平成 24 年度 ダイバータおよびPWI合同研究会 2012.7.22-23

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～

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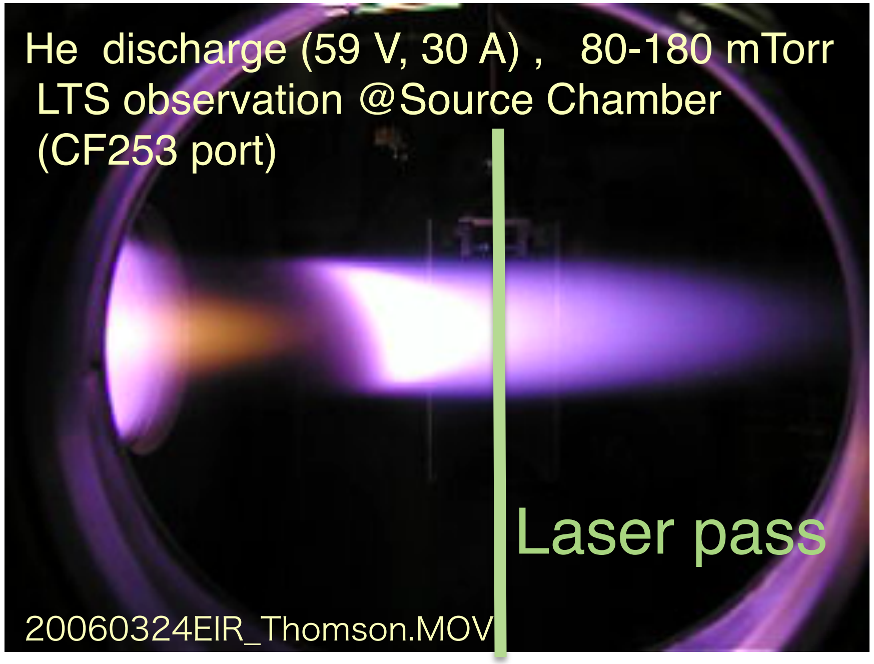
1) Introduction:
- Detached recombining plasma
- He I spectroscopy

2) Development of the LTS for recombining plasmas

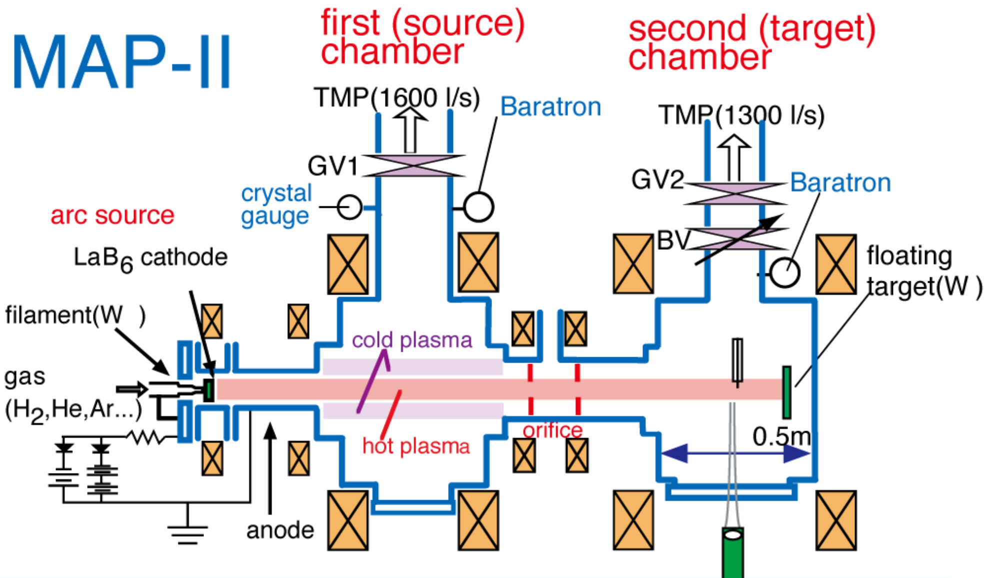
3) Development of the Doppler-Stark Spectroscopy (He I).

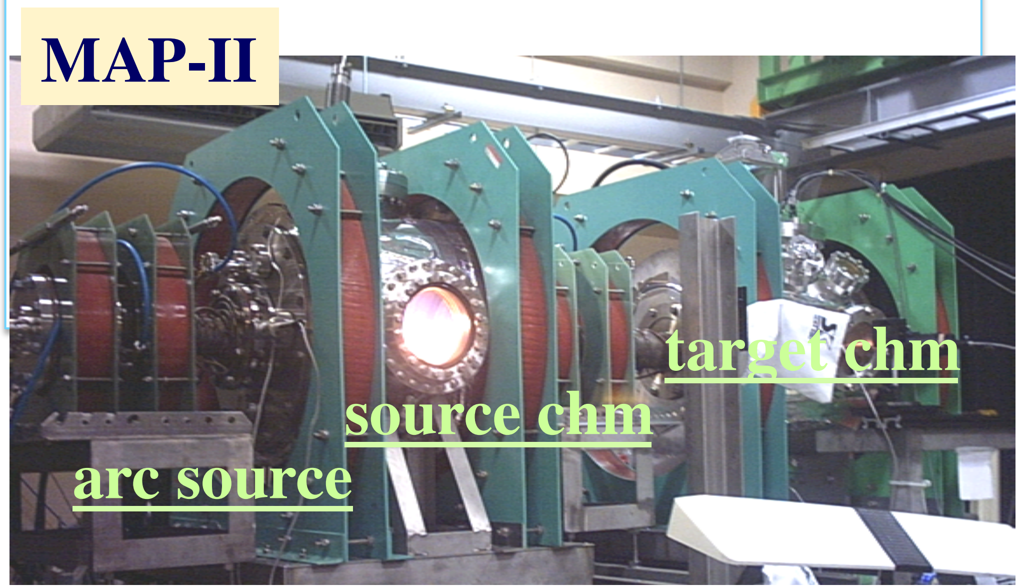
4) Results (LTS and OES)



MAP - II Divertor Simulator

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





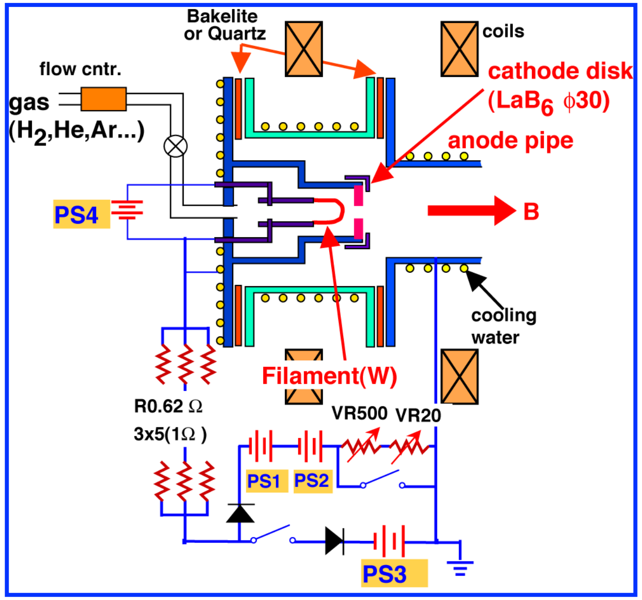
- 1st/source chamber: high n_e
  Probe measurements are limited in low density operations. ---> LTS.
- 2nd/target chamber: good controllability
  equipped with many diagnostics.
- Drift tube with two orifices:

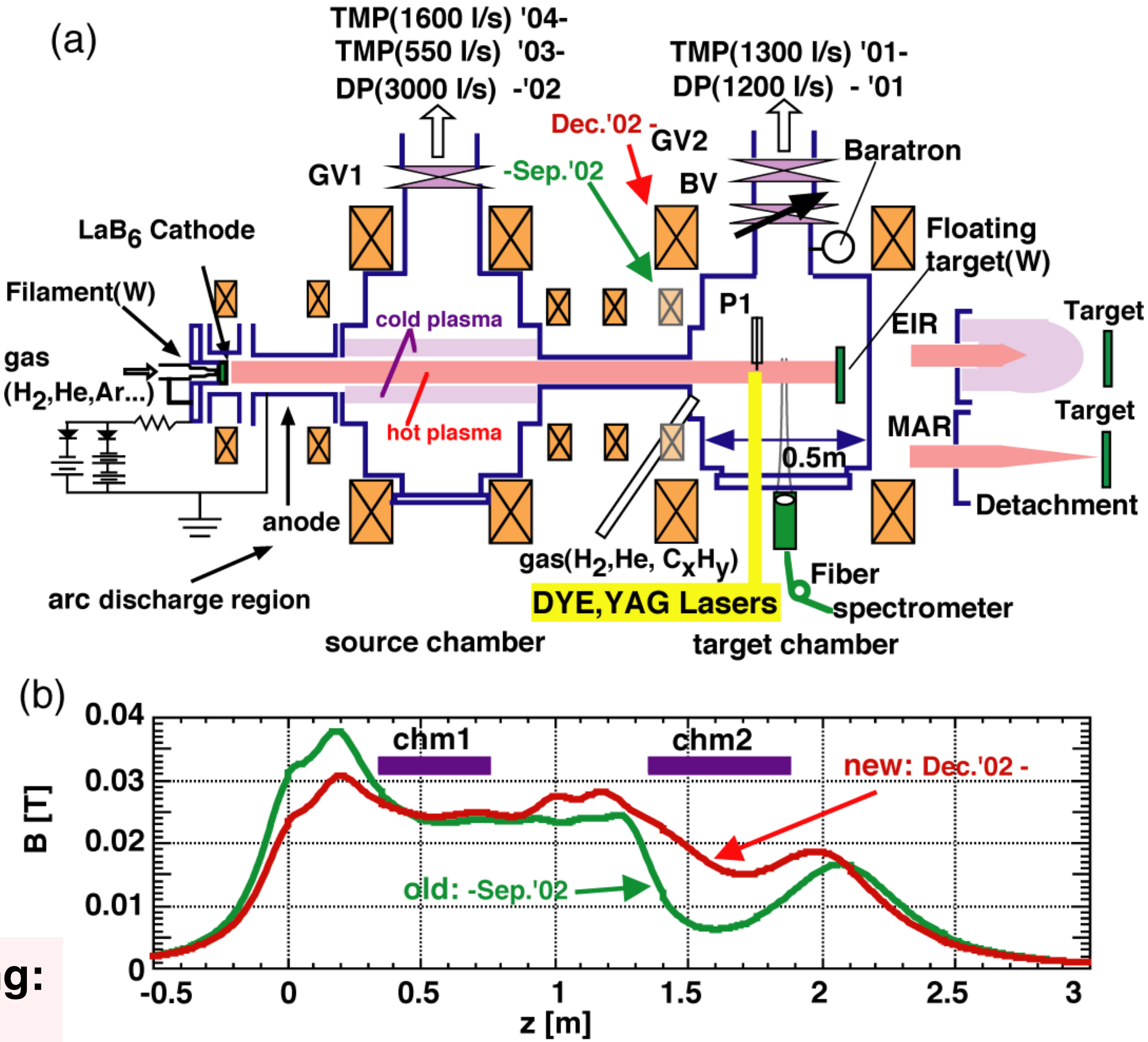
- arc source

Cathode: LaB_6 disk
(ϕ 30 mm with a hole ϕ 5mm)
Anode: Pipe
Discharge ~ 60-100 V
30-45 A,
Ballast resister 1 Ω
B- field ~ 20 mT
Working gases: H_2, He Ar
Puffing gases: He, H_2 C_xH_y
Pressure ~ 1~30 mTorr

MAP-II (Material And Plasma) Divertor Simulator

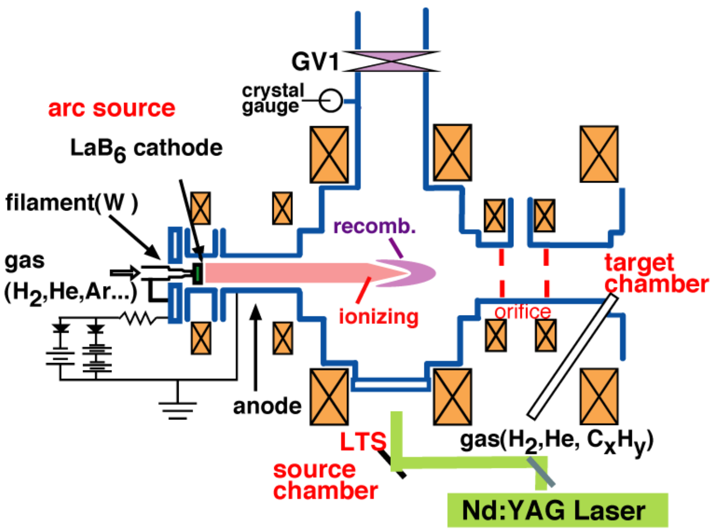
Arc discharge:
70-100V, 30-45A
B = 0.02T

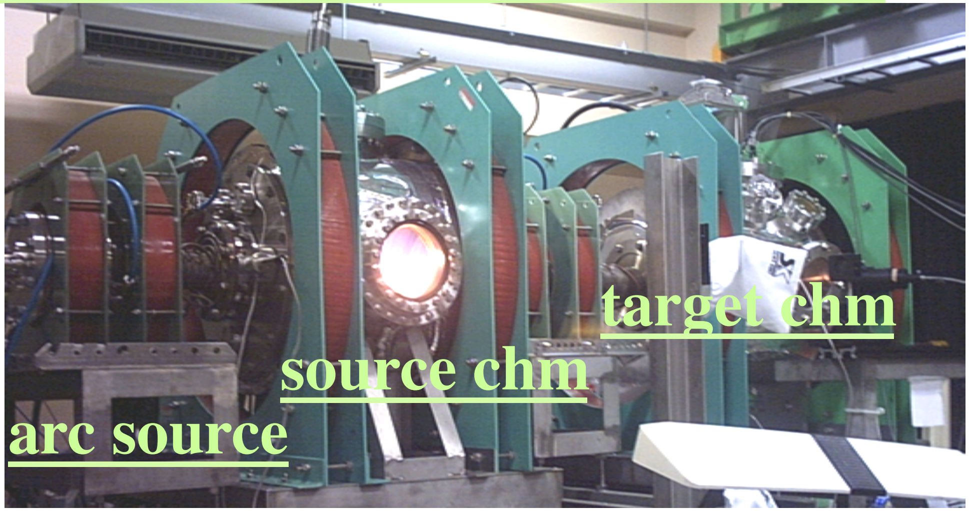




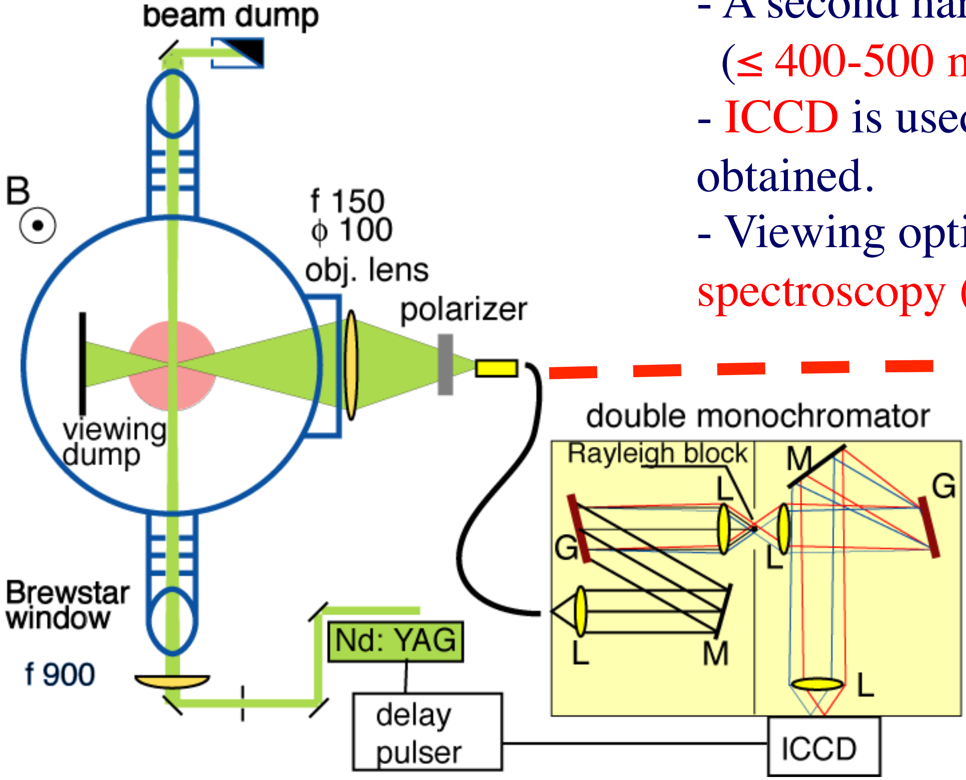
TMP for Differential Pumping:
on--> attached condition
off--> detached condition

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





- A second harmonic Nd:YAG Laser
  (≤ 400-500 mJ / pulse @532 nm, 7 ns, 10 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

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

For high-n

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

Volumetric Recombination Processes (H_2, He .....)

I. Electron-Ion Recombination (EIR)

3BR $M^+ + e + e \rightarrow M^* + e$

Rad.R $M^+ + e \rightarrow M^* + h\nu$

$T_e < 1$ eV

Rydberg spectra (high-n)

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

(1) DA $H_2(v) + e \rightarrow H_2^- \rightarrow H^- + H$

[Fulcher] [Photo-detachment]

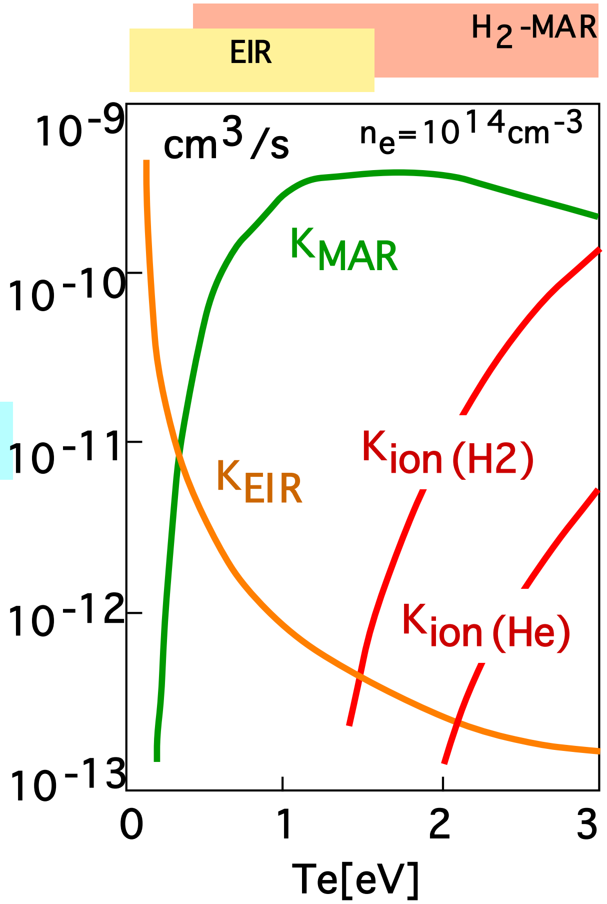
MN $H^- + H^+ \rightarrow H + H^*$

(2) IC $H_2(v) + H^+ \rightarrow H_2^+ + H$

DR $H_2^+ + e \rightarrow H + H^*$

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

complex excitation processes (low-n modified)



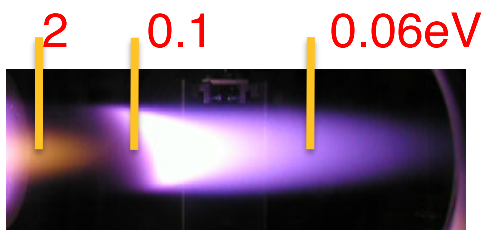
Krasheninnikov et al. Phys.Plasmas(1997)1638

Since the processes strongly depend on Te, requirement of the diagnostics yiels:

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

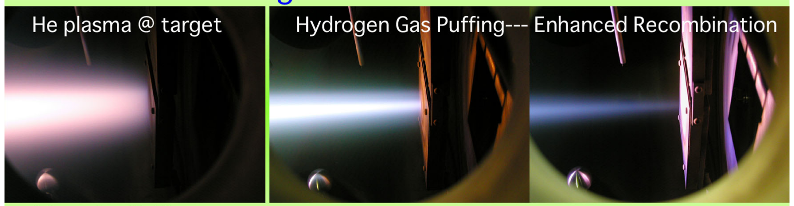
for H_2-MAR Min. $T_e \leq 2$ eV

for EIR Min. $T_e \leq 0.1$ eV



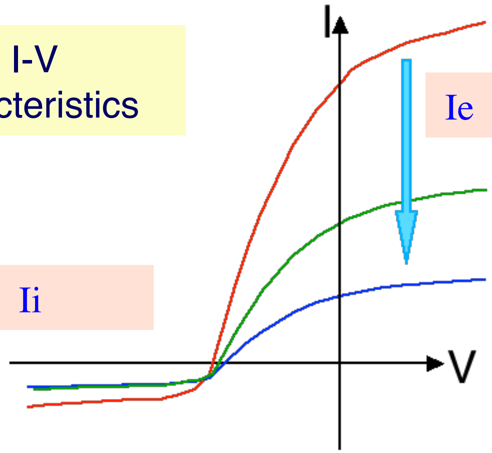
A problem in the measurement of Recombining Plasmas

Divertor/ Edge Plasma Simulator MAP - II

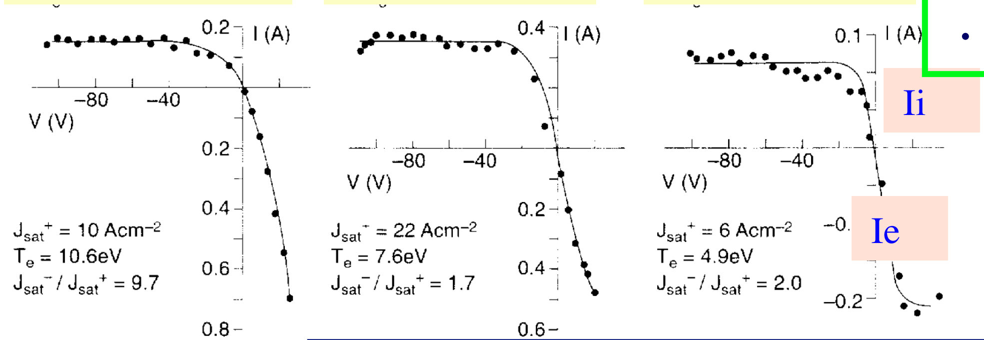


"Attached" Plasma   Plasma Detachment

Probe I-V characteristics



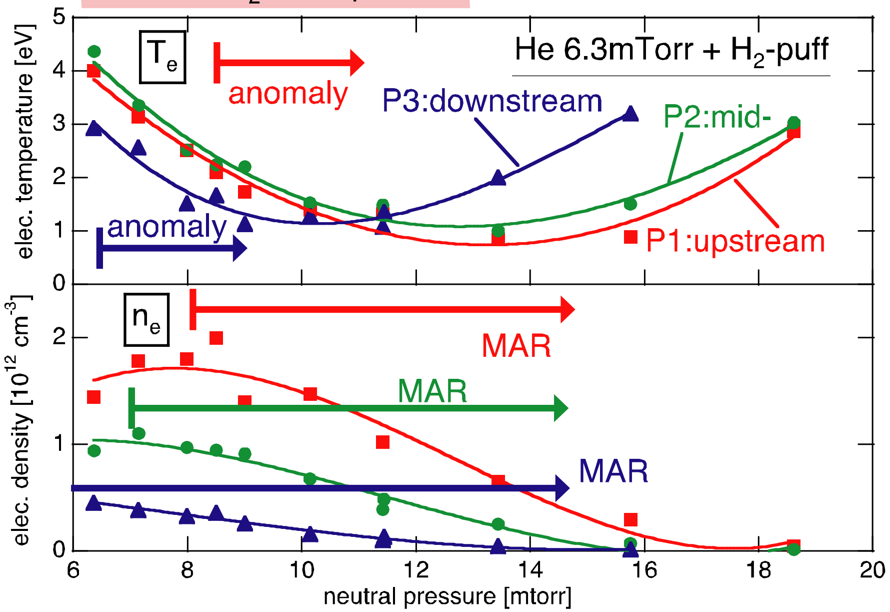
Low Recycle   High Recycle   Detached



D_2 -EIR(JET)

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

Probes in H_2-MAR plasmas **Kado et al., J. Nucl. Matt. (2003))**

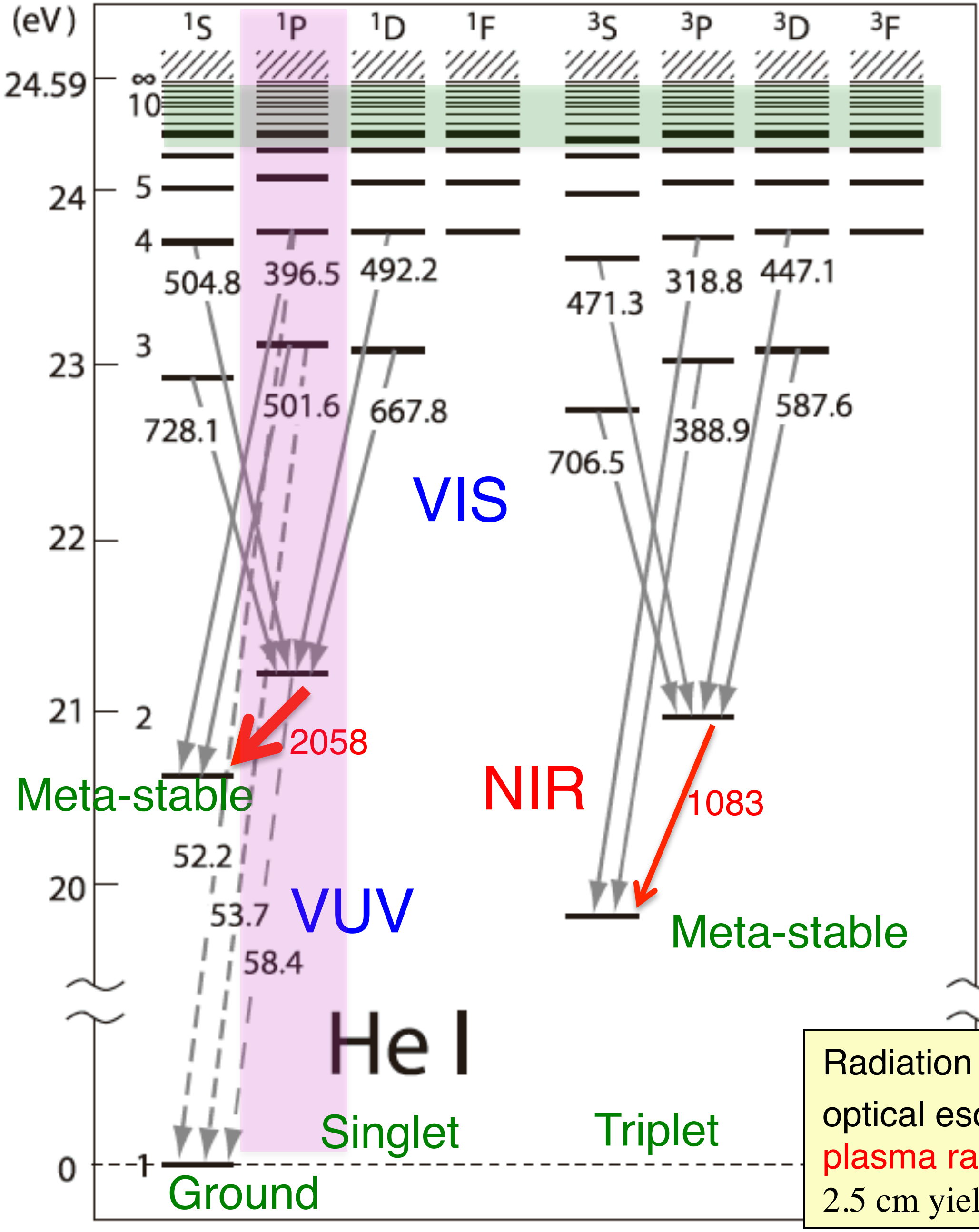


Anomalous I_e decrease, (Only I_i believable):

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

(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.

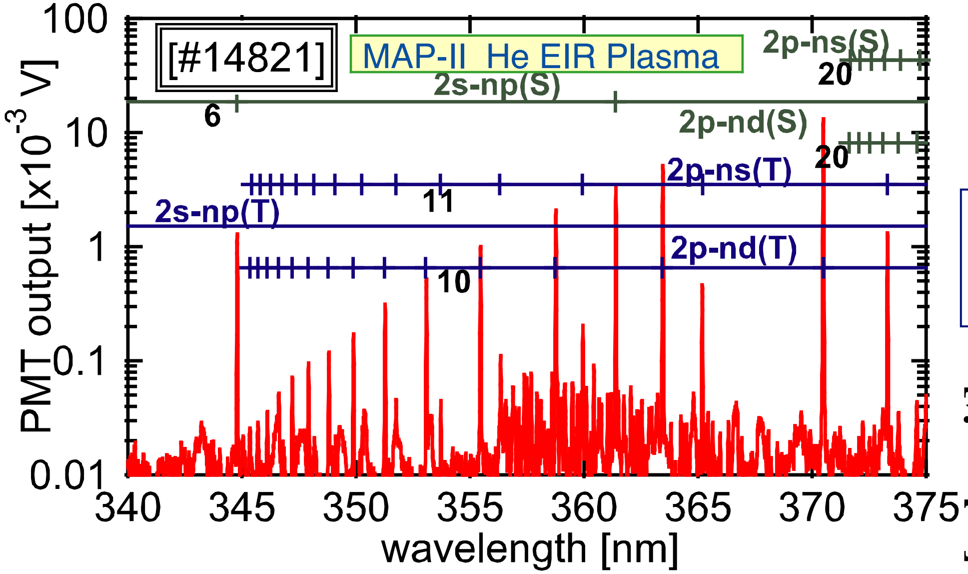
2) Collisional Radiative model
transitions to $n = 2$
(many useful lines, optically thin)
→ suitable for line ratio measurement.
Upper-states: mainly $n = 3, 4$
[*] Y.Iida, S.Kado, *et al.*, RSI **81**, 10E511 2010.

- 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

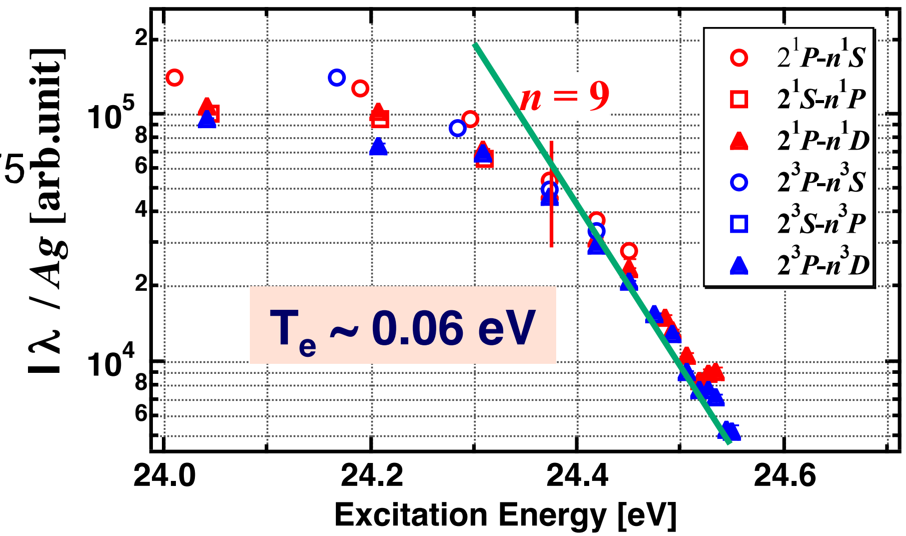
Radiation trapping for resonant 1^1S-n^1P(n=2~7): A -> ΛA
optical escape factor Λ, absorbtion length L [Otsuka(1979)]
plasma radius (2.5 cm) < L < chamber radius (25 cm)
2.5 cm yields good fit with data with T_{gas}=400K (~$T_{rot}(H_2)$)@center

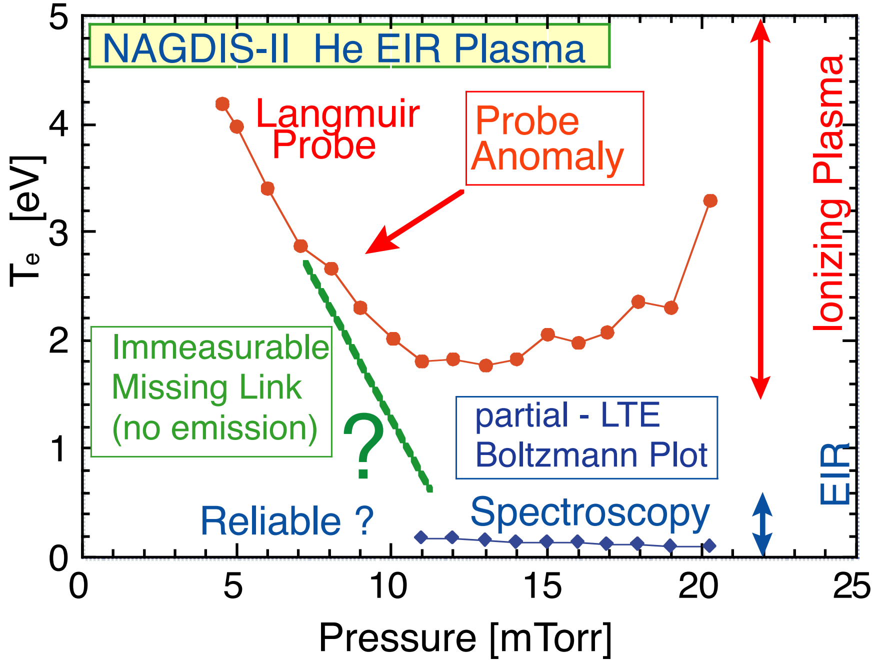
Rydberg spectra: Partial-LTE in the Helium EIR plasmas



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

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





[Ohno et al. Contrib.Plasma Phys. (2001)473]

- 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:

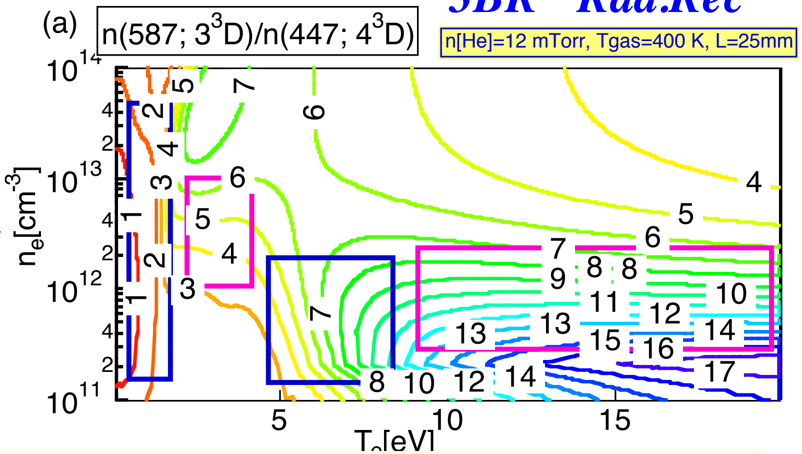
efflux *influx*

$$\frac{dn(p)}{dt} = -\left\{\sum_{q\neq p} C_{p\to q} n_{\mathrm{e}} + S_p n_{\mathrm{e}} + \sum_{q<p} A_{p\to q}\right\} n(q) + \sum_{q\neq p}\left\{C_{q\to p} n_{\mathrm{e}} + A_{q\to p}\right\} n(q) + \left\{\alpha_p n_{\mathrm{e}} + \beta_p\right\} n_{\mathrm{i}} n_{\mathrm{e}}$$

ex.&deex. *ion.* *decay* *3BR* *Rad.Rec*

$$n(p) = R_0(p) n_e n_z + R_1(p) n_e n_{1^1 S}$$

Recombining & Ionizing plasma



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 squire fit of the population ratio $r_i = n(i)/n(ref)$ to the evaluation function as follows:

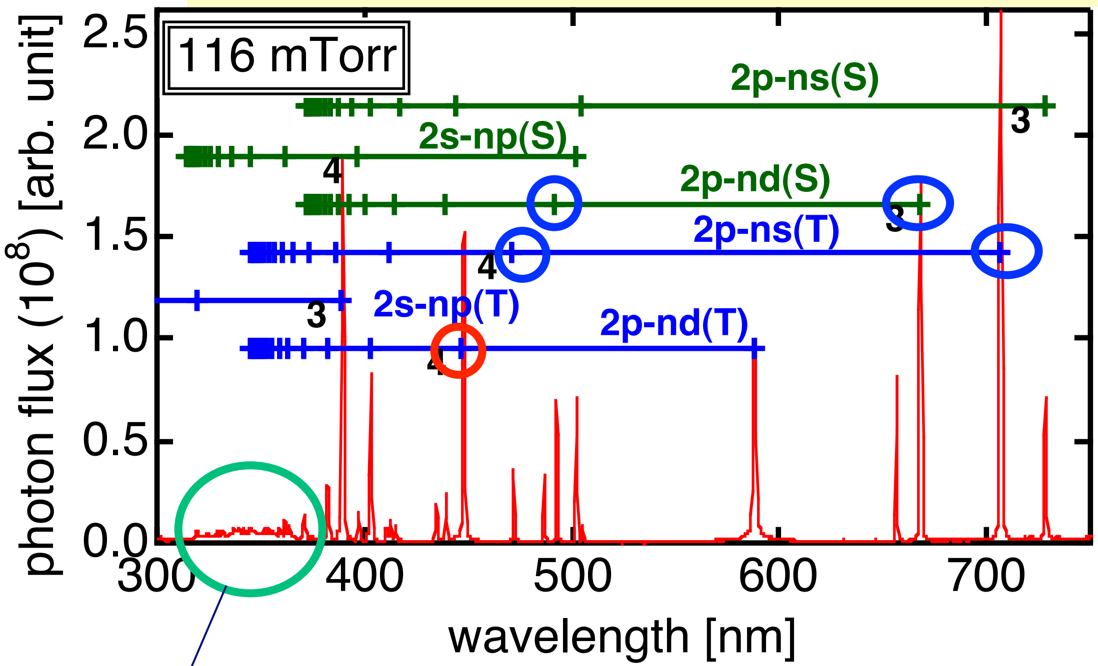
$$f(T_e,n_e) = \sum_i \left(\frac{r_i^{CR}(T_e,n_e) - r_i^{EXP}}{r_i^{CR}}\right)^2, \sum_i \frac{\left(r_i^{CR}(T_e,n_e) - r_i^{EXP}\right)^2}{r_i^{CR}}, \sum_i \left(\frac{r_i^{CR}(T_e,n_e) - r_i^{EXP}}{\Delta r_i^{EXP}}\right)^2, etc.....$$

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 monochomator (PMT) for Rydberg spectra.

Spectra obtained in the single acquisition



Merits (low-n states):

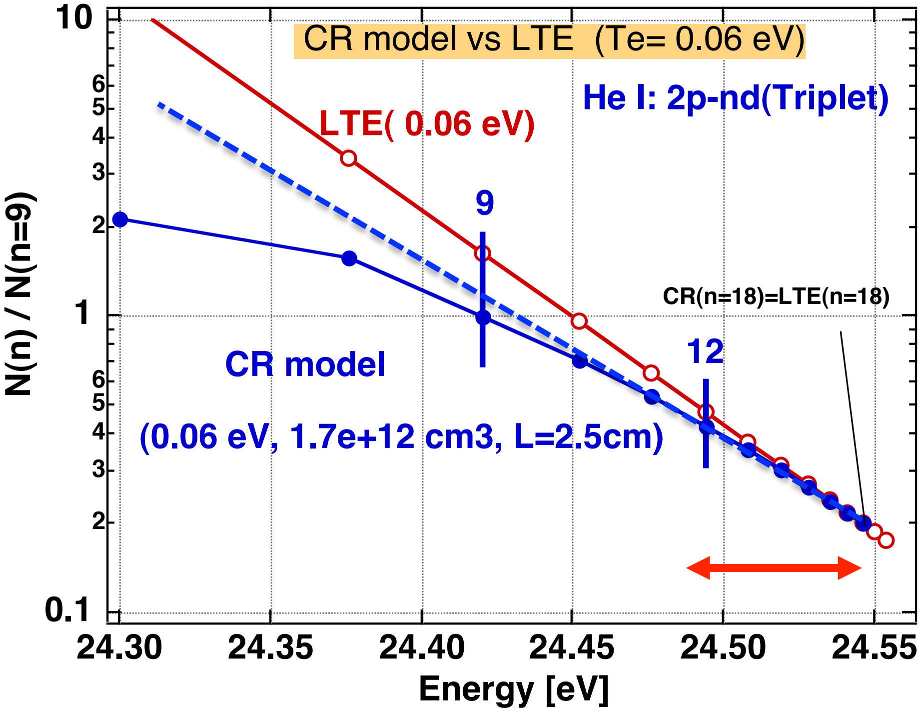
- Brighter line emissions
- Good line separation.
- Fast measurements (< minutes)

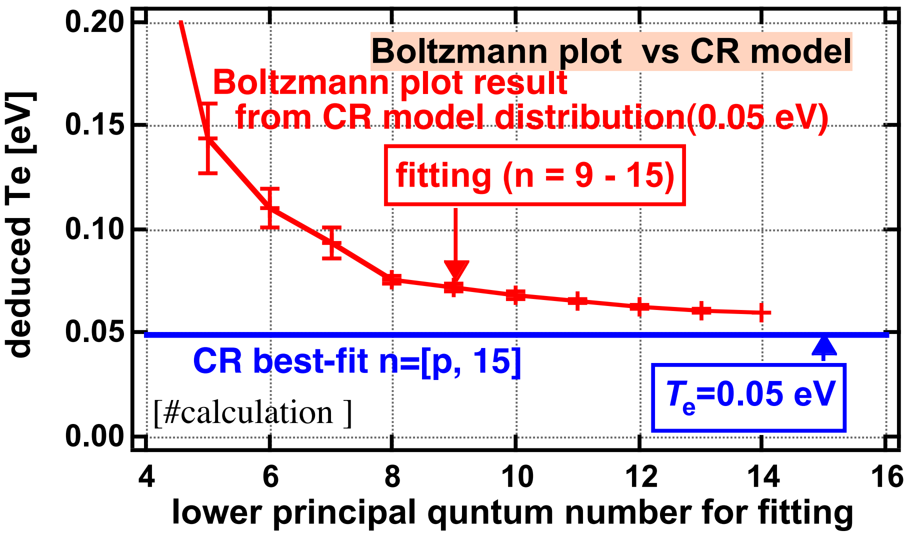
Demerits:

- 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≥9) -> ~ 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).

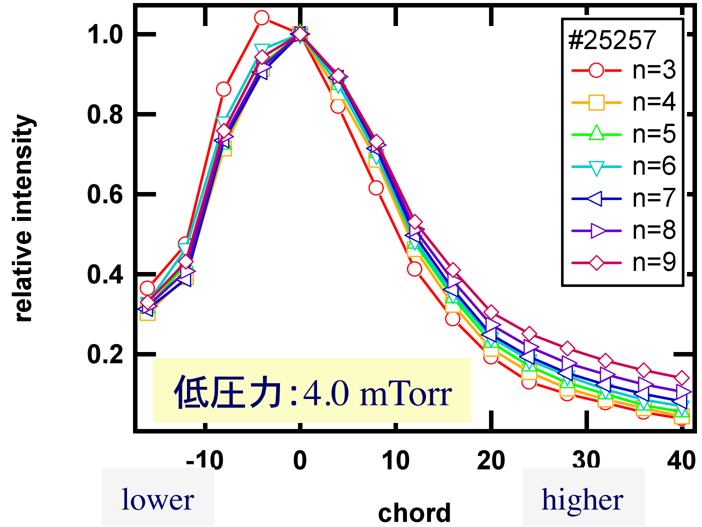
1) calculate 0.05 eV distribution (CR)
2) perform fitting to the distribution based on LTE (for n =[p , 15])
3) compare with each other

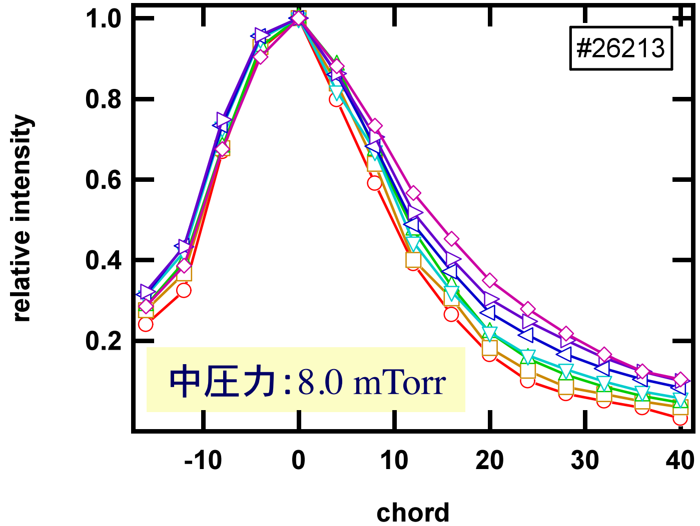
Results of Boltzmann plot converges to the best-fit value (0.05 eV) of CR model as lowest n increases.

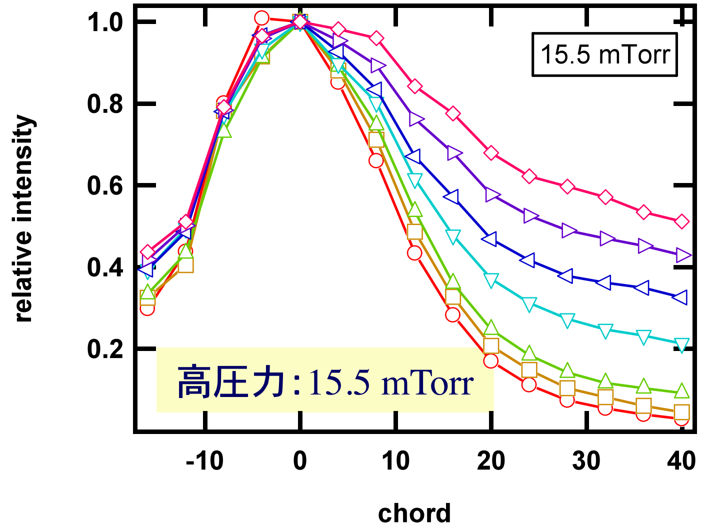
He I ^{3}D-system spatial distribution

［日本物理学会20aTJ-9 2010.3, 鈴木 M論 ］

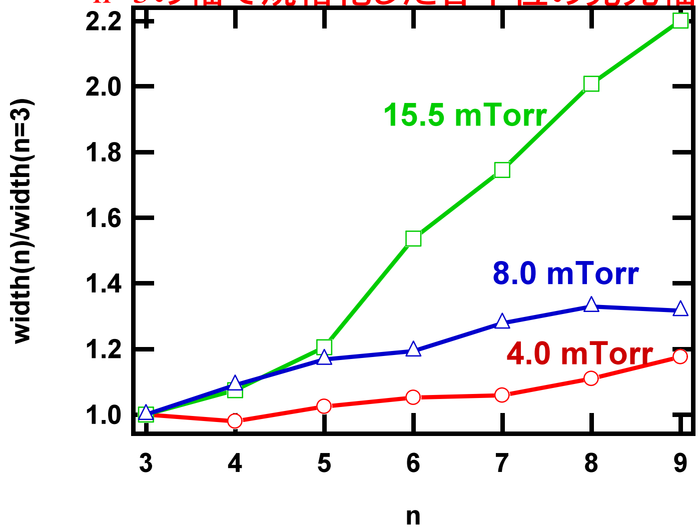
n=3〜9 ^{3}D terms, spatial distribution: n-dependence become more obvious for higher pressure

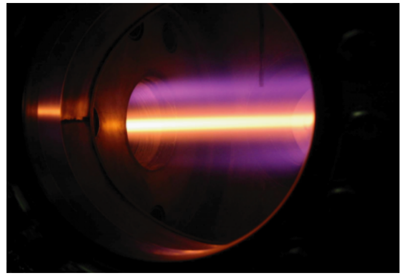






n=3の幅で規格化した各準位の発光幅



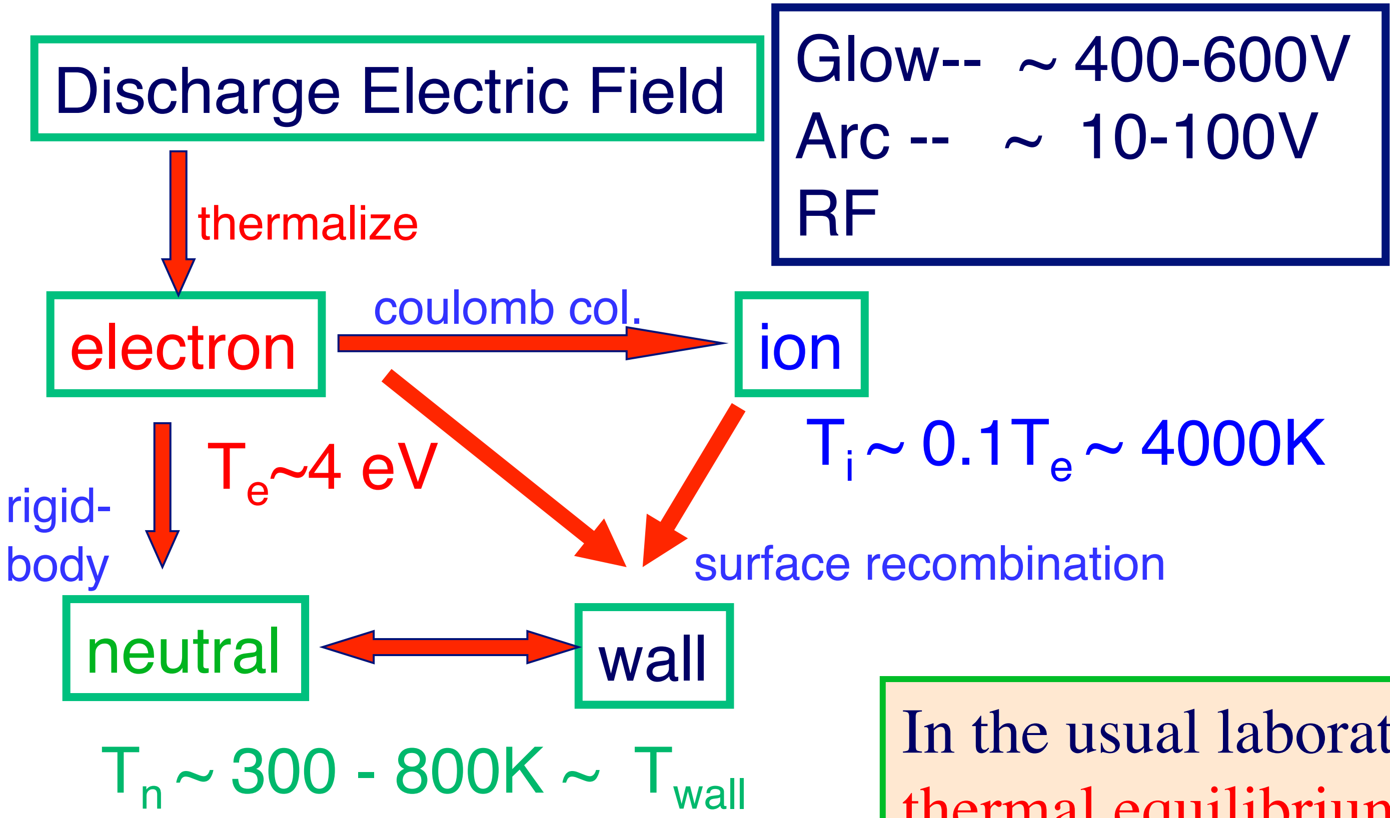


再結合プラズマ:
上下非対称
本研究では(プラズマ
上部が顕著)

空間構造を調べる必
要性

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

Temperatures of ion, electron and neutral (ionizing plasma)



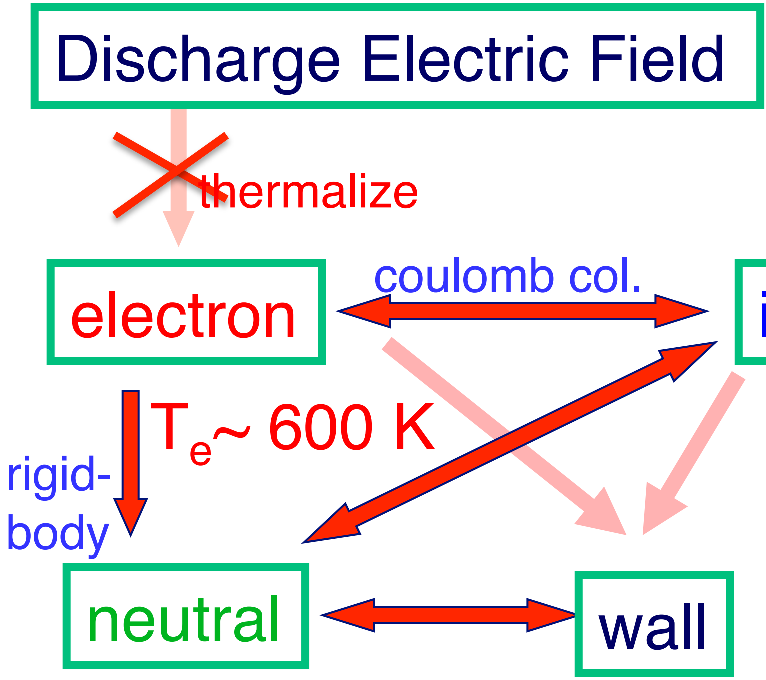
1 eV = 11604 K

$n_e \sim n_i \sim 10^{11\text{-}13}\ cm^{-3}$
$n_n \sim 10^{15}\ cm^{-3}$

In the usual laboratory plasmas, thermal equilibrium can be achieved ONLY in each species, and NOT between them.

How about the recombining plasma ?

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



Glow-- ~ 400-600V
Arc -- ~ 10-100V
RF

1 eV = 11604 K

$T_n \sim 300$ - 800K ~ T_{wall}

$n_e \sim n_i \sim 10^{11\text{-}13}$ cm^{-3}
$n_n \sim 10^{15}$ cm^{-3}

A hypothesis (by Kado)

- No energy input.
- Possibility that electrons, ions and neutrals are undistinguishable.
- Thermal equilibrium achieved ?

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

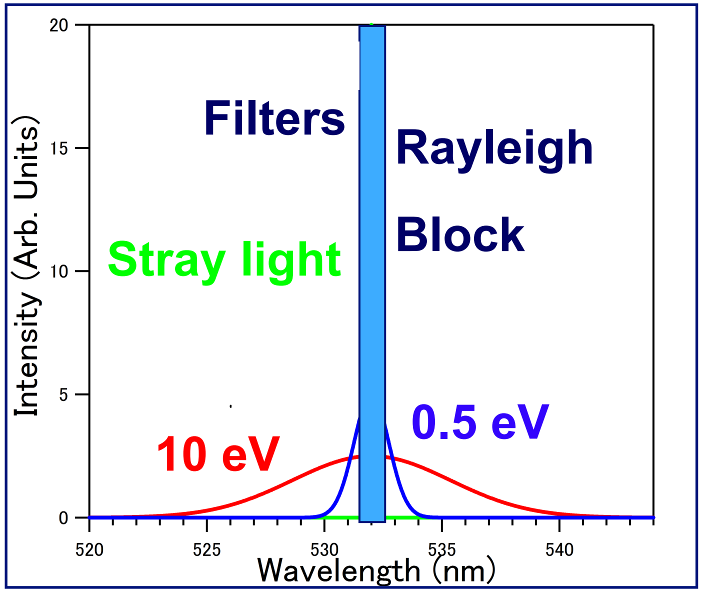
•Data accumulation

- Filter polychromator (≥ 1nm band width) or notch filter (~ 17 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**

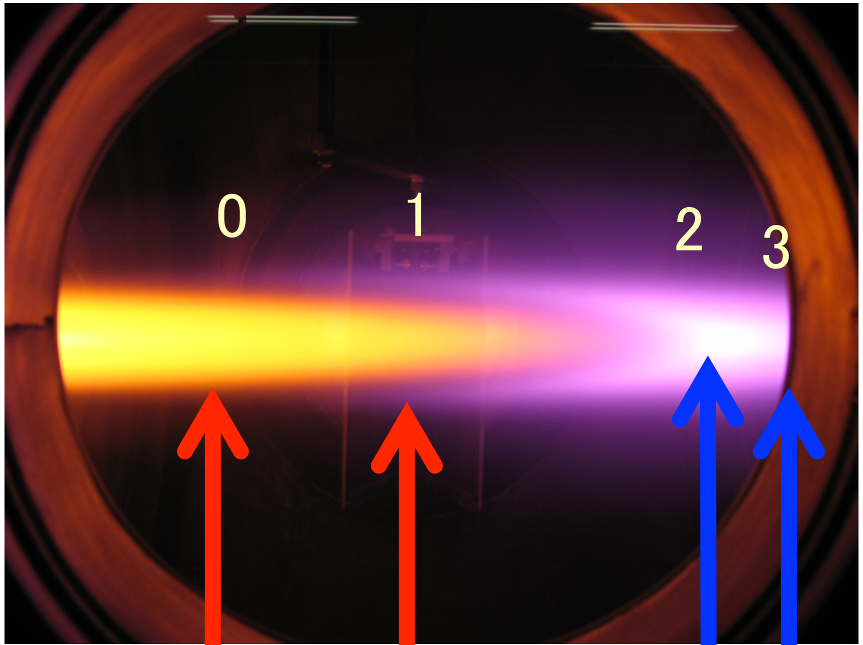
1-2 nm/mm for Te< 40 eV

Conventional filter polychromators system

experiments: MAP-II divertor simulator

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

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



Ionizing upstream

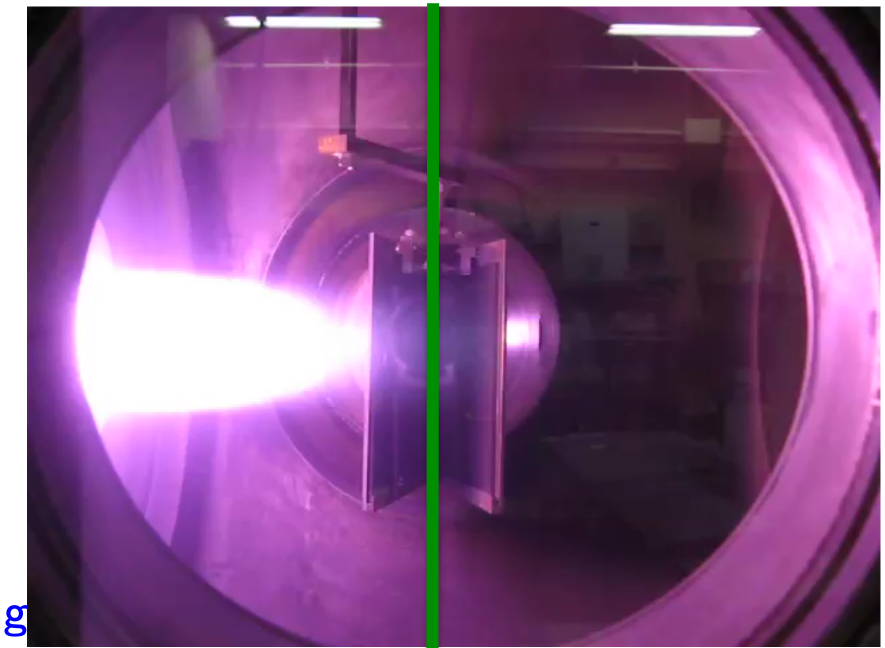
ionizing downstre am

Recombining front

Recombining Brightest point

$T_e > 2$ eV ～1eV ～0.2 eV ＜0.1 eV

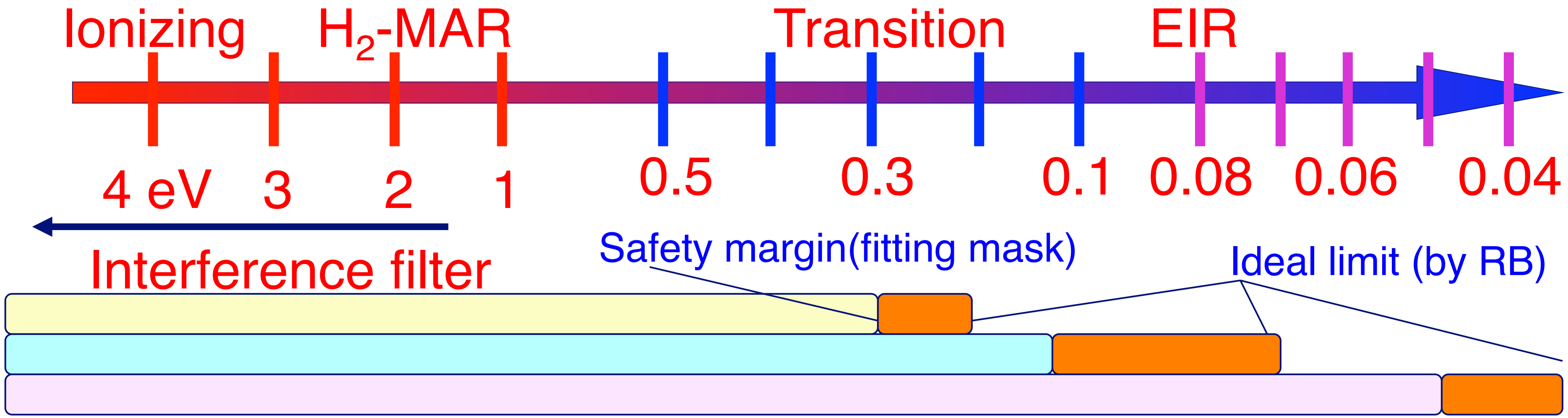
pure He (~ 60 V, 30 A) , 80-200 mTorr
pressure ＝ LTS position@Source Chamber



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 eV (2004- 2005)

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

System-I

0.07 - 0.13 $\leq T_e \leq$ 40 eV (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 eV (2007 -)

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

Rayleigh block:

Ø~0.3mm

Ø~0.2mm

DM: focal length

135 + 135 mm

(F/2.8)

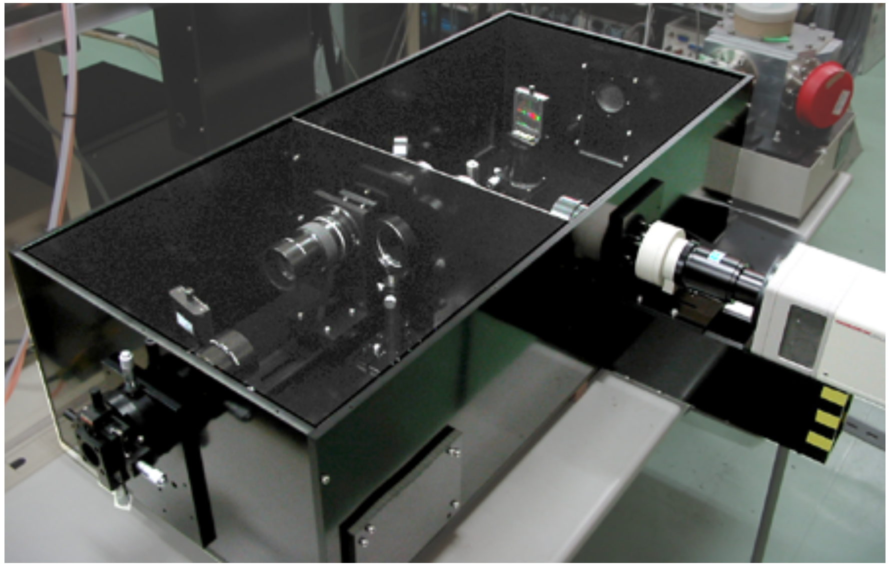
200 + 100 mm

(F/2)

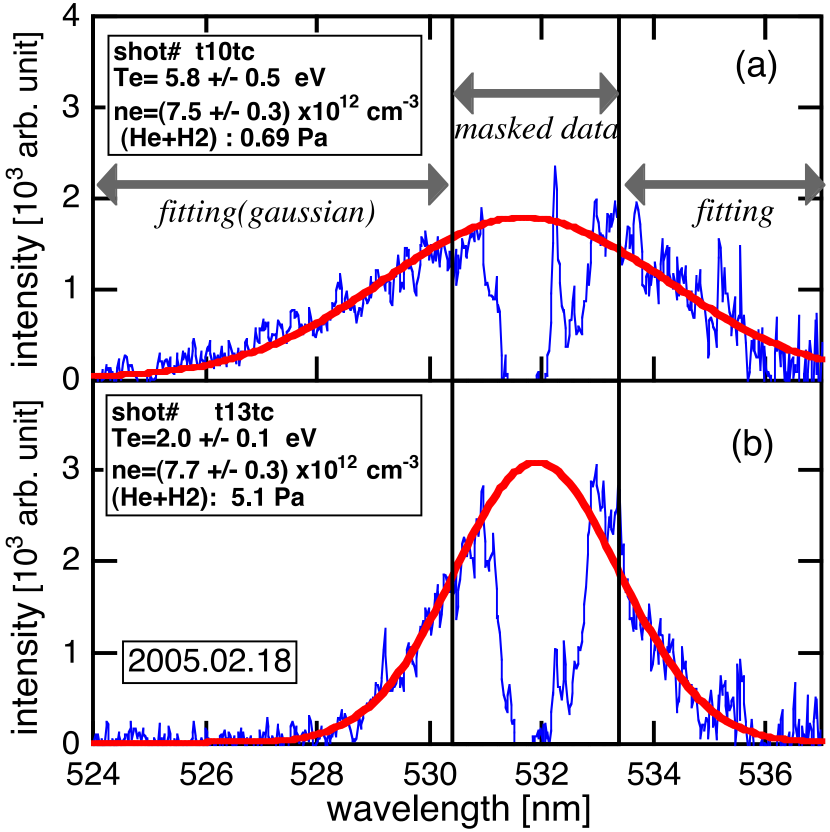
Example of the LTS spectra (H2-MAR, System 0)

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

hand-made double monochromater



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

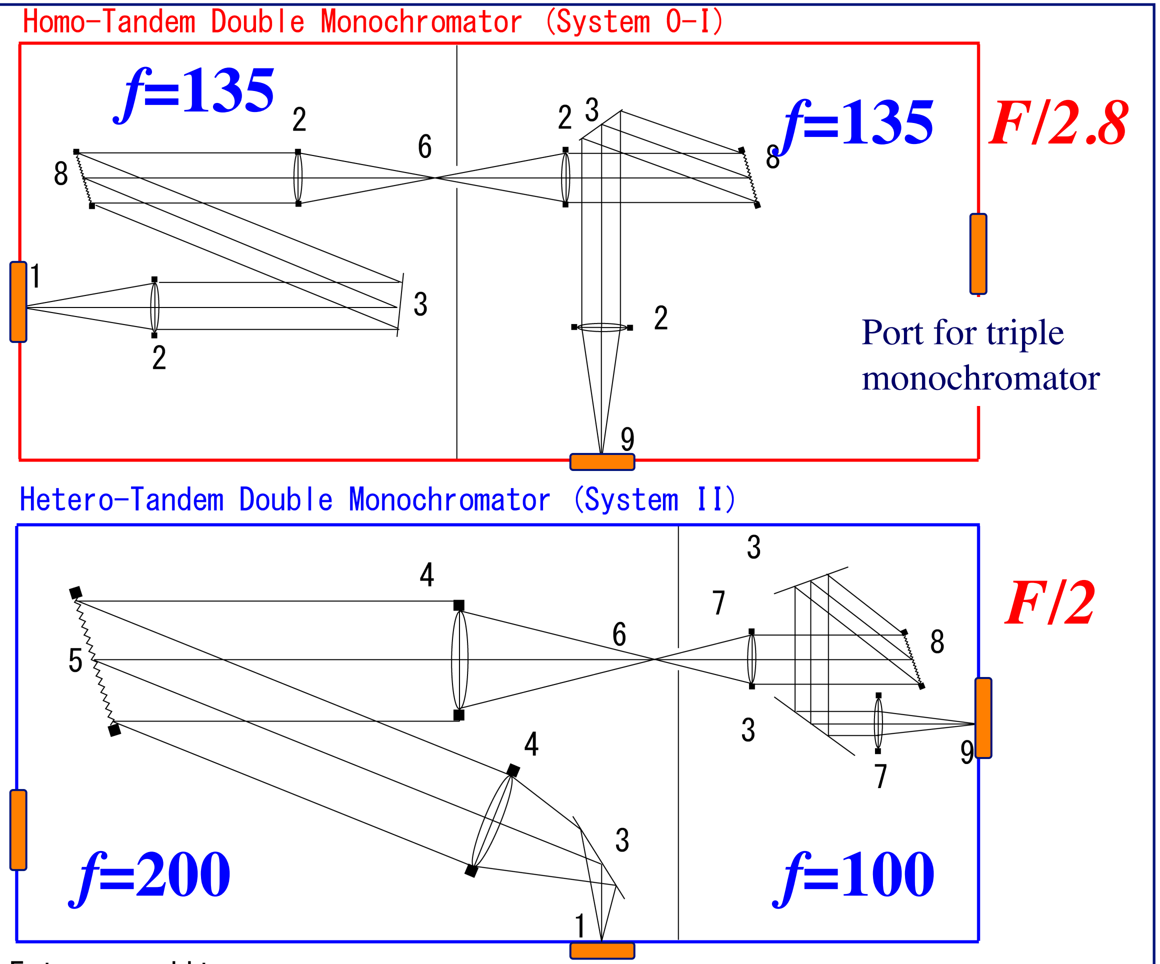


The Thomson signal is obtained after the subtraction of stray light.
The central notch filtered region is avoided in the Gaussian fitting by means of a mask function.

Upper : 5.8 eV

Lower : 2.0 eV

Hetero-Tandem Double Monochromator (hand-made)



1. Entrance slit
2. Camera lens F/2.8, f=135mm, Φ=48mm
3. Mirror
4. Achromatic lens F/2, f=200mm, Φ=100mm
5. Holographic grating 1800gr/mm, 100mmX135mm
6. Rayleigh block
7. Achromatic lens F/2, f=100mm, Φ=50mm
8. Holographic grating 1800gr/mm, 50mmX50mm
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: Ø~0.2mm

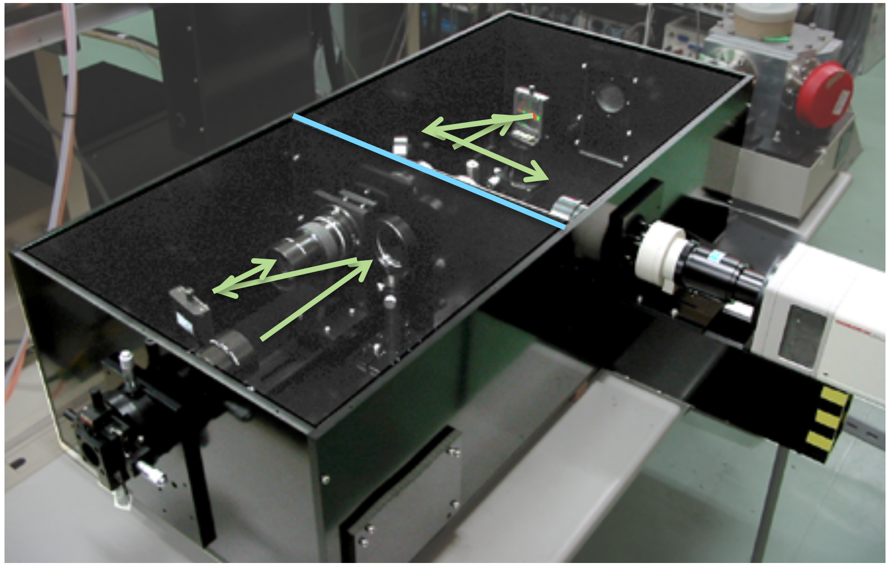
Groove frequency 1800 gr/mm

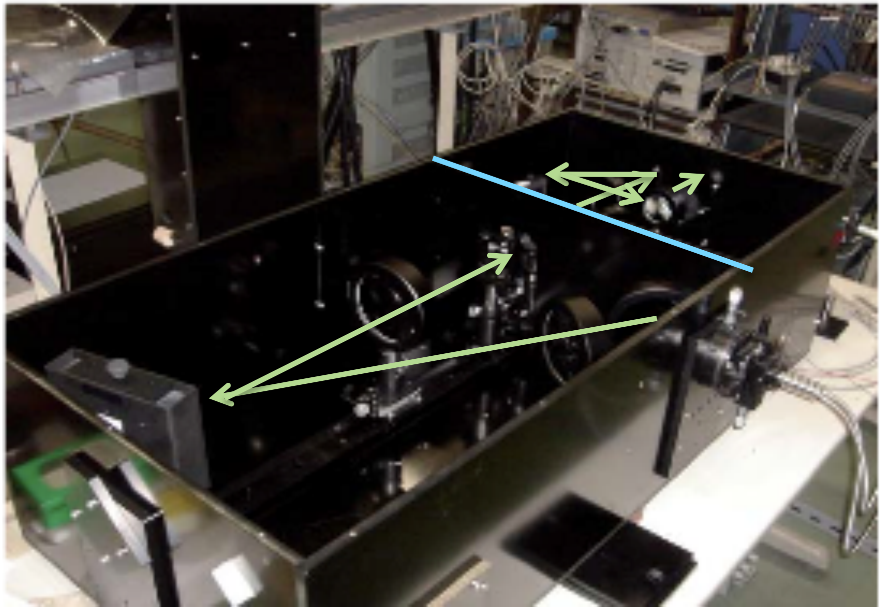
1st Rec.Lin.Disp.(nm/mm)
Sys. I: 3.14 → T_e=0.07eV
Sys. II: 2.03 → T_e=0.03eV

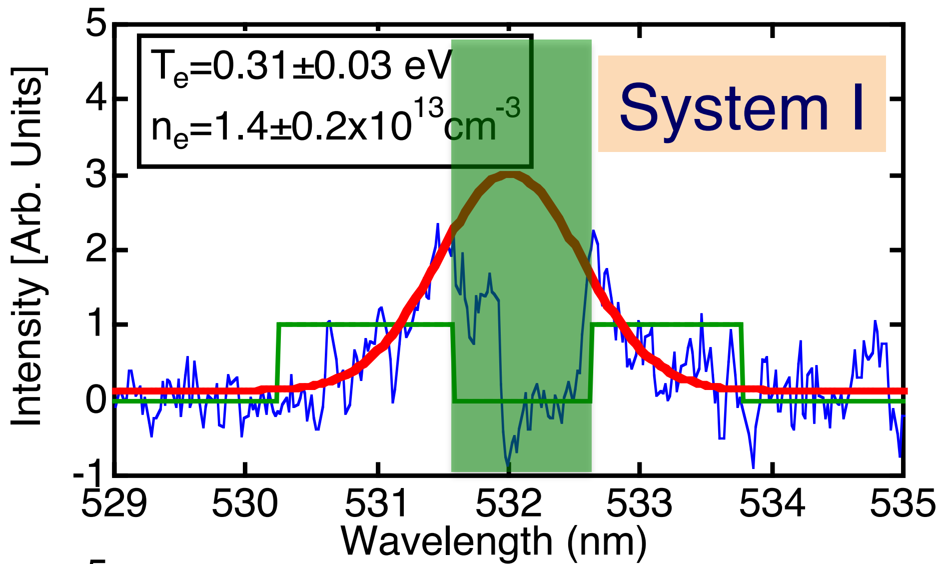
2nd Rec.Lin.Disp.(nm/mm)
Sys. I: 3.14
Sys. II: 4.05

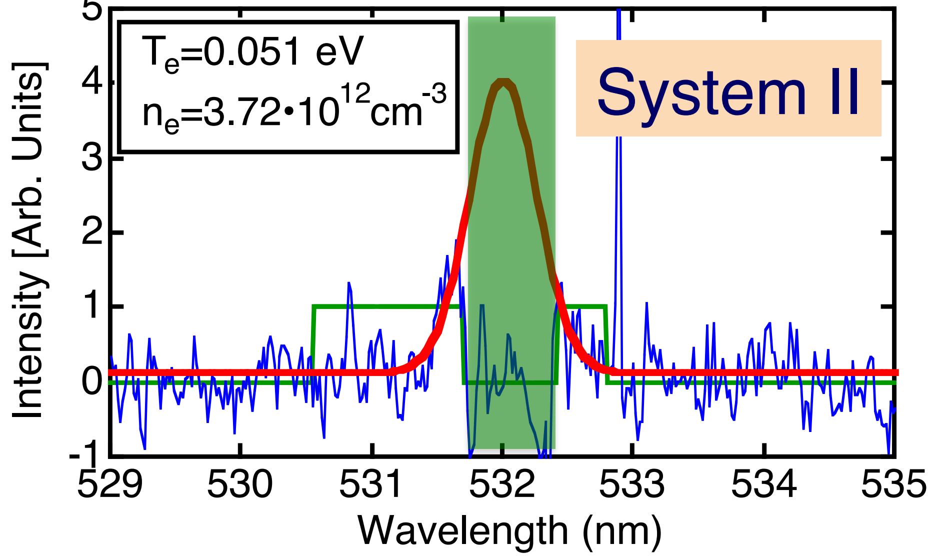
2X Rec.Lin.Disp.(nm/mm)
Sys. I: 1.57
Sys. II: 1.36
→ comparable

Upgrade of the spectrometer: Sys. 0, I → Sys. II





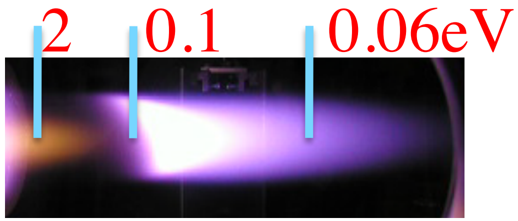




The practical lower limit was reduced from 0.13 to 0.048 eV

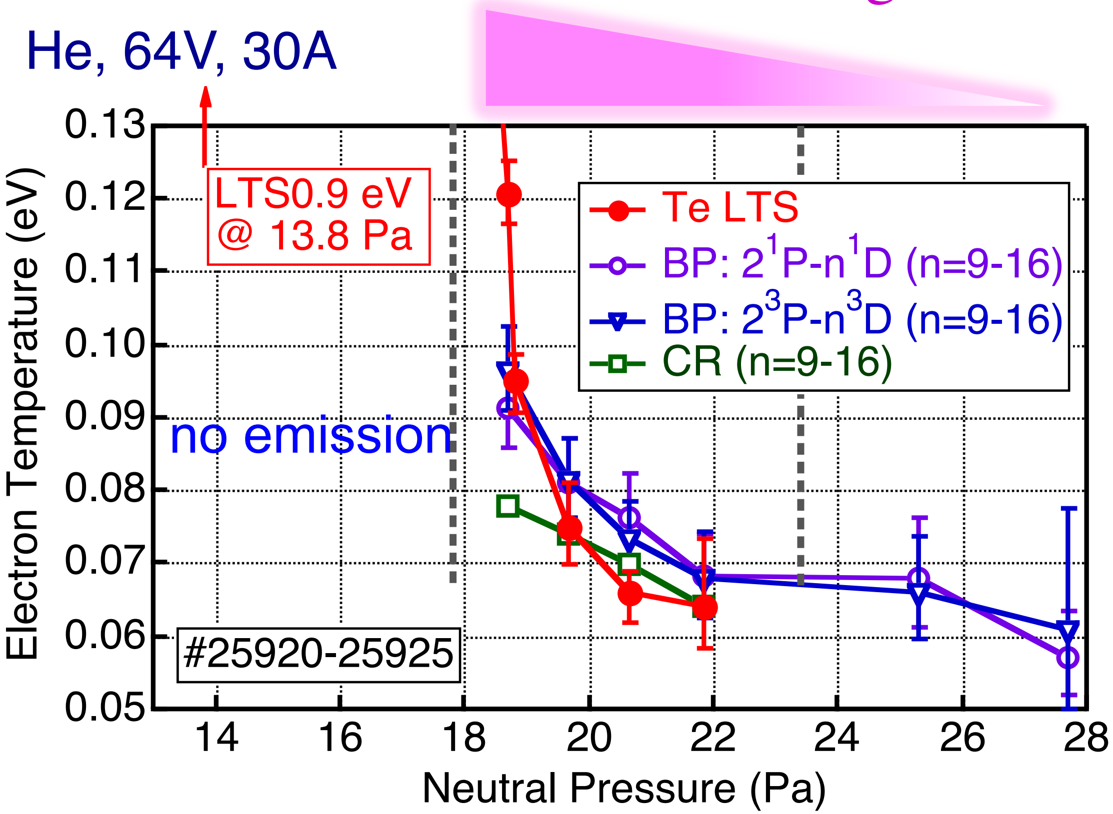
LTS vs Spectroscopy (high -n) at EIR front: Sys. II

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



Schematic line- integrated brightness

He, 64V, 30A



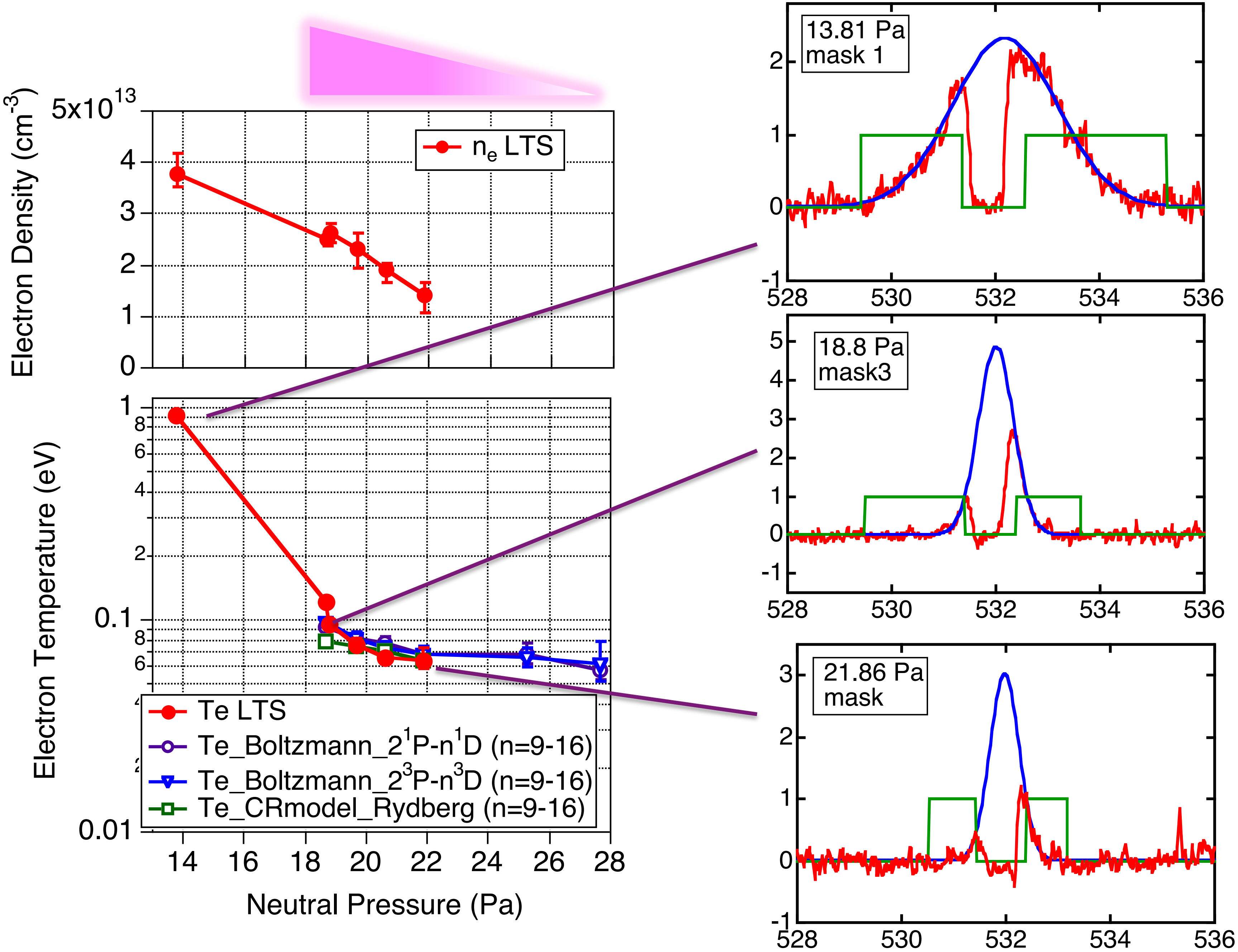
T_e (LTS) monotonically decreased until 0.065 eV, which agrees well with those obtained from the Boltzmann plot(BP) method (0.068 eV) for the Rydberg series and from CR model (high-n).

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) ～0.06 eV -- confirmed by LTS

[ ] Scotti and Kado, J. Nucl. Matter. **390-391**, 303-306 (2009)

LTS spectra

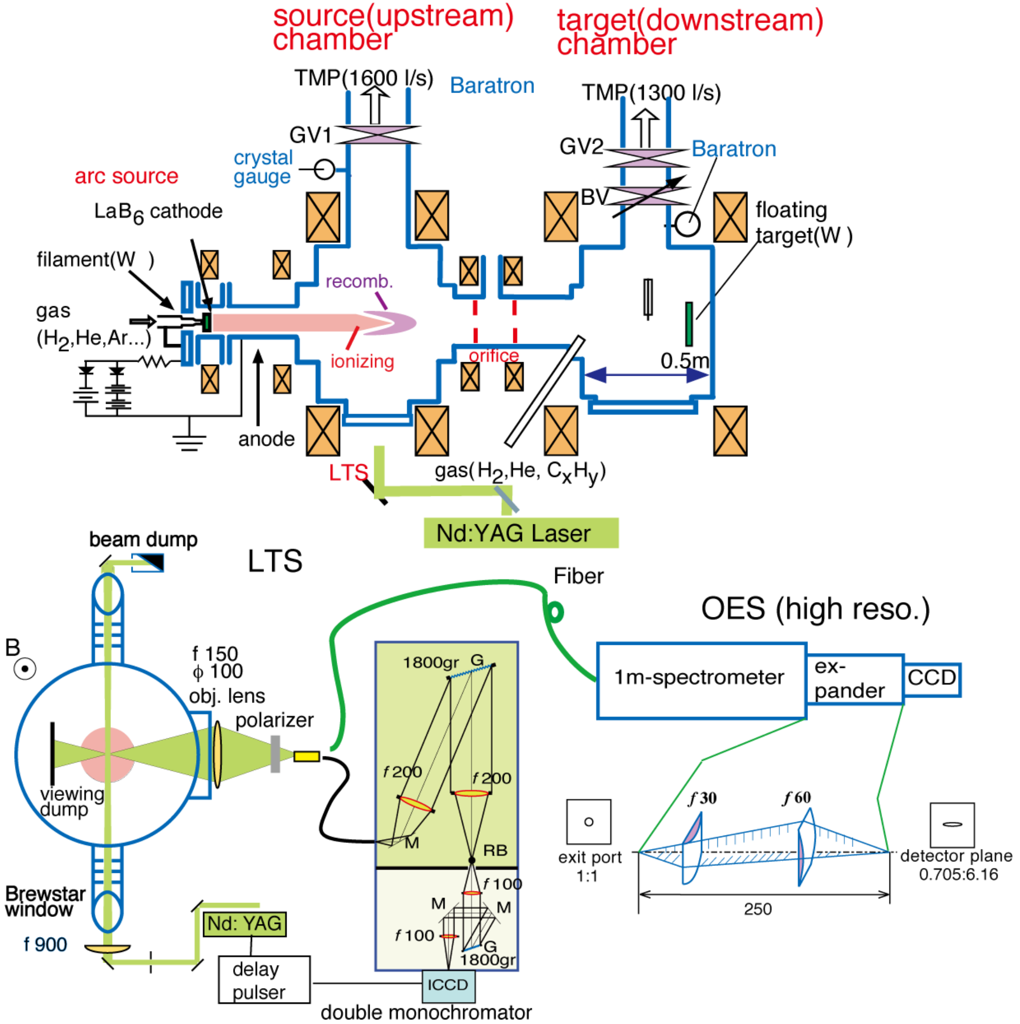


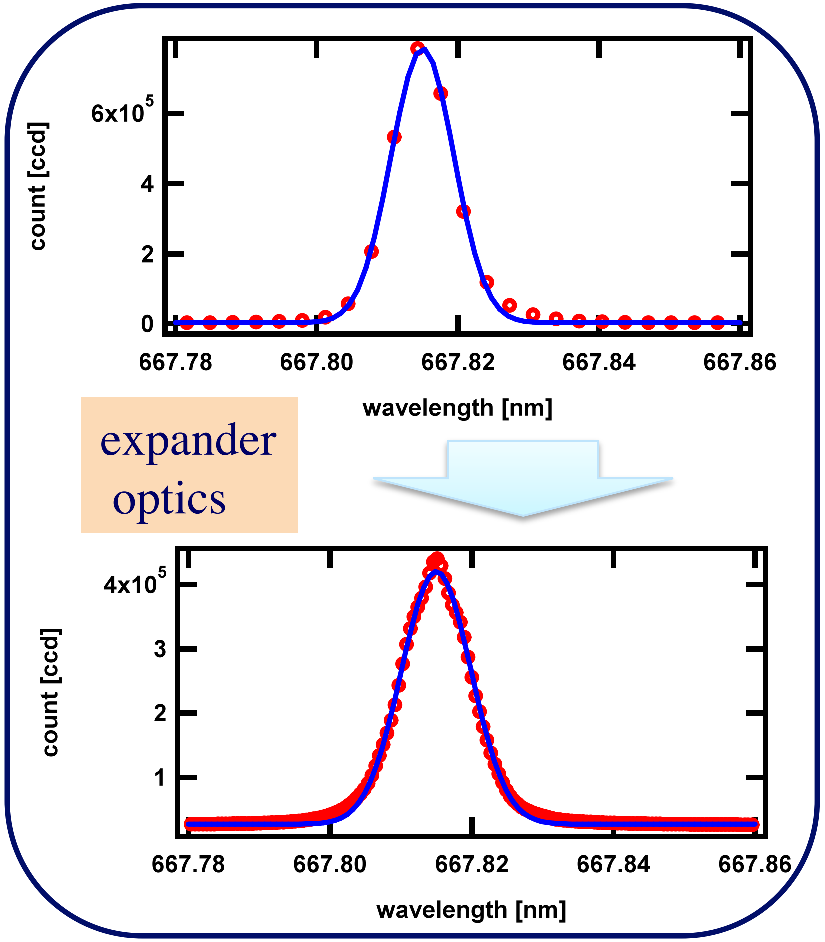
Electron Density (cm^{-3})
5x10^{13}
n_e LTS
Electron Temperature (eV)
Te LTS
Te_Boltzmann_2^{1}P-n^{1}D (n=9-16)
Te_Boltzmann_2^{3}P-n^{3}D (n=9-16)
Te_CRmodel_Rydberg (n=9-16)
Neutral Pressure (Pa)
13.81 Pa
mask 1
18.8 Pa
mask3
21.86 Pa
mask

LTS and Stark Spec. on MAP - II Divertor Simulator

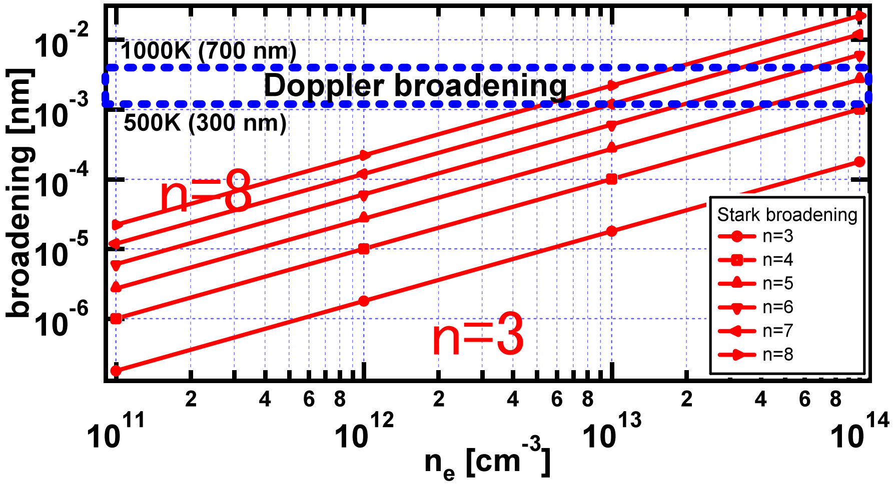
Arc source with B- fiel ~ 20 mT
Cathode disk (LaB_6 ϕ 30 mm), Anode: Pipe
Discharge ~ 60-100 V 30-45 A,

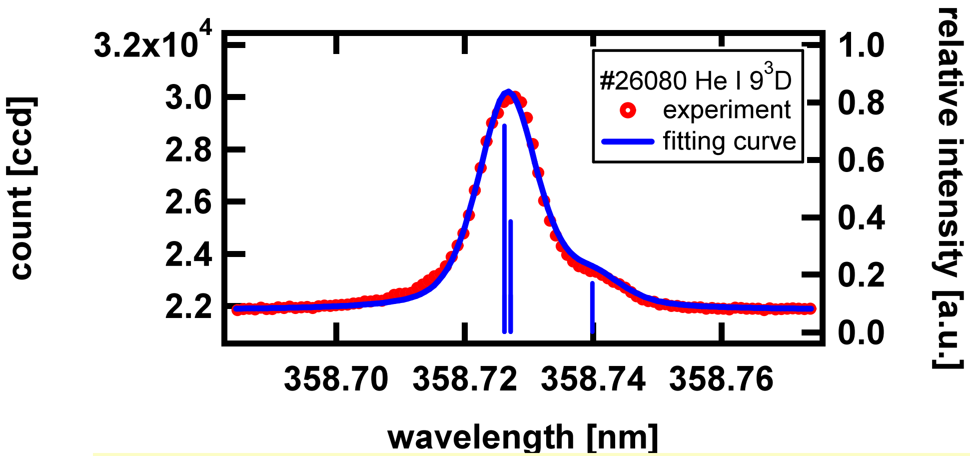
- 1st/source chamber: high n_e
  Probe measurements are limited in low density operations. ---> LTS.
- 2nd/target chamber: good controllability
  equipped with many diagnostics





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





He I line broadening：

i) instrumental function: with aberration

ii) Doppler (temperature): W_G Gaussian

iii) Stark　（density）：W_L Lorentzian
($n_e > 10^{13}$ cm^{-3},
principal quantum number n ≥ 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 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

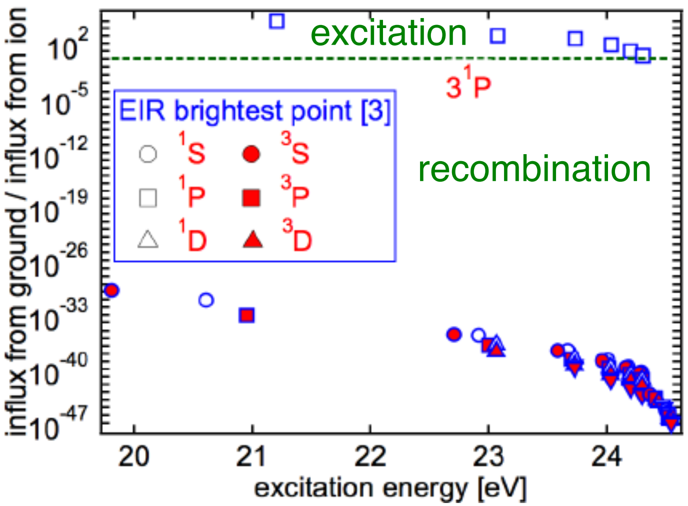
Question:　Temperature of which state ?

Origin of the Population in Recombining Plasmas

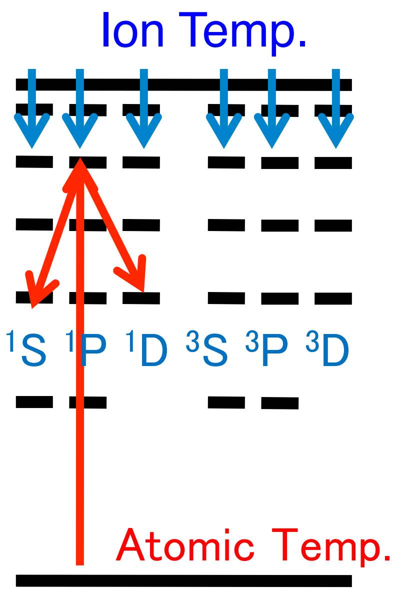
$$\frac{dn(p)}{dt} = -\left\{\sum_{q\neq p} C_{pq} n_e + S_p n_e + \sum_{q<p} \Lambda A_{pq}\right\} n(p) + \sum_{q\neq p}\left\{C_{qp} n_e + \Lambda A_{qp}\right\} n(q) + \left\{\alpha_p n_e + \beta_p\right\} n_i n_e$$

−efflux (Γ_{ef}) + influx: (Γ_{in})

ex.&deex. ion. decay *3BR Rad.Rec*

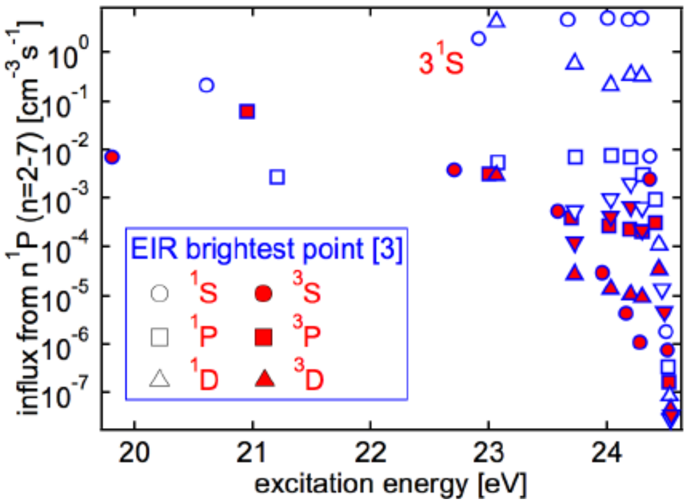


Influx from the Ground/Influx from Ion
Γ_{in}(1^1S−>p) / Γ_{in}(ion −>p)



Past research:
<u>Ionizing Plasma</u>:
Ion collision contributes to the high−n D series

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



Influx via ^{1}P states,
Γ_{in}(^{1}P->p)

The present research
<u>Recombining Plasma</u>:
^{1}P: Gas Temperature
^{1}S, ^{1}D: mixture
high−n ^{3}D: Ion temperature

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 has been proposed in ref.[*] as

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

$$+0.0016\left(1 - \frac{W_L}{W_V}\right)\frac{W_L}{W_V}\left(\exp\left(-0.4\left(\frac{\lambda - \lambda_0}{W_V}\right)^{2.25}\right) - \left(1 + 0.1\left(\frac{\lambda - \lambda_0}{W_V}\right)^{2.25}\right)^{-1}\right)$$

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

$W_V(3^1P) = W_G(3^1P) = W_G(T(He^0))$, ----> 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

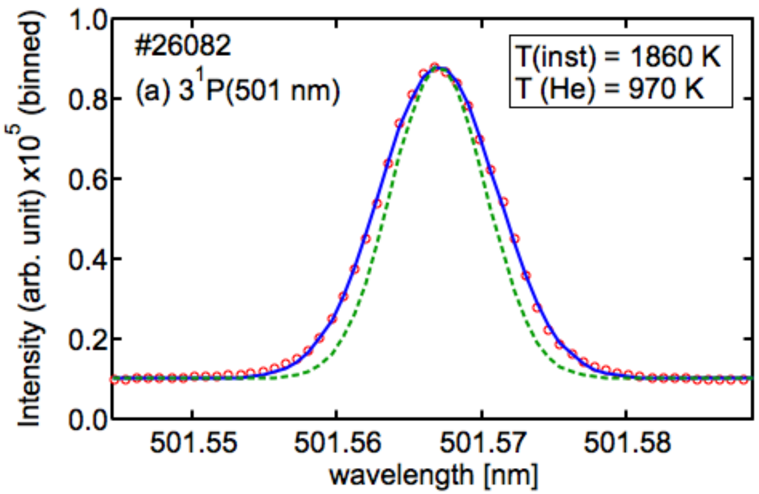
[*] E.E. Whiting, J. Quant. Spec. Rad. Trans. **8** (1968) 1379–1384

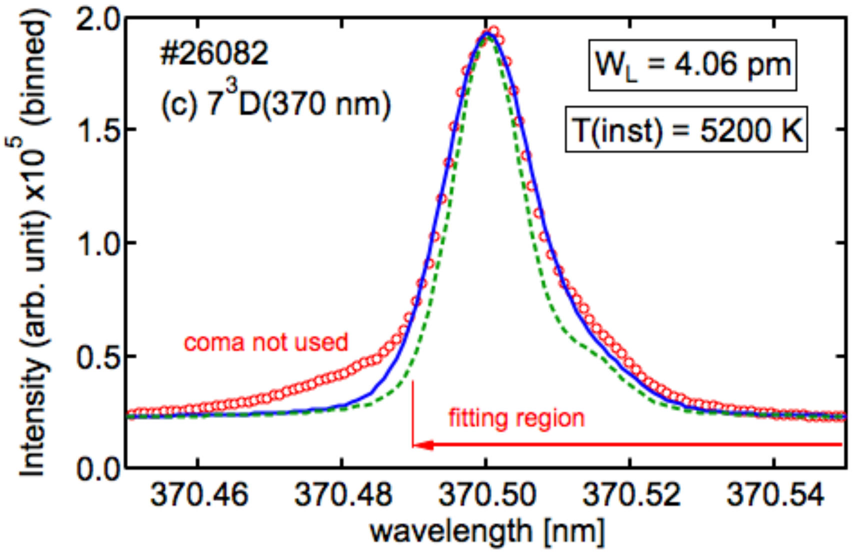
Results : Use of Line profiles of Three Transitions

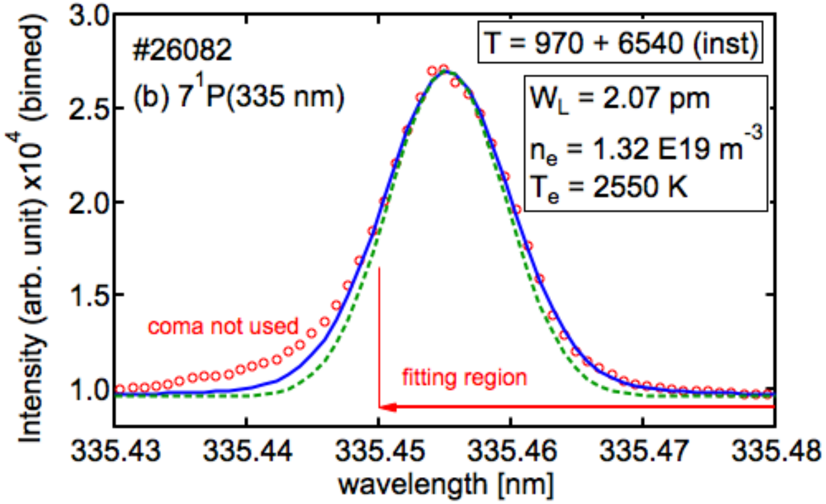
$W_V(3^1P) = W_G(3^1P) = W_G(T(He^0))$, ----> Atomic Temperature

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

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





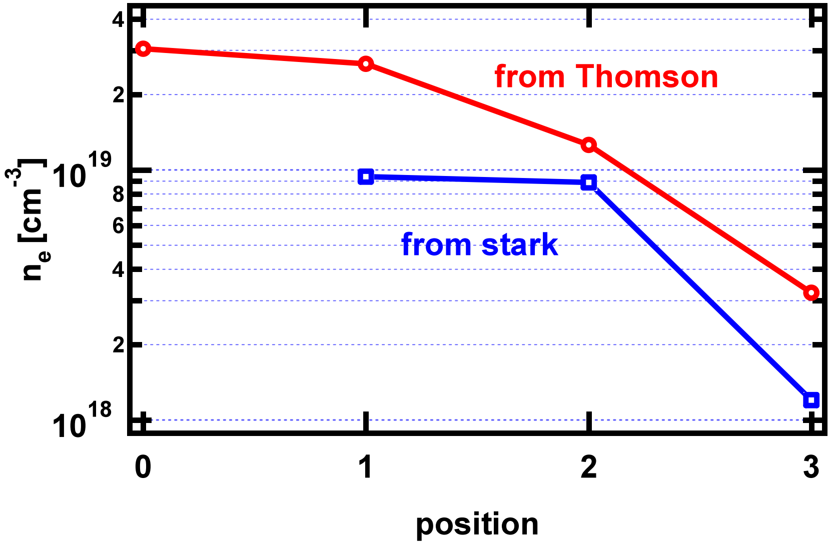


Fitting was performed in the region free from the coma aberration (blue wing in UV region)

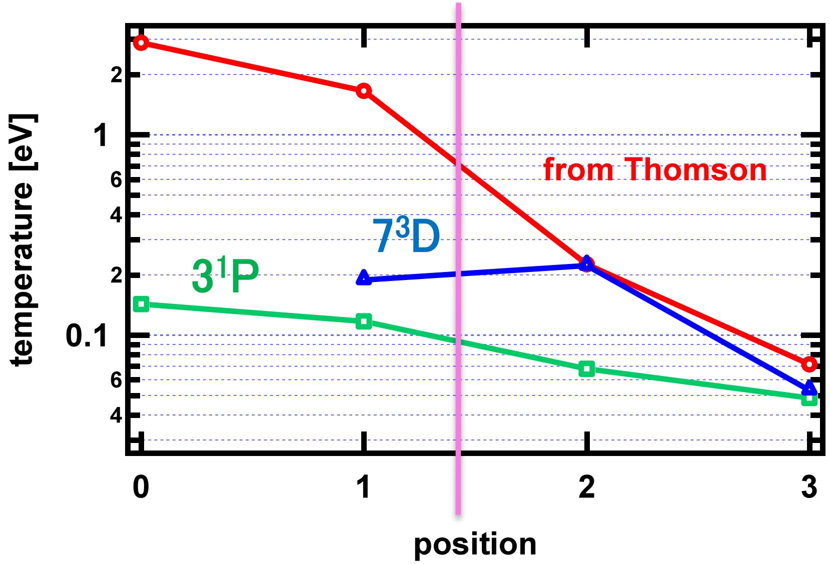
[*] **S. Kado**,et al., J. Nucl. Matter. **415**, S1174–S1177 (2011).

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(Thomson) > n_e(Stark:7^1P)

1/2 difference -> integration effect
Values from Stark are plausible.

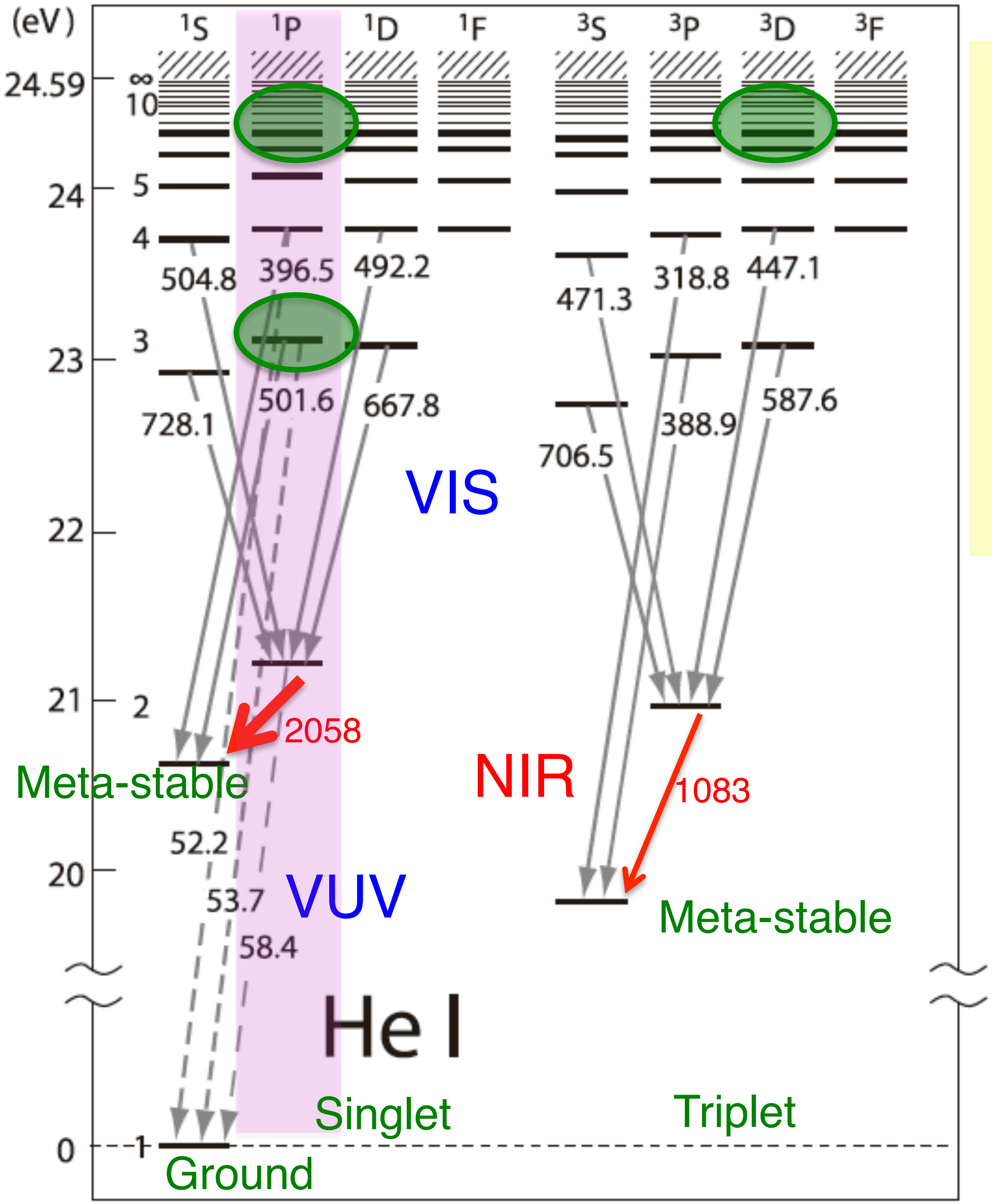
Using $n_e(7^1P)$ to determine $T(7^3D)$ from Voigt profile can be reasonable.

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

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

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

Doppler-Stark Spectroscopy for He I line broadening



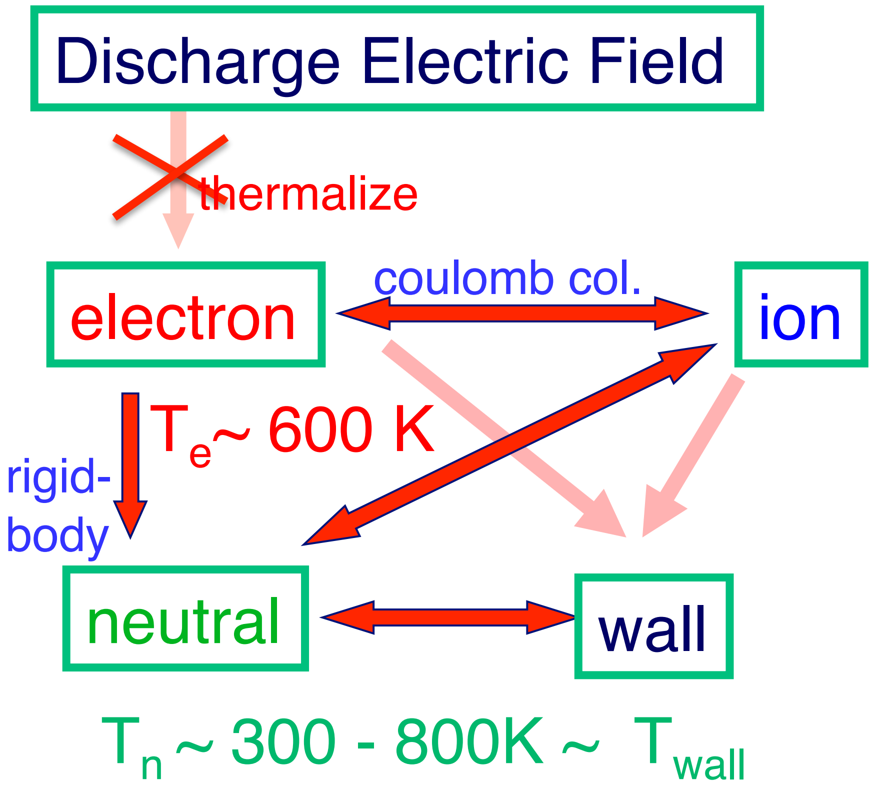
$W_V(3^1P) = W_G(3^1P) = W_G(T(He^0))$,
-----> Atomic Temperature

$W_V(7^1P) = W_G(T(3^1P))$ [+] $W_L(7^1P)$.
-----> 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 0.05-0.06 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 !