# Introduction

# Diagnosing OMEGA and NIF Implosions Using the D$^3$He Spectrum Line Width

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The National Ignition Campaign

# Abstract

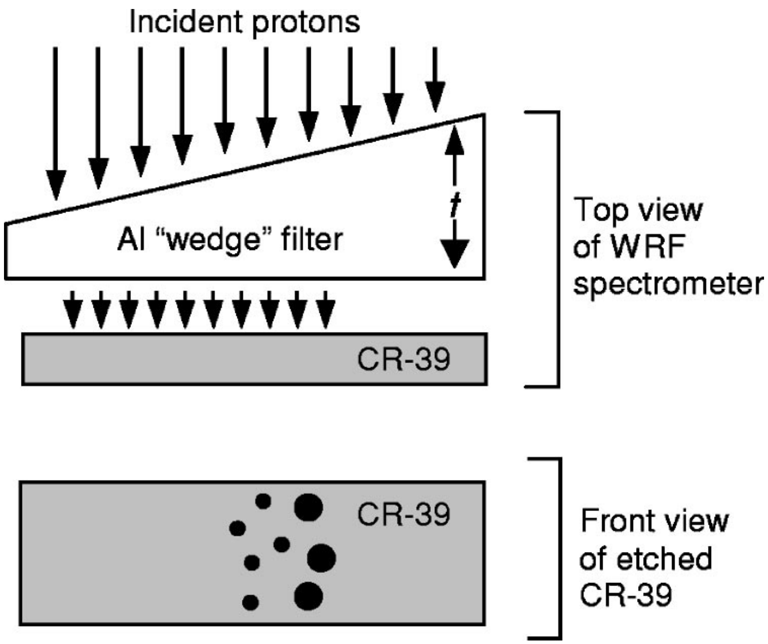
Wedge Range Filter (WRF) spectrometers are used to diagnose implosions containing D and $^3$He gas through measurements of the proton spectrum [D+$^3$He → p (14.7 MeV) + $^4$He (3.6 MeV)]. The total line width is due to the thermal Doppler broadening, instrumental broadening, and several other effects. The significances of these sources of broadening are calculated using a Monte Carlo code. Using this code we constrain the ion temperature in OMEGA exploding pusher shots. Alternatively, we constrain the amplitude of high-mode asymmetries in a NIF implosion from the previous campaign (N091123), and will apply these models to D$^3$He exploding pushers on the NIF during the Magnetic Recoil Spectrometer (MRS) calibration.

*This work was supported in part by the U.S. Department of Energy, the Fusion Science Center at the University of Rochester, the National Laser Users Facility, and the Laboratory for Laser Energetics at the University of Rochester. A. Zylstra is supported by the DoE NNSA Stewardship Science Graduate Fellowship.*

# Motivations

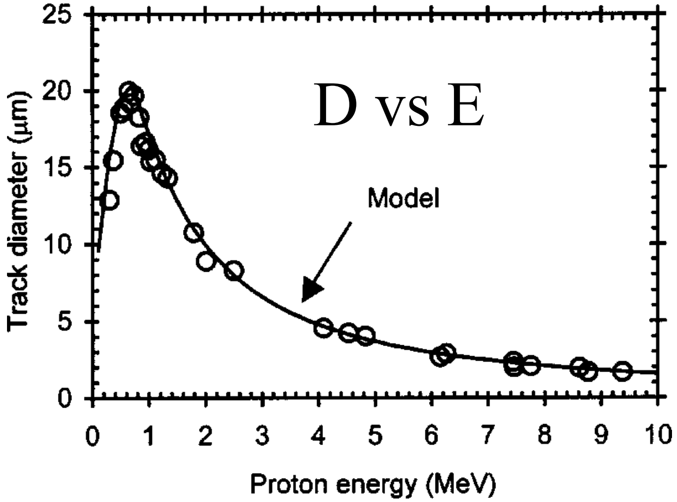
- To investigate the possibility of using WRFs as a compact and accurate/precise $T_i$ diagnostic based on the line width method
  - Calibrate vs the yield ratio method on OMEGA
  - Could be used to check the NIF neutron time of flight (nTOF) $T_i$ on the NIF ignition diagnostics commissioning shots
- To explore possible high-mode ρR asymmetry amplitude measurements
  - Could be used on NIF SymCap shots
  - No current diagnostic for high-mode ρR asymmetries on the NIF

# Wedge Range Filter (WRF) Spectrometers are used to measure proton spectra



We use the "D vs. E" curve to calculate $E_d$ from the track diameter and the slope of the wedge to determine the filter thickness based on linear position:

$$E_i = E_i(d,x)$$



WRF assembly used on the NIF:

Each WRF is individually calibrated on the MIT accelerator

For more information see: F.H. Seguin *et al.* Rev. Sci. Inst. 74, 2 (2003)

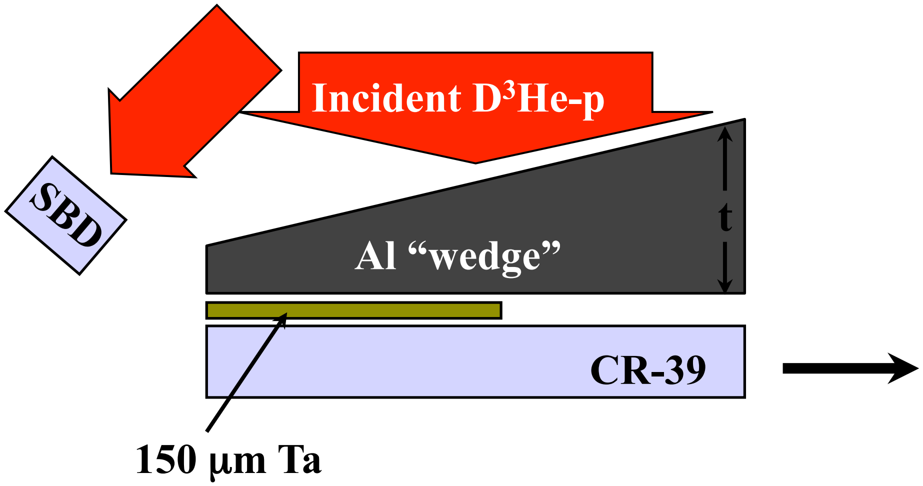
# Calculating contributions to the line width

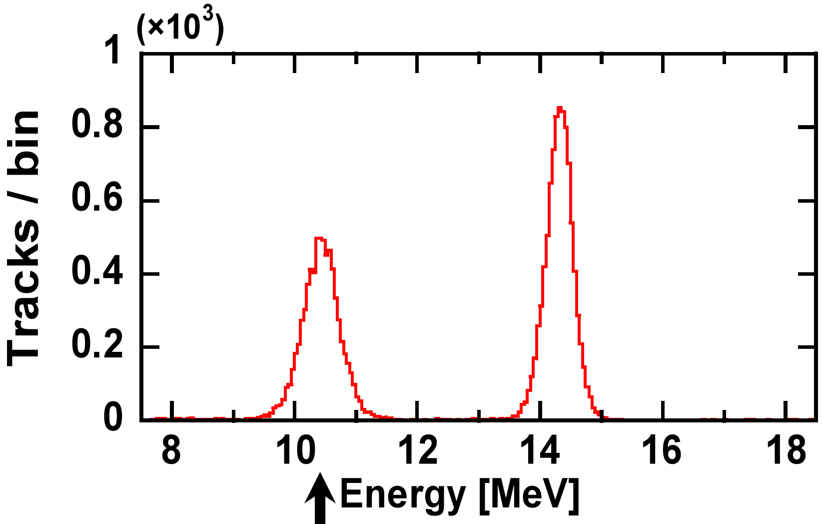
# We characterize each of the factors that contribute to the spectral broadening of the D³He-p spectrum

$\sigma^2_{\text{total}} =$

| **Source** | |
|---|---|
| $\sigma^2_{\text{instrumental}}$ | Response function of the WRF |
| $+ \sigma^2_{\text{thermal}}$ | Initial distribution due to finite temperature |
| $+ \sigma^2_{\text{dispersion}}$ | More downshift for lower energies |
| $+ \sigma^2_{\text{straggling}}$ | Not every proton is downshifted the same |
| $+ \sigma^2_{\text{temporal evolution}}$ | ρR evolution over shock burn duration |
| $+ \sigma^2_{\text{geometric}}$ | finite burn region; different cord lengths |
| $+ \sigma^2_{\text{low-mode modulations}}$ | Spatially-dependent ρR |
| $+ \sigma^2_{\text{high-mode modulations}}$ | High-mode ρR asymmetries |
| $+ \sigma^2_{\text{other}}$ | E-field, ablated mass, etc. |

# Calibrations on the MIT accelerator are used to infer the WRF instrumental broadening:





Also ranged through Ta filter

$$\sigma^2_{WRF} = \sigma^2_{\text{total on the WRF}} - (\sigma^2_{\text{total on the SBD}} - \sigma^2_{SBD})$$

$$\sigma_{WRF} = 166 \text{ +/- } 18 \text{ keV}$$

For more information see poster:
N. Sinenian et al. *“The MIT Nuclear Products Generator for development of ICF diagnostics at OMEGA / OMEGA-EP and the NIF”*

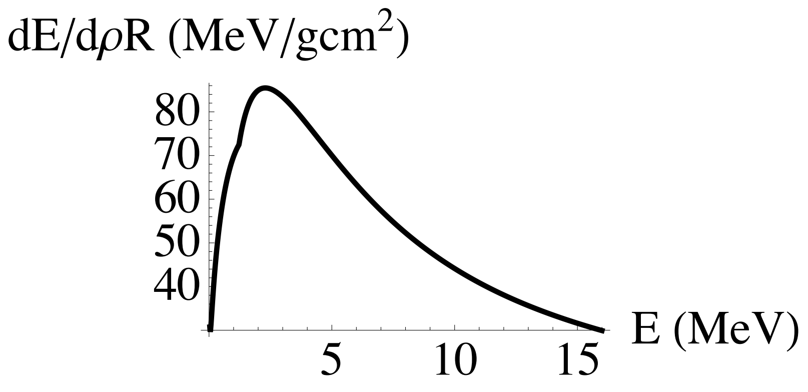
# A 3-D Monte Carlo code has been developed to characterize the broadening components

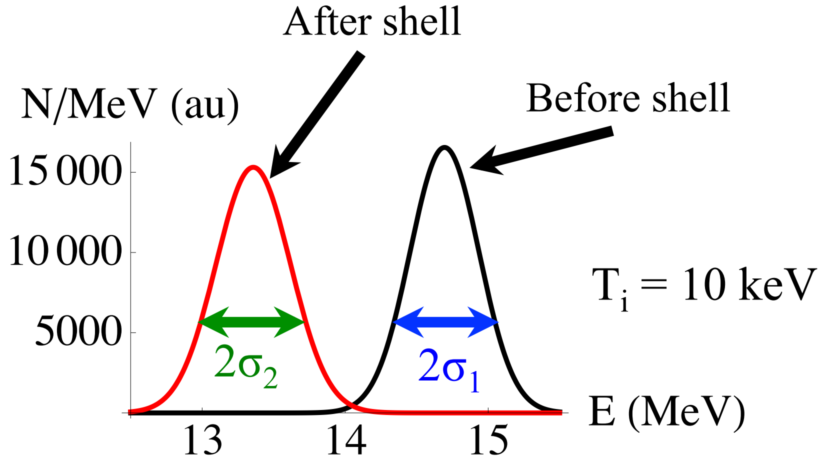
This code includes:

- Stopping power and straggling: Plasma [1,2,3] or cold matter (SRIM)
- Shell: arbitrary mode polar/azimuthal $\rho R$ asymmetries
- $D^3He$-p Source: Gaussian radial and temporal burn profile. Isotropic proton emission.
- Possible future additions:
  - Field structure around capsule, $\rho R$ and T profiles within target, ablated mass, plasma scattering.

[1]: C. K. Li and R. D. Petrasso, Phys. Rev. Lett. 70 (20), 3059 (1993).
[2]: S. T. Butler and M. J. Buckingham, Phys. Rev. 126 (1962).
[3]: N. R. Arista and W. Brandt, Phys. Rev. A. 23 (1981).

# Lower energies of a thermal distribution are ranged down more than higher energies (ρR Dispersion)

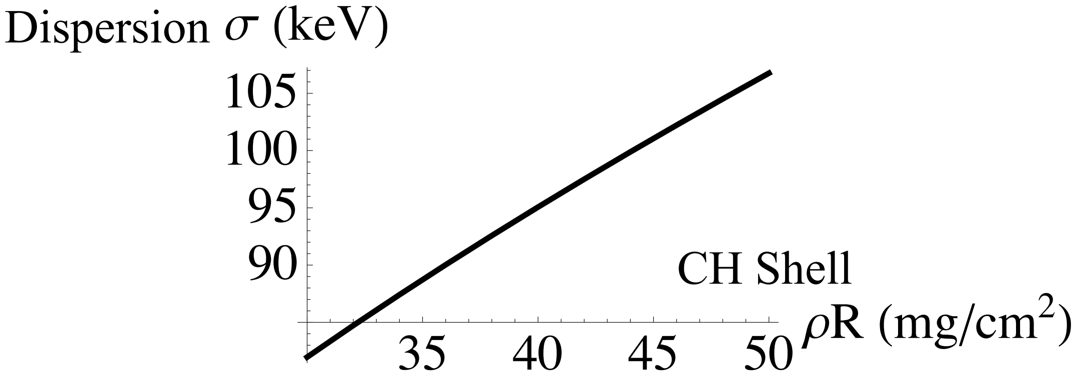

Plasma stopping power in CH:



Fit from simulation data

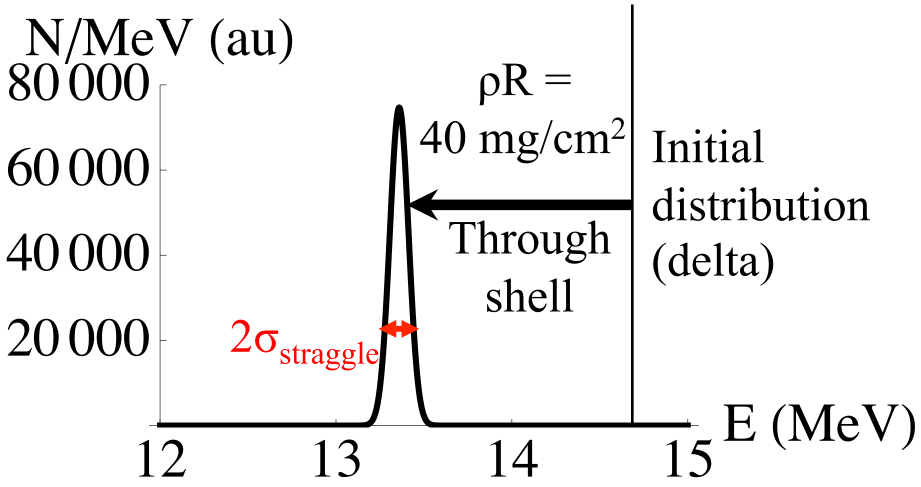
$$\sigma_1^2 = \sigma_{thermal}^2$$

$$\sigma_{dispersion}^2 = \sigma_2^2 - \sigma_1^2$$

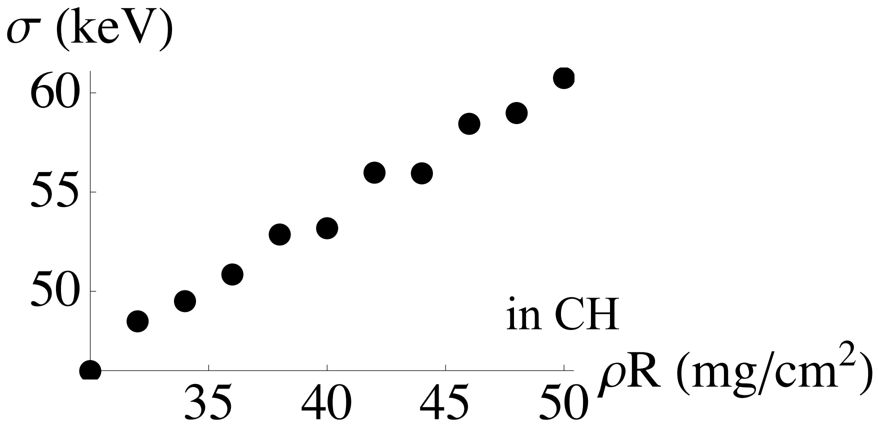

Broadening due to dispersion

# Calculating contributions to the line width (cont)

# Because collisional processes are random, a monoenergetic source broadens while ranging through matter (ρR Straggling)



Broadening due to straggling:

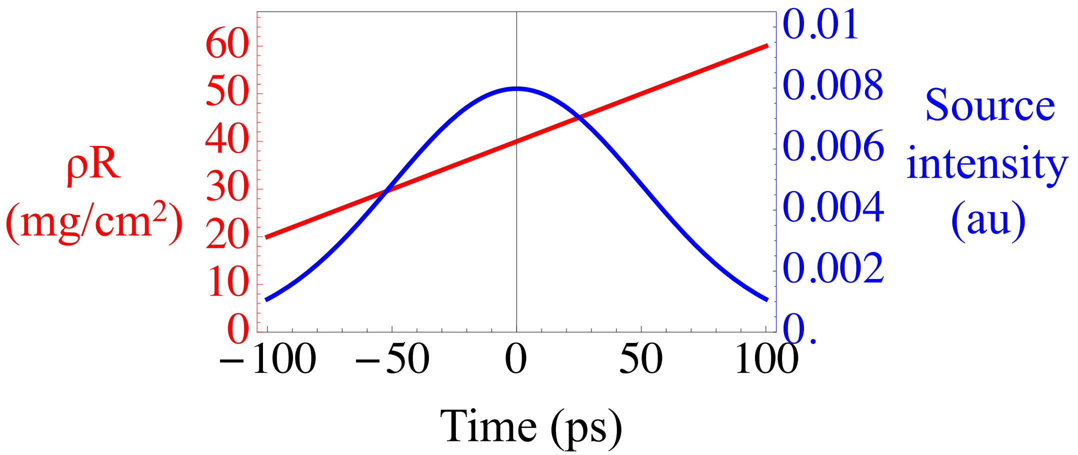


SRIM (cold matter) gives ≈ 10 keV more straggling broadening

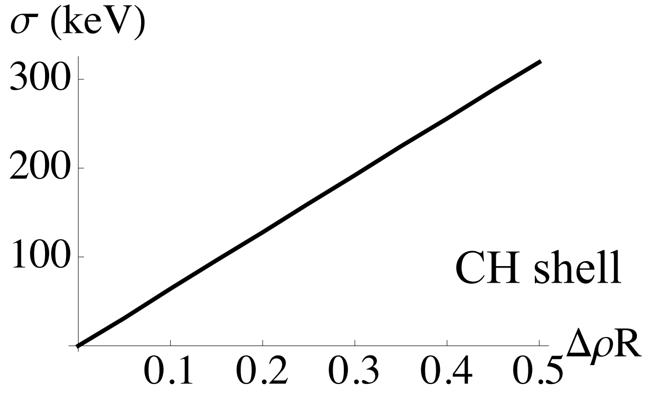
# Protons born at different times experience different downshifts due to ρR time dependence (ρR Evolution)

For a Gaussian shock burn in time, assume that
$\rho R(t) = \rho R_0 + t\times(\Delta\rho R/2\sigma_{burn,t})$

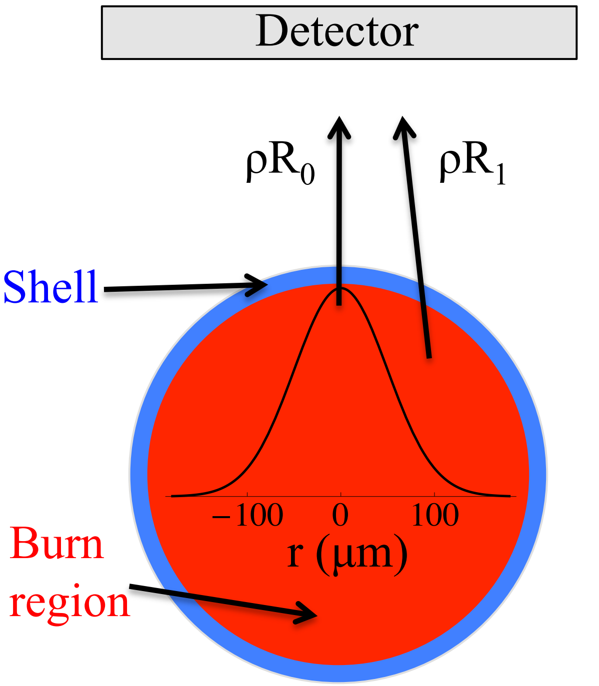
For $\Delta\rho R$=0.5, $\sigma_{burn,t}$ = 50ps



ρR Evolution Broadening



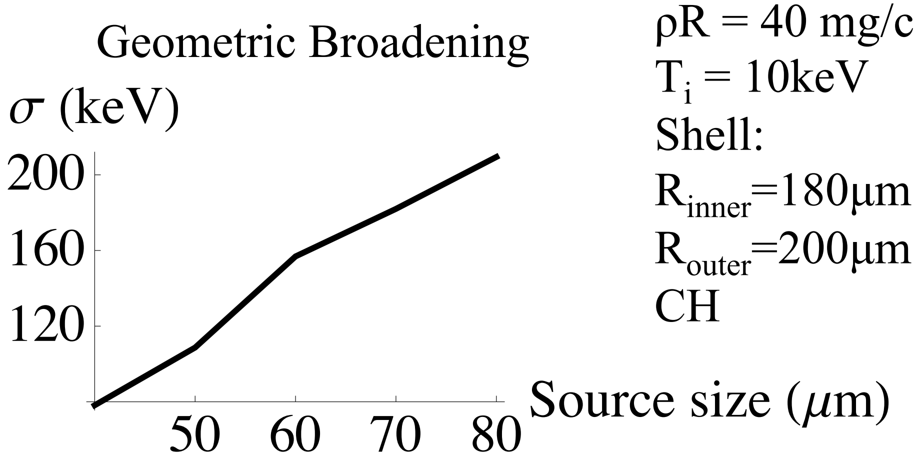
# An extended source creates broadening because protons experience different arc lengths in the shell



$\rho R_1 > \rho R_0$ creates broadening

Shown:
$\sigma_{burn,r} = 50\mu m$

The source is modeled as Gaussian with a variable $\sigma_{burn,r}$ on the order of tens of μm. Actual source profiles have been measured on OMEGA [4].



Parameters:
$\rho R = 40$ mg/cm$^2$,
$T_i = 10$keV
Shell:
$R_{inner}=180\mu m$
$R_{outer}=200\mu m$
CH

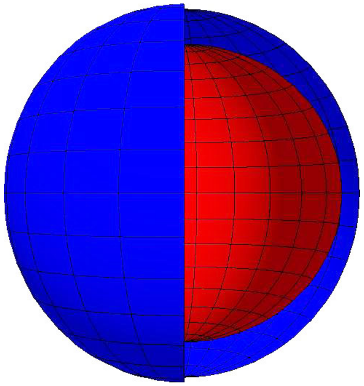
[4]: F. H. Seguin et al., Phys. Plasmas 13 , 082704 (2006).

# ρR asymmetries cause broadening due to varying ρR

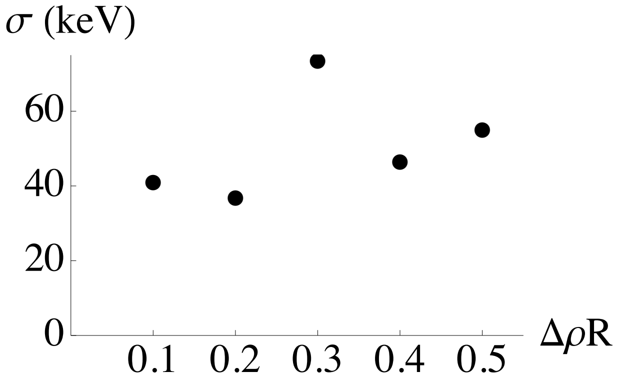
$\Delta\rho R$ is the fractional amplitude of ρR modulations.

$\rho R = \rho R_0[1 + \Delta\rho R\ (\cos[n\theta]+\cos[m\varphi])]$

40% P2 mode



Broadening due to low-mode asymmetry (P2)



Parameters:

$\rho R_0 = 40\ \mathrm{mg/cm^2}$

$T_i = 10\mathrm{keV}$

Shell:

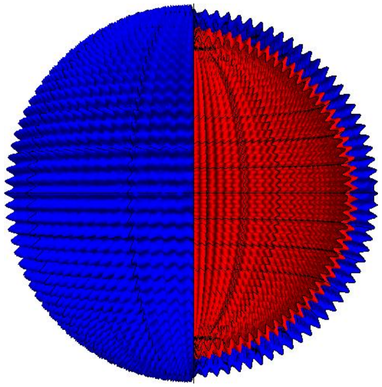
$R_{inner}=180\mu m$

$R_{outer}=200\mu m$

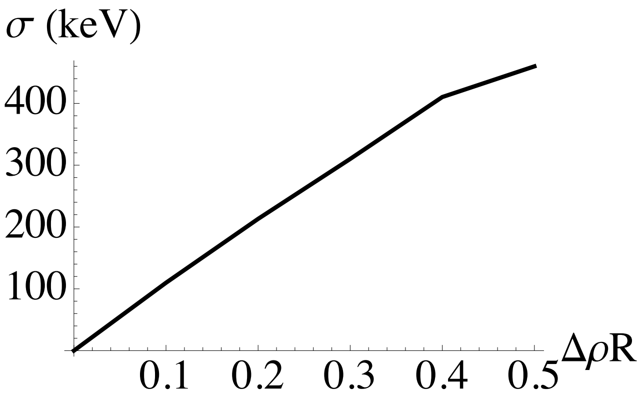
CH

Mode 100 (in both angles)

$\Delta\rho R = 0.5$



Broadening due to high-mode (100) modulations



Even a small amplitude asymmetry can contribute significantly to the total line width

# Applications

# Feasibility of using the line width as a temperature diagnostic for OMEGA Exploding Pushers

Goal: To precisely measure $T_i$ with the Doppler line width by eliminating other broadening sources.

Parameters: (with error estimates)

- $\rho R = 4 \pm 0.5$ mg/cm$^2$
- $R_{source} = 40 \pm 5$ µm
- Temporal evolution: $\Delta\rho R = 0.3 \pm 0.1$
- No modulations in $\rho R$

Shell: $R_{shell} = 200$ µm

$T_{i,shell} = 1$ keV

Most broadening consistent with above parameters: $\sigma_{max} = 245$ keV

Least broadening consistent with above parameters: $\sigma_{min} = 236$ keV

$\sigma_{instrumental} = 168 \pm 18$ keV

Uncertainty in $\sigma_{thermal} \cong (((\sigma_{max} - \sigma_{min})/2)^2 + 18^2)^{1/2} = 20$ keV

$Ti = \sigma_{thermal}{}^2 / 5880$

Temperature uncertainty: ± 20%

# Temperatures are calculated for OMEGA D$^3$He exploding pushers

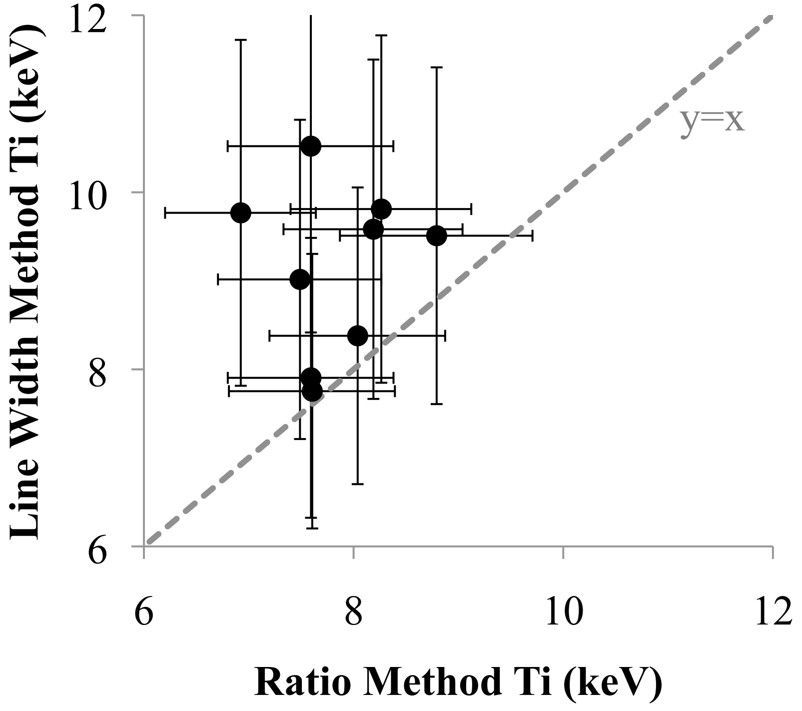
**Can use simulation results to infer the amount of non-thermal broadening:**

Parameters:

- $\rho R = 4$ mg/cm$^2$
- $R_{source} = 50$ µm
- Temporal evolution: $\Delta\rho R = 0.3$
- no $\rho R$ modulations

$\sigma_{non\text{-}thermal} = 45$ keV

$T_i$ uncertainty = 20% (See slide 13)



For more info on ratio method $T_i$ see [5]

May be some unmodeled broadening effect remaining (E-field evolution?) or burn region effect in the yield ratio method.

[5] Poster by M. Rosenberg et al.

# Feasibility of using the line width as a high-mode asymmetry diagnostic (NIF CH implosions)

Goal: To put a limit on the amount of high-mode ρR asymmetries in an implosion

Parameters: (with error estimates)

- $\rho R = 40 \pm 5$ mg/cm$^2$
- $R_{source} = 50 \pm 10$ μm
- Temporal evolution: $\Delta\rho R = 0.3 \pm 0.1$
- P2 mode with amplitude 0-0.4
- $T_i = 10 \pm 2$ keV

Shell: $R_{shell} = 200$ μm
$T_i = 1$ keV

Most broadening consistent with above parameters: $\sigma_{max} = 385$ keV
Least broadening consistent with above parameters: $\sigma_{min} = 275$ keV

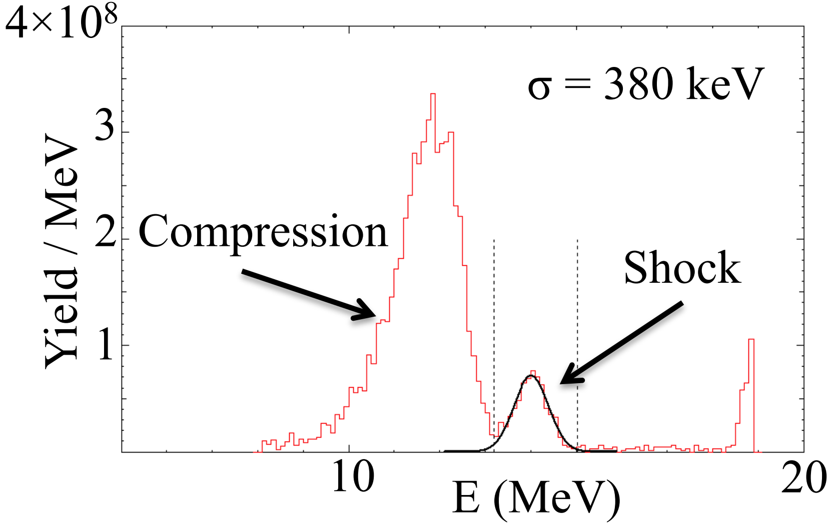
$\sigma_{instrumental} = 168 \pm 18$ keV

$\sigma_{unc} = \cong (((\sigma_{max} - \sigma_{min})/2)^2 + 18^2)^{1/2} = 57$ keV

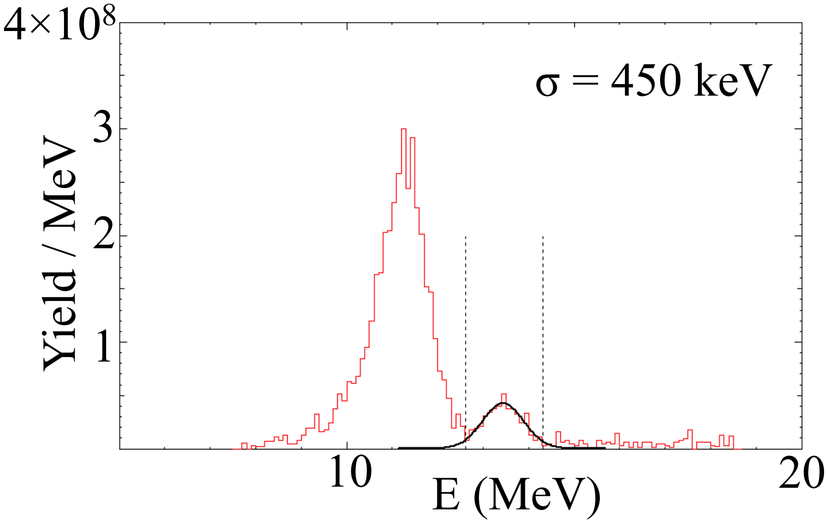
High-mode amplitude (ΔρR) uncertainty: ± .06

# We attempt to constrain high-mode amplitude with WRF data from NIF $D^3He$ indirect-drive CH shell targets

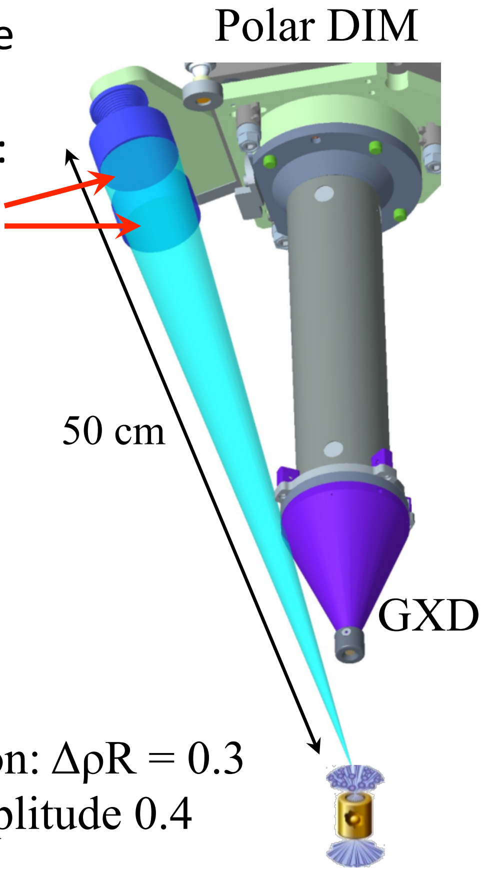
N091123 WRF #1



N091123 WRF #2



NIF Implosions were viewed through the laser-entrance hole:



**Can use simulation results to infer the amount of broadening due to high-mode ρR asymmetries:**

Parameters:

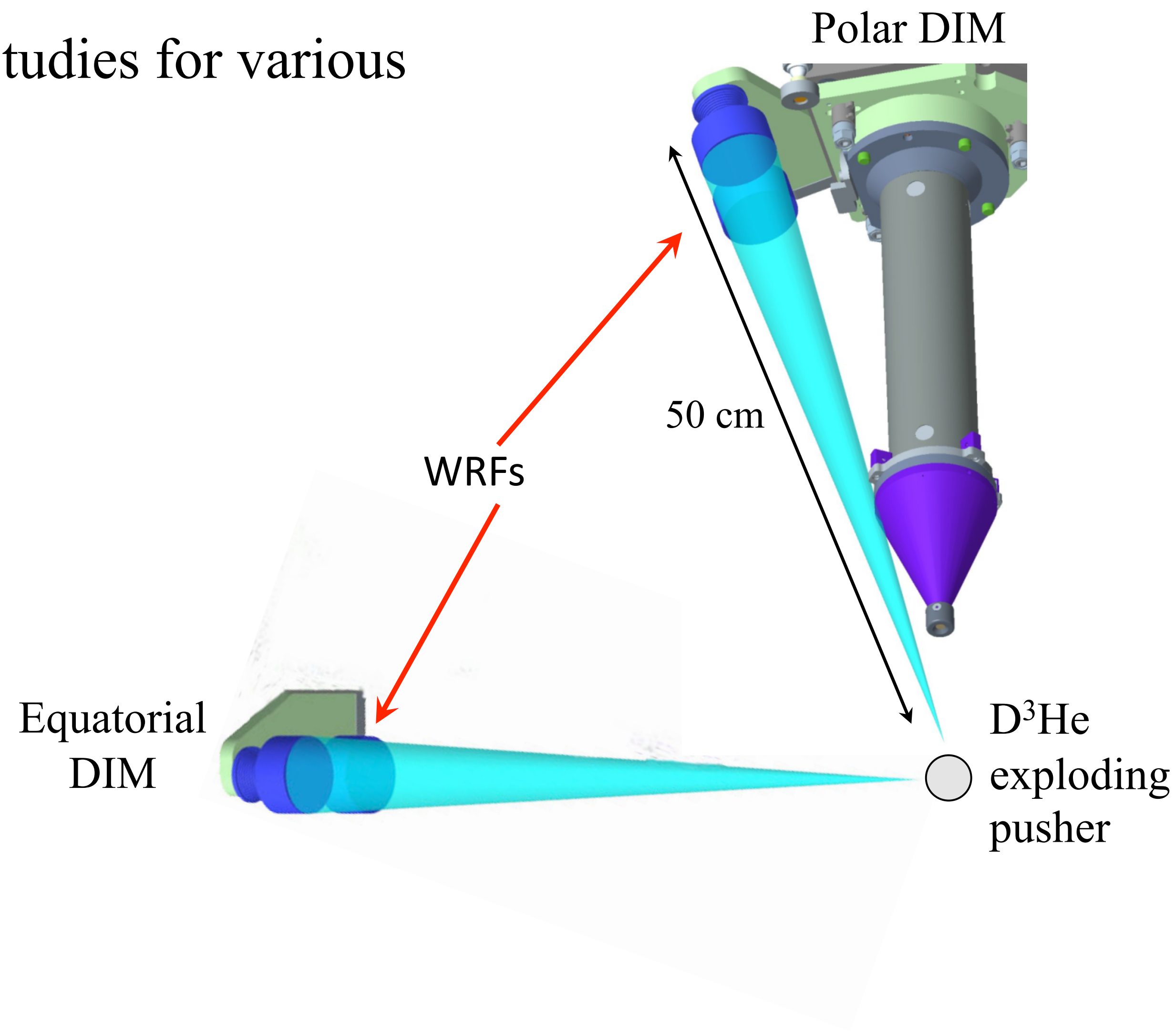
- $\rho R = 40$ mg/cm$^2$
- $R_{source} = 50\ \mu m$
- Temporal evolution: $\Delta\rho R = 0.3$
- P2 mode with amplitude 0.4
- $T_i = 10$ keV

$\sigma_{high\text{-}mode} = 0\text{-}230 \pm 60$ keV
High-mode $\Delta\rho R = 0\text{-}0.2 \pm .06$
$\Delta\rho R \leq 0.26$

# Future Work and Conclusions

# Future Work

- Additional modeling for existing data
- MRS calibration shots on the NIF (August)
- Sensitivity studies for various parameters



# Summary of broadening effects

| Source | $\sigma$ (keV) CH shell | $\sigma$ (keV) Expl. Pusher | Notes |
|---|---|---|---|
| **Instrumental** | 150-190 | 150-190 | Error in $\sigma$ of +/- 15 keV |
| **Thermal** | 170-240 | 170-240 | Very well characterized; for $5<T<10$ keV |
| **ρR Dispersion** | 98 | 28 | $\rho R = 40$ mg/cm$^2$ (CH), 4 mg/cm$^2$ (E.P.) |
| **ρR Straggling** | 53 | 16 | $\rho R = 40$ mg/cm$^2$ (CH), 4 mg/cm$^2$ (E.P.) |
| **ρR Evolution** | 120-250 | 10-25 | $\Delta\rho R=0.2\text{-}0.4$; $\rho R = \rho R_0(1\pm\Delta\rho R)$ for $t=\pm 2\sigma_{burn}$ |
| **Geometric** | 50-160 | ~20-30* | Source $r_0$=30-60μm |
| **Low mode ρR modulations** | 0-70 | ~0* | For $\Delta\rho R$ = 0-0.5, P2 Mode |
| **High mode ρR modulations** | 0-460 | 0-50 | For $\Delta\rho R$ = 0-0.5, mode 100 |
| **E-fields, Abl. mass** | ? | ? | Not modeled yet |
| **Total** | **280-640** | **230-310** | |

*: poor statistics in current simulations

# Conclusions

- Using a simple Monte Carlo code we model several broadening effects of an implosion that affect the $D^3He$ spectrum line width.
- Using these results we calculate an ion temperature based on the Doppler broadening for $D^3He$ implosions on OMEGA
  - Possible other source of broadening (E-fields?).
- With the developed code we constrain the amplitude of high-mode $\rho R$ asymmetries in a NIF implosion to $\leq 0.26$
  - More modeling work is necessary to increase the confidence in this result.