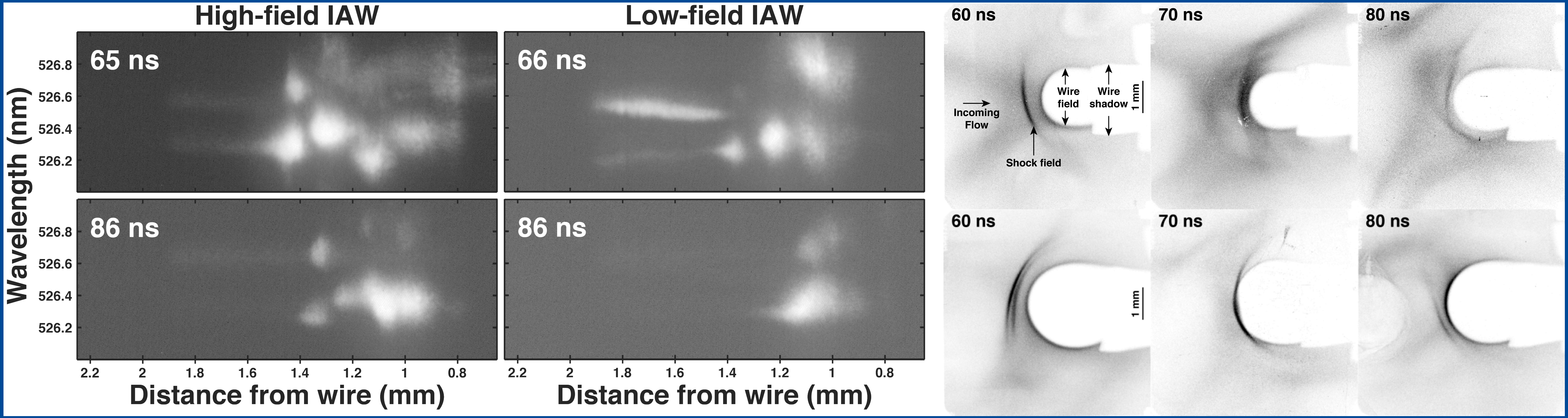
Observing Magnetized Shocks on OMEGA



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1. University of Michigan 2. Los Alamos National Laboratory 3. Rice University
4. General Atomics 5. Laboratory for Laser Energetics 6. Massachusetts Institute of Technology

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University of Michigan: Joseph Levesque, Carolyn Kuranz, Rachel Young, Mario Manuel (General Atomics), Sallee Klein, Gennady Fiksel, Matthew Trantham

Rice University: Patrick Hartigan, Andy Liao (LANL)

MIT: Chikang Li, Andrew Birkel (Proton Radiography)

LLE: Joseph Katz (Thomson Scattering)

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We have successfully observed magnetized bow shocks on OMEGA

- Campaign to create and observe astrophysically relevant laboratory-scale magnetized bow shocks
- Using a colliding plasma flow mechanism alongside MIFEDS we have achieved a β_{ram} regime in which magnetized shocks form
- We use proton radiography to measure the magnetic field topology
- We use the spatially resolved Imaging Thomson Scattering (ITS) diagnostic with 2ω probe beam to measure plasma properties across a shock
- By following reproducible features in the IAW spectra over multiple shots we find that the magnetic field affects the standoff distance of the shock from the wire

We want to create astrophysically relevant laboratory-scale magnetized bow shocks

- Magnetized bow shocks form when the incoming ram pressure of a plasma flow is equal to the magnetic pressure of the obstacle
- Define ram beta as ratio of ram pressure to magnetic pressure

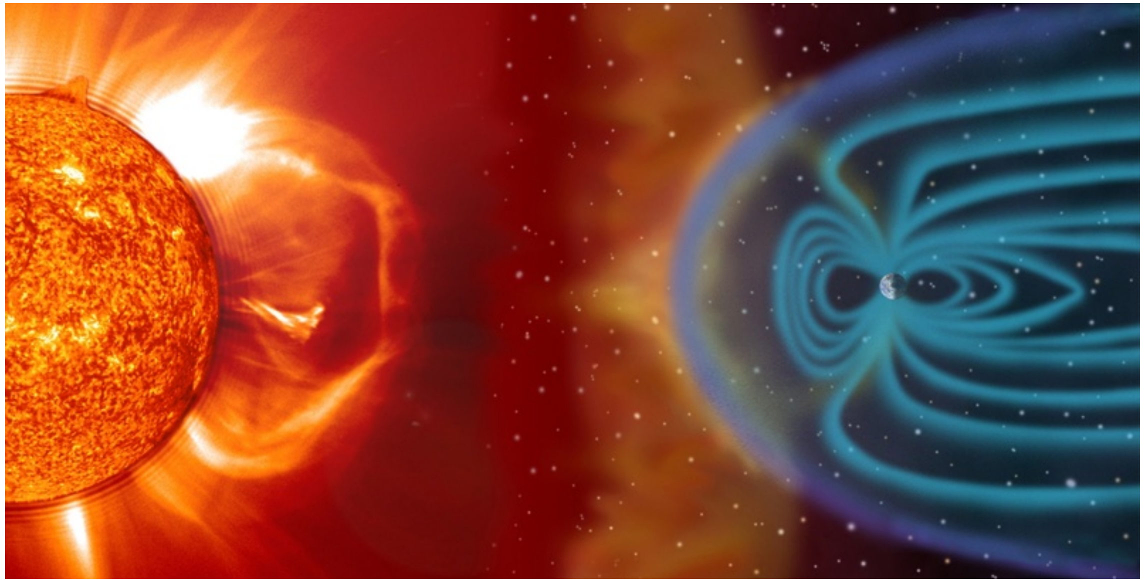


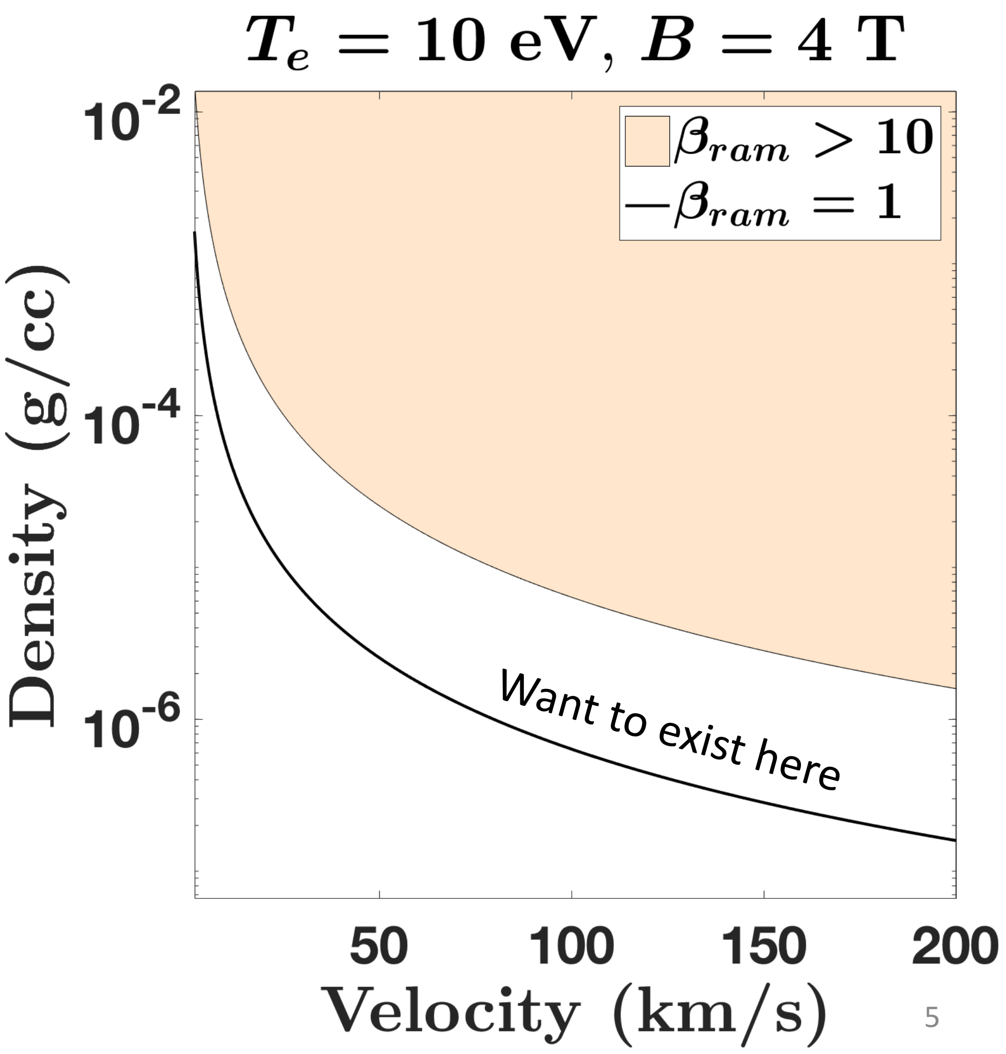
Image credit: SOHO (NASA / ESA)

$$P_{ram} = \rho u^2 \qquad P_B = \frac{B_0^2}{2\mu_0}$$

$$\beta_{ram} = \frac{P_{ram}}{P_B} = \frac{\rho u^2}{B_0^2/2\mu_0} \approx 1$$

Reaching low-β_{ram} on OMEGA is challenging

- Previous attempts to achieve low-β_{ram} systems on OMEGA have been unsuccessful
  - MIFEDS capable of ~15 T maximum field for multi-mm-scale systems
  - Laser-produced plasmas have high ram pressure
- The ram pressure must be reduced for the current limitations

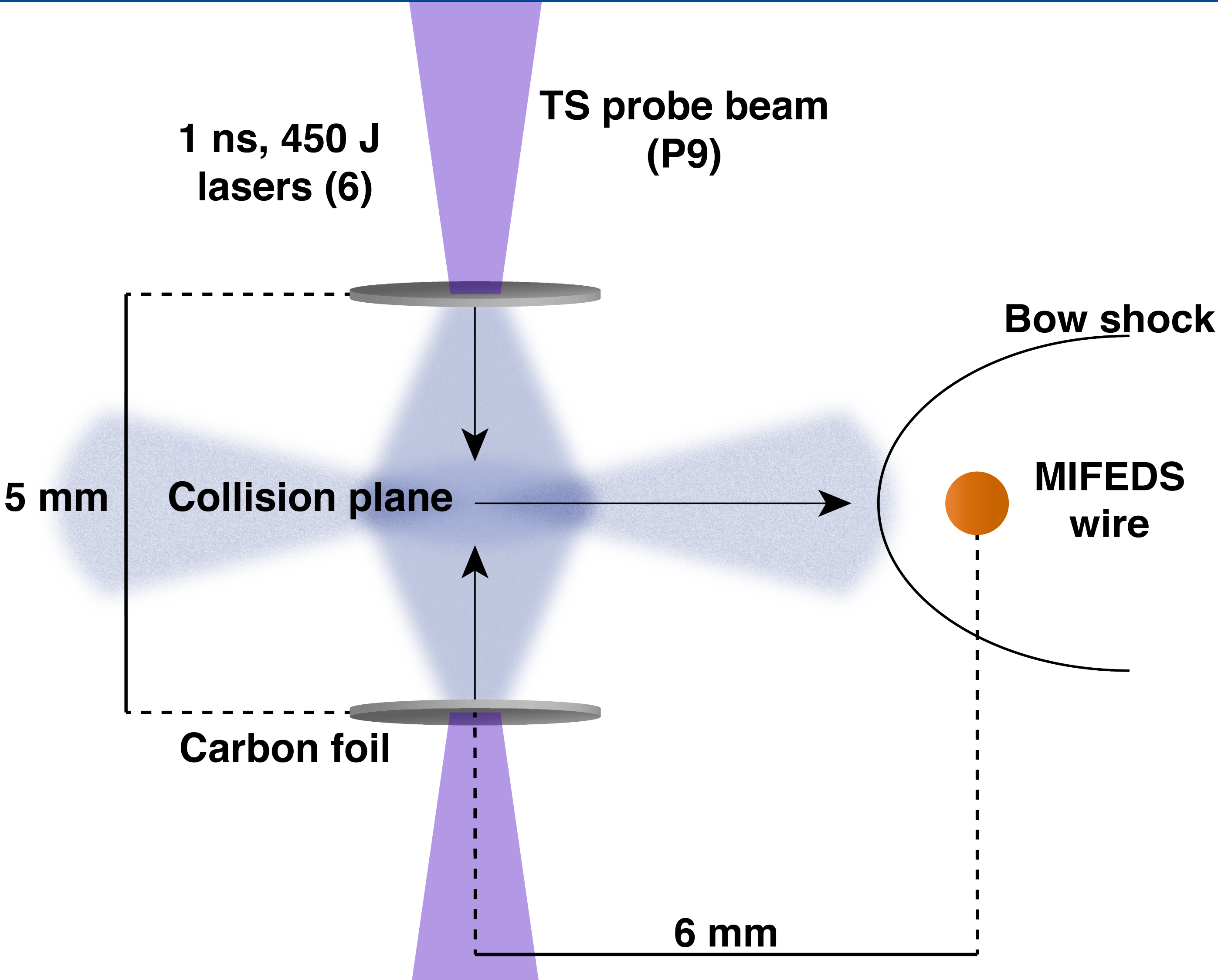


MIFEDS acts as the magnetized obstacle

- **Straight, current-carrying wire is the magnetized obstacle**
- **Wire diameter: 0.762 mm**
- **Driven currents: 25 kA and 17 kA (or 13.5 T and 9 T max field at wire surface)**

We use a multi-stage plasma source to reduce flow density and gradients

- Irradiate two counter-facing carbon foils
  - Diameter: 3.8 mm
  - Thickness: ~100 micron
- Collision redirects incoming flows outward from plane
- Expanding flow has lower density and velocity than constituents[1]
- V ~ 100 km/s, ρ ~10^{-5} g/cc



[1] Liao et al. High Energy Density Physics 17 (2015)

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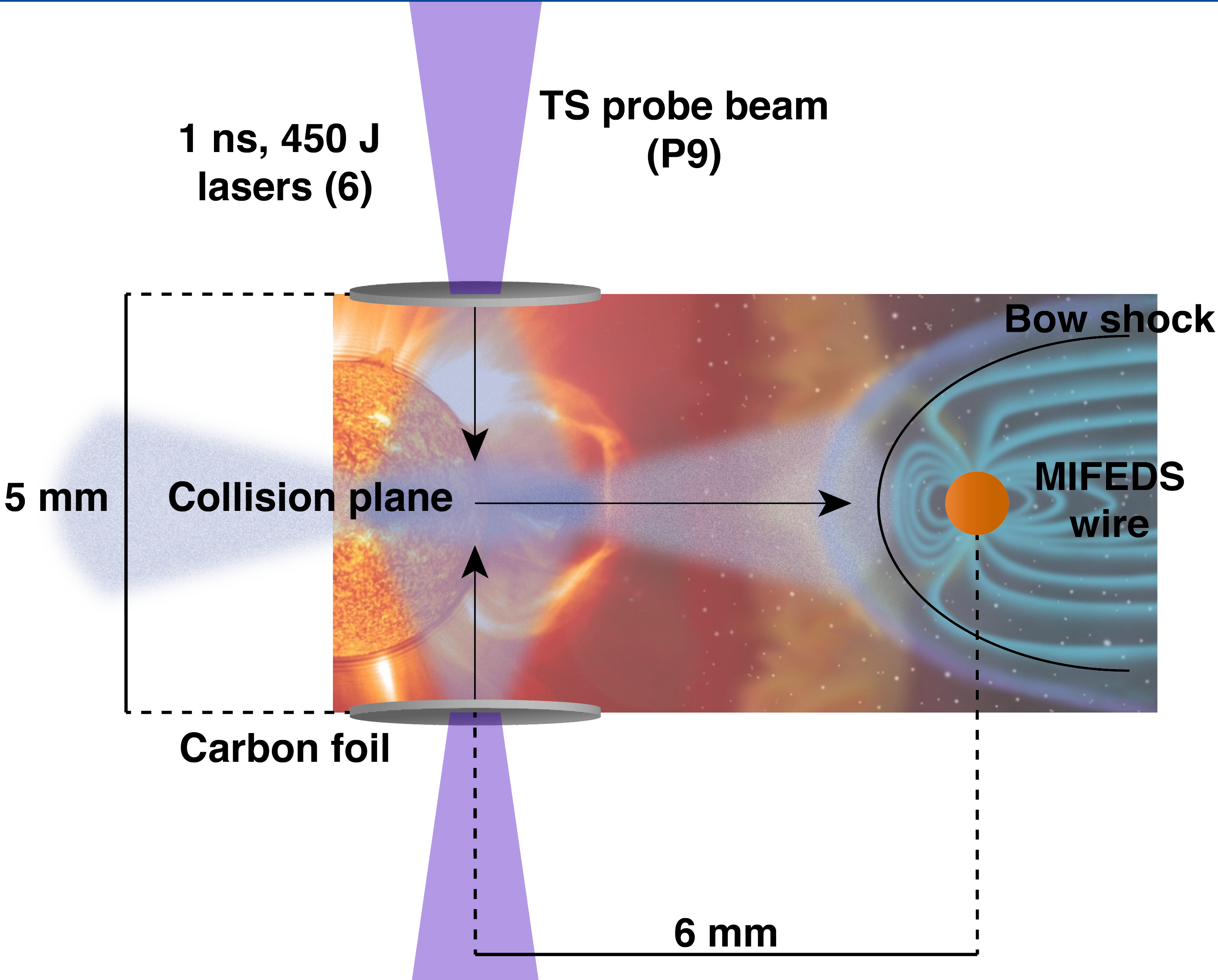
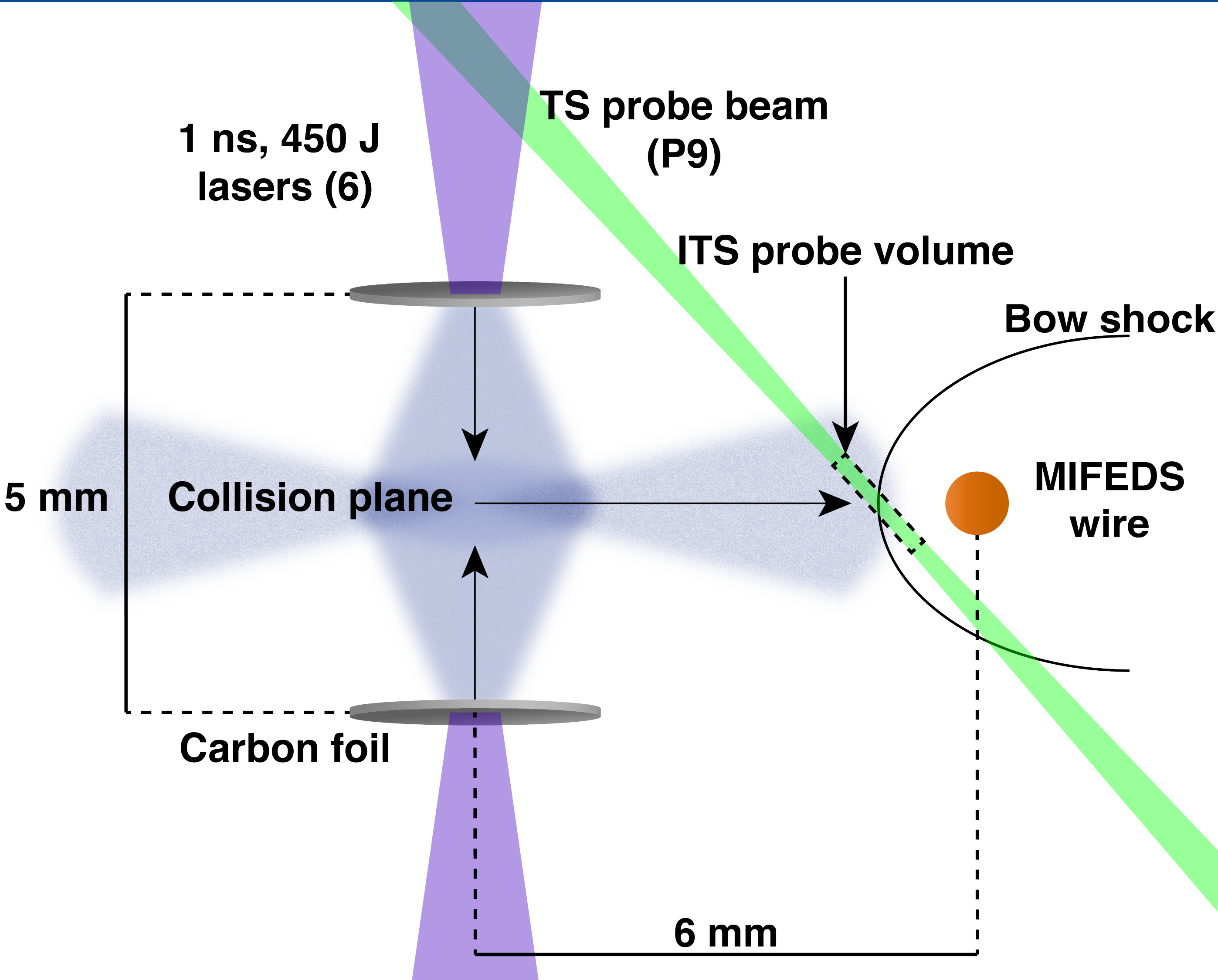
- This plasma acts as our solar wind



[1] Liao et al. High Energy Density Physics 17 (2015)

We probe the system with proton radiography and ITS

- Imaging Thomson scattering (ITS) diagnostic measures scattered spectra
  - Centered 1.45 mm from wire
  - ~43° angle from primary flow axis
- Two probe configurations:
  - 20 J, 100 ps (no proton radiography)
  - 300 J, 1 ns (offset from proton driver)



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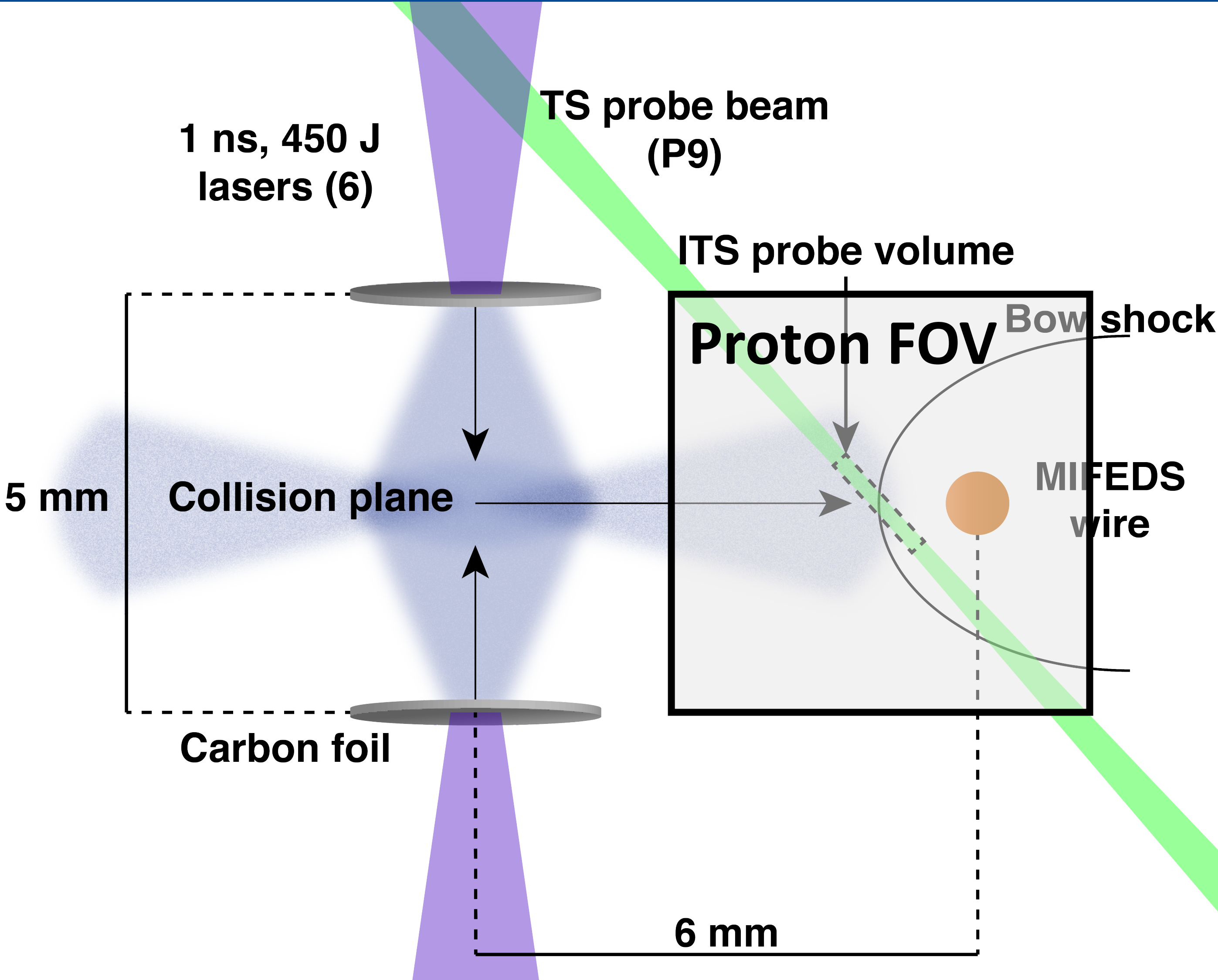
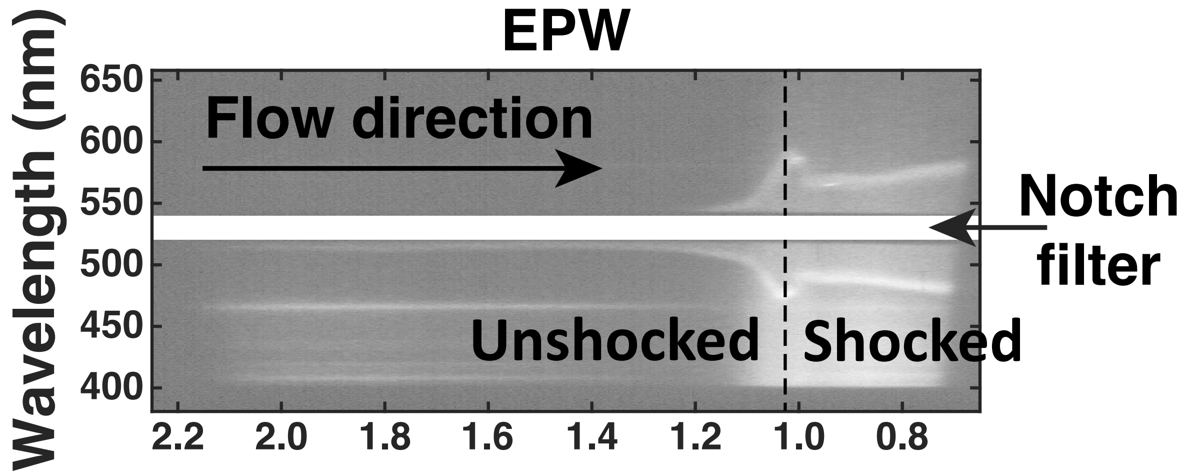
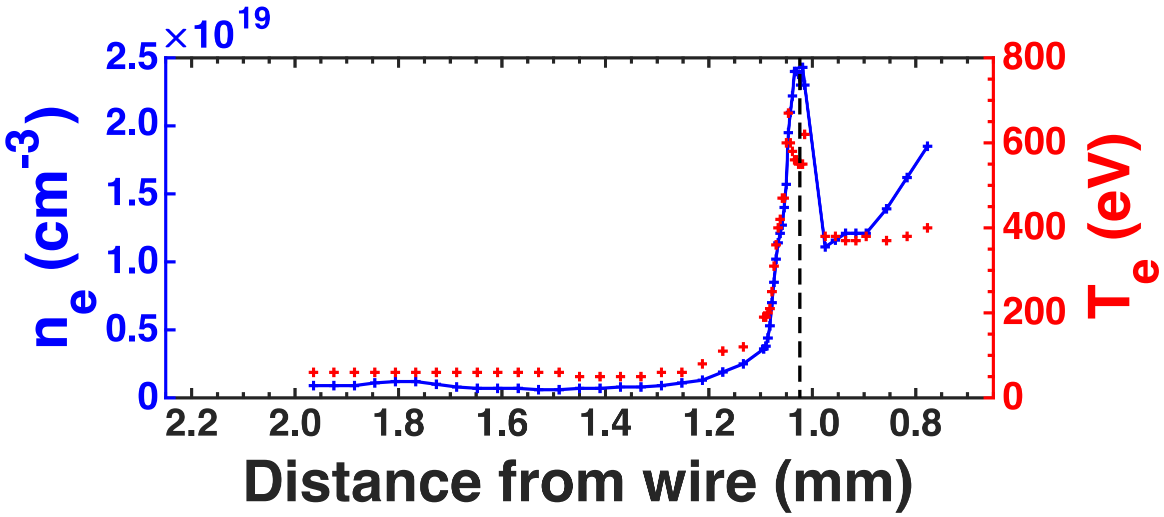
- Two probe configurations:
    - 20 J, 100 ps (no proton radiography)
    - 300 J, 1 ns (offset from proton driver)
- D ^{3}He proton source 1 cm from tcc
    - 3 and 15 MeV protons
- Protons flow antiparallel to wire current



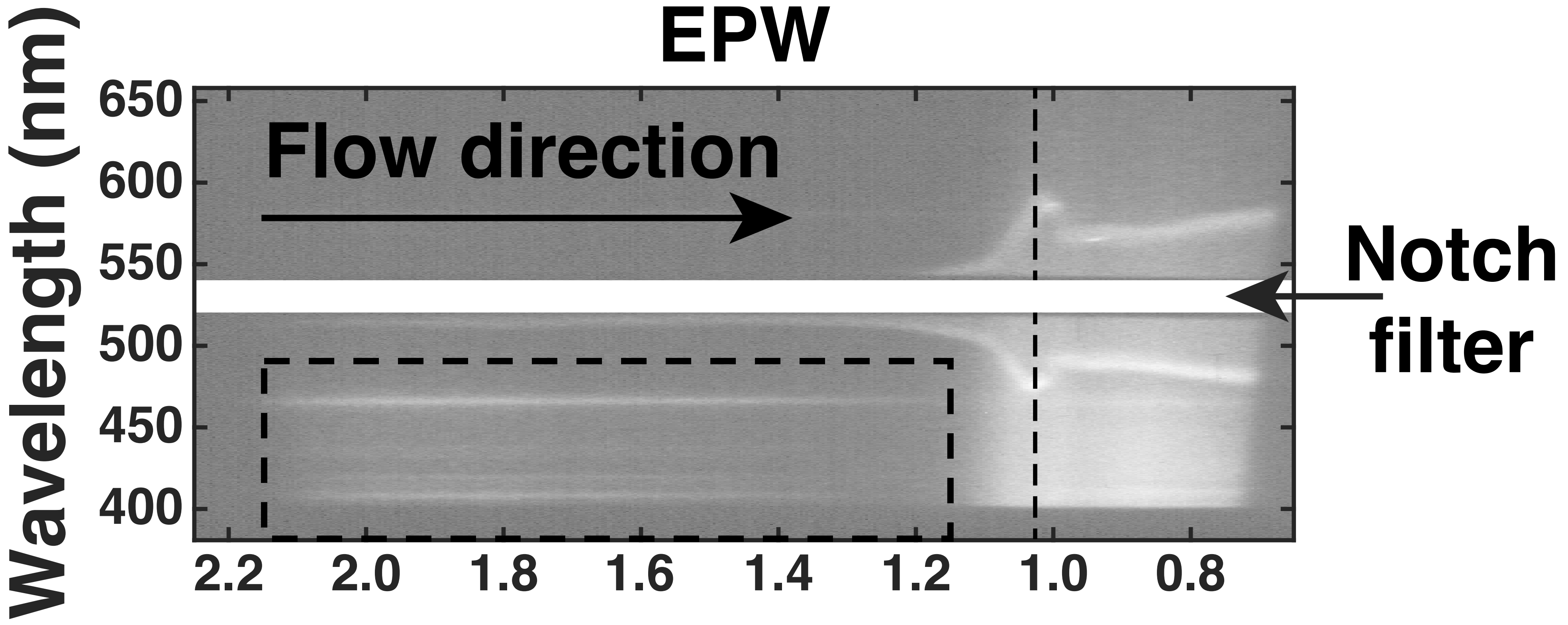
We see a sharp density jump at 50 ns

- We fit the electron number density using EPW spectra
- Inferred plasma properties:
    - Unshocked: $n_e = 1 \times 10^{18}$ cm^{-3}
    - Shocked: $n_e = 12 \times 10^{18}$ cm^{-3}
    - Peak: $n_e = 24 \times 10^{18}$ cm^{-3}
    - Spike width ~ 0.1 mm
- Probe laser:
    - 20 J, 100 ps
- Detector:
    - 3 ns gate



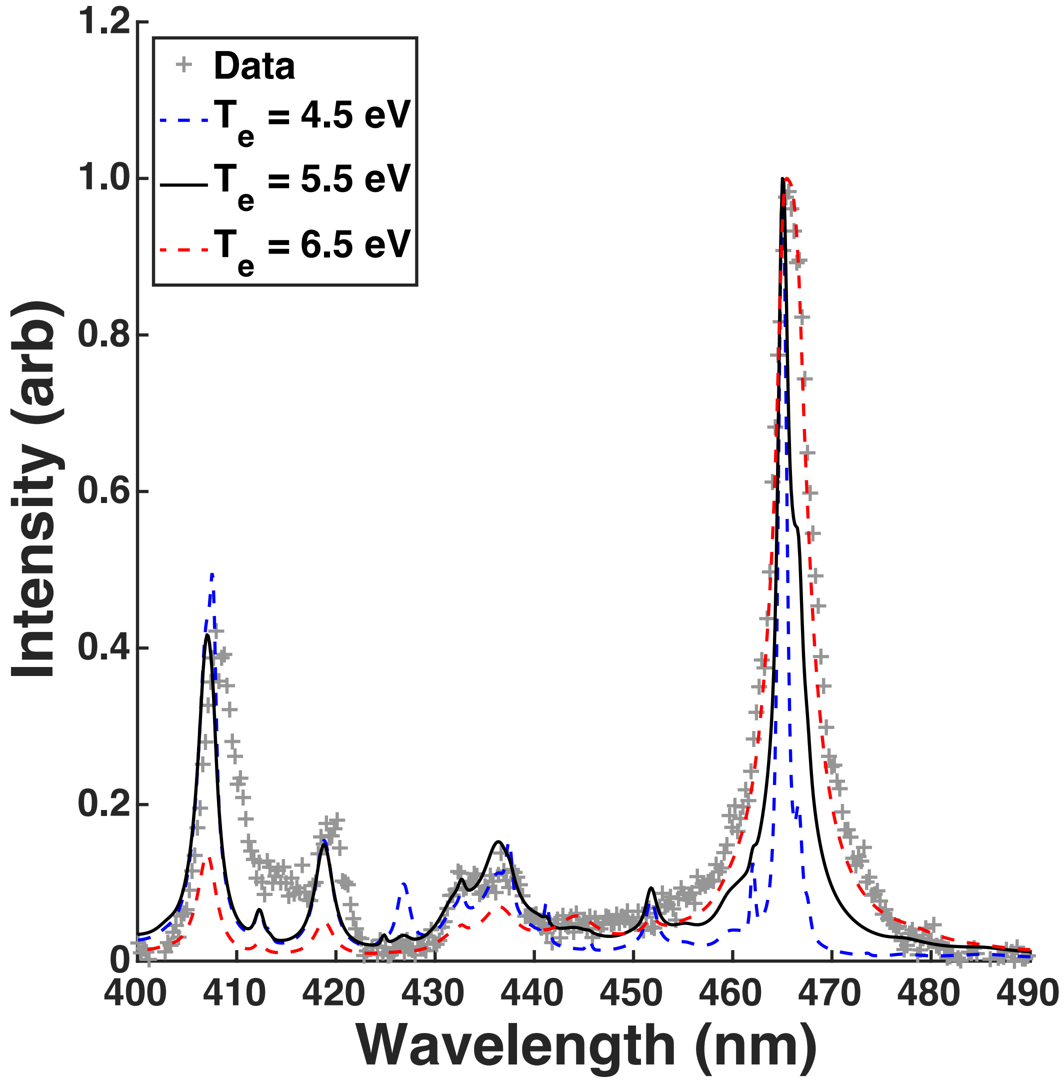


We observe optical emission lines in the spectra

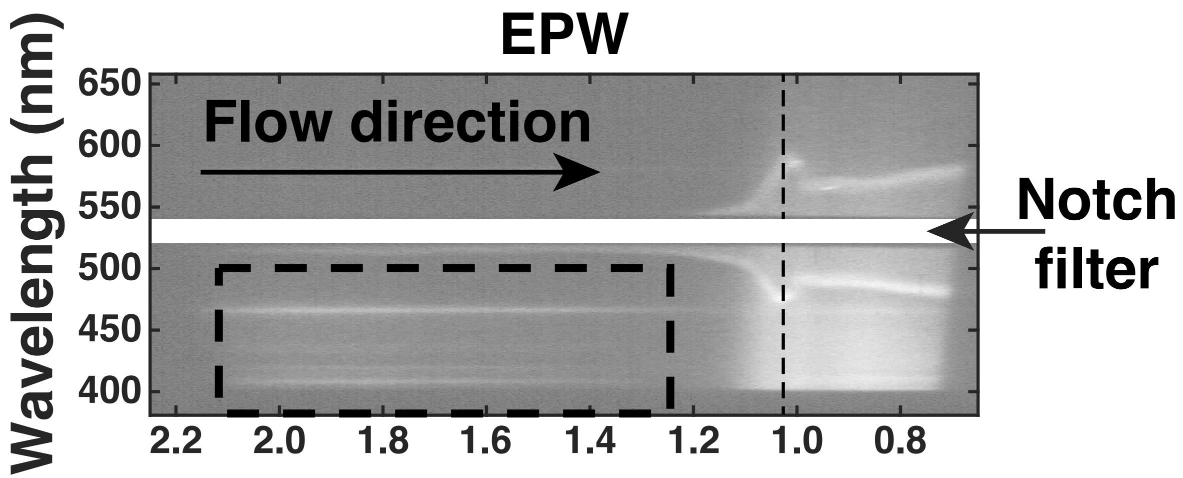


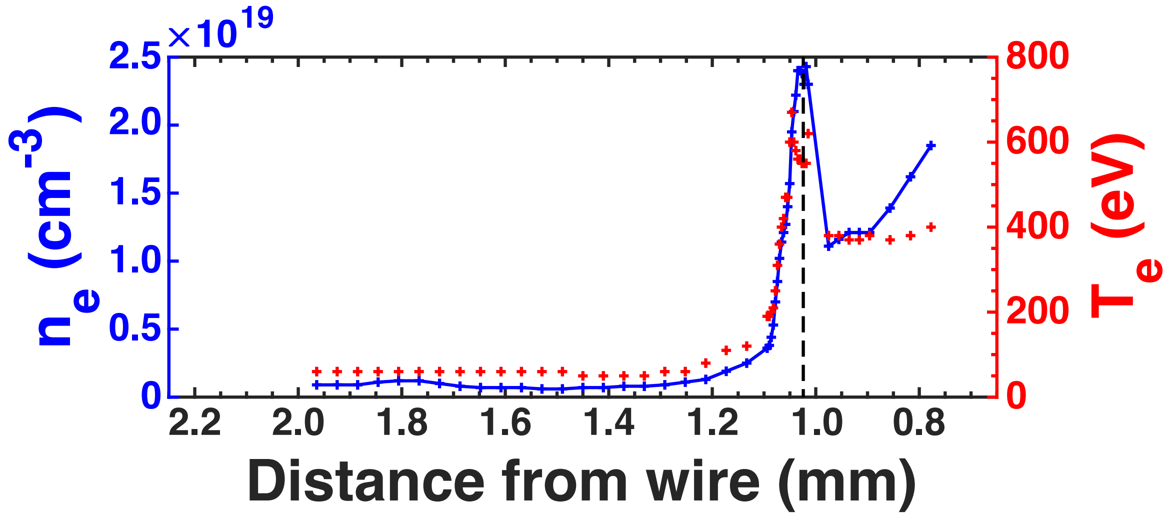
Optical emission spectra provides another measure of T_e

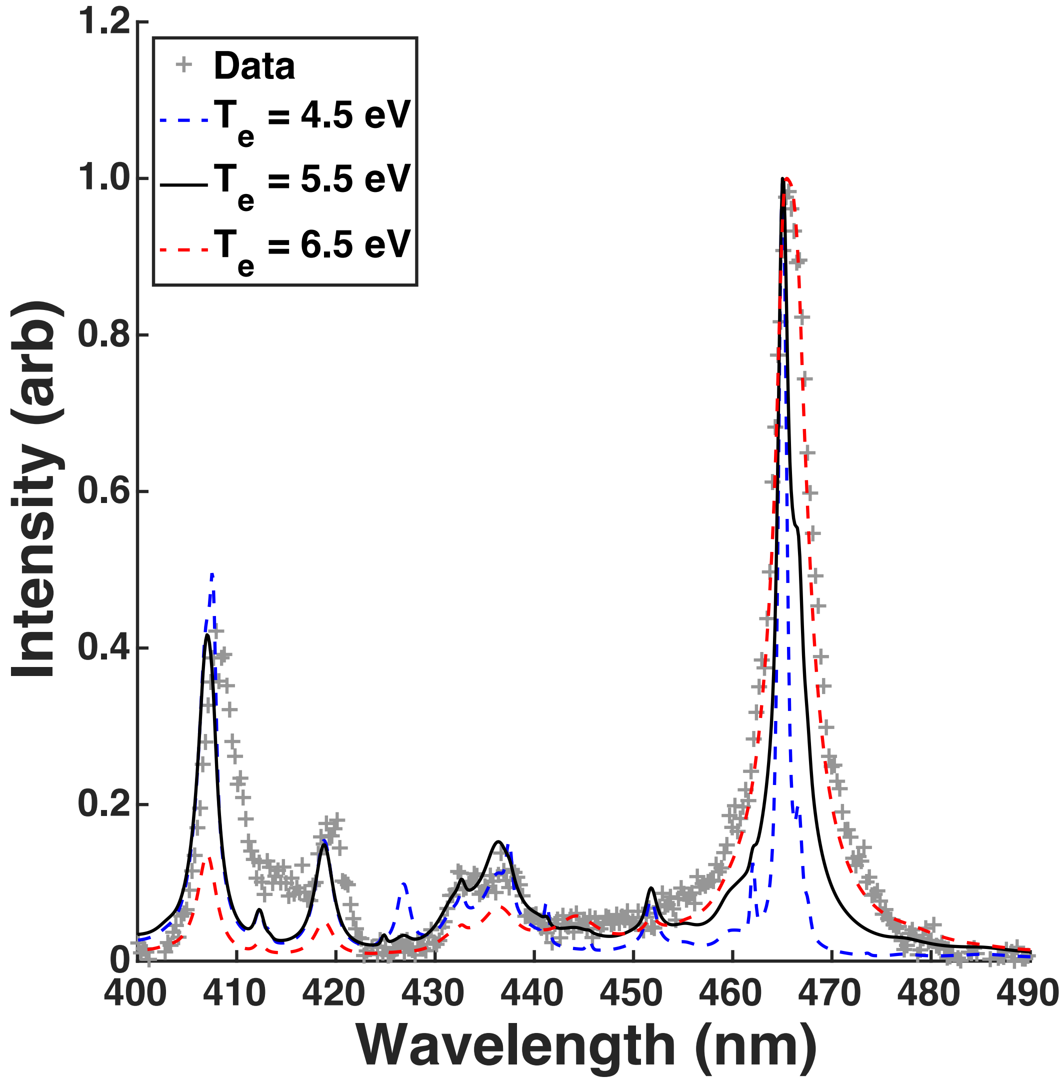
- Optical emission lines present in spectra
- PrismSPECT 0D, LTE line ratios match well for carbon at 5.5 eV
- This temperature should be of the unperturbed plasma
  - Line intensity comparable to Thomson scattered intensity due to long CCD gate
  - TS probe seems to greatly heat the plasma



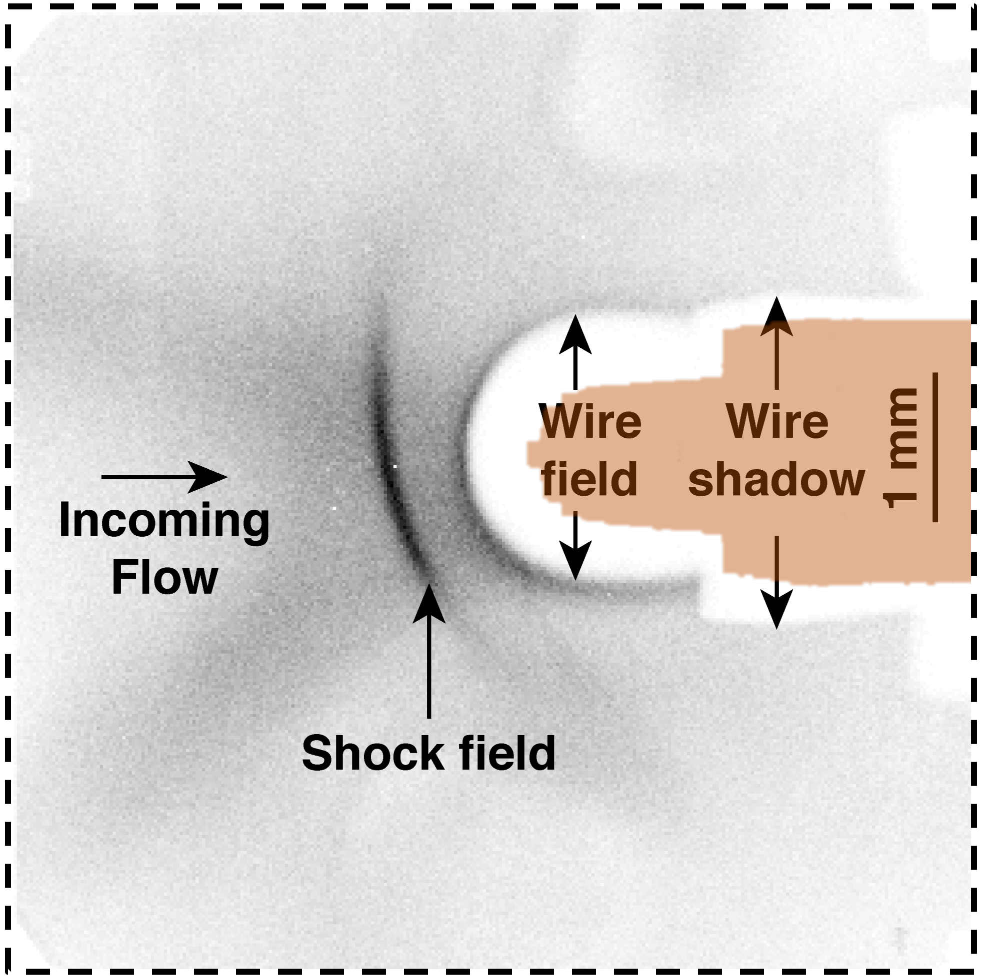
The temperature measurements do not agree

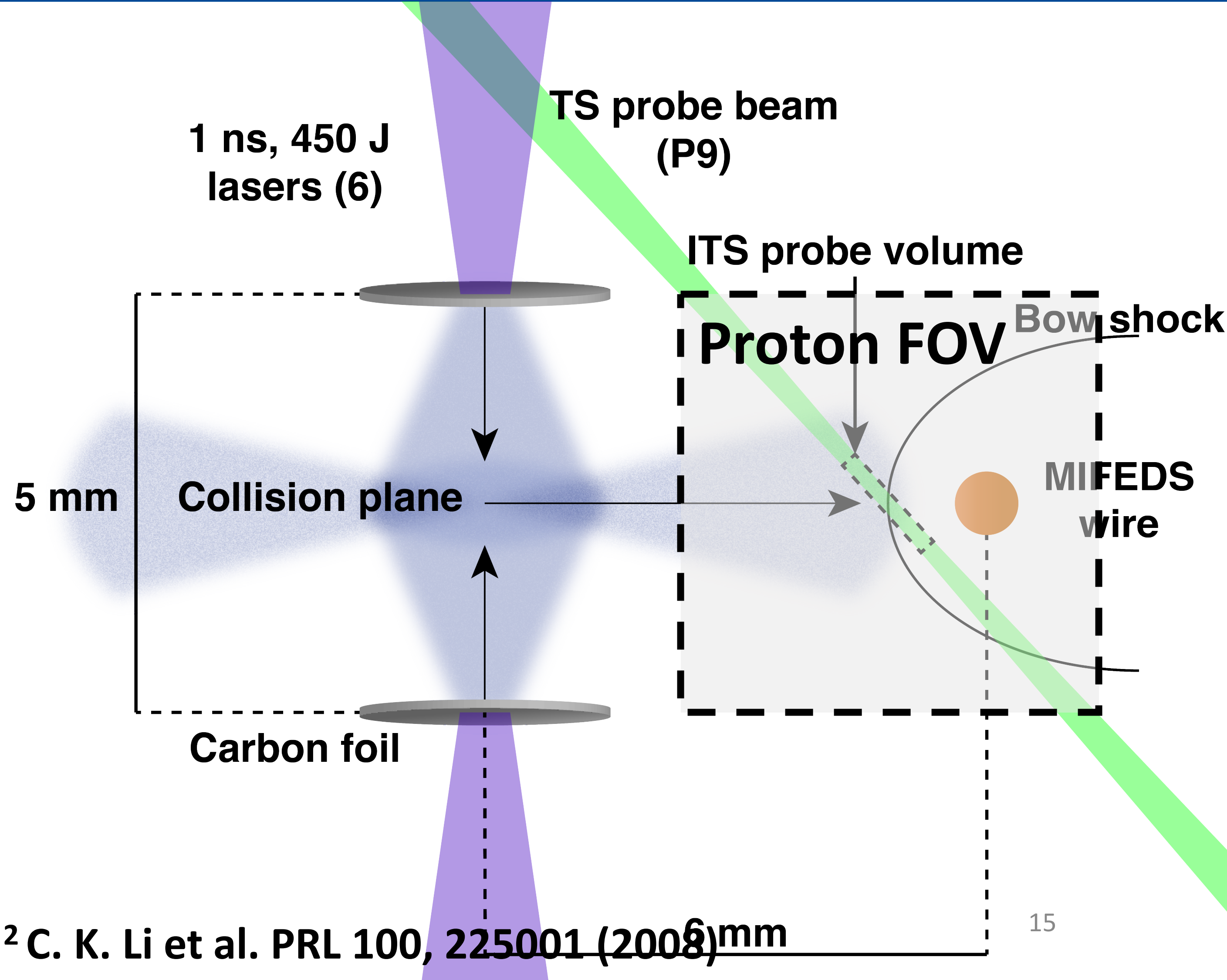






Proton images show clear evidence of magnetic compression





[2] C. K. Li et al. PRL 100, 225001 (2008)

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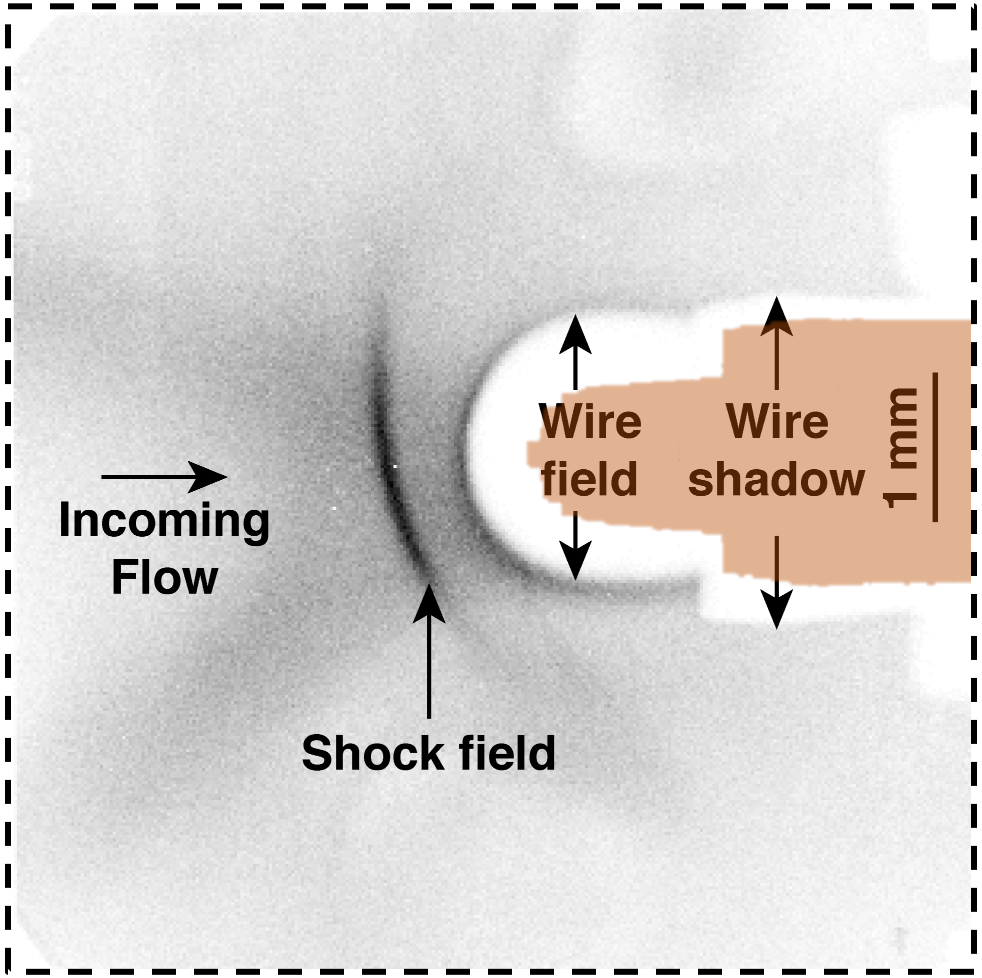
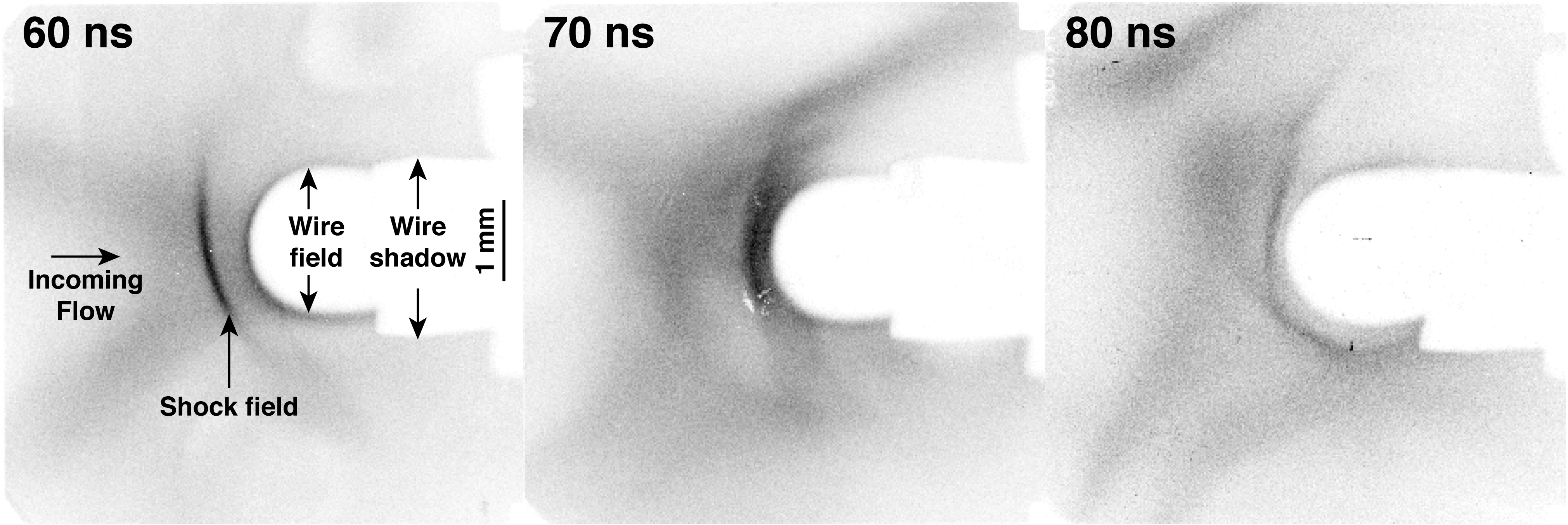


- Proton images are a deflection map of the magnetic topology
- Dependent on:
  - proton velocity
  - magnetic field strength
  - magnetic field orientation
- D ^{3}He proton source with CR39 detector[2]
  - 15 MeV image shown

[2] C. K. Li et al. PRL 100, 225001 (2008)

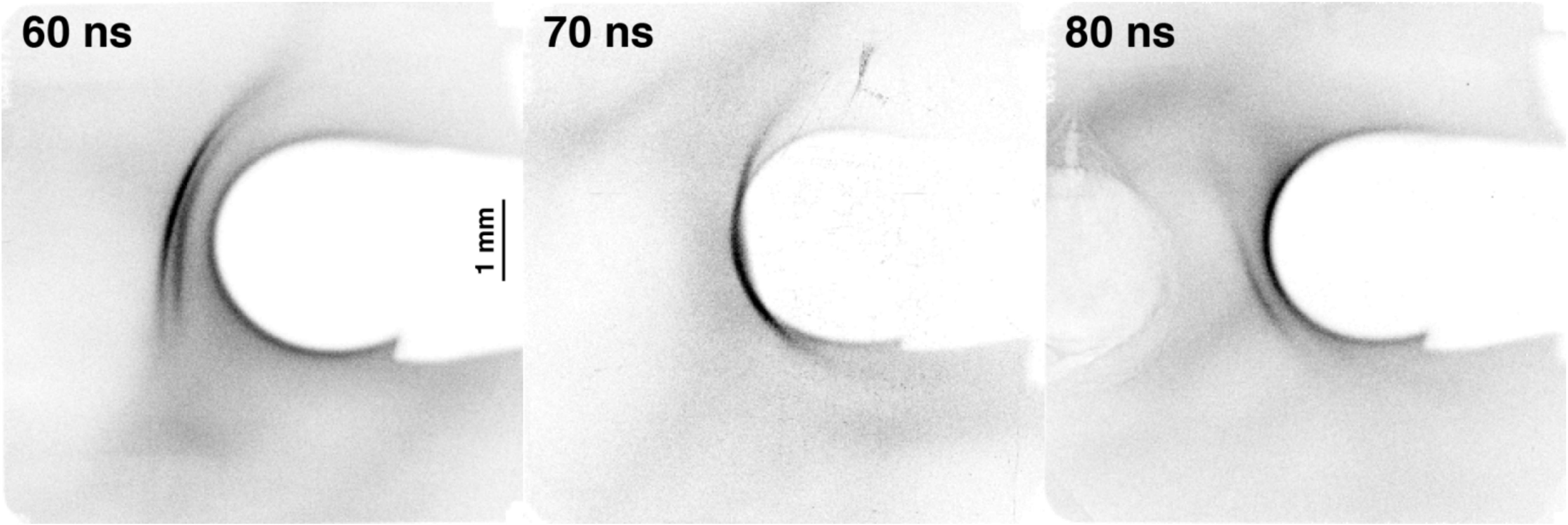
Proton images also show the field evolution…

- B_{max} = 9 T, E_p = 15 MeV, Magnification = 15 X
- Dark bands away from wire indicate magnetic compression
  - We don't really know what the field structure across the shock should look like



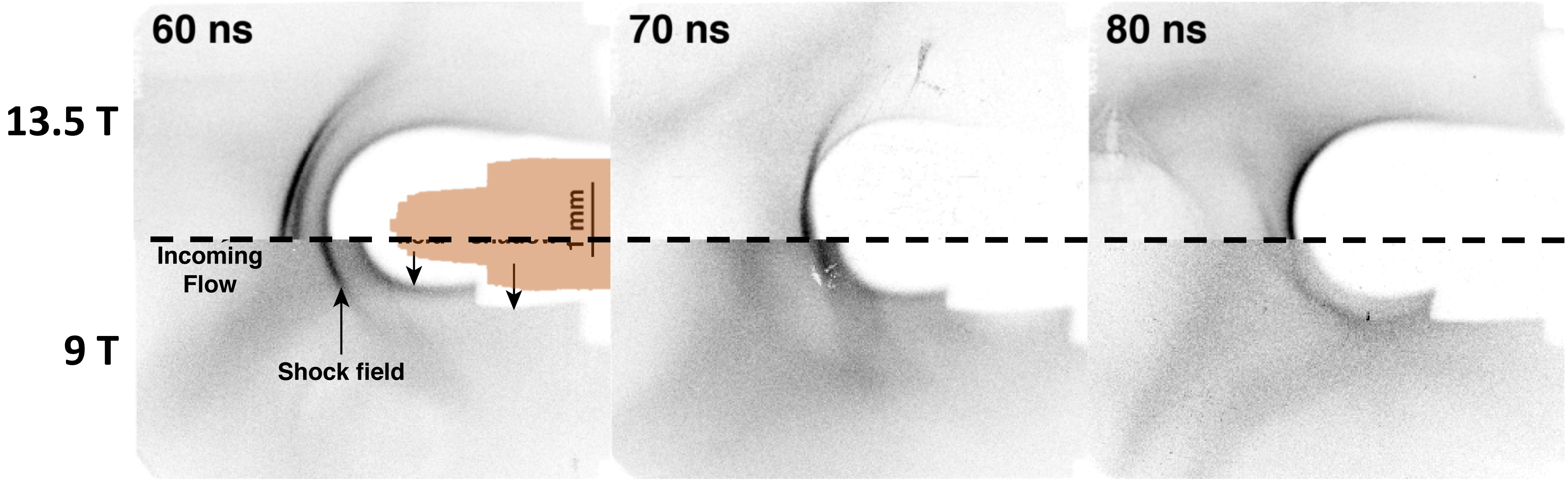
… which changes with magnetic field strength

- B_{max} = 13.5 T, E_p = 15 MeV, Magnification = 15 X
- Shock feature appears farther from the wire at 60 ns



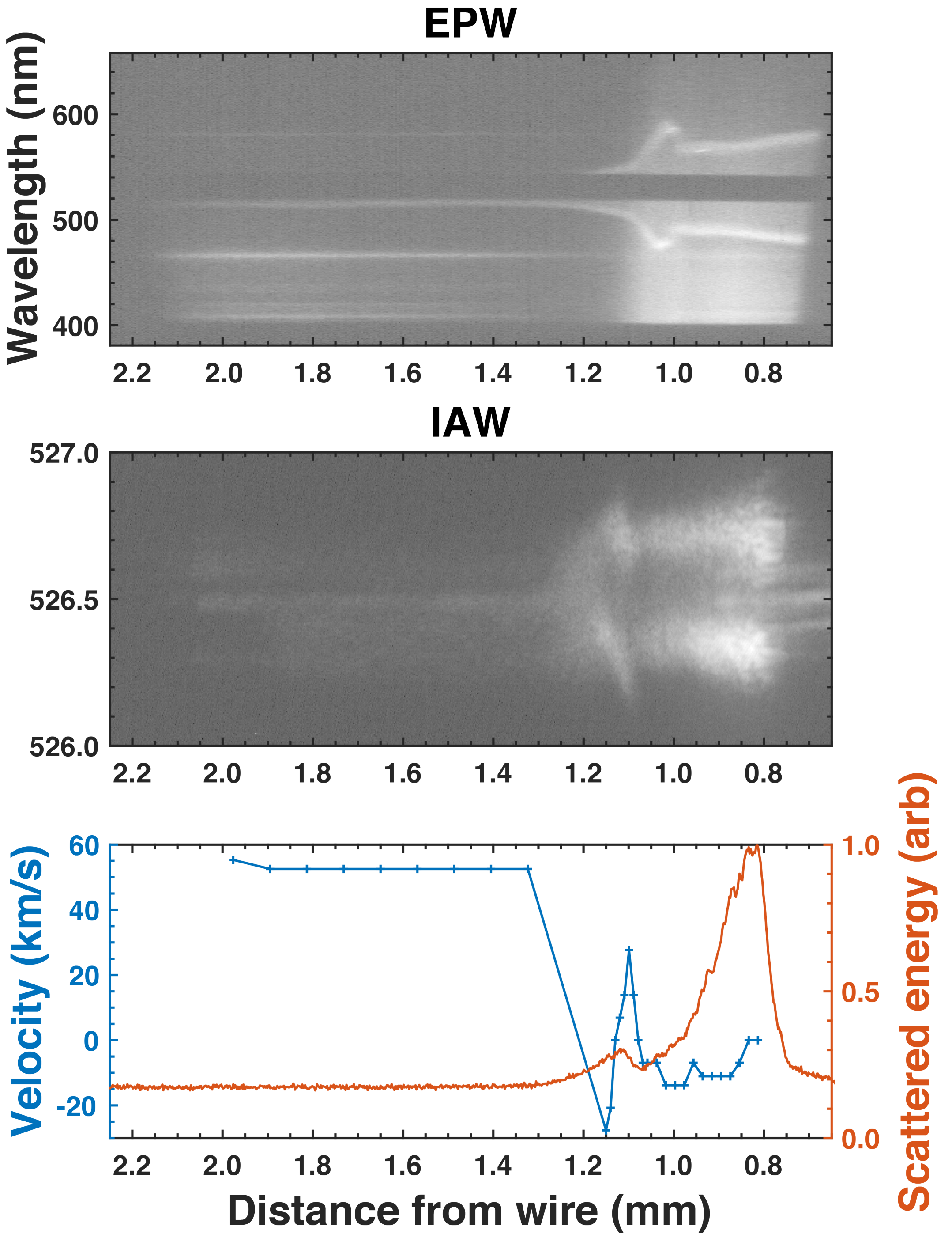
There is a clear difference in shock distance for the two field strengths

- The features move further out, but shock position is hard to decouple from deflectometry due to 3D effects



IAW spectra also shows sign of shock

- **Observe simultaneous changes in density (EPW) and velocity (IAW)**
- **Shock coincides with a brief decrease in scattered energy**



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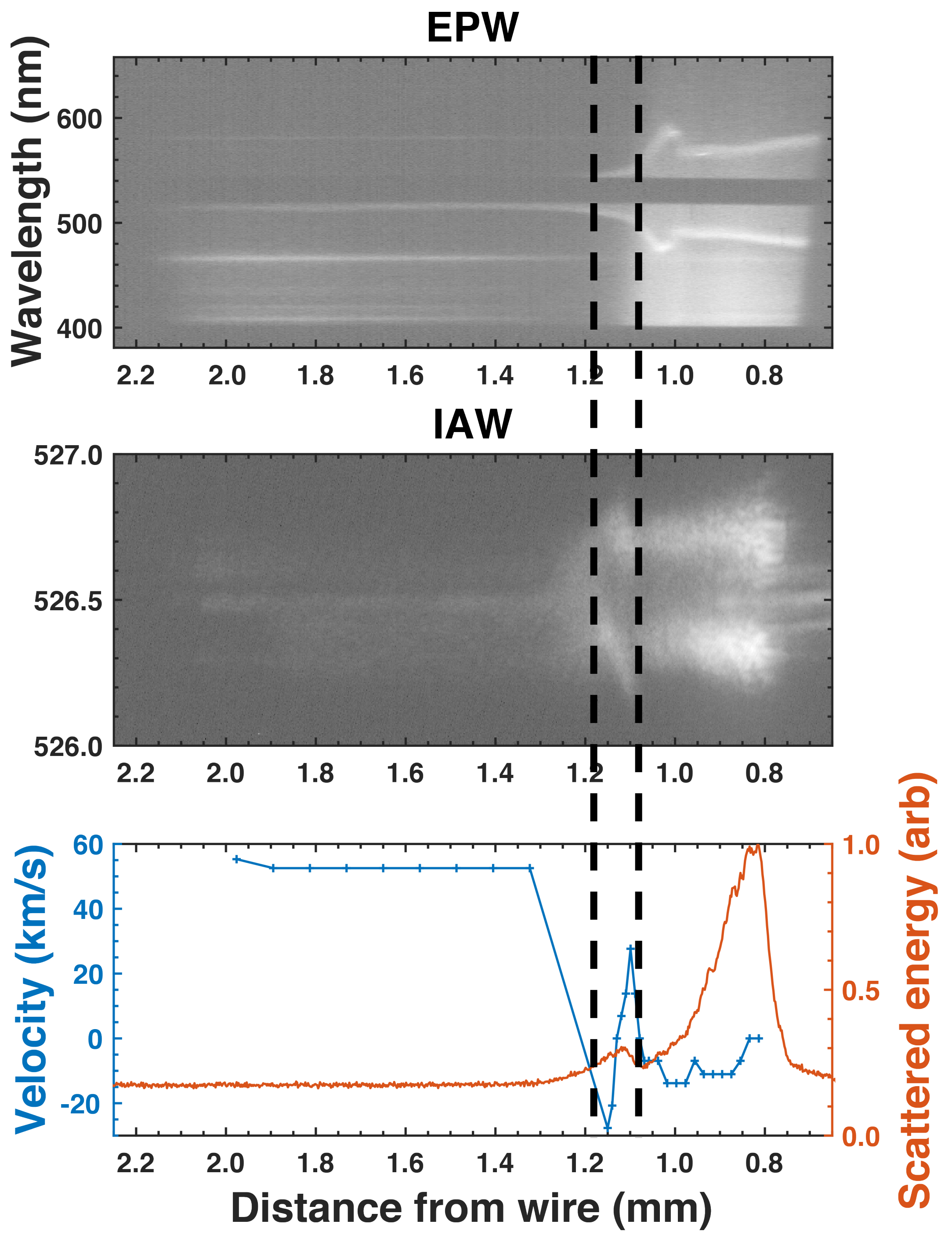
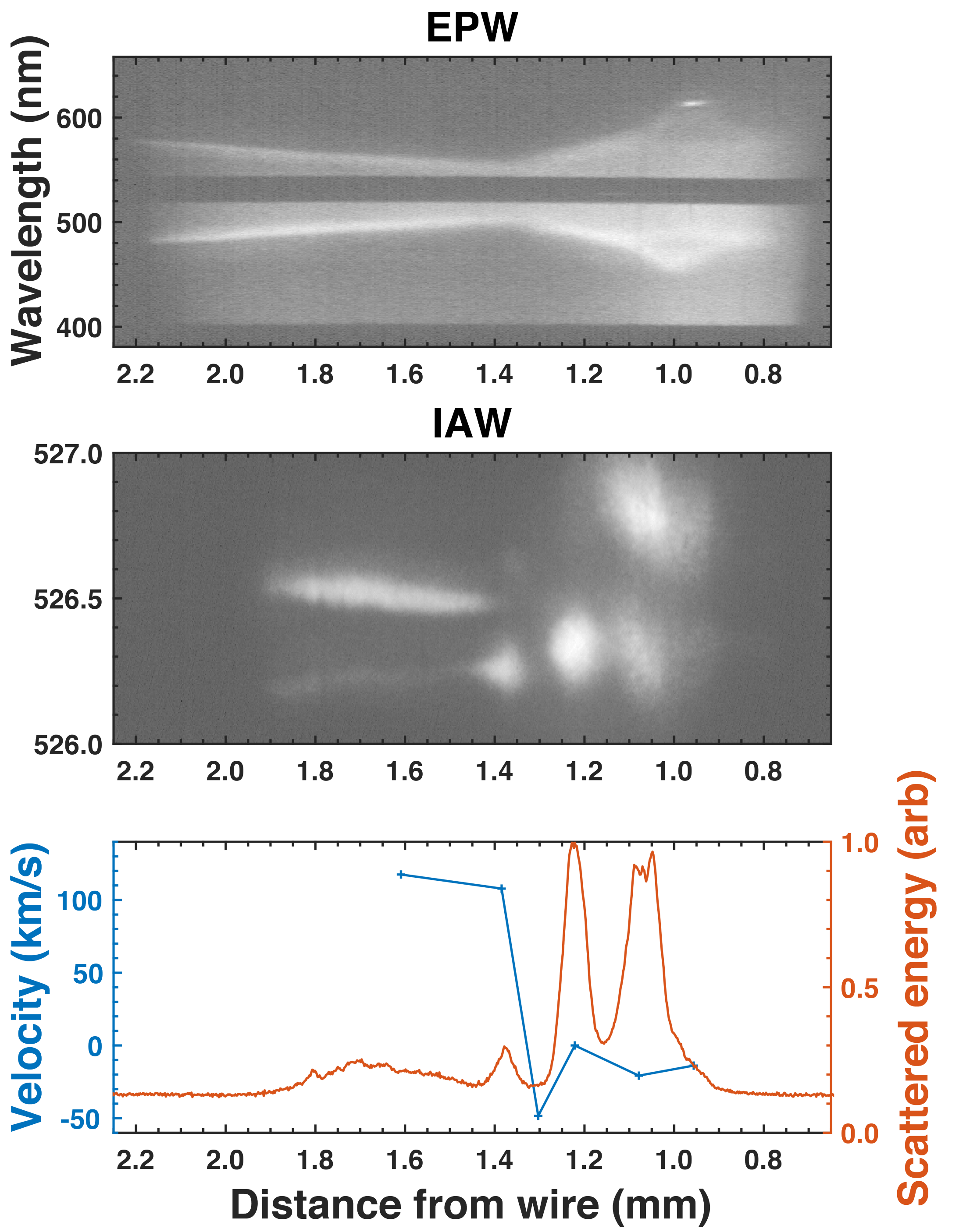


The longer pulse duration changes spectral features

- The EPW spectra appears to be spread out
  - Emission lines no longer present
- The IAW spectra exhibit additional features coincident with shock
  - Not entirely sure what they represent
- We can use these features to test the effect of changing magnetic field



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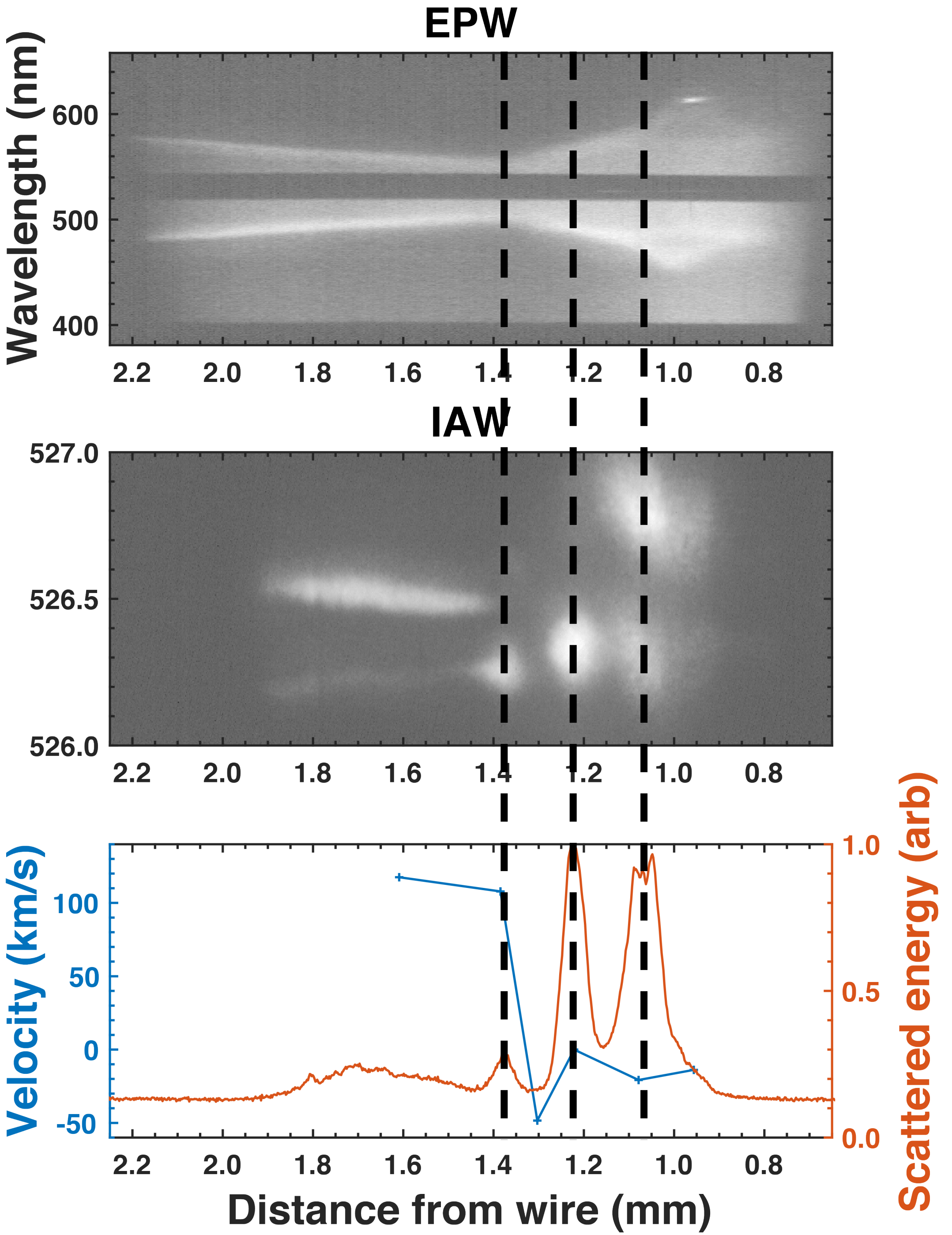
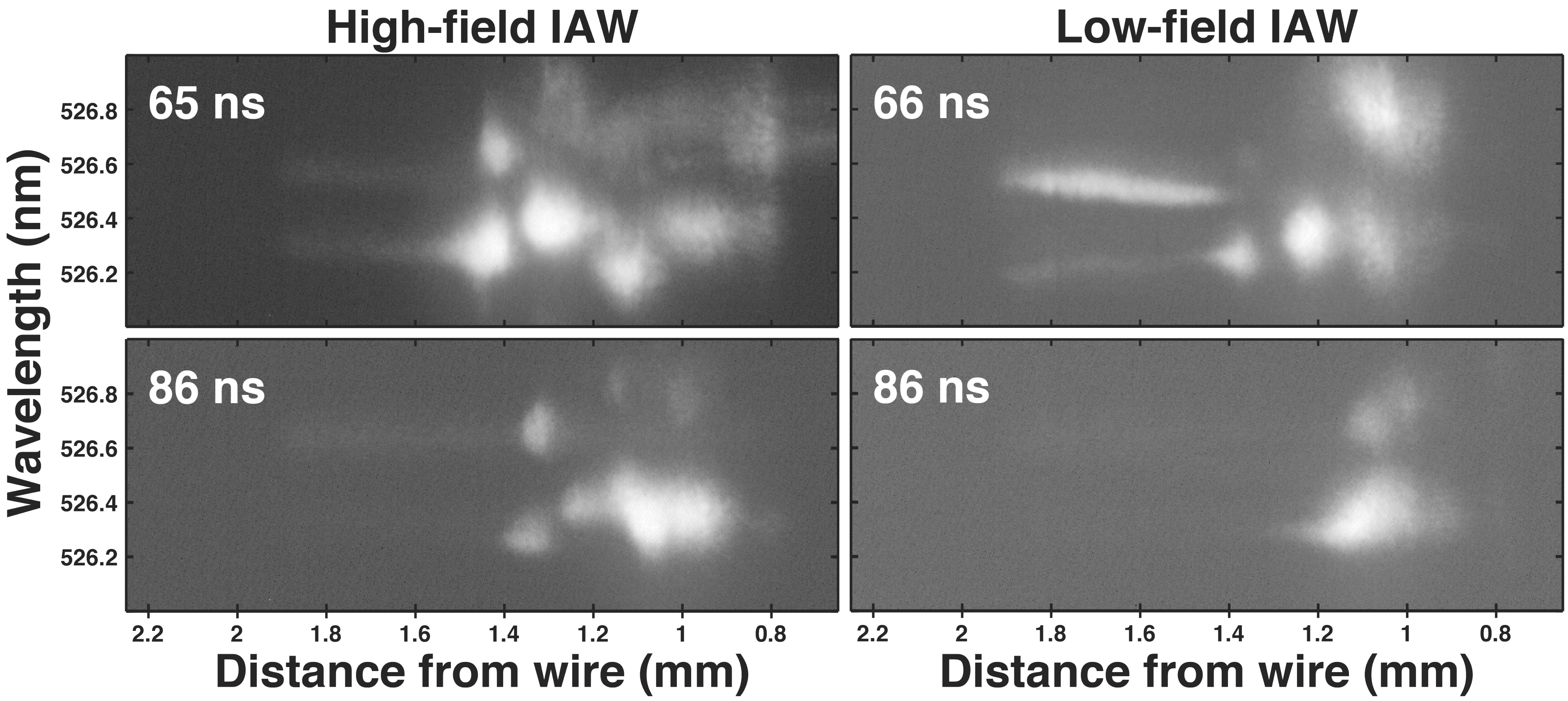
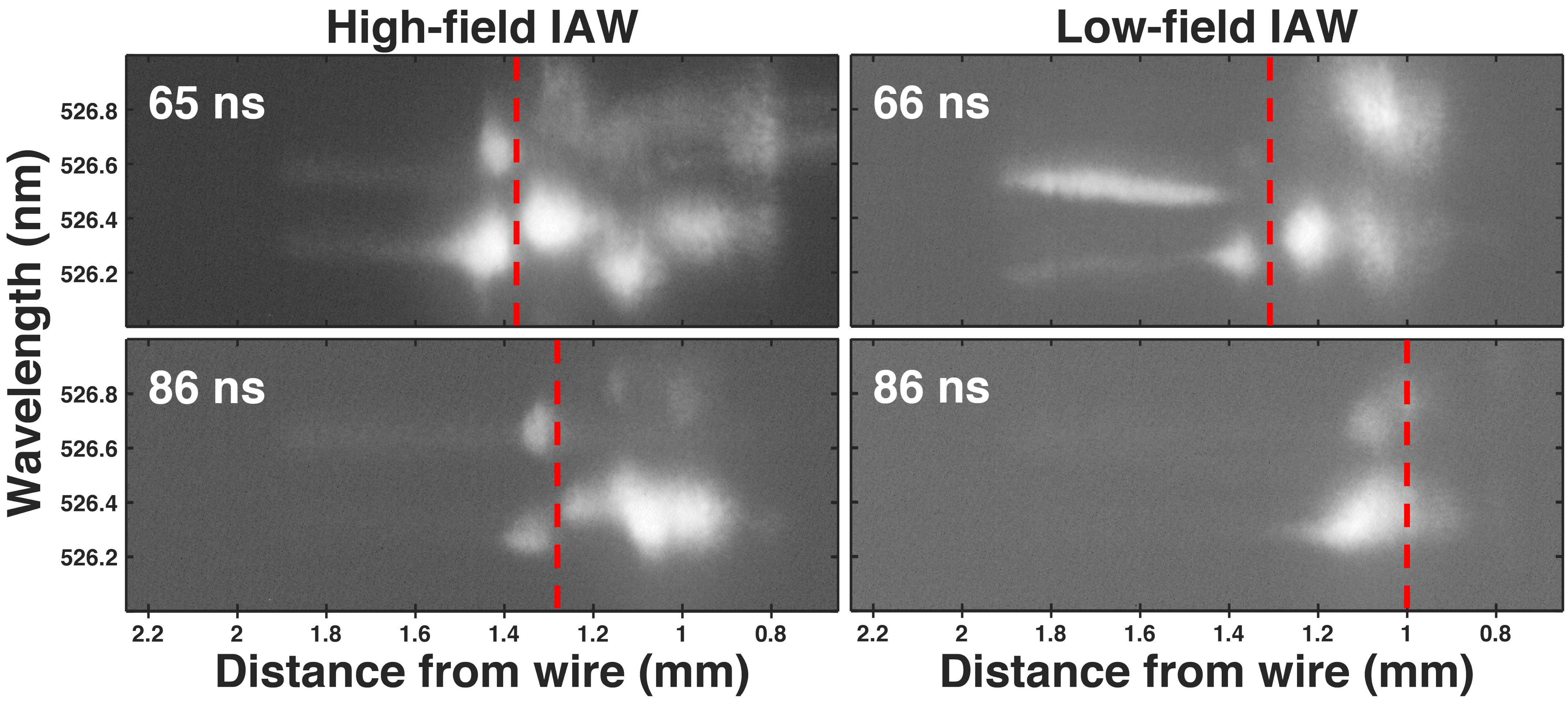


There are interesting, reproducible features in the IAW spectra



We follow these features to measure how the magnetic field affects the standoff



Changing the magnetic field strength changes the standoff distance

Table 1: IAW shock positions

Field strength	Time (ns)	Shock Position (mm)
High	65	1.37
High	86	1.28
Low	66	1.30
Low	86	1.00

- **The high-field (13.5 T) shots have a greater standoff distance than the low-field (9 T) shots**
- **Additionally, the shock moves closer to the wire between 66 and 86 ns for the low-field case than the high-field**

Changing the magnetic field strength changes the standoff distance... on both diagnostics

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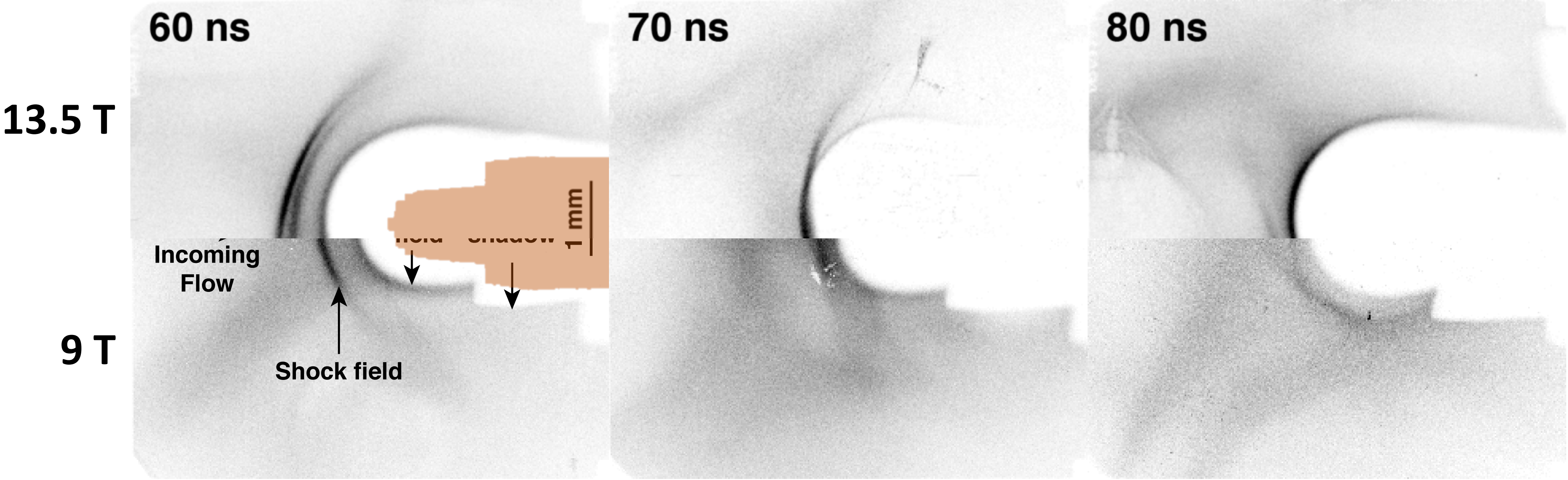

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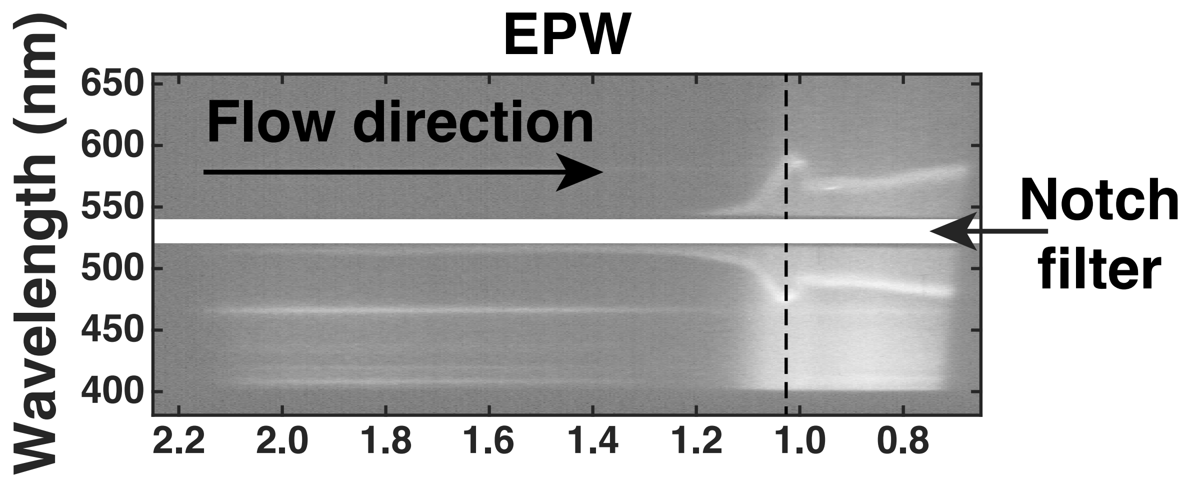

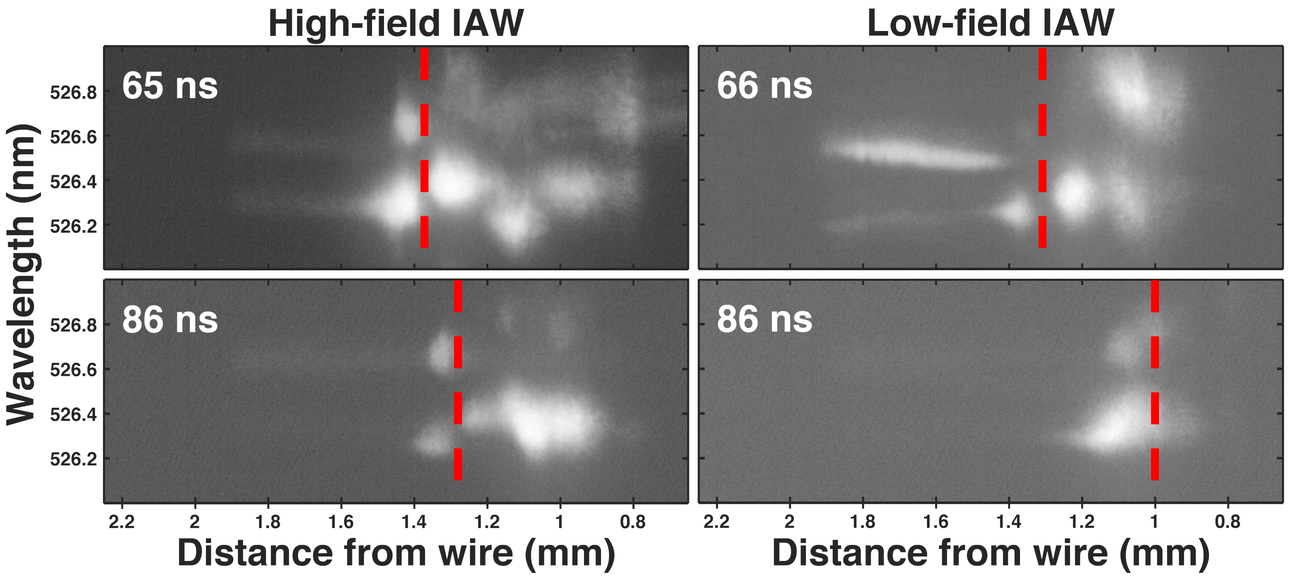

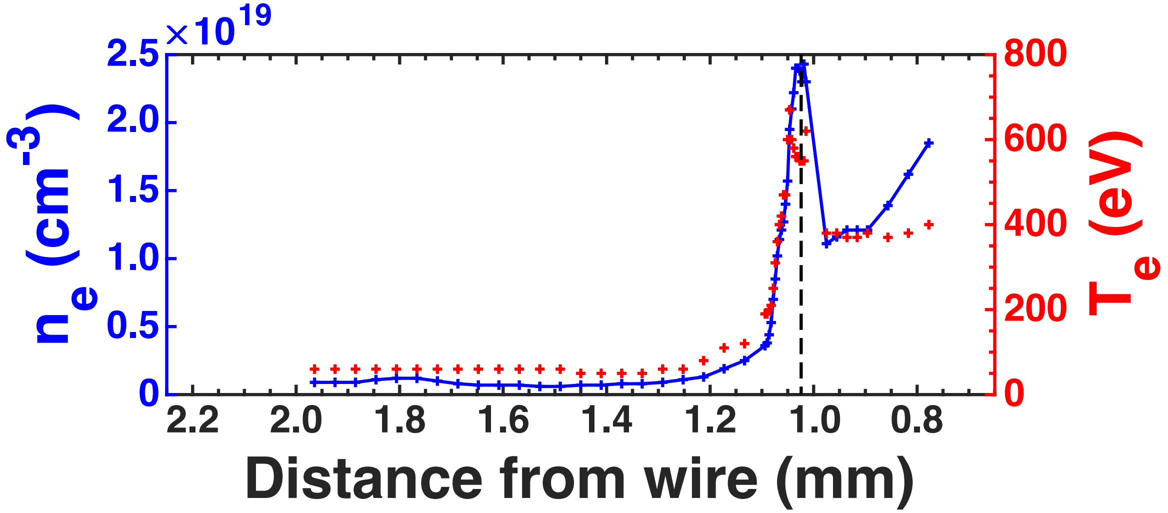

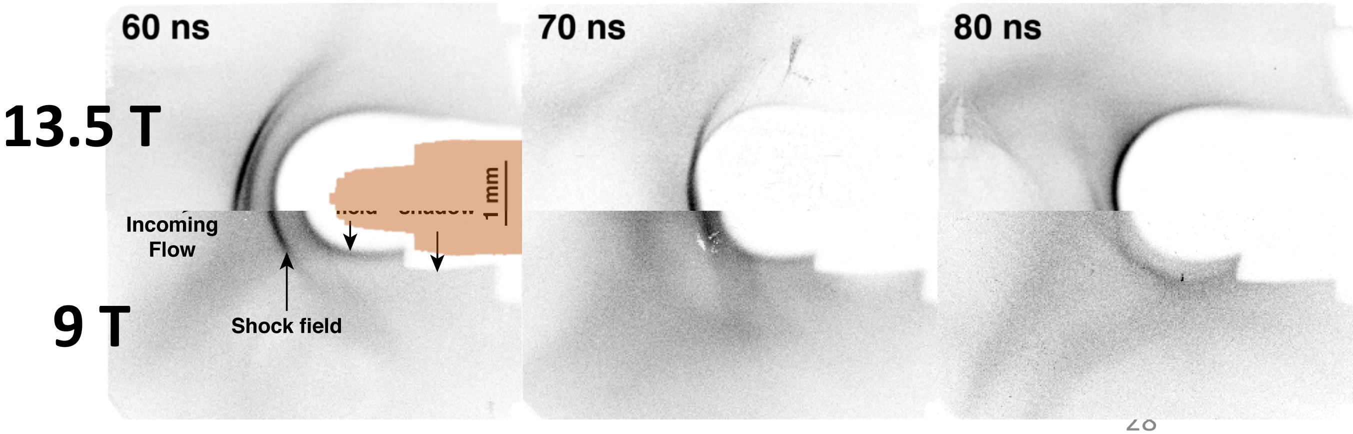

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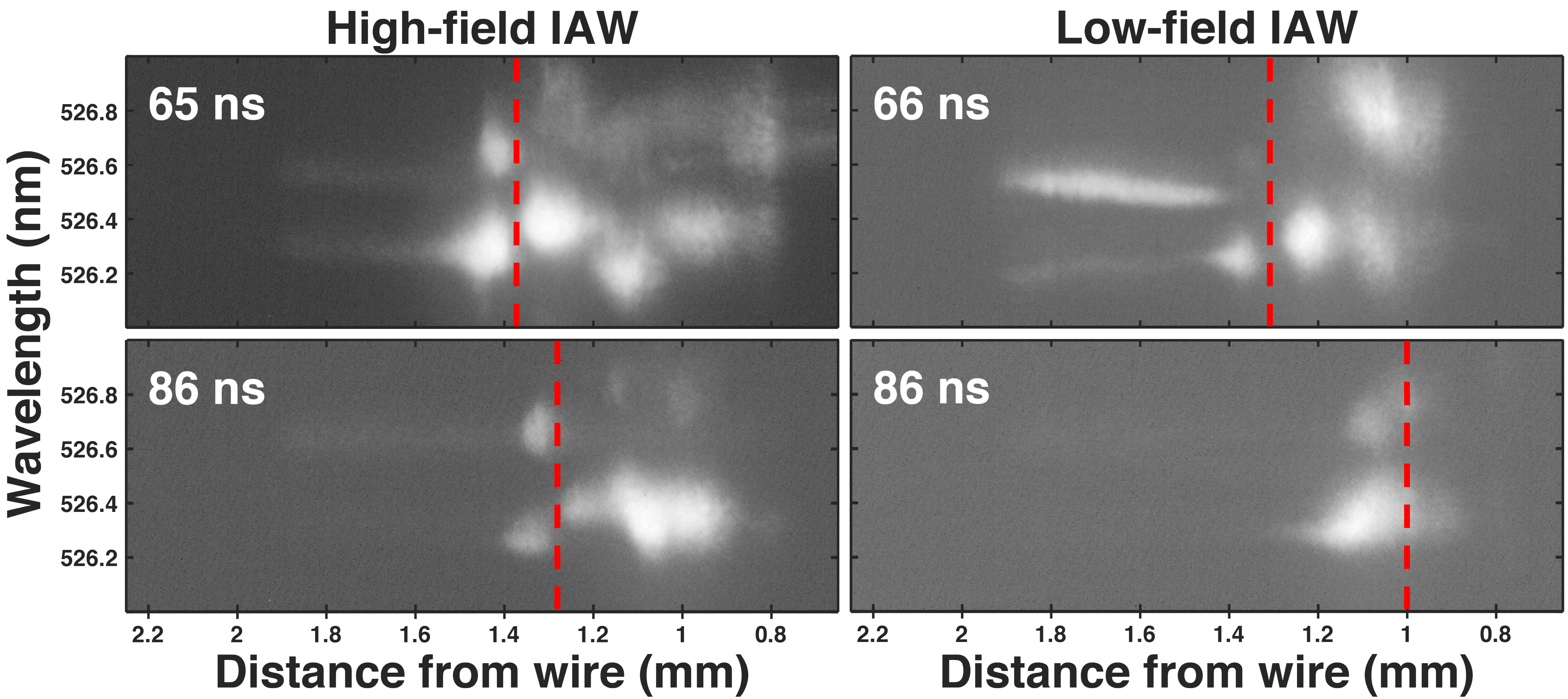

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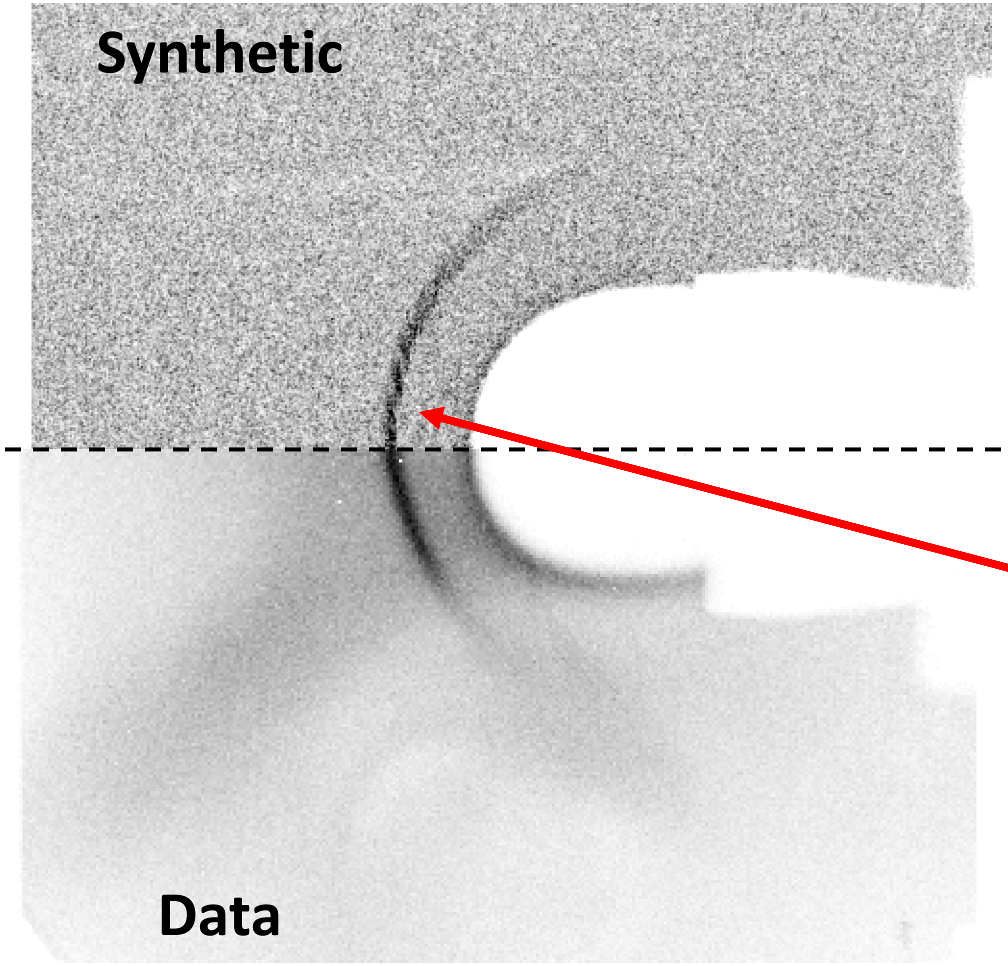
Using ITS in tandem with proton radiography, we can infer magnetic field properties at the shock



- Generate synthetic proton images based on imposed magnetic field using ITS data
- Distance of shock from wire: 1.2 mm
- Estimated Shock depth (into page): 0.8 mm
  - Doesn't change center position much
- Assume no magnetic field behind shock
- The field jump at the shock is primary cause of the dark band(s)

MIFEDS acts as the magnetized obstacle

- Straight, current-carrying wire as the magnetized obstacle
  - Wire diameter: 0.762 mm
  - Driven currents: 25 kA and 17 kA (or 13.5 T and 9 T max field at wire surface)
- Multi-stage plasma source (collisional)
- Parameters at shock formation:
  - r_{shock} = 1.05 mm at t=50 ns
  - v ~ 100 km/s
  - n_e ~ 1e18 cm^{-3}
  - T_e ~ 5.5 eV