

デタッチメント領域におけるプラズマ診断法 ～ダイバータ模擬装置MAP-II における開発事例～

Shinichiro KADO (門 信一郎), School of Engineering, The University of Tokyo

Contributors: 岡本敦 U-Tokyo (PD) --> Tohoku-U (~ 2005 LTS)
F. Scotti U-Tokyo -> PPPL, US (Ph-D) (~ 2007 LTS)
鈴木健二 U-Tokyo Master graduate. (~ 2009 Stark)

1) Introduction:

Detached recombining plasma

He I spectroscopy

2) Development of the LTS
for recombining plasmas

3) Development of the Doppler-
Stark Spectroscopy (He I).

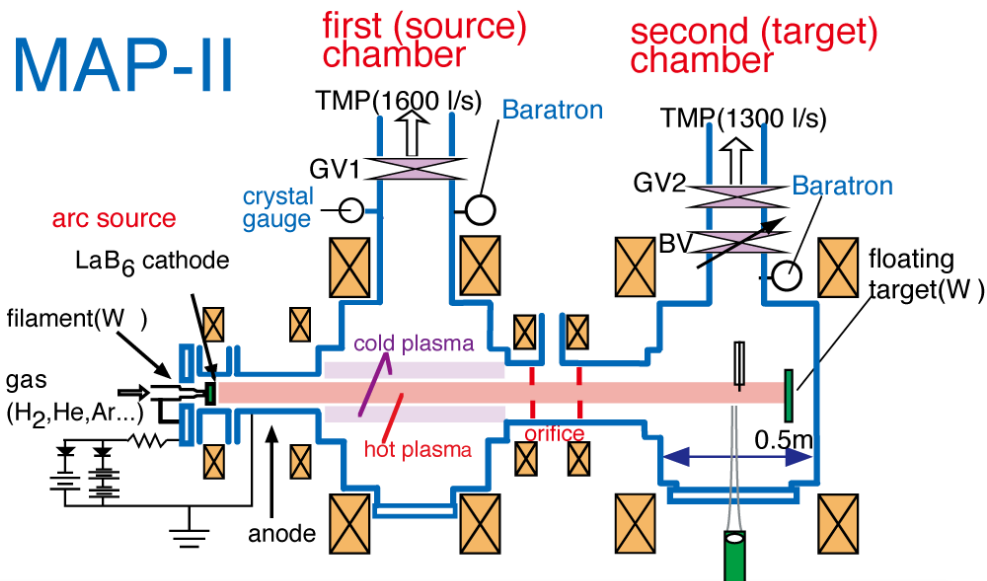
4) Results (LTS and OES)

He discharge (59 V, 30 A) , 80-180 mTorr
LTS observation @Source Chamber
(CF253 port)

Laser pass

20060324EIR_Thomson.MOV

MAP - II Divertor Simulator



S. Kado et al., *J. Plasma Fusion Res.* **81**, 810 (2005).

- 1st/source chamber: high n_e
Probe measurements are limited in low density operations. ---> LTS.
- 2nd/target chamber: good controllability
equipped with many diagnostics.
- Drift tube with two orifices:

- arc source

Cathode: LaB₆ disk
(ϕ 30 mm with a hole ϕ 5mm)

Anode: Pipe

Discharge ~ 60-100 V
30-45 A,

Ballast resistor 1 Ω

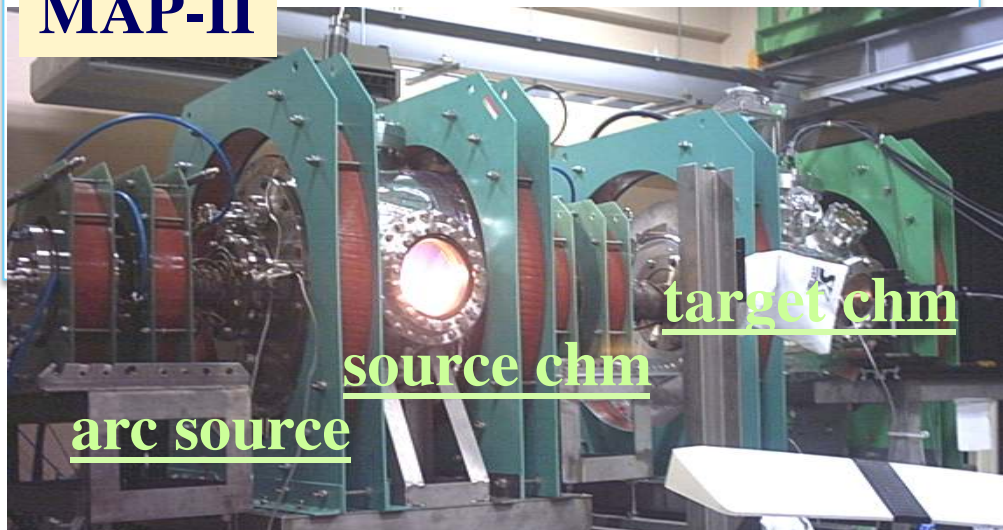
B- field ~ 20 mT

Working gases: H₂, He Ar

Puffing gases: He, H₂ C_xH_y

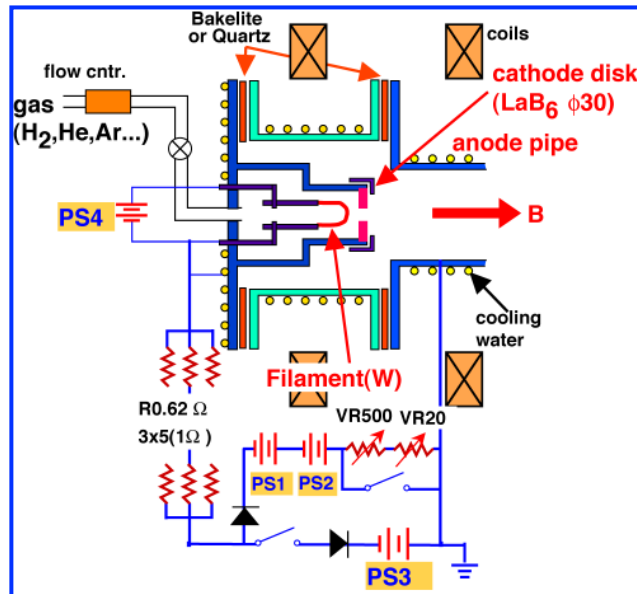
Pressure ~ 1~30 mTorr

MAP-II

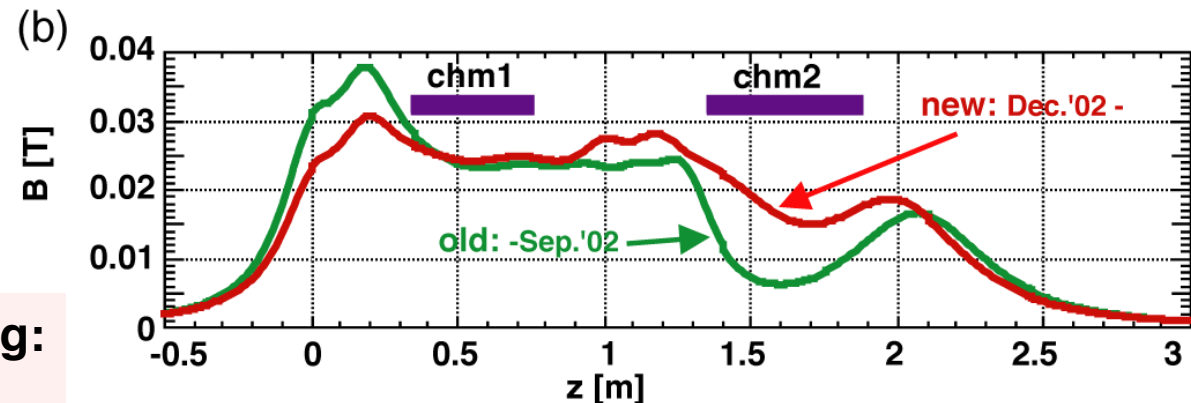
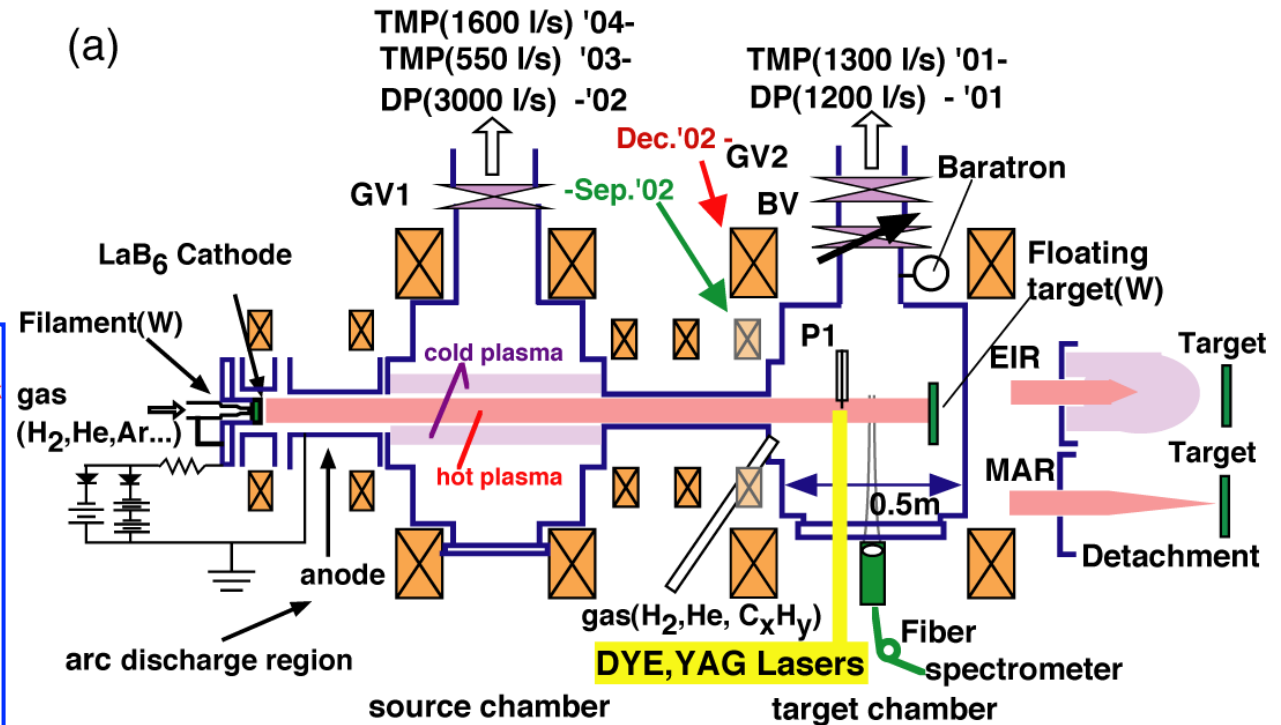


MAP-II (Material And Plasma) Divertor Simulator

Arc discharge:
70-100V, 30-45A
 $B = 0.02\text{T}$

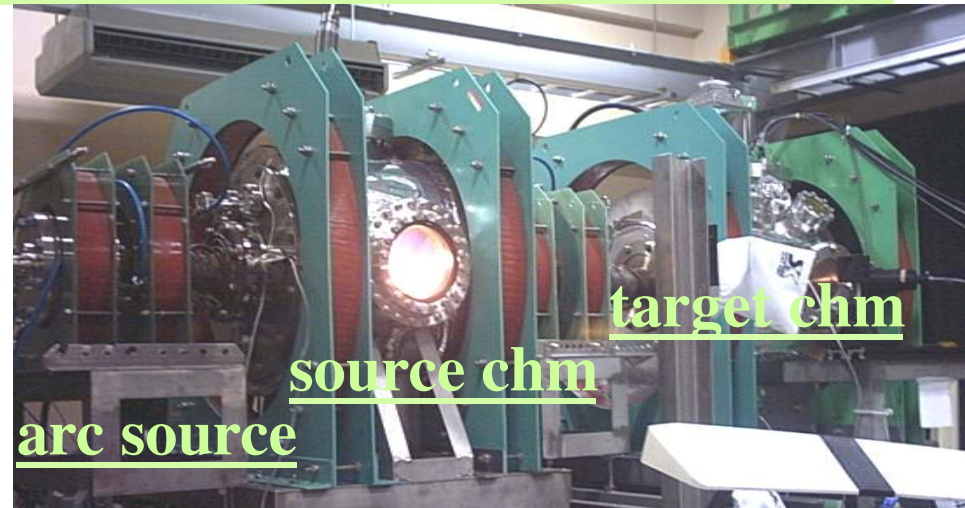
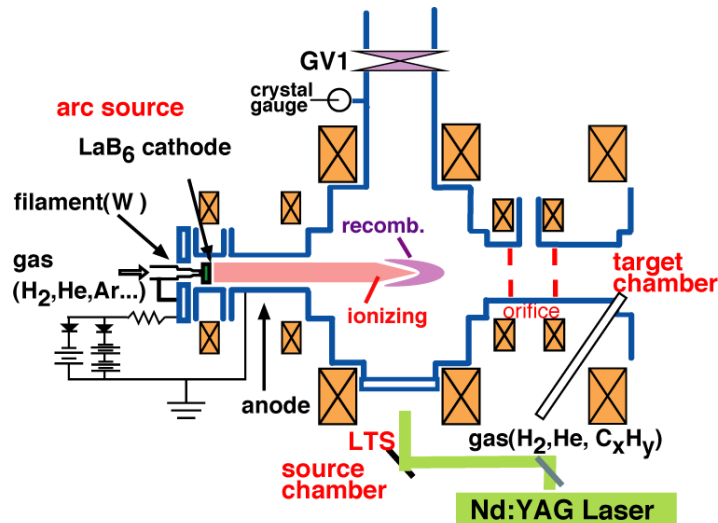


TMP for Differential Pumping:
on--> attached condition
off--> detached condition

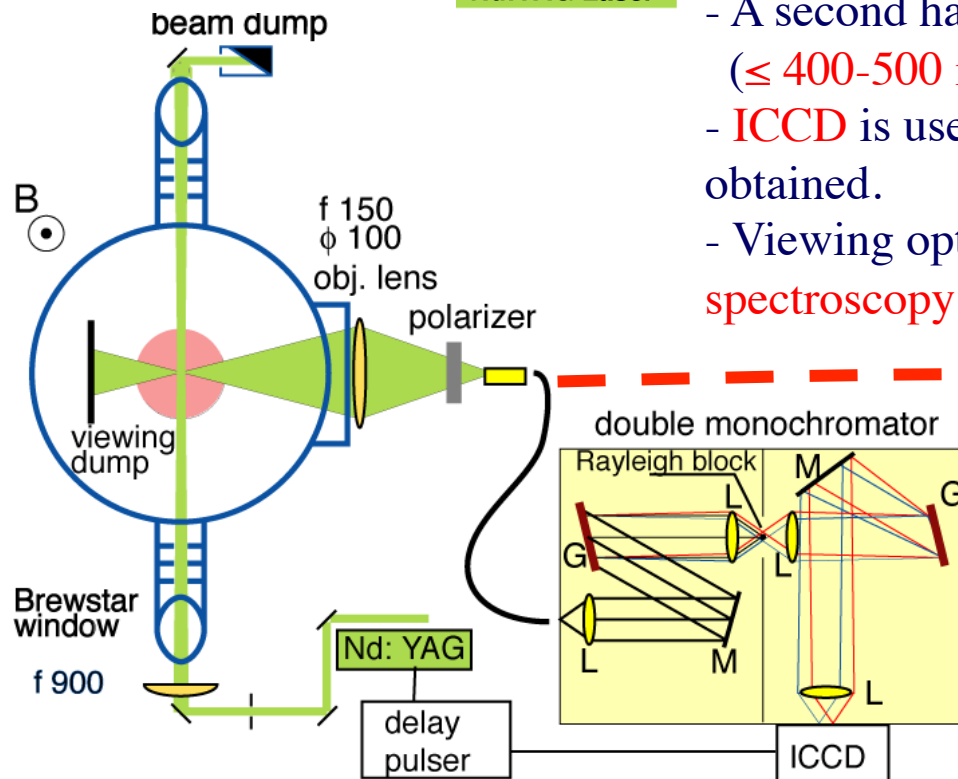


LTS and OES systems on MAP-II (source chamber)

7



- A second harmonic Nd:YAG Laser ($\leq 400\text{-}500\text{ mJ / pulse @}532\text{ nm, }7\text{ ns, }10\text{ Hz}$)
- ICCD is used (YAG-TVTS). Doppler profiles can be obtained.
- Viewing optics are also used for the optical emission spectroscopy (OES) for the comparison with LTS.



For low-n
For high-n

Low resolution
spectrometer
($\Delta\lambda \sim 0.5\text{ nm}$,
190-850 nm)
Linear CCD
(2048 pix, 12bits)

High resolution
scanning
monochromator
(1m, 2400gr/mm
 $\Delta\lambda \sim 0.03\text{ nm}$,)
PMT

Volumetric Recombination Processes (H_2 , He

I. Electron-Ion Recombination (EIR)



$$T_e < 1 \text{ eV}$$

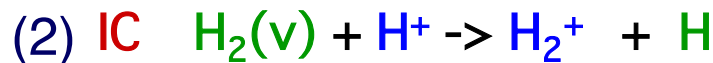
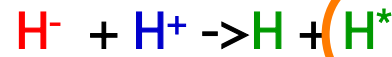
Rydberg spectra (high-n)

II. Molecular Assisted Recombination (MAR), H_2 , C_xH_y ,

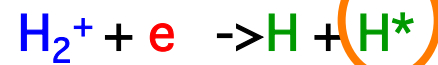


MN [Fulcher]

[Photo-detachment]

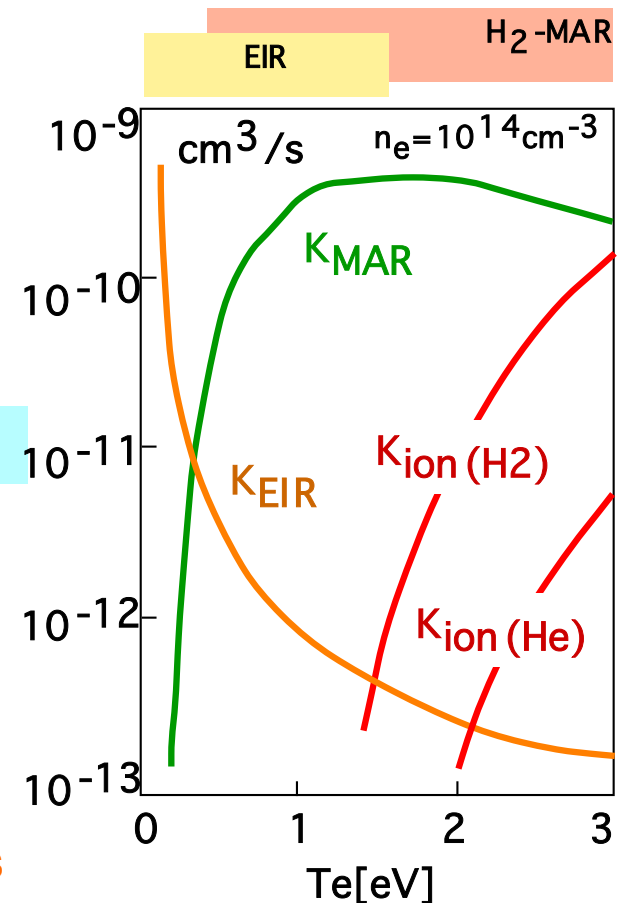


DR



$$T_e < 2-3 \text{ eV}$$

complex excitation processes
(low-n modified)



Krashennnikov et al. Phys.Plasmas(1997)1638

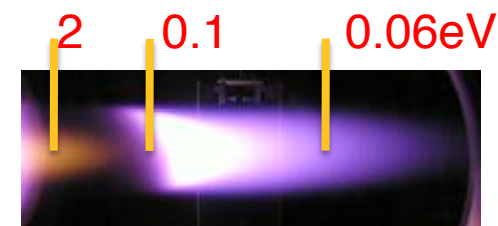
Since the processes strongly depend on T_e ,

requirement of the diagnostics yields:

Ionizing plasma (ex. glow discharge) $T_e \geq 2 \text{ eV}$

for H_2 -MAR Min. $T_e \leq 2 \text{ eV}$

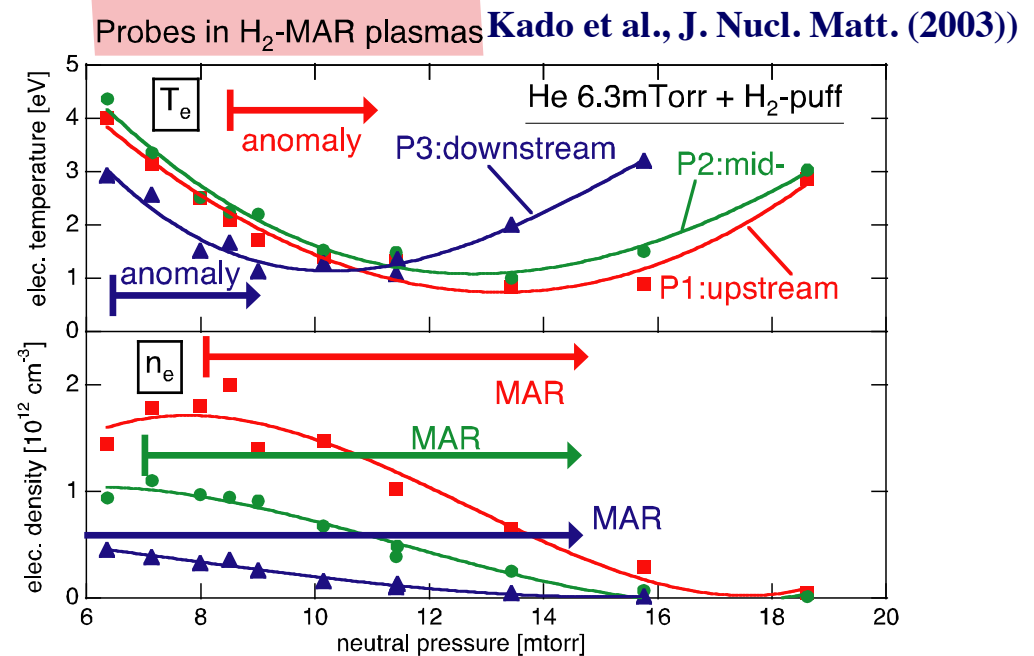
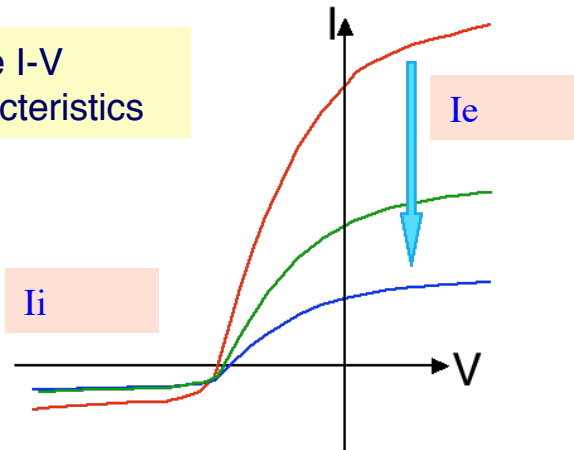
for EIR Min. $T_e \leq 0.1 \text{ eV}$



A problem in the measurement of Recombining Plasmas



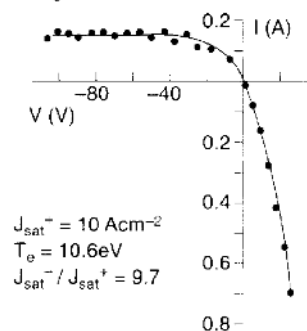
Probe I-V characteristics



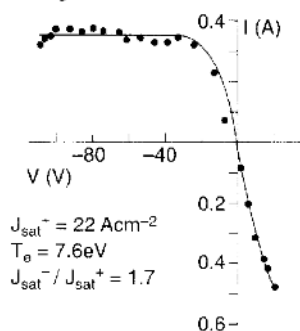
Anomalous I_e decrease, (Only I_i believable):

- Overestimation of T_e
- n_e becomes immeasurable (owing to T_e)
- also has an effect on negative ion diagnostics

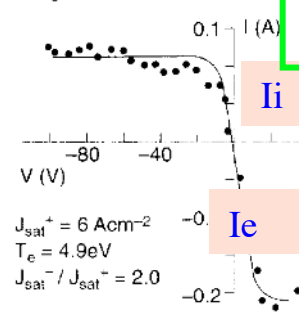
Low Recycle



High Recycle



Detached

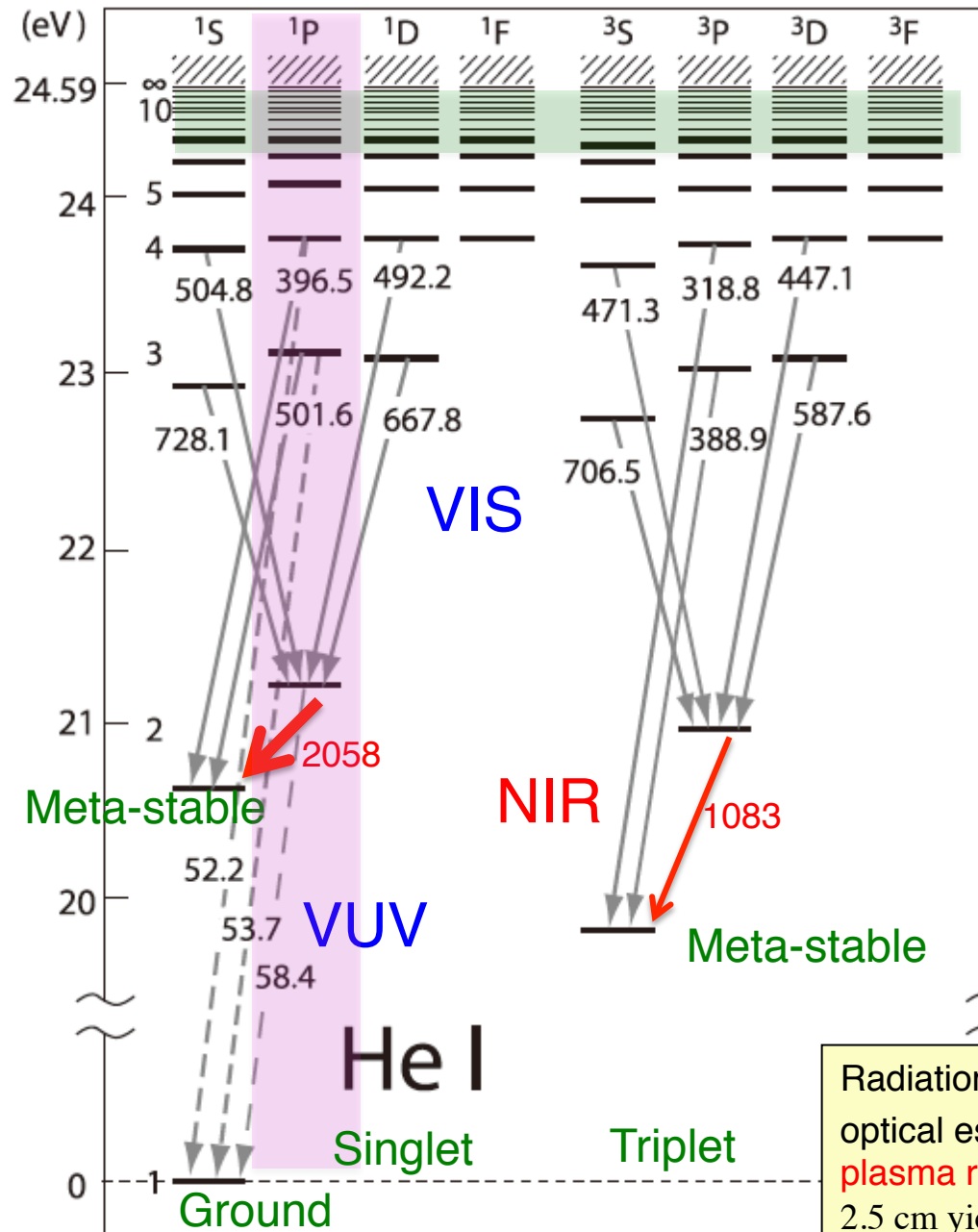


D₂ -EIR(JET)

Monk et al, J. Nucl. Mater. **241-243** (1997) 3960

- (1) probe contaminations
- (2) potential burst
- (3) Impedance of the plasma
- (4) Other unknown effects...

He I line emission spectroscopy



1) High-n Boltzmann plot method.

2) Collisional Radiative model

transitions to $n = 2$

(many useful lines, optically thin)

→ suitable for line ratio measurement.

Upper-states: mainly $n = 3, 4$

[*] Y.Iida, S.Kado, *et al.*, RSI **81**, 10E511 2010.

- Radiation trapping included for $1P$ states (resonant to $1S$)

Otsuka-model -- @center

Iida-model (2010) -- @arbitral

----> Imaging spectrometry

3) near-infrared spectroscopy for 2^1S

- 2^1P (2058.130 nm)

--- on-going

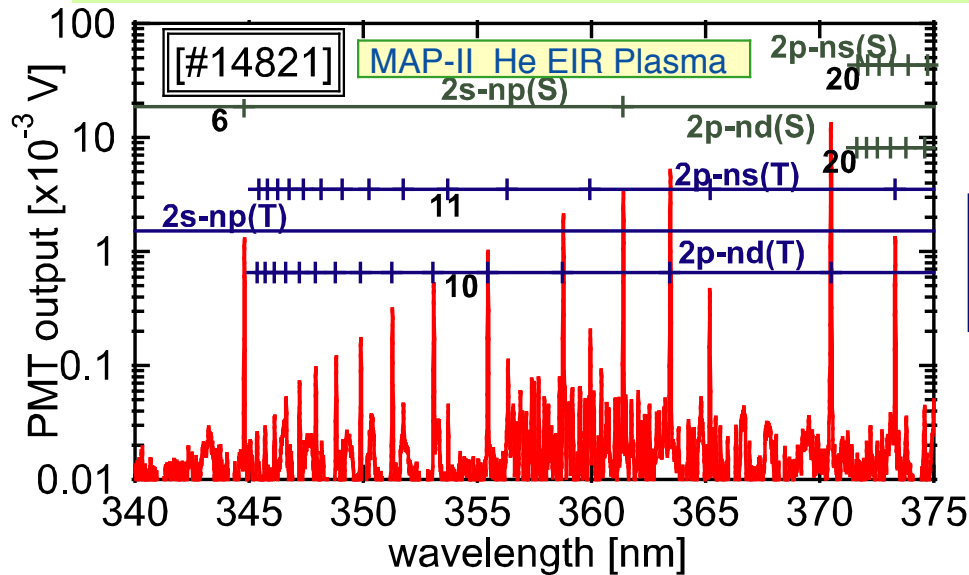
Radiation trapping for resonant $1^1S-n^1P(n=2\sim7)$: $A \rightarrow \Lambda A$

optical escape factor Λ , absorption length L [Otsuka(1979)]

plasma radius (2.5 cm) < L < chamber radius (25 cm)

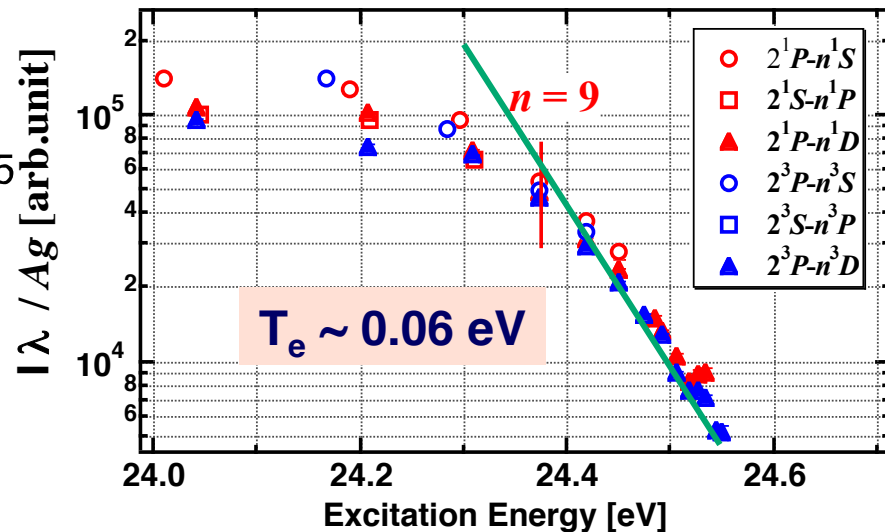
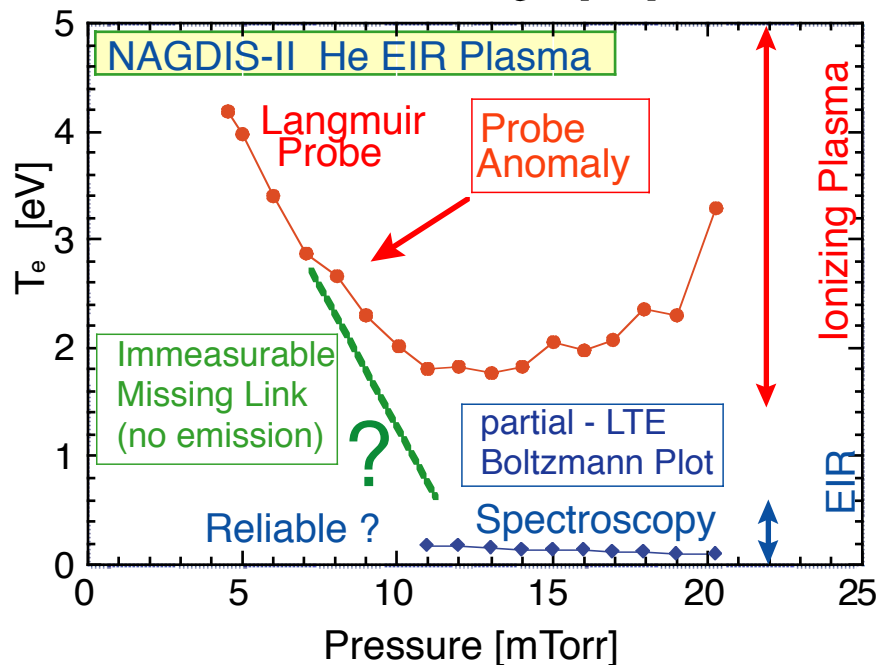
2.5 cm yields good fit with data with $T_{\text{gas}}=400\text{K}$ ($\sim T_{\text{rot}}(\text{H}_2)$)@center

Rydberg spectra: Partial-LTE in the Helium EIR plasmas



$$\log \left(\frac{I_p \lambda_{pq}}{A_{pq} g_p} \right) \propto \log \left(\frac{n(p)}{g_p} \right) = -\frac{\Delta E}{kT_e} + K$$

if the plot lies on the straight line above $n=p$, it is in **p-LTE** with free electrons



- Spectroscopic measurement always reflects the brightest point. Q: Really that low? .
- **Transition layer** cannot be measured either by a probe (due to the anomaly) or by passive spectroscopy (due to the absence of emissions).
- Laser Thomson Scattering (LTS) is expected to fill the gap between these measurements.

How to evaluate the lines based on the CR model

Rate equation:

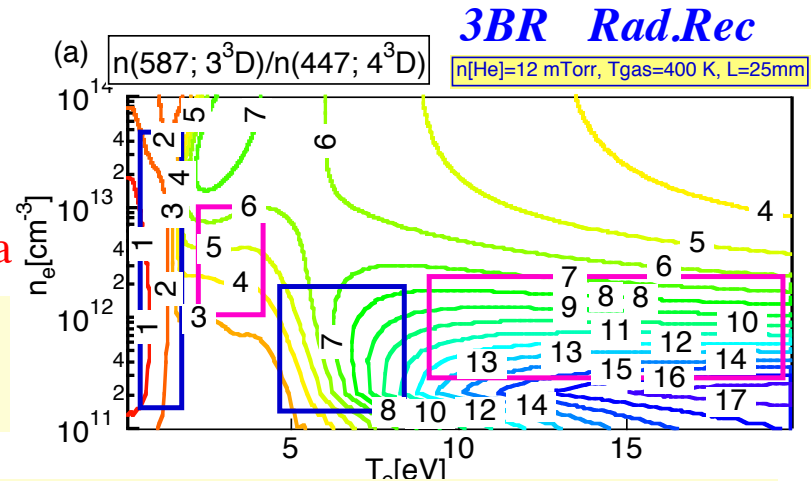
$$\frac{dn(p)}{dt} = - \left\{ \sum_{q \neq p} C_{p \rightarrow q} n_e + S_p n_e + \sum_{q < p} A_{p \rightarrow q} \right\} n(q) + \sum_{q \neq p} \{ C_{q \rightarrow p} n_e + A_{q \rightarrow p} \} n(q) + \{ \alpha_p n_e + \beta_p \} n_i n_e$$

ex.&deex. *ion.* *decay*

➡ $n(p) = \underbrace{R_0(p)}_{\text{Recombining}} n_e n_z + \underbrace{R_1(p)}_{\text{Ionizing plasma}} n_e n_{1^1 S}$

Model: Fujimoto(1979) Goto(2003)

Radiation trapping implemented : Iida (2006)



Sensitive parameter ranges for the line-ratio technique:

- (1) Contours **parallel** to T_e (or n_e) - axis ---- n_e (or T_e) measurement.
- (2) No parallel contours but **other pair with other tendency** (cross point)

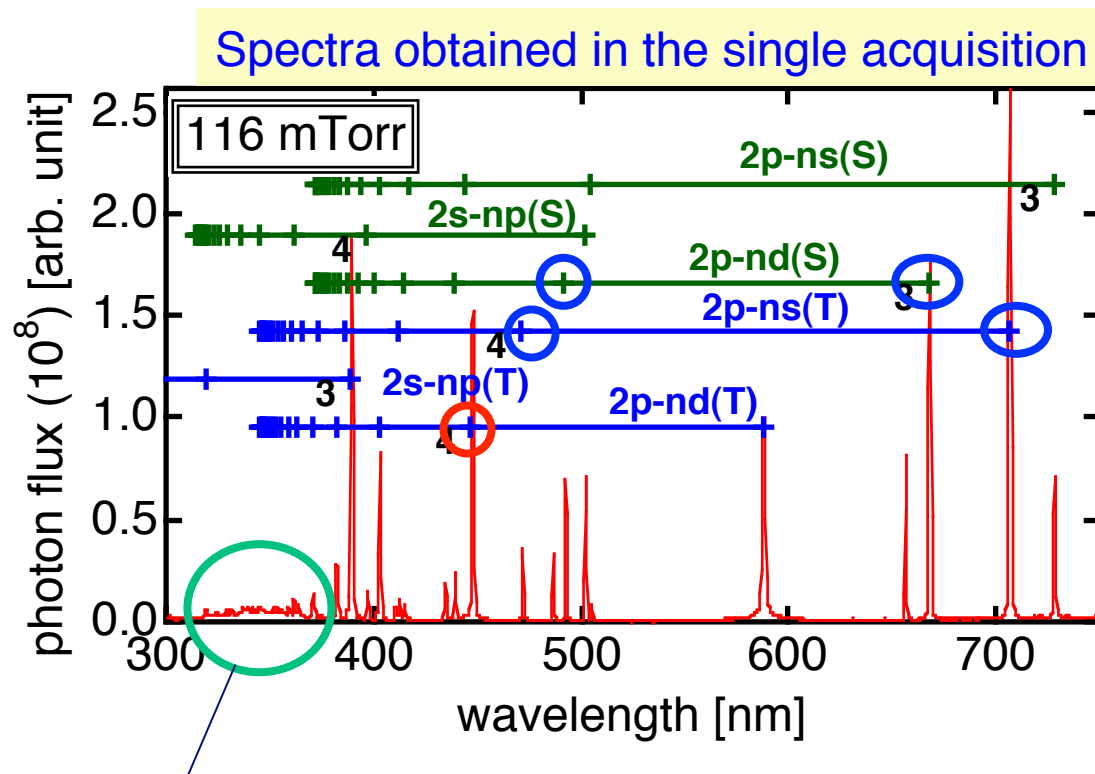
Simultaneous equations -- n_e - T_e

- (3) No clear dependence -- need to check **convergence properties** of the least square fit of the population ratio $r_i = n(i)/n(\text{ref})$ to the evaluation function as follows:

$$f(T_e, n_e) = \sum_i \left(\frac{r_i^{CR}(T_e, n_e) - r_i^{EXP}}{r_i^{CR}} \right)^2, \sum_i \frac{(r_i^{CR}(T_e, n_e) - r_i^{EXP})^2}{r_i^{CR}}, \sum_i \left(\frac{r_i^{CR}(T_e, n_e) - r_i^{EXP}}{\Delta r_i^{EXP}} \right)^2, \text{etc} \dots$$

Lines used for He I CR model ($n=3, 4$)

- Low-dispersion simple spectrometer (CCD of 2048 pixs, 12bits) was used for the low- n (3 and 4) spectra.
- High resolution scanning monochromator (PMT) for Rydberg spectra.



Merits (low- n states):

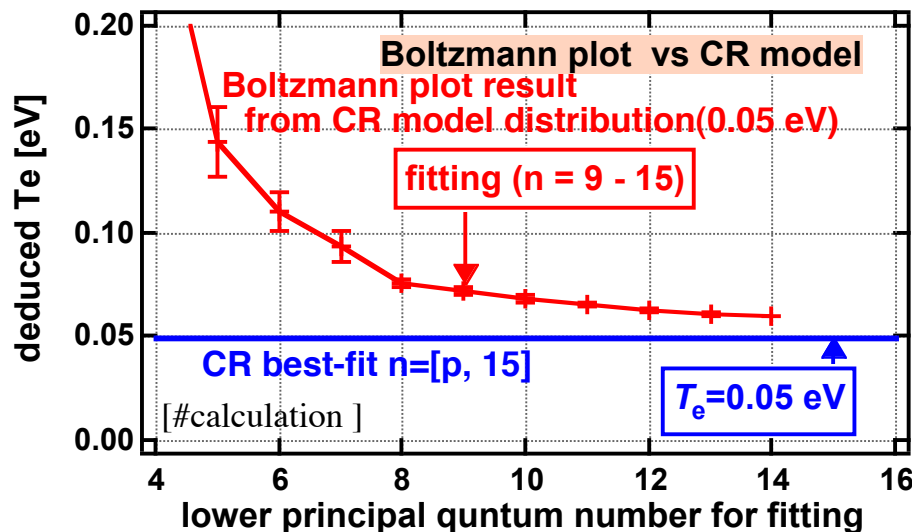
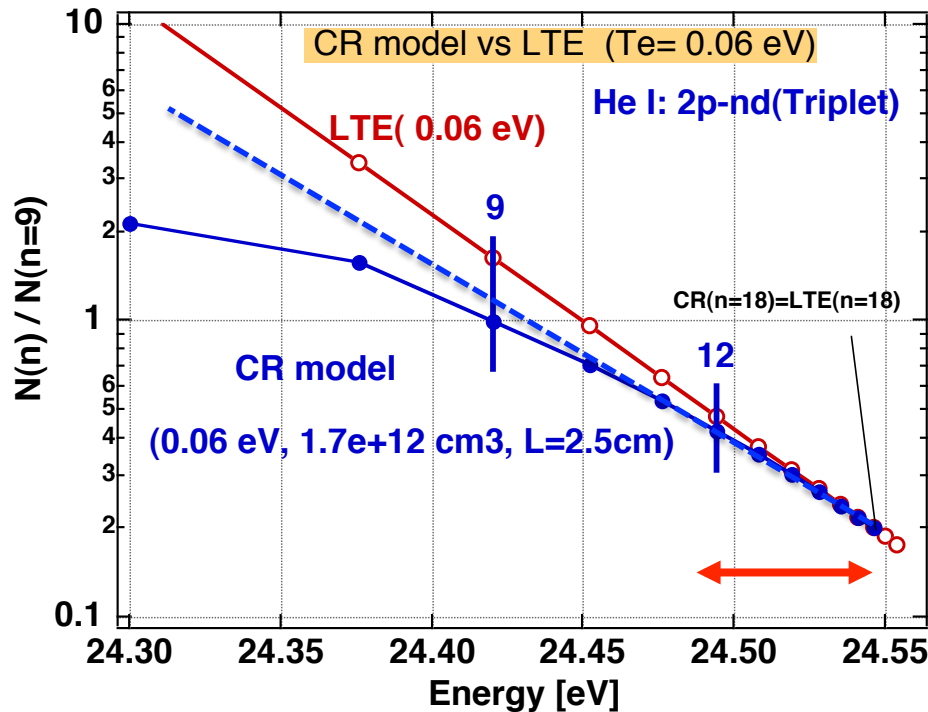
- Brighter line emissions
- Good line separation.
- Fast measurements (< minutes)

Demerits:

- Accuracy not examined.

- Rydberg series: dark, less separated (requires high resolution monochromator),
 --> requires very long scanning time.
- Supposed to be accurate in terms of Te determination (many sensitive lines).

CR-model (high-n) vs Boltzmann Plot method



BP: LTE($n \geq 9$) $\rightarrow \sim 0.06$ eV

$$\log\left(\frac{I_m \lambda_{mn}}{A_{mn} g_m}\right) = -\frac{\Delta E}{kT_e} + K$$

CR-model best fit (0.05 eV)

$$n(p) = r_0(p, T_e) n_e n_z$$

$$= r_0(p, T_e) n_e^2$$

LTE for $n > 12$ (It depends on density.)

T_e (p-LTE) $>$ T_e (CR) slightly (~ 0.01 eV).

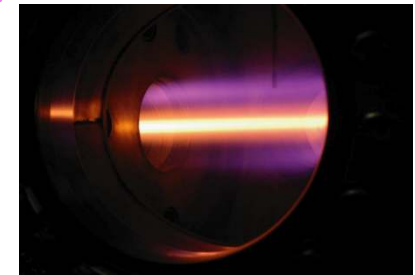
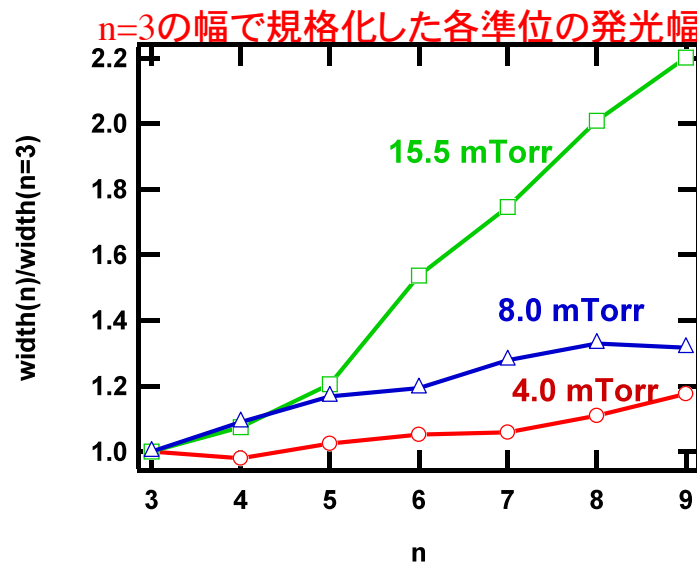
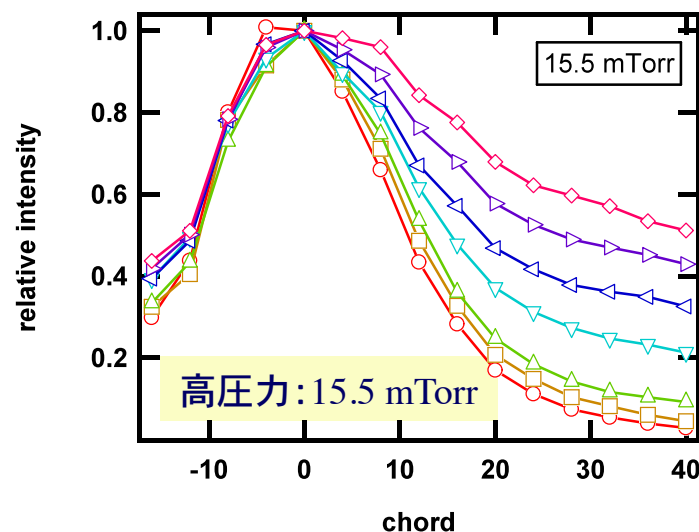
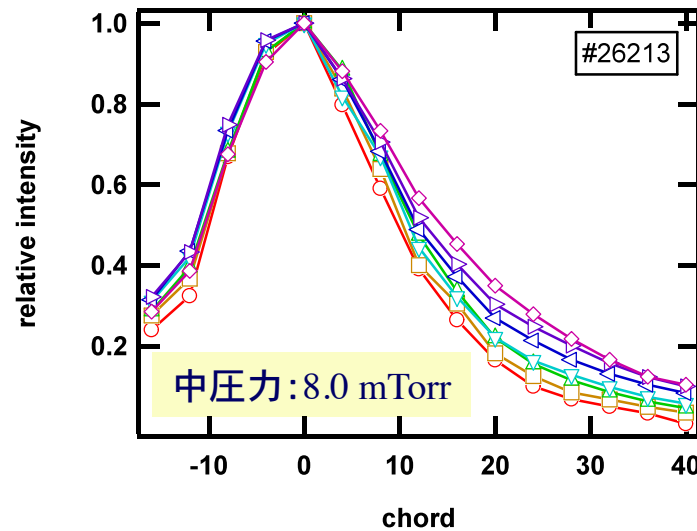
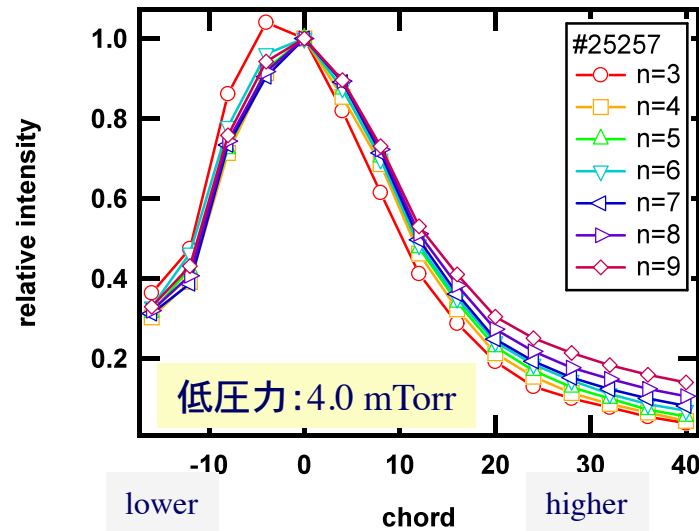
- 1) calculate 0.05 eV distribution (CR)
- 2) perform fitting to the distribution based on LTE (for $n = [p, 15]$)
- 3) compare with each other

Results of Boltzmann plot converges to the best-fit value (0.05 eV) of CR model as lowest n increases.

He I ^3D -system spatial distribution

[日本物理学会20aTJ-9 2010.3, 鈴木 M論]

$n=3\sim 9$ ^3D terms, spatial distribution: n -dependence become more obvious for higher pressure



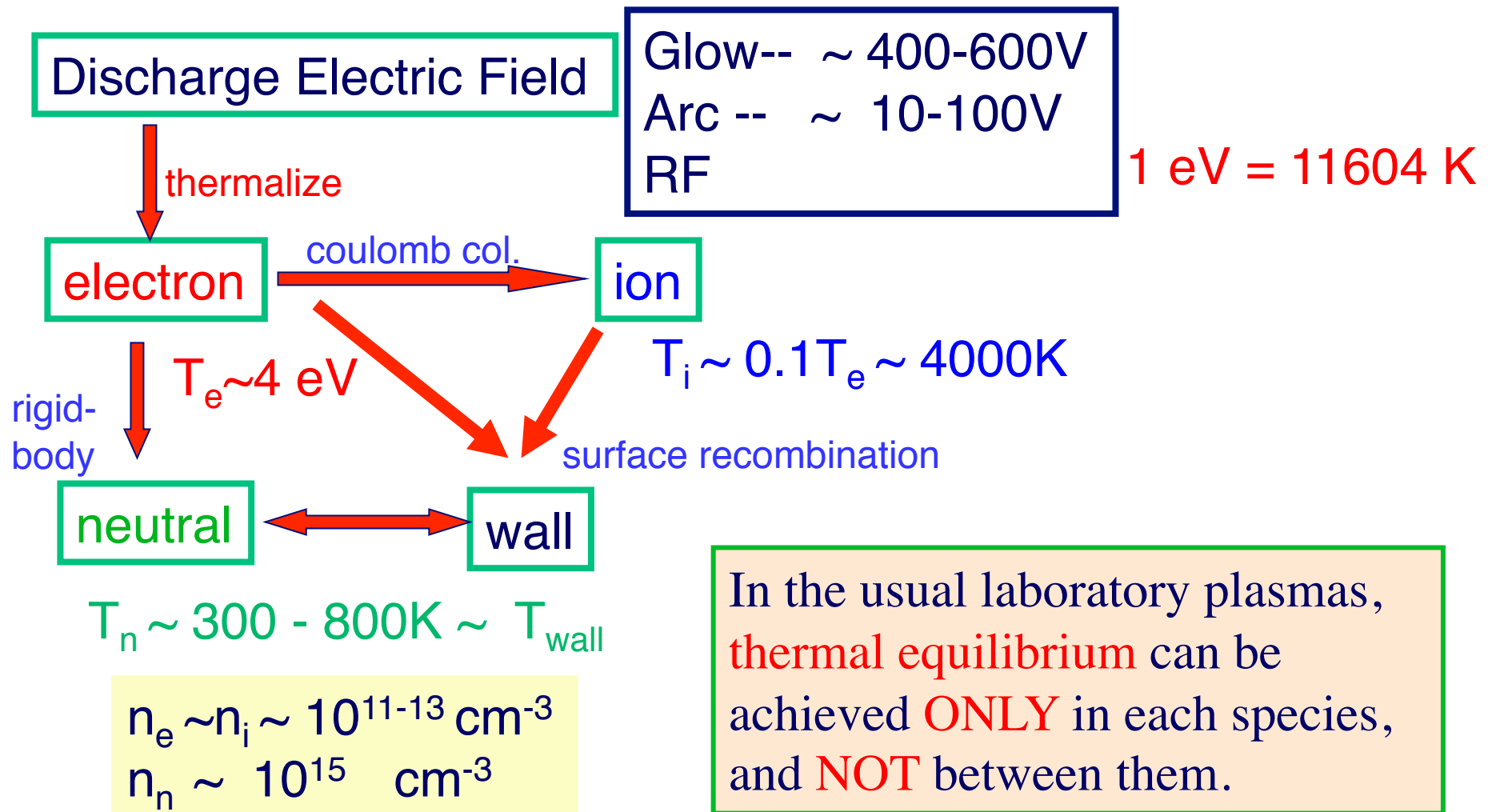
再結合プラズマ:
上下非対称
本研究では(プラズマ
上部が顕著)



空間構造を調べる必
要性

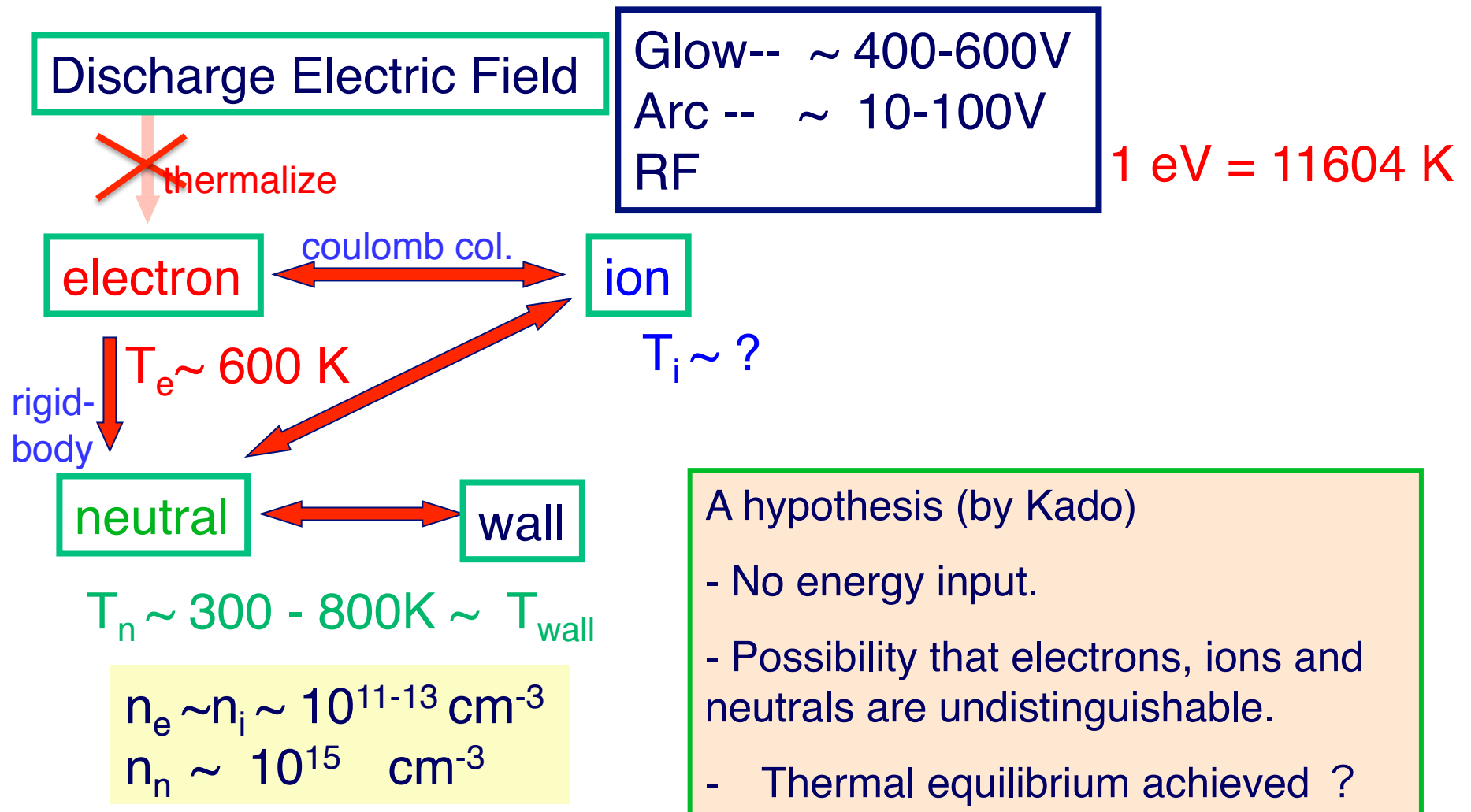
ここでは, ^3D 系列のみを示したが,共鳴線である ^1P 系列以外の系列は同傾向をしめす.

Temperatures of ion, electron and neutral (ionizing plasma)



How about the recombining plasma ?

Temperatures of ion, electron and neutral (recomb. plasma)

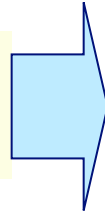


Motivation

Difficulty and the Solution to T_e Diagnostics for LTS

Main sources of difficulties in the application to **low T_e , n_e plasmas**:

- Small fraction of scattered photons
- High level of **stray light**



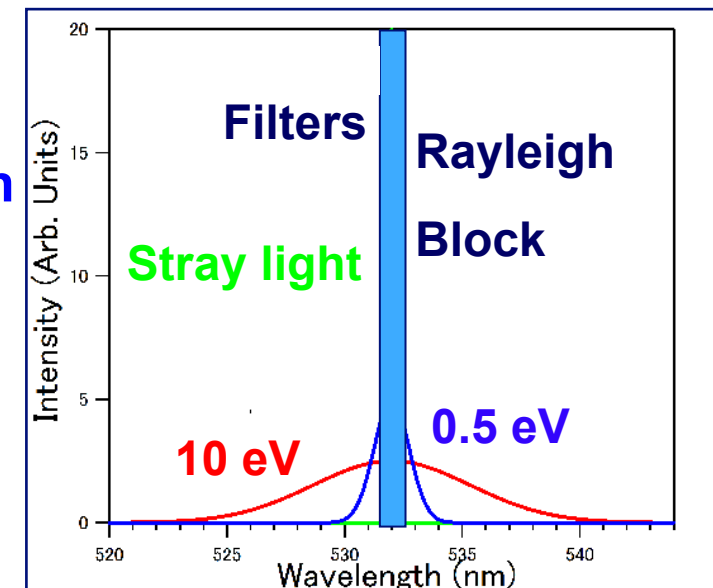
- Bright optics (low F-number)
- **Stray light rejection techniques**
- Data accumulation

- Filter polychromator ($\geq 1\text{ nm}$ band width) or notch filter ($\sim 17\text{ nm}$ stop band) cannot be used.

-Grating monochromator + stray light rejection

- High wavelength resolution, leading to a possibility of very low T_e measurements.
- Lower limit of T_e is determined by the size of the stop band: **Rayleigh Block (RB), in stead of the notch filter**

The stop-band can be reduced by **reducing RB dimension** and/or **increasing dispersion**



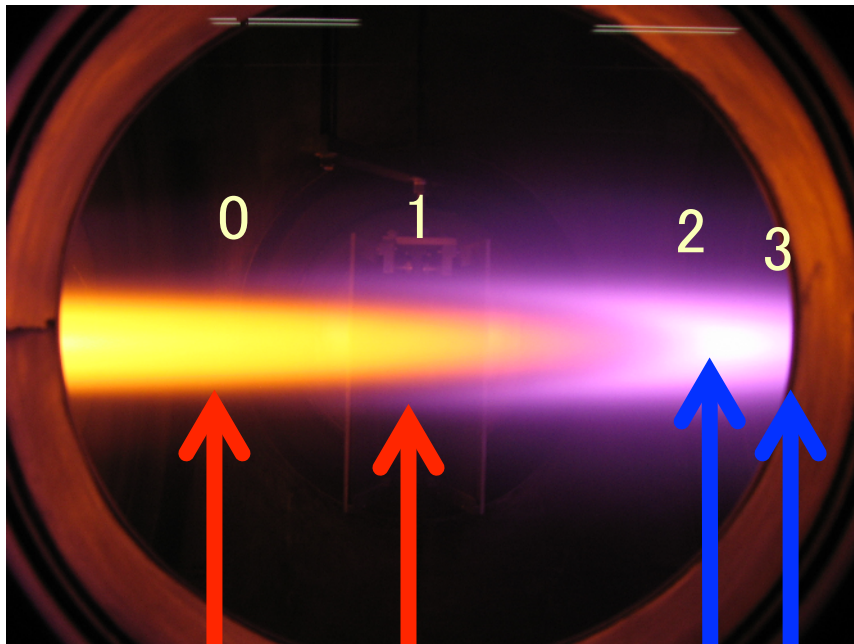
1-2 nm/mm for $T_e < 40\text{ eV}$

experiments: MAP-II divertor simulator

21

He Recombining Plasma: (Electron-Ion Recombination: EIR)

[#26100, 10.48, 83.3 mTor, 20081121/ IMG0057.JPG]



Ionizing
upstream

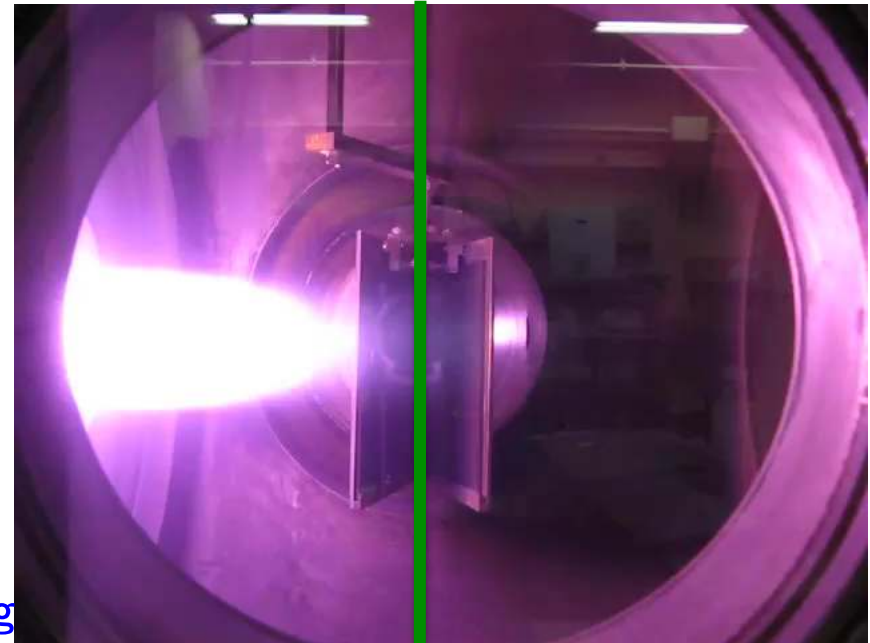
ionizing
downstre
am

Recombining
front

Recombining
Brightest point

$T_e > 2 \text{ eV}$ $\sim 1 \text{ eV}$ $\sim 0.2 \text{ eV}$ $< 0.1 \text{ eV}$

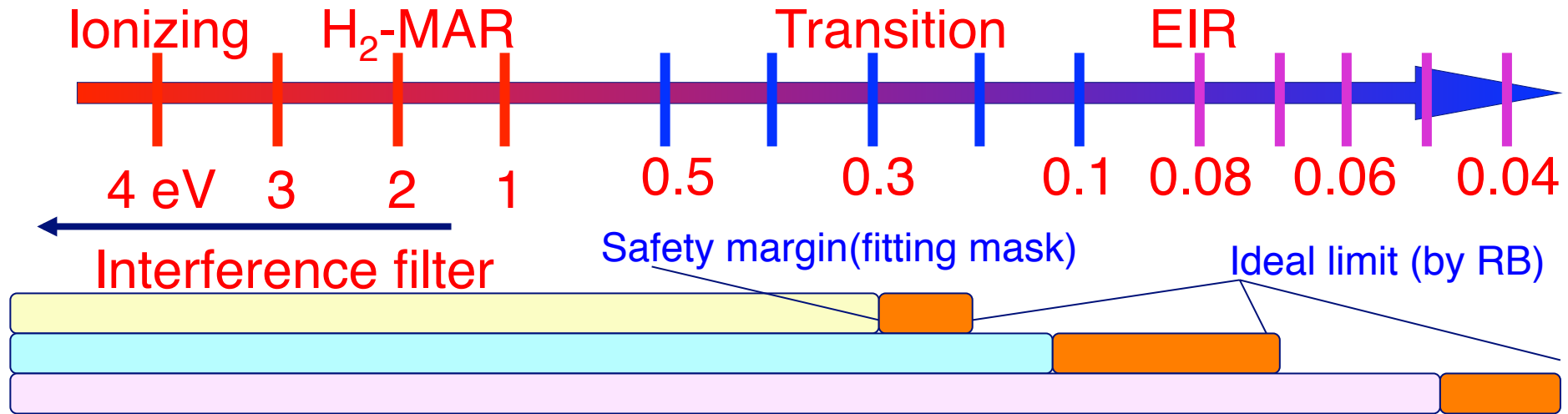
pure He ($\sim 60 \text{ V}$, 30 A) , $80\text{-}200 \text{ mTorr}$
pressure = LTS position@Source Chamber



Laser pass

20081121_Thomson_MVI_0064_trim.mp4

Stages of the development of Double Monochromator (DM)



System-0 : Conventional DM (= Homo-Tandem type)

$$0.2 - 0.3 \leq T_e \leq 40 \text{ eV} \quad (2004-2005)$$

A. Okamoto, S. Kado, *et al.*, *Rev.Sci.Instrum.* **76**(2005).

System-I

$$0.07 - 0.13 \leq T_e \leq 40 \text{ eV} \quad (2006)$$

F. Scotti, S. Kado, *et al.*, *Plasma Fusion Res.* **1** (2006) 054 .

System-II : Development of Hetero-Tandem DM

$$0.03 - 0.048 \leq T_e \leq 40 \text{ eV} \quad (2007 -)$$

F. Scotti, and S. Kado, *J. Nucl. Matter.* (2009).

Rayleigh block:

$\varnothing \sim 0.3 \text{ mm}$

$\varnothing \sim 0.2 \text{ mm}$

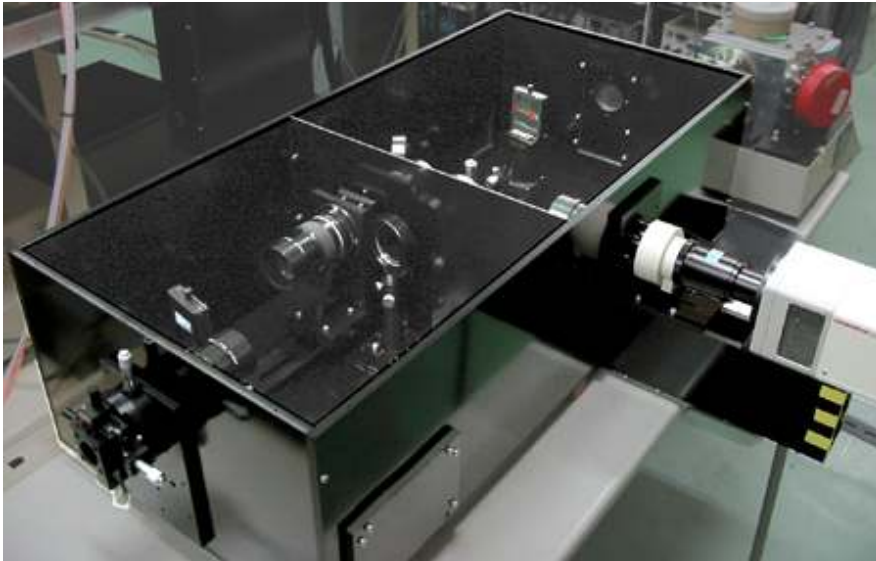
DM: focal length
 $135 + 135 \text{ mm}$
(F/2.8)

$200 + 100 \text{ mm}$
(F/2)

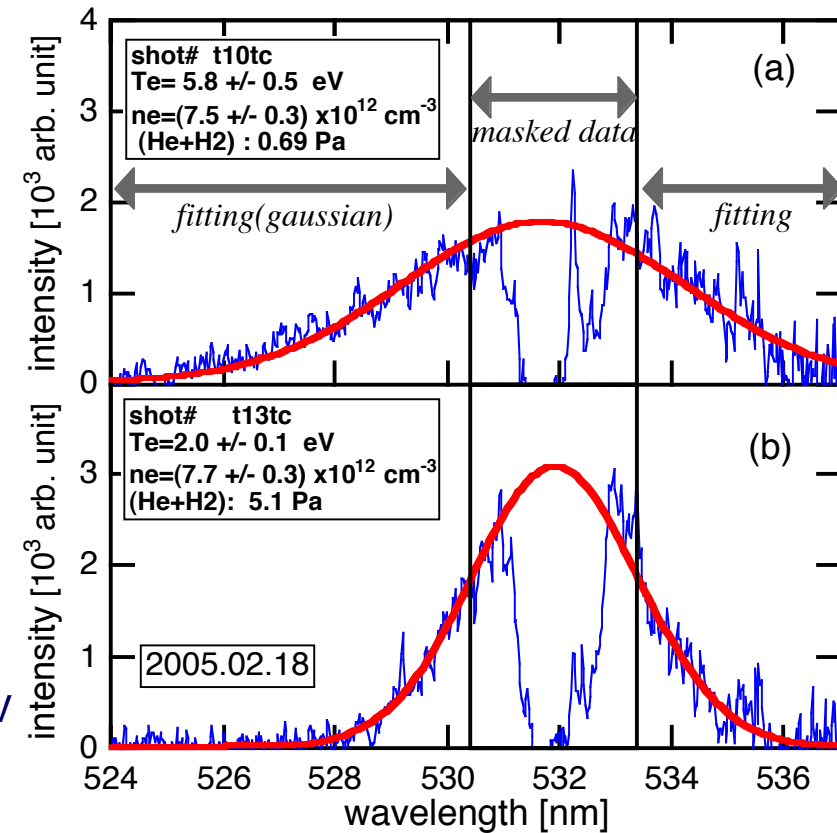
Example of the LTS spectra (H2-MAR, System 0)

probe beam -- Nd:YAG laser (532 nm, 300-400 mJ/pulse, dt =7 nm, 10 Hz)

hand-made double monochromator



block-0.35 mm ($f=135$ mm, 1800 lines/mm) $\rightarrow T_e > 0.3$ eV



The Thomson signal is obtained after the subtraction of stray light.

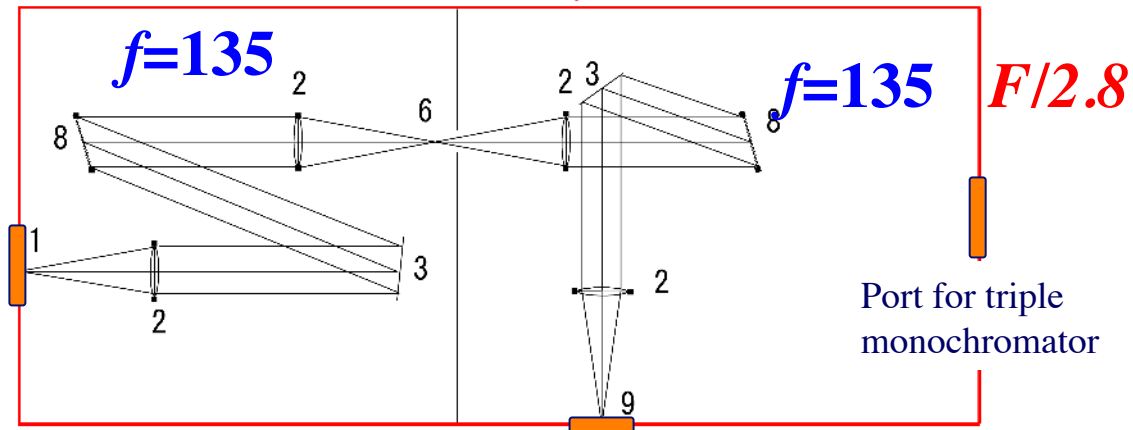
The central notch filtered region is avoided in the Gaussian fitting by means of a mask function.

Upper: 5.8 eV

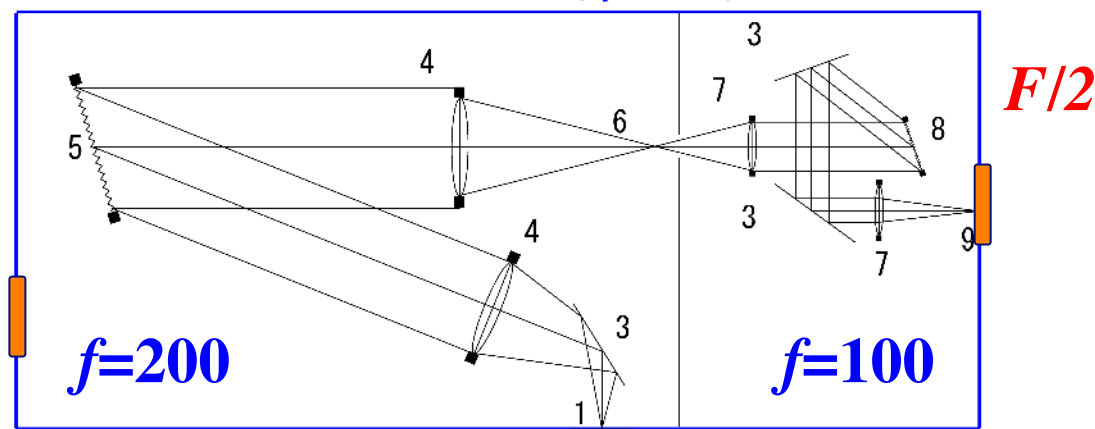
Lower: 2.0 eV

Hetero-Tandem Double Monochromator (hand-made)

Homo-Tandem Double Monochromator (System 0-I)



Hetero-Tandem Double Monochromator (System II)



1. Entrance slit
2. Camera lens $F/2.8$, $f=135\text{mm}$, $\Phi=48\text{mm}$
3. Mirror
4. Achromatic lens $F/2$, $f=200\text{mm}$, $\Phi=100\text{mm}$
5. Holographic grating 1800gr/mm , $100\text{mm} \times 135\text{mm}$
6. Rayleigh block
7. Achromatic lens $F/2$, $f=100\text{mm}$, $\Phi=50\text{mm}$
8. Holographic grating 1800gr/mm , $50\text{mm} \times 50\text{mm}$
9. ICCD Camera

Reciprocal linear dispersion

$$\frac{1}{\left(\frac{d\lambda}{dx}\right)_{2X}} = \frac{1}{\left(\frac{d\lambda}{dx}\right)_{1st}} + \frac{1}{\left(\frac{d\lambda}{dx}\right)_{2nd}}$$

Rayleigh block: $\varnothing \sim 0.2\text{mm}$

Groove frequency 1800 gr/mm

1st Rec.Lin.Disp.(nm/mm)

Sys. I: 3.14 $\Rightarrow T_e = 0.07\text{eV}$

Sys. II: 2.03 $\Rightarrow T_e = 0.03\text{eV}$

2nd Rec.Lin.Disp.(nm/mm)

Sys. I: 3.14

Sys. II: 4.05

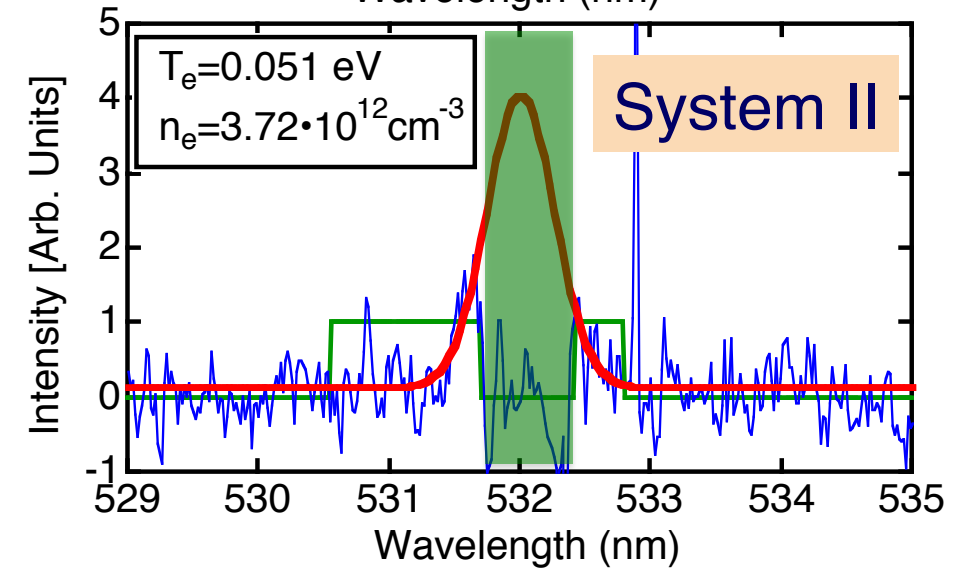
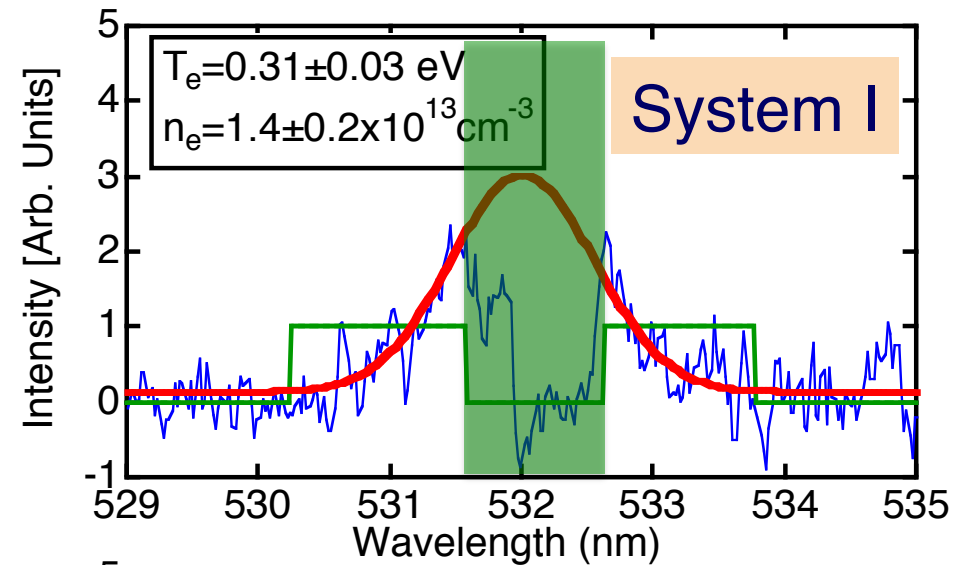
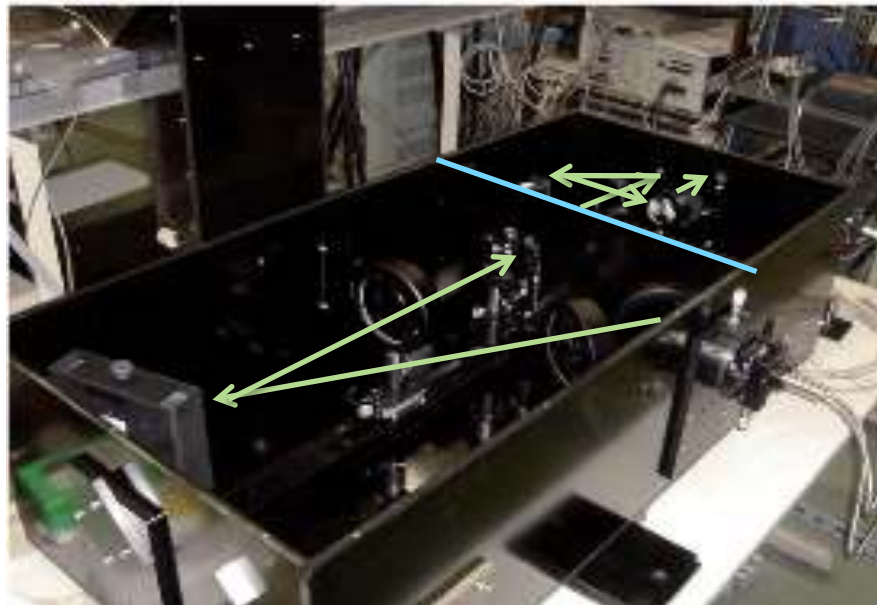
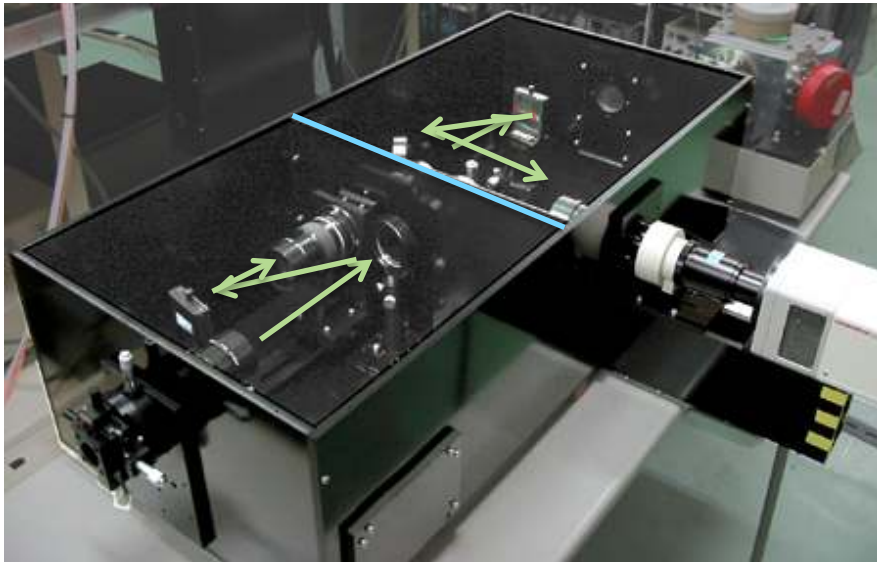
2X Rec.Lin.Disp.(nm/mm)

Sys. I: 1.57 $\Rightarrow$ comparable

Sys. II: 1.36

Upgrade of the spectrometer: Sys. 0, I $\rightarrow$ Sys. II

25

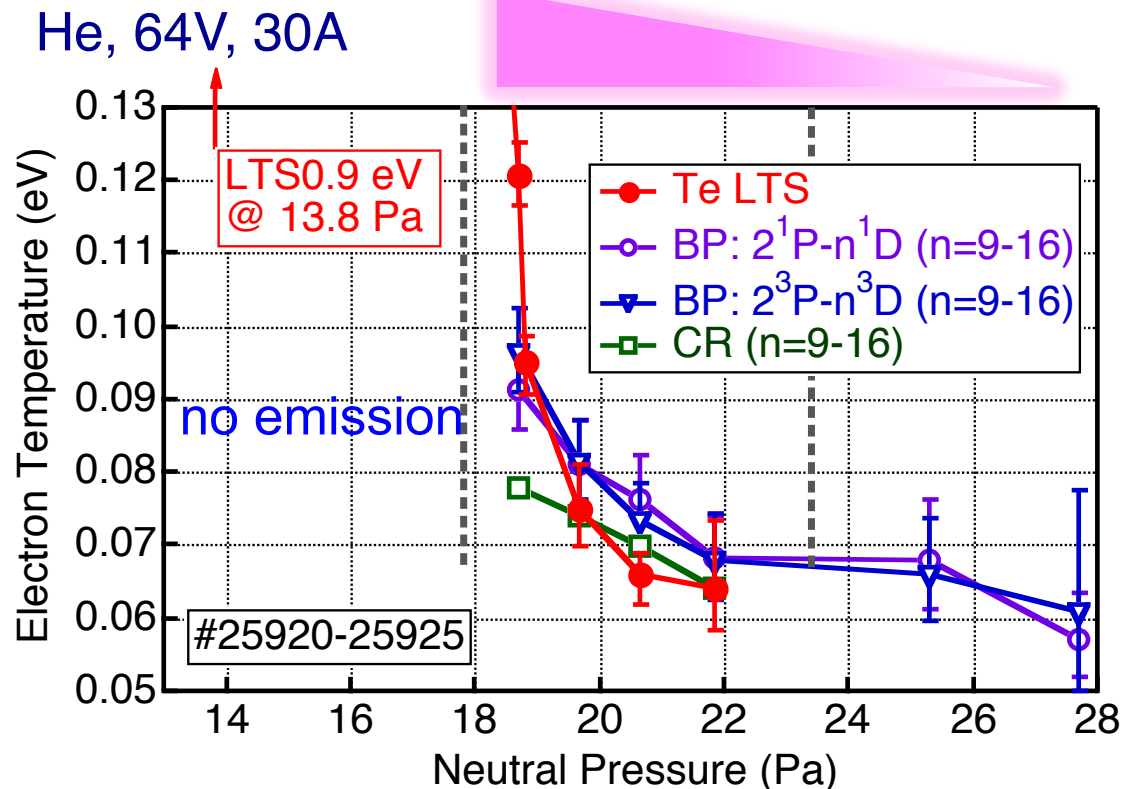


The practical lower limit was reduced from 0.13 to 0.048 eV

LTS vs Spectroscopy (high -n) at EIR front: Sys. II

Precise comparison of LTS and OES
(BP&CR) for the EIR front.

Schematic line- integrated
brightness



T_e (LTS) monotonically decreased until 0.065 eV, which agrees well with those obtained from the Boltzmann plot(BP) method (0.068 eV) for the Rydberg series and from CR model (high-n).

Deviation around the brightest point is attributable to the integration effect:

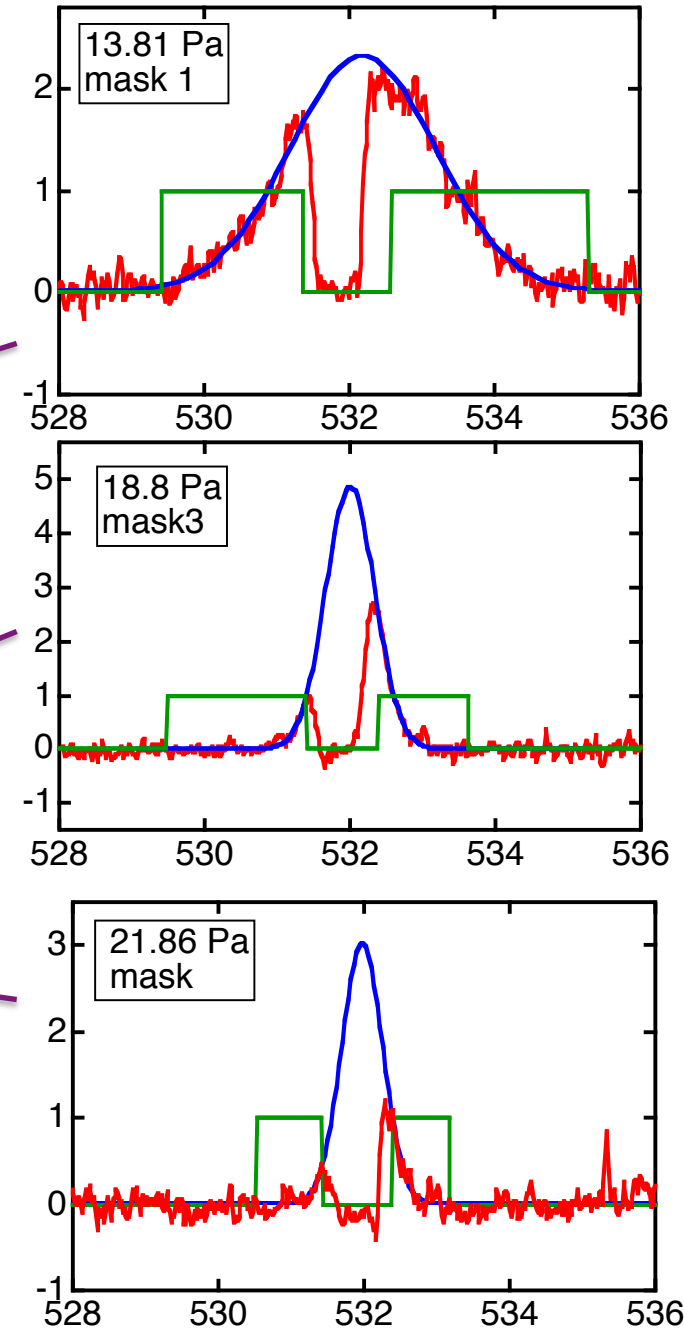
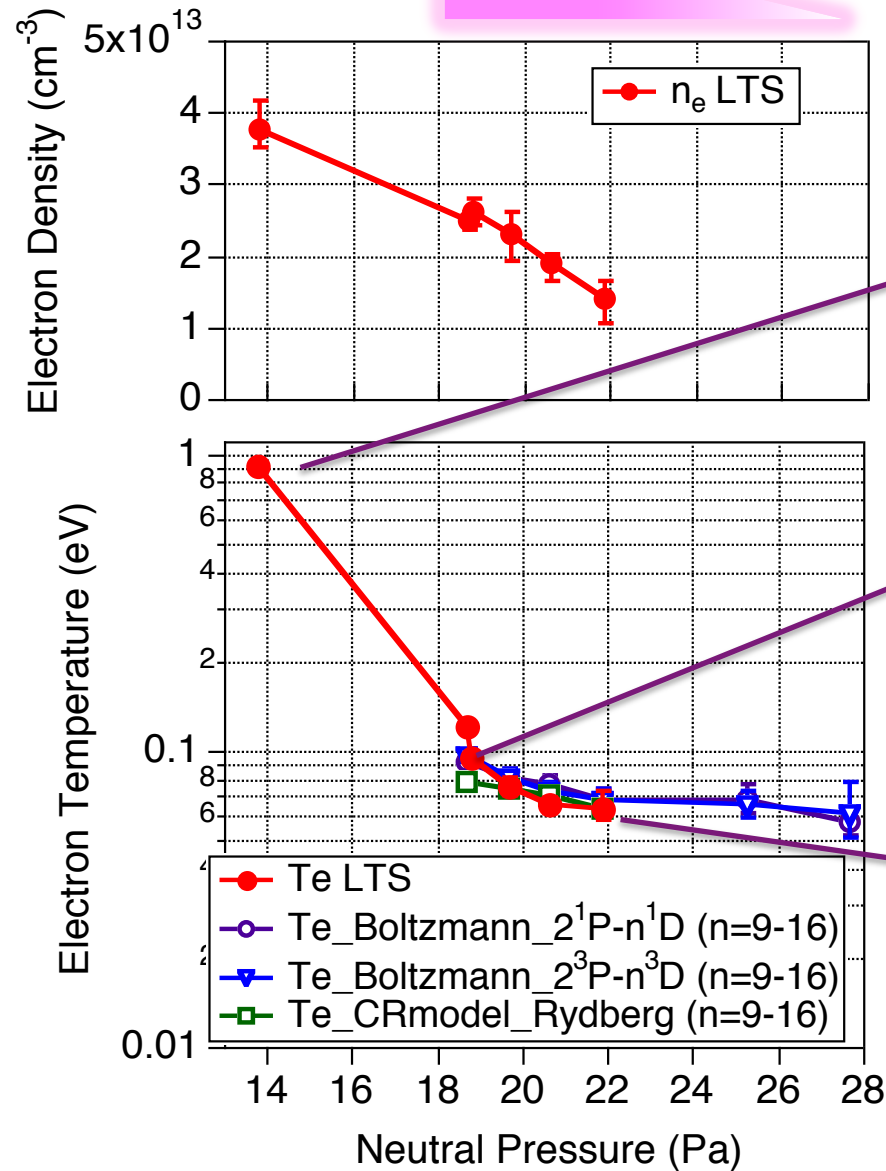
LTS -- T_e at the tip

Spec. -- T_e in the bright cone.

T_e (high-n, BP and CR) $\sim$ 0.06 eV -- confirmed by LTS

LTS spectra

27



LTS and Stark Spec. on MAP - II Divertor Simulator

Arc source with B- field ~ 20 mT

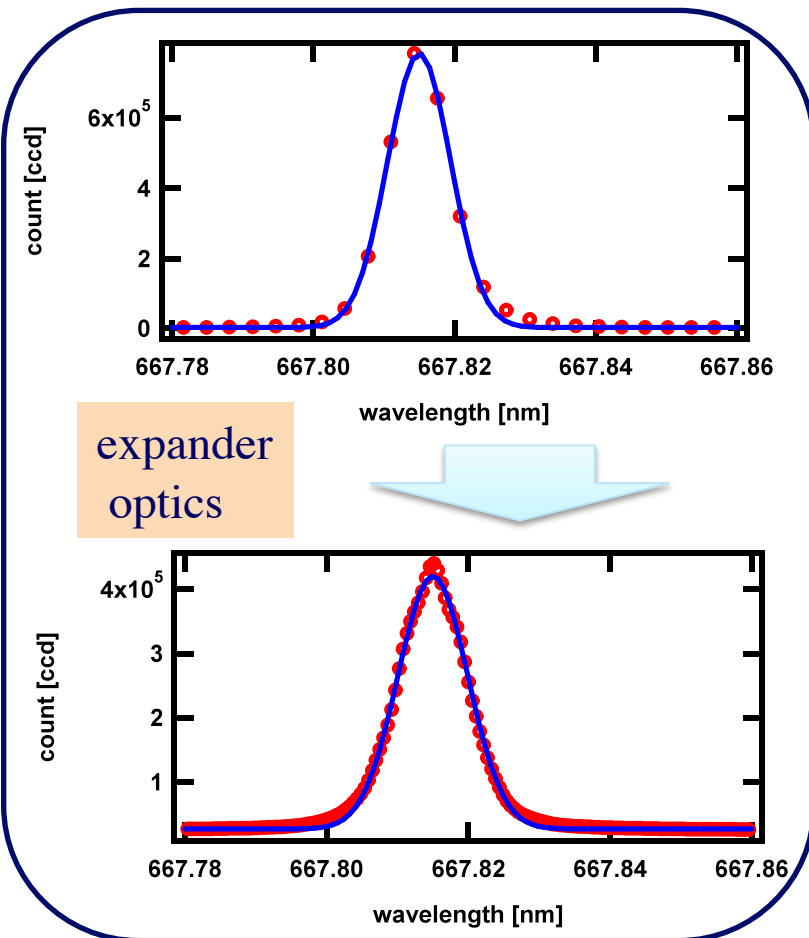
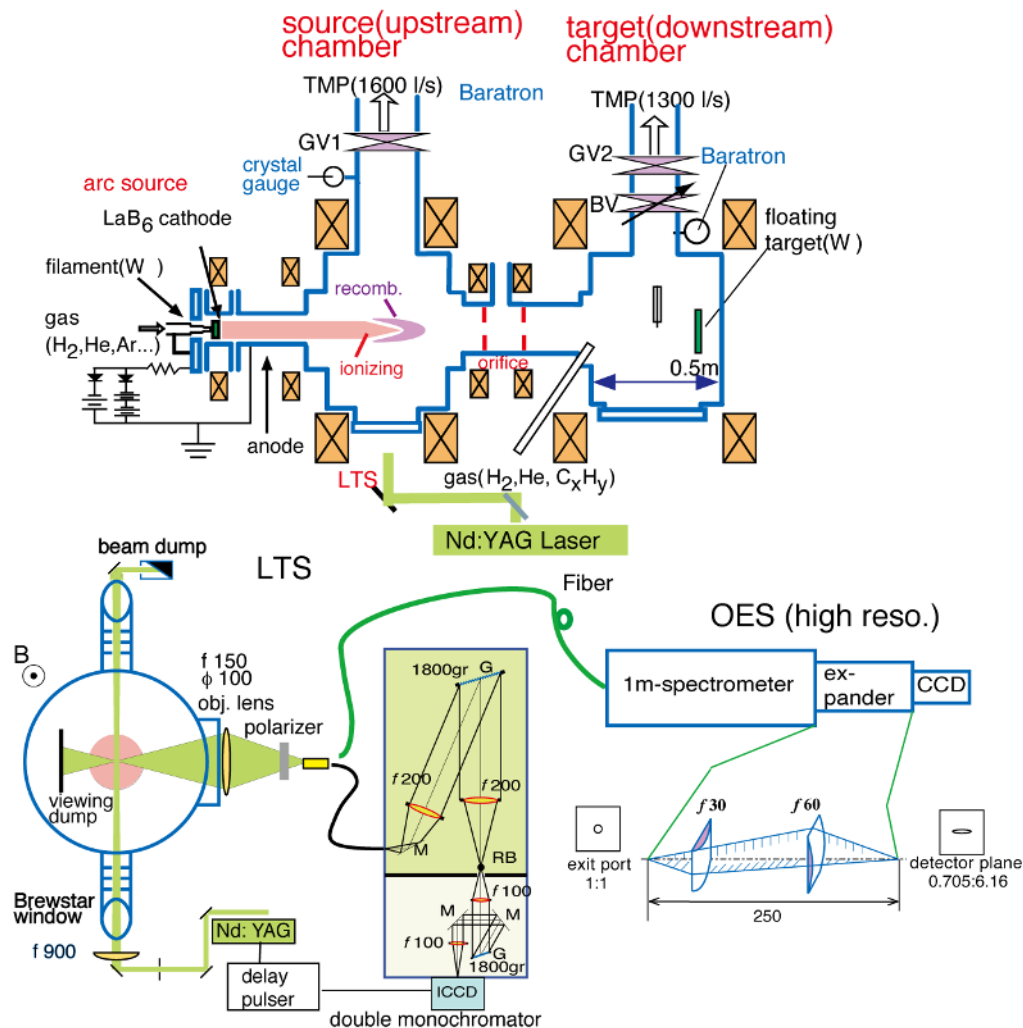
Cathode disk (LaB₆ ϕ 30 mm), Anode: Pipe

Discharge ~ 60 -100 V 30-45 A,

- 1st/source chamber: high n_e

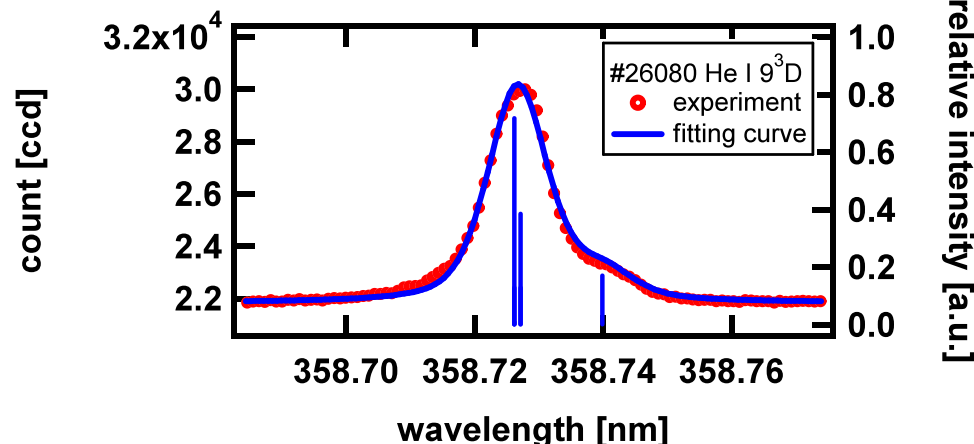
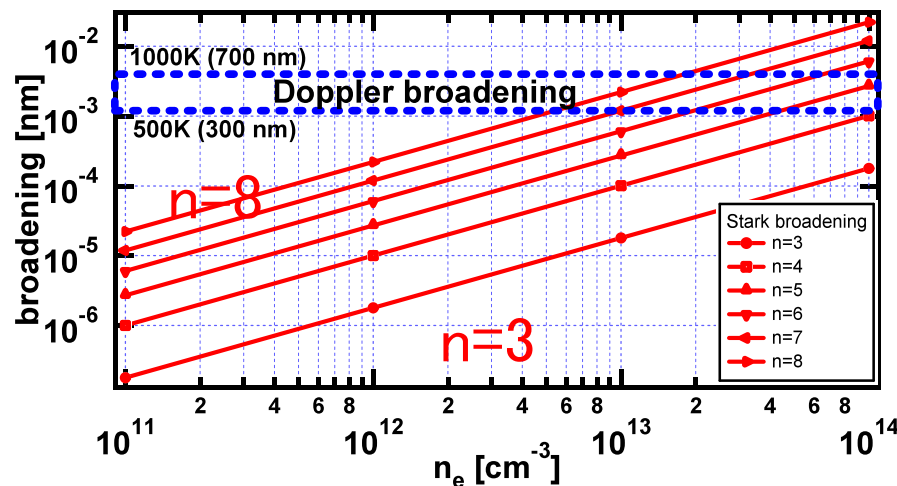
Probe measurements are limited in low density operations. ---> LTS.

- 2nd/target chamber: good controllability
equipped with many diagnostics



Difficulty and the Solution to $T(p)$ Diagnostics for OES

29



He I line broadening :

- i) instrumental function: with aberration
- ii) Doppler (temperature): W_G Gaussian
- iii) Stark (density) : W_L Lorentzian
($n_e > 10^{13} \text{ cm}^{-3}$,
principal quantum number $n \geq 6$)

ex. 9^3D (6 fine structures)
1m 2400 g/mm, x6
dispersion: 0.5~1 pm/pixel
Inst_FWHM 7.5~12.5 pm

Practically, however, it is difficult to determine W_L and W_G at the same time (freedoms for both could be compensated for each other)

Therefore, we have proposed measuring line profile of several spectra, in which the contribution balance of Gaussian and Lorentzian is different:

low-n More Doppler ---- Atomic temperature

high-n Doppler and Stark ---- Temperature and electron density

Question: Temperature of which state ?

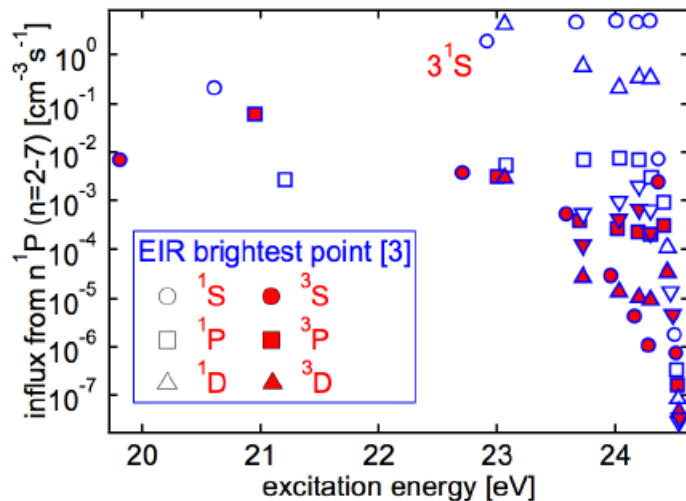
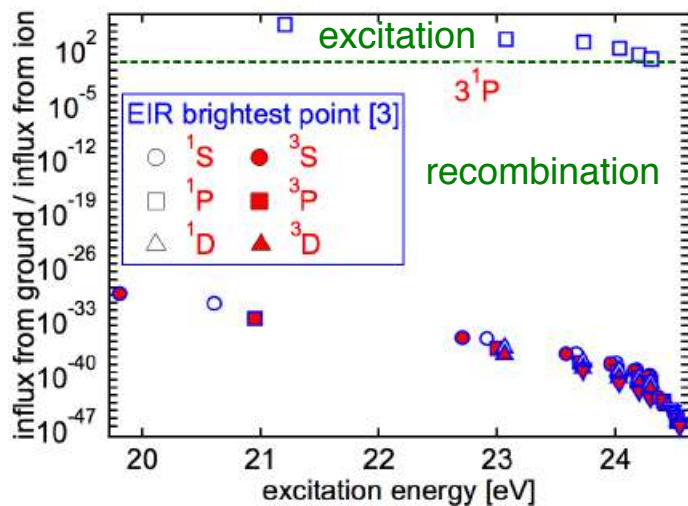
Origin of the Population in Recombining Plasmas

$$\frac{dn(p)}{dt} = - \left\{ \sum_{q \neq p} C_{pq} n_e + S_p n_e + \sum_{q < p} \Lambda A_{pq} \right\} n(p) + \sum_{q \neq p} \left\{ C_{qp} n_e + \Lambda A_{qp} \right\} n(q) + \left\{ \alpha_p n_e + \beta_p \right\} n_1 n_e$$

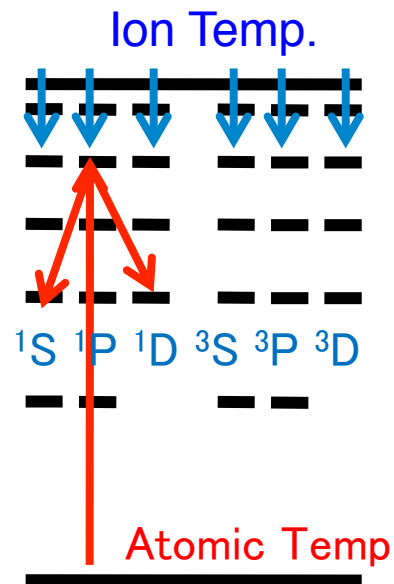
-efflux (Γ_{ef}) + influx: (Γ_{in})

ex.&deex. ion. decay

3BR Rad.Rec



Influx from the Ground/Influx from Ion
 $\Gamma_{in}(1^1S \rightarrow p) / \Gamma_{in}(\text{ion} \rightarrow p)$



Past research:

Ionizing Plasma:

Ion collision contributes to the high- n D series

• [K. Suzuki, master thesis, U-Tokyo(2010)]

The present research
Recombining Plasma:

1^1P : Gas Temperature

$1^1S, 1^1D$: mixture

high- n 3^3D : Ion temperature

Influx via 1^1P states,
 $\Gamma_{in}(1^1P \rightarrow p)$

Proposal of the Selection of Spectral Line Shapes

Empirical equation of the **Voigt Profile** (convolution of **Gaussian** and **Lorentzian**) as a function of wavelength normalized to its peak centered at λ_0 has been proposed in ref.[*] as

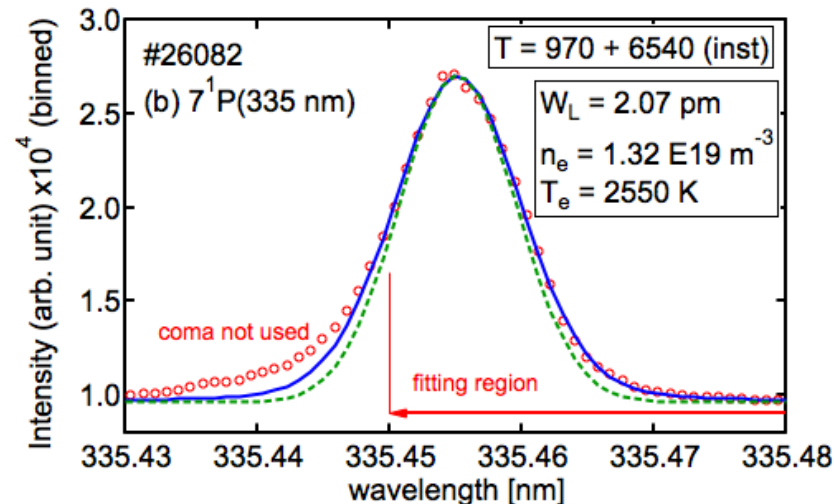
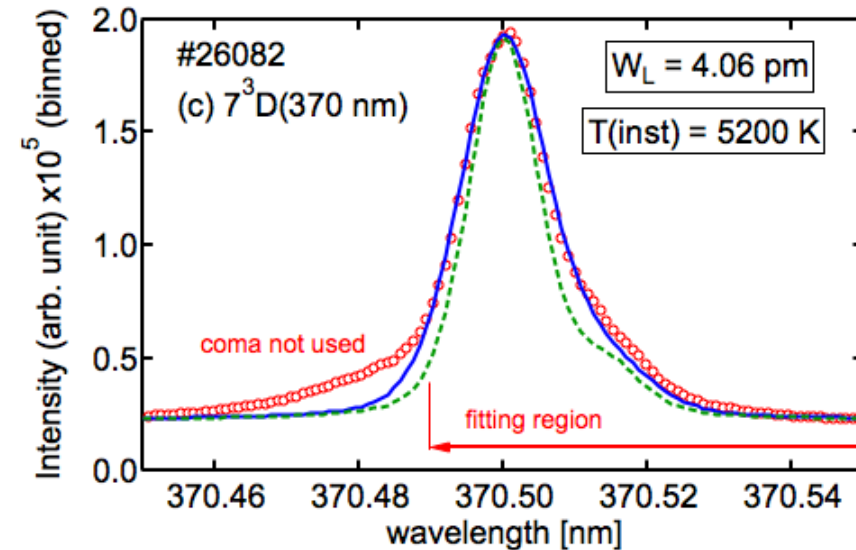
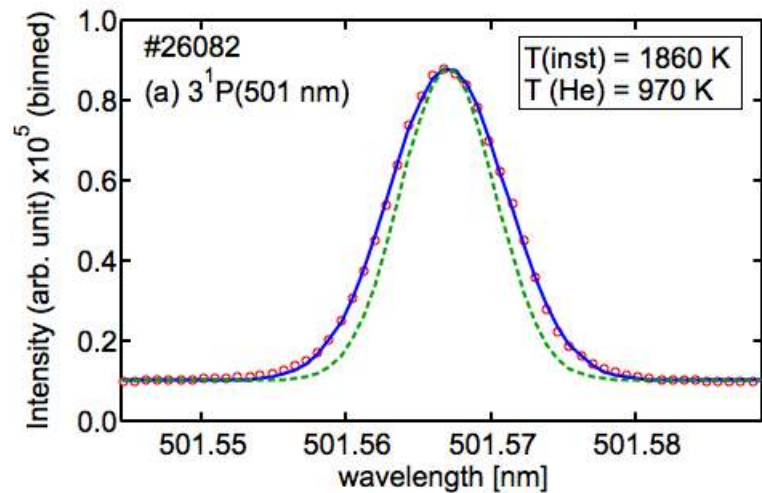
$$\frac{I(\lambda)}{I_0} = \left(1 - \frac{W_L}{W_V}\right) \exp\left(-2.772\left(\frac{\lambda - \lambda_0}{W_V}\right)^2\right) + \frac{W_L}{W_V} \left(1 + 4\left(\frac{\lambda - \lambda_0}{W_V}\right)^2\right)^{-1} \\ + 0.0016 \left(1 - \frac{W_L}{W_V}\right) \frac{W_L}{W_V} \left(\exp\left(-0.4\left(\frac{\lambda - \lambda_0}{W_V}\right)^{2.25}\right) - \left(1 + 0.1\left(\frac{\lambda - \lambda_0}{W_V}\right)^{2.25}\right)^{-1} \right)$$

$$W_V = \frac{W_L}{2} + \sqrt{\frac{W_L^2}{4} + W_G} \equiv W_L [+] W_G$$

$W_V(3^1P) = W_G(3^1P) = W_G(T(\text{He}^0)),$ -----> Atomic Temperature
 $W_V(7^1P) = W_G(T(3^1P)) [+] W_L(7^1P).$ -----> Electron Density
 $W_V(7^3D) = W_G(7^3D) [+] W_L(n_e(7^1P)),$ -----> Ion temperature

Results : Use of Line profiles of Three Transitions

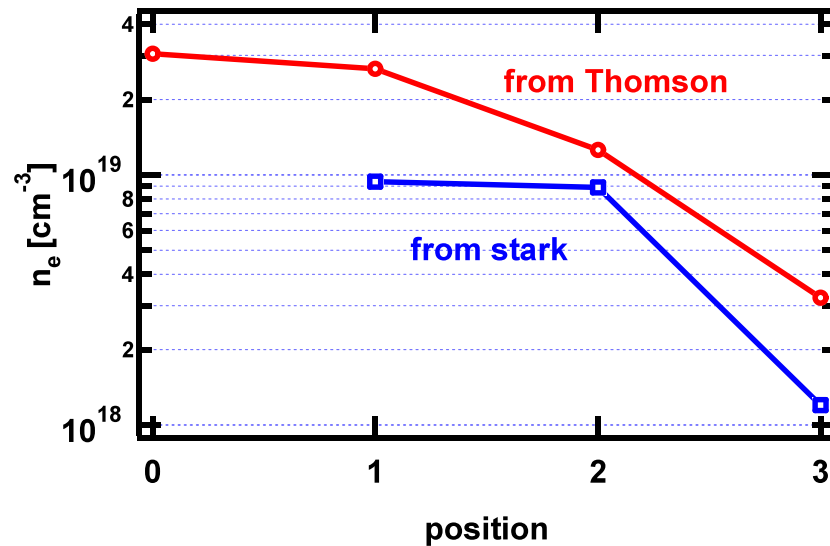
$W_V(3^1P) = W_G(3^1P) = W_G(T(\text{He}^0)),$ ----> Atomic Temperature
 $W_V(7^1P) = W_G(T(3^1P)) [+] W_L(7^1P).$ ----> Electron Density
 $W_V(7^3D) = W_G(7^3D) [+] W_L(n_e(7^1P)),$ ----> Ion temperature



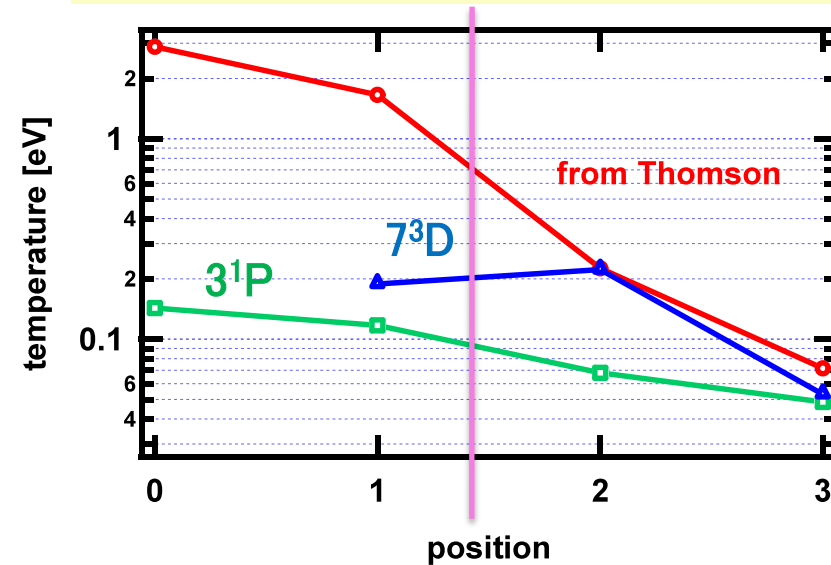
Fitting was performed in the region free from the coma aberration (blue wing in UV region)

Comparison between LTS and Doppler-Stark : (preliminary)

ne: LTS vs Stark(7^1P)



T: LTS vs Doppler (3^1P , 7^3D)



$T(3^1P) = T(7^1P) = T(1^1S)$: assumed
 $n_e(\text{Thomson}) > n_e(\text{Stark:}7^1P)$

1/2 difference $\rightarrow$ integration effect
 Values from Stark are plausible.

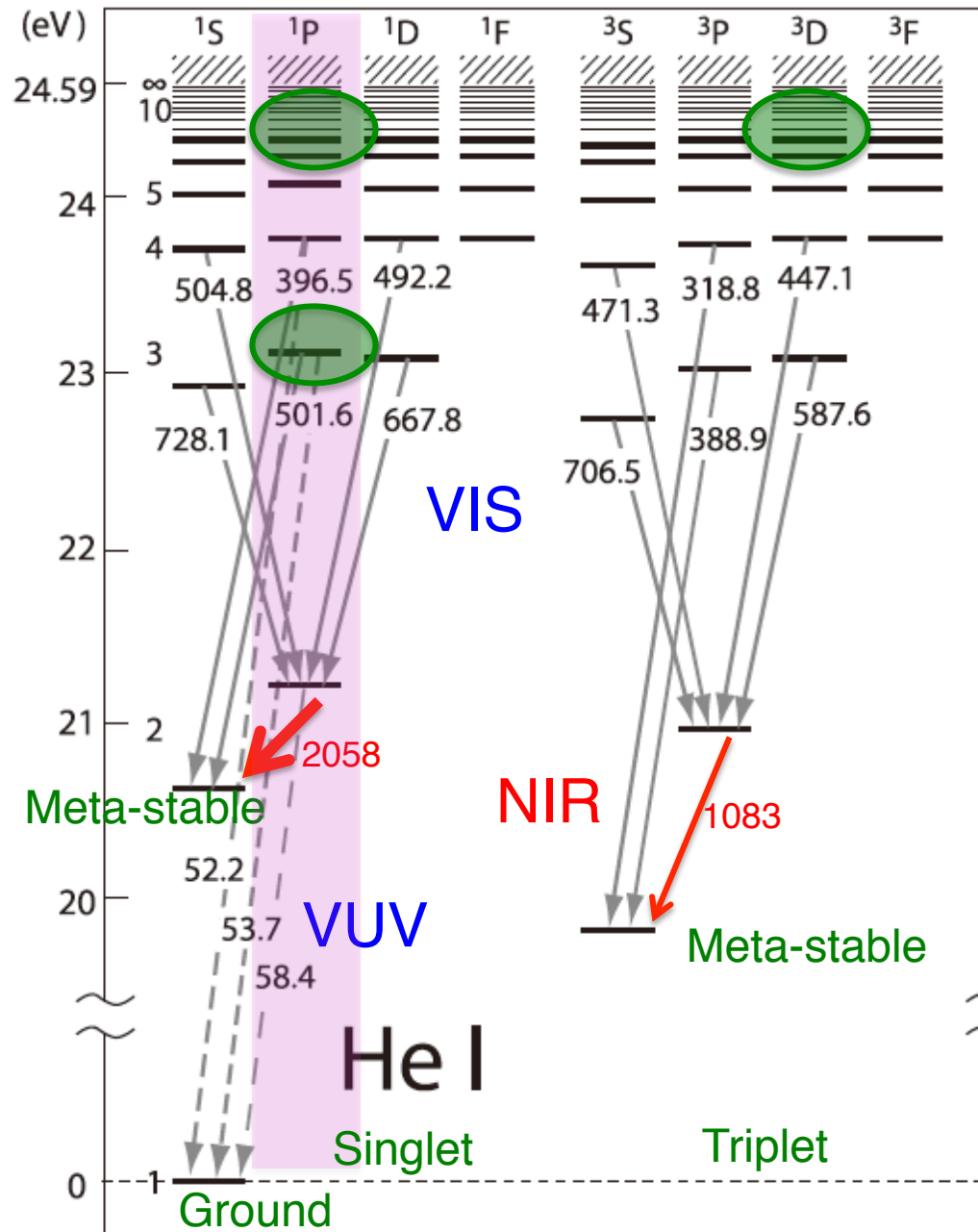
Using $n_e(7^1P)$ to determine $T(7^3D)$ from
 Voigt profile can be reasonable.

ionizing
 $T(1^1S) < T(7^3D) < T_i$

Recombining
 $T_i = T(7^3D)$

Recombining regime,
 $3^1P(\text{atom})$, $7^3D(\text{ion})$ and electron are
 achieving thermal equilibrium among
 them.

Doppler-Stark Spectroscopy for He I line broadening



$$W_V(3^1P) = W_G(3^1P) = W_G(T(\text{He}^0)),$$

-----> Atomic Temperature

$$W_V(7^1P) = W_G(T(3^1P)) [+] W_L(7^1P).$$

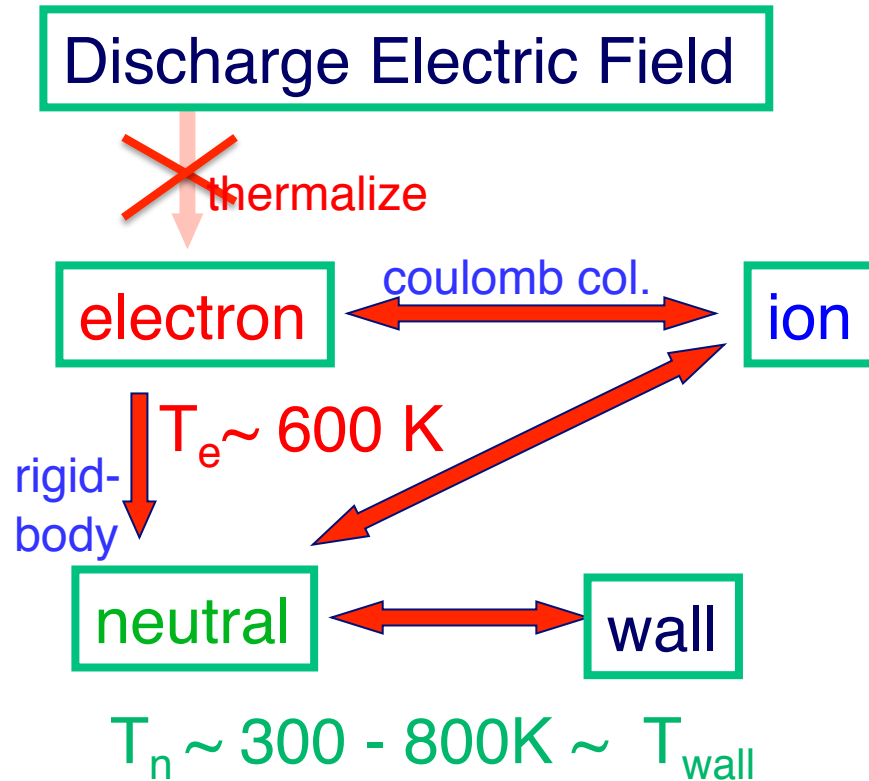
-----> Electron Density

$$W_V(7^3D) = W_G(7^3D) [+] W_L(n_e(7^1P)),$$

-----> Ion temperature
(in recombining plasmas)

[*] **S. Kado**, K. Suzuki, Y. Iida, A. Muraki, "Doppler and Stark broadenings of spectral lines of highly excited helium atoms for measurement of detached recombining plasmas in MAP-II divertor simulator" J. Nucl. Matter. **415**, S1174–S1177 (2011).

Conclusions



Doppler-Stark line broadening for 3 lines, (3^1P), (7^1P), (7^3D) enabled the determination of Atomic Temperature, Electron Density, Ion temperature in recombining plasma.

LTS for the study of low-temperature detached recombining plasmas.

Conventional Homo-tandem double monochromator(system 0 to system I) yielded 0.13 eV . (transition region)

Major upgrade to the system II has achieved the requirement of 0.06 eV , for the EIR plasmas.

It was confirmed that the T_e from the Rydberg series spectra of He I, about $0.05\text{--}0.06\text{ eV}$, is actually the Boltzmann temperature.

Thus it was verified experimentally that the ion, electron and neutral atoms tend to achieve thermal equilibrium among them in recombining plasmas.

Thank you !