Our role in fusion research

Plasma Spectroscopy and Lasers laboratory – PSL lab
Institute of Physics, Belgrade Serbia

Milivoje Ivković

Plasma Spectroscopy & Lasers laboratory

- **Founded by:** Acad. Nikola Konjević
- **Research area:** Laser physics, technology and applications
  Plasma spectroscopy
  Plasma diagnostics – OES
  Stark broadening of spectral lines
  Laser aided PD – interferometry, scattering
  Laser induced breakdown spectroscopy
  Pulsed laser deposition
- **Stuff**


Marko Cvejić

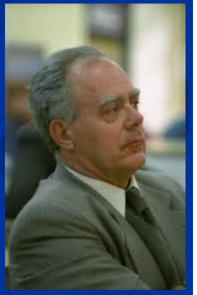

Marijana Gavrilović


Milica Vinić


Biljana Stankov


Milivoje Ivković


Sonja Jovićević


Nikola Konjević

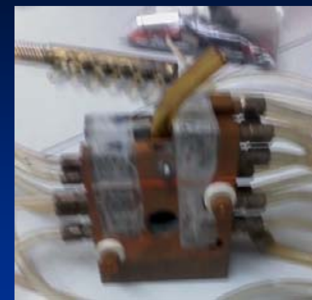
Plasma Spectroscopy & Lasers laboratory

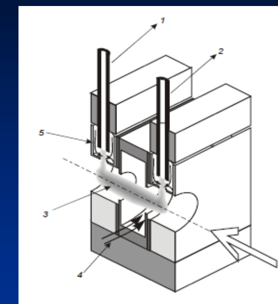
WHAT WE HAVE

CW RADIATION SOURCES

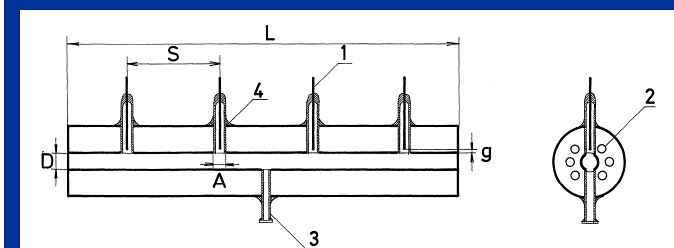
High pressure Hg lamps

Wall stabilized arc



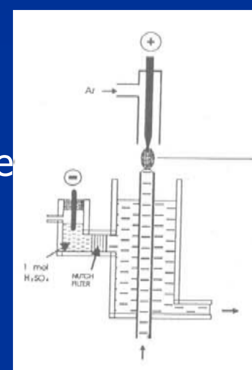


U shaped Ar stabilized arc



Hollow cathode discharge – DBD

Glow discharge with water cathode

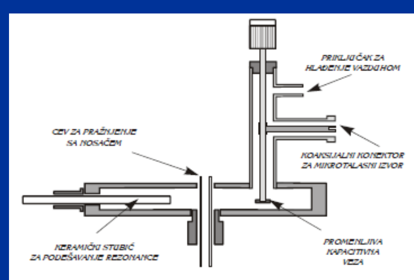


Micro- discharges

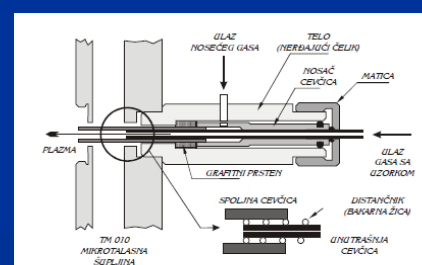
Atmospheric pressure glow discharges

Microwave induced plasma sources – modified Beenakker caity

Low pressure



Open capillary



Mini MIP torch

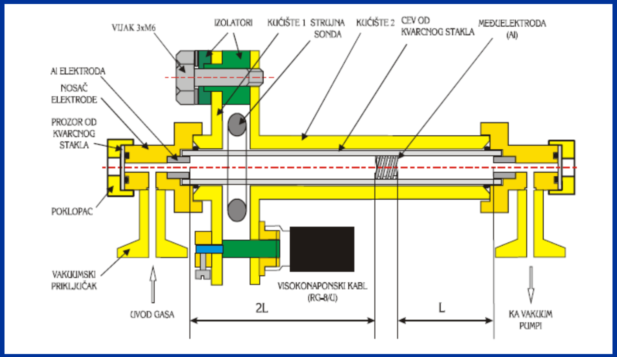
Microwave induced plasma
Evans resonant cavity

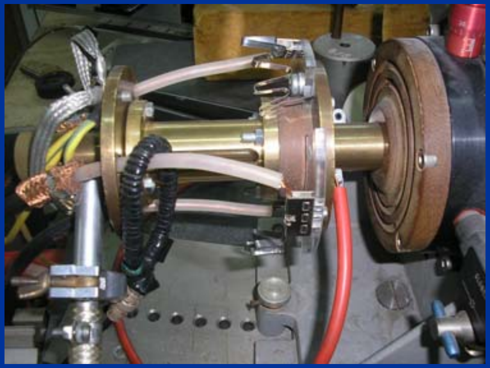
PULSED RADIATION SOURCES

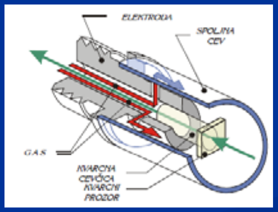
Flashlamp with quartz windows

Capillary discharge

Laser ablation induced fast pulse discharge







Low pressure pulsed discharges "Z pinch" like

Laser induced plasmas

LIBS

PLD

POWER SUPPLIES

PULSED POWER SUPPLIES

Triggered spark gap

Hg ignitrons

DC POWER SUPPLIES

2 kV, 10 mA (He-Ne laser

20 kV, 100 mA (CO_2 laser)

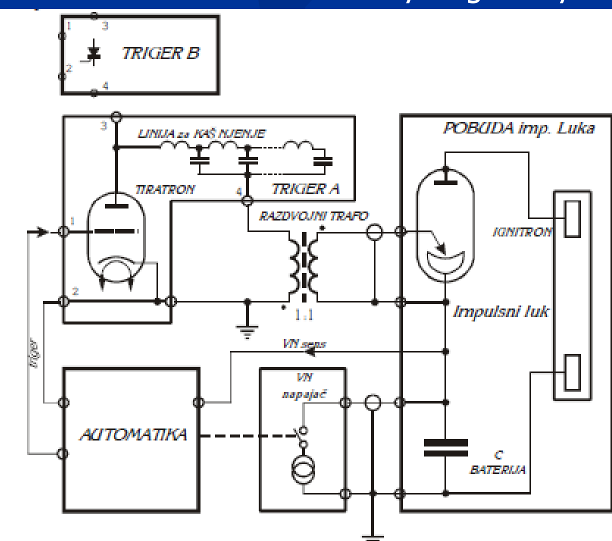
200 – 400 V, 15 - 30 A (Ar laser)

Glass thyratron

Grounded grid deuterium thyratron

Ceramic hydrogen thyratron

Krytron



SPECTRA RECORDING SYSTEMS

MONOCHROMATORS – Scanning Ebert, Czerny-Turner, Rowland circle
VUV, VIS, IR (100 nm – 20 μm)

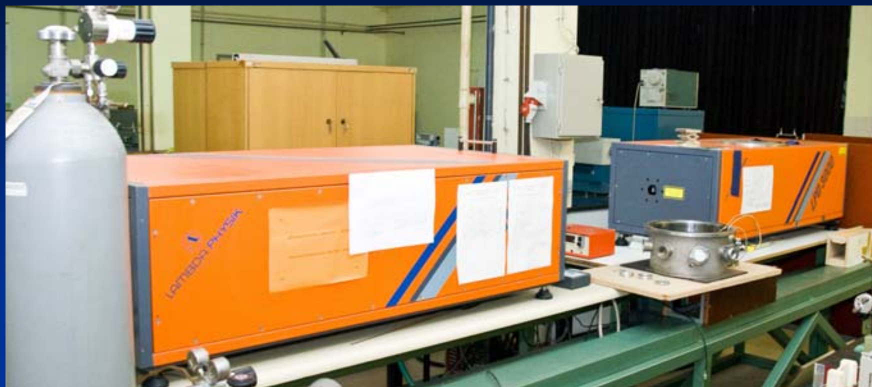
IMAGING SPECTROMETER

ECHELLE

DETECTION SYSTEMS

- Photo plates and films
  (microdensitometer)
- CCD
-- Photomultipliers, photodiodes, IC detectors
  (pA meter, lock-in amplifier)
  (Boxcar averager, digital oscilloscopes)
- ICCD cameras

LASERS



He-Ne
Argon-ion
N_2
dye

Excimer pumped dye laser
$\lambda = 200 – 1200$ nm

Nd:YAG laser
100 mJ 30 ns 10 Hz

CO_2 laser pumped FIR laser
λ up to 300 μm

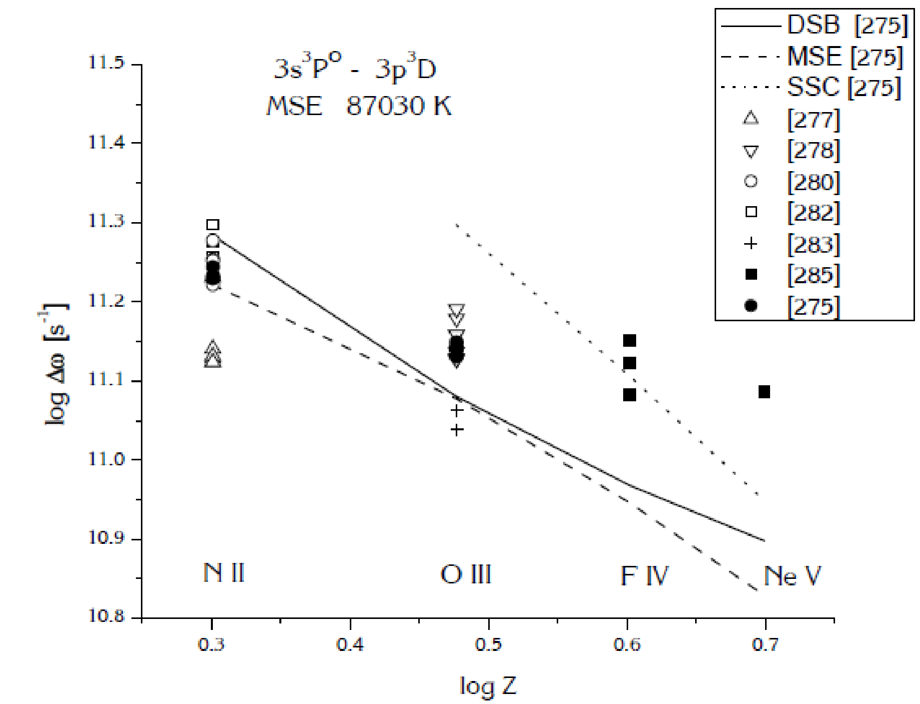
CO_2 laser

Nd:glass laser
1 kJ 80 ns

WHAT WE MEASURED

SPECTRAL LINES OF IONIZED ATOM

Regularities along isoelectronic sequences



Slika 4.3.7. *Zavisnost Stark-ovih poluširina (u jedinicama ugaone učestanosti, normalizovanih na Ne=10^{17} cm^{-3} i Te=87030 K pomoću MSE formule) od spektoskopskog broja Z za multiplet $3s\,^3P^o$ - $3p\,^3D$.*

M.Ivković, N. Ben Nessib, N.Konjević, 2005
J.Phys.B: At.Mol.Opt.Phys.**38**,713

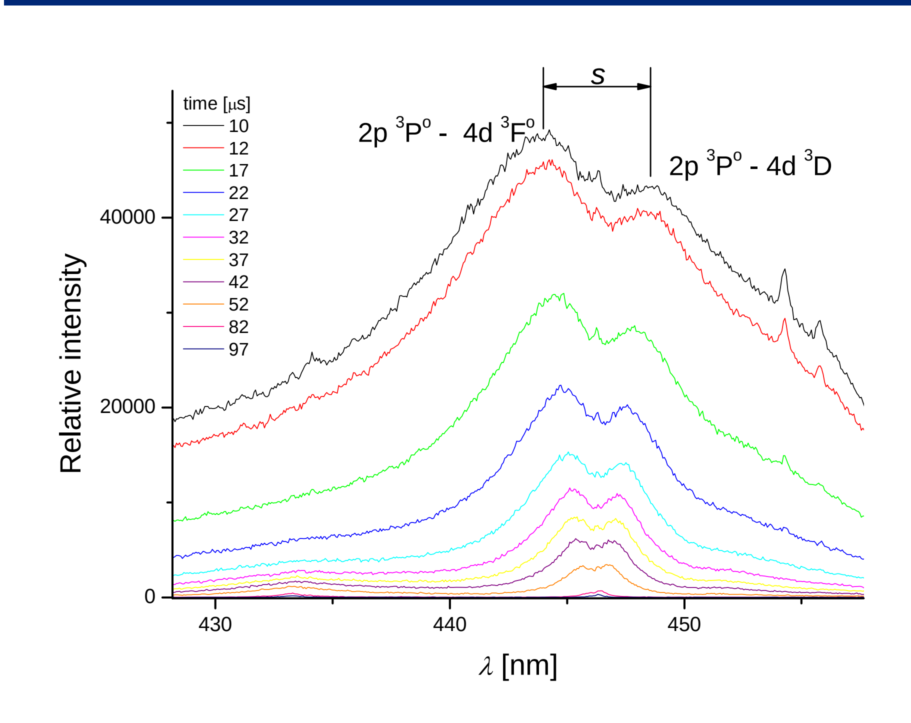
- B.Blagojević, M.V.Popović and N.Konjević,M.S.Dimitrijević, JQSRT 61, 361-375 (1999)
- B.Blagojević, M.V.Popović and N.Konjević, Physica Scripta 59, 374-378 (1999)
- B.Blagojević, M.V.Popović and N.Konjević, J.Quant.Spectrosc.Radiat.Transfer 67, 9-20 (2000)

SPECTRAL LINES OF NEUTRAL ATOMS

Kr S.Jovićević, M.Ivković, R.Žikić and N.Konjević, J.Phys.B: At.Mol.Opt.Phys. 38, 1249-1259 (2005)

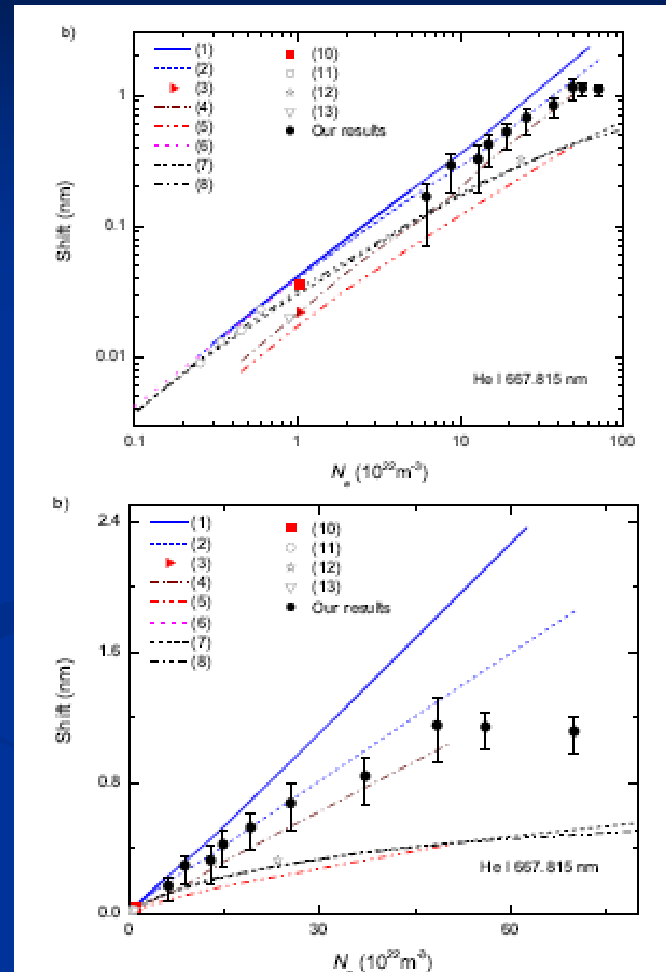
Ne M Ivković, R Zikic, S Jovićević, N Konjević, J. Phys. B: At. Mol. Opt. Phys. **39** (2006) 1773 – 1785

He



M. Ivković, M. A. Gonzalez, S. Jovićević, M. A. Gigosos, N. Konjević
SAB: **65**, 234 - 240 (2010)

Ivković M., Gonzalez M. A., Lara N., Gigosos M. A., Konjević N.,
JQSRT **127** (2013) p.82-89



T. Gajo, M. Ivkovic, N. Konjevic, I. Savic, S. Djurovic, Z. Mijatovic,R. Kobilarov,
MNRAS (2015) **455,** 2969–2979

The spectral profile of the He I singlet line (667.82 nm) emitted from the divertor region of JT-60U,
Plasma Phys. Control. Fusion 41 (1999) 747–757

B. Omar, A. Wierling, **Sibylle Gunter** and G. Ropke
Journal of Physics: Conference Series **11** (2005) 147

HYDROGEN LINES

$N_e < 10^{14}\ cm^{-3}$

- Line merging
- Higher member of
  Balmer series
  a) halfwidths
  b) profile shapes

$10^{14}\ cm^{-3} < N_e < 10^{17}\ cm^{-3}$

- Balmer beta
  a) halfwidths
  b) profile shapes
  Program NED
- Balmer alpha and gamma

$N_e > 10^{16}\ cm^{-3}$

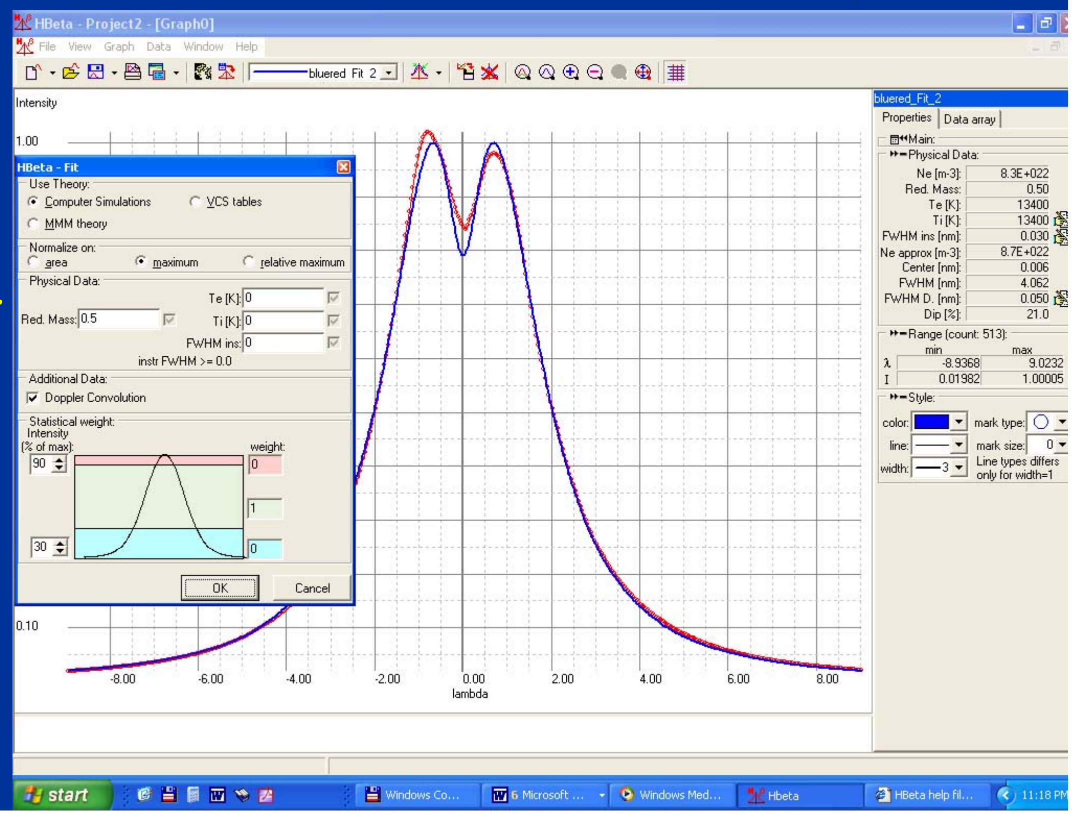
- Balmer beta
a) peaks separation
b) profile shapes

Ivković, N.Konjević, Z.Pavlović,
Hydrogen Balmer beta: The separation between line peaks for..
JQSRT 154(2015)1–8

M.Ivković, S. Jovićević, N. Konjević:
Low electron density diagnostics REVIEW
Spectrochimica Acta B **59**, 591 - 605, (2004)

N.Konjević, M.Ivković and N.Sakan,
Hydrogen Balmer lines for low electron number density plasma diagnostics, REVIEW
Spectrochimica. Acta B **76**, 16–26 (2012)

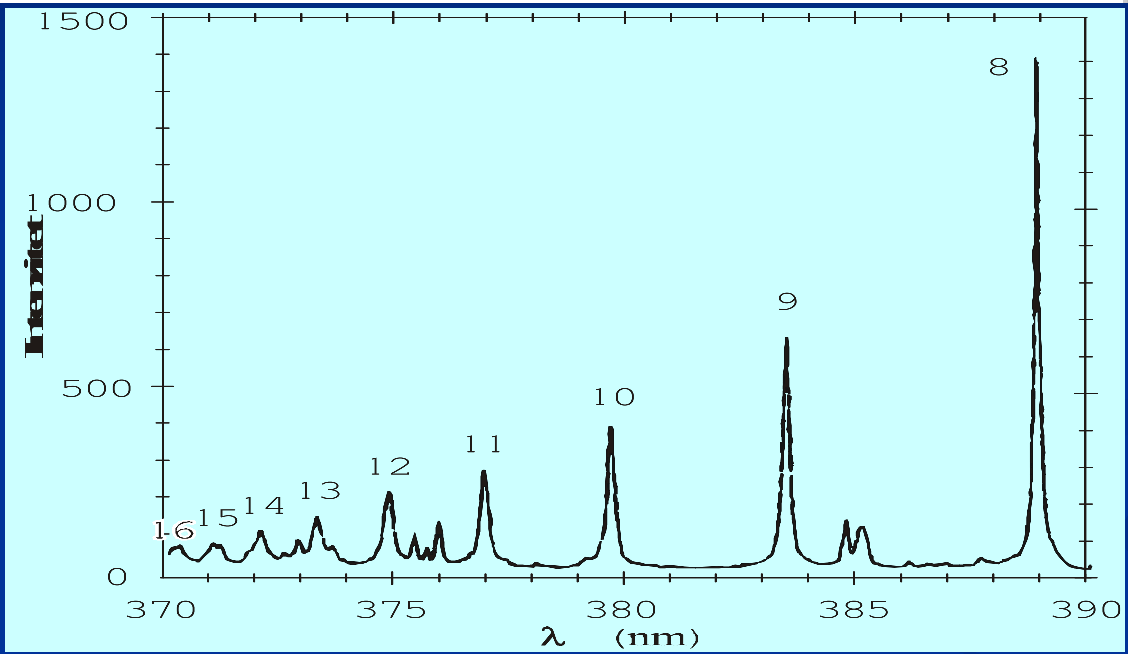
R.Zikić, M.A.Gigosos, M.Ivković,
M.A.Gonzalez, N.Konjević,
A program for …,
SAB **57**, 987 - 998 (2002)



HYDROGEN LINES $N_e < 10^{14}$ cm^{-3}

Line merging - Inglis Teller relation

$$\log\left(N_i + N_e[cm^{-3}]\right) = 23.26 - 7.5 \log n_{max} + 4.5 \log Z$$



n_{max}	7	8	9	10	11	12	13	14	15	16	17
N_e [10^{14}cm^{-3}]	417	153	63.4	28.7	14.08	7.33	4.02	2.31	1.37	0.85	0.54

M.Ivković, S. Jovićević, N. Konjević:
Low electron density diagnostics REVIEW
Spectrochimica Acta B **59**, 591 - 605, (2004)

B.L. Welch, H.R. Griem, et al.
Density measurements in the edge, divertor and X-point regions of Alcator C-Mod from Balmer series emission,
Phys. Plasmas 2 (1995)4246–4251.

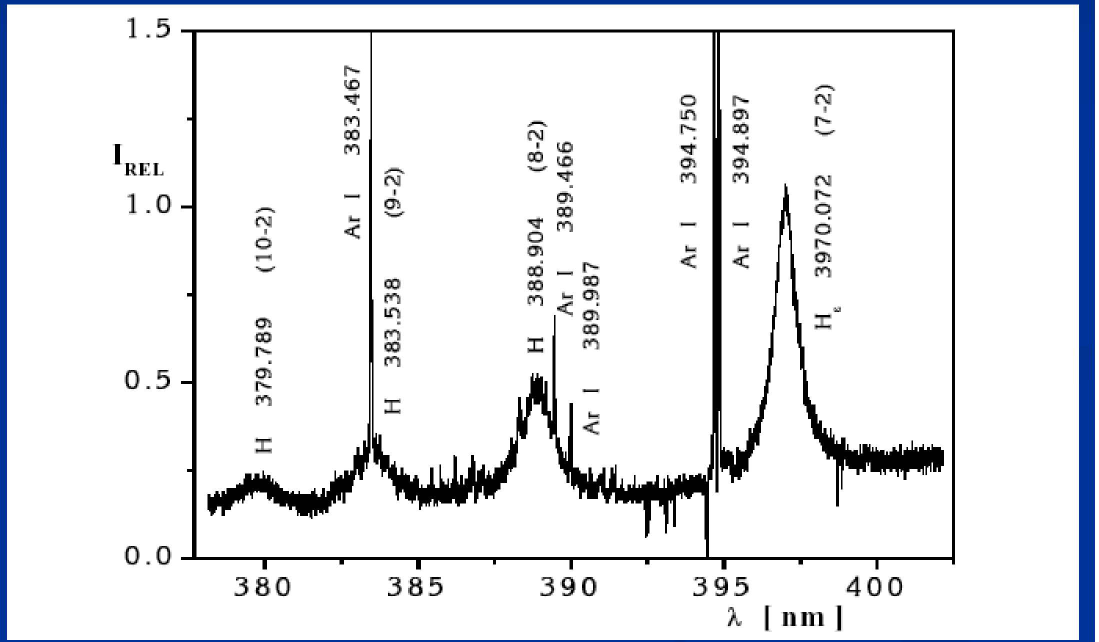
HYDROGEN LINES $N_e < 10^{14}$ cm^{-3}

Higher members of Balmer series

From line halfwidths

$$N_e\,[m^{-3}] = 8.0\ x\ 10^{18}\left(\frac{w\,[0.1\,nm]}{\alpha^{n}_{1/2}}\right)^{3/2}$$

Transition	$\alpha_{1/2}^{n}$	W_m [nm]	W_g [%]	N_e [cm^{-3}]
6 – 2	0.150	0.73	5.6	2.71 x 10^{15}
7 – 2	0.184	0.86	4.7	2.56 x 10^{15}
8 – 2	0.283	1.30	3.1	2.49 x 10^{15}
9 – 2	0.345	1.56	2.5	2.43 x 10^{15}
10 – 2	0.458	2.30	1.7	2.84 x10^{15}

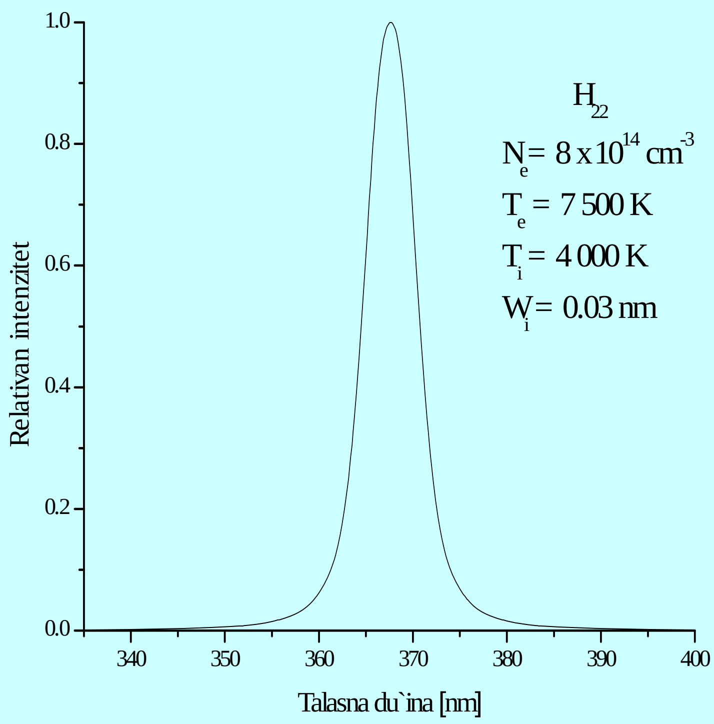


From Inglis-Teller relation 1.4 – 2.9 x 10^{15} cm^{-3}
from H_β profile shape $N_e = 2.54 \times 10^{15}$ cm^{-3}

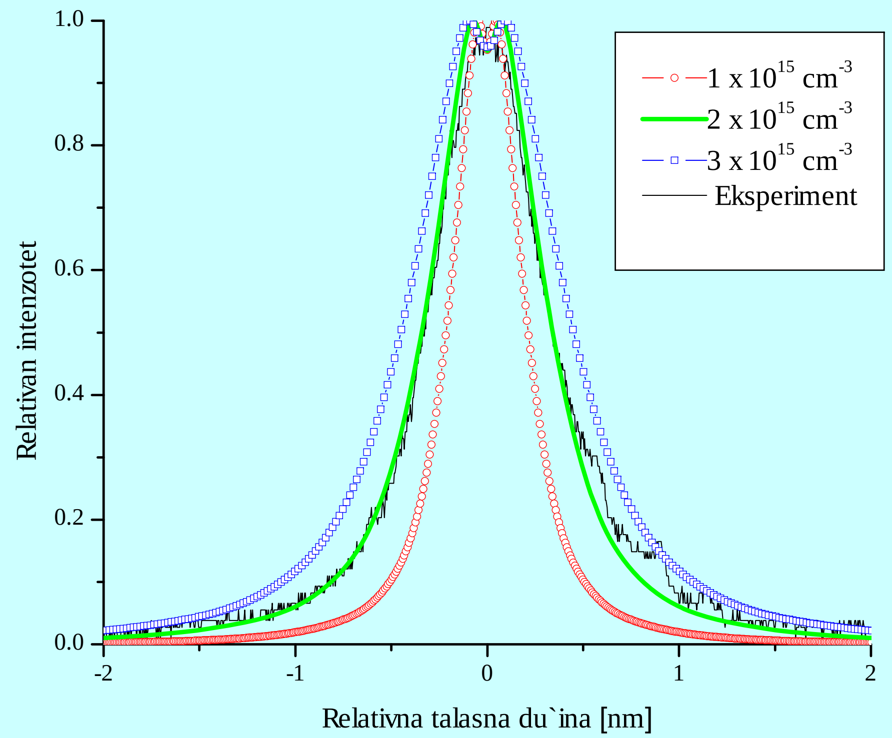
M.Ivković, S. Jovićević, N. Konjević:
Low electron density diagnostics…. REVIEW
Spectrochimica Acta B **59**, 591 - 605, (2004)

HYDROGEN LINES $N_e < 10^{14}$ cm^{-3}

Comparison of experimental and theoretical profiles

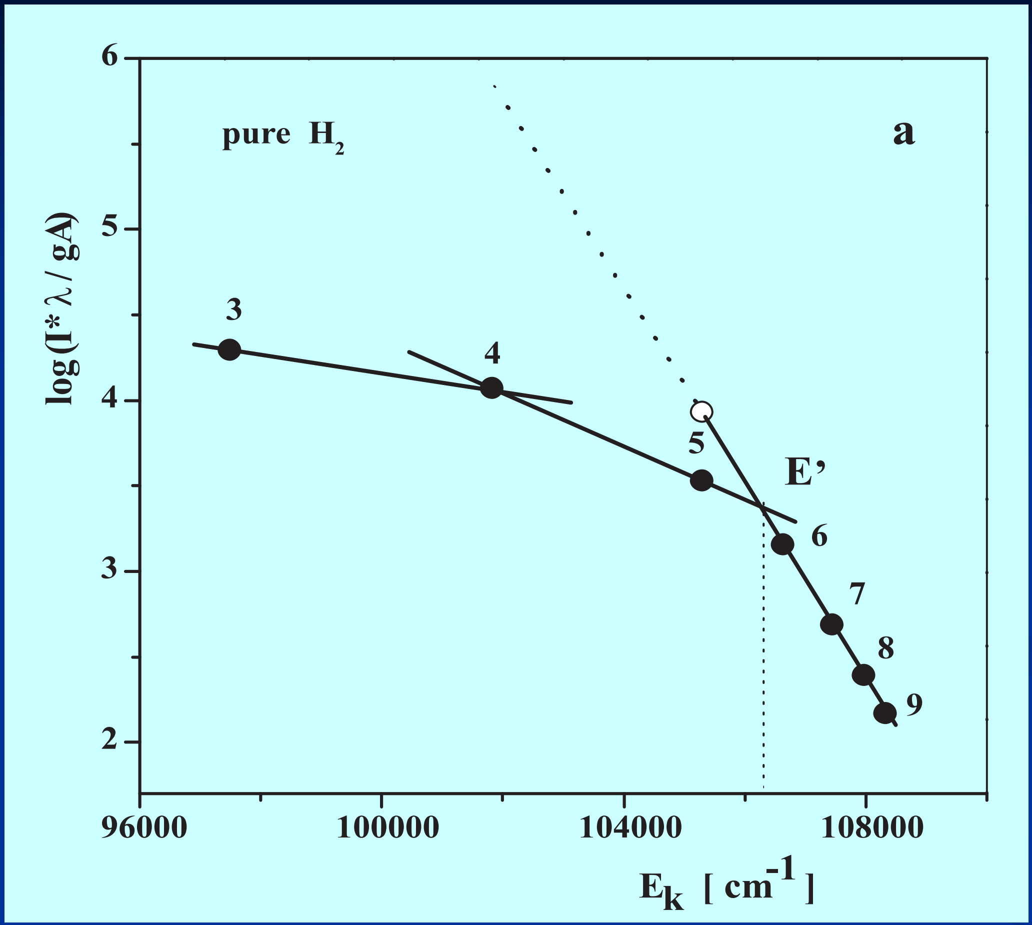


Theoretical line shape for Balmer line ***n=22***



Theoretical and experimental line shape of ***H_δ line*** *(**n=6,** T_e=T_i=8000K, W_i=0.03nm)*

N_e and T_e FROM BOLTZMANN PLOTS



$$N_e \; [cm^{-3}] \geq 7.4 \times 10^{18} \frac{Z^6}{n^{17/2}} \sqrt{\frac{k \; T_e}{E_H}}$$

E′ = R (1 – 1/n′2) ; R = 109 678 cm-1

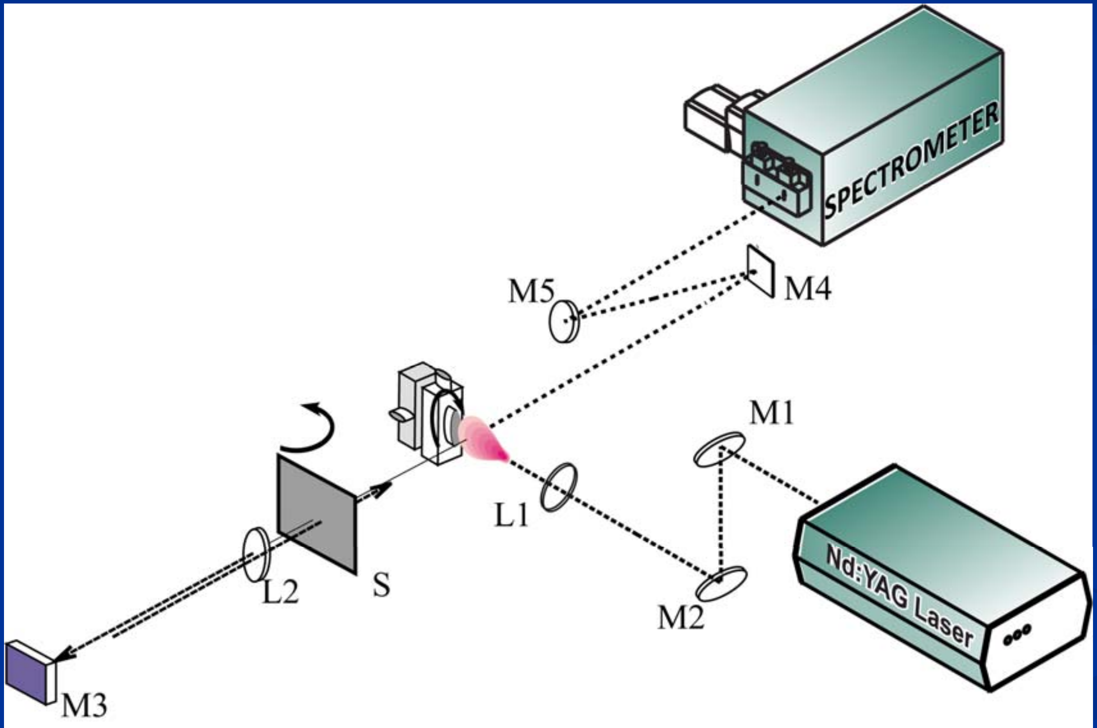
N Konjević, S.Jovićević, M. Ivković
Physics of plasmas **16**, 103501, (2009).

PLASMA FACING COMPONENTS STUDY

Spectroscopic diagnostics of laser-induced plasmas ***REVIEW***

N. Konjević, M. Ivković and S. Jovićević, Spectrochimica Acta Part B: **65**, 593 - 502 (2010)

- **LIBS DEVELOPMENT – Eurofusion project proposal**



Phys4PicoLIBS PHYSICS OF THE PICOSECOND LASER PULSE –
TUNGSTEN INTERACTION FOR THE LIBS MEASUREMENT OF LIGHT ELEMENT (He, D, T, N AND O) IMPLANTATION IN TOKAMAK PLASMA FACING COMPONENT MATERIALS

WHAT ELSE WE CAN DO

Besides - N_e **diagnostics from spectral lines in divertor region and**
- **analysis of plasma facing components**

FIR LASER HETERODYNE INTERFEROMETRY

He-Ne laser interferometry, CO_2 laser interferometry

VUV SPECTROSCOPY

M. L. Reinke et al. **VUV Impurity Spectroscopy on the Alcator C-Mod Tokamak,** 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, May, 2010.

LIF - Third harmonic of excimer pumped dye laser – Lyman alpha

D/T RATIO – Halpha

MSE – Motional Stark Effect

THOMSON SCATTERING, SHADOWGRAPHY, SCHLIEREN …………..