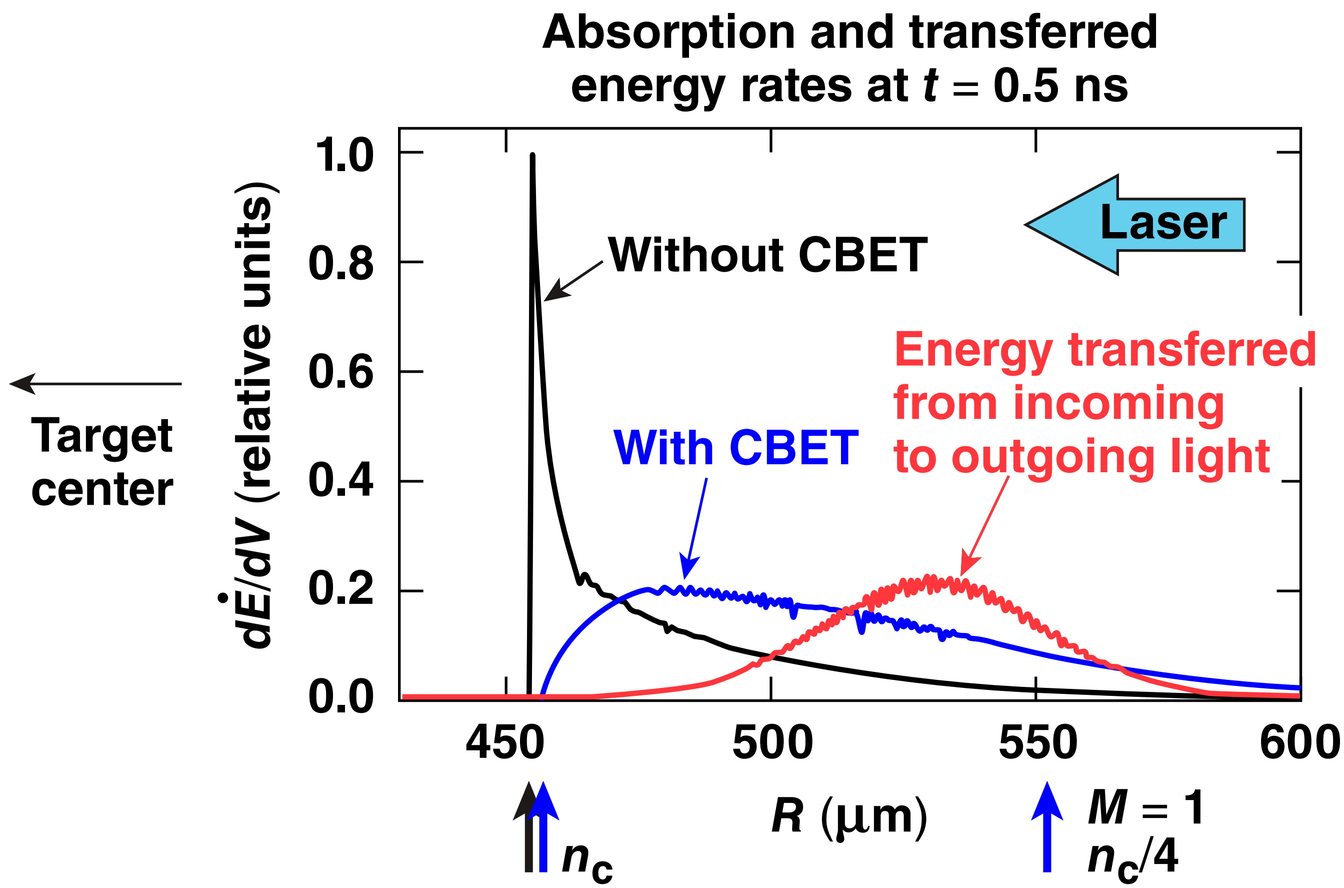
Time-resolved scattered-light spectra from a spherical implosion



CBET extracts the energy from the center-beam incoming rays and transfers it to outgoing rays.

E19972c

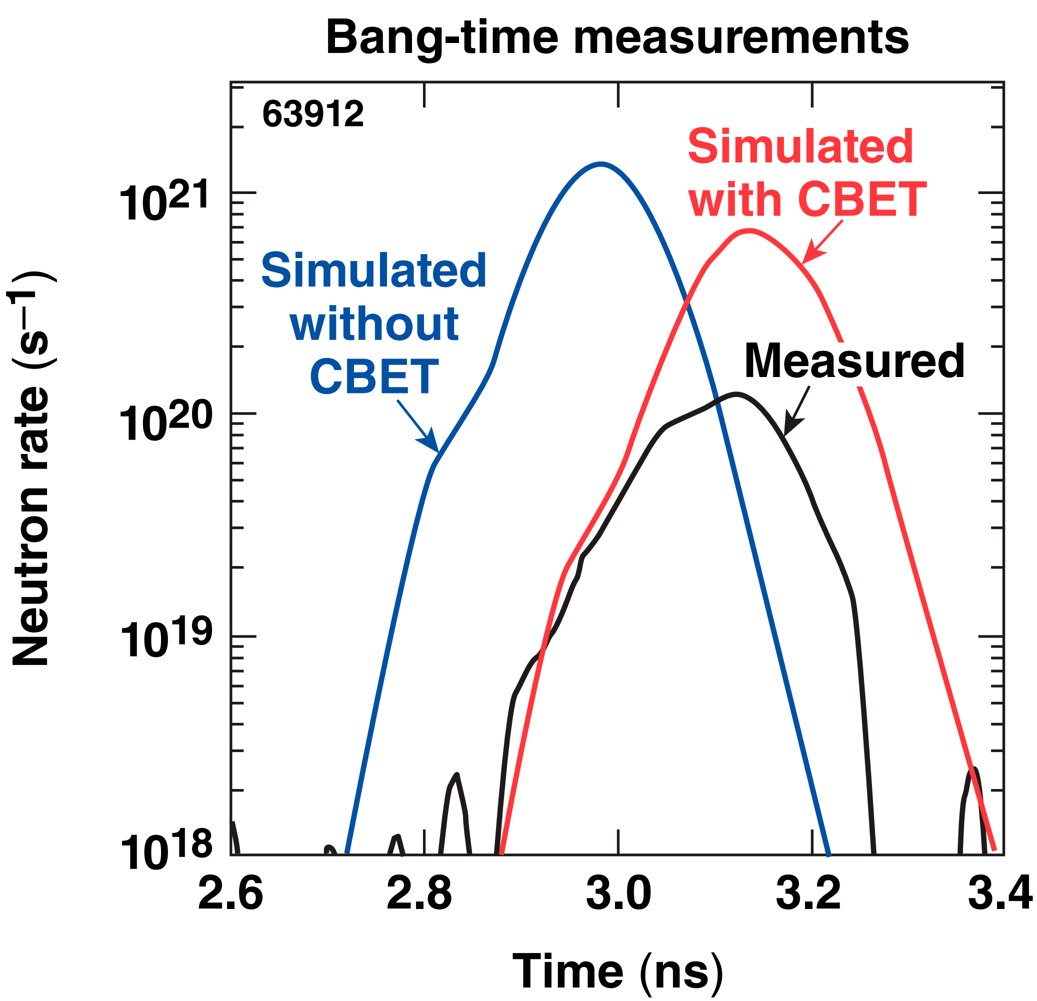
CBET reduces the absorption by ~10%, but the implosion hydrodynamic efficiency is reduced by ~20%



Energy deposition area is shifted outward, reducing hydrodynamic efficiency.

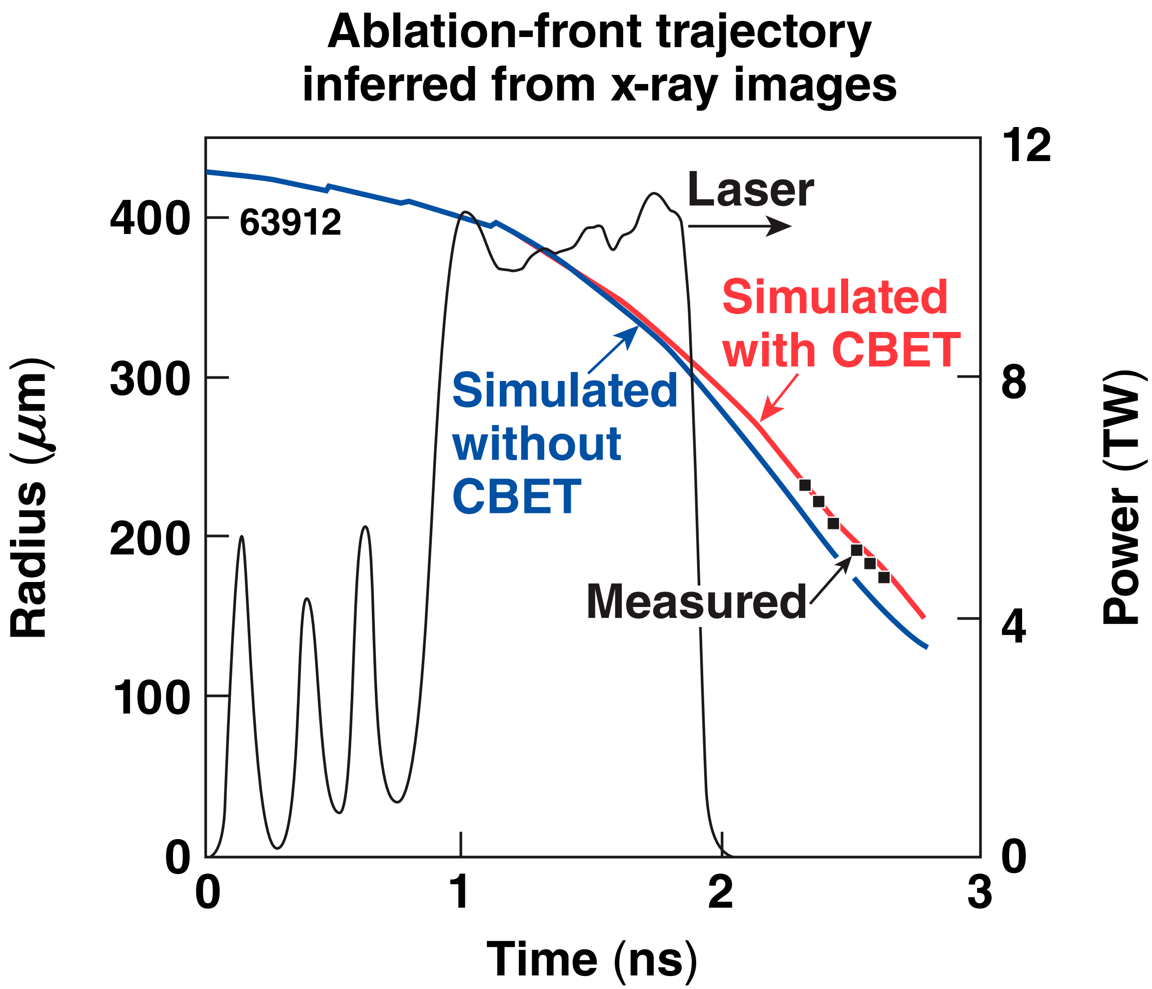
TC8628a

Laser coupling at intensities up to $I \sim 6 \times 10^{14}$ W/cm^2 is accurately predicted by the CBET model



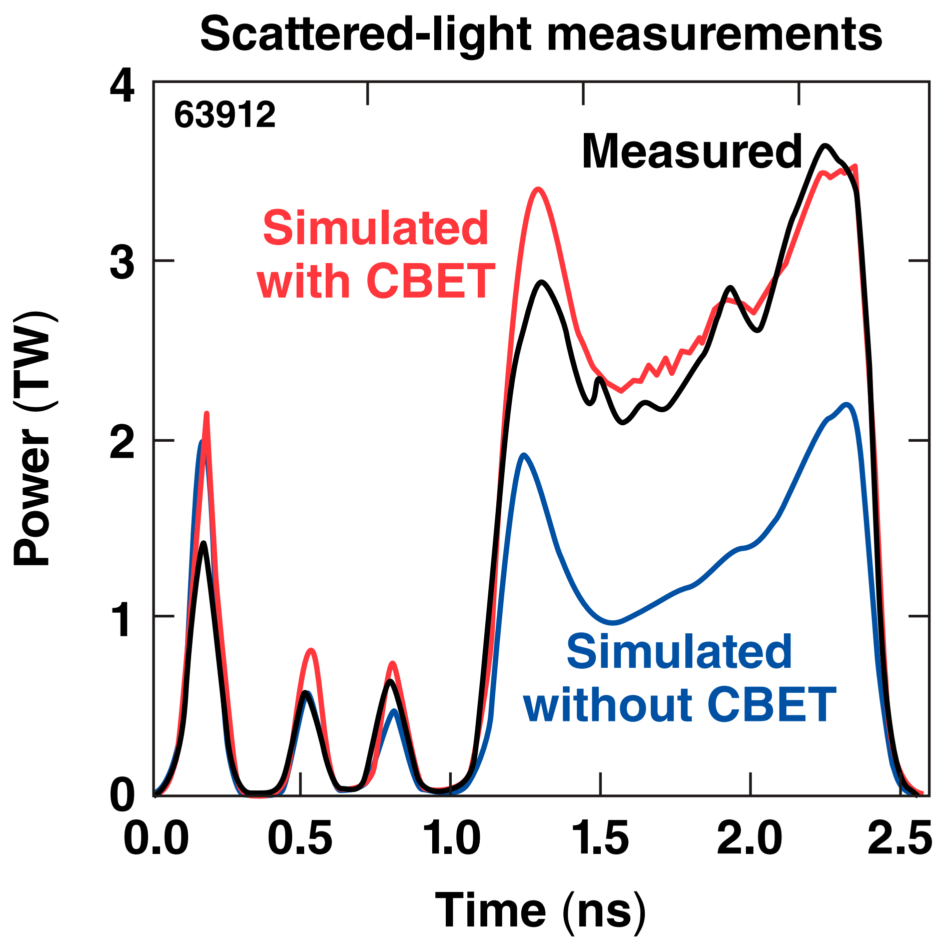
TC9764

Laser coupling at intensities up to $I \sim 6 \times 10^{14}$ W/cm^2 is accurately predicted by the CBET model



TC9764a

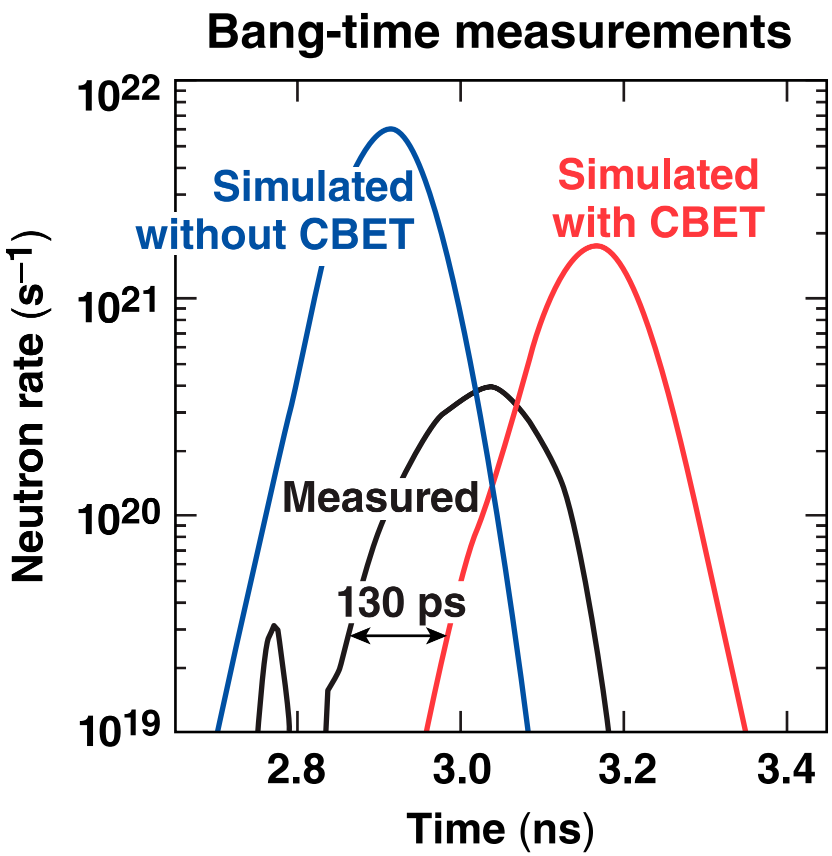
Laser coupling at intensities up to $I \sim 6 \times 10^{14}$ W/cm^2 is accurately predicted by the CBET model

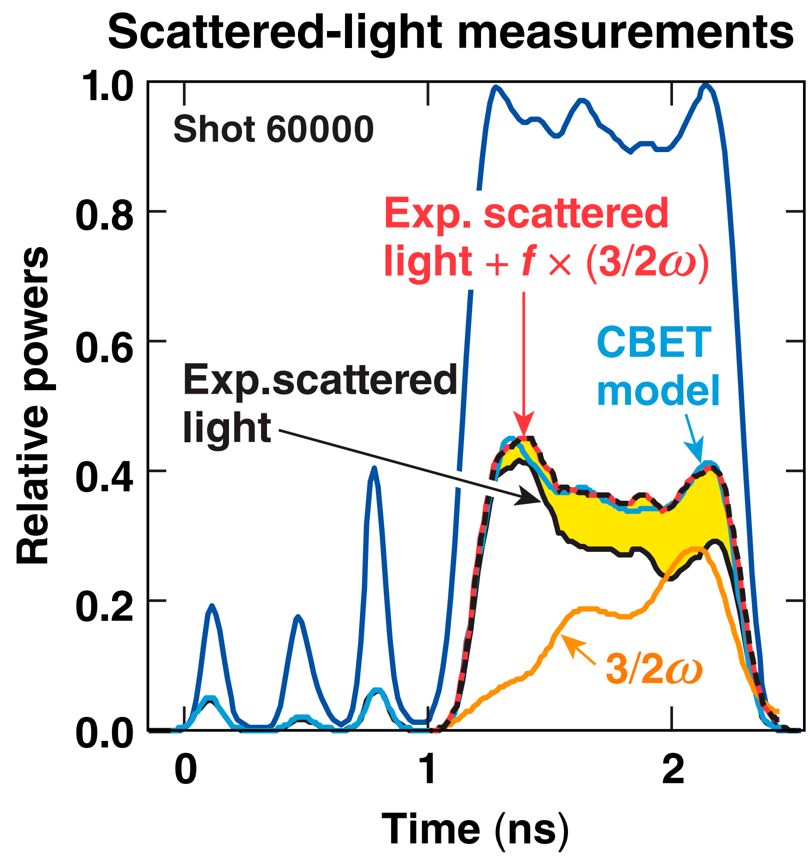


The accuracy of the CBET model was demonstrated using OMEGA implosions with different pulse shapes and targets.

TC9764b

High-intensity implosions ($I \sim 10^{15}$ W/cm^2) show disagreements with the CBET model





The missing scattered light may be caused by

– two-plasmon-decay instability*

– enhanced absorption in laser hot spots**

TC9864

* W. Seka, U06.00005

** A. V. Maximov, UO6.00007

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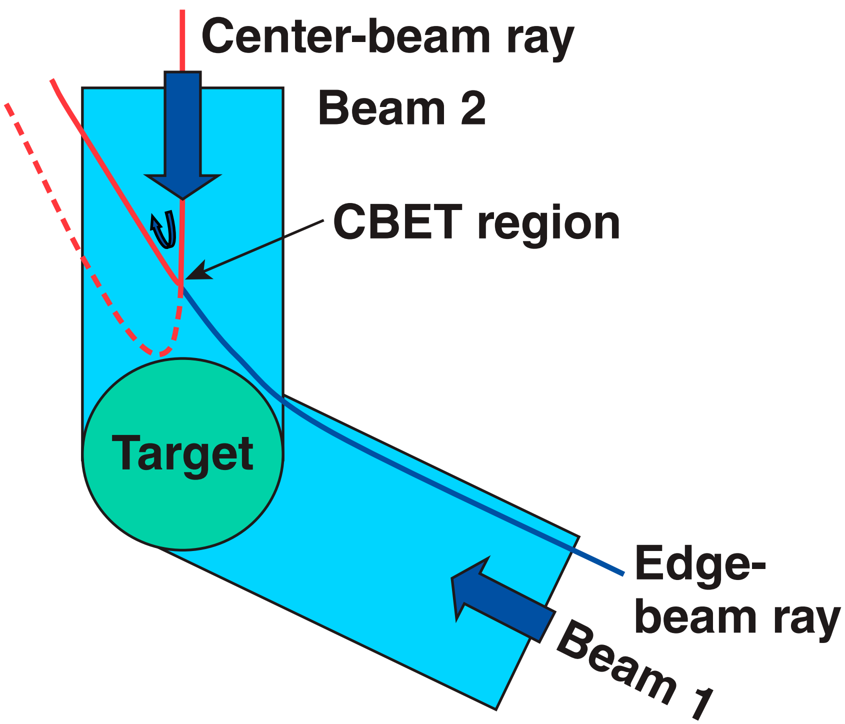
CBET can be mitigated in symmetric direct-drive implosions by reducing the energy in beam edges



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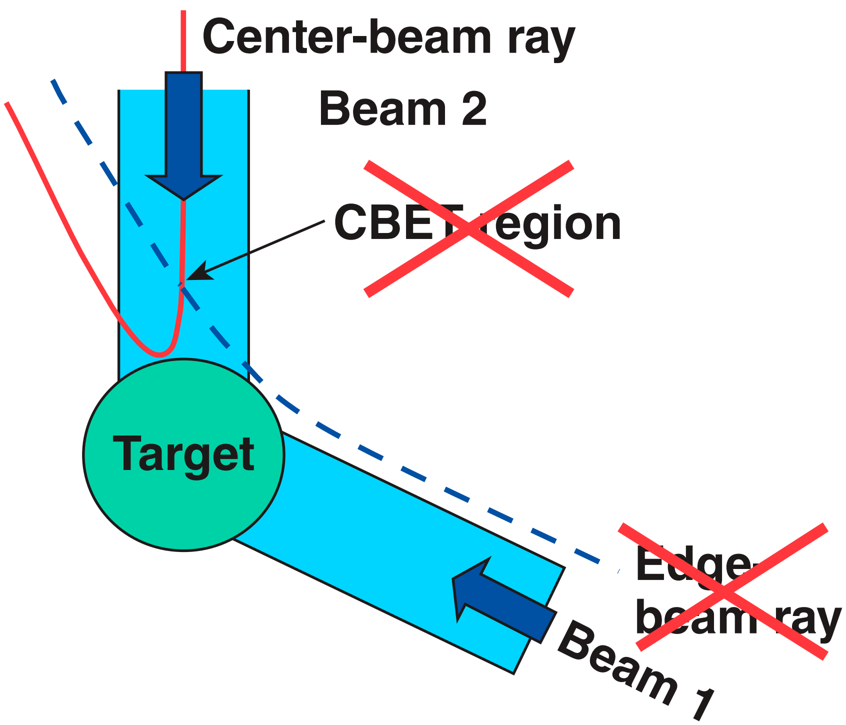
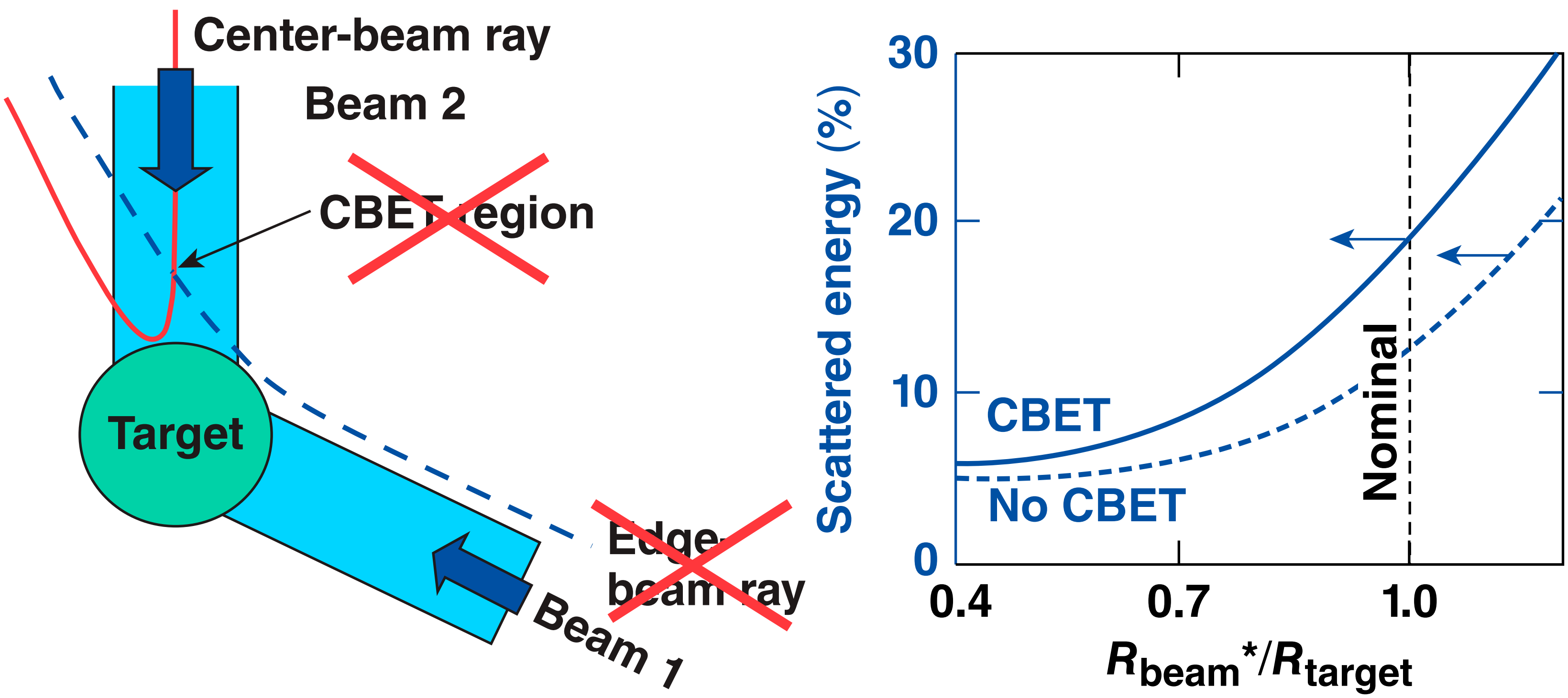


TC9767a

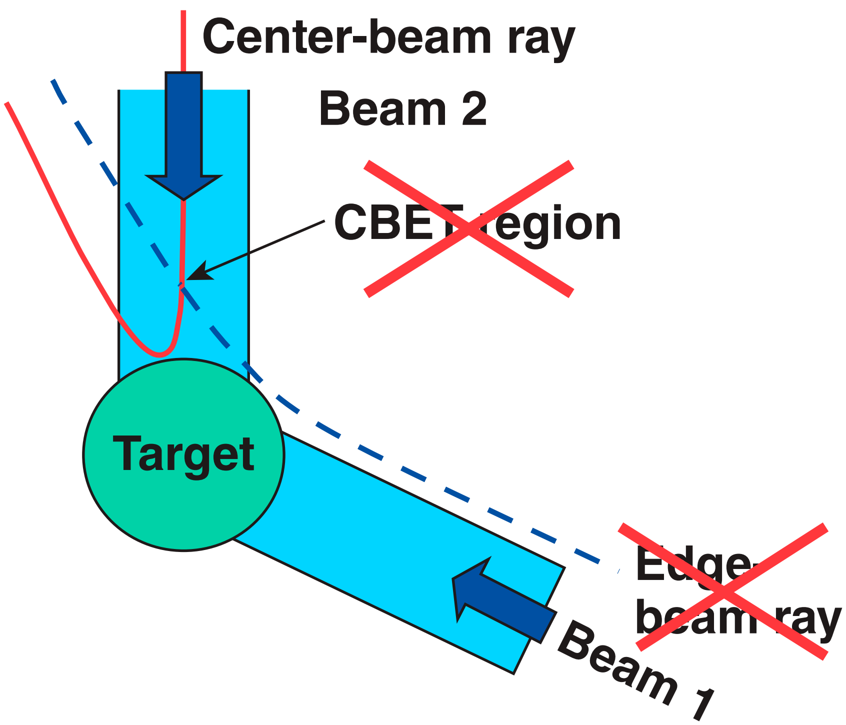
CBET can be mitigated in symmetric direct-drive implosions by reducing the energy in beam edges

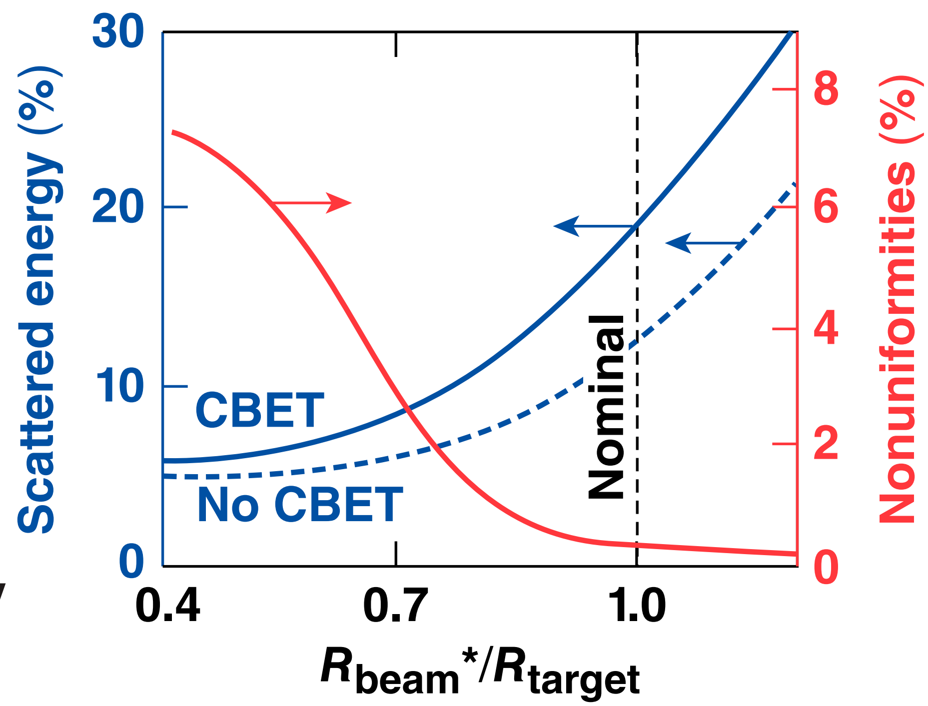


TC9767b

*R_{beam} defined at 95% energy

CBET can be mitigated in symmetric direct-drive implosions by reducing the energy in beam edges





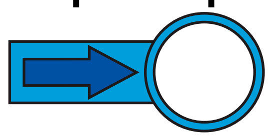
Simulations suggested an optimum neutron yield can be achieved on OMEGA by reducing the laser beam to R_{beam}/R_{target} ~ 0.8.

*R_{beam} defined at 95% energy

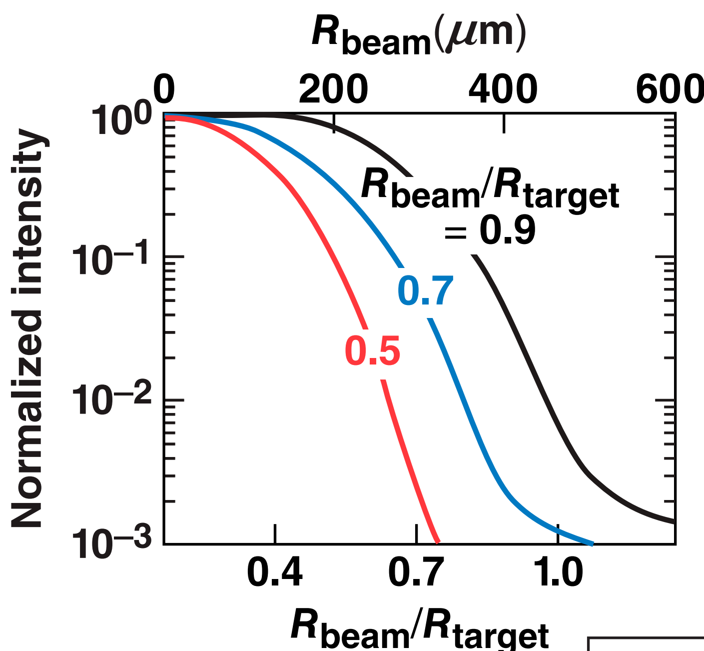
Experiments* on OMEGA are investigating the optimum laser-beam diameter by balancing CBET with nonuniformities in low-adiabat implosions

Fixed targets

Small phase plates

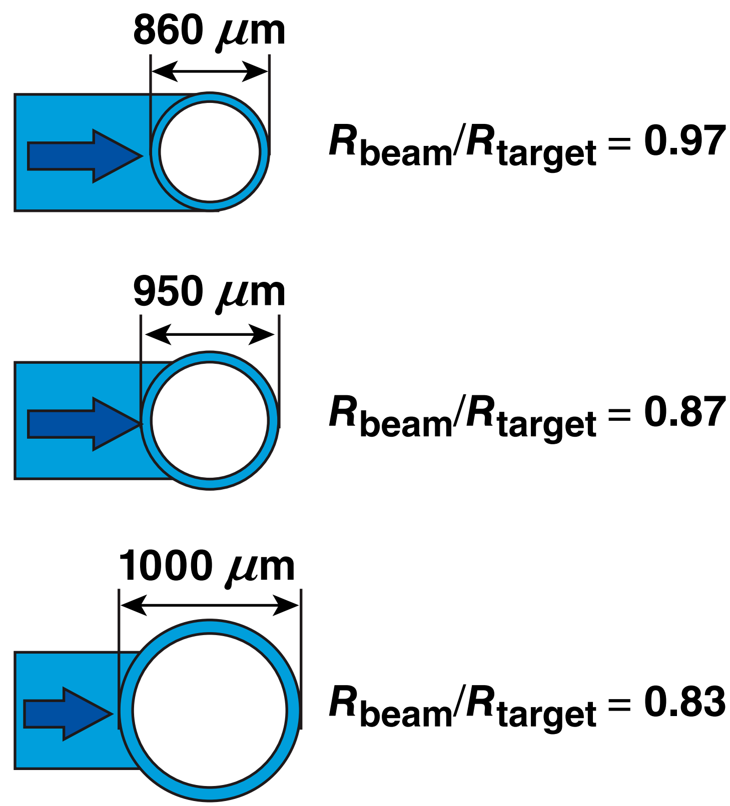


Beam profiles for different defocusing



Fixed beams

Standard SG4 phase plates



$I \approx 4.5 \times 10^{14}$ W/cm^2

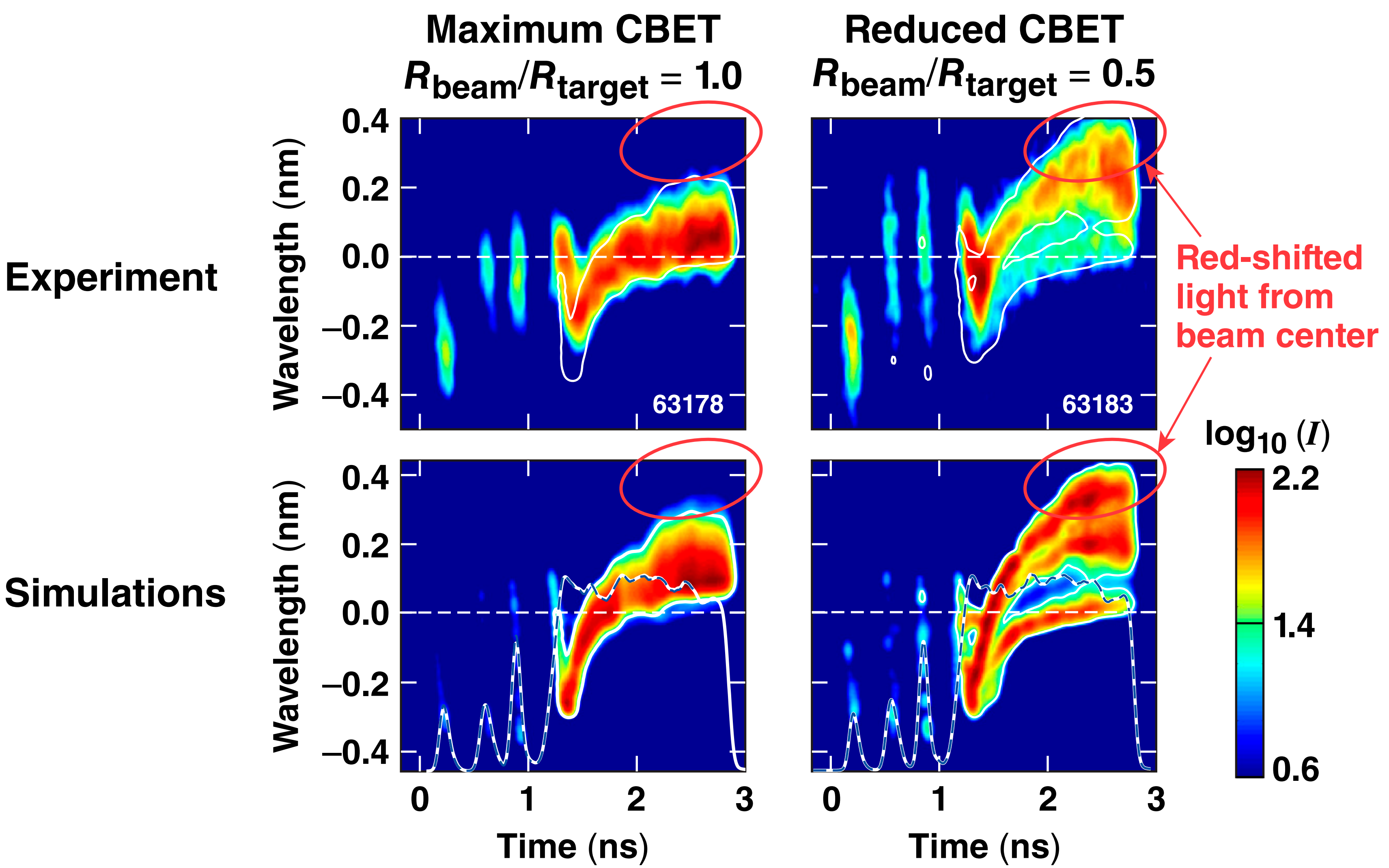
Not optimal single-beam uniformity

Optimal single-beam uniformity

TC9768

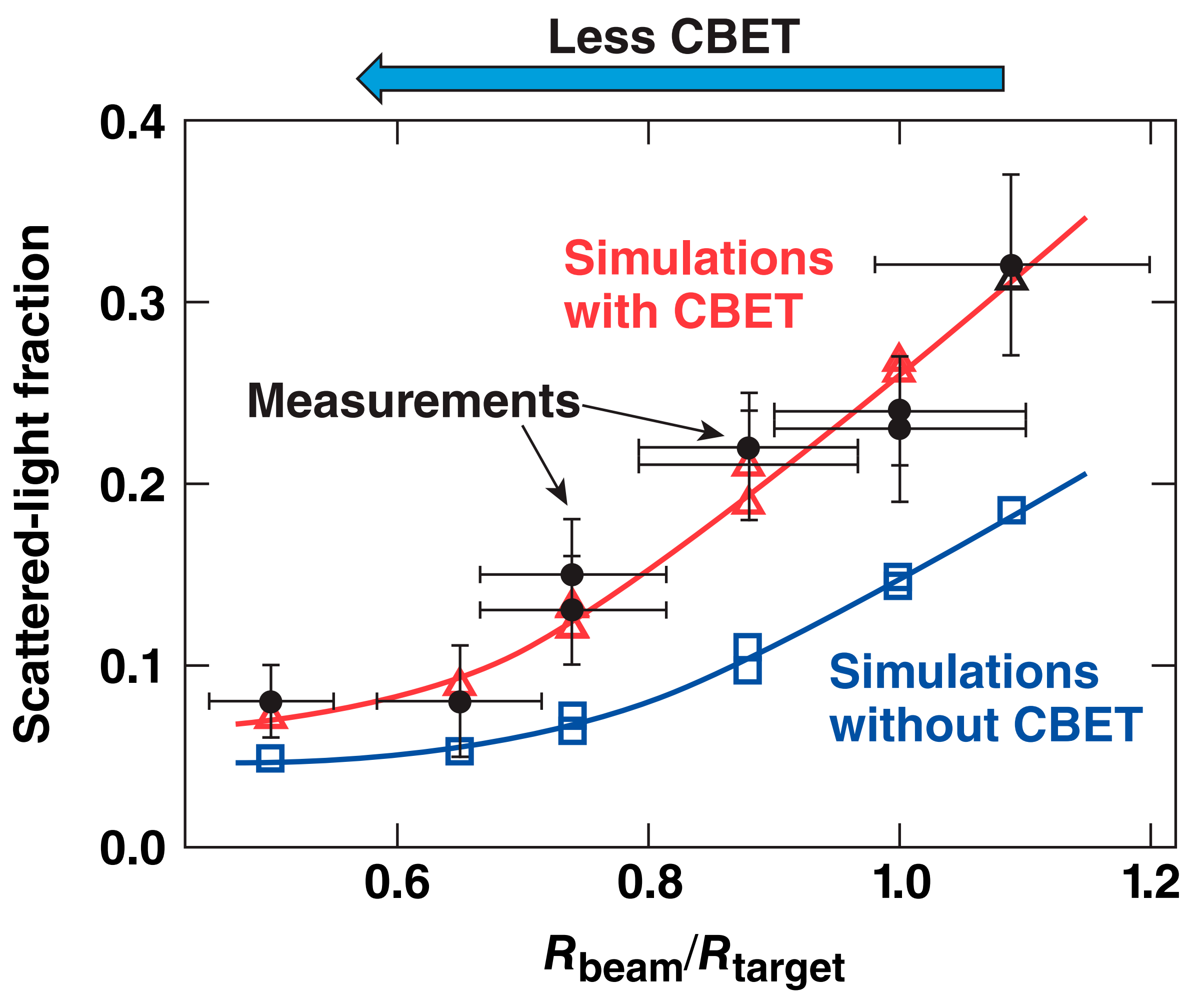
*D. Froula, UO6.00009

Experiments with small beams recover the red-shifted part of the spectrum



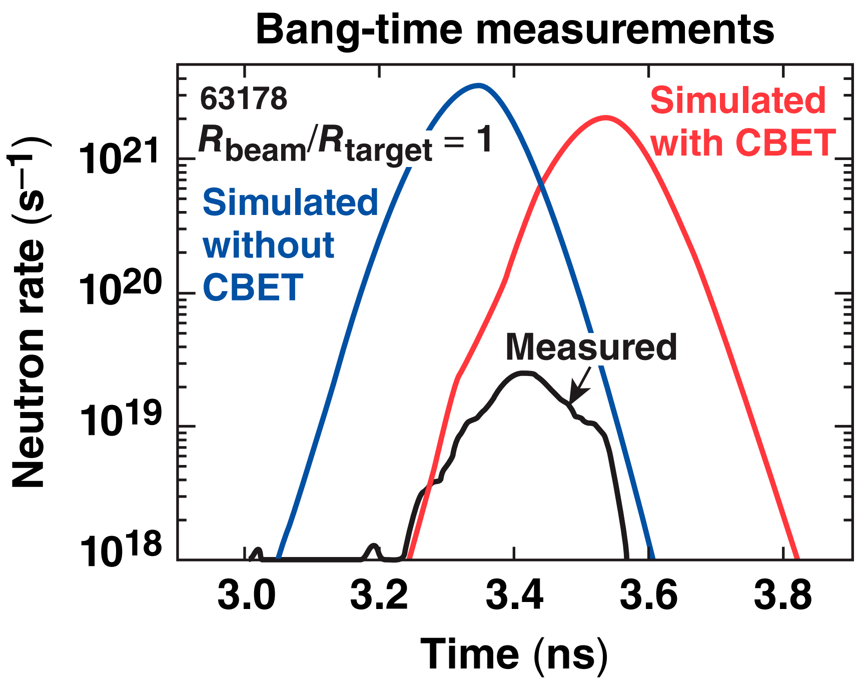
E20481b

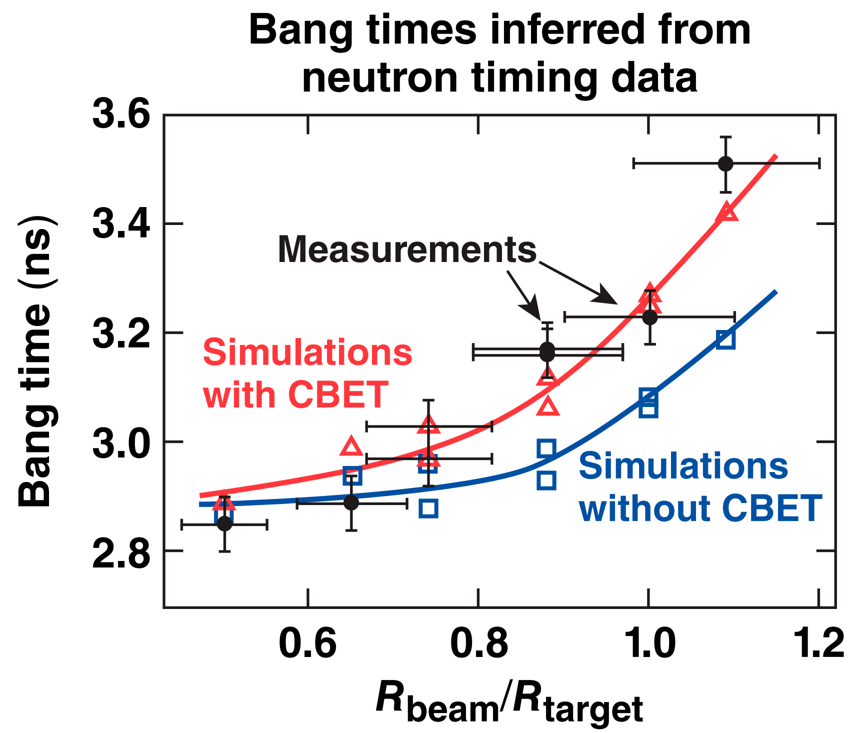
The scattered light decreases rapidly with reduced beam size



TC9770

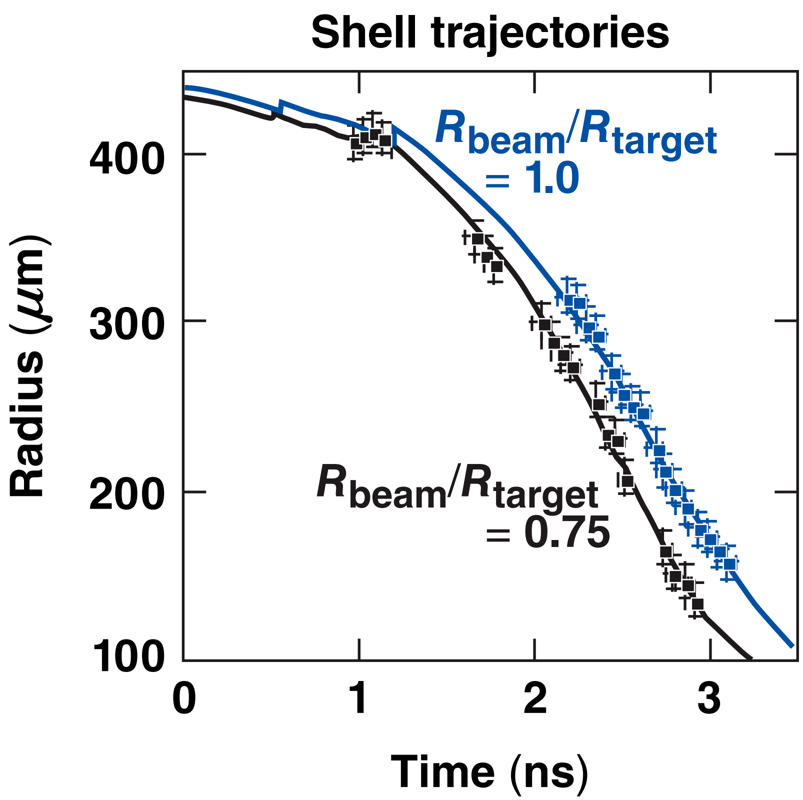
The increased absorption results in earlier bang time

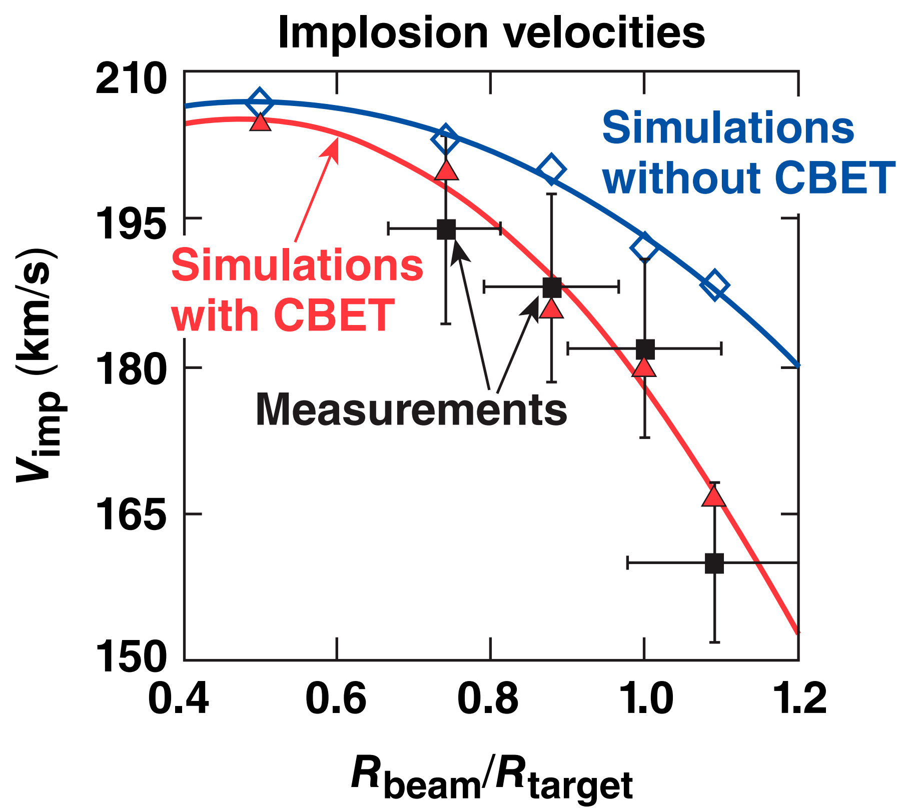




Bang time shifts ~20% earlier, indicating increasing hydro efficiency.

Higher implosion velocities are achieved with smaller beams



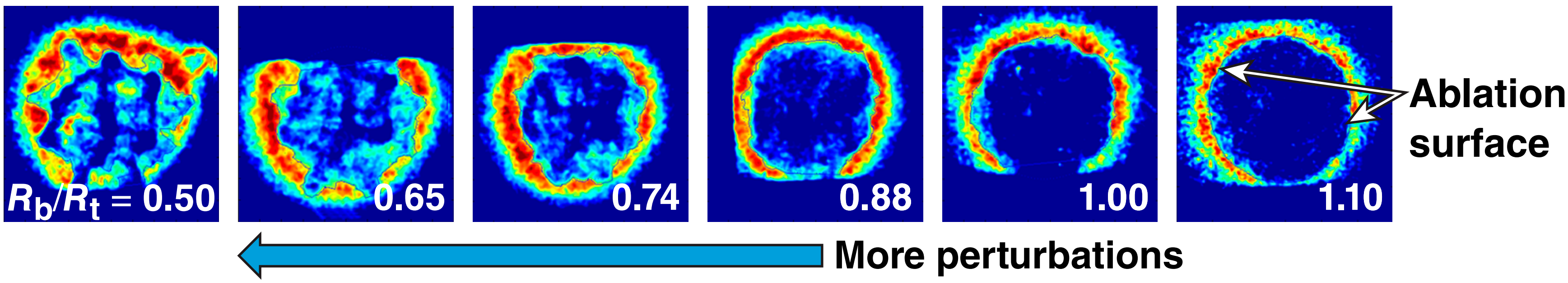


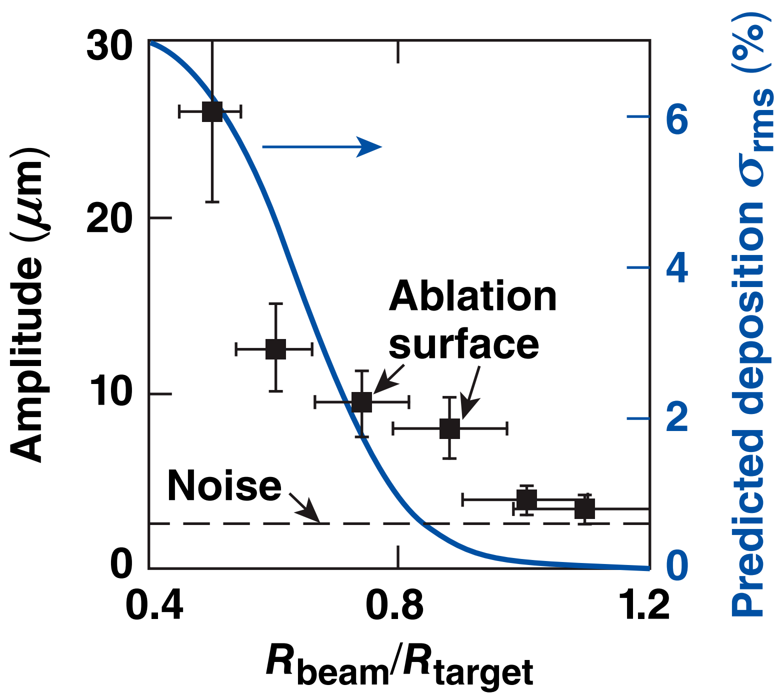
Predicted effects of small beams are consistent with scattered-light, bang-time, and shell trajectory measurements.

TC9771

Smaller beams introduce more nonuniformities caused by the laser-beam geometry

X-ray framing-camera images at the same target radius

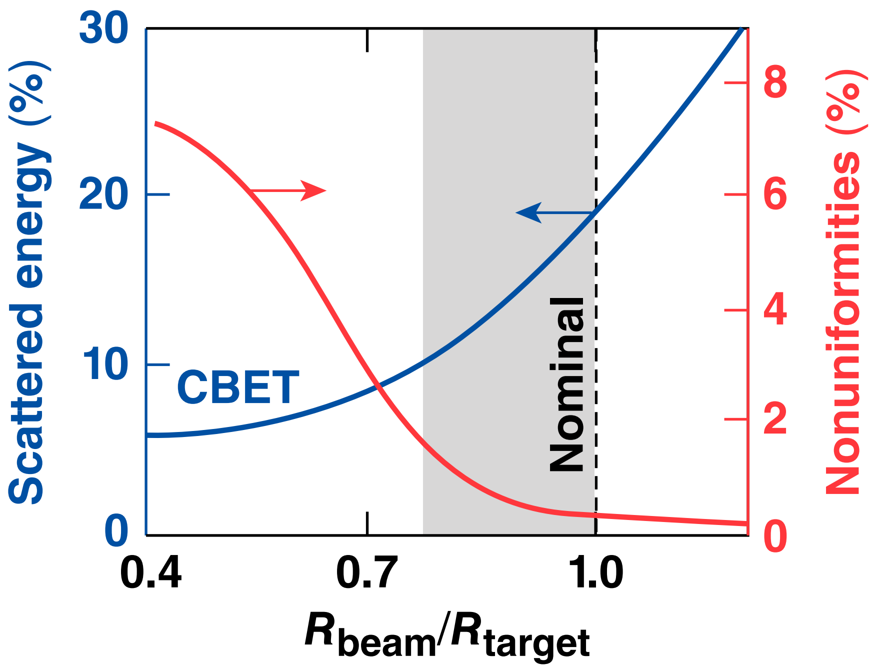




- For beam radii < 70% to ~80% of the target radius, significant nonuniformities develop
- Neutron yields in these experiments are affected by single-beam nonuniformities

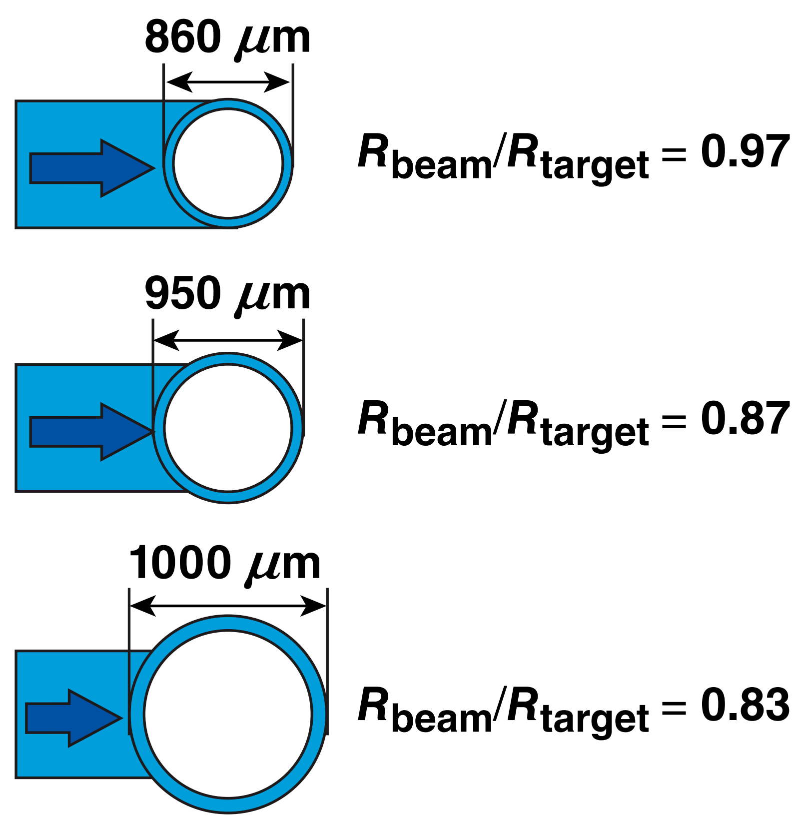
TC9772

Experiments* on OMEGA are investigating the optimum laser-beam diameter by balancing CBET with nonuniformities in low-adiabat implosions



Fixed beams

Standard SG4 phase plates

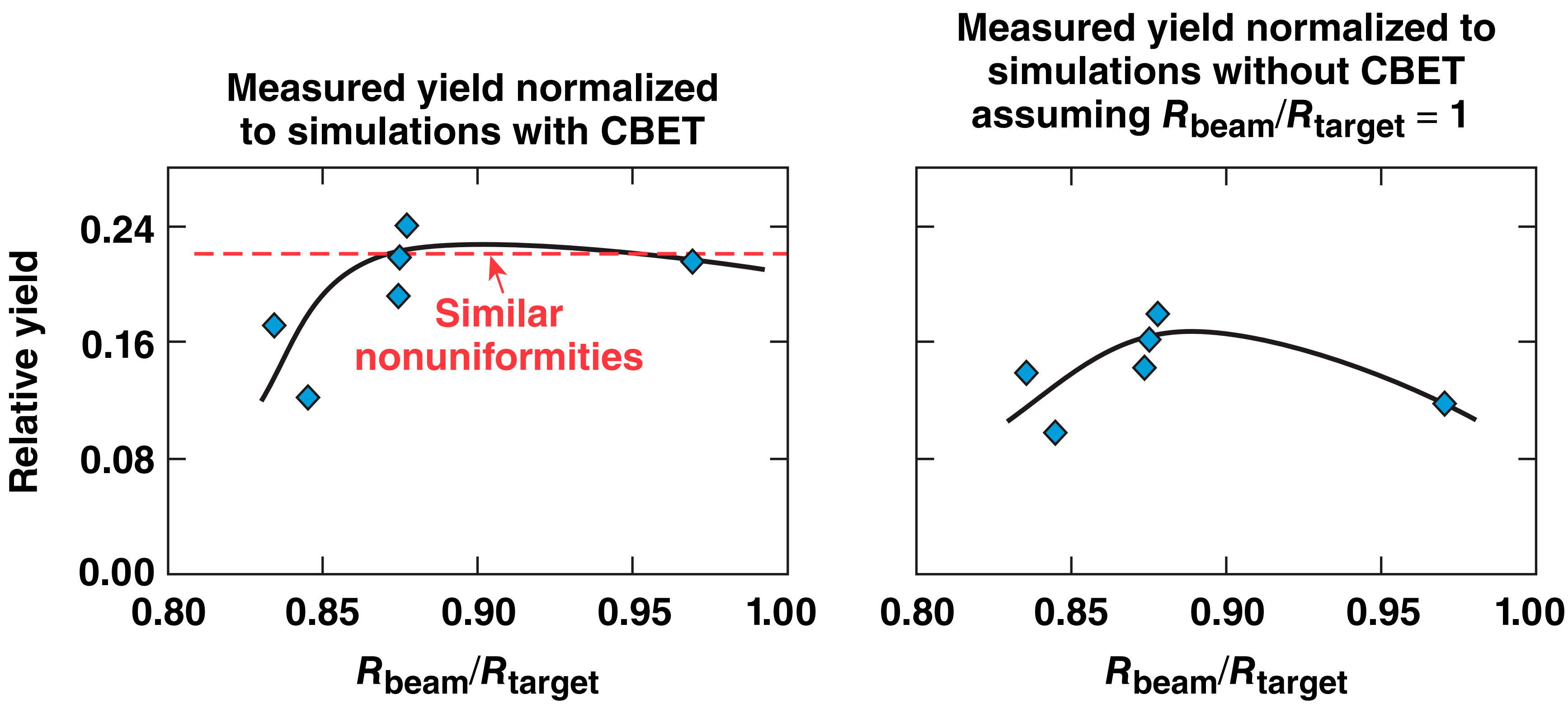


Optimal single-beam uniformity

TC9884

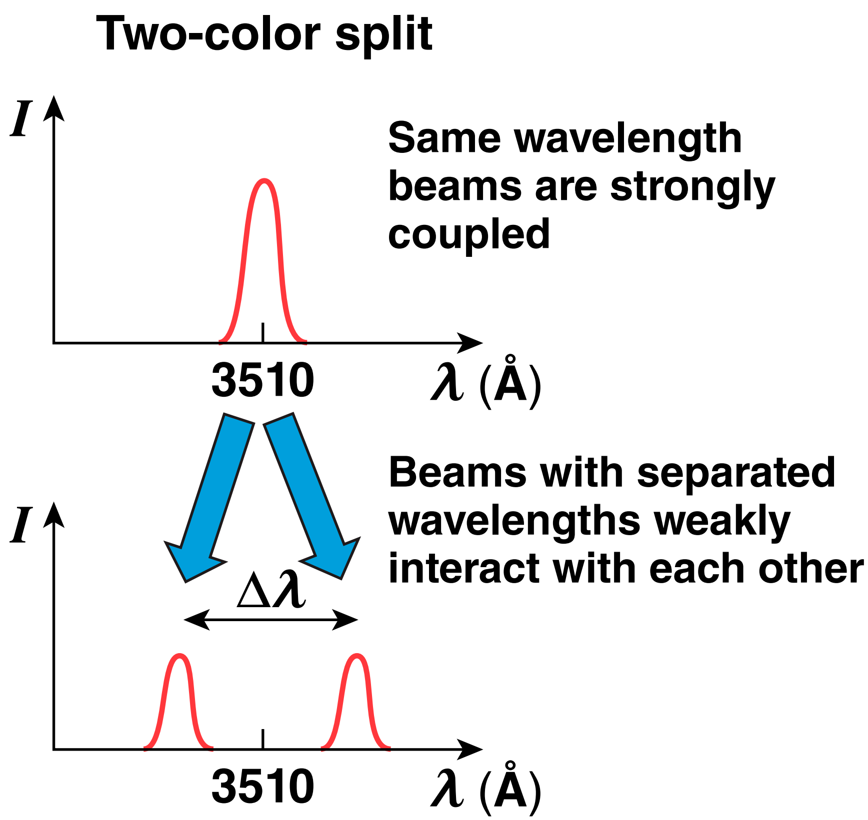
*D. Froula, UO6.00009

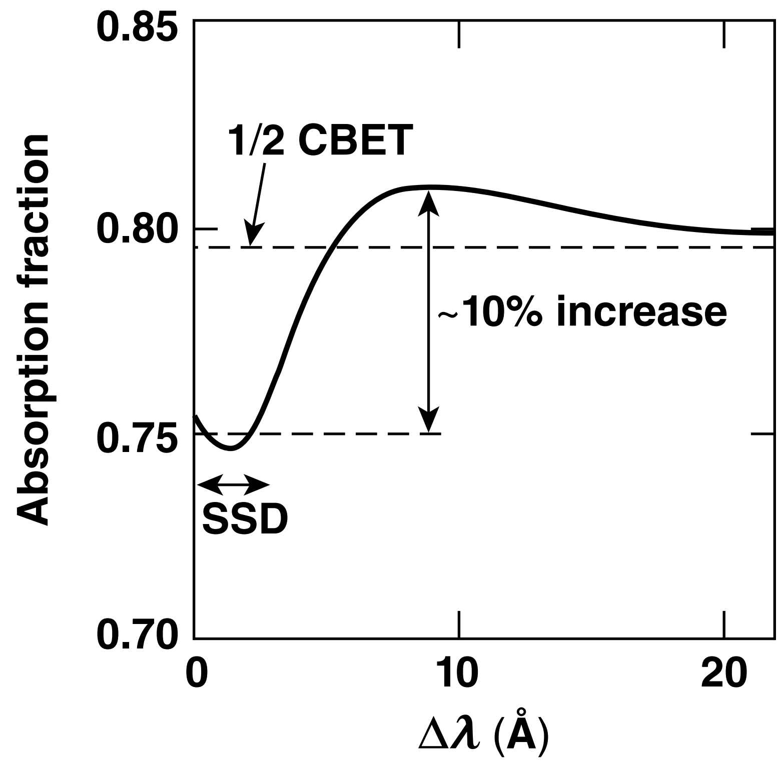
Neutron yield sensitivity was addressed in experiments with varying target size



Experiments demonstrate beneficial effects of reducing beam sizes.

CBET can be mitigated by using multiple-color laser beams





Separation of the wavelengths by $\Delta\lambda > \lambda_L(c_a/c) \sim 5$ Å (for a 351-nm laser) reduces the CBET by a factor of 2.

TC9774

Future work

- Implementation of the CBET model in 2-D* to simulate polar-drive designs
- Using truncated phase plates to mitigate CBET
- Optimization of phase plates for polar drive when including CBET

*J. A. Marozas, PO8.00003

Summary/Conclusions

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