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WDM experiments at Tokyo Tech (I)

Development of a shock-driven plasma target for nonlinear ion-stopping experiments

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Outline

1. Motivation and objectives
2. Nonlinear ion-stopping in dense matter
3. Estimation of shock plasma parameters
4. Shock plasma generation with an electromagnetic shock tube and plasma diagnostics.
5. Conclusion

Motivation

- Ion stopping in dense plasma is an important issue in heavy ion fusion research.
- Coulomb coupling effects in dense plasma bring nonlinearity to plasma stopping power.
- The nonlinear effect could modify the beam energy deposition profile and shift the Bragg peak.
- So far, no experimental result on the nonlinear ion-stopping has been obtained.

Objectives

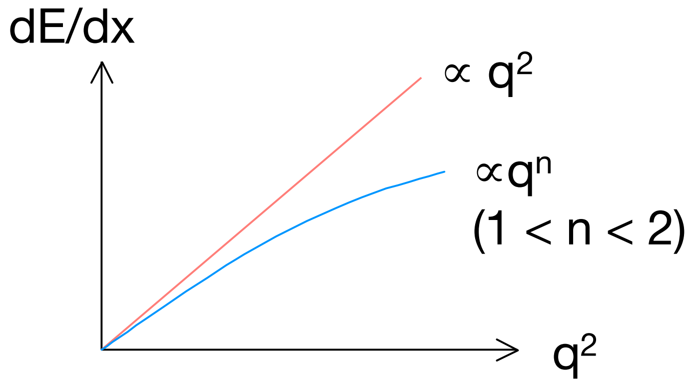
- To develop a plasma target suitable for nonlinear ion-stopping experiments with low-energy projectiles.
- To develop an energy-loss-measurement system specialized for the nonlinear stopping experiment.
- To experimentally demonstrate the nonlinear ion-stopping in dense plasma.

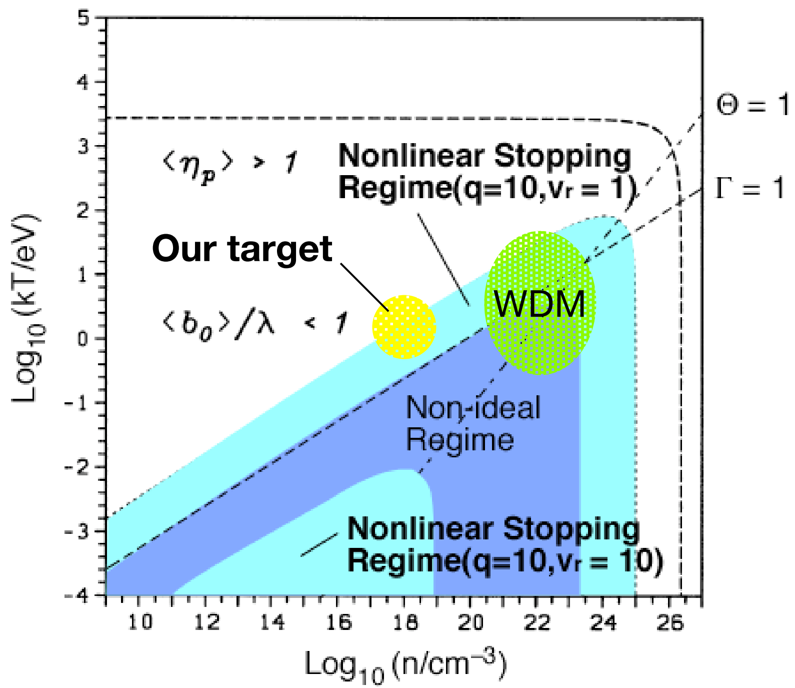
Nonlinear effects are expected for projectile stopping in dense plasmas

- Ideal plasmas ~ Linear stopping
  - Induced decelerating field $E_{ind} \propto q$
  - $dE/dx = q \times E_{ind} \propto q \times q = q^2$ (q: projectile charge)
- Non-ideal (dense, not hot) plasmas ~ Nonlinear stopping
  - Induced decelerating field $E_{ind} \propto q^m$ ($m < 1$)
  - $dE/dx = q \times E_{ind} \propto q \times q^m = q^{1+m} = q^n$ ($1 < n < 2$)
- Beam plasma coupling constant:

$$\gamma \equiv \frac{\sqrt{3}q\Gamma^{3/2}}{\left(1+v_r^{\,2}\right)^{3/2}} > 1 \Rightarrow \textbf{Nonlinear stopping}$$

- MD simulation predicted nonlinear stopping is observable even in a semi-nonlinear regime. $\gamma \geq 0.1$





Methods for dense plasma generation

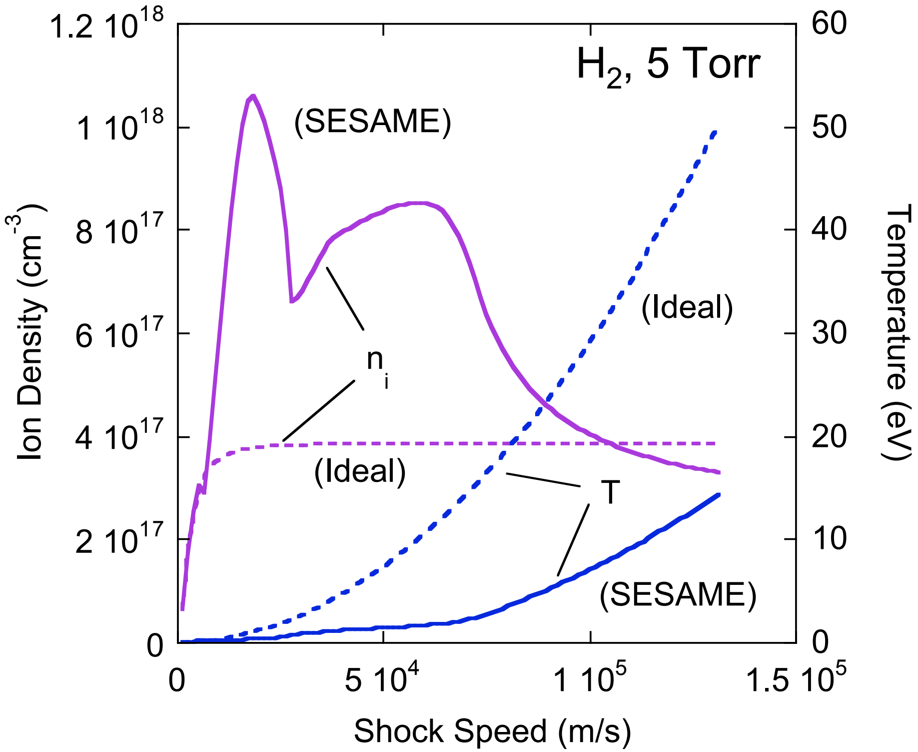
Driver	Advantages	Disadvantages
Laser	High density	High temperature Short lifetime
Z-pinch	High density Long lifetime	High B
Shock (in gas)	Low temperature Small B	Vacuum interface

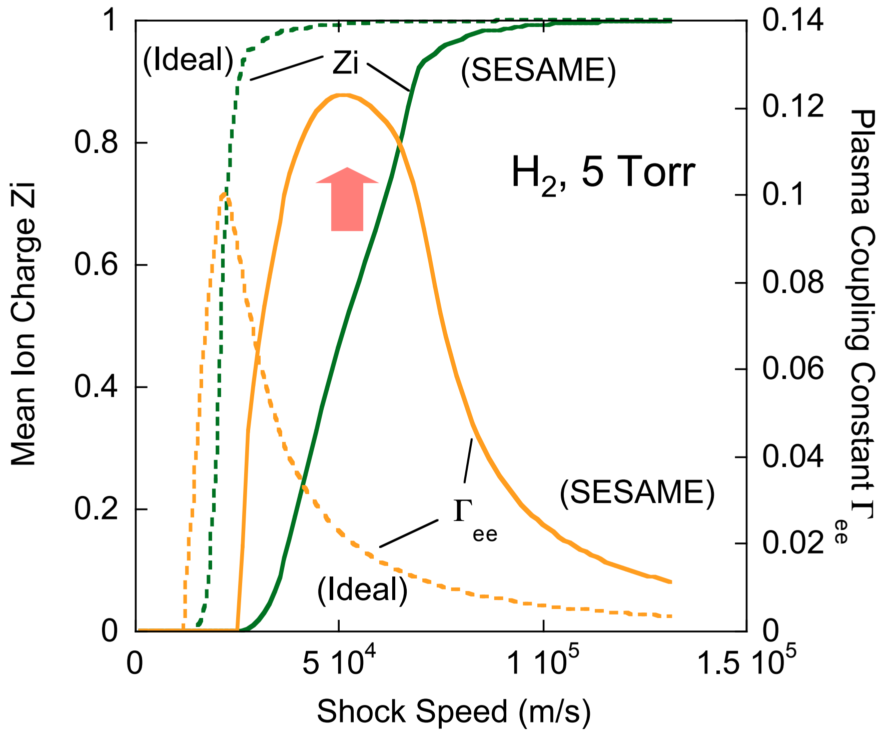
Basic requirements for plasma target

- Beam-plasma coupling constant: $$\gamma \equiv \frac{\sqrt{3}q\Gamma^{3/2}}{\left(1 + (v_{proj}/v_{th})^2\right)^{3/2}} > 0.1$$
  - To observe nonlinear ion stopping.
  - γ strongly depends on projectile charge and velocity.
  - Plasma coupling constant $\Gamma > 0.1$ can be alternative.
- Ionization degree $\alpha >> 0.5$
  - Free-electron stopping power must be comparable or larger than bound-electron stopping power.
- Target thickness > 5 mm
  - To avoid deleterious effects of boundary layer on the uniformity of shock plasma.
- Energy loss $\Delta E/E < \sim 0.2$
  - To assume almost constant projectile velocity in a target.

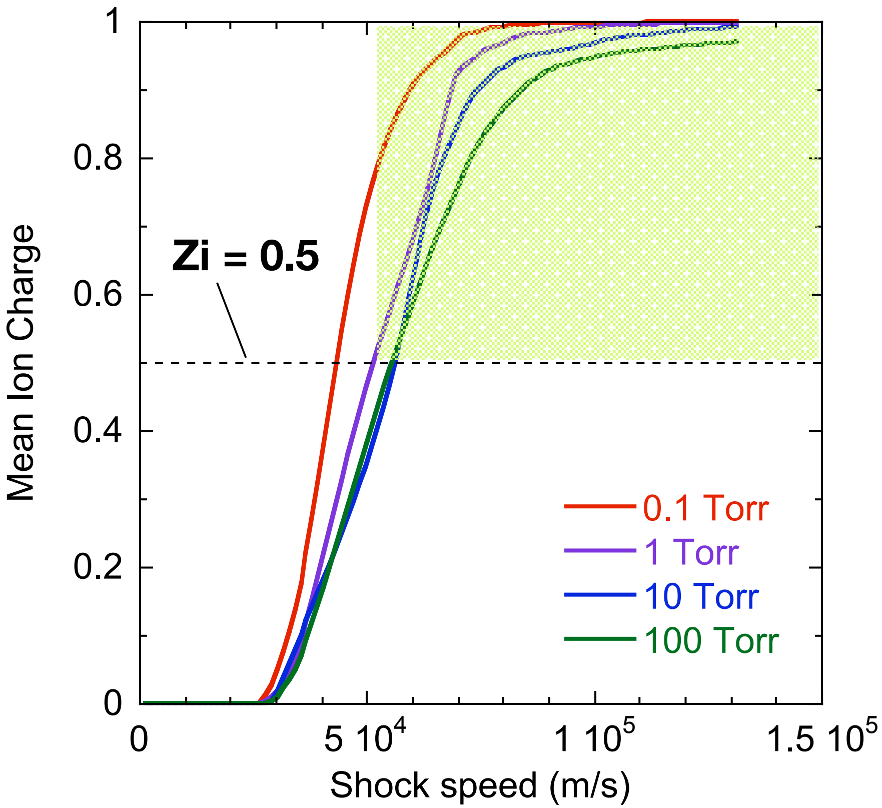
Expected target plasma parameters were examined by using the Rankin-Hugoniot relation.

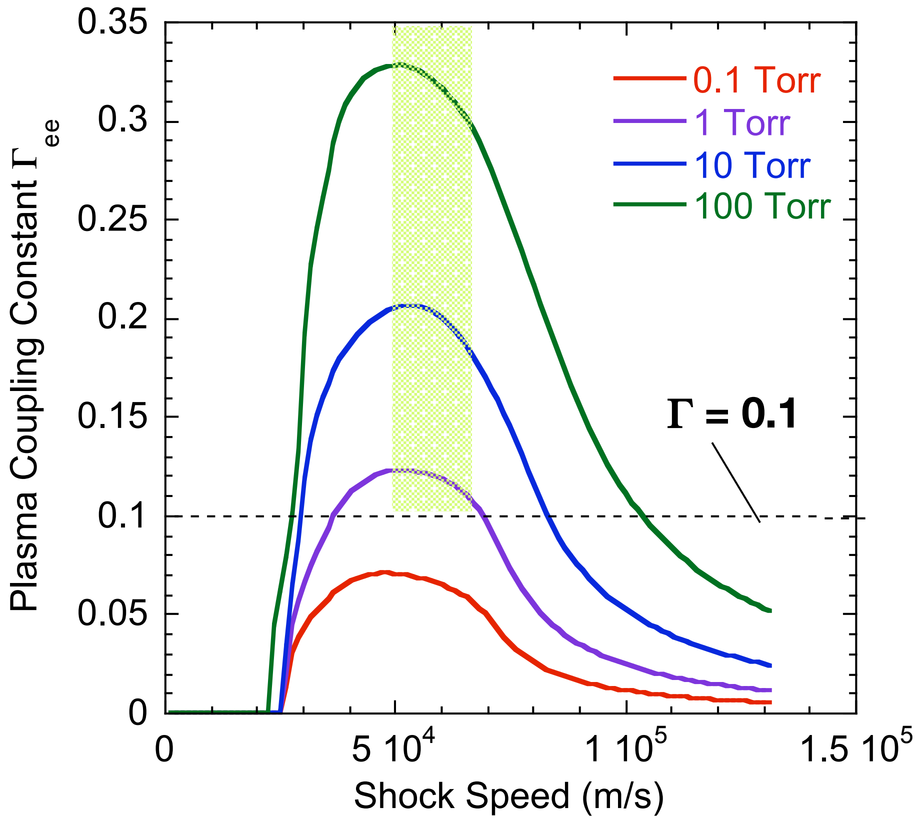
- To take into account "real-gas" effects, we use SESAME EOS data.
- Plasma coupling constant has the maximum with respect to shock speed, which indicates that the optimum condition exists.





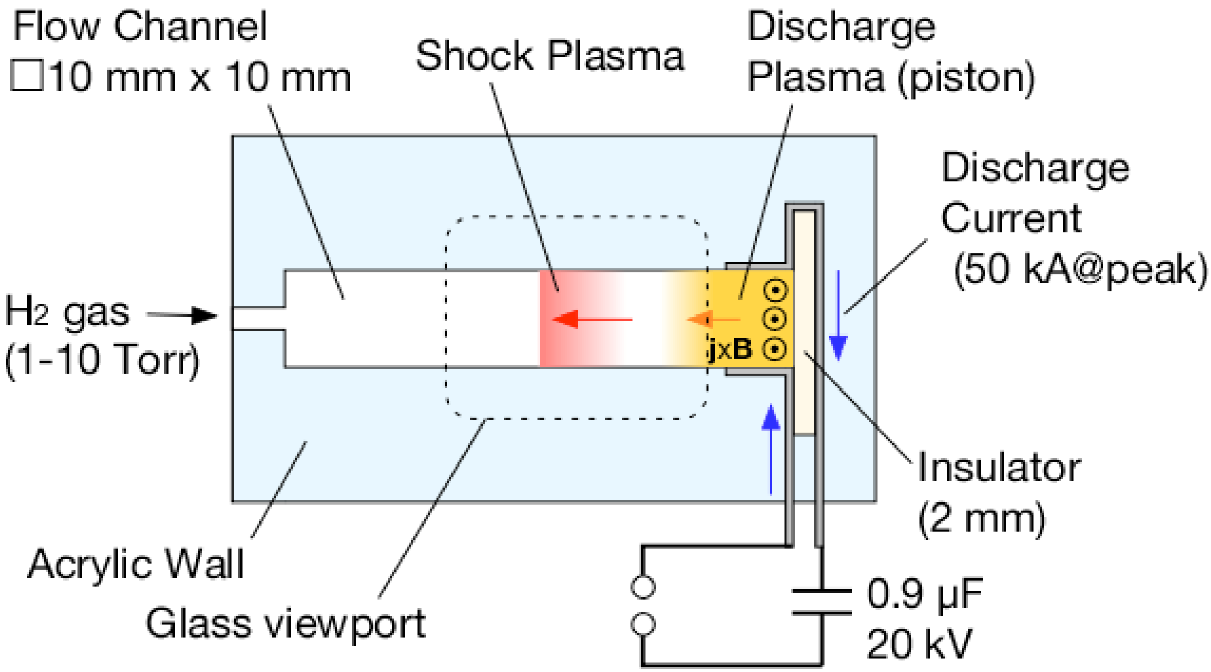
To meet requirements for target plasma, shock speed must be larger than 50 km/s (M≈38).

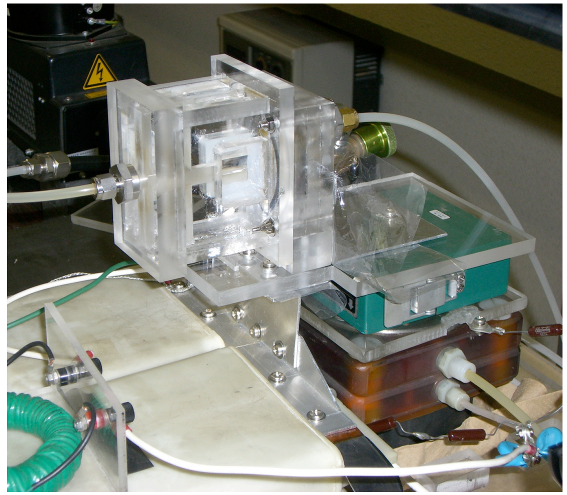




- Low pressure was advantageous to obtain high ionization degree, but lower limit was determined by $\Gamma > 0.1$.

An electromagnetically driven shock tube was developed for off-beam plasma experiments.





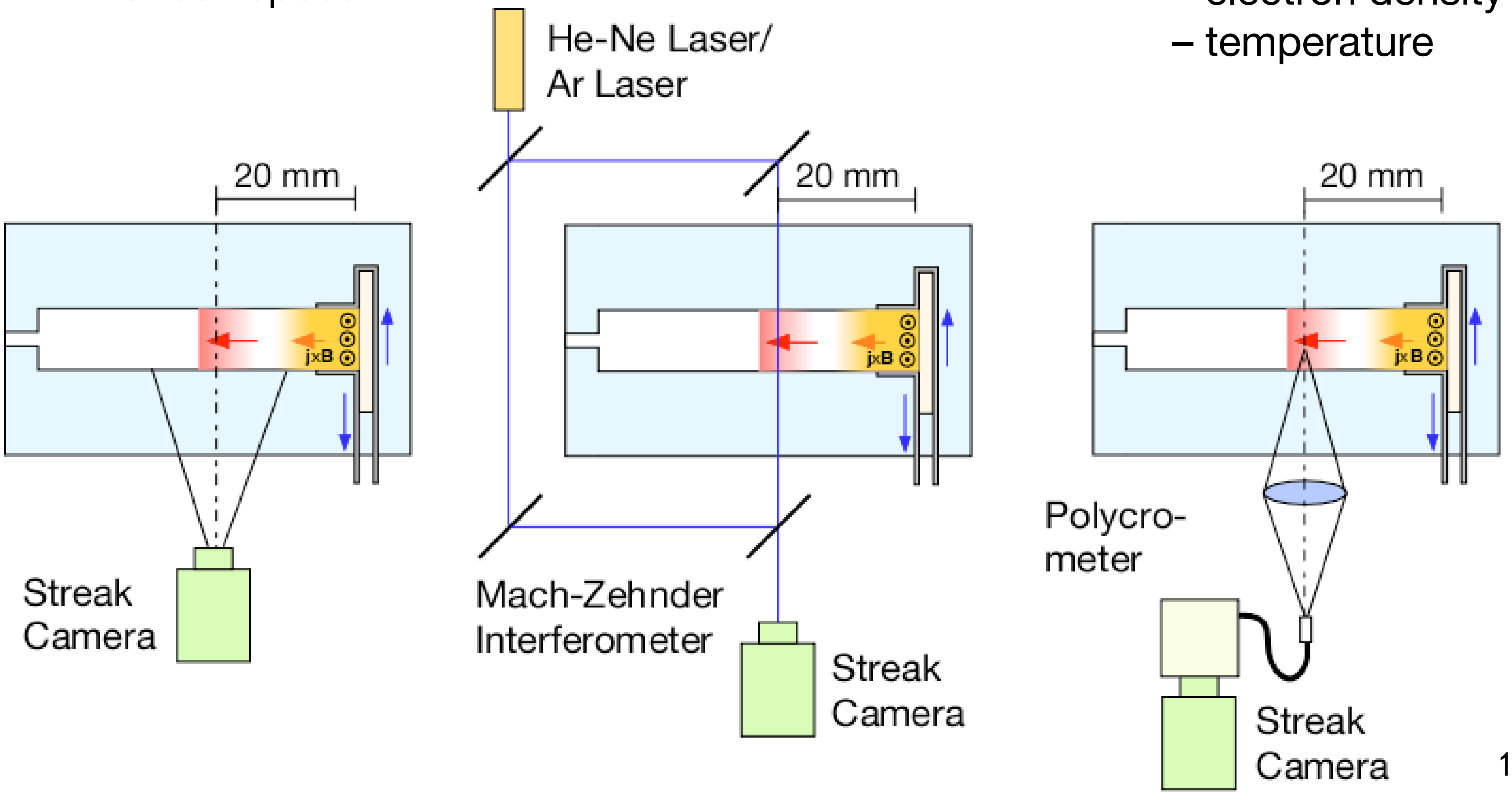
- A strong shock wave was driven by the piston discharge plasma accelerated by **jxB** force.

Experimental setups for shock plasma diagnostics

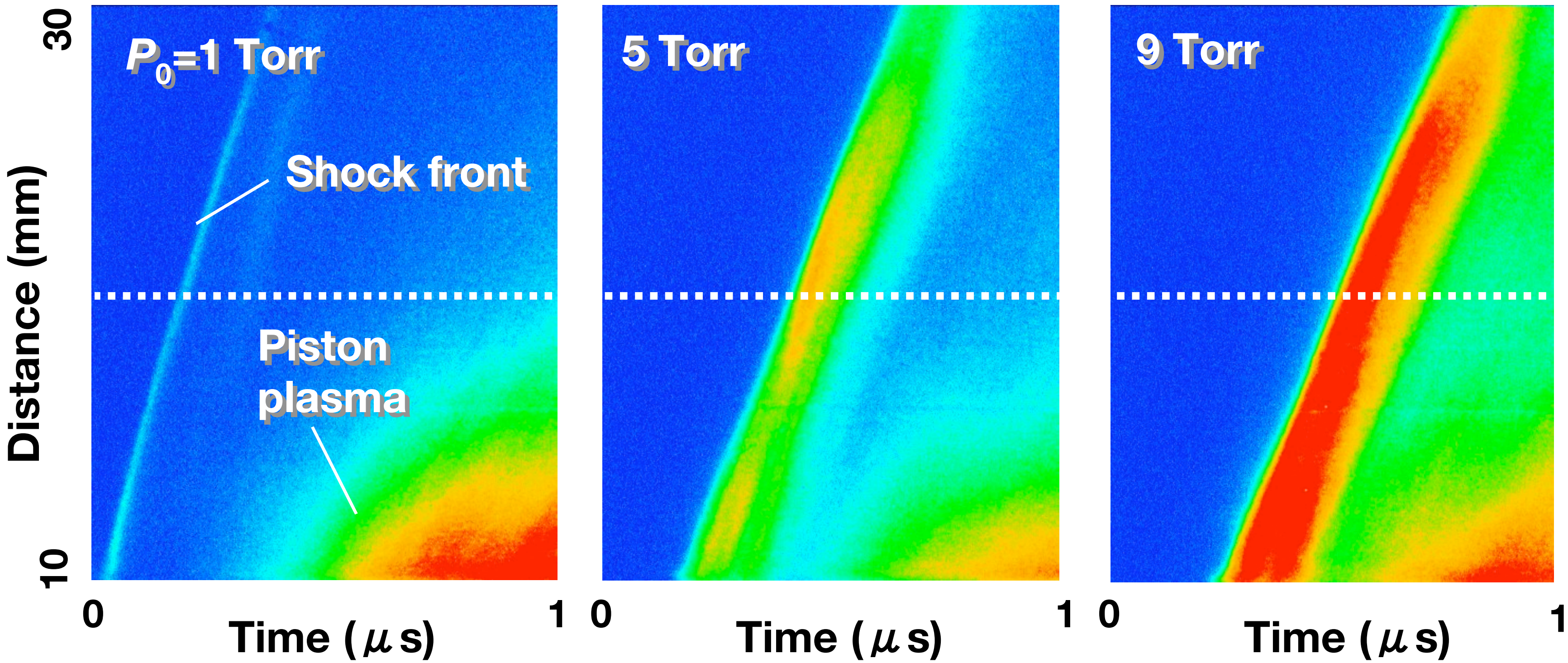
(1) Imaging with streak camera:
– shock speed

(2) Laser interferometry:
– electron density distribution

(3) Time-resolved spectroscopy:
– electron density
– temperature

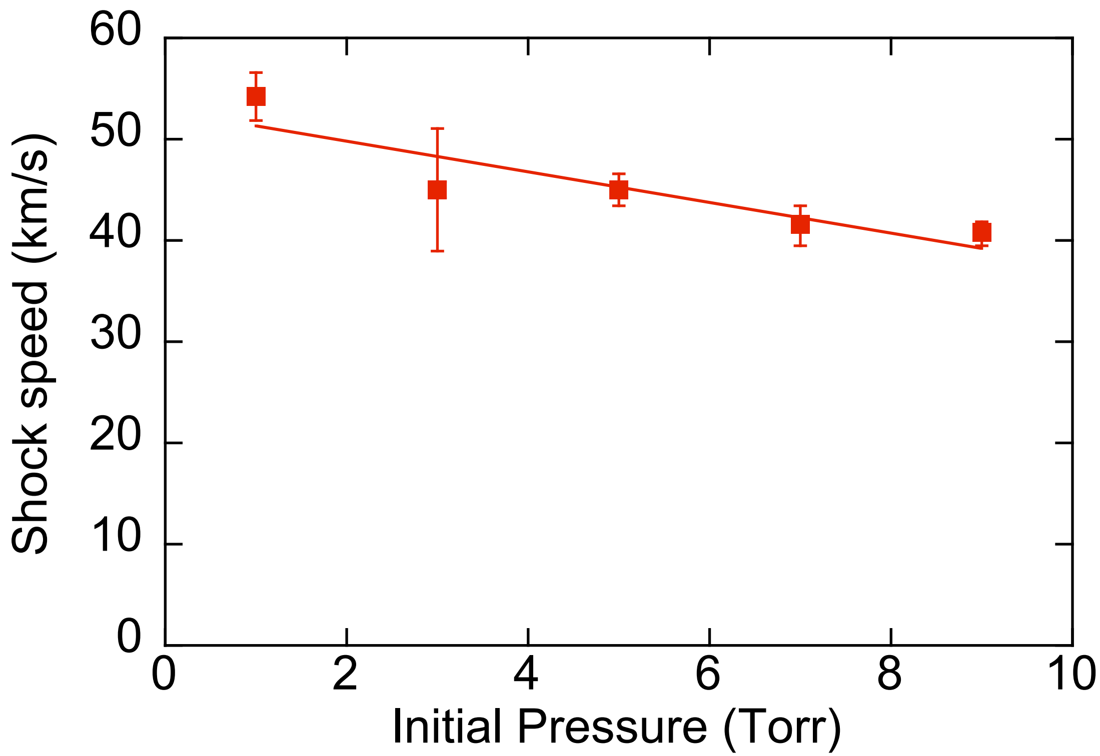


Shock plasma and piston plasma were clearly observed with a fast streak camera.



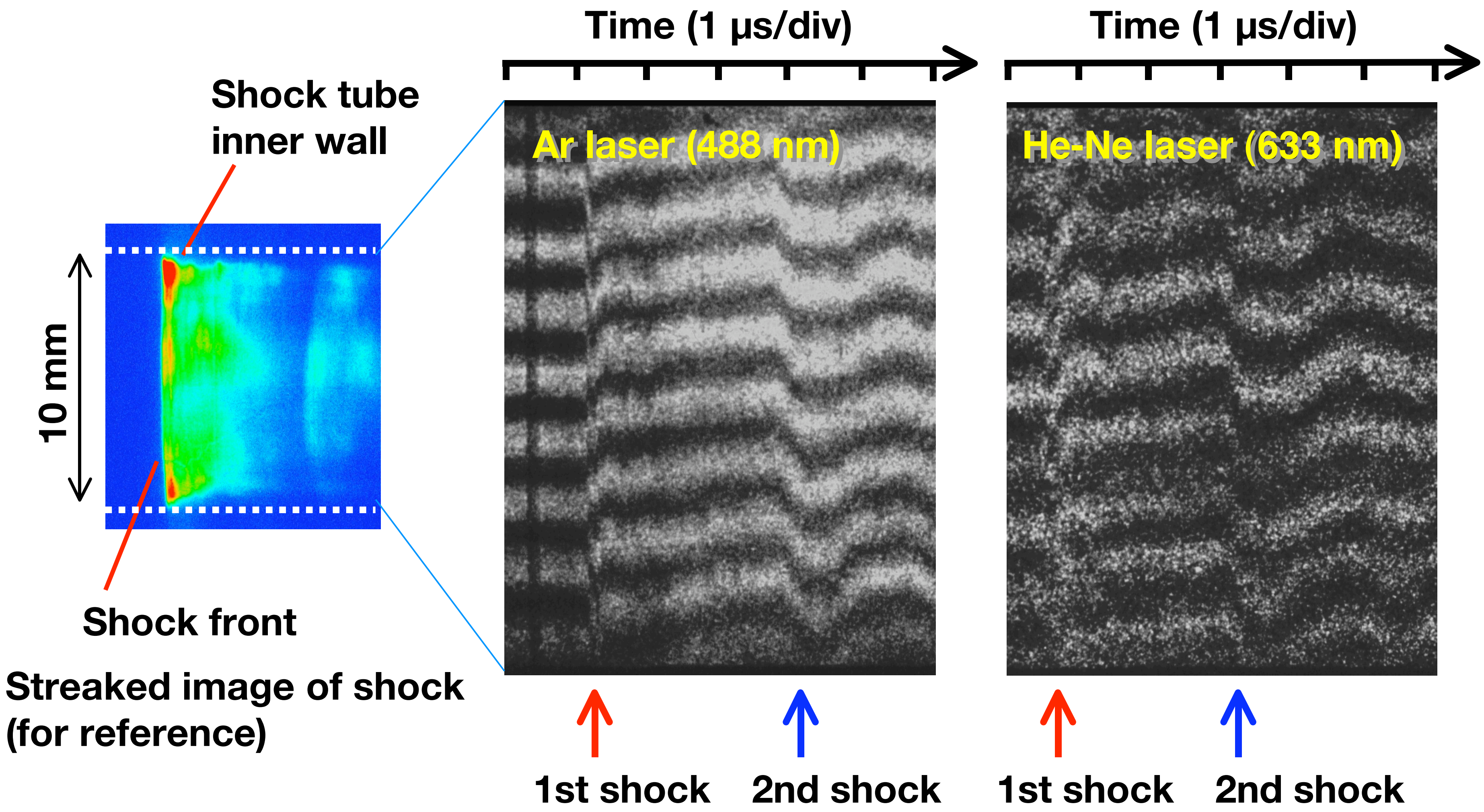
- Emission strength from shock plasma depends on the initial pressure.
- Shock speed was evaluated from the slope of the shock trace.

Shock speeds over 50 km/s (M≈38) were obtained at lower initial pressure.



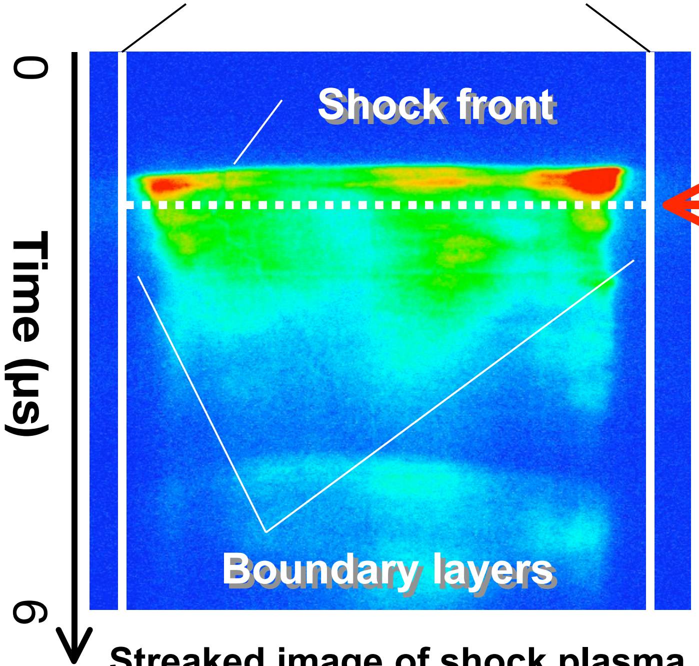
- The shock speed decreases with increasing pressure.
- To get higher shock speed, we need to upgrade the driving discharge circuit.

Electron density distribution was measured by two-wavelength laser interferometry.

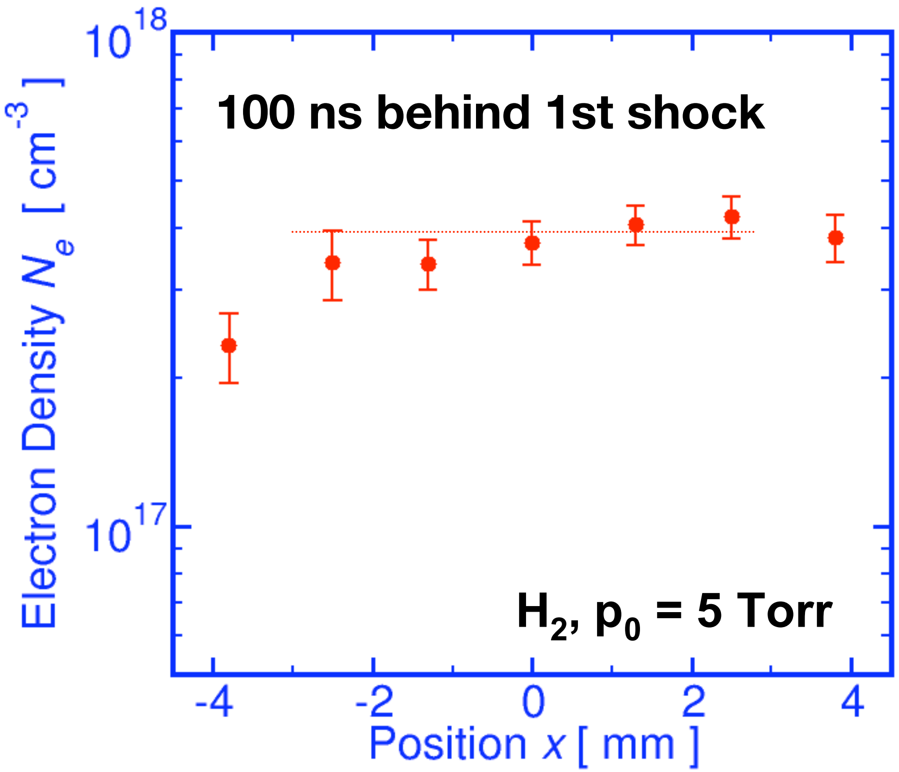


The uniformity of electron density across the tube was acceptable just behind the first shock.

Shock tube inner wall



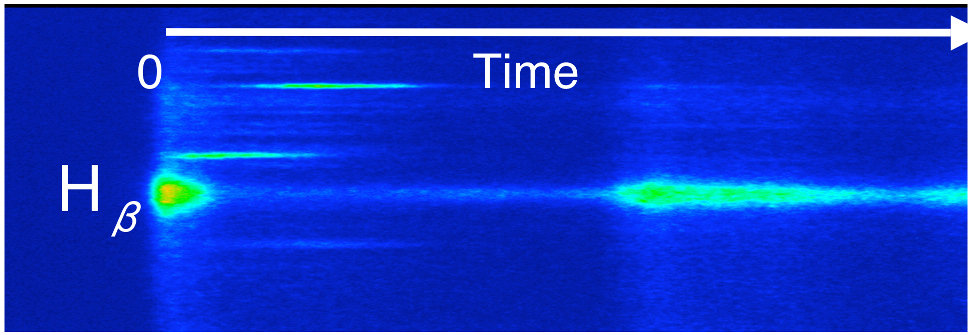
Streaked image of shock plasma
(for reference)

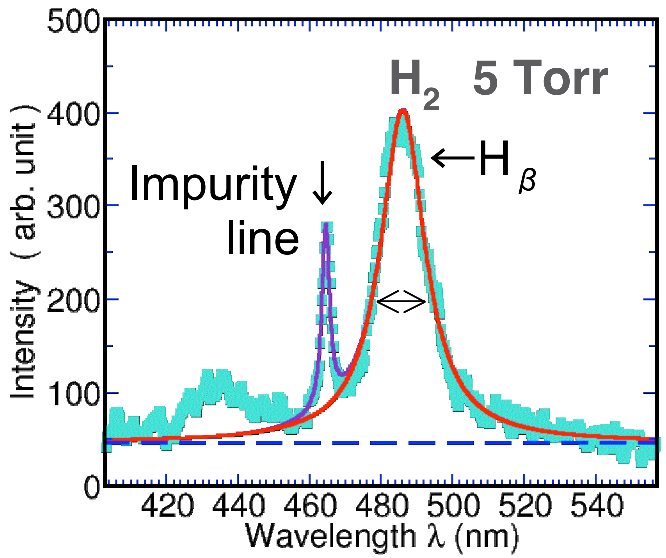


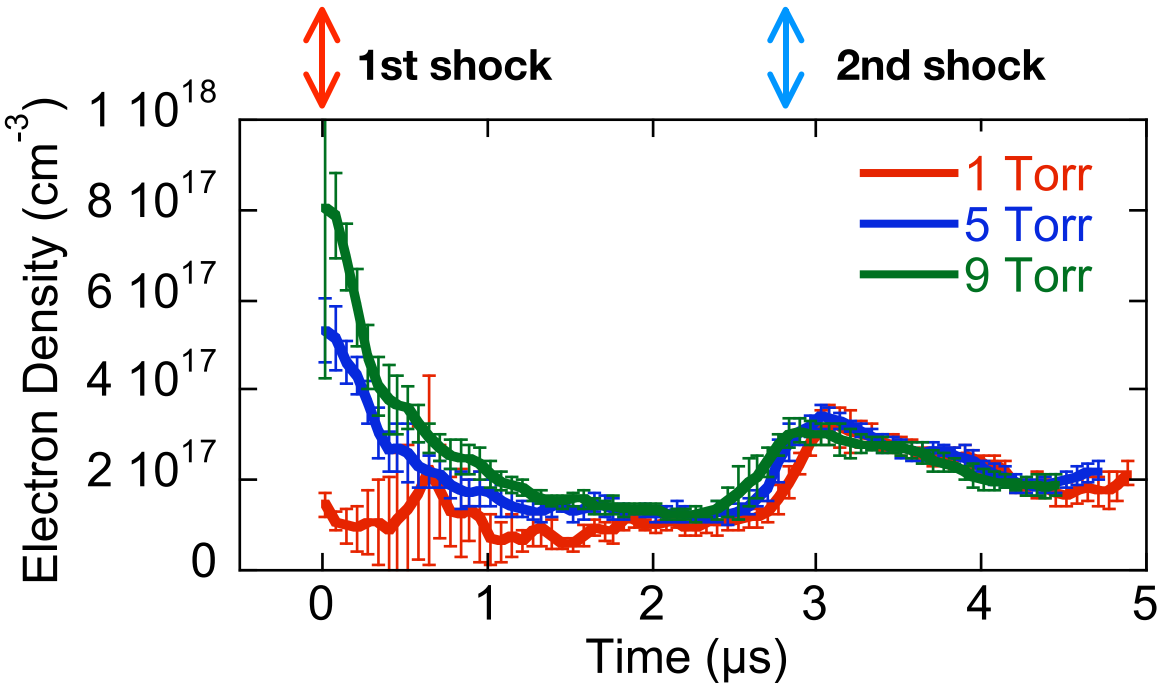
- The spatial distribution of the electron density was examined at 100 ns behind the first shock.
- The electron density dropped near wall, which is due to the growth of boundary layers.

Electron density was also evaluated from the Stark broadening of Hβ line.

A streaked image of Hβ spectrum:

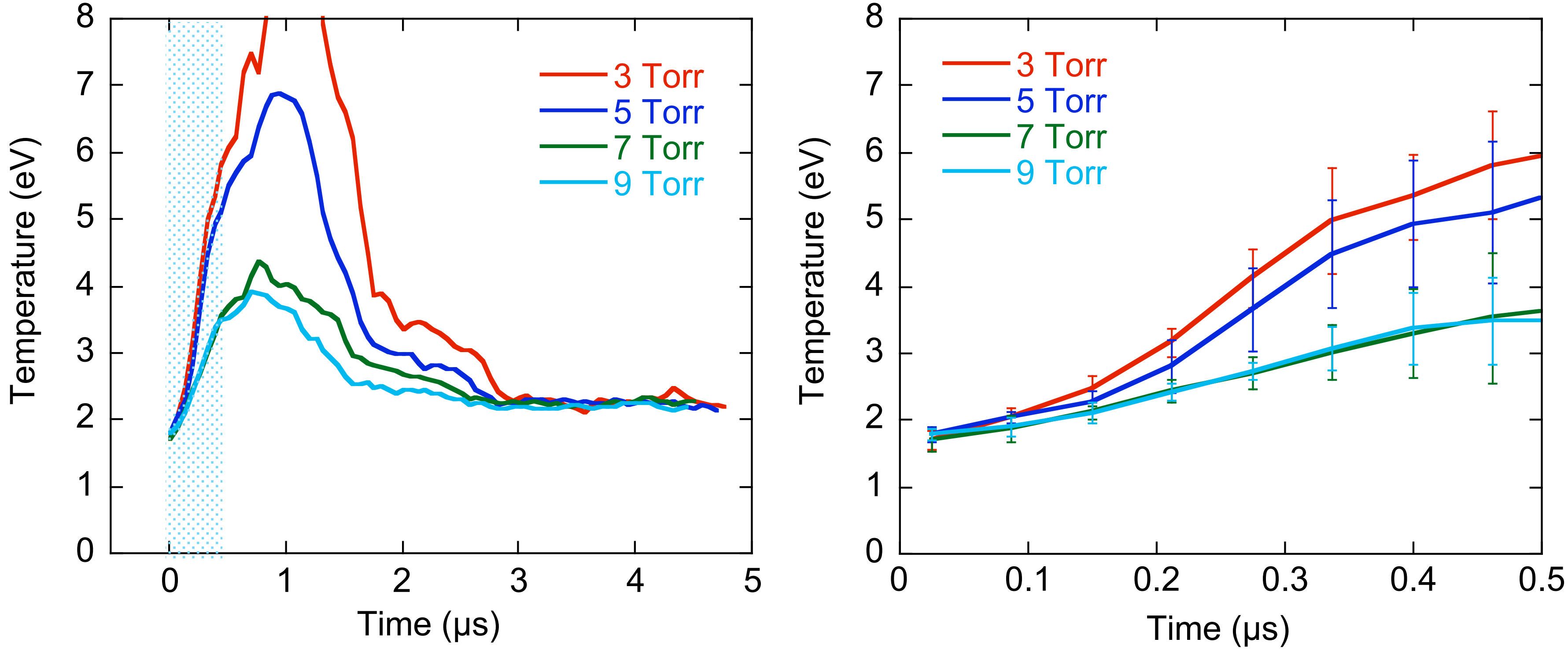






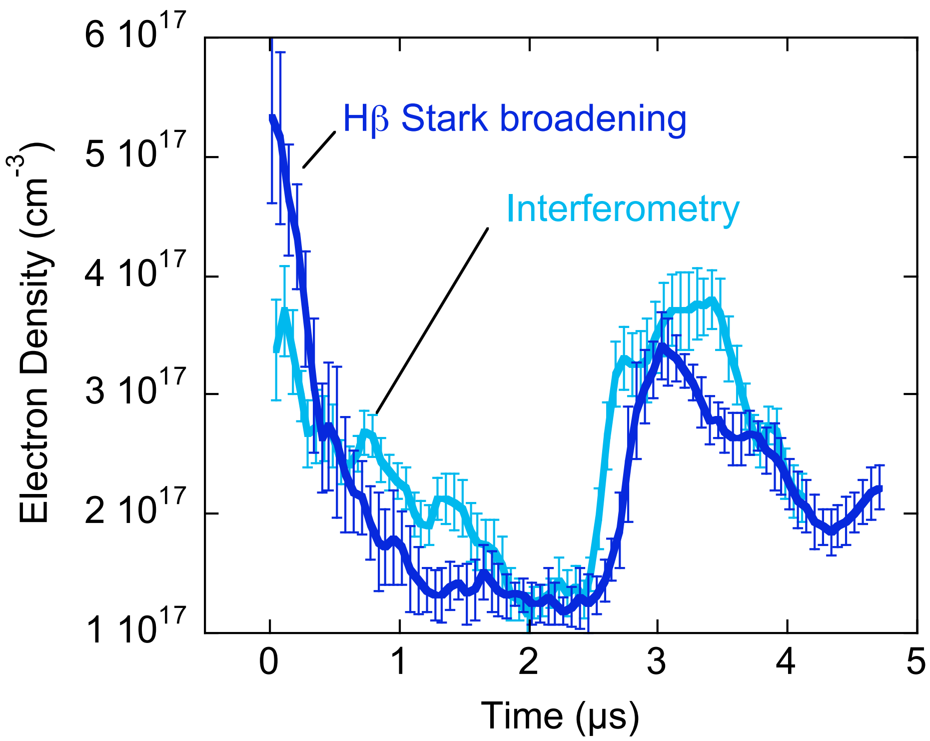
- An electron density of 6 x 10^{17} cm^{-3} was obtained just behind the 1st shock.
- The electron density increased with increasing initial pressure.

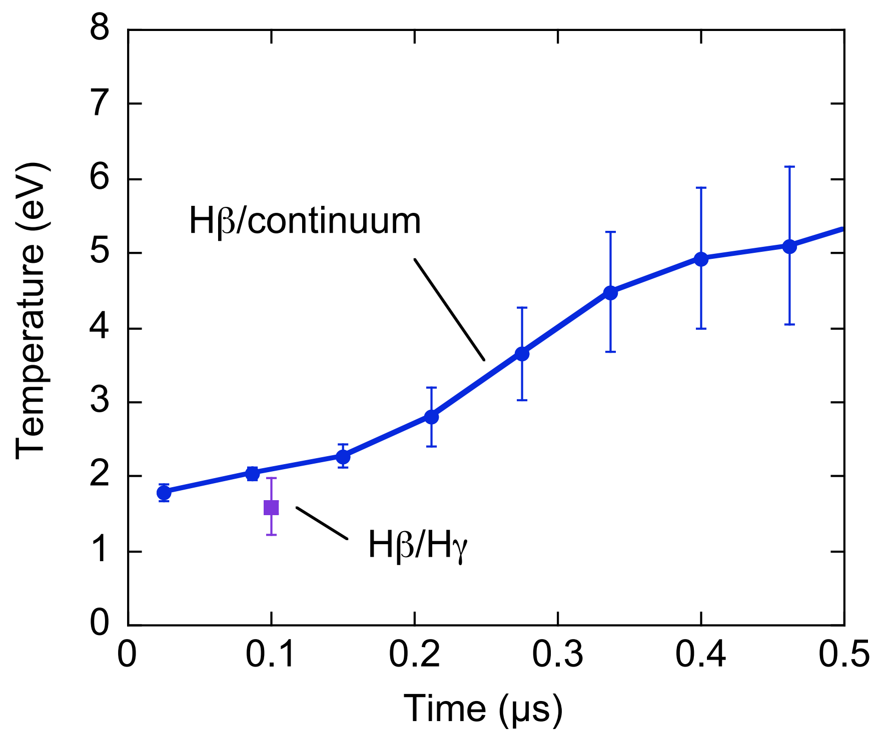
Temperature was determined to be about 1.6 eV behind the shock from Hβ/continuum ratio.



- The observed temperatures was almost the same for different initial pressures.
- Rapid temperature rise around 1 μs was due to the arrival of the discharge plasma (these values are doubtful because of the limitation of the method).

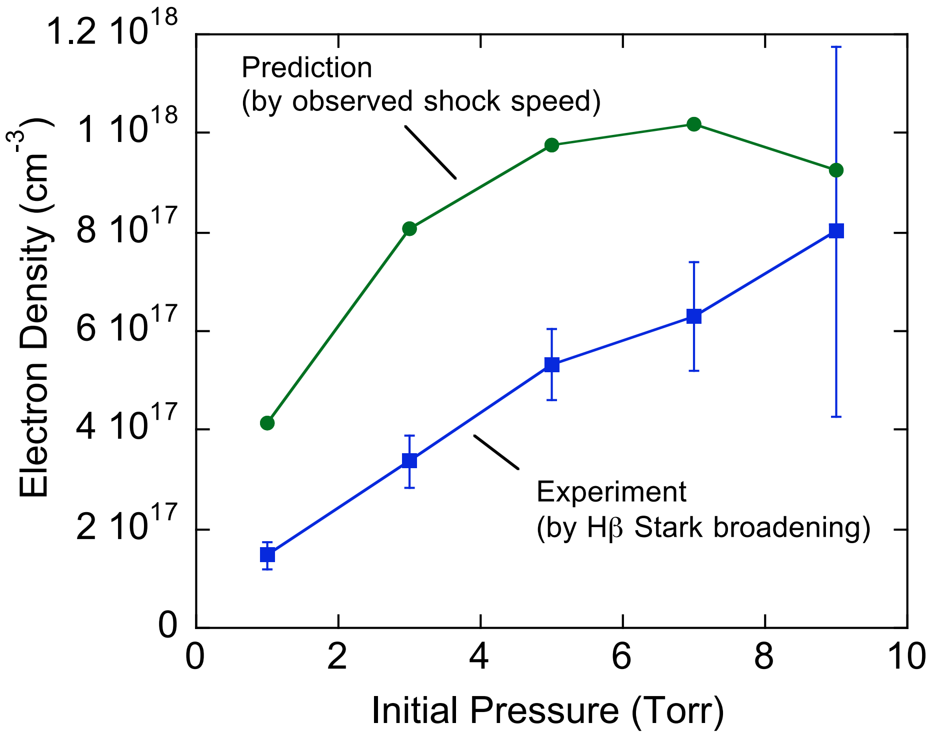
To check the reliability of the diagnostics, we compared the values obtained different methods.

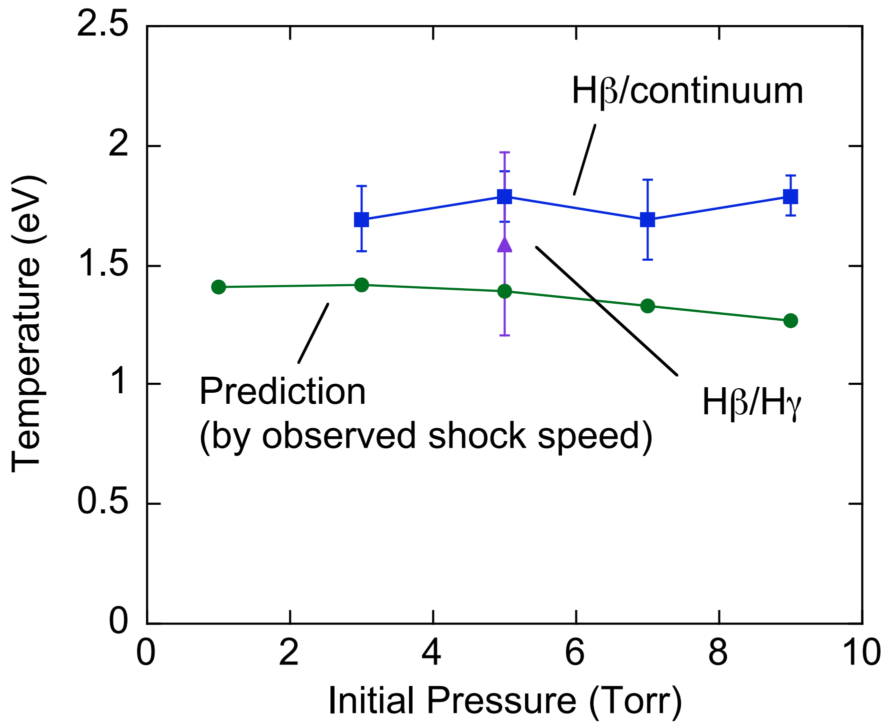




- The densities obtained by spectroscopy and interferometry showed good agreement with each other except for the values just after the first shock.

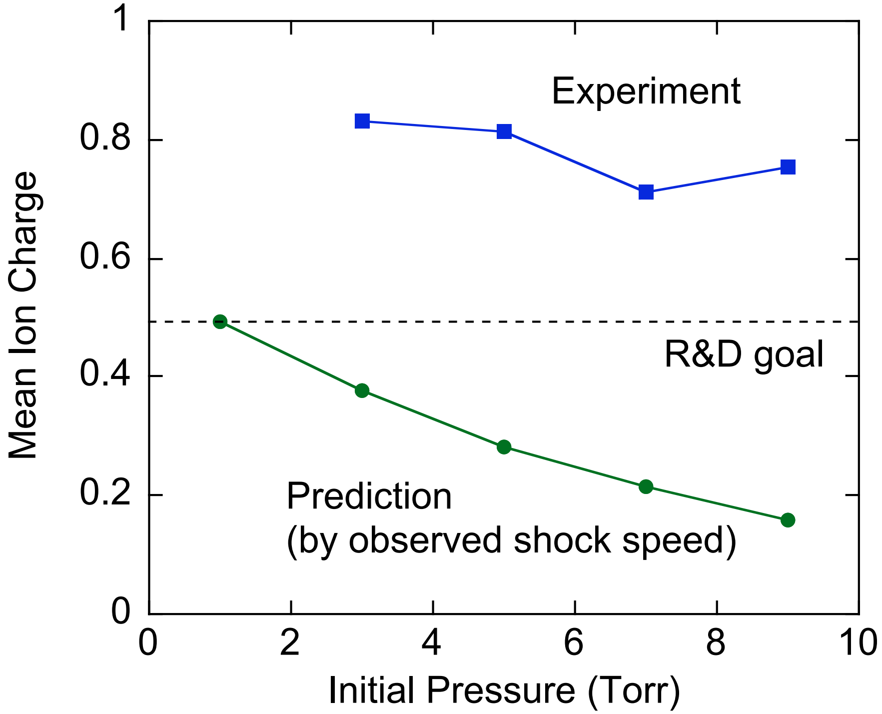
Observed densities and temperatures were qualitaitively consistent with the predictions.

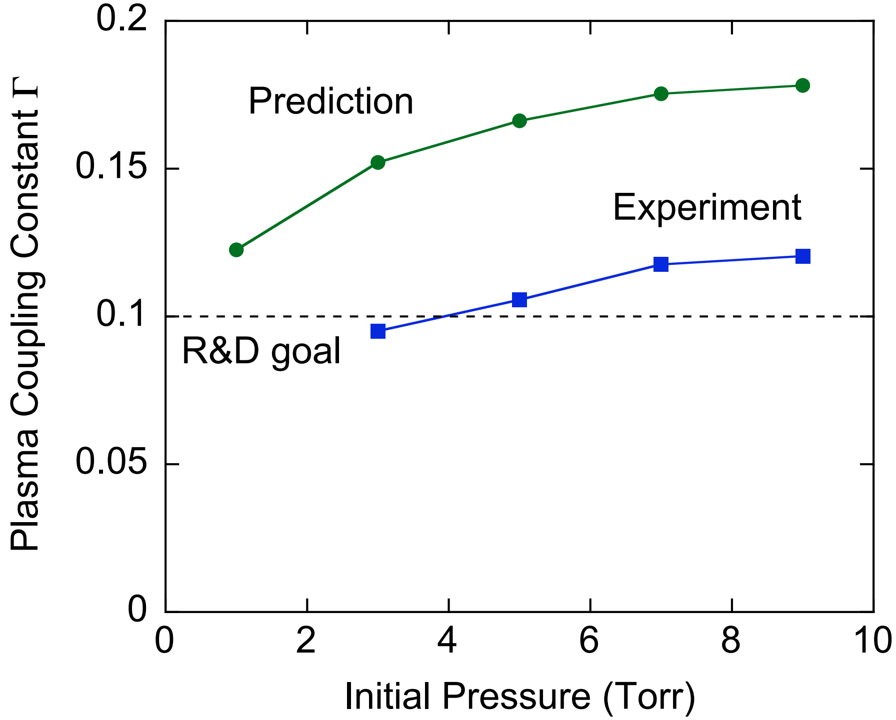




- Measured densities were smaller than the predictions by a factor of 2.
- Measured temperatures were higher than the predictions.

Mean ion charge and plasma coupling constant Γ almost satisfied the requirements.





- Because of higher temperature than the predictions, the mean ion charge was high enough, but plasma coupling constant was limited.

Conclusion

- We developed a shock-driven plasma generator for off-beam experiments and achieved a shock speed more than 50 km/s ($M \approx 38$) with an initial pressure of 1 Torr.
- We examined the shock plasma properties with laser interferometry and spectroscopy.
- Measured electron density and temperature were almost consistent with the prediction by the Hugoniot relation.
- Requirements for mean ion charge Zi and plasma coupling parameter Γ were almost satisfied, but higher shock speed is needed to get higher Γ values.