A Simulation-Driven Approach to Infer Hot-spot Conditions in Inertial Confinement Fusion Implosions

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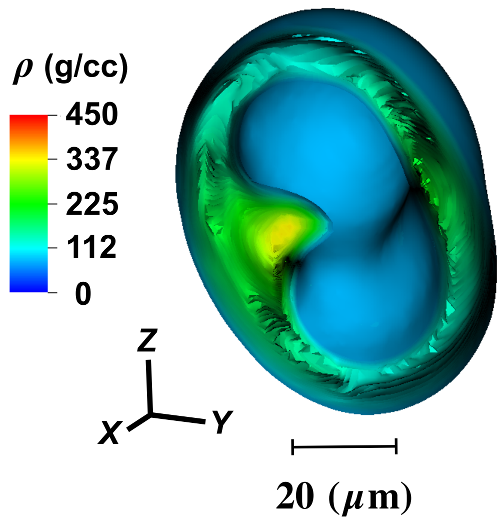
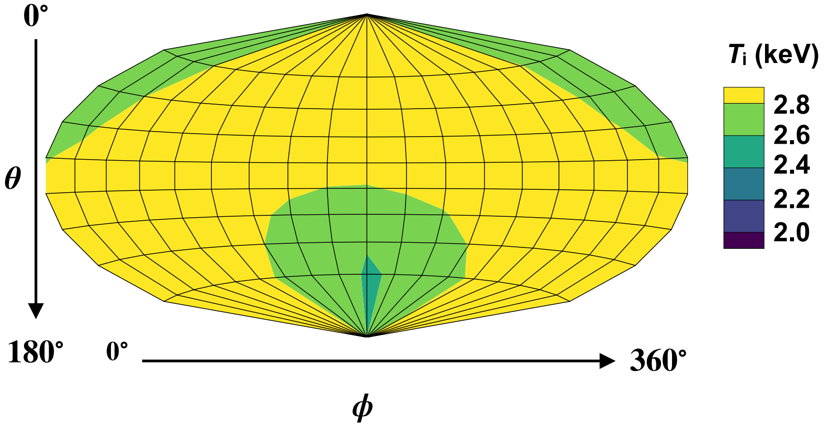
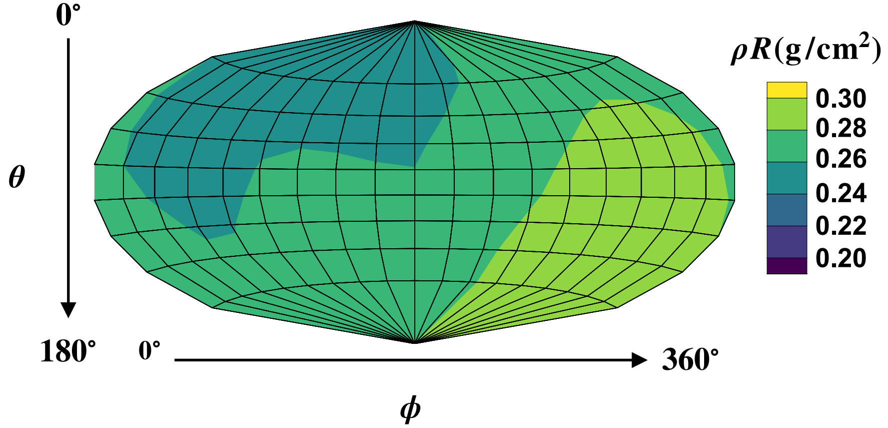
Mass density ρ



Apparent T_i



ρR inferred from down-scattered ratio



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A simulation-driven approach is used to infer hot spot and shell nonuniformities by matching experimental observables

- A 3-D plasma model is derived to reconstruct 3-D ion temperature, pressure and mass-density profiles. Good agreements were obtained in synthetic x-ray and knock-on deuteron image reconstructions.

- A deceleration-phase simulation strategy is developed to reconstruct a limited set of experimental observables based on optimizing 1-D and 3-D initial conditions at the beginning of the deceleration phase.

- A sine-squared variation in apparent ion temperatures is simulated for a strongly perturbed mode 2 interacting with a mode 1. This experimental signature indicates the impact of mode 2 in ICF implosions.

Collaborators

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A 3-D reconstruction platform has been developed to infer hot-spot conditions and shell nonuniformities in ICF implosion experiments

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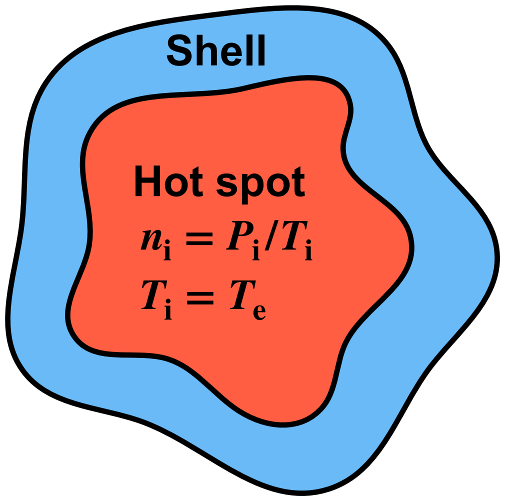
A 3-D static core model (SM) to reconstruct x-ray and nuclear data.

Synthetic "diagnostics"

- ***Spect3D*** X-ray images
- ***IRIS3D*** Deuteron images



Mapping

Experimental observables

- Neutron yields
- Ion temperatures
- Hot-spot flows
- Areal densities
- X-ray images
- Knock-on deuteron images (KODI)

Mapping

A 3-D dynamic model to reconstruct experimental observables.

Uses *DEC3D* simulations with an ad hoc 3-D velocity field and 1-D corrections to start the deceleration phase.

$Q_{1D} + \delta Q_{1D}$

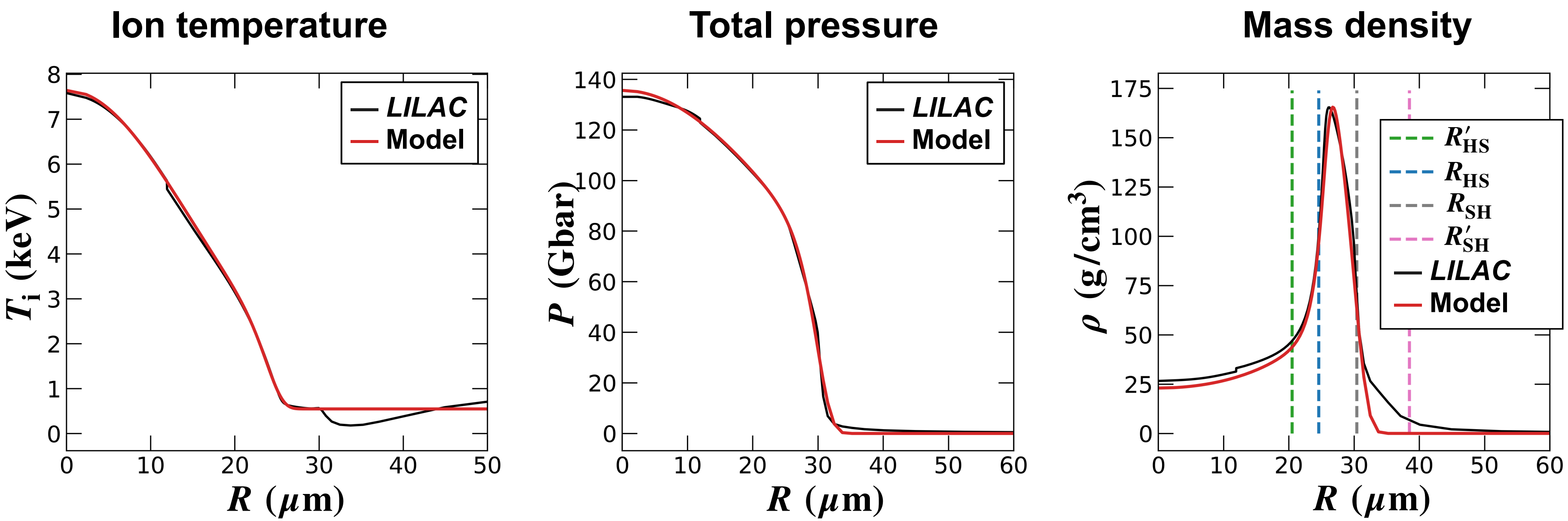
$V_{1D} + \delta V_{3D}$

A simple functional form of temperature and pressure profiles is well suited to accurately reproduce 1-D simulated core profiles

1-D static core model

Capture the "peak" core profile — Capture the "sharp" boundary

$$T_i \approx T_{SH} + T_{HS} \cdot \mathrm{Exp}\left[-\left(r/R'_{HS}\right)^2 - \left(r/R_{HS}\right)^{16}\right] \qquad P_i \approx P_{HS} \cdot \mathrm{Exp}\left[-\left(r/R'_{SH}\right)^2 - \left(r/R_{SH}\right)^{16}\right]$$



A simplified 3-D static core model with 13 fitting parameters is shown able to reconstruct mode 1's ion-temperature and mass-density profiles

3-D static core model

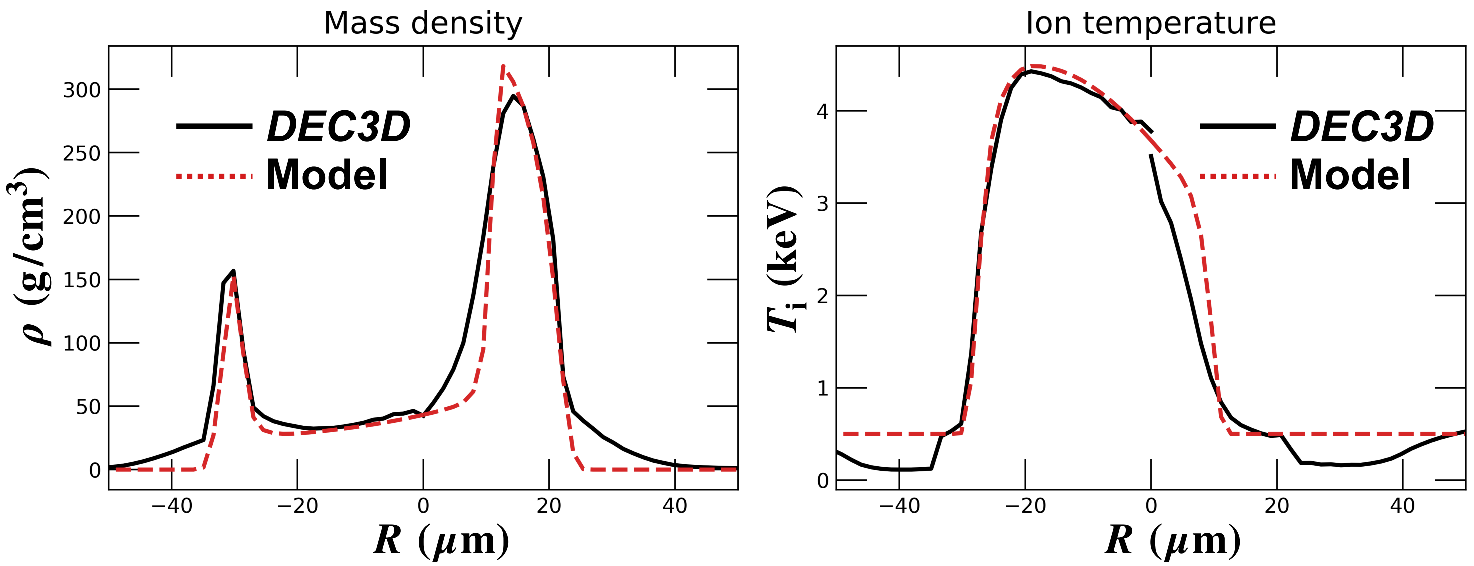
Capture the offset

Capture the rotation

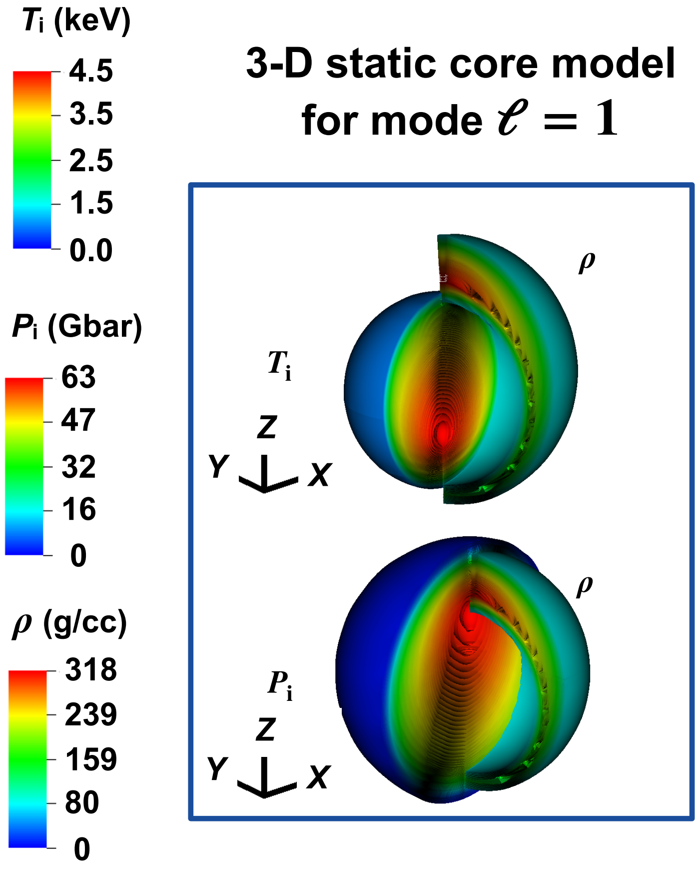
Capture the mode amplitude as a function of radius

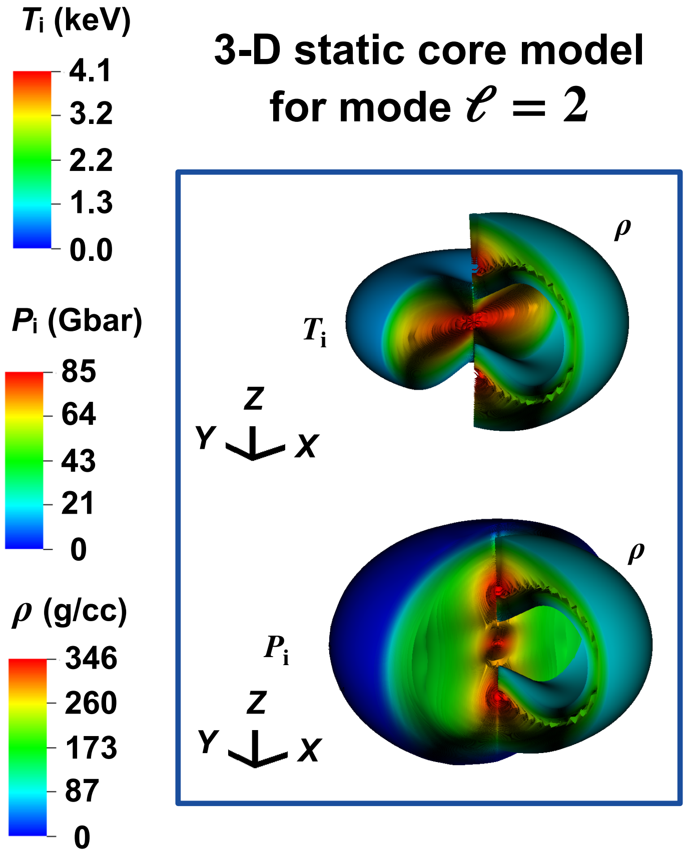
$$r \rightarrow \vec{r}(\theta,\phi) = \vec{R}_0 + \vec{R}\left[1 + \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell} A_\ell^m(R)Y_\ell^m(\theta,\phi)\right]$$

Mode $\ell = 1$



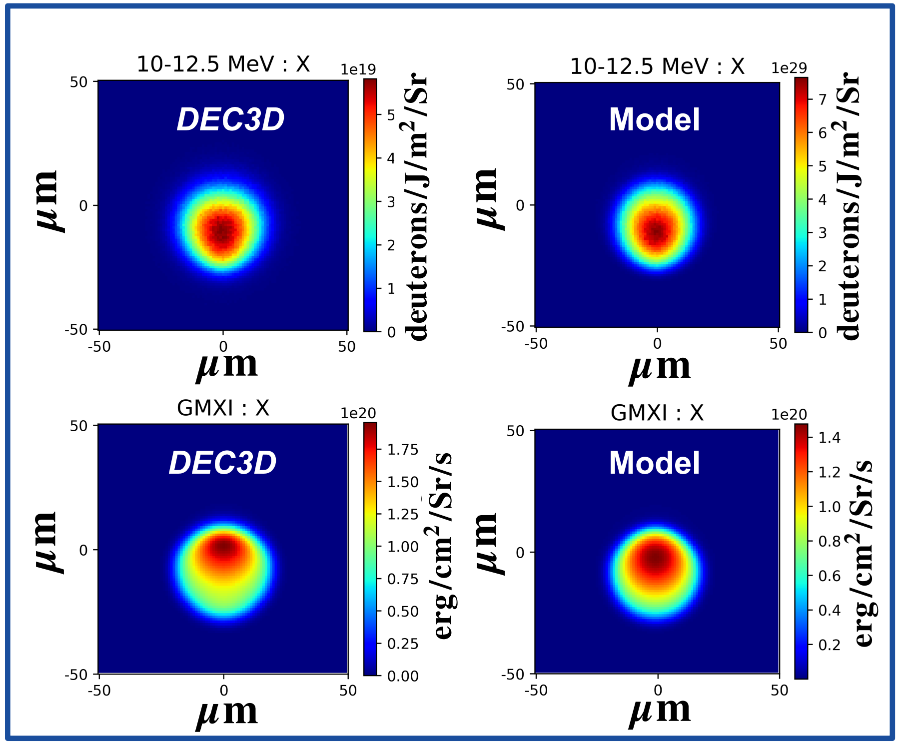
The 3-D hot-spot and shell static model reconstruction for modes 1 and 2 agree well with *DEC3D* simulations within about <6% fitting errors



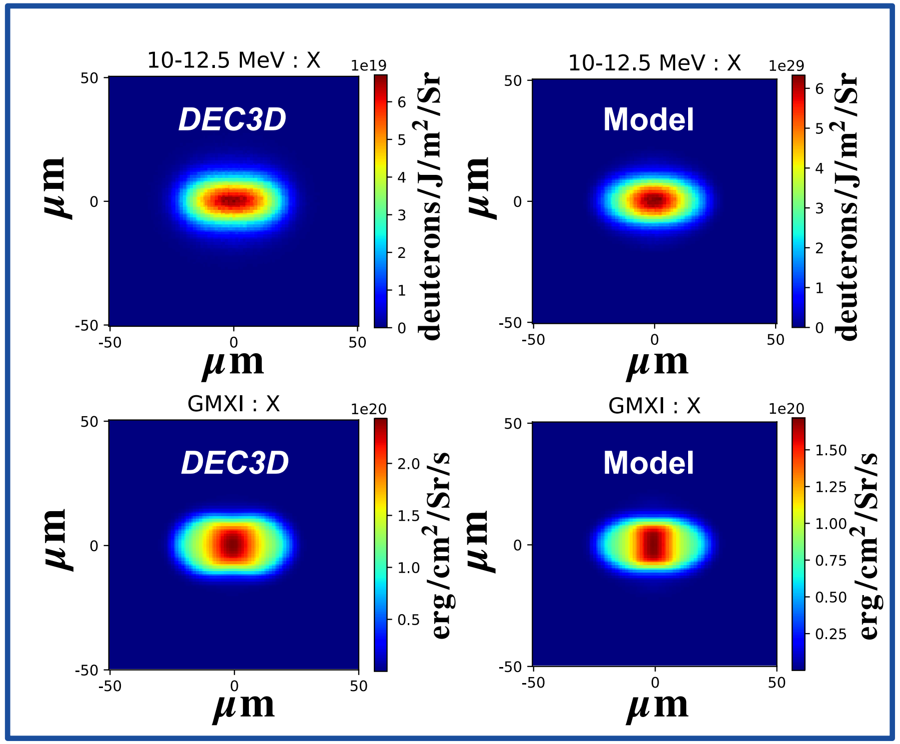


The 3-D static core model reconstruction for the hot spot and shell is in good agreement with synthetic x-ray* and knock-on deuteron images**

Mode $\ell = 1$



Mode $\ell = 2$

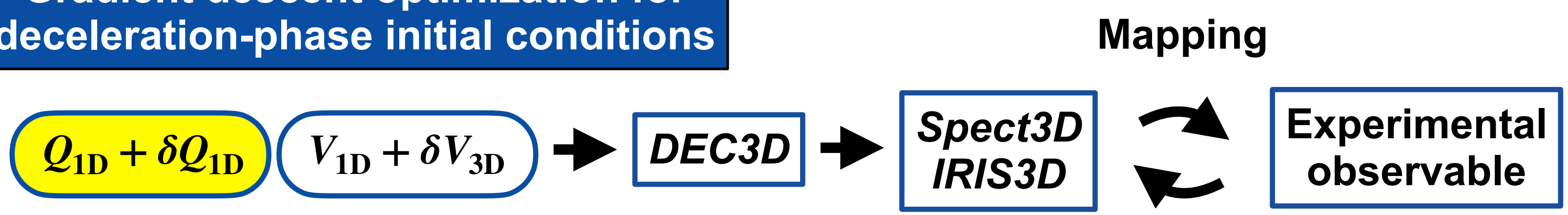


Sequential color maps need to be considered to avoid misleading visual perception.

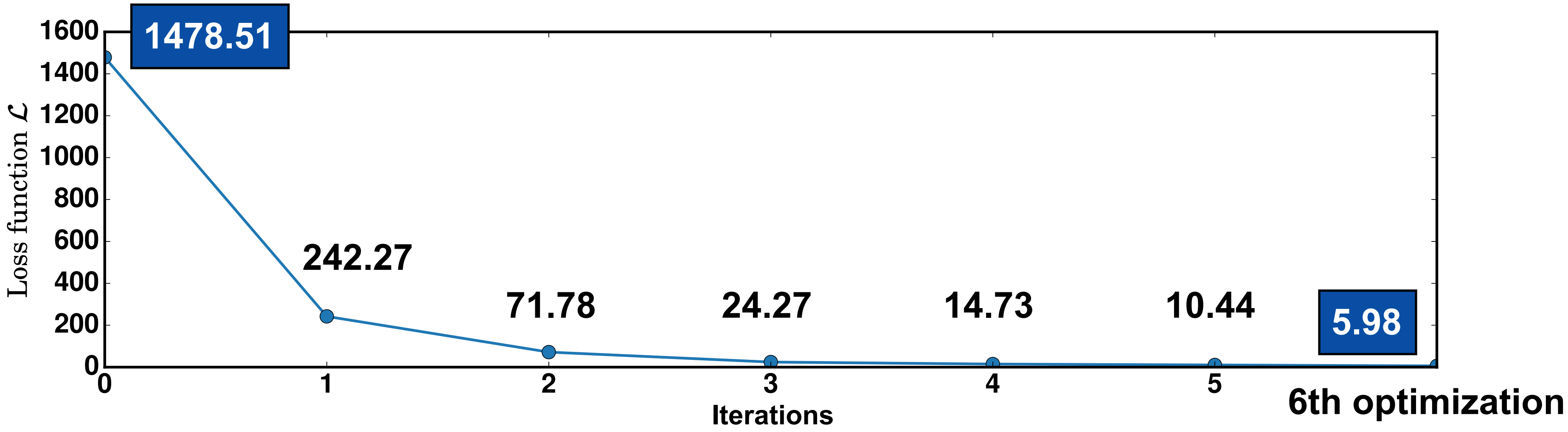
* J. J. MacFarlane *et al.*, High Energy Density Physics 3, 181-190 (2007).
** F. Weilacher *et al.*, Phys. Plasmas 25, 042704 (2018).

The dynamic model imposes corrections to 1-D initial profiles and an ad hoc 3-D initial velocity perturbation in reconstructing a limited set of experimental observables

Gradient descent optimization for deceleration-phase initial conditions



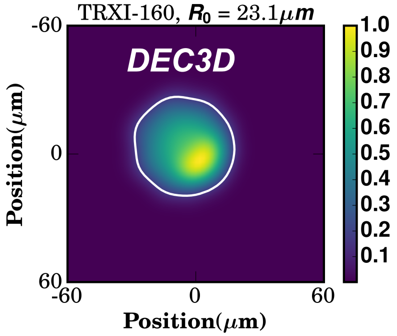
The initial guess is given by a clean simulation in *DEC3D.*

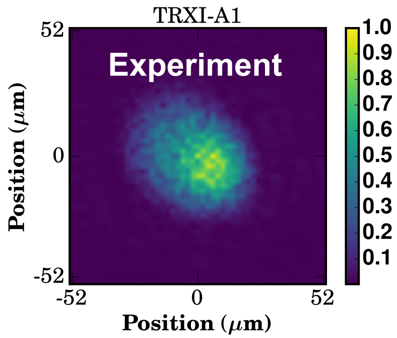


The *DEC3D* deceleration-phase simulation strategy is shown to reproduce experimental data within <10 iterations

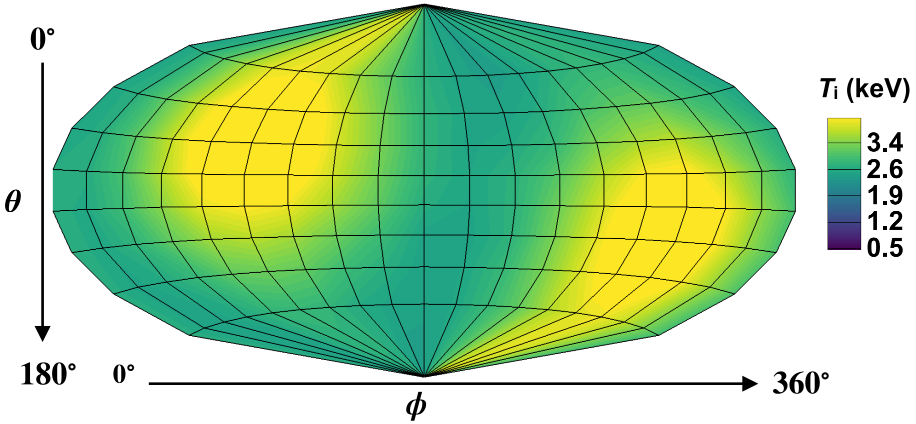
The optimized *DEC3D* simulation — ***DEC3D* hot-spot conditions**

Shot 94017	Yield (10^{13})	MRS (mg/cm^2)	H10 T_i (keV)	10.4m T_i (keV)	12m T_i (keV)	15.8m T_i (keV)	15.9m T_i (keV)	Burn-width (ps)	Bang time	Pressure (Bar)	T_e (keV)	T_i (keV)
Experiment	1.2	214	5.21	3.05	3.9	3.23	2.92	67	2.506	-	-	-
Simulation	1.00	232	4.01	2.49	3.06	3.26	2.49	61.6	2.572	37.8	2.48	2.66
Experimental error	0.0837	22	0.36	0.21	0.27	0.23	0.20	5	0.05	-	-	-

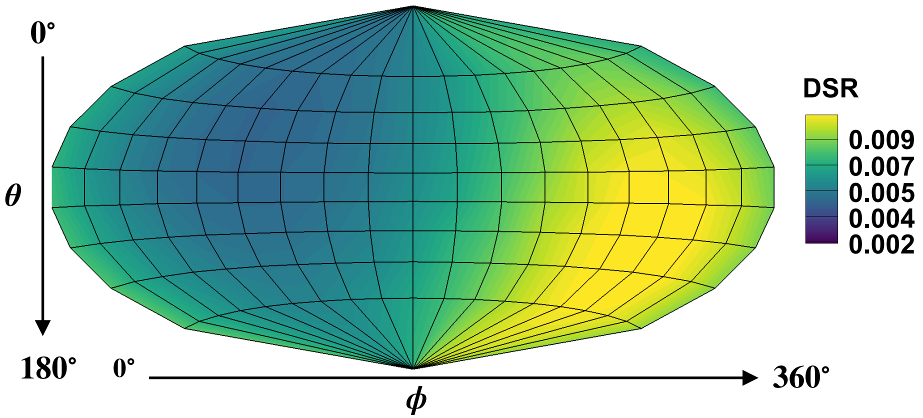




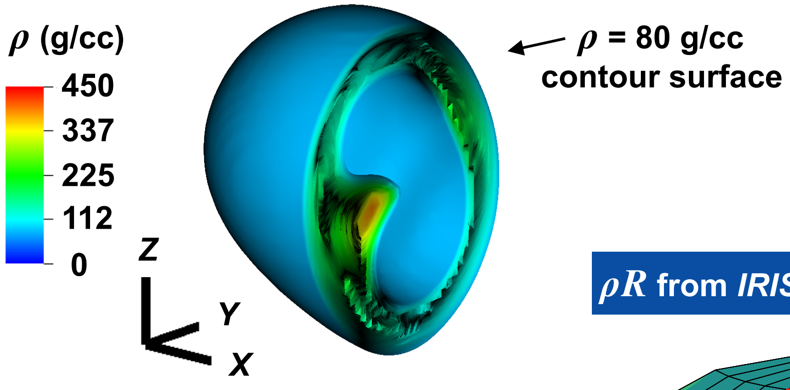
Apparent T_i from *IRIS3D* simulation



Down-scattered ratio (DSR) from *IRIS3D* simulation



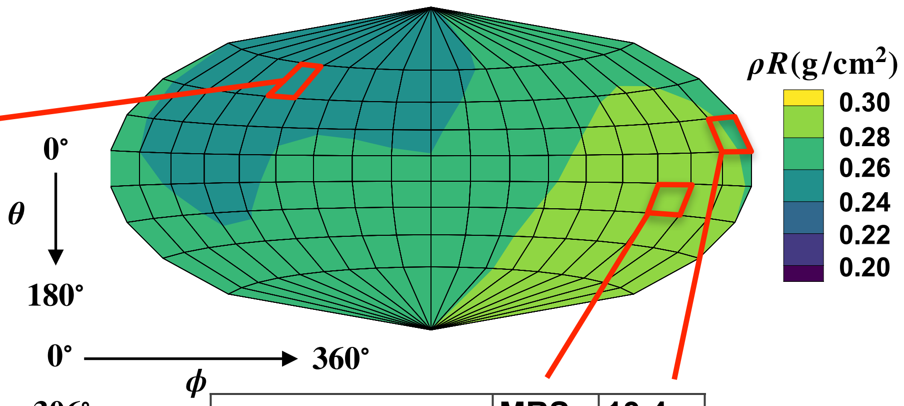
The presence of a strong mode 2 causes decoupling of the T_i asymmetries from ρR asymmetries distribution



Hot-spot flow vector

$(\theta, \phi)_{\text{flow}} = (25°, 57°)$

ρR from *IRIS3D* simulation at stagnation

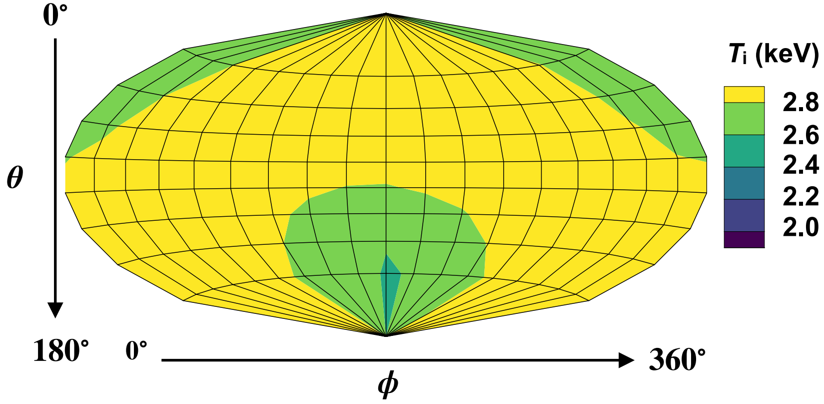


MRS : $\theta = 117°, \phi = 306°$

13.4 opposite : $\theta = 63°, \phi = 342°$

	MRS	13.4m
ρR (mg/cm²)	301	246

T_i from *IRIS3D* simulation at stagnation



	H10	10.4m	12m	15.8m	15.9m
T_{sim} (keV)	2.9	2.89	2.87	2.78	2.95

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