Modeling Laser-Plasma Interaction over a Suite of NIF Experiments

D. J. Strozzi, R. L. Berger, T. Chapman, O. S. Jones, D. T. Woods, S. A. MacLaren, P. Michel, L. Divol

APS DPP 2017

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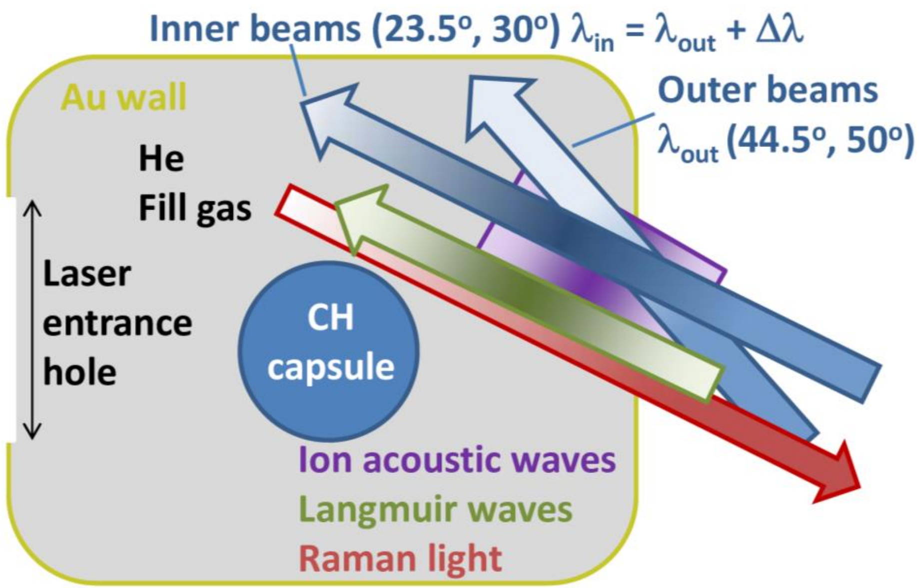
Laser-Plasma Interaction (LPI) in hohlraums



Important for high hohlraum fill density

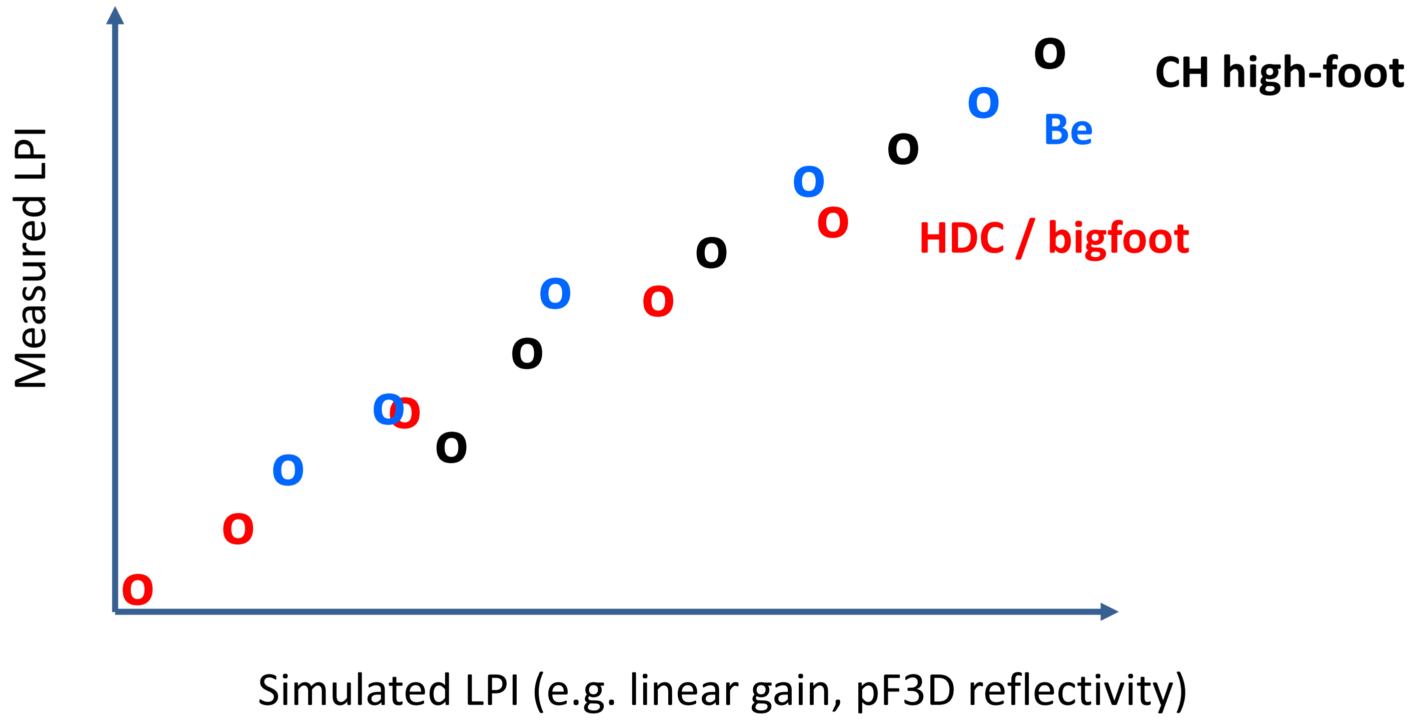
Low-foot, high-foot designs

- **Cross-Beam Energy Transfer (CBET) : $\Delta\lambda$**
  - Form of Brillouin scattering
  - Laser 1 γ → Laser 2 γ + ion acoustic wave
  - To longer wavelength laser in plasma frame
- **Stimulated Raman scattering (SRS)**
  - Laser γ → scattered γ + Langmuir wave
  - Energy lost
  - Energetic or “hot” electrons → preheat
  - Also affect shape
- **Stimulated Brillouin scattering (SBS)**
  - Laser γ → scattered γ + ion acoustic wave

“Inline” LPI models recently added to HYDRA and LASNEX:
D. J. Strozzi et al., *Phys. Rev. Lett.* 2017

LPI scaling study: understand and model trends in NIF LPI data

Nirvana: universal “fruit plot”:
simulated LPI figure of merit collapses
data from different targets



Summary: towards predictive rad-hydro + laser-plasma modeling

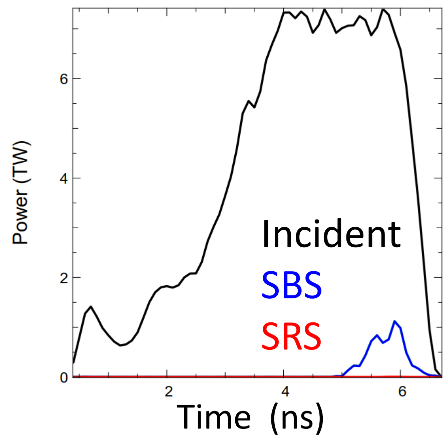
Lasnex rad-hydro model: O. Jones et al., PoP 2017
- Converged numerics
- No per-shot multipliers
- DCA non-LTE model
- Low electron flux limit f = 0.03
- **New:** Inline CBET: clamp $\delta n_e/n_e$=0.01

Plasma maps

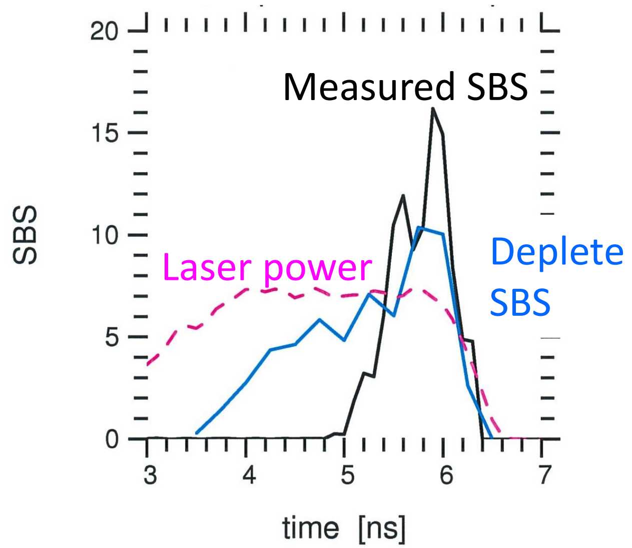
NIF "bigfoot" shot [C. Thomas, APS-DPP 2016]
- CBET (calculated) to outer cones
- Outer-cone SBS: 10-15% end of pulse

Outer SBS modeling
- **DEPLETE:** ray-based extension of linear gain
- **pF3D:** paraxial-envelope code
    - speckles, polarization smoothing, SSD, …
- SBS Increases with time, but less than data
- SBS from gold bubble

Bigfoot shot: outer beam BS



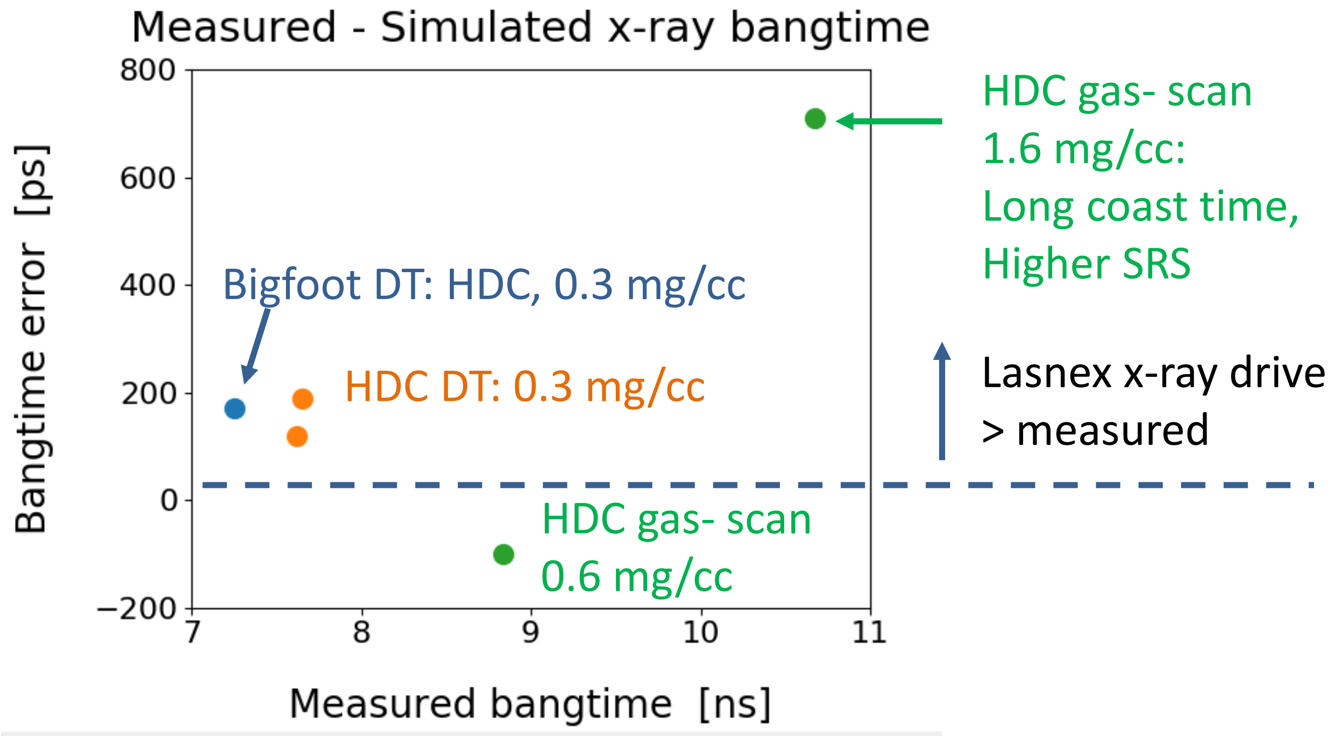
Outer SBS reflectivity [%]



Energetics across a set of NIF shots

“Drive deficit”

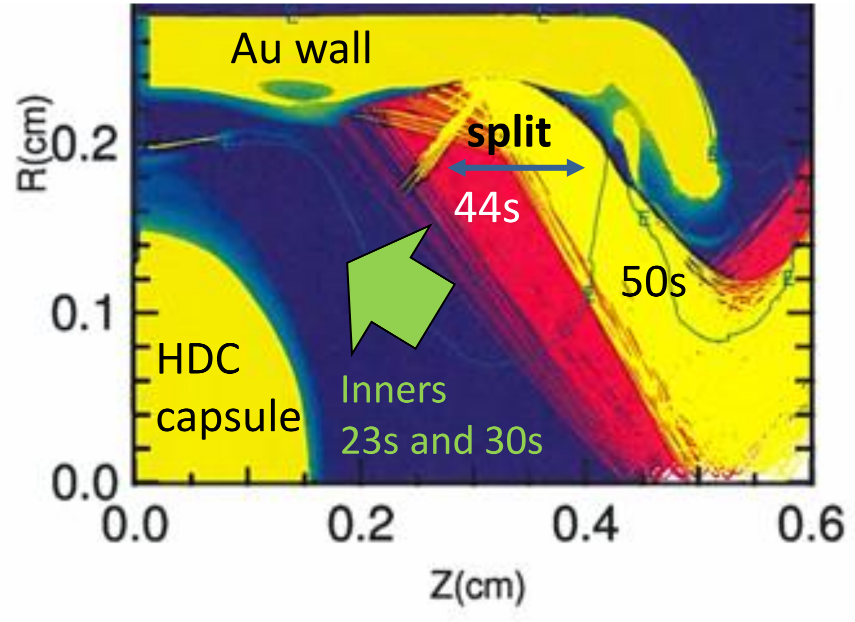
- Rad-hydro modeling generally over-predicts x-ray drive in NIF hohlraums
- Especially for long pulses, high gas fill density, high backscatter



LPI simulated for "Bigfoot"[1] shot N170109

Bigfoot
- 1st and 2nd shocks merge in ablator, before reaching DT fuel
- "Robust" hostspot: high adiabat, high rho*R
- Less prone to hydro instabilities
- Price: lower 1D fusion gain

$\Delta\lambda$ = 0: CBET due to plasma flow only



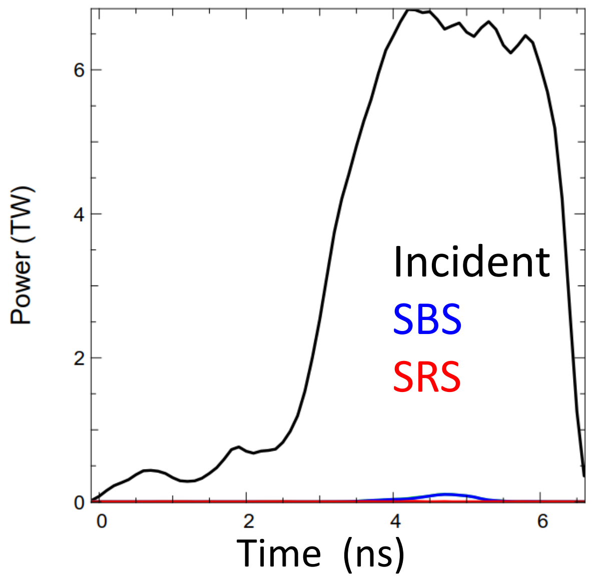
Outer beams: "Quad splitting"
- Spread out outer beam spots on wall
- 4 beams in an outer quad split in azimuth
- 44's and 50's separated in Z

Benefits:
- Less azimuthal asymmetry
- Lower intensity at wall → lower SBS
- Less M-band x-rays
- Less wall / bubble motion

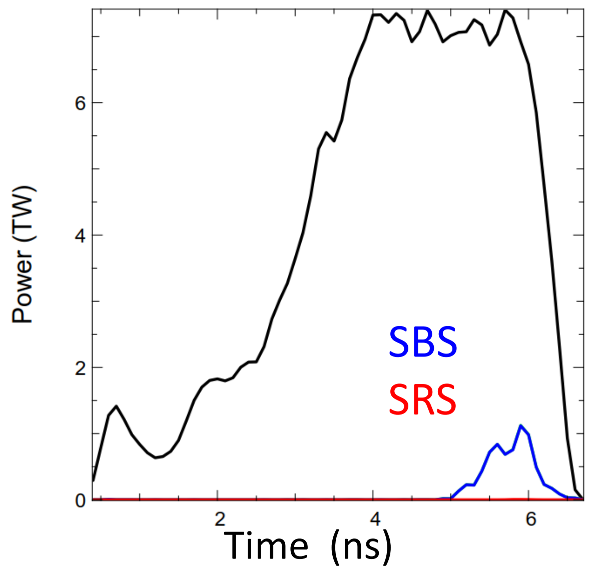
[1]C. A. Thomas, APS DPP 2016 invited talk

Bigfoot shot N170109: SBS late in time on cone 50

Q31B FABS: Inner cone, 30º



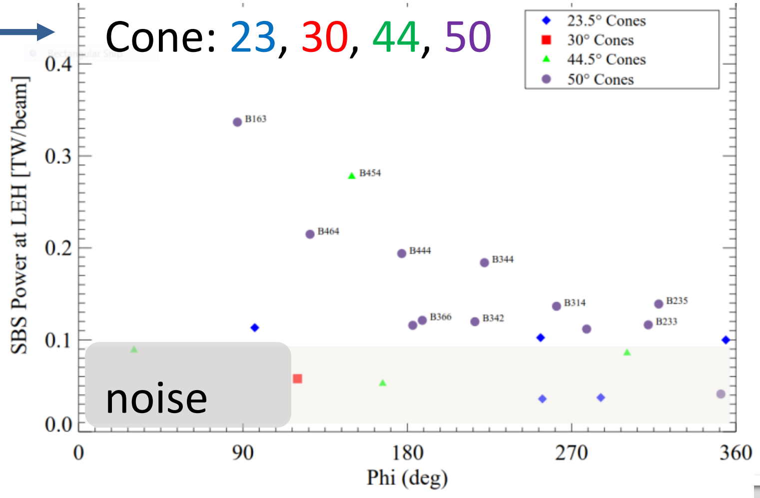
Q36B FABS: Outer cone, 50º



DrD (Drive diagnostic) sensors

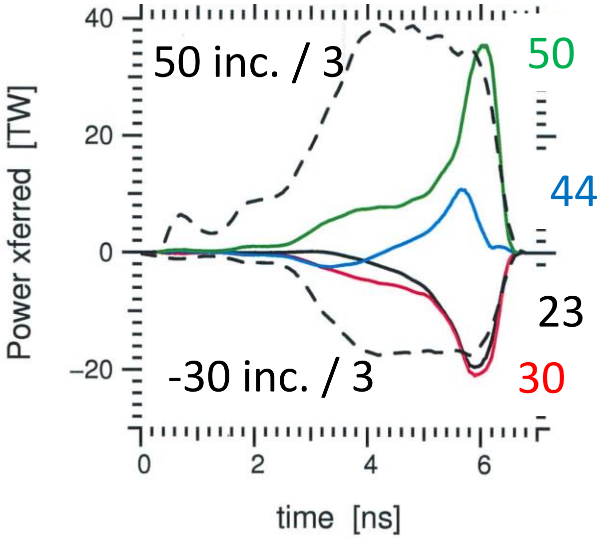
SBS in >= one beam on every quad:

- More SBS on cone 50 than 44

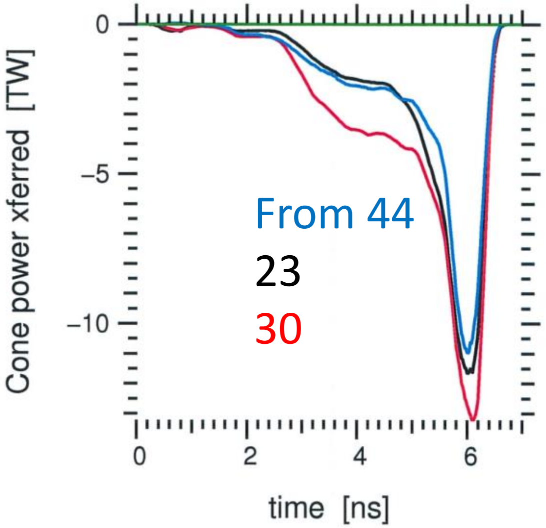


Bigfoot: calculated CBET to outers, especially 50’s

Net transfer to each cone

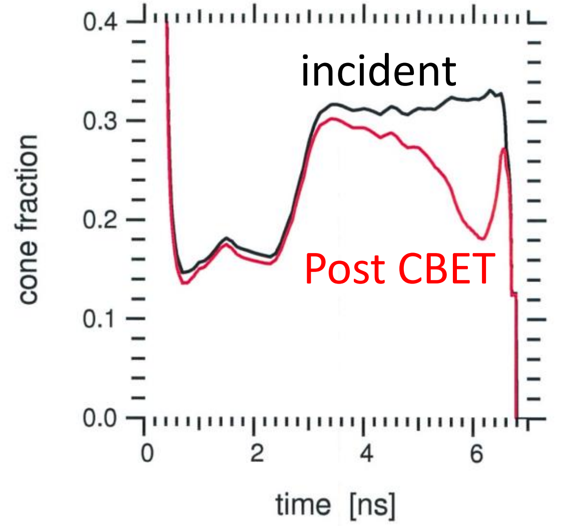


cone 50: transfer FROM all other cones



NIF Shot N170109

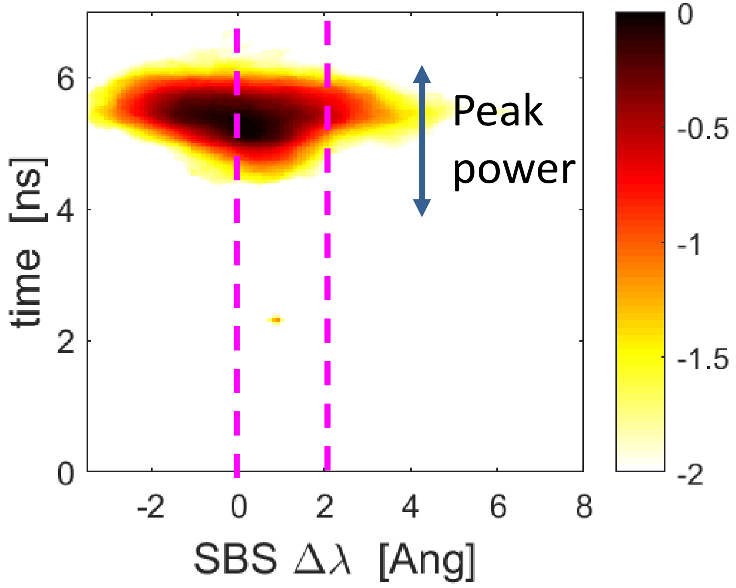
Cone fraction = Inner / Total power



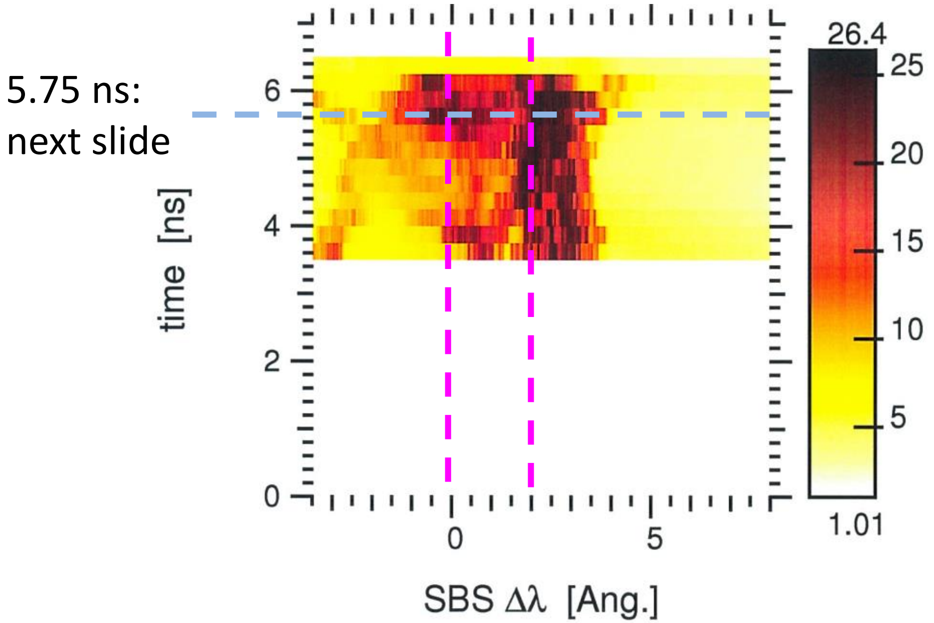
CBET may be part of reason SBS higher on cone 50 than cone 44

Bigfoot: Cone 50 SBS spectrum vs. DEPLETE[1]

Measured SBS spectrum: Shot N161204 (Symcap)



Ray-averaged DEPLETE gain spectrum: Shot N170109: layered DT: no SBS spectrum

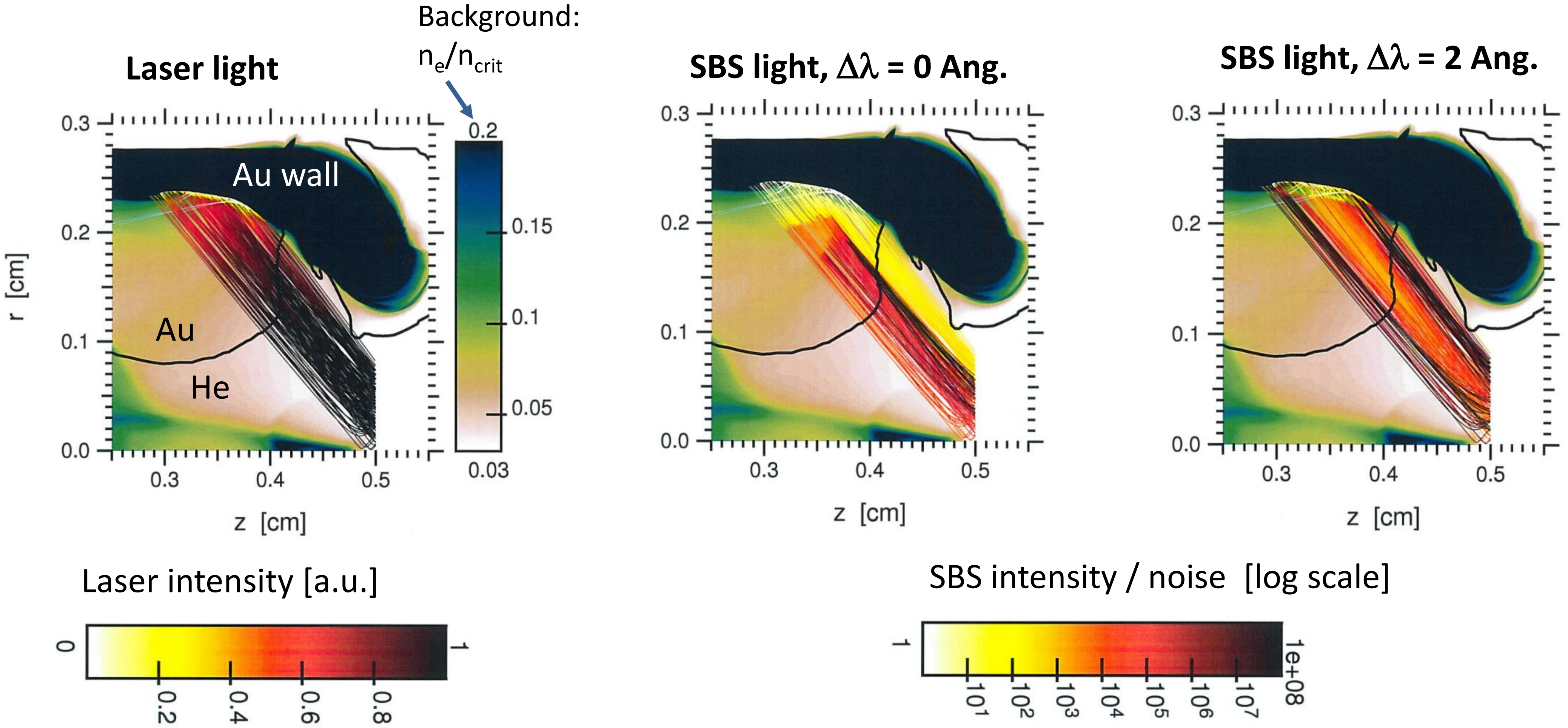


- DEPLETE spectrum redshifted by ~ 2 Ang. vs data
- Depends on sound speed and flow velocity
- Neglects SSD bandwidth, “Dewandre effect:” wavelength shift from $\partial n_e / \partial t$

[1]D. J. Strozzi, E. A. Williams, D. E. Hinkel, D. H. Froula, R. A. London, D. A. Callahan, *Phys. Plasmas* 2008

DEPLETE: Cone 50 SBS develops in gold bubble

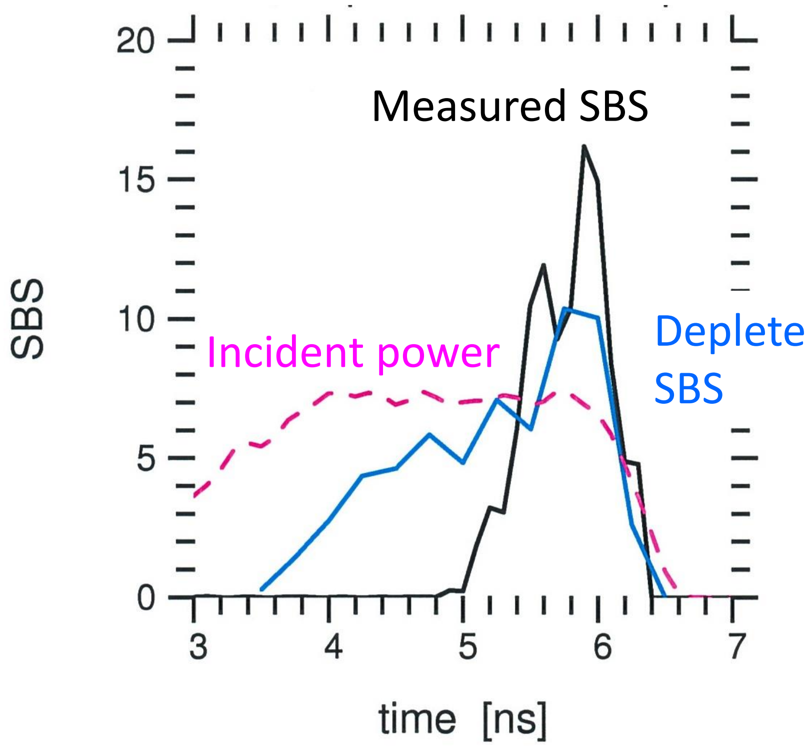
N170109
5.75 ns: late peak power



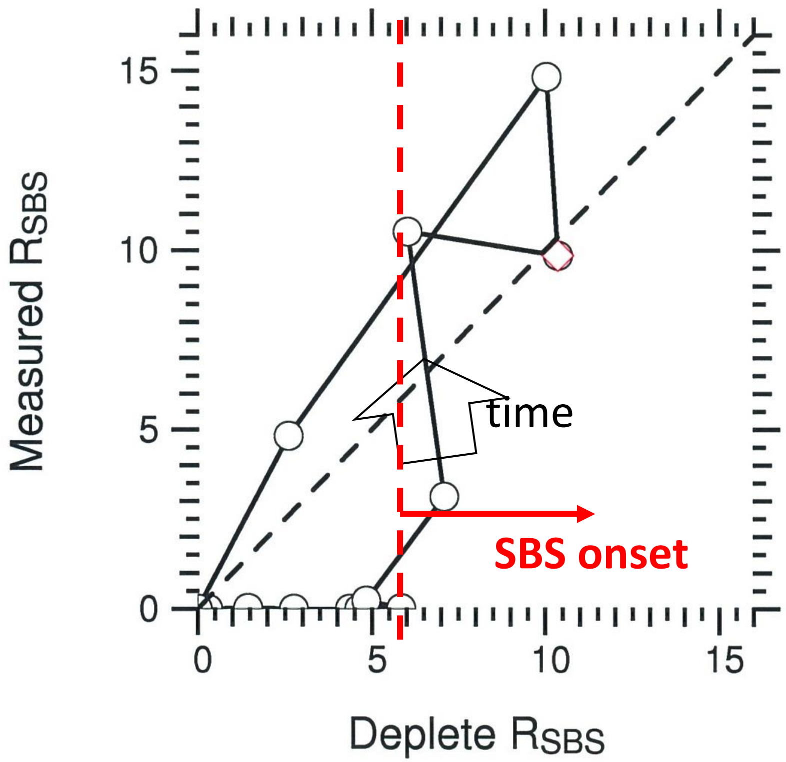
Cone 50 SBS: Measured and DEPLETE reflectivities qualitatively track vs. time

NIF Shot N170109

SBS reflectivity [%]



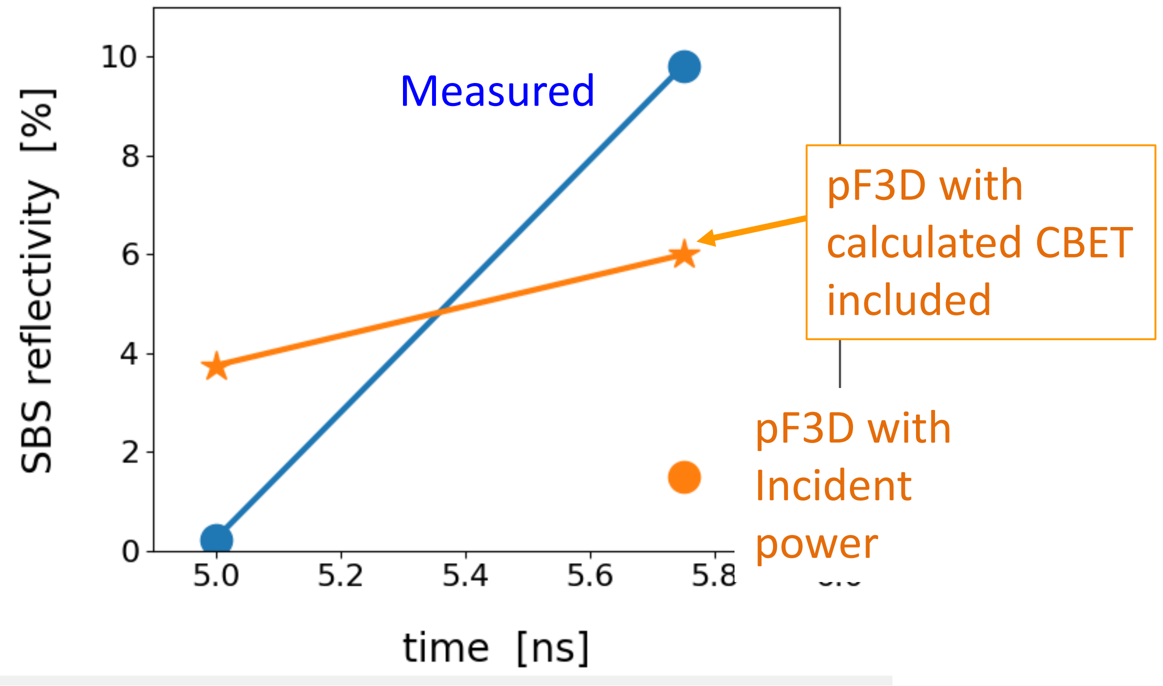
Fruit plot: SBS Reflectivity [%]



Deplete reflectivity: sum over rays of wavelength-integrated SBS intensity

Cone 50 SBS: pF3D[2] simulations close to measured reflectivity, when CBET included

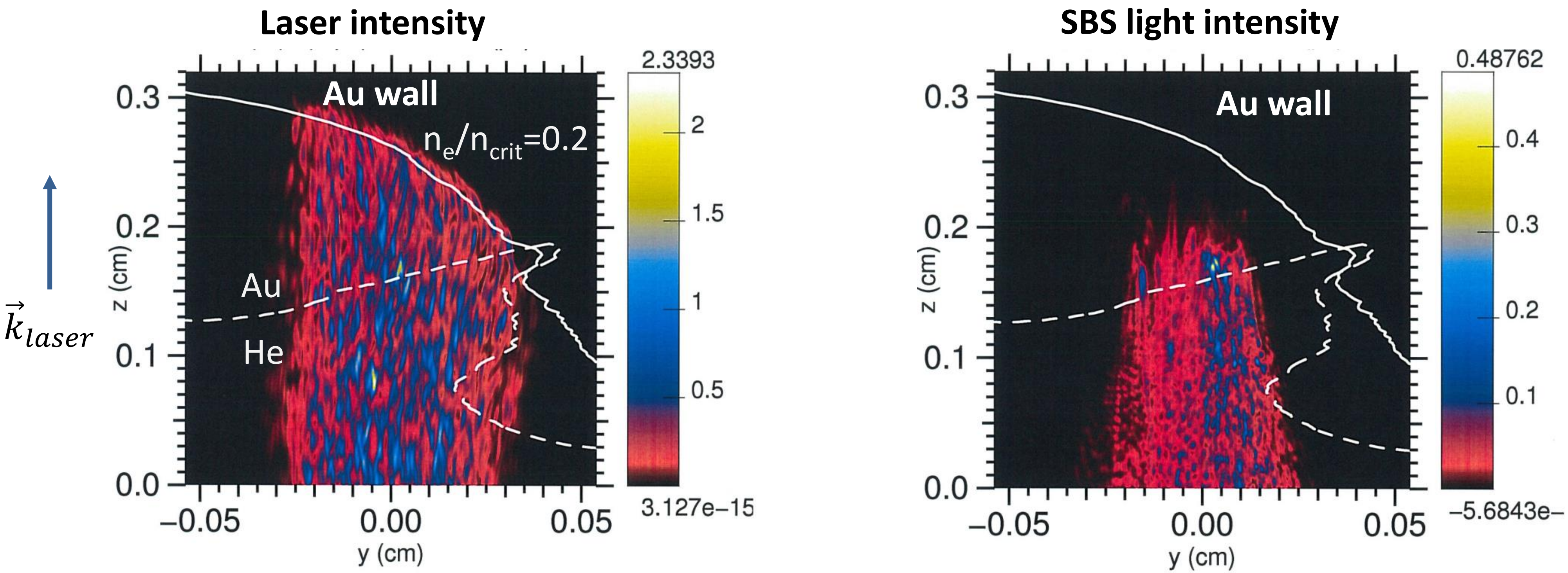
NIF bigfoot shot N170109



pF3D simulations by R. L. Berger

[2]R. L. Berger, C. H. Still, E. A. Williams, A. B. Langdon, Phys. Plasmas 1998

pF3D: outer SBS grows in gold bubble



- pF3D run includes one 48^o and one 52^o beam – each orthogonally polarized
- 50^o quad has two other beams: spatially separated at wall due to "quad splitting"
- Plots in pF3D coordinates: laser propagates in z

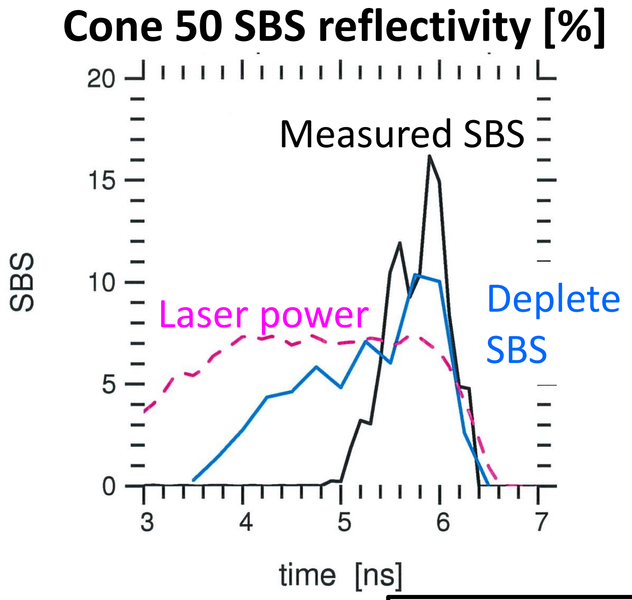
LPI scaling study: status and future work

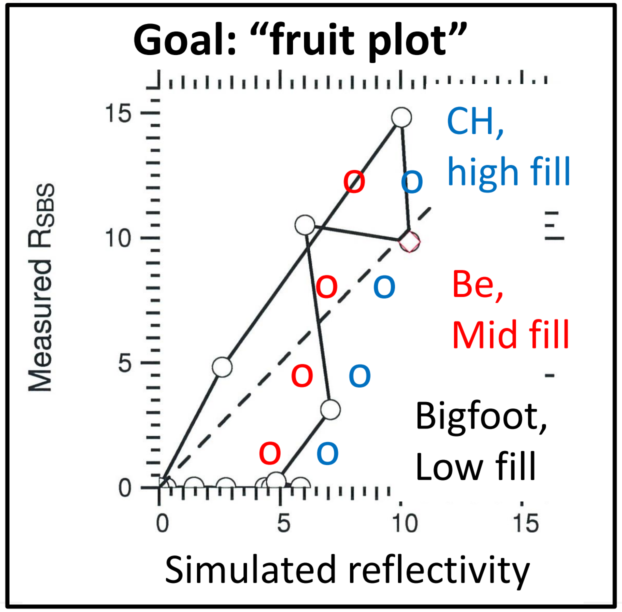
LPI on "Bigfoot" shot N170109

- CBET modeling: CBET to outers, increases in time
- Backscatter: mostly cone 50 SBS, peaks late in time
- Cone 50 SBS modeling: DEPLETE and pF3D
    - Similar reflectivity to data, when CBET included

Future work

- Apply to more shots, more LPI data – inner SRS, SBS in beams within quad
- Suggest rad-hydro and LPI modeling improvements, e.g. gold bubble





BACKUP BELOW

LPI a key and *varying* player on NIF ignition shots

CH ablator campaigns long pulse 15-25 ns	low foot '09-12 low adiabat	high foot 12-14 higher adiabat	CH672 14-now large scale 672 hohlraum
hohlraum He fill, mg/cc	0.96	1.6	0.6
CBET: $\Delta\lambda = \lambda_{in} - \lambda_{out}$	high (to inners)	high (to inners)	0 usually
Inner BS	high SRS	high SRS	moderate SRS SBS with $\Delta\lambda$: mirror damage
Outer BS	low	low	SBS throughout peak

→ year

HDC ablator campaigns short pulse 5-9 ns	near-vacuum hohlraum 12-15 symmetry dynamic, hard	bigfoot + HDC 15-now
hohlraum He fill, mg/cc	0.032	0.3
CBET: $\Delta\lambda = \lambda_{in} - \lambda_{out}$	0	0
Inner BS	low	modest SRS
Outer BS	low	high SBS at end of long pulse

Be campaigns intermediate pulse

Be high foot 12-14
Analogous to CH high foot
LPI similar

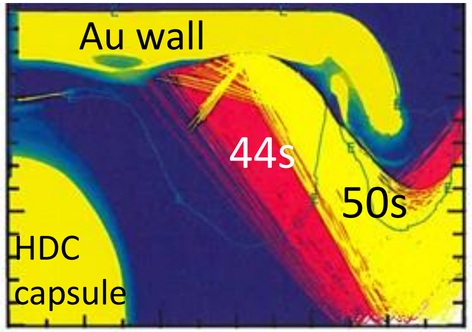
Be672 15-now
similar to CH672
LPI similar, somewhat lower

LPI modeling: two-step process

Rad-hydro code
- Hydra, Lasnex
- Inline models (CBET, SRS)

output

plasma maps
low-density conditions
$n_e < n_{crit} = 9*10^{21}$ /cm^3



input

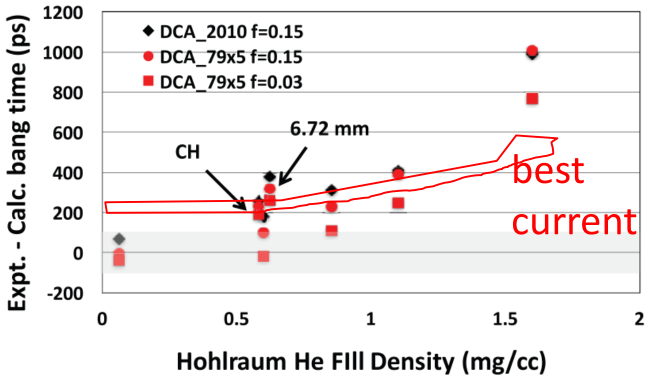
LPI code
- NEWLIP: linear gains
- DEPLETE: extended gains
- CBET script (P. Michel)
- New ray-based tool (A. Colaitis)
- pF3D: paraxial-envelope, speckles
- SLIP: steady-state pF3D

Validated LPI model can guide future designs:
- Current "hybrid" campaigns
- Innovative hohlraum concepts
  - Foam liners, new geometries
- 2-2.5 MJ blue-light NIF
- 3 MJ green-light NIF
- Imposed B field

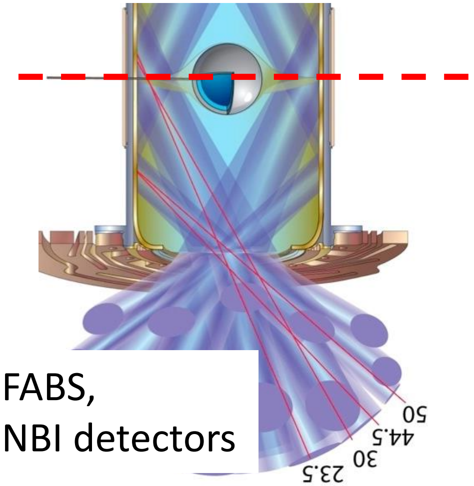
Rad-hydro model: "best current" physics in Lasnex[1]

- **Opacity + EOS**
  - LTE tables for $T_e < T_{crit}$, non-LTE DCA for $T_e > T_{crit}$
  - T_{crit} = 300 eV in wall, 50 eV elsewhere (capsule)
  - DCA models: March 2014
  - Gold: dca_79x5 – improved "bubble" physics
- **Laser**
  - No inline SRS/SBS
    - Backscatter removed from incident laser
  - Inline CBET: unpolarized quads
    - Saturation $\delta n_e/n_e = 0.01$
  - Inverse brem. with Langdon effect
  - Ponderomotive force: needed for CBET momentum deposition
- **Electron heat conduction**
  - Heat flux $q = \min(q_{SH}, f\, n_e T_e v_{Te})$
  - q_{SH} = Spitzer-Harm + Lee-More corrections
  - Low flux limit f = 0.03 everywhere
  - No MHD, nonlocal, ion turbulence models

Simulations: too much x-ray drive, esp. for long pulses, high fill density



2D RZ, Only bottom half: BS diagnostics there



FABS,
NBI detectors

[1]O. Jones et al., *Phys. Plasmas* 2017

Rad-hydro: high-resolution numerics, ALE mesh

- **Numerical resolution:** O. Jones' "hi-res" settings from convergence study[1]
  - Capsule: 72 angular zones in 90° → $\Delta\theta = 1.25°$
  - Wall: innermost zone Δr=4 nm, Δr increases by 1.03x
  - 180 radiation energy groups
  - 10 zones across LEH window thickness

- **Mesh:** "As Lagrangian As Reasonably Achievable"*
  - ALE (Arbitrary Lagrangian-Eulerian) mesh management: R. Tipton
  - Hohlraum: ALE from t=0, may freeze mesh after laser is off
  - Capsule: ALE from user-determined t>0, mesh not frozen

- **Laser:** 600 rays per quad, CBET iteration options

- **LHT (Lasnex Hohlraum Template)** git version-controlled input deck
  - Needed to handle multiple shots + multiple designers
  - Based on deck from Cliff Thomas, from Richard Town, Peter Amendt, etc.
- No ad-hoc / per-shot multipliers: power, cone fraction, …
- Same Lasnex version: 13 April 2017

[1]O. Jones et al., Phys. Plasmas 2017

*N. Meezan, private communication (2007)

Computing resources pretty modest for high-resolution hohlraum simulation

Lasnex run of N170109 bigfoot DT shot

- 170807 code – several fixes / improvements
- 2 nodes of mica: 72 TOSS_3 cores
- One-sided hohlraum
- Laser: 14,400 rays, inline CBET
- DCA: dca_79x6 (results in talk use x5): 3923 levels
- Hi res: zones: 32k gold, 20k others

On 72 CPUs:
15 hours to laser off
10 more hours to bang

time	6.5 ns: laser off	7.1 ns: just after x-ray bangtime
wall-hours := wh	14.9	25.0
CPU-hours (wh*72)	1073	1800
DCA [%wh]	32	48
laser [%wh]	38	24
other [%wh]	31	28

Hats off to Lasnex team, esp. D. Bailey, G. Zimmerman, J. Harte

DEPLETE[1]: ray-based, steady-state backscatter calculations, extension of linear gain

laser $$\frac{d}{dz} I_0(z) = -\kappa_0 I_0 \qquad - I_0 \int d\omega_1 \frac{\omega_0}{\omega_1}(\tau_1 + \Gamma_1 i_1)$$

$$-\frac{\partial}{\partial z} i_1(z, \omega_1) = -\kappa_1 i_1 \ - \ \Sigma_1 \ - I_0(\tau_1 \ + \ \Gamma_1 i_1)$$

scattered light | inv. brem. damping | brem. noise | Thomson scattering | SBS/SRS coupling

DEPLETE gain:

$$G = \ln \frac{i_1(\omega, z_0)}{i_1^{brem}(\omega, z_0)}$$

noise level without laser = scattered light with just brem. emission + absorption

Features of DEPLETE:

- Uses 1-D plasma conditions from 3-D ray-trace
- Spectrum of scattered frequencies
- Strong damping limit for plasma waves
- Pump depletion of laser
- Linear kinetic coupling coefficients
- Collisional plasma-wave damping

DEPLETE lacks:

- Temporal effects
- Laser speckles
- PS, SSD
- Dewandre effect
- Multi-D effects, e.g. refractive intensification

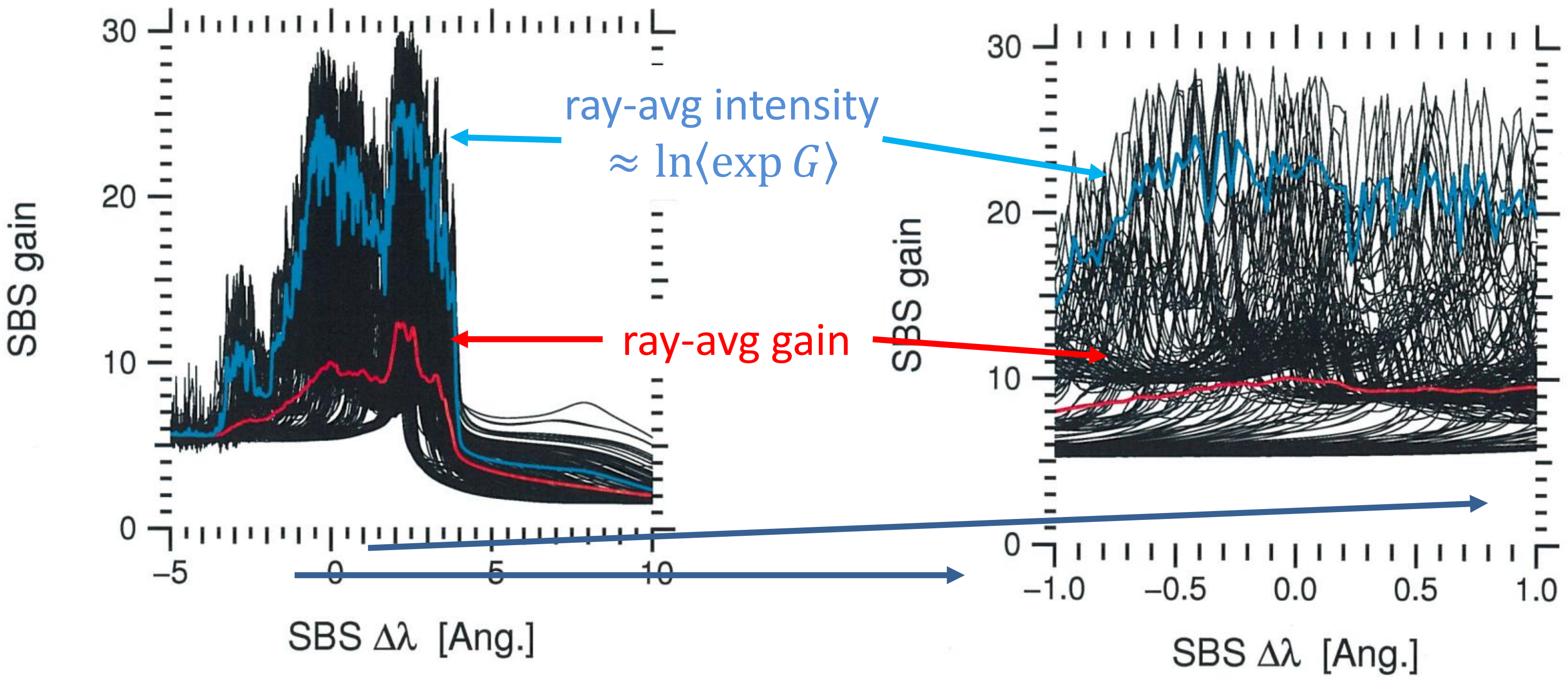
[1] D. J. Strozzi, E. A. Williams, D. E. Hinkel, D. H. Froula, R. A. London, D. A. Callahan, Phys. Plasmas 2008

Each ray has narrow SBS resonance at different wavelength[1]

N170109
5.75 ns: late peak power

Cone 50 SBS gain spectrum: all rays

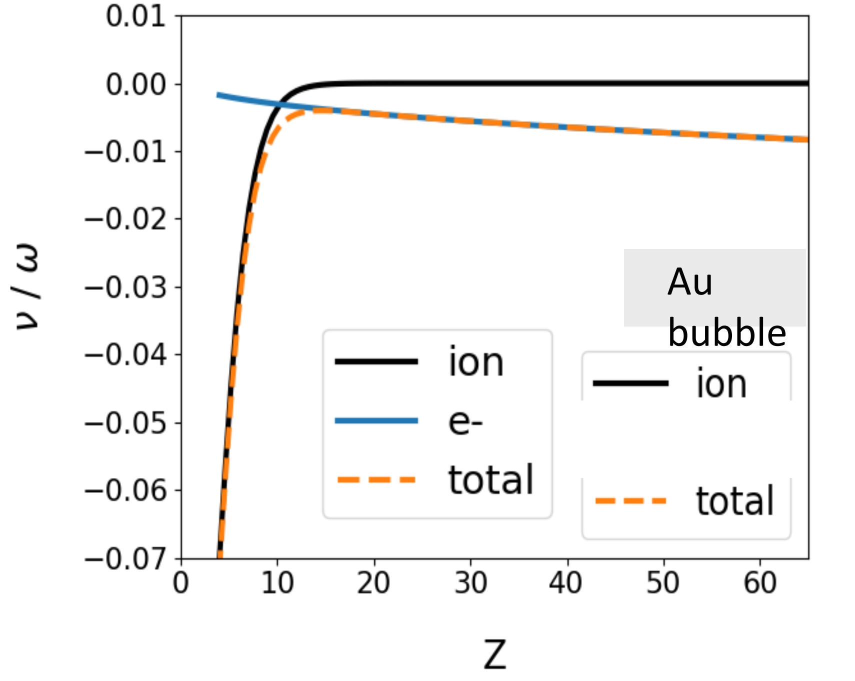
Zoom near 0 Ang.



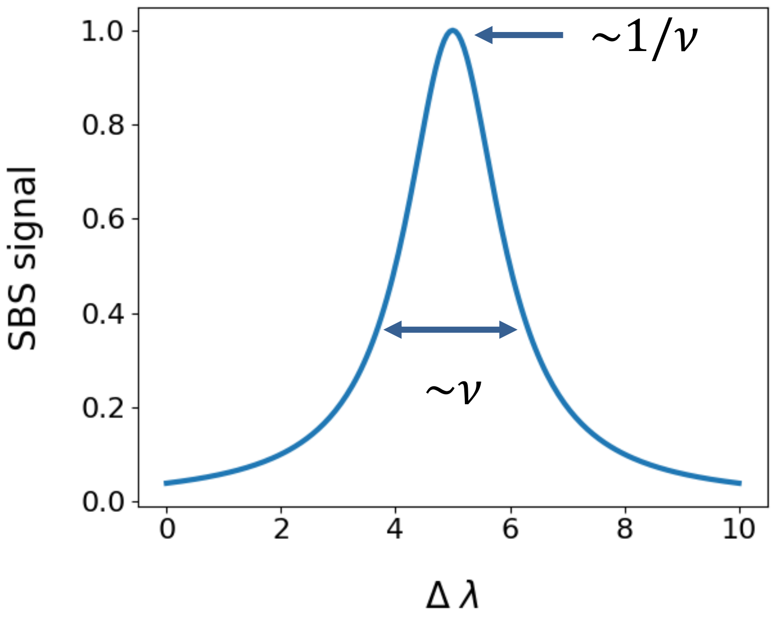
[1]L. Tolstoy, *Anna Karenina* (1878)

Ion waves weakly damped for $ZT_e/T_i >> 1$: e.g. gold

IAW Landau damping rate: gold
$T_e = 2T_i$, $k\lambda_{De} = 0.6$



SBS spectrum



Electrons **Ions**

$$\frac{\nu}{\omega} \propto \left(\frac{Zm_e}{m_i}\right)^{\frac{1}{2}} \exp\left[-\frac{Zm_e}{2m_i}\right] + \frac{1}{2}\left(\frac{ZT_e}{T_i}\right)^{\frac{3}{2}} \exp\left[-\frac{ZT_e}{2T_i}\right]$$

plus collisions (not included)

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