Plasma spectroscopy for magnetically confined fusion plasma

M. Goto and S. Morita
National Institute for Fusion Science

contents

- introduction of visible spectroscopy for LHD (Large Helical Device)
- two-dimensional neutral flux measurement — Zeeman spectroscopy
- Serpens mode — formation of extremely low temperature plasma in confinement region
- verification of helium CR model

Introduction

plasma diagnostics with spectroscopic measurement can be classified into two groups

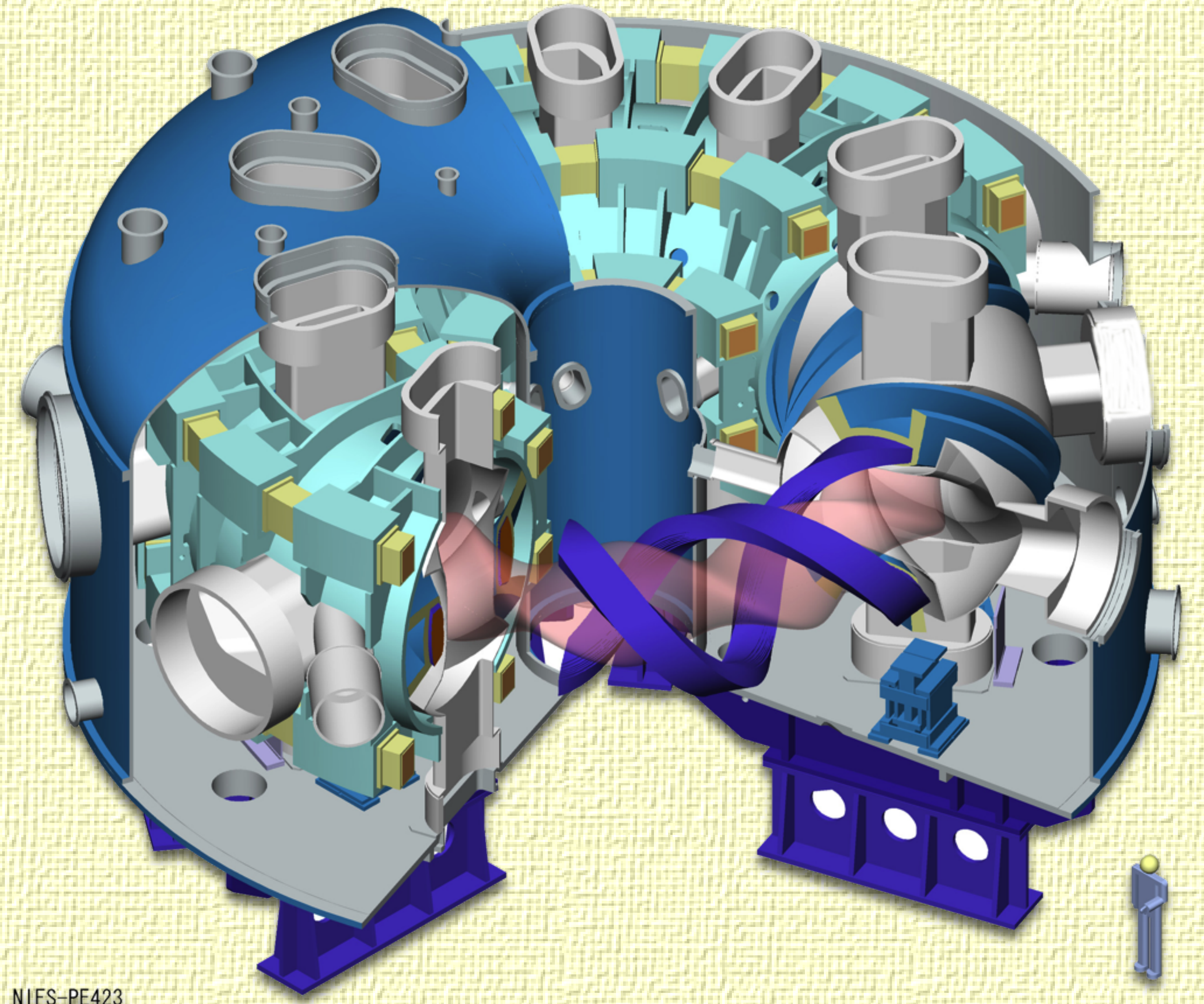
- high wavelength resolution measurement
  - shift, detailed line profile, etc.
- wide wavelength range measurement
  - intensity distribution of various emission lines

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

high resolution measurement (shift, broadening, splitting)

wide range measurement (intensity ratios, intensity distribution, intensity)

Large Helical Device (LHD)



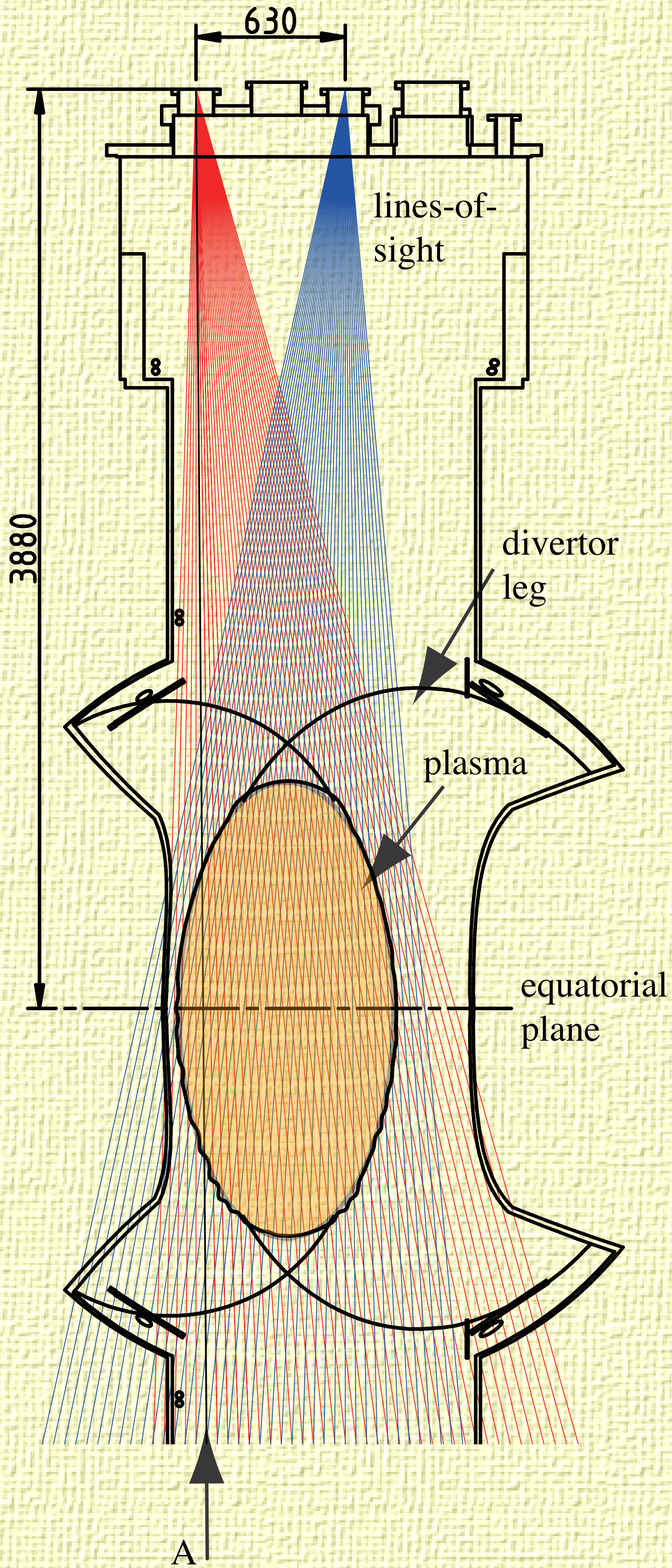
specifications

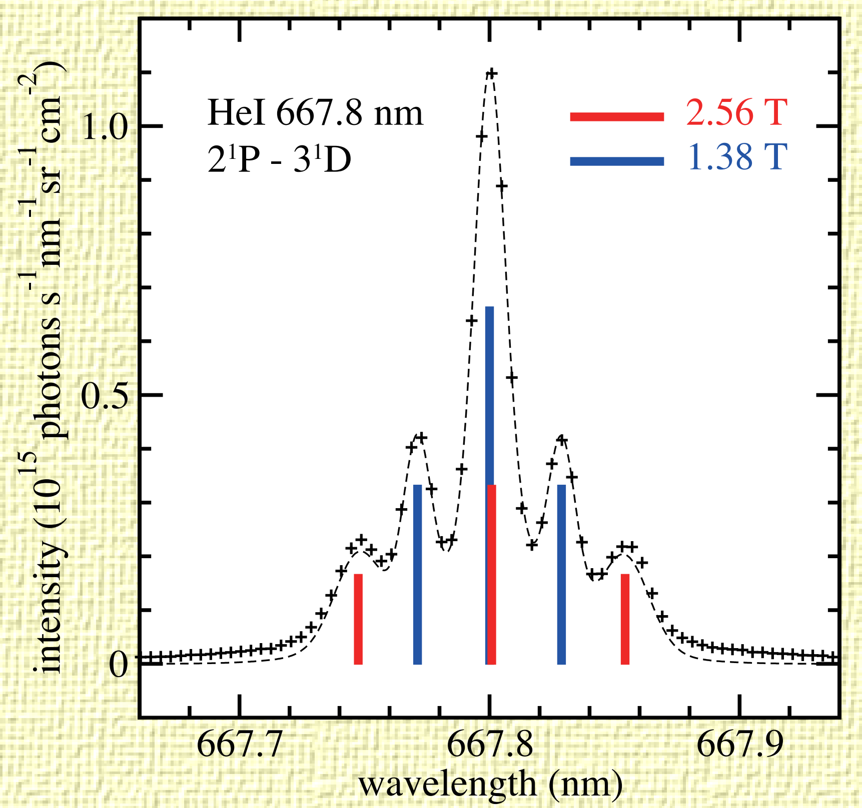
major radius	3.5 – 4.2 m
minor radius	~ 0.6 m
B on axis	< 3 T
volume	~ 30 m^3

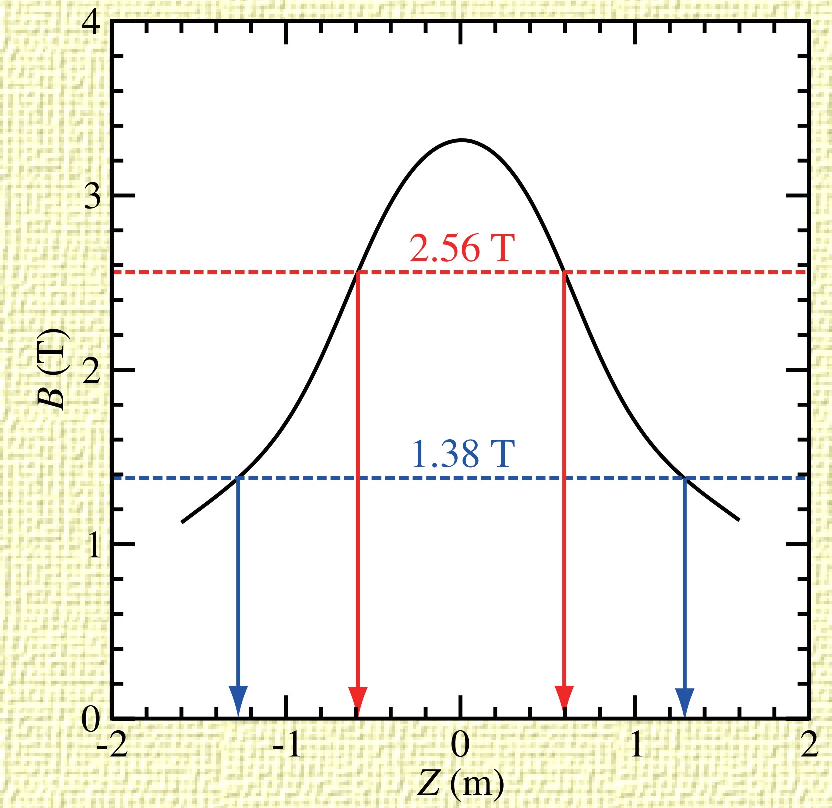
achievements

$$P_{\text{in}} = 15\,\text{MW}$$
$$T_{\text{e}} = 10\,\text{keV}$$
$$T_{\text{i}} = 13\,\text{keV}$$
$$n_{\text{e}} = 3 \times 10^{20}\,\text{m}^{-3}$$

Zeeman spectroscopy

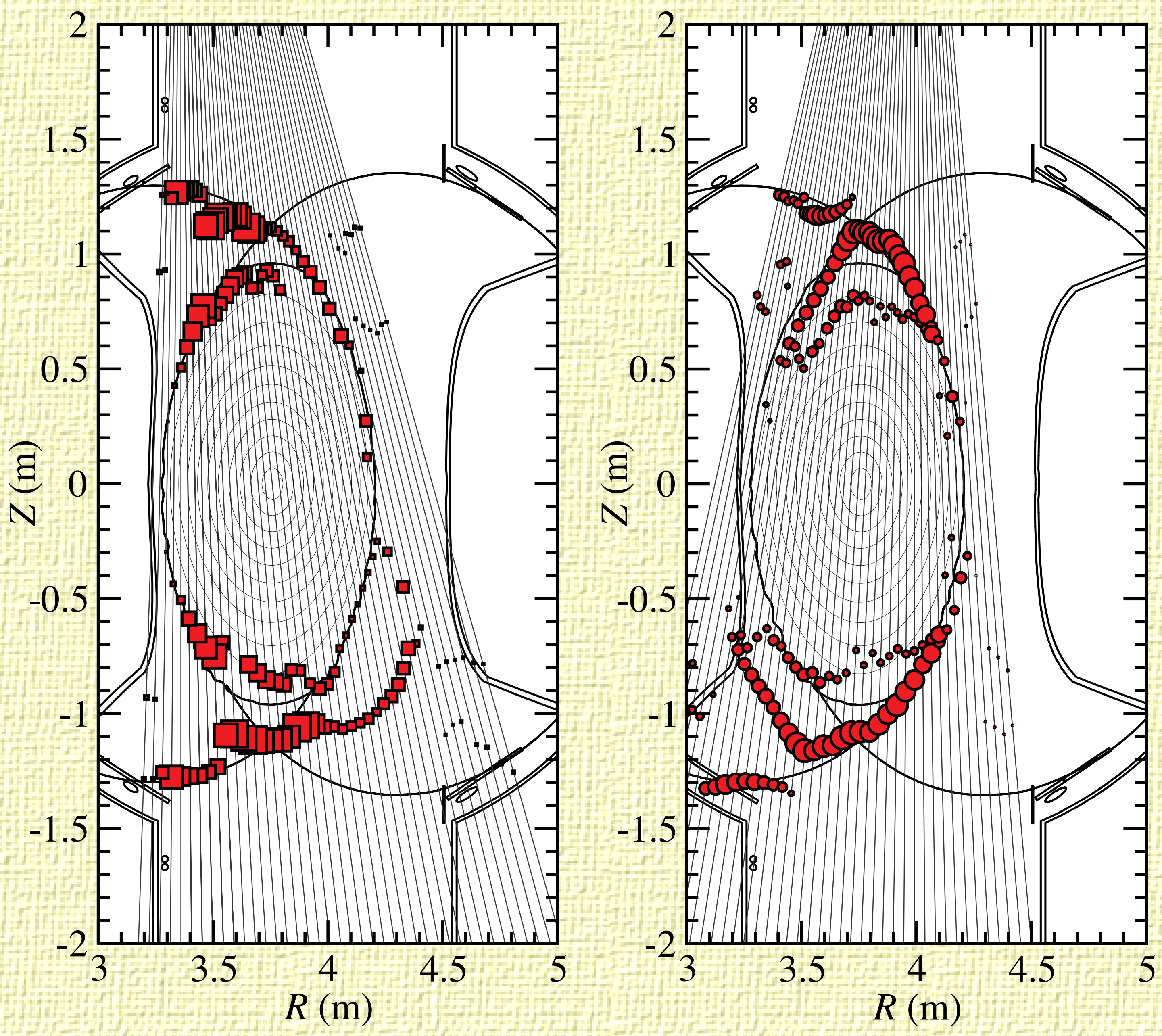






- magnetic field strengths are obtained from Zeeman splittings
- emission locations on line of sight are derived from magnetic field data
- typically two locations arises from one field strength because field strength has a maximum

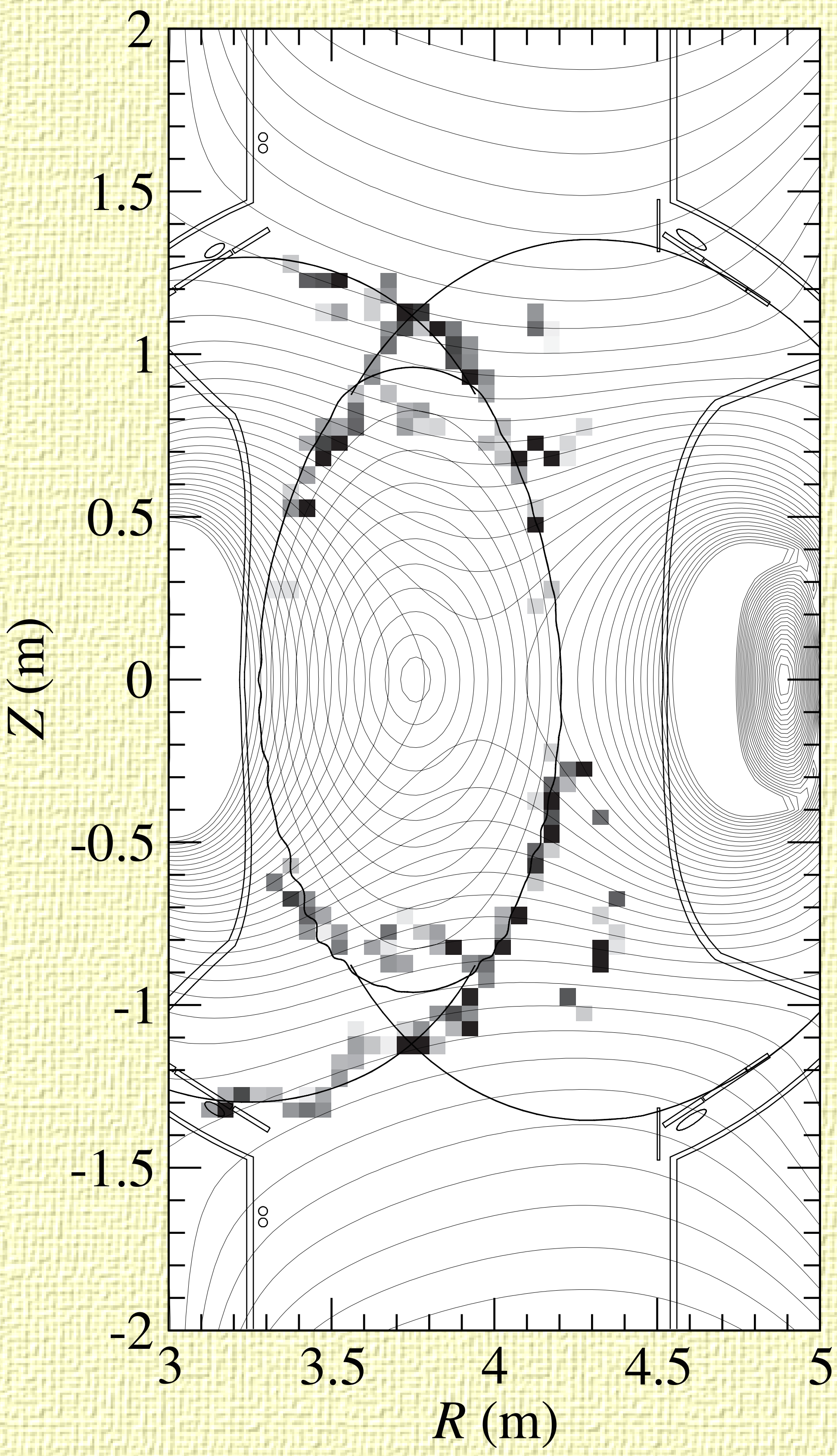
- emission locations are picked up independently with two arrays
- apparently false locations are designated but difficult to be excluded systematically
- comprehensive analysis from two results might be possible



- plane is divided into square cells and define intensity distribution function $f(x)$

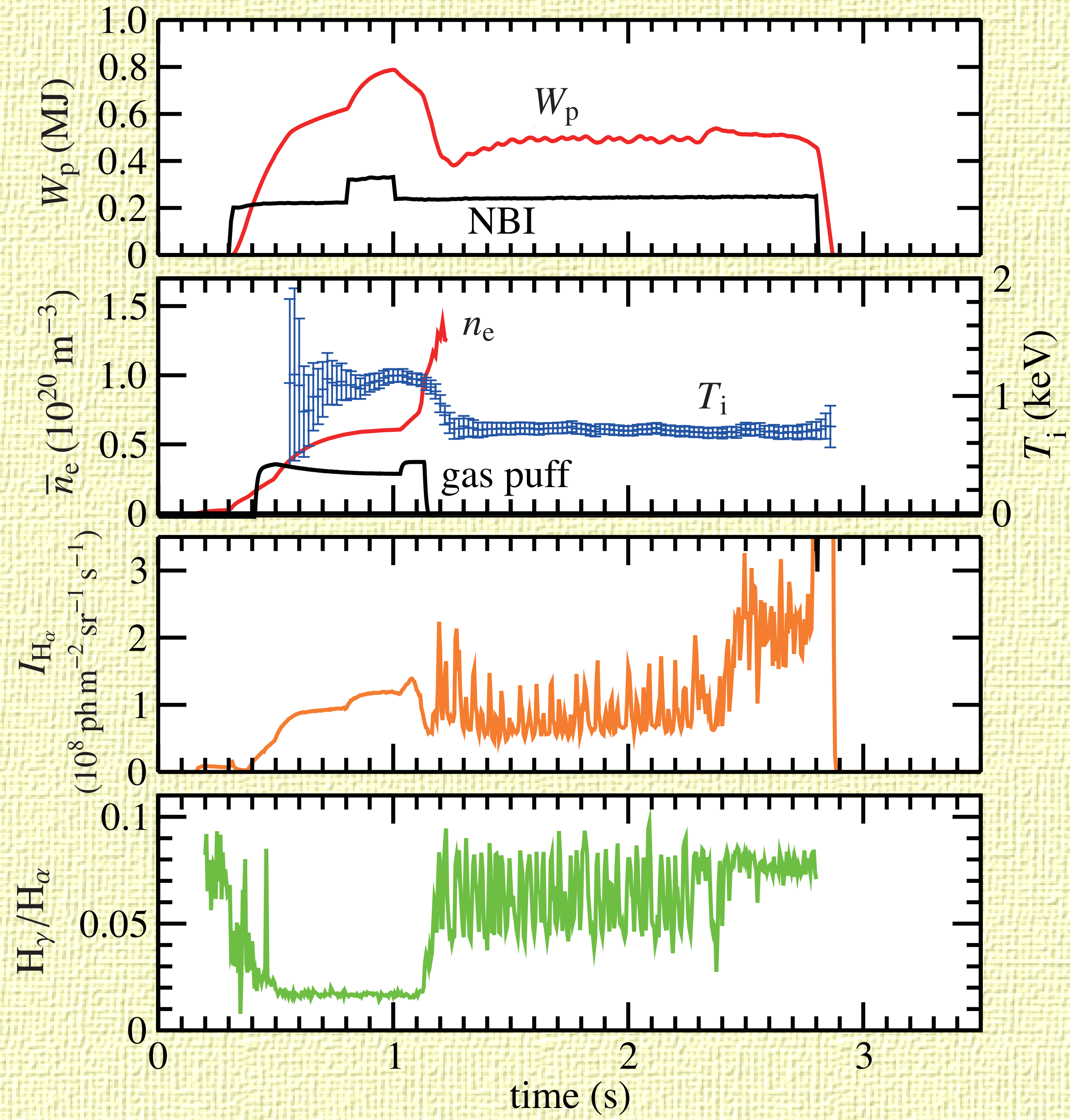
- $f(x)$ is determined so as to minimize the following evaluation function

$$\varepsilon(f(x)) = \sum_i \left(I_i^{\mathrm{cal}}(f(x)) - I_i^{\mathrm{obs}}\right)^2$$

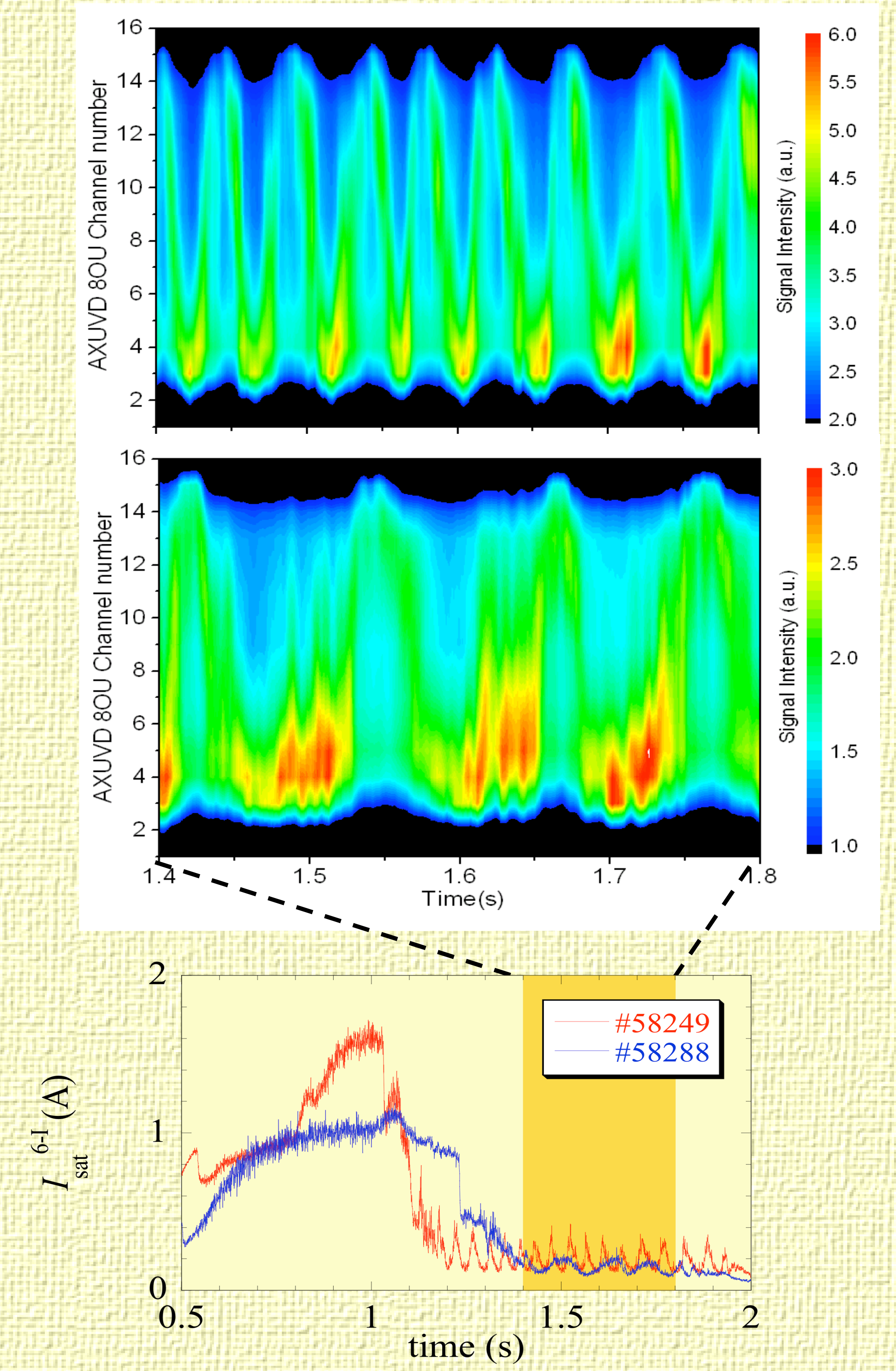


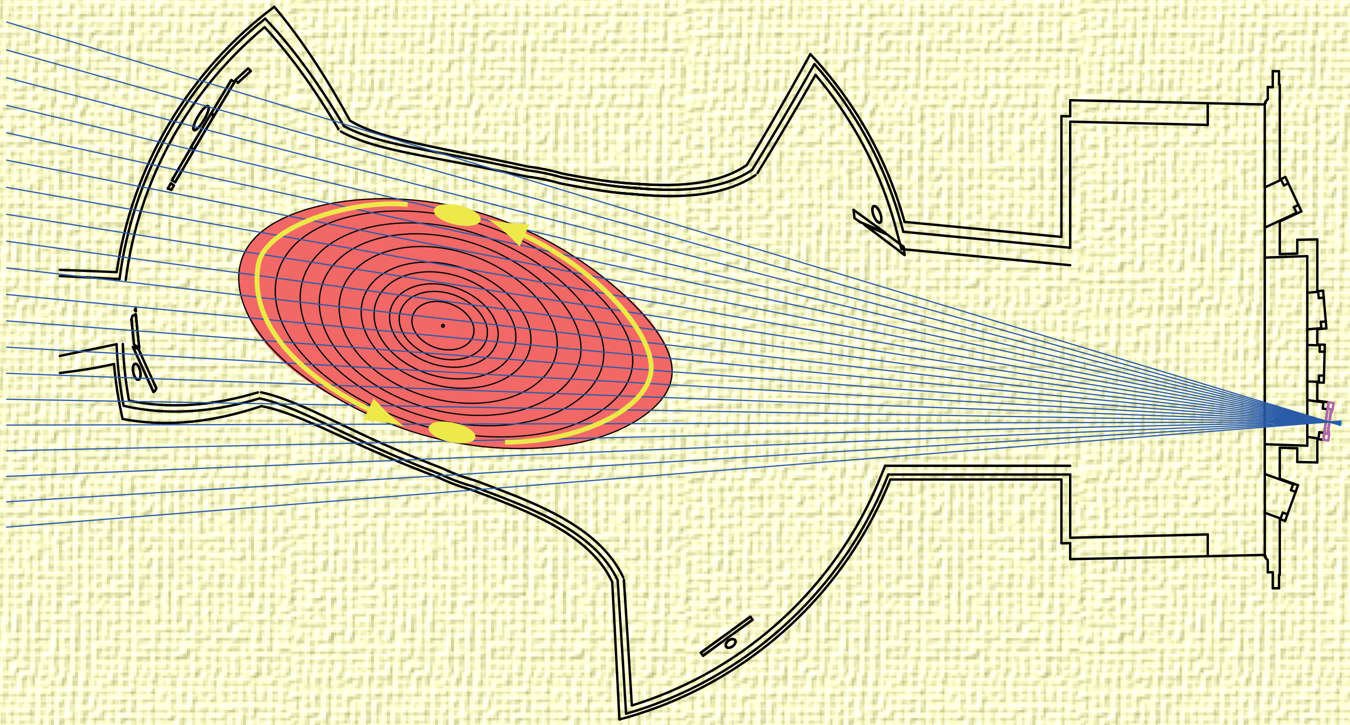
Serpens mode

- Serpens mode is triggered by strong gas puff
- H_α oscillation indicates rotation of luminous small body
- increase of H_γ/H_α implies formation of recombining plasma

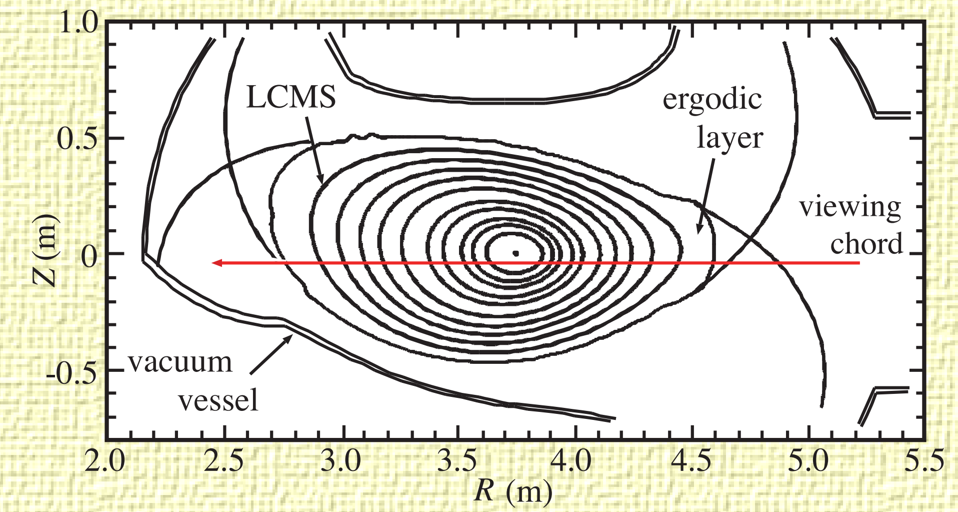


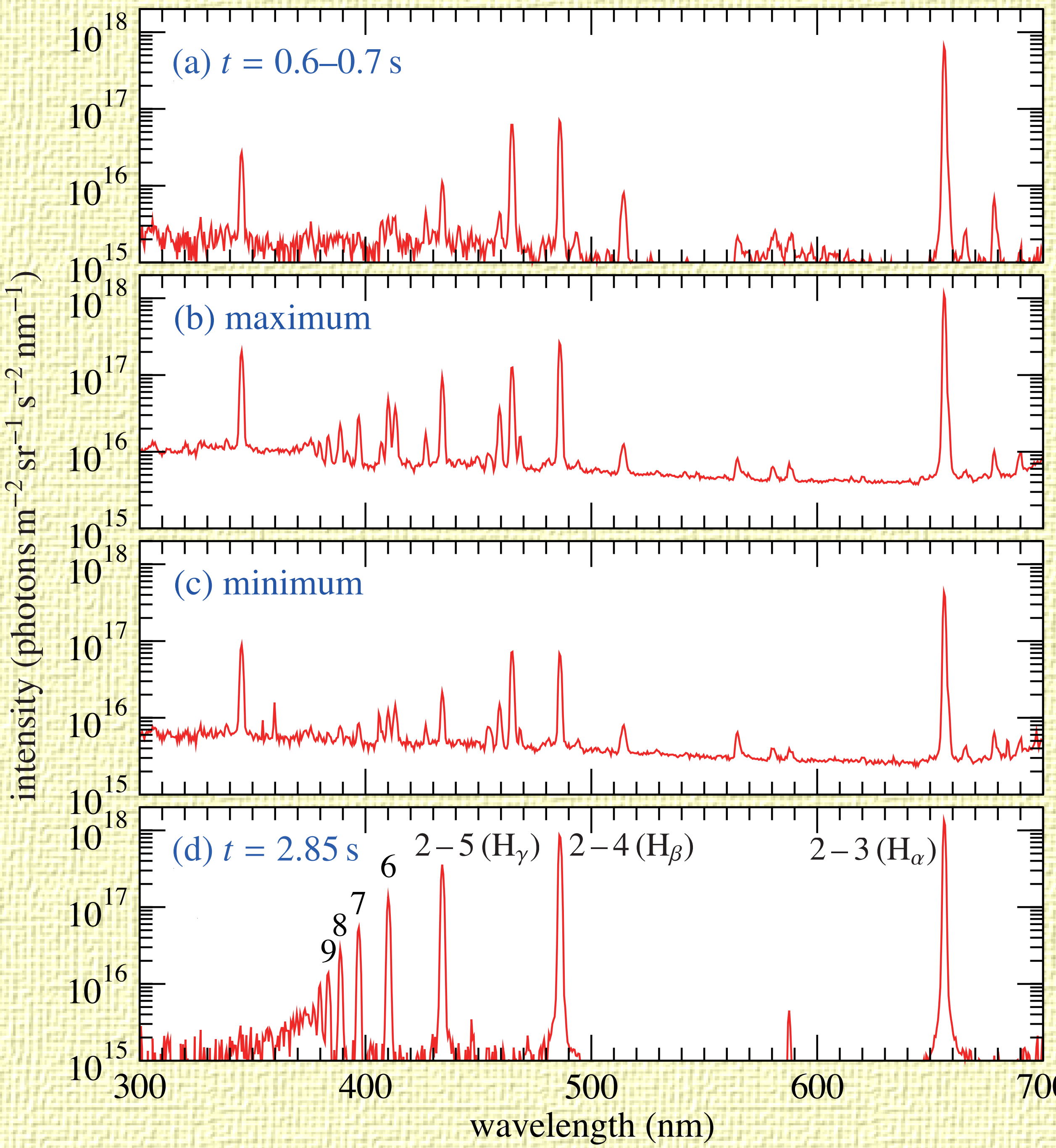
Serpens mode is characterized by complete divertor detachment and emergence of narrow luminous body in confined region

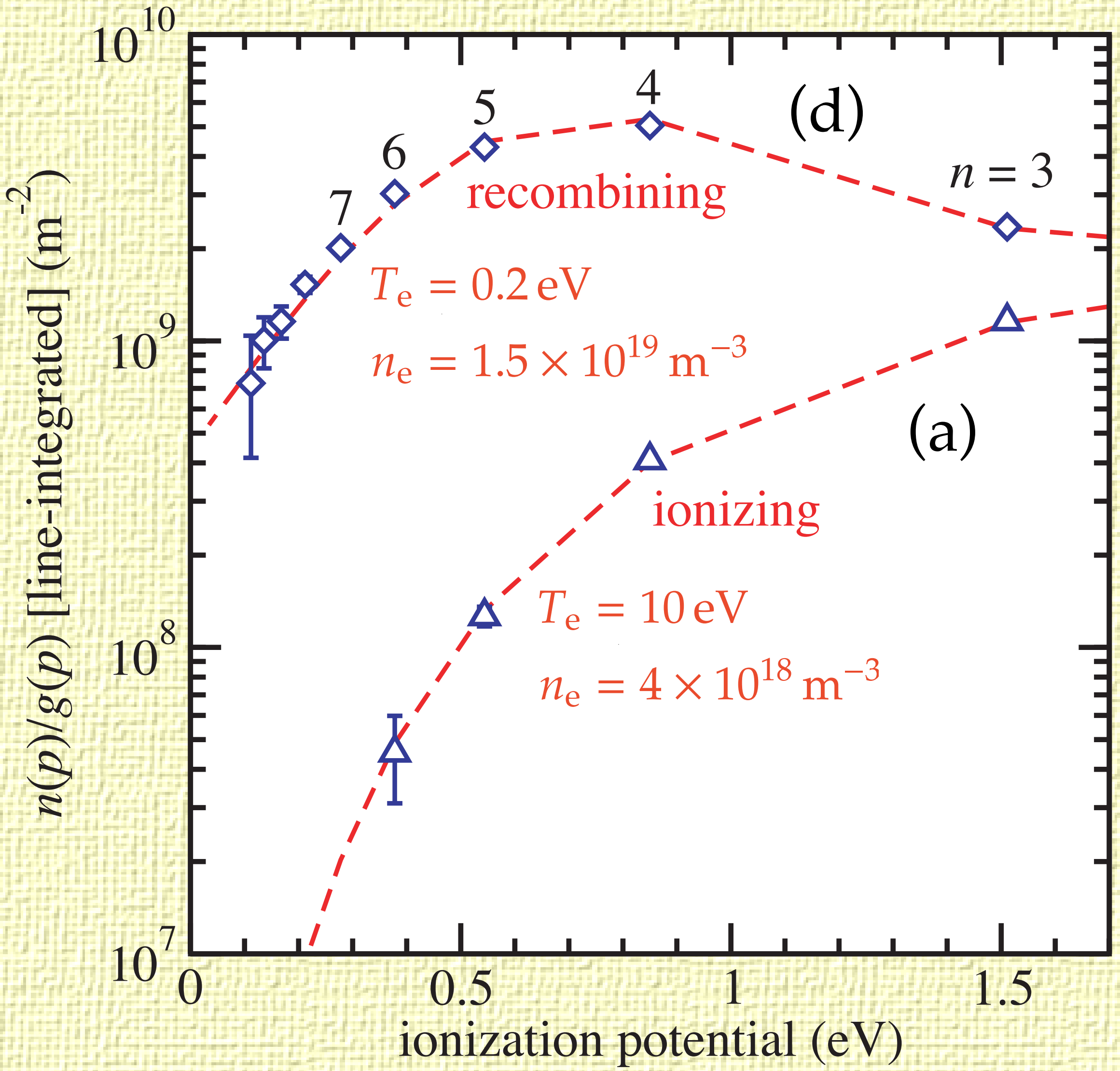




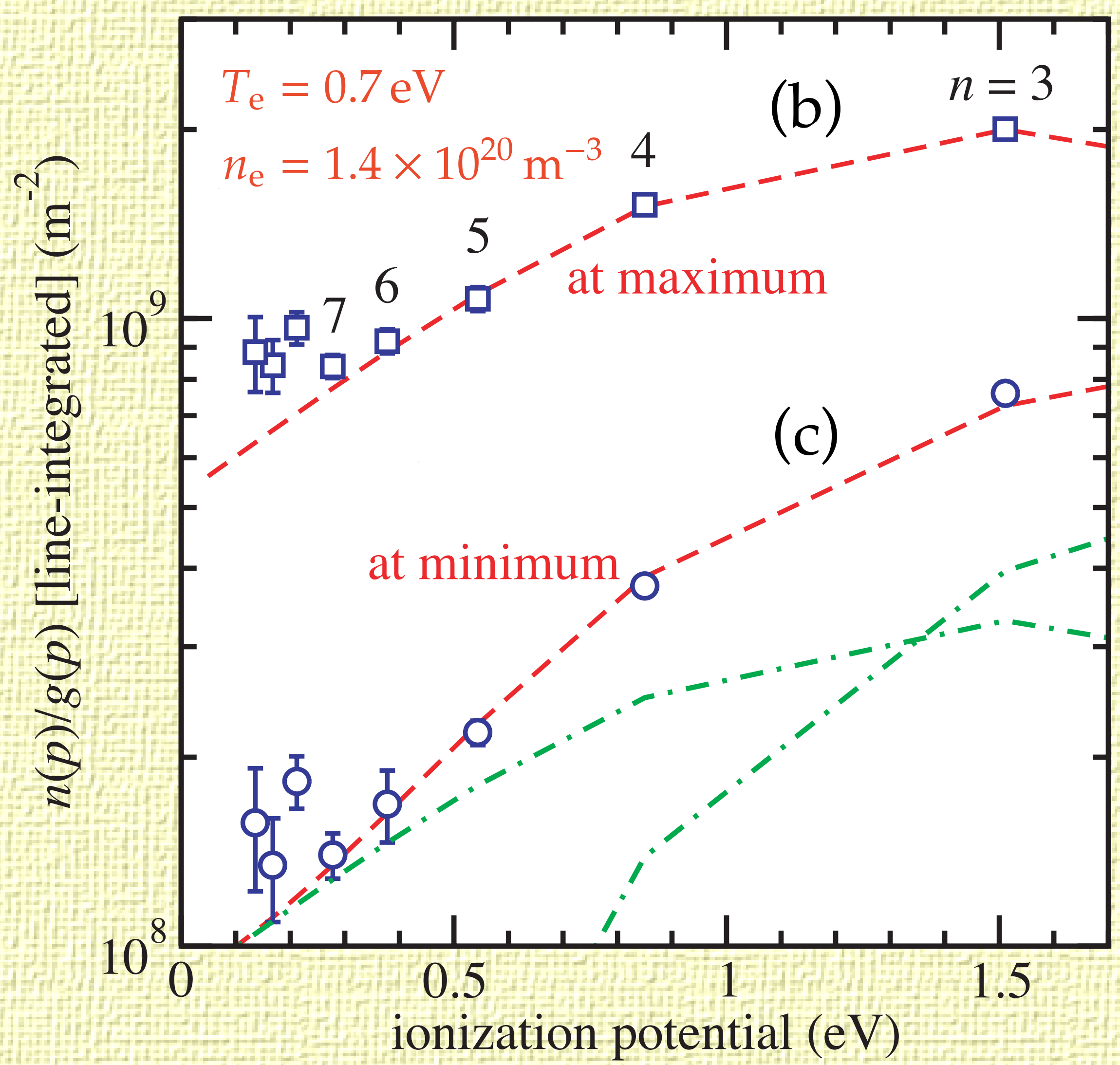
- single channel measurement with time resolution of 5 ms is made
- wide wavelength range is covered, and all the Ballmer series lines are involved
- spectra show various faces according to plasma conditions





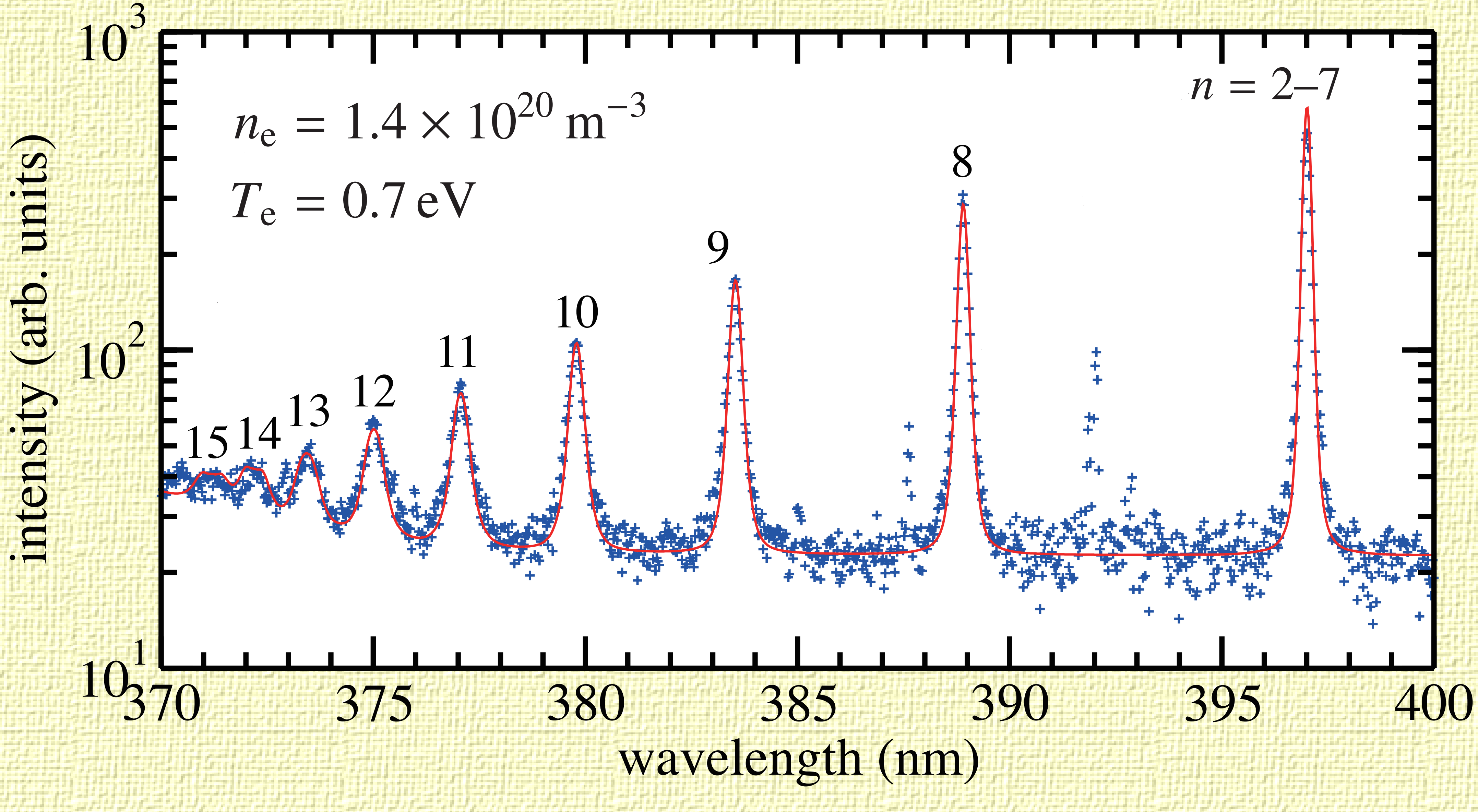


- distribution implies ionizing plasma in the steady-state phase (a)
- determination of plasma parameters is difficult
- in the plasma terminating phase (d), pure recombining plasma is observed
- plasma parameters are derived with precision

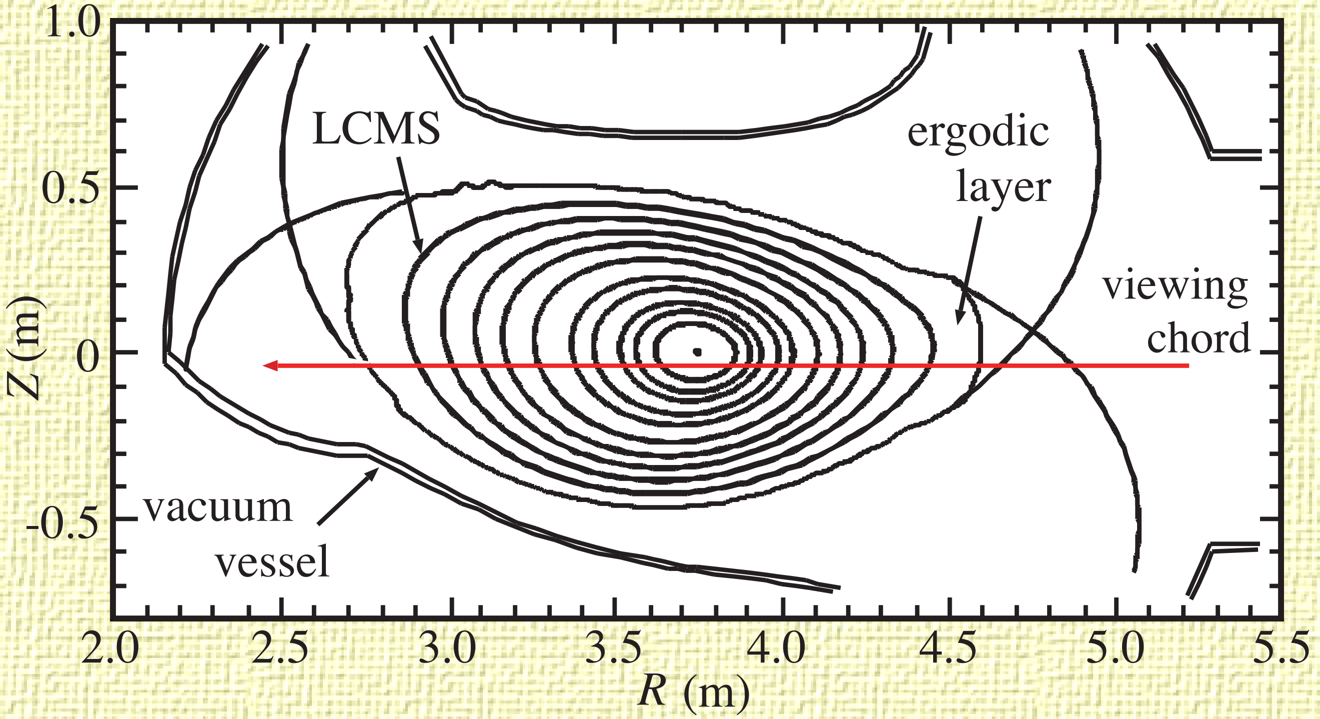


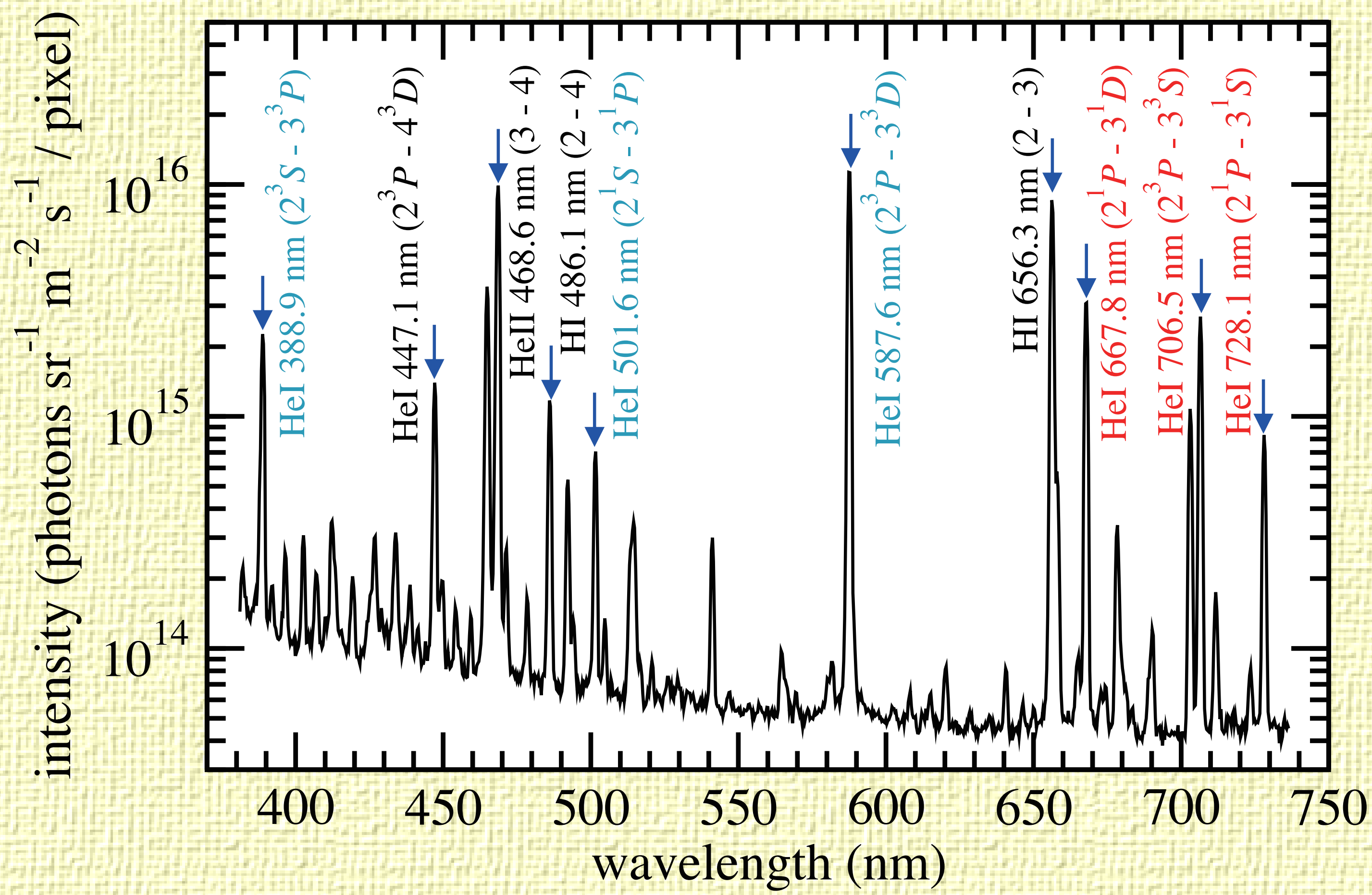
- distribution suggests recombining plasma at intensity maximum (b)
- result at intensity minimum (c) is well reproduced with superposition of ionizing and recombining plasma components

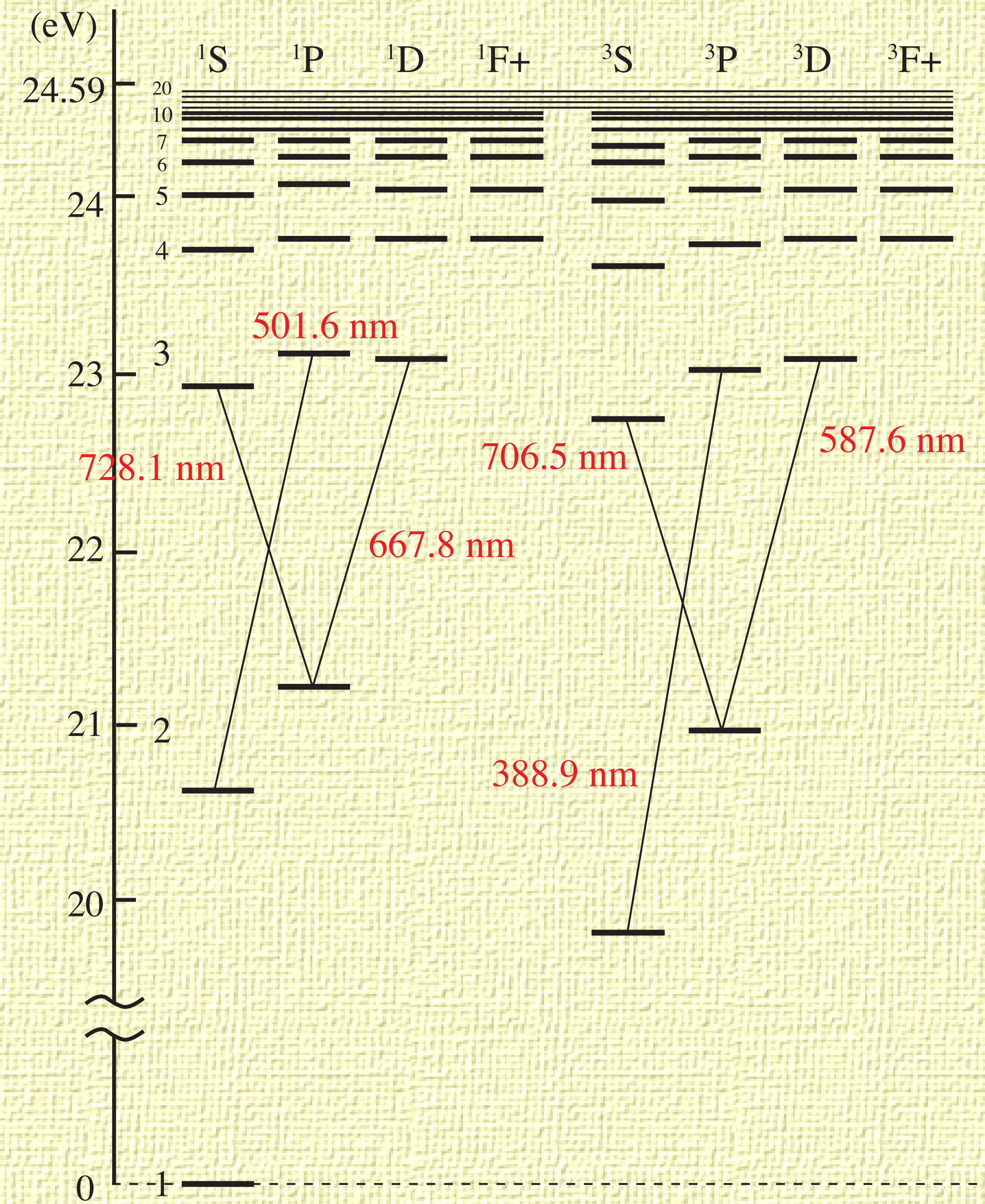
- with moderate resolution measurement, lines from higher levels are resolved
- line profiles are found dominated by Stark broadening
- synthetic spectrum with already derived T_e and n_e agrees with measurement
- LTE is assumed for $n(p)$'s and Stark broadening is based on Stehlé (1999)

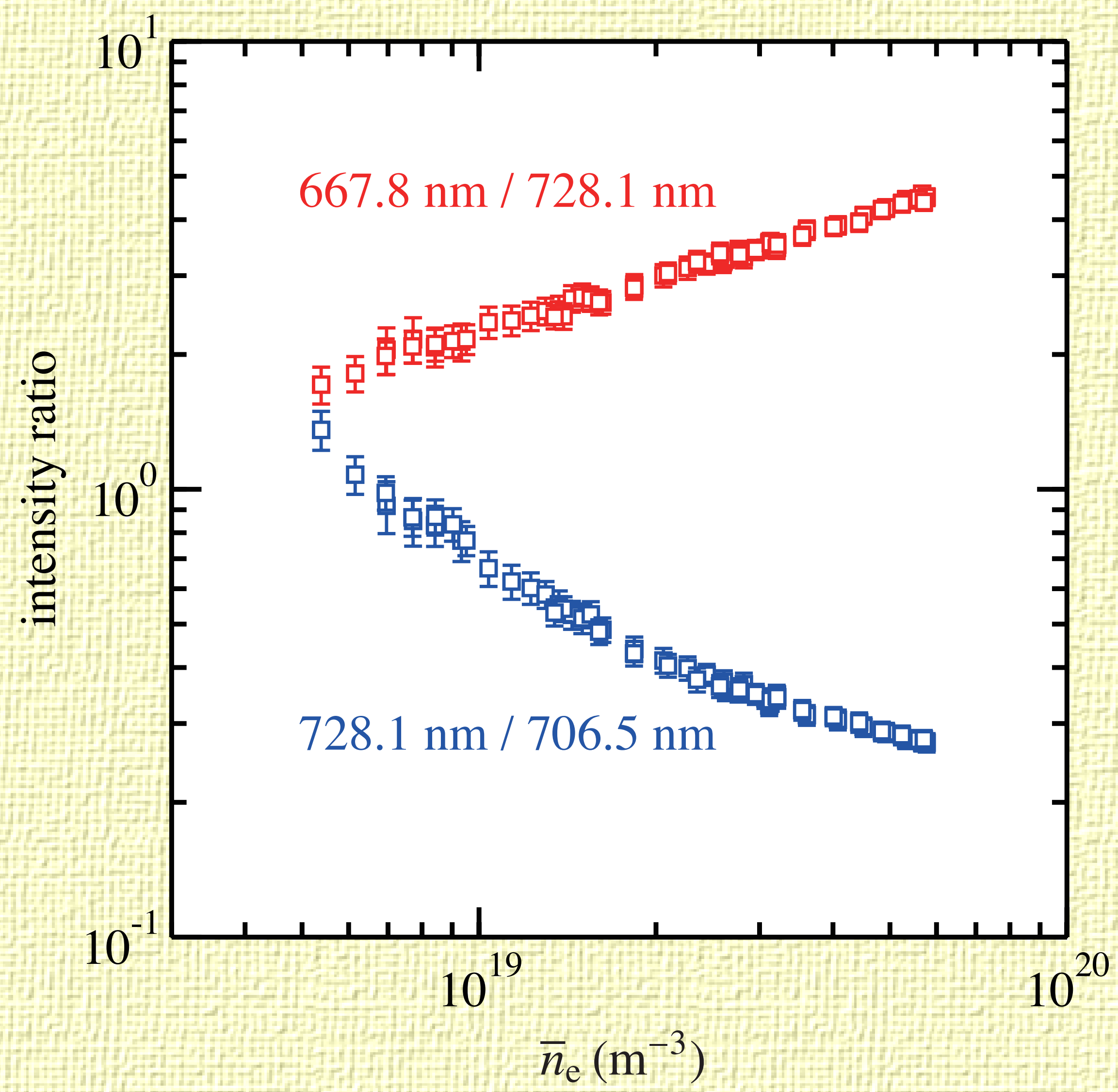


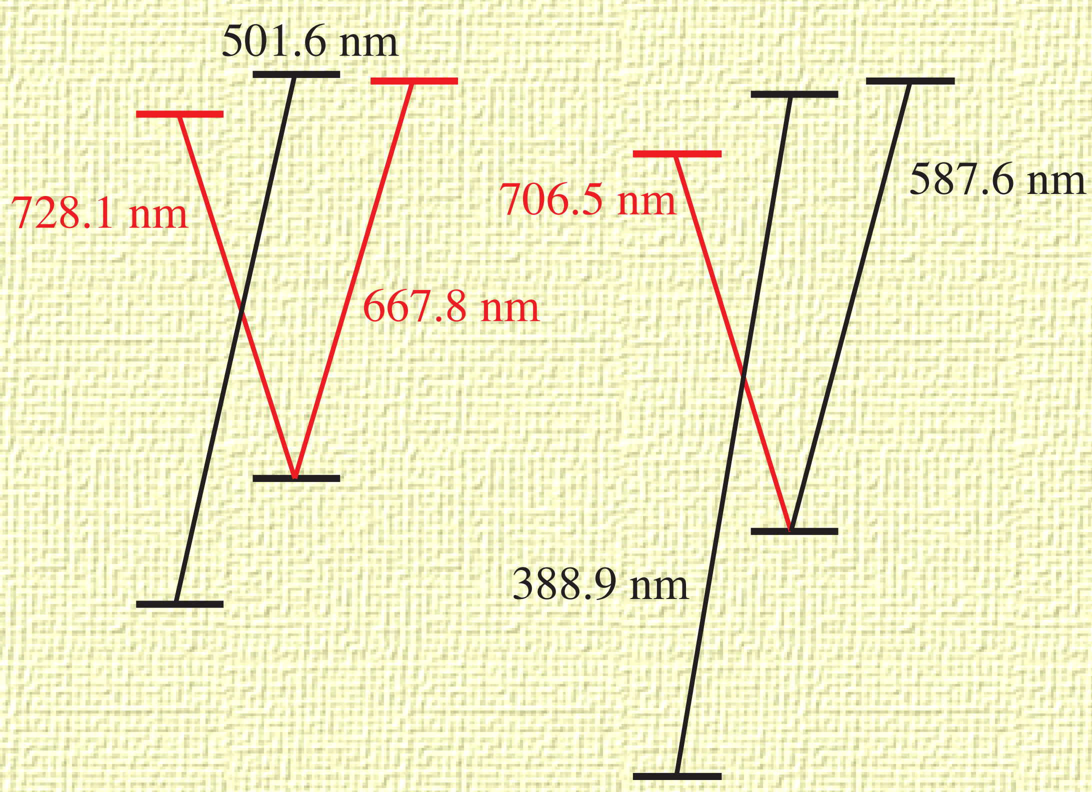
He CR model


LCMS
ergodic
layer
viewing
chord
vacuum
vessel
Z (m)
R (m)
1.0
0.5
0
-0.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5


HeI 388.9 nm (2³S - 3³P)
HeI 447.1 nm (2³P - 4³D)
HeII 468.6 nm (3 - 4)
HI 486.1 nm (2 - 4)
HeI 501.6 nm (2¹S - 3¹P)
HeI 587.6 nm (2³P - 3³D)
HI 656.3 nm (2 - 3)
HeI 667.8 nm (2¹P - 3¹D)
HeI 706.5 nm (2³P - 3³S)
HeI 728.1 nm (2¹P - 3¹S)
intensity (photons sr⁻¹ m⁻² s⁻¹ / pixel)
wavelength (nm)
10¹⁶
10¹⁵
10¹⁴
400
450
500
550
600
650
700
750

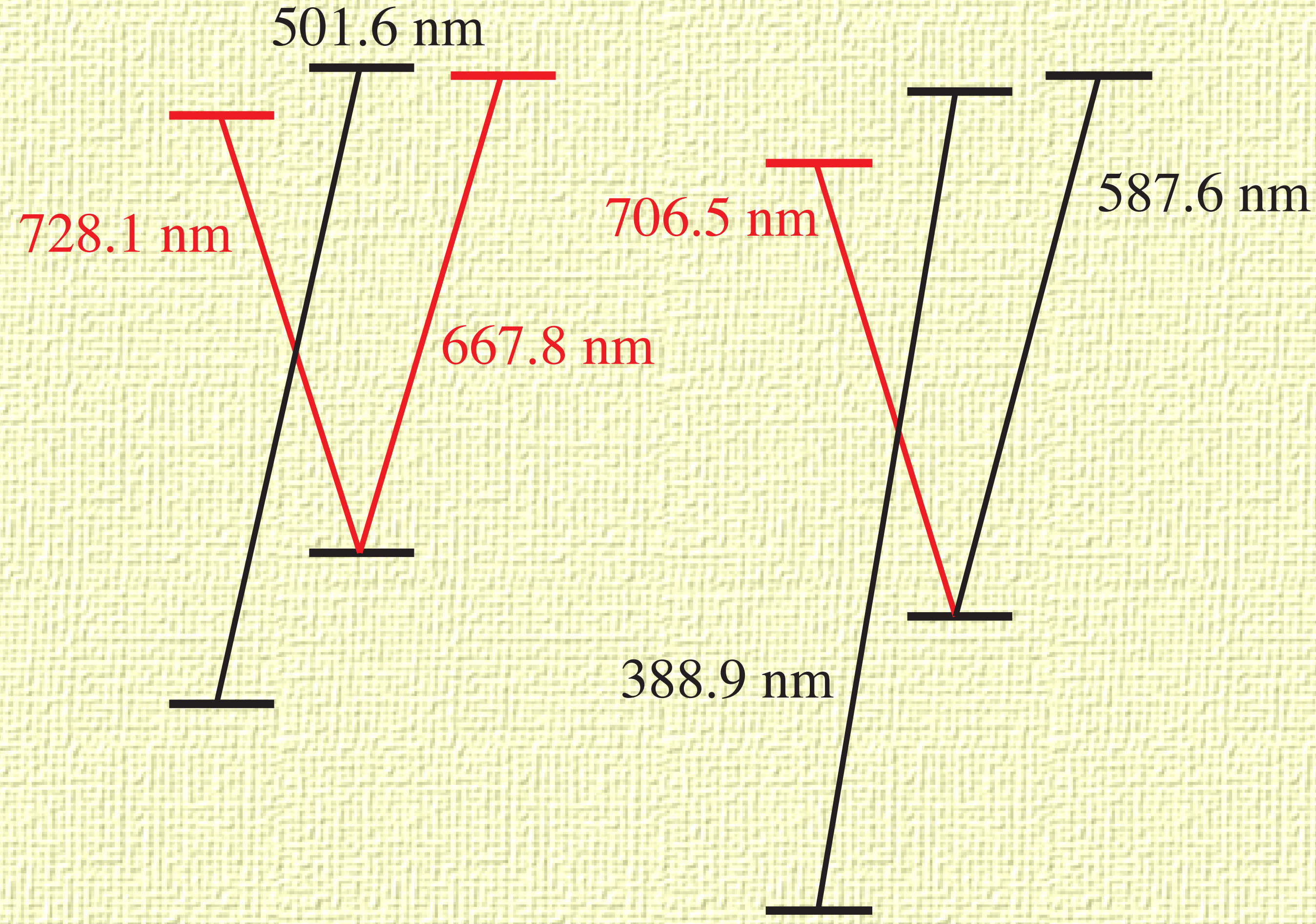

(eV)
¹S
¹P
¹D
¹F+
³S
³P
³D
³F+
24.59
24
23
22
21
20
0
20
10
7
6
5
4
3
2
1
501.6 nm
728.1 nm
667.8 nm
706.5 nm
587.6 nm
388.9 nm

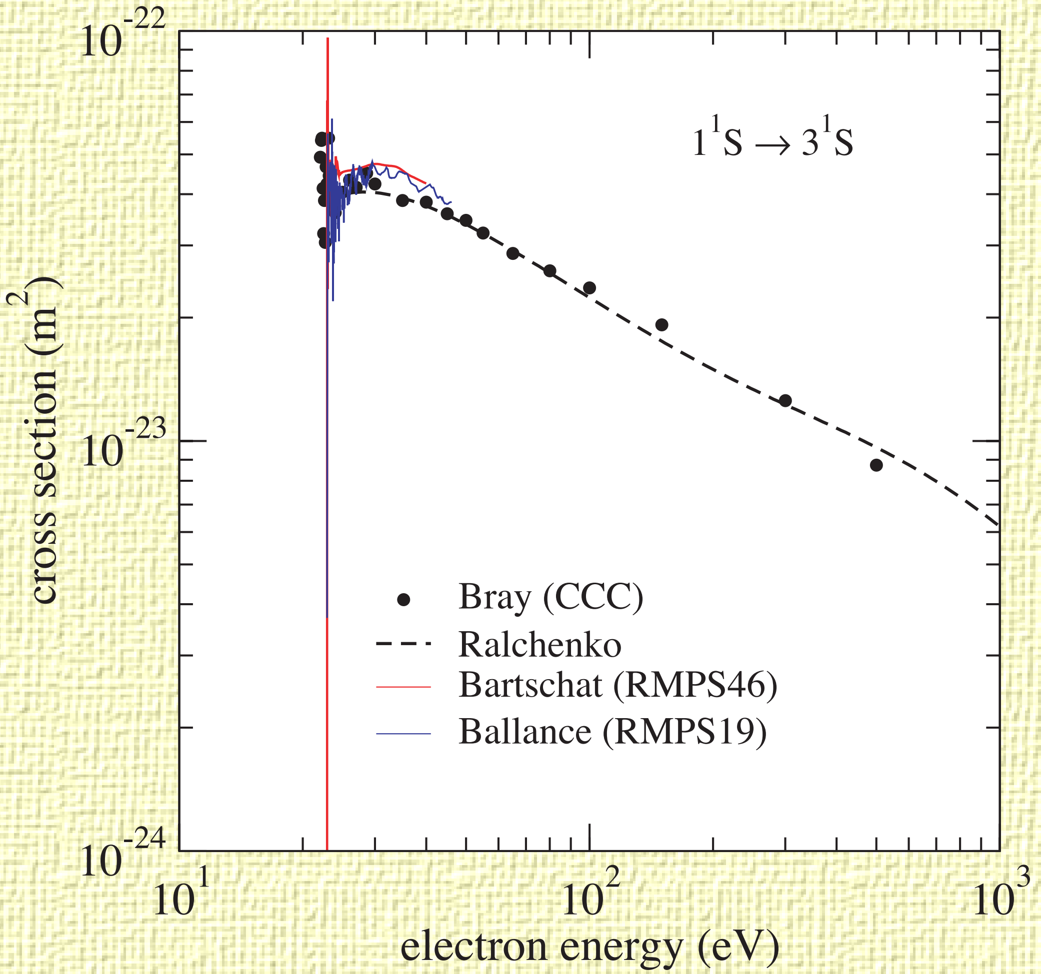


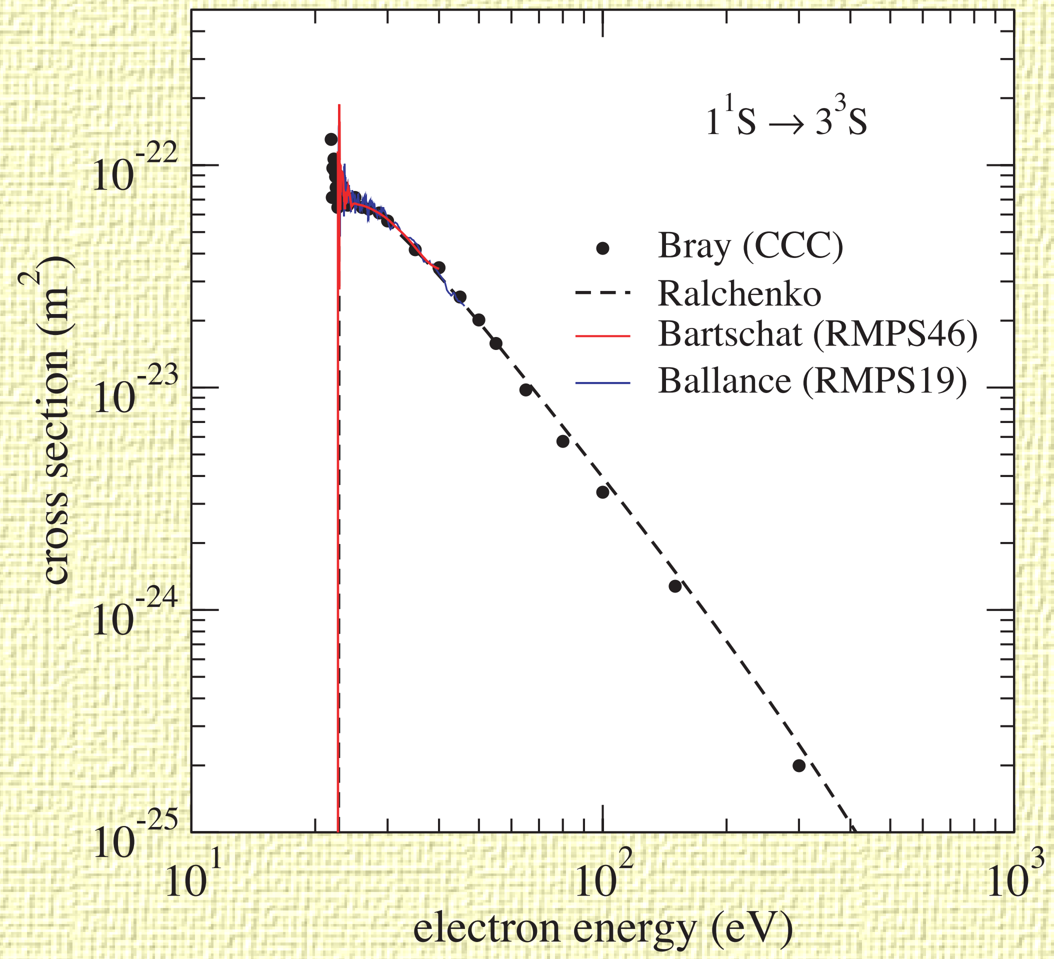


- according to Schweer (1992), 667.8/728.1 and 728.1/706.5 reflect n_e and T_e, respectively
- T_e and n_e are estimated with a help of CR model calculations

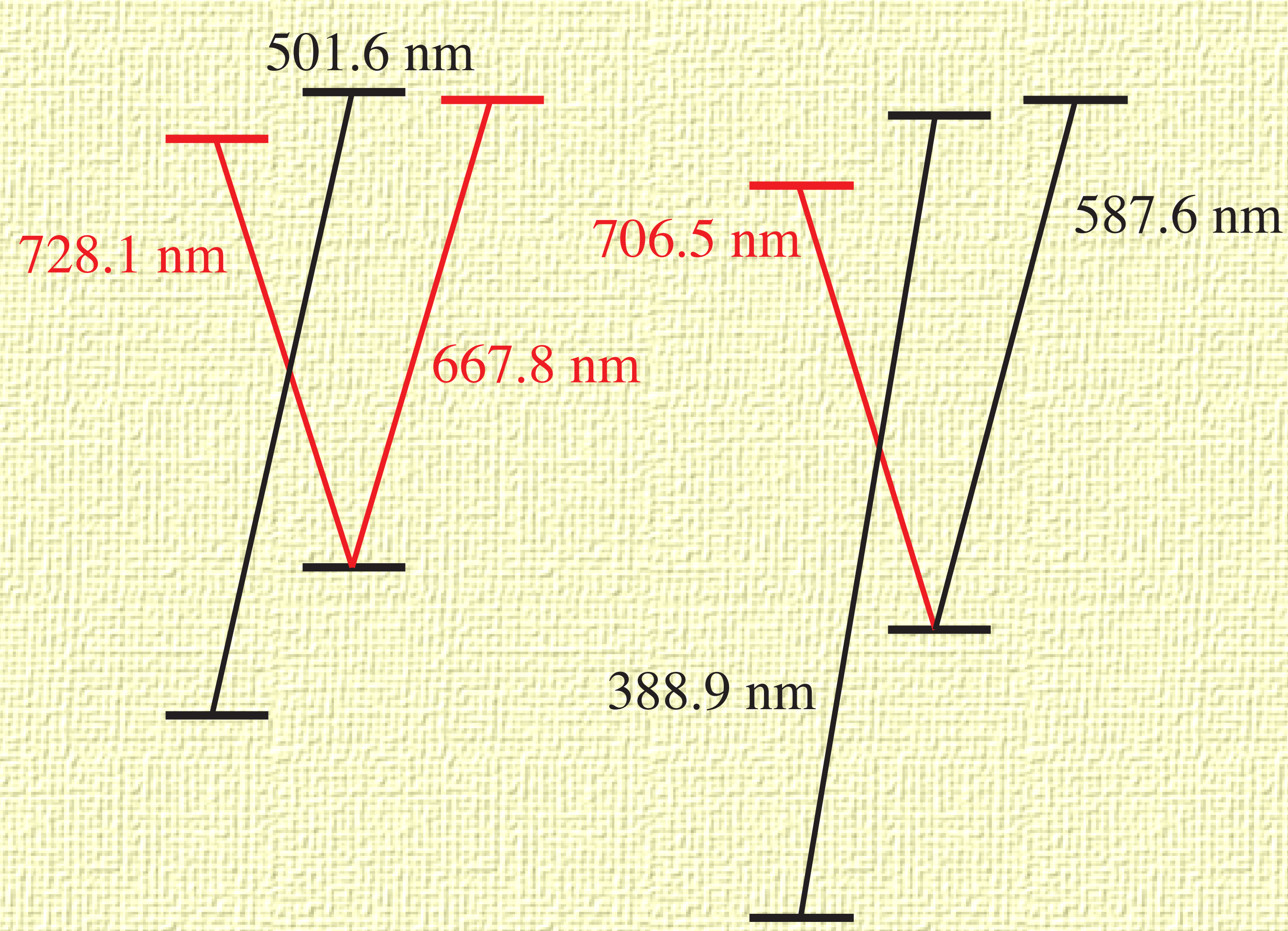
- T_e dependence arises from different asymptotic behaviors of excitation cross section

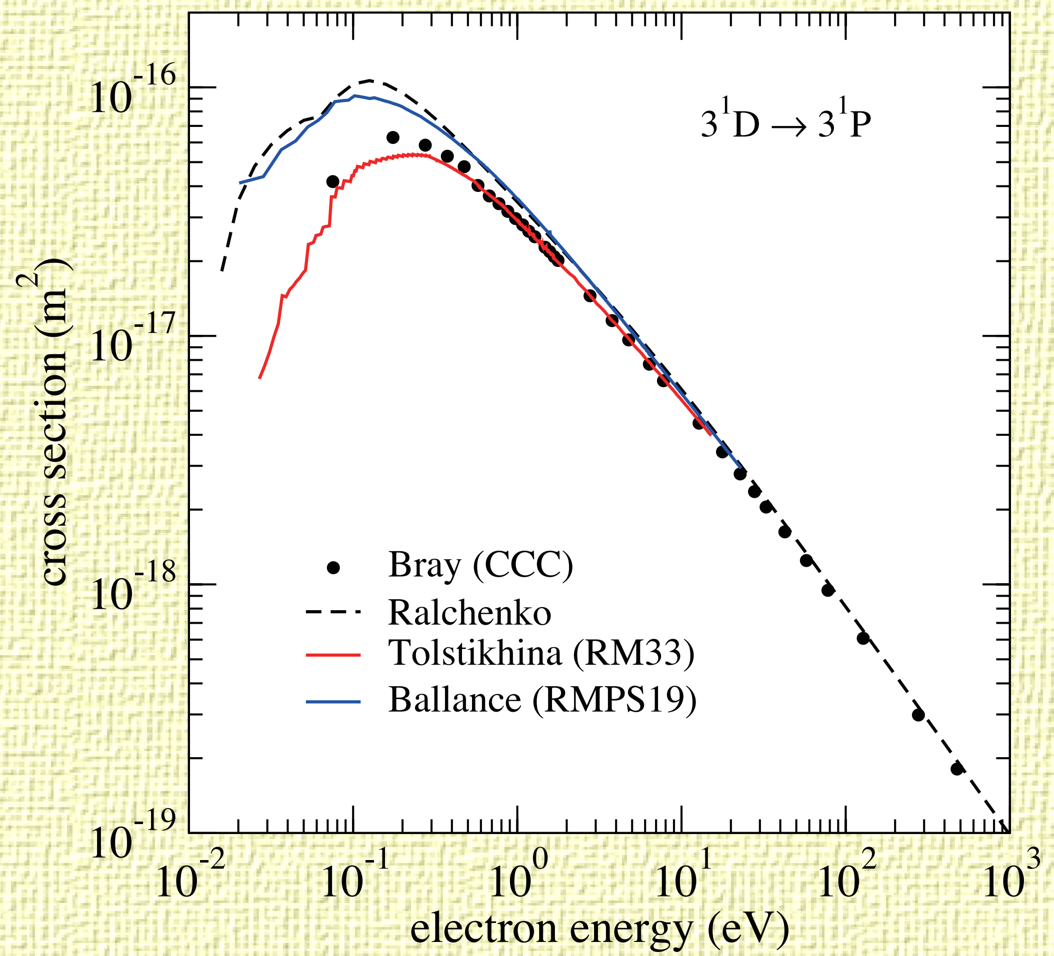


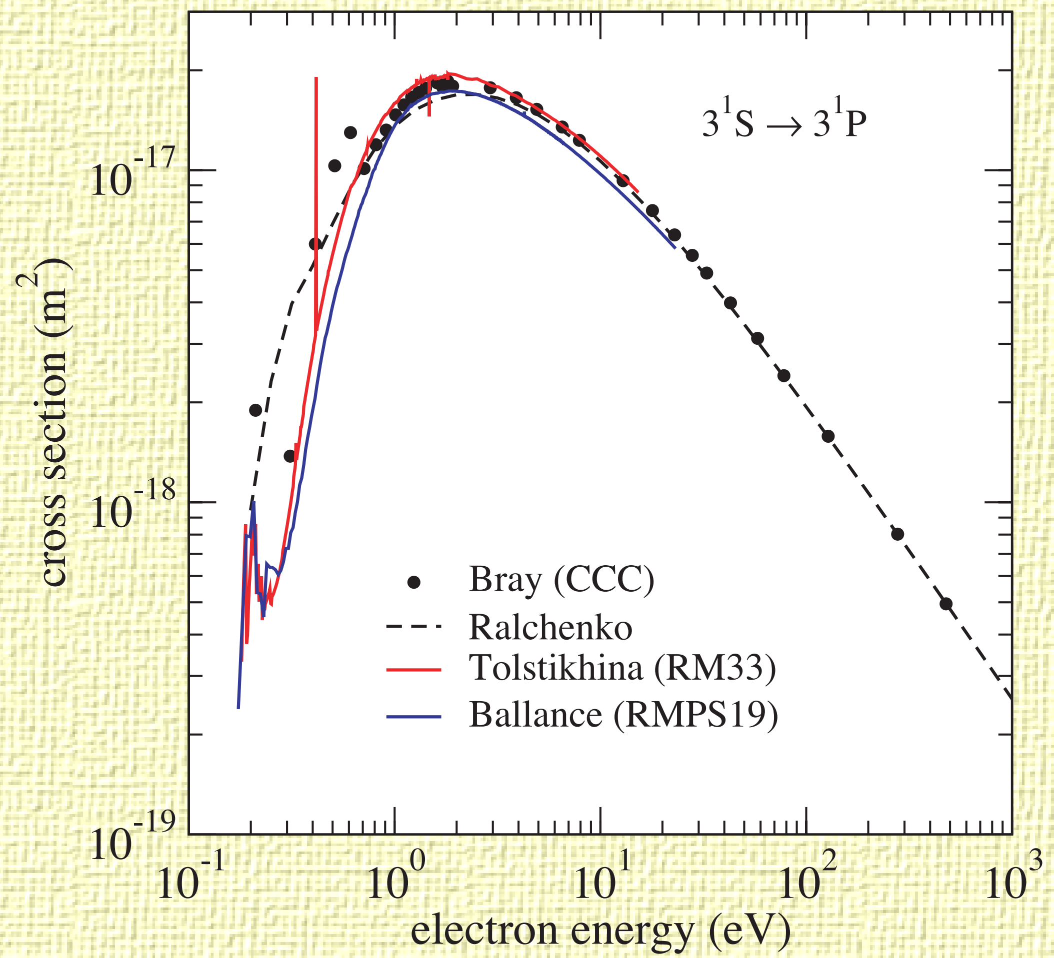




- *L*-changing data plays an essential role especially for n_e measurement



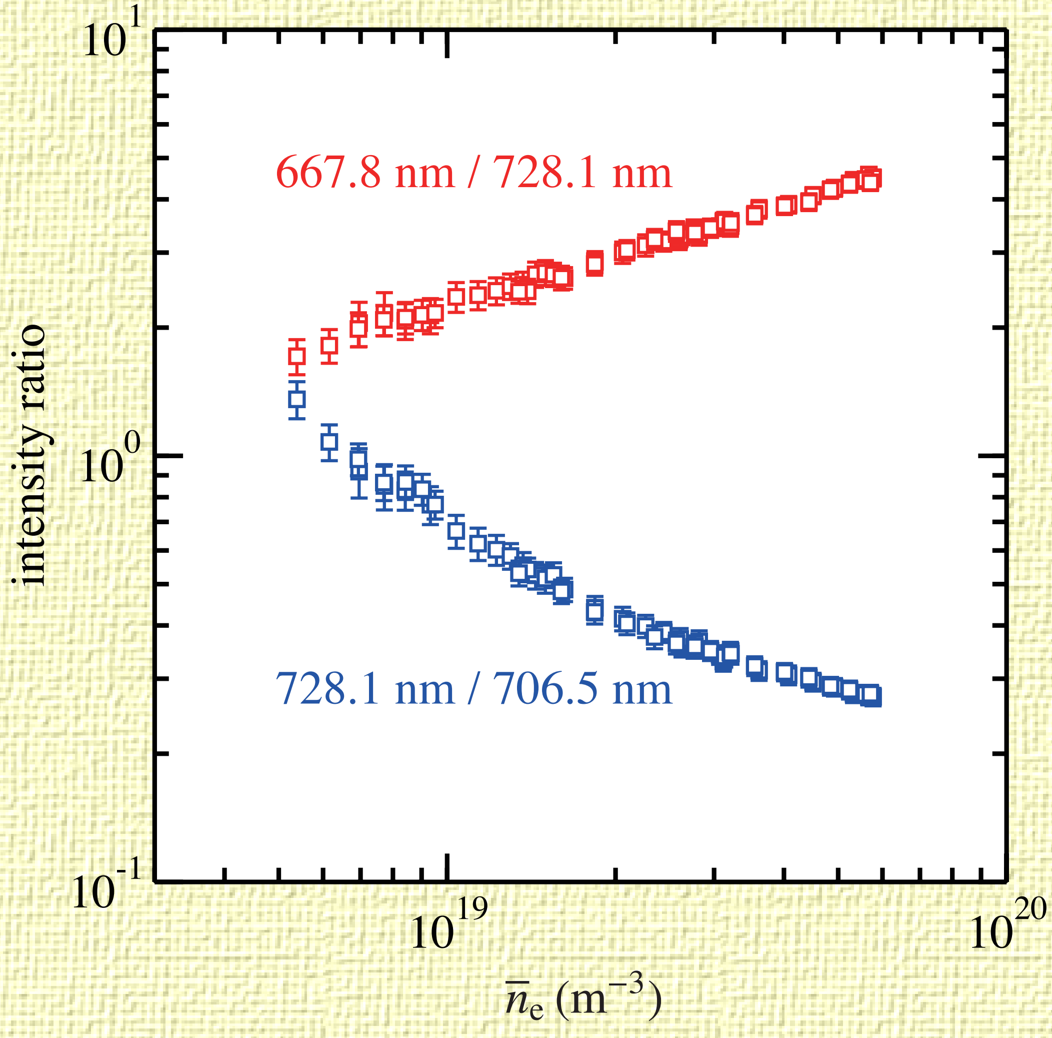


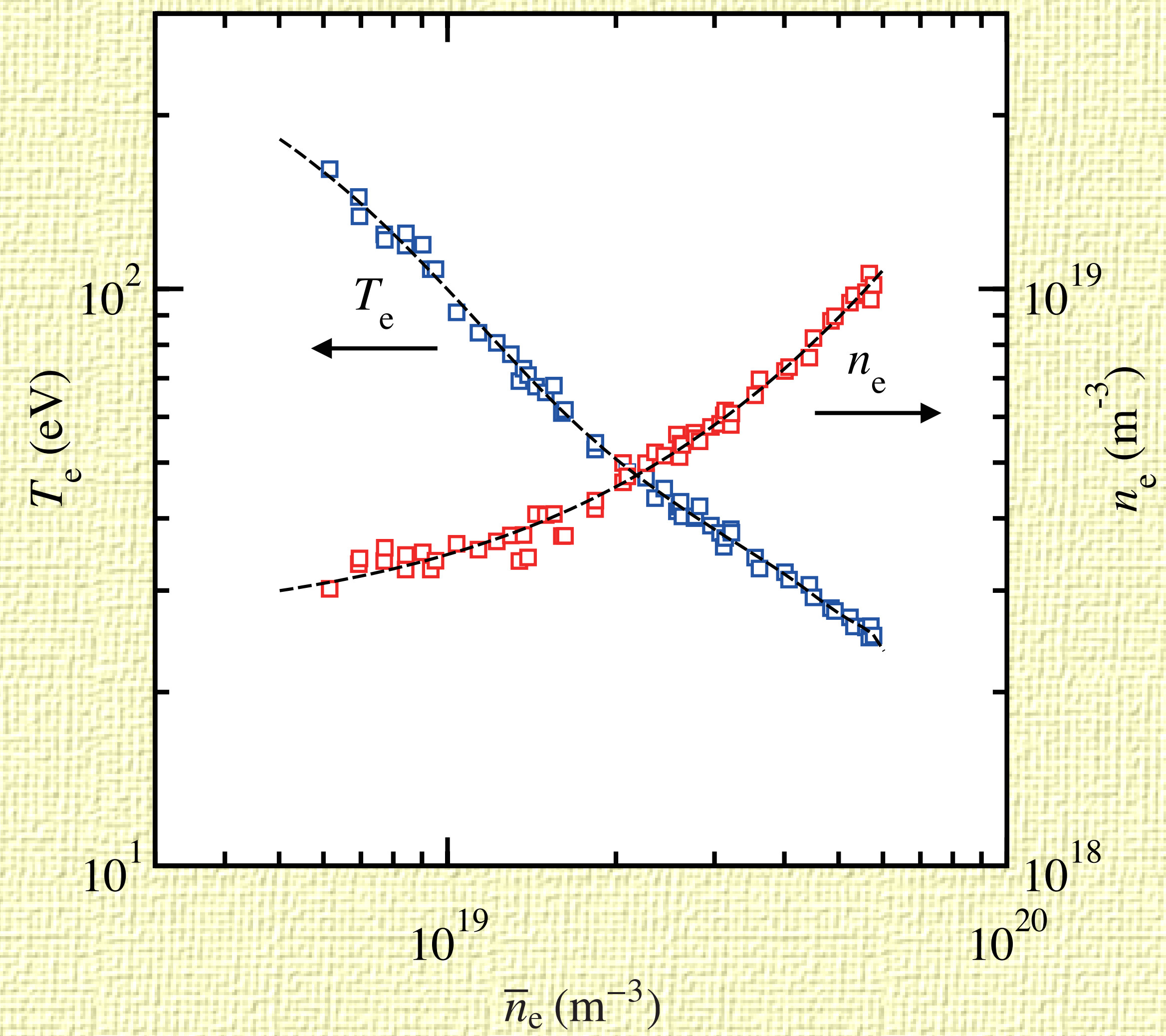


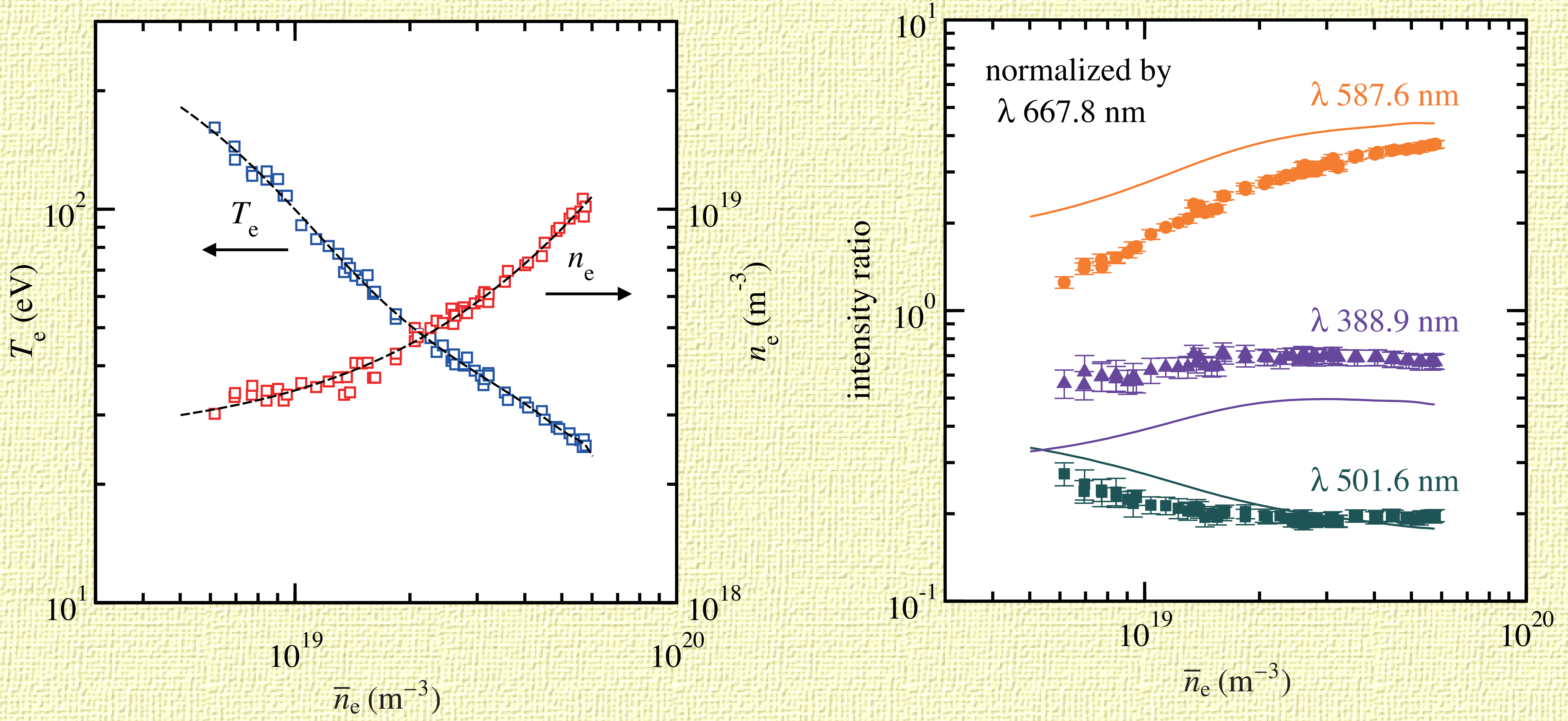
- T_e and n_e are determined so that the following function is minimized

$$f(T_e, n_e) = \sum_i \left(\frac{\kappa_i^{\exp} - \kappa_i^{\text{calc}}(T_e, n_e)}{\kappa_i^{\exp}} \right)^2,$$

where κ_i stands for two ratios







- agreement is satisfactory, but there still exists some inconsistency
- reason for the discrepancy is unclear

Summary

- owing to improvements in observation system and quite stable plasma production, highly quantitative measurements have been realized
- as for analysis, thanks to recent accurate atomic data, reliability of the spectroscopic diagnostics has been elevated