Strong radiative shocks relevant for stellar environments

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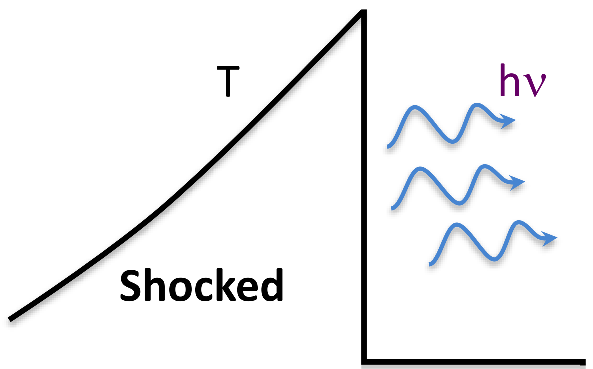
Radiative Shock waves

Temperature (T) = $\frac{2(\gamma-1)}{(\gamma+1)^2}\frac{m}{k}u_s^{\,2}$

- ✓ **M>> 1 thus high temperature. Converts a substantial fraction of its energy as radiation.**
- ✓ **This radiation modifies, in turn, the dynamic and structure of the shock wave.**

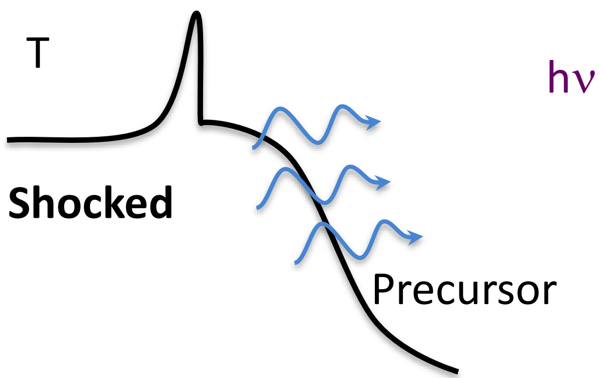
Depending on the opacity, two classes of radiative shocks

Optically thin (low density)



- The photons are escaping
- ***Post shock cools*** gradually
- Simple (local) coupling with radiation
- Electromagnetically launched shocks
- Stellar jets

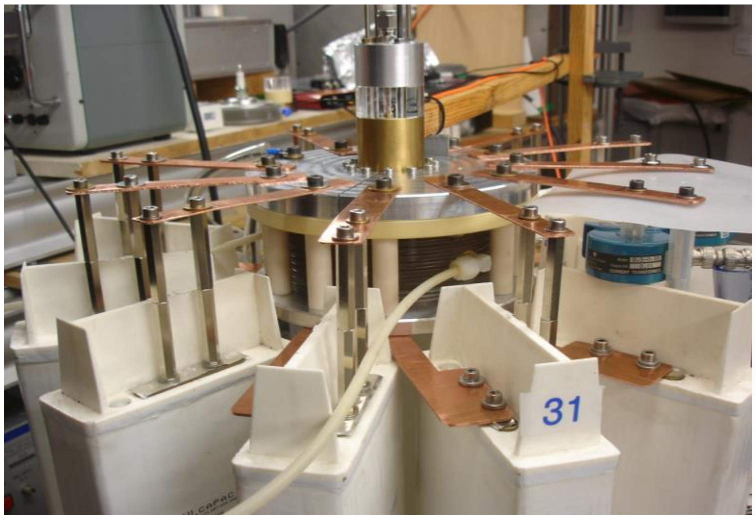
Optically thick (high density)



- The photons are absorbed by the cold medium.
- ***Radiative Precursor***.
- Complex (non local) coupling with radiation.
- Laser Driven shocks
- Accretion shocks, breakthrough of supernovae, pulsation of stellar envelopes and in between heads of stellar jets at high velocity.

Experiments to generate Shocks

- Table top electromagnetic generator



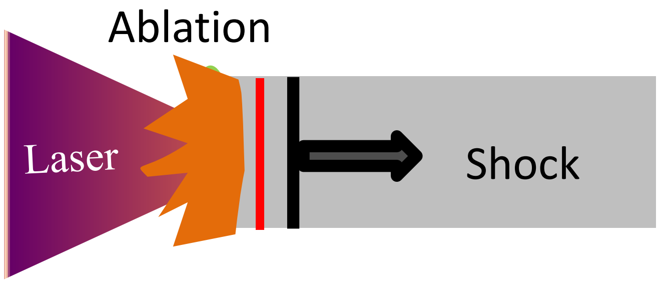
LPP / 600 J Generator

- 600 J bank.
- Argon 0.2–10 mbar
- 20 km/s at low pressure.
- **~ 1 mbar**

Kondo et al. (2006, 2008, 2009), Larour et al. (2015)

- High energy laser facilities:

PALS, LULI, GEKKO XII, ORION, OMEGA, LIL



Rocket effect

$$I\,(W\,cm^{-2}) = \frac{E}{S \times t}$$

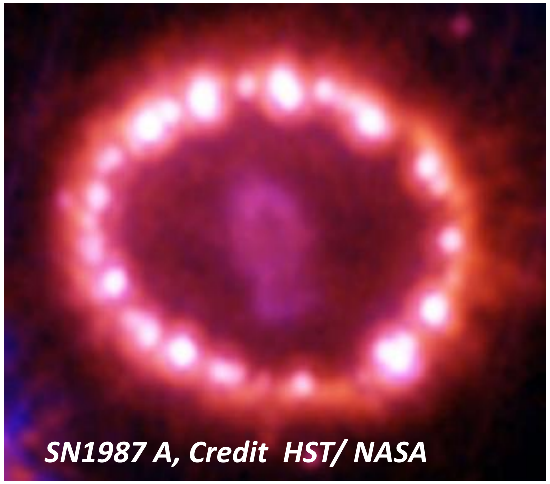
$I \sim 10^{14}$-$10^{15}\,Wcm^{-2}$

Radiative shock (v ~ 50- 150 km/s) in Xenon >1 bar

Fleury et al. 2002, Kuranz et al. 2005, Gonzalez et al. 2006, Koenig et al. 2006, Doss et al. 2009, Stehle et al. 2010, Diziere et al. 2011, Stehle et al. 2012, Burdiak et al. 2013, Chaulagain et al. 2015

Collision of two shocks

- All previous experiments were performed to study a single radiative shock wave evolution.
- Most of the astrophysical phenomena exhibit strong radiative shocks interaction with an obstacle or with another shocks.



SN1987 A, Credit HST/ NASA

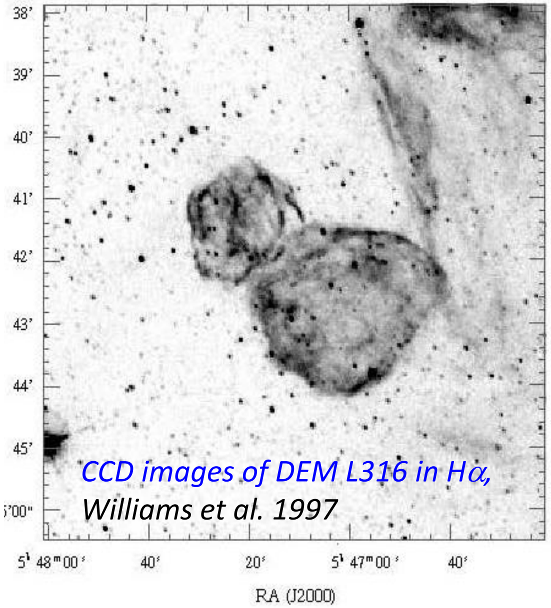
Shocks collision is a special case of shock interaction:

- ❑ Interaction of two supernovae remnants [Williams et al. (1997)]
- ❑ Collision of two jets [Li et al., (2013)]

Collision of two radiative shock experiments (collision of a shock with an obstacle or with another shocks):

1) ORION (Collison of two equal speed shocks)

2) PALS (Collision of two unequal shock speeds)

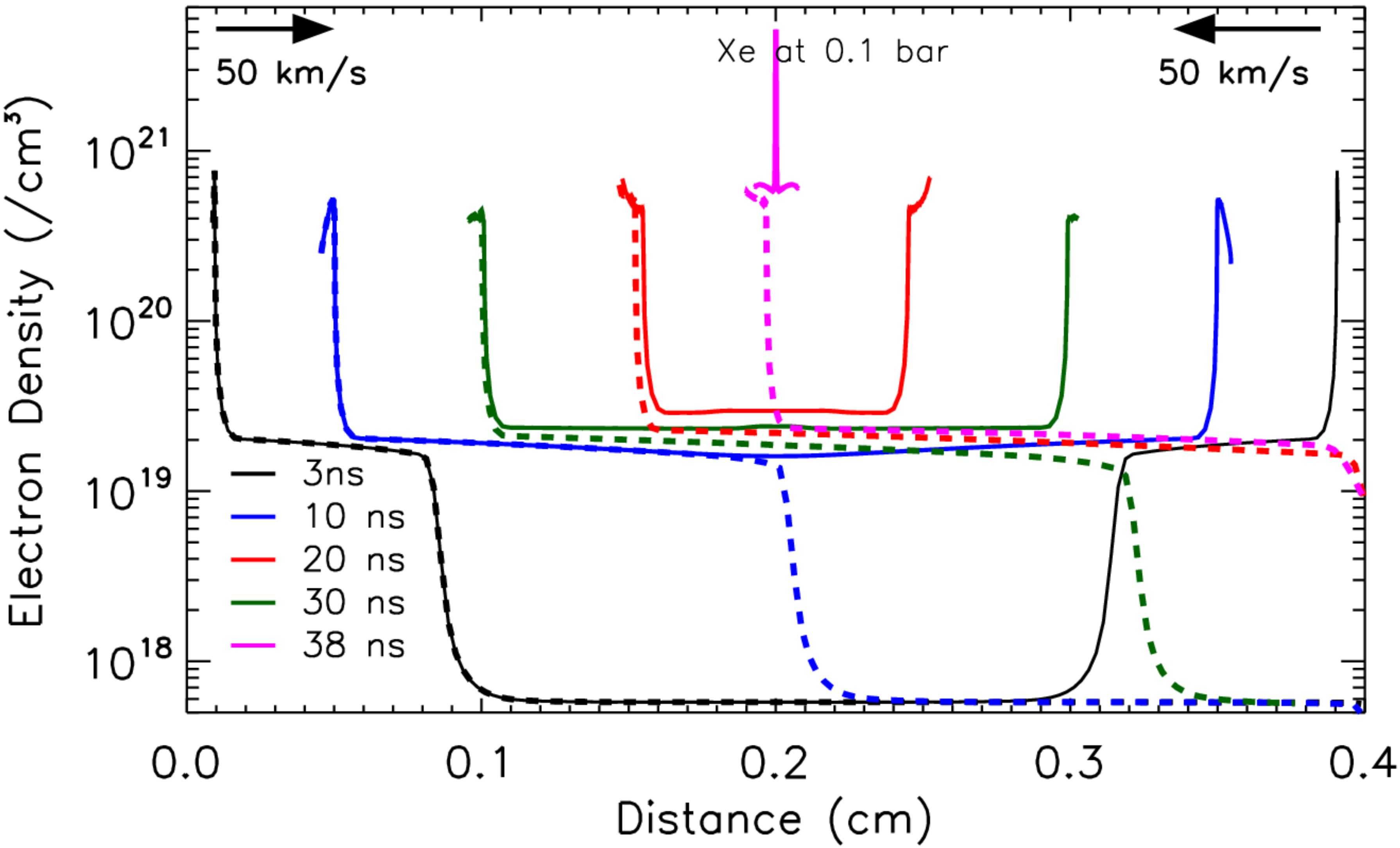


CCD images of DEM L316 in Hα, Williams et al. 1997

Objectives: to study the physics of shock collision and the interaction their precursors

Collision of two shocks

Interaction of two counter propagating shocks

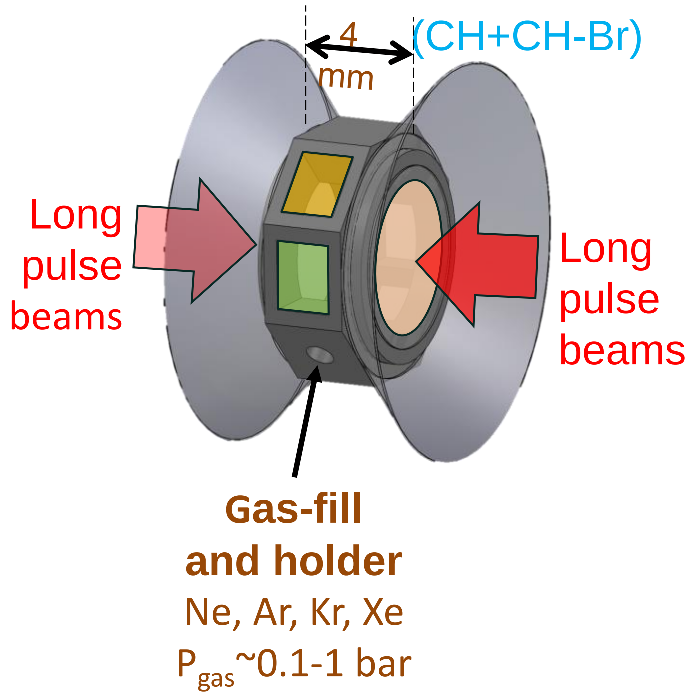


Radiative case

Precursors interaction

Collision of two shocks: ORION results

Interaction of two counter propagating shocks

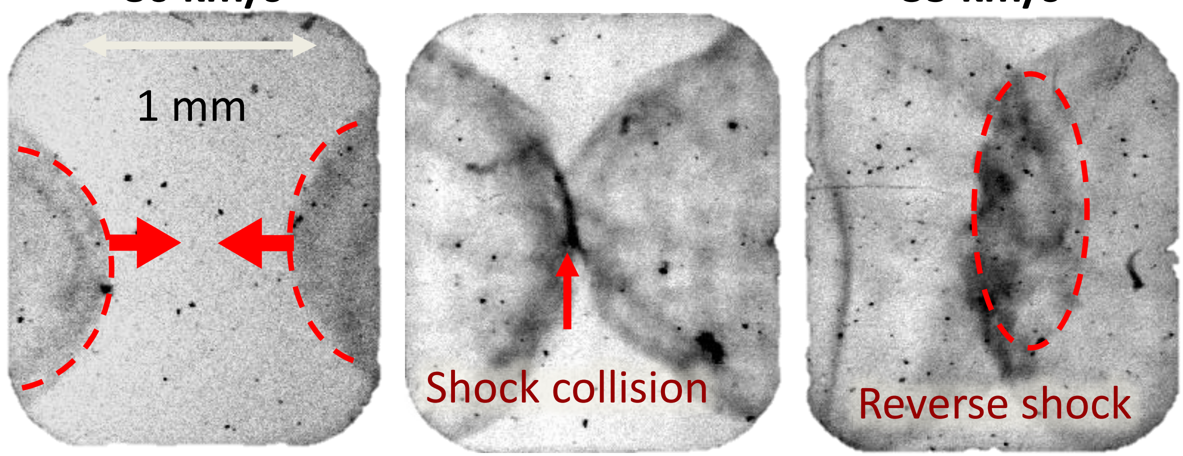


4 beams
1.6 kJ total
λ=351 nm
1 ns square
~6 x 10^{14} W/cm^2

Xenon 0.3 bar

25 ns | 30 ns | 35 ns

~ 80 km/s | **~ 35 km/s**

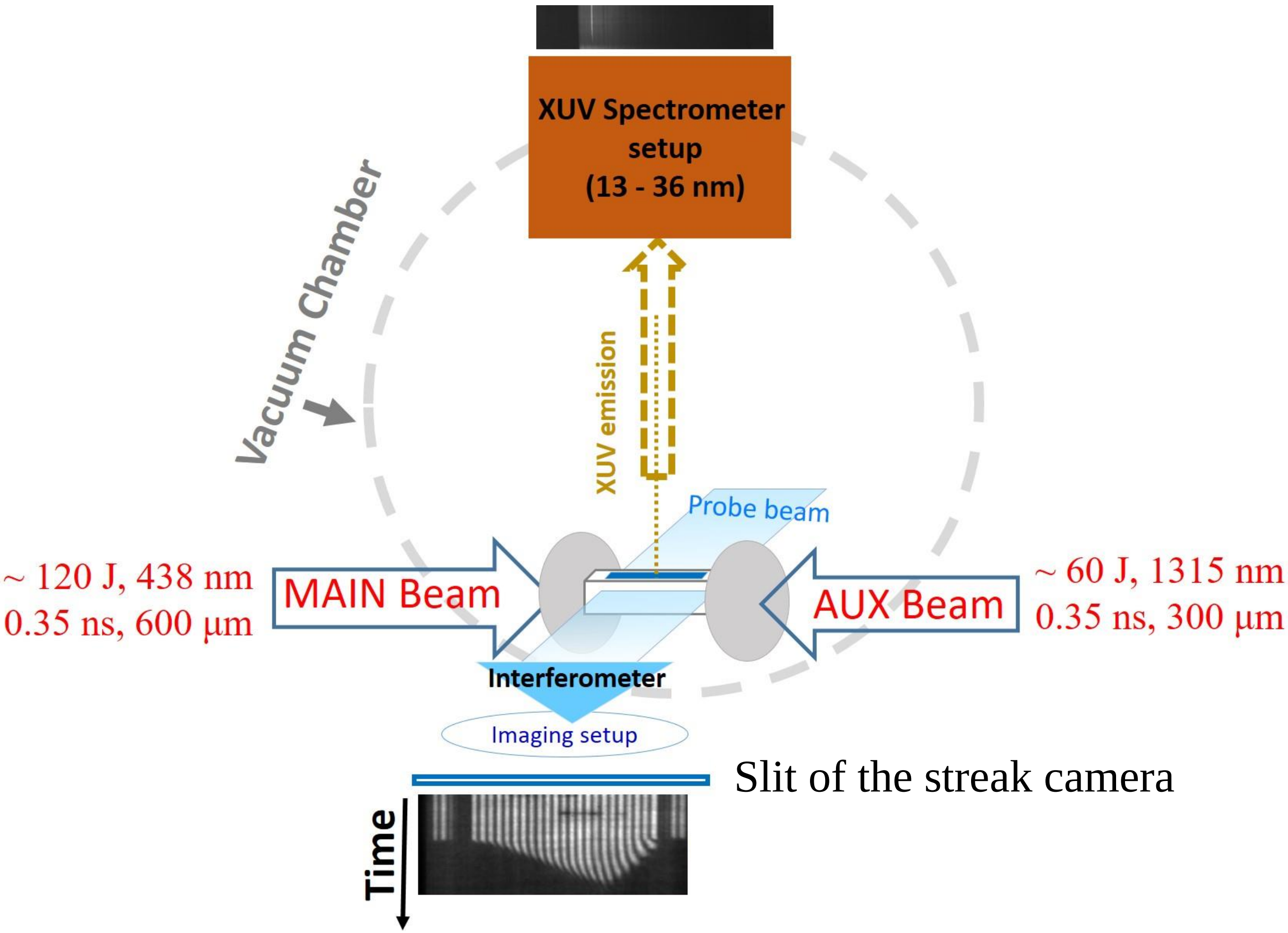


Good agreement with 2D simulations from AWE
1D simulation -> larger velocities
Compression x 25 (due to radiation + ionisation)

Suzuki Vidal et al. (2018), Clayson et al. (2017)

Experimental setup

First laboratory experiment dealing with the collision of two radiative shocks



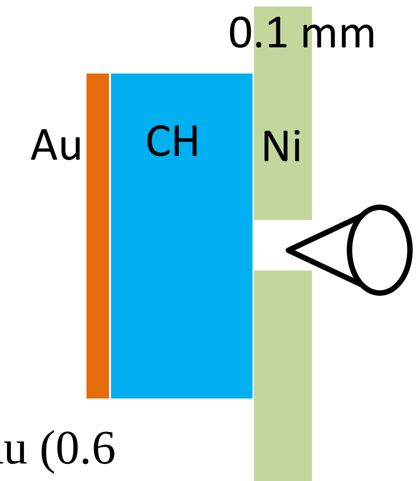
Singh et al. (2017)

Collision of two shocks: PALS

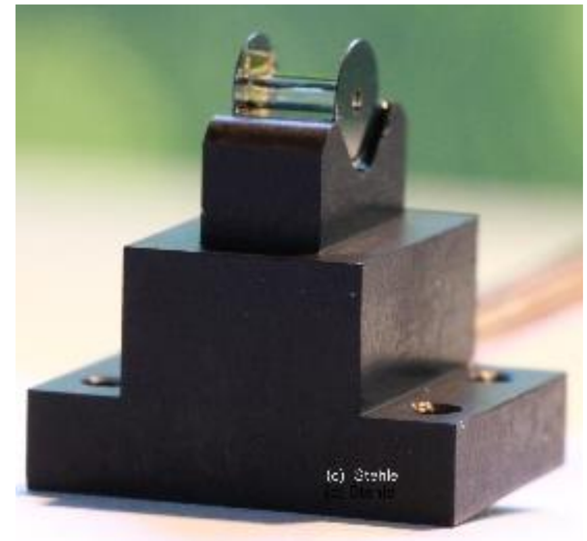
The Target

Dimensions: 0.9 x 0.6 x 4 mm^3

(GEPI, Observatoire de Paris)



4 mm



Main components

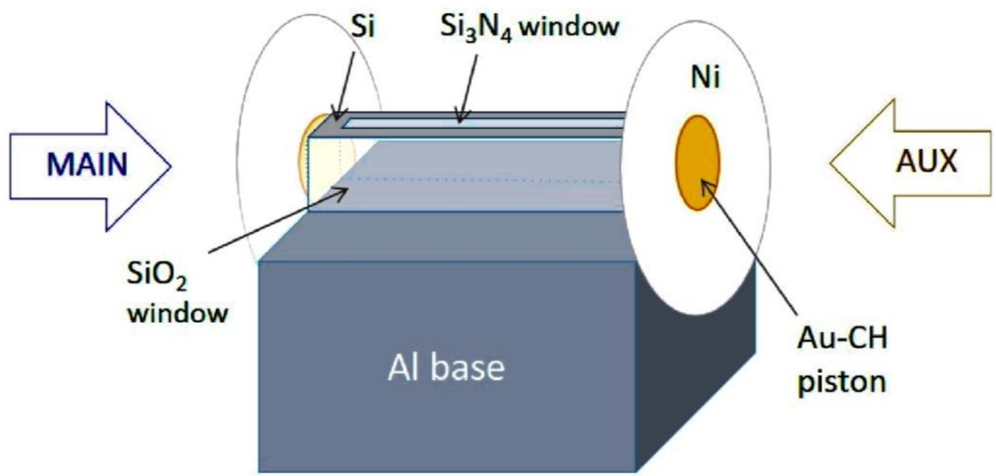
❑ Piston (to drive the shock)

Parylene N (CH, 11 μm) coated with Au (0.6 μm) **fixed on** a Ni disk (with aperture)

- ✓ CH: ablator
- ✓ Au: X-ray shield

❑ Lateral windows

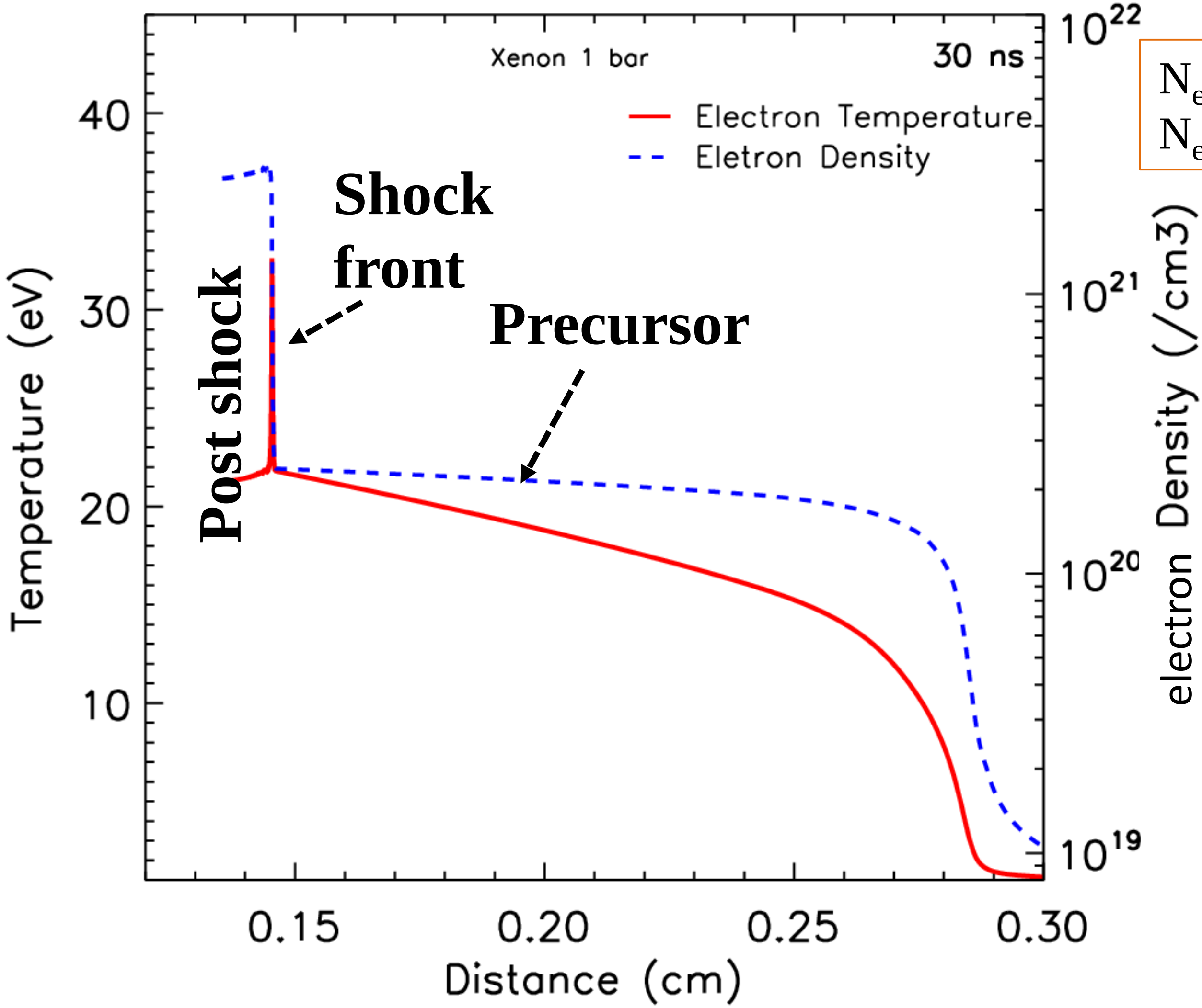
- Si_3N_4 window (thickness = 100 nm) on a Silicon frame
- Two SiO_2 windows (0.5 mm thick each)



Collision of two shocks: PALS

Diagnostics

Shock generated in **Xe at 1 bar** through a piston moving with a constant speed of **50 km/s (t = 30 ns).**



N_e at precursor $\approx 10^{18}$ -10^{20} cm^{-3}
N_e at post-shock $\approx 10^{21}$ -10^{22} cm^{-3}

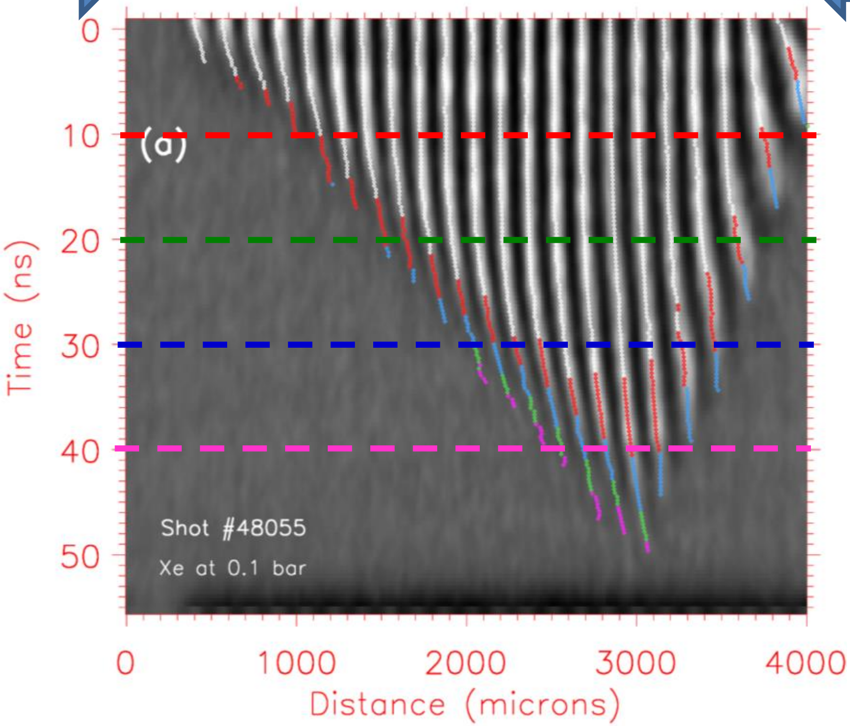
- Radiative precursor: **visible** laser interferometry
  $n_c \sim 5 \times 10^{21}$ cm^{-3} for λ = 500 nm
- Post-shock and precursor: XUV Spectroscopy

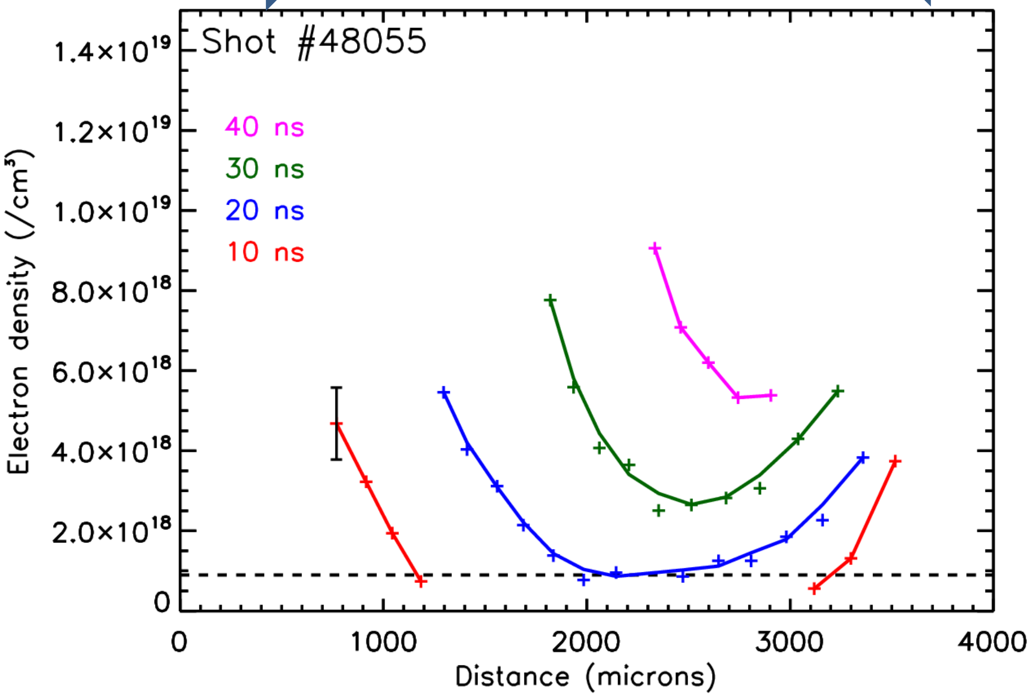
Collision of two shocks: PALS

Visible Interferometry

Shot# 48055: Xe, 0.1 bar

~ 135 J ~ 70 J ~ 53 km/s ~ 23 km/s





Error in the finding zero position on x axis is ~ 120 µm.

$N_e < 3.9 \times 10^{18}$ cm^{-3} (white)

$3.9 - 5.7 \times 10^{18}$ cm^{-3} (red)

$5.7 - 7.5 \times 10^{18}$ cm^{-3} (cyan)

$7.5 - 9.3 \times 10^{18}$ cm^{-3} (blue)

$> 9.3 \times 10^{19}$ cm^{-3} (magenta)

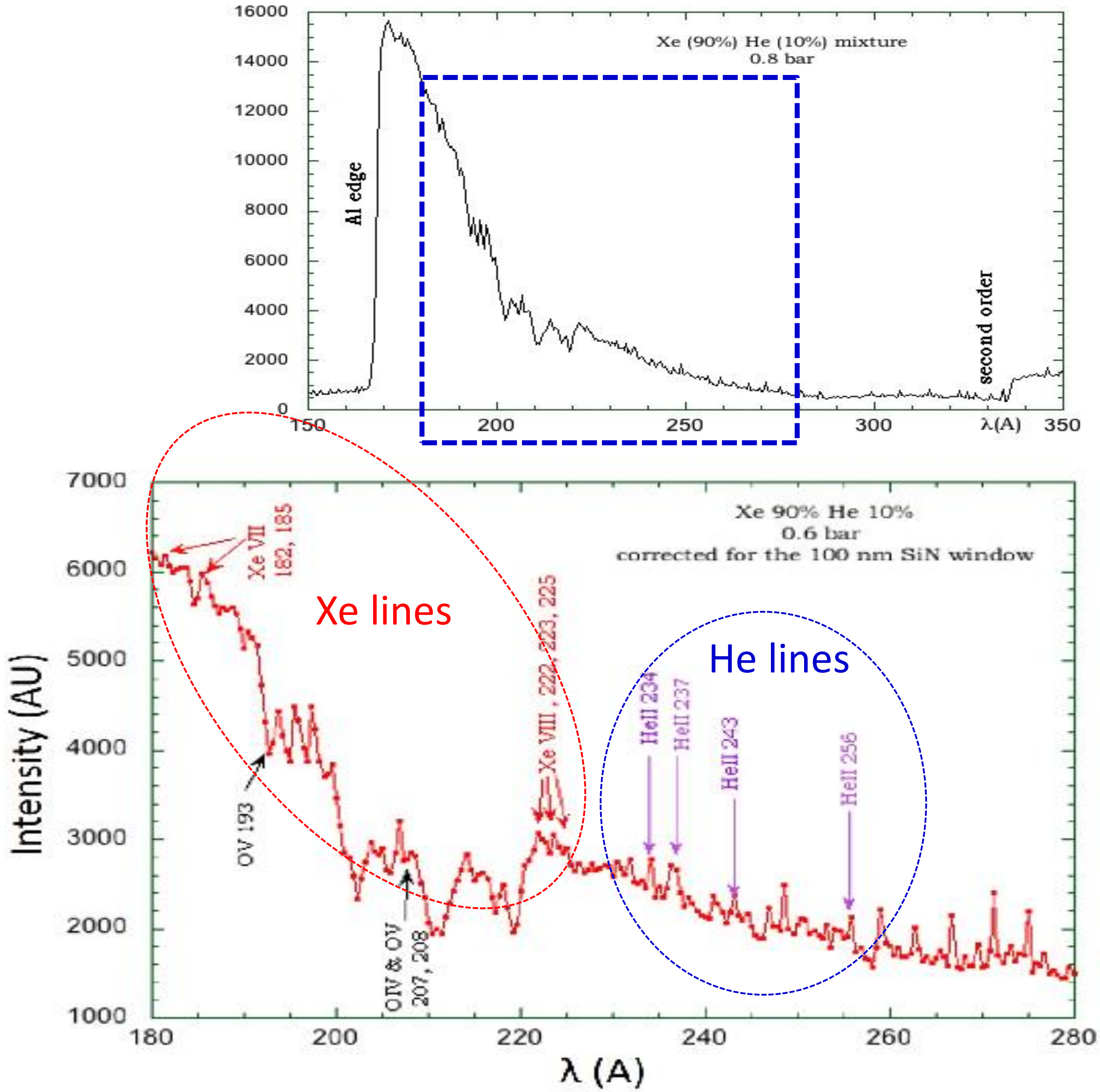
- ❑ Collision time of two shocks is near 47 ns.
- ❑ Maximum $\langle N_e \rangle$ recorded 1.1×10^{19} cm^{-3}
- ❑ The interaction between the two precursors is clearly visible.

XUV Spectroscopy
-> temperature

- ❑ Calibration
- ❑ Xenon lines recorded
  - ➔ z(Xe) > 6
- ❑ HeII Lyman lines
  - ➔ T ~ 12 – 15 eV

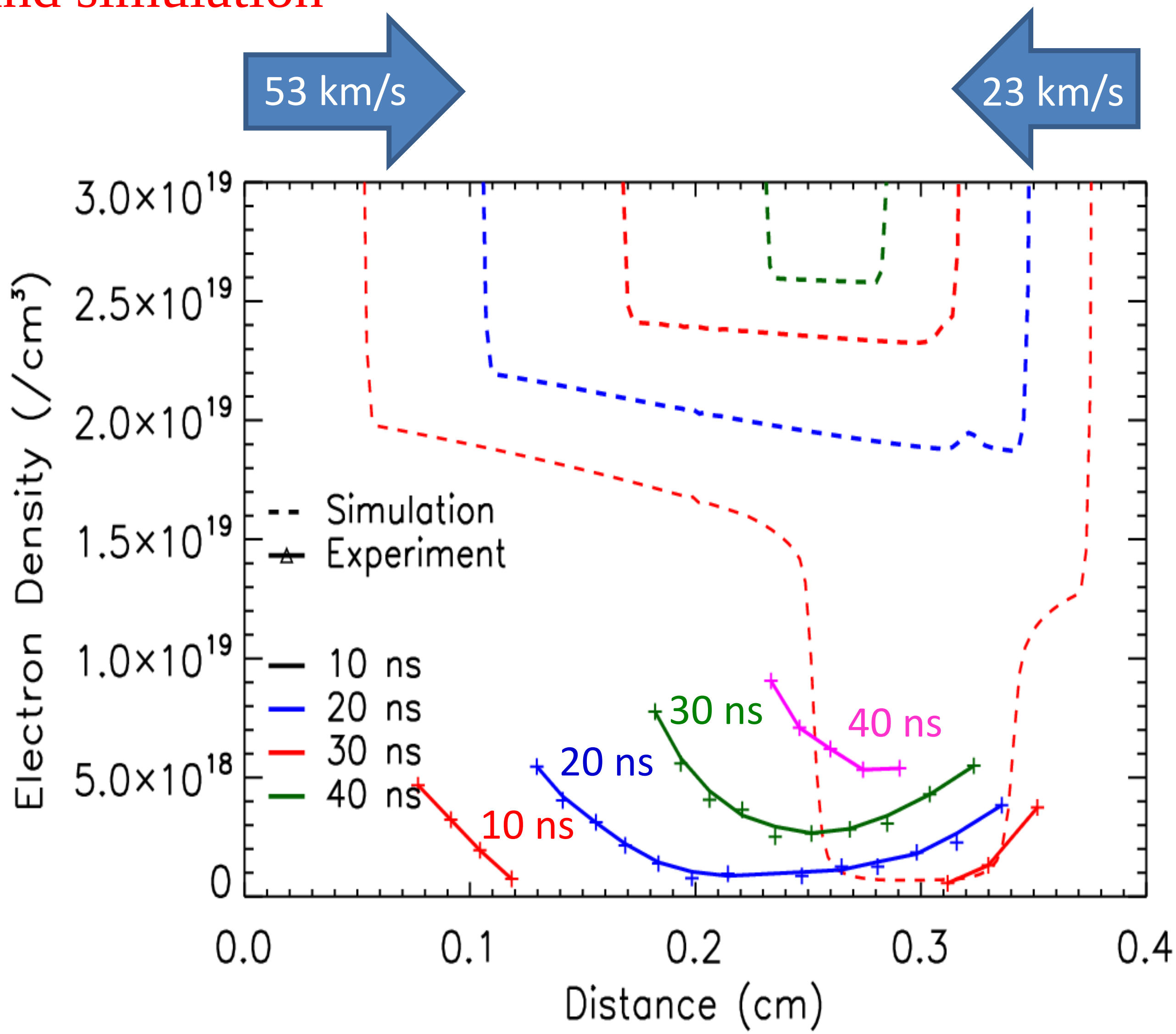
(R. R. Perez private comm.)

Xe+He at 0.6 bar



Experimental results and simulation

$\langle N_e \rangle$ from experimental data and HELIOS 1D simulations:



Not in agreement in *shape* as well as in *values*

(experimental values are smaller by a factor of ~ 4).

Summary

- PALS experiments: Collision of two radiative shocks
  - Shock of speed range 20 -55 km/s.
  - Electron density in the precursor region is order of 10^{19} cm^{-3}.
  - Strong precursor interaction of the two radiative shocks.
  - Disagreement with 1D simulations (Cause: *multidimensional effects and inaccurate opacities*).
- Future course:
  - Relevant averaged opacities for lab astrophysics.
  - Spectroscopic tools for post processing of simulations, coupled to 1D or 3D radiative transfer codes.
  - More direct diagnostic to study shock temperature (*Thomson scattering*).
  - Increasing the number of simultaneous diagnostics to study the parameters and structure of the shock.
  - Analysis of the instabilities in the post-shock seen at ORION (*rad. cooling, Rayleigh Tailor etc..*)

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