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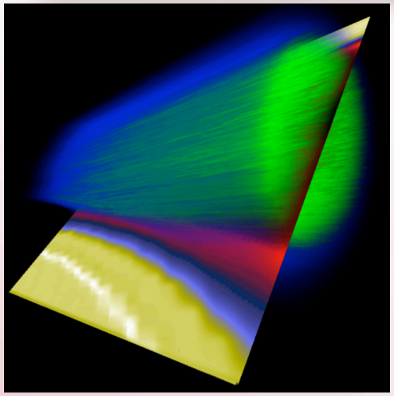
LLNL-PRES-558099

Laser-Plasma Interactions (LPI) in National Ignition Campaign (NIC) Hohlraums



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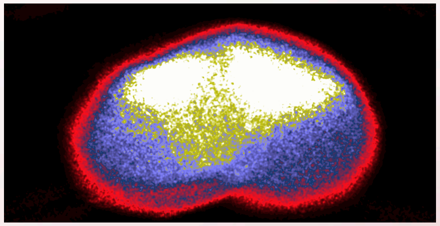

In collaboration with:
M. D. Rosen, P. A. Michel, J. D. Moody, R. L. Berger, E. A. Williams, A. B. Langdon, C. H. Still, D. A. Callahan, L. Divol, S. H. Langer, L. J Suter

May 10, 2012

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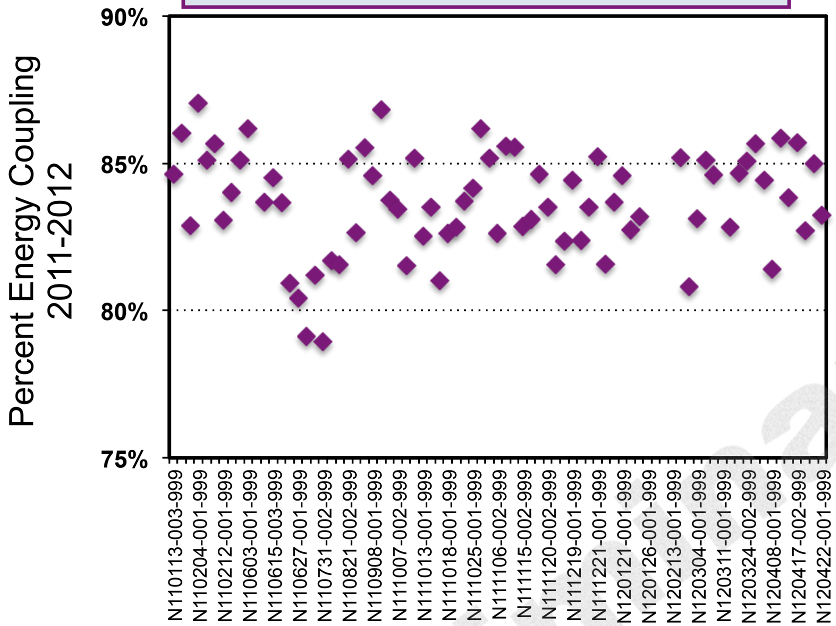
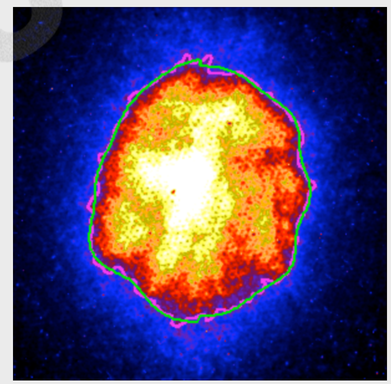
The NIC hohlraum provides high radiation drive and near-round capsule implosions

- To meet drive and symmetry requirements:

Drive: sufficient laser energy must couple to hohlraum



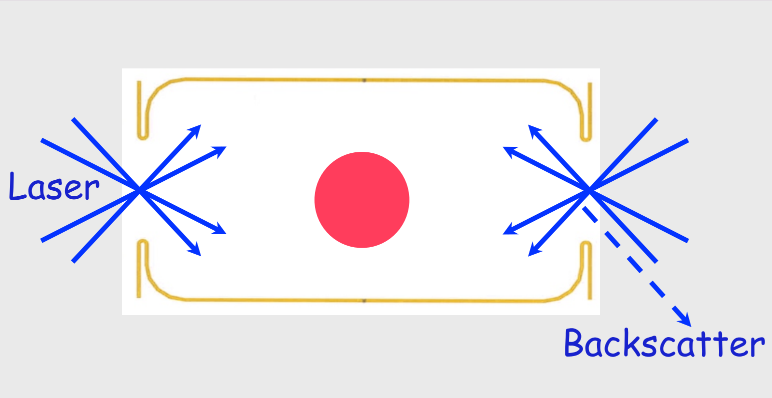
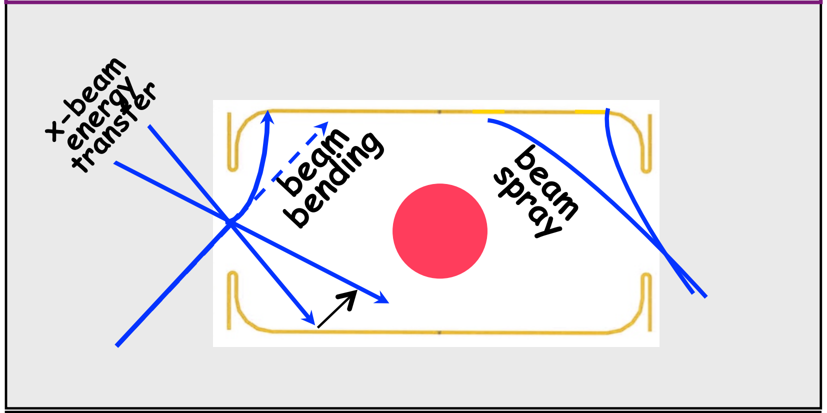
Symmetry: to within ~ 10% of round, and tunable



- NIC Laser-Plasma Interactions (LPI): reduce energy coupling; provide symmetry tuning

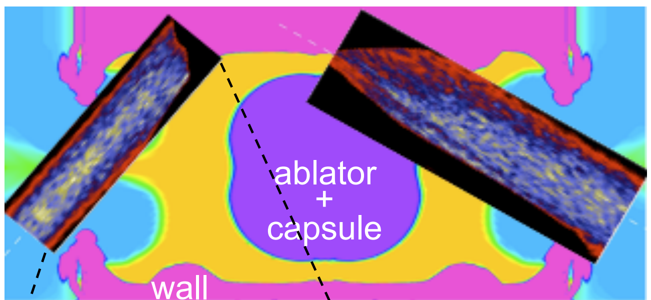
Can we improve coupling?

LPI can modify how laser energy couples to the hohlraum target

Energy Coupling ➔ T_r	Energy Re-direction ➔ symmetry change
	
SBS: laser scatters off self-generated ion acoustic waves (iaws) **SRS**: laser scatters off self-generated electron plasma waves (epws)	**Beam spray**: intensifies & scatters light **Beam bending**: moves light pattern on wall **Cross-beam transfer**: moves laser power among beams **Re-absorption of scattered light:** alters symmetry

LPI processes span a wide range of length and time scales

macroscale

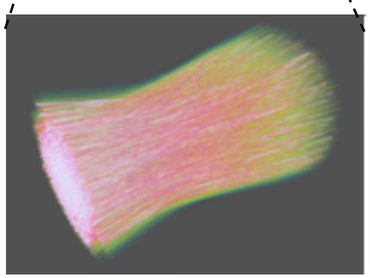


- Hydrodynamic length and time scales are set by target size **[O(mm)]** and laser pulse length **[O(ns)]**

environment -- plasma parameters and scale lengths

need accurate plasma conditions

mesoscale

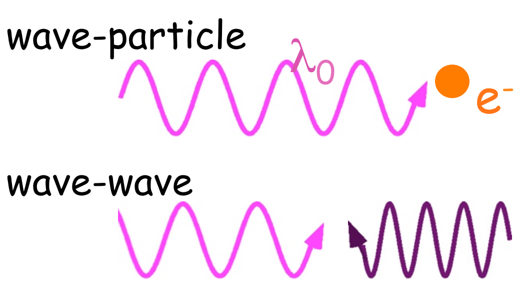


- LPI evolves on: **μm length** and **ps time** scales

beam propagation

need accurate beam model (including effects of cross-beam energy transfer, pump depletion, competition)

microscale



- Detailed processes of LPI occur on **"light" spatial and temporal scales**

kinetic effects

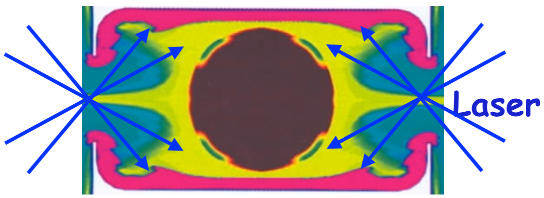
need accurate interactions – when do kinetic effects matter?

Our approach to multi-scale modeling uses a suite of tools

NIC

macroscale

Lasnex/Hydra



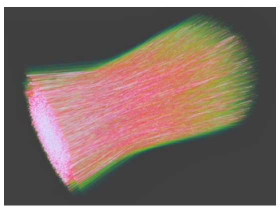
Radiation/Hydrodynamics simulations

laser energy → heat e⁻'s → make x-rays; transport; hydro motion → implosion & burn

Calculate Gain Exponent G: R = ηexp(G)

mesoscale

pF3D



Wave propagation simulations

incident laser propagation ↔ fluid plasma model ↔ scattered light propagation ↔ incident laser propagation

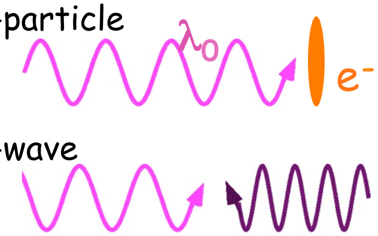
Calculate Reflectivity, Energy Deposition

microscale

Z3/BZohar

wave-particle

wave-wave



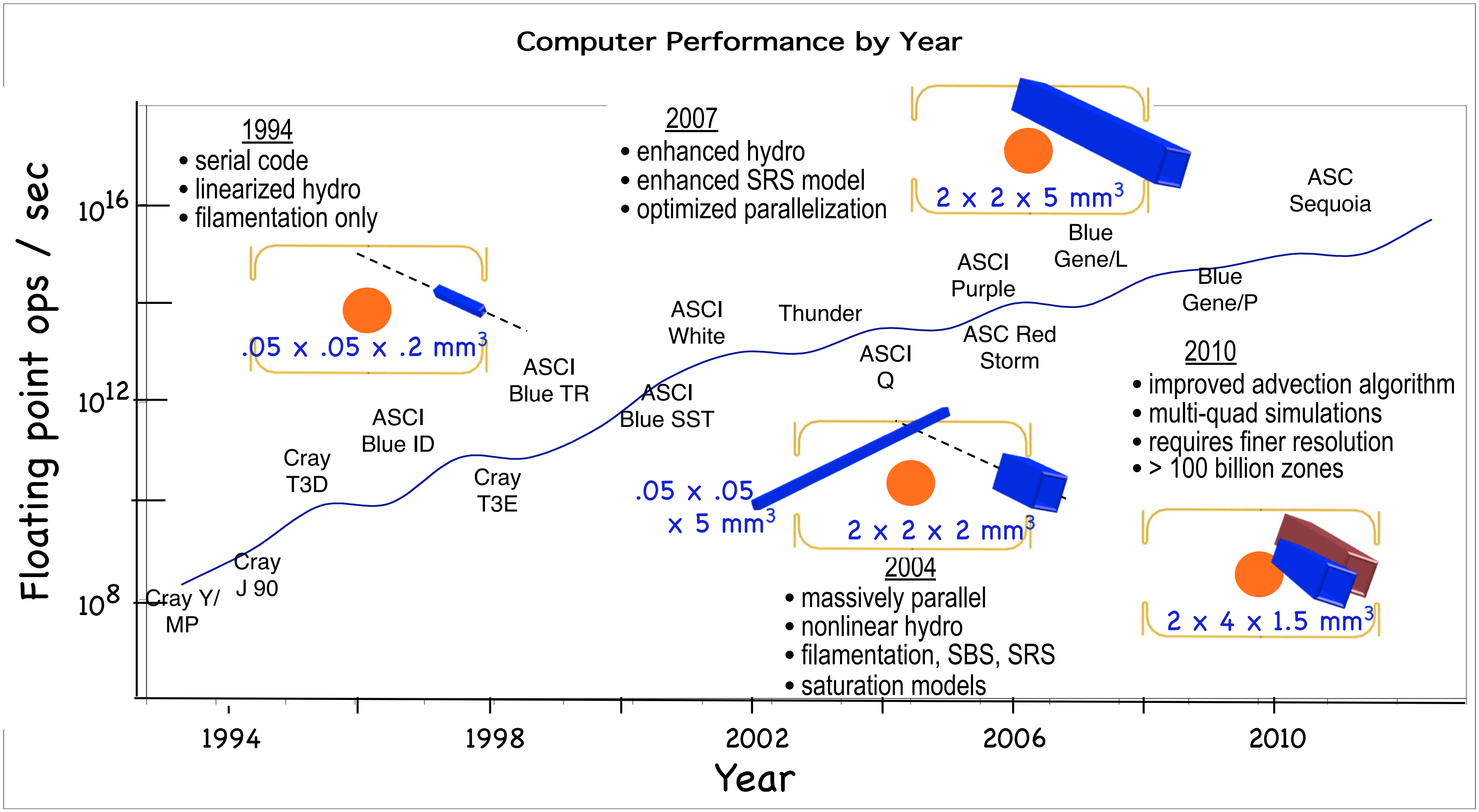
Particle in cell (PIC) simulations

particle phase space → Maxwell Equations (ρ,**j**) → EM fields → Lorentz Force → particle phase space

Study Saturation Mechanisms

At ~ 10's of petaflops, we can just begin to couple macroscale to mesoscale

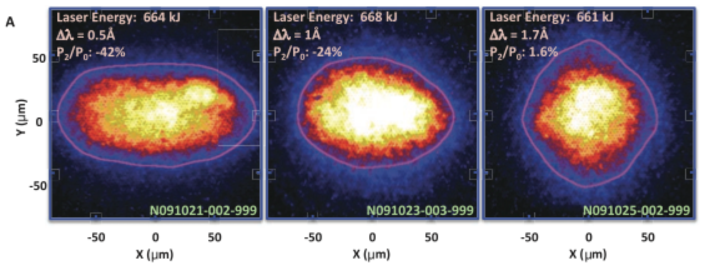
Rapidly increasing computer performance enables LPI calculations unimaginable just twelve years ago



Cross-beam energy transfer is in a non-linear, saturated regime (2009 = linear regime)

P. A. Michel

Early NIC results (2009): transfer and symmetry are indeed tunable by Δλ



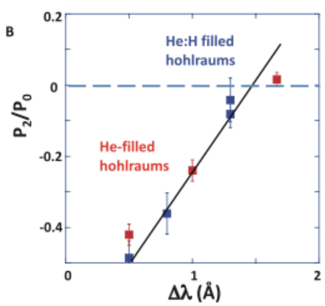


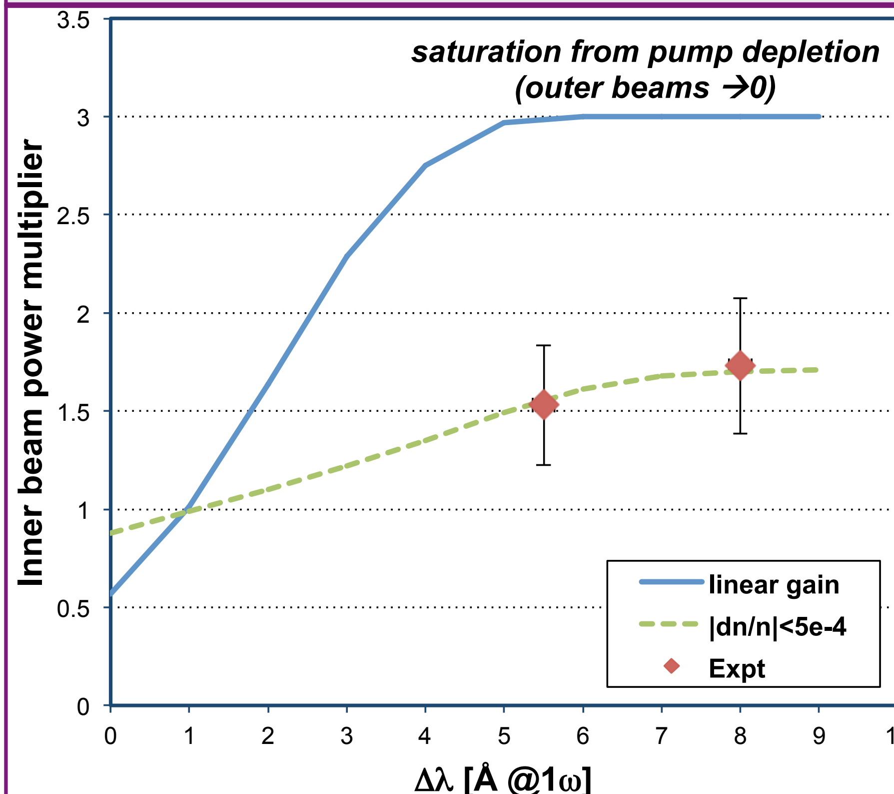
Fig. 3. (**A**) Capsule x-ray emission images at 9-keV energy from helium-filled hohlraums and 16-ns-long pulses are shown as a function of the wavelength difference between the laser beams on the inner and outer cones. Data are shown at peak x-ray emission at t = 18 ± 0.15 ns. The hohlraum axis of symmetry is vertical. (**B**) The low-order, even Legendre polynomial is shown at peak emission for helium-filled hohlraums heated with 16-ns-long laser pulses (red symbols) and hohlraums filled with a mixture of helium and hydrogen heated with a shorter, 11-ns-long pulse (blue symbols). The data indicate a linear scaling in agreement with calculations. The error bar is estimated from determining the Legendre polynomial from multiple simultaneously measured images. The dashed curve indicates a symmetric implosion, and the solid curve is the scaling calculated from two-dimensional radiation hydrodynamic simulations.

S. Glenzer et al., Science (2010)

Symmetry is now exclusively tuned by adjusting cross-beam transfer:

- **equatorial symmetry: inner vs. outer beams energy balance ("2-color")**
- **polar symmetry: 23.5° vs. 30° beams energy balance ("3-color")**

2010+: Operation at 1.5 MJ+ and larger Δλ; xbt still robust/tunable, but simulations require non-physical plasma wave saturation

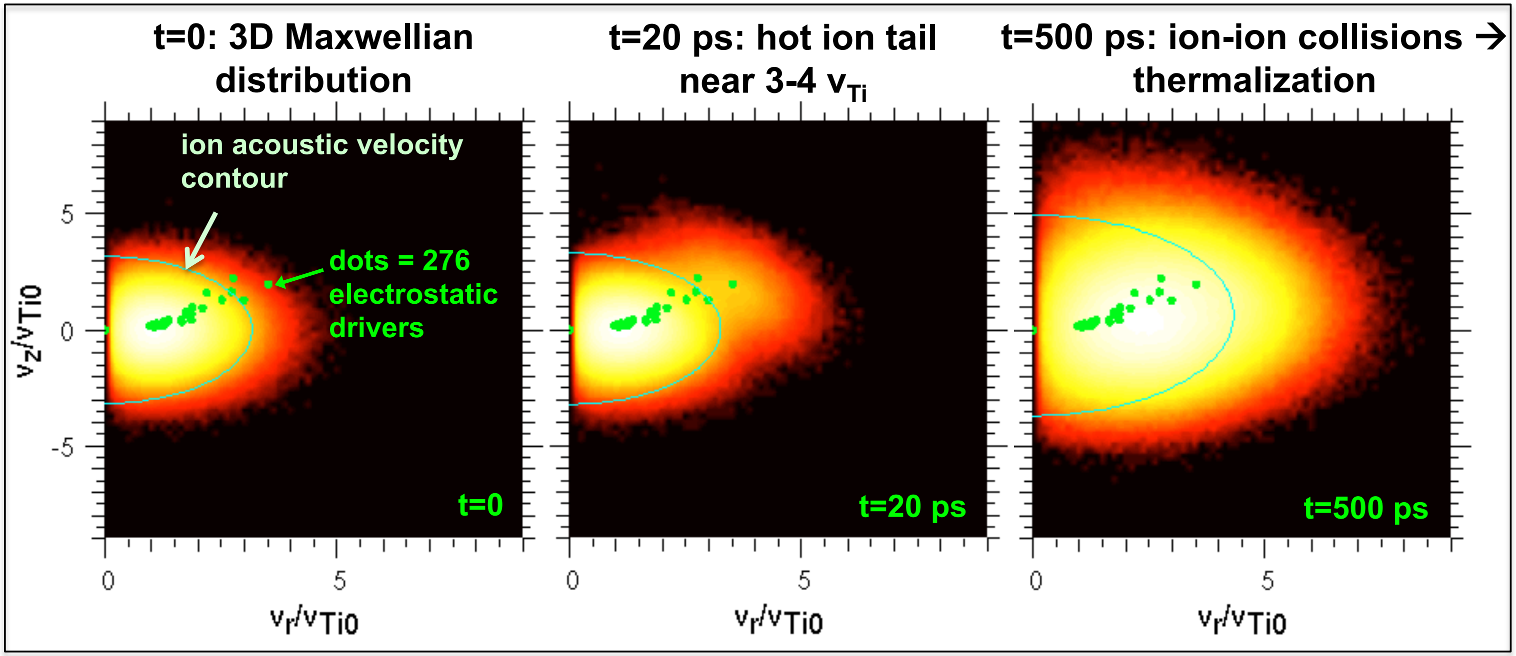


P. A. Michel finds ion heating to be a key saturation mechanism

Calculations show strong stochastic ion heating at the LEH, saturating x-beam transfer (P. A. Michel)

P. A. Michel

At each LEH: 276 possible pairs of quads (i.e. 276 beat waves, i.e. 276 electrostatic drivers): → ion acoustic turbulence



3D "gridless" particle code: self-consistent plasma response given by ion susceptibility via $f(\mathbf{v},t)$

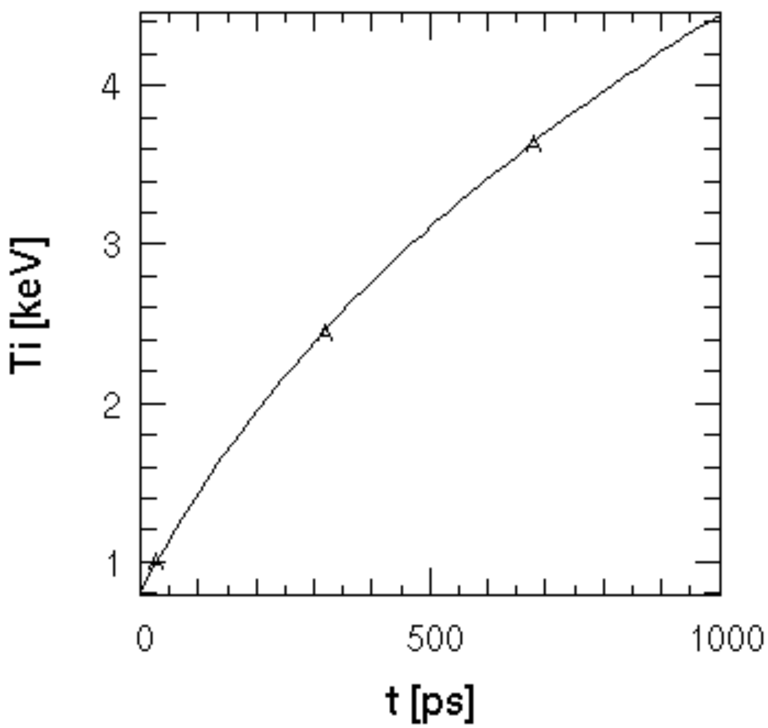
We have developed new numerical tools to calculate the effects of turbulence on cross-beam energy transfer

2012: XBT

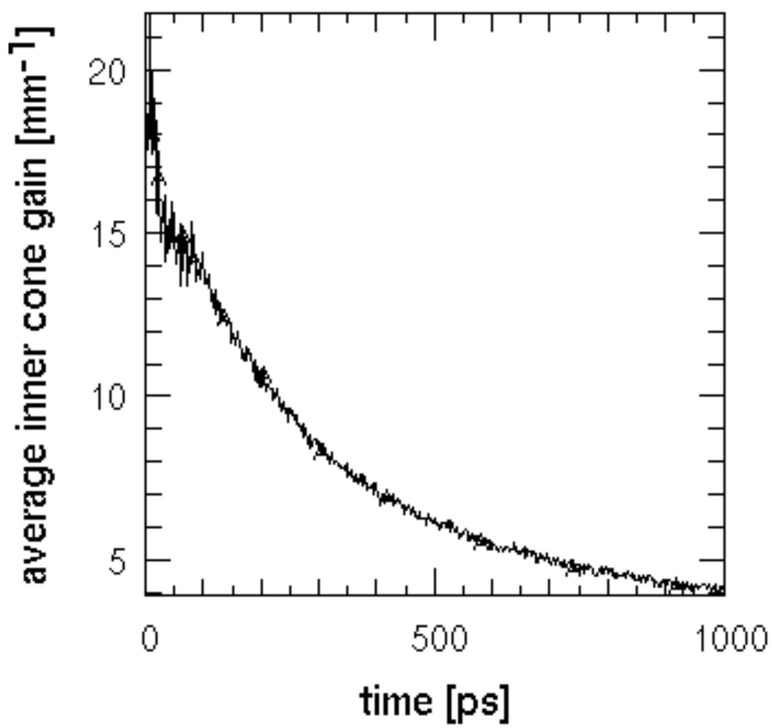
Stochastic heating → strong increase of T_{ion}, which saturates cross-beam transfer over a few 100's ps

P. A. Michel

Ion temperature increases at a rate of ~ few keV/ns



Cross-beam transfer gains decrease by 4-5x over < 1 ns



We are working on a self-consistent LPI-hydro implementation of this effect in our hydro codes

2010+: SRS/SBS

With laser and plasma modeling improvements, backscatter simulations begin to match experimental data

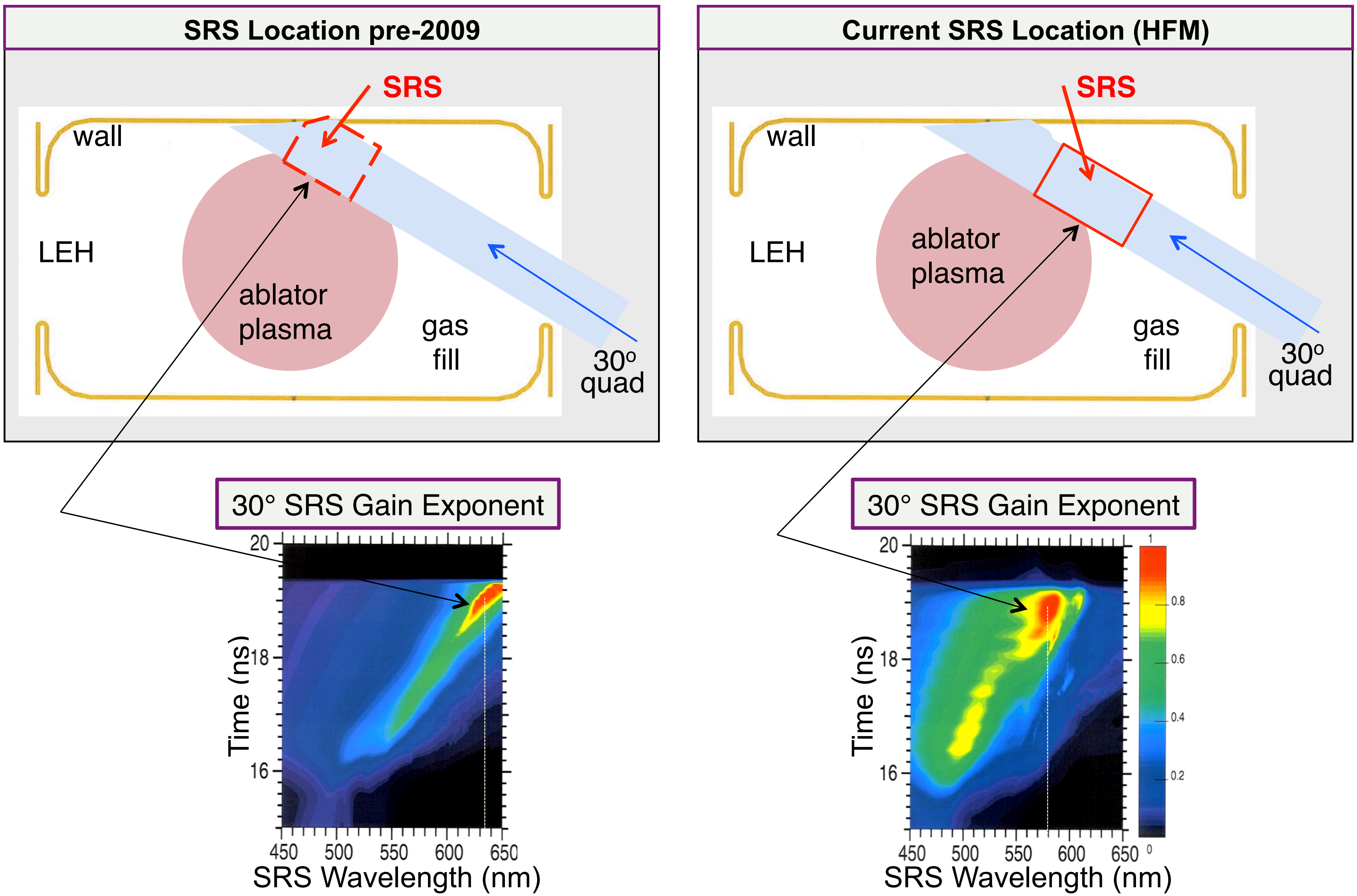
- Modified plasma conditions from improved hohlraum modeling (high flux model, or "HFM")
  - -- results in a cooler plasma – SRS region moves closer to LEH
  - -- experimental and synthetic SRS spectra show SRS at similar wavelengths

- Realistic laser beams that include the effects of cross-beam energy transfer (XBT)
  - -- increased power on inner beams (symmetry)
  - -- spatial non-uniformity in cross section

- Laser quad overlap: simulate beam propagation (pF3D) for two quads of beams (overlap contributes to the intensity; simulate 3-5 quads of beams?)

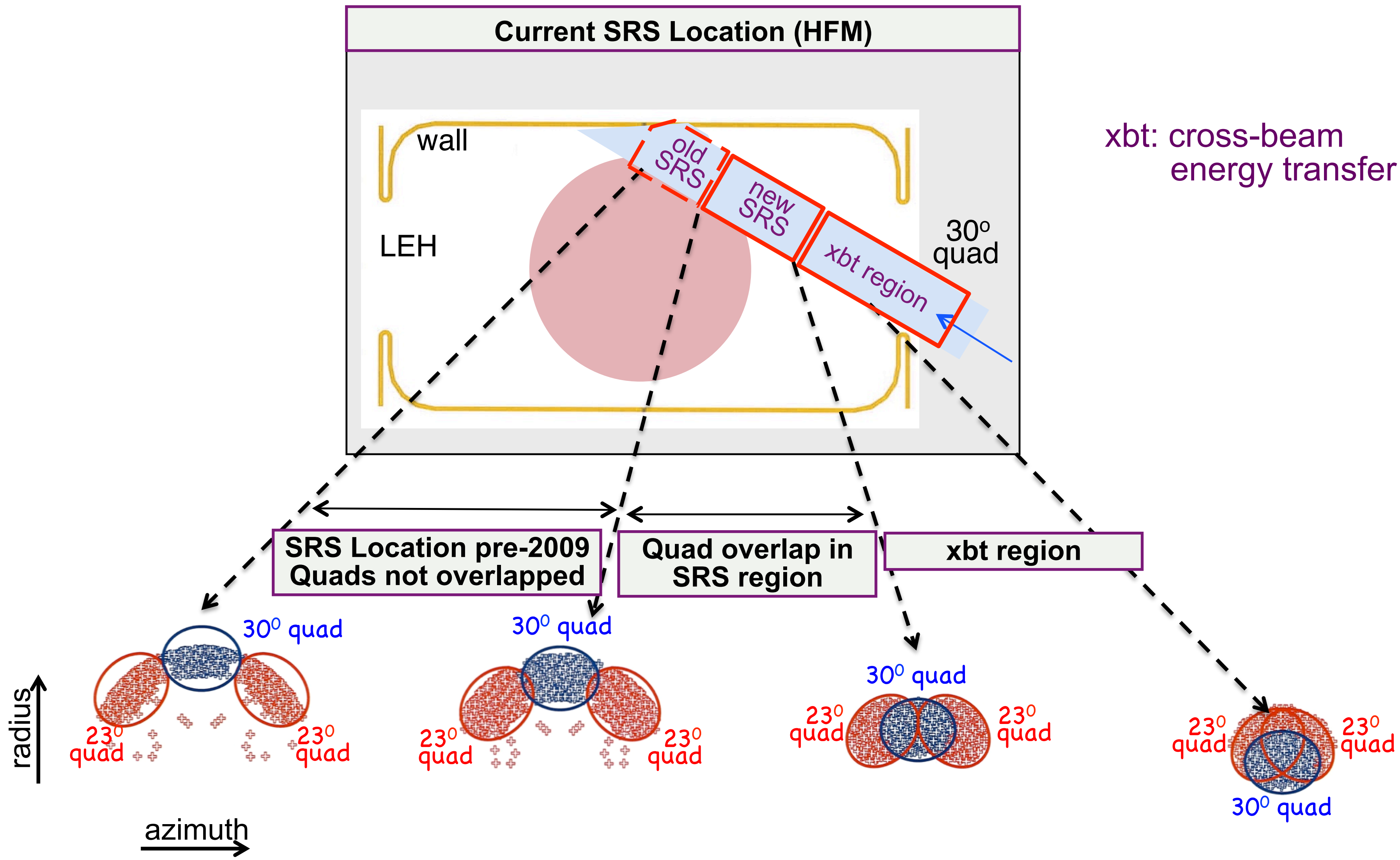
2010: SRS/SBS

LPI: Hohlraum modeling improvements (HFM) have resulted in a change in backscatter location



2010: SRS/SBS

LPI: 30° SRS now occurs where there is overlap with nearest neighbor 23° quads

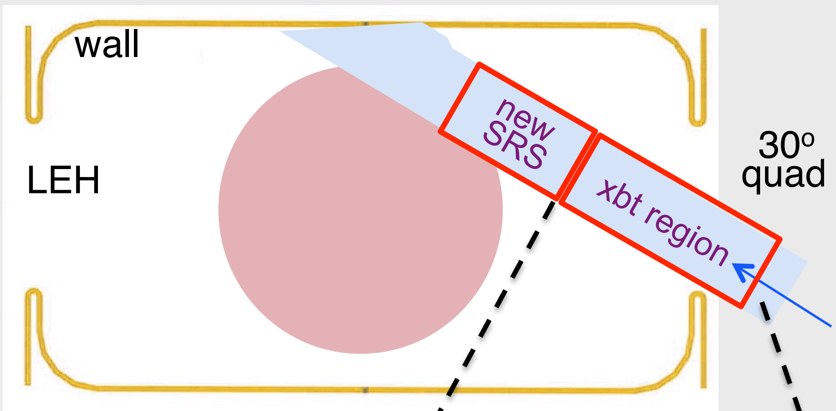


xbt: cross-beam energy transfer

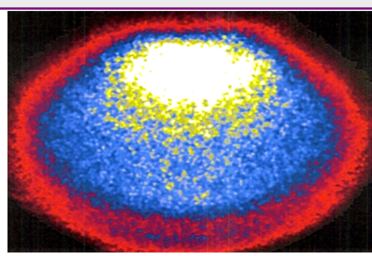
2010: SRS/SBS

LPI: Cross-beam energy transfer near the LEH results in a spatially non-uniform intensity distribution

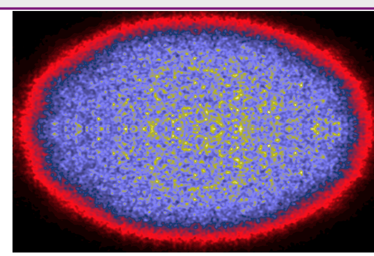
Current SRS Location (HFM)



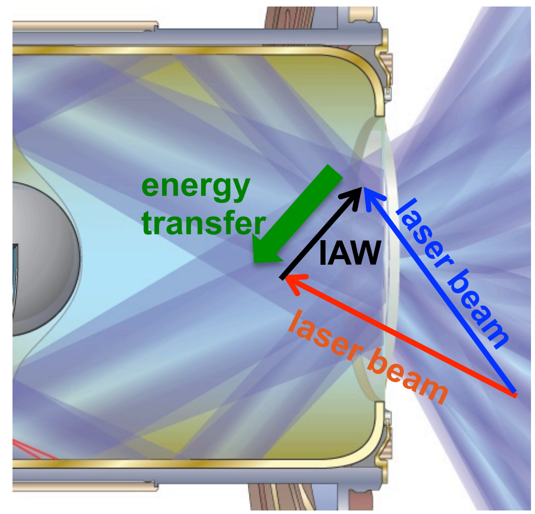
Beam after xbt, refraction, absorption



Beam before xbt, refraction, absorption



- Cross Beam Energy Transfer (xbt):
  laser forward scatters off ion acoustic waves
  (P. A. Michel *et al.*, PoP, May 2010)



2011+: SRS/SBS

NIC

A promising start: simulated reflectivity approaches experimental levels when these models are used

Experimental Result Vs Single Quad pF3D Simulations

Shot	Energy (MJ)	Time (ns)	30° SRS (TW)
N091204	1.05	19	1.3
2009 pF3D: 1 Quad pre-2009 plasma spatially uniform beam			~ 0.1
2010 pF3D: 1 Quad high flux model plasma spatially uniform beam			0.18
2011 pF3D: 1 Quad high flux model plasma spatially non-uniform beam			0.43

Experimental Result Vs Double Quad pF3D Simulations

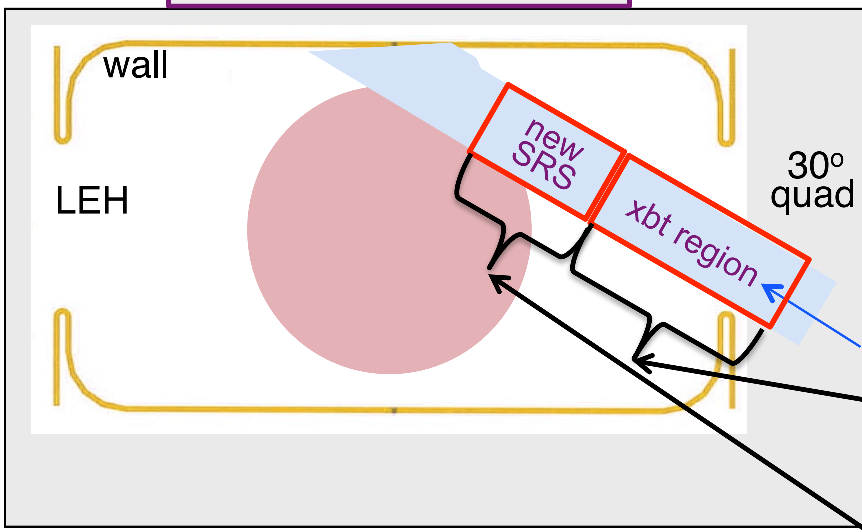
Shot	Energy (MJ)	Time (ns)	30° SRS (TW)
N091204	1.05	19	1.3
2010 pF3D: 2 Quads high flux model plasma spatially uniform beams			0.62
2011 pF3D: 2 Quads high flux model plasma spatially non-uniform beams			0.67
2012 pF3D: 3 Quads high flux model plasma spatially non-uniform beams			~0.9-1.0

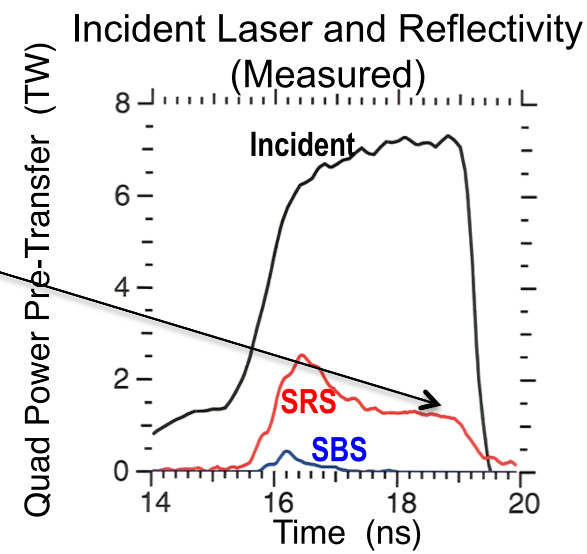
Simulation in progress on Dawn machine

2010: SRS/SBS

Proof-of-principle simulation: propagate two quads (23°, 30°) through the resonance region

Simulation @ 19 ns
1.05 MJ Laser Energy
N091204





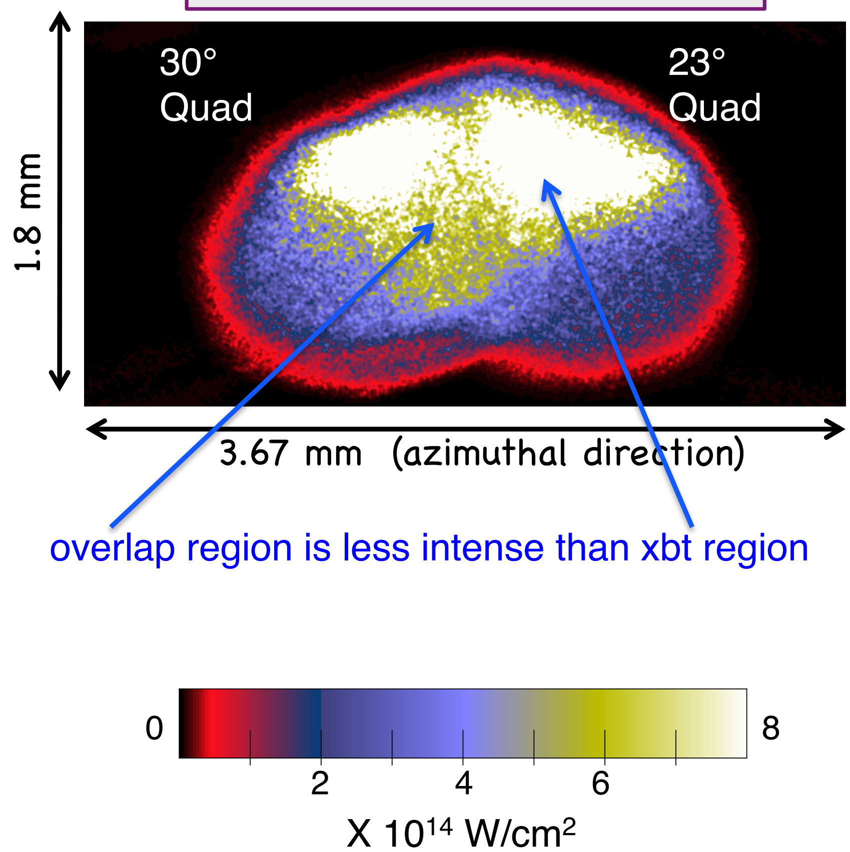
- Laser Input: use SLIP* to propagate quads through the LEH to the input plane (*E. A. Williams*)
- pF3D: propagate two quads of beams (23°, 30°) through SRS region (*A. B. Langdon*)

*SLIP code, P. A. Michel and L. Divol

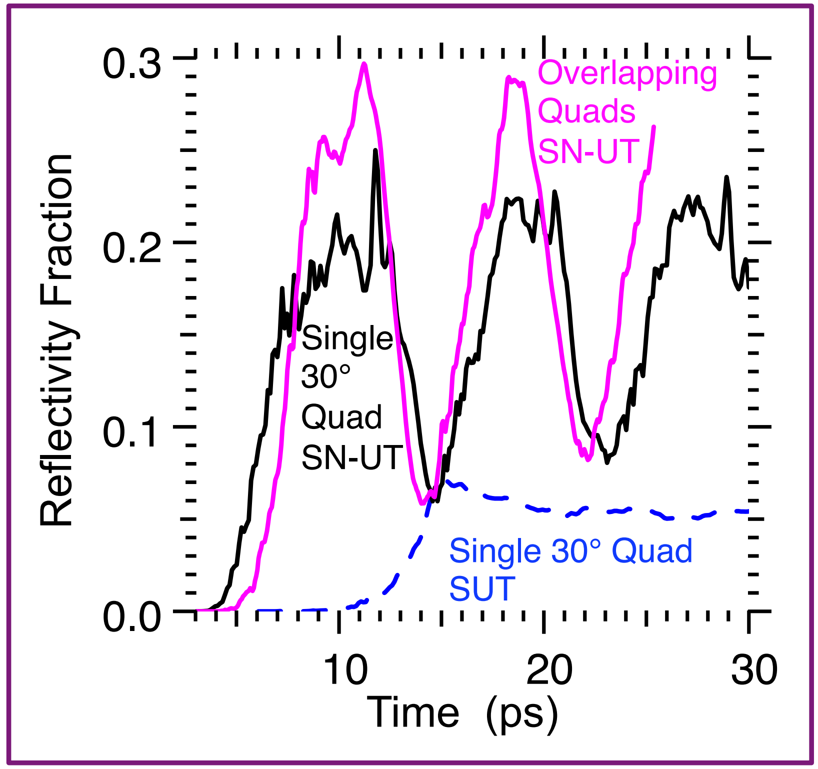
2010+: SRS/SBS

Both quad overlap and spatial non-uniformity increase reflectivity

Laser Quads on Input Plane to “New SRS” Region



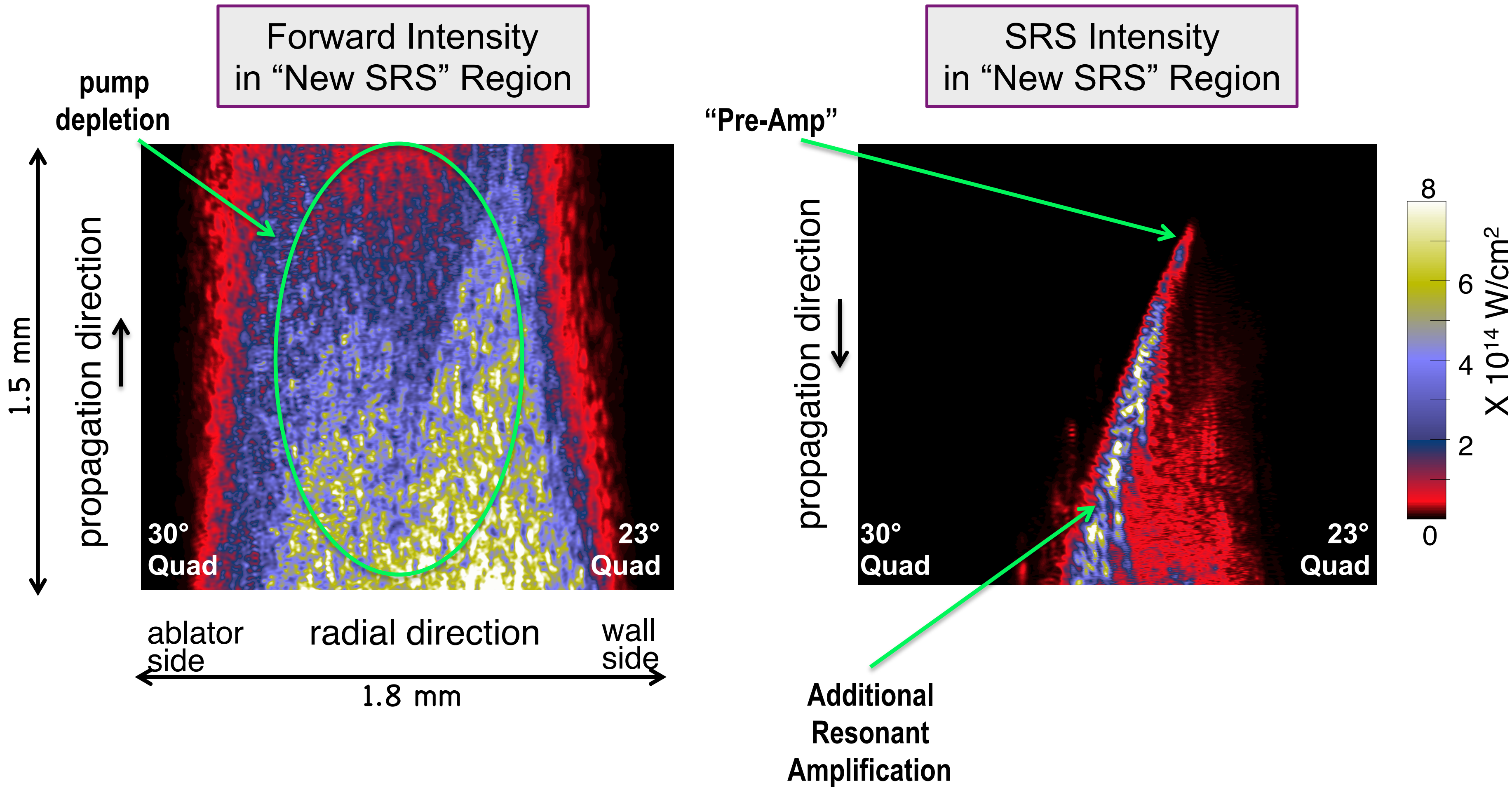
SRS Reflectivity on Input Plane of “New SRS” Region



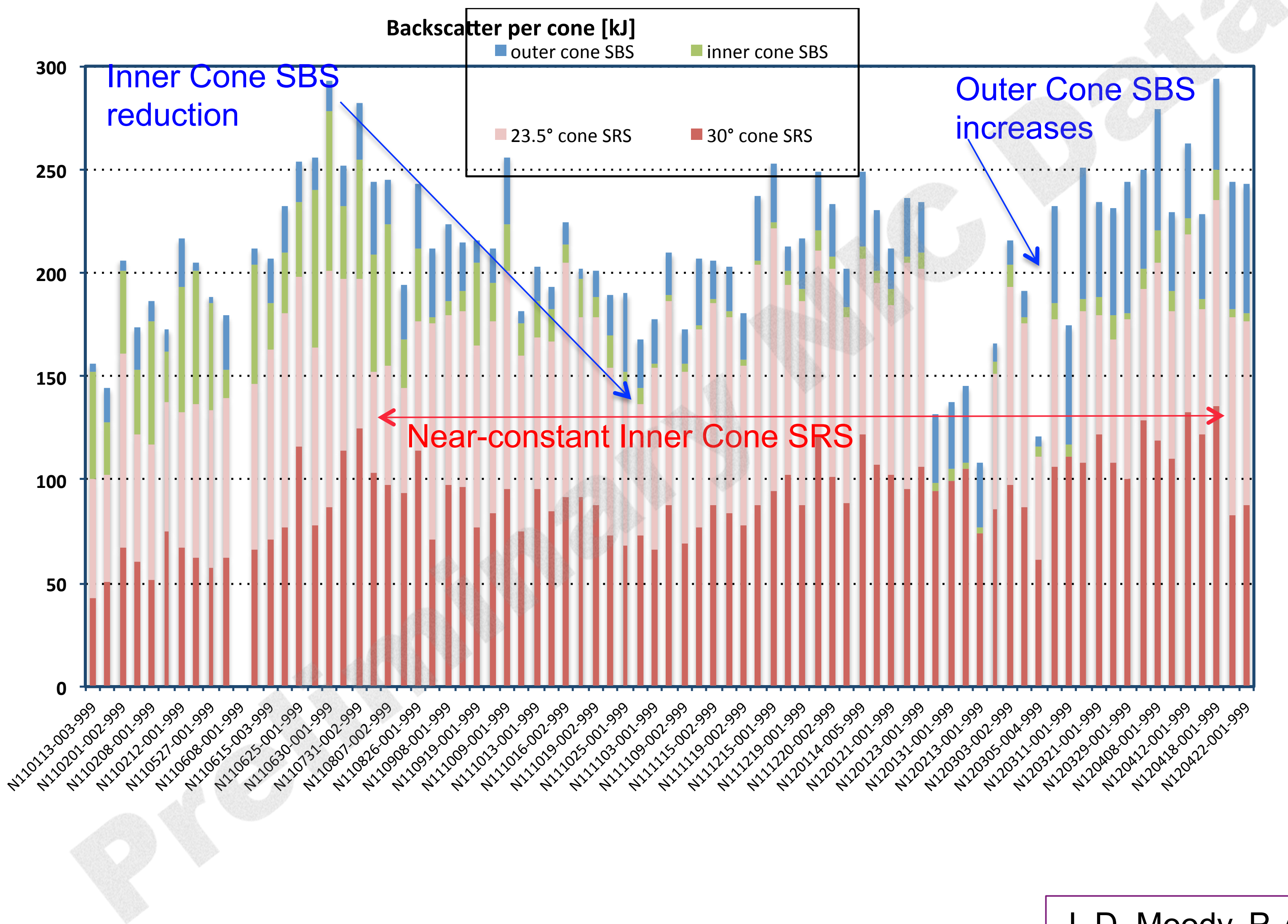
SUT = Spatially Uniform Transfer
SN-UT = Spatially Non-Uniform Transfer

*We thank the Office of Science INCITE program for computational resources and the ALCF staff for computational support

SRS generated by single quads is resonantly amplified in the overlap region

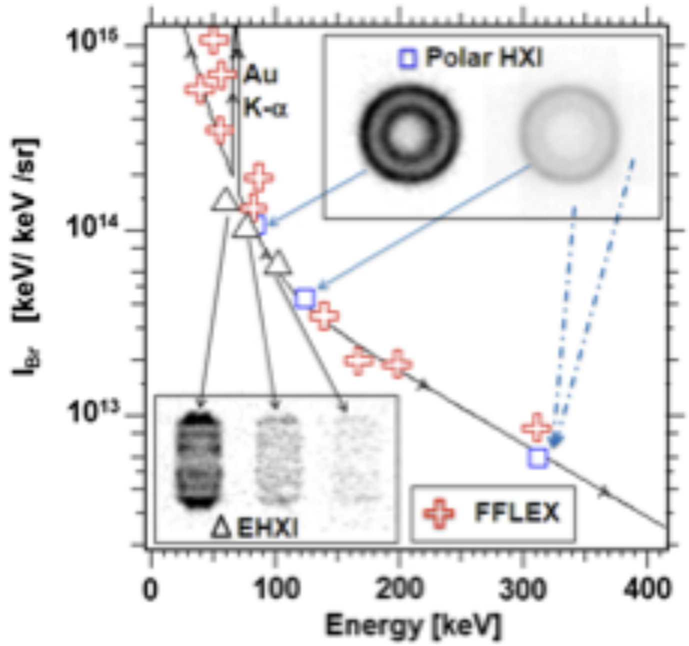


2011-2012 backscatter levels:



J. D. Moody, P. A. Michel

A typical NIC hot electron spectrum:



What are the leverage points for improved coupling, and how do we best manipulate them?

(1) $$G = \int_{z_0}^{z_f} dz' \left\{ \frac{k_0^2 \mathrm{v}_{\mathrm{osc}}^2 \omega_{p2}^2}{\mathrm{v}_1 \omega_0 \omega_2} \frac{\Gamma_2}{\Gamma_2^2 + \mathrm{v}_2^2 \mathrm{K}'^2 z'^2} - \frac{\Gamma_1}{\mathrm{v}_1} \right\}$$

0 = incident; 1 = reflected; 2 = plasma wave

$\Gamma \equiv$ damping rate

$\omega_{p2} \equiv$ plasma freq.

v = group velocity

$$\mathrm{v}_{\mathrm{osc}} \equiv c\sqrt{I\lambda^2 / 1.37x10^{18}}$$

CAPABILITIES FOR IMPROVED UNDERSTANDING:

- LPI depends on n_e, T_e, T_i (Γ, ω_2, ω_{p2}, K', k_0)
  - -- currently inferred from HFM rad-hydro simulations
  - -- Thomson scatter/spectroscopy provides experimental opinion
    - (i) optical Thomson scatter at LEH;
    - (ii) dope various regions of target?
- Reflectivity in pF3D/VPIC simulations show pumps depletion
  - -- corroborate with time-resolved (~ 1-2 ps) backscatter diagnostic
- Integration of multi-scale modeling:
  - -- requires exaflops
- LPI Computational Physicists

(1): E. A. Williams, generalized Rosenbluth gain; applies to backscatter, xbt

What are the leverage points for improved coupling, and how do we best manipulate them?

$$G = \int_{z_0}^{z_f} dz' \left\{ \frac{k_0^2 v_{osc}^2 \omega_{p2}^2}{v_1 \omega_0 \omega_2} \frac{\Gamma_2}{\Gamma_2^2 + v_2^2 K'^2 z'^2} - \frac{\Gamma_1}{v_1} \right\}$$

0 = incident; 1 = reflected; 2 = plasma wave

$\Gamma \equiv$ damping rate

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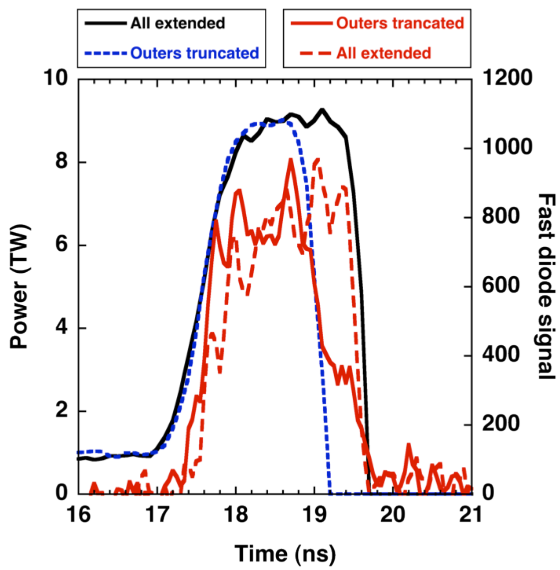
v = group velocity

$v_{osc} \equiv c\sqrt{I\lambda^2 / 1.37x10^{18}}$

DESIGNS/EXPTS FOR IMPROVED UNDERSTANDING AND COUPLING:

- Design a target to mock up xbt at LEH:
  - -- measure beam transmission through xbt region (LPI depends on laser intensity)
  - -- provides information on spatial non-uniformity of beams after xbt

- Design a target that doesn't require xbt for symmetry
  - -- doesn't require knowledge of beam cross section to understand backscatter
  - -- might reduce inner cone SRS/hot electrons
  - -- increase T_e by doping higher-Z material into foam fill?
  - -- hybrid foam-fill/vacuum hohlraum?



- Design an "SBS-only" target
  - -- tests our understanding of hot electrons
  - -- improved coupling?

What are the leverage points for improved coupling, and how do we best manipulate them?

$$G = \int_{z_0}^{z_f} dz' \left\{ \frac{k_0^2 v_{osc}^2 \omega_{p2}^2}{v_1 \omega_0 \omega_2} \frac{\Gamma_2}{\Gamma_2^2 + v_2^2 K'^2 z'^2} - \frac{\Gamma_1}{v_1} \right\}$$

0 = incident; 1 = reflected; 2 = plasma wave

$\Gamma \equiv$ damping rate

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v = group velocity

$$v_{osc} \equiv c\sqrt{I\lambda^2 / 1.37x10^{18}}$$

LPI MITIGATION/CONTROL:

- Laser Technology Improvements (affect laser intensity)
  - -- increased bandwidth
  - -- STUD Pulses (B. B. Afeyan)
  - -- increase spot size?
- Reduce scalelength over which SRS/SBS amplifies:
  - -- introduce density inhomogenieties (“zebra foam fills”)
  - -- introduce temperature inhomogenieties (embedded high-Z materials in hohlraum fill?)
- Reduce n_e in hohlraum:
  - -- shape hohlraum (rugby?) to increase volume between capsule and wall
  - -- reduces backscatter; less xbt required
- Increase T_e in hohlraum:
  - -- improves beam propagation
  - -- reduces backscatter; less xbt required
- Increase damping, reduce ne, increase T_e:
  - -- alternate materials for hohlraum fill, ablator, wall

Increased capabilities, dedicated experiments, and testing LPI mitigation will promote improved coupling in ignition hohlraums

CAPABILITIES	EXPERIMENTS	CONTROL/MITIGATION
• Thomson Scatter (optical, x-ray) • Spectroscopy • Time-resolved backscatter diagnostic • HPC allocation -- meso/macro-scale cplg -- meso/micro-scale cplg -- expand at mesoscale • Dedicated computational physicist to LPI	• Transmitted beam thru xbt region • Hohlraum that doesn't require xbt for symmety • Hohlraum that only generates SBS	• LASER: -- bandwidth -- STUD pulses • PLASMA: -- increase T_e (add high-Z fill dopant) -- reduce density (change hohlraum shape) -- introduce inhomogeneities ("zebra" foam fills) -- improve beam propagation, increase damping (alternate ablators, fills, walls, high-Z dopants)


NIC