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IAEA Technical Meeting on Atomic, Molecular and Plasma Material Interaction Data for Fusion Science and Technology (2014.12.15-19 @Daejeon Convention Centre (DCC), room 101/102, Korea)

Excited State Temperature of Atomic Helium in MAP-II Steady-state Linear Divertor Simulator

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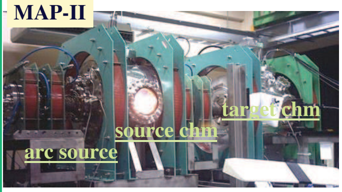
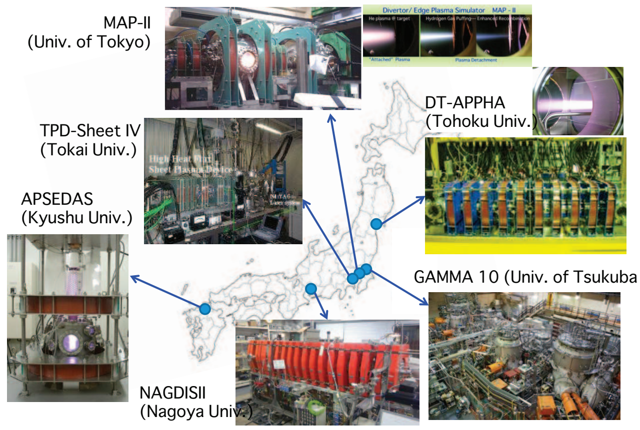
Visiting Professors: BJ. Xiao (ASIPP, China), KS. Chung (Hanyang Univ. Korea)

1) Introduction
   MAP-II Divertor Simulator
2) Method:
   Laser-Thomson Scattering (LTS)
   Doppler-Stark Spectroscopy
3) Equilibrium feature: T_e, T_i, T_n.
4) Disequilibrium feature: $T_n(p)$



Plasma Material Interaction Facilities (PMIFs) in Japana



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Dedicated PWI facilities to investigate plasma-wall interactions for future fusion reactors (non-exclusive list)

PWI facilities	Special capabilities
NAGDIS II (Nagoya-U)	Divertor studies at high densities, detachment studies
GAMMA-10 (U-Tsukuba)	Divertor studies in the largest mirror machine, high ion energy flux under high magnetic field, core-edge coupling like SOL plasmas
<< MAP-II (U-Tokyo) >>	Sophisticated diagnostics for near surface plasmas and materials
Quest (Kyushu-U)	PSI studies with hot walls
PISCES-B (UCSD)	Be operation, extensive set of post-mortem analysis methods
TPE (Idaho National Lab)	Tritium plasmas, moderately neutron activated targets
PMTS (ORNL)	High particle and energy flux density, RF heating, reactor relevant divertor conditions, neutron activated targets
VISION I (SCK-CEN, TEC)	Inside Tritium laboratory, Tritium plasma, moderately neutron activated targets
MAGNUM-PSI (FOM, TEC)	High particle and energy flux density, reactor relevant divertor conditions, sophisticated target analysis and exchange chamber
PILOT-PSI (FOM, TEC)	High particle and energy flux density, forerunner of MAGNUM-PSI
JULE-PSI (FZJ, TEC)	Located inside Hot Cell, Be operation, neutron activated targets, sophisticated target analysis and exchange chamber
PSI-2 Jülich (FZJ, TEC)	Forerunner of JULE-PSI, sophisticated target analysis and exchange chamber under fabrication

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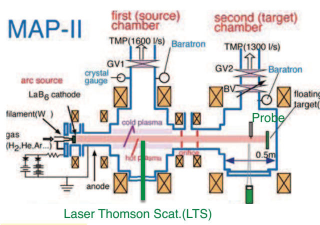
MAP - II Divertor Simulator @ U-Tokyo (~2013)

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



Objectives: A&M processes in divertor region, Detachment, Diagnostic method, etc.
- 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
(30 mmφ with a hole 5 mmφ)
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 ; attached
< 250 mTorr ; detached

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Temperatures of ion, electron and neutral (ionizing plasma)

Fusion Core Heating

Glow-- ~ 400-600V
Arc -- ~ 10-100V
RF, Fusion.....

1 eV = 11604 K

thermalize
coulomb col.
electron → ion
rigid-body
T_e~4 eV
T_i ~ 0.1T_e ~ 4000K [Kado and Shikama., JPFR,79 (2003) 841]
surface recombination
neutral ↔ wall

T_n ~ 300 - 800K ~ T_{wall}
[Shikama, Kado et al., POP16, 033504 (2009)]

n_e ~n_i ~ 10^{11-13} cm^{-3}
n_n ~ 10^{15} cm^{-3}

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

Thermal disequilibrium between species is a common feature.

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

Discharge Electric Field

Glow-- ~ 400-600V
Arc -- ~ 10-100V
RF, Fusion.....

1 eV = 11604 K

thermalize
coulomb col.
electron ↔ ion
rigid-body
T_e~ 600 K
T_i ~ ?
neutral ↔ wall

T_n ~ 300 - 800K ~ T_{wall}

n_e ~n_i ~ 10^{11-13} cm^{-3}
n_n ~ 10^{15} cm^{-3}

A hypothesis (by Kado)
- No apparent energy input.
- Possibility that electrons, ions and neutrals are undistinguishable.
- Thermal equilibrium achieved ?

Motivation #1

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Diagnostic Methods

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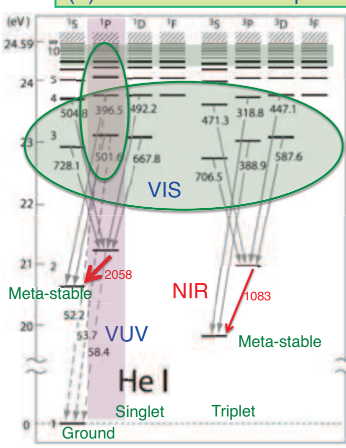
(1) He I line emission spectroscopy ~Excited States~



Transitions to $n = 2$ (many useful lines)
1) High-n Boltzmann plot method.
2) Collisional Radiative model
3) near-infrared spectroscopy for 2^1S - 2^1P (2058.130 nm) for radiation trapping [Kado et al., JPSCP (2014)]

Also, conventionally, Doppler broadening of the excited states has been used to determine the atomic temperature.

Then the questions arise:
- How temperature can be measured?
- Which temperature the measured temperature value in fact reflects?
- Whether or not these temperatures are equal ?

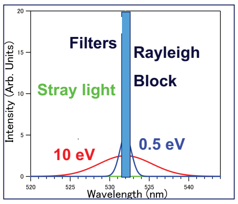
Thermal disequilibrium among excited states has not been addressed. ---> Motivation #2

(2) Laser Thomson Scattering for very low Te plasmas

Laser Thomson Scattering (LTS) - Principally, a direct observation of EEDF -

Corona (Thomson scattering) can be observed in the solar eclipse when incident component (sun) is shielded by the moon.

- Filter polychromator (≥ 1nm band width) or notch filter (~ 17 nm stop band) cannot be used. Grating double monochromator applied.



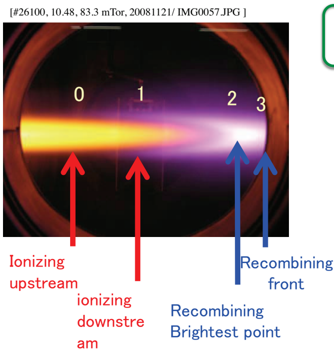
1-2 nm/mm for Te< 40 eV

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

Measurement of the Electron Temperature

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

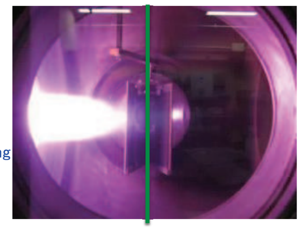
[#26100, 10.48, 83.3 mTor, 20081121/ IMG0057.JPG]



$T_e > 2$ eV ~ 1eV ~ 0.2 eV < 0.1 eV

3BR	$He^+ + e + e$ -> $He^* + e$
Rad.R	$He^+ + e$ -> $He^* + h\nu$

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



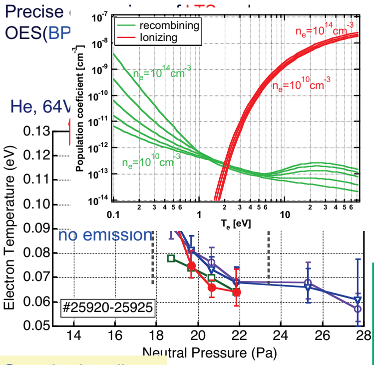
Laser pass

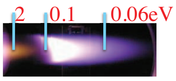
20081121_Thomson_MVI_0064_trim.mp4

LTS vs Spectroscopy (high -n) at EIR front

Precise ... of LTS ...
OES(BP...

He, 64V...





T_e (LTS) monotonically decreased down to 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).

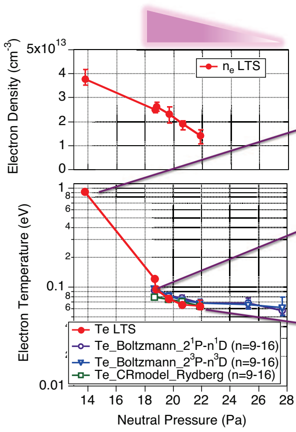
Deviation around the brightest point is attributable to the integration effect:
LTS -- T_e at the tip
Spec. --T_e in the bright cone.

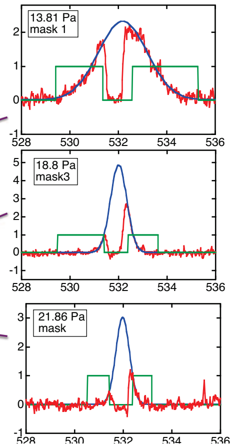
Conclusion #1

T_e(high-n, BP and CR) ~0.06-0.07 eV -- confirmed by LTS

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

cf. LTS spectra

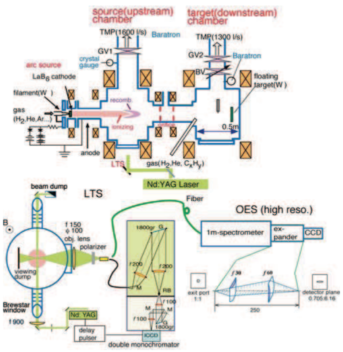


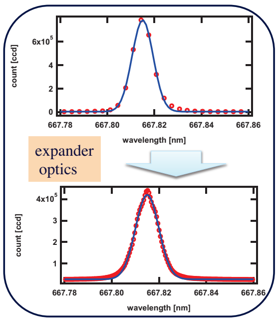


LTS vs Doppler-Stark spectroscopy

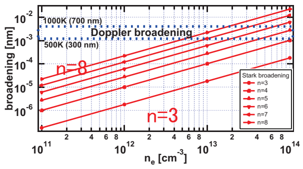
Arc source with B- fiel ~ 20 mT
Cathode disk (LaB_6 30 mmφ), Anode: Pipe
Discharge ~ 60-100 V 30-45 A,

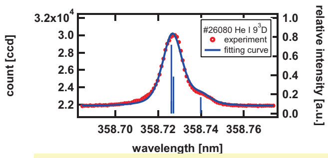
- 1st/source chamber: high n_e
  Probe measurements are limited in low density operations. ---> LTS.
- 2nd/target chamber: good controllability equipped with many diagnostics





Difficulty and the Solution to T(p) Diagnostics





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)

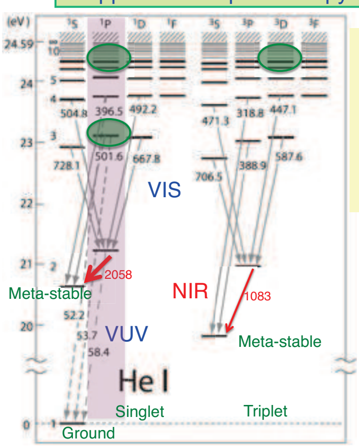
ex. 9^3D (6 fine structures)
1m 2400 g/mm, x6
dispersion: 0.5~1 pm/pixel
Inst_FWHM 7.5~12.5 pm

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 state: More Doppler ---- Atomic temperature
high-n state: Doppler and Stark ---- Temperature and electron density
Question: Temperature of which state ?

Equilibrium Feature

Doppler-Stark Spectroscopy for He I line broadening



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

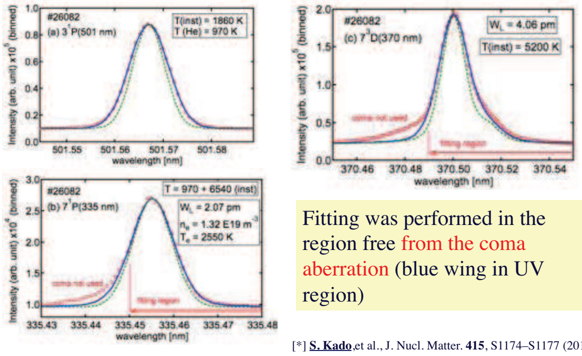
$W_V(7^1P) = W_G(T(3^1P))$ [+]$W_L(7^1P)$.
-----> Electron Density

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

Results : Use of Line profiles of Three Transitions

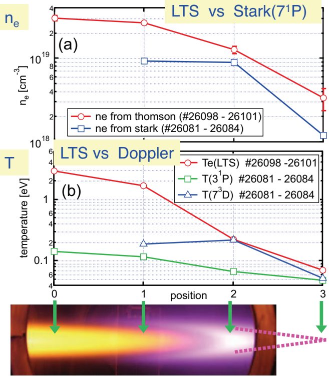
$W_V(3^1P) = W_G(3^1P) = W_G(T(He^0))$, ----> Atomic Temperature
$W_V(7^1P) = W_G(T(3^1P))$ [+] $W_L(7^1P)$. ----> Electron Density
$W_V(7^3D) = W_G(7^3D)$ [+] $W_L(n_e(7^1P))$, ----> Ion temperature



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).

Achieving Thermal Equilibrium in Recombining Plasma



Ionizing Plasma
$T(3^1P) < T(7^3D) < T_i << T_e$

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

$T(3^1P)=T(7^1P)=T(1^1S)$: 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.

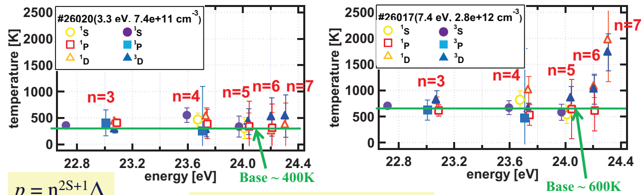
Conclusion #2

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

In addition, thermal disequilibrium feature has been recognized in ionizing plasma.

Disequilibrium Feature

T(p) @ Ionizing Plasma ~ low-mid Electron Density



$p = n^{2S+1}\Lambda$

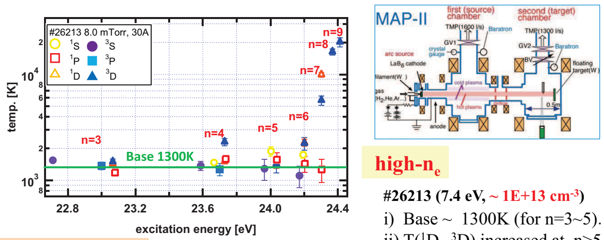
(no Stark component observed)

low-n_e #26020 (3.3 eV, 7.4E+11 cm^{-3})
i) Base temp. ~ 400 K
ii) T(p) not dependent on p.

mid-n_e #26017 (7.4 eV, 2.8E+12 cm^{-3})
i) Base ~ 600K (for n=3~5).
ii) T(^{1}D, ^{3}D) increased at n>5.

Base Temperature = Atomic temperature heated by electron collision
(CX collision is still small)
T(^{1}D, ^{3}D) ---- reflect the excess-heated excited state temperature

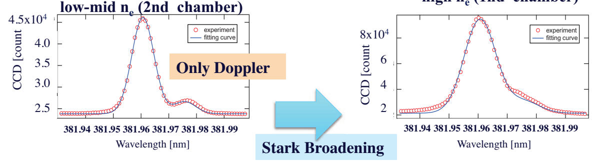
T(p) @ Ionizing Plasma ~ High Electron Density



high-n_e

#26213 (7.4 eV, ~ 1E+13 cm^{-3})
i) Base ~ 1300K (for n=3~5).
ii) T(^{1}D, ^{3}D) increased at n>5.

6^3D : spectral shape



Thermal Disequilibrium Feature in the Excited Atoms

Consideration of the equilibrium feature of the excited state is important because observed line emission reflects the excited state information.

Also, since we have observed that the atoms and ions are not in the thermal equilibrium state in the ionizing plasmas ($T_i \neq T_n$) , next we'd like to know if we need to pay attention to the excited level to be measured or not.

Thus, rigorous explanation to the observed disequilibrium feature in the ionizing plasma might be a *hint* to clarifying the underlying physics, and also might address requirements for the A&M data.

Ionizing Plasma: Possible heating mechanisms (hypothesis)

(hypothesis) atoms are heated while the bounded electron is excited. Plus, the D state more reflects the heated components. --- because the lifetime of each excited state is too short

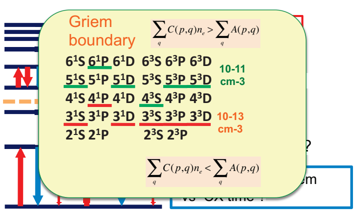
for the verification ⇒ 1)whole excited states are heated 2) ratio of the ex-heated to normal-heated components in the emission.

1) heating of the excited states.

$n(p) = n_e n_{1S} R_1$(ionizing)
+ ~~$n_e n_i R_0$(recombining)~~
+$n_e n_i R_{cx}$(CX)

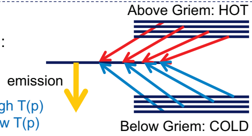
elastic collision by electrons and ions
⇒ too small during the lifetime

CX rate ~ ∝ n^4
n: principal quantum num.



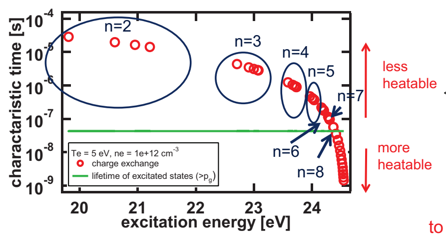
2) .Contribution to the observed emission lines
Average resident ratio of excitation before emission:

$$\alpha_{ex}(p) = \frac{\text{influx from above Griem}}{\text{influx from below Griem}}$$



large α_{ex} : seemingly high T(p)
small α_{ex} : seemingly low T(p)

Heating Mechanism of the Excited State by CX



CX time (rough)

$$<\frac{1}{\tau}> = \frac{\sum_p n_e <\sigma_{CX}(p)v> n(p)}{\sum_p n(p)}$$

where $\sigma_{cx} \propto n^4$

more accurate data would be helpful

Resident time
= average loss from p > p_g.

$$<\frac{1}{\tau_{ex}}> = \frac{\sum_{p>p_g}\{\Sigma_{q<p_g}\{C(p,q)n_e + A(p,q)\} + S(p)n_e\}n(p)}{\sum_{p>p_g} n(p)}$$

to p < p_g — to ion

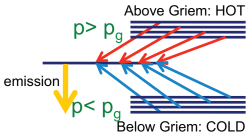
Shot	resident time [sec]	Charge exchange [sec]	resident time / cx time
26020(low n_e)	5.47x10^{-8}	1.85x10^{-7}	0.88
26017(mid n_e)	2.51x10^{-8}	4.56x10^{-7}	0.91
26080(high n_e)	2.97x10^{-9}	1.55x10^{-9}	1.35

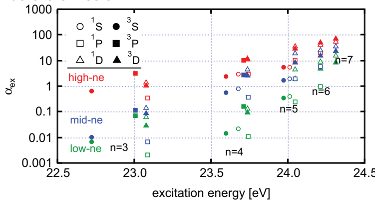
Conclusion #3

CX "can" heat the high-n states during the characteristic (resident) time.

Contribution to the Observed Emission

Average resident ratio of excitation before emission:





$$\alpha_{ex}(p) = \frac{\text{influx from above Griem}}{\text{influx from below Griem}}$$

large α_{ex} : seemingly higher observed T(p)
small α_{ex} : seemingly lower observed T(p)

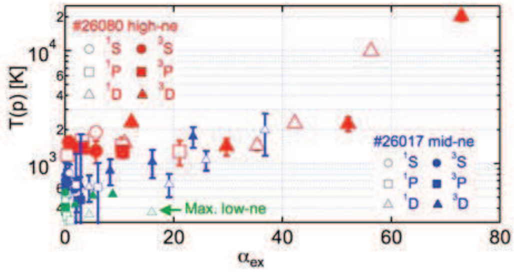
Review: experiments
- low-n_e : T(p) is constant.
- mid-&high-n_e: only T(^{1}D, ^{3}D) exhibits excess increase with n.
- ^{3}P cannot be observed (short wavelength)

- α_{ex} is larger in high-n states.
- α_{ex} is larger for high electron density.
- fine-structure dependence among same n. $\alpha(^1P, ^1S, ^3S) < \alpha(^1D, ^3D)$.

It seems a good agreement with the experiments.
Note: low-n_e: heating was not sufficient to be detected.

a kind of criteria to judge the contribution above/below Griem

$$\alpha_{ex}(p) = \frac{\text{influx from above Griem}}{\text{influx from below Griem}}$$



Conclusion #4

One needs to pay careful attention to choose the line to measure "atomic temperature"

Conclusions

Usually, plasma is in the thermal equilibrium states only for each species --- Boltzmann distributions with different temperatures.
(This is due to the existent of the energy flow)

Equilibrium

Electrons: Thermal equilibrium is achieved in very low temperature below 0.1 eV for the recombining plasmas.

Thermal equilibrium between electron, ion and neutral is achieved in the recombining plasma

Disequilibrium:

Plausible origin of the disequilibrium feature observed among the excited states in high density ionizing plasma was revealed to be the heating of atoms during the lifetime above Griem boundary (ladder-like travels within the excited states) via CX processes.
State-selective CX rates are demanded.

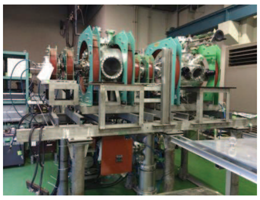
MAP-II in the University of Tokyo, 2014 (S. Kado)

The final experiments in Tokyo were conducted in the end of 2013.

----Theme----
- Electron Energy Distribution Function measurements
- Imaging spectrometry for He I by making use of Liquid crystal tunable Lyot filter.

- MAP-II has carried out of Tokyo on 11/Sep/2014 AM

MAP-II in the future in Tsukuba-Univ.



- MAP-II has carried in into Tsukuba-Univ. on 11/Sep/2014 AM

- no discharge planned in 2014

Plans for 2015 (Tsukuba-Univ.)

- Power cable connection
- Cooling water supply
- Evacuation test
.... etc.
Then,
restating plasma discharge (hopefully).