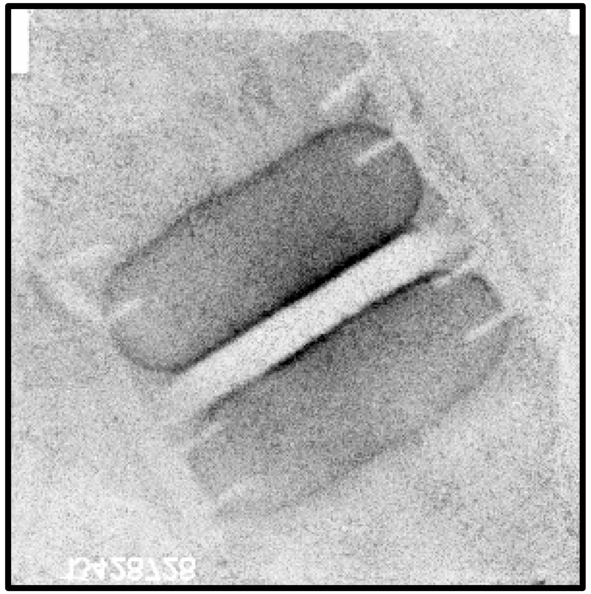
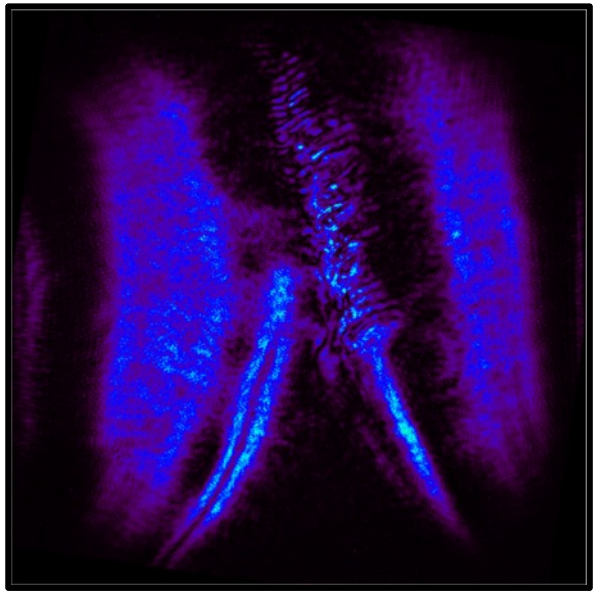
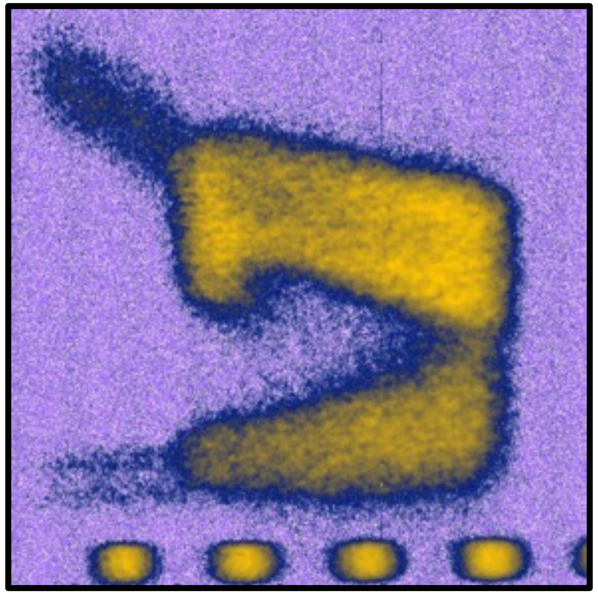
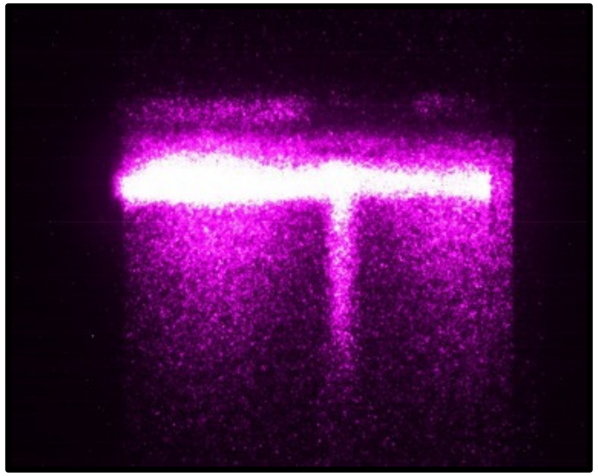
High-Energy-Density Plasma Diagnostics









Derek Schaeffer
Princeton University

PPPL Graduate Summer School
August 20, 2021

Outline

- Introduction to HEDP
- Detectors
- Optical Diagnostics
  - **Thomson scattering**
  - Refractive imaging
- X-ray Diagnostics
  - **Pinhole imaging**
  - Emission Spectroscopy
- Particle Diagnostics
  - **Proton deflectometry**
  - Particle spectrometers

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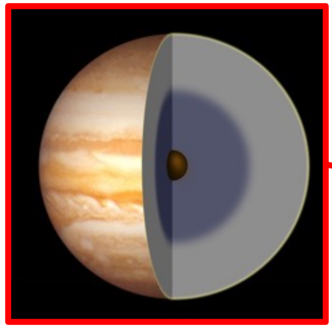
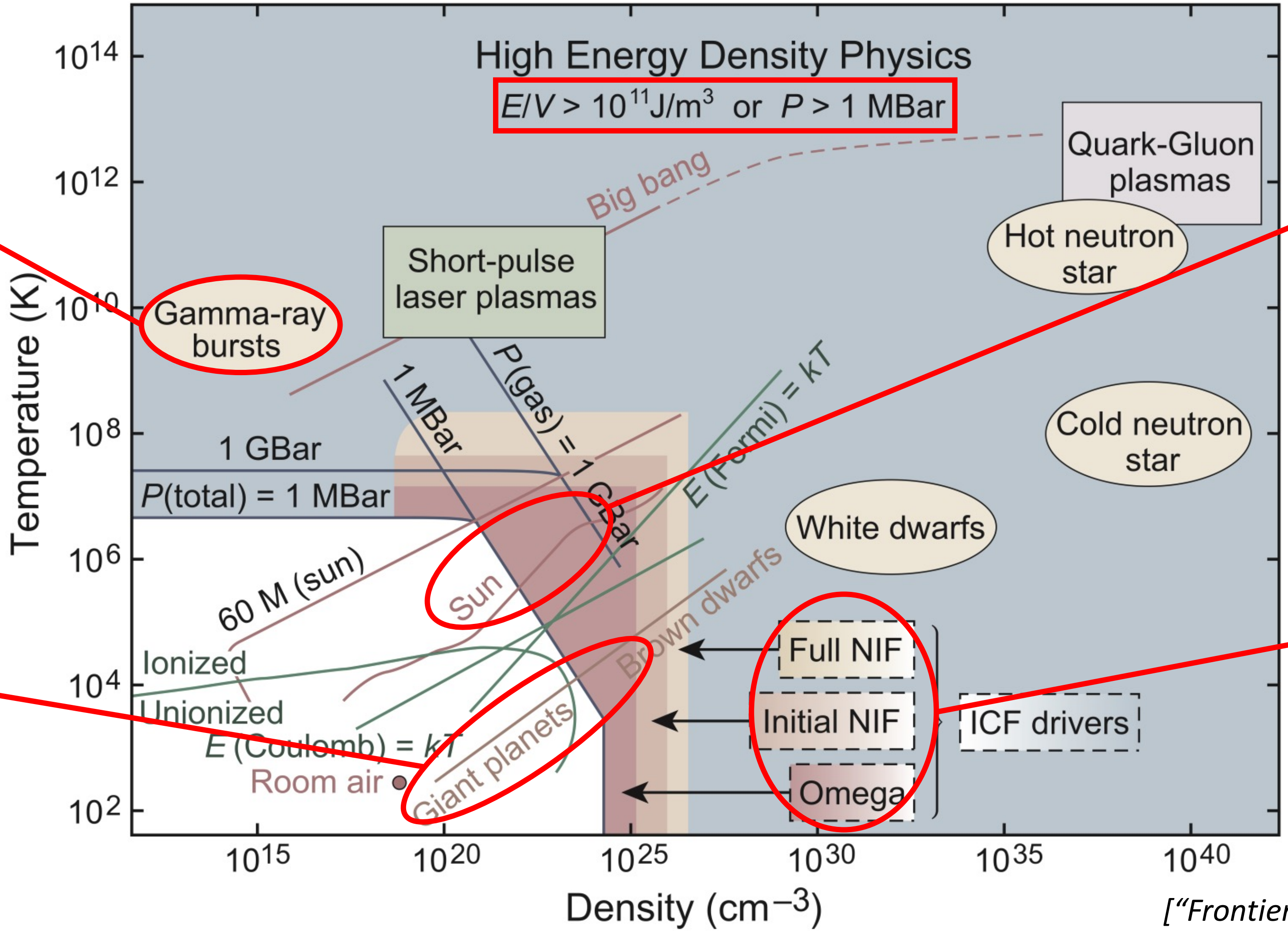
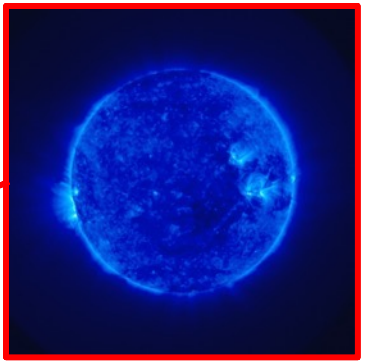
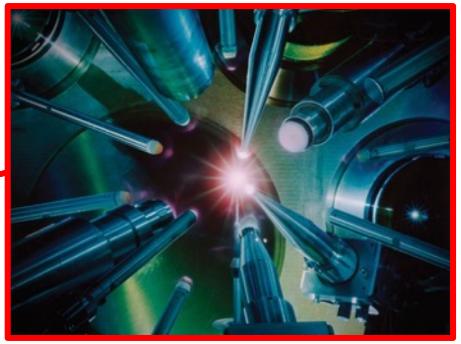
High-Energy-Density (HED) Physics Concerns the Study of Matter at High Densities and Extreme Temperatures



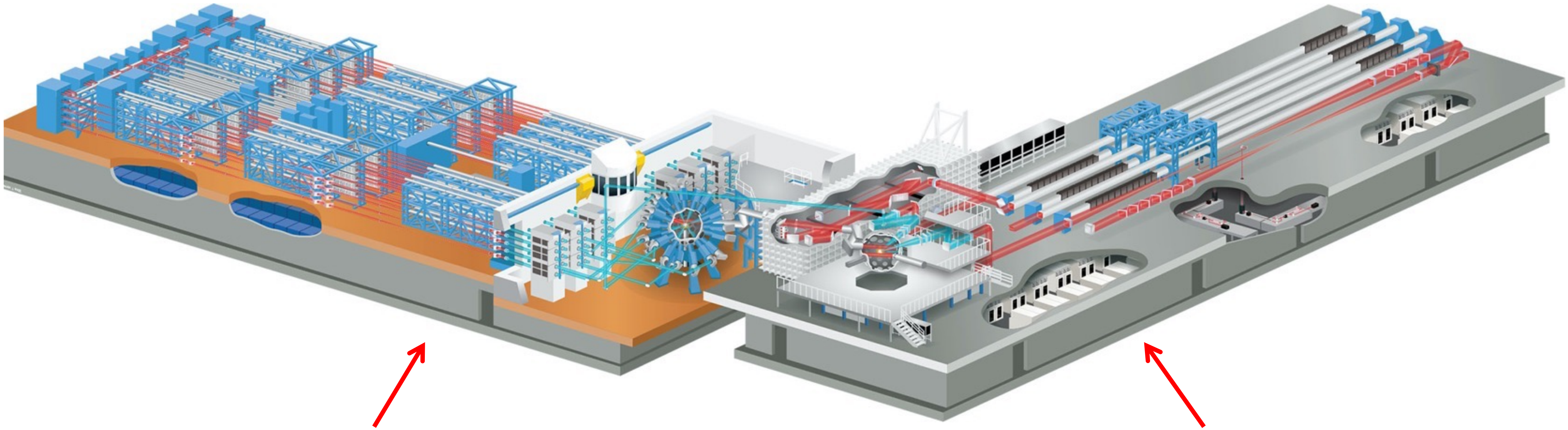






[“Frontiers in high energy density physics: The X-games of contemporary science.” 2003]

Laboratory for Laser Energetics (LLE) at University of Rochester Operates Two of the World's Largest Lasers



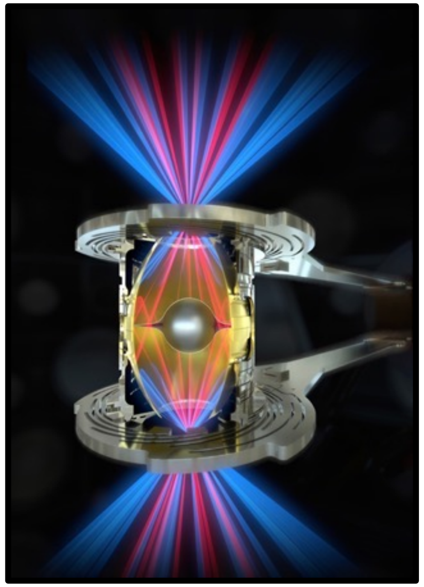
OMEGA 60
• Competed 1995 • 60 beams, each up to 500 J • 45 min shot cycle • Dozens of diagnostics • Up to 1500 shots/year

OMEGA EP
• Competed 2008 • Four beams, each up to 6.5 kJ • Two beams can be PW   • 2.6 kJ in 10 ps • 1.5 hr shot cycle

More than half of Omega's shots are for external users.

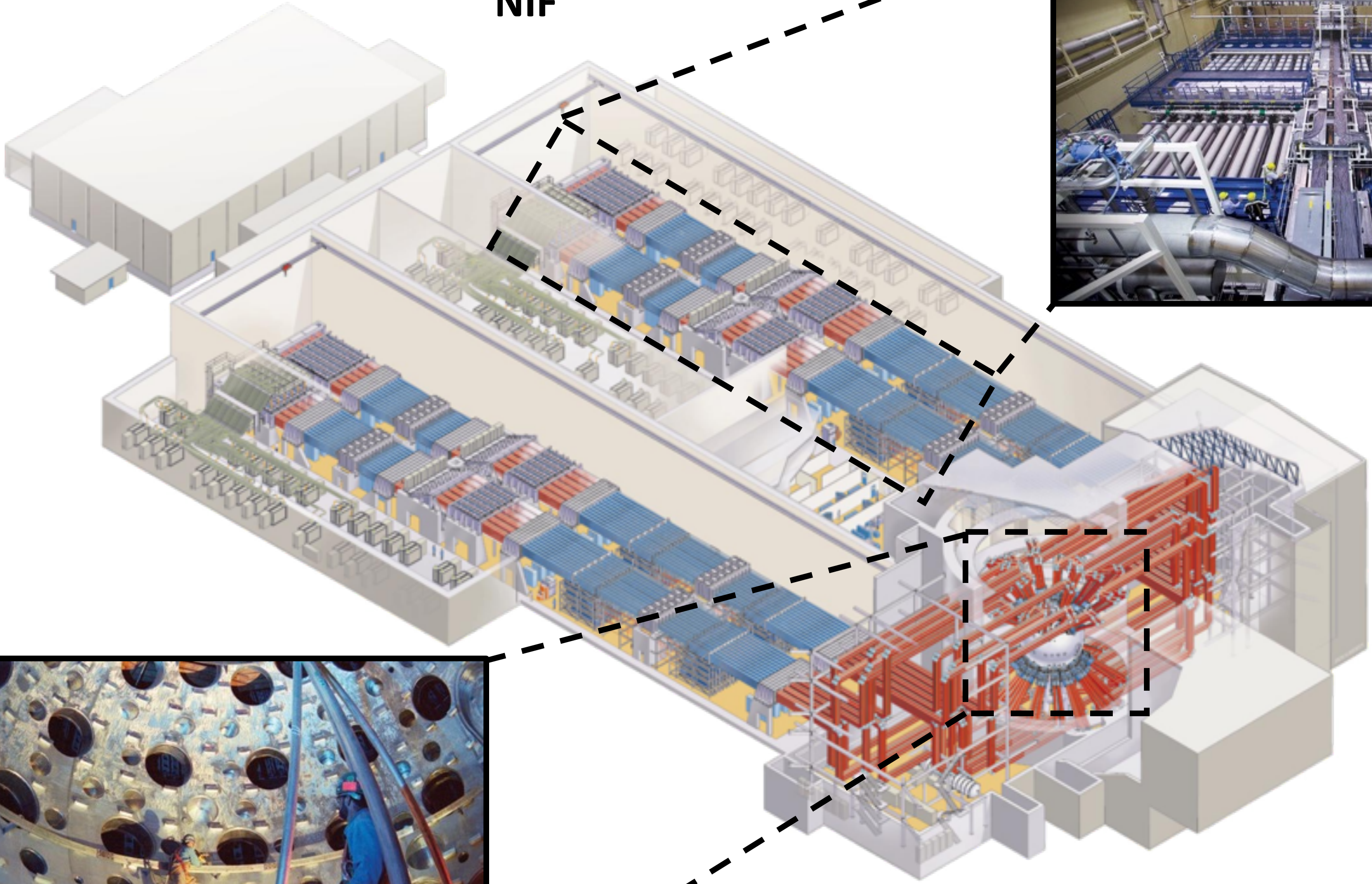
The National Ignition Facility (NIF) at LLNL Aims to Demonstrate Fusion Ignition

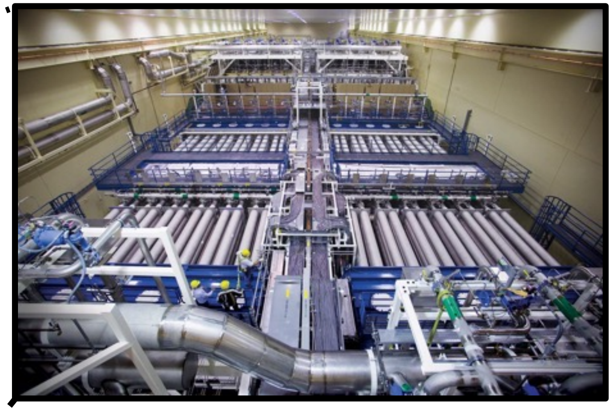
- Competed 2009
- World’s largest laser
- 192 beams with total energy of ~2 MJ
- Performing experiments to achieve ignition through inertial confinement fusion (ICF)



Hohlraum

NIF

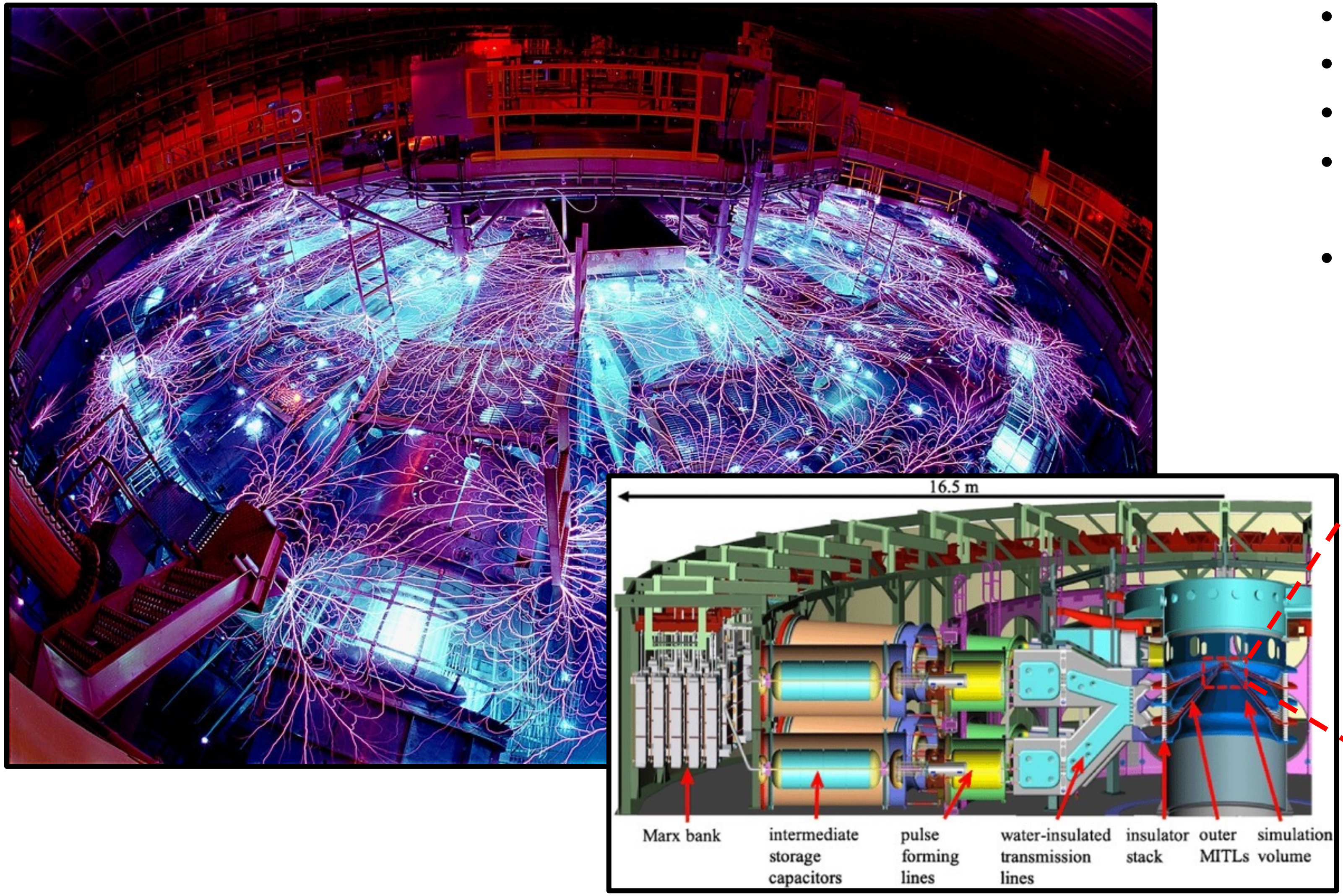




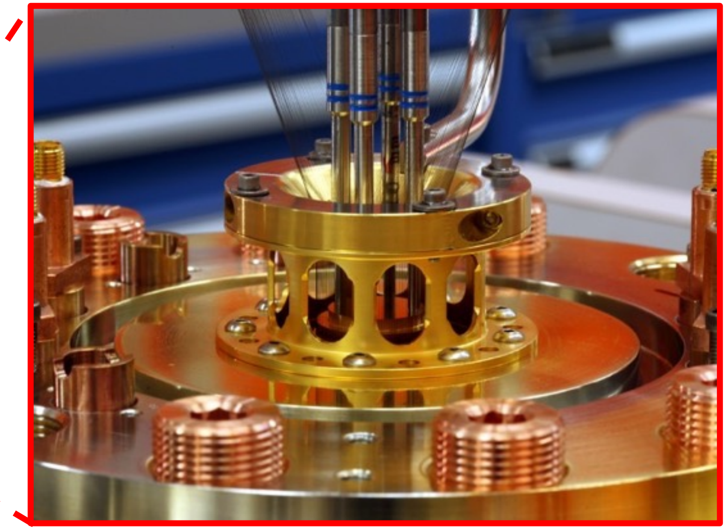
Achievement of ignition a “national grand challenge”

Magnetic Drive ICF Being Pursued at the Z Pulsed Power Facility at Sandia National Laboratory (SNL)

Z Machine



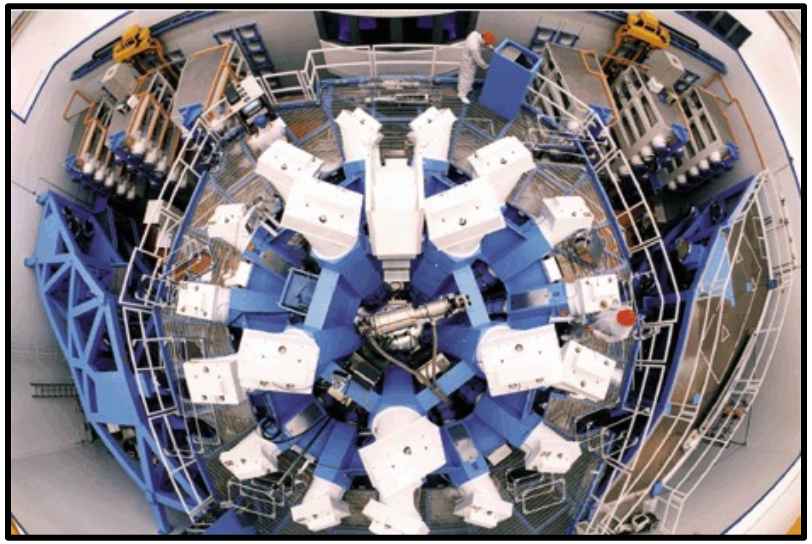
- Competed 1996
- World's most powerful radiation source
- Z-pinch configuration
- 20 MA peak current, 1 MJ peak energy, 80 TW peak power
- Studies magnetized ICF, laboratory astrophysics, and extreme material states

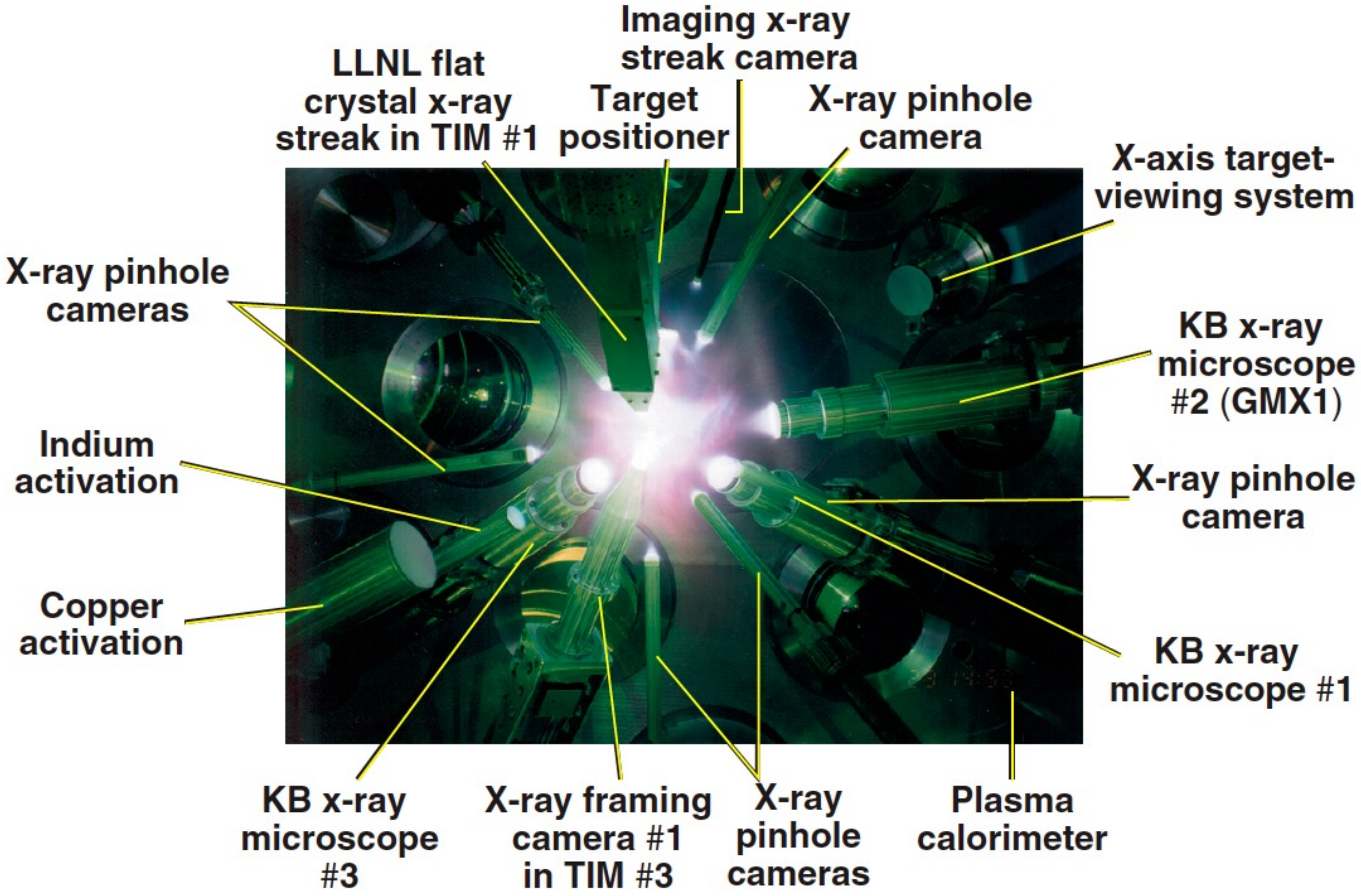


Z-pinch wire array

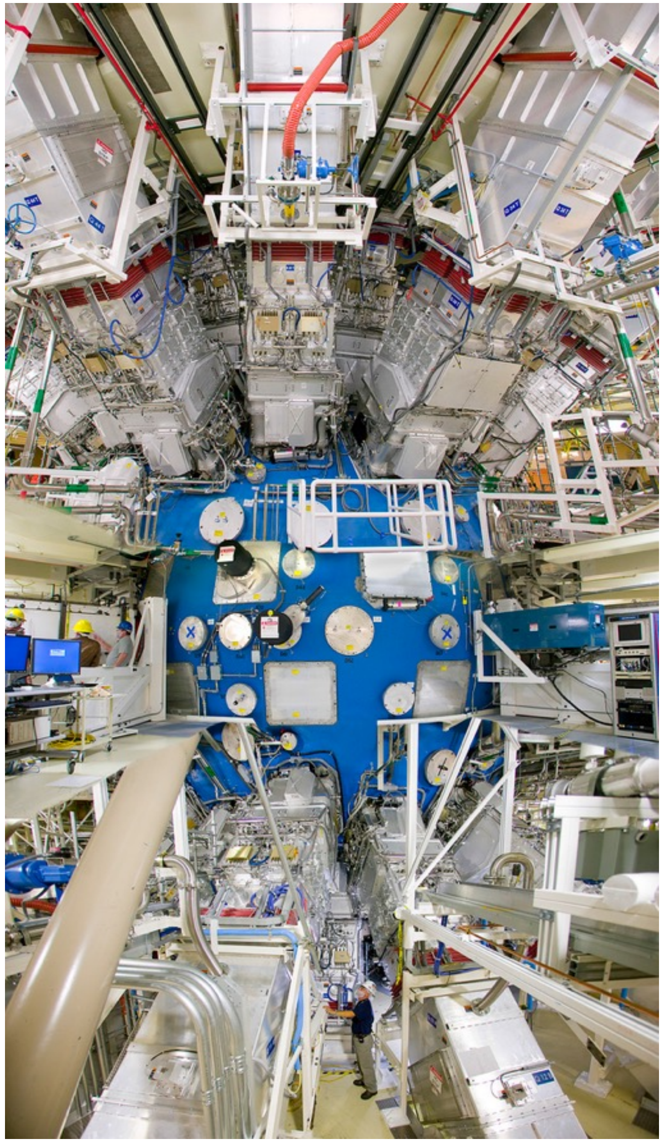
Many Diagnostics Fielded on HED Experiments

OMEGA 60 Target Chamber

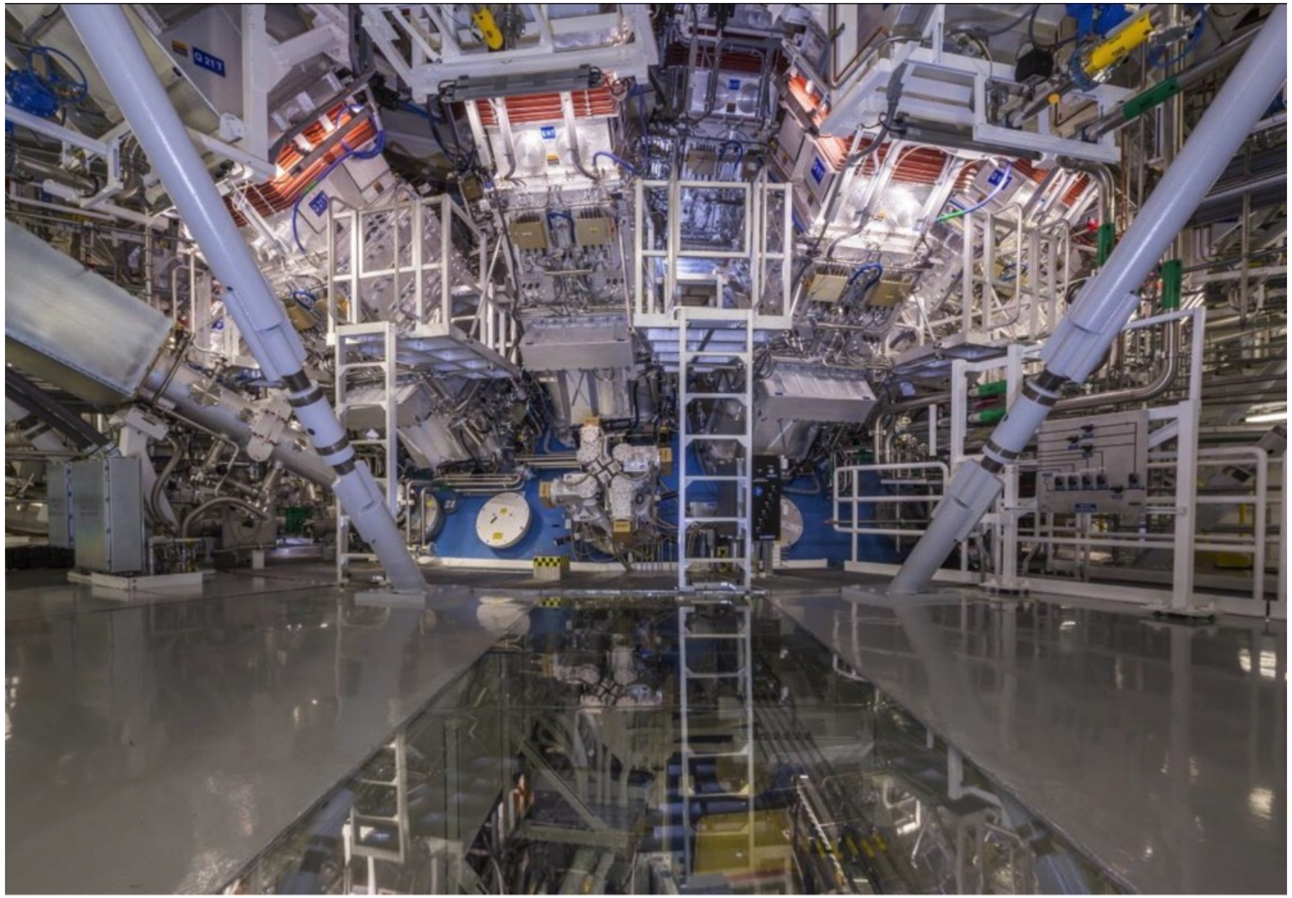




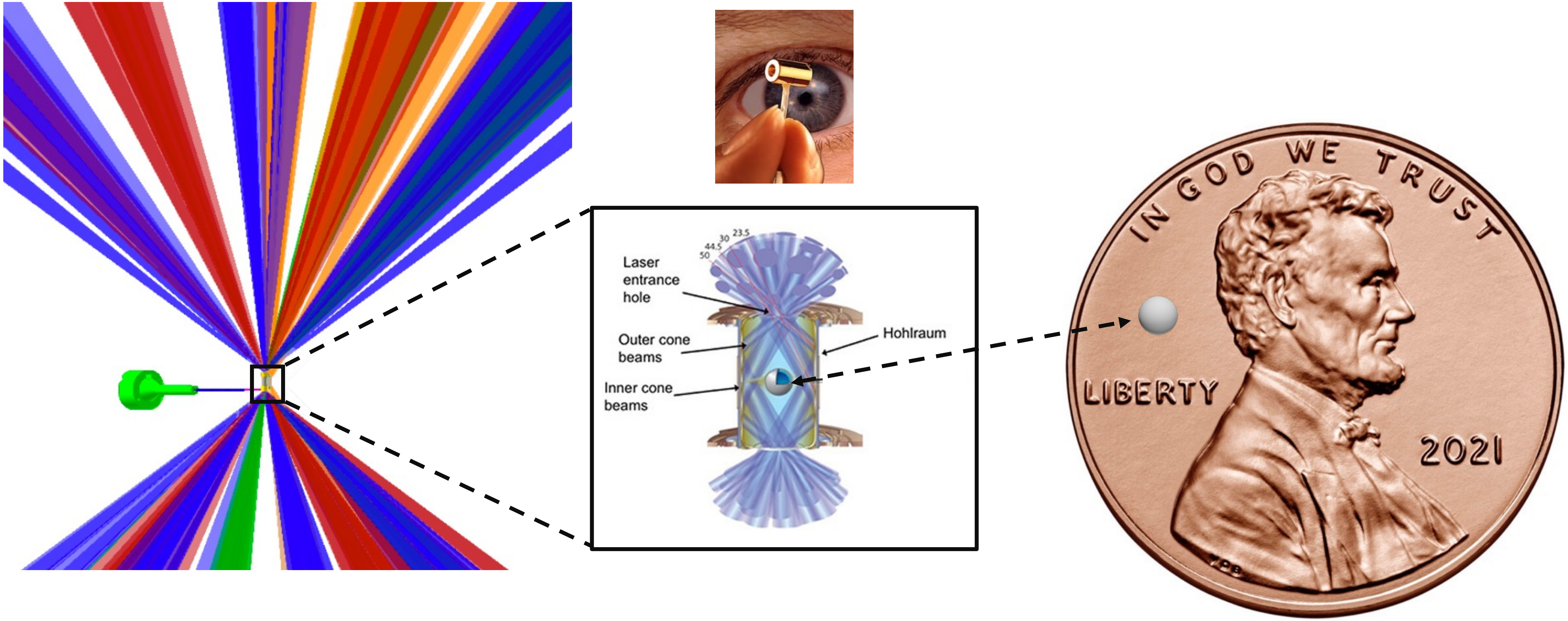
Many Diagnostics Fielded on HED Experiments



NIF Target Chamber



HED Experiments Deposit a Large Amount of Energy into a Small System Extremely Quickly



Deposit $10^2 – 10^6$ J into a mm-scale target in billionths of a second

Key Challenge of HED Science is Measuring HED Systems

- Require very fast measurements (<ns) at high spatial resolution (10 um)
- HED systems generate:
  - optical, UV, and x-ray photons
  - charged particles
  - neutrons
  - strong electromagnetic fields
- Comprehensive diagnostic suite allows much to be learned: plasma parameters (temperature, density, flows), field strength and topology, energy spectra, particle dynamics, etc.
- Primarily rely on both active and passive, non-intrusive, light-based and particle-based diagnostics

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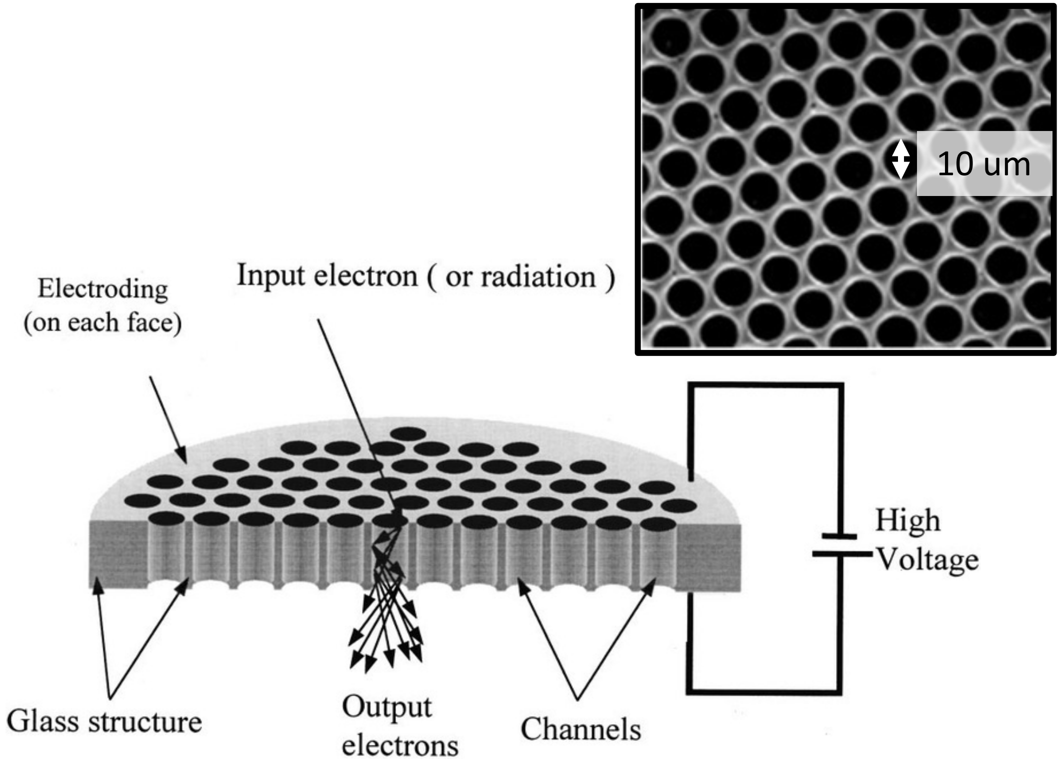
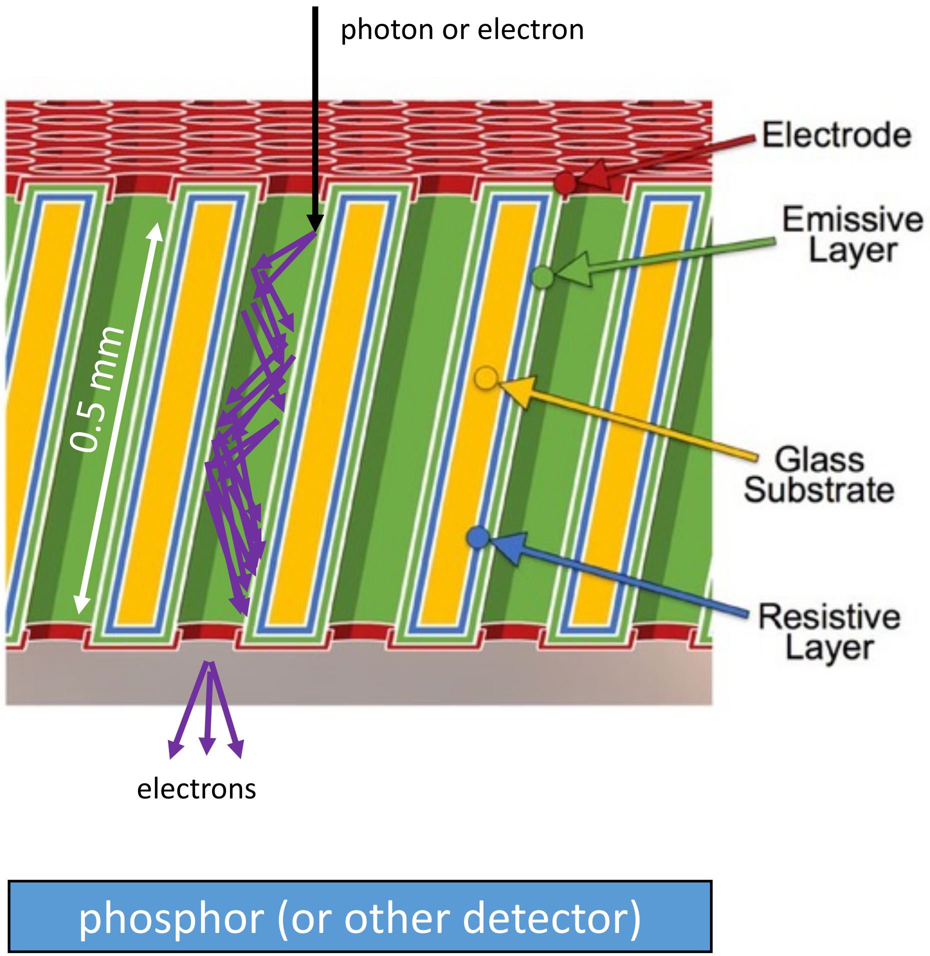
Microchannel Plates (MCPs) Enable the Detection of Very Low Signals

MCP

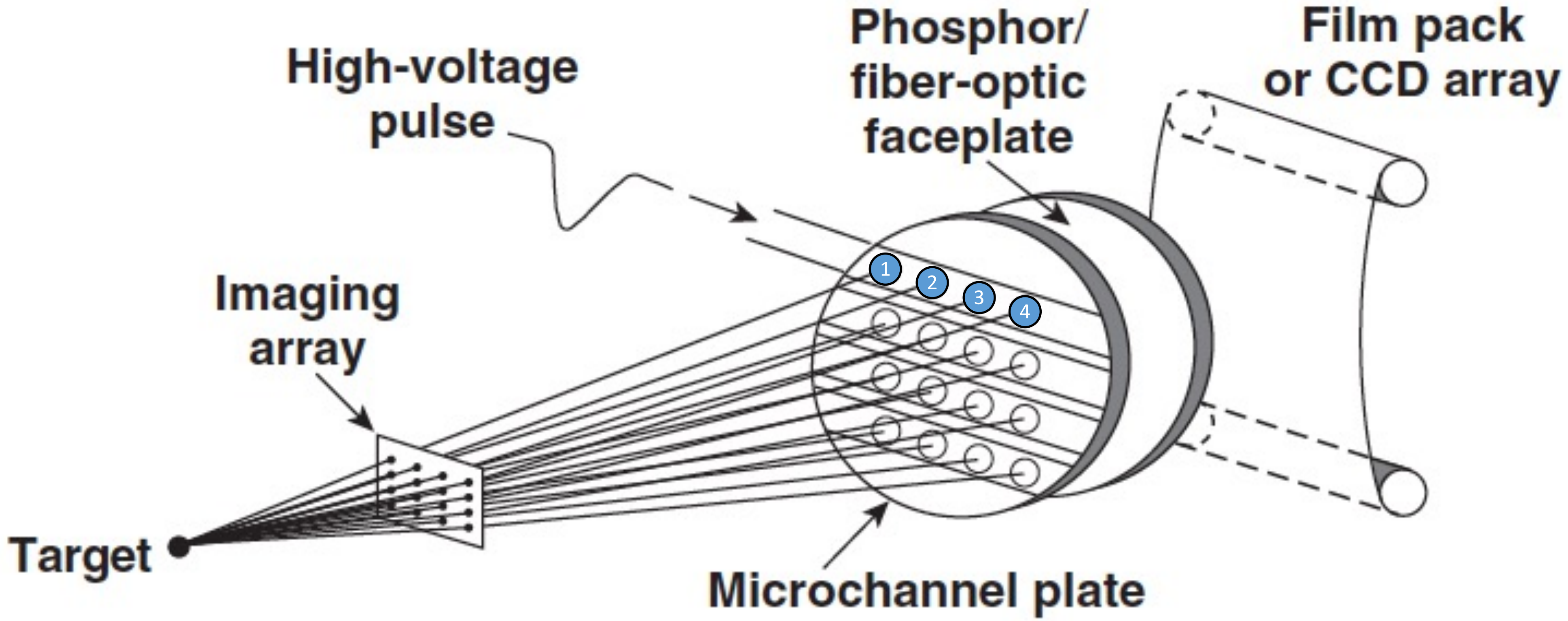


- High speed gating (~10 ps)
- Minimal image distortion
- Large dynamic range (~100)
- Noisy

Operation



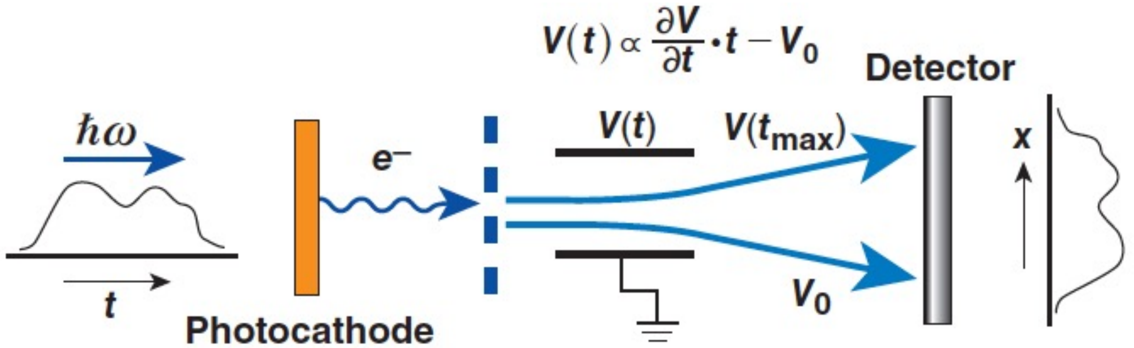
Framing Cameras Provide Series of Time-Gated 2D Images, Like a Movie



- Array of images projected onto HV strip on MCP
- As HV travels along strip, each image recorded
- Total strip time set by HV pulse and strip length (usually of order ~100 ps)
- Different strips can have different start times
- Provides high temporal resolution (~40 ps)

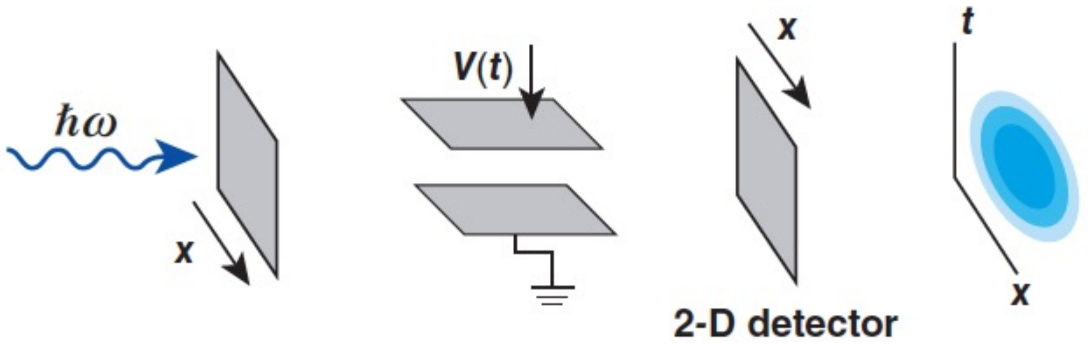
Streak Cameras Provide Temporal Resolution of 1D Data

Streak Operation



- Photoelectrons accelerated from photocathode
- Pass through two plates with applied voltage
- Voltage ramped in time, causing electrons arriving later to be deflected differently from those arriving earlier

Streaked Images



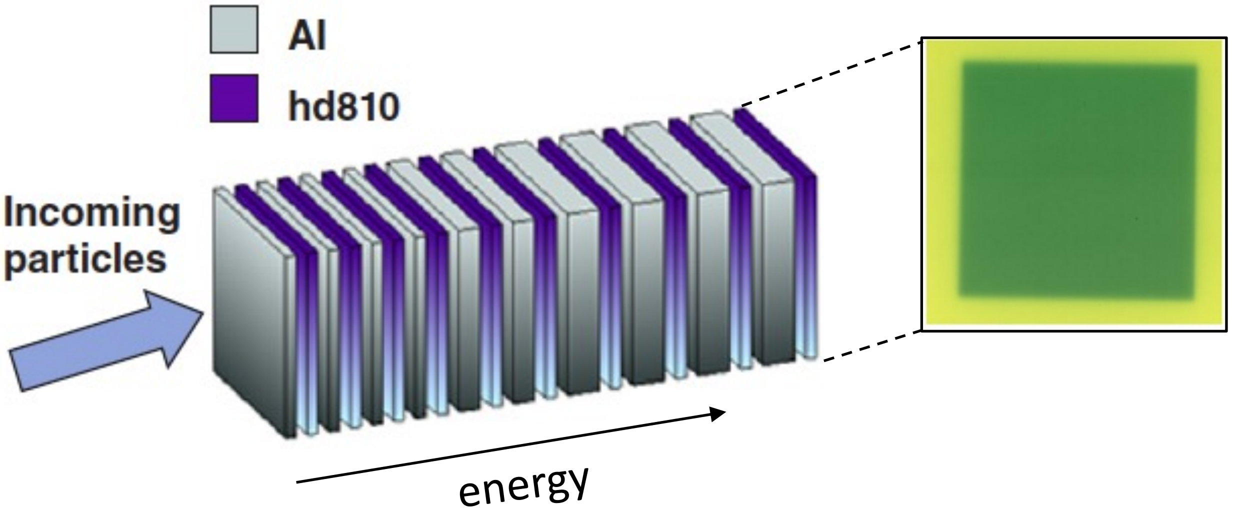
- Incident 1D data (e.g. spectra) that evolves in time
- Camera streaks data in perpendicular direction, converting time to a spatial axis
- Creates 2D *x-t* image
- Temporal resolution ~50 ps

X-rays and Charged Particles can be Measured with Image Plates or Radiochromic Film

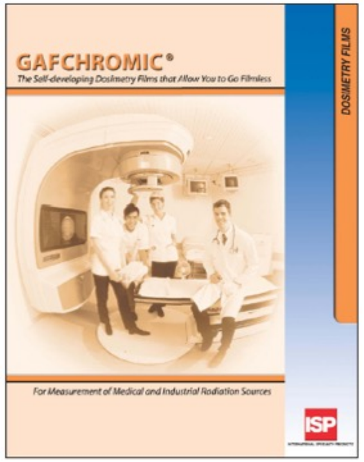
Image Plates

- Large dynamic range (>10^5) and insensitive to strong EM pulses
- Incident ionizing radiation traps electrons in metastable state
- Electrons released when exposed to visible laser (provided by special scanner), emitting detectable line radiation (photostimulated luminescence [PSL])

Radiochromic Film (RCF)



- Commonly used in medical, industrial, and scientific applications
- Self-developing and insensitive to visible light
- Multiple layers of film and filters allow energy/time discrimination

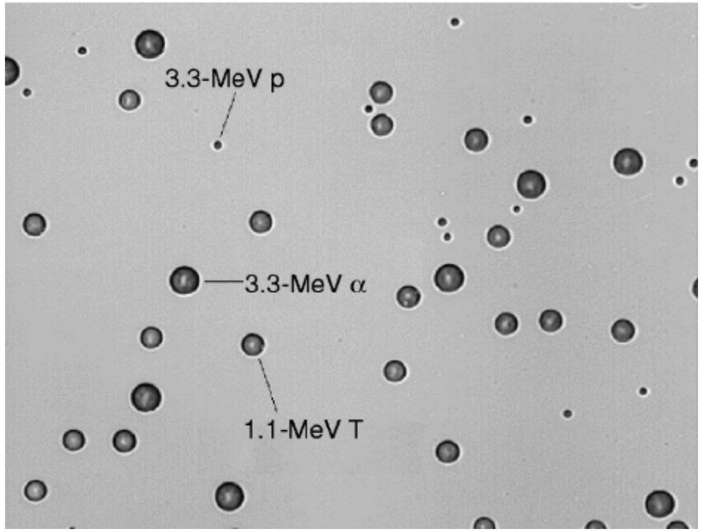


Energetic Protons can be Measured with CR-39

CR-39

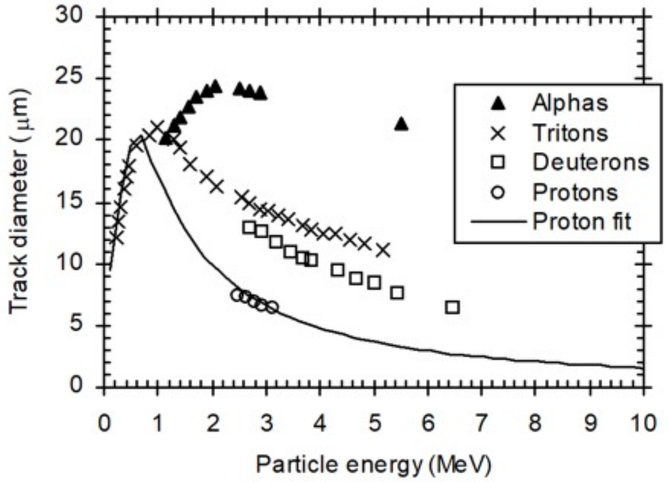
- Transparent plastic sensitive to charged particles
- Insensitive to photons

Microscope Image



- Particles leave tracks in CR-39
- Track diameter and depth indicative of particle energy and type

Track Diagram



- Tracks made visible through chemical etching
- Digitized with automated microscope scanner
- Particle flux directly counted

[Seguin+ RSI 2003]

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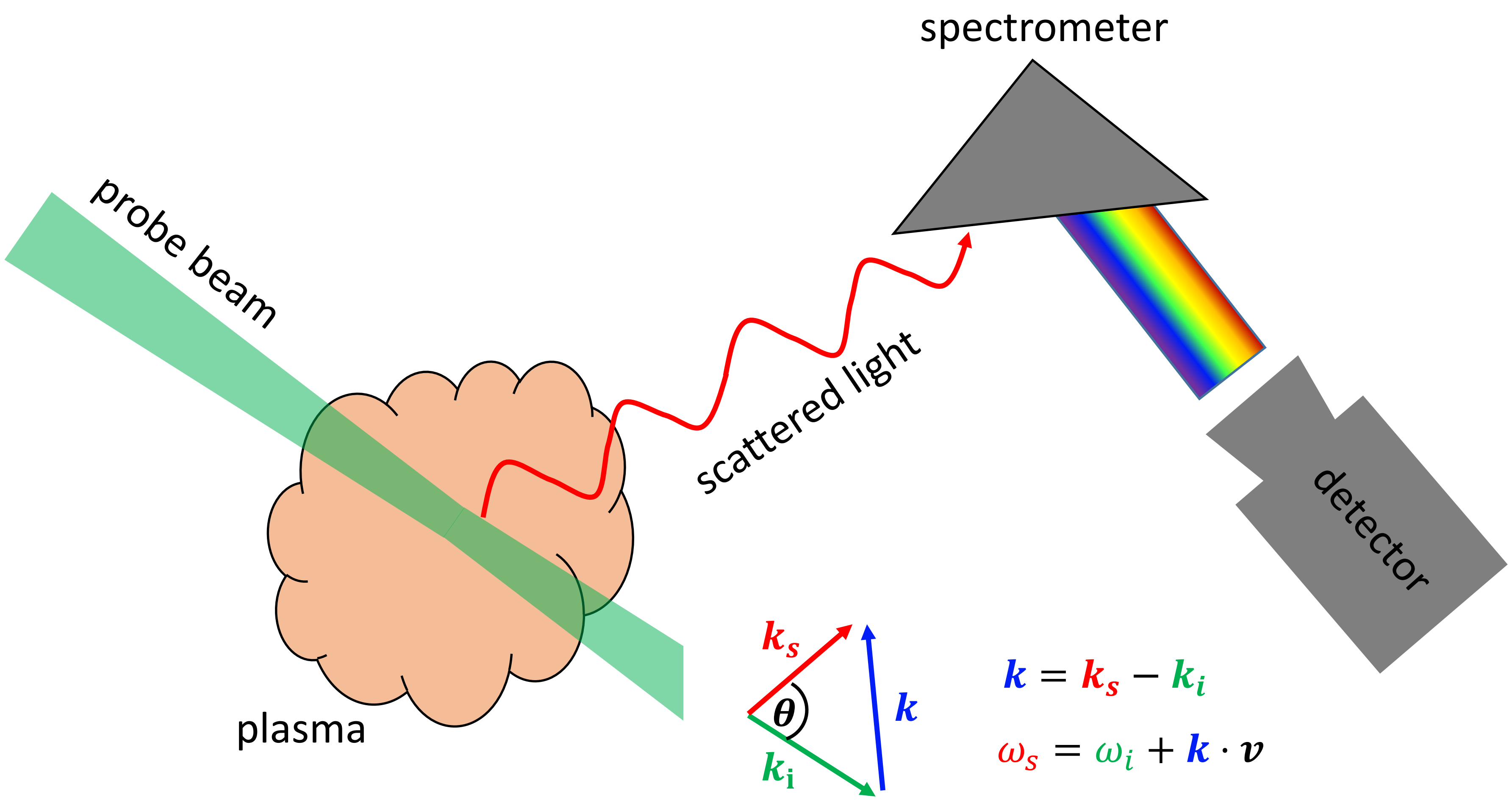
Thomson Scattering Diagnoses Local Plasma Conditions by Observing Spectrum of Light Scattered from Probe Beam



$$\boldsymbol{k} = \boldsymbol{k_s} - \boldsymbol{k_i}$$

$$\omega_s = \omega_i + \boldsymbol{k} \cdot \boldsymbol{v}$$

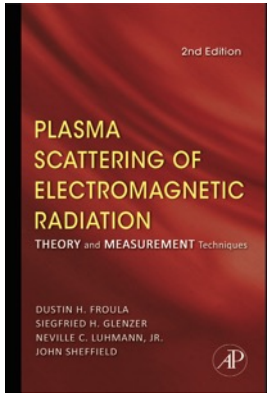
Scattered Power Dependent on Velocity Distribution Functions (VDFs)

Scattered Power

$$P_s(\boldsymbol{k},\omega) \propto P_i \left|\hat{s}\times(\hat{s}\times\hat{E}_i)\right|^2 n_e S(\boldsymbol{k},\omega)$$

Initial power
Scattering angles
Electron density
Spectral density

[Froula+ "Plasma Scattering of Electromagnetic Radiation" 2nd ed. 2011]



Spectral Density

$$S(\boldsymbol{k},\omega) = S_e(\boldsymbol{k},\omega) + S_i(\boldsymbol{k},\omega)$$

$$S_e(\boldsymbol{k},\omega) = \frac{2\pi}{k}\left|1-\frac{X_e}{\epsilon}\right|^2 \overbrace{f_{e,0}(\omega/k)}^{\text{electron VDF}}$$

$$S_i(\boldsymbol{k},\omega) = \frac{2\pi Z}{k}\left|\frac{X_e}{\epsilon}\right|^2 \overbrace{f_{i,0}(\omega/k)}^{\text{ion VDF}}$$

$$\underbrace{X_s(\boldsymbol{k},\omega)}_{\text{susceptibility}} = \frac{4\pi e^2 n_s}{m_s k^2}\int dv\, \frac{\boldsymbol{k}\cdot \overbrace{df_s/dv}^{\text{Landau damping}}}{\omega - \boldsymbol{k}\cdot v}$$

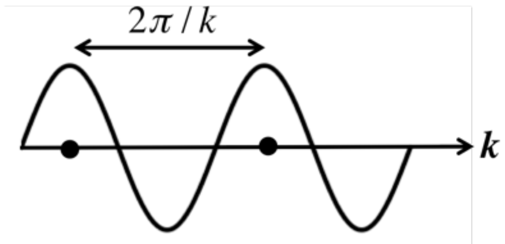
$$\underbrace{\epsilon}_{\text{dielectric function}} = 1 + X_s + X_i$$

Scattering Parameter

$$\alpha = 1/k\,\lambda_{De}$$

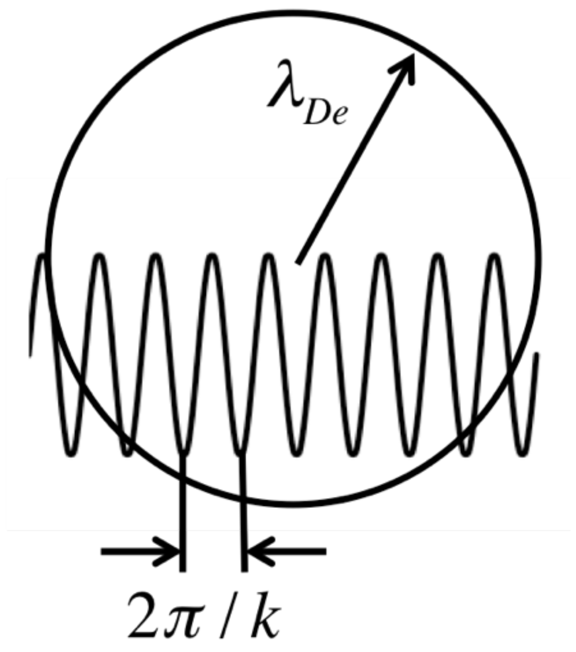
$$k \approx 4\pi \sin(\theta/2)/\lambda_i$$

$$\lambda_{De} = (k_B T/4\pi n_e e^2)^{\frac{1}{2}}$$

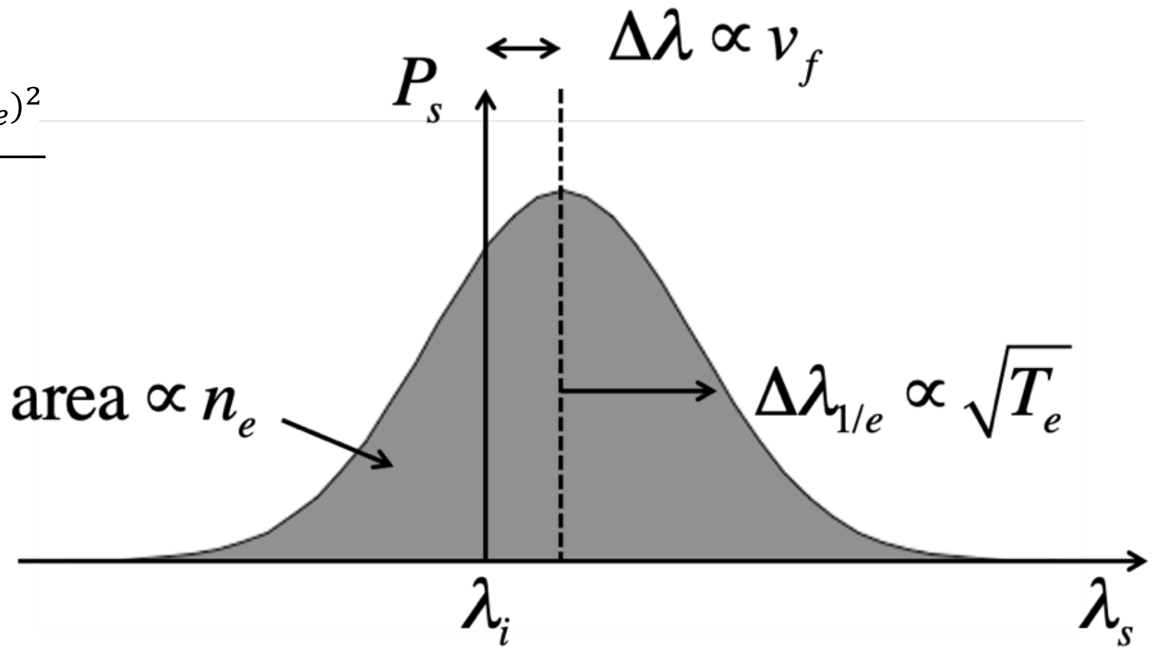


In Non-Collective Regime, Electrons Scatter Incoherently

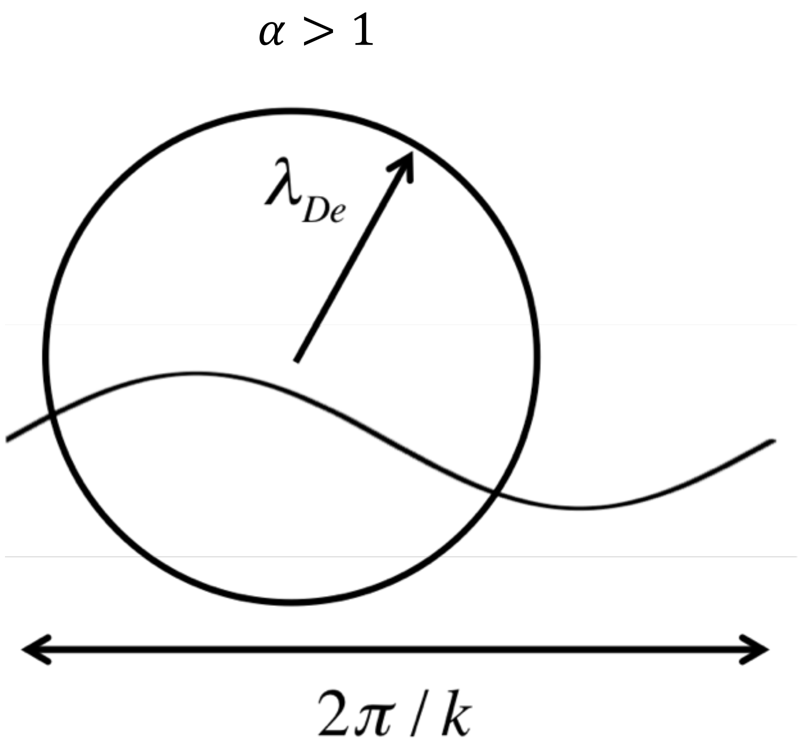
$\alpha < 1$

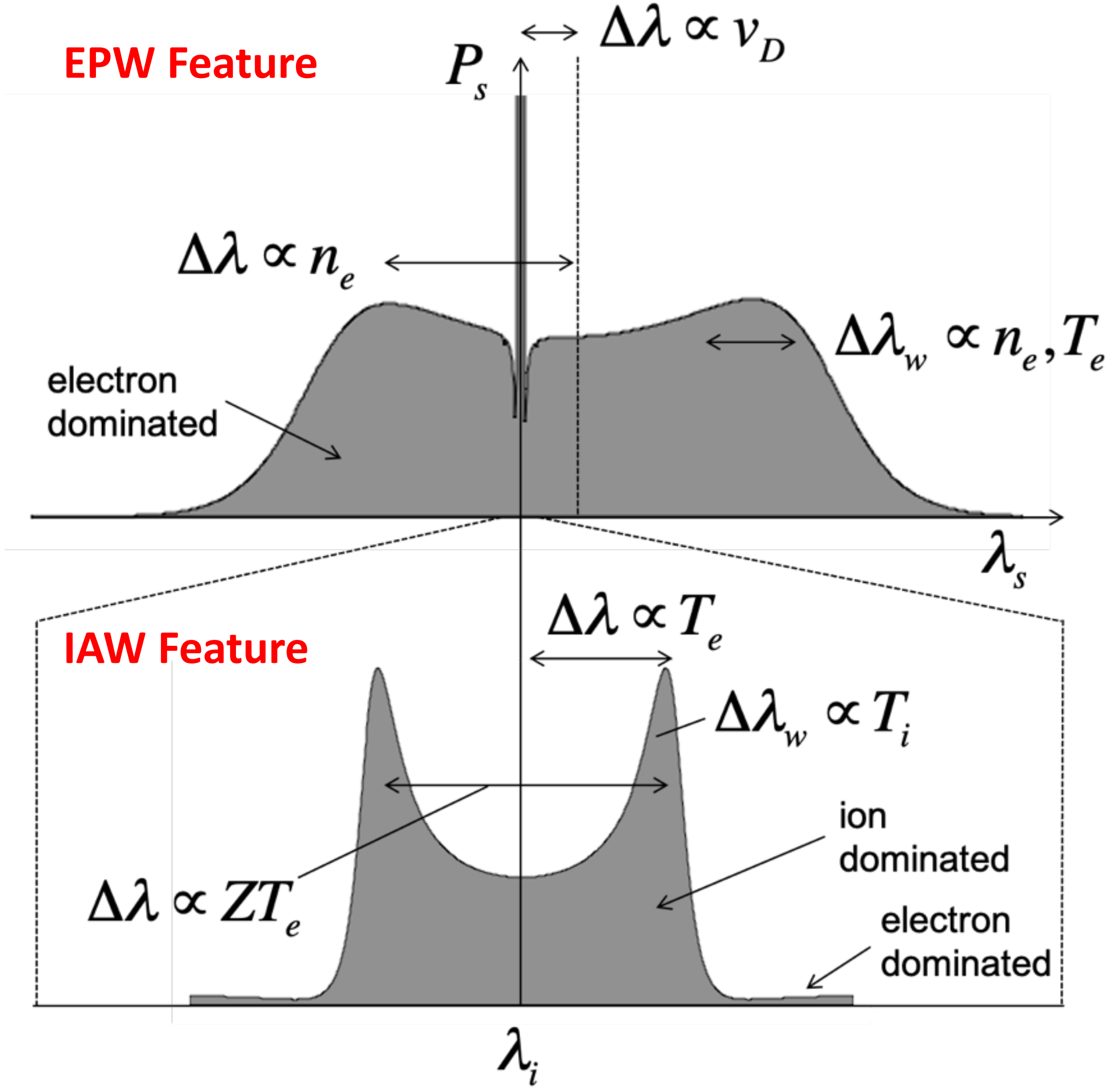


$$S(\boldsymbol{k}, \omega) \propto \frac{e^{-(\omega/k \mathrm{v}_{Te})^2}}{|\epsilon^2|}$$



In Collective Regime, Light Scattered from Plasma Waves

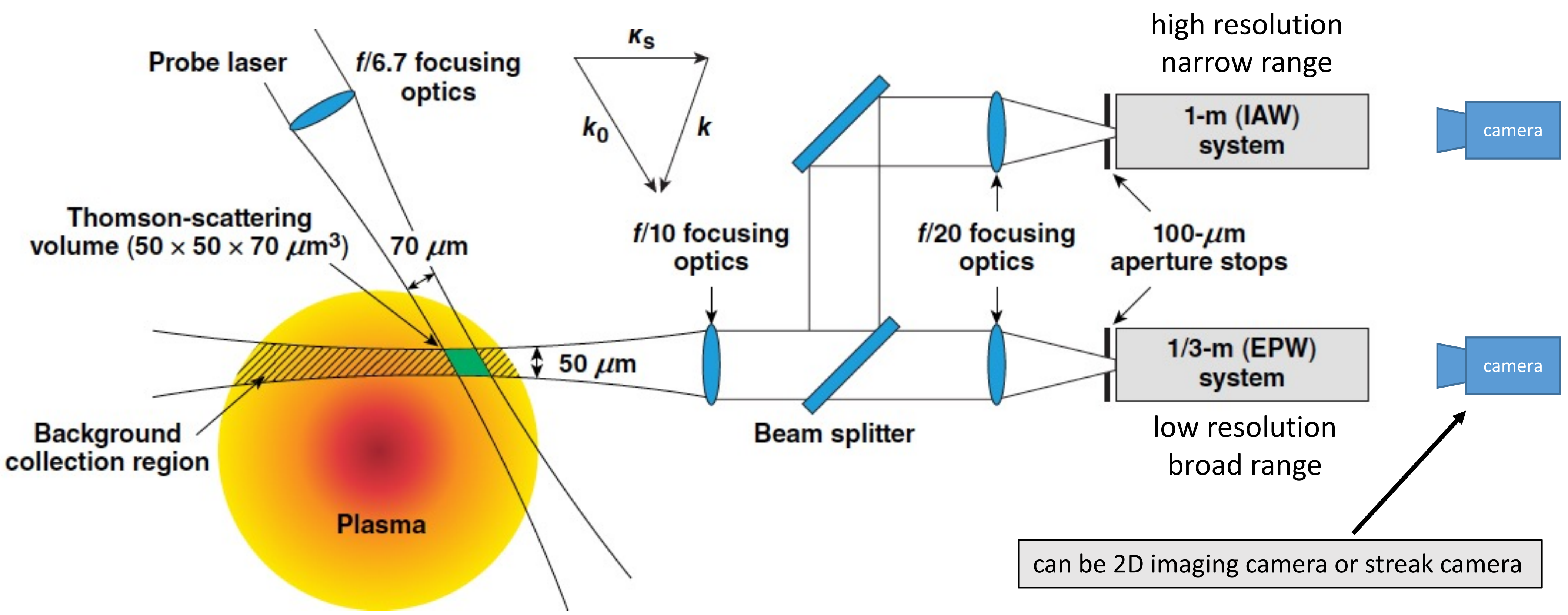




Density modulations in plasma propagate as high frequency electron plasma waves (EPW) and low frequency ion acoustic waves (IAW)

Thomson Scattering Makes *Local* Measurements of Plasma Parameters

OTS System on Omega60

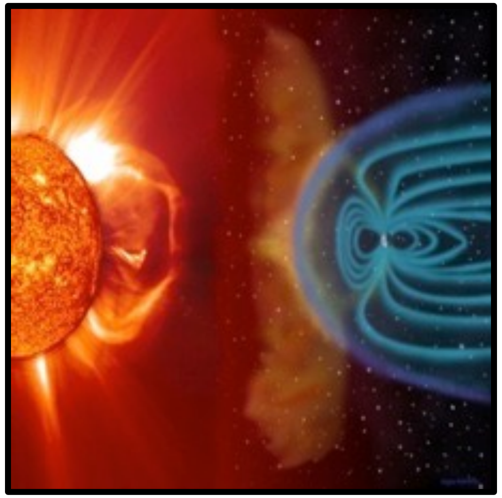


[Follet+ RSI 2016]

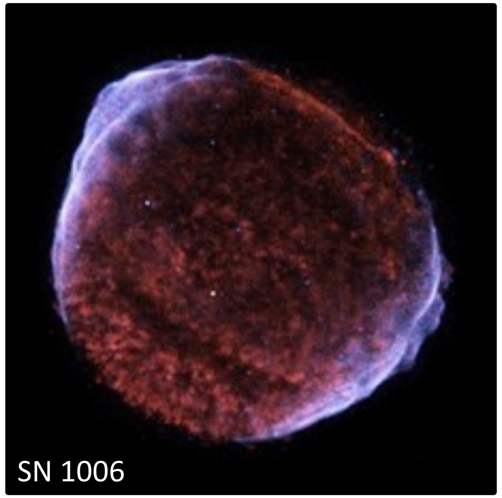
Experiments Study VDFs in Laser-Driven Collisionless Shocks on Omega

Collisionless Shocks

Planetary Bow Shocks



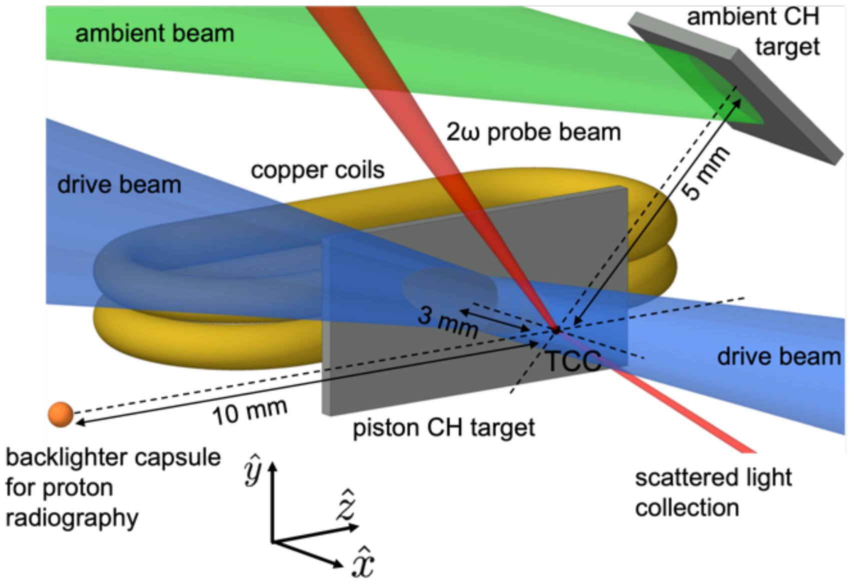
Supernova Remnants

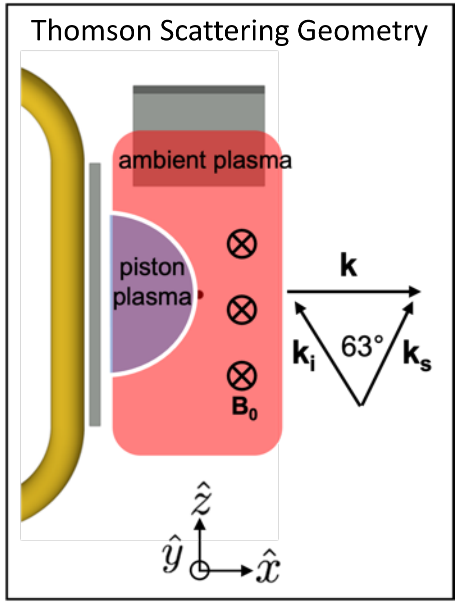


Images: NASA

- Shocks observed in astrophysical systems with scale lengths orders of magnitude smaller than the collisional mean free path
- Known to be the source of very high-energy particle acceleration, including cosmic rays
- Laboratory experiments enable detailed studies using high-energy lasers

Experimental Setup on OMEGA60



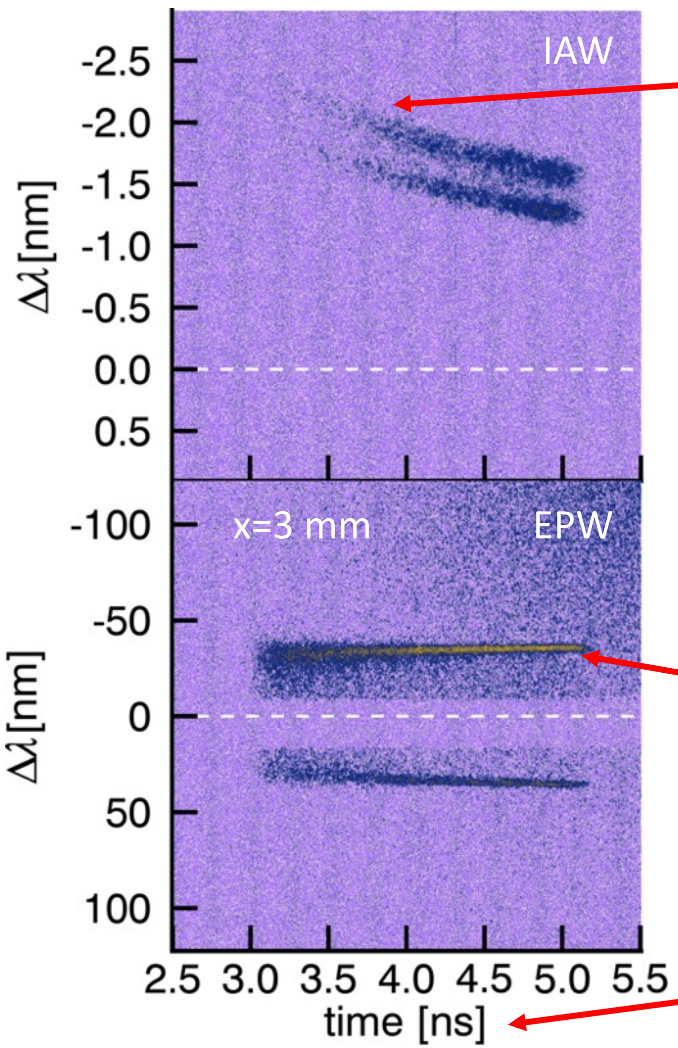


- Lasers drive piston plasma into magnetized ambient plasma
- Ambient ions and magnetic flux swept up and accelerated to super-magnetosonic speeds, driving shock
- VDFs parallel to shock normal diagnosed with Thomson scattering

[Schaeffer+ PRL 2019]

Spectra Reflect 1D Ion Velocity Distributions

Null shot: piston plasma only

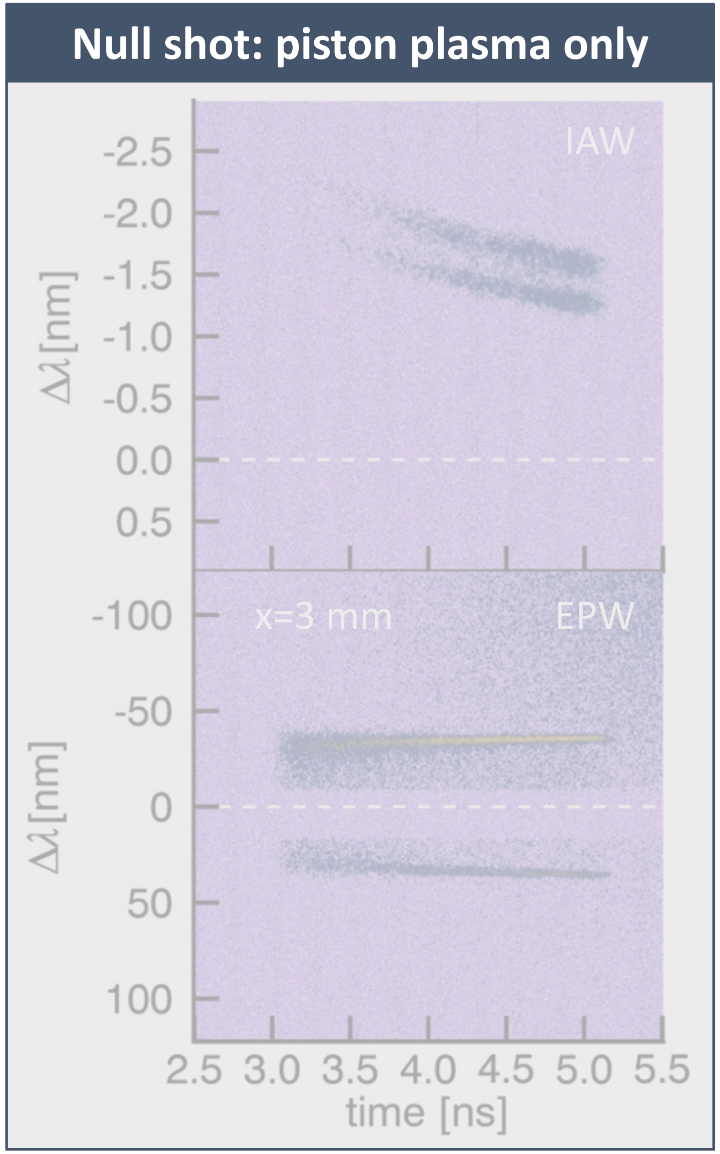


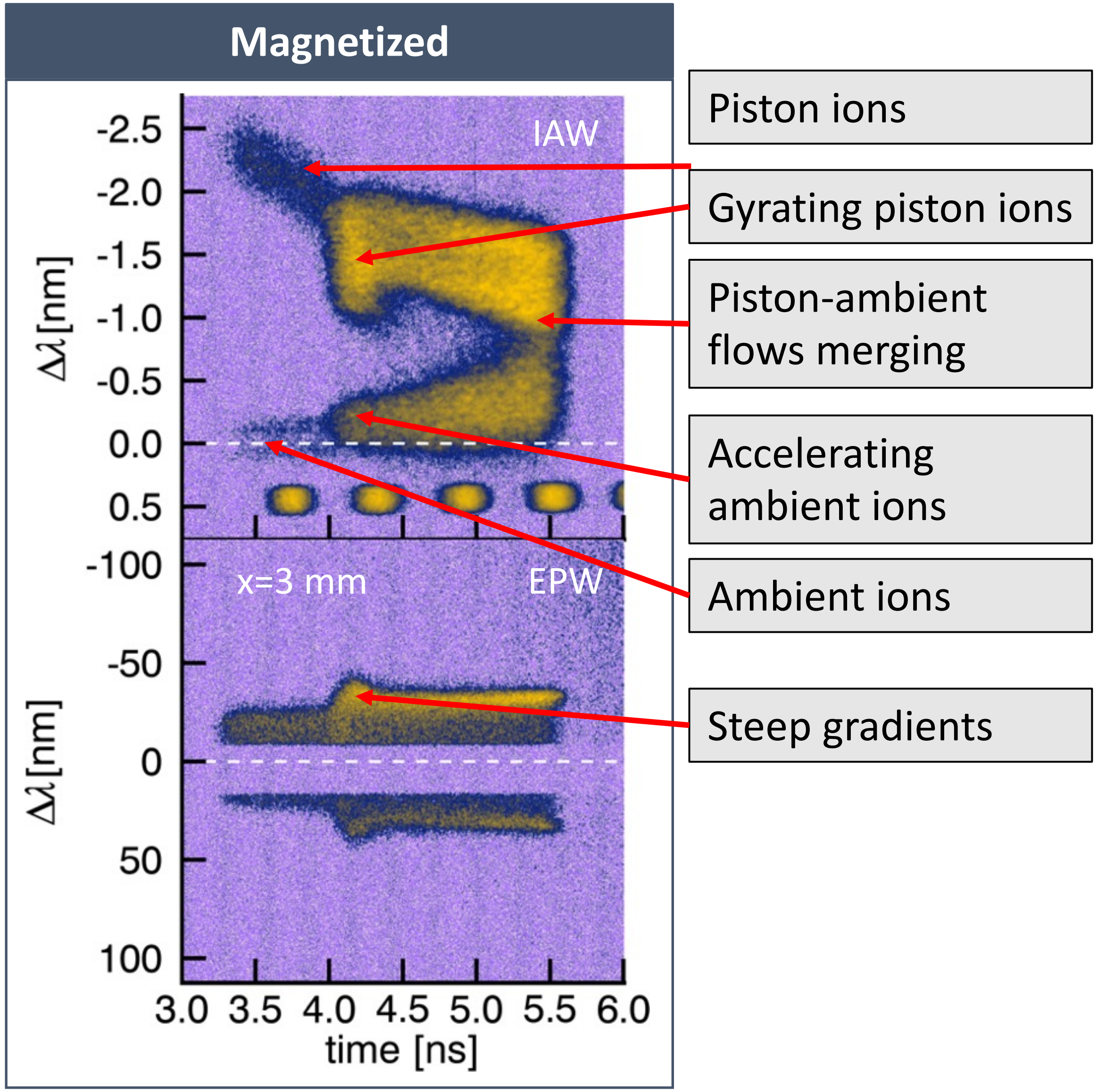
Fast moving piston ions (500-1000 km/s)

Spectra show passing of simple ablation flow (increasing density, decreasing speed and temperature)

Streaked in time

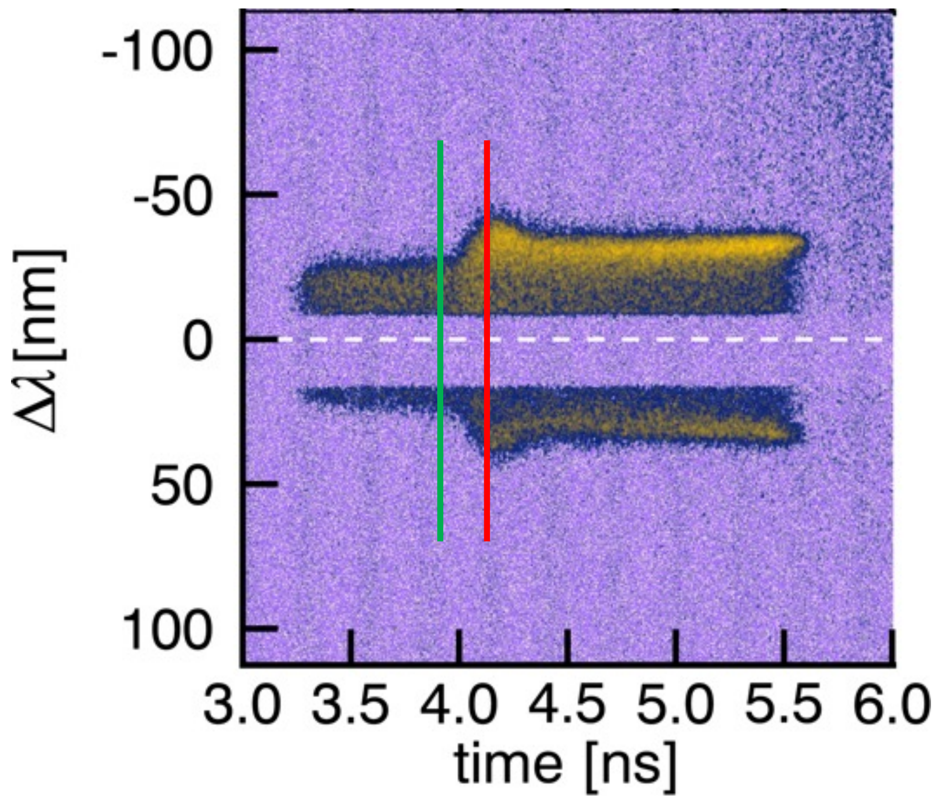
Strong Flow Deformations Observed with Magnetic Field



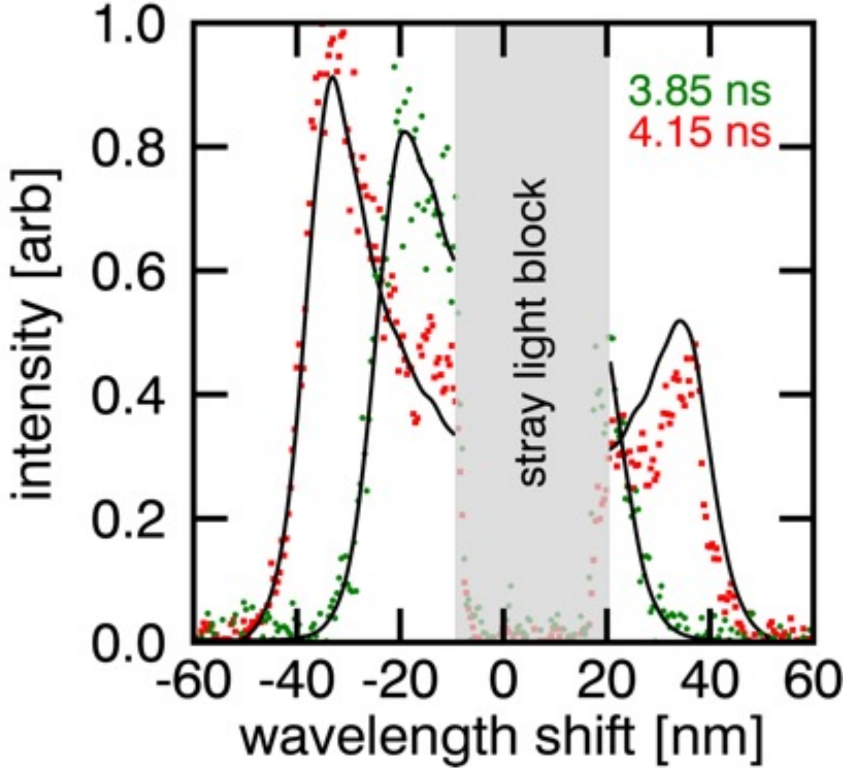


Plasma Parameters Extracted by Iteratively Fitting Data with Calculated Spectra

EPW Feature

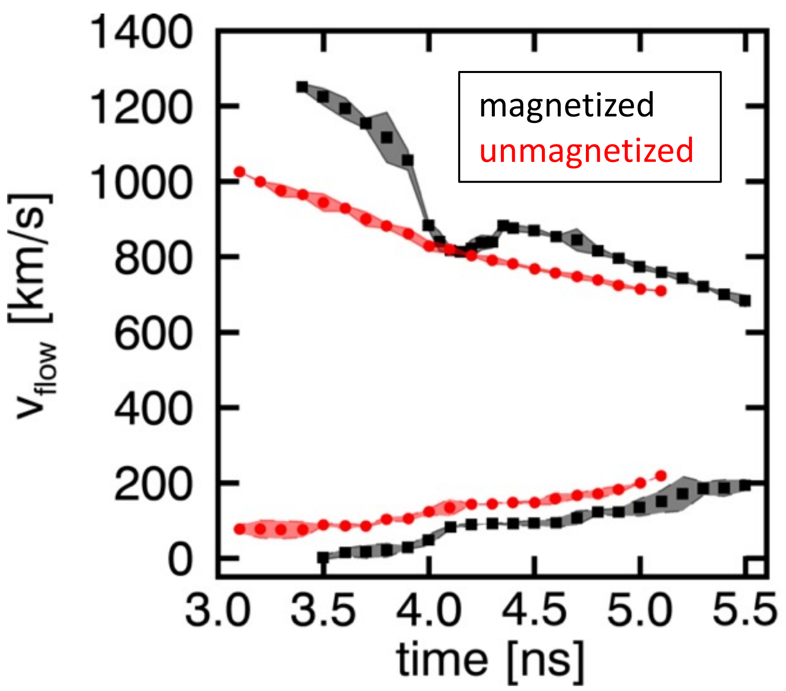


EPW Lineouts with Best Fits



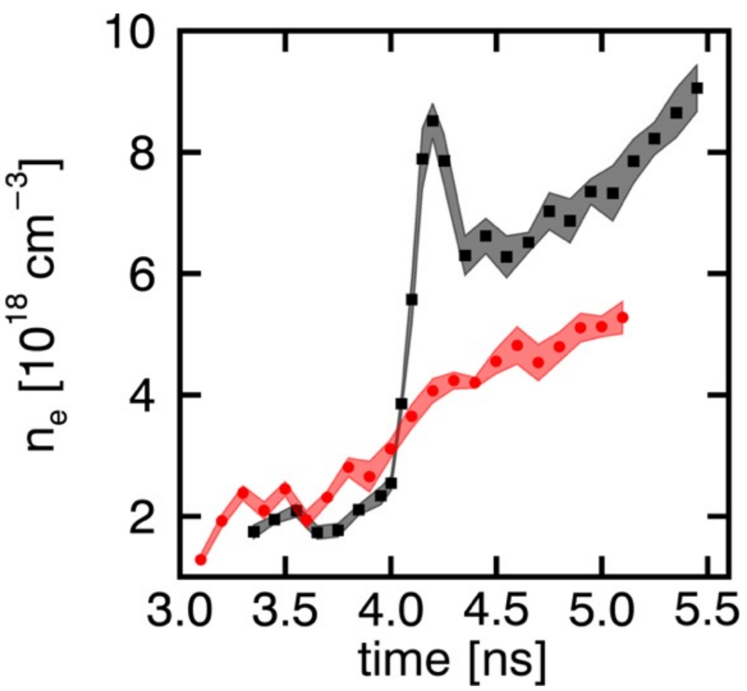
Thomson Scattering Data Demonstrate Piston-Ambient Coupling Process

Ion Flow Speed



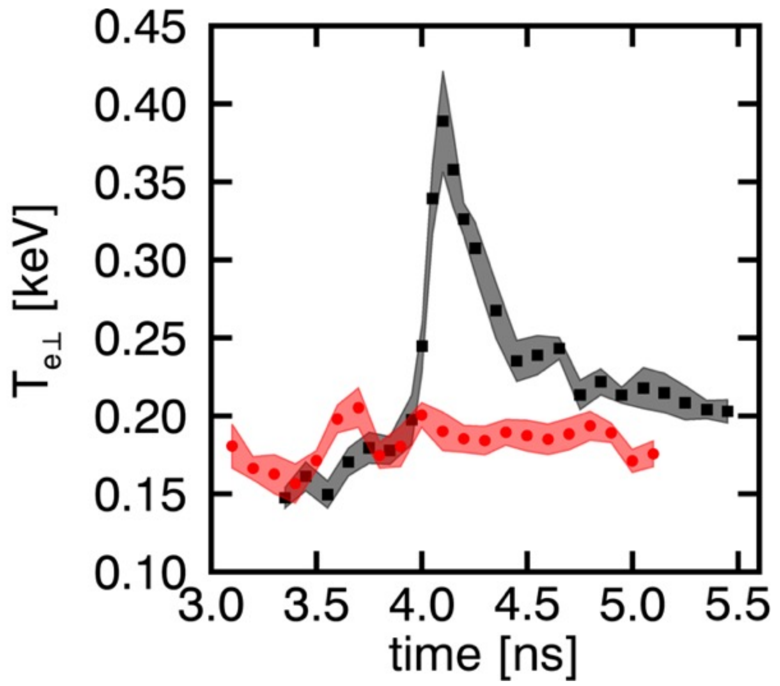
- Decelerated piston flow
- Accelerated ambient flow
- Results from electric fields near piston-ambient interface

Electron Density



- Strong density compression as plasma piles up behind magnetic compression

Electron Temperature



- Significant adiabatic electron heating from compression

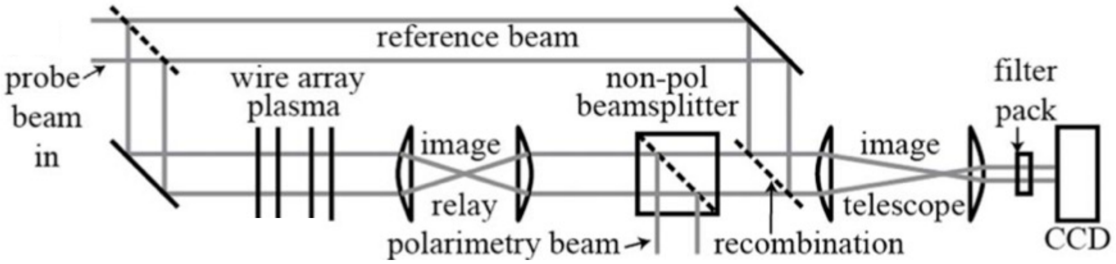
[Schaeffer+ PRL 2019]

Line-Integrated Density Maps can be Measured with Interferometry

PRINCETON UNIVERSITY

PPPL

Laser Interferometry



- Plasma has index of refraction $n = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}$

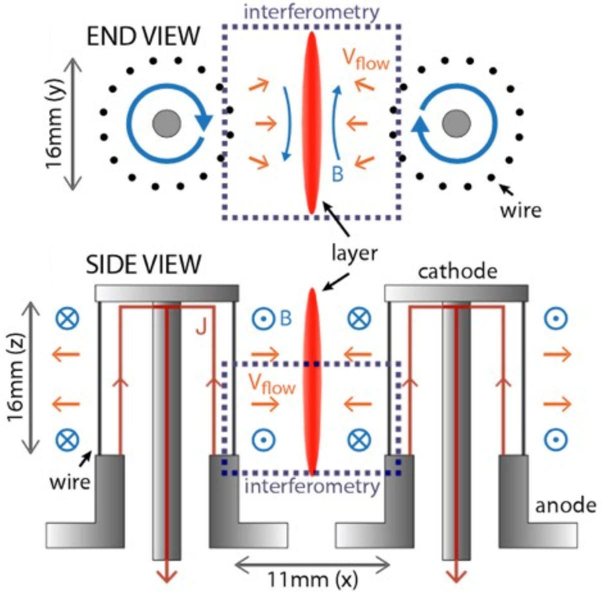
$$\omega_p = \left(\frac{n_e e^2}{m_e \epsilon_0}\right)^{1/2}$$

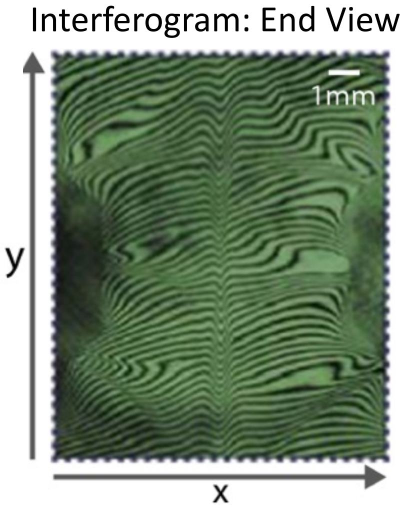
- Mach-Zehnder interferometer: probe beam sent along two paths, one reference and one through plasma
- Resulting interference pattern related to plasma density through refraction angle

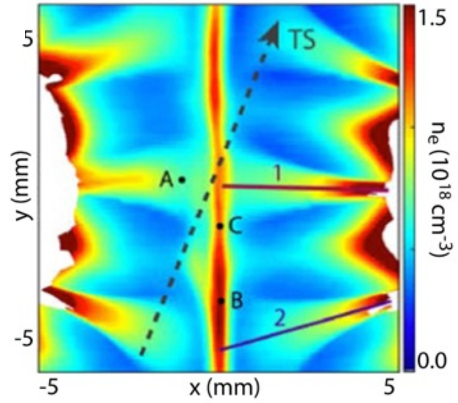
$$\theta_\alpha = \frac{1}{2n_{cr}} \int_{-\infty}^{\infty} \frac{\partial n_e}{\partial \alpha} dz$$

[Swadling+ RSI 2014]

Reconnection Experiments on MAGPIE





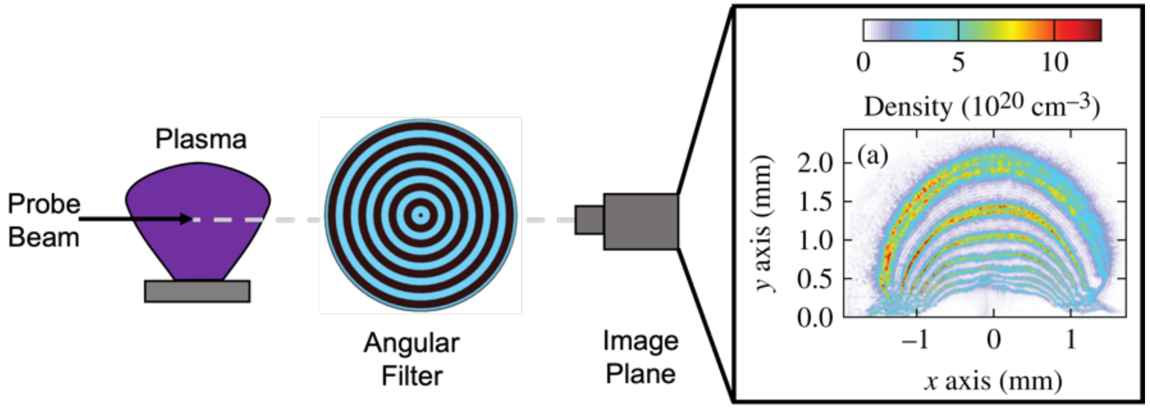


- Exploding wire arrays used to study magnetic reconnection
- Interferometry shows reconnection current sheet

[Suttle+ PRL 2016]

Angular Filter Refractometry Measures Contours of Path-Integrated Density Gradients

AFR Concept

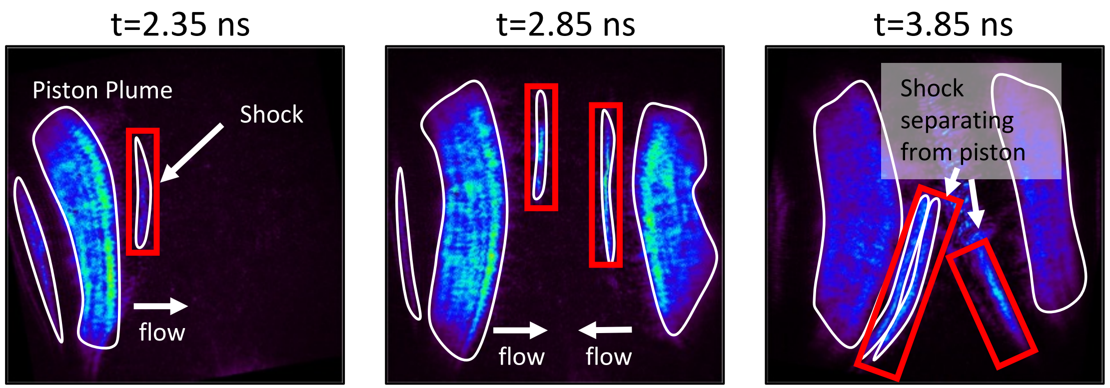


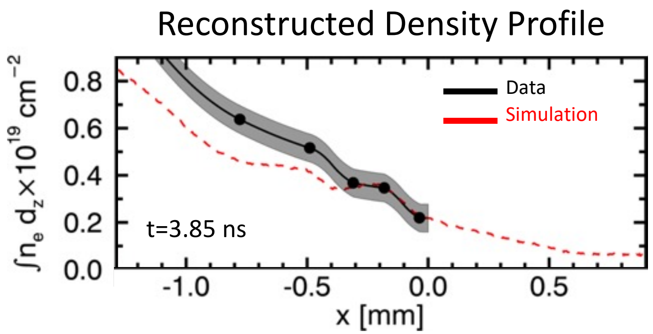
- Probe beam is refracted by plasma
- Passes through angular filter placed in Fourier plane
- Results in discrete set of bands corresponding to specific plasma refraction angles
- The angles are proportional to the path-integrated plasma density gradient

$$\theta_\alpha = \frac{1}{2n_{cr}} \int_{-\infty}^{\infty} \frac{\partial n_e}{\partial \alpha} dz$$

[Haberberger+ PoP 2014]

Shock Experiments on OMEGA EP





- Experiments studying piston-driven collisionless shocks
- Observe steep density gradients in shock front
- At late times, observe shock separate from piston

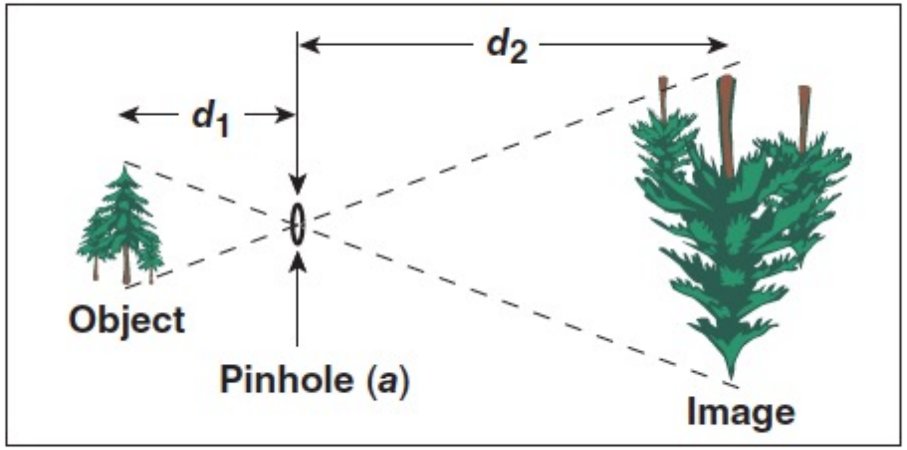
[Schaeffer+ PRL 2017]

Outline

- Introduction to HEDP
- Detectors
- Optical Diagnostics
  - Thomson scattering
  - Refractive imaging
- X-ray Diagnostics
  - **Pinhole imaging**
  - Emission Spectroscopy
- Particle Diagnostics
  - Proton deflectometry
  - Particle spectrometers

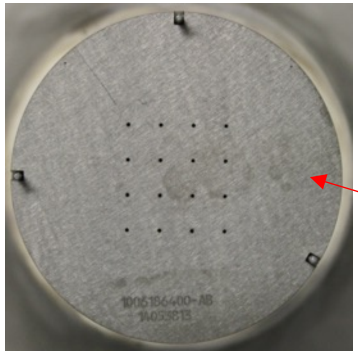
X-ray Pinhole Imaging Commonly Used in HED Experiments

Pinhole Imaging

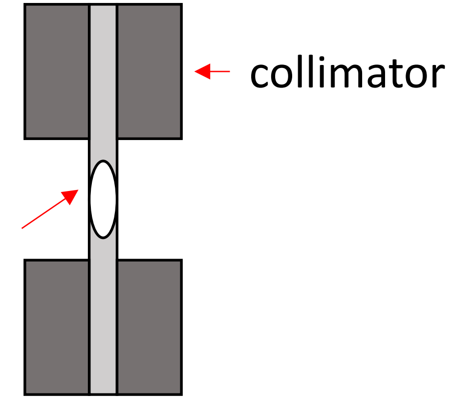


- Magnification $M = d_1/d_2$
- Pinhole diameter a sets
  - resolution $R \sim a$
  - light collection $\Omega \approx \frac{\pi a^2}{4d_1^2}$
- Coupled with 2D detector (e.g. film, IP, CCD, framing camera)

Pinhole Arrays



Cross-Section

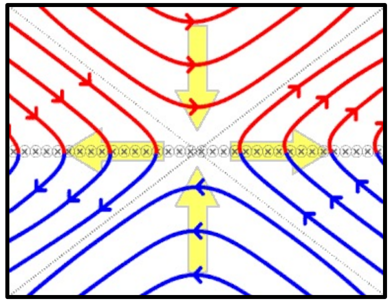


- 2D pinhole arrays frequently used
- *Why?* Noise reduction, time series, differential filtering
- Collimators used to block background when using small pinholes

NIF Used to Produce and Observe Reconnection in Highly-Extended Current Sheets

Magnetic Reconnection

Reconnection



Earth's Magnetosphere

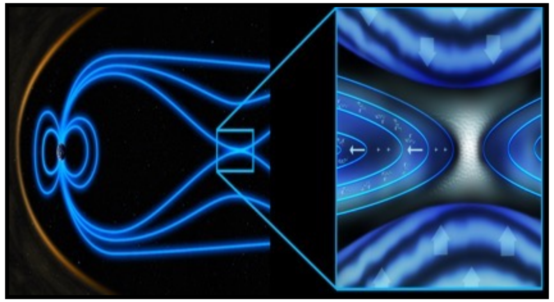
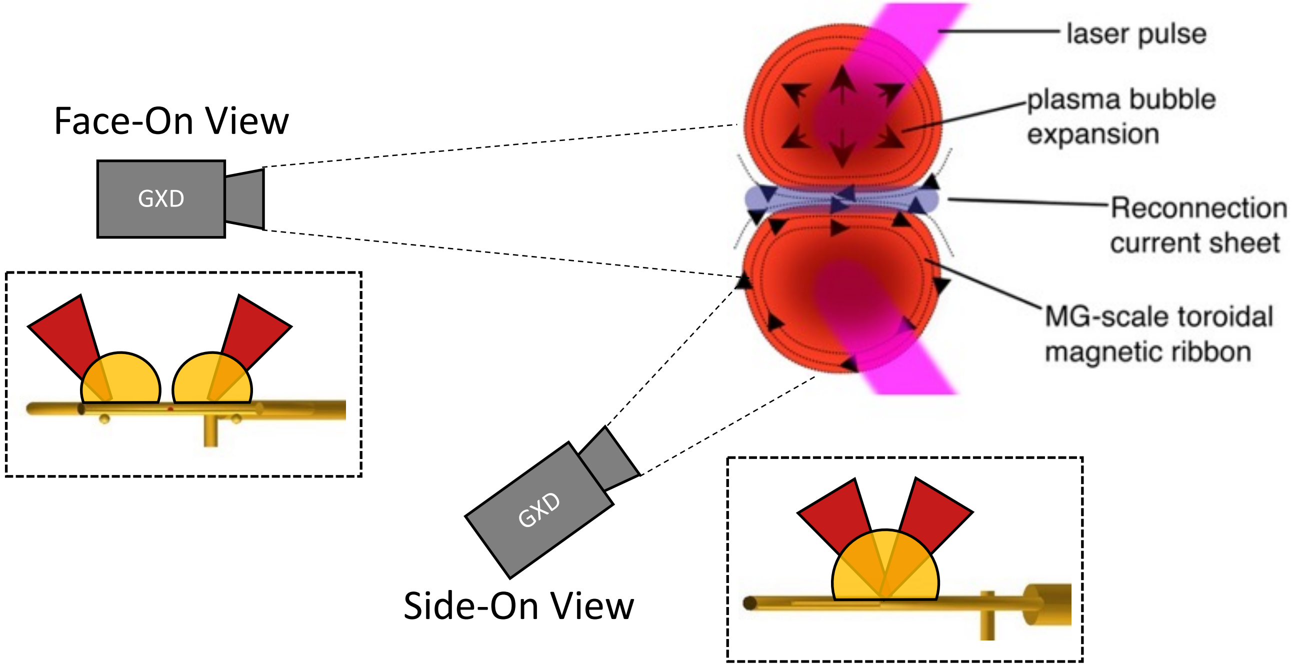


Image: ESA

- Reconnection converts magnetic energy to kinetic and thermal energy by breaking field lines
- Commonly observed in laboratory and astrophysical plasmas
- For large system sizes with low dissipation, current sheet can break up into magnetic islands ("plasmoids")
- Laboratory experiments enable detailed studies using high-energy lasers

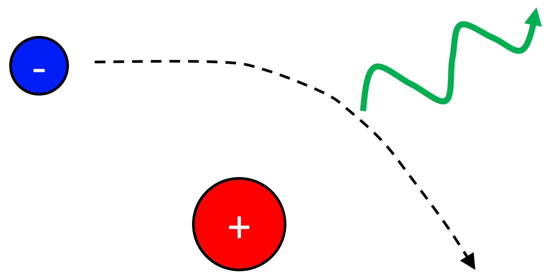
Experimental Setup on NIF



- Lasers create large expanding plasma plumes
- Magnetic fields self-generated through Biermann Battery Effect $\left(\frac{\partial B}{\partial t} \propto \nabla T_e \times \nabla n_e\right)$
- Fields reconnect as plumes collide
- X-ray self-emission measured to infer plasma temperature

X-Ray Bremsstrahlung from Plasma Observed Through Different Filters

X-Ray Bremsstrahlung

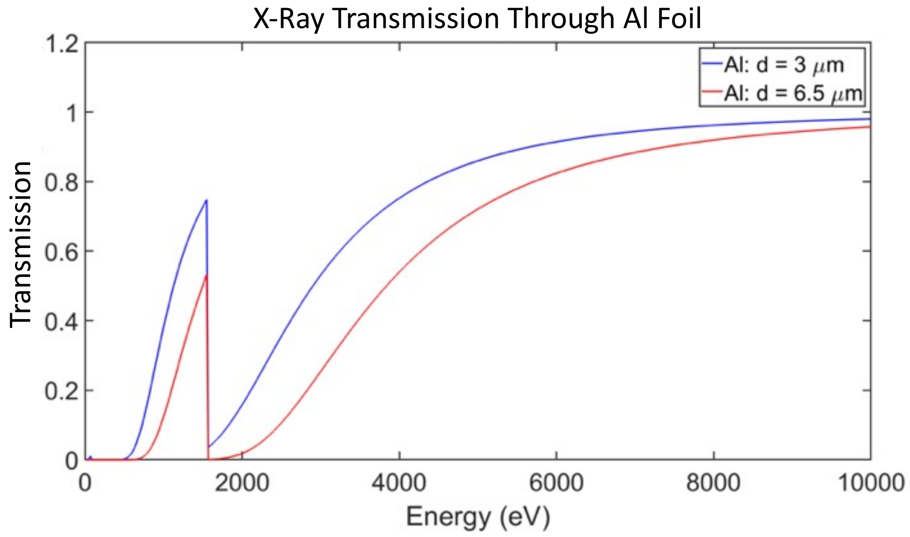


- "Braking Radiation" from deceleration of electrons
- Characteristic energy dependence which can be exploited to measure fundamental plasma parameters like T_e

$$j(\nu, Te) \propto \frac{Zn_e^2}{\sqrt{T_e}} e^{-h\nu/T_e} \bar{g}$$

Emissivity (power/unit frequency/unit volume)
Gaunt factor (of order unity)

Estimate of Electron Temperature



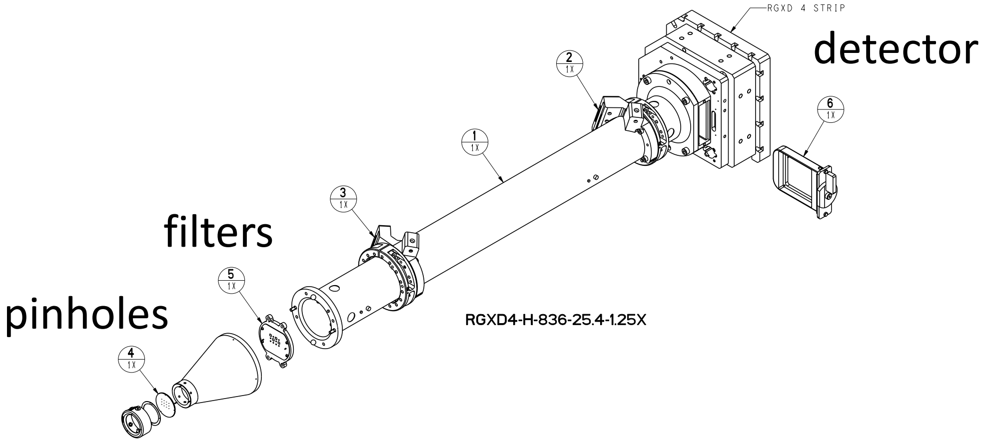
$$R(T_e) = \frac{\int_{-\infty}^{\infty} d\nu\, j(\nu, T_e)\, K(\nu)\, \boldsymbol{W_1(\nu)}}{\int_{-\infty}^{\infty} d\nu\, j(\nu, T_e)\, K(\nu)\, \boldsymbol{W_2(\nu)}}$$

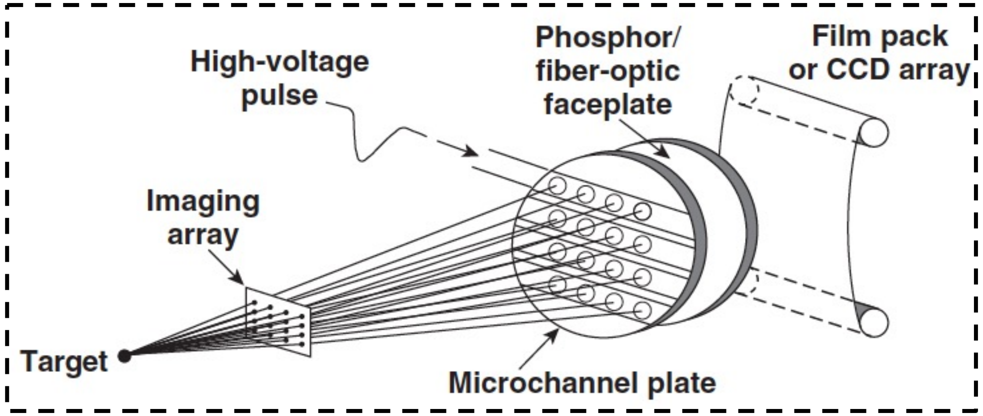
Emissivity
Detector response
Filter response

- X-ray signal attenuated based on filter material and thickness
- Temperature can be estimated by comparing signal through two filters

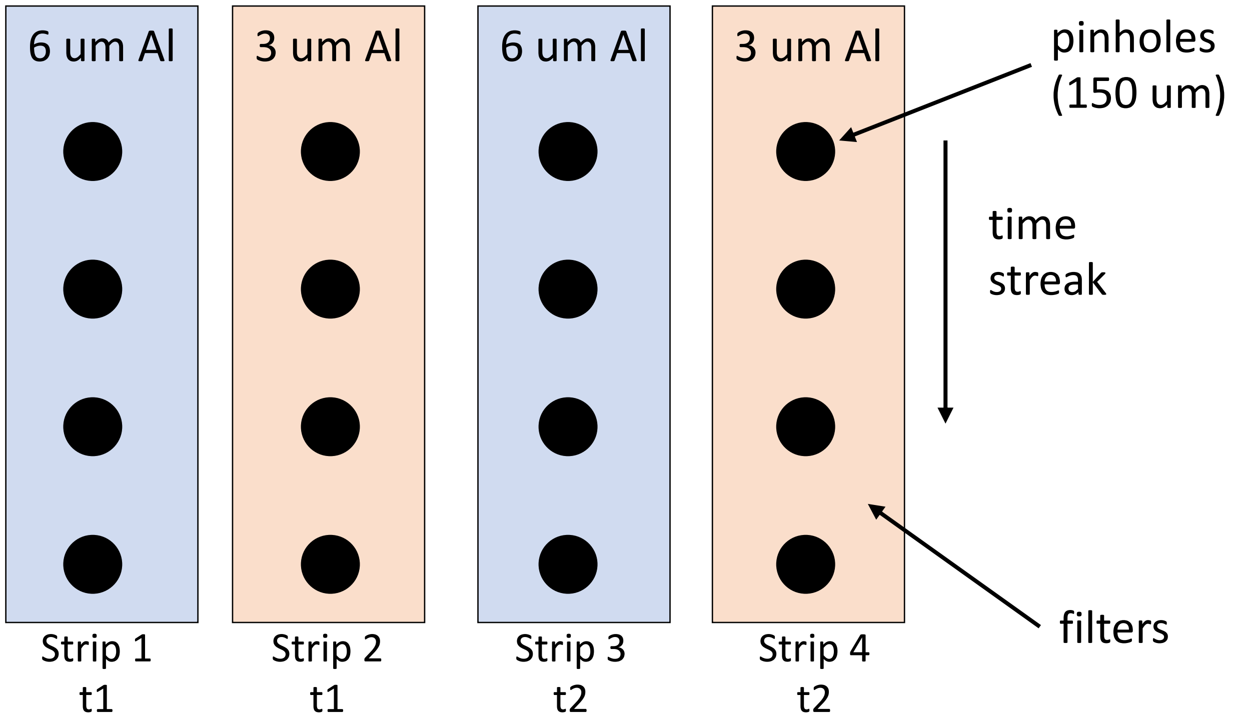
X-rays Measured with NIF Gated X-ray Detector (GXD)

GXD Snout





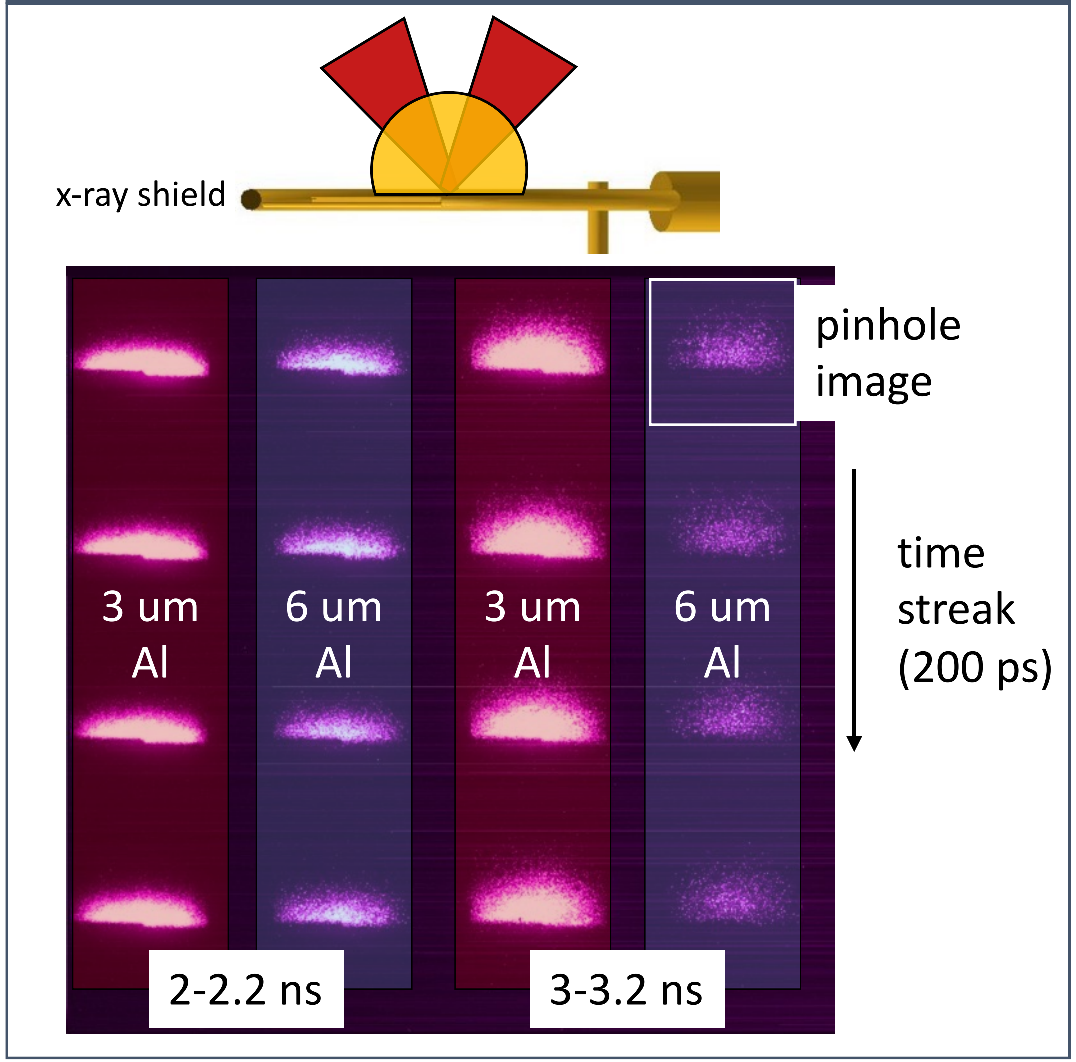
Example Filter Setup



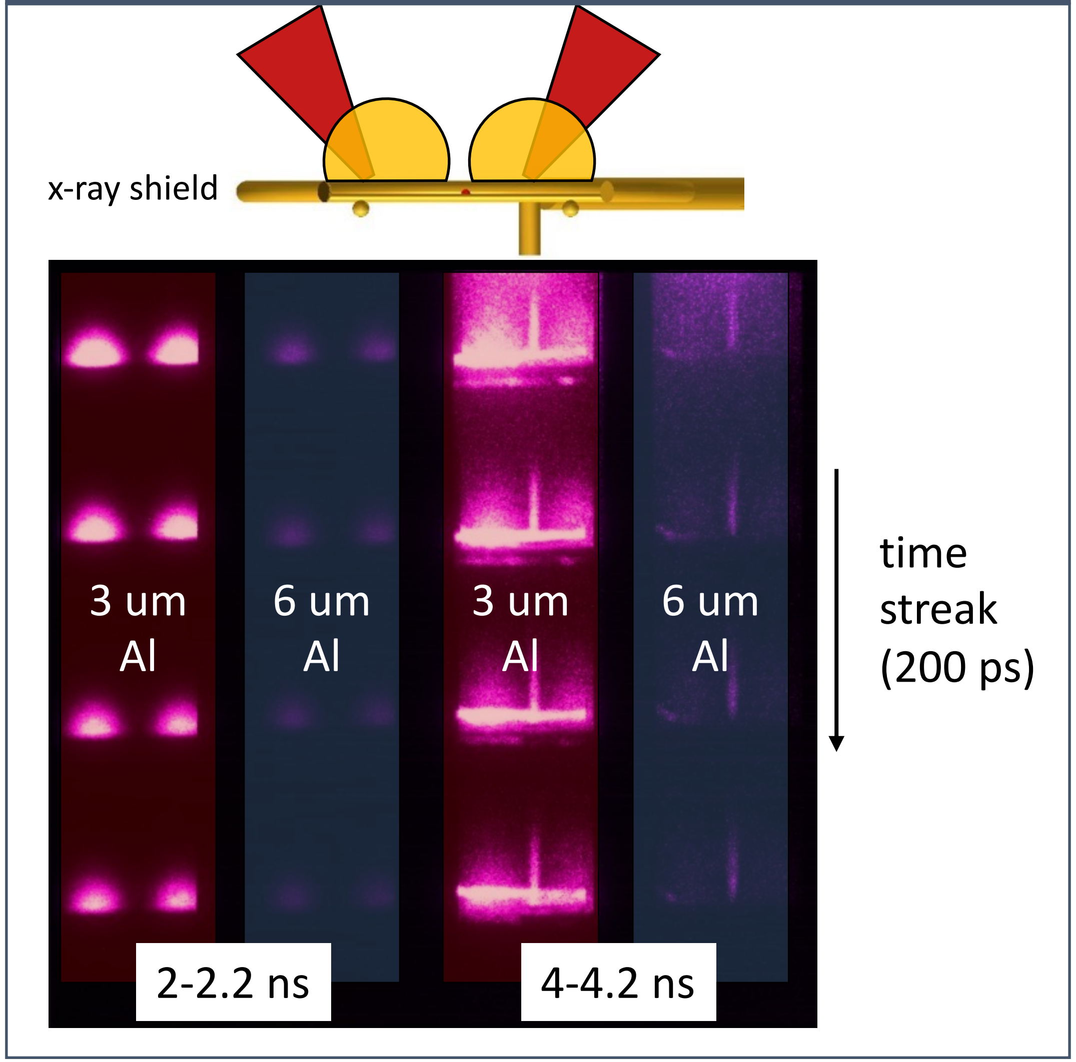
- X-rays pass through filtered pinhole array
- 4 independently timed strips embedded in MCP
- X-rays captured by time-gated framing camera

X-ray Images Show Evolution of the Plasma and Current Sheet

Side-On View

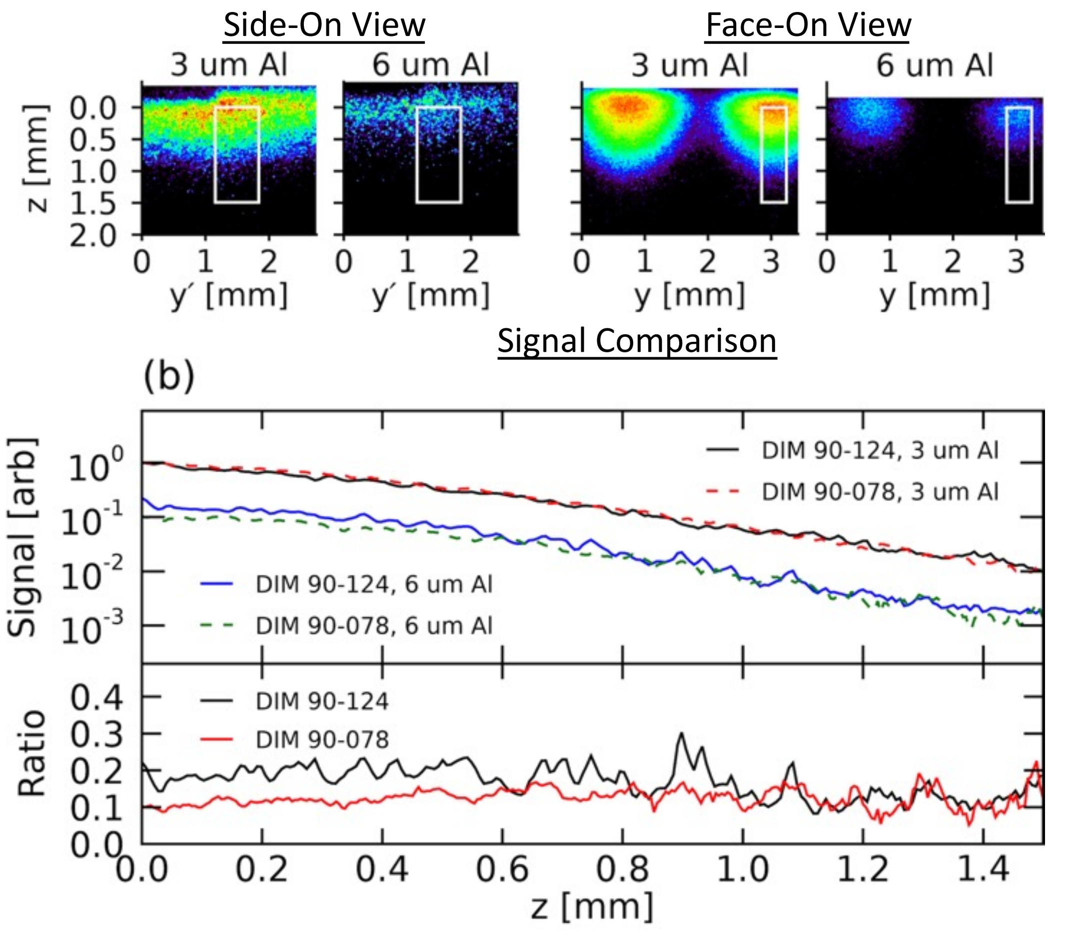


Face-On View



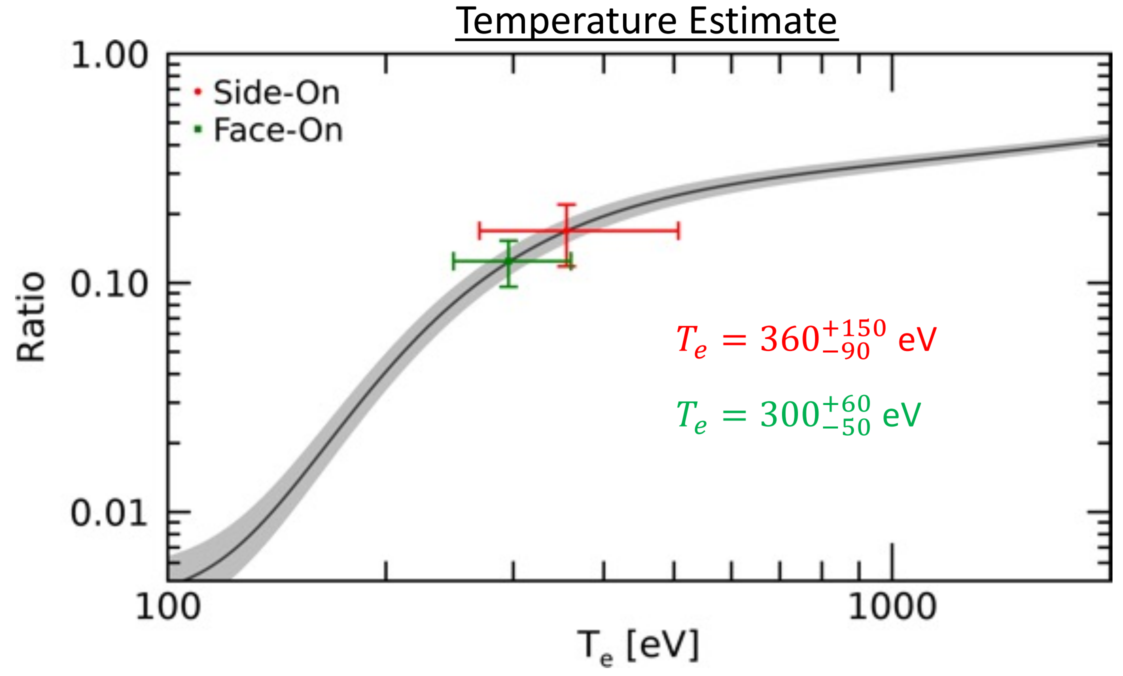
Electron T_e Measured by Comparing Filtered Signals

Filtered Pinhole Images



[Schaeffer+ RSI 2021]

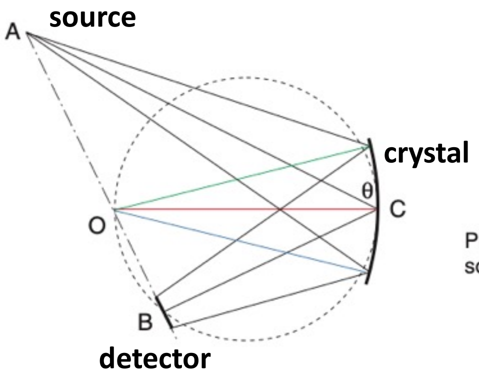
Electron Temperature

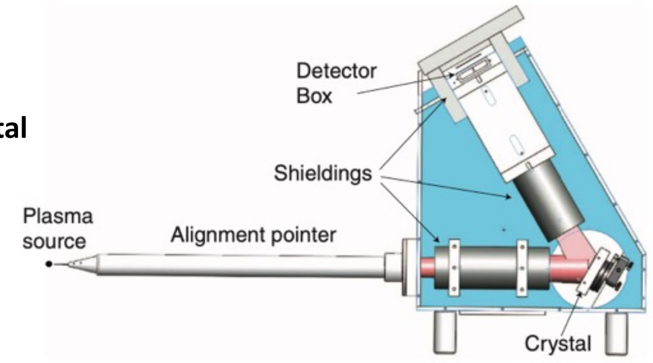


- X-ray signal compared through two filters at same time
- Similar temperatures measured from side-on and face-on images

X-Ray Spectroscopy

Imaging Crystal Spectrometer





- X-rays incident on crystal reflected if Bragg condition met

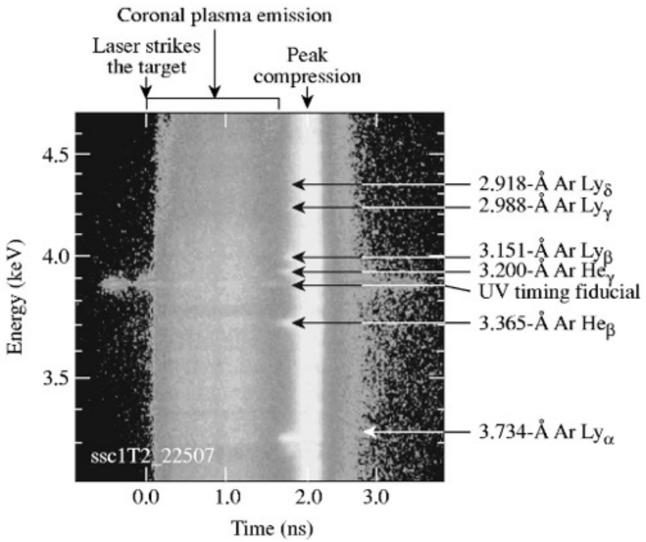
$$n\lambda = 2d\sin(\theta)$$

diffraction order
wavelength
atomic spacing

- Typical crystals: quartz, Ge, Si
- Spherically bent crystals allow focusing and improved signal

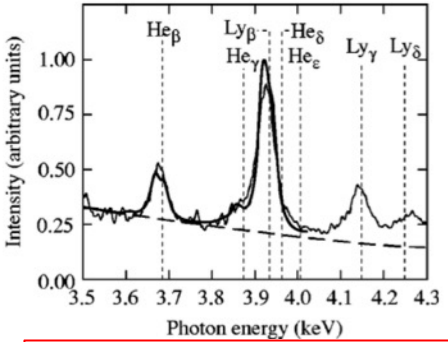
[Chen+ RSI 2014]

Ar K-Shell Spectroscopy on OMEGA 60



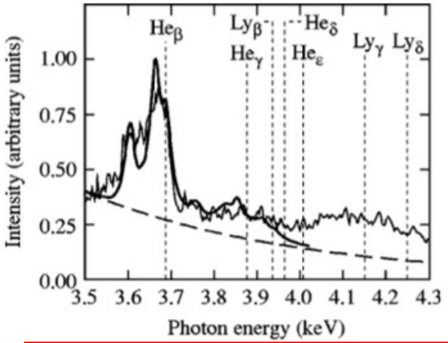
- Experiments studied direct-drive implosions of Ar-doped D-filled capsules
- K-shell lines compared to model spectra to extract temperature and density evolution

t=1.89 ns



$T_e = 1.9$ keV, $n_e = 1.25\times10^{24}$ cm^{-3}

t=2.15 ns



$T_e = 0.75$ keV, $n_e = 1.7\times10^{24}$ cm^{-3}

[Regen+ PoP 2002]

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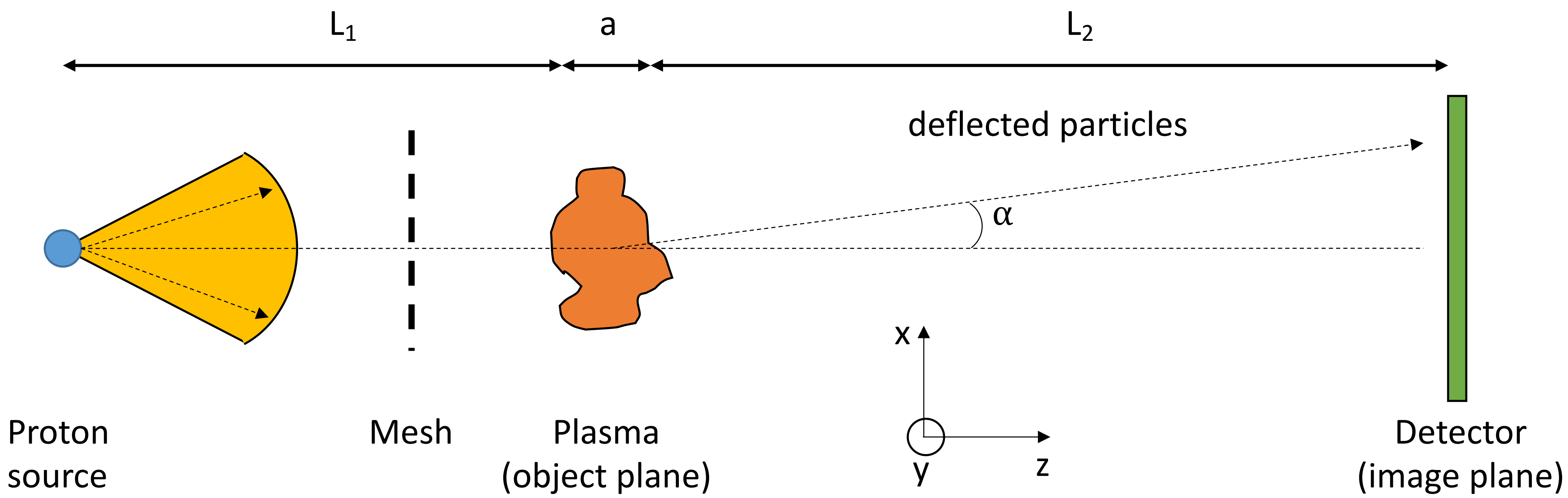
- Particle Diagnostics
  - **Proton deflectometry**
  - Particle spectrometers

Proton Deflectometry Used to Infer E and B Fields Present in Plasma



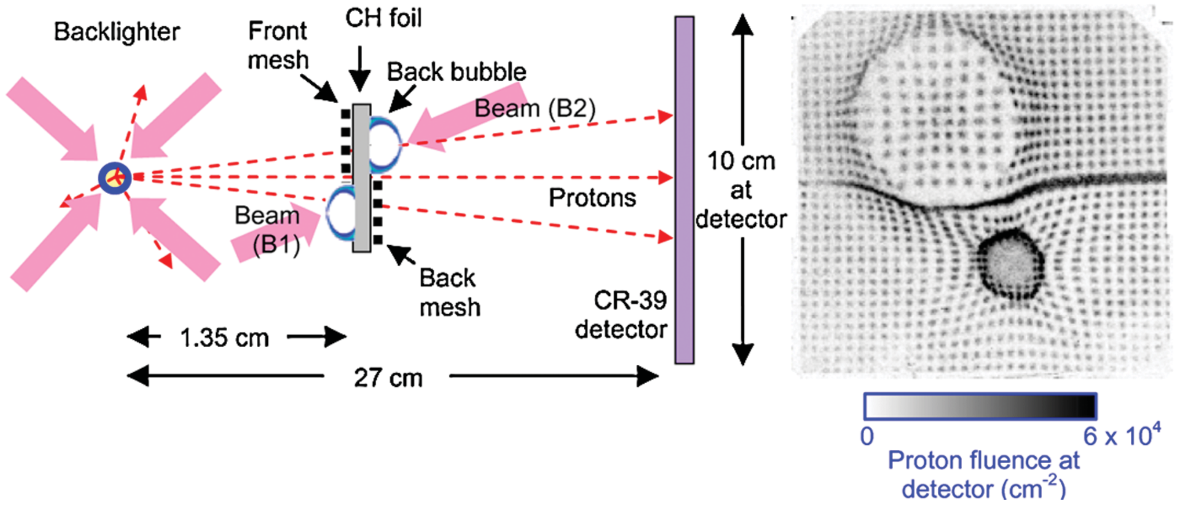
$$\Delta\alpha_B = \frac{e}{m_p V_p}\int \mathbf{B}\times \mathbf{d}\ell$$

$$\Delta\alpha_E = \frac{e}{m_p V_p^2}\int \mathbf{E}_\perp\, d\ell$$

$$\boldsymbol{x}_i = M\boldsymbol{x}_0 + L_2\Delta\boldsymbol{\alpha}_B$$

Proton Observations can be Quantitatively Converted to B Fields

Direct Mapping of Proton Beamlets



- Protons broken up into *beamlets* by mesh grid
- By comparing to reference grid, can directly calculate deflection

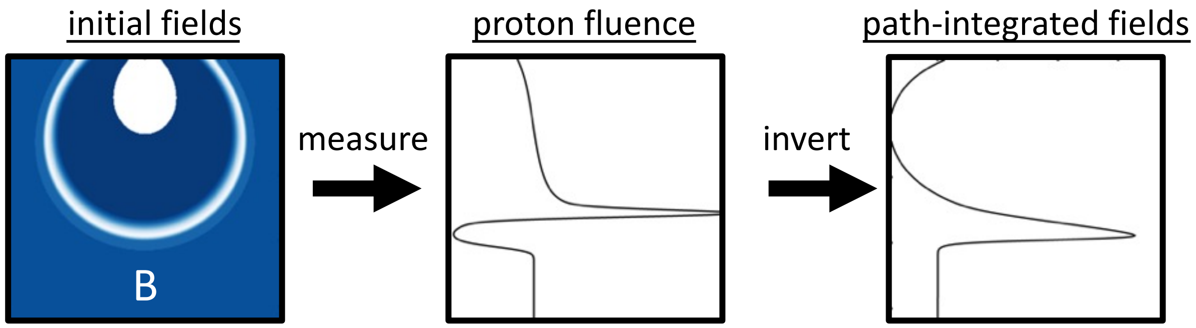
[Petrasso+ PRL 2009]

Numerical Inversion

Solve $\nabla \cdot \mathbf{\Delta\alpha} = \delta I / I$

Deflection angle

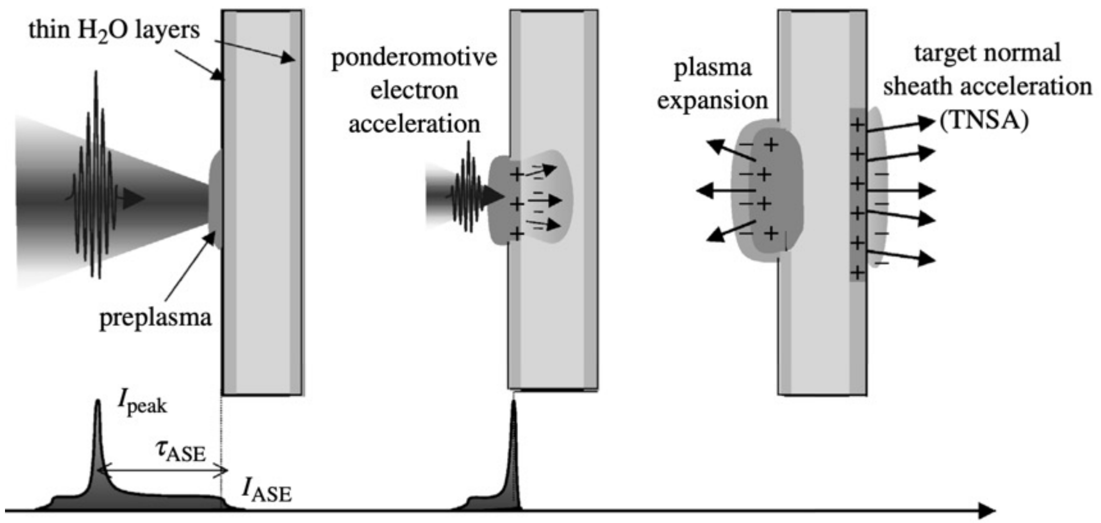
Proton fluence



[Kugland+ PoP 2012, Bott+ JPP 2018]

Target Normal Sheath Acceleration Generates MeV Proton Beams

TNSA

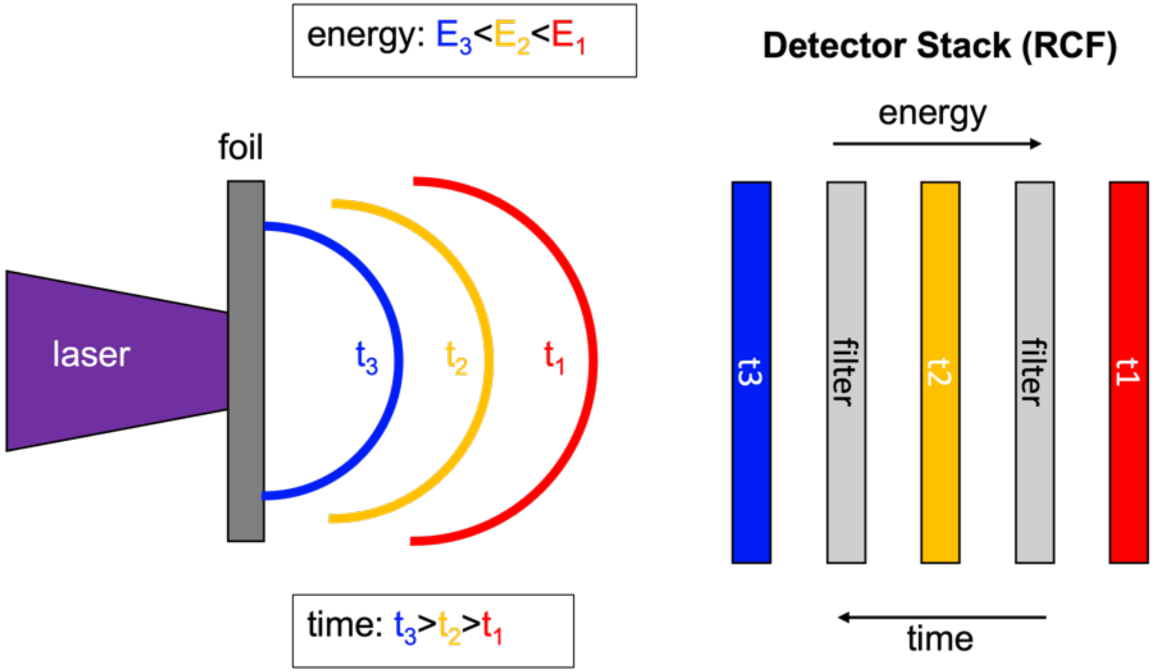


[McKenna+ PTRSA 2006]

- Short pulse laser (~ps, ~100 J) incident on thin metallic foil
- Hot electrons escape from rear side of target
- Electrostatic field develops of order MeV/um
- Accelerates protons up to tens of MeV

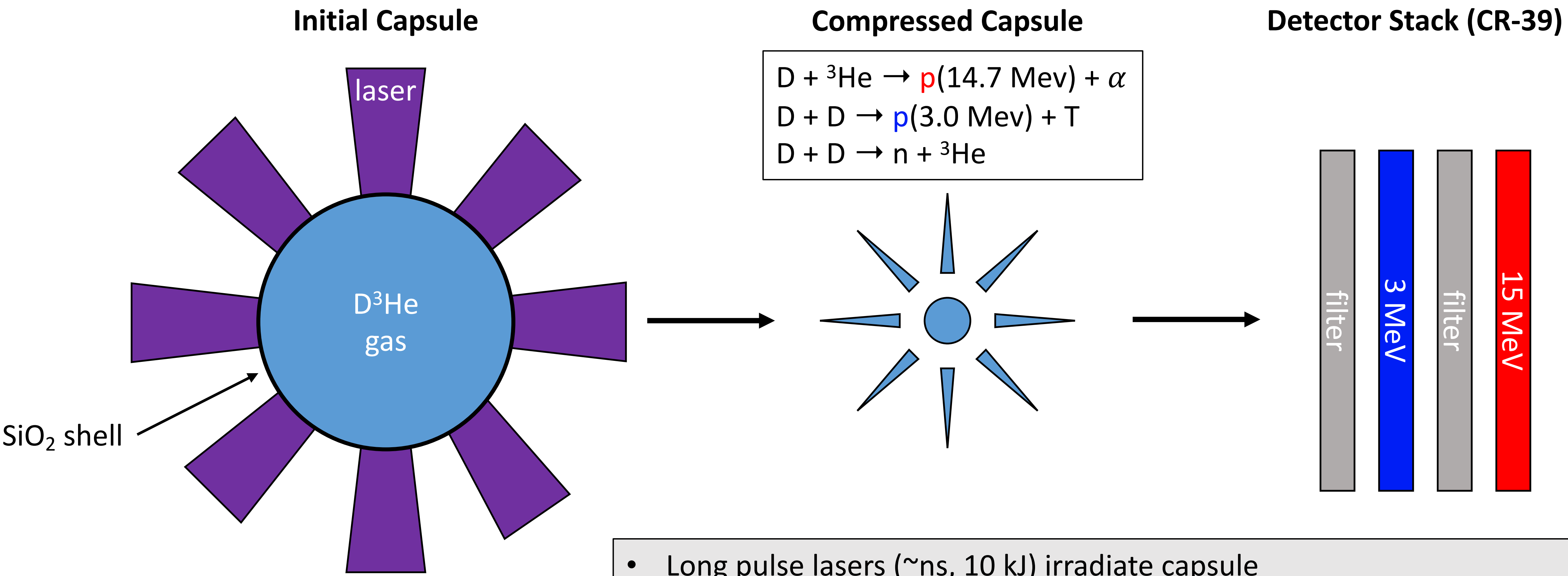
Detector

- Time-of-flight dispersion allows multi-frame imaging



- Ultra bright, extremely collimated, high peak energy (~60 MeV), high spatial resolution (~10 um), and short duration (~ps)

Monoenergetic Protons Created by Imploding D^3He Capsule

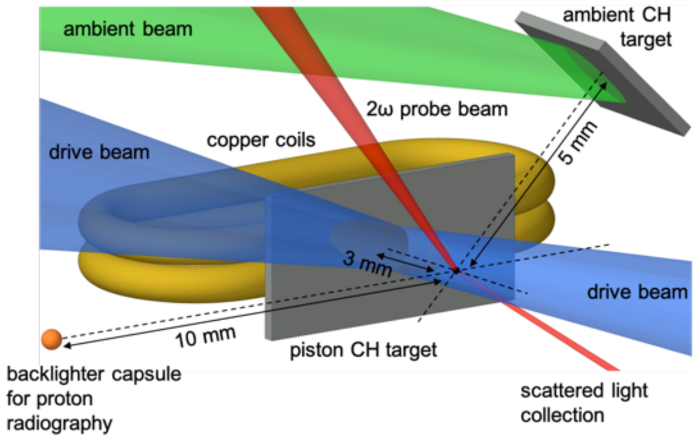


- Long pulse lasers (~ns, 10 kJ) irradiate capsule
- Spatial resolution set by compressed capsule diameter (~40-80 um FWHM)
- Temporal resolution ~100ps
- Expands into 4π
- Two energies/times

[Seguin+ RSI 2003, Li+ PRL 2006, Li+ RSI 2006]

Magnetic Cavity and Compressions Observed in Shock Experiments on Omega

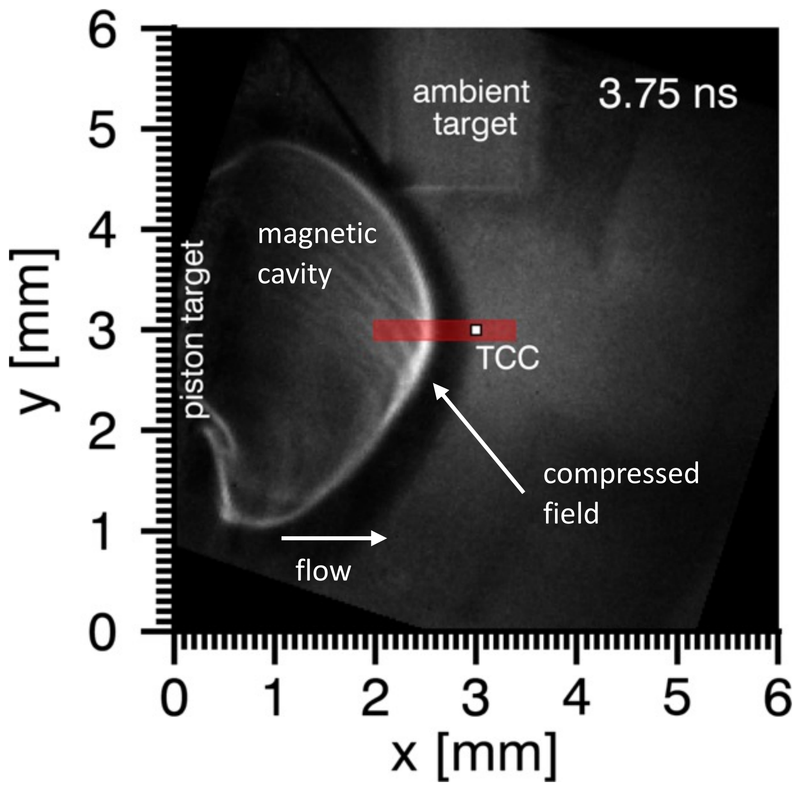
Experimental Setup on OMEGA60



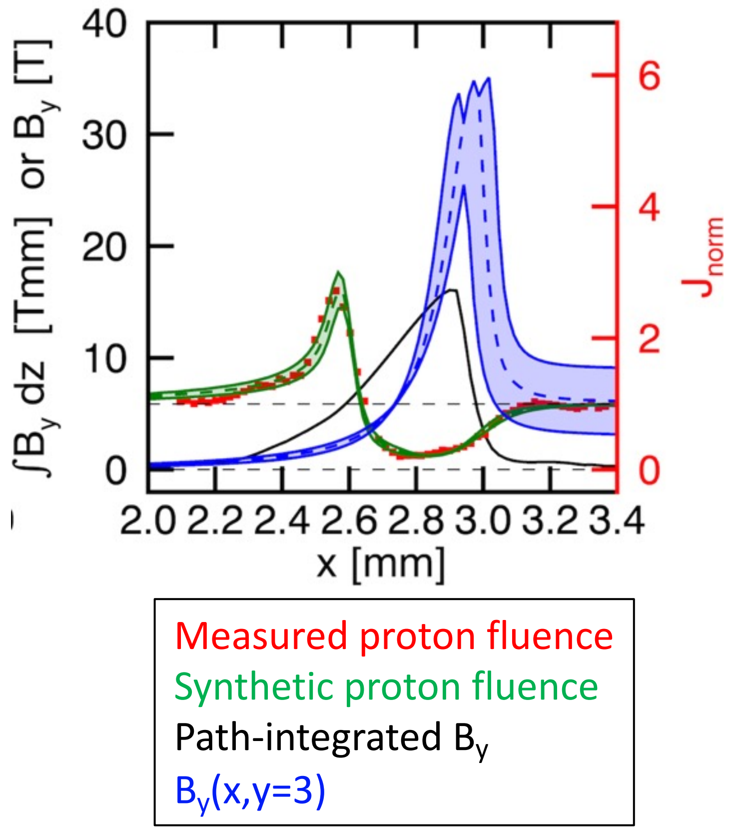
- 3 & 15 MeV protons generated by imploding D^3He capsule
- Proton deflected by shock-compressed fields

[Schaeffer+ PRL 2019]

15 MeV Proton Image

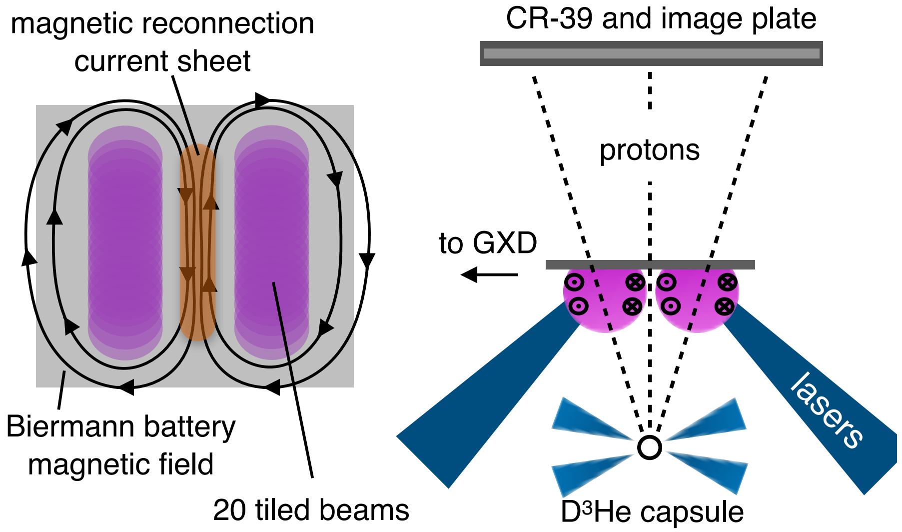


Measured B-Field



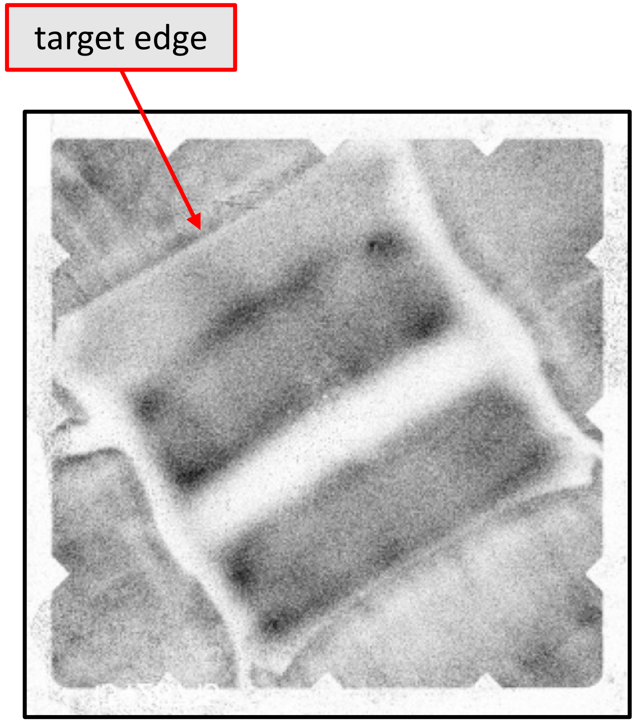
Highly-Extended Current Sheet Observed in Magnetic Reconnection Experiments on NIF

Experimental Setup

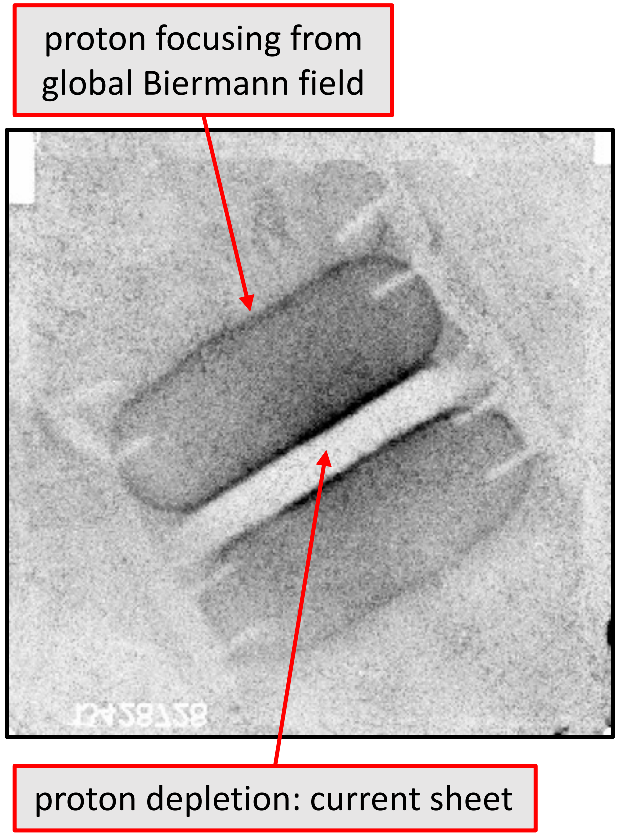


[Fox+ 2020]

3 MeV (DD) Proton Image

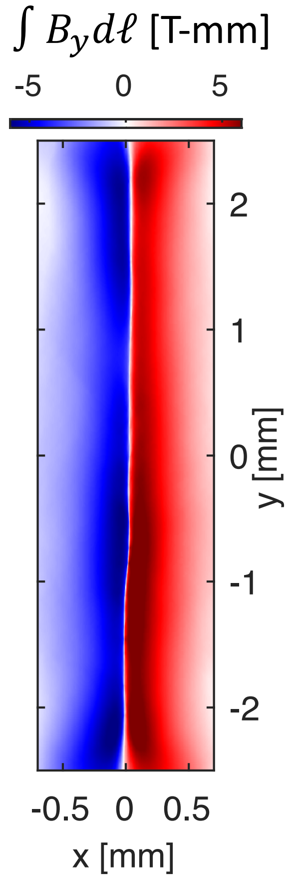


15 MeV (D^3He) Proton Image



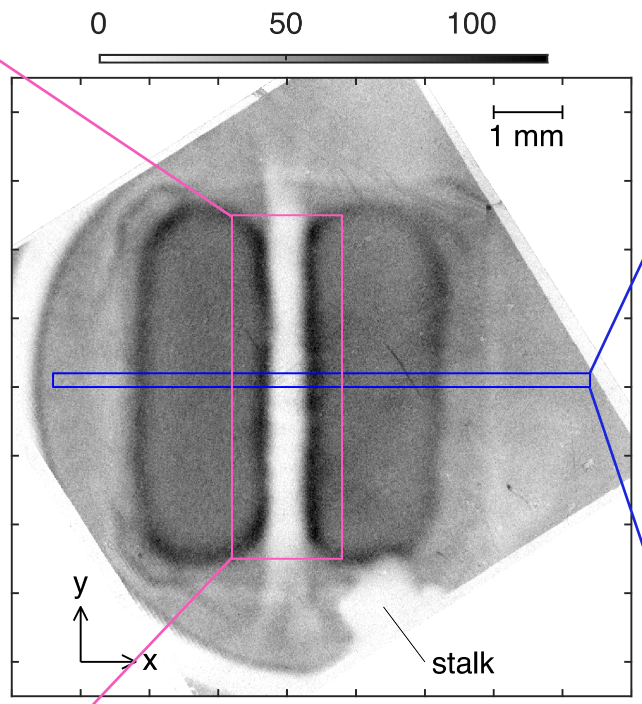
Highly-Extended Current Sheet Observed on NIF

2D PROBLEM Reconstruction



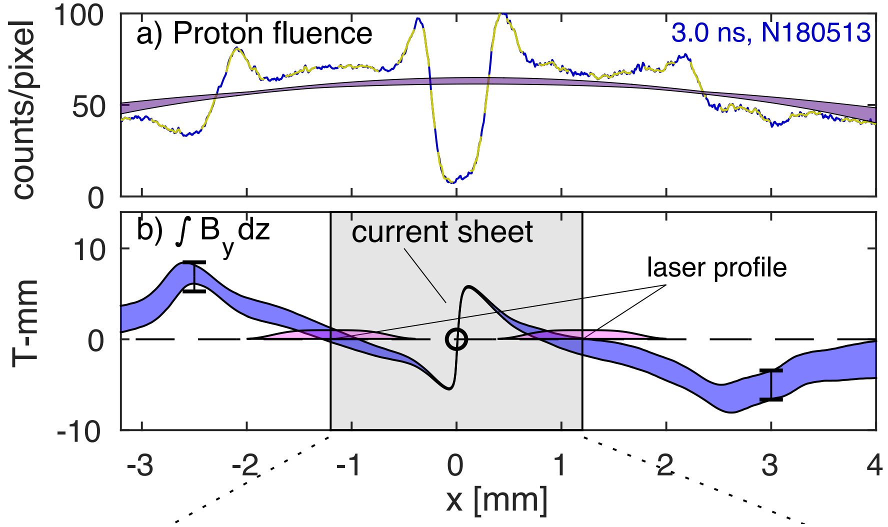
[Bott+ JPP 2018]

15 MeV (D³He) Proton Image



- High aspect ratio current sheet: 6 mm x 25 um
- Laminar structure indicates instabilities not yet formed

1D PRADICAMENT Reconstruction

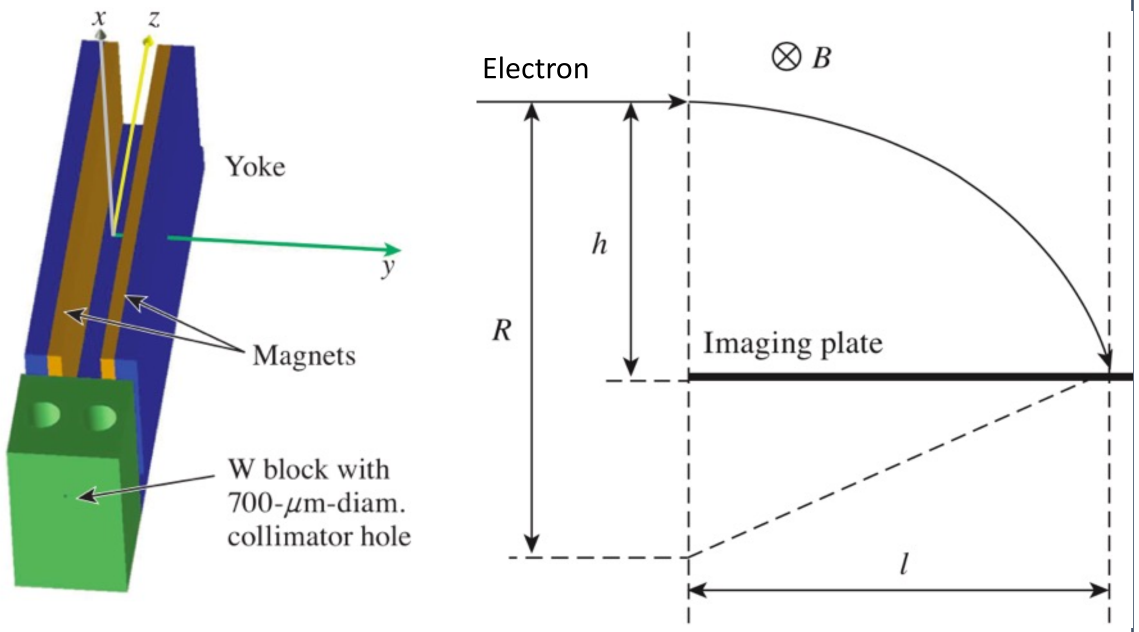


- Near-zero proton fluence indicates very strong deflections
- Non-uniform initial fluence assumed
- Edge features used to constrain family of solutions
- Shows pile up of magnetic flux at center

[Fox+ 2020]

Energy Spectrum of Charged Particles can be Measured with a Magnetic Spectrometer

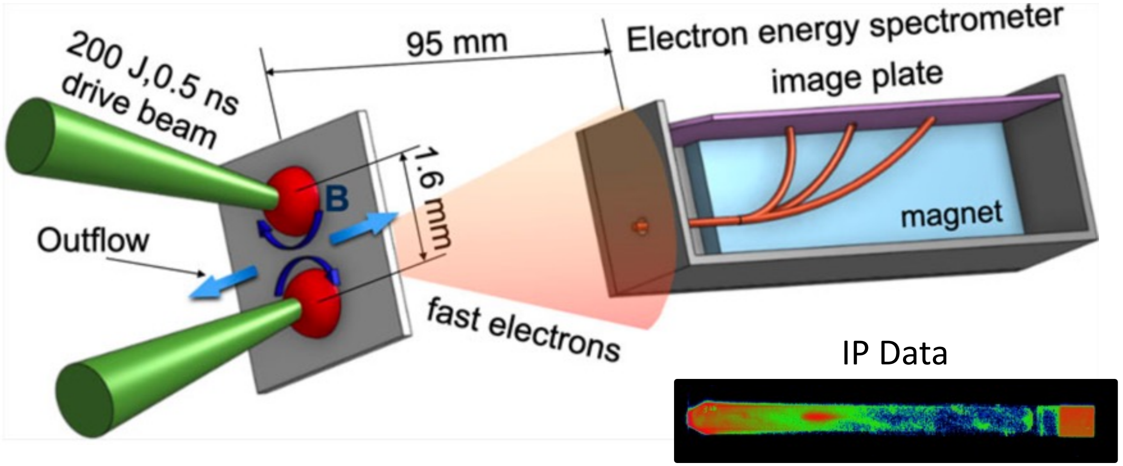
Osaka University Electron Spectrometer (OU-ESM)



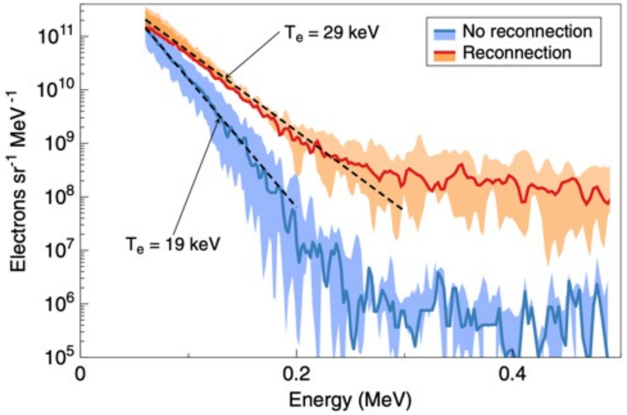
$$E(l) = mc^2\left[\sqrt{\left(\frac{l^2+h^2}{2h}\right)^2\left(\frac{eB}{mc}\right)^2+1}-1\right]$$

[Habara+ RSI 2019]

Magnetic Reconnection Experiments on OMEGA EP



- Study of electron energization due to reconnection
- Observe increased temperature compared to null shots



[Fiksel+ JPP 2021]

Key Challenge of HED Science is Measuring HED Systems

- Require very fast measurements (<ns) at high spatial resolution (10 um)
- HED systems generate:
  - optical, UV, and x-ray photons
  - charged particles
  - neutrons
  - strong electromagnetic fields
- Comprehensive diagnostic suite allows much to be learned: plasma parameters (temperature, density, flows), field strength and topology, energy spectra, particle dynamics, etc.
- Large suite of HED diagnostics have been developed, enabling understanding of new physics