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Modeling of Plasmas and Neutrals Including Plasma-Wall Interaction for Long Term Tokamak Operation

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1. Background/Motivation (1)

- **Density control** of the **core/main plasma** in future fusion reactors like **ITER/DEMO** is one of the **critical issues**, especially **for** their **long term operation**.

- **Metal plasma facing materials** (**PFM**s) are expected to be one of the promising **candidates** for such **future fusion power plants**.

- Recently, **experimental studies** :

  the **effects** of the **long time scale plasma – PFM wall interaction on** the main **plasma density** and **its control** have been done in the **QUEST** tokamak [1,2,3].

⇨ suggest that the **wall H atom-inventory play a key role !**

[1] K. Hanada, et al., Nucl. Fusion **57**(2017)126061.
[2] K. Hanada, et al., Plasma Science and Technology **18**(2016) 1069.
[3] T. Honda, Department of Advanced Energy Engineering Science, Kyushu University, Master's thesis (2014).

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1. Background/Motivation (2)

- The **purpose of this study** is
  to develop a simple plasma and neutral model which
  includes the long term plasma-wall interaction, especially
  the interaction between the **plasma** and **metal PFMs**

- in order to understand **basic characteristics of the long term behavior**
  of **particle balance in the overall system including :**

  a) **Main Plasma, b) SOL/Divertor/Limiter Plasma, c) Wall**

- **Conventional 2D/3D Edge plasma-neutral code**
  (e.g. SOLPS(B2.5-Eirene), EDGE2D, UEDGE, SONIC) is **too massive**
  to simulate **for such a long time dynamics of the system**

adopt **zero-dimensional (0D) approach** taking into account
the profile effect from the 2D/3D code results

2. Model (1) : Basic Model Concept

Particle Balance model for the **overall system**:

(a) Main Plasma, (b)SOL/Divertor/Limiter Plasma, (c)Wall

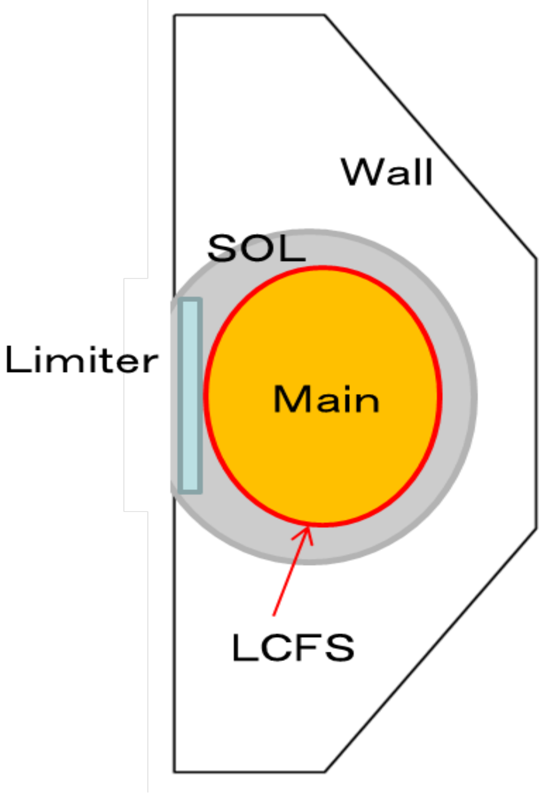


Fig.1 Schematic drawing of the **model geometry**
(**QEST limiter configuration**)

Particle Species
in the System

i) **Plasma:**
elec.,H^+,H_2^+,H_3^+
ii) **Neutrals**
H_2, H
iii) **Wall**
Material

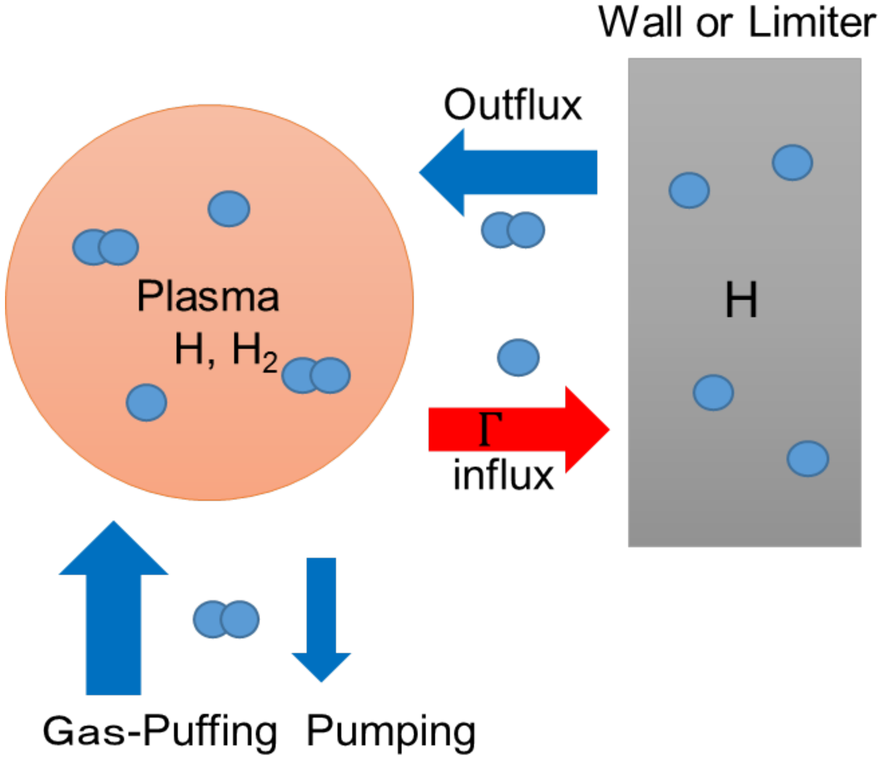


Fig.2 Overall **concept of the present model**

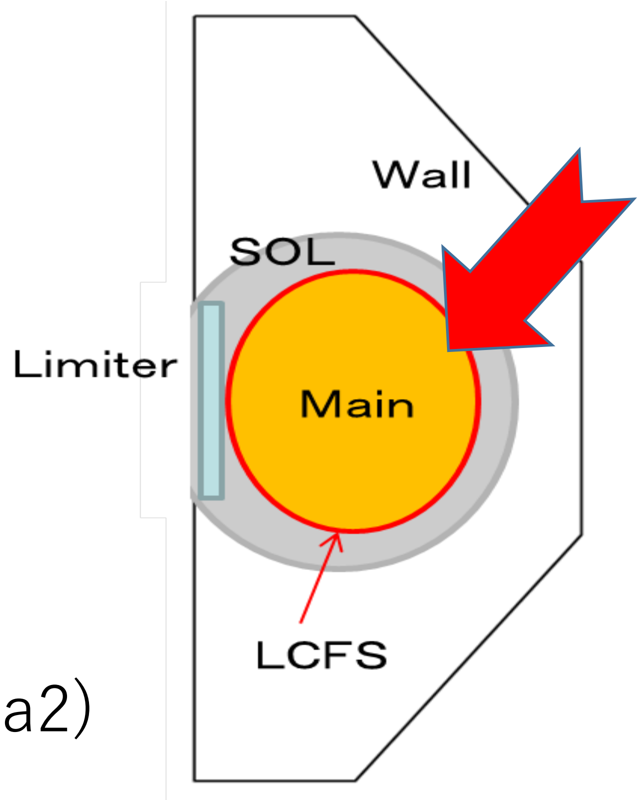
2. Model : Plasma Model (1)

(1a) Main Plasma

$$\frac{d\bar{n}_M}{dt} = -\frac{\bar{n}_M}{\tau_M} + \bar{S}_M, \qquad (1a1)$$

Plasma transport loss across the magnetic field line

Plasma ionization Source in the main plasma



$\bar{n}_M$: Volume averaged **plasma density** $\bar{n}_M = \frac{1}{V_M}\int_{V_M} n_M dV$ (1a2)

$\bar{S}_M$: Volume averaged **ionization source** $\bar{S}_M = \frac{1}{V_M}\int_{V_M} S_M dV$ (1a3)

τ_M : the particle **confinement time** of main plasma

$$\tau_M \equiv \frac{a^2}{2\alpha_M D_M} \qquad (1a4)$$

a : Minor radius of tokamak

D_M : Diffusion coefficient across B

α_M : **profile factor** which relates the density at the LCFS n_{LCFS} with the volume averaged density $\bar{n}_M$

$$n_{LCFS} = \alpha_M \bar{n}_M \qquad (1a5)$$

2. Model : Plasma Model (2)

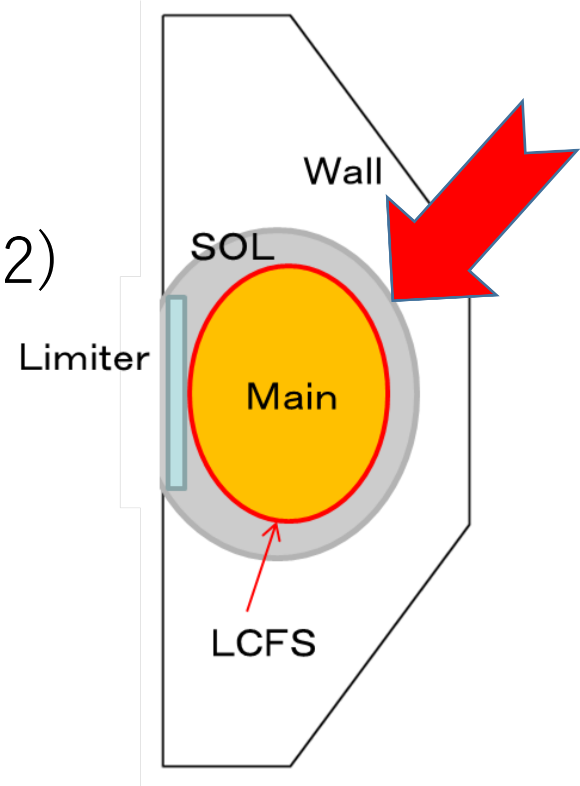
(1b) SOL/Limiter Plasma

$$\frac{d\bar{n}_{SOL}}{dt} = (1-f_{wall})\bar{S}_{Diff} - \frac{\bar{n}_{SOL}}{\tau_{//}} + \bar{S}_{SOL}, \quad (1b1) \qquad \bar{S}_{Diff} = \frac{\bar{n}_M}{\tau_M} \quad (1b2)$$

Plasma Source from the main plasma

Plasma loss along the magnetic field line

Recycling Source from the limiter plate



$\bar{n}_{SOL}$: Volume averaged **plasma density** in **the SOL/Limiter** region

$$\bar{n}_M = \frac{1}{V_M}\int_{V_M} n_M dV \quad (1b3)$$

$\bar{S}_{Diff}$: **Diffusion source** from the main plasma across the LCFS

f_{wall} : **fraction** of $\bar{S}_{Diff}$ **to the wall**

$\bar{S}_{SOL}$: Volume averaged **ionization source**

$$\bar{S}_{SOL} = \frac{1}{V_{SOL}}\int_{V_{SOL}} S_{SOL} dV \quad (1b4)$$

$\tau_{//}$: the plasma **confinement time** in the SOL region

$$\tau_{//} = \frac{L_{//}}{2\alpha_{SOL} C_s} \quad (1b5)$$

$L_{//}$: SOL connection length along B-field

C_s : Ion sound speed along B-field

α_{SOL} : **profile factor** which relates the density in front of the limiter plate n_{LIM} with the volume averaged density $\bar{n}_{SOL}$:

$$n_{LIM} = \alpha_{SOL}\bar{n}_{SOL} \quad (1b6)$$

2. Model : Neutral Model (1)

(2a) H2 Molecules

$$\frac{d\bar{n}_{H_2}}{dt} = \underline{\bar{S}_{H_2}^{Gas\text{-}Puff}} + \underline{\bar{S}_{H_2}^{Wall/Lim}} + \underline{\bar{S}_{H_2}^{gain} - \bar{S}_{H_2}^{loss}} - \underline{\bar{S}_{H_2}^{Pump}} - \underline{\frac{\bar{n}_{H_2}}{\tau_{H_2}}} \qquad (2a1)$$

Gas-puffing source

Recycling source from the Wall and Limiter

Discuss later in the wall model

Gain and Loss due to **H2 reactions in the gas phase**

Table 2.1 Main reactions taken into account

Gas-pumping sink

Neutral transport loss

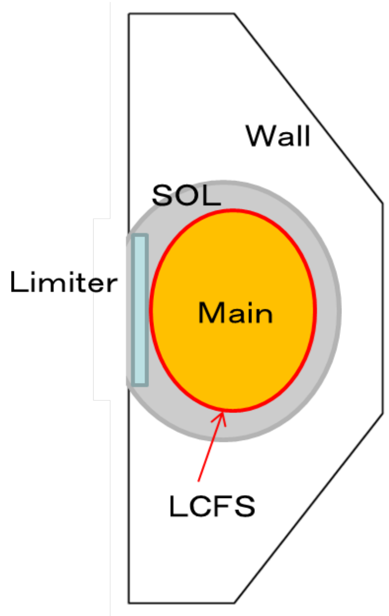
$$\tau_{H_2} = \frac{(V_V / A_V)}{\alpha_{H2} v_{H2}} \qquad (2a2)$$

V_V : Volume of vacuum vessel

A_V : Surface area of vacuum vessel

α_{H2} : Profile factor

v_{H2} : average speed of H2 molecules



Profile effect is taken into account by the 2D neutral transport simulation

2. Model : Neutral Model (2)

(2b) H atom in gas phase

$$\frac{d\bar{n}_H}{dt} = \bar{S}_H^{gain} - \bar{S}_H^{loss} - \bar{S}_H^{CX} - \frac{\bar{n}_H}{\tau_H} \qquad (2b1)$$

Gain and Loss
due to **H reactions in the gas phase**

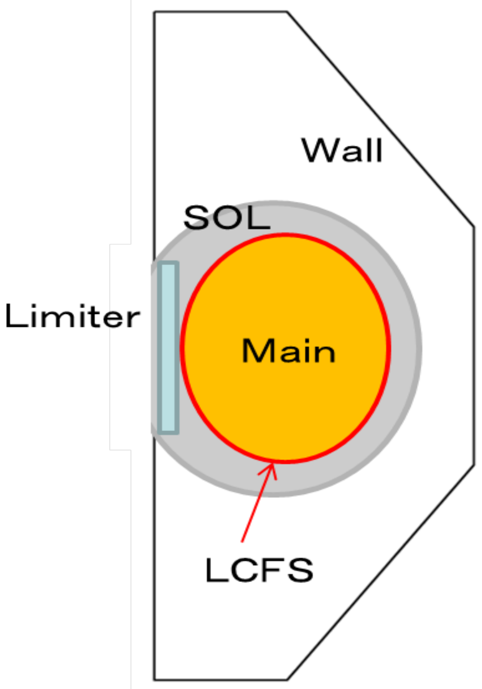
Table 2.1
Main reactions taken into account

CX loss

Neutral transport loss

$$\tau_H = \frac{(V_V / A_V)}{\alpha_H v_H} \qquad (2b2)$$

V_V : Volume of vacuum vessel
A_V : Surface area of vacuum vessel
α_H : Profile factor
v_{H2} : average speed of H atoms



Profile effect is taken into account by the 2D neutral transport simulation

2. Model : Neutral Model (3)

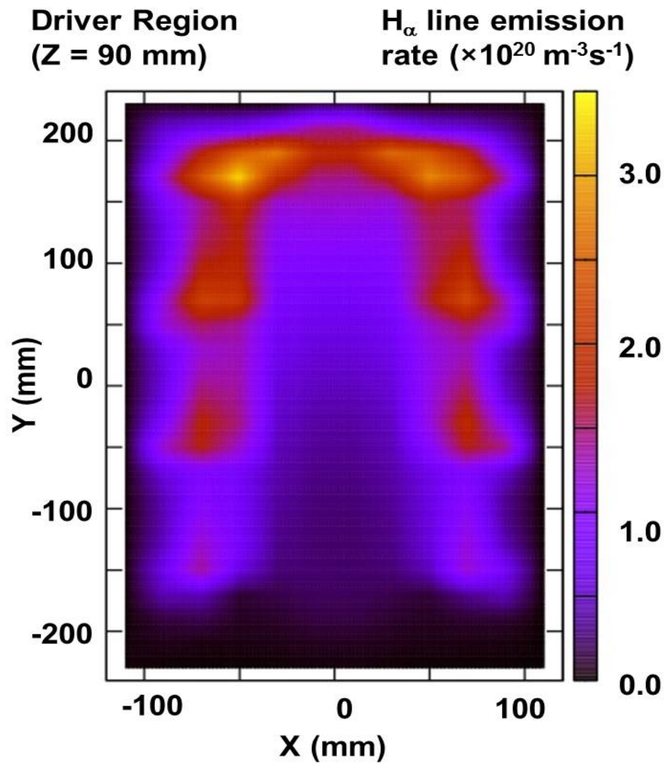
Table 2.1 Main reactions taken into account in the model.

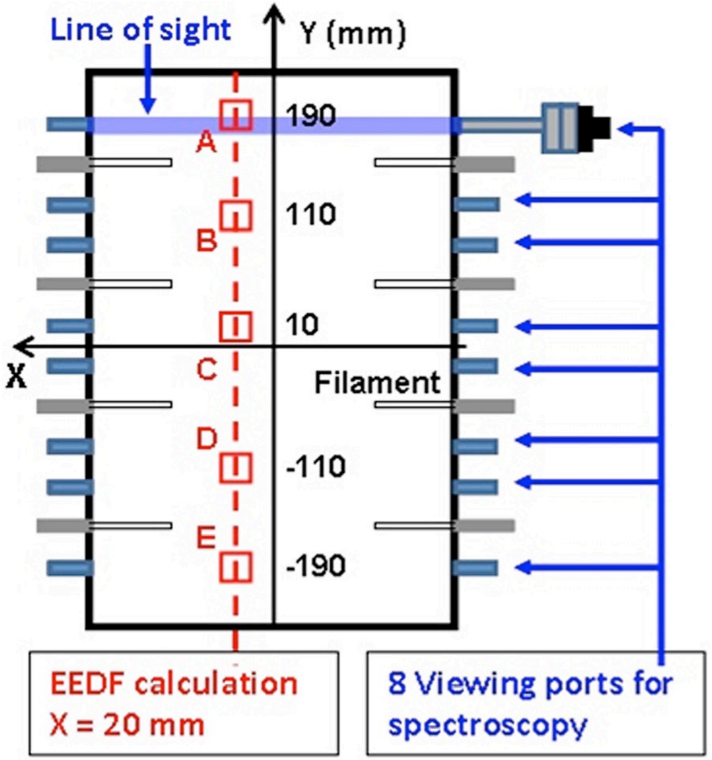
Reaction	Eq.
H ionization	$H(p) + e \rightarrow H^+ + 2e$
H_2 dissociation	$H_2\ (v) + e \rightarrow 2\,H + e$
H_2 ionization	$H_2\ (v) + e \rightarrow H_2^+ + 2e$
H_2 dissociative ionization	$H_2 + e \rightarrow H + H^+ + 2e$
H_2^+ dissociation	$H_2^+ + e \rightarrow H + H^+ + e$
H_2^+ dissociative recombination	$H_2^+ + e \rightarrow 2H$
H_3^+ dissociative recombination	$H_3^+ + e \rightarrow 3H\ (\text{or } H_2 + H)$
H_3^+ dissociative recombination	$H_3^+ + e \rightarrow 2\,H + H^+ + e$
H, H^+ charge exchange	$H + H^+ \rightarrow H^+ + H$
H_2, H^+ charge exchange	$H_2 + H^+ \rightarrow H_2^+ + H$
H_3^+ production	$H_2 + H_2^+ \rightarrow H_3^+ + H$
H ionization by H^+	$H + H^+ \rightarrow 2H^+ + e$
H_2^+ dissociative ionization	$H_2^+ + e \rightarrow 2H^+ + 2e$

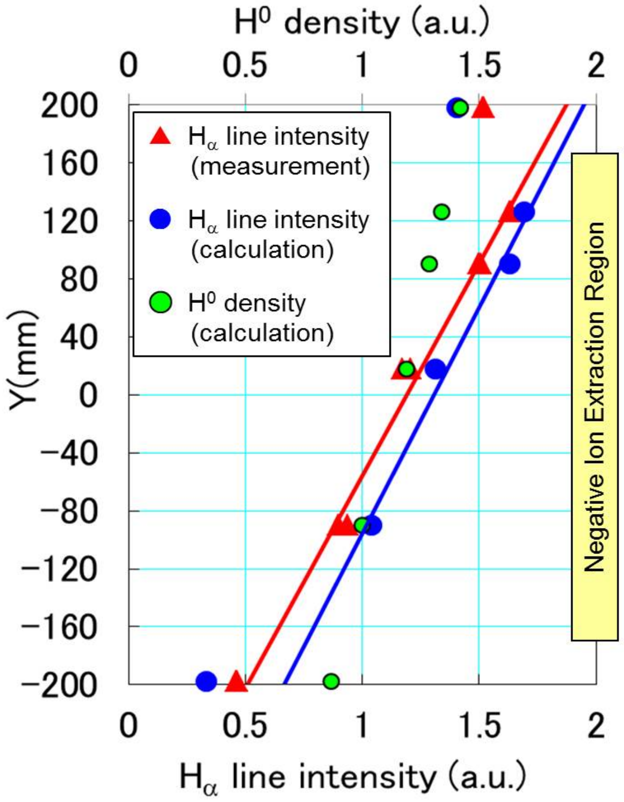
2. Model : Neutral Model (4)

In addition to the ground-state atom modeled above, we solve a system of simultaneous rate equations for **the population density of excited atoms** with the **quasi-steady state collisional-radiative model (QSS-CR) to compare the Hα intensity measured in the experiments.**

T. Shibata, et al, J. Appl. Phys. 114 (2013)143301.







Model validations of the QSS-CR model have been **already done in several H^- ion sources** (QST 10A H^- source, CERN Linac4 H^- source, ⋯ etc.)

2. Model : Wall & Limiter Model (1)

(3a) Wall

$$\frac{d\bar{n}_{Wall}}{dt} = \underline{\frac{\Gamma_{Wall}}{d_{Wall}}} - \underline{\frac{2k_{Wall}}{d_{Wall}}\bar{n}_{Wall}^{2}} \quad (3a1)$$

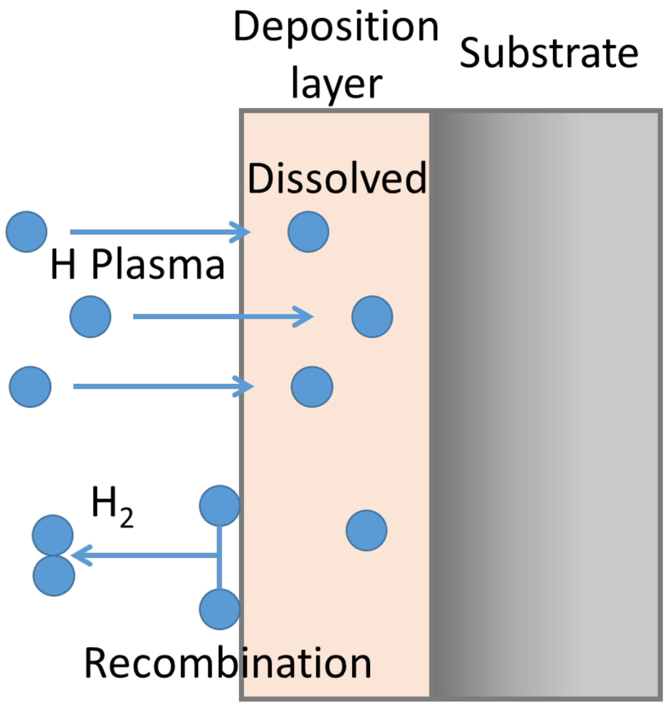
$\bar{n}_{Wall}$: H atom wall-inventory (in the re-deposition layer)

Plasma in-flux to the wall

H2 out-flux from the wall

k_{Wall} : **H atom recombination rate** in the re-deposition layer

d_{Wall} : **thickness of the re-deposition layer**



$$\Gamma_{Wall} = \underline{f_{wall}\Gamma_{LCFS}\left(\frac{A_{LCFS}}{A_{Wall}}\right)} + \underline{\frac{A_{Wall}}{A_{Wall}+A_{Lim}}\bar{S}_{H}^{CX}\left(\frac{V_{M}}{A_{LCFS}}\right)} \quad (3a2)$$

Ion flux from the main plasma
Calculated by main plasma model Eq.(1a1)

CX H atom flux
Calculated by H atom model Eq.(2b1)

A_{LCFS} A_{Wall} A_{Lim} : Surface area of LCFS, Wall and Limiter, respectively

2. Model : Wall & Limiter Model (2)

(3b) Limiter $$\frac{d\bar{n}_{Lim}}{dt} = \frac{\Gamma_{//,\,Lim}}{d_{Lim}} - \frac{2k_{Lim}}{d_{Lim}}\bar{n}_{Lim}^{2} \qquad (3b1)$$

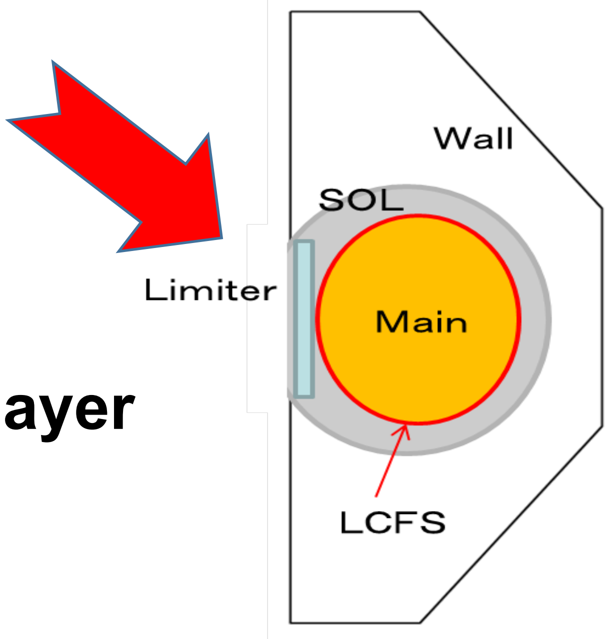
$\bar{n}_{Lim}$: H atom limiter-inventory (in the re-deposition layer)

Plasma in-flux to the limiter

H2 out-flux from the limiter

k_{Lim} : **H atom recombination rate** in the re-deposition layer

d_{Lim} : **thickness of the re-deposition layer**



$$\Gamma_{//,\,Lim} = \frac{\bar{n}_{SOL}}{\tau_{//}}\frac{V_{SOL}}{\alpha_{SOL}A_{Lim}} + \frac{A_{Lim}}{A_{wall}+A_{Lim}}\bar{S}_{H}^{CX}\left(\frac{V_{M}}{A_{LCFS}}\right) \qquad (3b2)$$

Ion flux from the SOL plasma
Calculated by SOL plasma model Eq.(2a1)

CX H atom flux
Calculated by H atom model Eq.(2b1)

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3. Initial Model Application to QUEST(1)

(1) Main Assumptions / Calculation Conditions

- **Low density** sheath limited **attached state in front of the limiter** has been assumed
- **Wall** and **Limiter Material** are **the same** for simplicity

Table 3.1 Device and Plasma Dimensions

Major radius :	R=0.68 m
Minor radius :	a=0.4 m
Volume of main plasma :	Vp=1.28m^3
Volume of vacuum vessel :	Vv=12.8 m^3
Surface area of vacuum vessel :	Av=26.5 m^2

Table 3.2 Gas puffing and pumping parameters

Gas puffing rate : 3.5x10^{18} /puffing for 10ms
Gas pumping rate : 1.7x10^{17} /s

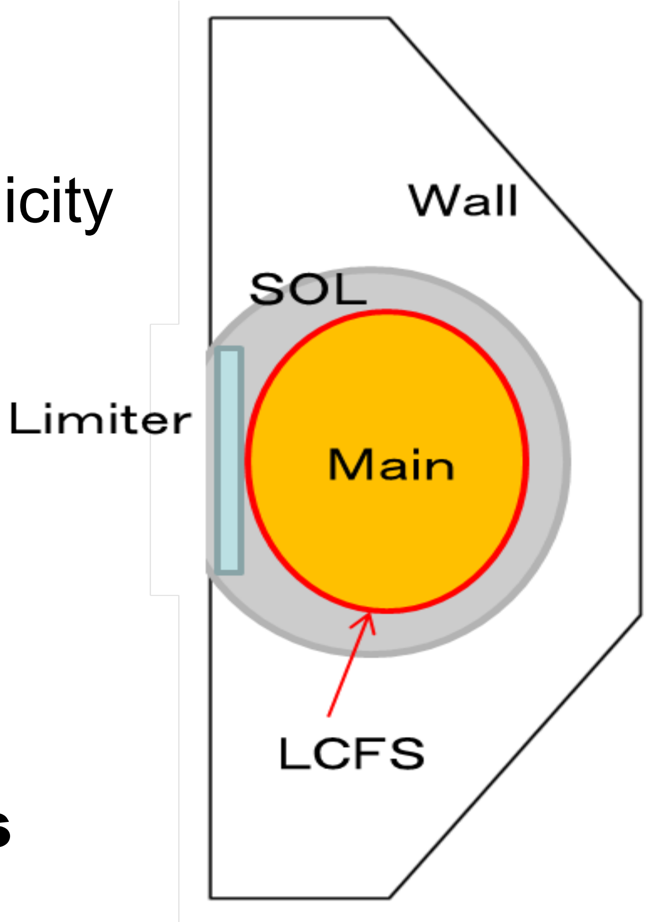


Fig.2 Schematic drawing of the model geometry (QEST limiter configuration)

3. Initial Model Application to QUEST(1)

Table 3.3 Initial density for each particle species

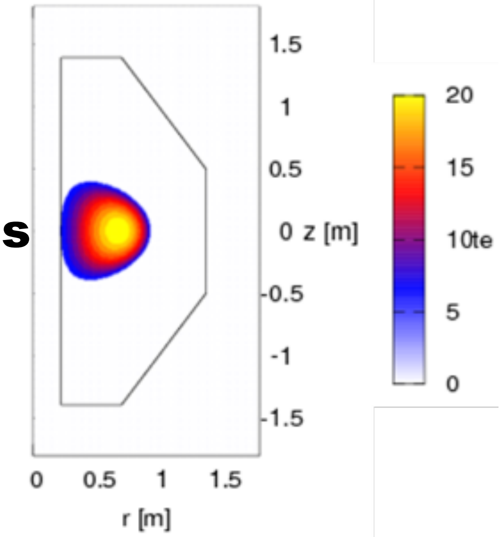
Plasma : $n_{\mathrm{e}} = n_{\mathrm{H^+}} = 1\times10^{17}\mathrm{m^{-3}}$,
H2 Molecule : $n_{\mathrm{H_2}} = 1\times10^{15}\mathrm{m^{-3}}$,
H atom : $n_{\mathrm{H}} = 1\times10^{10}\mathrm{m^{-3}}$
Plasma particle diffusion coeff. : $D = 0.3\ \mathrm{m^2/s}$

Table 3.4 Profile factor of plasma & neutral density

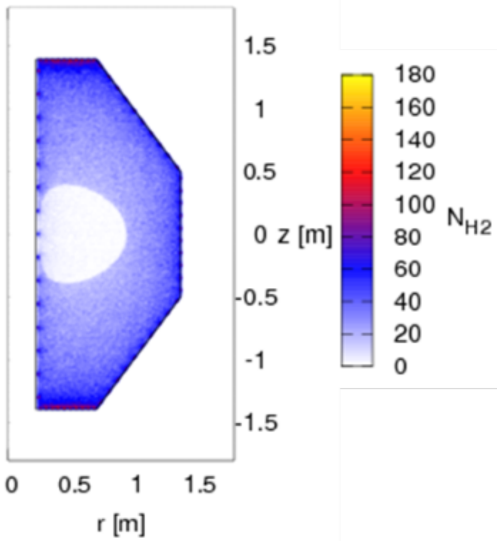
Plasma profile factor : $\alpha = 0.3$
Neutral profile factor for H_2 : $\beta = 0.1$

Table 3.5 Temperature for each particle species

Electron : $T_{\mathrm{e}} = 10\ \mathrm{eV}$
Ion : $T_{\mathrm{i}} = 1\mathrm{eV}$
H2 Molecule : $T_{\mathrm{H_2}} = 0.01\mathrm{eV}$
H atom : $T_{\mathrm{H}} = 0.1\mathrm{eV}$



2D T_e profile



2D H2 profile

Table 3.6 Wall parameters

H recombination coefficient for the wall : $k_{\mathrm{wall}} = 1\mathrm{x}10^{-38}\ \mathrm{m^4/s}$
Thickness of the re-deposition layer : $d_{\mathrm{wall}} = 50\ \mathrm{nm}$

3. Initial Model Application to QUEST(2)

(2) Time evolution of main plasma and wall parameters

T_e=10eV, T_i=1eV D=0.3 m^2/s

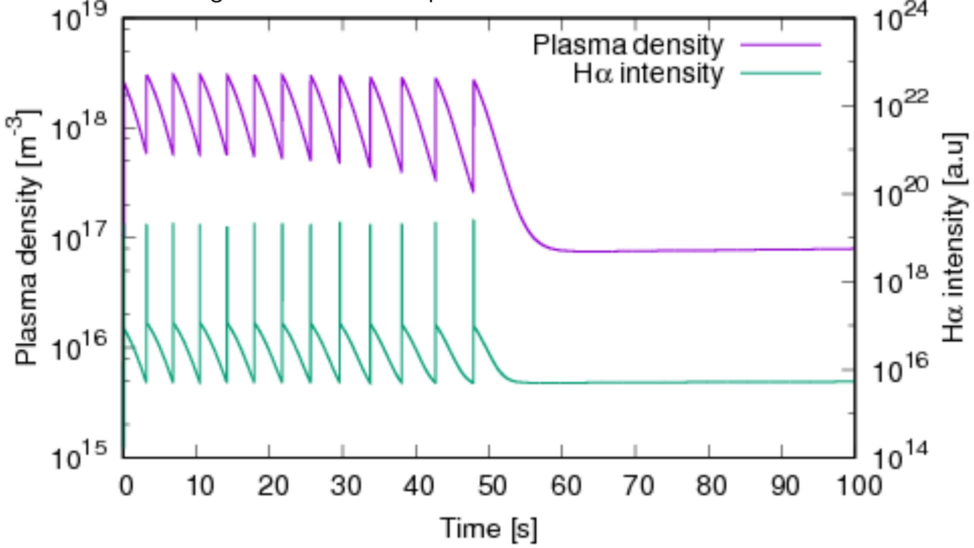


Fig. 3.1 (a) plasma density and Hα intensity

k_w=1.0x10^{-38} m^4/s

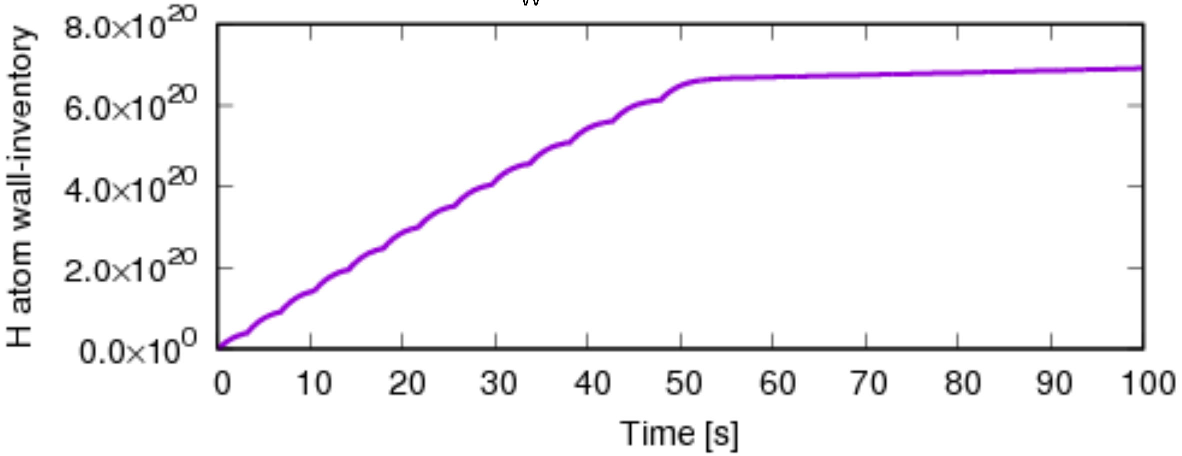


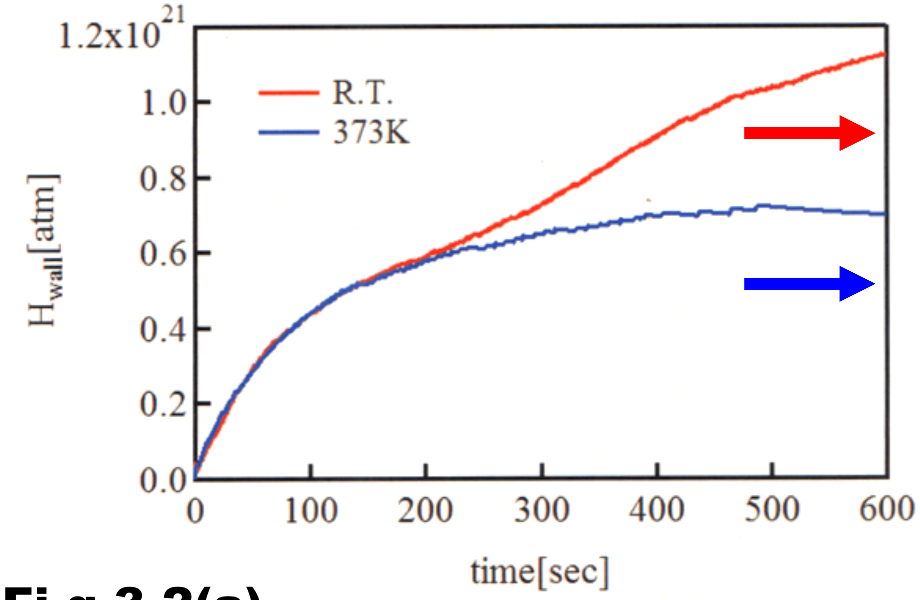
Fig.3.1 (b) Wall H atom-inventory

- **During early phase** $0 \le t \le 30$ s **before the saturation of the H atom wall-inventory frequency of gas puffing** (corresponding to the **rapid increase in Hα signal**) is **large**
- **After the saturation** of wall H atom inventory $t \ge 60$ s **Hα signal** is **almost constant** and the **plasma density** is **mainly sustained** by the **gas feed** from **the wall**.
- **Saturation level** of H-atom wall inventory **agrees with** that estimated **in the experiments** with **a reasonable value** of **wall recombination coefficient.**

3. Initial Model Application to QUEST(3)

(3) Comparison with the experiments
- Effect of the wall temperature on the H atom wall-inventory

Experimental results [3]

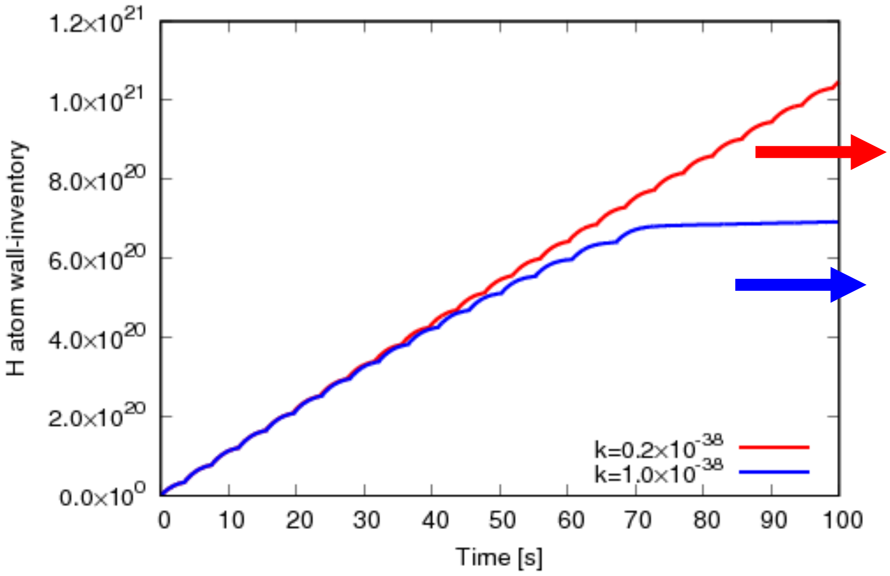


Low Wall Temp. : Room Temp

High Wall Temp. : 373K

Fi.g.3.2(a)

Modeling results



Fi.g.3.2(b)

Low Wall Temp.

kw= 0.2×10^{-38} m^4/s

High Wall Temp.

kw= 1.0×10^{-38} m^4/s

Modeling results reproduces basic trend of the **effect of the wall temperature on the H atom wall inventory** **with varying k_w** in **a reasonable range at the reasonable saturated values !**

- **Quantitatively, however, time to reach the saturation in the modeling** is relatively **short (~ 60 -70 s) compared with those (> 100s) in the modeling**

[3] T. Honda, Department of Advanced Energy Engineering Science, Kyushu University, Master's thesis (2014).

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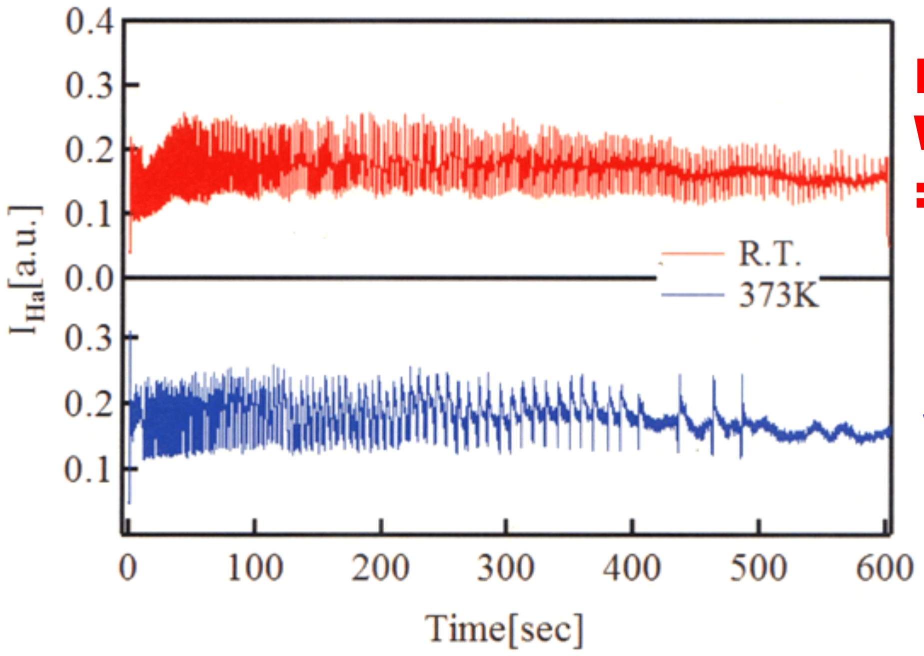
3. Initial Model Application to QUEST(4)

(3) Comparison with experiments : Time evolution of Hα signal

Experimental results [3]

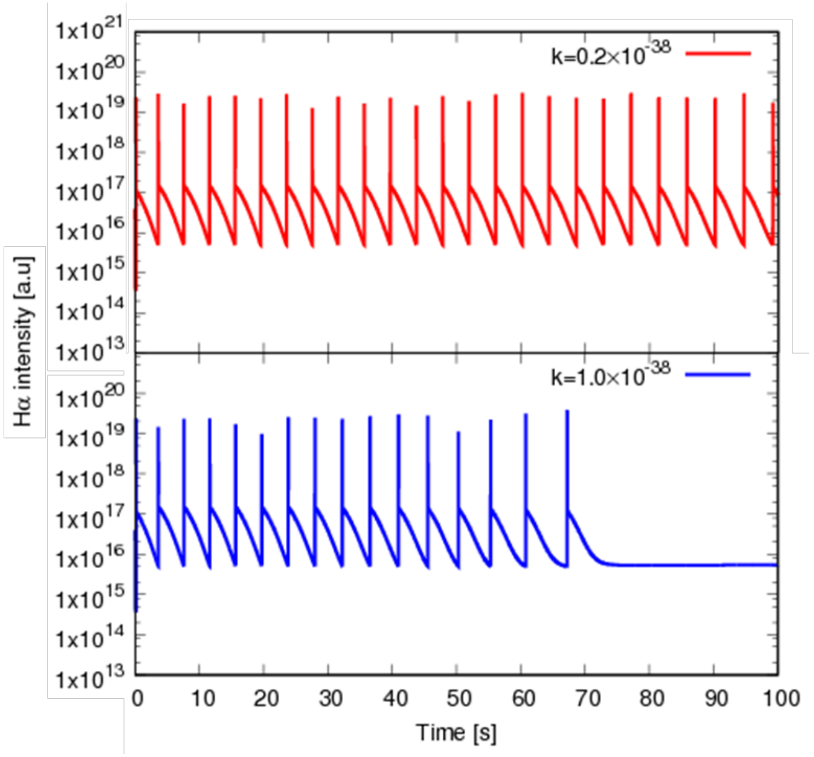


Low Wall Temp. : Room Temp.

High Wall Temp. : 373K

Fi.g.3.3 (a)

Modeling results



Low Wall Temp.

kw= 0.2x10^{-38} m^4/s

High Wall Temp.

kw= 1.0x10^{-38} m^4/s

Fi.g.3.3 (b)

Modeling results reproduces basic trend of Hα signal

- In **High Wall Temp. Case**, **Hα signal** becomes **almost constant more earlier than** in **Low Temp. Case** – **main plasma density is mainly sustained/controlled not by the external gas puffing, but by the wall out-flux after the saturation**

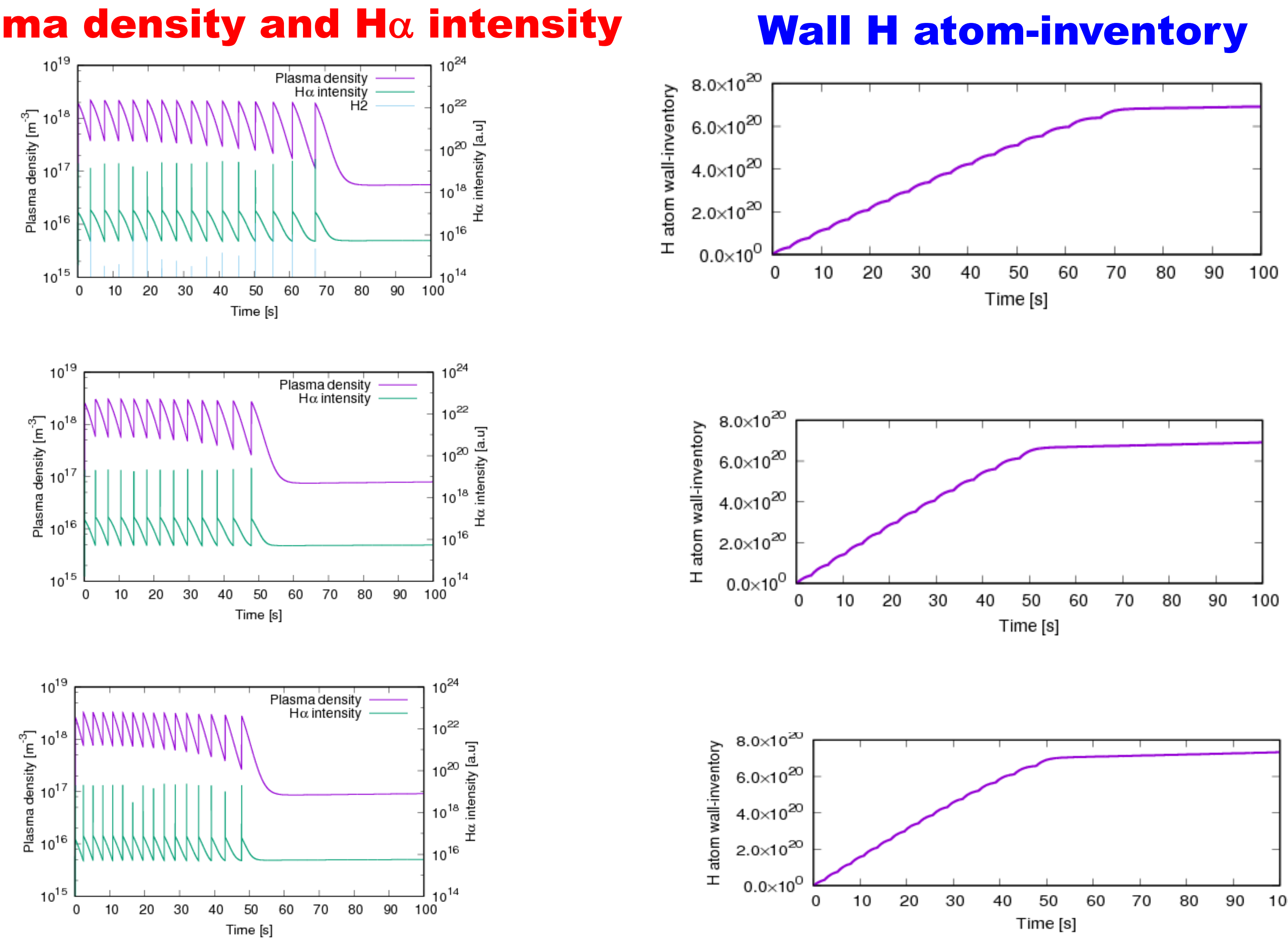
[3] T. Honda, Department of Advanced Energy Engineering Science, Kyushu University, Master's thesis (2014).

3. Initial Model Application to QUEST(6)

(4) Our model really robust ?

- Sensitivity analysis of the results on key assumptions/parameters – T_e

Fig.3.4



(a) T_e=10eV

(b) T_e=30eV

(c) T_e=50eV

3. Initial Model Application to QUEST(7)

(4) Our model really robust ?

- Sensitivity analysis of the results on key assumptions/parameters – *D*

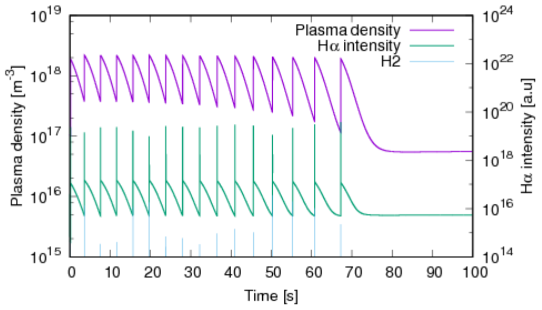
plasma density and Hα intensity

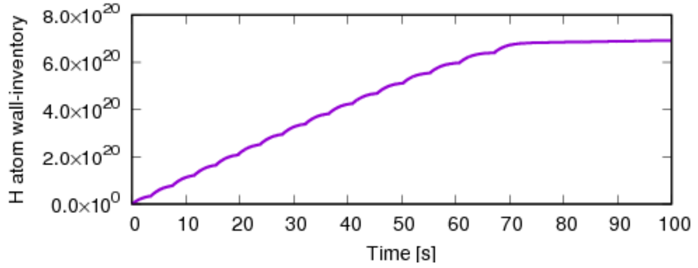
Wall H atom-inventory

Fig.3.6

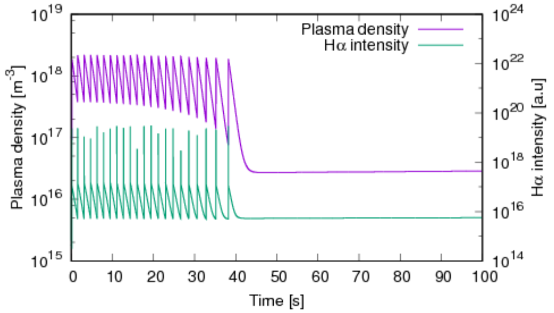
(a) D=0.3 m^2/s

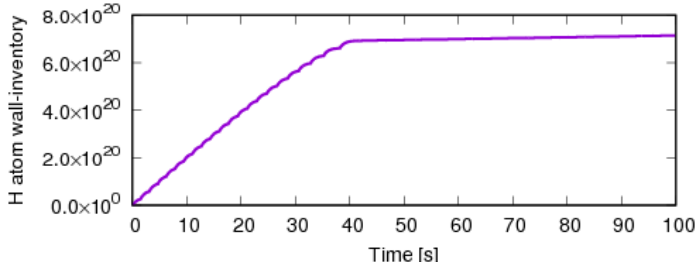
* typical value in most of 2D Edge Plasma simulations





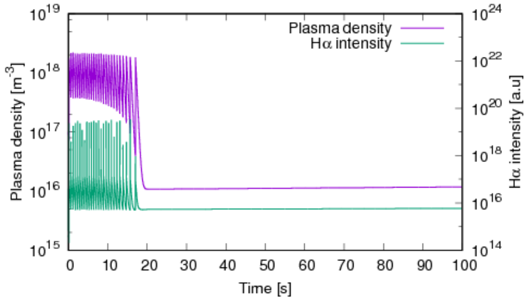
(b) D=0.6 m^2/s

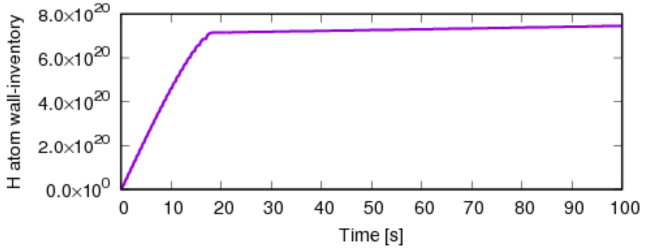




(c) D=1.2 m^2/s

* estimated by Bohm diffusion
D~(1/16)(Te/B)





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4. Summary & Future Problem (1)

- we have **developed** a simple **zero dimensional (0D) model** which consists of the **particle balance equations** for the following **three different particle species**:

  i) hydrogen **plasma** (elec. , H^+, H_2^+, H_3^+),
  ii) neutral hydrogen **atoms (H)** and **molecules(H_2)** in the **gas phase**
  iii) **wall-stored H atoms**.

- The **model** has been **applied** to **a long term operation (up to ~100-200 s)** with the limiter configuration in the **QUEST tokamak**.

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CALAMVS GLADIO FORTIOR 1858

4. Summary & Future Problem (2)

- **Modeling results** of the long time evolution (~ 100-200 s) **reasonably reproduce experimental tendencies**:

  - **Density feedback control** by **Hα signal and external gas puffing** is **efficient in the early phase** (<100s)
  - **For more long time scale** (>100s), the **particle balance** of the system is mainly **sustained**
    not by the **external particle source/pumping**,
    but by the **wall recycling source**.
  - Modeling results of the **H-atom wall inventory** **reasonably agree well** with those **in the experiments** **with a reasonable value of wall recombination coeff.**

4. Summary & Future Problem (3)

- However, **further model validation** and **improvement** will be needed:
  - **More Systematic sensitivity analysis of the results on the main assumptions and input parameters:**

    e.g. T_e, T_i, D, **profile factor from 2D/3D Edge simulation**, …

    As for the T_e, D, **the "*basic tendencies*" are *not so sensitive*** on these parameters, if we change these parameters **in the *reasonable range***: T_e ~10~50eV, D~ 0.3-1.2 m^2/s

- For **more long term phenomena** (~ several 100-1000s,) **further model improvement** will be necessary :

  e.g. taking into account **effects of the H trapping site in deposition layer**[1]

[1] K. Hanada, et al., Nucl. Fusion **57**(2017)126061. & this Conf.