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The role of laser-plasma interactions in laser energy coupling at the National Ignition Facility

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**Joint Meeting of the 19 Topical Conference
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Newport, Rhode Island, USA
June 1, 2011**

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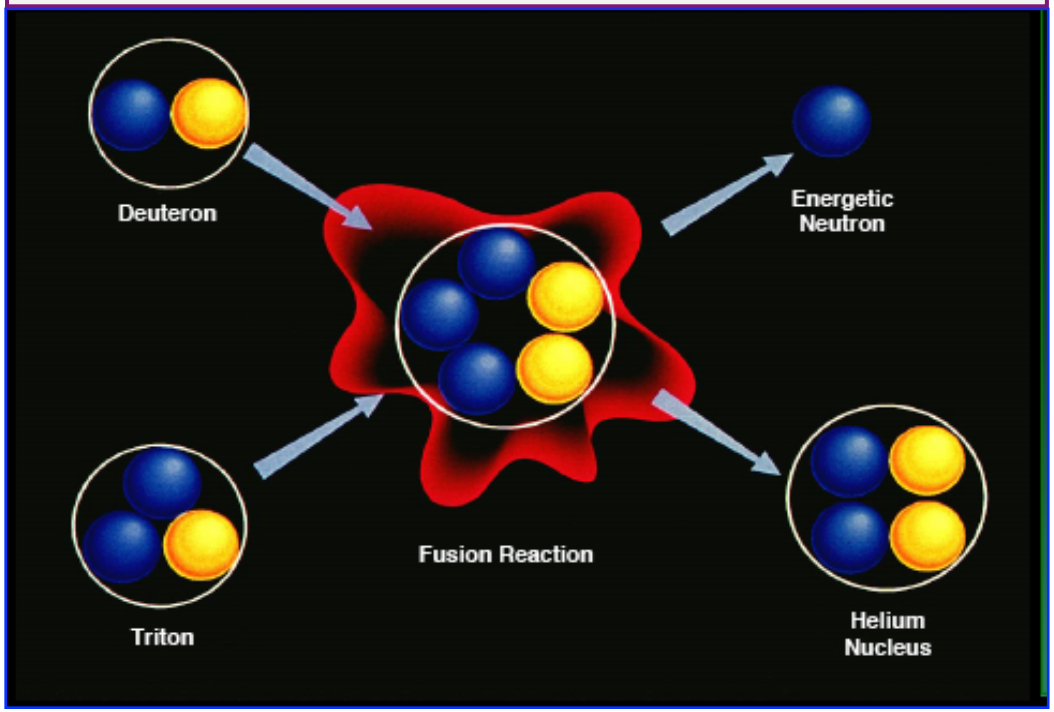
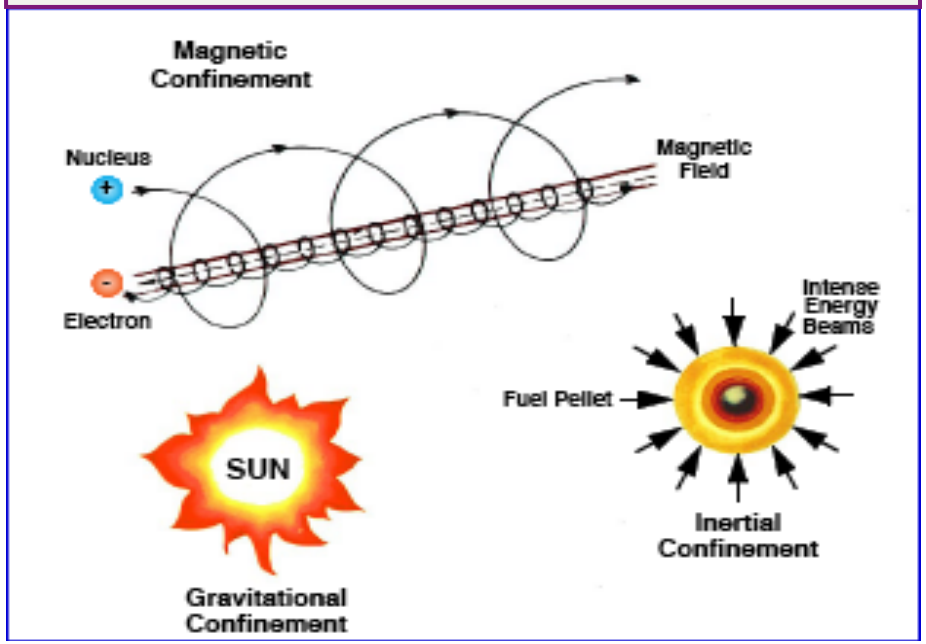
Fusion powers the sun and the stars … and maybe one day our communities

Fusing deuterium and tritium into a helium nucleus releases an energetic neutron



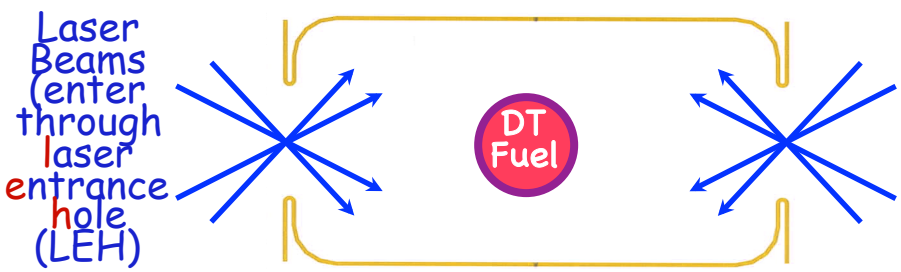
Fusion is accomplished via gravitational, magnetic and inertial confinement



The goal of experiments at the National Ignition Facility (NIF) is to achieve inertial confinement fusion in a laboratory setting

Inertial confinement fusion (ICF) relies on the inertia of the fuel to provide confinement

- INDIRECT DRIVE: laser energy is converted to x-ray energy by target

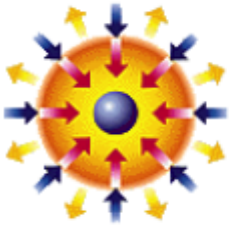


Hohlraum (laser target)

- x-rays bathe ICF capsule, heating it up -- it expands

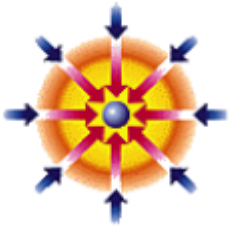
Ablator heats up

- conservation of momentum: ablated shell expands outward, rest of shell (frozen DT) is forced inward



Rocket effect

- fusion initiates in a central hot spot containing ~ 5% of the fuel, and a thermo-nuclear burn front propagates outward

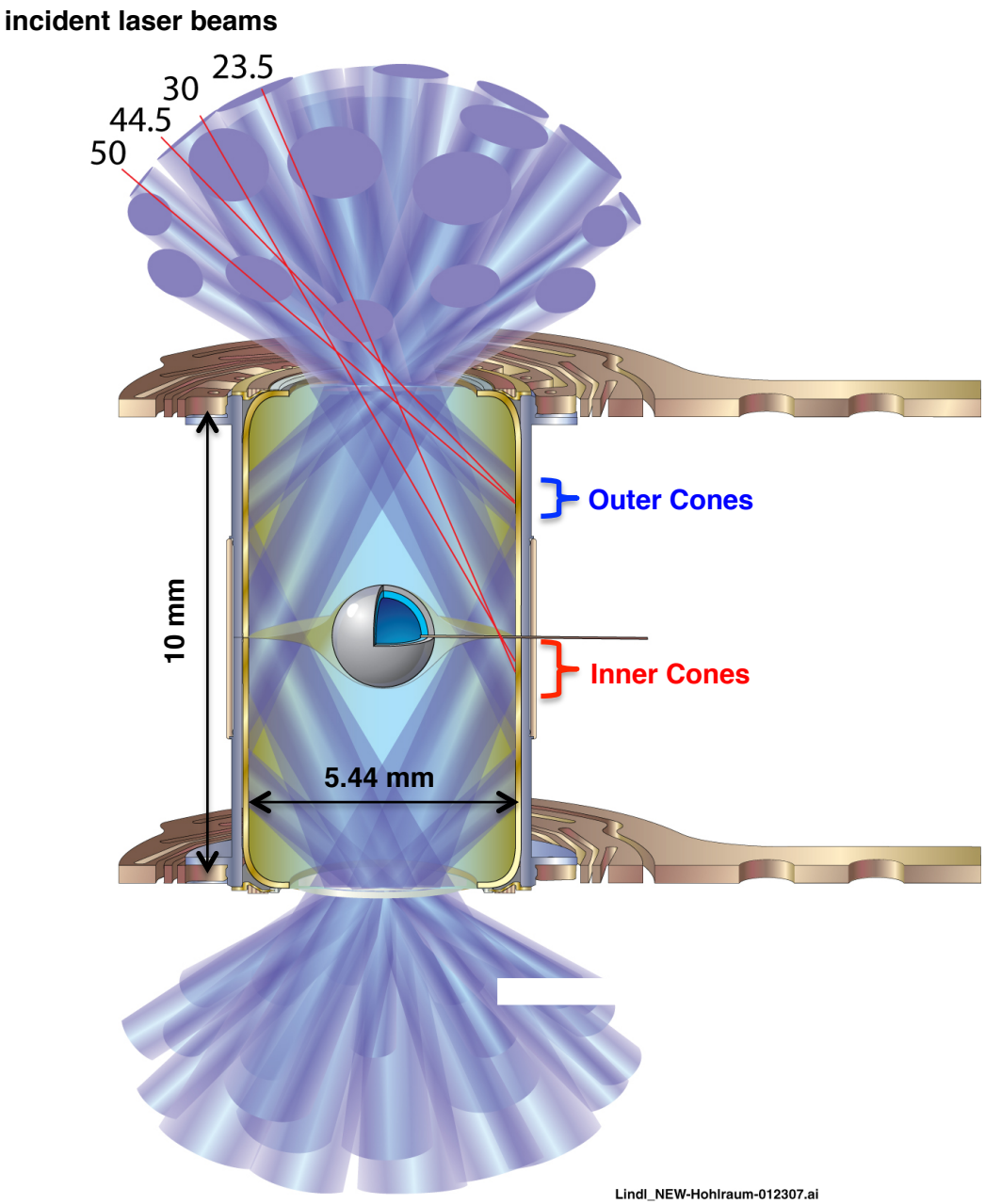


Ignition

Burn wave

In this movie, we “ride along” a NIF beamline

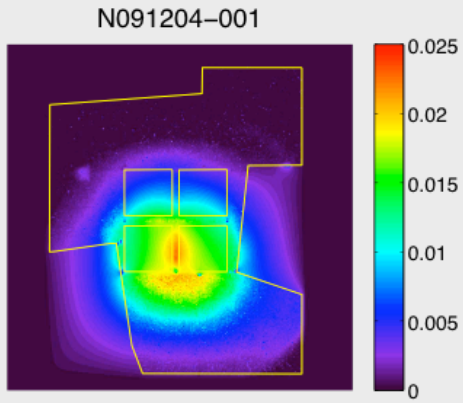
The “hohlraum” is the environment for the NIF indirect drive capsule



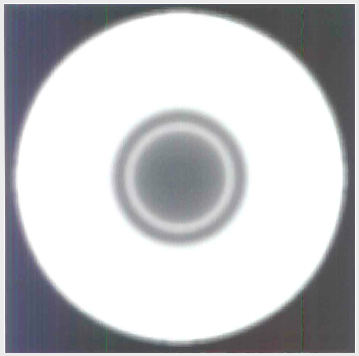
- “Hot”: the hohlraum provides the radiation drive to implode the capsule
- “Round”: the hohlraum provides the radiation symmetry to keep the imploding capsule round

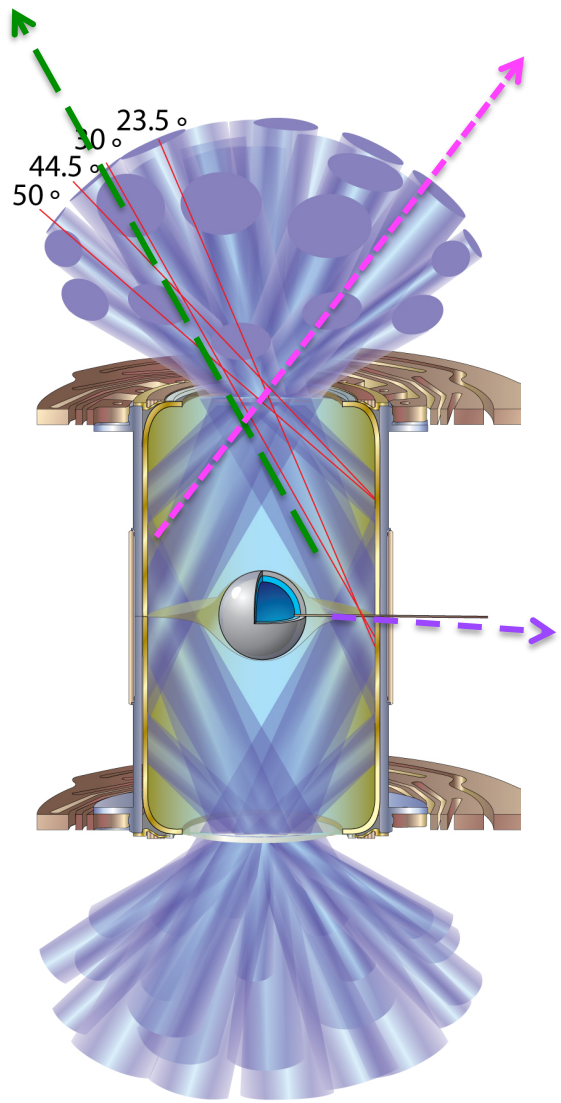
An ignition-scale hohlraum must provide good coupling, drive, and symmetry

Coupling: LPI must be sufficiently low that enough energy is available for drive

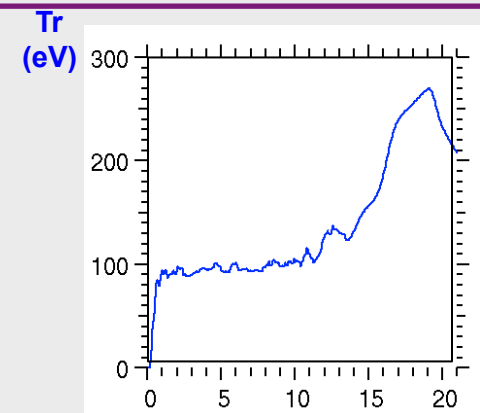


Coupling: LPI must be sufficiently low that hot electrons do not pre-heat the capsule

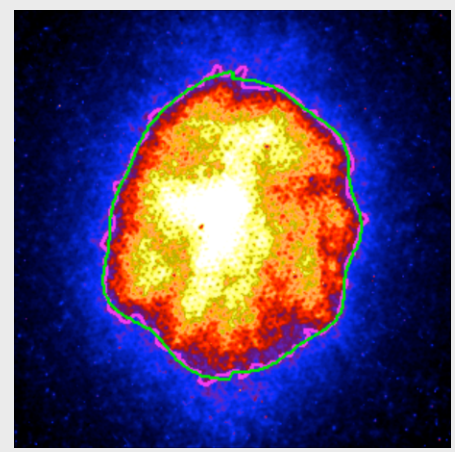




Drive: Must be high enough to implode a stable shell fast enough to get hot & ignite

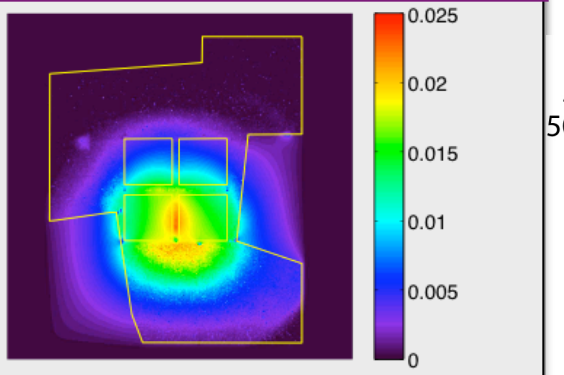


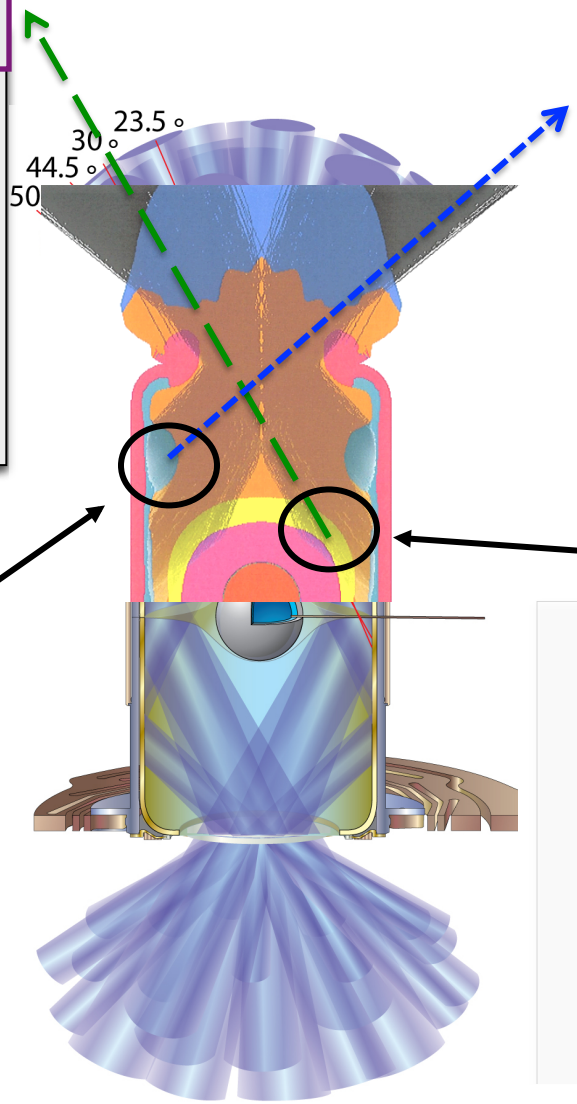
Symmetry: Must be round enough at high convergence to get dense & ignite



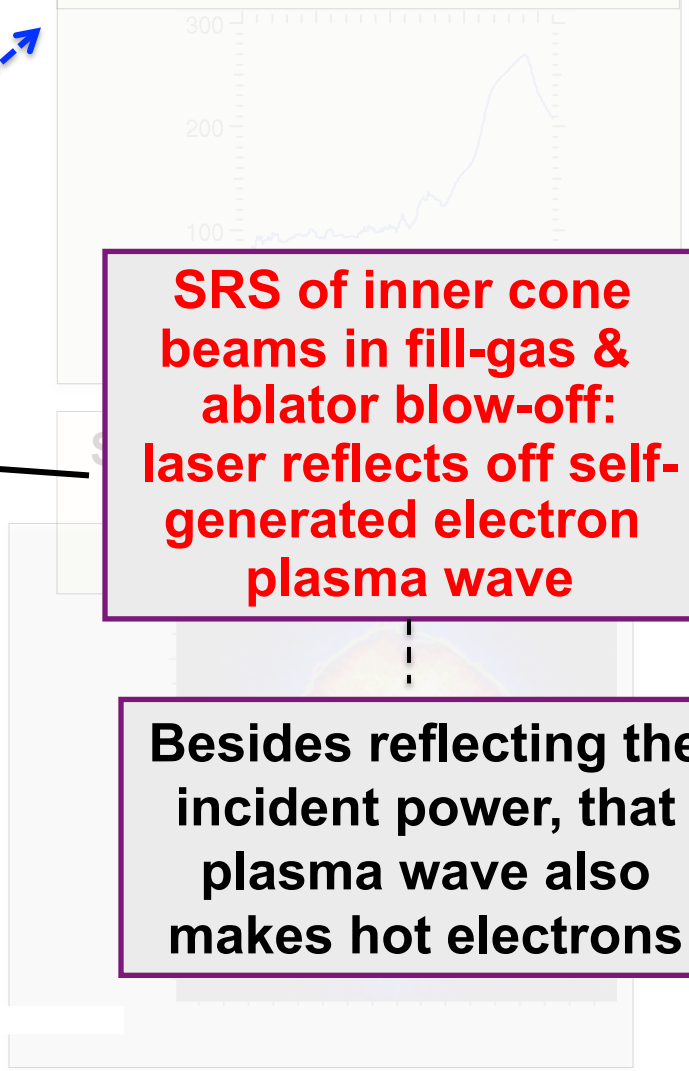
Coupling: Stimulated scatter within the hohlraum can lead to energy loss: incoming laser reflects back out

Coupling: LPI must be low enough, so that enough energy is available for drive





Drive: Must be high enough to implode a stable shell fast enough to get hot & ignite



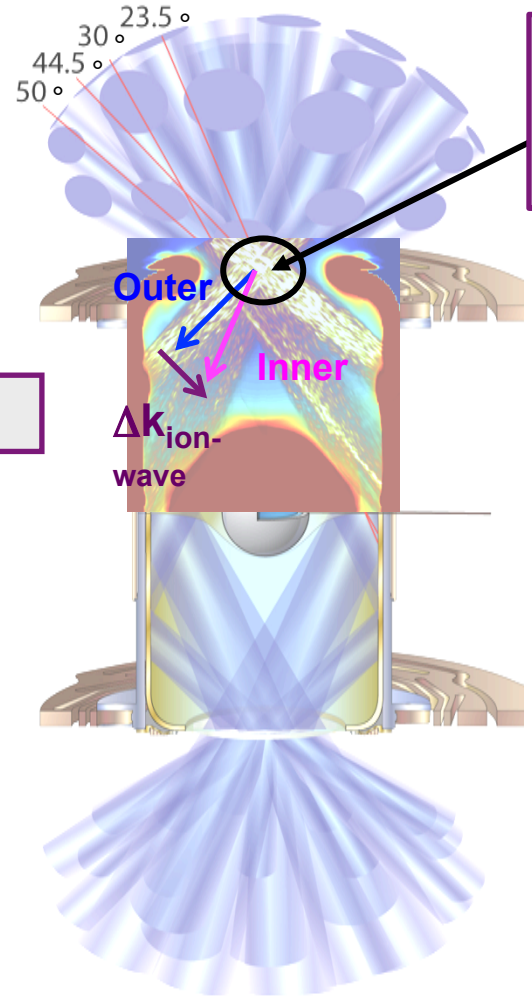
SRS of inner cone beams in fill-gas & ablator blow-off: laser reflects off self-generated electron plasma wave

SBS of outer cone beams in "gold bubble": laser reflects off self-generated ion wave

Besides reflecting the incident power, that plasma wave also makes hot electrons

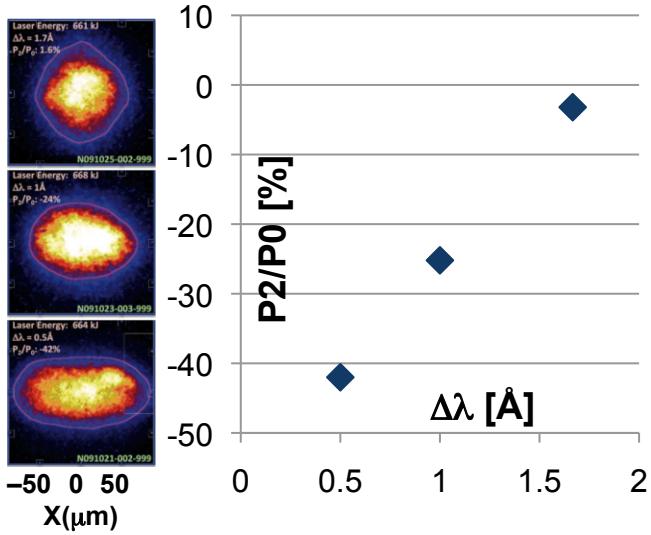
Symmetry: requires a controlled energy balance between the inner and outer beams

We use a plasma-optical-switch to transfer energy from outer to inner beams by increasing $\Delta\lambda = \lambda_{inners} - \lambda_{outers}$

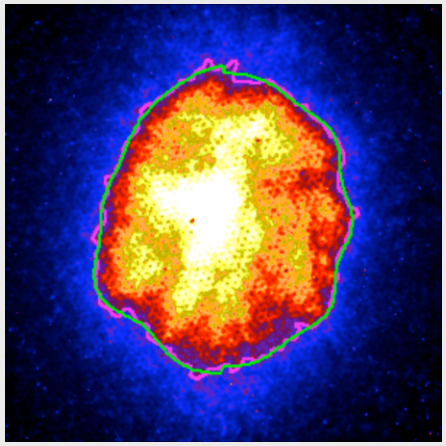


The beams transfer energy to one another via Brillouin scattering from ion waves

NIC '09 9 keV Capsule emission

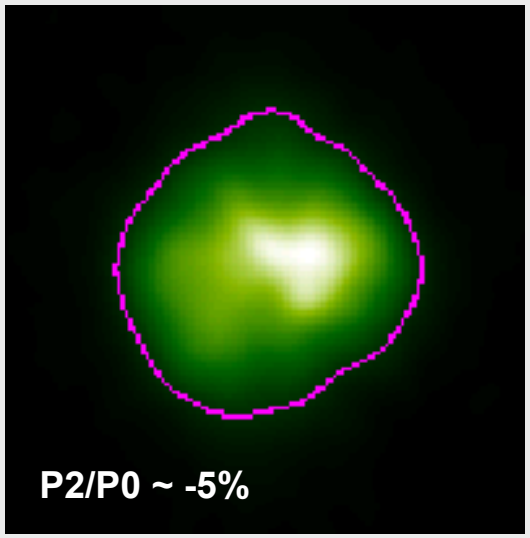


Symmetry: Must be round enough at high convergence to get dense & ignite

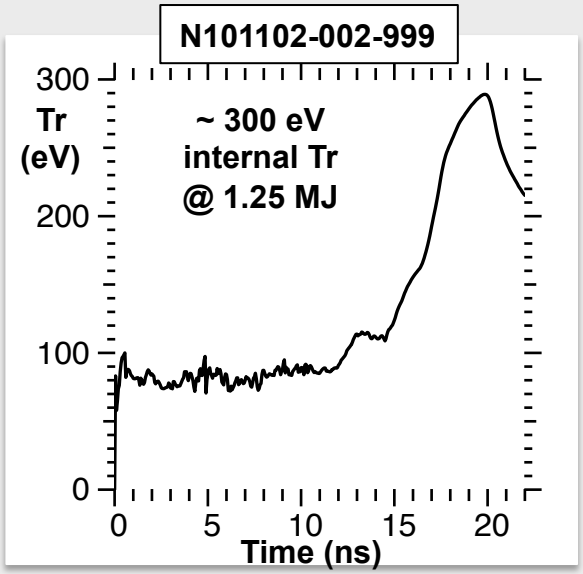


We have successfully commissioned the NIF hohlraum by demonstrating acceptable drive and symmetry*

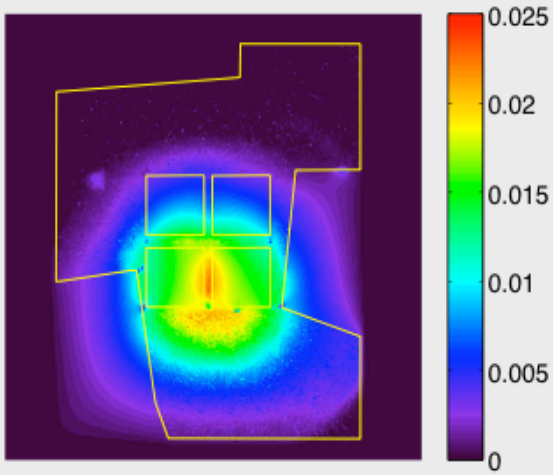
Tunable Symmetry



Drive needed for ignition



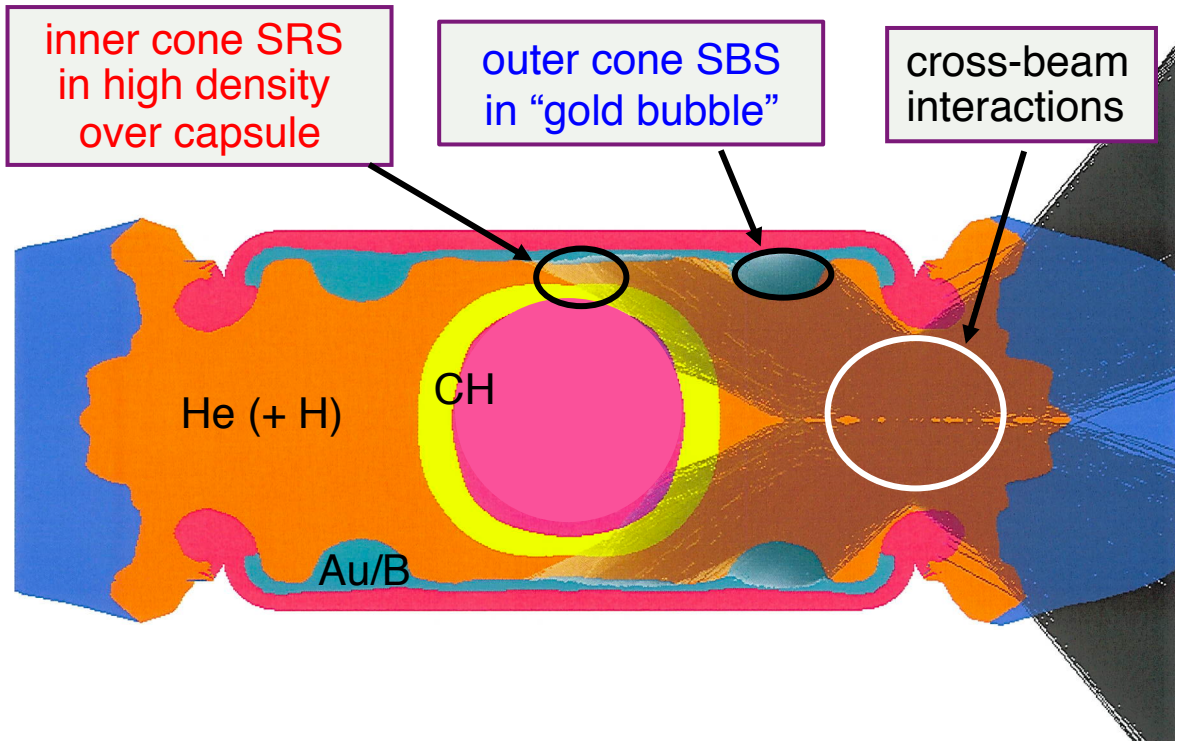
Laser-Plasma Interactions (LPI) low enough to meet drive/symmetry requirements

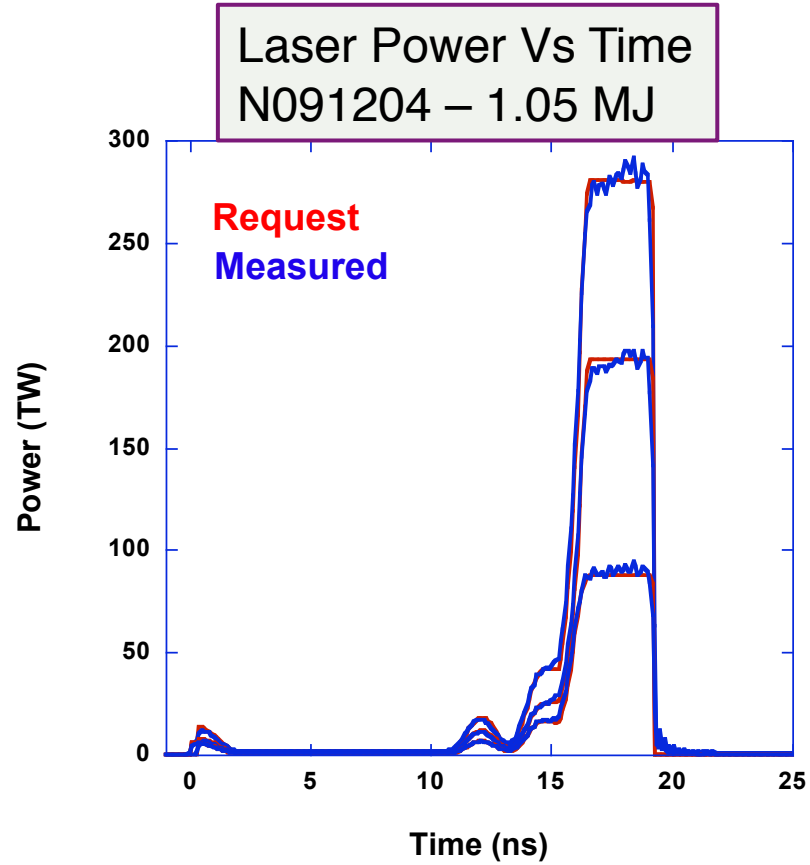


- What have we learned?
- What improvements do we plan to make based on improved knowledge?

S. H. Glenzer et al., www.sciencexpress.org / 28 January 2010 / Page 1 / 10.1126/science.1185634

Before NIF experiments began, modeling had addressed three "peak-power" LPI concerns



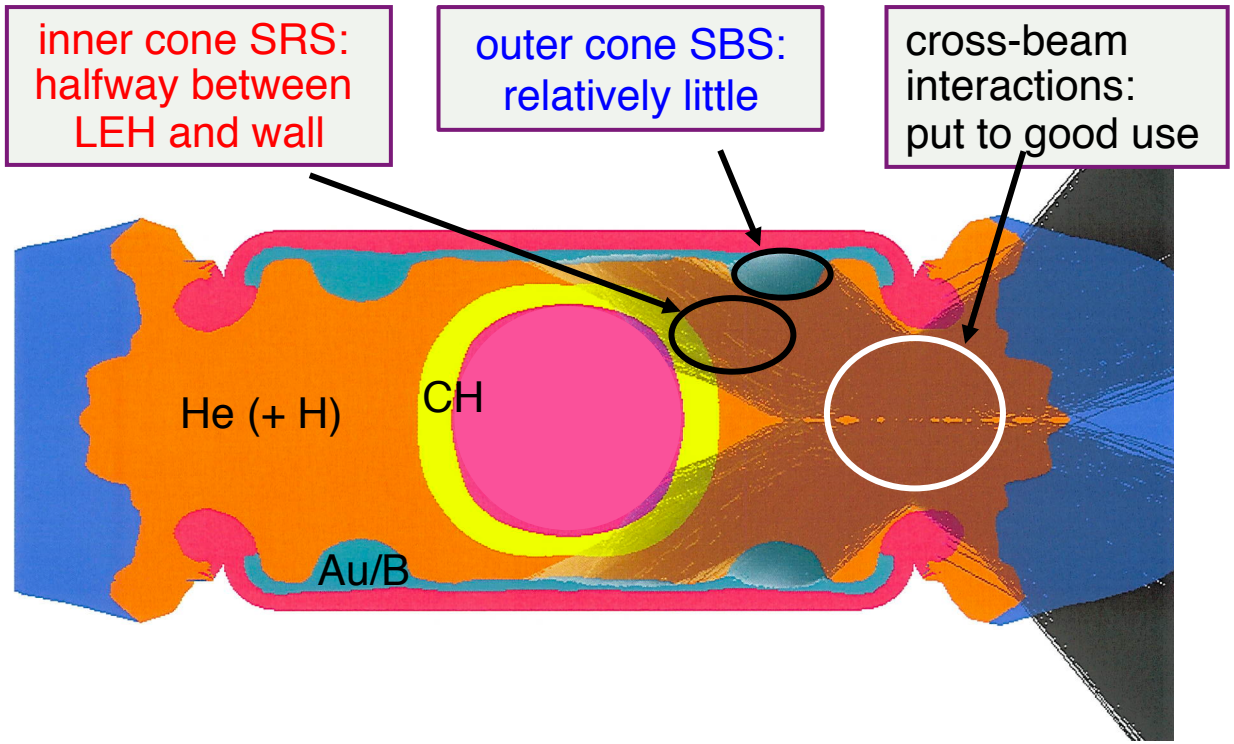


Our strategy:

- cross-beam interactions: control with inner/outer wavelength separation
- SBS on outer beams: add boron to gold bubble to more strongly damp iaws
- SRS on inner beams: make spots as large as possible to reduce intensity

As predicted, the most significant LPI was SRS on the inner beams

NIF experiments revealed discrepancies between diagnosed quantities and pre-campaign predictions

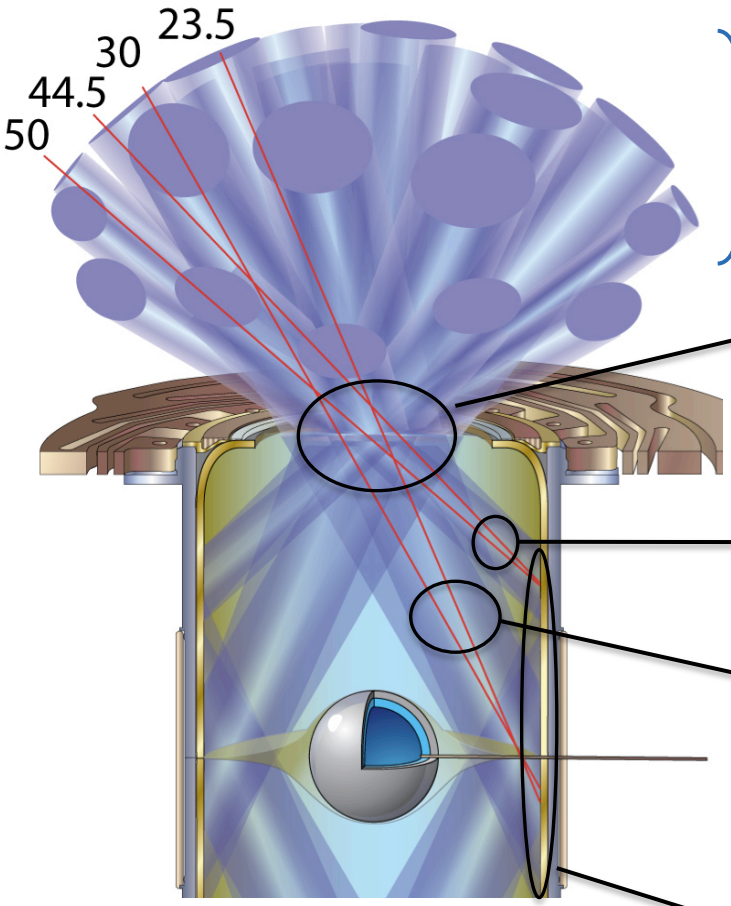


- 2/3 of beams (outer) demonstrate excellent coupling
- 1/3 of beams (inner) show reduced coupling
- at 1.3 MJ: 88% coupling

- cross-beam interactions: transfer energy from outer to inner beams to tune symmetry (our LPI "friend")
- SBS on outer beams: negligible (reduced intensity and gold bubble size)
- SRS on inner beams: occurring at a different wavelength and intensity

Why is SRS "different" than in our pre-campaign predictions?

One-slide summary of LPI on NIF



Input laser energy (1/3 on inners, 2/3 on outers: c.f.=1/3)

Crossed beam energy transfer (typically: inner beams x1.6 , outer beams x0.7)
→ energy after transfer (c.f.~50%)

outer beams: negligible (<1%) backscatter so far

inner beams:

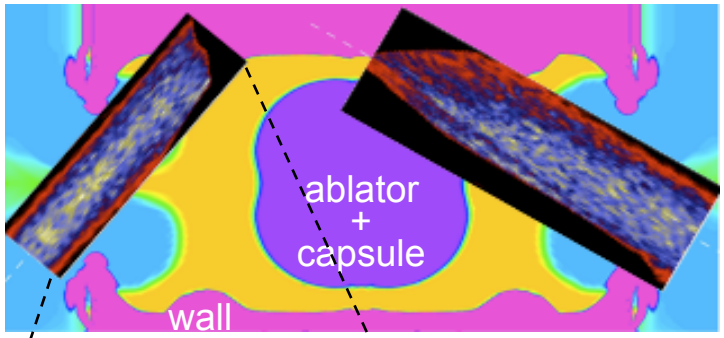
- **SRS in a saturated regime**
- **SBS in ablator blow-off (CH)**

hot electrons from laser energy near $n_c/4$

At 1.3 MJ, we lose ~15% of the total laser energy in SBS (~5%) and SRS (~10%)

To assess LPI we use a multi-scale approach

macroscale

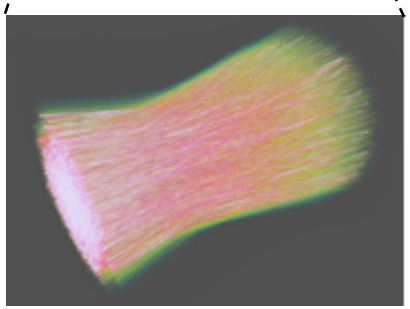


- Hydrodynamic length and time scales are set by target size **[O(mm)]** and laser pulse length **[O(ns)]**

environment -- plasma parameters and scale lengths

LPI assessment in bulk plasma from rad-hydro calculations (spectra, gain exponent)

mesoscale

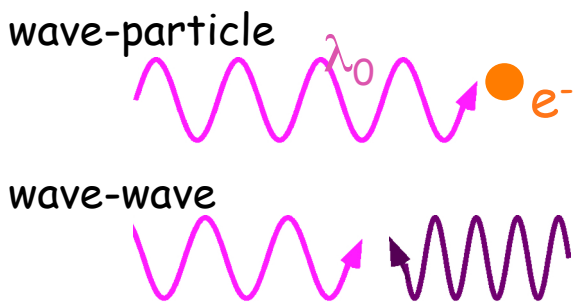


- LPI evolves on: **μm length** and **ps time** scales

beam propagation

LPI reflectivity/transmission/energy deposition is calculated with pF3D

microscale



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

kinetic effects

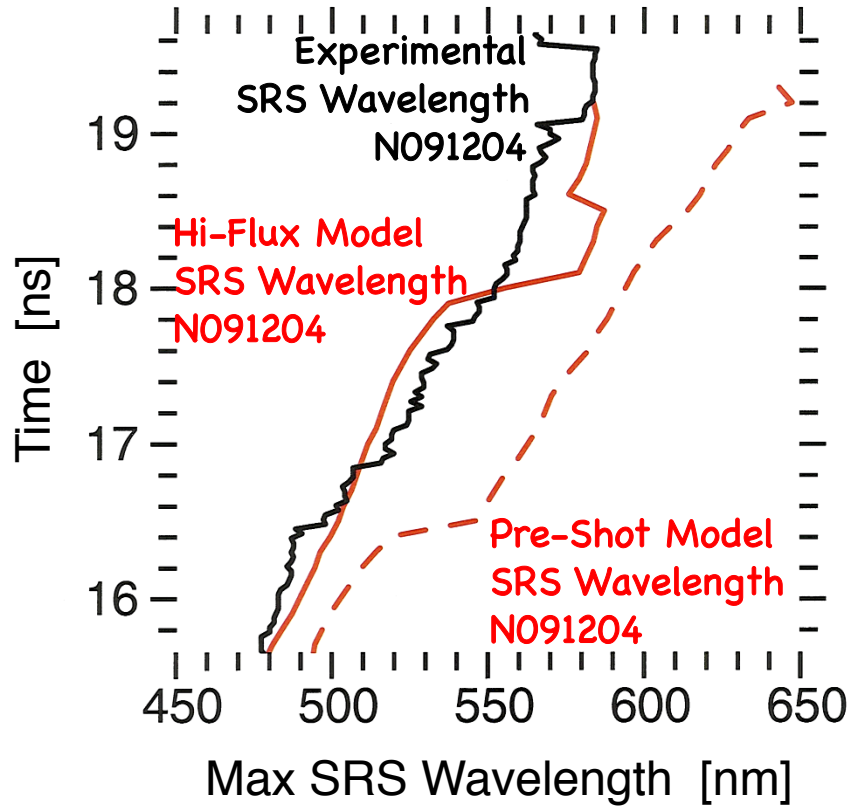
We assess kinetic effects with PIC and Vlasov simulations

An improved hohlraum model generates plasma conditions consistent with experimental diagnostics

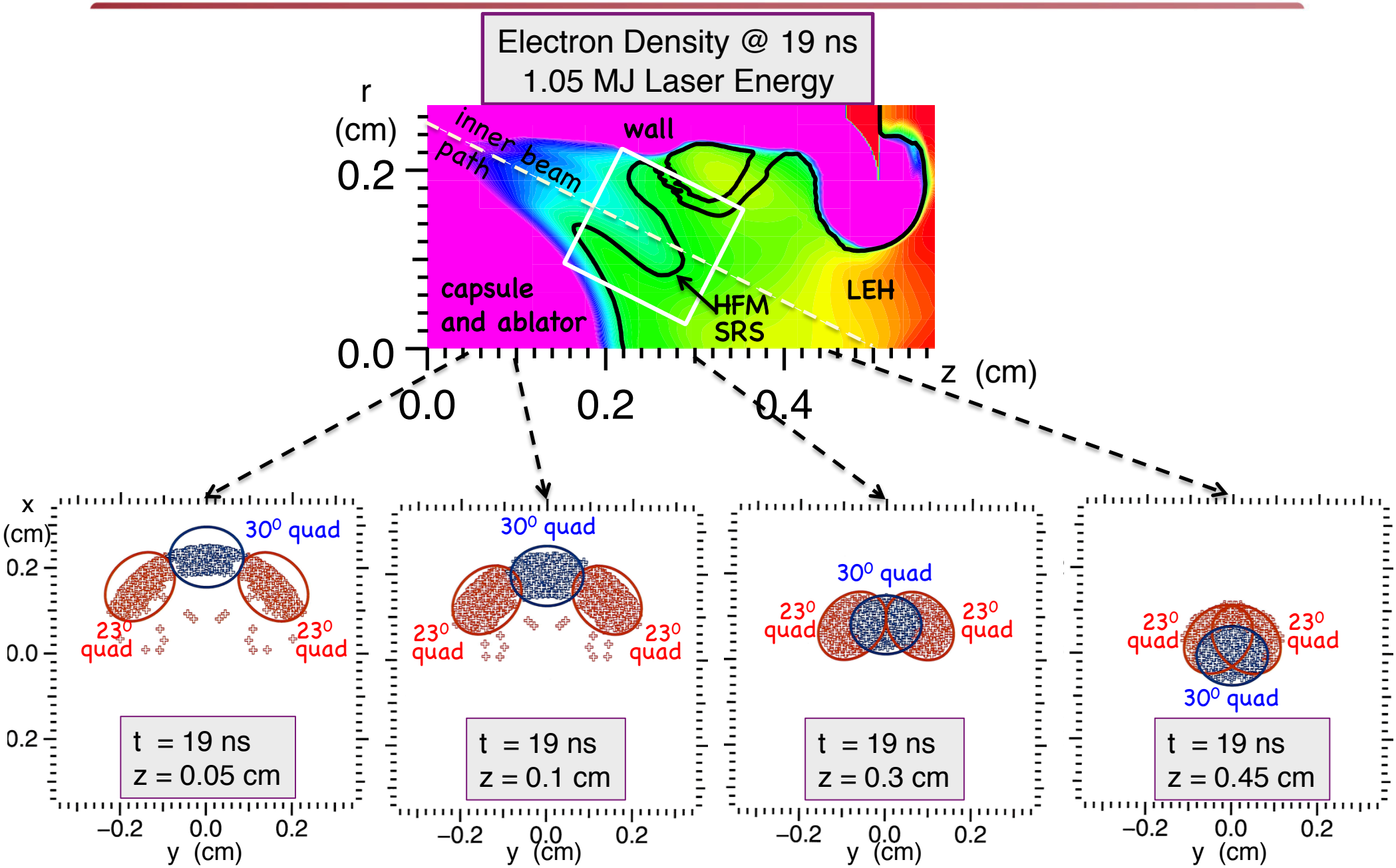
- **Pre-shot rad-hydro models:**
  - SRS predicted at higher density/ temperature than in expt. (at higher wavelength)

- **The High Flux Model:**
  - more accurate atomic physics
  - less inhibited electron transport
  - includes crossed-beam transfer
  - LPI gain includes nearest neighbor beam intensity

Max SRS Wavelength Vs Time

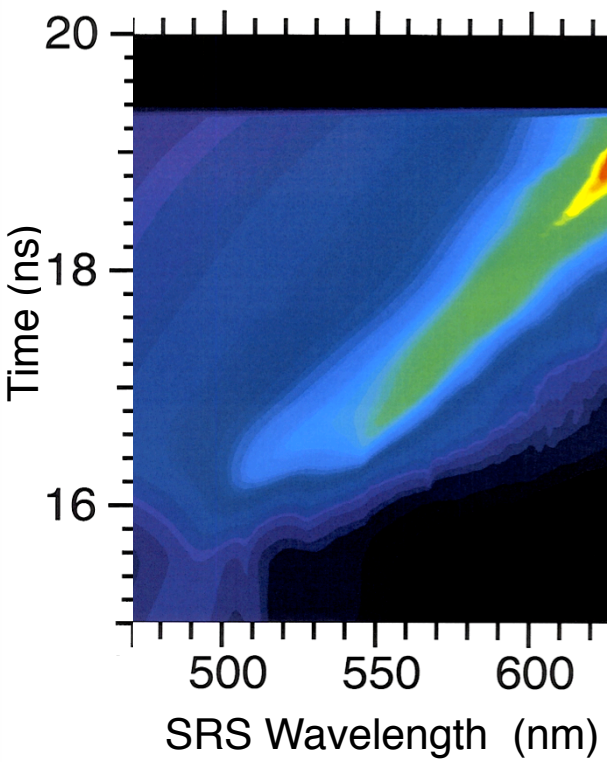


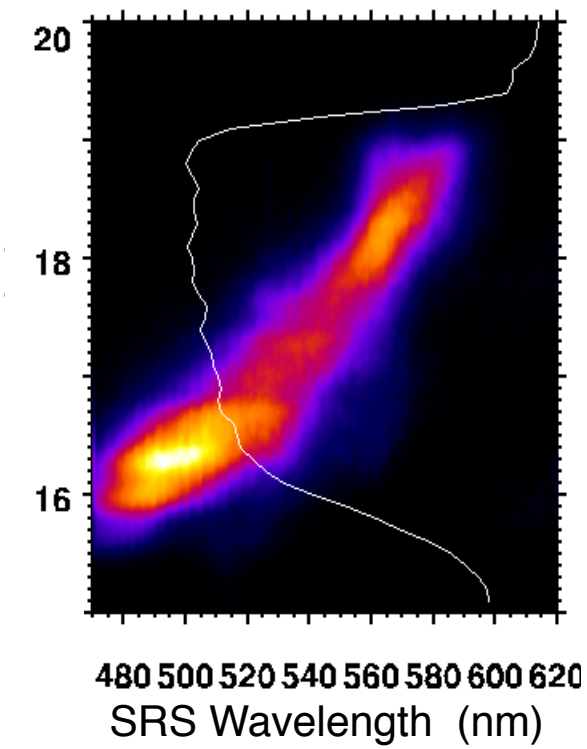
With the improved hohlraum model, 30° SRS occurs where there is overlap with 23° quads

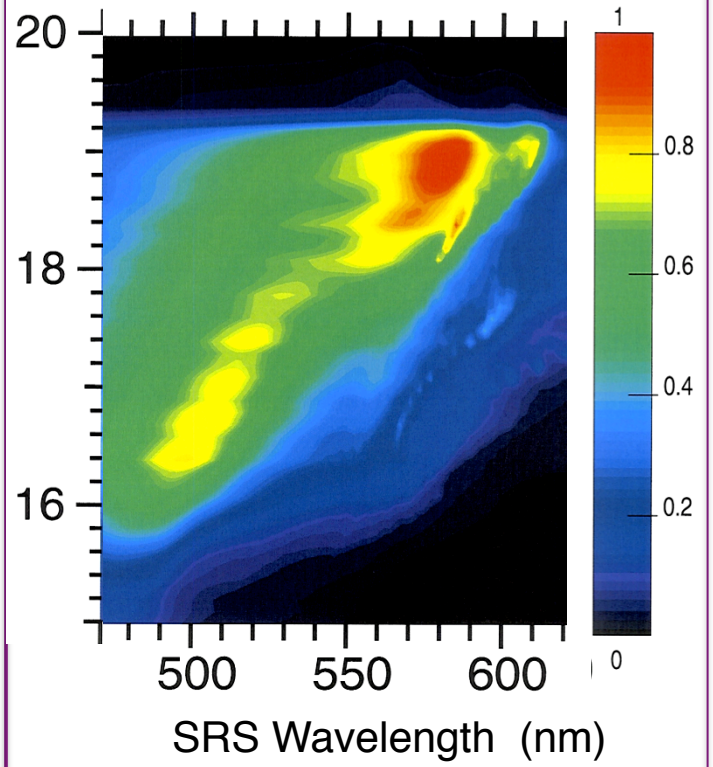


The SRS spectrum better agrees with experiment when we use the high flux model

30° SRS Gain Exponent 1.05 MJ Pre-Shot Model	Experimental 30° SRS Spectrum N091204: 1.05 MJ	30° SRS Gain Exponent N091204: 1.05 MJ Post-Shot Hi-Flux Model

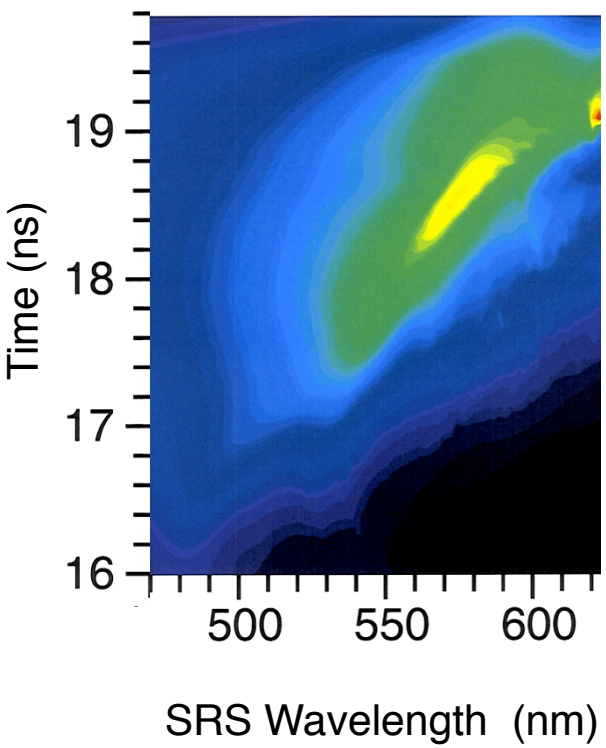
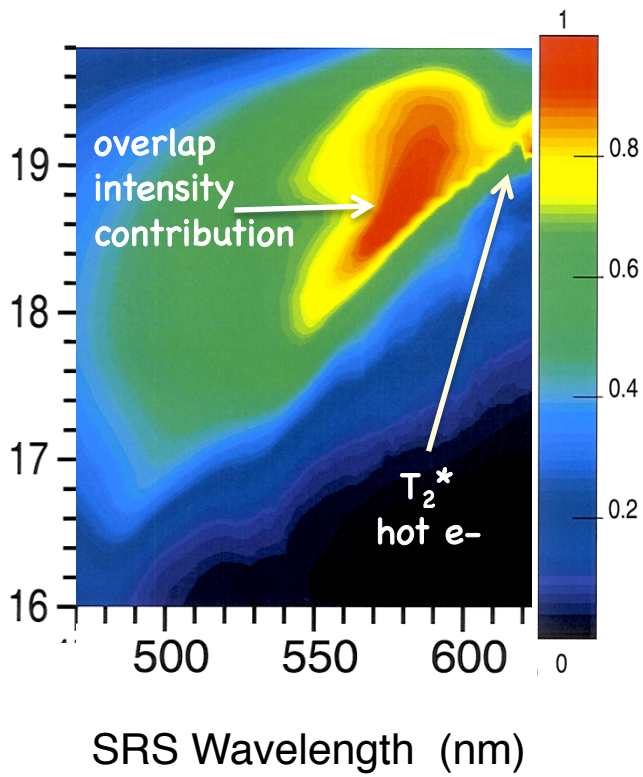
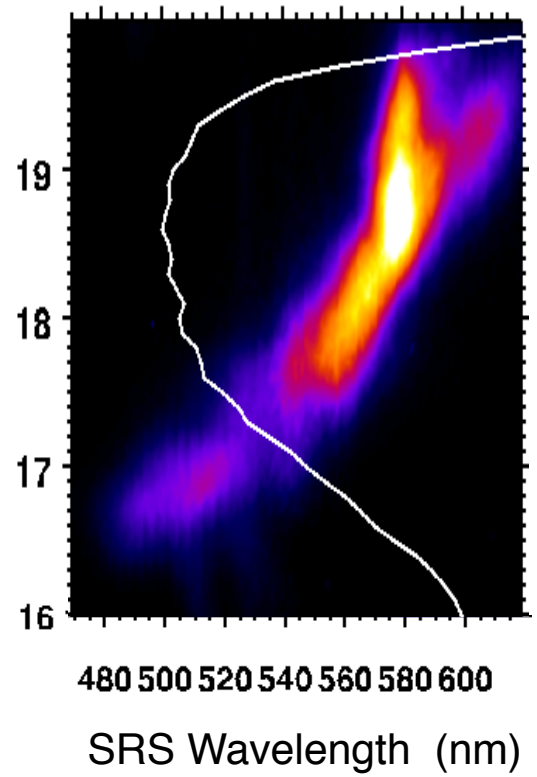




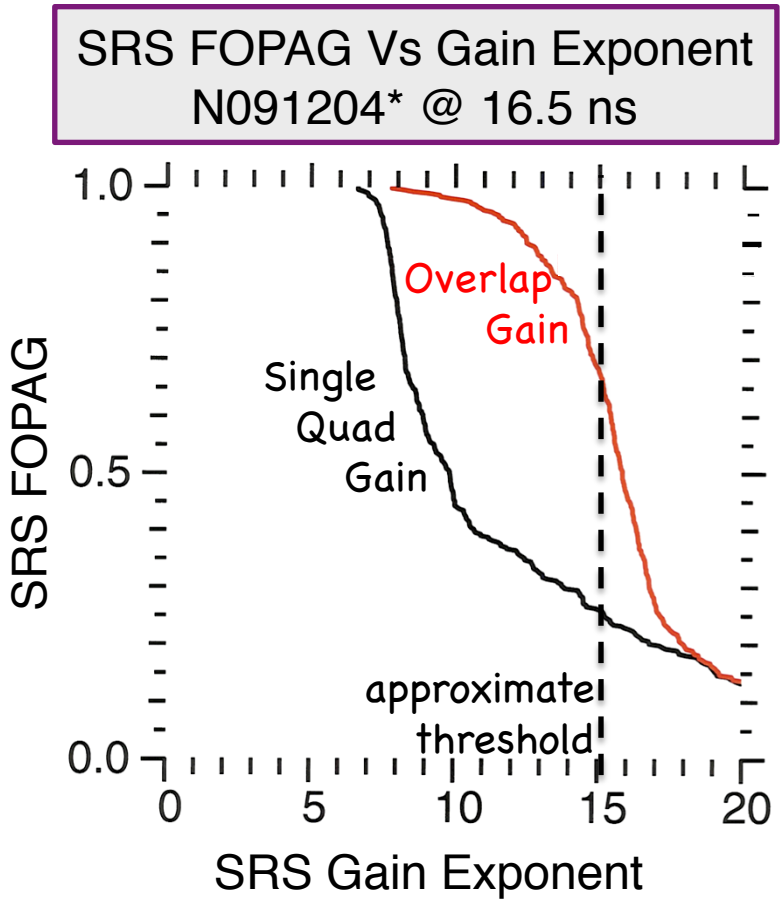


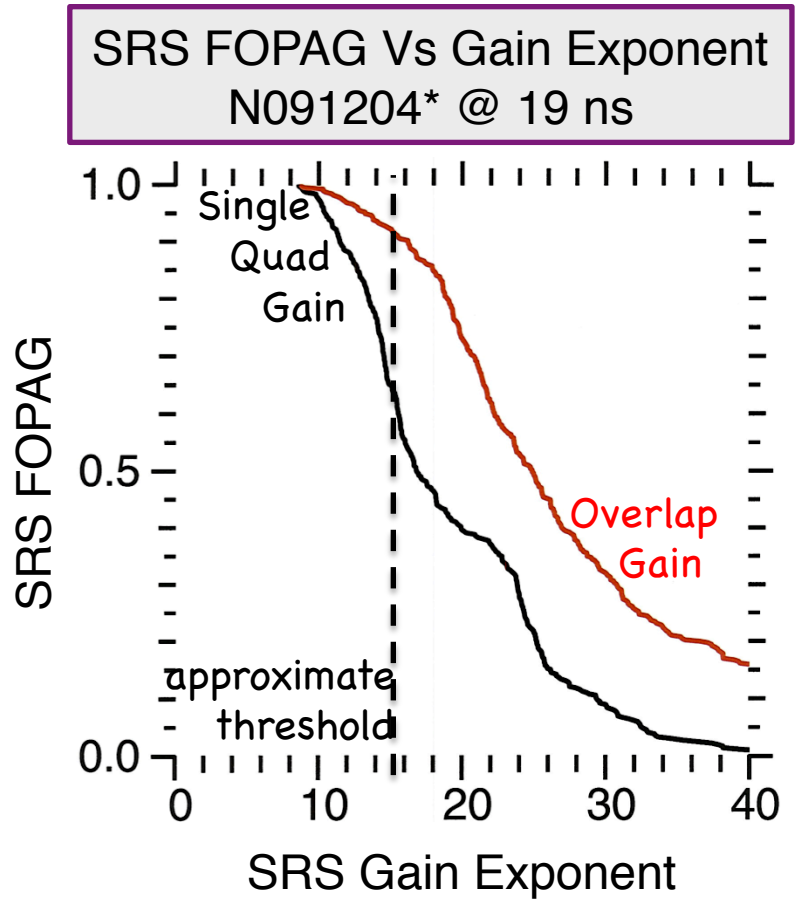
A further success – our pre-shot SRS spectrum prediction agrees well with experiment at 1.3 MJ

Pre-Shot Prediction:
August, 2010

30° SRS Spectrum 1.3 MJ Single Quad Intensity	30° SRS Spectrum 1.3 MJ Overlap Intensity	30° SRS Spectrum 1.3 MJ N101102
		

When we account for overlap intensity, we find gains above threshold across peak power





To test the importance of this concept, we upgraded pF3D and simulated the overlap beam intensity region at Argonne

*M. D. Rosen's town120423j design: 865 kJ absorbed, 49% CF, DCA, f=0.2

We further assess the accuracy of HFM plasma conditions + realistic laser spots using pF3D

- pF3D provides beam transmission, reflectivity and energy deposition by numerically solving equations of the form:

$$\left(\mathcal{L}_{\text{adv}} + \mathcal{L}_{\text{prop}} + \mathcal{L}_{\text{abs}}\right) A_0 = \mathbb{C}\left(\delta n_f A_0 + \delta n_A A_1 + \delta n_L A_2\right)$$

propagation

advection

absorption

refraction

SBS coupling

SRS coupling

Fields

A_0 : incident laser

A_1 : SBS; driven by $\delta n_A A_0$

A_2 : SRS; driven by $\delta n_L A_0$

Plasma Response

δn_A (iaw): driven by $A_0 A_1$

δn_L (epw): driven by $A_0 A_2$

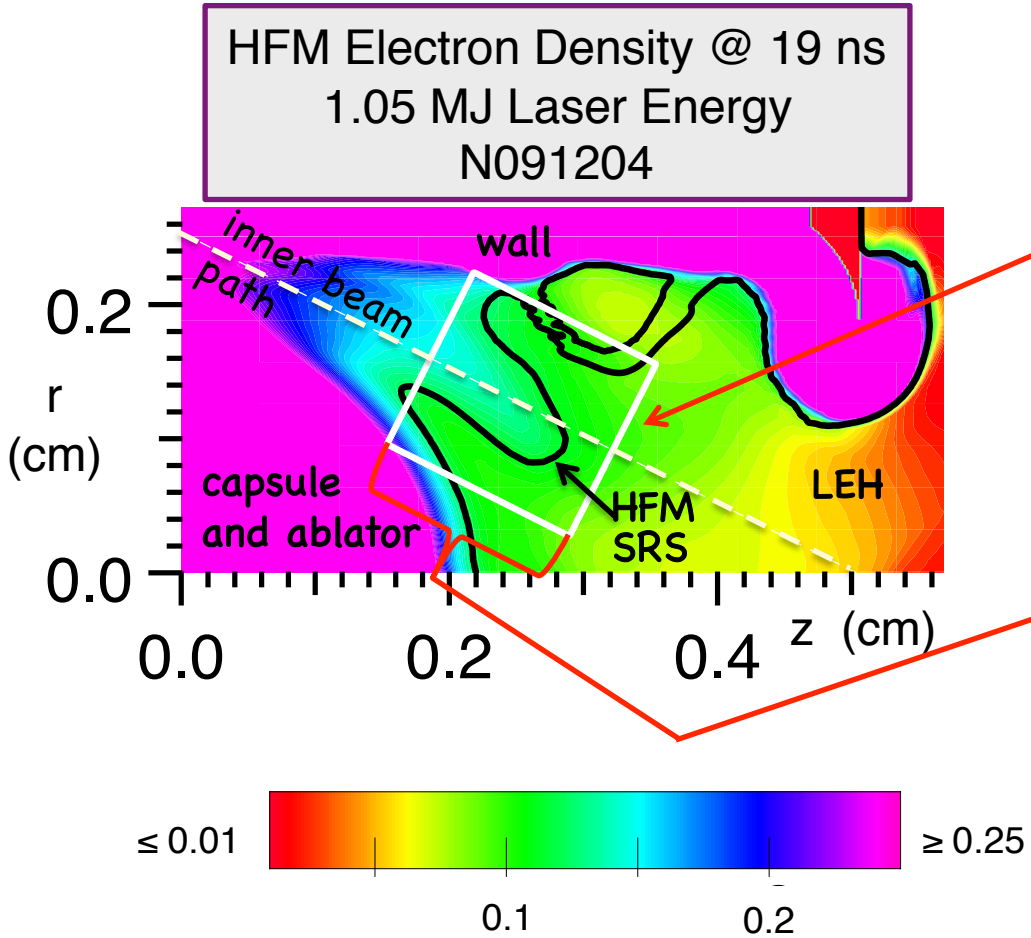
- satisfy respective wave equations

Background plasma:

- described by nonlinear fluid model (with multiple materials)
- couples to laser via ponderomotive (radiation) pressure, inverse brehmsstrahlung

pF3D resolves physics on the μm length and ps time scales

We propagate two quads (23°, 30°) through the resonance region

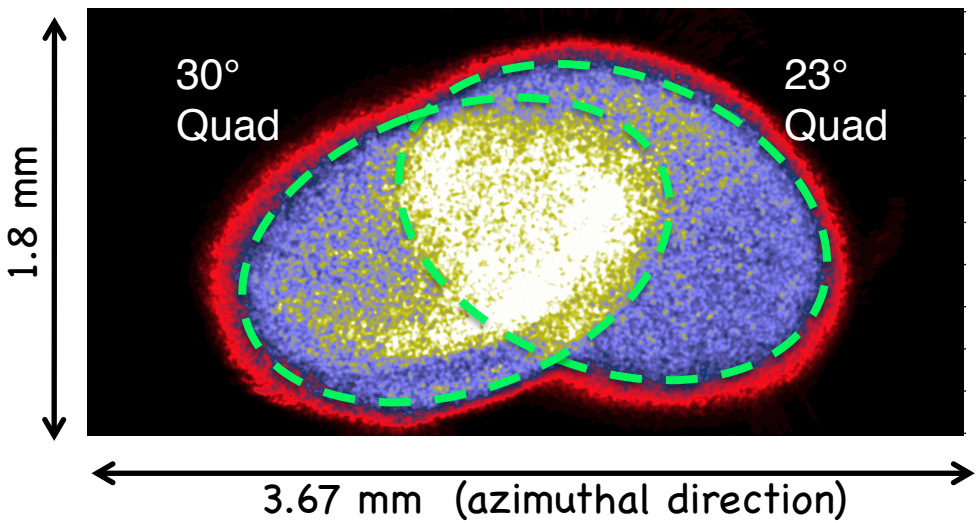


- Laser Input: use SLIP* to propagate quads through the LEH to the input plane (E. A. Williams)
- pF3D: propagate two quads of beams (23°, 30°) through resonance region (A. B. Langdon)

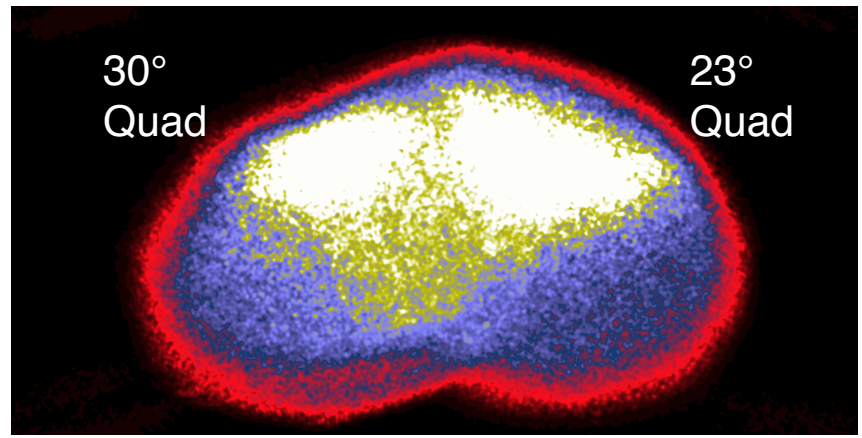
*SLIP code, P. A. Michel and L. Divol (~ pF3D in steady state, forward propagation)

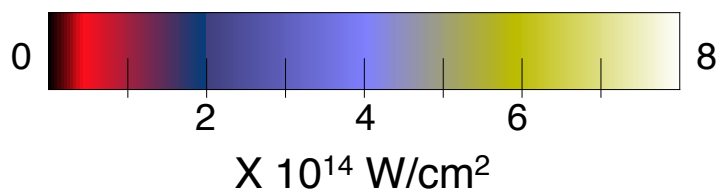
We have separated the effects of overlap and non-uniformity by performing two different simulations

Laser:
Two Quad Input*
Spatially Uniform



Laser:
Two Quad Input*
Spatially Non-Uniform

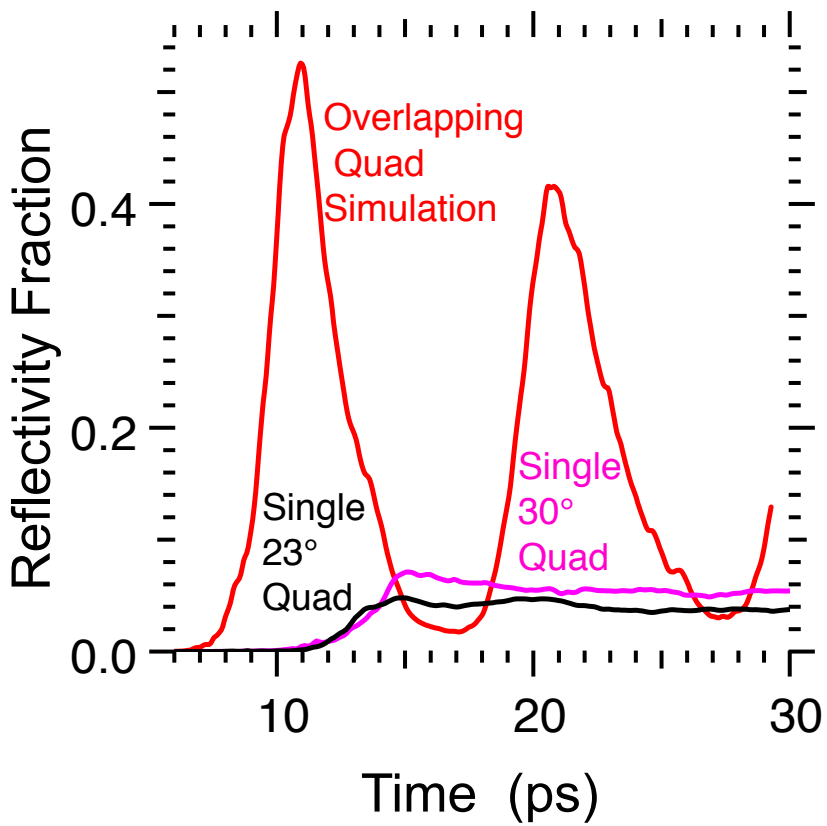




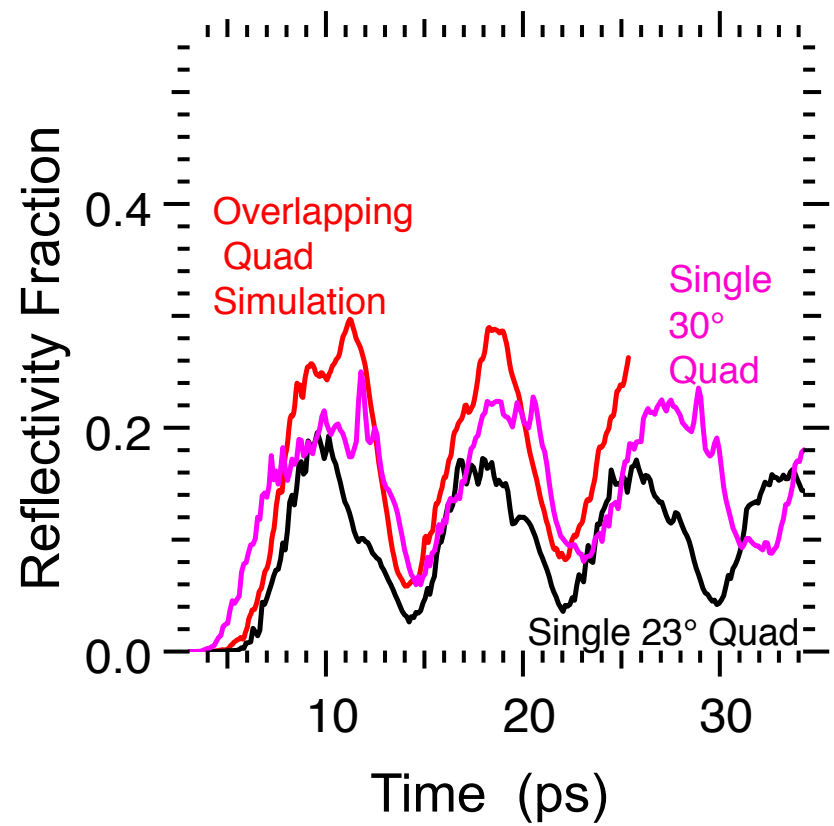
*SLIP code, P. A. Michel and L. Divol

With spatially non-uniform laser intensity, the effect of overlapping quads effect increases reflectivity ~40%

pF3D Reflectivity Vs Time
Double Vs Single Quad Simulations
With Spatially Uniform Quads



pF3D Reflectivity Vs Time
Double Vs Single Quad Simulations
With Spatially Non-Uniform Quads

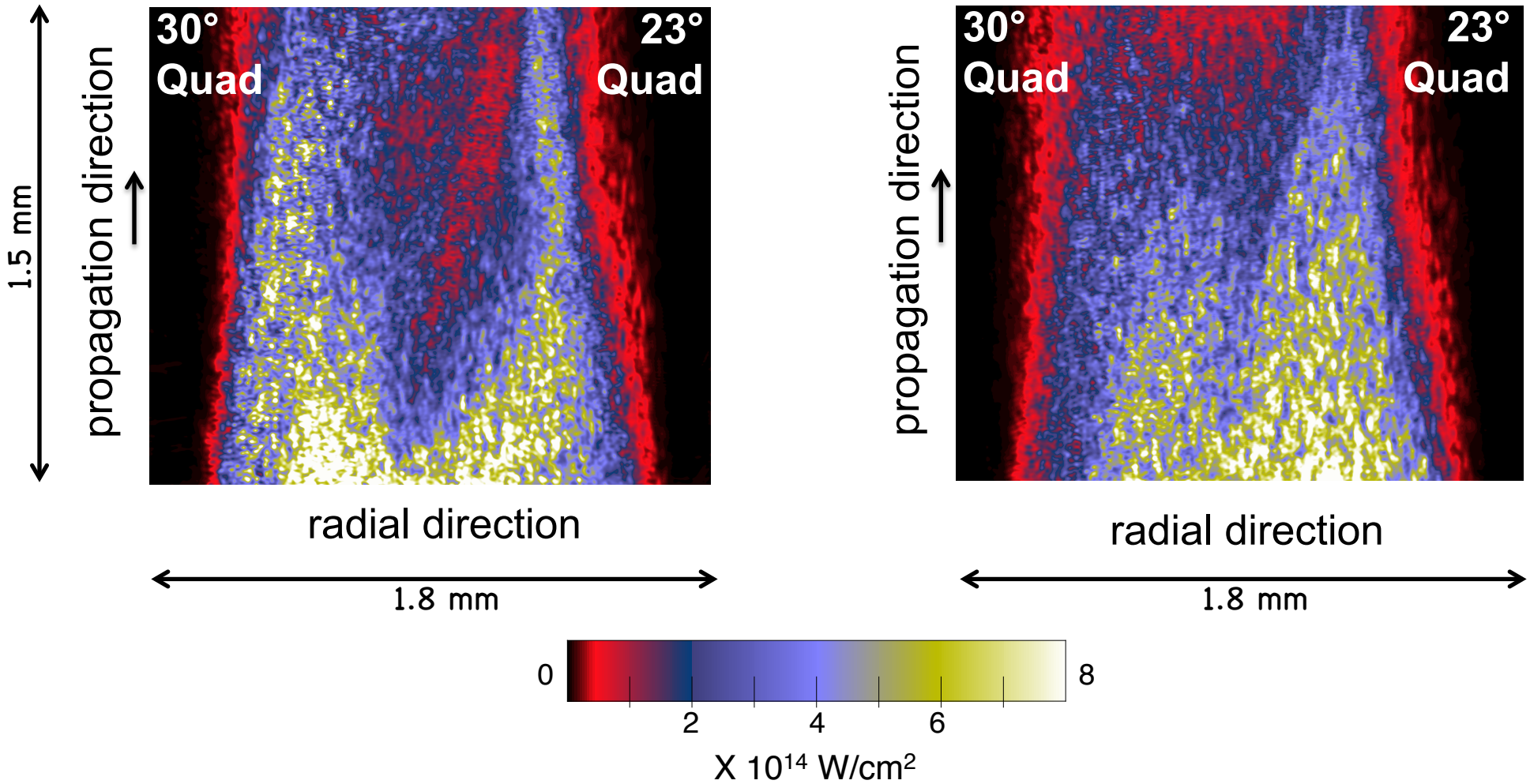


* We thank the Office of Science INCITE program for computational resources and the ALCF staff for computational support

A central azimuthal slice of the forward intensity pattern shows pump depletion in the overlap region

Forward Intensity
Double-Quad Propagation
Spatially Uniform Quads

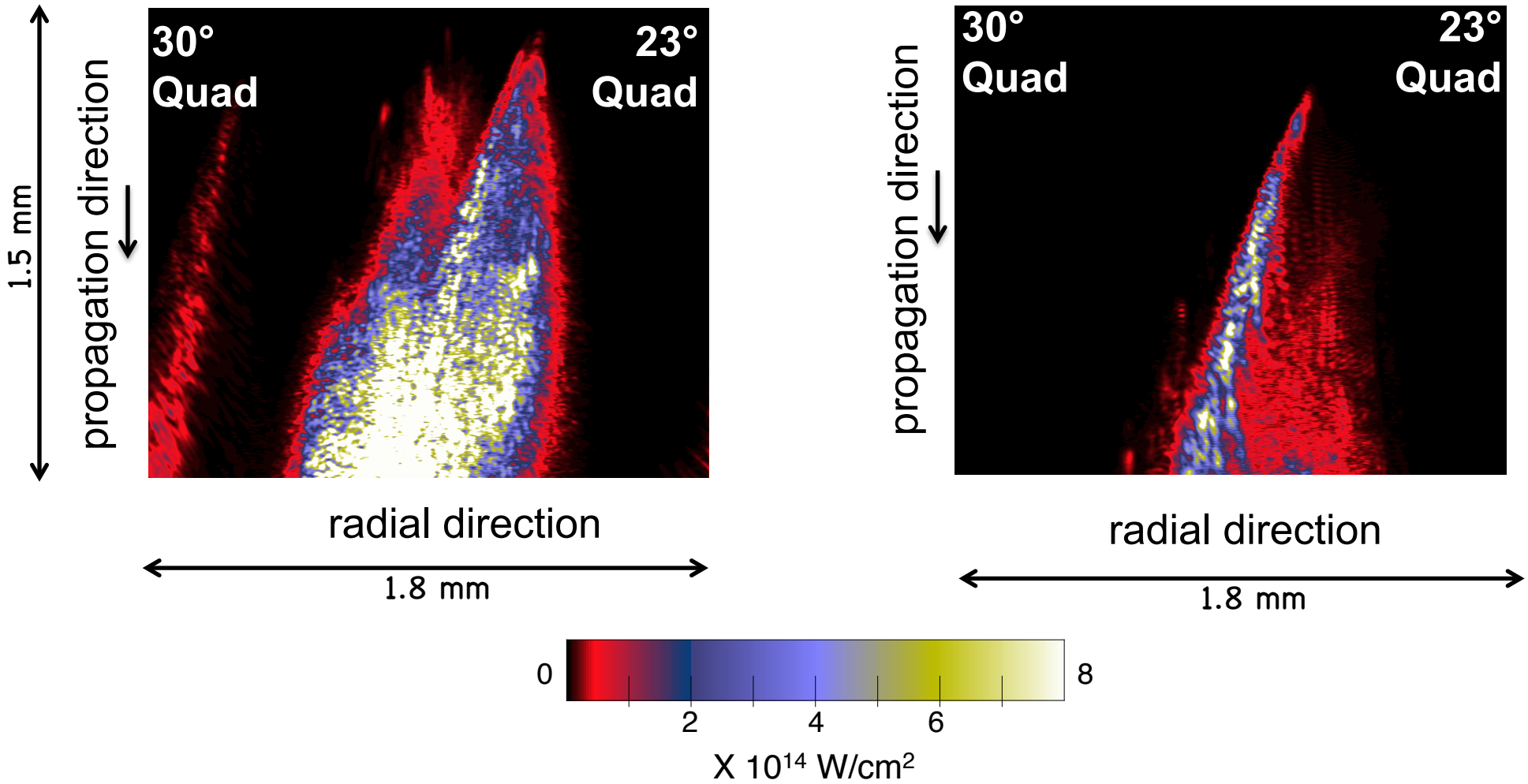
Forward Intensity
Double-Quad Propagation
Spatially Non-Uniform Quads



A central azimuthal slice of the reflected SRS light shows additional amplification in the overlap region

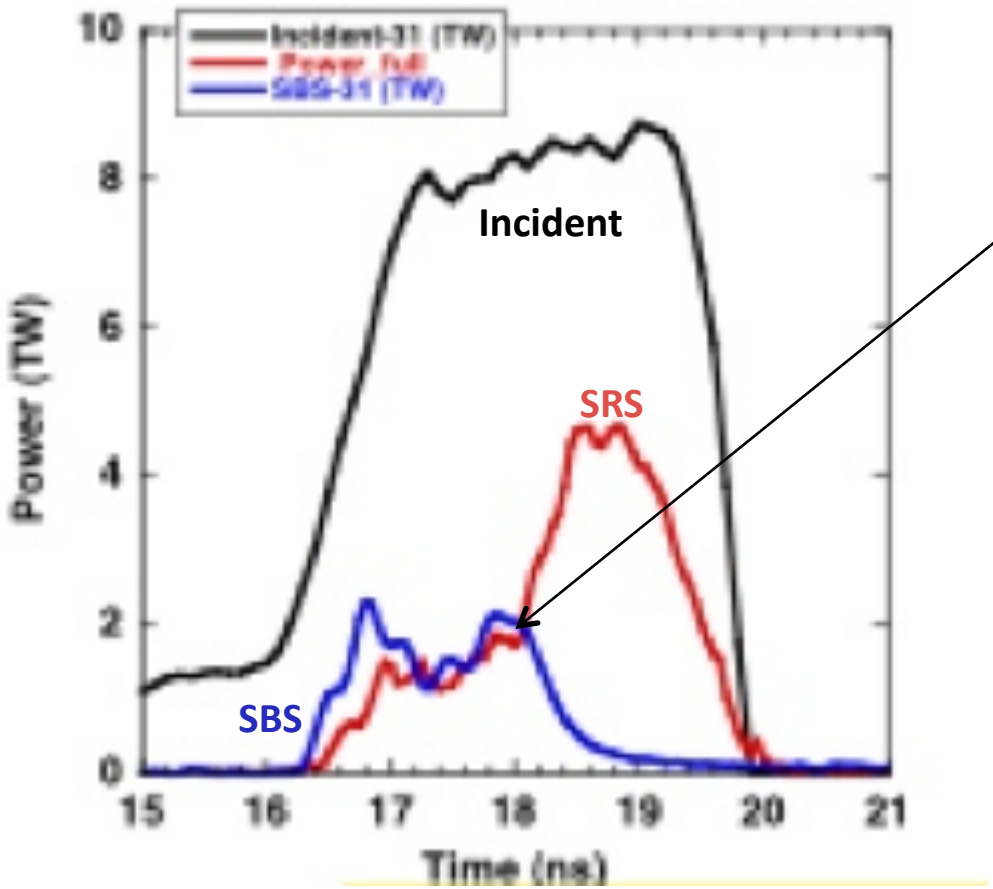
SRS Reflected Light
Double-Quad Propagation
Spatially Uniform Quads

SRS Reflected Light
Double-Quad Propagation
Spatially Non-Uniform Quads



We are currently simulating LPI for a 1.3 MJ shot at 18 ns – where SBS and SRS are comparable

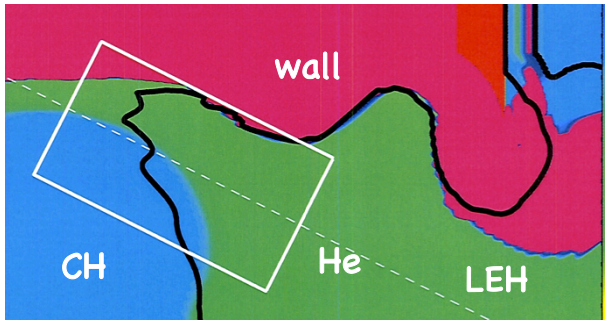
Power Vs Time
N110214



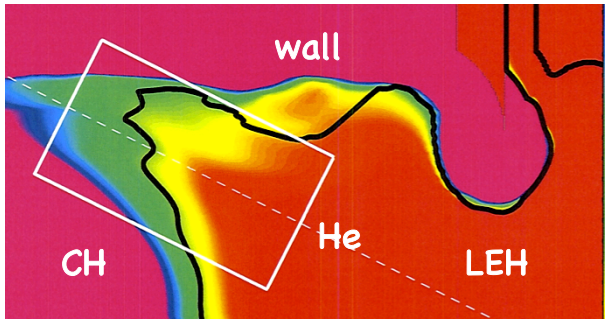
- Simulation at 18 ns: test SRS/SBS competition
- Currently performing single quad simulation
- Double quad simulation is running on early science user time on the Cielo machine at Los Alamos

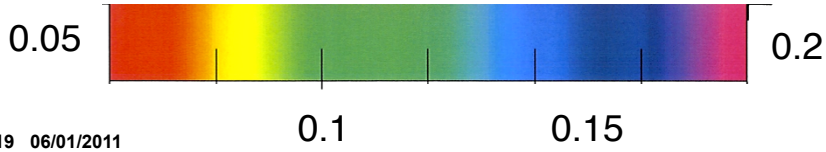
With just a single quad, there is significant SRS and SBS generated at 18 ns

Materials Plot
N110214 @ 18 ns
With pF3D Simulation Box

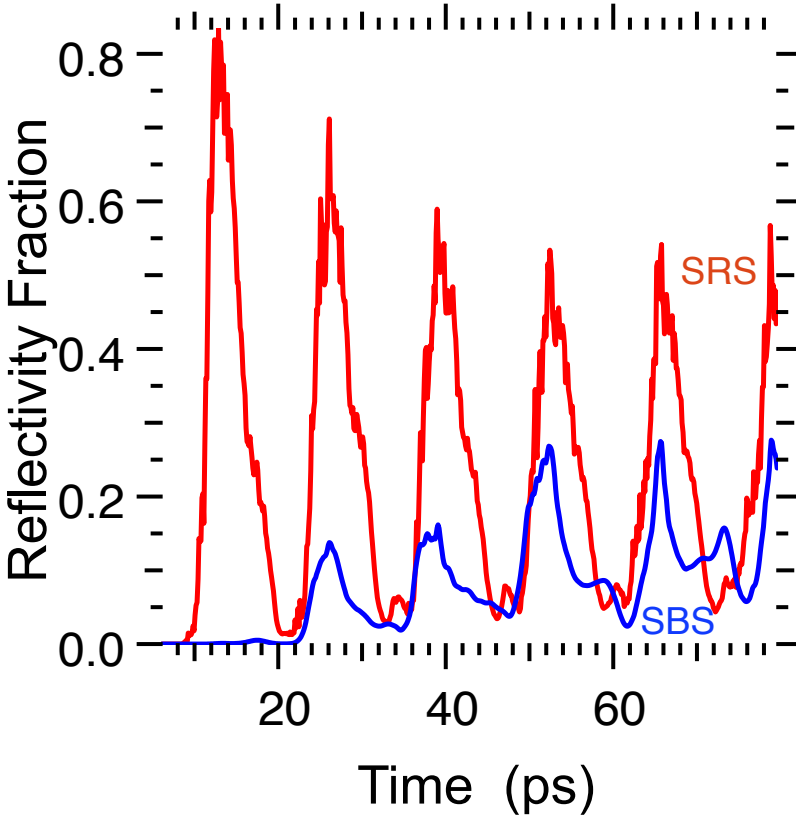


Electron Density
N110214 @ 18 ns
With pF3D Simulation Box



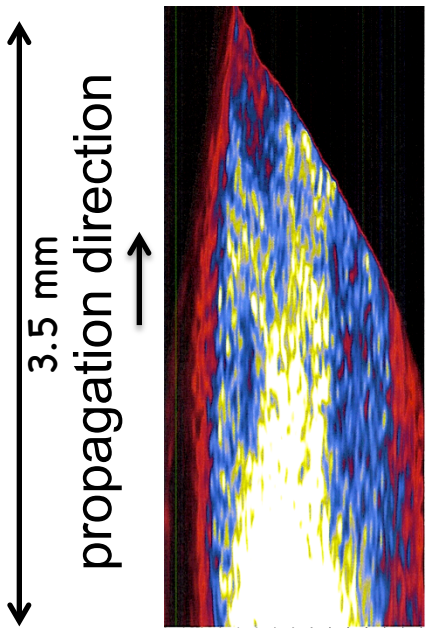


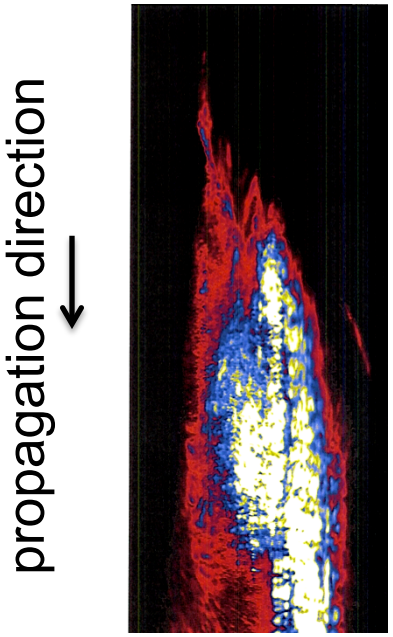
pF3D Reflectivity Vs Time
N110214, Single Quad
Spatially Non-Uniform

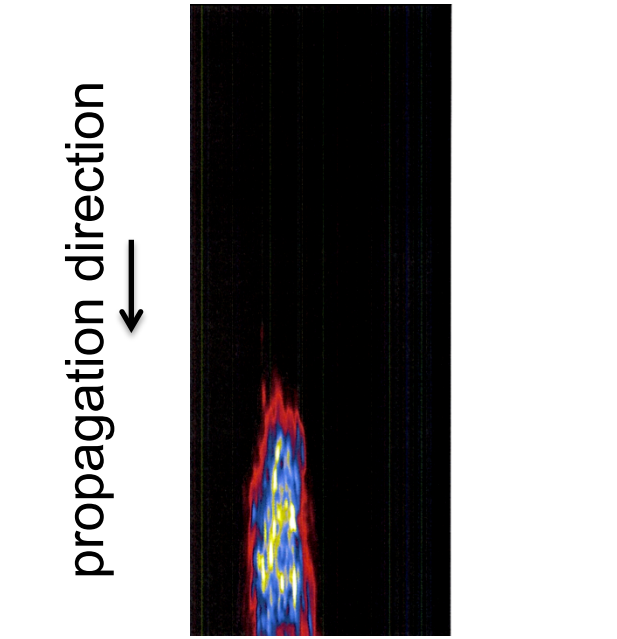


A central azimuthal slice* of the intensity patterns shows where the reflectivity occurs

Incident Intensity Pattern N110214 Spatially Non-Uniform XBT	SRS Intensity Pattern N110214 @ 18 ns Spatially Non-Uniform XBT	SBS Intensity Pattern N110214 @ 18 ns Spatially Non-Uniform XBT







X 10^{14} W/cm^2

* taken at ~ 62 ps into simulation

Our mesoscale analyses better match experiment with realistic macroscale inputs

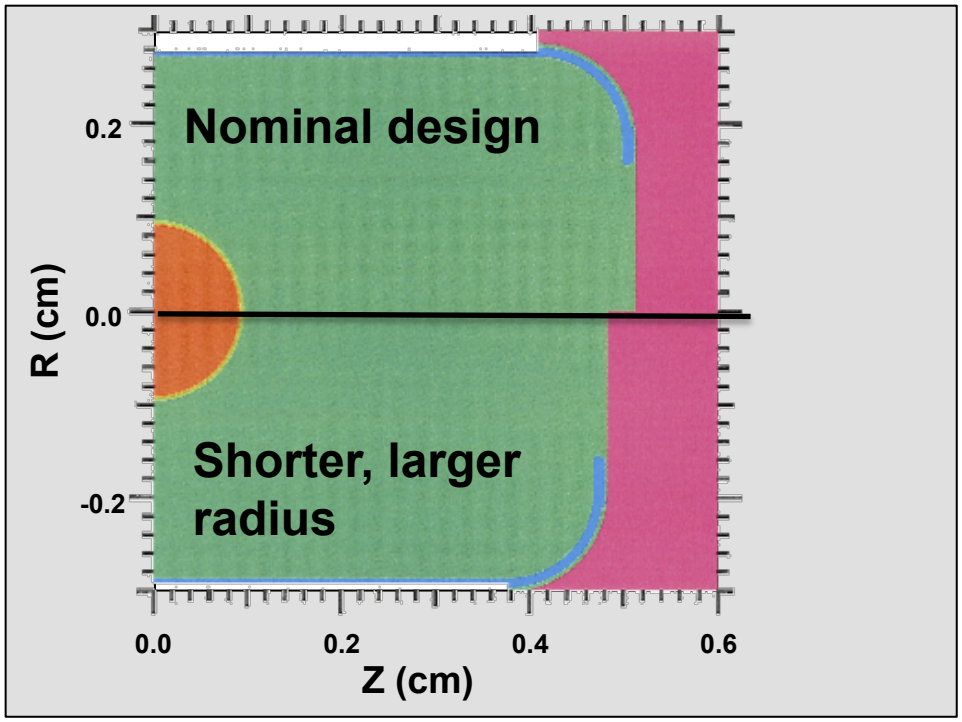
- With "HFM" plasma conditions and realistic laser spots:

	Early in Peak Power	Middle of Peak Power	End of Peak Power
Experimental SBS	Yes	Yes	No
Simulated SBS	Untested	Yes	No
Experimental SRS	No	Yes	Yes
Simulated SRS	Untested	Yes	Yes

- Our pF3D simulations provide an integrated test of knowledge of plasma and laser conditions

How do we use our improved understanding to optimize the platform?

An optimized hohlraum* has a shorter inner beam path, with more volume over the capsule



Original aspect ratio:
5.44 mm Diameter
10.01 mm full Length
L/D = 1.84

Optimized aspect ratio:
5.74 mm Diameter
9.41 mm full Length
L/D = 1.64

~ Quoting M. D. Rosen:
Golden Ratio !
("GolRaum" ?)

This re-optimized hohlraum needs less cross-beam transfer to the SRS-prone inners

*Simulations by D. A. Callahan

This re-optimized hohlraum is part of the NIC strategy to drive a DT implosion at 370 km/s

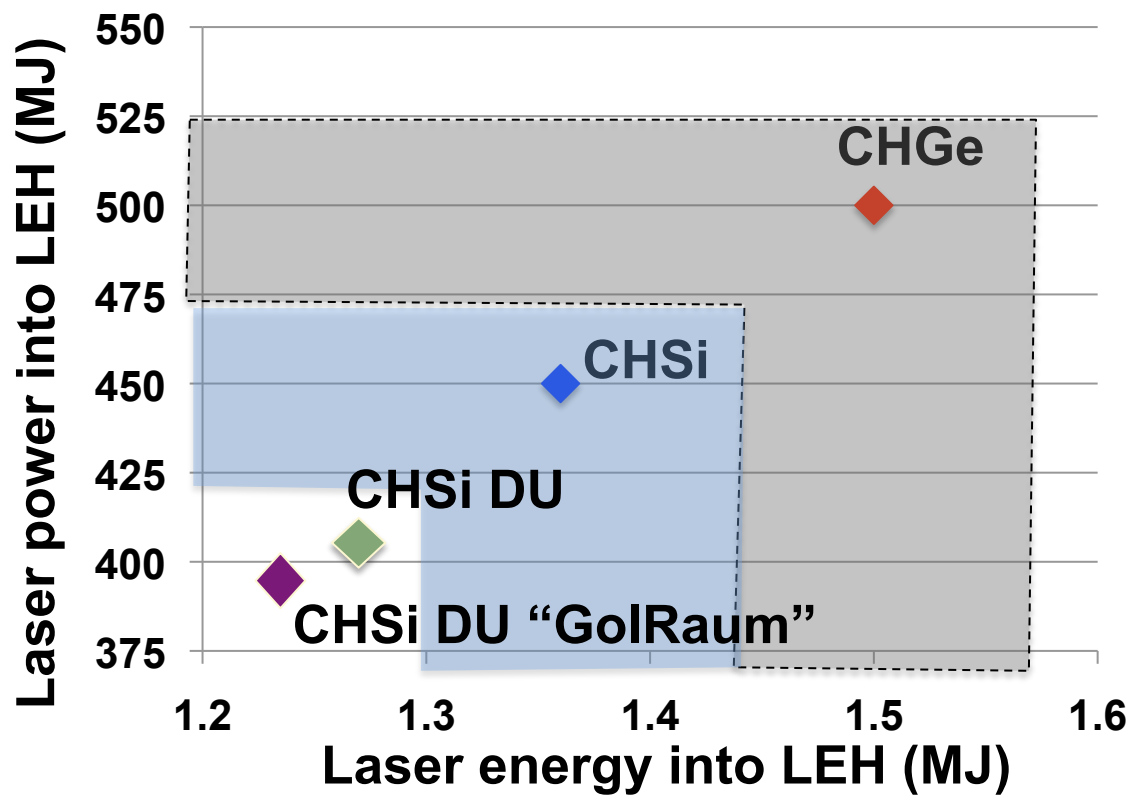
- We want the cryogenic DT fuel to reach 370 km/s
  -- we have achieved the equivalent of ~ 345-360 km/s

- We want 10% of the initial ablator mass remaining (unablated) at peak fuel velocity
  -- more ablator remaining means less feed-through of outer-surface Rayleigh-Taylor to the hot-spot

- Achieving 370 km/s without any hohlraum or capsule modifications:
  -- requires ~ 470 TW of laser power

- Hohlraum re-optimization:
  -- saves ~25-50 kJ in SRS losses

- Other target improvements:
  -- replace ablator Ge dopant with Si
  -- replace hohlraum gold wall with depleted uranium (DU)



With exascale computing on the horizon, we have a vision for higher fidelity simulations

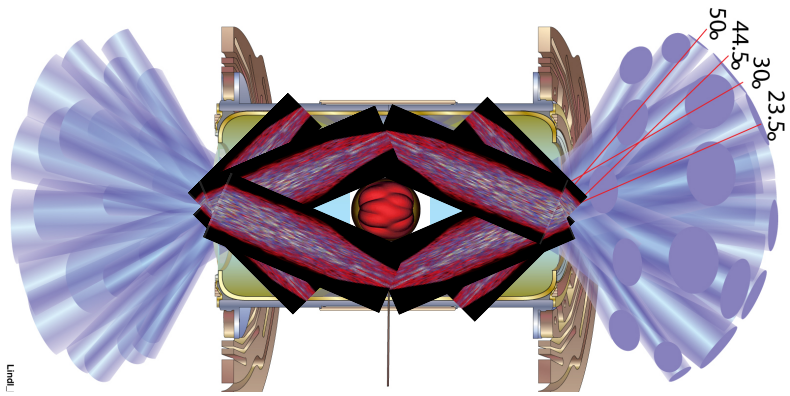
macroscale simulations with

embedded mesoscale simulations

accounting for microscale physics

- macroscale + mesoscale:
  100x more cpus (by ~ 2018)
- at multiple times:
  100x more cpus (by ~ 2030)
- reduced model descriptions of kinetic effects through PIC/Vlasov studies

Uses of Ignition



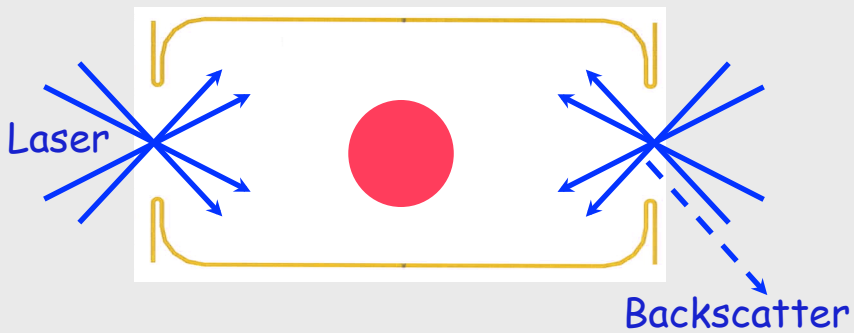
3D integrated macro-microscale simulations:

hohlraum, beams, capsule -- 2-10,000 exaflop-days

NIC

In a NIF target, laser-plasma interactions (LPI) impact energy coupling and re-direction

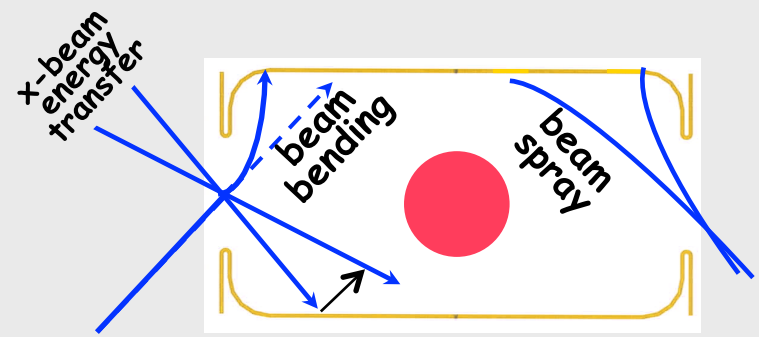
Energy Coupling ➔ T_r



✓ **SBS**: laser scatters off self-generated ion acoustic waves (iaws)

SRS: laser scatters off self-generated electron plasma waves (epws)

Energy Re-direction ➔ symmetry change



✓ **Beam spray**: laser hotspots dig density wells -- refract, intensify & scatter light

✓ **Beam bending**: in transverse flow, light advects with density wells

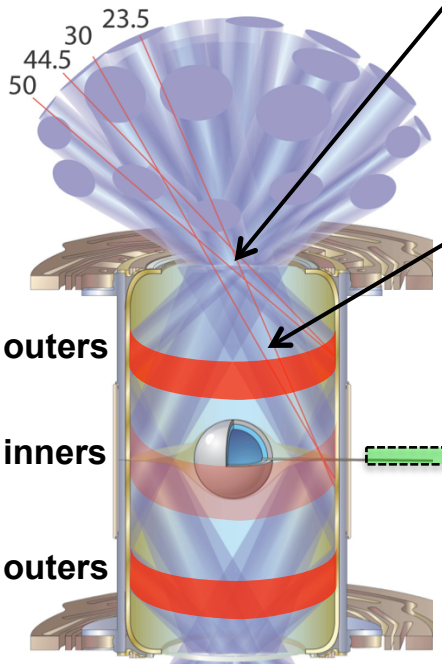
✓✓ + **Cross-beam transfer**: outer-to-inner energy transfer via scatter from mutually driven iaws (can improve symmetry!)

Re-absorption of scattered light: alters energy deposition profile

NIF achieved the necessary drive and symmetry; can we further mitigate SRS for even higher drive?

NIF experiments rely on crossed-beam energy transfer to achieve round implosions

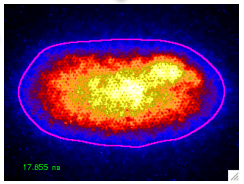
First 2009 NIF experiment: goal was zero net transfer; → "pancake" implosion



no net inner/outer transfer ($\Delta\lambda$=1.5 Å*)

+

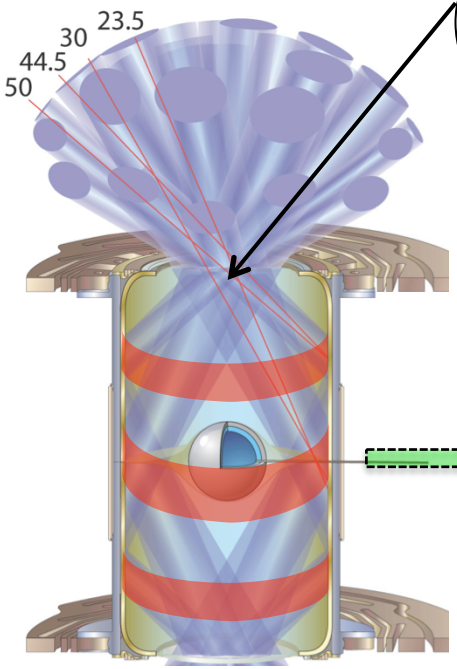
impaired inner beams propagation (SRS + absorption in cold plasma**)



"pancake" (pole-high) implosion

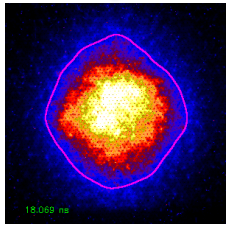
** 1.5 Å to compensate for flow-induced transfer*

Now: ~50% transfer from outer to inner beams → round implosions



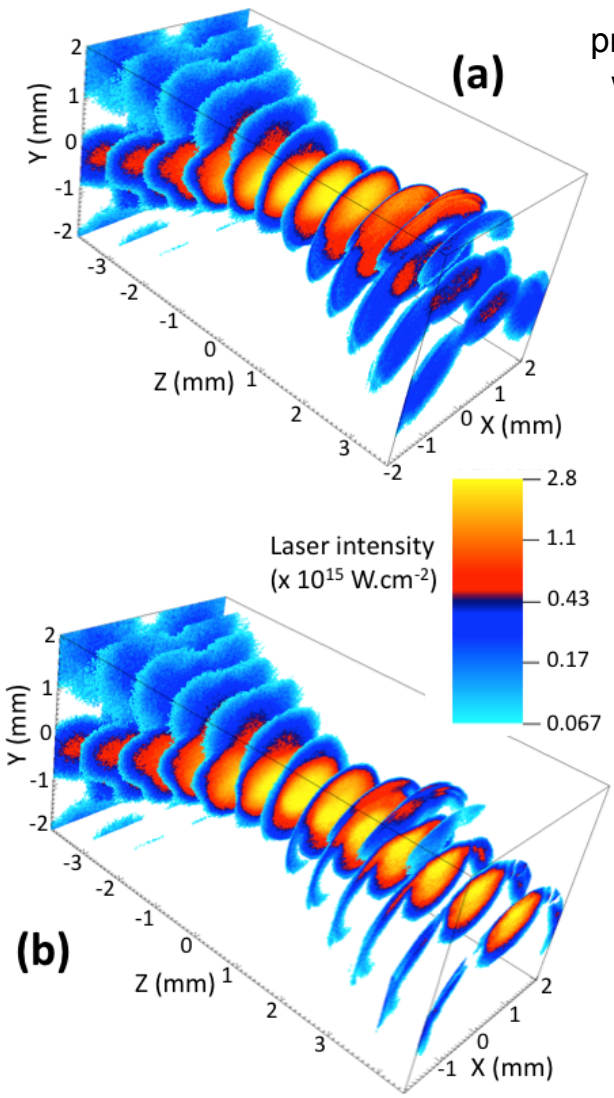
transfer outer → inner beams (x1.4 to 1.8, $\Delta\lambda$=5 to 8.5 Å)

→ compensates inner beams' impaired propagation



round implosion

We have developed a massively-parallel code to study crossed-beam transfer in NIF geometry



$$\left(\partial_z - \frac{i\nabla_\perp^2}{k_0+\sqrt{k_0^2+\nabla_\perp^2}} + \frac{k_0'}{2k_0} + \frac{i\omega_{pe}^2\delta n}{2\omega_0 v_{g0} n_e} + \frac{\nu_{ei} n_e}{2 v_{g0} n_c}\right)\begin{pmatrix} a_{sx} \\ a_{sy}\end{pmatrix} = -i\sum_{p=1}^{Np}\frac{k_{p-s}^2}{8\mathbf{k_s}\cdot\mathbf{z}}\frac{\chi_{e,p-s}(1+\chi_{i,p-s})}{1+\chi_{e,p-s}+\chi_{i,p-s}}\begin{pmatrix} a_{sx}|a_{px}|^2 + a_{sy}a_{py}^* a_{px} \\ a_{sy}|a_{py}|^2 + a_{sx}a_{px}^* a_{py}\end{pmatrix}$$

- propagation & diffraction with modified paraxial operator
- refraction
- energy flux conservation
- enveloped laser fields (measured NIF phase fronts: phase plates etc.)
- collisional absorption
- sum over Np pump fields
- linear kinetic plasma response to beat wave of (a_s, a_p)
- projections on orthogonal polarization direction (→ NIF polarization smoothing scheme)

Model valid only for nearest-neighbors beams (~up to 6, max. angle ~20°)

This model is used for:

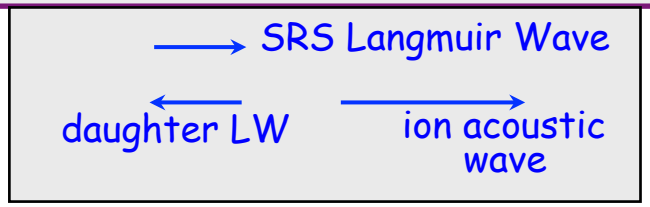
- **basic studies (effects of speckles, smoothing, etc.)**
- **input E-field with crossed-beam transfer for pF3d calculations**

We are now using a simpler model for crossed-beam transfer, integrated to hydro calculations

What about kinetic effects?

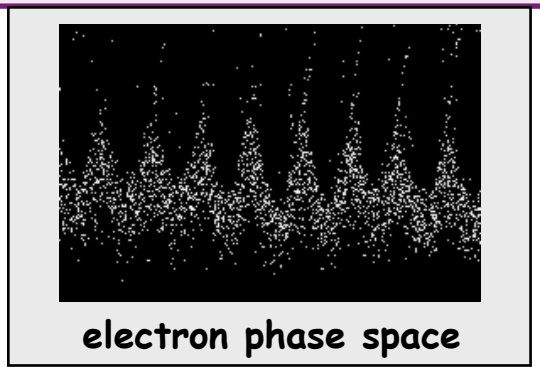
- Langmuir Decay Instability (LDI):
  - -- likely occurring in NIF sub-scale targets
  - -- or over capsule in full-scale targets

LDI depletes SRS Langmuir Wave



- Electron Trapping:
  - -- can "inflate" reflectivity via damping reduction
  - -- can "deflate" reflectivity via de-tuning, incoherence …
  - -- D. J. Strozzi is applying his "bounce number" trapping metric

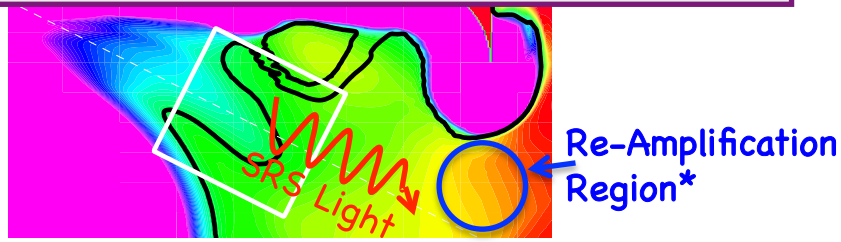
Electron trapping in Langmuir Wave



- Re-scatter?

SRS light further amplified non-resonantly near LEH?

- Re-amplification of SRS Light:

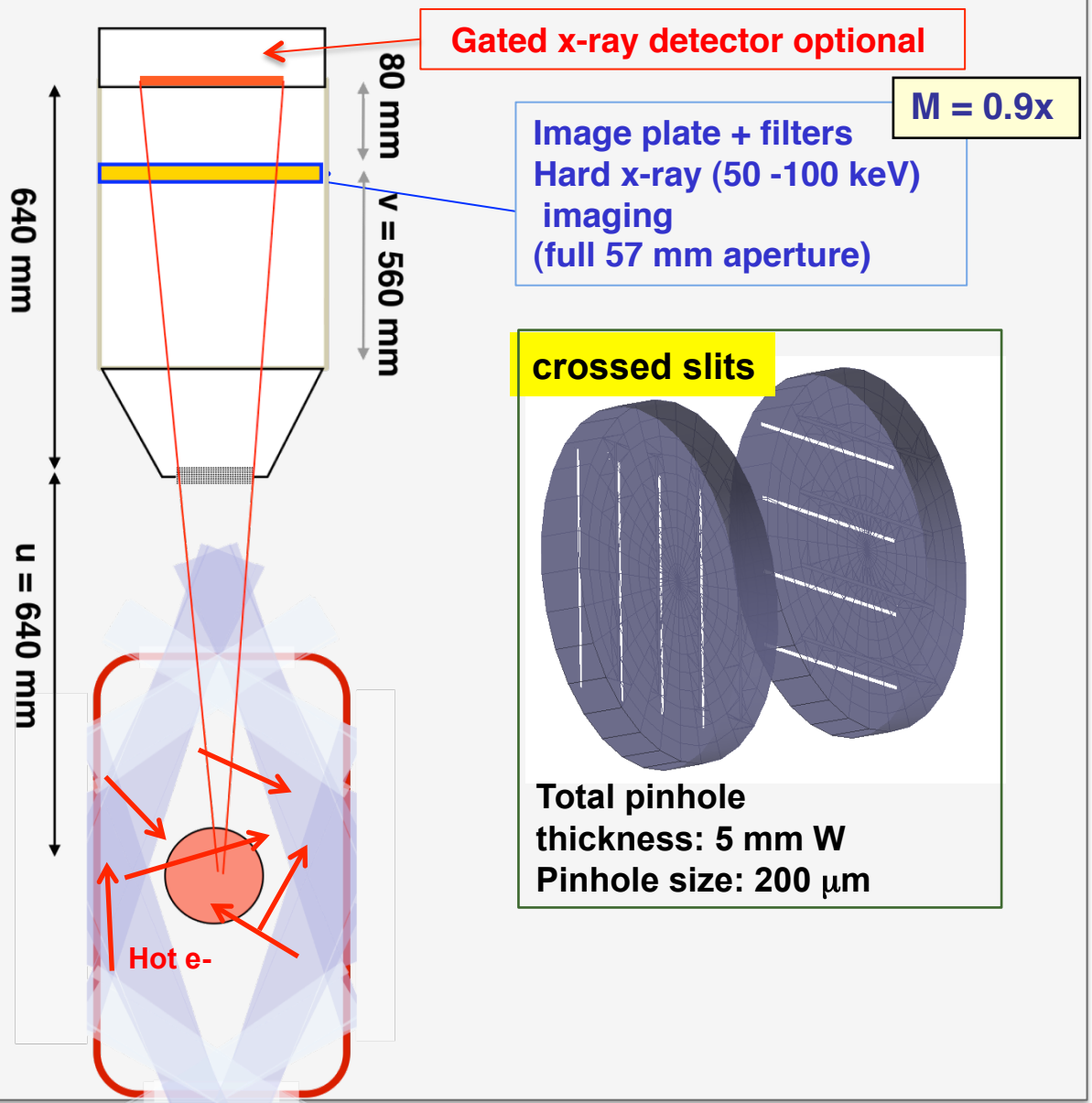


Incorporating these effects into pF3D allows for their interplay with geometry

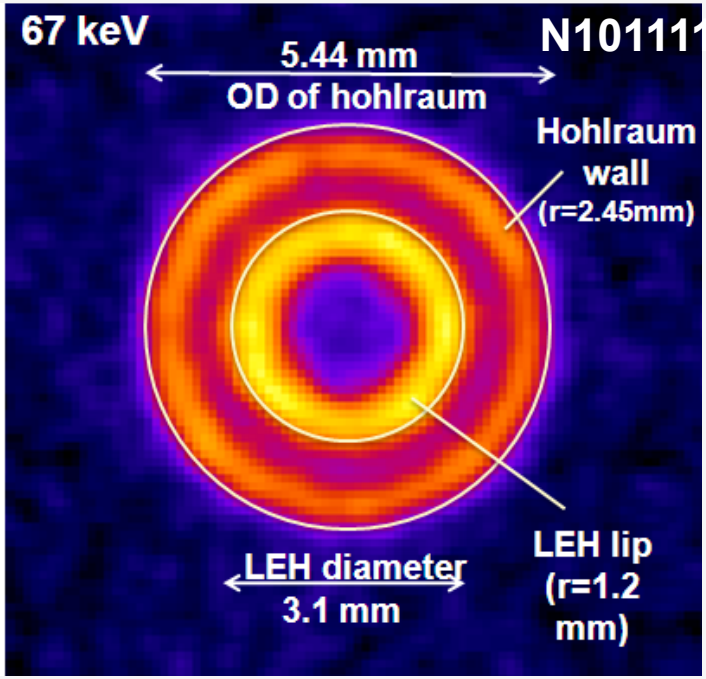
*P. A. Michel *et al.*, PoP **17**, 056305 (2010)

HXI is a hard x-ray (50 – 125 keV) imager to study hot electron coupling and stopping

Setup for standard 1x imager snout

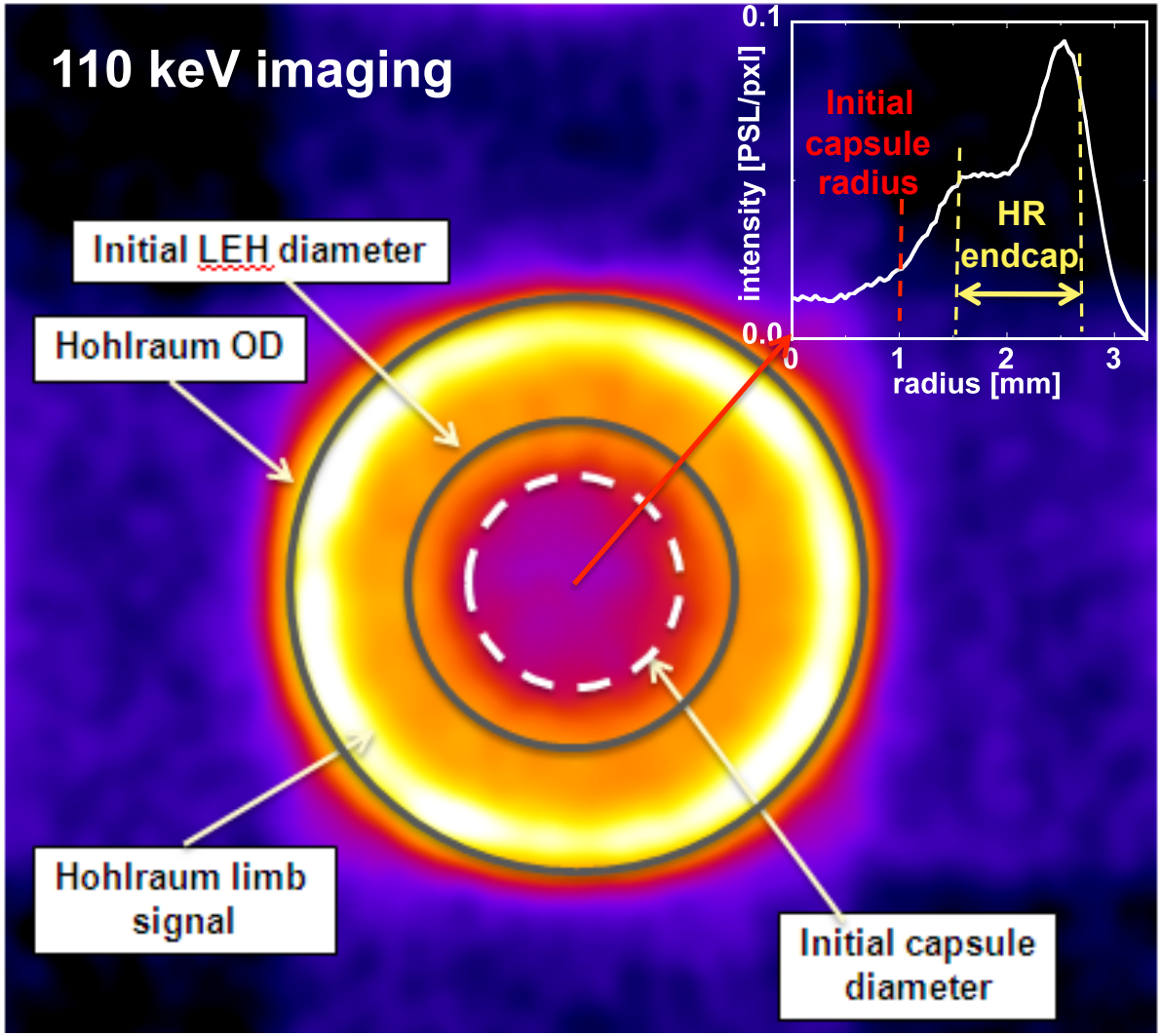


Data taken on N101111

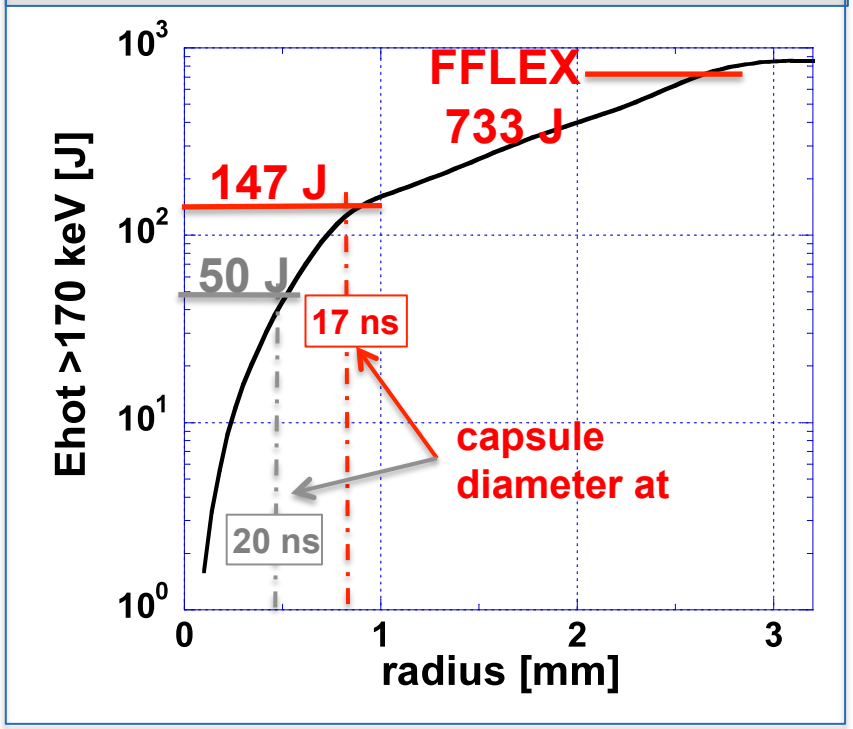


We use ratio of capsule to hohlraum Bremsstrahlung intensity at < 100 keV, normalized to space-integrated FFLEX spectra, to infer >170 keV electron energy coupling to capsule

HXI can provide information on coupling of hot electrons to capsule



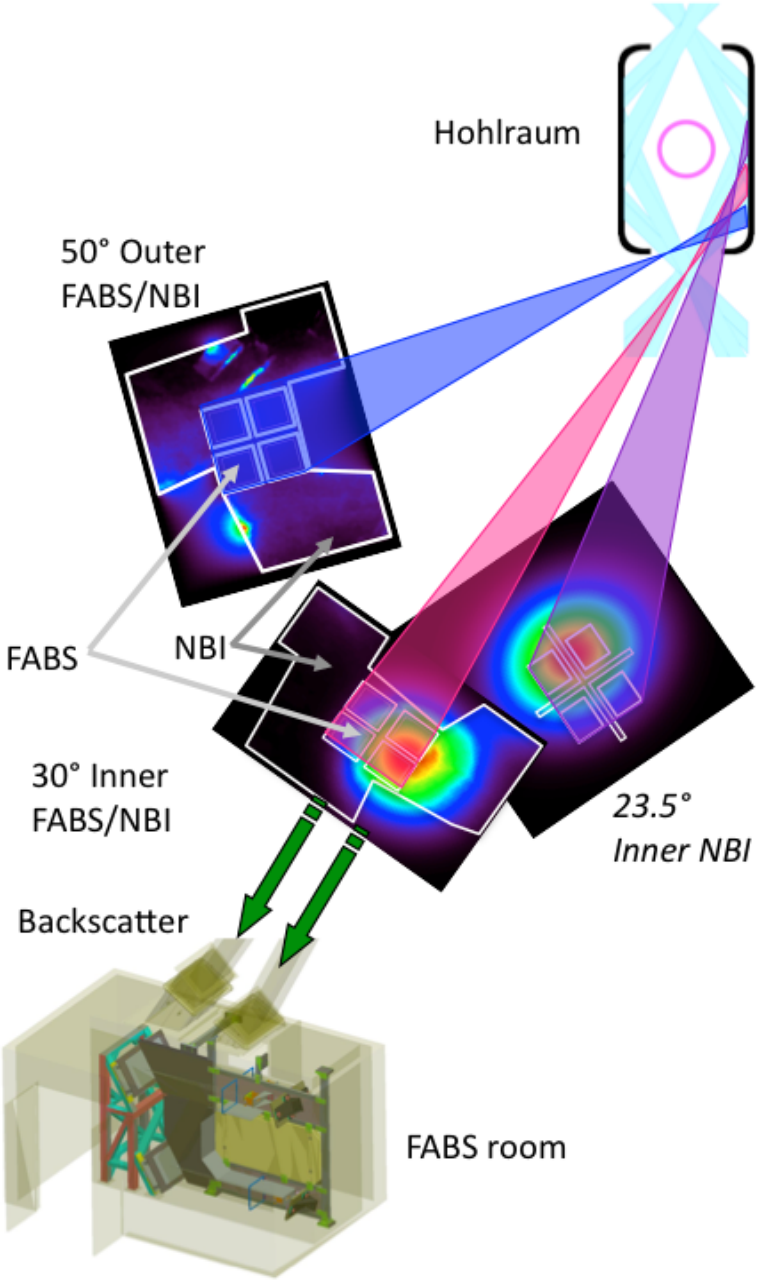
Hot electron energy inferred from signal integrated up to radius r



per FFLEX, hot electron peaks at end of laser drive, i.e. at capsule radii of ~ 0.5 mm

Preheat on the capsule (electrons @>170 keV) is <147 J, i.e. <20% of total measured by FFLEX

SRS and SBS are measured using the recently upgraded FABS and NBI diagnostics



FABS: energy and time-resolved spectra in lenses

NBI: time-integrated and time-resolved energy on a scatter plate around the lenses

Recent upgrades:

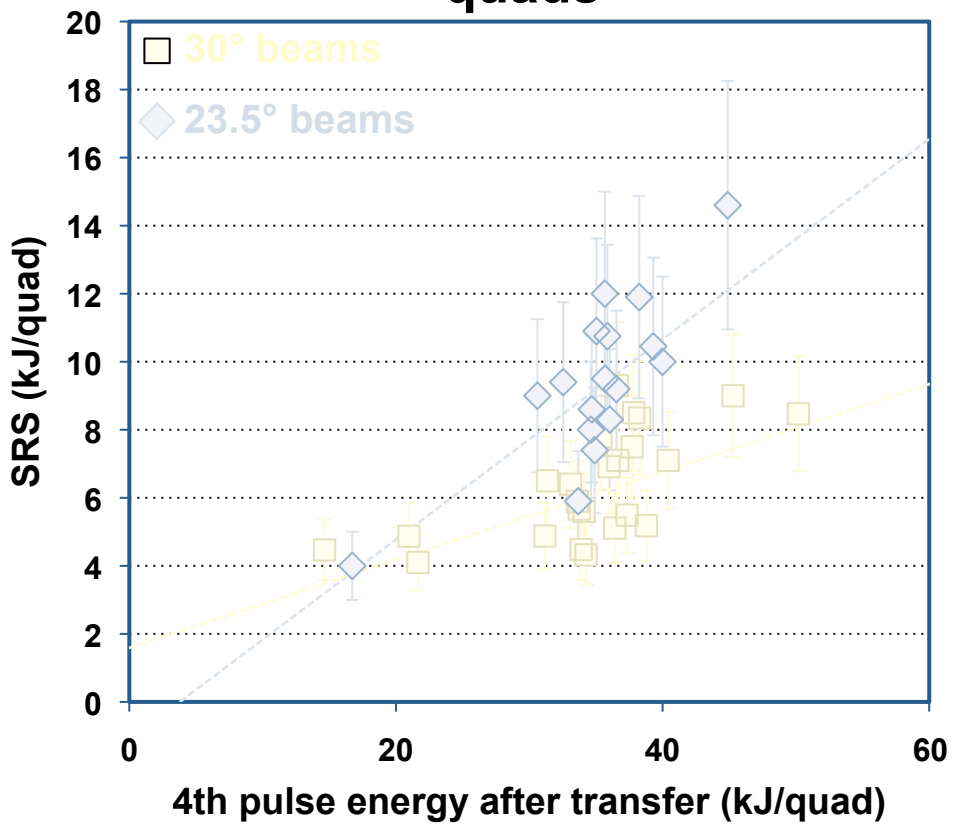
- **23.5° SRS NBI (central cross only): since 2010**
- **23.5° SBS NBI: since last week (May 2011)**

Upcoming upgrades:

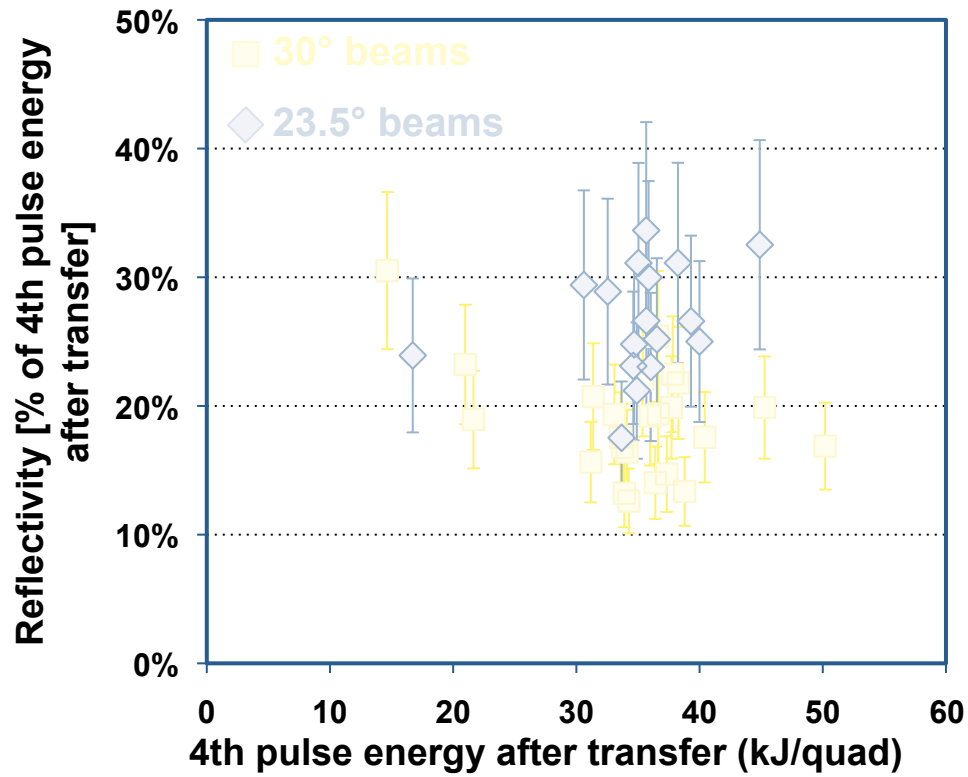
- **23.5° NBI time-resolved spectrum (~July)**
- **23.5° 3/2ω capability (~August?)**
- **high yield capability (~October?)**

SRS is responsible for most of backscatter losses; it is scaled using observed experimental trends

SRS follows fairly reproducible trends on the 23.5° and 30° quads

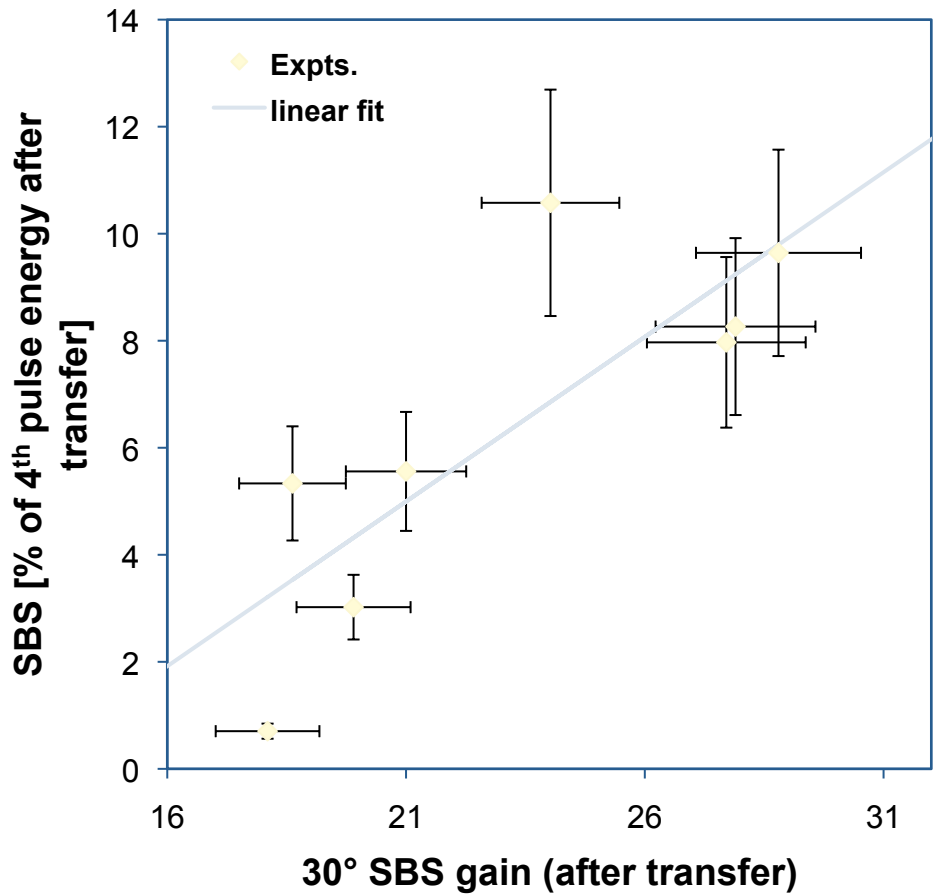


SRS in saturated regime, with ~constant reflectivity (~15-20% on 30°, 25-30% on 23.5°)



We use an empirical scaling based on measured SRS to scale up to higher laser energies; depends on x-beam transfer (i.e. required c.f.)

The measured SBS reflectivities on the inner beams scale with calculated LIP gains



- SBS gains are calculated with the laser power after x-beam transfer

=> LIP gains capture the essential LPI and hydrodynamics necessary to scale SBS

The LIP gains appear to be a good metric to estimate SBS reflectivity from laser and plasma conditions