Analysis of the recent LLNL-LMJ COMPAS campaign on foam-filled hohlraums and future directions

CEA - Commissariat à l'énergie atomique et aux énergies alternatives

LMJ

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LLNL-PRES-XXXXXX

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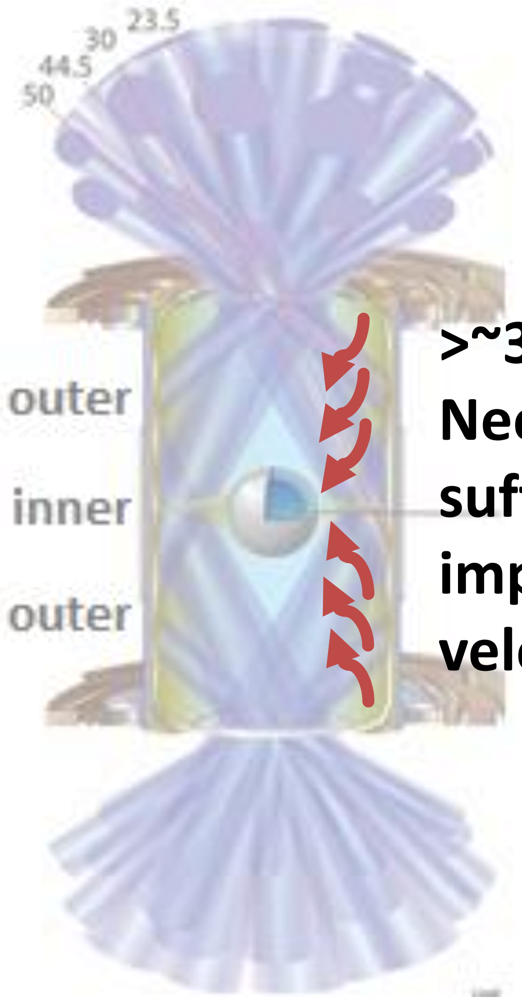
1 Lawrence Livermore National Laboratory

In the indirect drive approach to ICF, lasers irradiate a high-Z wall creating a radiation bath to implode a capsule of DT fuel

NIF configuration

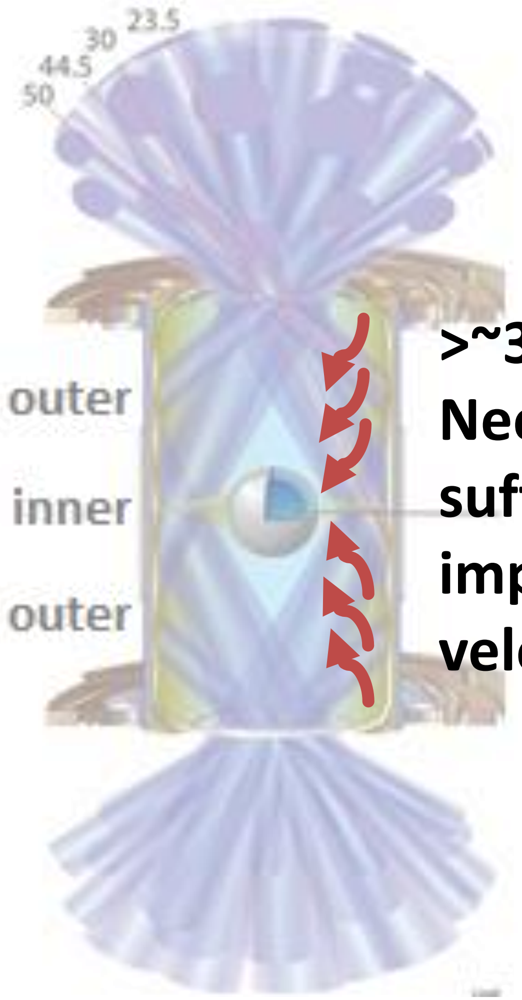


>~300 eV x-rays
Needed for sufficient implosion velocity

In the indirect drive approach to ICF, lasers irradiate a high-Z wall creating a radiation bath to implode a capsule of DT fuel

LPI = Laser Plasma Instabilities

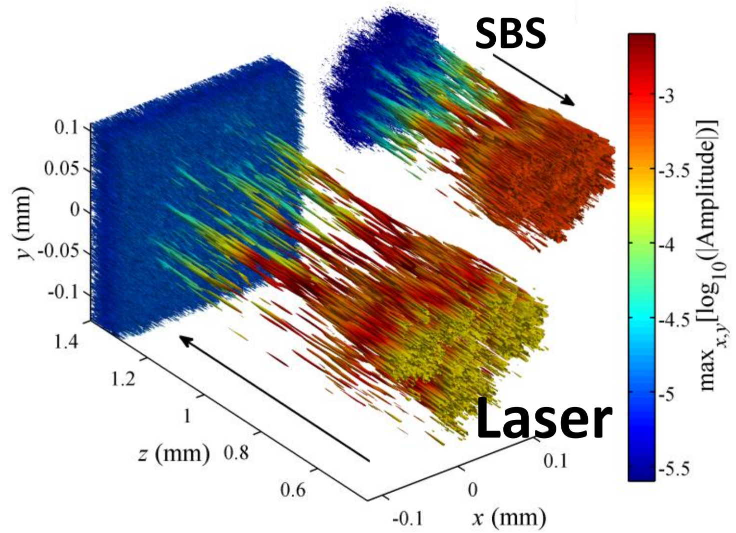
NIF configuration



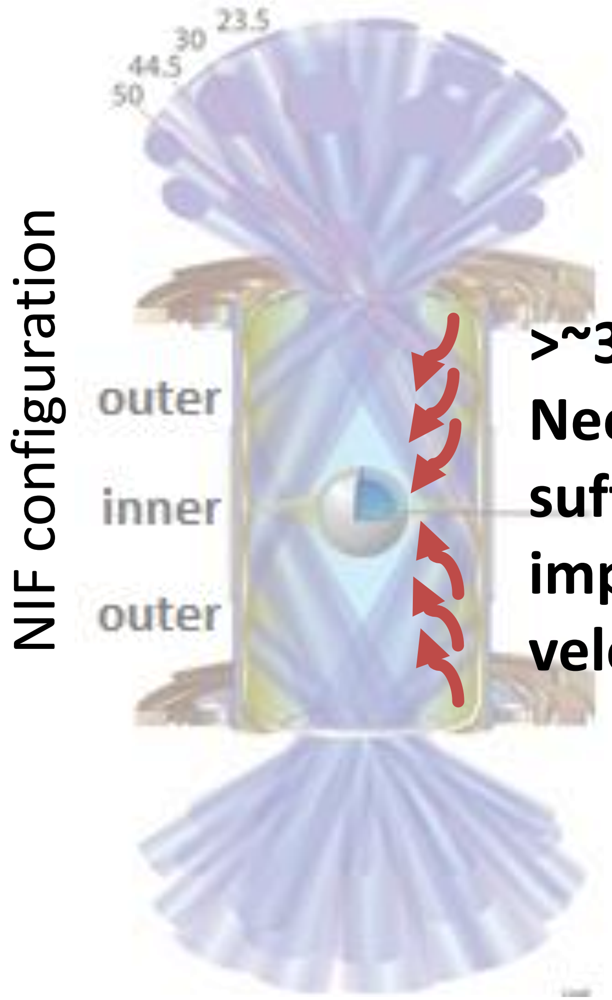
>~300 eV x-rays Needed for sufficient implosion velocity

However…

Laser light excites plasma waves that can scatter light back out the hohlraum ("backscatter")



A big challenge is to produce a symmetric high convergence implosion



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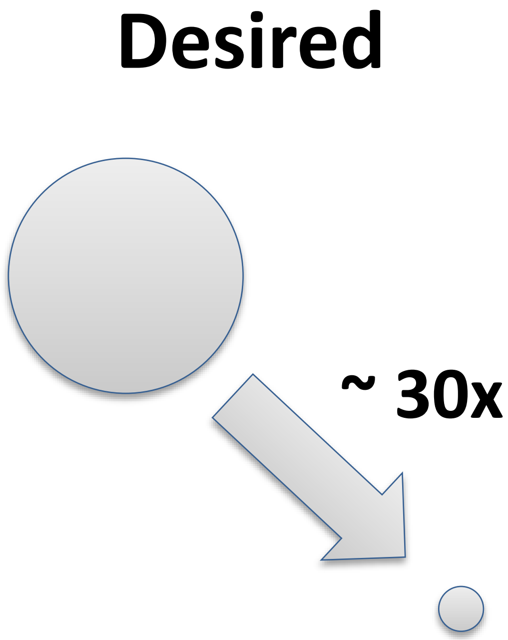
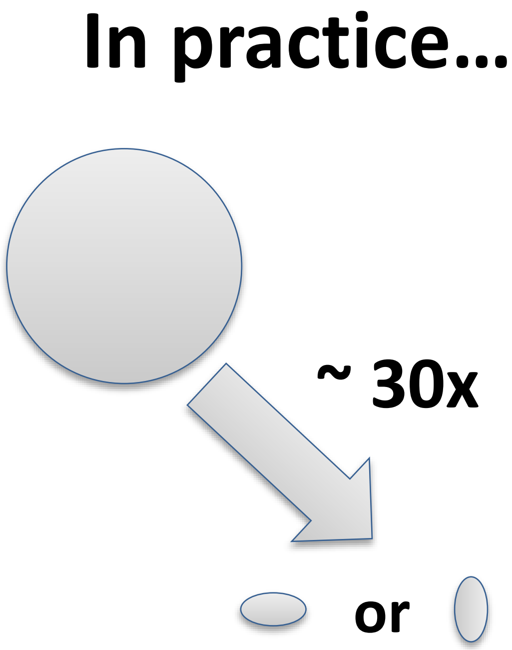




Distortions from sphericity reduce efficiency and may quench ignition

Late-time symmetry is hindered by the material ablated from the hohlraum wall

Early NIF experiments used high hohlraum gas fill to control symmetry

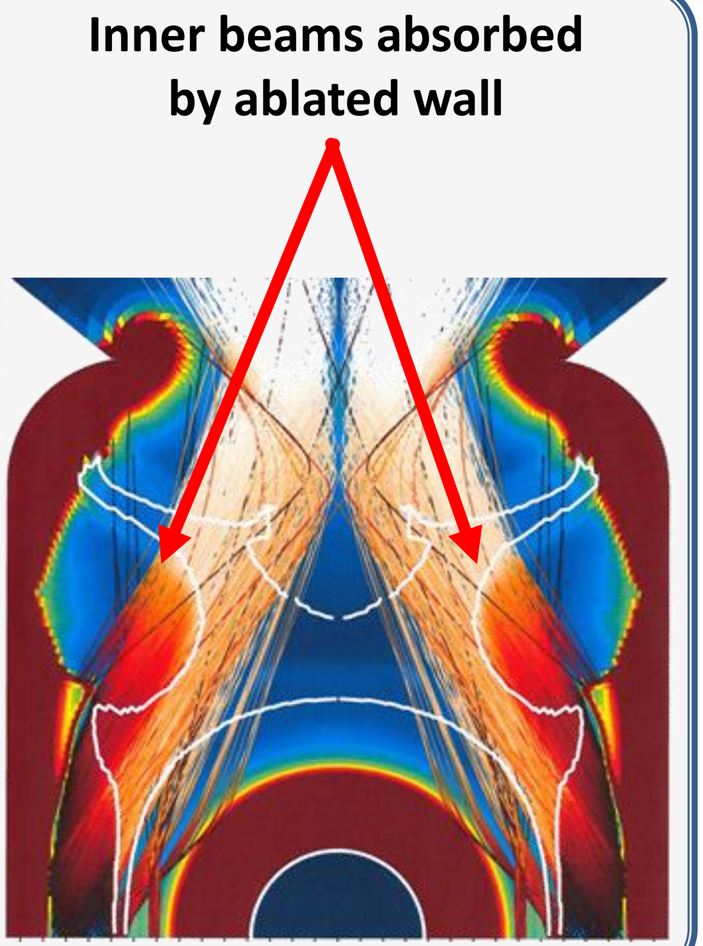
- ➢ High level of LPI were produced reducing the energy coupled to the capsule

Currently, NIF experiments used low hohlraum gas-fill

- ➢ Reduces LPI

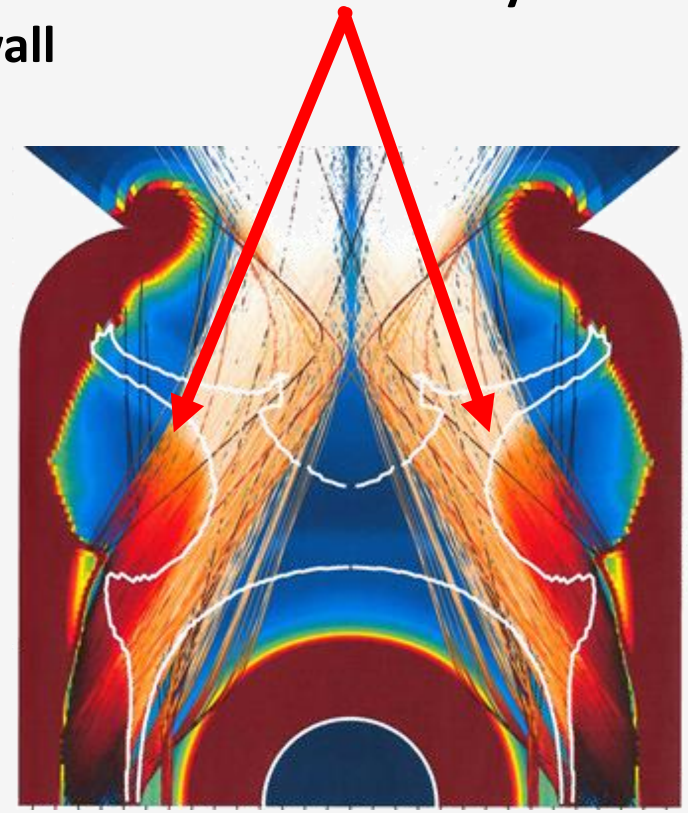
  but

- ➢ Challenges symmetry control



Cross-beam energy transfer (CBET*) is used to restore symmetry

- Inner beams absorbed by ablated wall



But may not be sufficient

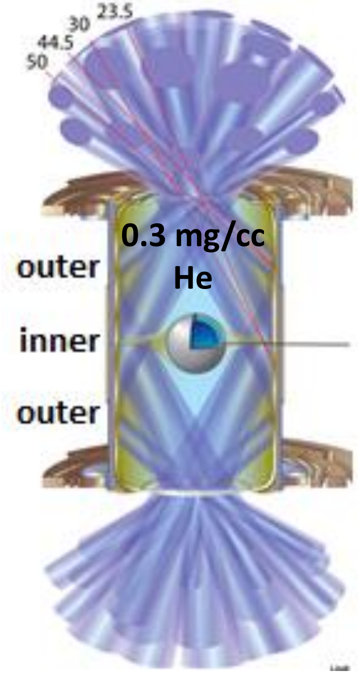
as targets scale up

CBET: A process whereby a beam exchanges energy with another beam of similar wavelength by exciting an ion acoustic wave

This technique was successful in producing an implosion with yields larger than the energy delivered to the fuel

Current State of Art

E_{cap} ~ 232 kJ



CCR ~2.85

Shot N221205* achieved
Y ≥ 3 MJ
using a low-gas fill hohlraum shown to mitigate LPI instabilities

$$CCR = R_{Hohl}/r_{cap}$$

However, yields in excess of 10 MJ in ICF at fixed laser energy requires increasing the capsule absorbed energy

Shot N221205* achieved
Y ≥ 3 MJ
using a low-gas fill hohlraum shown to mitigate LPI instabilities

$$CCR = R_{Hohl}/r_{cap}$$

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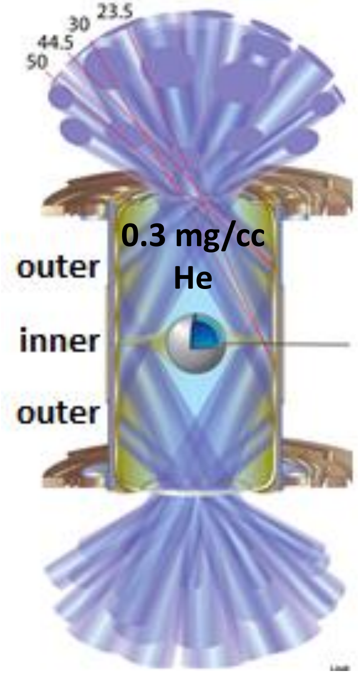


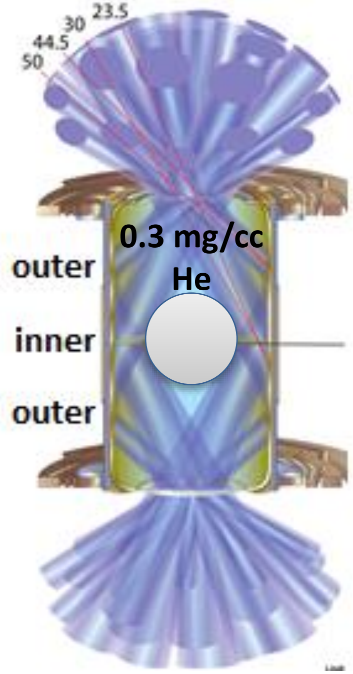
CCR ~2.85

At fixed laser energy

Larger capsules are needed

Y ~ 10 MJ requirement

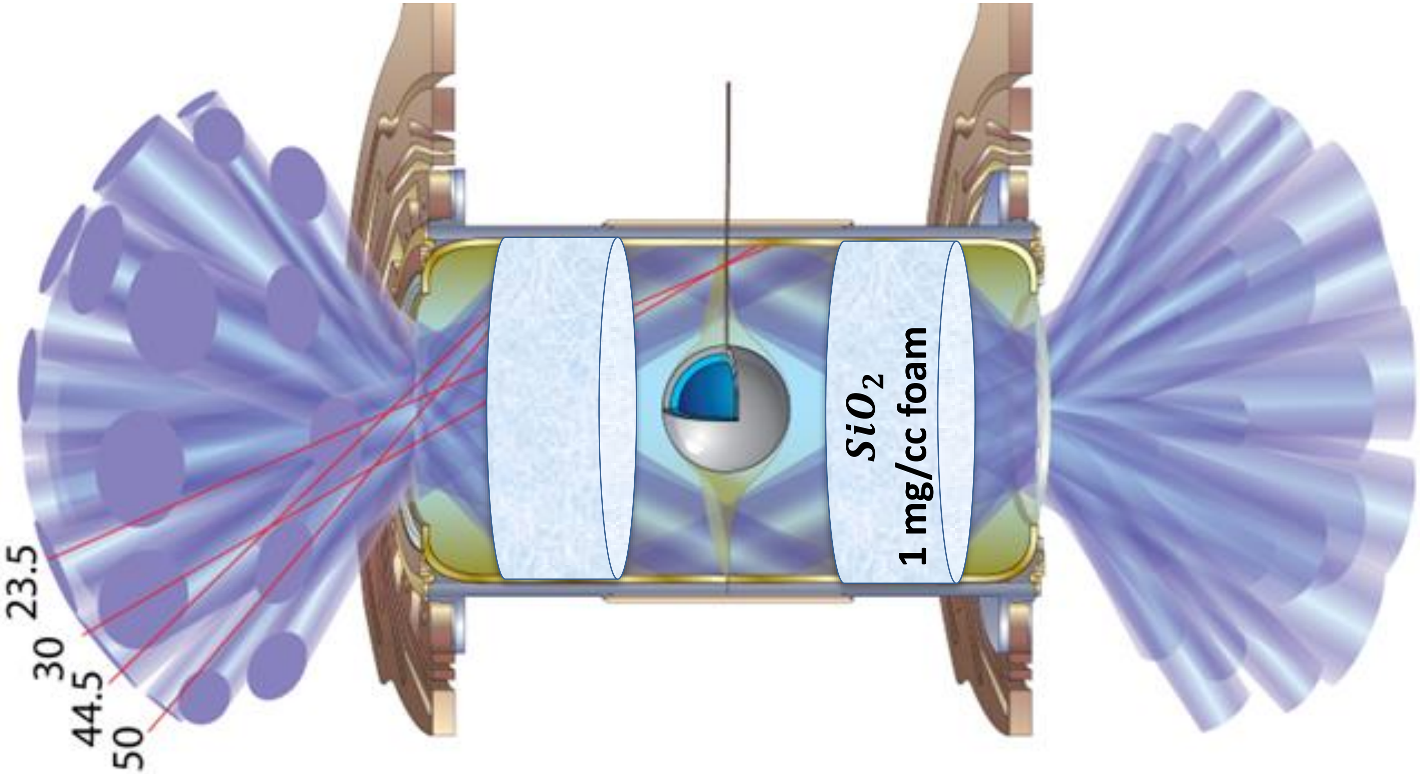
E_{cap} > 300 kJ



CCR ~2.5

Selective foam-filling combines the advantages of a high-fill (bubble tamping) and a low-gas fill (low LPI) hohlraums

Goal: to pursue an alternate hohlraum path to a lower CCR* hohlraum design



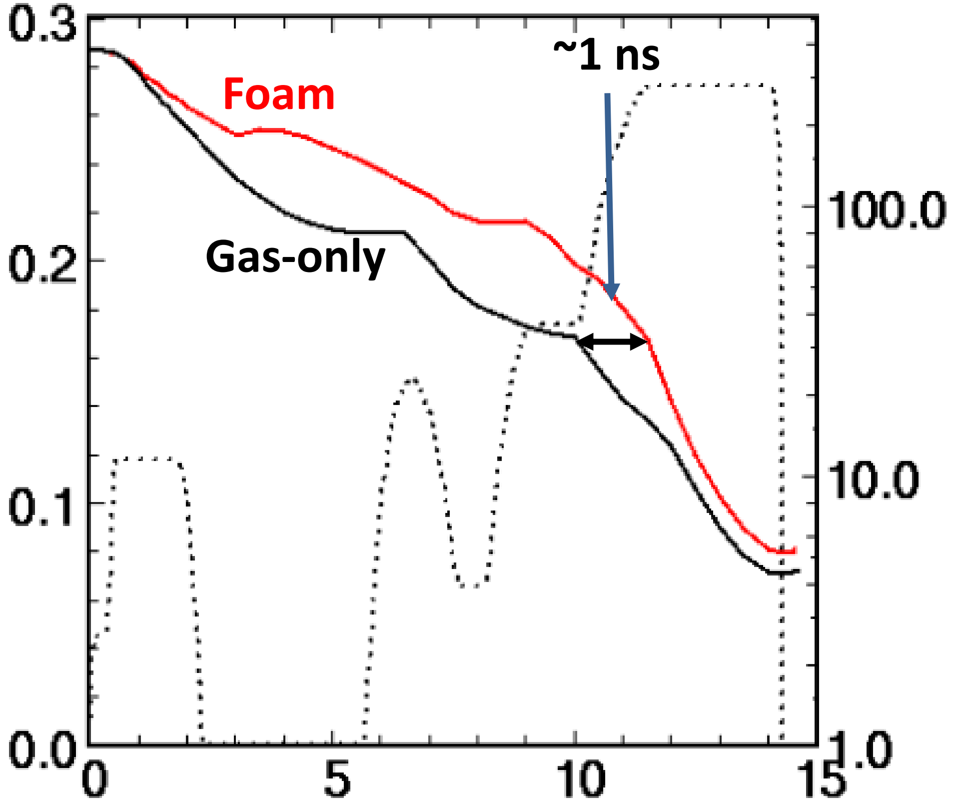
- ***Foam rings located at outer beam spots tamp wall expansion and maximize inner beam power to midplane***
- ***Partially filled hohlraum eliminates potential imprinting of the foam structure onto the capsule surface, reducing RT instability seeds (Casey N160724)***
- ***Foam porosity allows for hohlraum gas permeation potentially reducing SBS***

Engineered foam fills can potentially suppress LPI in ways not possible with gas fills using selected dopants at cryo temperatures

$*CCR = R_{Hohl}/r_{cap}$

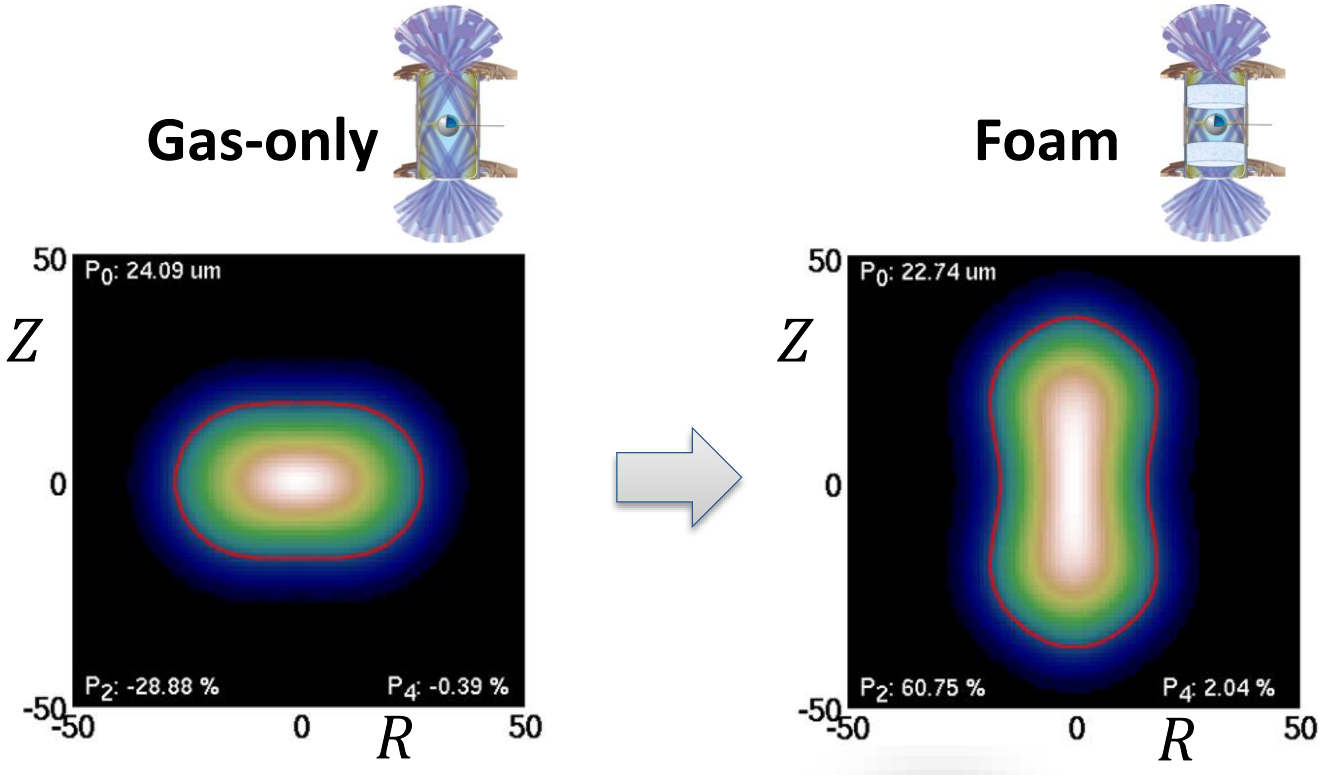
Pre-shot simulations of a CH ignition design using foams show improved inner beam transport, avoiding the need for CBET

Bubble radial position (cm)



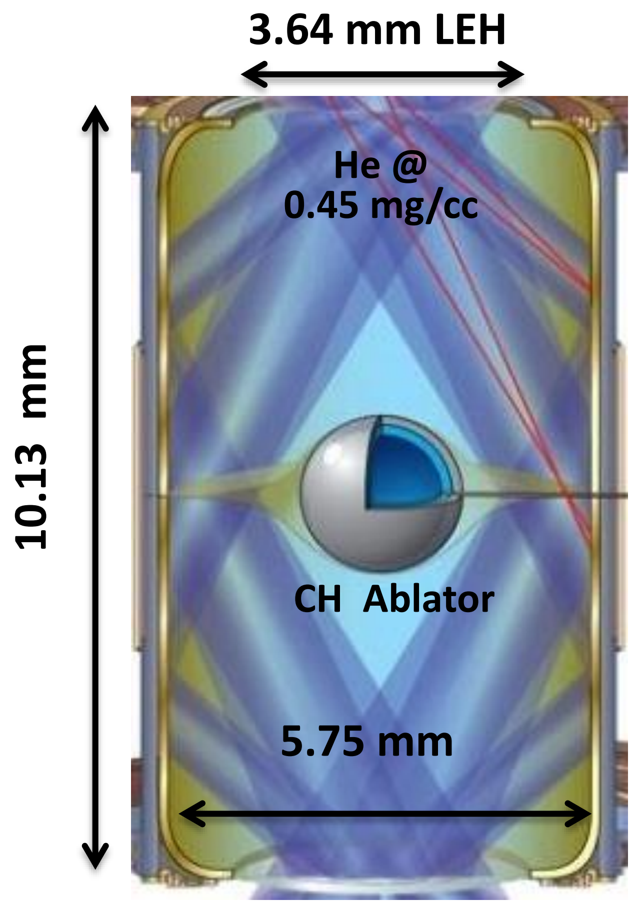
High compression (~30x) CH design

Delay in Au bubble motion significantly changes the shape of the hot spot self-emission, restoring control of symmetry via peak cone-fraction tuning



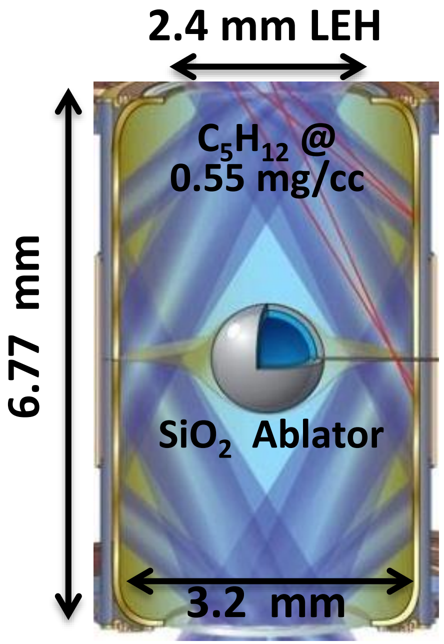
Experiments at the LMJ* (CEA) facility provided a first look at the viability of the selective foam hohlraum concept

NIF (cryo)

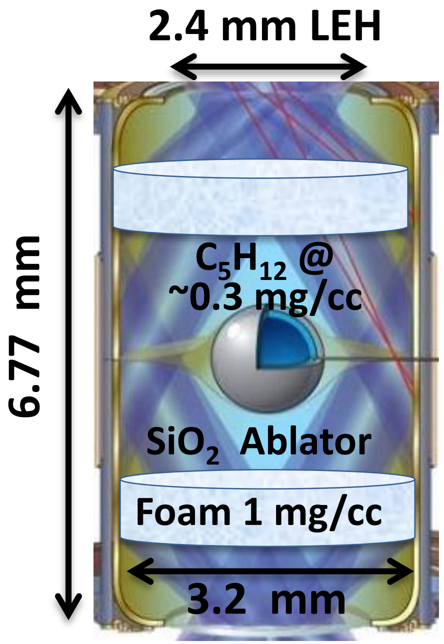


CCR: 2.9

LMJ (room temperature)



Gas-only



Foam

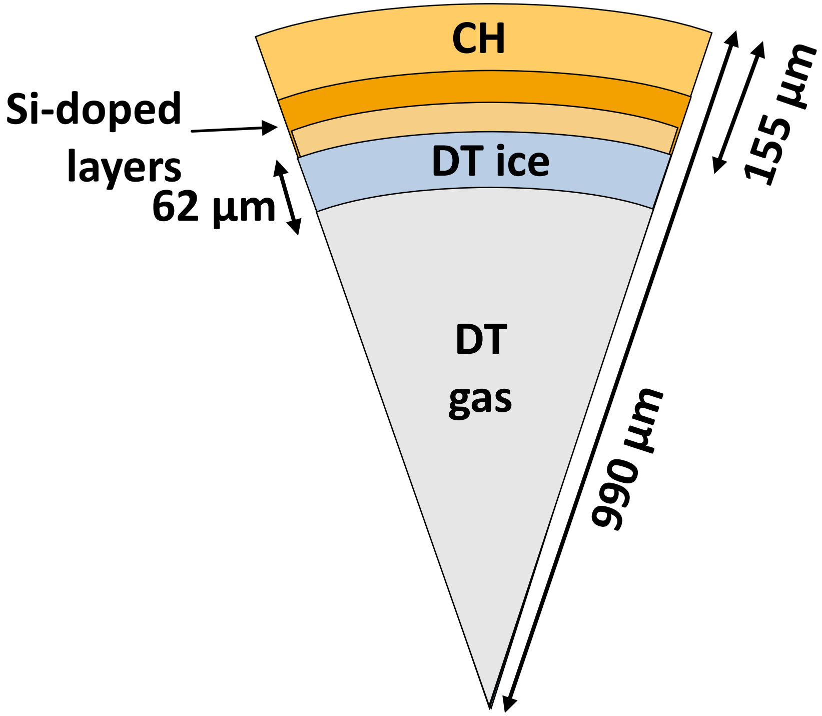
C_5H_{12} gas-fill density was chosen to maintain same $< n_e >$ for both hohlraums.

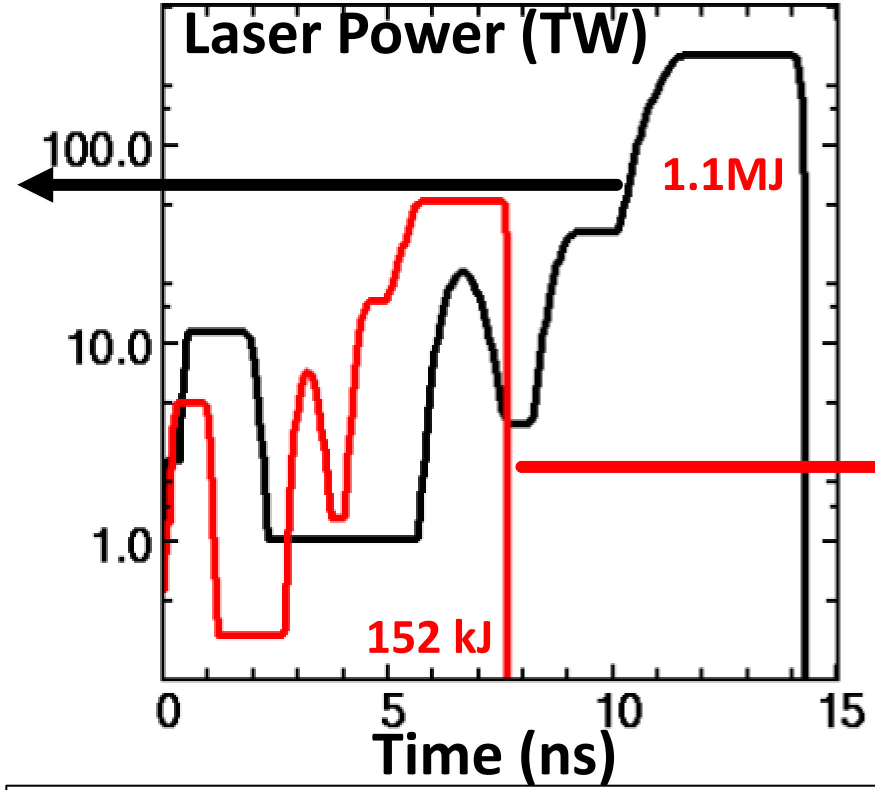
CCR: 2.65

*C. Lion, Journal of Physics: Conference Series 244, 012003 (2010);
JL. Miquel et al, Review of Laser Engineering 42, 131-6 (2014)

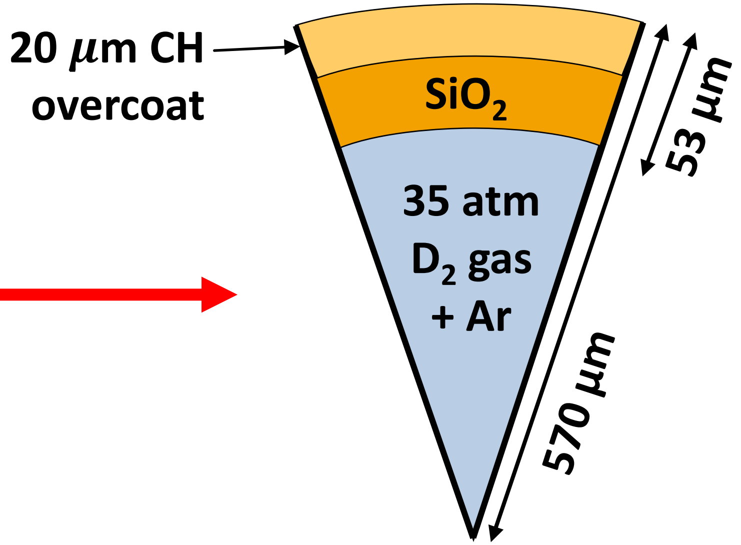
Fielding requirements and ease of transport necessitated a redesign of the original capsule to avoid the use of a fill tube

Cryo-layered target
Scale 0.9 target





RT non-layered target
LMJ Target

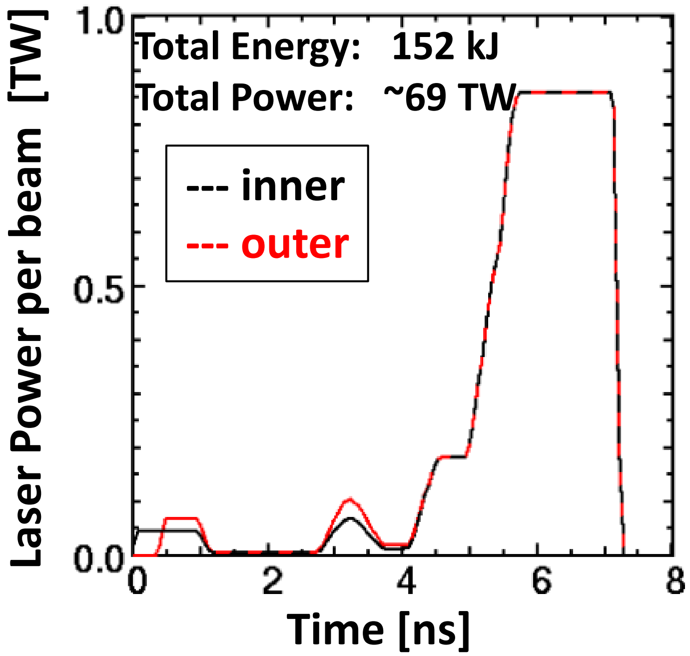


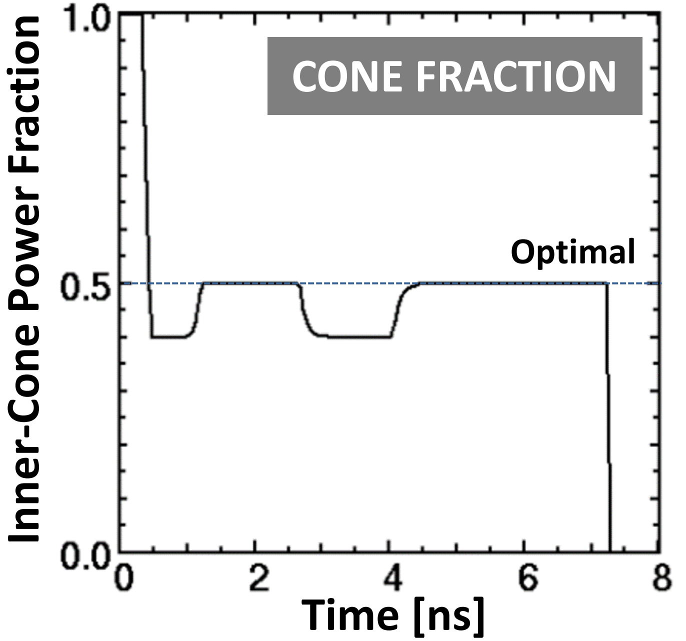
Peak power chosen to reduce laser intensity (for LPI control) since LMJ phase plates are ~ 80% or ~55% smaller area than the NIF inners or outers respectively

Capsule is a ~0.6x scale to simultaneously test smaller CCR (2.9 → 2.6)

The experiments assessed several key properties of hohlraum dynamics using the current LMJ capabilities

- ➢ The laser power used the optimal LMJ configuration

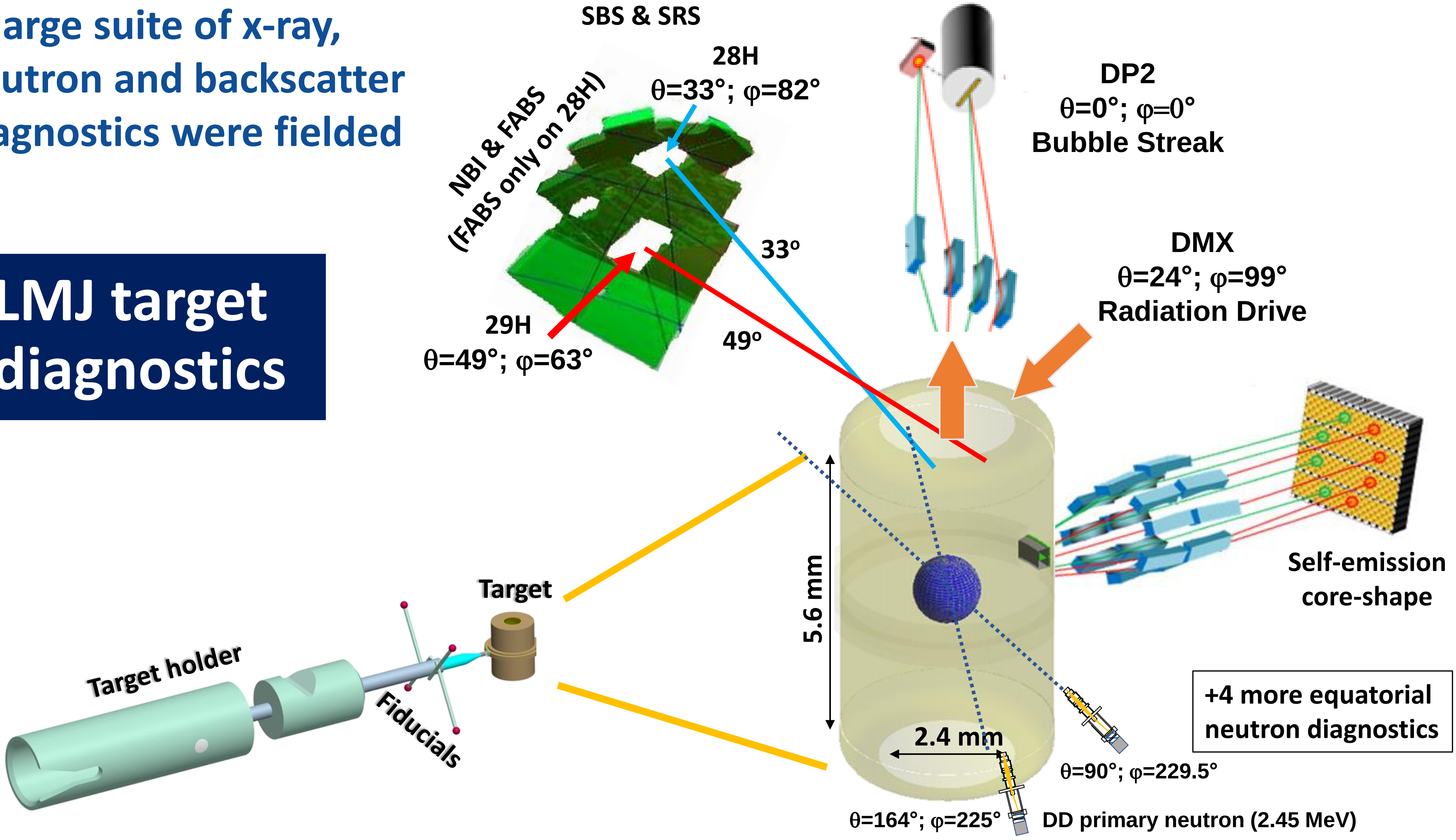




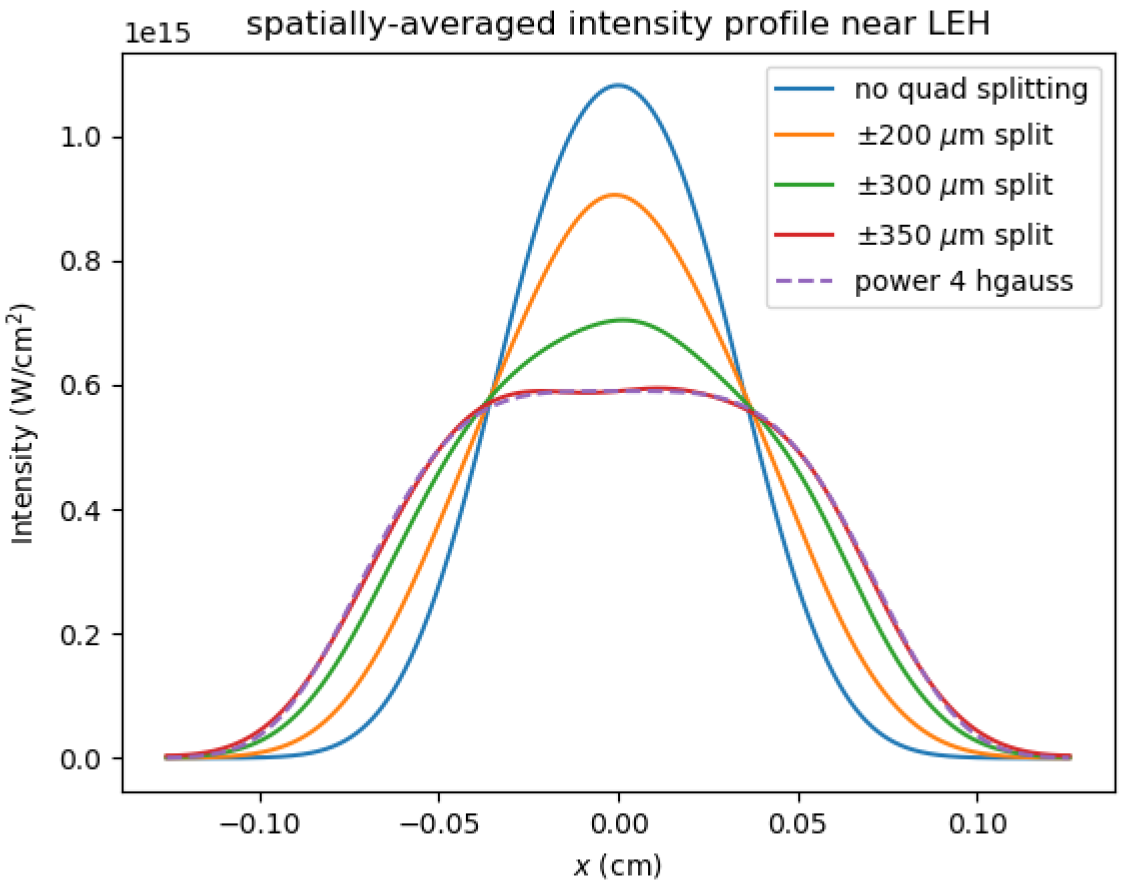
- ➢ Two primary objectives
  - ➢ Ascertain LPI instabilities in the presence of the foam disks
  - ➢ Assess the reduction in bubble motion to improve symmetry control

A large suite of x-ray, neutron and backscatter diagnostics were fielded

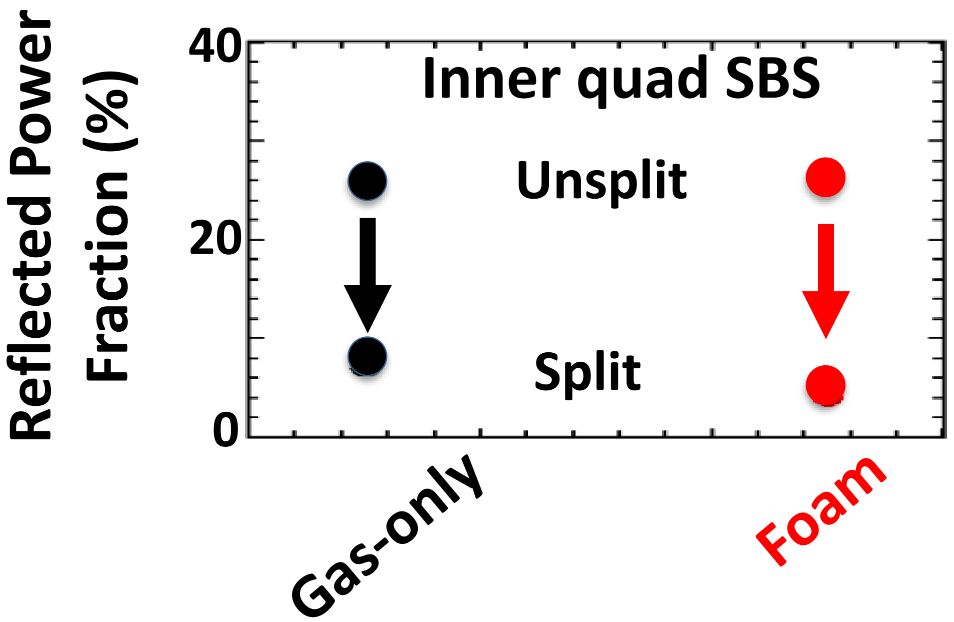
LMJ target diagnostics



Further analysis suggested that LPI control could benefit from ~2x reduced intensity from inner quad-splitting

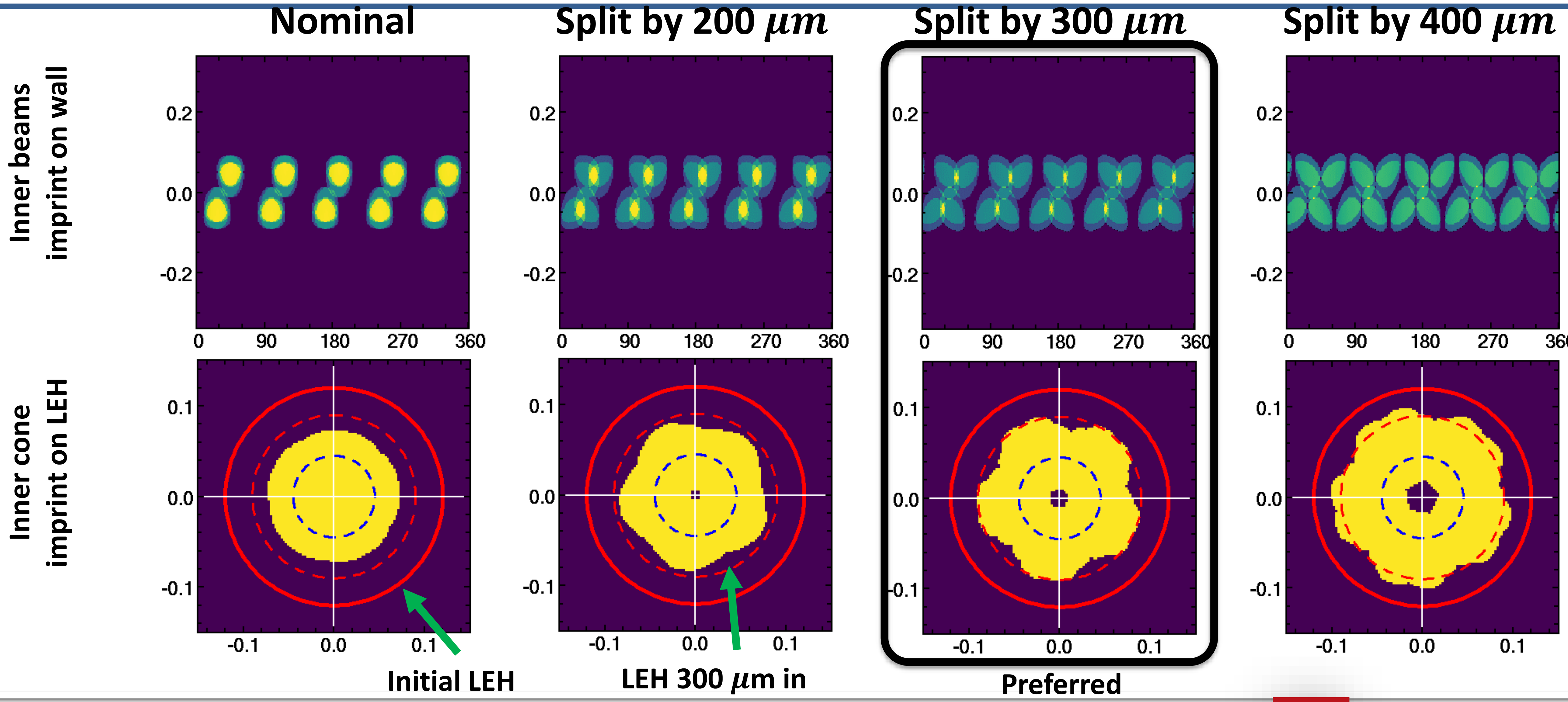


Gas-only	(26 %)
Foam	(26%)
Gas-only, quad split 370 μm	(7 %)
Foam, quad split 370 μm	(4 %)



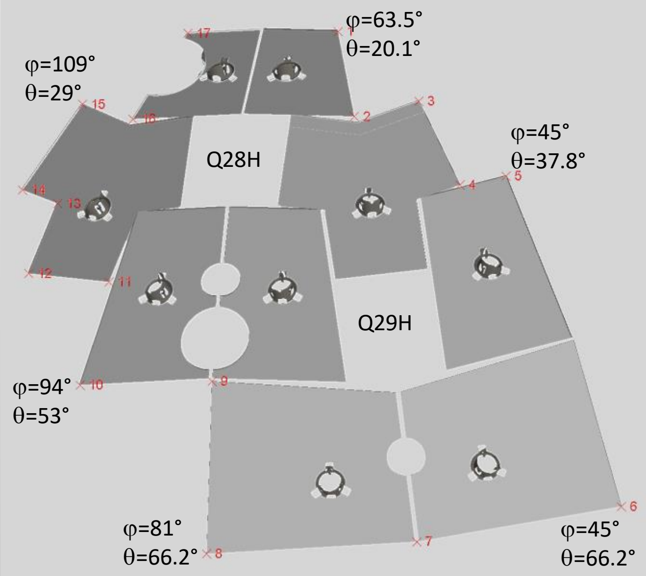
Optimal quad splitting is ±350 microns.

LMJ experiments used inner quad-splitting (300 μm) to balance LPI and LEH clipping risks

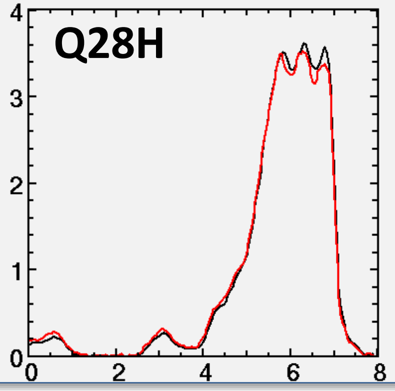


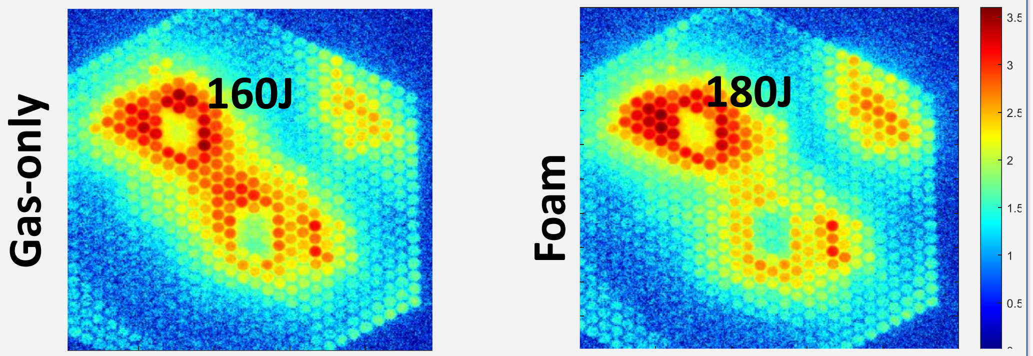
The measured SBS was comparable between the 2 targets while SRS on outer beams was reduced ~20x for the foam case

- Time resolved spectra is available only on inner quad Q28H
- NBI plates with ~64° angular range coverage is available for both cones



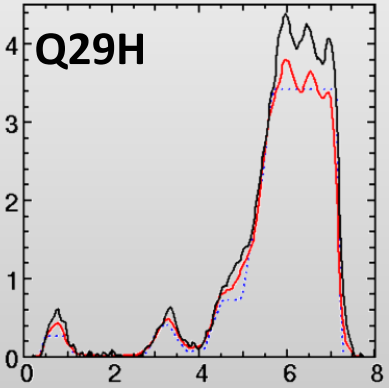
Q28H laser delivery was comparable between the 2 shots with similar SBS

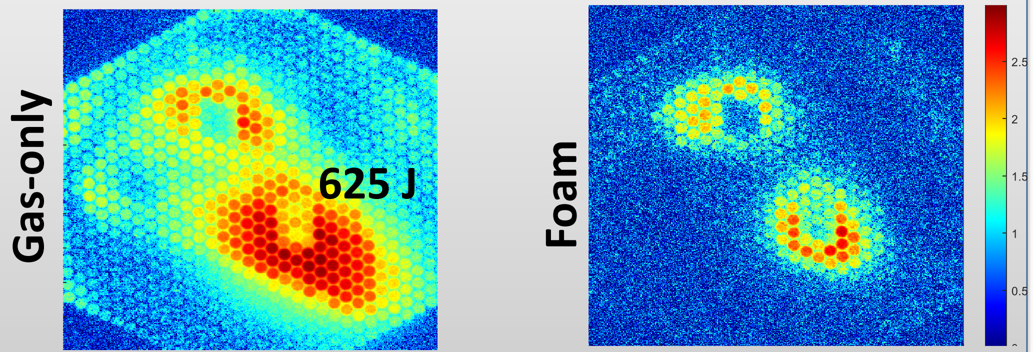




Inner SBS ~< 10% in line with predictions

While SRS is much reduced in the foam despite higher laser delivery Q29H



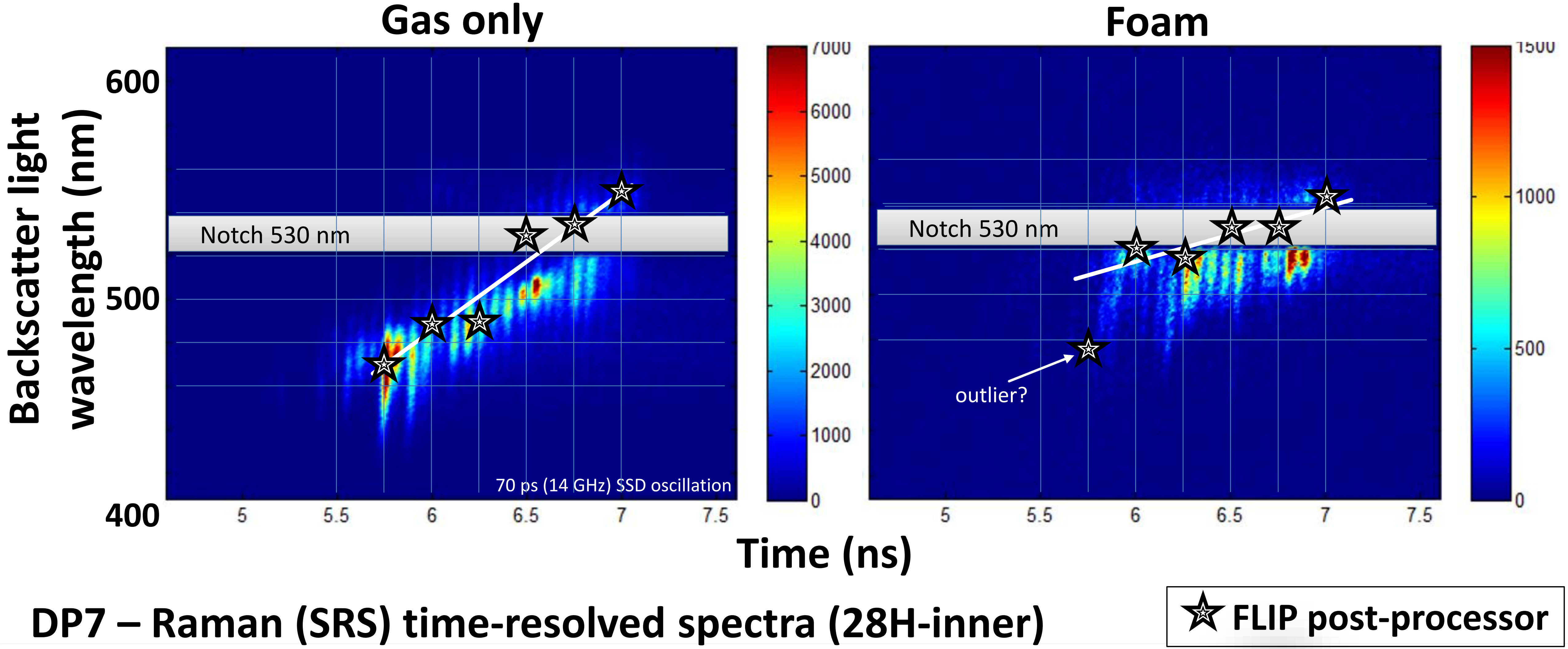


Outer SRS reduced by 20x

Inner SRS ~< 1% in line with predictions

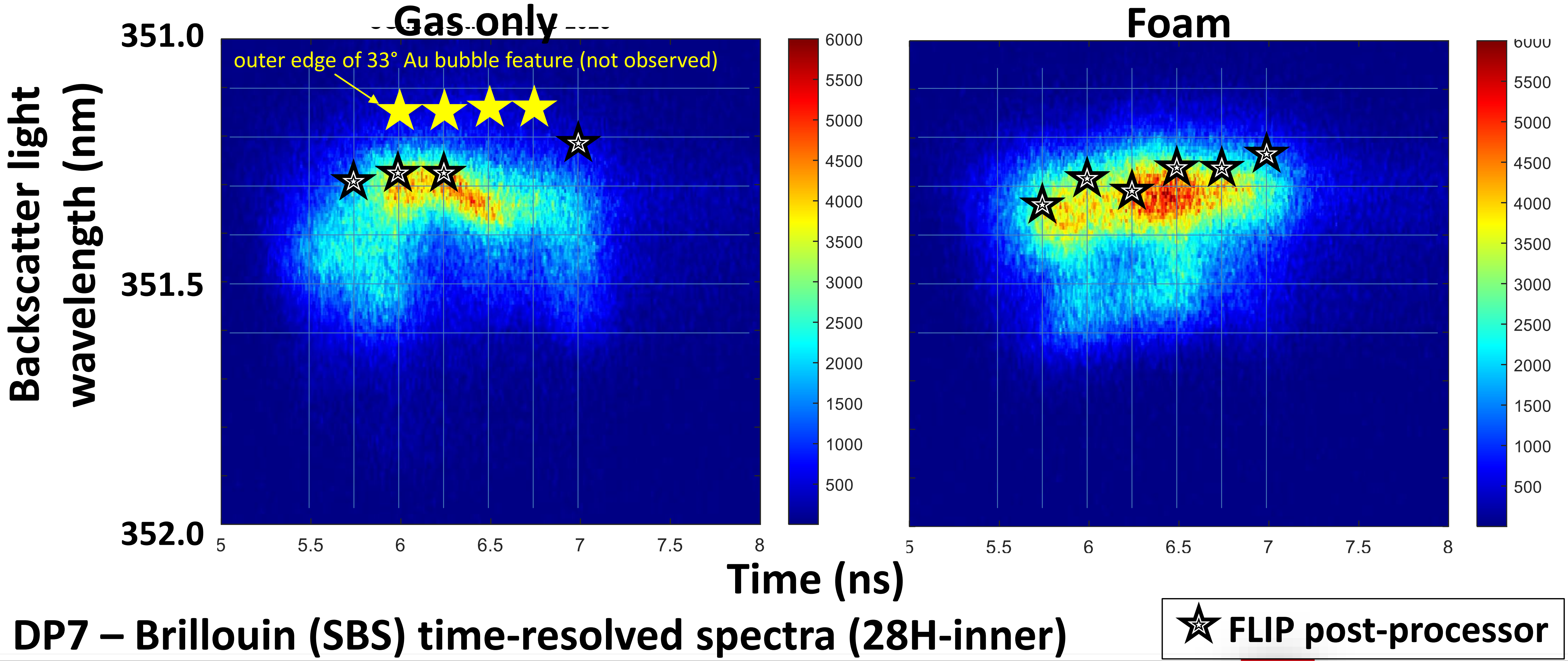
PF3D simulations are underway to understand these results

Our current models calculate plasma conditions that reproduce the measured data fairly well



DP7 – Raman (SRS) time-resolved spectra (28H-inner)

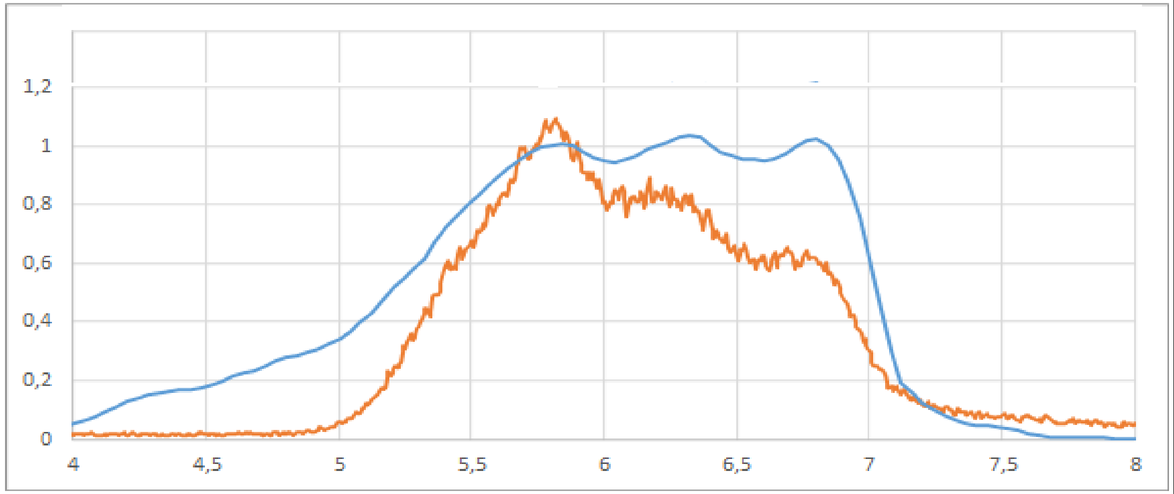
Our current models calculate plasma conditions that reproduce the measured data fairly well



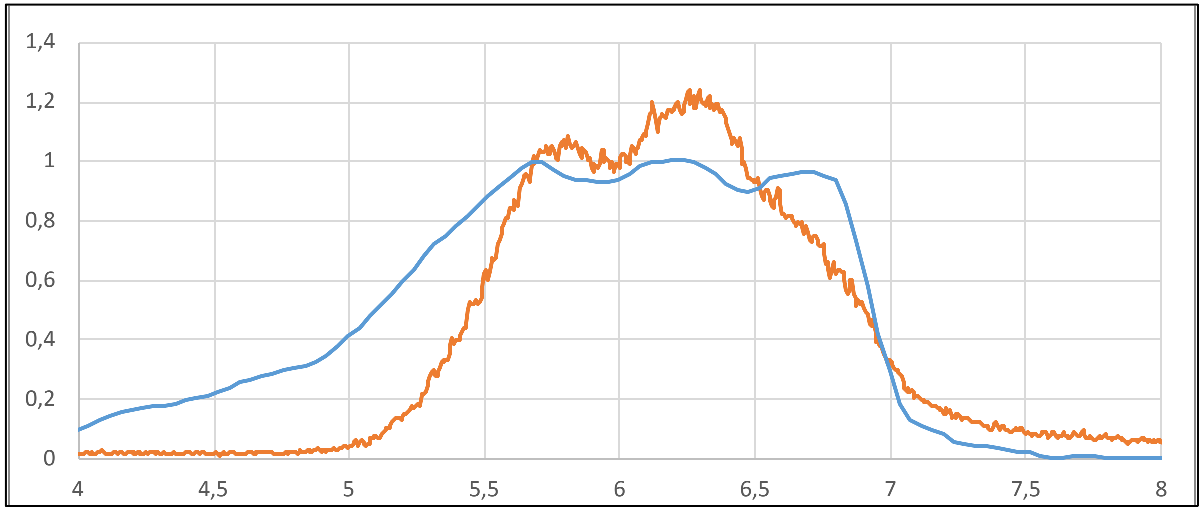
DP7 – Brillouin (SBS) time-resolved spectra (28H-inner)

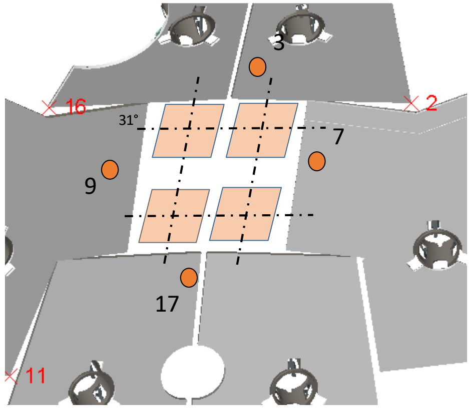
BRILLOUIN Back-Scatter in the FABS (Q28H) time histories are similar for both shots, details being explored with pF3D

Gas-only

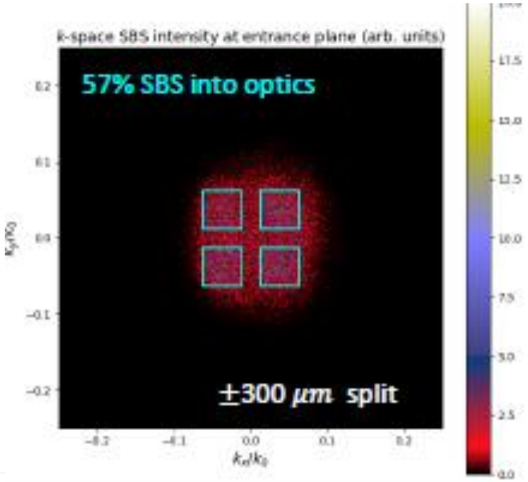


Foam



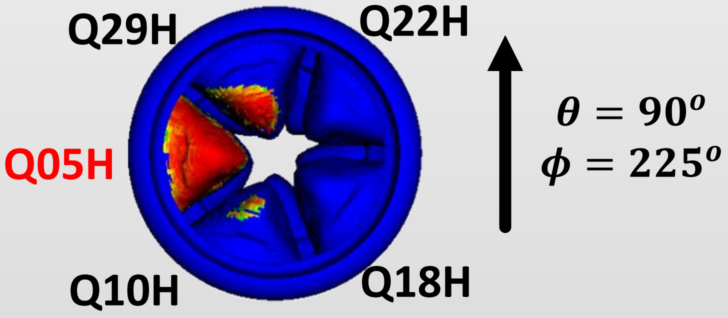


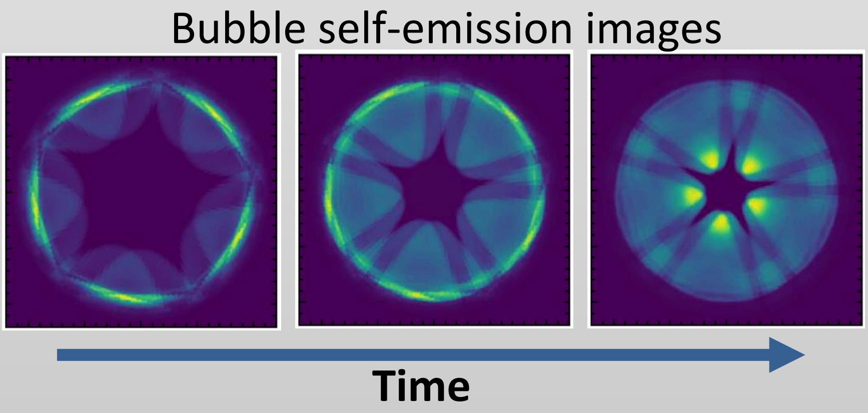
600 J total in f/6
170 J in NBI



DP2 streak camera successfully measured the bubble trajectory

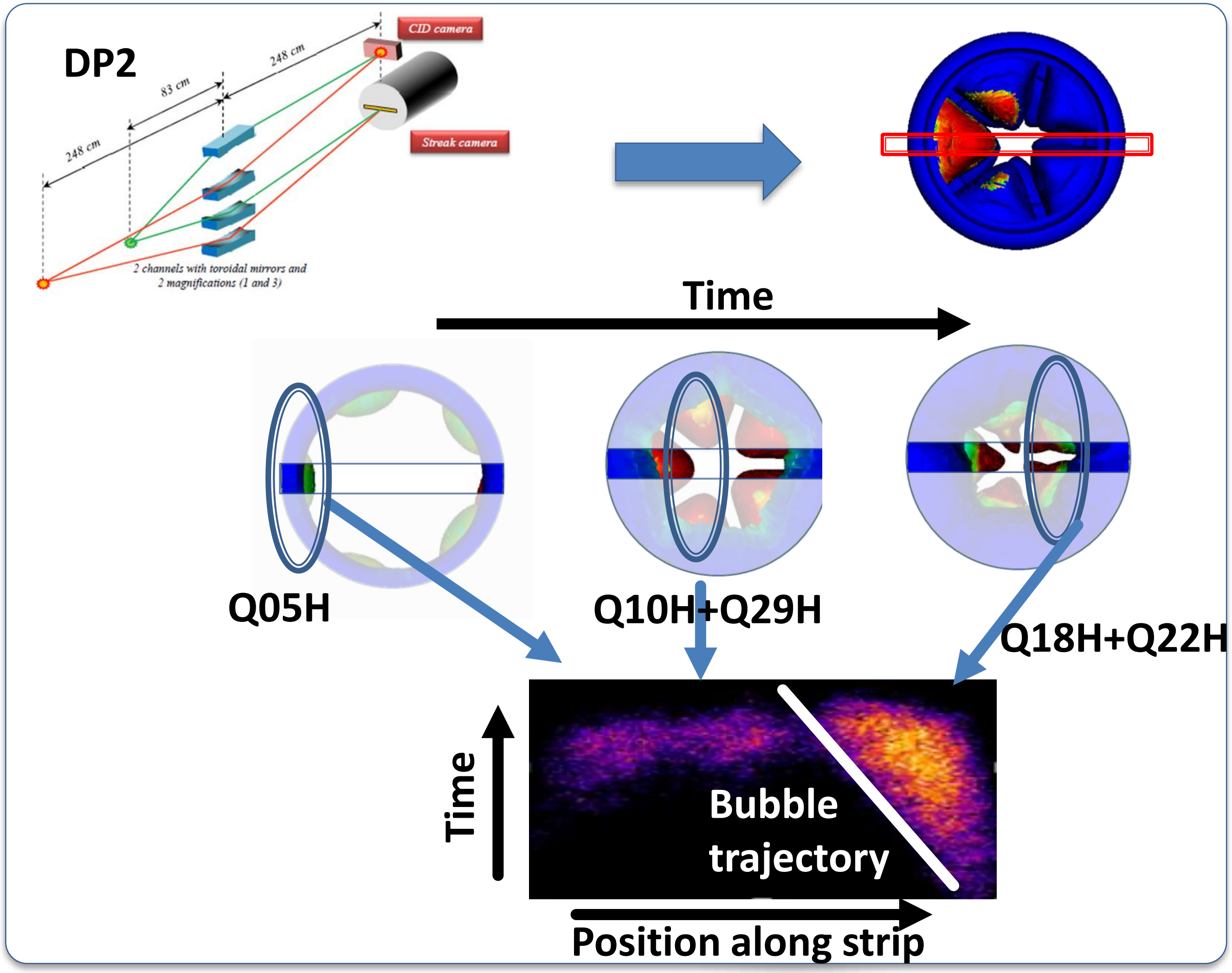
With a gated imager bubble position is measured from a set of time frames



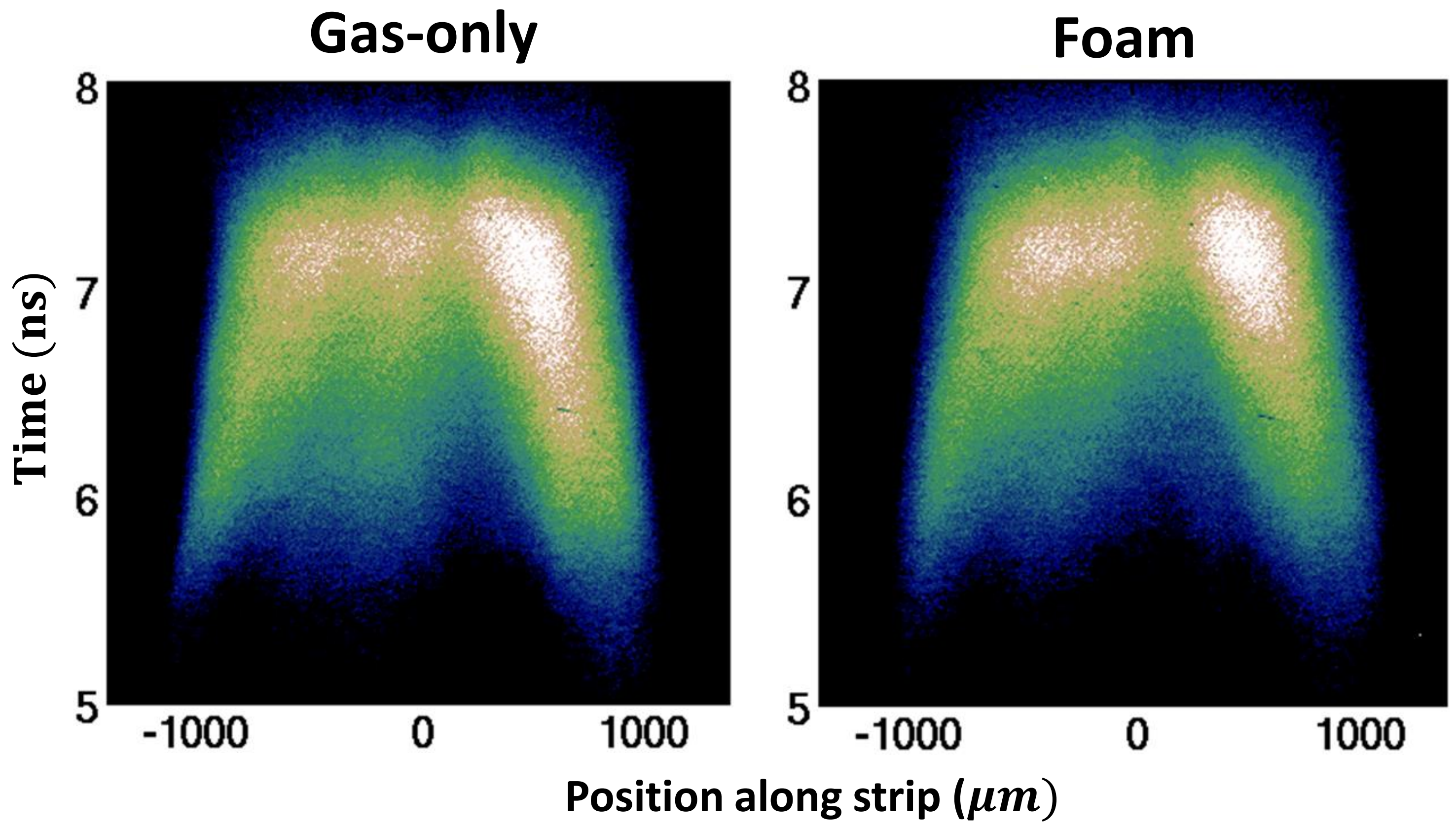


3D simulation of LMJ experiment

Instead

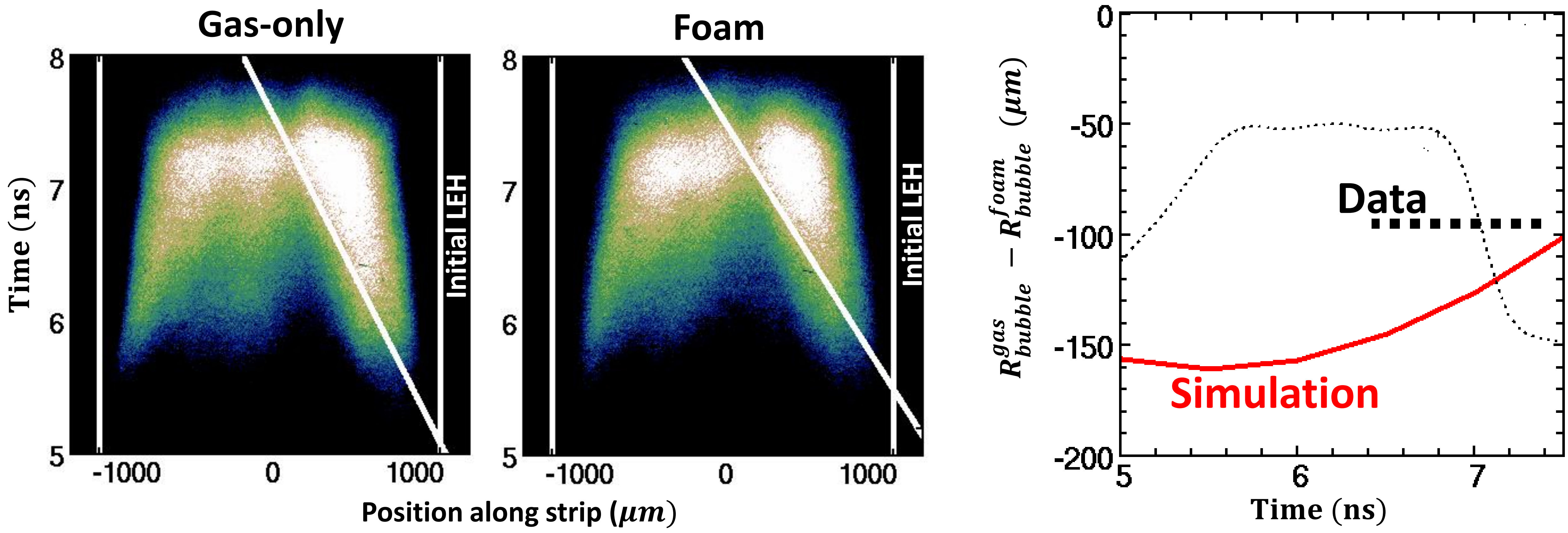


The DP2 instrument collected good data showing that the bubble was delayed in the foam target



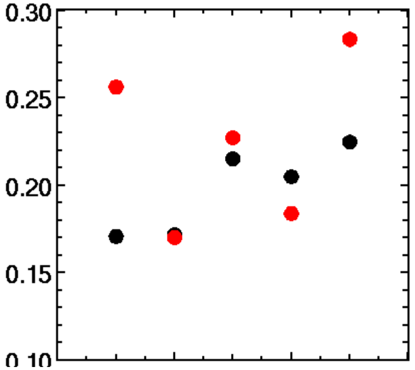
Analysis is still ongoing; A new calibration is needed to properly quantified the advantage provided by the foam

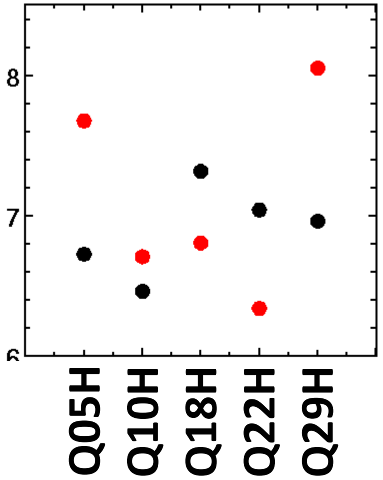
The DP2 instrument collected good data showing that the bubble was delayed in the foam target - but less than simulated



Preliminary

Laser quad delivery impacts bubble position; 3D post-processing analysis is ongoing

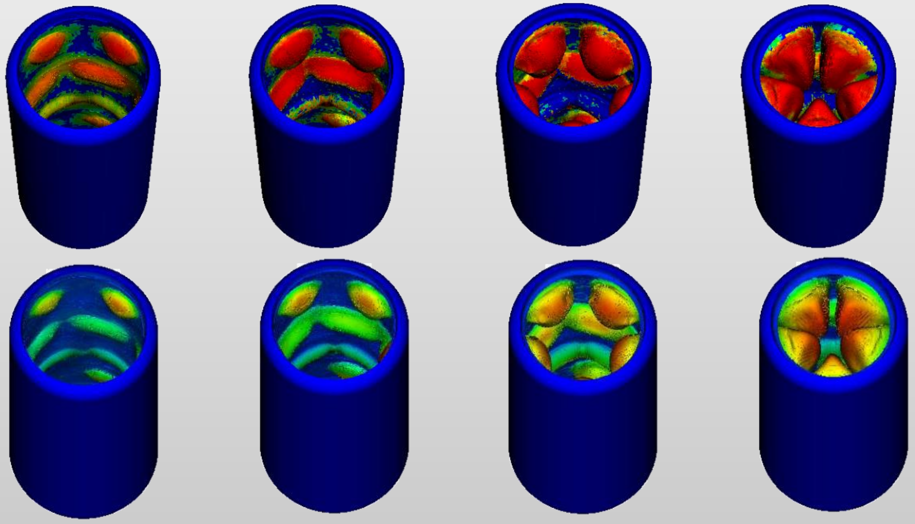




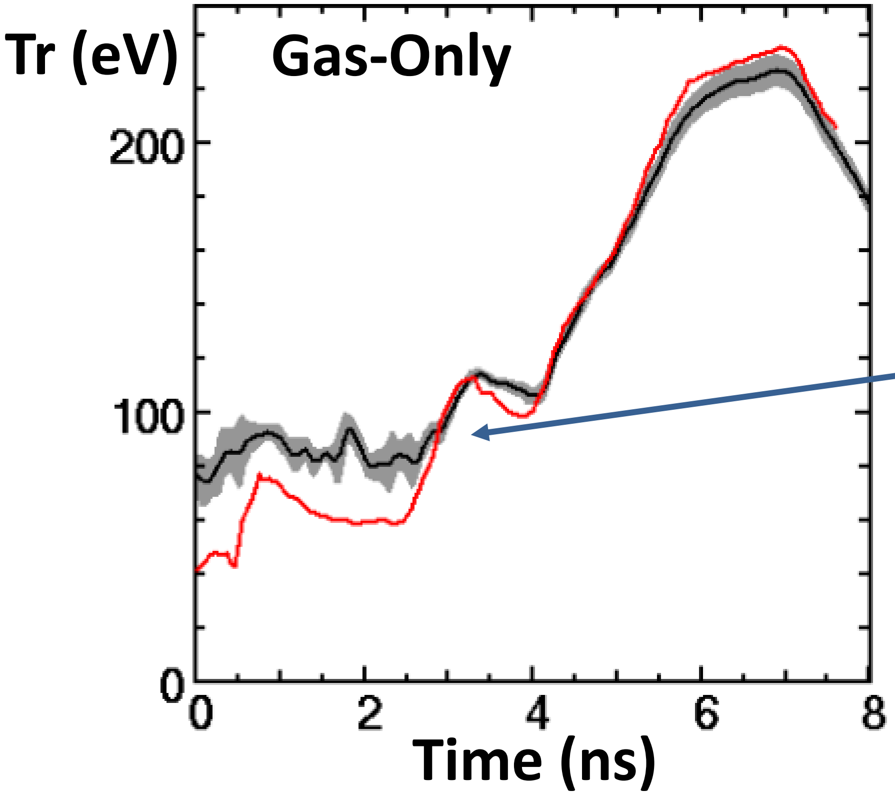
Gas-only
Foam

2D playbooks indicate that the impact is small (< 20%)

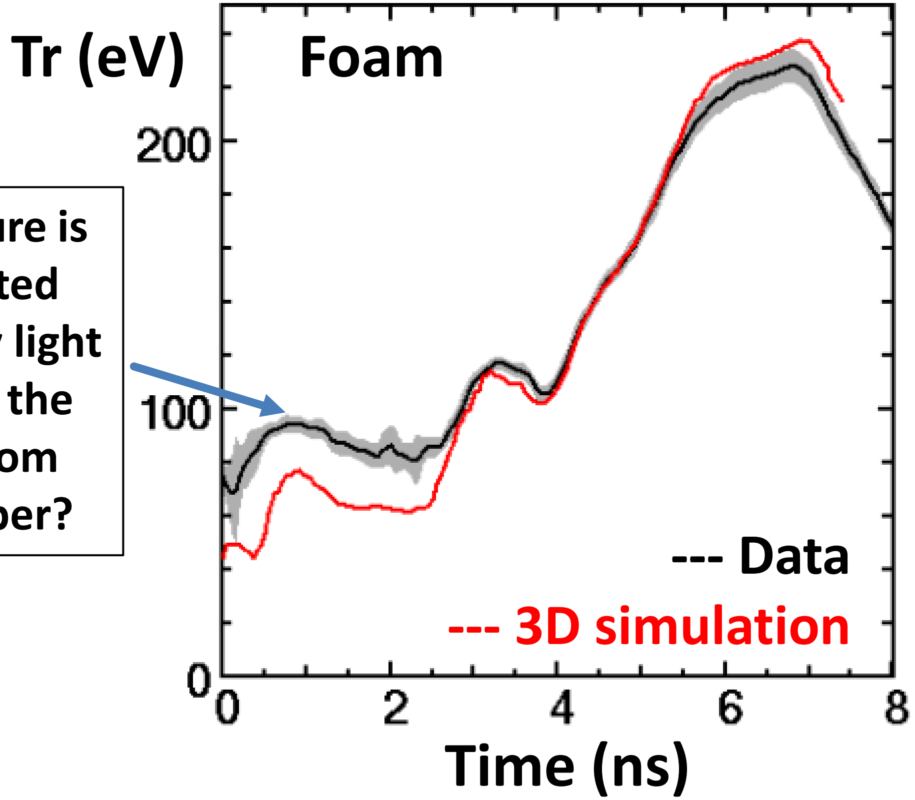
2D Playbooks`	Foot $\Delta c_f \pm 20\%$	$\Delta P_{peak} \pm 10\%$	$\Delta P_{foot} \pm 10\%$
Gas-only	$< \pm 5\ \mu m$	$\pm 20\ \mu m$	$< \pm 2\ \mu m$
Foam	$< \pm 5\ \mu m$	$\pm 30\ \mu m$	$< \pm 2\ \mu m$



Simulations not accounting for backscatter show a 16% deficiency in the peak drive as measured by DMX



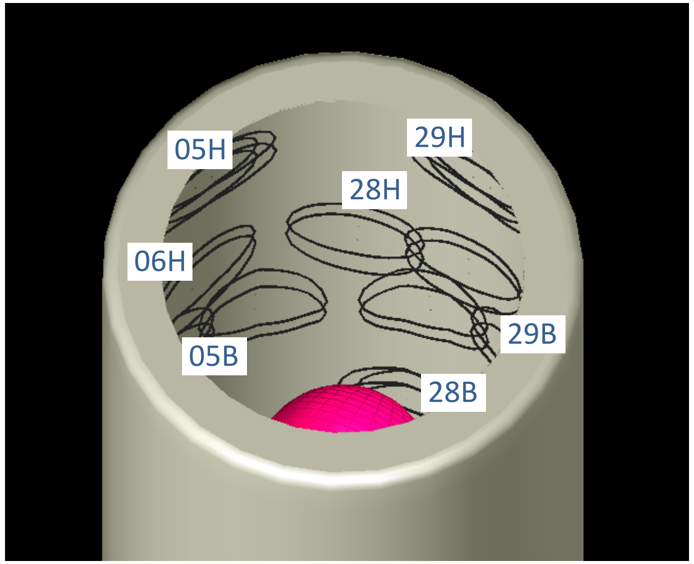
Measured foot temperature is much larger than predicted perhaps due to some stray light that comes in the FOV of the detector at early time from somewhere in the chamber?

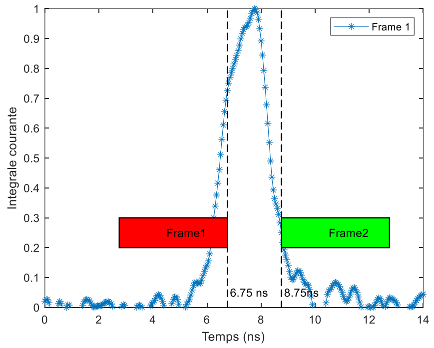


Data for Tr drive is ~10 ev lower than calculated in the peak corresponding to a ~ 16% deficiency in flux. Accounting for BS (~ 5-10%) the remaining 7-14 % missing energy would correspond to ~ 0.93x multiplier comparable with current hohlraums at the NIF

The DMX instrument also includes a 2D x-ray imager, that records 2 gated (4 ns long) images on a HCMOS camera

DMX view



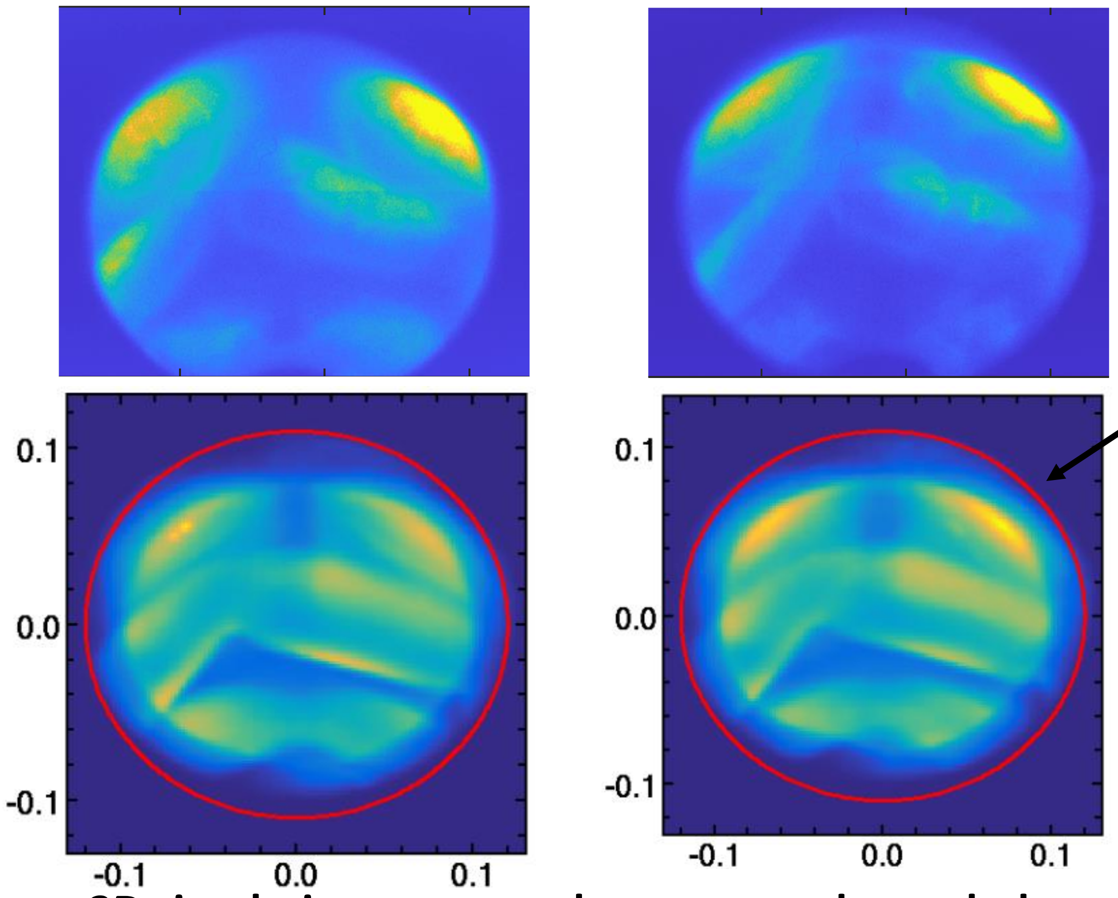


Periods where images are recorded

Gas only **Foam**

Data

3D Simulation

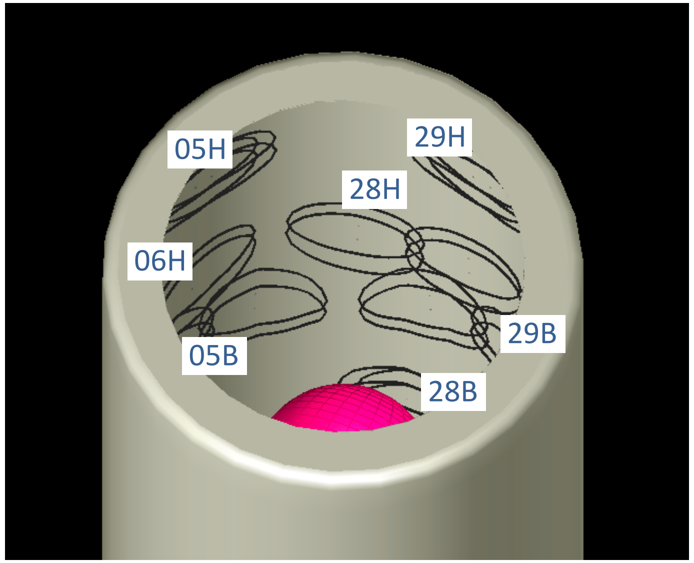


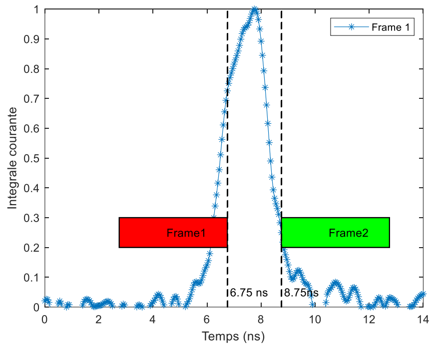
Initial LEH

3D simulations capture the extent and morphology of the wall as measured through the DMX imager

While the morphology of the wall emission is captured well in 3D simulations, some details merit further investigation

DMX view





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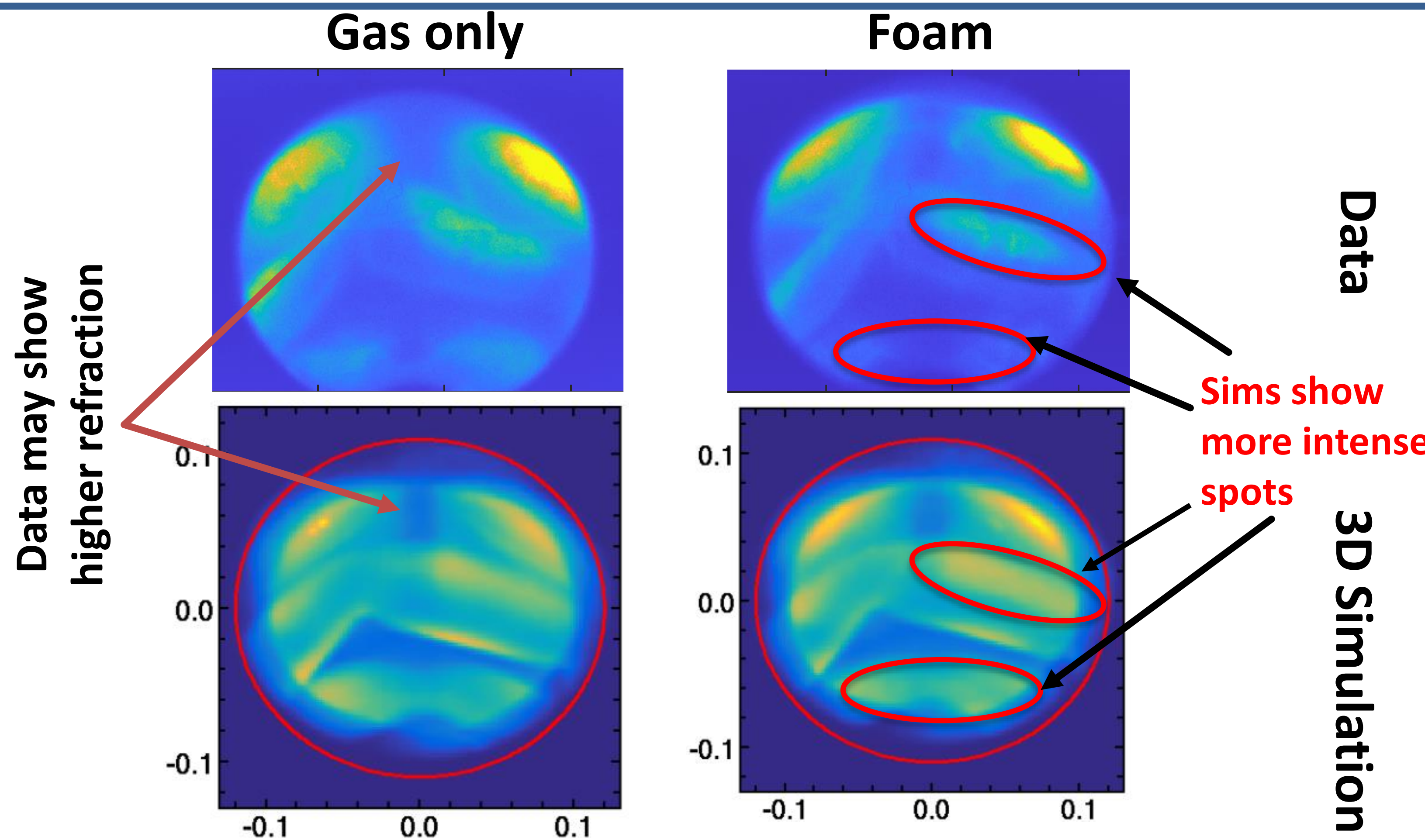
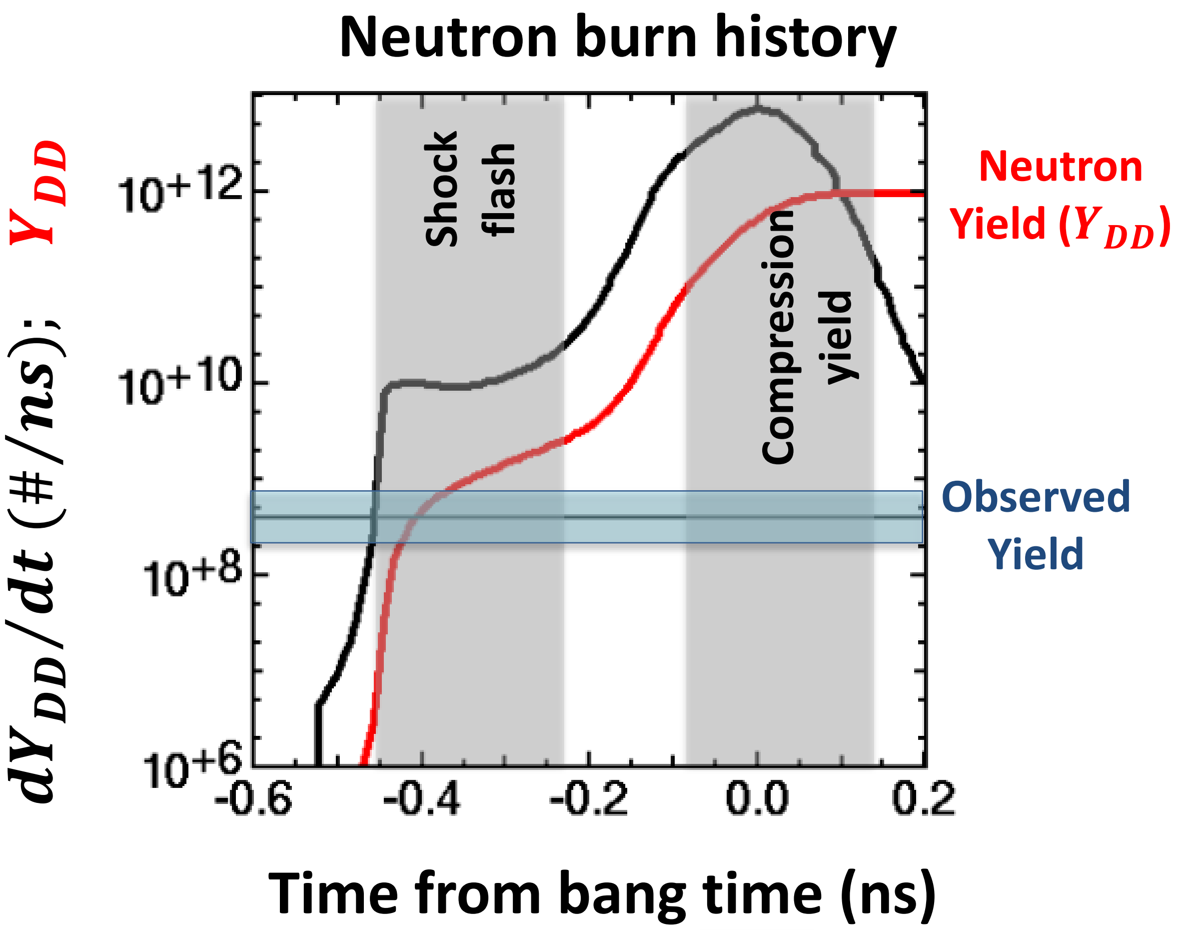


3D simulations capture the extent and morphology of the wall as measured through the DMX imager

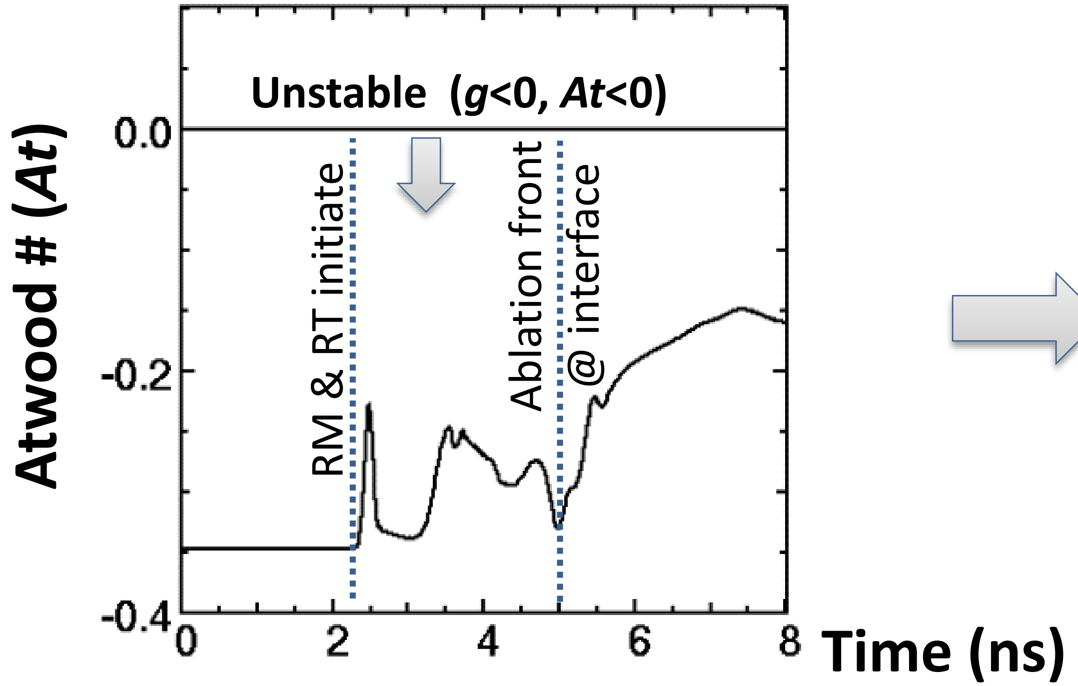
The measured number of neutrons (2-5x10^8) is consistent with shock flash yield and minimal compression yields

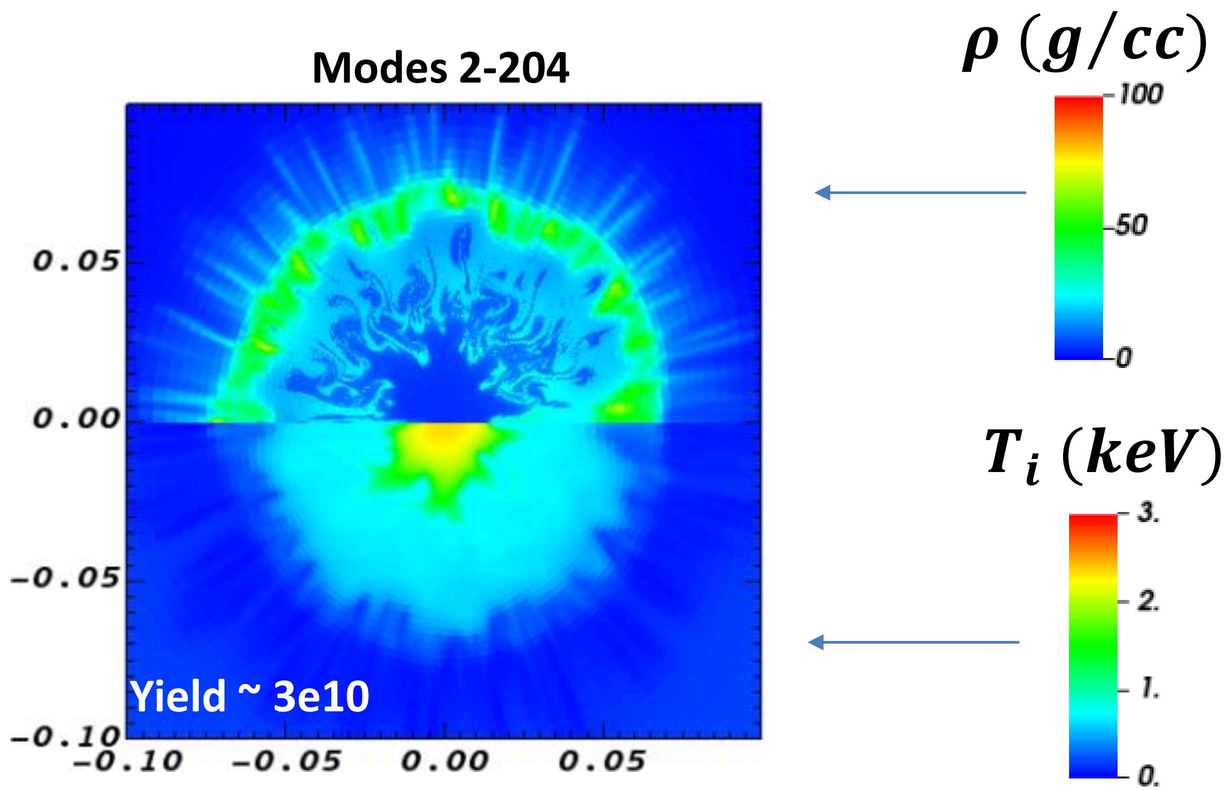
Post-shot simulations of the LMJ shots show that the measured neutrons come mostly from the first shock with very little, if any, coming from the compression phase



A plausible explanation is that the classically unstable SiO_2/CH interface promoted shell break up even at low convergence (~14-15)

- ➢ **Capsule-only simulations support this hypothesis**



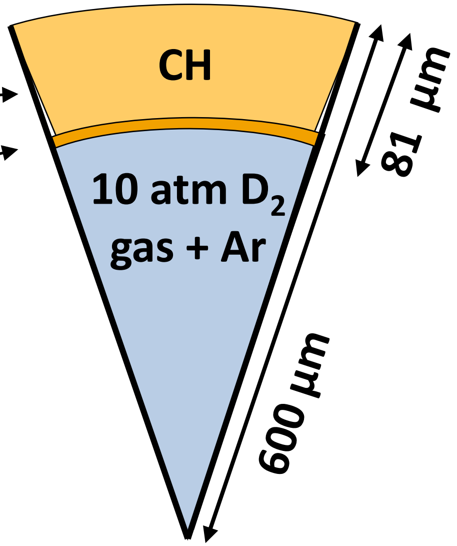


- ➢ **When combined with other degradations, it is likely that only shock flash yield was observed**
- ➢ **Capsule leakage was ruled out after GA verified that the capsules held the requested pressure**

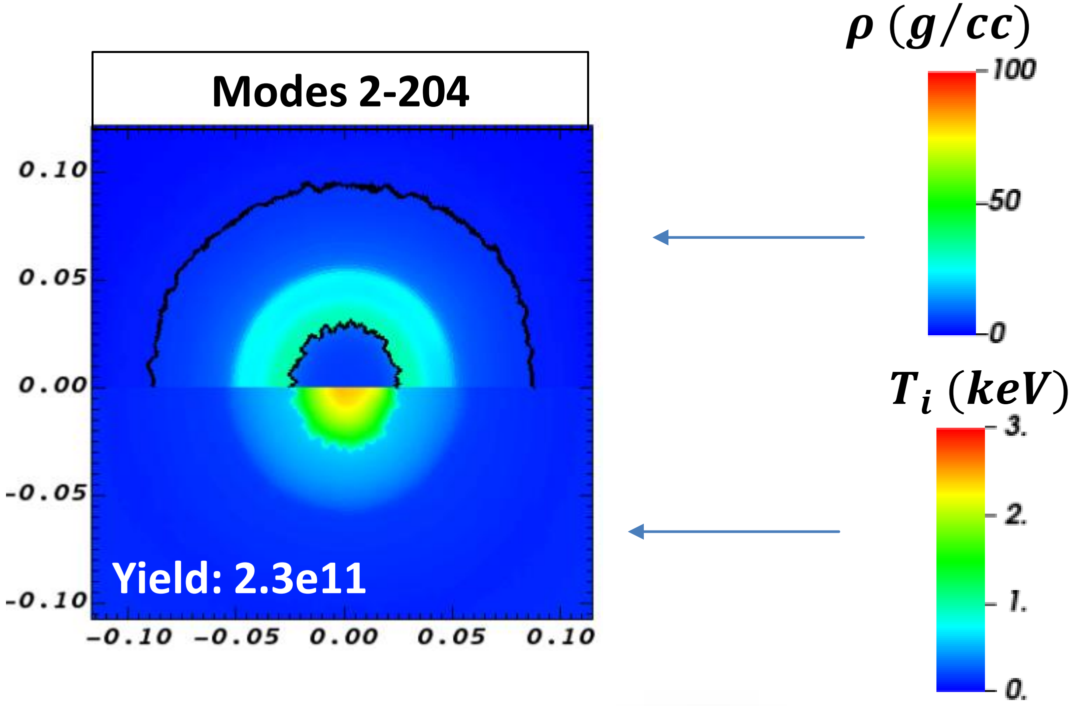
A robust capsule re-design prevents shell break up and allows core imaging

Mitigating capsule instability to enable self-emission imaging under the current (RT) fielding constraints, requires minimizing the amount of SiO_2 mandrel

A capsule that has improved instability properties (but with higher convergence has been identified.



5 μm SiO_2 can hold up to 10 atm of D_2 for several months



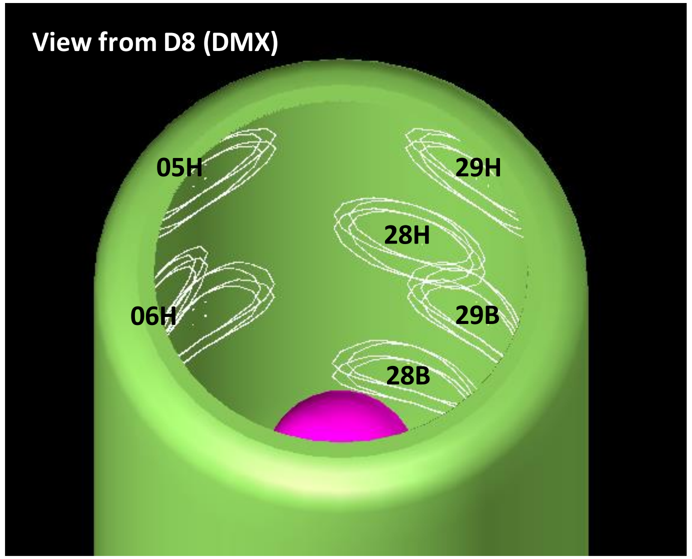
A follow up LMJ campaign should resolve outstanding issues from the inaugural March shots

- We have investigated the possibility of using foams to improve on a high-compression CH design
- Experiments at the LMJ facility have shown that foams slow down the outer beam bubble
- LPI concerns addressed using PF3D predicted that split inner quads significantly reduce the calculated SBS
- Experiments show that this strategy was successful in producing SBS ~< 10%.
  - Also showed that the presence of foams does not lead to higher SBS than in gas only hohlraums
  - Evidence found for SRS of outer beams to be significantly reduced with foams
- Additional foam benefits include the ability to introduce mid-Z dopants (only possibility at cryo conditions) to manage LPI risk
- We propose a new capsule design to recover compressional yield and enable core-imaging

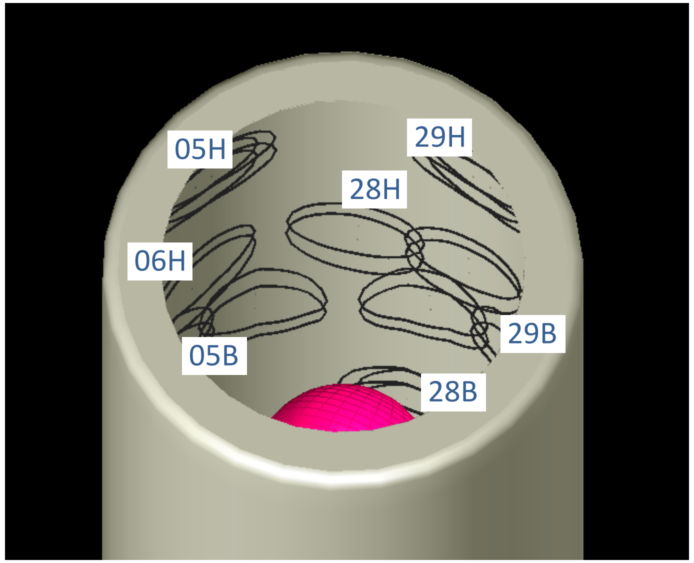
Lawrence Livermore National Laboratory

Backups

Inners not splitted

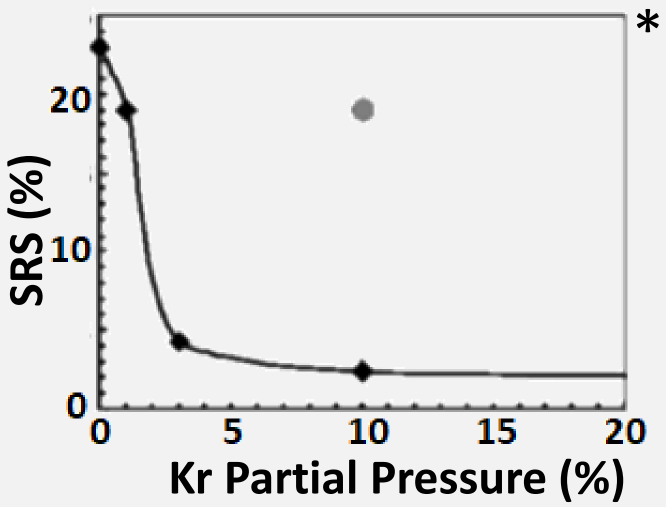


Inners splitted



Previous work suggest low density foams may add additional benefits to control backscatter and symmetry

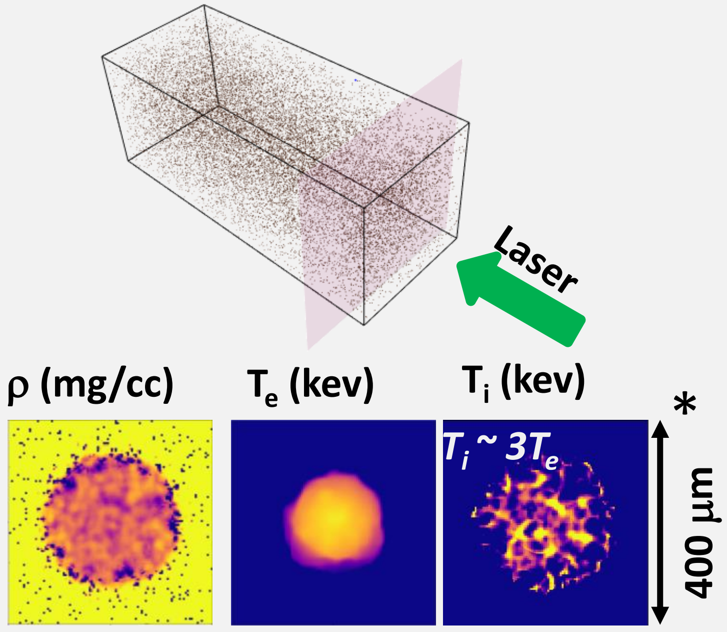
SRS mitigation by mid-z dopants



- Mid-Z dopants of hohlraum gas at cryo temperatures is not possible due to freezing
- Foam structure is ideal to allow the addition of dopants in cryo experiments

* Stevenson, et al., PoP **11** (2004)

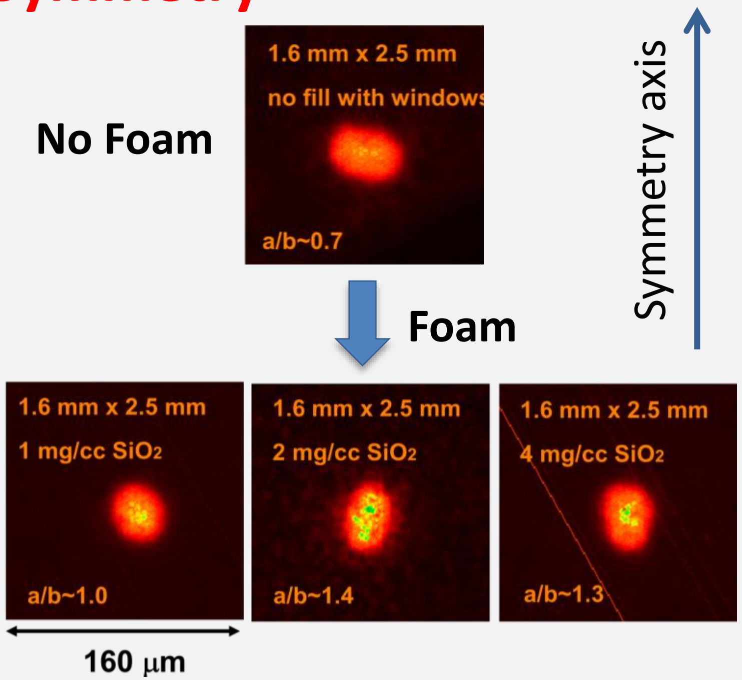
SBS mitigation by foam structure



Foams provide natural SBS reduction due to ion heating (from collision of expanding filaments) that increase ion damping

* Milovich, et al., PPCF **63** (2021)

Symmetry

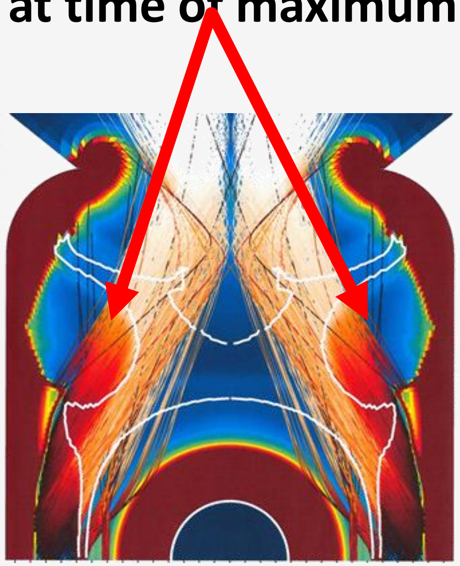


Omega experiments* using 200 eV 2.5 ns drive showed no deleterious effects with up to 2 mg/cc SiO_2 foam fills

* Iaquinta, Amendt, Gregori (in preparation)

Late-time symmetry control requires the use of CBET particularly for larger scale capsules

- Inner beams absorbed by ablated wall at time of maximum power



- Compromises symmetry control

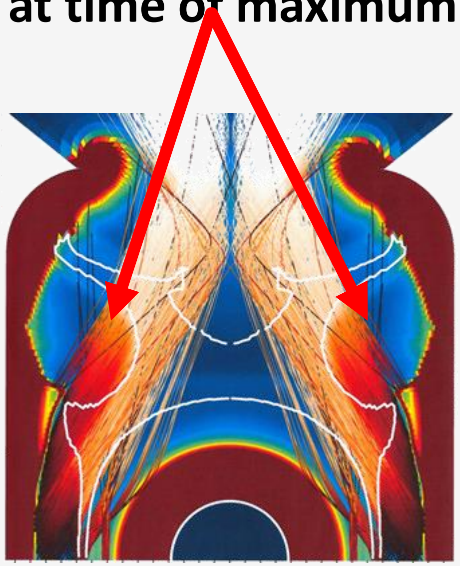
Poor inner beam propagation to the waist

- Presently cross-beam energy transfer (CBET) is exclusively used to control implosion symmetry

- As targets scale up, CBET may not be sufficient to control late time-dependent asymmetries

Late-time symmetry control requires the use of CBET particularly for larger scale capsules

- Inner beams absorbed by ablated wall at time of maximum power



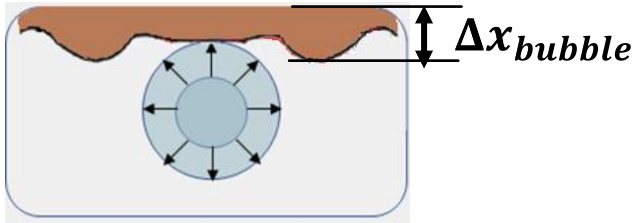
- Compromises symmetry control

Poor inner beam propagation to the waist

- Presently cross-beam energy transfer (CBET) is exclusively used to control implosion symmetry
- As targets scale up, CBET may not be sufficient to control late time-dependent asymmetries

Improving the energy coupled to larger capsule increases the risk of bubble growth and potential loss of late-time symmetry

SCALING



Euler scaling

- Fixed hydro quantities (ρ, P) requires:
- $t, x \rightarrow s \; * (t, x)$
- $P_L \rightarrow P_L \; * s^2$
- $E_L \rightarrow E_L * s^3$
- $E_{cap} \rightarrow E_{cap} \; * s^3$

- Bubble motion can be estimated as

$$\Delta x_{bubble} \sim c_s t \sim \sqrt{T_e(1+Z)}\, t \sim \sqrt{(1+Z)(I\lambda^2)^{2/3}} \;\; t$$

$$\sim \sqrt{(1+Z)\left(P_L\lambda^2/A_q\right)^{2/3}} \;\; t$$

for area of quad $A_q \sim s^{2/3}$ †, Euler-scaling leads to

$$\Delta x_{bubble}^{scaled} \sim s^{13/9} \quad (> s^1 \;\; !)$$

- Thus, larger hohlraum scale gives relatively larger bubble growth and potentially earlier impediment of inner-beam propagation

† T. Chapman, accurate up to 50% larger scaling private comm.

The foam-fill hohlraum concept attempts to provide additional margin for high convergence and low CCR targets

Motivated by:

- Challenges in symmetry at low case-to-capsule (CCR) for more efficient hohlraums
  - Uncertainties in CBET to provide needed symmetry control at more demanding CCRs
    - Foams may provide sufficient tamping of outer bubble expansion eliminating the need for CBET

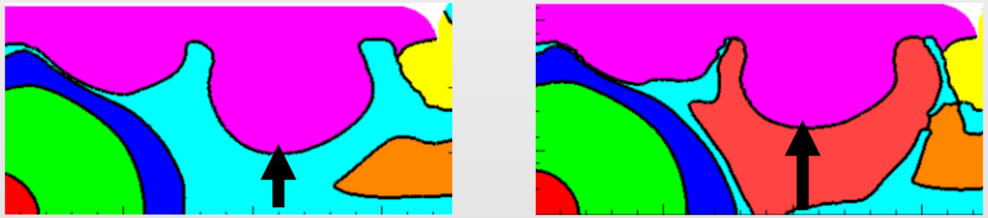
      or

    - Foams may add additional control even when using CBET

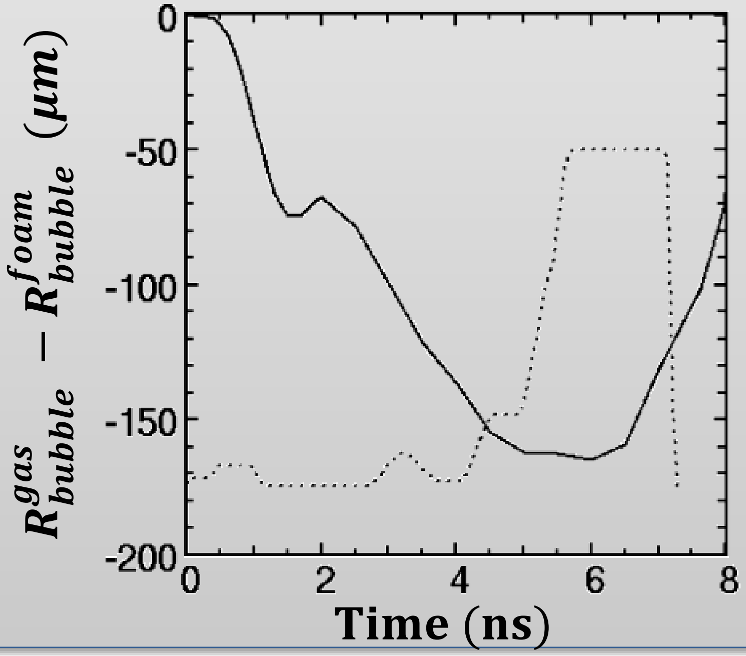
- Potential for higher LPI at larger scales (longer laser pathlengths)
  - Foams allow for LPI mitigation by high-Z dopants at cryo temps

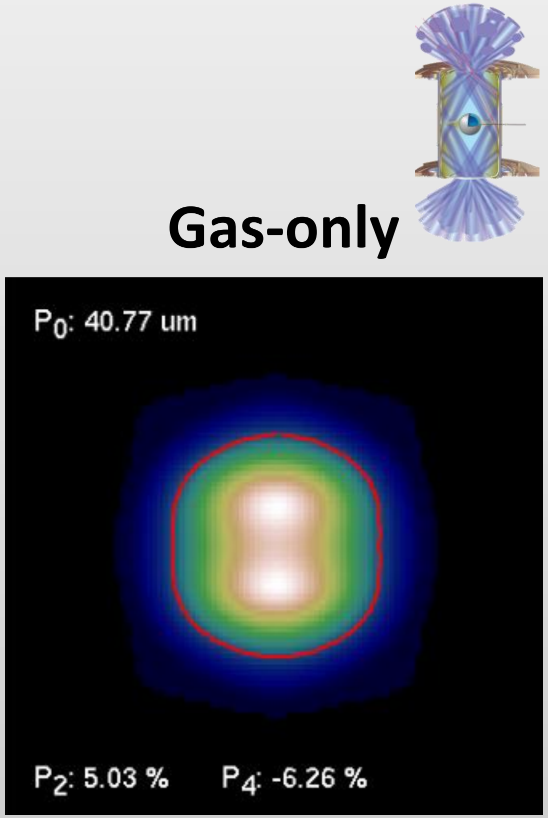
Simulations, using the requested pulses and as fielded targets, suggested modest but measurable changes in capsule symmetry and bubble motion.

Gas-only Foam



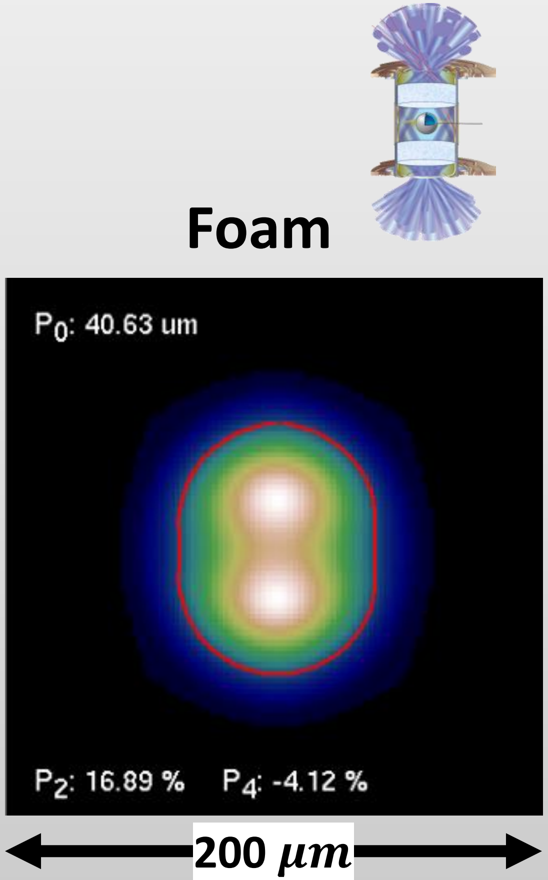
R_{bubble}





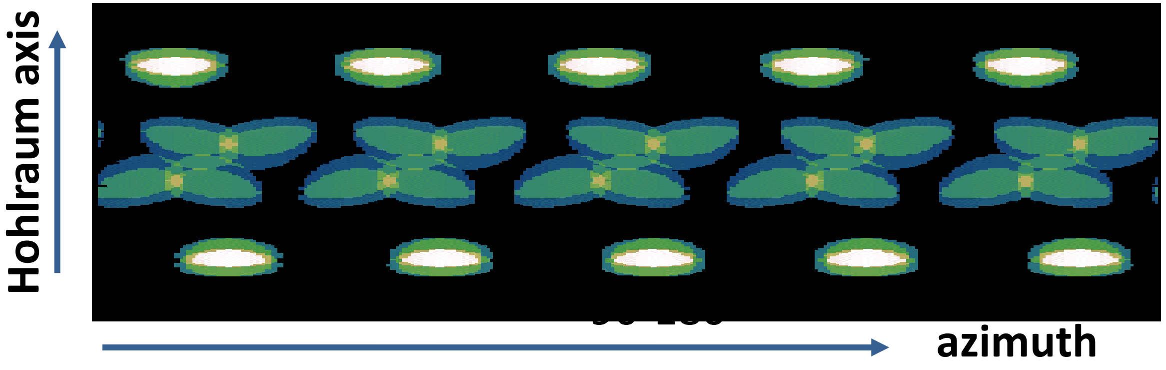
$\Delta(P_2/P_0)$

$\sim +10\%$

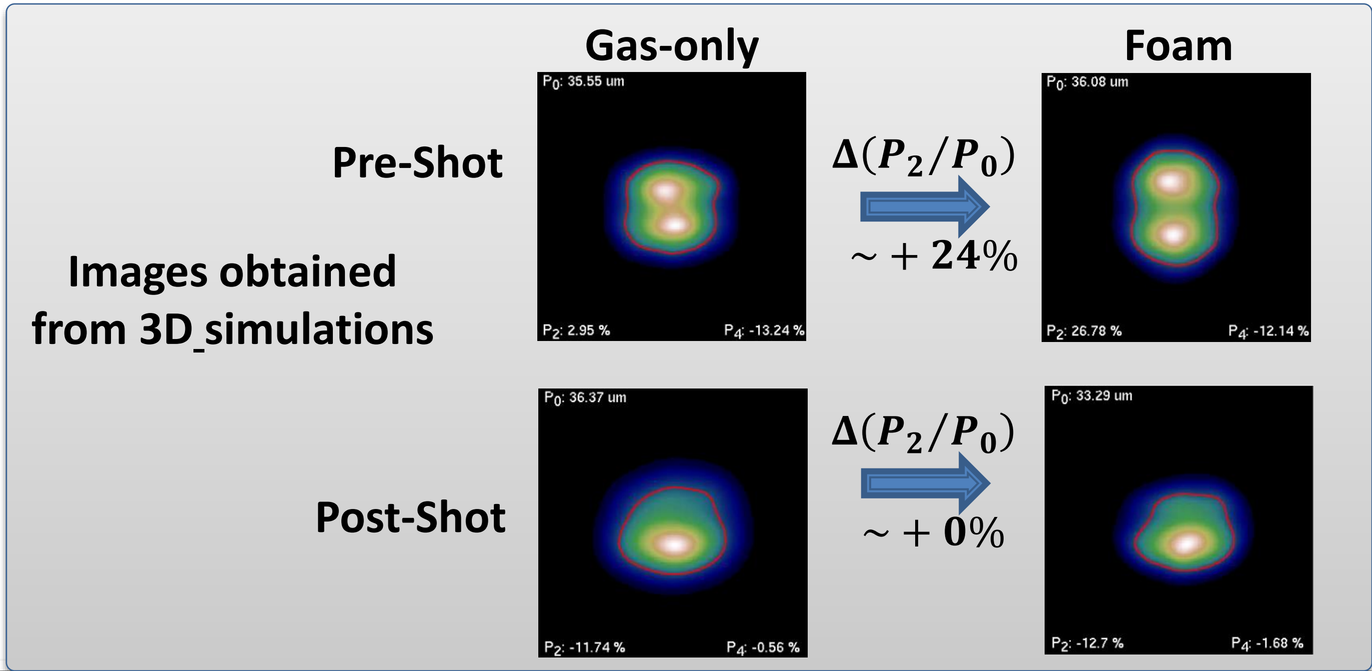


Capsule implosion symmetry can be assessed by performing simulations, since no data was obtained.

3D simulations were used to ascertain capsule symmetry since the hohlraum wall is not fully azimuthally irradiated in the current LMJ configuration

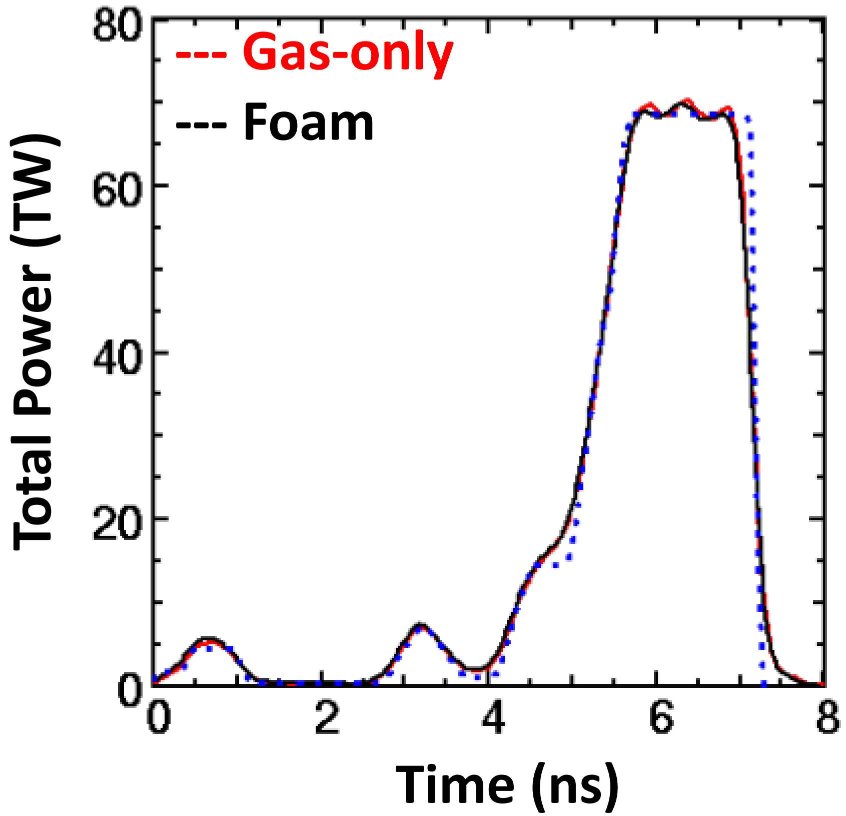


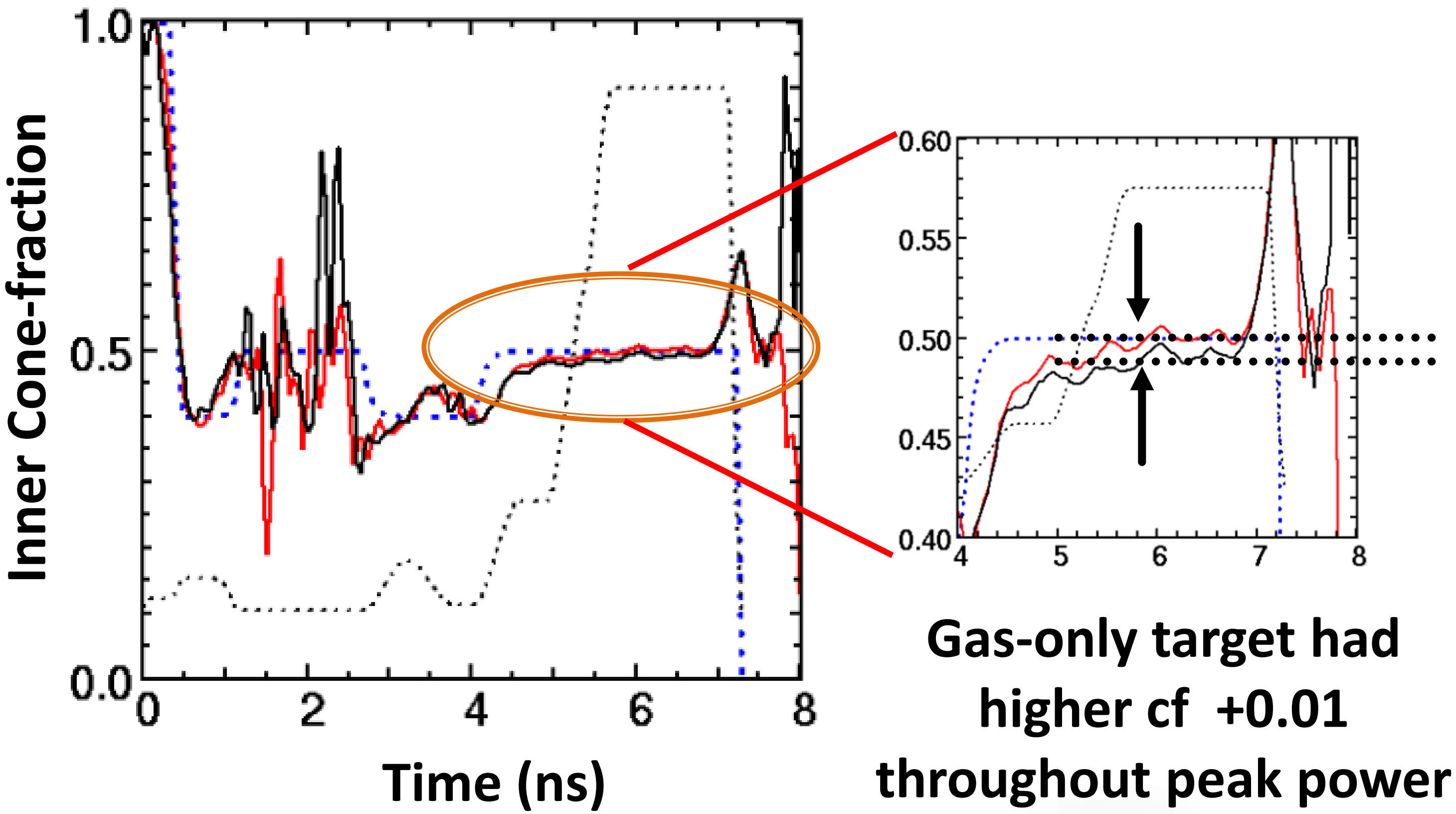
- **Pre-shot 3D simulations predict larger changes in P2 in the presence of foams**
- **However, accounting for laser delivery present some challenges in interpreting the data**



While laser delivery was good, the peak cone fraction was systematically different across the peak

- **Laser delivery was reasonably good with some quad-to-quad variations that needs to be accounted for in the data analysis**



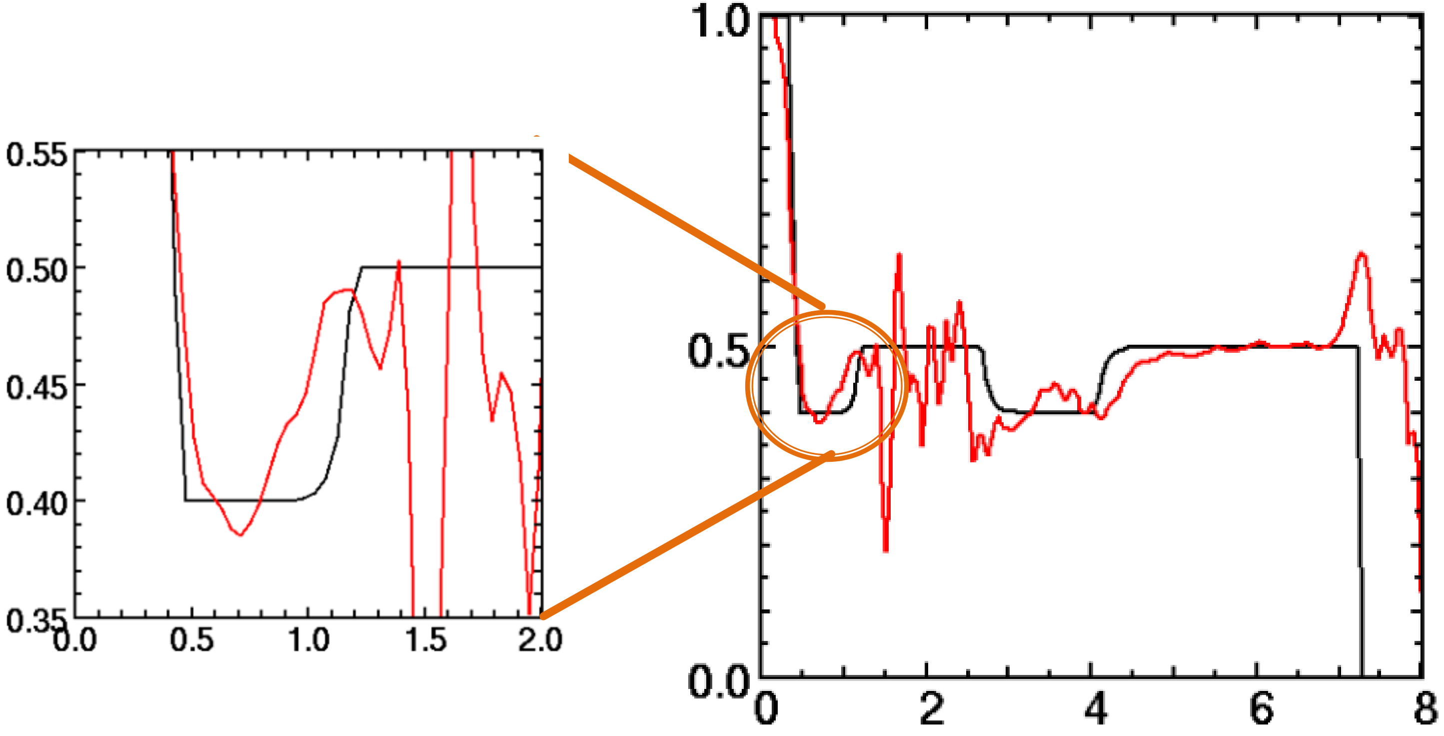


Gas-only target had higher cf +0.01 throughout peak power

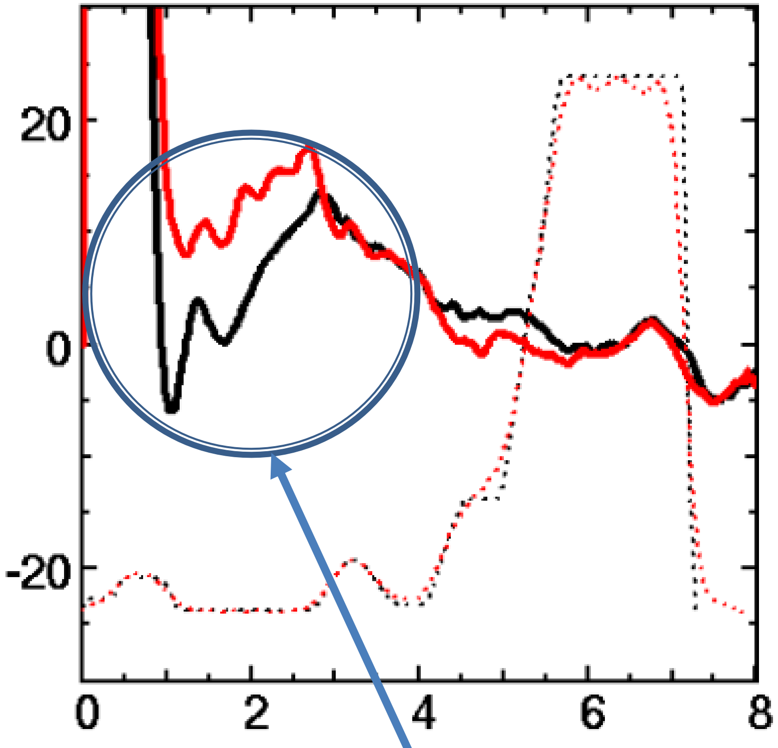
Additionally, the cone fraction during the picket delivered too high leading to a late-time symmetry inversion

Gas-only case

Cone-fraction



Radiation Flux P_2/P_0 (%)
@ ablation front



Leads to significant peak symmetry changes

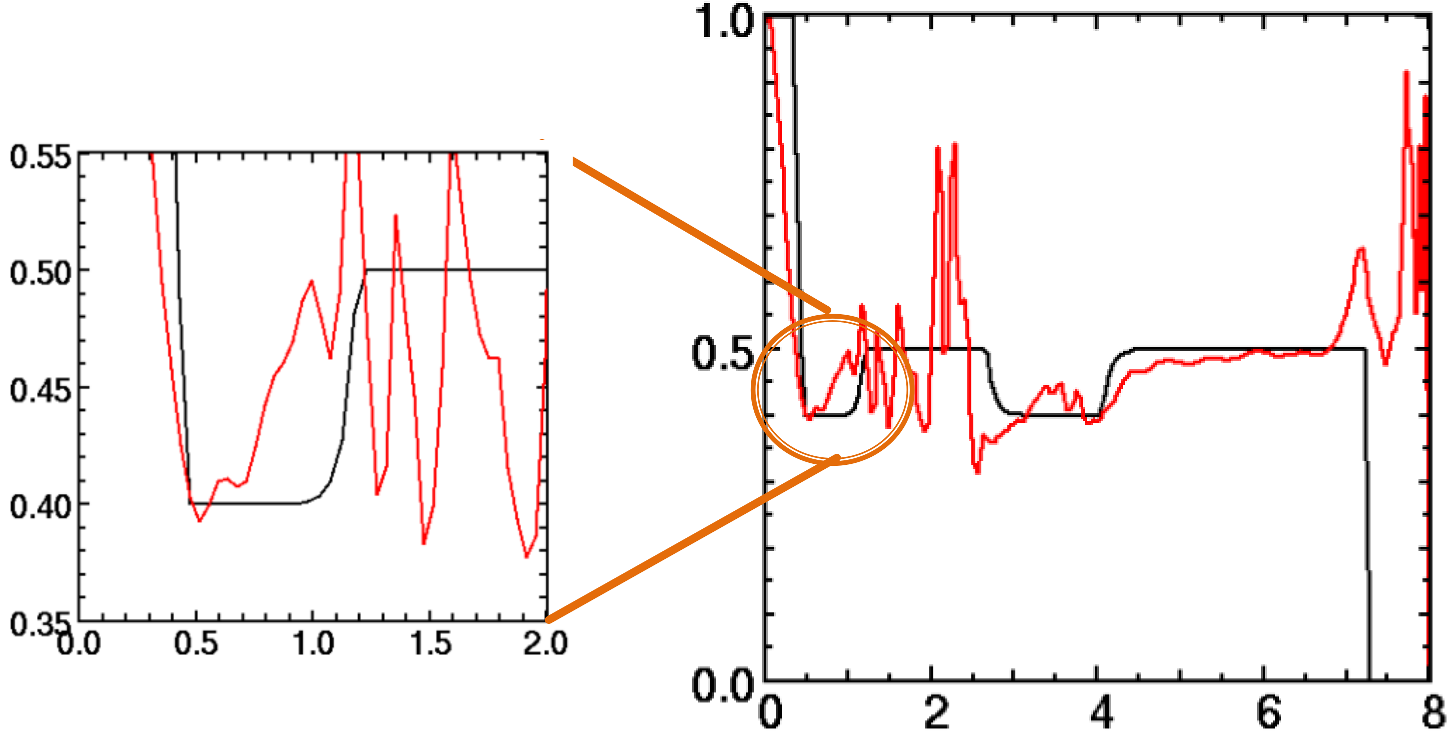
--- Requested

--- Gas-only Hohlraum (to match rise time of 4th pulse was advanced by 75 ps)

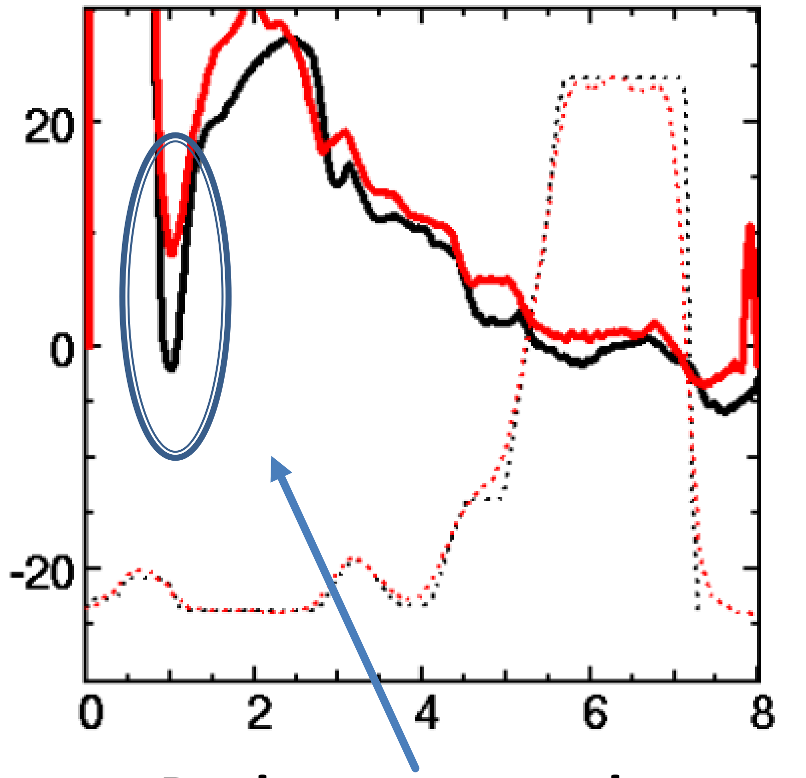
Additionally, the cone fraction during the picket delivered too high leading to a late-time symmetry inversion

Foam case

Cone-fraction



Radiation Flux P_2/P_0 (%) @ ablation front



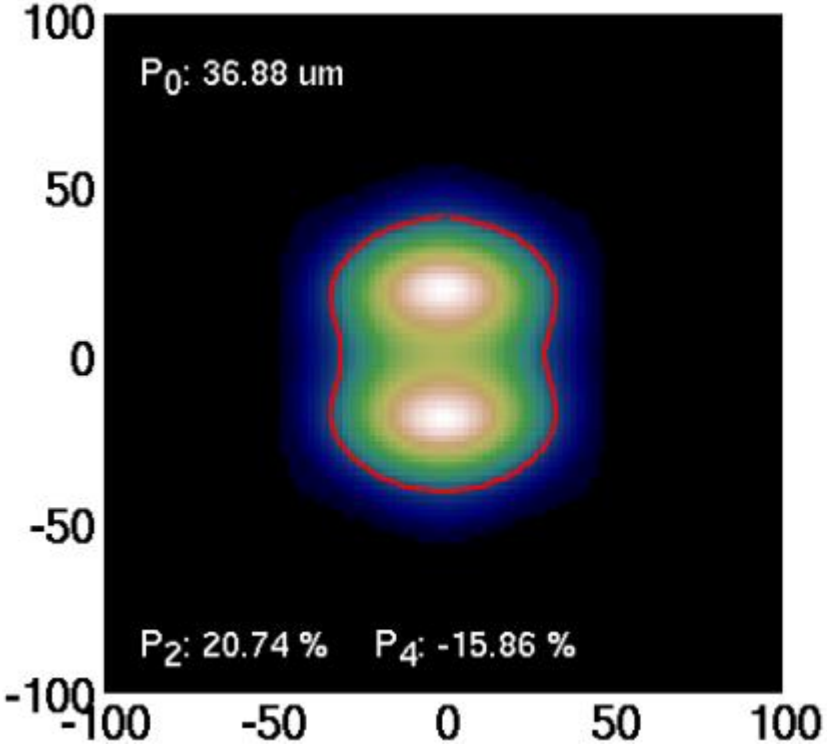
Peak symmetry changes mitigated by the foam

--- Requested

--- Gas-only Hohlraum (to match rise time of 4th pulse was advanced by 75 ps)

As a result, postshot simulations show a departure from the expected symmetry change

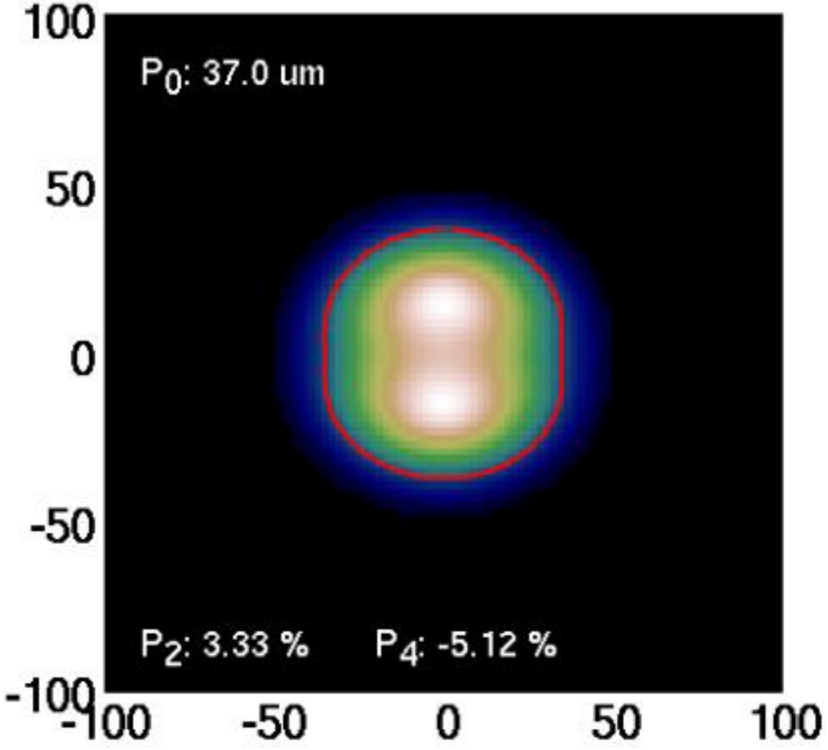
Gas-only



$\Delta(P_2/P_0)$

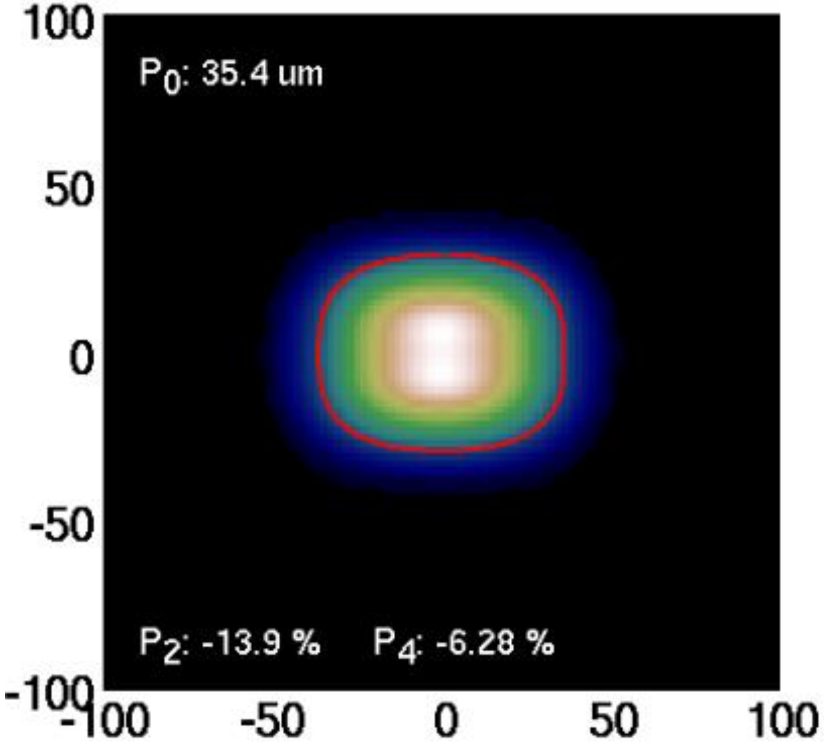
$-24\ \%$

Foam case

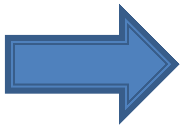


Simulations using the fielded targets, but swapped laser pulses, confirm that laser delivery is the culprit for the symmetry calculated

Gas-only

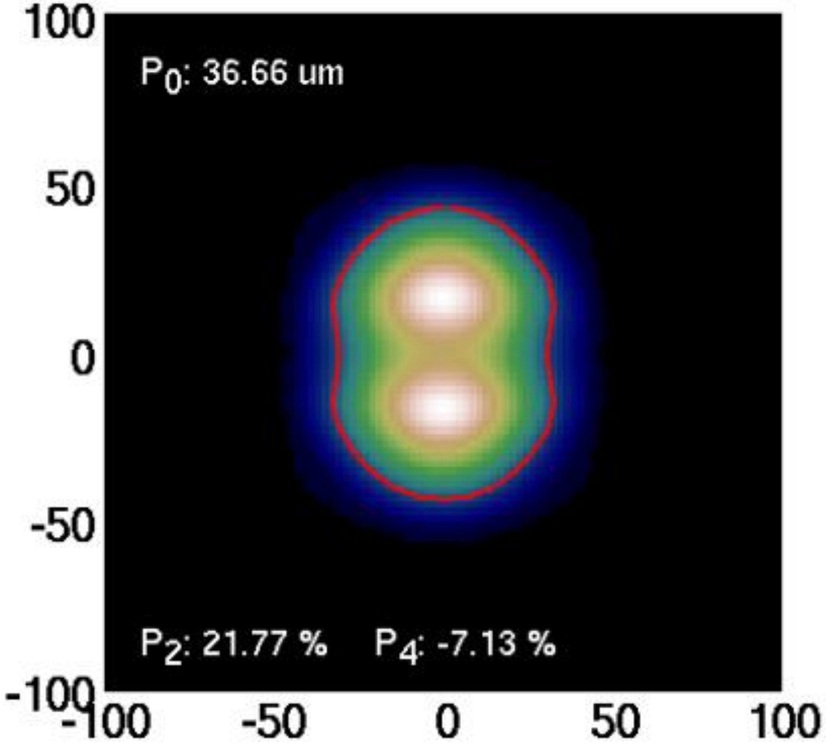


$\Delta(P_2/P_0)$



$+ 35\ \%$

Foam case



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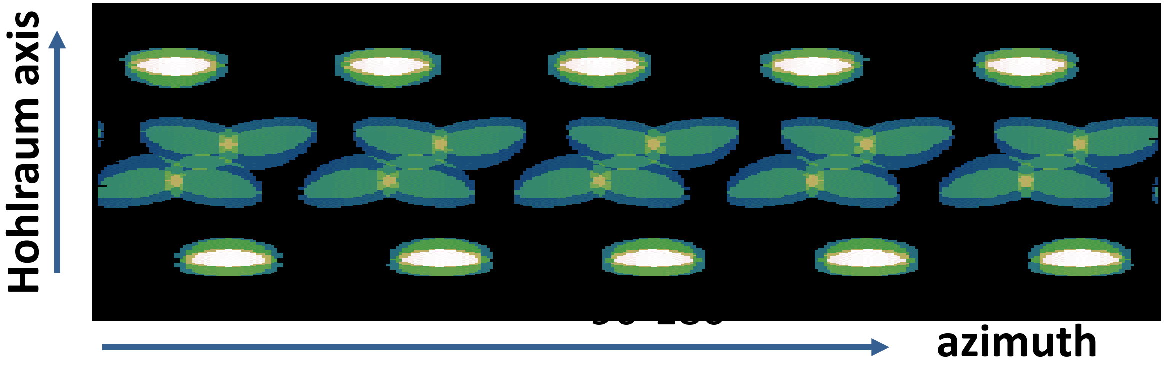
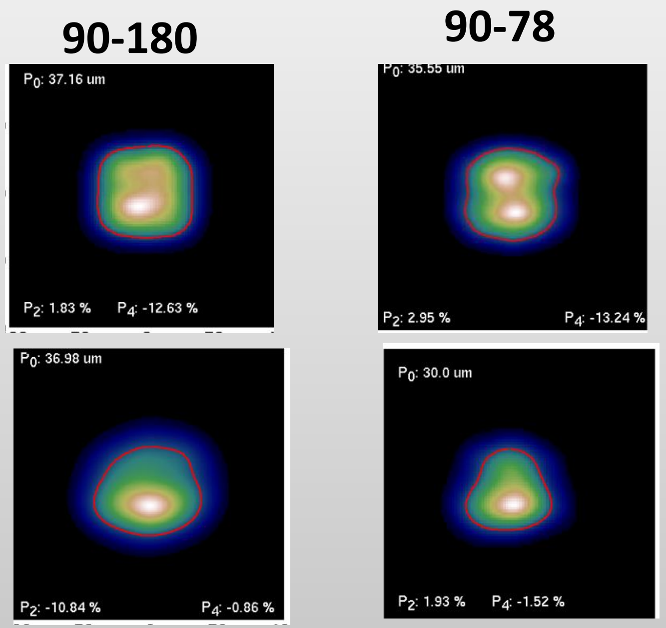


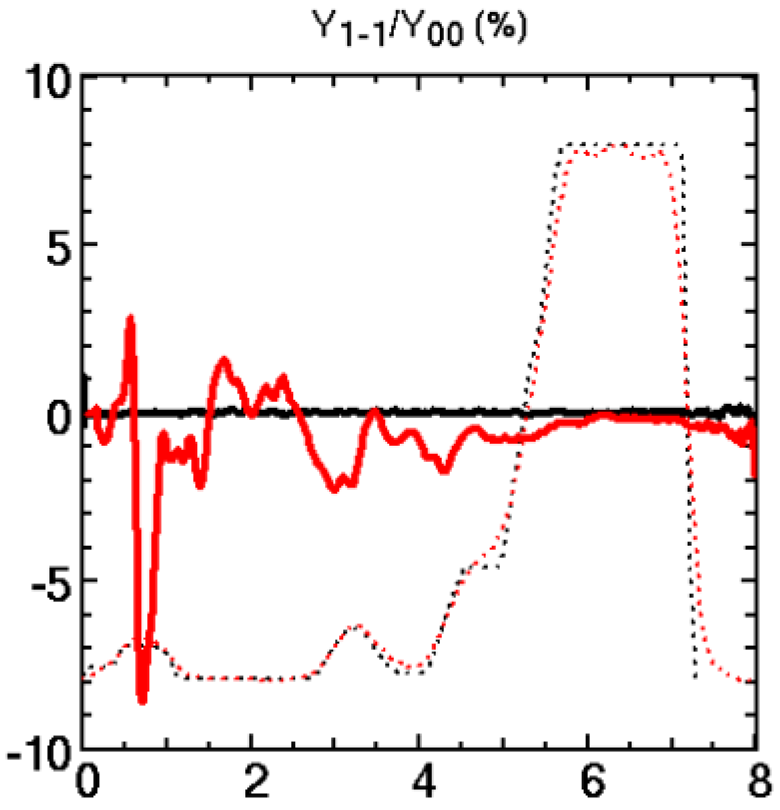
- **We found that for a perfect laser simulations predict that capsule symmetry is for the most part ndependent of viewing angle**

- **However, accounting for laser delivery present some challenges in interpreting the data**

Images obtained from a 3D simulation using 2 different lines of sight

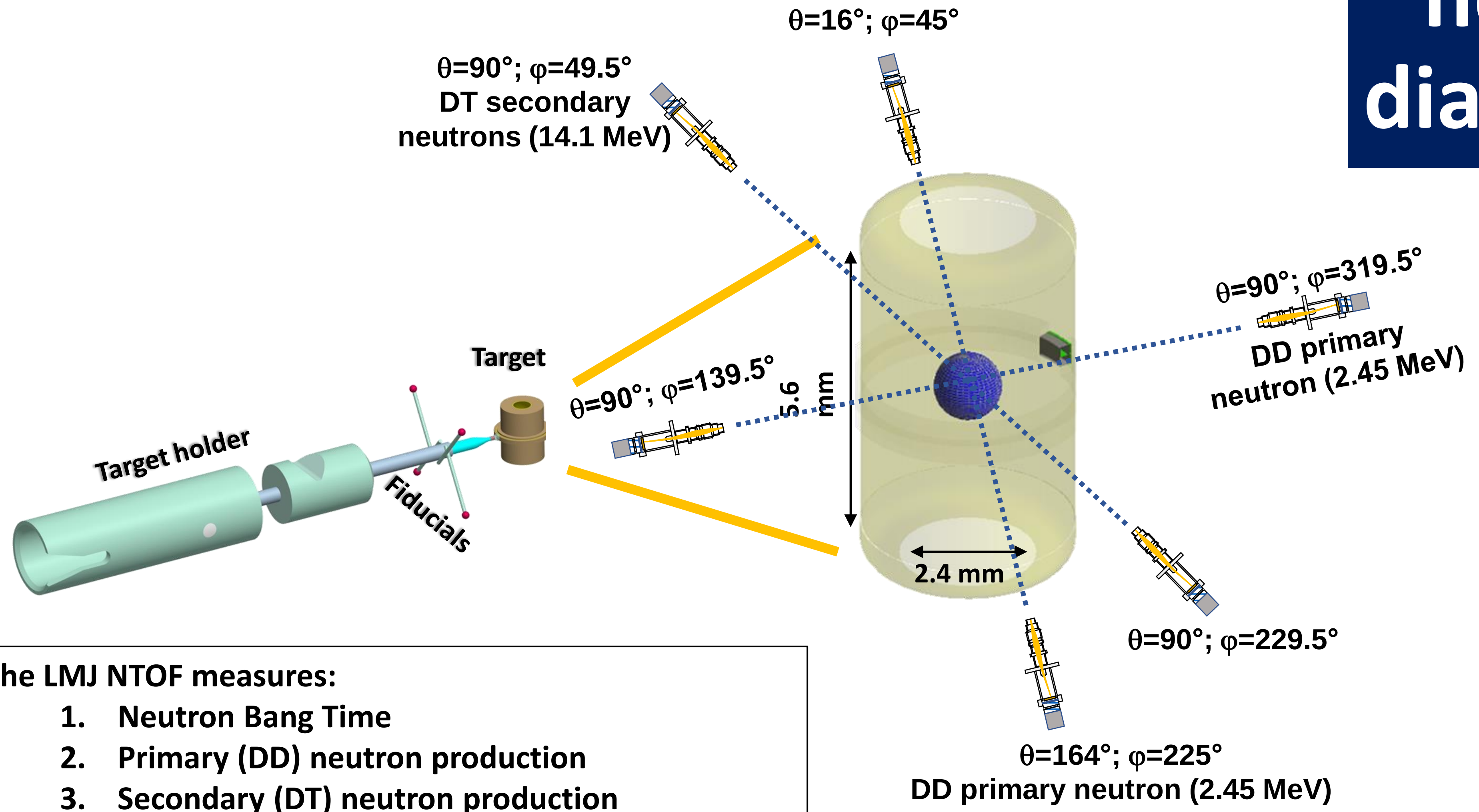


Laser delivery had a significant top/bottom imbalance, creating a significant mode 1 on the implosion symmetry



Three pairs of neutron NTOF detectors were fielded

LMJ neutron diagnostics



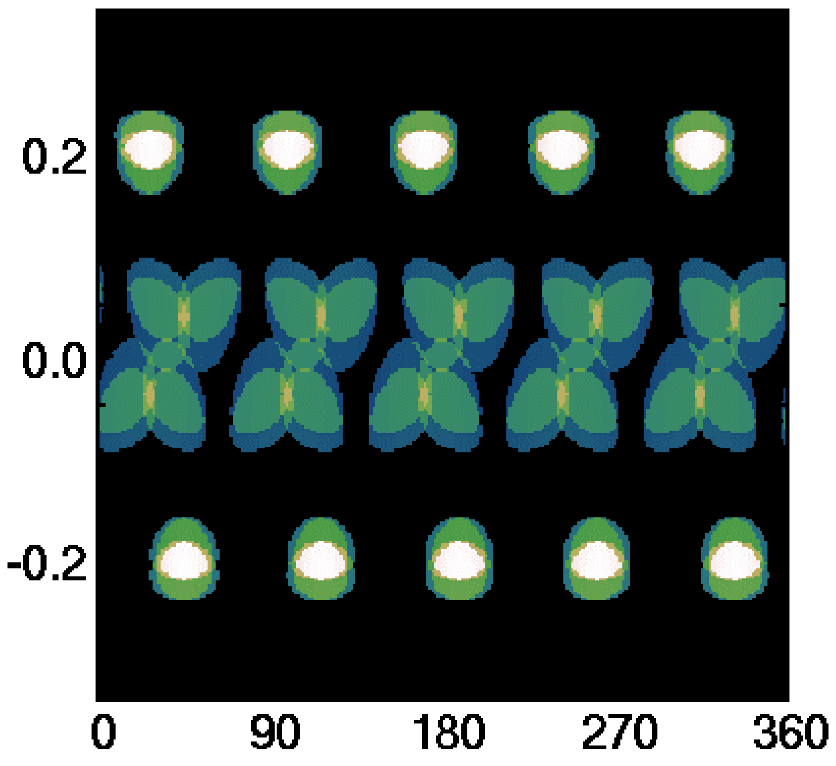
The LMJ NTOF measures:

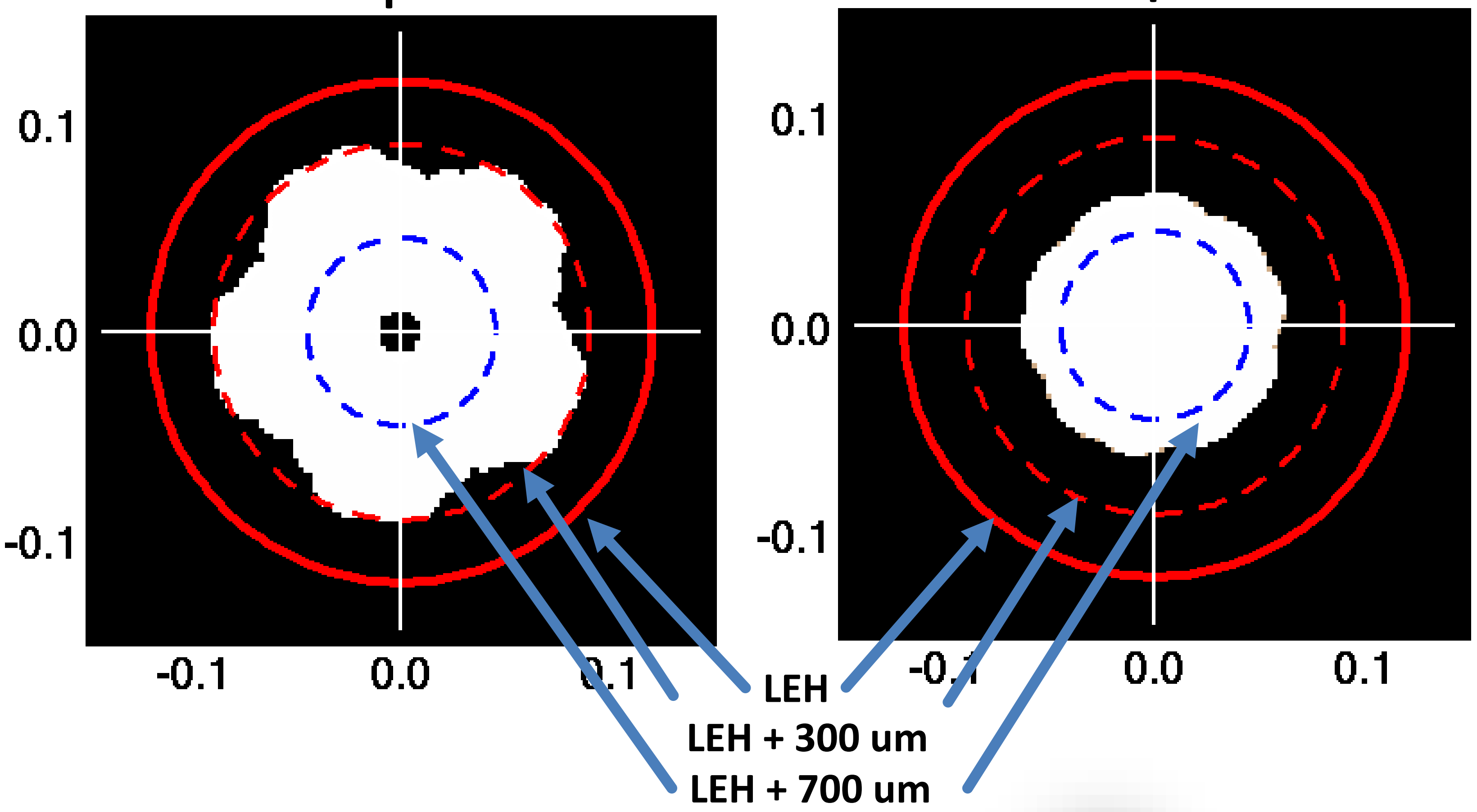
1. Neutron Bang Time
2. Primary (DD) neutron production
3. Secondary (DT) neutron production
4. Ion temperature

10^8 DD neutron threshold

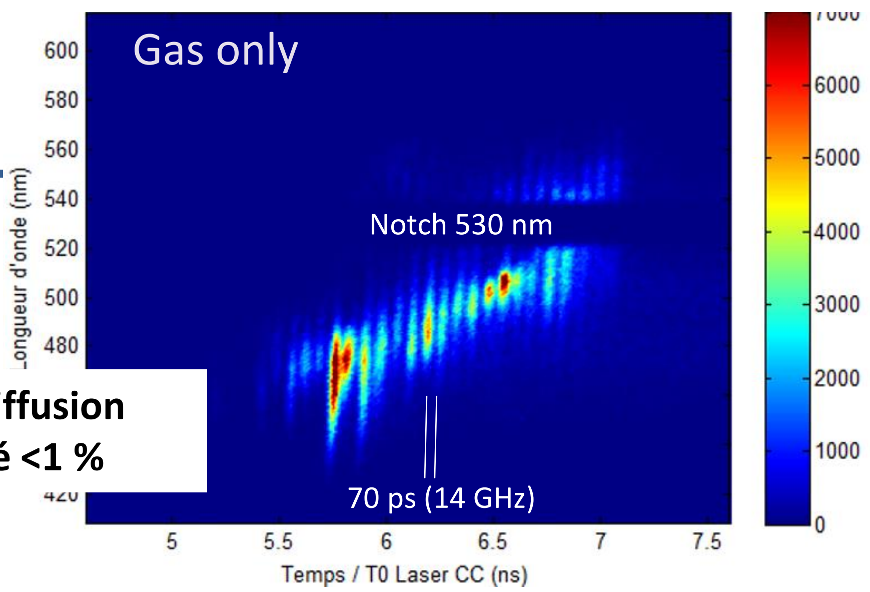
LMJ experiments used reduced inner quad-splitting (300 μm) to balance LPI and LEH clipping risks

Inners splitted by 300 μm

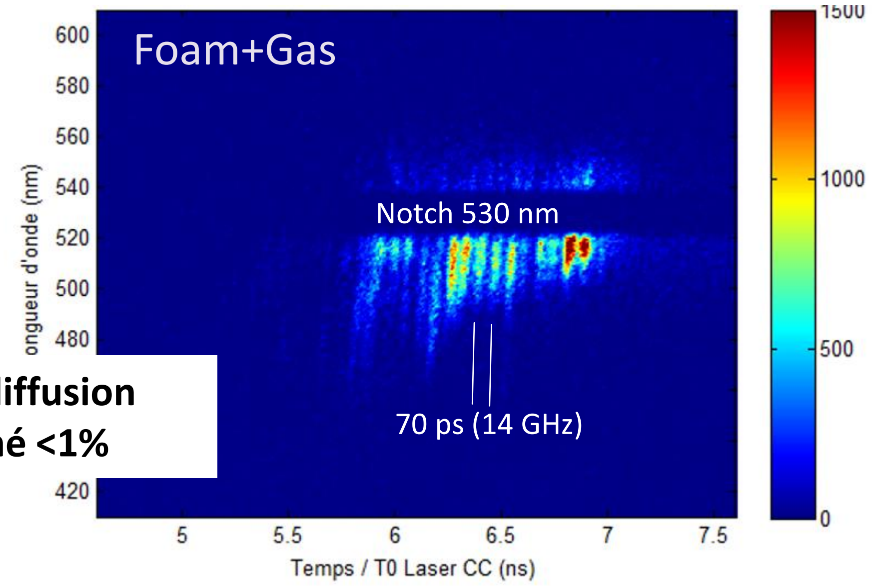




DP7 – time-resolved spectra for RAMAN backscattering (28H-inner)

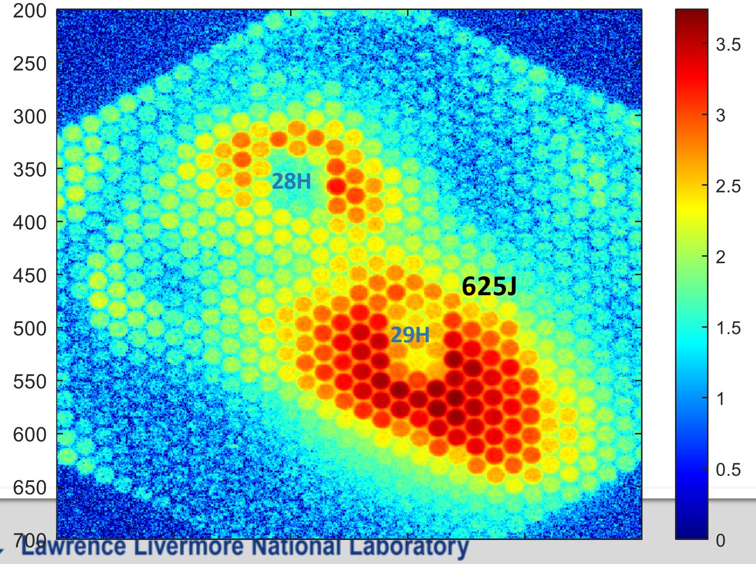


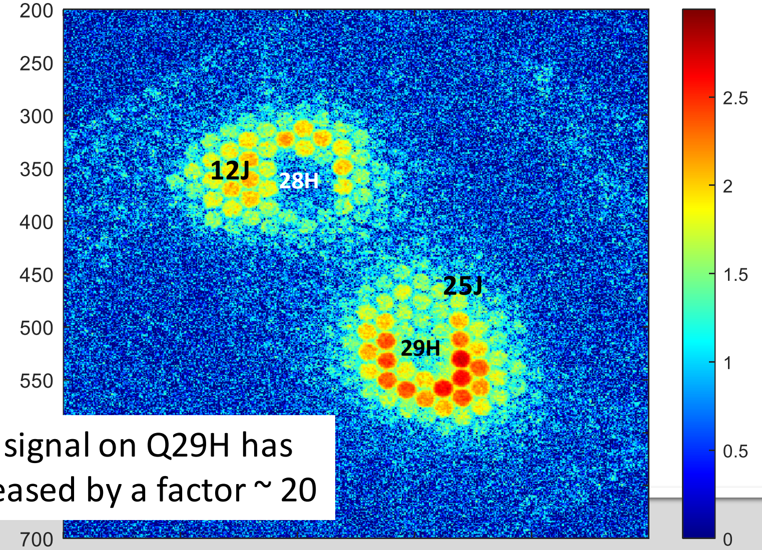
Taux de rétrodiffusion
Raman estimé <1 %



Taux de rétrodiffusion
Raman estimé <1%

DP8 – NBI RAMAN around 28H-inner and 29H-outer



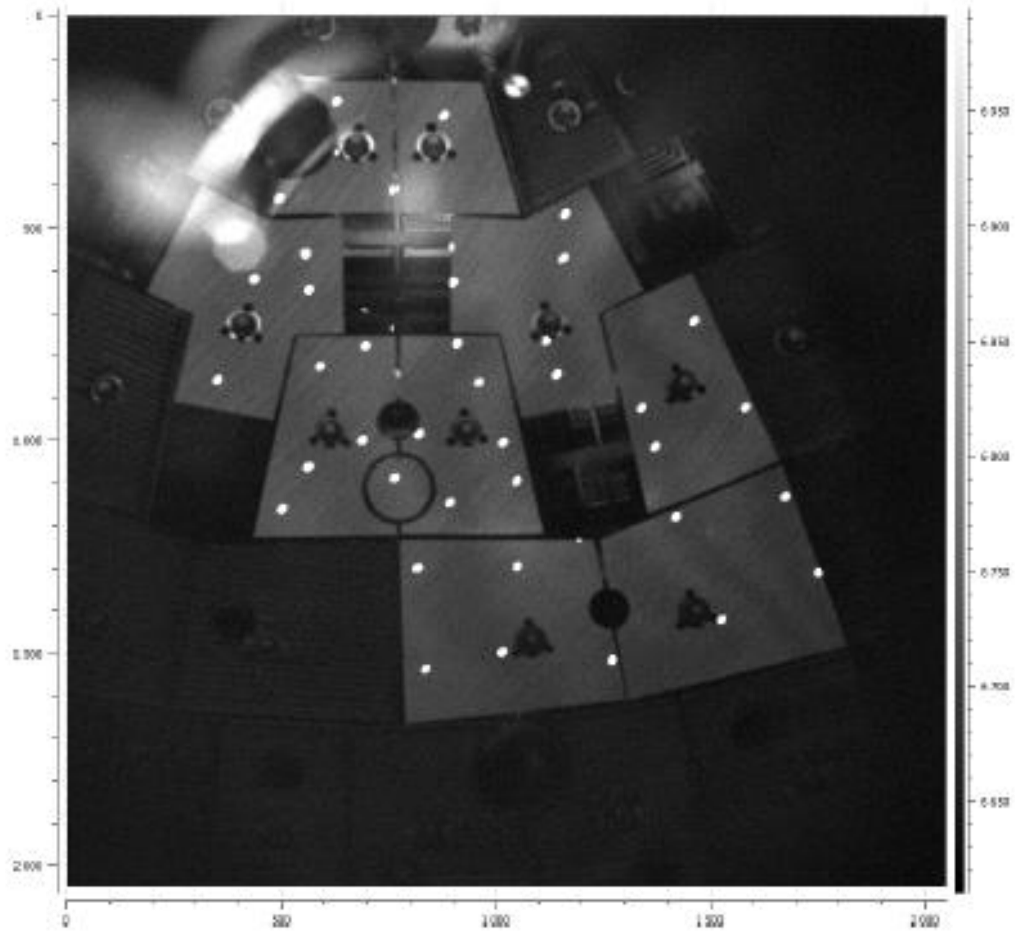


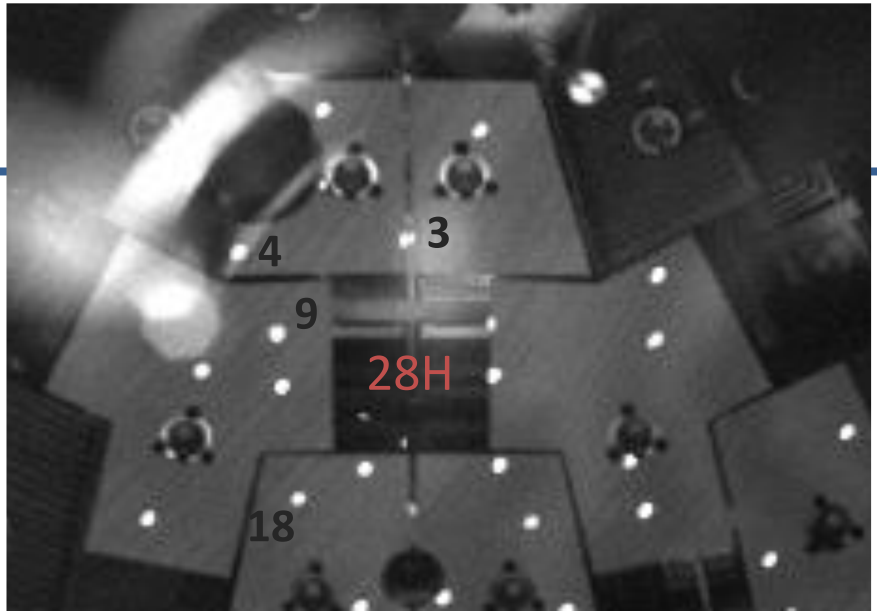
The signal on Q29H has decreased by a factor ~ 20

RAMAN scattering losses are dominated by the outers' losses (significant only in the gas only shot)

In case of question

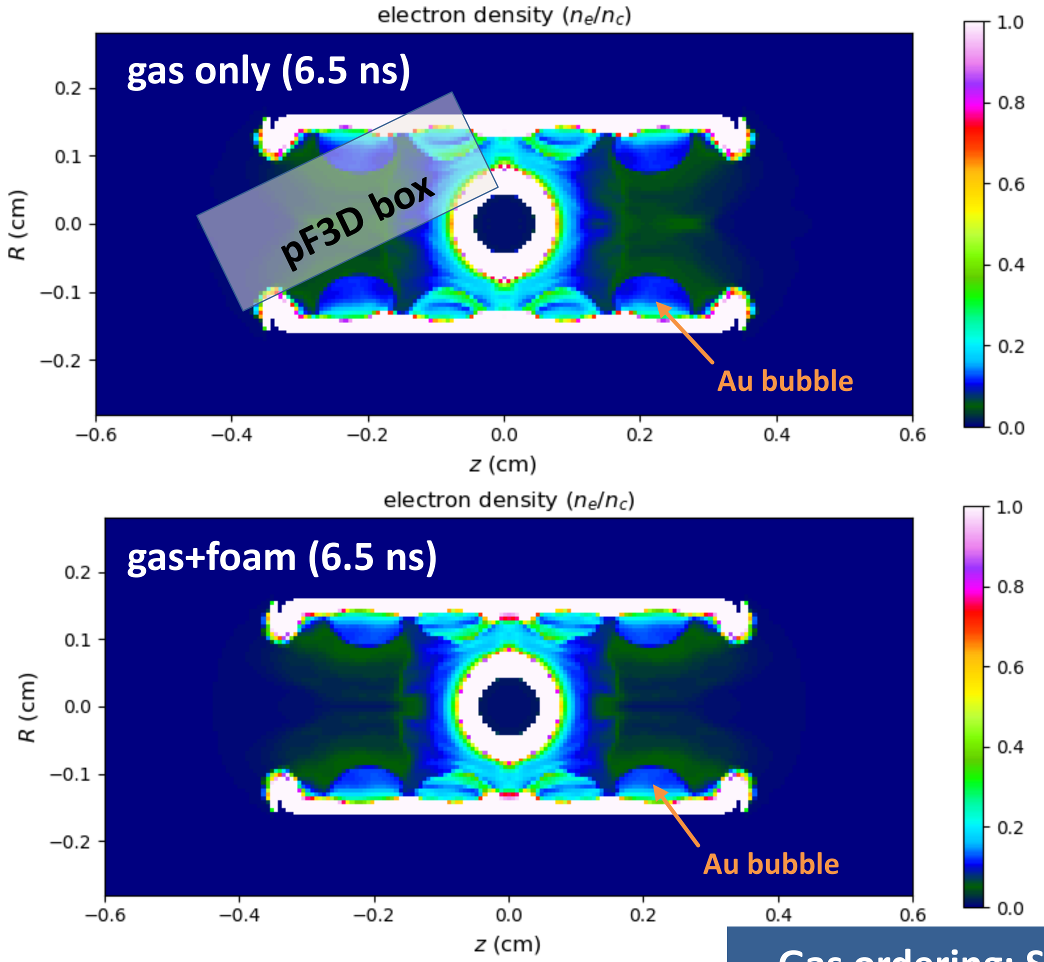
Time resolved Brillouin is measured on 40 points with DP8

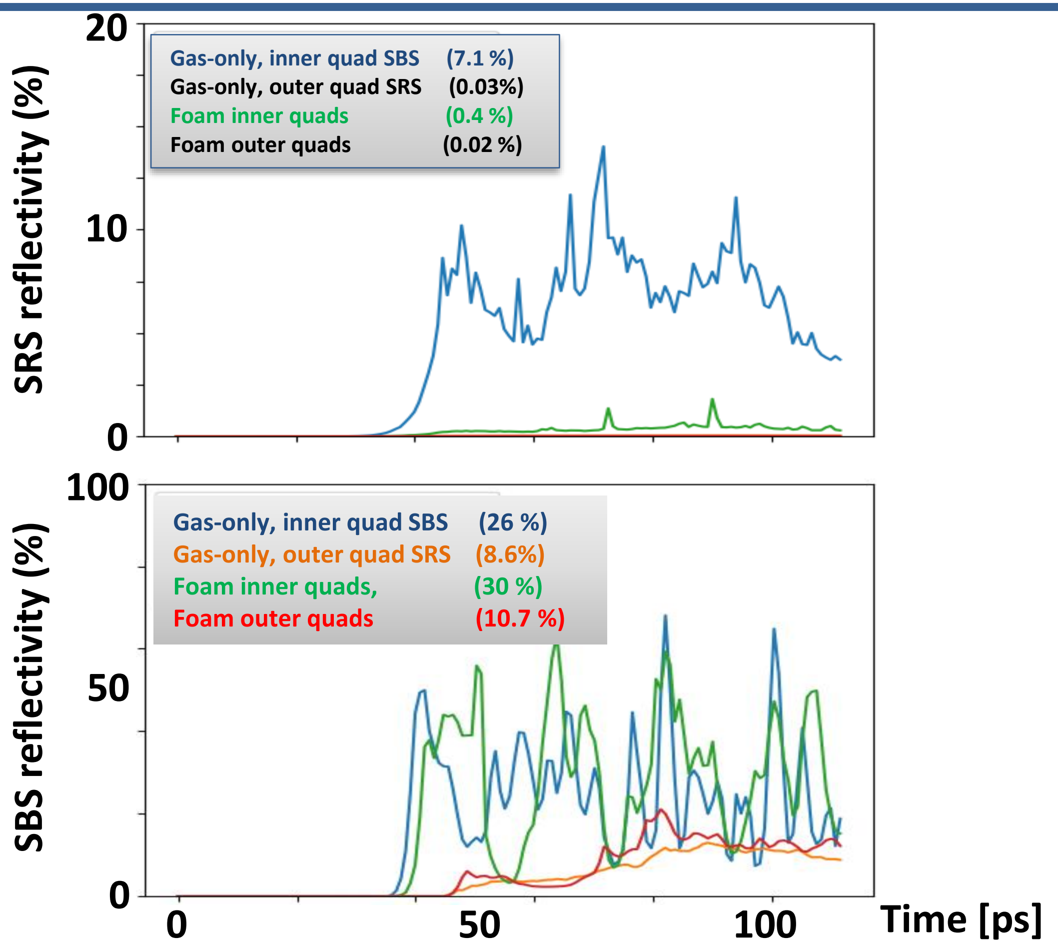




SBS on NBI around Q28h is of shorter duration (~ 1 ns) than SBS in the FABS

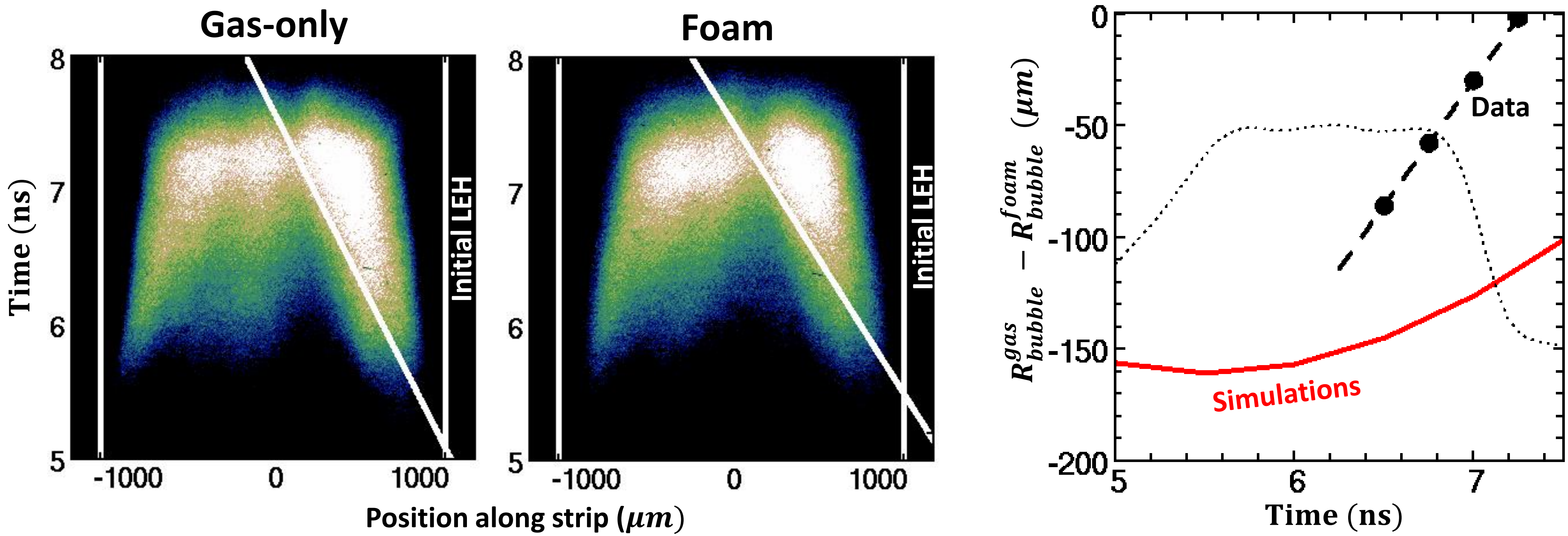
pF3D analysis of HYDRA simulations showed high inner quad SBS reflectivity for both gas-only and foam targets



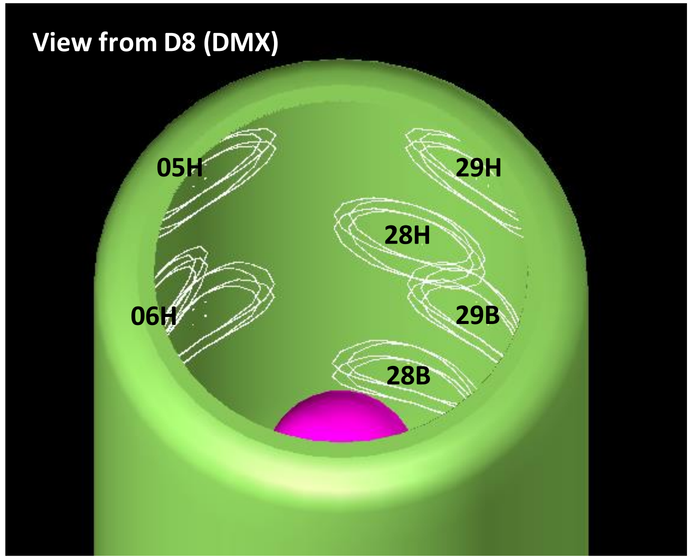


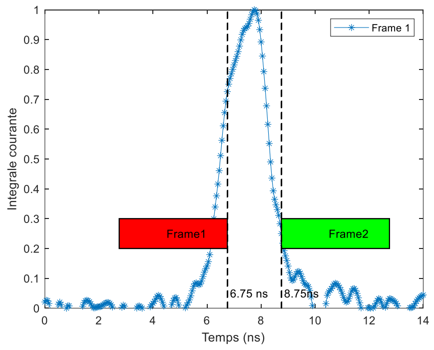
Gas ordering: SBS inner > SBS outer ~ SRS inner > SRS outer
Foam ordering: SBS inner > SBS outer > SRS inner > SRS outer

The DP2 instrument collected good data showing that the bubble was delayed in the foam target - but less than simulated

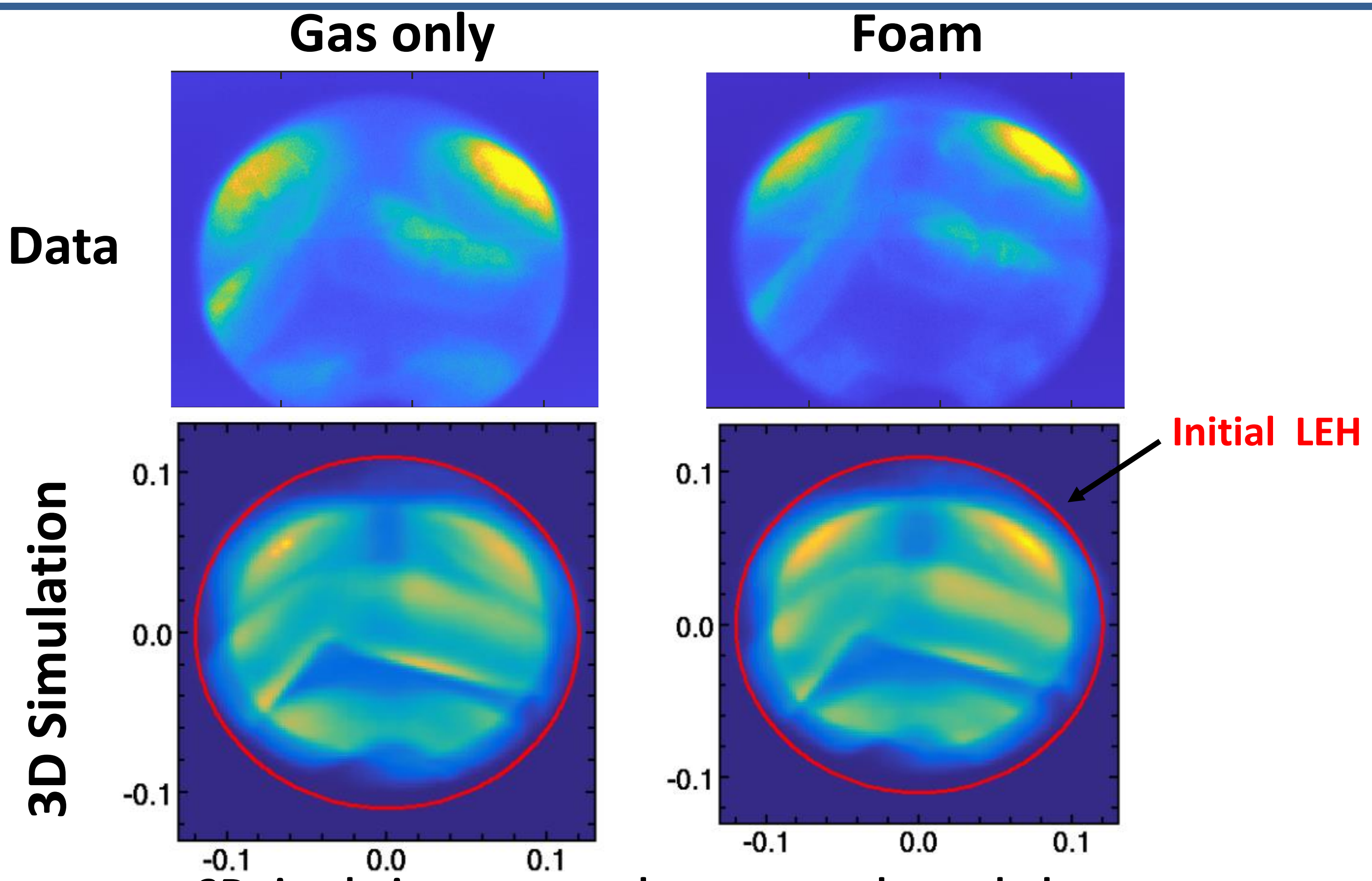


The DMX instrument also includes a 2D x-ray imager, that records 2 gated (4 ns long) images on a HCMOS camera



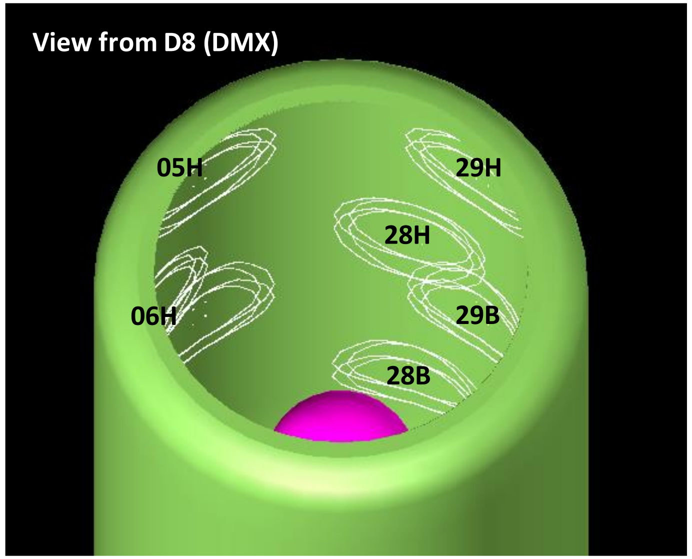


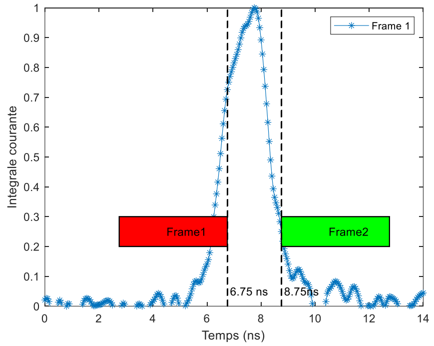
Periods where images are recorded



3D simulations capture the extent and morphology of the wall as measured through the DMX imager

While the morphology of the wall emission is captured well in 3D simulations, some details merit further investigation



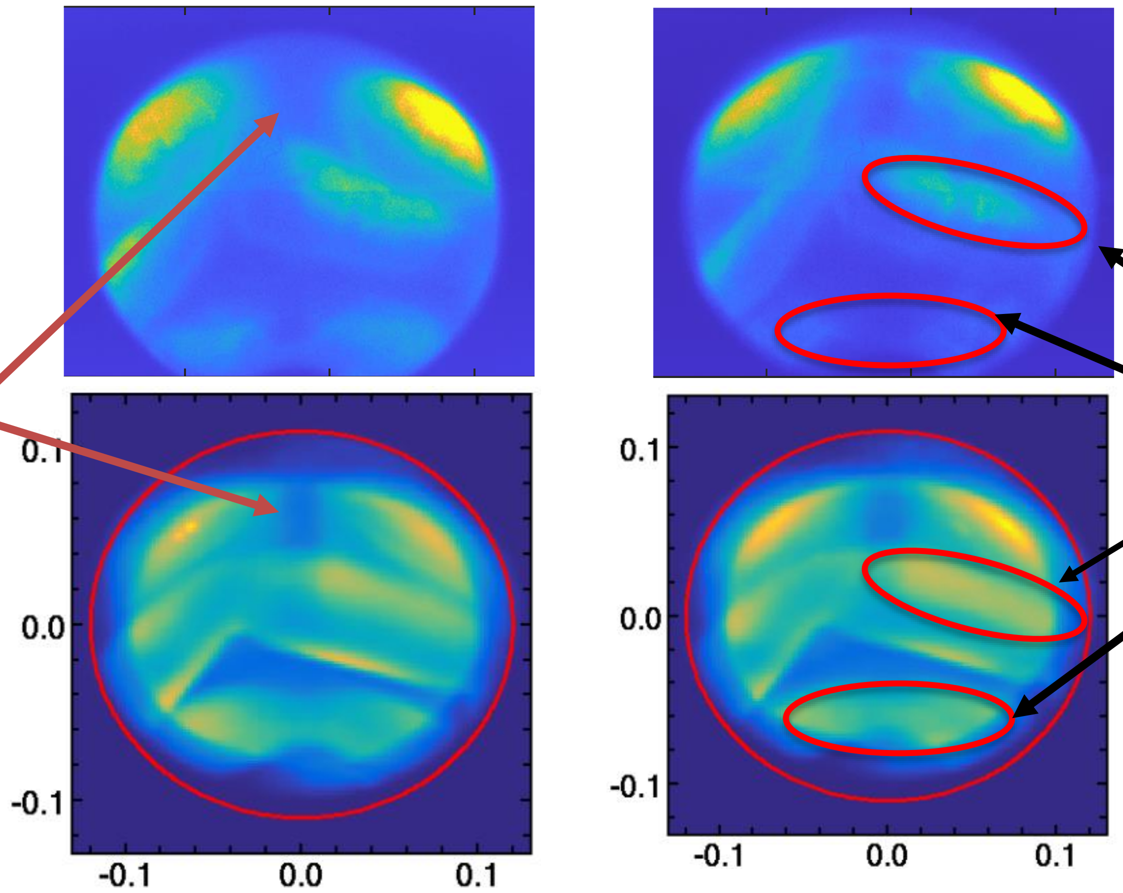


Periods where images are recorded

Gas only

Foam

Data may show higher refraction



Data

Sims show more intense spots

3D Simulation

3D simulations capture the extent and morphology of the wall as measured through the DMX imager