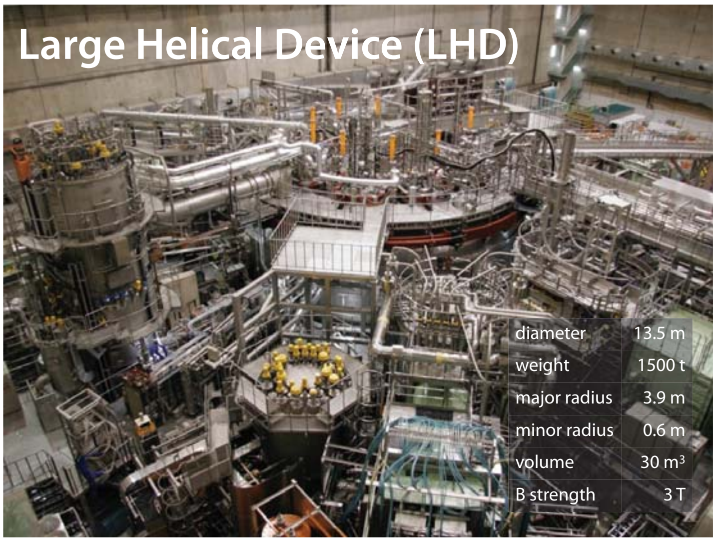
Two categories of spectroscopic measurements and analyses for the fusion plasma diagnosis

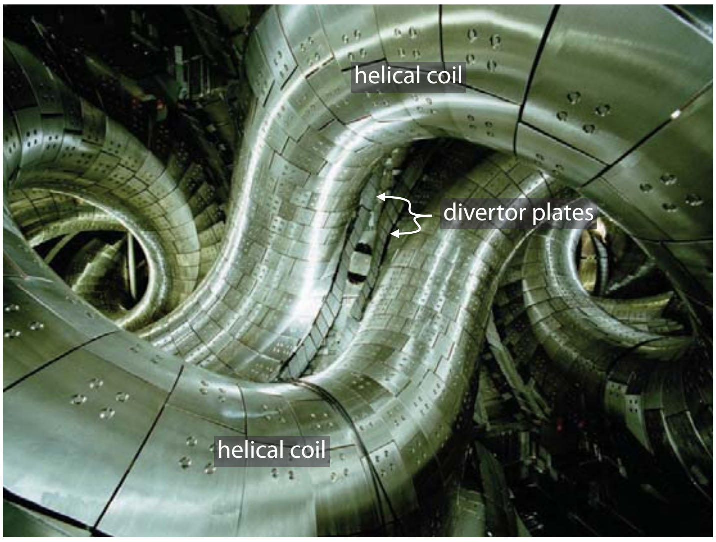
M. Goto[1], K. Sawada[2], K. Fujii[3], T. Oishi[1], M. Hasuo[3], and S. Morita[1]

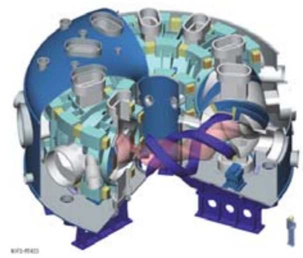
[1]*National Institute for Fusion Science*
[2]*Department of Applied Physics, Shinshu University*
[3]*Department of Mechanical Engineering, Kyoto University*

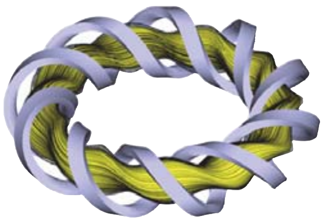
- spectroscopic diagnosis can be classified into two categories
- high wavelength resolution measurement
  - shift, broadening, splitting, etc.
- wide wavelength range measurement
  - intensity distribution of various emission lines, line intensity ratio, continuum

observable		obtainable	
shift		ion velocity	high resolution measurement
splitting	Zeeman	magnetic field	
	Stark	electric field	
broadening	Doppler	T_i	
	Stark	n_e	
intensity ratios intensity distribution		T_e, n_e ionizing or recombining	low resolution measurement
intensity		n_i	









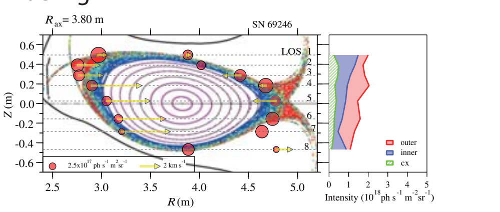
- heliotron-type device, i.e., no inductive plasma current
- advantageous for steady-state operation (no disruption)

achievements

T_e	20 keV
T_i	8 keV
n_e	10^{21} m^{-3}

H_α profile analysis

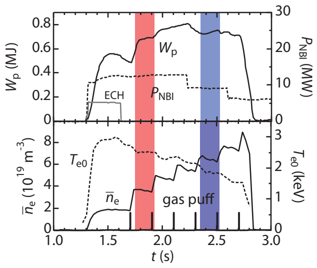
- dominant ionization location of hydrogen is outside LCFS, which means no direct contribution for fueling

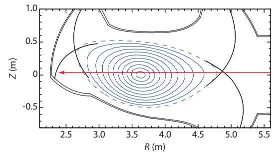


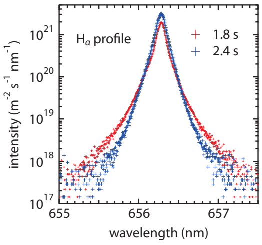
A. Iwamae, Physics of Plasmas **17**, 090701 (2010)

- nevertheless, n_e can be controlled by gas puff and detailed fueling mechanism is still unknown

- H_α line profile generally has a broad tail and is not expressed with single Gaussian function
- broad component is thought to originate in CX process between cold atoms and hot protons
- hot atoms should have taken over VDF, or temperature, of protons in CX process
- line profile can be understood as superposition of Gaussian profiles having different width, namely, at different locations in the plasma







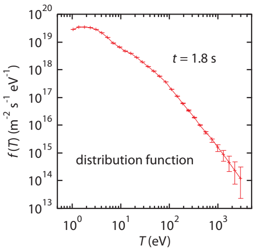
$$I(\lambda) = \int_0^{T_0} f(T) \frac{1}{\sqrt{\pi} w(T)} \exp\left[-\left(\frac{\lambda - \lambda_0}{w(T)} \right)^2 \right] dT$$

$$s = (\lambda - \lambda_0)^2$$
$$t = 1/w^2 = Mc^2/2kT\lambda_0^2$$
$$T_0 \to \infty$$

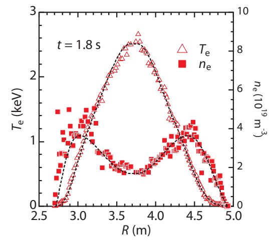
$$\mathscr{F}(s) = \int_0^{\infty} F(t) \exp(-st) dt \quad \text{(Laplace transform)}$$

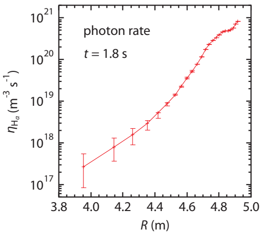
$$\left(F(t) = f(T) \frac{1}{\sqrt{\pi} w(T)} \frac{dT}{dt} \right)$$

$F(t)$ and then $f(T)$ are obtained by numerical inversion of the Laplace transform

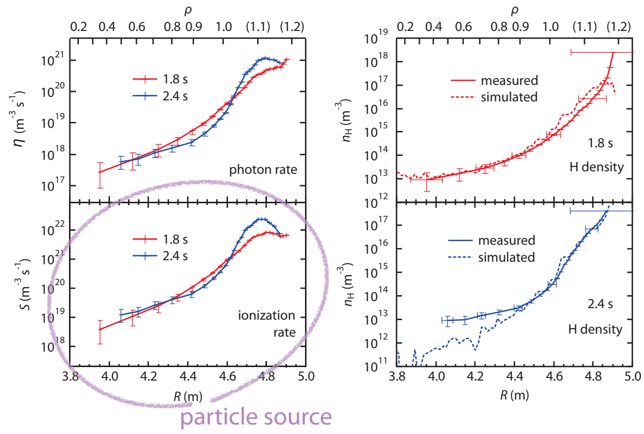


$$\eta(R) = f(T) \Bigg/ \left\{ \left| \frac{dR_{in}}{dT_e} \right|_T + \left| \frac{dR_{out}}{dT_e} \right|_T \right\}$$





under assumption of $T_i = T_e$



- particle confinement time, τ_p, is defined as

$$\tau_p(\rho) = \frac{\int^\rho n_e(\mathbf{r}) dV}{\oint^\rho \boldsymbol{\Gamma}(\mathbf{r}) \cdot d\boldsymbol{\sigma}} = \frac{\int^\rho n_e(\mathbf{r}) dV}{\int^\rho \nabla \cdot \boldsymbol{\Gamma}(\mathbf{r}) dV}$$

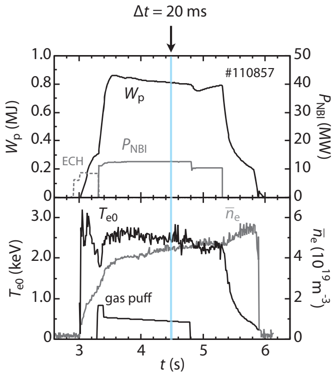
- from the continuity equation

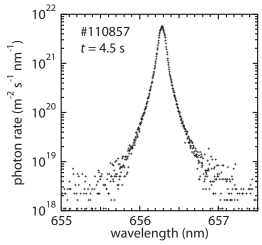
$$\frac{\partial n_e(\mathbf{r})}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}(\mathbf{r}) = S(\mathbf{r})$$

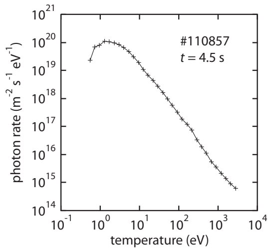
- volume-integration up to ρ gives

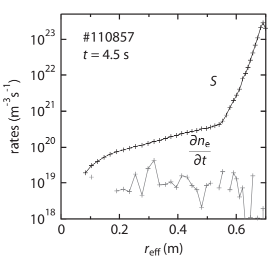
$$\tau_p(\rho) = \frac{\int^\rho n_e(\mathbf{r}) dV}{\int^\rho S(\mathbf{r}) dV - \int^\rho \frac{\partial n_e(\mathbf{r})}{\partial t} dV} \Rightarrow \frac{\partial}{\partial t} \int^\rho n_e dV$$

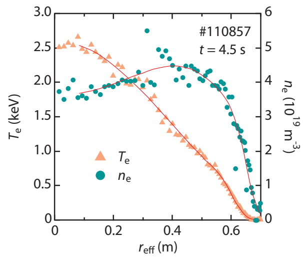
high field case
($B = 2.75$ T)

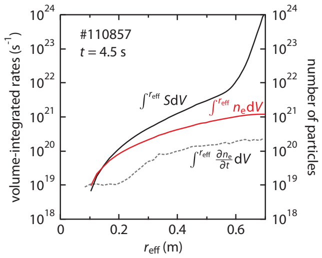


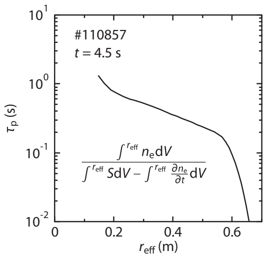




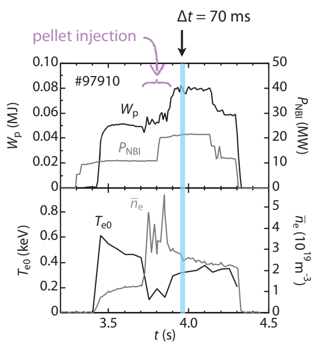


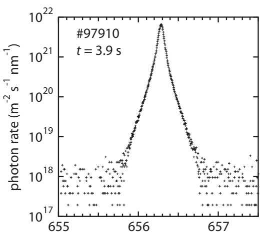


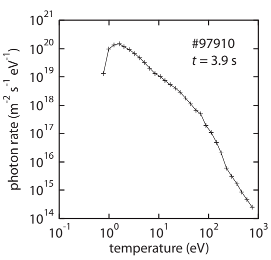


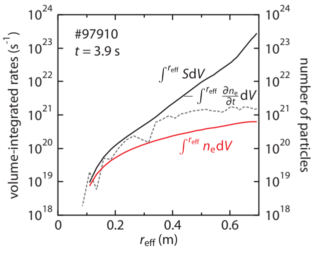


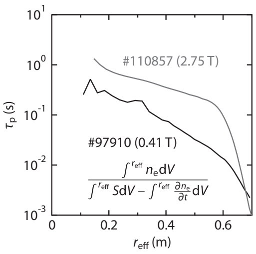
low field case
($B = 0.41$ T)



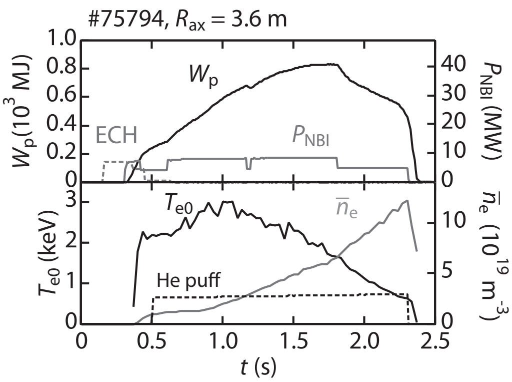






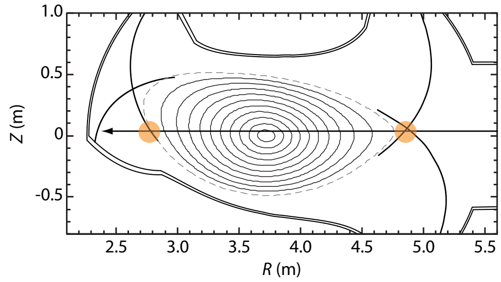


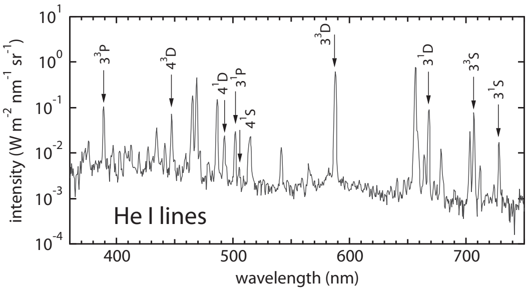
- in high field case, plasma boundary seems to be clearly seen
- τ_p is approximately one order smaller in low field case



Helium line intensity analysis

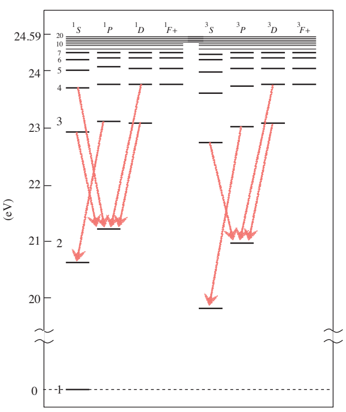
- definition of plasma boundary is difficult due to stochastic nature of the magnetic field structure
- helium line spectroscopy may gives information





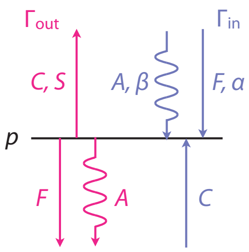
- excited level populations are determined from line intensities

$$\int_{\text{line}} I(\lambda)\mathrm{d}\lambda = h\nu n(p) A(p,q)$$



- collisional-radiative (CR) model calculates $n(p)$'s for given T_e and n_e
- T_e and n_e giving the best agreement with measured $n(p)$'s are sought
- CR model usually deals with only collisional and radiative transitions

collisional-radiative model



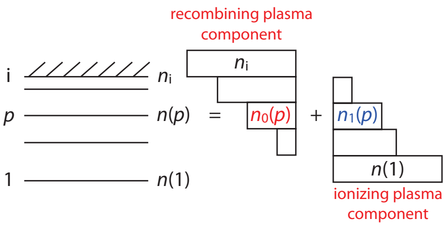
$$\frac{\mathrm{d}}{\mathrm{d}t}n(p) = \Gamma_{in} - \Gamma_{out} = 0$$

quasi steady-state approximation

$$\begin{pmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{pmatrix}\begin{pmatrix} n(2) \\ \cdot \\ n(p) \\ \cdot \end{pmatrix} = \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} n_i + \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} n(1)$$

$$\begin{pmatrix} n(2) \\ \cdot \\ n(p) \\ \cdot \end{pmatrix} = \begin{pmatrix} r_0(2) \\ \cdot \\ r_0(p) \\ \cdot \end{pmatrix} n_e n_i + \begin{pmatrix} r_1(2) \\ \cdot \\ r_1(p) \\ \cdot \end{pmatrix} n_e n(1)$$

$$n(p) = r_0(p) n_e n_i + r_1(p) n_e n(1) = n_0(p) + n_1(p)$$

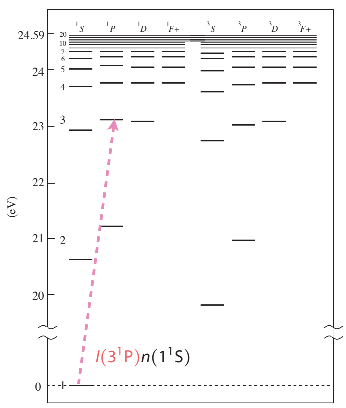


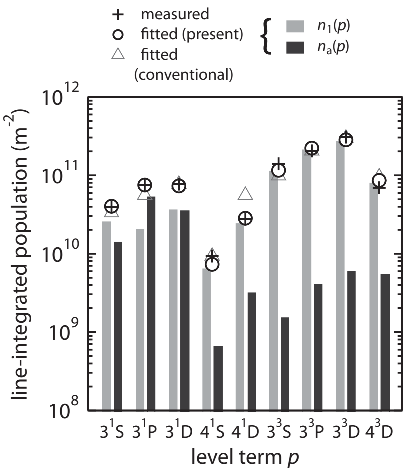
- reabsorption is taken into account in CR-model
- under CR-model scheme, $n(p)$ is expressed as

$$n(p) = R_1(p) n_e n(1^1\mathrm{S}) + R_a(p) I(3^1\mathrm{P}) n(1^1\mathrm{S}) = n_1(p) + n_a(p)$$

where $R_1(p)$ and $R_a(p)$ are each function of T_e and n_e

- fitting of $n(p)$ is made with parameters T_e, n_e, $I(3^1\mathrm{P})$, and $n(1^1\mathrm{S})$



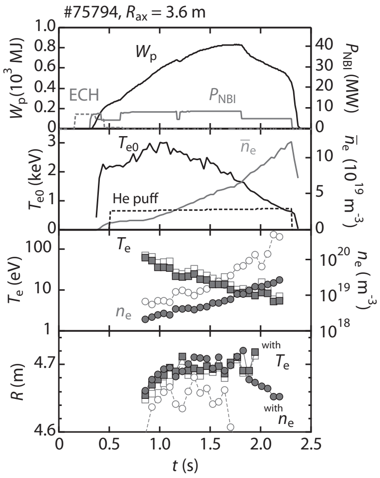


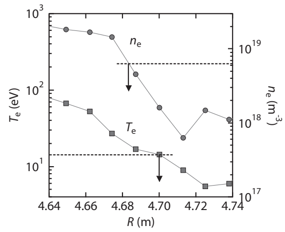
- present model

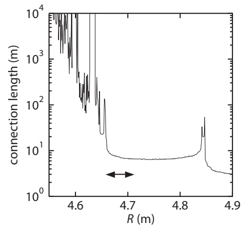
  T_e = 14 eV
  n_e = 6.3 x 10^{18} m^{-3}

- conventional

  T_e = 20 eV
  n_e = 2.0x10^{19} m^{-3}







Summary

- detailed H_α line profile analysis can be used for particle transport diagnosis in the plasma core region
- helium lines analysis with CR-model could give a definition of plasma boundary that is important to discuss the characteristics of the confinement
- use is still found for the conventional passive spectroscopy