XDV: A proposal for an X-ray Doppler Velocimetry diagnostic

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Thanks to John Field, Brian Spears, Dave Munro at LLNL

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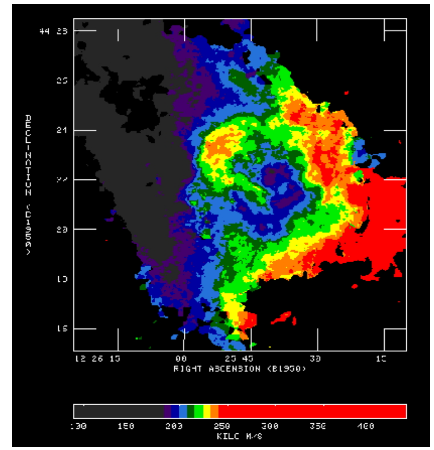
Motion in an object can be mapped using multi-spectral imaging of Doppler shifts

NGC 4449, white light visible map



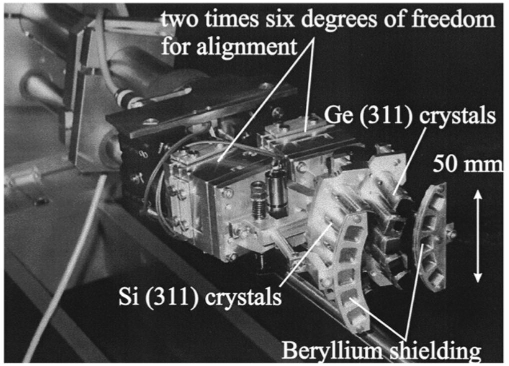
NGC 4449, multispectral microwave map

- **Multi-spectral imaging (sensitive to Doppler *frequency* shifts) is used to map line-of-sight velocities in astronomy**
  - **Galaxy NGC 4449 is irregular in white light optical images**
  - **It is revealed to be rotating as a whole, with counter-rotating portions indicating an ancient galaxy merger, in multi-spectral microwave (21 cm) images**

We can use multi-spectral x-ray imaging (sensitive to Doppler *wavelength* shifts) to map line-of-sight velocities in laboratory plasmas

Multiple monochromatic imaging with bent crystals can provide multi-spectral x-ray images

- **Near-normal-incidence crystals can provide high-brightness, large solid-angle, and quasi-monochromatic x-ray images[1]**
  - **Bandpass set by meridional aperture width**
  - **Resolution set by Bragg angle, meridional and sagittal aperture widths**



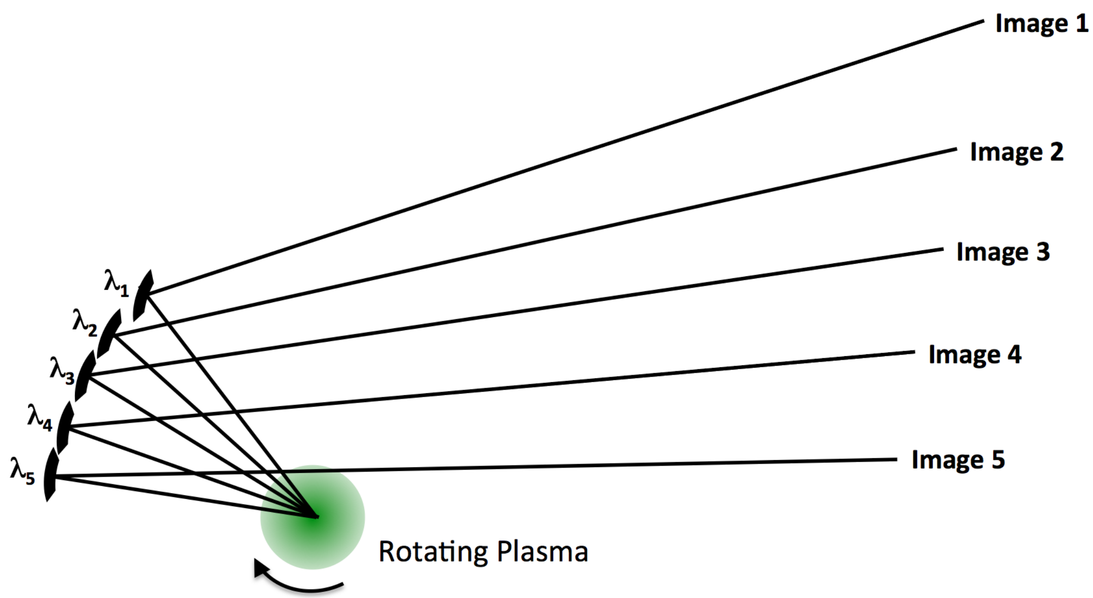
- **We can arrange several crystals, tuned to different center wavelengths within the profile of an emission line, to produce a multi-spectral image mapping wavelength shift to line-of-sight velocity[2]**
  - **Similar instruments have produced wide-range (multiple emission lines) multi-spectral images of implosion plasmas[3], here we need much closer separations and much narrower bandpasses**

[1]Koch *et al.*, Appl. Opt. 37, 1784 (1998)
[2]Koch, NSTec Technology Abstract 3/17/15, U.S. Provisional Patent 62/142,985, NSTec SDRD LO-004-2016
[3]Uschmann et al., Appl. Opt. 39, 5865 (2000)
[4]Spears et al., Phys. Plasmas 21, 042702 (2014)

- **Mapping bulk motional velocities in ICF implosion plasmas could be important for understanding energy balance and making further progress towards ignition at the NIF[4]**

Many other applications exist for emission and absorption imaging (DPF, Z, U1a)

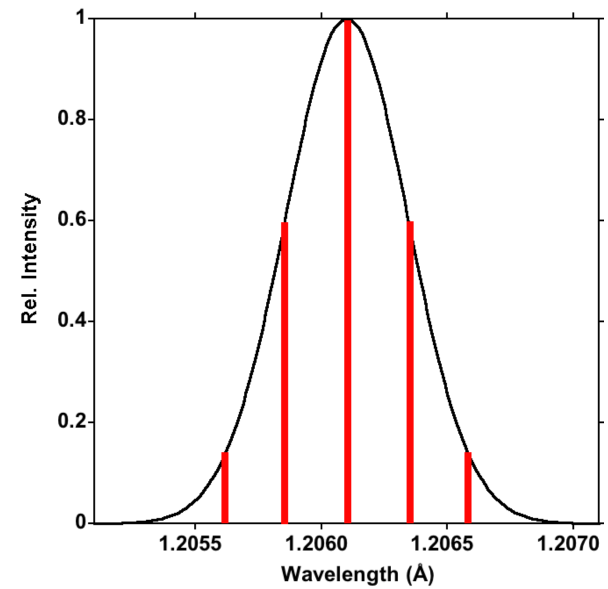
We can simulate XDV data from a rotating plasma ball using 3D ray tracing



- Optically-thin rotating core 40 µm in diameter, maximum velocity at R = 20 µm of 120 km/s
- Five crystals, tuned to very slightly different center wavelengths to emphasize different line-of-sight velocities at the source
- Set the meridional plane of all imagers to be the equatorial plane of the rotating plasma (avoids parallax complications)

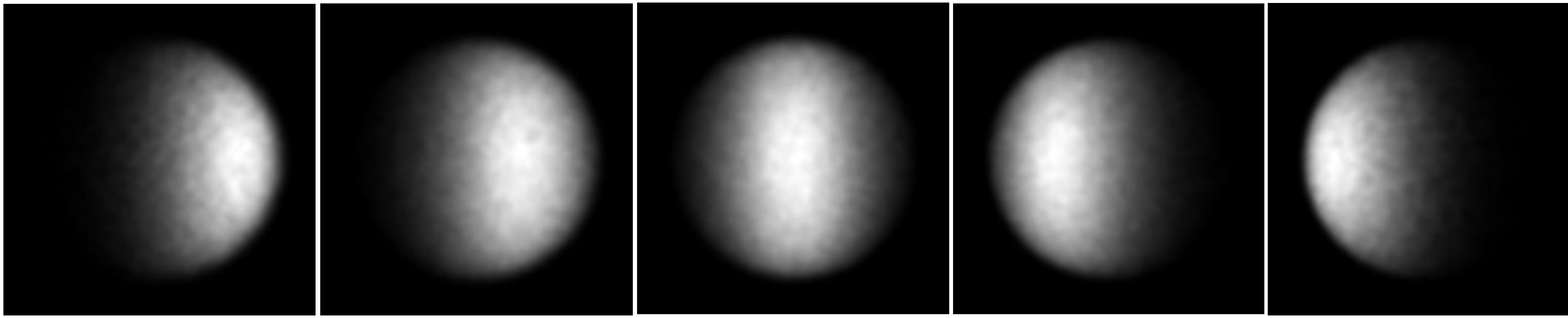
We can use realistic instrument parameters in the raytrace simulation

- Ge He-α $^1P_1$ upper state component, λ = 1.2061 Å, assume uniformly doped
- Spherical quartz (0,7,1), 2d = 1.2068 Å
- 2.8 mm diameter crystal at an object distance p = 200 mm, 31x magnification (Landen spreadsheet), photometrics look fine
- Thermal Doppler broadened line with T_i = 4 keV (ΔE = 5.9 eV, $\Delta\lambda$ = 0.57 mÅ)
- 5 monochromatic images, with central wavelengths ranging from 1.20562 – 1.20658 Å, to span +/- 120 km/s shifts
  - Corresponds to 87.5 - 89 degrees, may or may not be practical but serves to illustrate the concept
  - Larger velocity range would require a larger crystal 2d spacing; in principle, maximum velocities accessible are "cosmological"



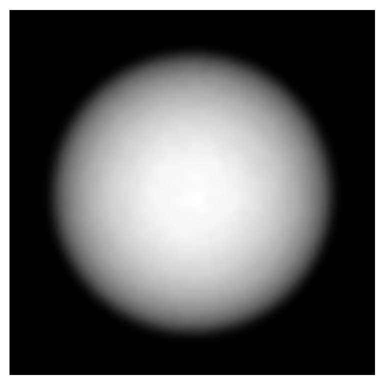
- Outputs are simulated gray-scale images in the detector plane that can be compared and summed to produce a multi-spectral image

XDV monochromatic images are strikingly different from broadband images



λ_1 λ_2 λ_3 λ_4 λ_5

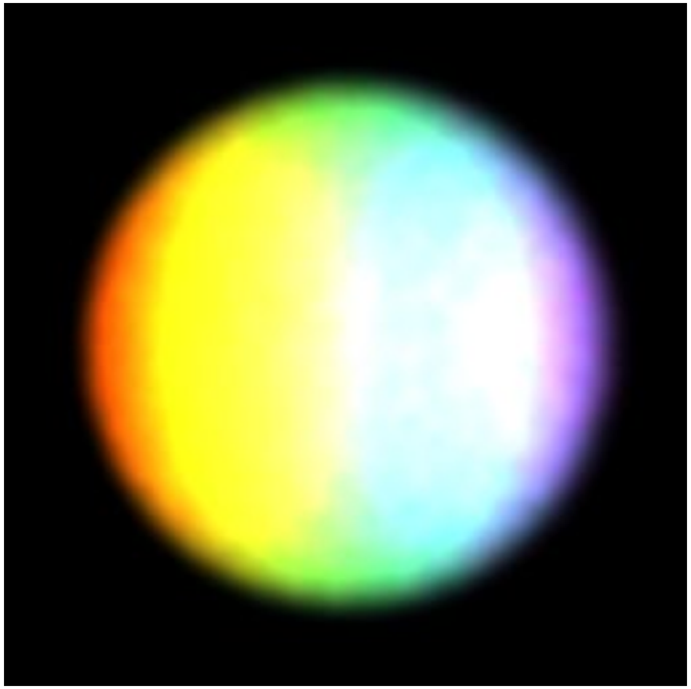
Monochromatic images map velocities into wavelength shifts



Broadband image (pinhole, KB, Wolter) of the same object is insensitive to velocities

Monochromatic images provide much more information

Color coding yields a summed multi-spectral image showing the rotation of the object



Distribution of colors allows reconstruction of the rotational velocity of the plasma

Broadband imaging systems (pinhole, KB, Wolter) cannot yield this kind of information

We have begun to explore realistic 3D Hydra simulations of NIF implosion plasmas

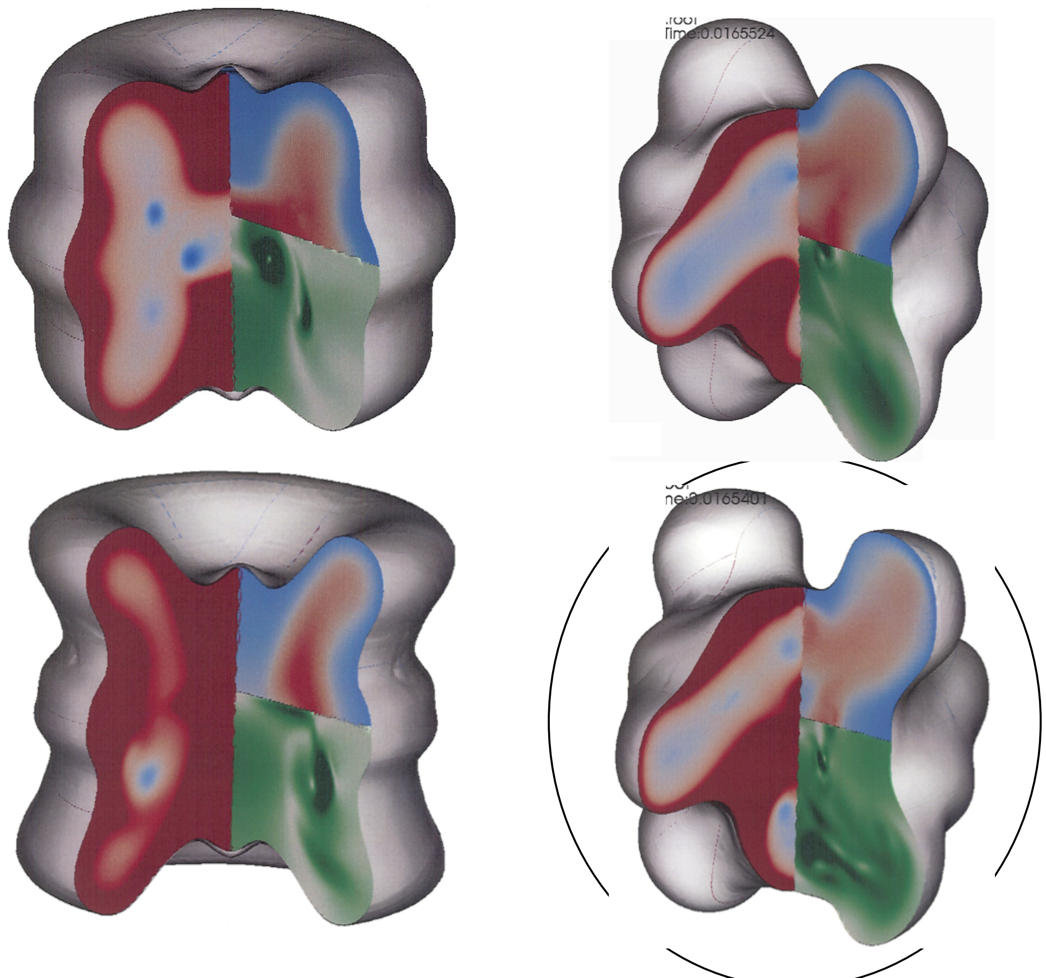
More realistic 3D perturbations amplify weak spots[5]

2D → 3D

CR ~ 30
Standard capsule fill

Increased CR worsens asymmetry

CR ~ 33
Reduced fill 0.33x



Weak spots relieve pressure

Weak spots are more exaggerated at high CR

[5]Slide from B. Spears, LLNL
Post-shot of N130927

First step was to generate map files that can be examined and run through an XDV raytrace

- **John Field generated three maps from Brian Spears' 3D high-convergence post-shot simulation of N130927 (previous slide, circled)**
  - **Integrated line of sight intensity**

$$I = \int_{Line} N_e^2(x,y,z)\exp\left(\frac{-12.5keV}{T_e(x,y,z)}\right)dL$$

  - **Integrated line of sight velocity**

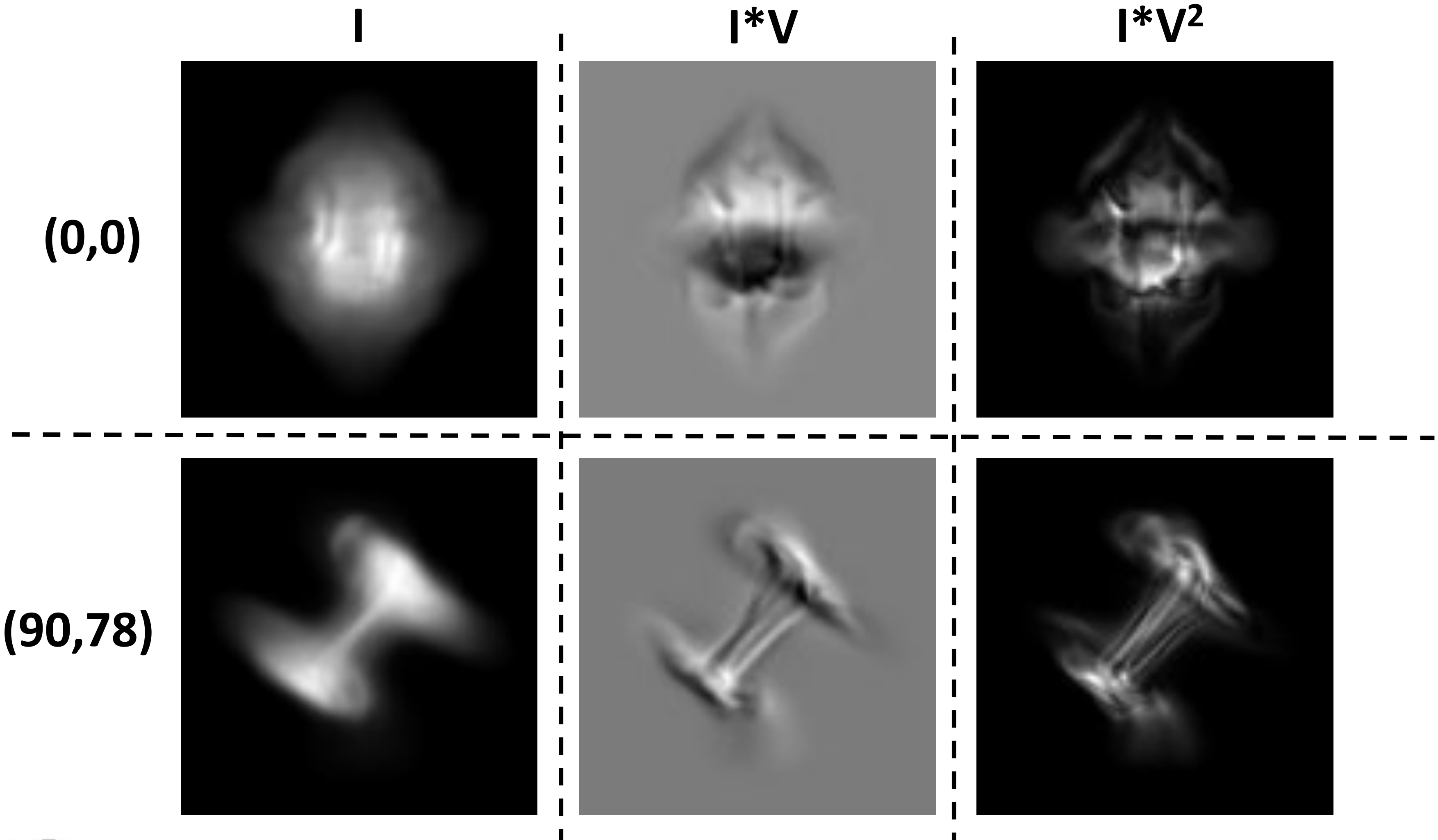
$$I * V = \int_{Line} V_L * N_e^2(x,y,z)\exp\left(\frac{-12.5keV}{T_e(x,y,z)}\right)dL$$

  - **Integrated line of sight velocity squared**

$$I * V^2 = \int_{Line} V_L^2 * N_e^2(x,y,z)\exp\left(\frac{-12.5keV}{T_e(x,y,z)}\right)dL$$

- **Line-center wavelength map calculated from I and I*V, local motion+Doppler broadened line width map calculated from I, I*V and I*V^2**
- **Multiple lines of sight**
- **No spatial or temporal blurring**

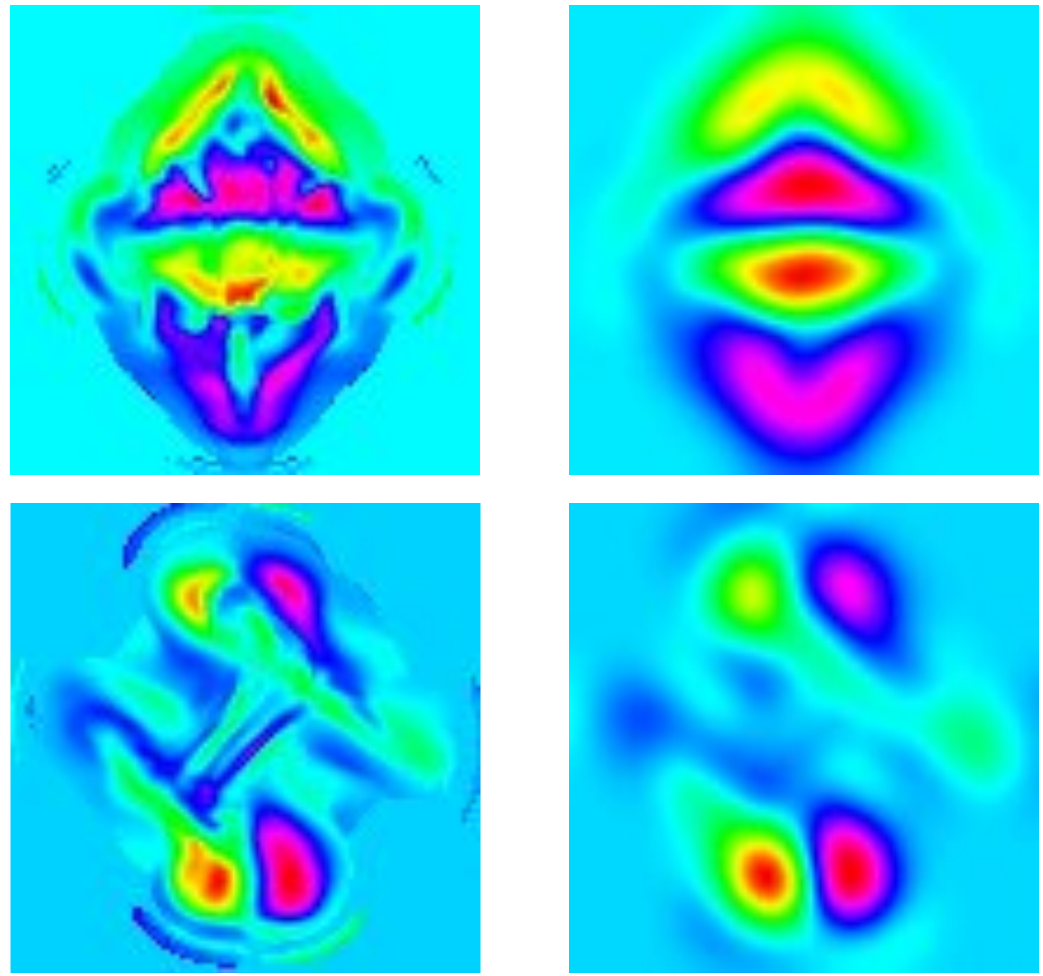
Maps are strikingly different from different lines of sight; compare (0,0) and (90,78)



2D maps of weighted line-averaged velocity shows significant variations

- Weighted velocities exceed +/- 200 km/s even with line of sight averaging
- Blurring the maps by 10 µm still shows obvious structure, +/- 100-150 km/s maximum velocities
- Indicates spatial resolution of 5-20 µm is adequate to observe
  - Time resolution requirements TBD

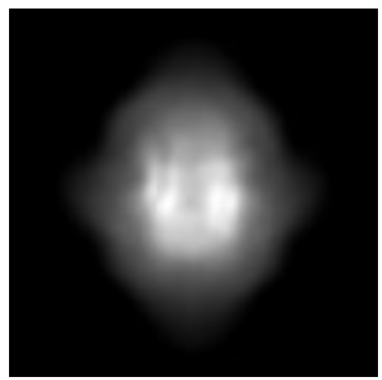
I*V/I　　　I*V/I (10 µm smooth)



Preliminary polar XDV monochromatic images from 3D implosion are strikingly different

λ_1 λ_2 λ_3 λ_4 λ_5

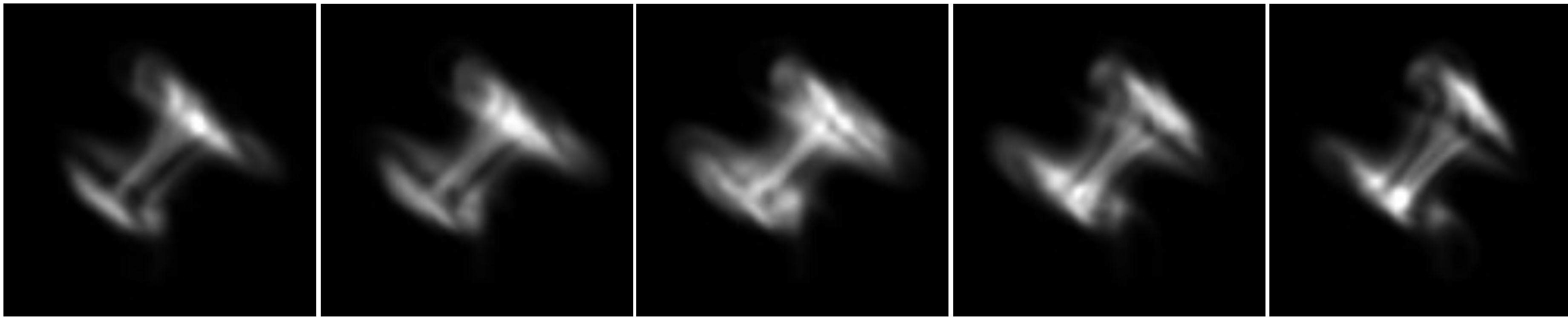
Monochromatic images (polar view) at the same five wavelengths



Broadband image (pinhole, KB, Wolter) of the same object is insensitive to velocities

Diagnostic potential is huge:
Survives analysis of 3D implosion with line-of-sight averaging

Preliminary equatorial XDV monochromatic images from 3D implosion are more subtly different



λ_1 λ_2 λ_3 λ_4 λ_5

Monochromatic images (90-78 view) at the same five wavelengths

Broadband image (pinhole, KB, Wolter) of the same object is insensitive to velocities

Visibility of bulk motion effects depends on the line of sight

Conclusions

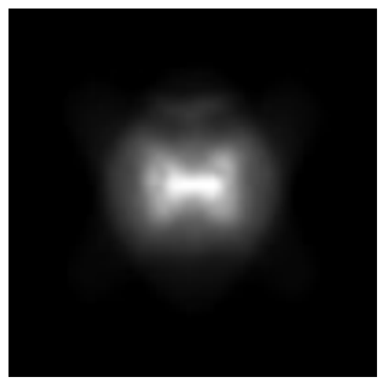
- **Multiple narrow-band crystal imagers, tuned to different wavelengths within the motional-Doppler-broadened profile of a suitable emission line, can be used to measure the distribution of bulk velocities in a NIF implosion plasma**
  - **Direct diagnostic of how much implosion energy is partitioned into non-thermal motional energy**
  - **Potentially critical diagnostic for ignition on the NIF**
  - **Analysis of a simple rotating-ball plasma is promising**
  - **Preliminary analysis of 3D implosion simulations from Hydra (high-CR post-shot of N130927) is promising**
  - **Photometrics are promising**
- **Extensions to other HEDP plasmas (Z, DPF, UNR-Zebra) seem straightforward, possibly easier than NIF applications (cooler temperatures, larger spatial scales); we will explore a 2-crystal prototype for UNR-Zebra first**
- **Extensions to cold plasmas (e.g. explosive-driven implosions at NNSS) are possible in backlit absorption geometries**
- **Exploration of these applications in more detail is supported by NSTec SDRD program (LO-004-2016)**

Backups

Preliminary 45-00 XDV monochromatic images from 3D implosion are strikingly different

λ_1 λ_2 λ_3 λ_4 λ_5

Monochromatic images (90-78 view) at the same five wavelengths



Broadband image (pinhole, KB, Wolter) of the same object is insensitive to velocities

Diagnostic potential is huge:
Survives analysis of 3D implosion with line-of-sight averaging