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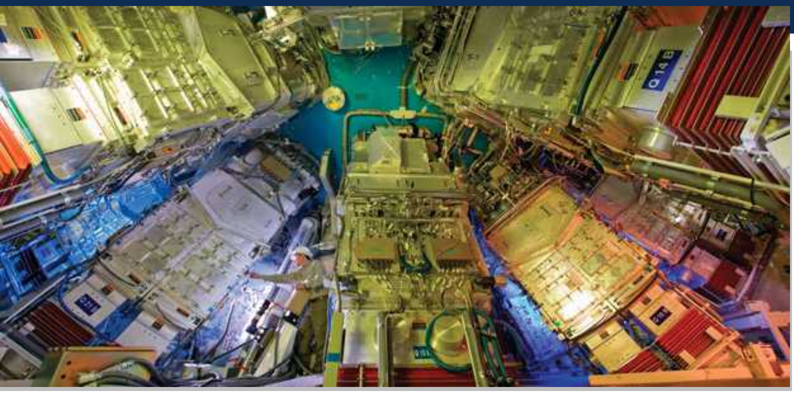

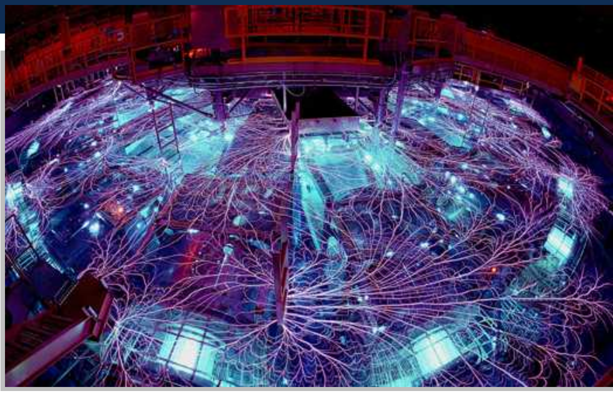

# Transformative Diagnostics for HED Science

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Sandia National Laboratories

ICHED 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# Thank you to the HED Diagnostics community

**National HED diagnostic leadership team**

Joe Kilkenny, Greg Rochau, Craig Sangster, Steve Batha, Ray Leeper, Mike Campbell, Johan Frenje, Warren Hsing, Jeff Koch, Doug Larson, Rich Petrasso

# Outline

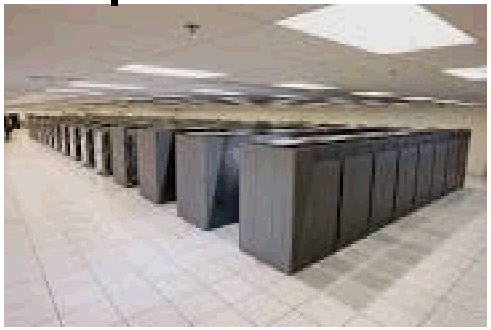
1. Why it's 'The best of times' for HED science…
2. …but yet, it's not good enough. What are we missing?
3. How the needs of the HED science community and advances in technology come together to form a national plan
4. The transformative diagnostic capabilities we will deploy in the coming years

# These are exciting times for HED science

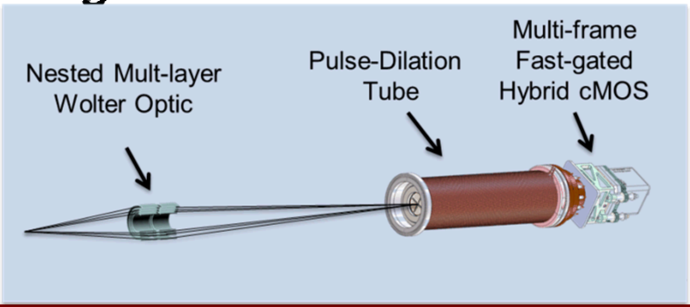
- HED facilities are operating at an unprecedented level of energy, power, and precision
- Simulations have unprecedented fidelity with fewer approximations and tunable parameters
- ICF on NIF is achieving significant alpha heating
- Z and Omega have demonstrated the utility of B-fields and preheat to relax fusion requirements
- All facilities can now access >10 Mbar regimes

**Facilities**

**Computers & Codes**

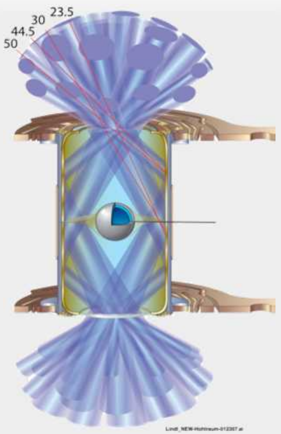


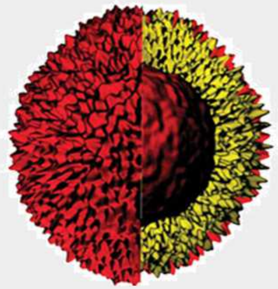
**Diagnostics**



# Indirect drive ICF has reached unprecedented fusion yield while a new approach is showing promise.

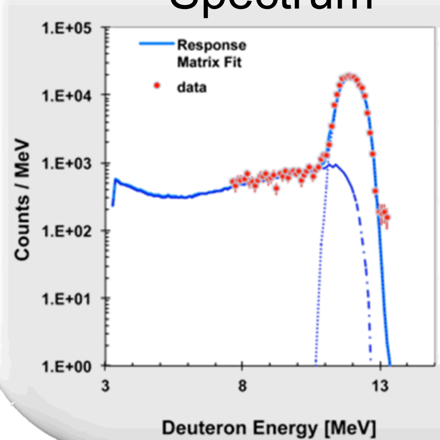
**Indirect Drive on NIF***

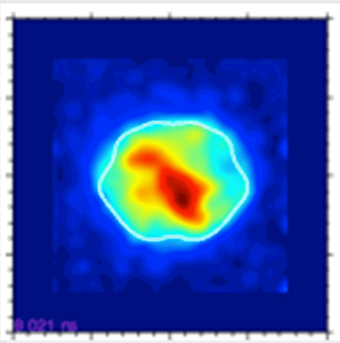


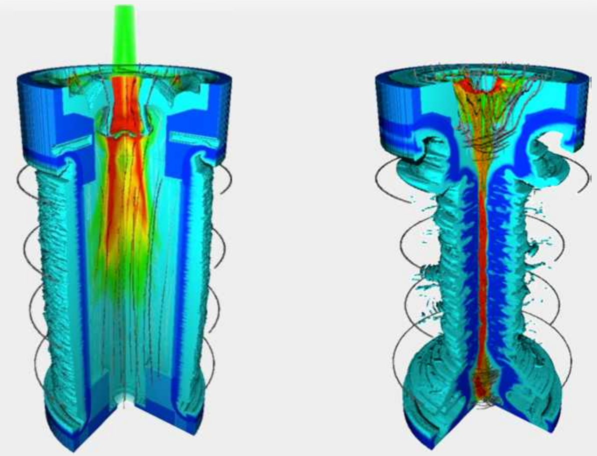
Neutron Spectrum

10 ps gated pinhole image

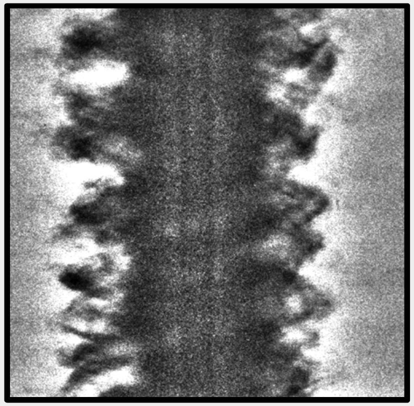


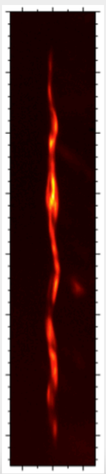



**Magnetized Liner Inertial Fusion**



Spherical Crystal Imaging





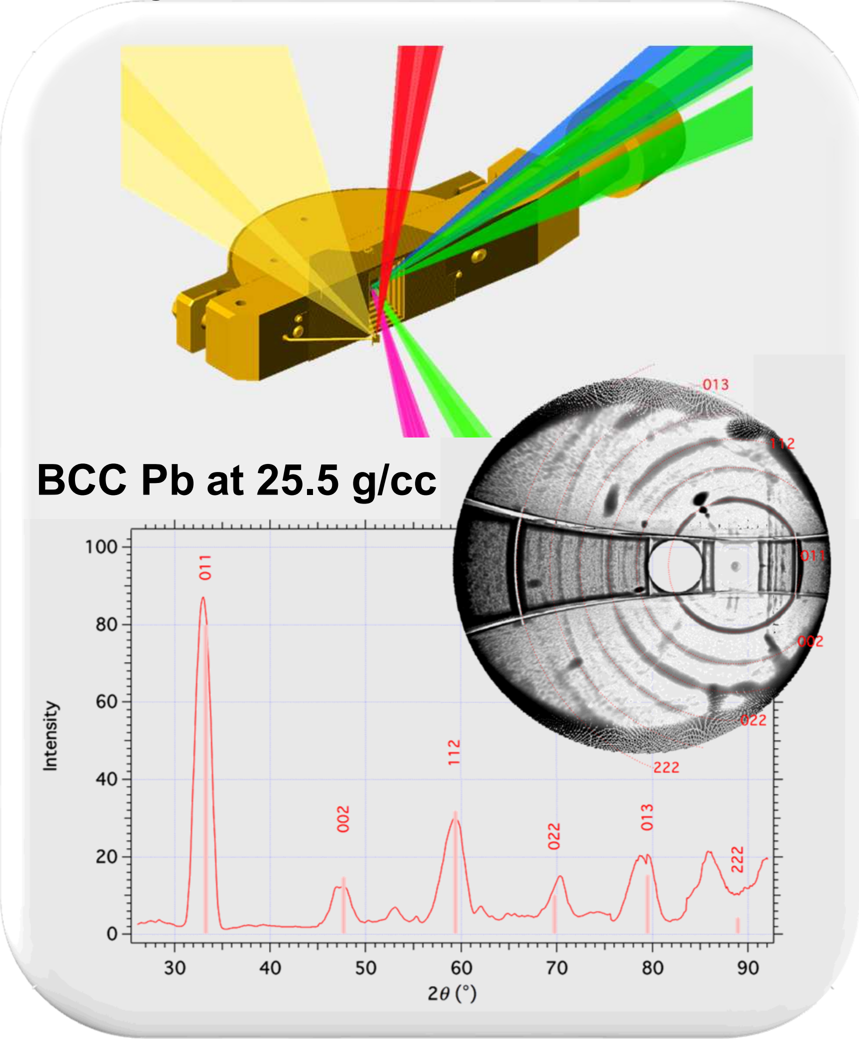


*Frenje (MIT) et al.; Hillsabeck (GA) et al.

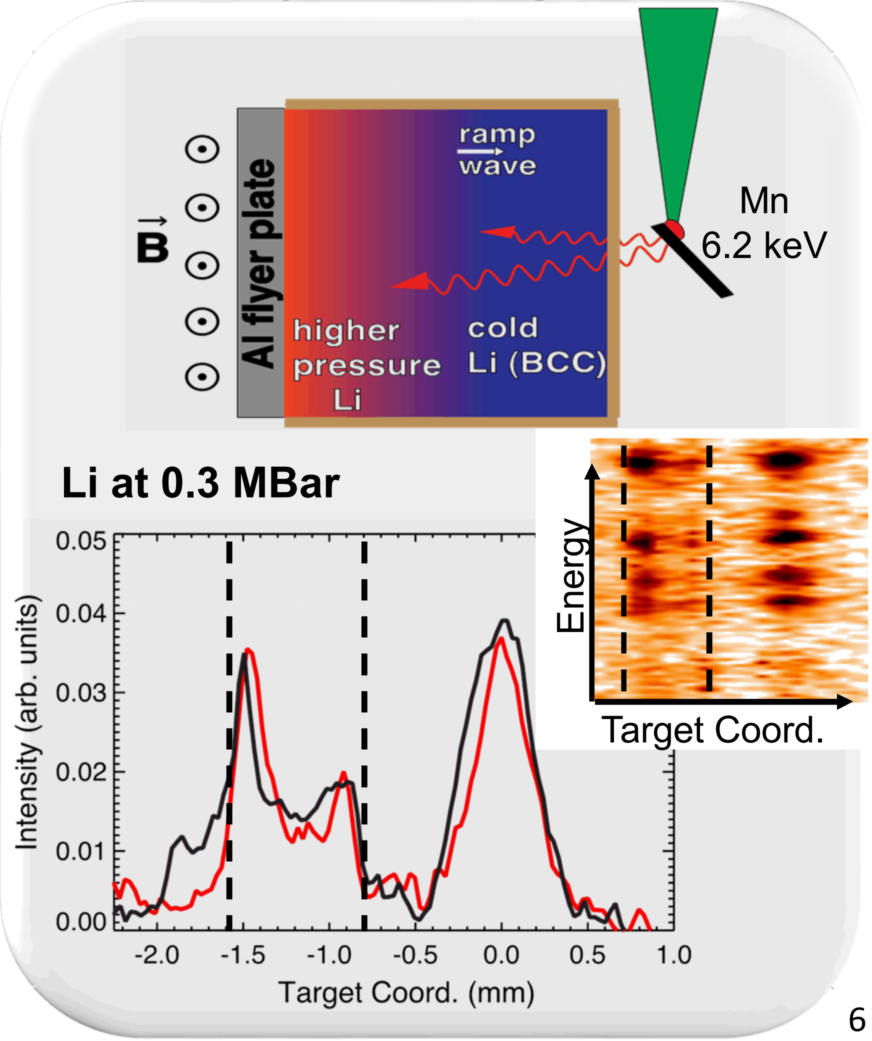
**Awe, Harding (SNL) et al.

# Implementation of advanced diagnostics for materials science is opening the window to new understanding.

## Dynamic Diffraction on NIF*




## X-ray Scattering on Z**



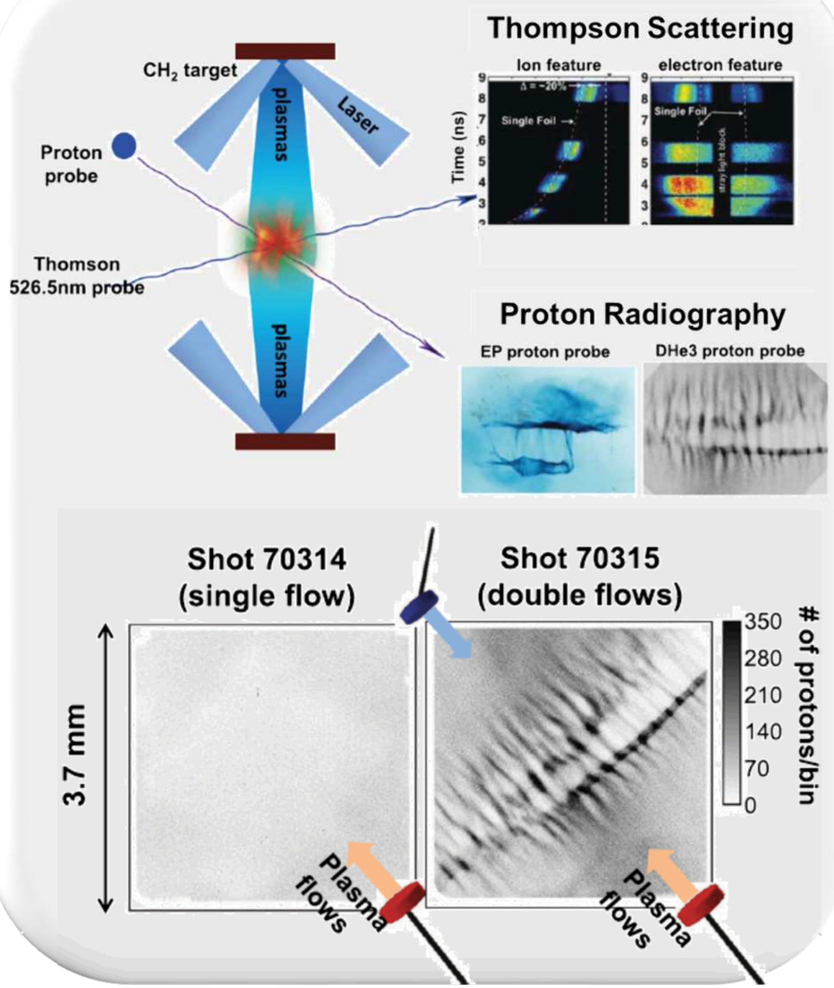



*Eggert (LLNL) et al.

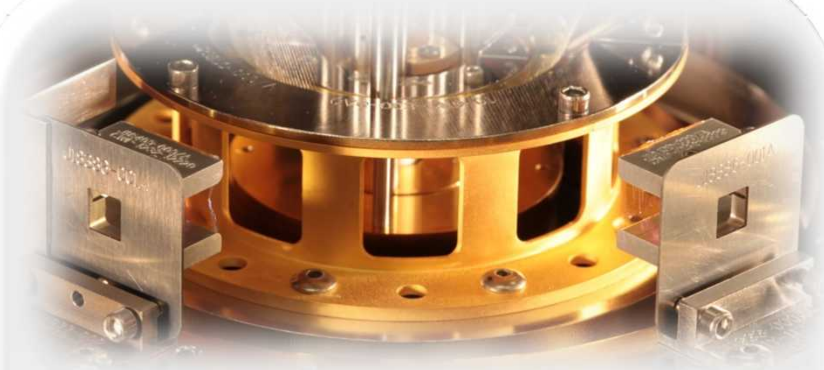
**Harding (SNL) et al.

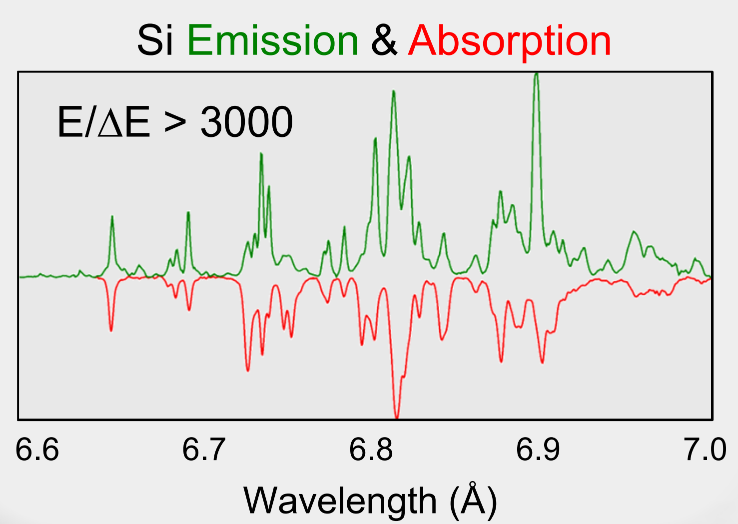
# Fundamental science experiments on HED facilities are providing new insight into complex plasma interactions

## Collisionless Shocks on Omega*




## Photoionized Plasmas on Z**







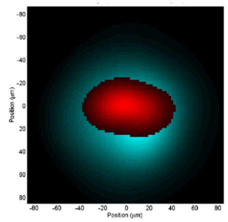

*Park et al., POP (2015)

**Loisel (SNL) et al.

# The combination of many well-understood diagnostics is vital to interpret the complex, multi-scale behavior of HED plasmas

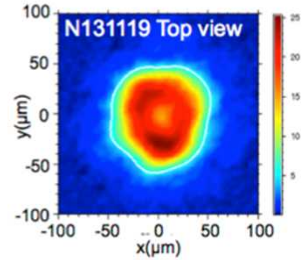
**Neutron Imaging**

LANL, LLNL



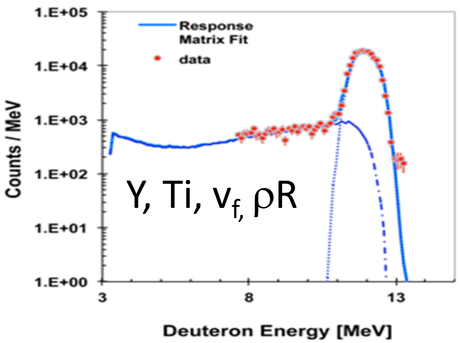
**X-ray Imaging**

LLNL, NSTec



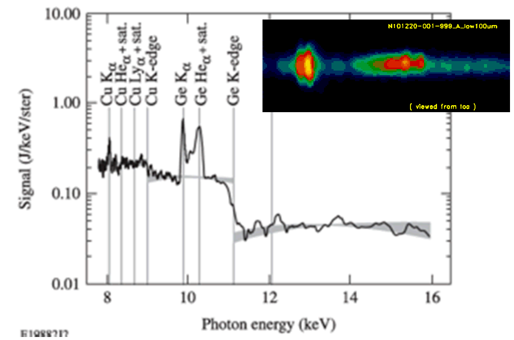

**Neutron spectra**

MIT, LLE, LLNL

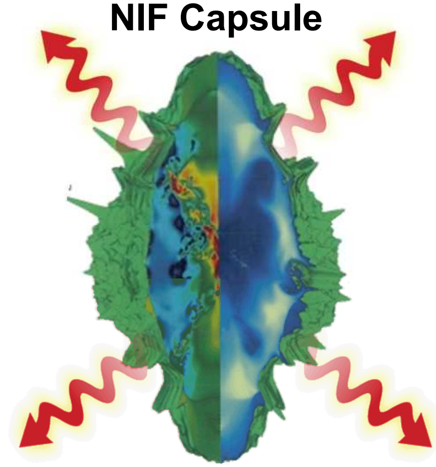



**X-ray Spectra**

LLE, LLNL, NSTec

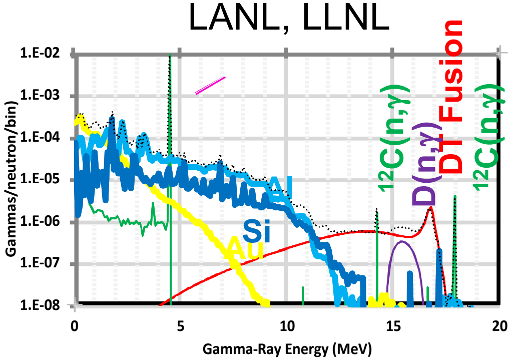



**NIF Capsule**



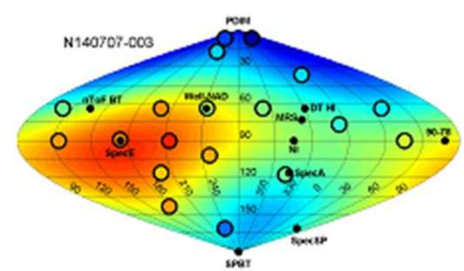
**Gamma Spectra**

LANL, LLNL




**Nuclear Activation**

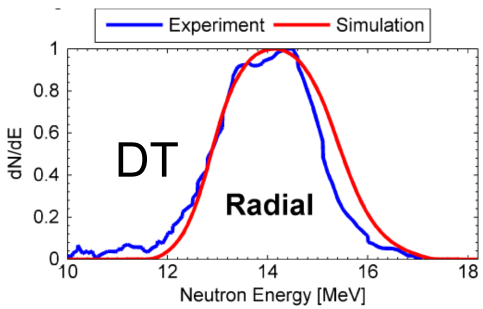
LLNL, SNL

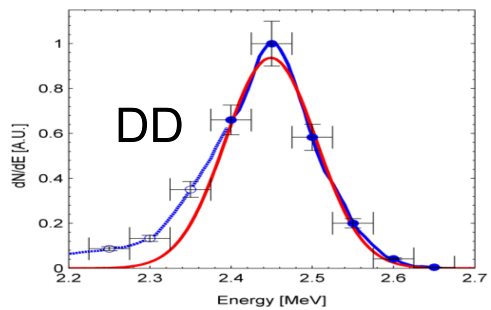



…and Many More

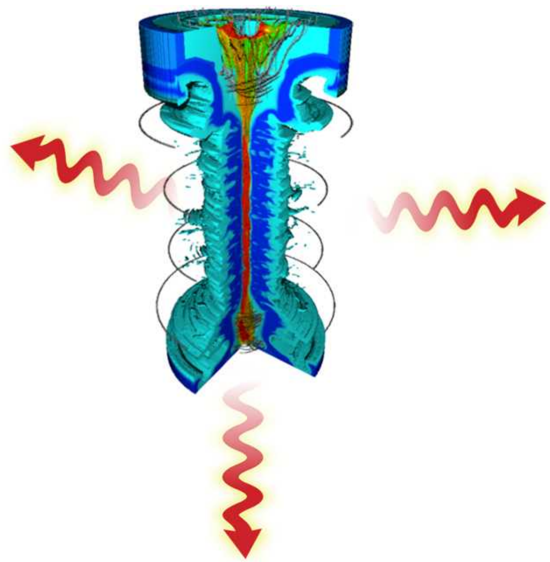
# The combination of many well-understood diagnostics is vital to interpret the complex, multi-scale behavior of HED plasmas

## Neutron spectra

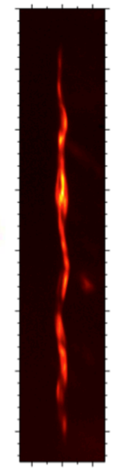


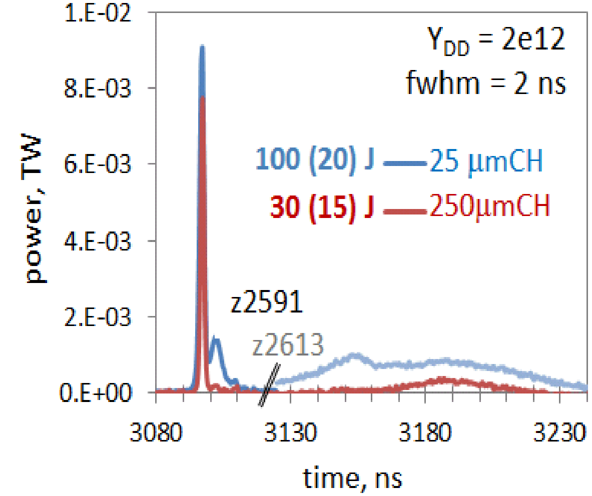

## MagLIF Z pinch



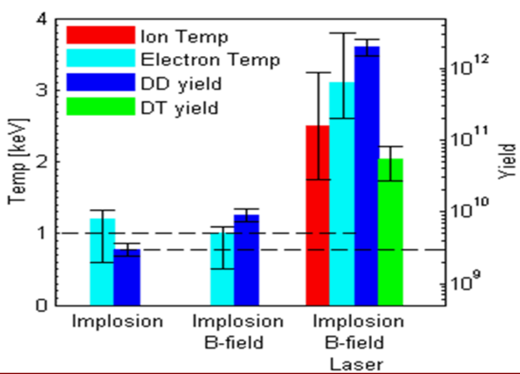
## X-ray Imaging



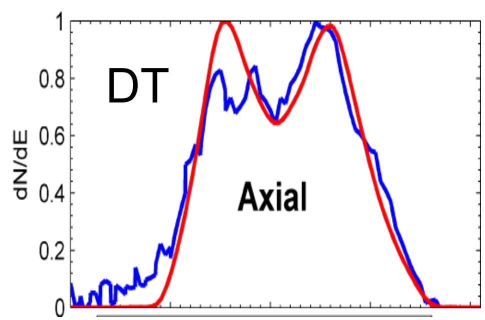
## X-ray Power



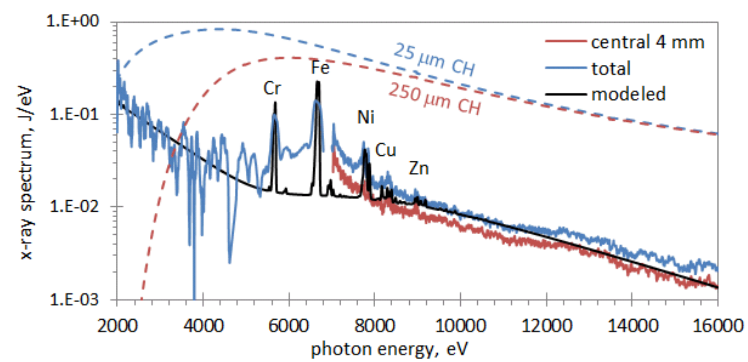

## Nuclear Activation




## Neutron spectra



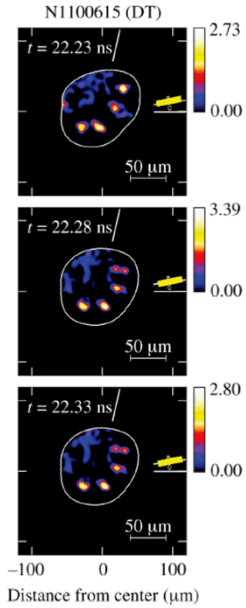

## X-ray Spectra



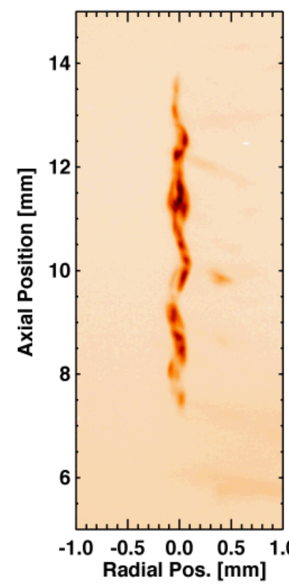
# The significant challenges in ICF and HED science require a new generation of diagnostics

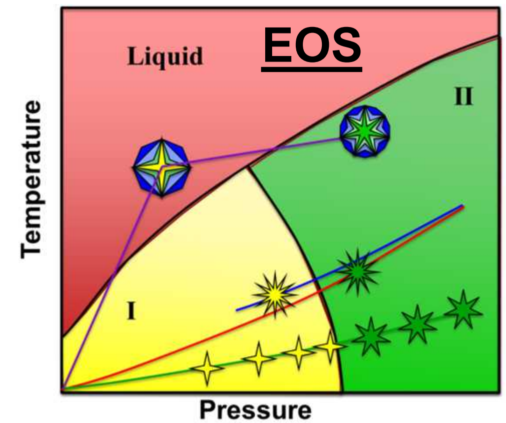
- **How does a capsule or z-pinch stagnate?**
  - Is the 2-D picture reasonable or do 3-D physics always dominate at high convergence?
  - How is the ion energy distributed and how does it evolve in time?
  - How does mix occur and what impact does this have on the burning plasma?
  - How/where are non-thermal electrons generated in z pinches and can we control/optimize the K-$\alpha$ production?
- **How does the NIF hohlraum plasma evolve?**
  - How does the plasma evolution affect laser propagation and overall energetics?
- **How do high pressure materials evolve in time?**
  - How do materials melt and re-freeze at high pressure?
  - Can we detect the time-dependent kinetics during a phase transition at high pressure?

**Indirect Drive***




**MagLIF****



# A first ever National Diagnostics Plan (NDP) will steward a new generation of HED diagnostics at all the facilities

2012
- **National Diagnostic Working Group formed following the end of the National Ignition Campaign**
  - **Representation from each NNSA laboratory, LLE, NRL, and academia**

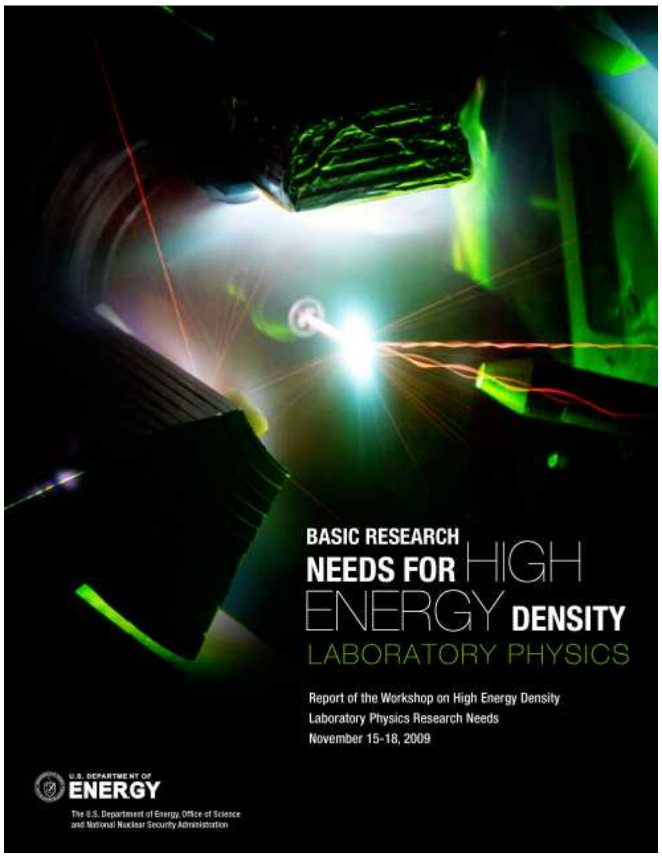
2013
- **A series of workshops held since 2009 on ICF diagnostics broadened to include all facilities and additional HED needs.**

2014
- **The Senate Energy and Water Development Subcommittee requests a national diagnostics plan to ensure we capitalize on the potential for HED science**

2015
- **The National Diagnostics Plan is formed, reviewed by an advisory panel, and put into action.**
  - **A multi-million dollar effort that will steward the development of advanced diagnostics and coordinate resources across the NNSA complex**

# The National Diagnostic Plan begins with the needs; These are well documented by the national community

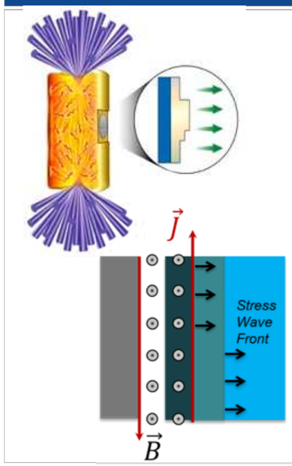
HEDLP Research Needs Workshop (ReNeW) 2009




NNSA HED Stockpile Stewardship Workshop 2014

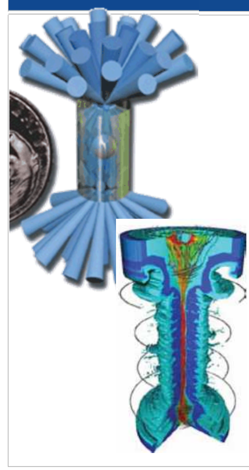
# The research needs span a wide range of platforms, plasma conditions, and measurement requirements

## High Pressure Materials



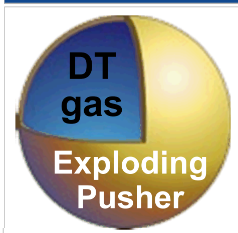

- Phase and structure
- Strength
- Conductivity
- Temperature

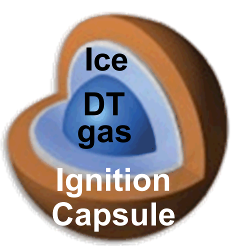
## Complex Hydrodynamics



- High convergence radiography
- 3-D plasma conditions
- Meso-scale / Multi-shock hydro instabilities
- Mix fraction

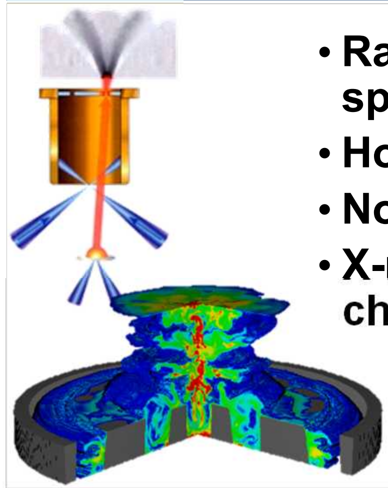
## Ignition Applications and Burn




- Electron, ion temperature equilibration
- Ionization state
- Stopping power of alphas
- Radiochemistry
- Radiography/Imaging
- Burn history

## Radiation Transport, Opacity, & Effects



- Radiation T, ne in 3D spatial, time
- Hohlraum conditions
- Non-thermal electrons
- X-ray source characterization

# 18 major diagnostic efforts were discussed at the National Diagnostic Working Group meeting Sept. 9-11, 2014

- 9th in a series dating back to 2009
- 117 participants from 13 institutions
- 69 presentations in 3 parallel sessions
- 10 plenary talks summarizing present efforts and needs at NIF, Z, and OMEGA

| X-ray Imaging |
|---|
| Single LOS gating |
| 'small dν' imaging |
| High energy imaging |

| X-ray Spectroscopy |
|---|
| High resolution |
| High energy (20-80 keV) |
| Diffraction |

| Calibration |
|---|
| Neutron sources |
| Pulsed x-ray sources |
| High energy x-ray cals |

| Neutron & Gamma |
|---|
| Gamma spectroscopy |
| 3-D neutron imaging |
| Alpha heating diag. |
| Furlong |
| Radchem |

| Optical |
|---|
| Thomson Scattering |
| PDV |

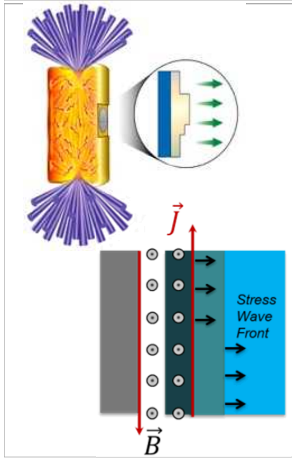
| Other |
|---|
| Radiation Hardening |
| Magnetic Fields on NIF |

# Eight major national efforts emerged with the potential to transform experimental capability for the most critical needs

- **Broad enabling capability of multi-frame single line-of-sight (SLOS) time-gating at 10 ps – 1 ns**
  - Hybrid CMOS and Pulse-Dilation
- **Local probing of plasma conditions and evolution in low-density plasmas**
  - Optical Thomson Scattering at deep UV
- **2- and <u>3-D</u> visualization of the plasma evolution with the potential for very high spatial (<10 micron) and temporal (<10 ps) resolution at a broad range of photon energies (5-50 keV)**
  - Multi-layer Wolter, KB, Crystal microscopes coupled to SLOS
- **Detailed determination of fusing plasma evolution and burn propagation**
  - Time-resolved Gamma Spectrometers, Time-Resolved Magnetic Recoil Spectrometers, Orthogonal Neutron & Gamma Imaging, High Resolution X-ray Spectroscopy
- **Time-dependent phase change and temperature at high pressure**
  - Time-resolved x-ray diffraction
  - Temperature from EXAFS

# ‘Transformational’ diagnostics are at the intersection between the most compelling needs and the most promising technologies

## High Pressure Materials




<u>Phase and Structure</u>

**Time-Dependent X-ray diffraction**

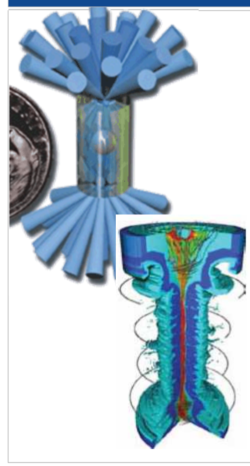
<u>Strength</u>

**Multi-layer Wolter**

<u>Temperature</u>

**High-Res Spect.**

## Complex Hydrodynamics



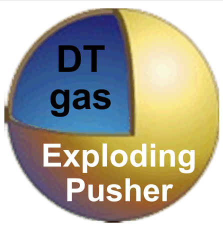
<u>Meso-Scale Hydro Instabilities</u>

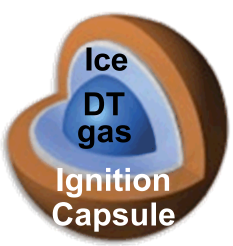
**Multi-Layer Wolter**

<u>Mix Fraction</u>

**Time-Resolved $\gamma$ Spect**

## Ignition Applications and Burn




<u>Time-Resolved Burn</u>

-vs. Energy

**Time-Resolved n/$\gamma$ Spect.**

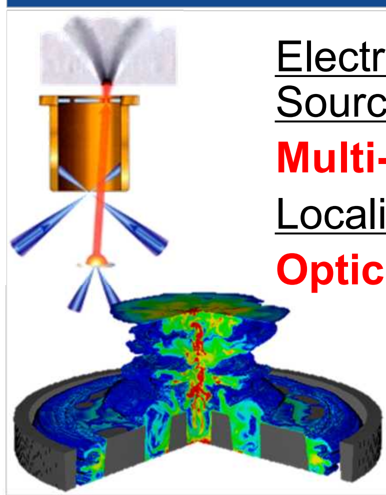
-vs. Space

**3-D n/$\gamma$ Imaging**

-Equilibration

**High-Res X-ray Spect.**

## Radiation Transport, Opacity, & Effects



<u>Electron transport and X-ray Source Formation</u>

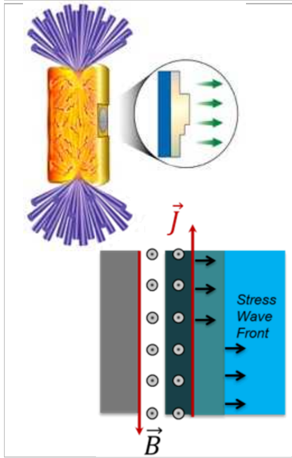
**Multi-Layer Wolter**

<u>Localized Te/ne</u>

**Optical TS**

# ‘Transformational’ diagnostics are at the intersection between the most compelling needs and the most promising technologies

## High Pressure Materials



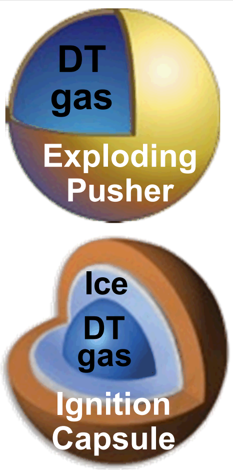

Phase and Structure
**Time-Dependent X-ray diffraction**
Strength
**Multi-layer Wolter**
Temperat
**High-**

## Complex Hydrodynamics

Meso-Scale Hydro Instabilities
**Multi-Layer Wolter**
Mix Fraction
**Time-Resolved $\gamma$ Spect**

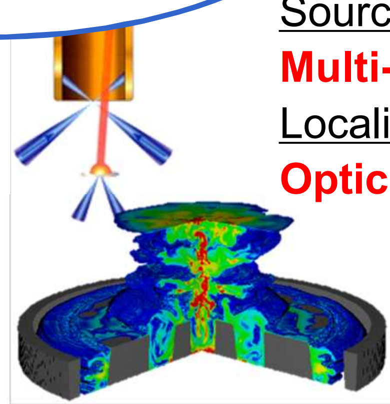
**High Res, Many-Frame SLOS Gating**
Hohlraum Character.
**Optical TS**

## Ignition Applicatio




Time-Resolved
-vs. Energy
**Time-Resolved n/$\gamma$ Spect.**
-vs. Space
**3-D n/$\gamma$ Imaging**
-Equilibration
**High-Res X-ray Spect.**

## port, Opacity, & Effects

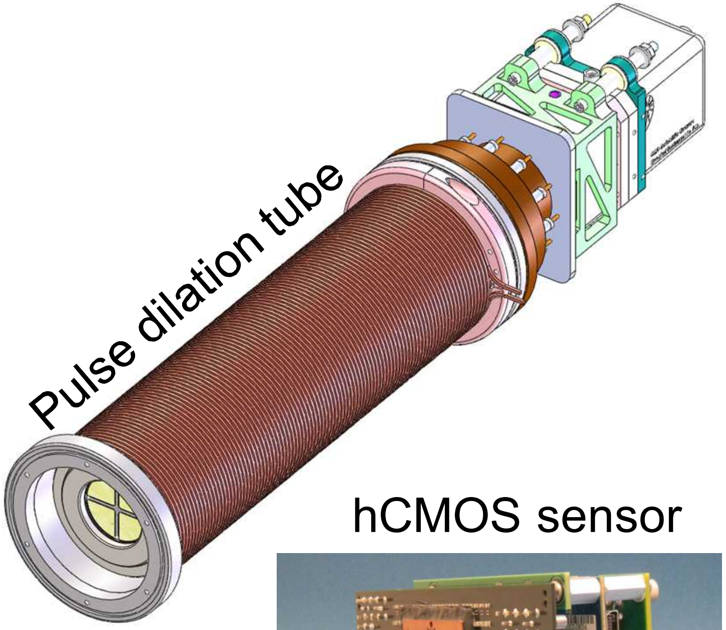


Electron transport and X-ray Source Formation
**Multi-Layer Wolter**
Localized Te/ne
**Optical TS**

# **Research Thrust:** Broad enabling capability of multi-frame single line-of-sight (SLOS) time-gating

### Science Drivers

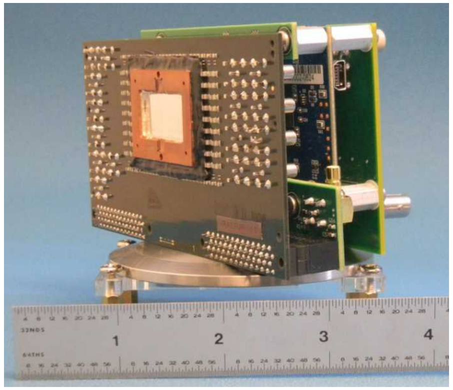
- Multi-frame gating at 10 ps -1 ns for high res, large solid angle imaging and backlighting
- Time-resolved x-ray diffraction
- Time-resolved absolute x-ray spectroscopy
- MCP and image plate replacement




### Transformational Diagnostic Approach

- Up to 16-frame Hybrid CMOS (hCMOS) sensors for direct optical or x-ray detection at gates > 1ns
- hCMOS coupled to pulse-dilation for gates 0.01 – 1 ns

hCMOS sensor



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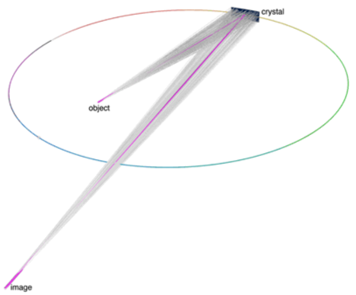
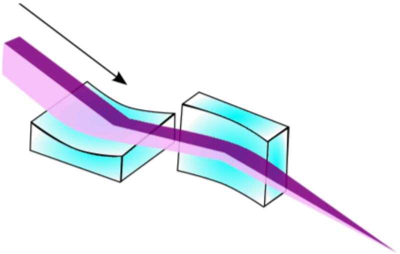
# Advanced imaging systems require single line-of-sight (SLOS) gated detection with many frames

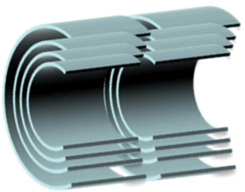
**Spherical Crystal**




**Kirkpatrick-Baez**



**Wolter**



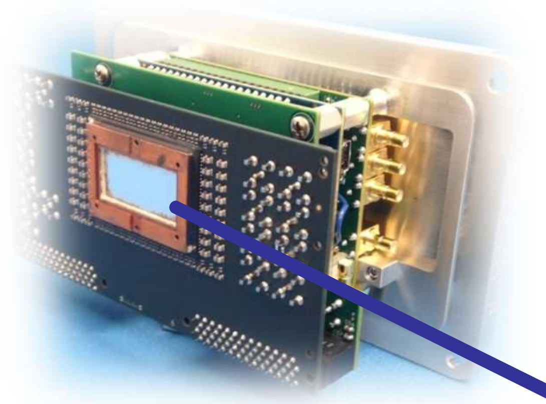
- High time-resolution requires many frames of data to achieve the necessary temporal coverage
  - **On Z**, eight 200 ps time-gates across a ~1.5 ns MagLIF stagnation requires >28 frames of data due to +-2 ns machine jitter
  - **On NIF**, eight 20 ps time-gates across a ~150 ps capsule stagnation requires >28 frames of data assuming +-200 ps bangtime uncertainty

- High sensitivity, high resolution optics are delicate (expensive) and take up space

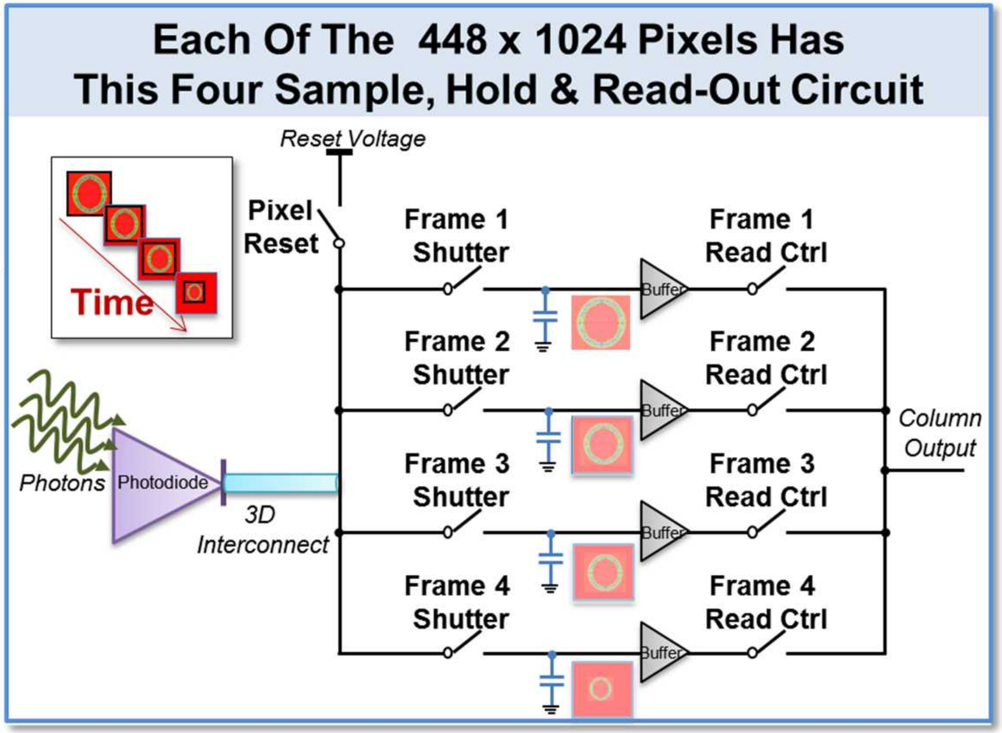
*Spherical crystal optics on Z are 'disposable' so you can't just build a huge array of them*

# A new a high speed CMOS camera is enabling multi-frame 2-D x-ray detection along a single line-of-sight

hybrid CMOS camera



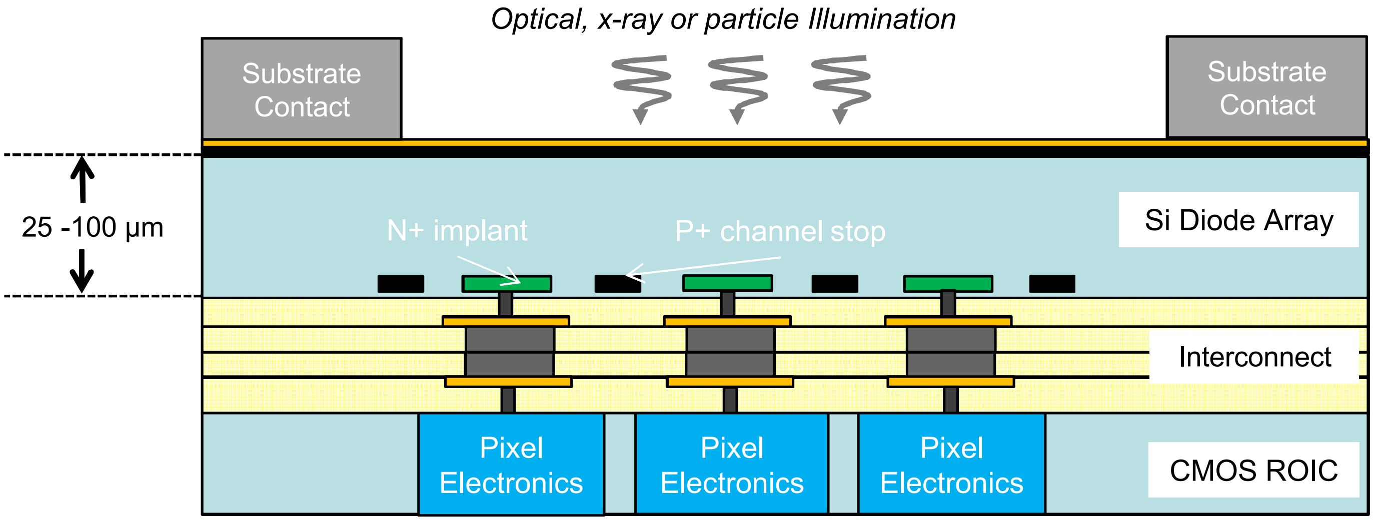
- 25 um x 25 um pixels
- Sensitive to visible light and 0.7-10 keV x-rays




designed and built in collaboration with the MESA facility

# Hybridizing enables independent optimization of the diode array and the readout electronics

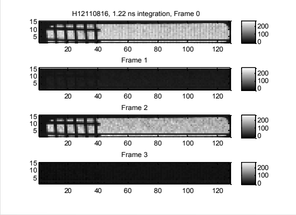
- Photodiodes can be optimized for sensitivity to relevant spectrum of interest (visible light, x-rays, electrons).
- ROIC stores charge from each photodiode on in-pixel capacitors during selected integration time for each frame.
- Each pixel of photodiode array is directly connected to CMOS ROIC through wafer-to-wafer bonding (Ziptronix 3D oxide-to-oxide bond process).




CMOS Hybrid Image Sensor

# In the next 3 years, we will deploy a 1 MP hCMOS imager with 1 ns gate times over 8+ frames

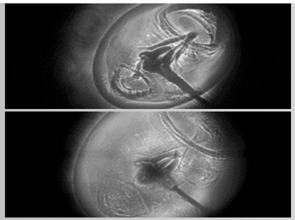
## GRIFFIN
1.5ns, 4 Frames
15x128 pixels
350nm Sandia Process



*Calibration Mesh X-ray 1.5ns Images*

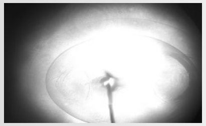
FY13

## FURI
1.5ns, 2 Frames
448x1024 pixels
350nm Sandia Process



*10ns Blast Wave Visible Images*

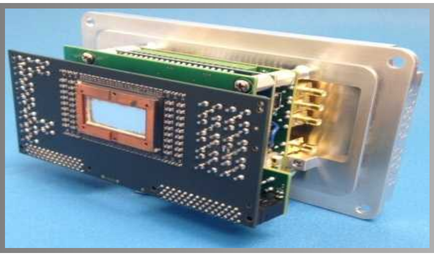
vs.

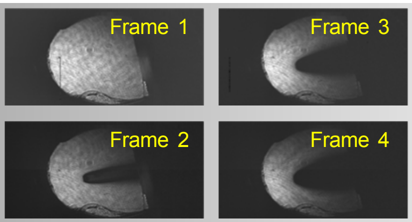


*Commercial Double Exposed CCD*

FY14

## HIPPOGRIFF (FURI II)
1.5ns, 2-8 Frames (Interlacing)
448x1024 pixels
350nm Sandia Process



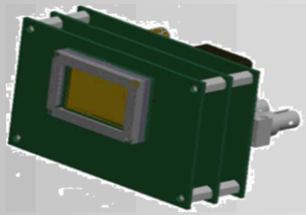



*4ns Gas Cell Shadowgraphs*

FY15

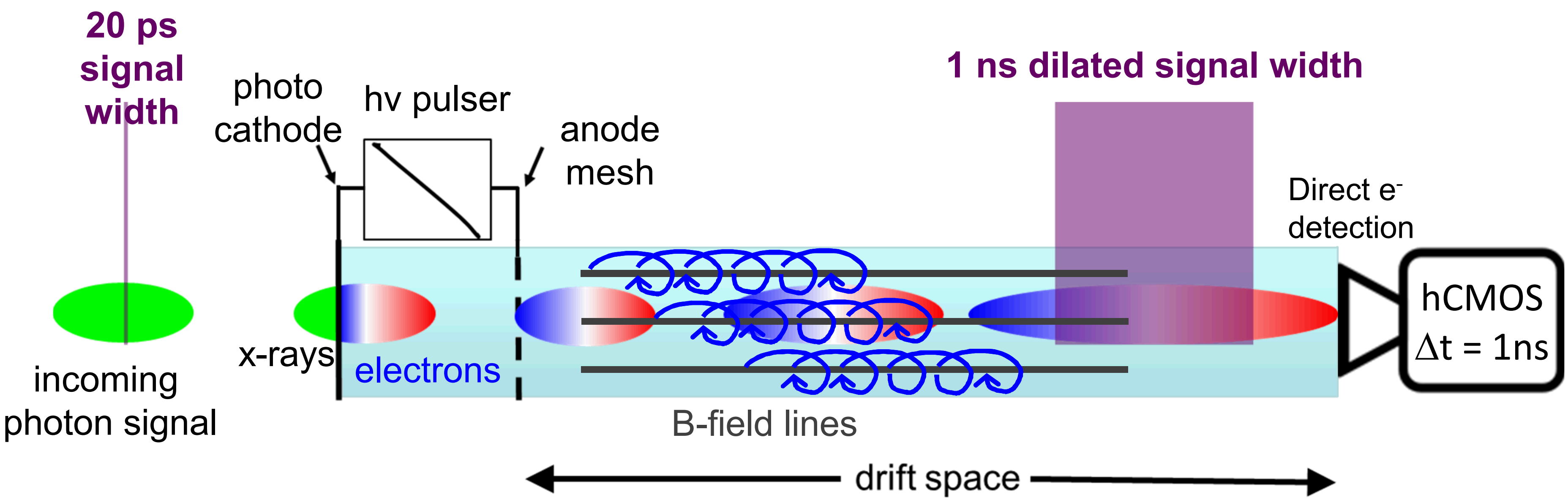
## ICARUS
1.5ns, 4-16 Frames (Interlaced)
512x1024 pixels
350nm Sandia Process

## ACCA
1ns, 8 Frames
1024x1024 pixels (tiled)
130nm IBM Process



FY16-18

# Electron pulse-dilation will act as a tele-temporal lens to significantly increase the time-resolution for SLOS detection




temporal magnification

$$M \approx 1 + \frac{L}{2v_d(\phi)}\frac{|\dot{\phi}|}{\phi} = 50$$

$L = 25\ \mathrm{cm}$ drift length

$\phi = 1000\ \mathrm{V}$ drift potential

$v_d = 19\ \frac{\mathrm{mm}}{\mathrm{ns}}$ drift velocity

$|\dot{\phi}| = 4\ \frac{\mathrm{kV}}{\mathrm{ns}}$ PC ramp

Pulse-dilation separates input information enough to enable multiply gated back-end detector to capture consecutive frames with much slower gate time



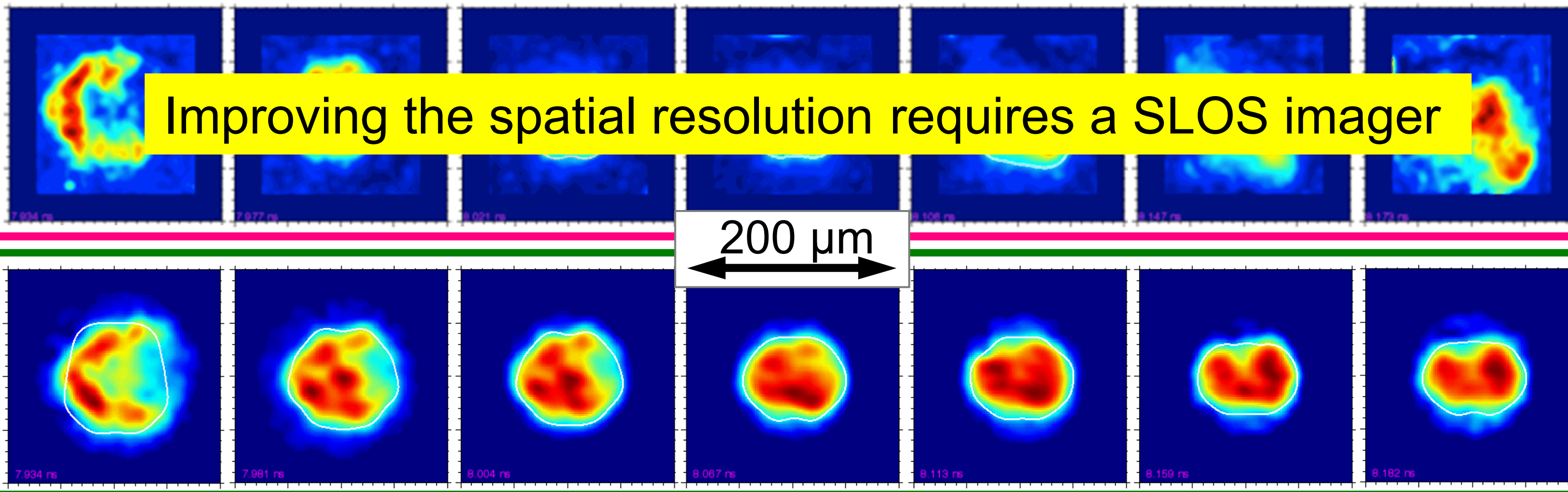
*Hilsabeck (GA), Nagel (LLNL) et al.

# Pulse-dilation on NIF has achieved 10 ps time-resolution, providing a more detailed picture of ICF stagnation

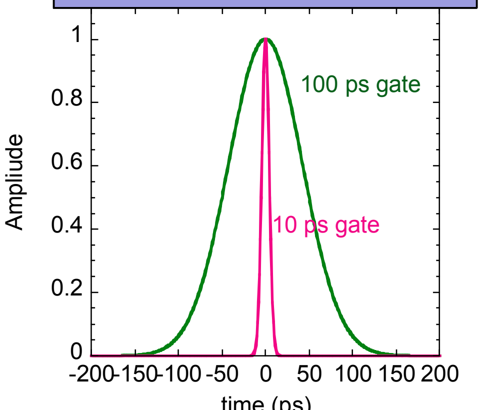
time → | - 130 ps | - 80 ps | - 40 ps | 0 ps | + 40 ps | + 80 ps | + 100 ps

**DIXI with 10 ps gate width**

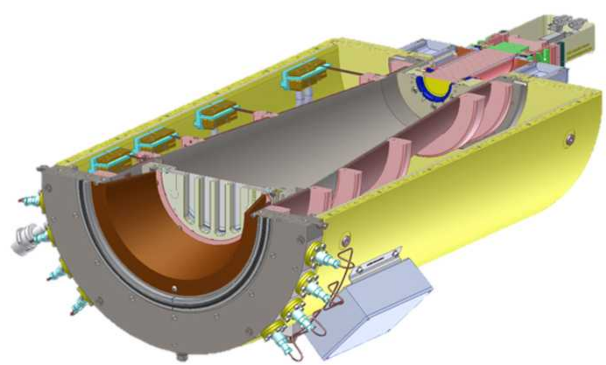
**Framing camera with 100 ps gate width**

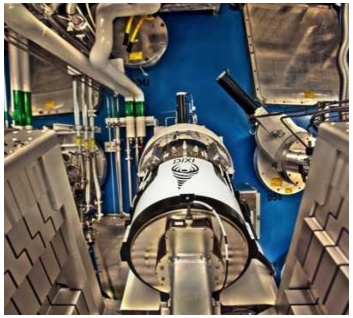



Gate width comparison

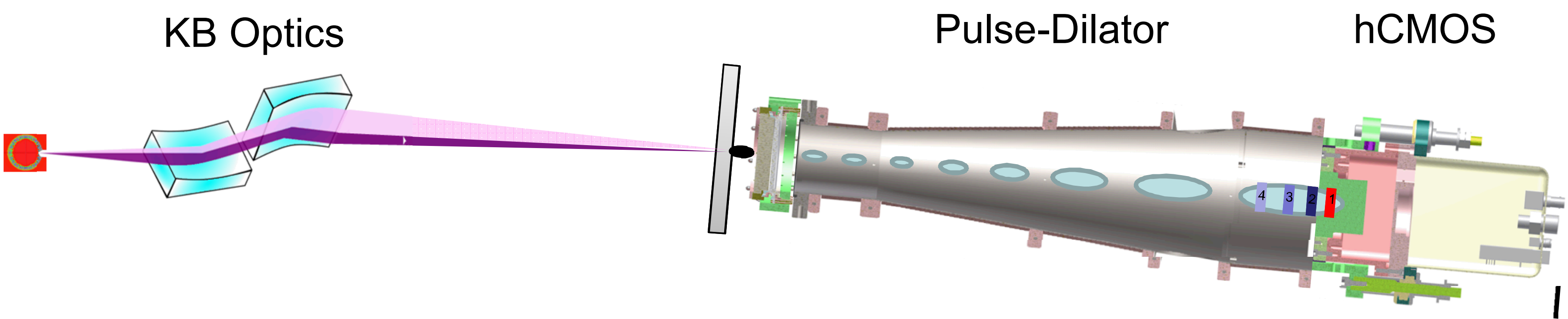



**DIXI – Dilation x-ray imager**

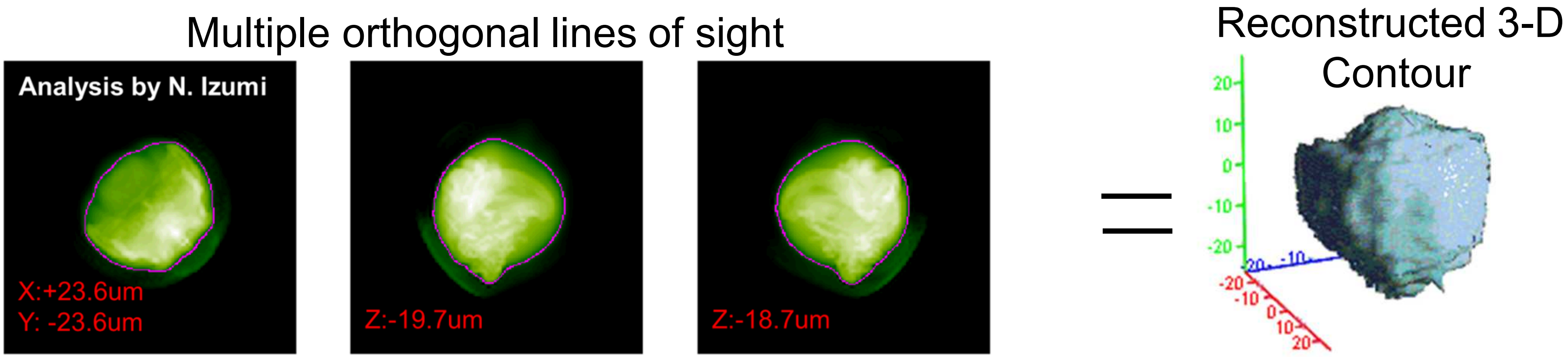




# The first implementation of pulse-dilation SLOS will be on NIF with pinhole optics and then K-B microscopes




**Three orthogonal LOS can theoretically provide 3-D information***



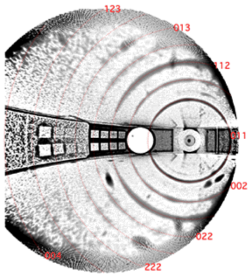



*Izumi (LLNL) et al.

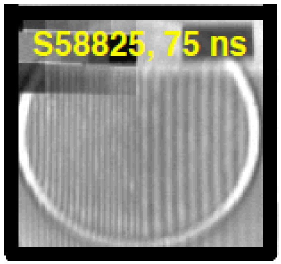
# Fast-gated multi-frame CMOS sensors will transform capability across all HED programs

## High Pressure Materials

Diffraction

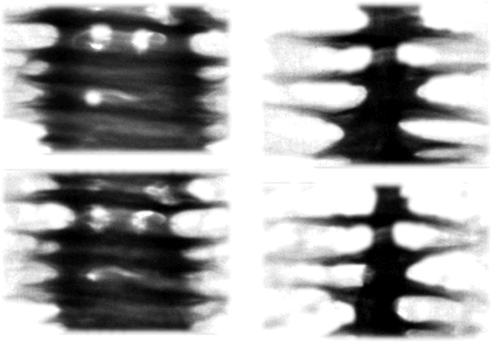


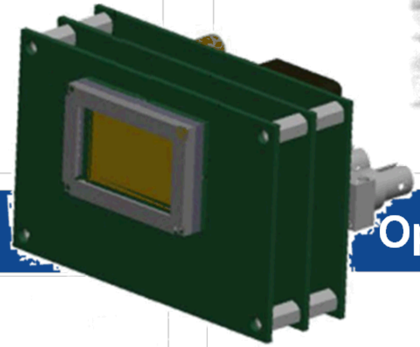
Strength




## Complex Hydrodynamics

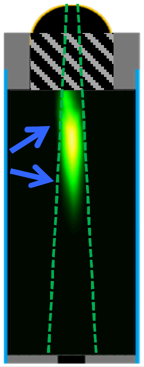
Radiography



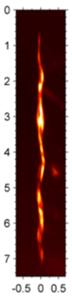


## Ignition Applications

Laser Preheat



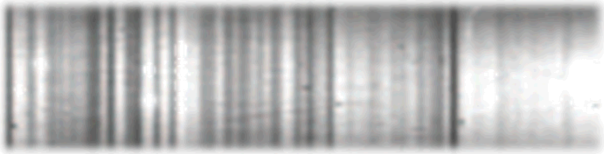
Stagnation



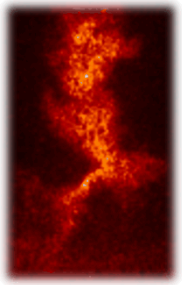

Spectroscopic Mix

## Opacity, Outputs & Effects

Absolute Gated Spectra

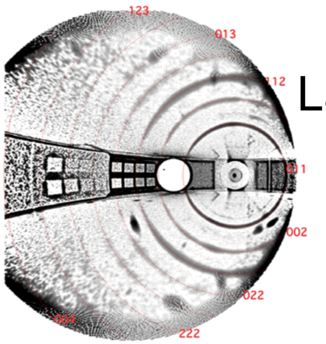


High-Z K-$\alpha$ Imaging



# Coupling hCMOS sensors to pulse-dilation provides ultra-fast gating and flexible detection area

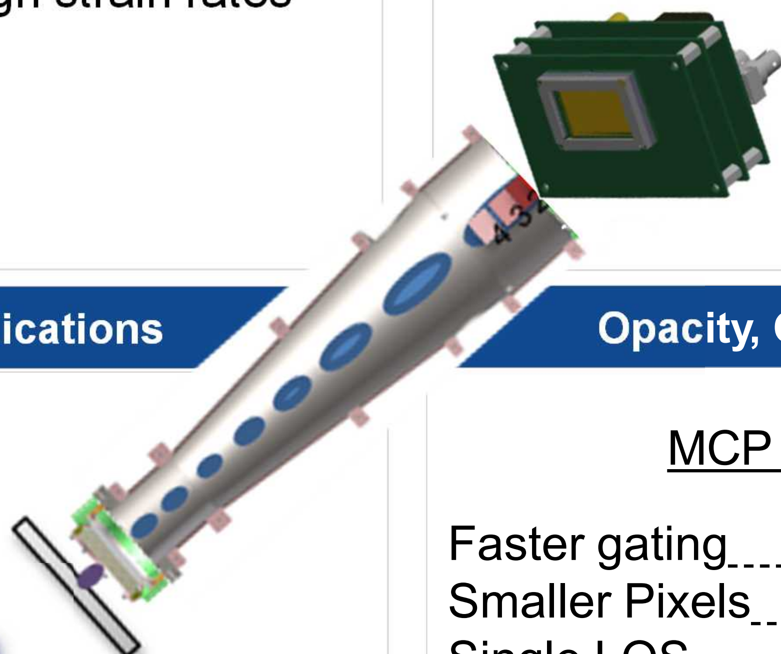
## High Pressure Materials

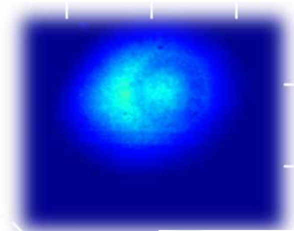


Diffraction
Large angular coverage
High strain rates

## Complex Hydrodynamics

High Speed Radiography

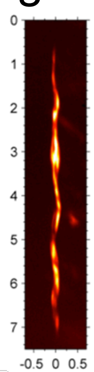




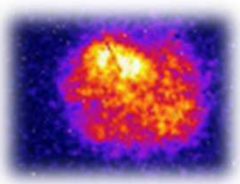
UNIVERSITY of ROCHESTER

## Ignition Applications

Z-Pinch Stagnation




Hot-Spot Imaging



3-D
$T_e\ (r,\theta,\phi,t)$

## Opacity, Outputs & Effects

MCP replacement

Faster gating______<10 ps up to 1 ns
Smaller Pixels_____25 μm
Single LOS________Better optics

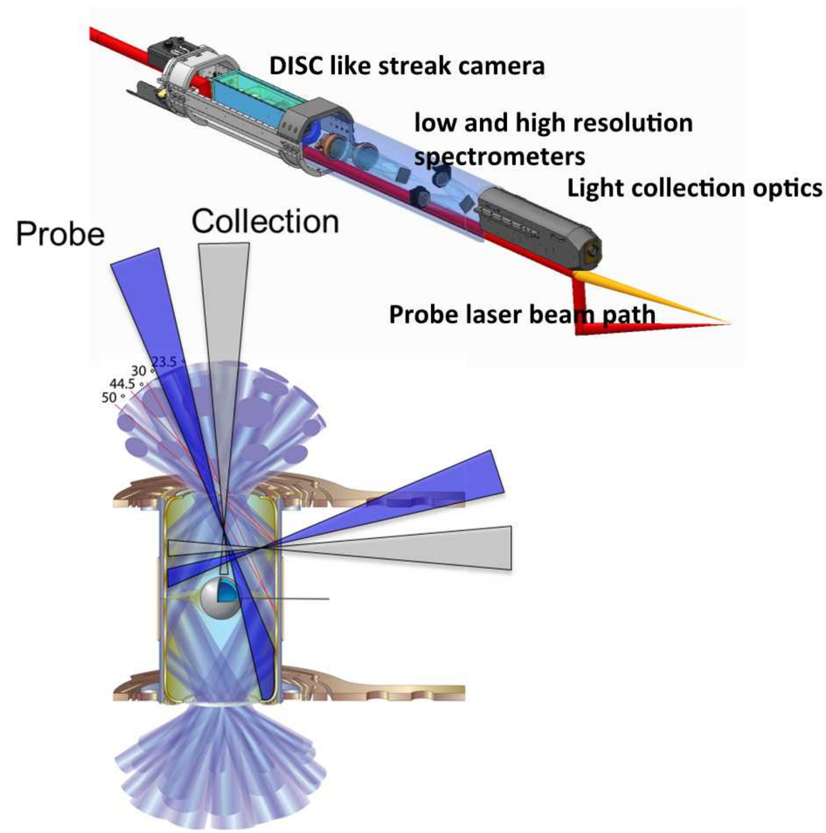
# **Research Thrust:** Local determination of the plasma conditions in low-density plasmas.

## Science Drivers

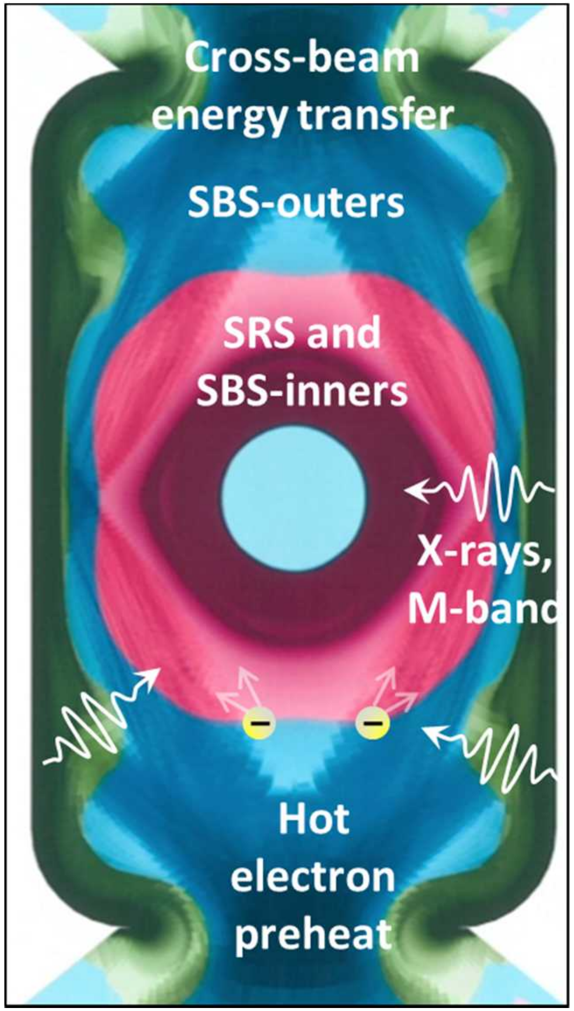
- Hohlraum plasma formation and energetics
- Radiation channel evolution
- MagLIF LEH window interaction and gas heating
- Coronal conditions of direct-drive capsules
- Electron transport
- Independent of spectroscopy

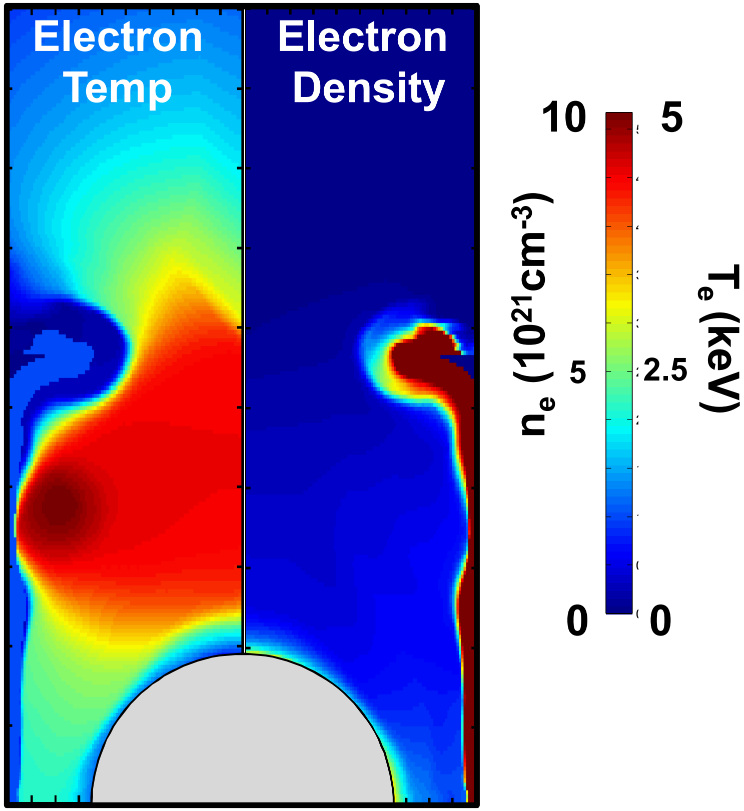
## Transformational Diagnostic Approach

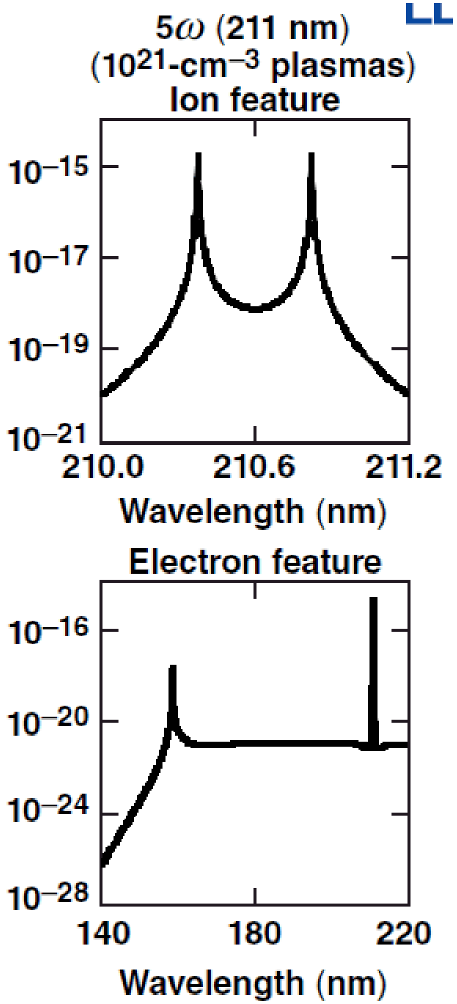
- Time-resolved Optical Thomson Scattering at deep UV for localized probing of electron temperature and density



# NIF hohlraums have a complex plasma evolution that effects the beam propagation and system energetics



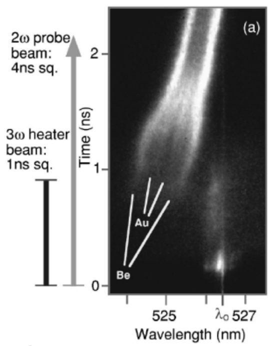




**Thomson scattering provides first principle, local, time-resolved measurements of under-dense plasma conditions ($T_e$, $T_i$, Z, $N_e$)**

# Every modern NNSA laser facility has implemented Thomson scattering

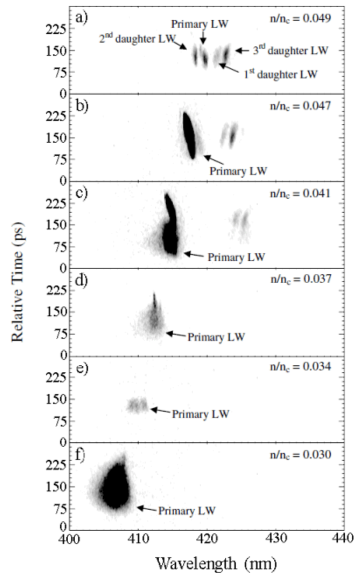
**NOVA**




Thomson scattering from laser plasmas

S. H. Glenzer et.al.,
Phys. Plasmas **6**, 5 (1999)

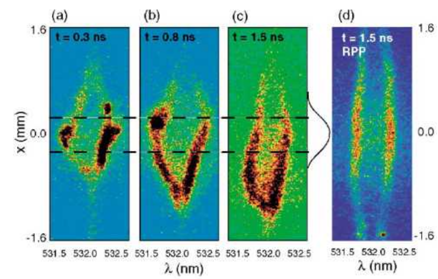
**Trident**




Observation of a Transition from Fluid to Kinetic Nonlinearities

J. L. Kline et.al.,
Phys. Rev. Lett. **94**, 175003 (2005)

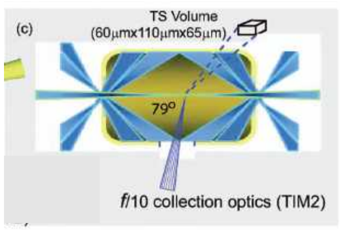
**JLF**

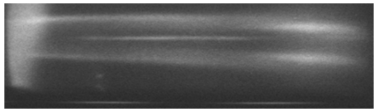



Effect of Nonlocal Transport on Heat-Wave Propagation

G. Gregori et.al.,
Phys. Rev. Lett. **92**, 20 (2004)

**OMEGA**

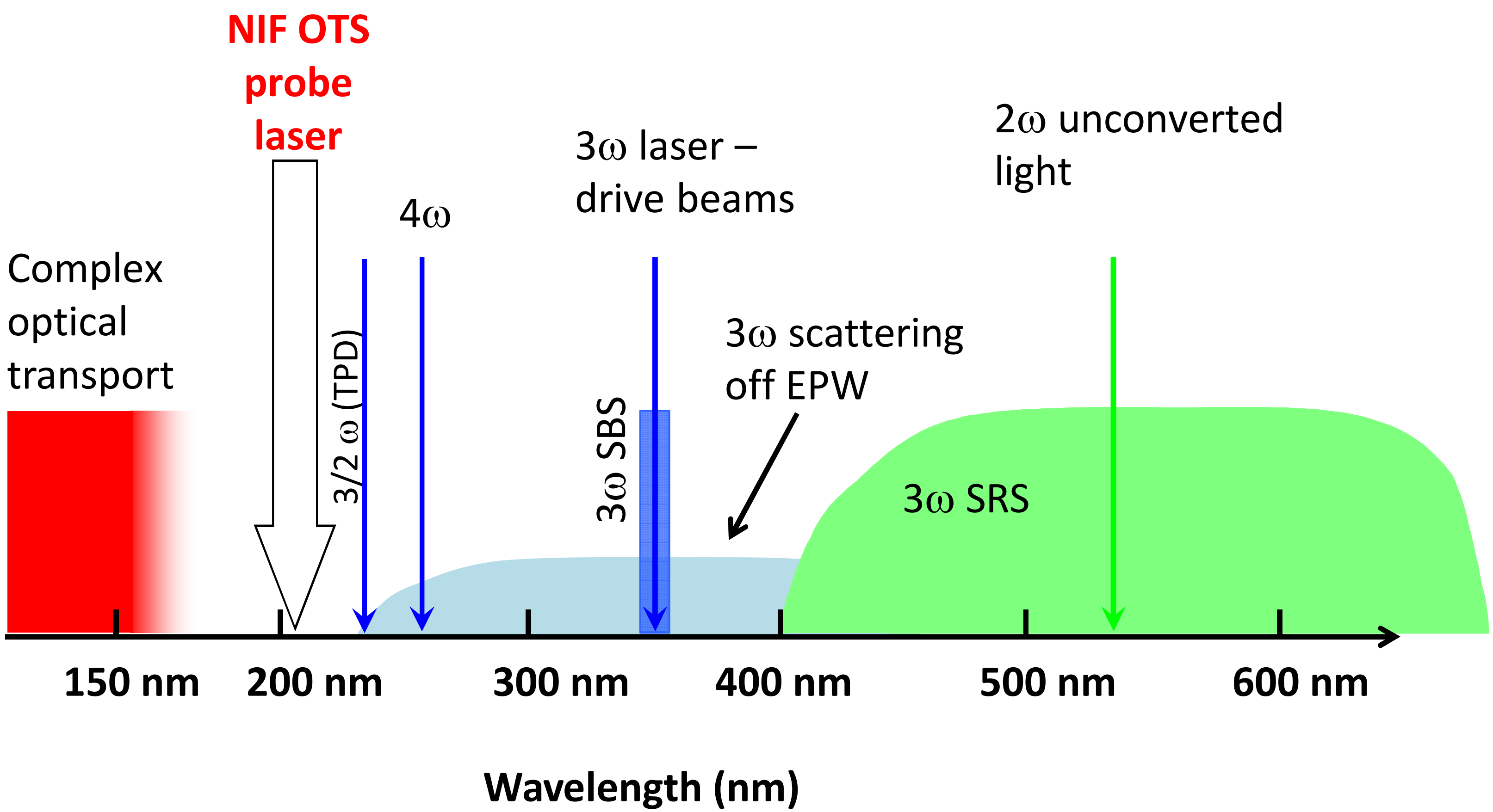


Thomson-scattering of high Te hohlraum plasmas

D. H. Froula et.al.,
Phys. Plasmas **13**, 052704 (2006)

# The harsh optical environment of a NIF hohlraum requires operation of Thomson Scattering in the deep-UV



# Realizing a high power 5ω laser requires new technology advancement in large crystals for frequency conversion

- **LLE is developing a compact laser driver suitable for delivering 200 GW of IR to be frequency converted for Thomson scattering**
- **A large aperture 5ω crystal testbed at LLE is developing the necessary technologies for efficient frequency conversion**
  - **ADP/KDP crystals require temperature tuning and stability around 230 K**
  - **CLBO crystals require heating to prevent structural failure**
- **5ω Thomson scattering probe will**
  - **Provide access to higher densities**
  - **Reduce refraction**
  - **Avoid LPI generated background from 351 nm drive beams**
  - **Allow standard large aperture optics to be used**

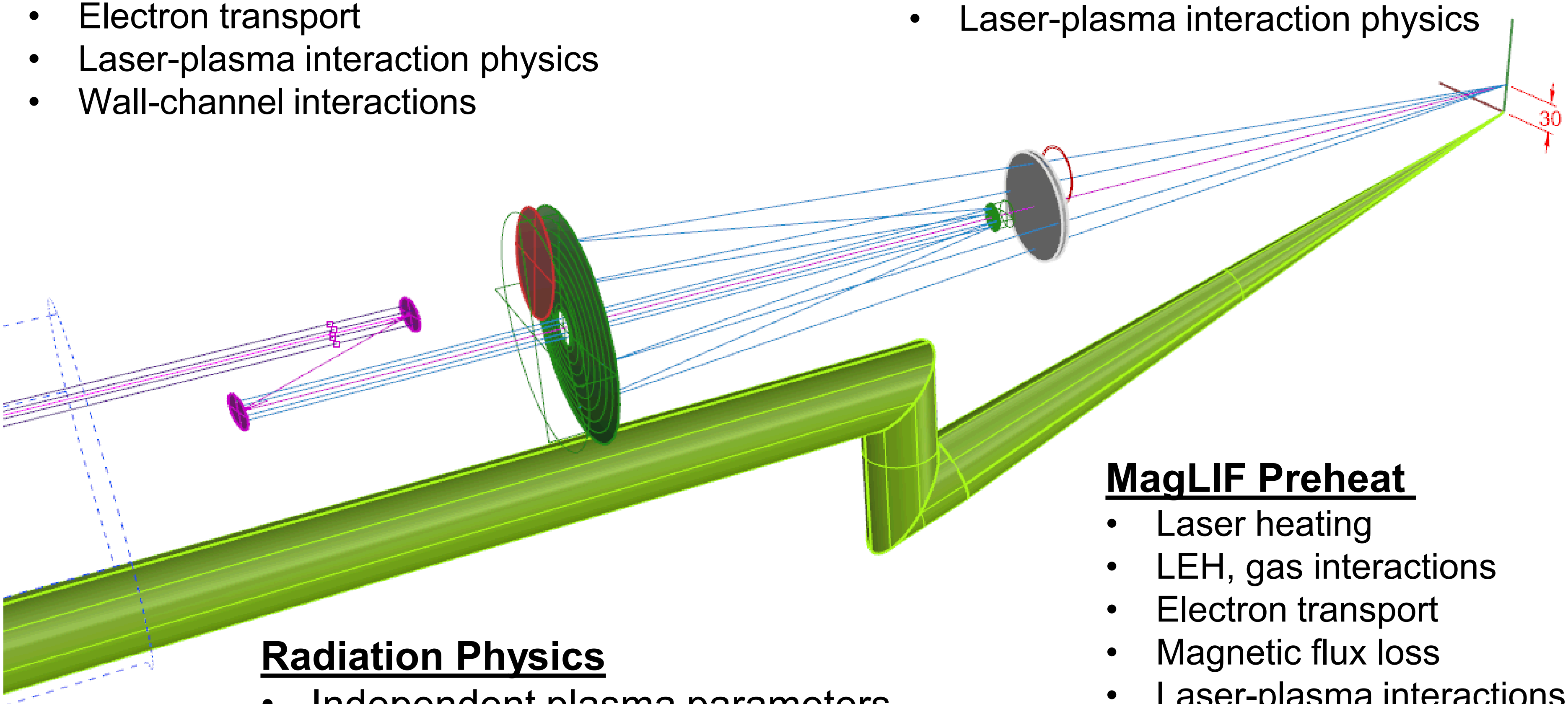
# This robust and precise deep UV OTS platform will transform our understanding across multiple missions

**Hohlraum Underdense channel plasma**

- Laser propagation
- Electron transport
- Laser-plasma interaction physics
- Wall-channel interactions

**Direct Drive Underdense Plasma**

- Laser propagation
- Electron transport
- Laser-plasma interaction physics




**MagLIF Preheat**

- Laser heating
- LEH, gas interactions
- Electron transport
- Magnetic flux loss
- Laser-plasma interactions

**Radiation Physics**

- Independent plasma parameters
- Cross-check of line broadening models

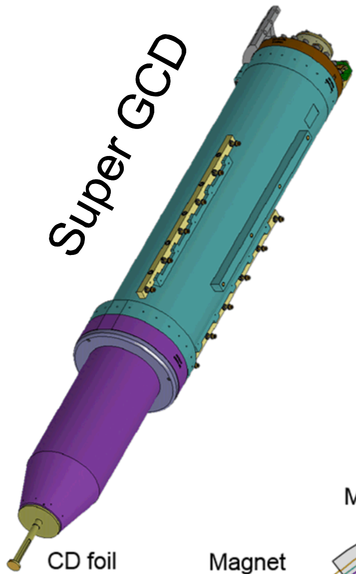
# **Research Thrust:** Detailed determination of fusing plasma evolution and burn propagation.

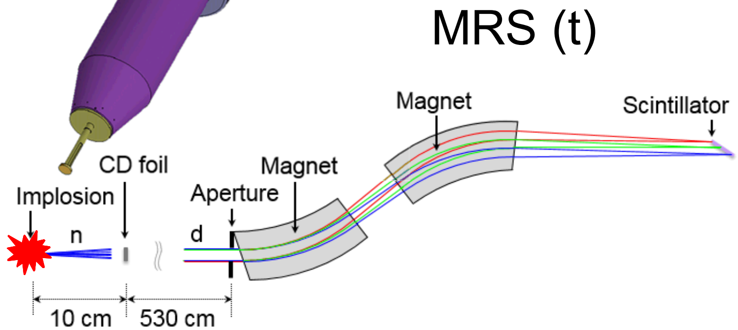
### Science Drivers

- Hot spot formation
- Ablator – hot spot mixing
- rho-r evolution
- Fusion propagation
- Ion – electron equilibration
- Nuclear Astrophysics

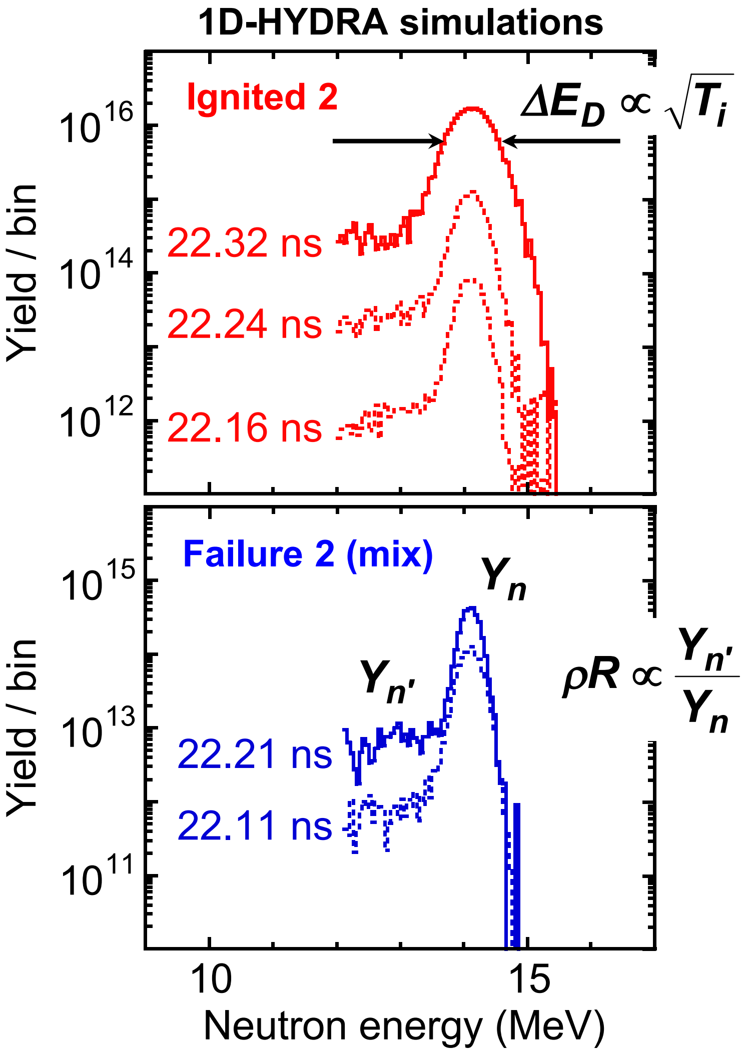
### Transformational Diagnostic Approach

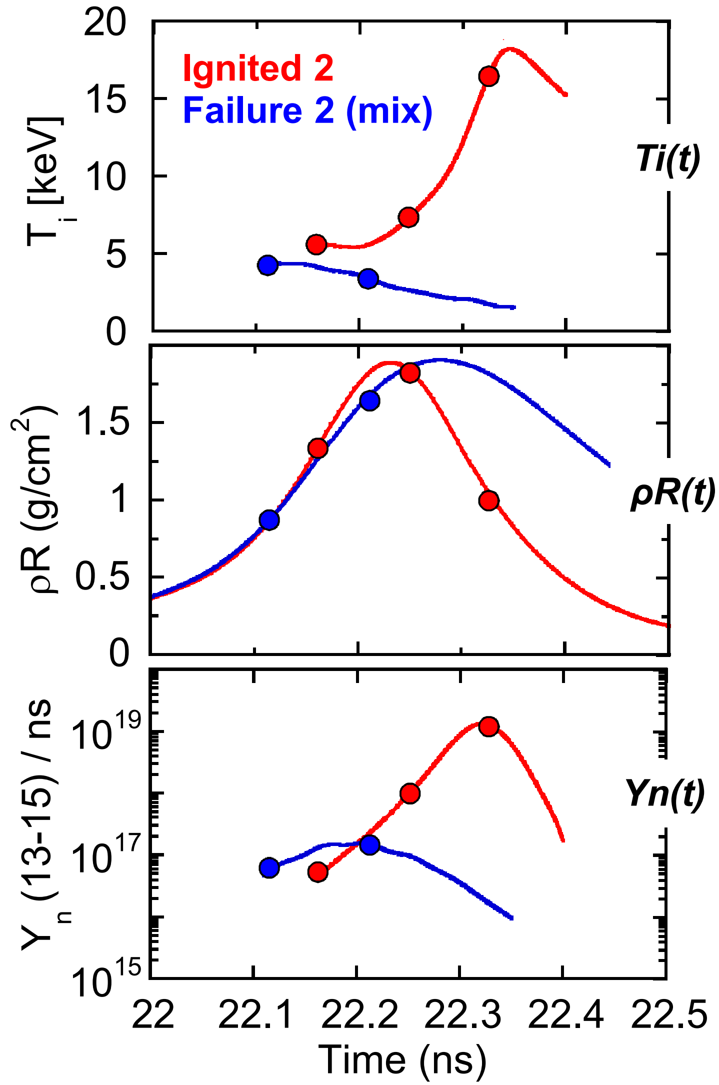
- Neutron/gamma imaging from multiple orthogonal directions
- High sensitivity Gas Chenkov Detectors (GCD) for high resolution fusion gamma spectroscopy
- Magnetic Recoil Spectrometer (MRS) coupled to time-resolved detectors (>1E16 yields)
- High resolution x-ray spectrometer for Ti, Te, ne



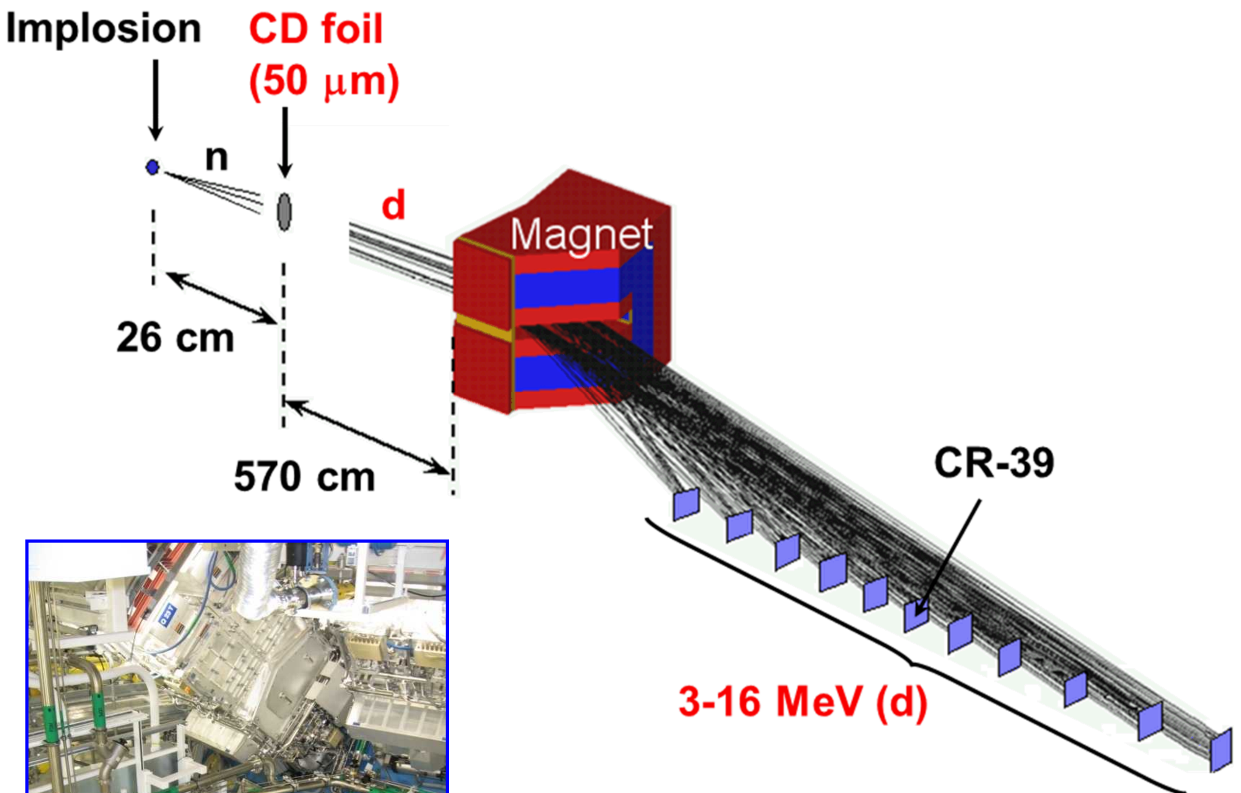



# Info on the ρR-Ti trajectory and burn history can be obtained through time-resolved measurements of the neutron spectrum

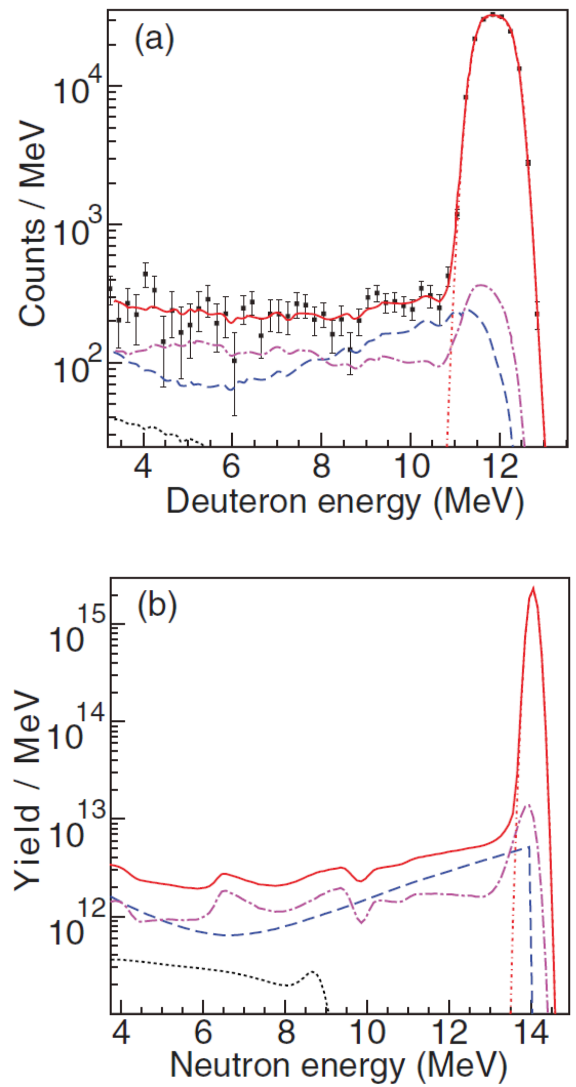


# The present MRS system on NIF measures the time-integrated neutron spectrum in the range of 4 – 20 MeV





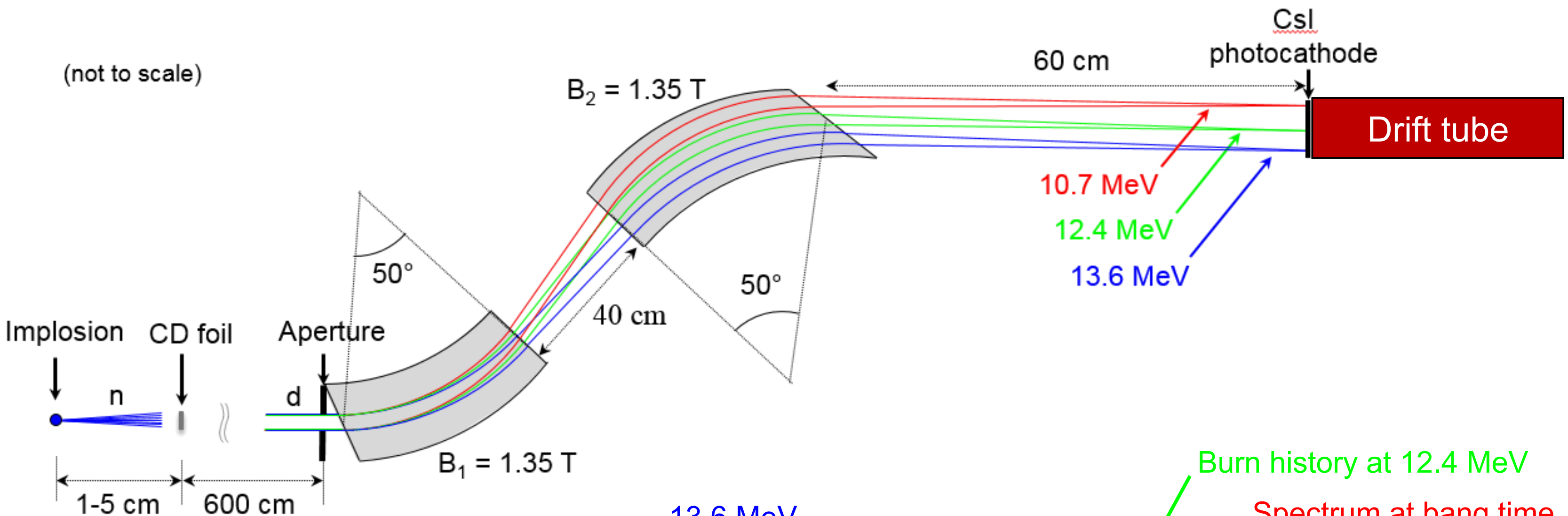


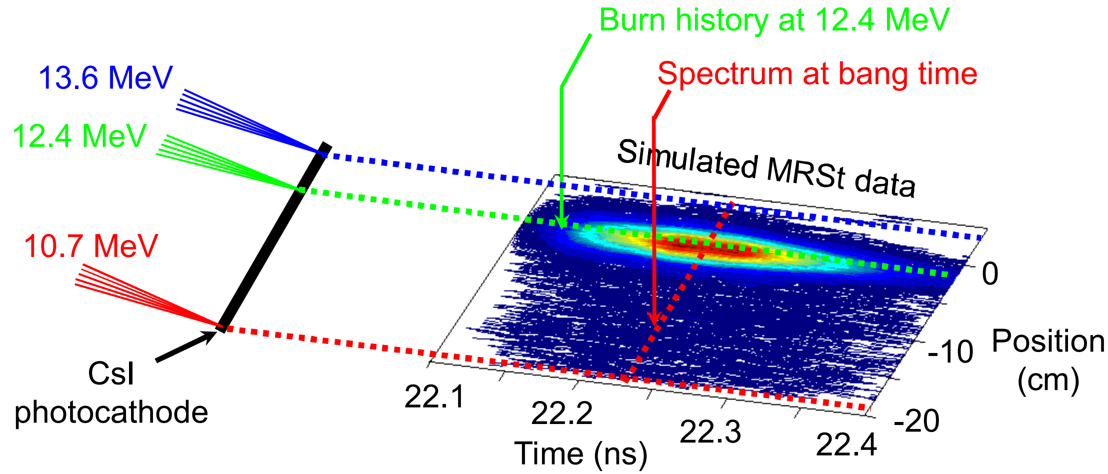



Frenje et al., POP (2010), Gatu-Johnson et al., RSI (2014)

# The MRSt concept combines the well-established MRS principle with a second magnet and a fast drift-tube system

**<u>Design goals</u>:** $\Delta t$ < 20 ps and $\Delta E$ < 200 keV for Yn> $10^{16}$

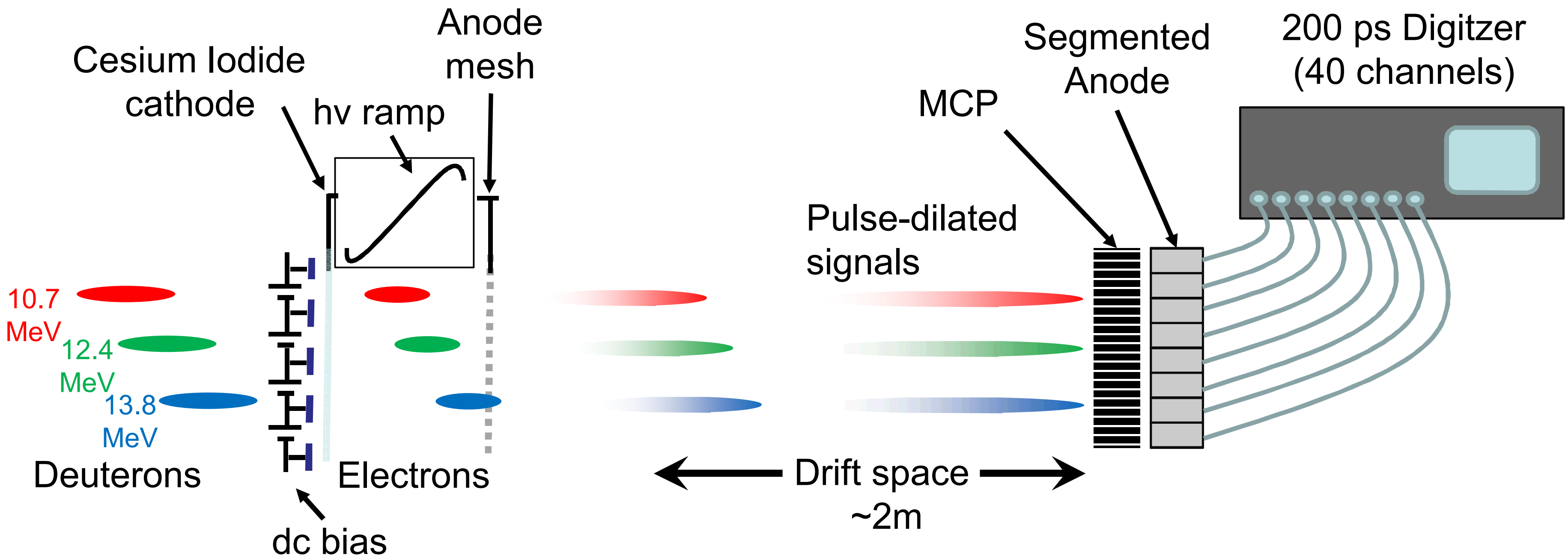



The path-length difference must be close to zero for deuterons with same energy

Frenje et al., POP (2010). Hilsabeck et al., RSI (2011).

# A new photo-detector based on pulse-dilation technology will enable high temporal resolution neutron spectroscopy

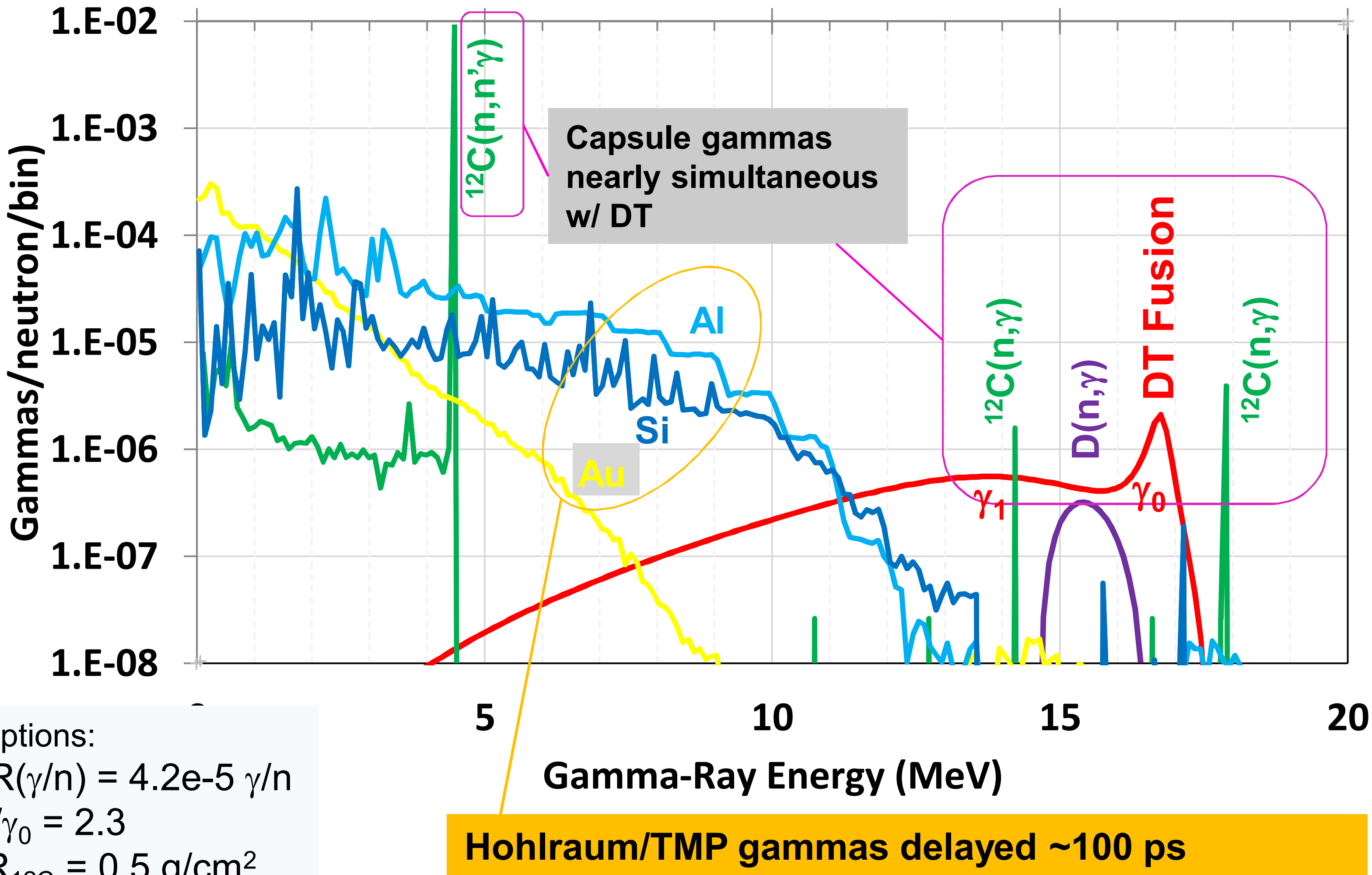



Deuterons arrive at photocathode with a 20 cm spatial & 15 ns temporal spread across the energy band

Instrument requires 750 digitizer channels with 20ps response time (impractical with standard methods)

Spatial voltage gradient superimposed on temporal voltage ramp provides correct potential to align spectrum in time while stretching the signals 10X so required digitizer response is 200ps.

# The Prompt γ-Ray Energy Spectrum from Indirect-Drive, Cryo-Layered Implosions carries valuable information.

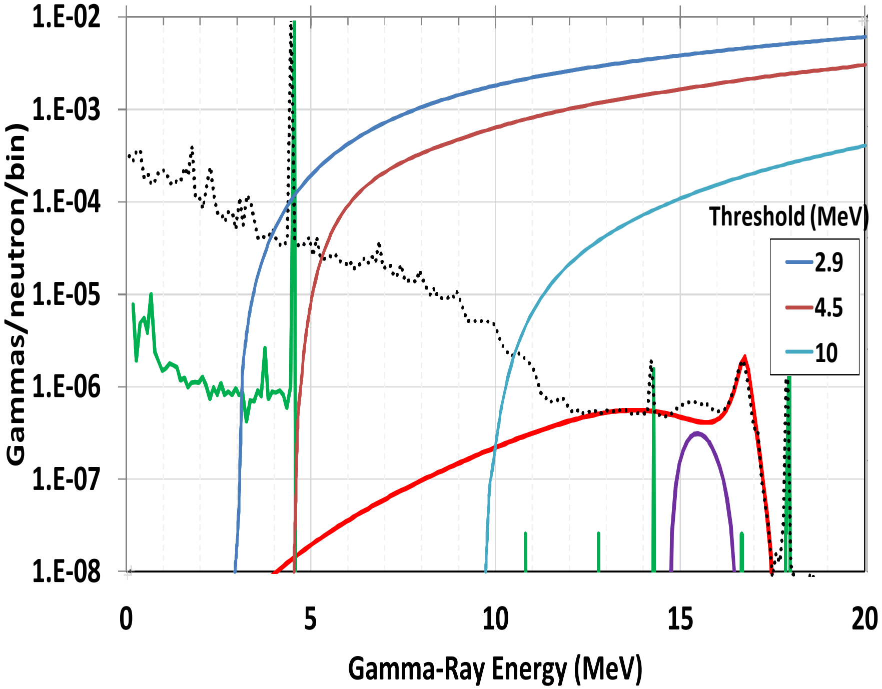



Assumptions:

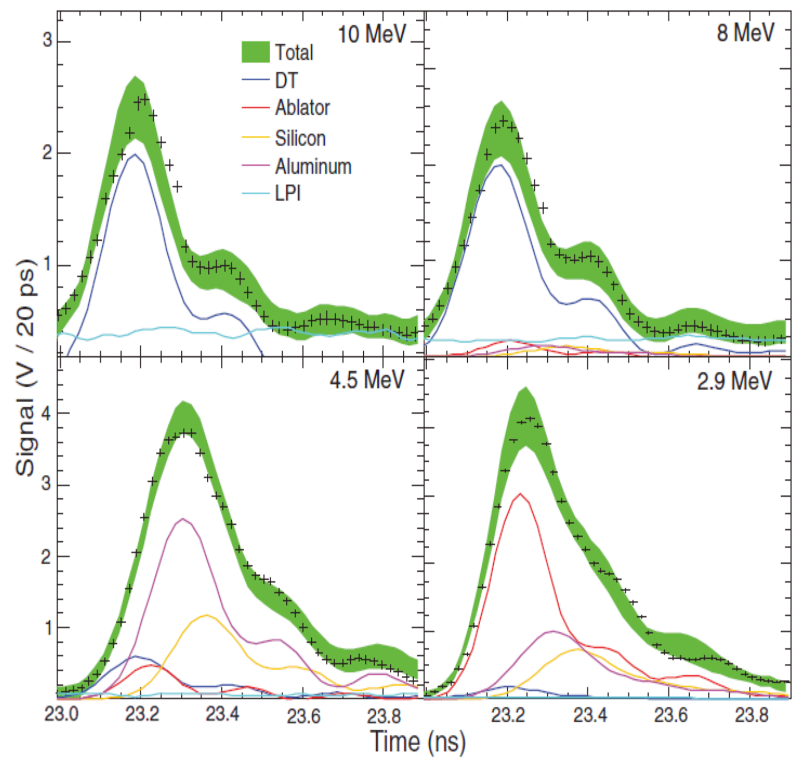
- $BR(\gamma/n) = 4.2e\text{-}5\ \gamma/n$
- $\gamma_1/\gamma_0 = 2.3$
- $\rho R_{12C} = 0.5\ g/cm^2$
- $\rho R_{DT} = 1.5\ g/cm^2$

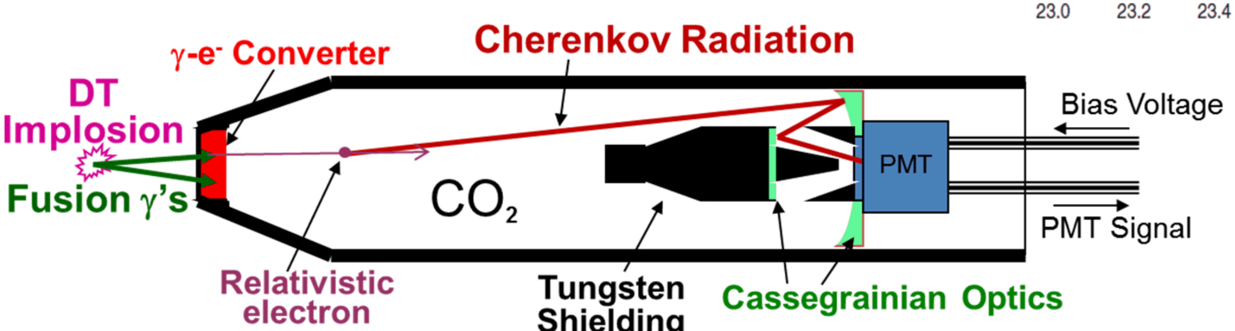
# Presently, the gamma reaction history on NIF is measured using Gas Cherenkov Detectors* (GCD) with energy thresholds.

**Calculated Gamma Spectrum**




**Measured Gamma History****



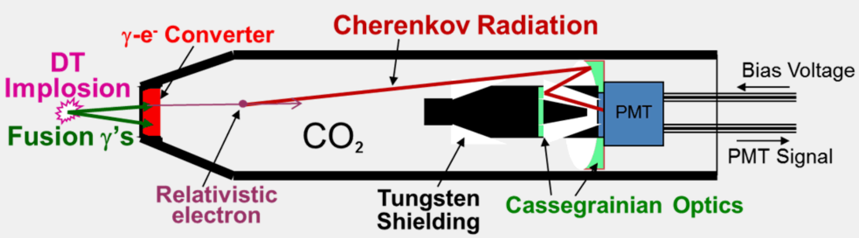






*Herrmann et al., RSI (2010) **Sayre et al., RSI (2012)

# Future capability will provide both higher time-resolution and a direct measure of the detailed fusion gamma spectrum.

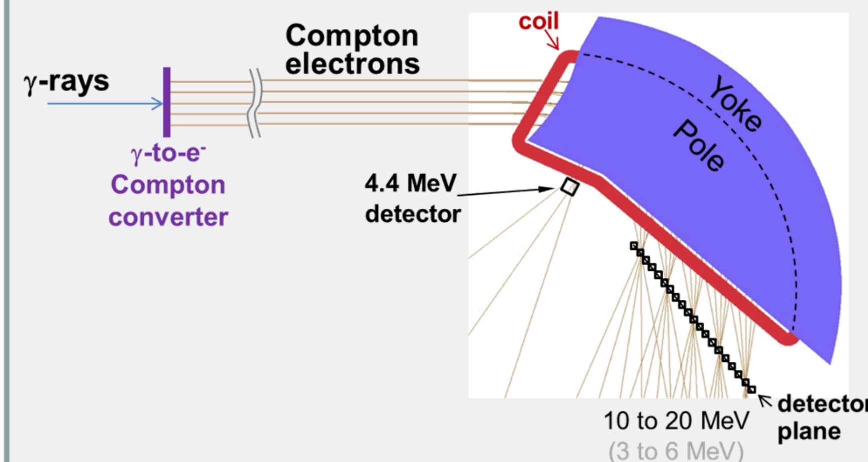
## Enhanced Gas Cherenkov Detectors for Reaction and $\rho R_{Abl}$ Histories




### Super GCD Design Goals:

- High Sensitivity (~200x GRH-6m)
- High Temporal Resolution (10 ps goal, ~10x faster than GRH-6m)

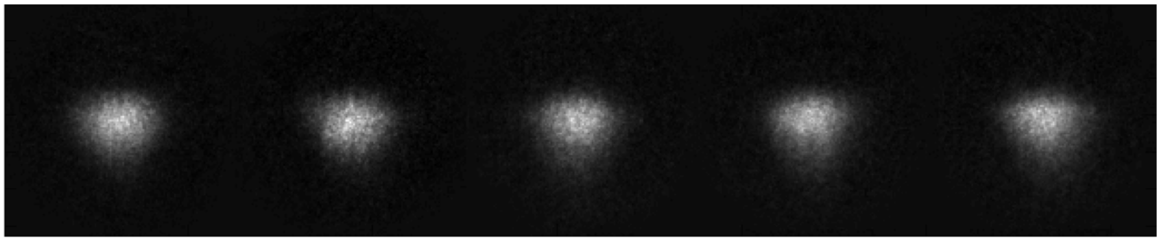
## Compton Spectrometer for gamma spectral measurements

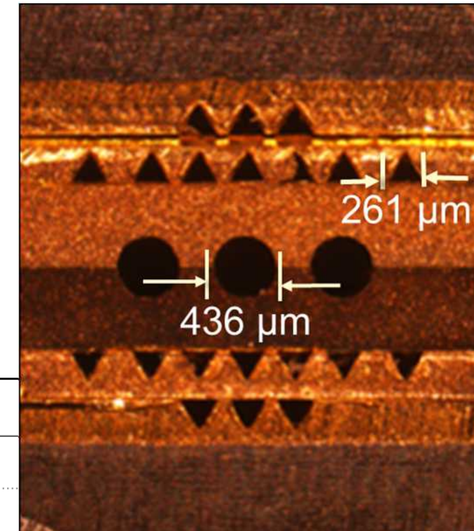


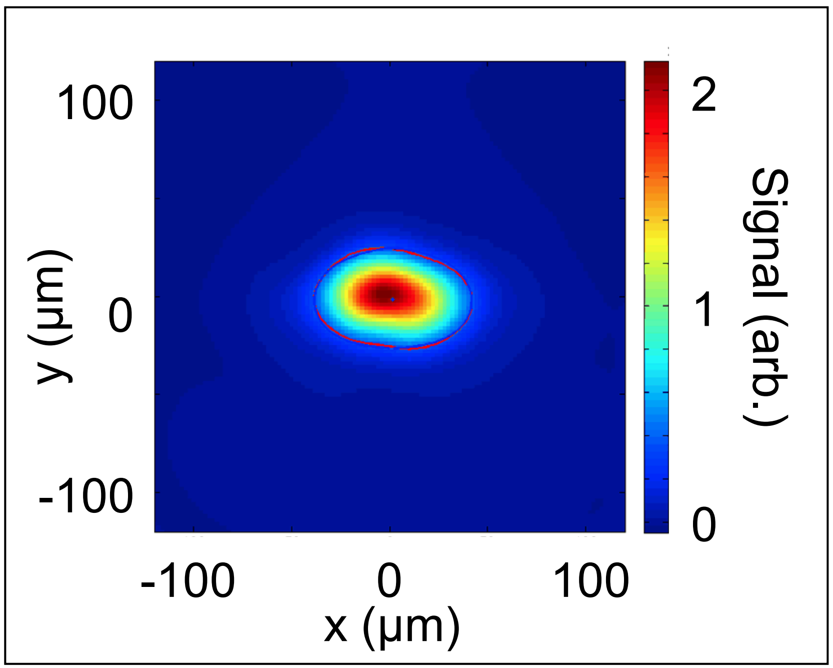

### GEMS Design Goals:

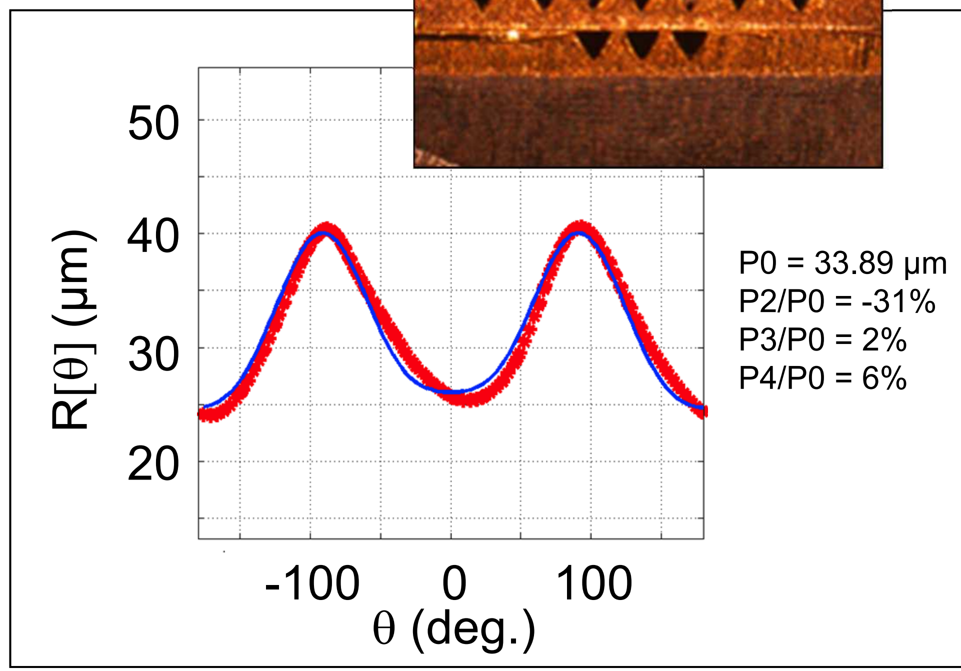
- Energy Resolution: $\Delta E/E \leq 5\%$
- Energy Range: $E_0 \pm 33\%$ within 2-25 MeV
- Temporal response < 1.5 ns
- Viable at $Y_{DTn} \geq 5e14$

# Neutron imaging on the NIF is done with an array of triangular pinholes analyzed through a forward reconstruction

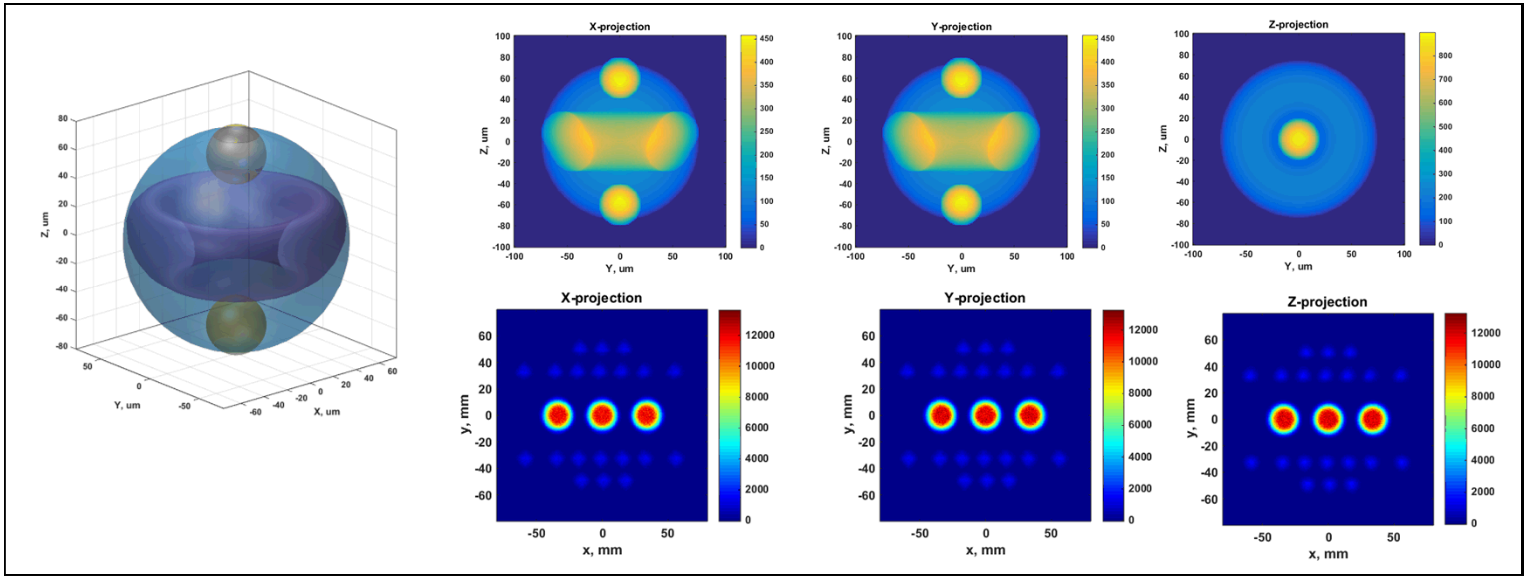




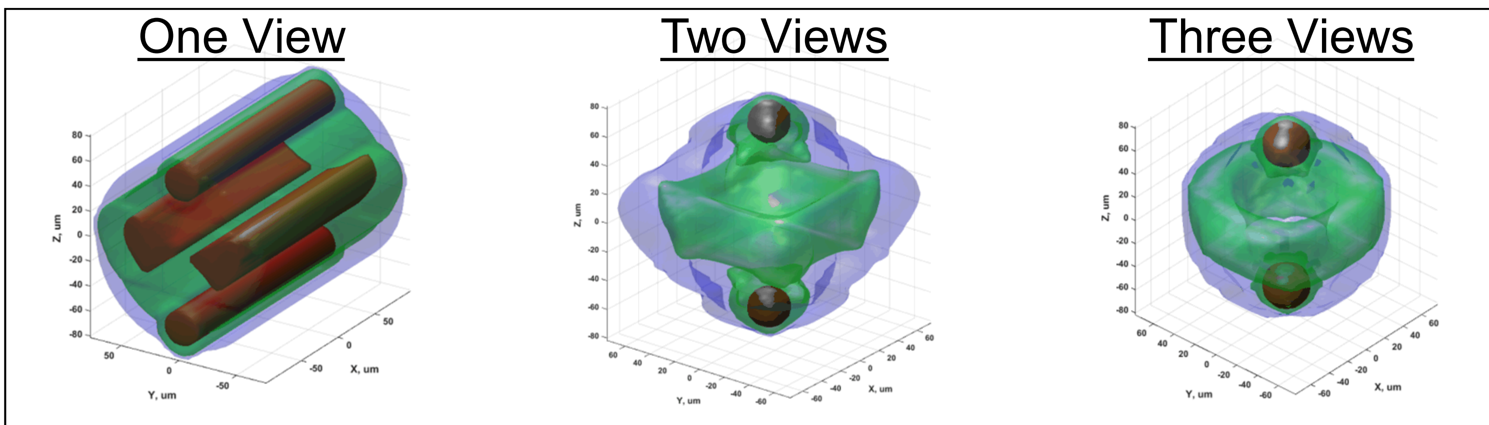



# Synthetic data tests indicate that complex hot-spot shapes can be measured through imaging from three ~orthogonal LOS

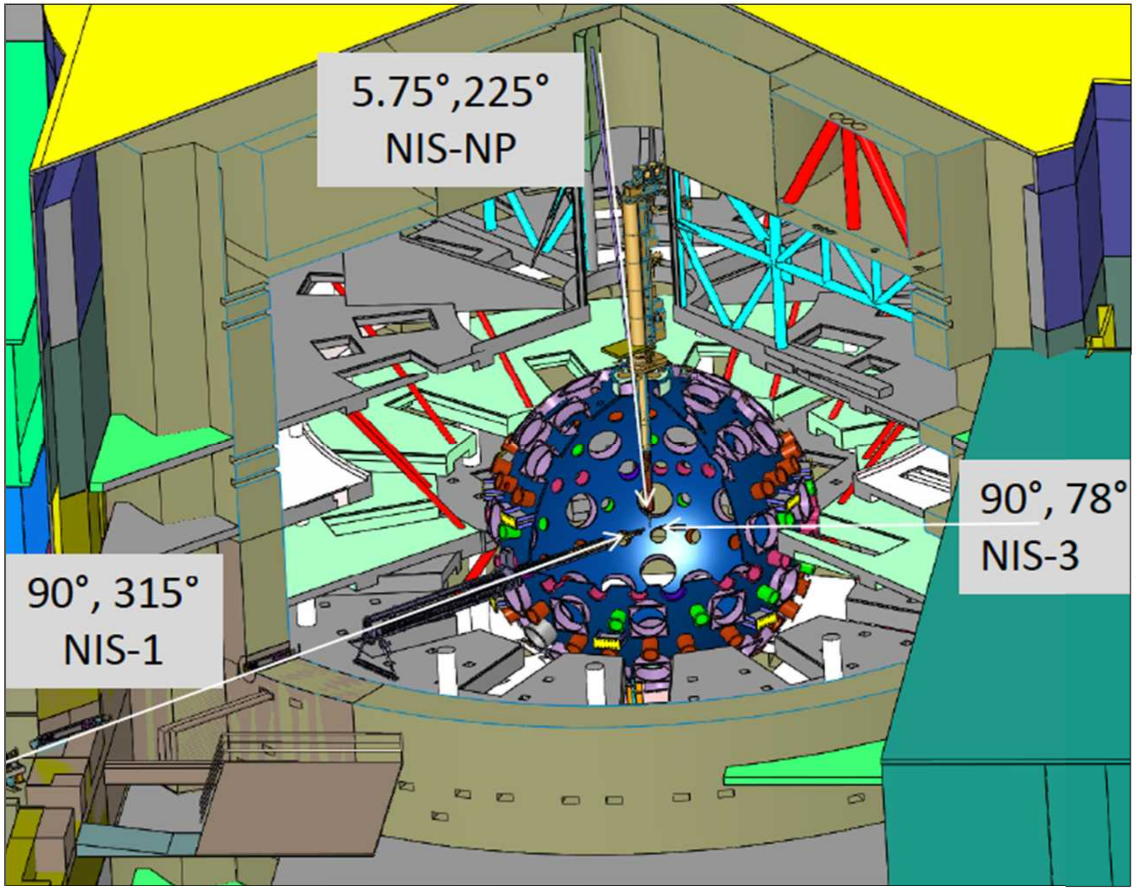



Generate projections

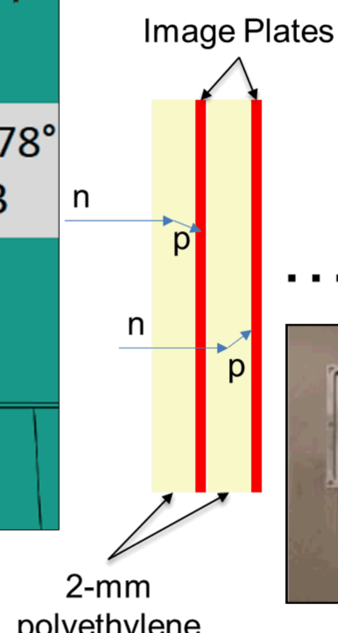
Forward model through pinholes with $10^{14}$ neutrons.



# Two new imagers will be added to the NIF to enable 3-D reconstructions of ICF implosion cores



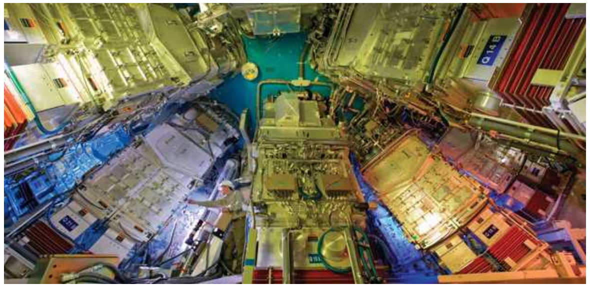

- Neutron Yield (13-17 MeV): 1e15 to 1e19
- Resolution (after reconstruction): 10 μm or better
- Reconstructed Field of View: 200 μm
- Total Field of View of Aperture Array: 700 μm




# Extra

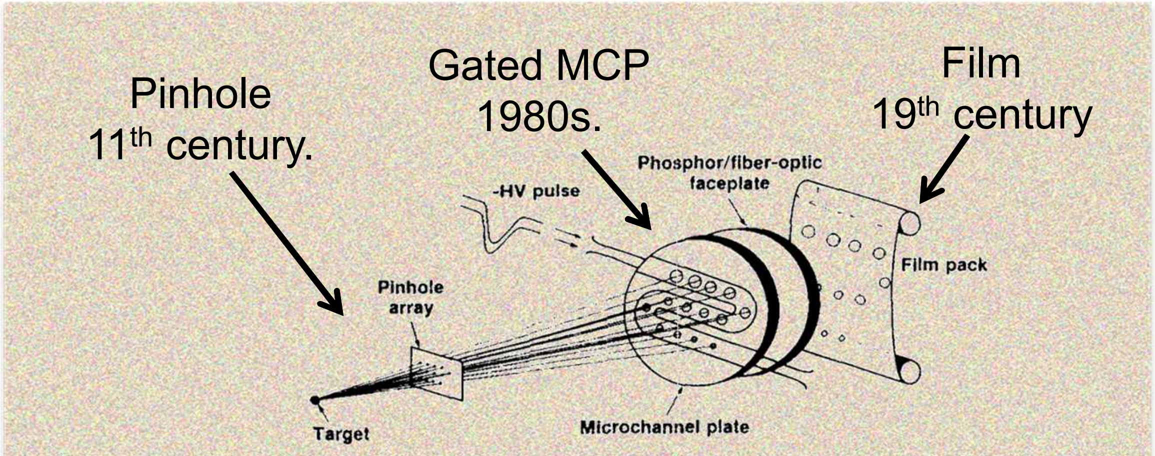
# Major investments in facilities and computation are ongoing but diagnostics are largely based on old technology

**Sequoia Petascale Computer 2011-2012**



**NIF-Operational in 2009**

**A standard HED imaging system**

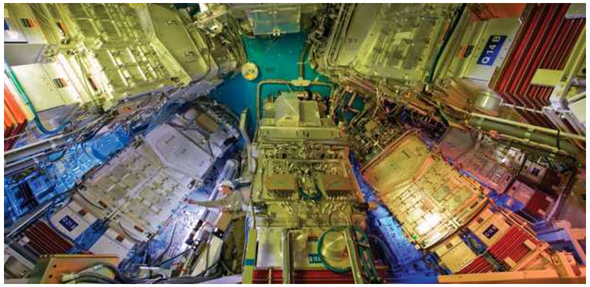



Bradley, Bell, Kilkenny et al., NOVA & OMEGA, c. 1990

We understand these technologies better and significant improvements in engineering and automation have resulted in increased precision, reliability, and efficiency.

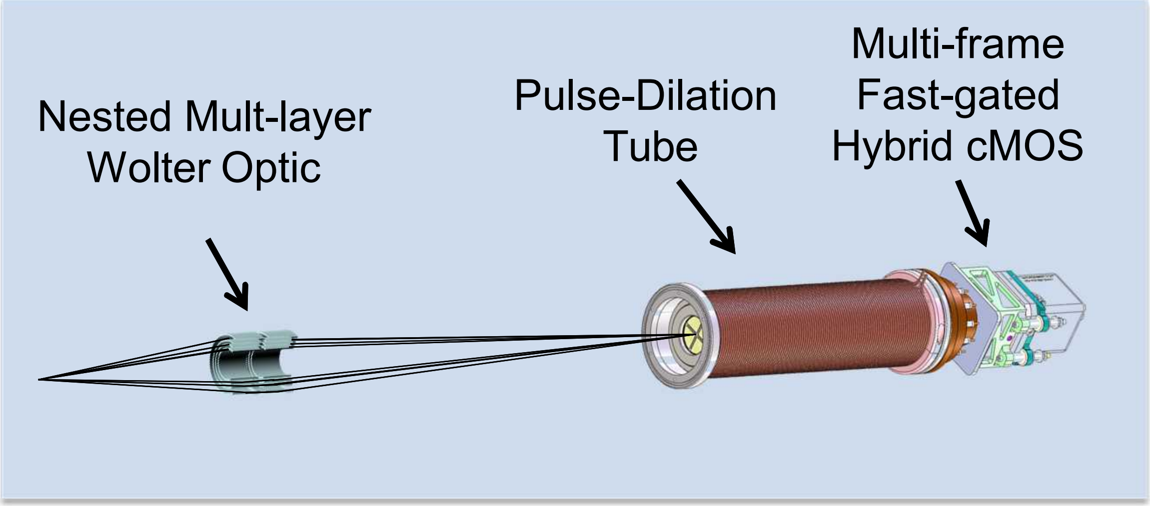
# Major investments in facilities and computation are ongoing but diagnostics are largely based on old technology

**Sequoia Petascale Computer 2011-2012**



**NIF-Operational in 2009**

**A future HED imaging system**




| | **Conventional** | **Future** |
|---|---|---|
| Spatial Res | 10s of microns | < 5 micron |
| Time Res | ~100 ps | < 10 ps |
| Frames | Few | 10s |
| Solid Angle | $\sim 10^{-7}$ | $\sim 10^{-5}$ |
| Bandwidth | Broad (filters) | Narrow (Multi-layers) |

# The diagnostic management group binned activities into three categories: Transformational, Broad, and Local

**Transformational:** Major national efforts with the potential to transform experimental capability for the most critical science needs across the complex

**Broad:** Significant national efforts that will enable new or more precise measurements across the complex

**Local:** Important efforts involving implementation of known technology for a local need

| Transformational | Broad | Local |
|---|---|---|
| 16-frame high time-res gating | Particle Temporal Diagnostic | KB microscope |
| UV Thomson Scattering | Precision nToF | High energy spectroscopy |
| Fusion Gamma($t,h\nu$) | B-fields on NIF | Various NIF/Omega snouts |
| 3-D fusion burn imaging | Pulsed x-ray cal source | Crystal imaging & backlighting |
| Fusion Neutron($t,h\nu$) | Pulsed neutron cal source | Radchem |
| X-ray($t,h\nu$) $\lambda/\delta\lambda$ ~ 10000 | High-res x-ray streak cameras | Photonic Doppler Velocimetry |
| 30-50keV image,10 ps, <10$\mu$m | High energy detectors | …many more… |
| Diffraction(t) | Radiation hardening | |
| High resolution n/$\gamma$ spectra | | |

# The National Diagnostic Plan builds on exciting recent developments in transformative technologies

- A hybrid CMOS camera recording presently 4, and soon more, ~1 ns x-ray gates on each of a 512 x 1024 array of 25 micron pixels.

- The ability to magnify in time ( DIXI) and space an x-ray image, and in the future to read out with the above cMOS array, x-ray gate times <10 ps.

- The capability of increasing the ~100 ps speed of today's photomultipliers down to ~ 10 ps.

- The ability to image and detect with good spectral and spatial resolution, x-rays up to energies of 50 keV.

- The cost effective design of a stand alone laser system to provide up to 10 Joules in < nsec pulses in the deep u.v. ( 210nm) for optical Thomson scattering in holhraums.

# The National Diagnostic Plan will make a significant difference in experimental capabilities across the complex

**Stimulating Innovation and Impacting Other Fields**

- Pulse-dilation PMT
- hCMOS detectors for High-energy and particle physics

**Cross-fertilization**

DIXI (GA/LLNL)
hCMOS (SNL)
} Single LOS (SLOS) fast gated imaging →
- KB Imaging of 3-D plasmas
- Wolter Imaging for Strength & K-$\alpha$ source development
- Time-resolved Diffraction

**Cost-Effectiveness**

- Better facility Utilzation: Many-frame backlit or stagnation images per shot
- Problem solve and demonstrate capability on one facility before implementing on the others
- Most cost effective engineering

**Revitalizing Experimental Science and Motivating Improved Mod/Sim**

Change the dimensionality, time-scale, and energy resolution by which we view the HED world

# The national plan focuses on the transformational technologies, but we will monitor efforts at each facility to identify synergies

- There are dozens of diagnostic capabilities proposed at the three major ICF facilities over the next 5 years.
  - All are important, but many involve implementing known technologies to fill gaps in capability for near-term experiment goals

- All facilities need a level of discretion on new capabilities.
  - Facilities have unique requirements
  - React to near-term deliverables
  - Respond to facility-specific user communities
  - Capitalize on strengths of the local facilities and science community

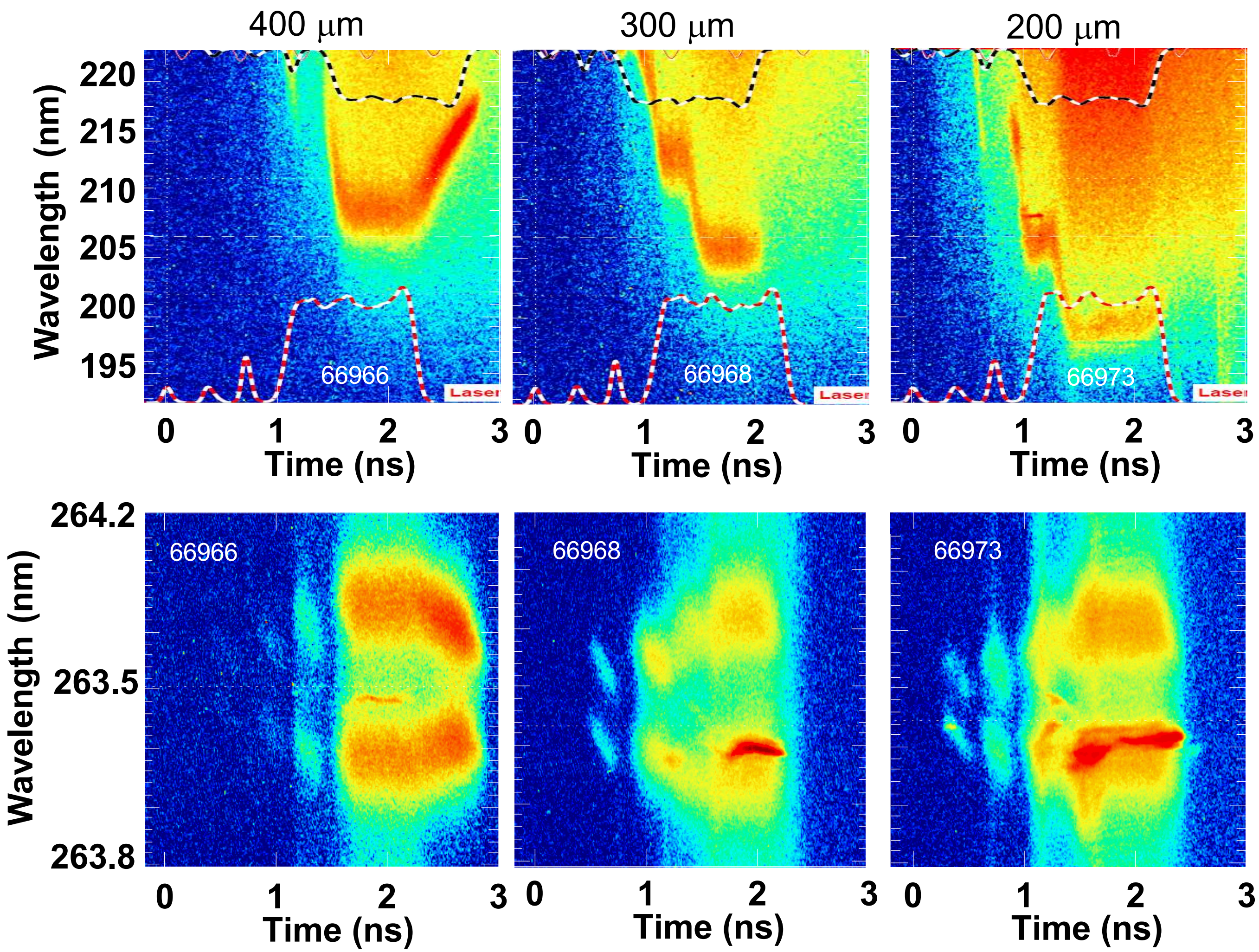
- Maximizing impact requires staying focused on transformational technologies
  - Fundamentally change our experimental capabilities
  - Require multiple years and stable funding to realize

# We've developed an integrated roadmap to realize these transformational diagnostic technologies in the next 5 years.

## Transformational Diagnostics

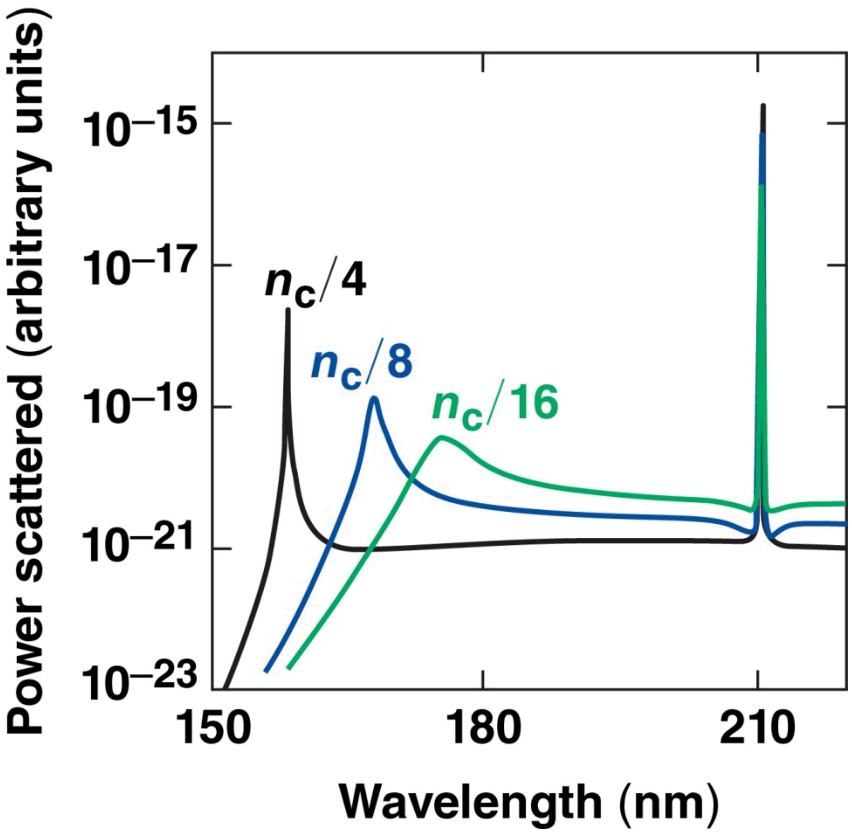
| Measurement needs | | Technology | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 |
|---|---|---|---|---|---|---|---|---|---|
| Multi-frame single line-of-sight detection | SLOS | Hybrid CMOS sensors & drift tubes | 2-frame; Z & NIF | 4-frame; Z/NIF/Ω | SLOS+KB | 8-frame | 40 keV diodes; SLOS+Wolter | 16-frame | |
| Localised low-density plasma ρ & T | OTS | Deep UV Optical Thomson Scattering | Xtal (LLE) | Laser | Emission NIF | Ω, NIF | | | |
| Time/space resolved Burn-Boost | Super GCD | Time-resolved γ spectrometer (GCD) | | Bkg | 20ps; ~1 meter | start GEMS | | | |
| | NIS/GRI | Three-dimensional n & γ imaging | | | GRI 90-315 | | Polar n/g(time) | Eq NIS/GRI | 3D n & γ |
| Time resolved Te, Ti and ρr in burn-boost | HiRES | High-resolution x-ray spectrometer | | EP (static) | EP (t), NIF (static) | NIF (t); Ω (t) | NIF Exo-chamber | | |
| | MRS-t | Time-resolved n spectrometer | | | | CD-readout | NIF | | |
| Time resolved phase change | Tardis-t | Time-resolved x-ray diffraction | | | NIF (GXD) | Z (static) | NIF (SLOS) | Z (t) | |
| High energy, x-ray imaging/ hi ρr | Wolter | Multi-layer Wolter | | | Z (static) | NIF (SLOS) | Z (SLOS), NIF (50 keV) | | |

# The methodology for the NIF system design is based on the 4ω Thomson-scattering system at OMEGA



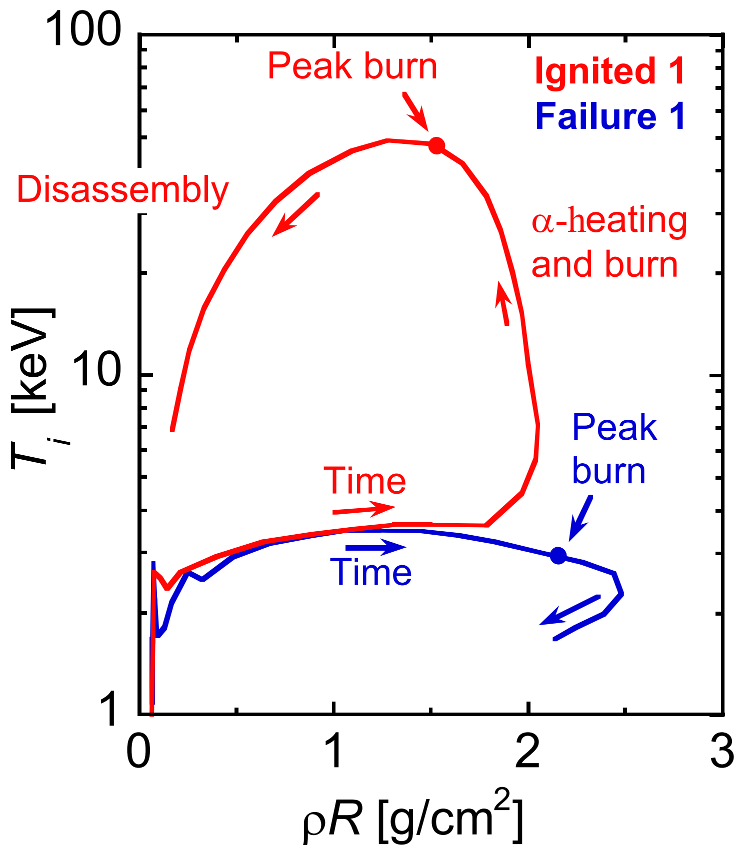
# A 5ω probe beam will generate Thomson scattered light in the deep-UV

- **The primary technology challenges are associated with 5ω scattering**
  - **Photocathode sensitivity**
  - **Optical filters/coatings**

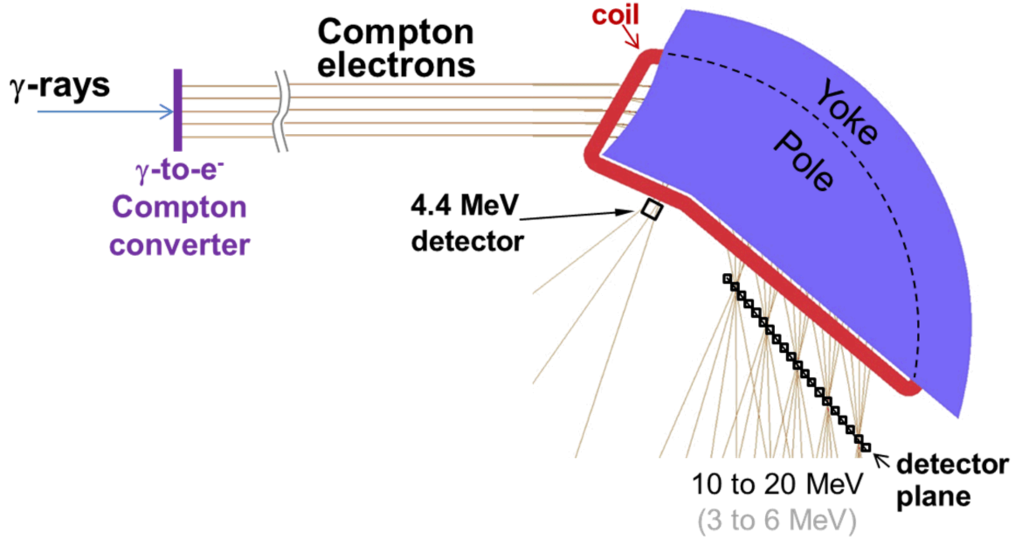


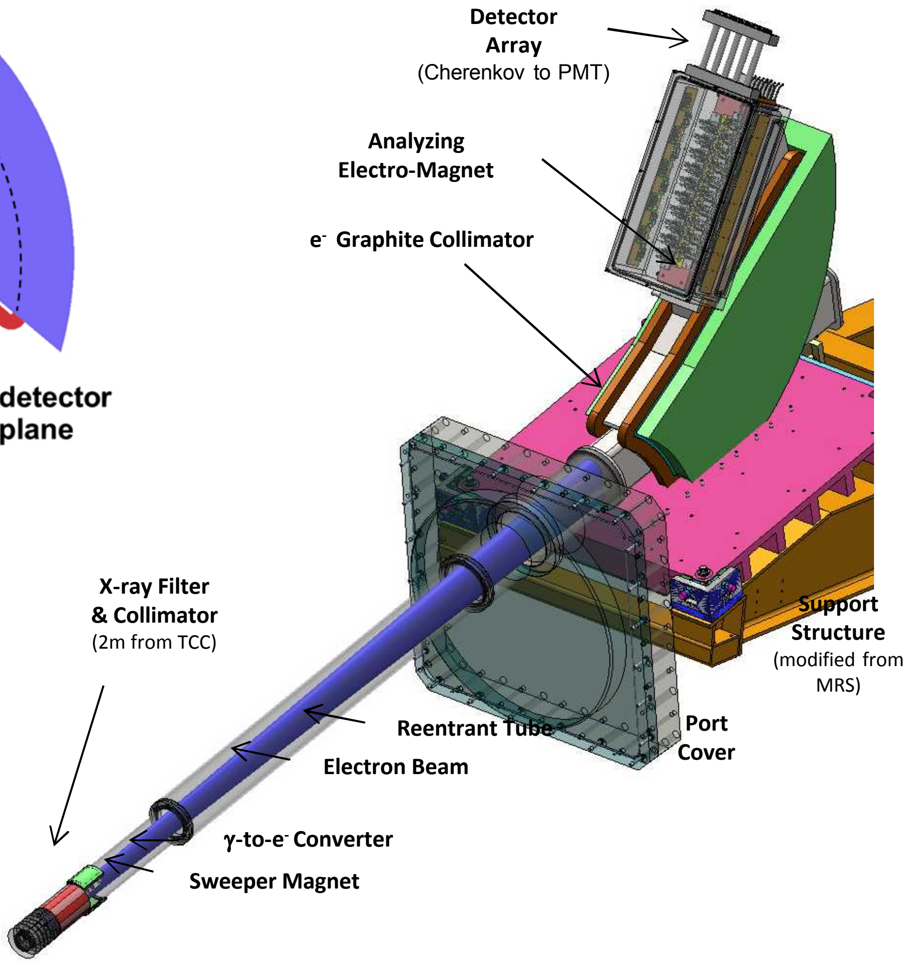

A Phase I diagnostic is currently being implemented to measure the background and define the 5ω laser power required

# *ρR-Ti* trajectory data will provide new information about the evolution of fuel assembly, hot-spot formation and alpha heating



# The Gamma-to-Electron Magnetic Spectrometer will be a transformative capability for diagnosing capsule implosions.




## Performance Goals

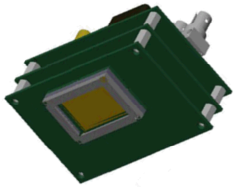
- Energy Resolution: $\Delta E/E \leq 5\%$
- Energy Range: $E_0 \pm 33\%$ within 2-25 MeV
- Temporal response < 1.5 ns
- Viable at $Y_{DTn} \geq 5e14$

# **Research Thrust:** High energy, high resolution many-frame imaging.

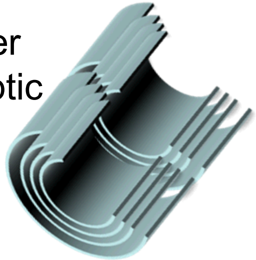
**Science Drivers**

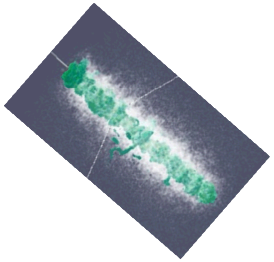
- Non-thermal x-ray production
- Material strength with high-energy radiography
- Complex hydro
- Three-dimensional ICF implosion dynamics
  - Characterize final stages of implosions and propagating burn
  - 3-D through multiple views

Hybrid CMOS



Multi-Layer Wolter Optic





K-alpha z-pinch source

**Transformational Diagnostic Approach**

- Multi-layer Wolter microscopes for flexible field-of-view and high solid angle with high spatial res
- Coupled to SLOS for time-res

| Diagnostic | Facility | Collaborating Institutions |
|---|---|---|
| **KB + SLOS** | NIF | **LLNL**, GA, LLE |
| **Wolter + SLOS** | Z, NIF, Omega | **LLNL**, SNL, LLE |
| **Spherical Crystal + SLOS** | Z, Omega | **SNL**, GA, LLE |

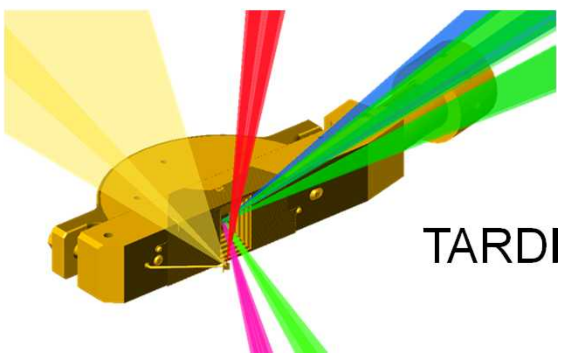
# **Research Thrust:** Time-dependent phase change in materials at high pressure.

### Science Drivers

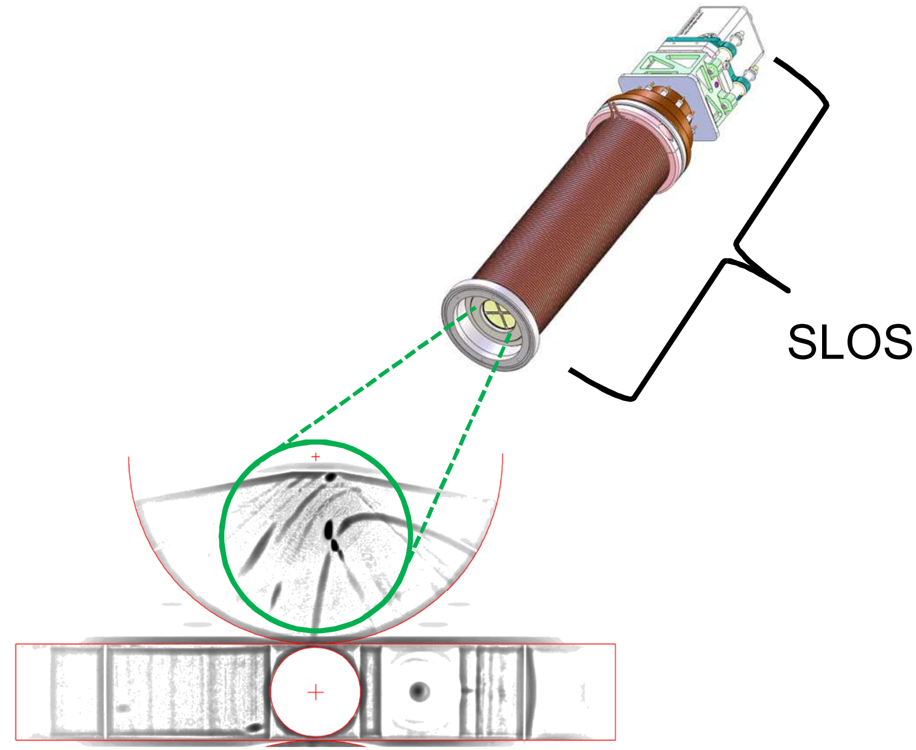
- Phase determination at high pressure
- Lattice deformation at high stress

### Transformational Diagnostic Approach

- Time-gated x-ray diffraction



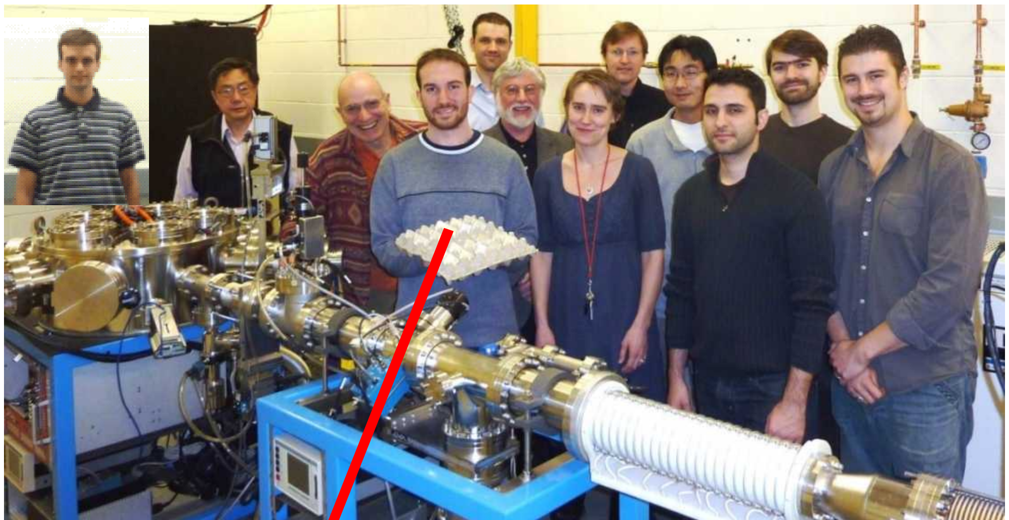
TARDIS



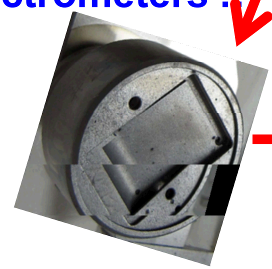

| Diagnostic | Facility Implementation | Collaborating Institutions |
|---|---|---|
| **Fast Phosphors** | Z | **SNL, NSTec** |
| **TARDIS + SLOS** | NIF | **LLNL**, GA, SNL |

# MIT develops diagnostics for OMEGA and the NIF and uses them to study ICF, HEDP, and plasma nuclear physics

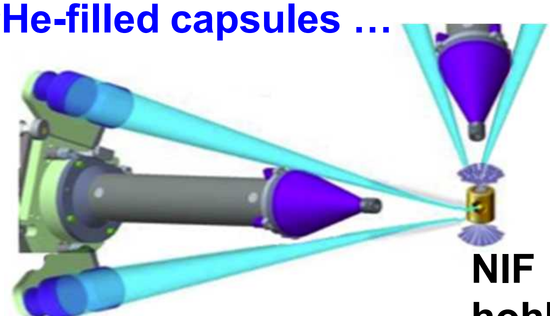
**The MIT Accelerator Facility for Diagnostic Development is used for testing and calibrating ICF diagnostics …**



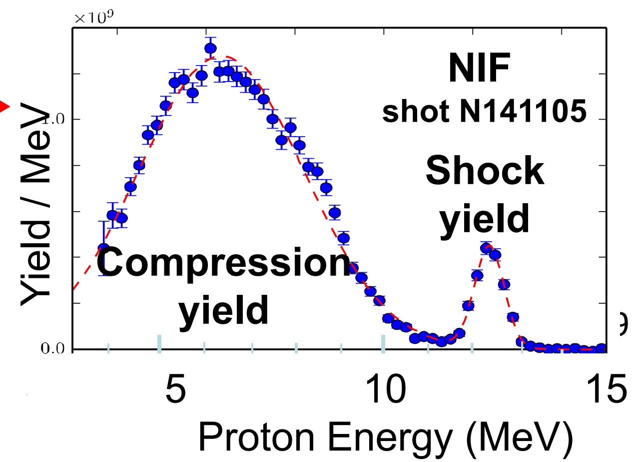
**… such as compact proton spectrometers …**



**… for diagnosing implosions of $D^3He$-filled capsules …**




**… producing $D^3He$-p spectra like this …**




**… for studying:**

- **Shock and compression yields**
- **Areal densities at shock- and compression-bang times**
- **Asymmetries in areal density**