Behavior of Hydrogen Fueled by Pellet Injection in the GAMMA 10 Tandem Mirror

Y. Kubota, M. Yoshikawa, Y. Nakashima, T. Kobayashi, Y. Higashizono, K. Matama, M. Noto, and T. Cho

Plasma Research Center, University of Tsukuba
Present Address: Toyota Technological Institute, kubota@toyota-ti.ac.jp

1_Introduction

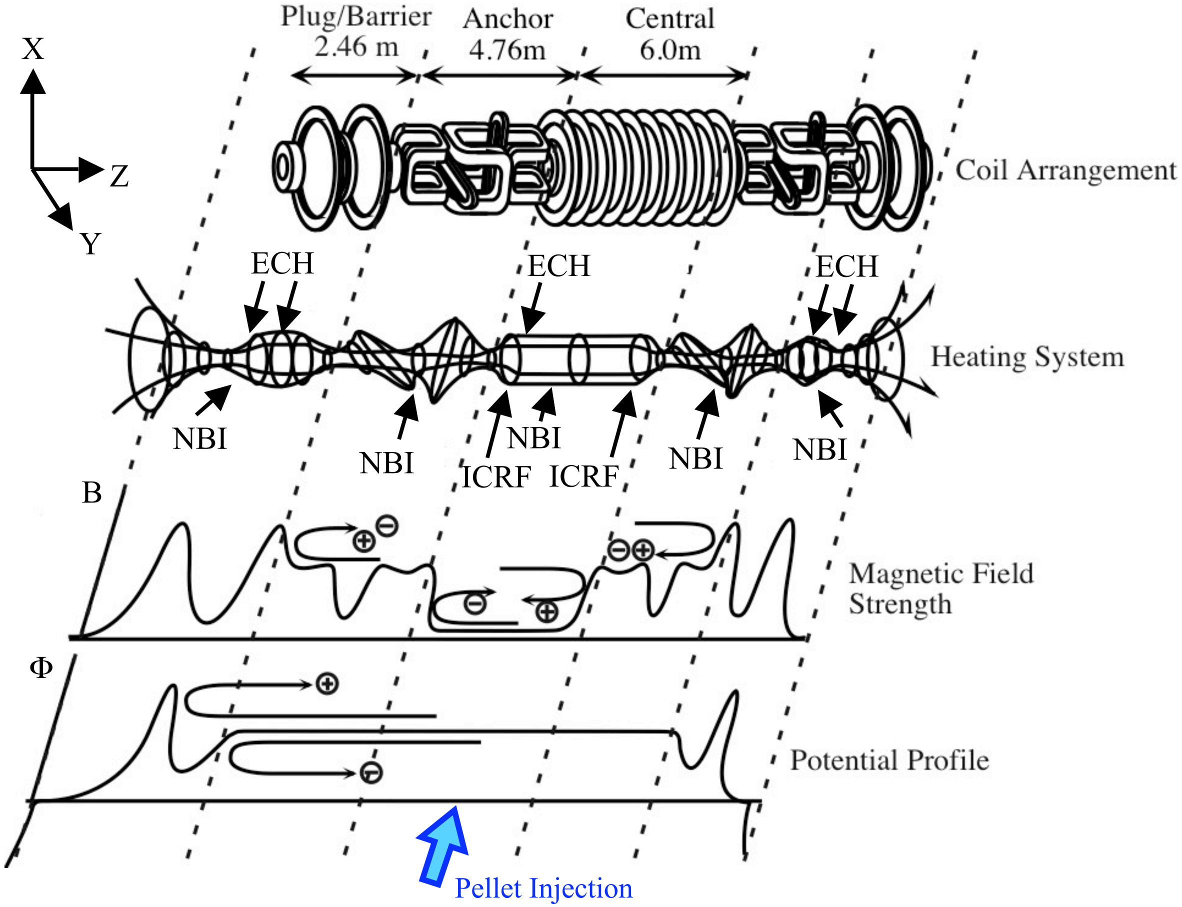
Sustainment of the steady state plasmas with higher densities and temperatures is one of the most important subjects to realize the fusion reactor. The development and optimization of the fueling method enable us to increase and sustain plasma density. In the present plasma experiments, there are three major fueling methods; namely, gas puff, neutral beam injection and pellet injection. The importance of pellet injection is highlighted under the condition at high density and high temperature plasmas.

In the GAMMA 10 tandem mirror, the study of particle fueling has been carried out for the purpose of producing high performance plasma discharges. In recent experiments, hydrogen pellets are injected with electron cyclotron resonance heating at the plug/barrier and central cells. The neutral gas shielding (NGS) model is effective for the analysis of the results.

The pellets ejected from barrel reaches the plasma through the 6 m length curved guide tube in GAMMA 10. In almost cases, the pellet cracks and slows down somewhere of the injection path. Therefore, the pellets are injected to the plasma with different size and velocity compared with the expected size and velocity.

In this poster, we show the experimental results of the plasma discharge with the pellet that cracks to some pieces, and discuss the behavior of fueled particles based on those results and the calculation results of NGS model.

2_GAMMA 10



The pellets are injected to plasma from the bottom side of the mid-plane of the central cell.

GAMMA 10 Device

- Tandem mirror device
- Total length: 27 m

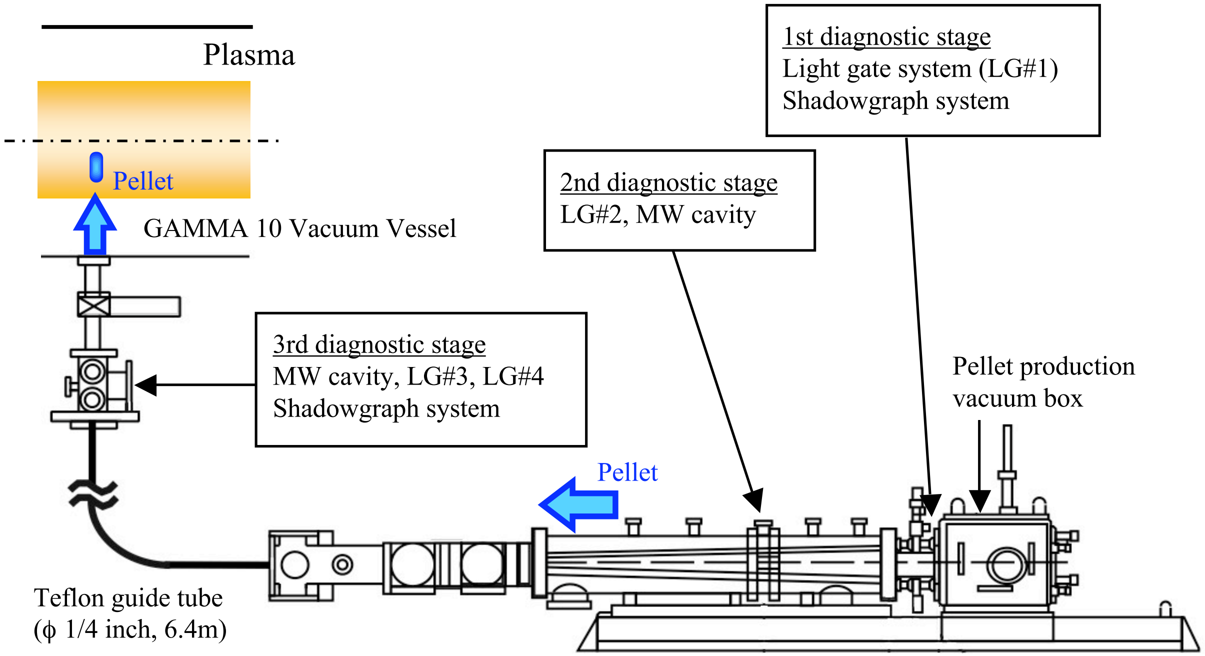
Plasma Parameter

- ^{1}H plasma
- $n_e \sim 3\text{x}10^{12}$ [cm^{-3}]
- $Ti_{\perp} \sim 5$ [keV], $Ti_{//} \sim 300$ [eV]
- Te ~ 100 [eV]

Heating System

- ICRF
  - Generation and sustain of plasma
- ECRH
  - Formation of confinement potential
  - Electron heating at the central cell
- NBI
  - Plasma heating and particle fueling
  - Sustain of high-beta plasma
  - Generation of sloshing ion distribution

3_Pellet Injection System



Pellet Injector

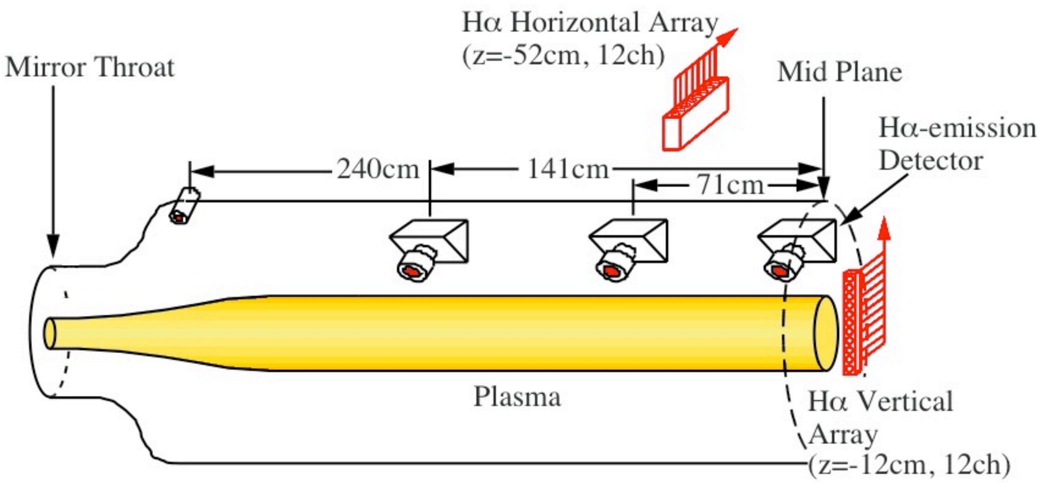
- Pipe-gun type pneumatic injector
- The eight barrels are mounted
  ϕ: 0.39, 0.58, 0.79, 0.99 mm
  This Experiments: 0.79 mm
- Cylindrical pellet
  Aspect ratio: 0.5 ~ 2
  Velocity: 600 ~ 1000 m/s

Pellet diagnostic system

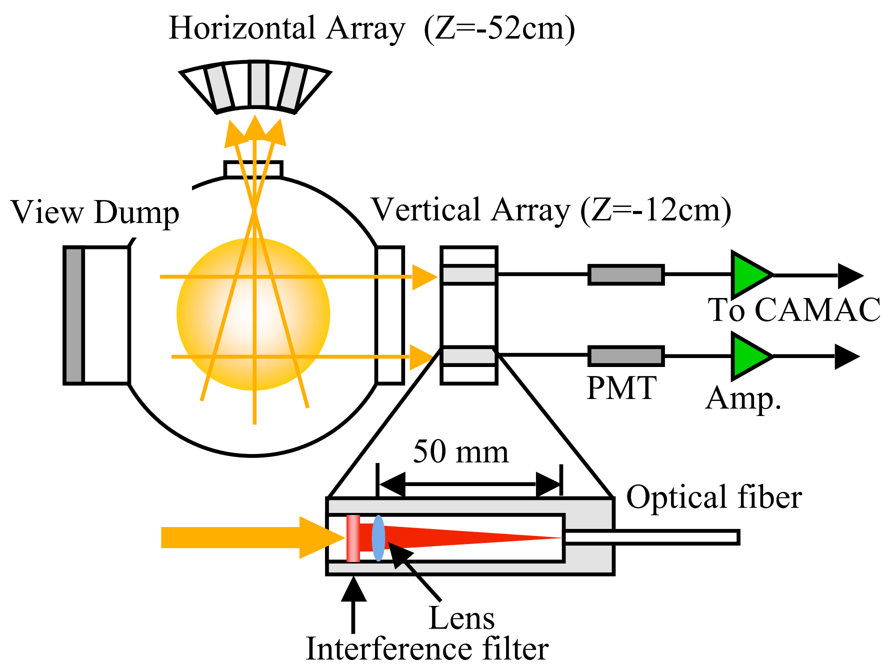
- 1st diagnostic stage: Light gate system (LG#1) for velocity measurement
  Shadowgraph system to obtain the pellet shape
- 2nd diagnostic stage: LG#2 (Pellet velocity is measured by TOF between LG#1 and LG#2)
  Microwave cavity to evaluate a pellet mass
- 3rd diagnostic stage: Pellet velocity, mass and shape are obtained in this stage
  LG#3, LG#4, MW cavity and shadowgraph are installed

4_H_α Line Emission Detector

Measurement position



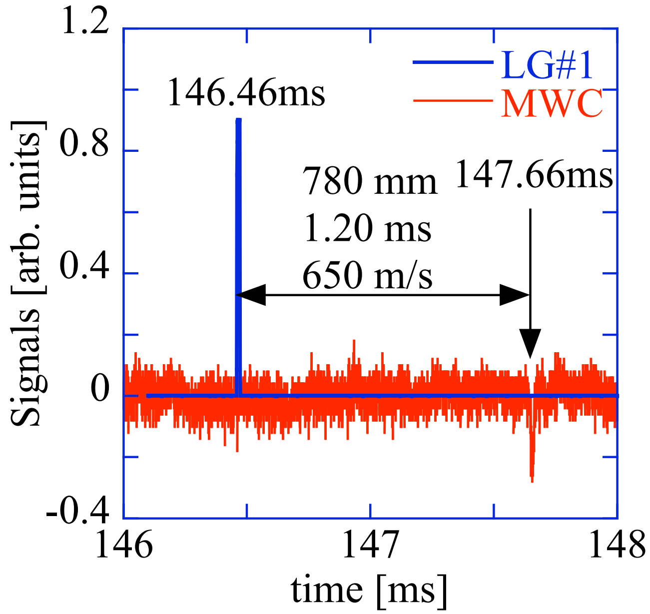
2-dimensional H_α detector arrays

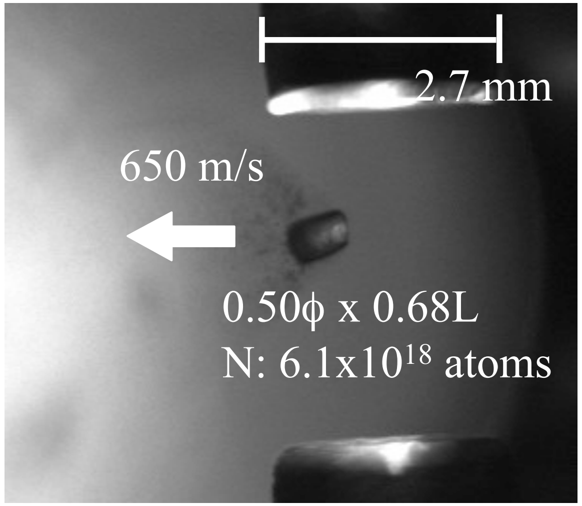


- H_α line emission detector: H_α interference filter, focusing lens, optical fiber and photomultiplier tube
- Installed position: Z = -1 cm, -71 cm and -141 cm
- Vertical (Z = -12 cm) and horizontal (Z = -52 cm) arrays are mounted to measure the radial profiles of H_α line emission.
- Each array has 12 channel detectors.
- These detectors are absolutely calibrated by a standard lamp.

5_Ejected Pellet Parameters

The signal of light gate (LG#1), that of microwave cavity and the shadowgraph of pellet obtained in the 1st and 2nd diagnostic stages

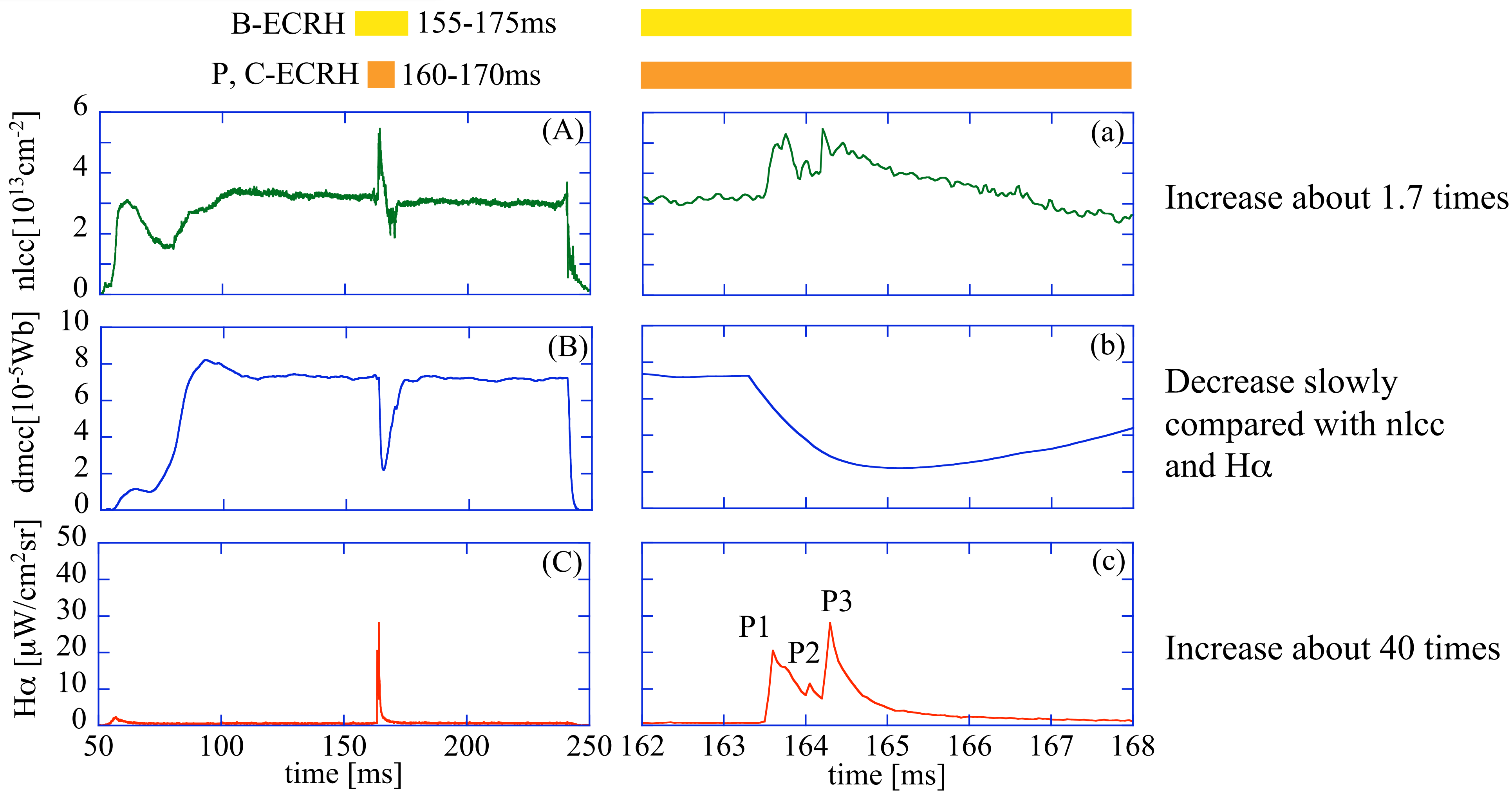




Pellet Parameters

- velocity: 650 m/s
- size and shape: cylinder, ϕ0.50 x L0.68
- number of atoms: 6.1×10^{18} atoms

6_Plasma Parameters

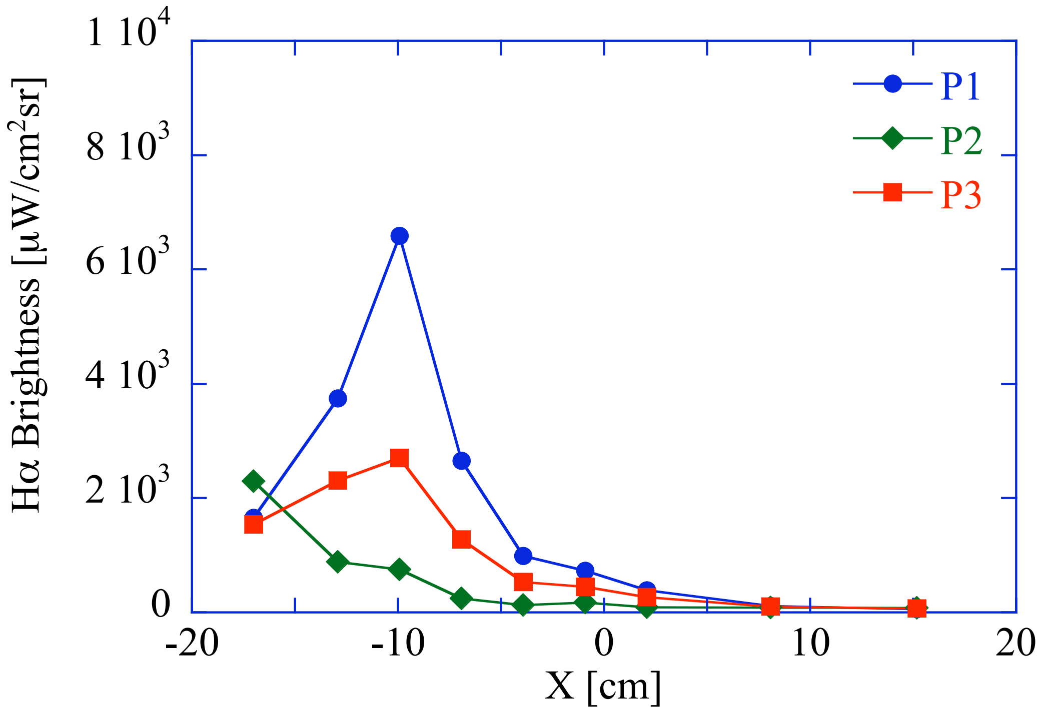


- The three pieces are defined pellet 1 (P1), pellet 2 (P2) and pellet 3 (P3).
- The velocities of each pellet are 610 m/s, 594 m/s and 586 m/s.

=> The pellet cracks into at least three pieces and slows down somewhere of the injection path.

7_H_α Profiles

The H_α brightness profiles at the each peak time measured by the vertical array of H_α line emission detector.

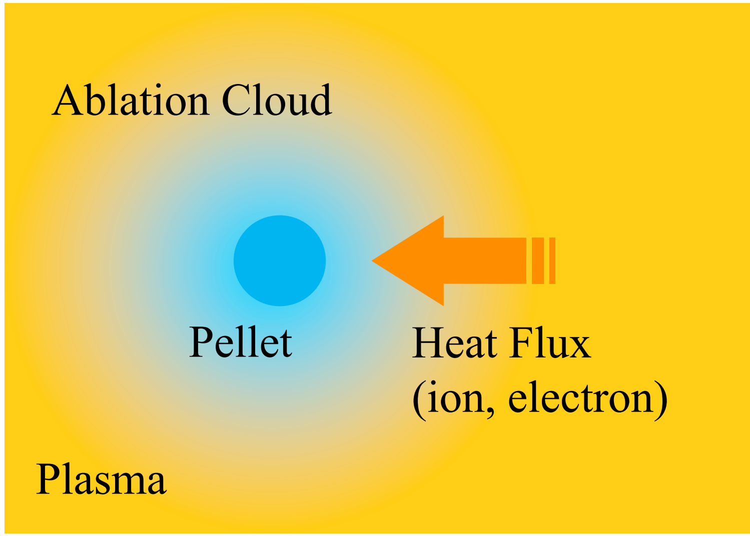


- H_α brightness profile is greatly changed by the pellet injection.
- The profile of X-direction has a peak in the peripheral region of the injection side.
- The peak value of these profiles reaches to about several thousands times before the pellet injection.

- The profiles of P1 and P3 have a peak about X = -10 cm.
- The profile shape of P1 is peaked and the peak value of P1 is large compared with that of P3.
- The profile of P2 has a peak near the edge of the plasma.

  => It is thought that these differences are based on pellet size, pellet velocity and plasma parameters.

8_Neutral Gas Shielding Model



Neutral Gas Shielding (NGS) model

- NGS model is a simple theoretical model to estimate the ablation rate of the pellet in the plasma.
- A neutral shielding cloud around the pellet is formed by the incident energy flux from background plasma.
- The 1-dimension spherically symmetric hydrodynamic model of the expansion in the ablation cloud is solved.
- The recession speed of the pellet surface (ablation rate) is given by the scaling laws.

Dominant heat flux: electron

$$\frac{dr_p}{dt} = 1.74\times10^{-6} n_e^{1/3} E_e^{1/6} L(E_e)^{1/3}\left[E_e + 8.5\times10^{-4} E_e^{2} - 850 E_e^{-1} + 75\right] r_p^{-2/3}$$

r_p : radius of pellet
$L(E_e)$: energy loss function

Dominant heat flux: ion

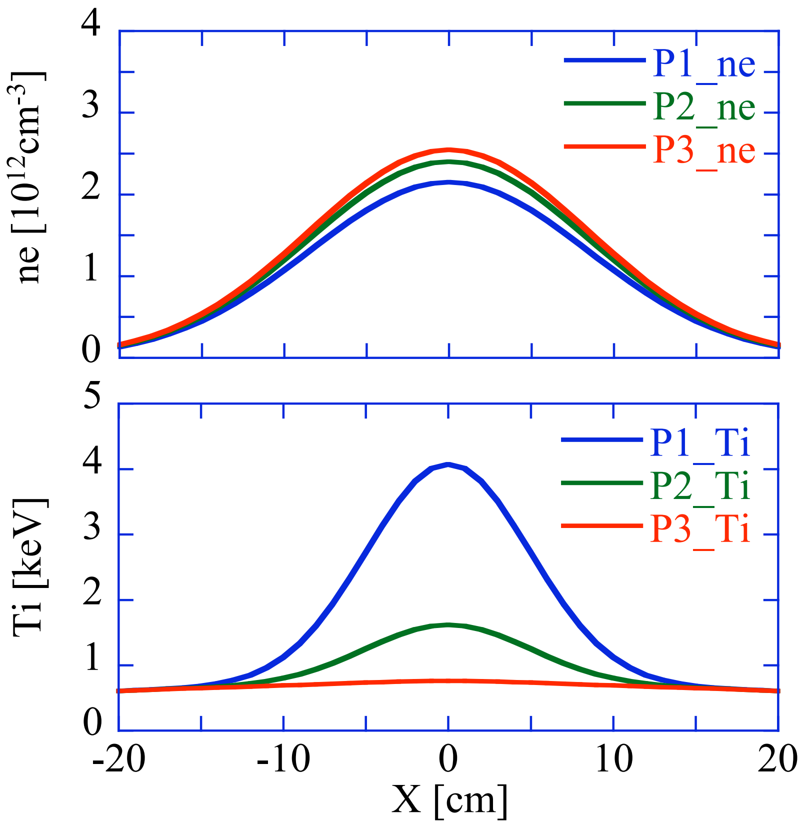
$$\frac{dr_p}{dt} = 4.55\times10^{6} \rho_s^{-1} m^{2/3} \left(G_i n_i\right)^{1/3} E_i^{0.9} r_p^{-2/3}$$

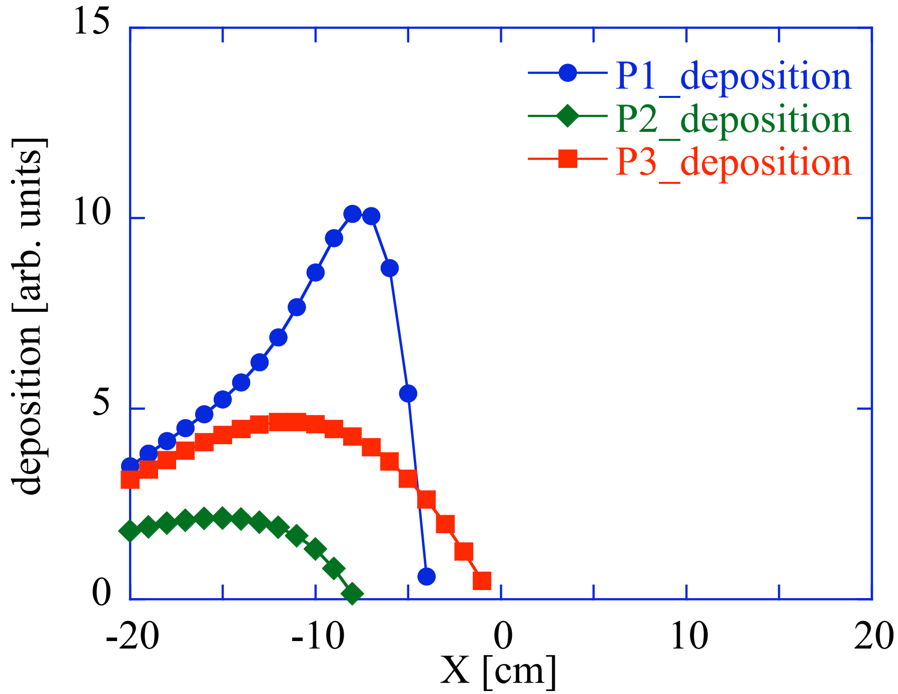
$G_i = 1/2\cdot(e/\pi m_i)^{1/2}$
r_p: radius of pellet
ρ_s: mass density of solid hydrogen

In this discharge: Dominant heat source is ion

9_Caluclation Results of NGS Model

The pellet ablation is calculated from the plasma parameters and the scaling law of NGS model.





Calculation parameters

	$n_e(0)$ [cm^{-3}]	Ti(0) [keV]	v_{pellet} [m/s]	ϕ [mm]
P1	2.15e12	4.1	610	0.44
P2	2.40e12	1.6	594	0.26
P3	2.55e12	0.76	586	0.38

10_Discussion

In the calculation of NGS model:

• Assuming that the profile shape of the plasma is the Gaussian, the electron density and ion temperature profiles are obtained by the line-integrated electron density and diamagnetism.

• The pellet velocity is known from the experimental results.

• The pellet size is decided to almost agree the peak position of the deposition and that of H_α brightness.

From the calculation and experimental results:

• The pellets cannot reach to upper side ($X > 0$) of the plasma.

=> The increase of H_α brightness in upper side of the plasma is caused by the hydrogen gas ablated from the pellet.

• The total number of particles included in P1, P2 and P3 is 3.8×10^{18} atoms.

=> This is about 62% of the number of particles included in the pellet just after the ejection.

=> The other particles are lost in the injection path or injected to the plasma as the small piece.

• Although the pellet size of P3 is smaller and the velocity of P3 is slower than those of P1, the penetration depth of P3 is larger than that of P1.

=> This situation is occurred by the change of the plasma parameters, especially ion temperature, caused by the injection of P1 and P2.

11_Summary

• In GAMMA 10, hydrogen pellets are injected with ECRH at the plug/barrier and central cells for the purpose of producing high performance plasma discharges.

• From the experimental results:
  - The electron density increases about 1.7 times.
  - The diamagnetism decreases slowly compared with the c the electron density and the H_α brightness.
  - H_α brightness increases quickly and the peak brightness increases about 40 times.
  - There are three peaks in the temporal behavior of the electron density and H_α brightness.

    => We discuss about these three pieces based on the experimental results and NGS model.

• In the discussion:
  - The pellets cannot reach to upper side ($X > 0$) of the plasma.

    => The increase of H_α brightness in upper side of the plasma is caused by the hydrogen gas ablated from the pellet.
  - The total number of particles included in P1, P2 and P3 is 3.8×10^{18} atoms.

    => This is about 62% of the number of particles included in the pellet just after the ejection.
  - Although the P3 is smaller and slower than P1, the penetration depth of P3 is larger than that of P1.

    => This situation is occurred by the change of the plasma parameters caused by P1 and P2.