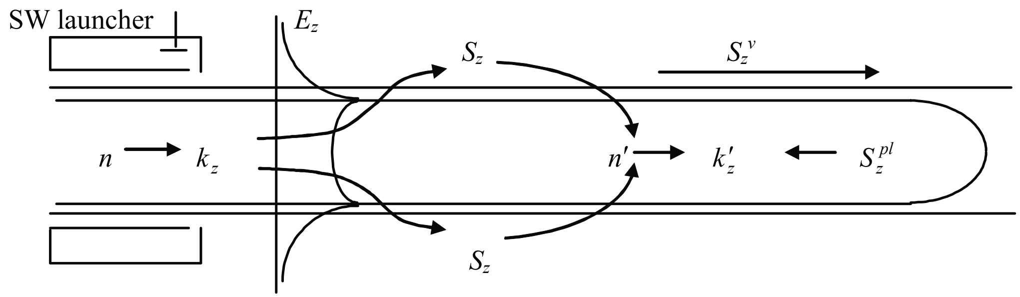
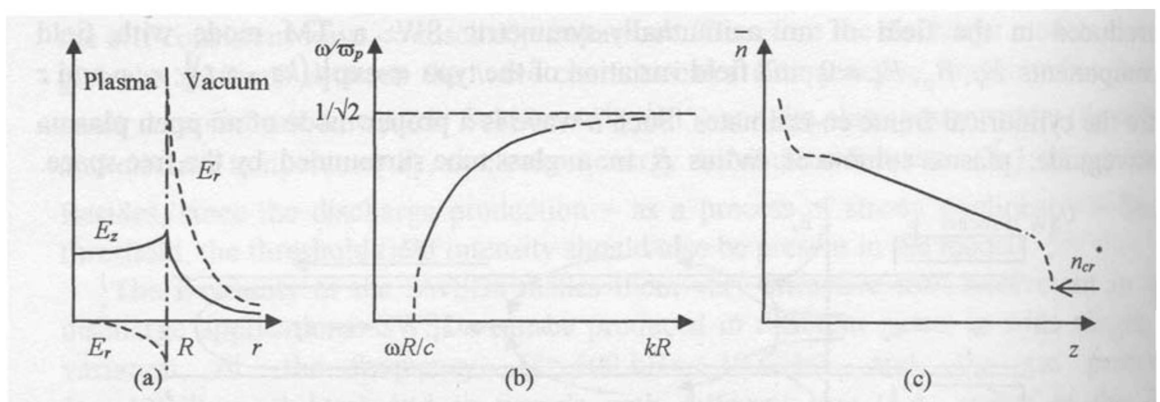
On the broadenings of spectral lines emitted in surface wave discharges

M. Christova, L. Christov and M. S. Dimitrijević

Surface wave sustained discharge

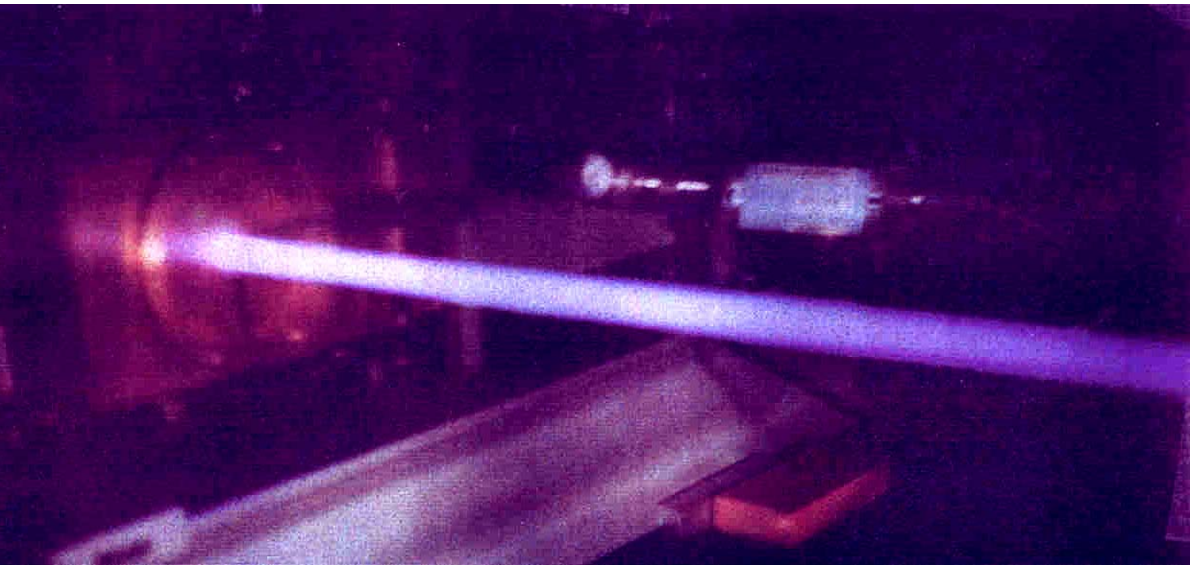
$$n \Leftrightarrow \langle E^2 \rangle$$

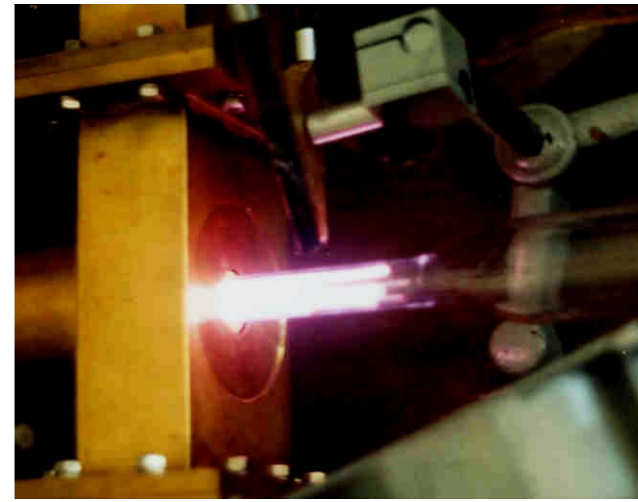


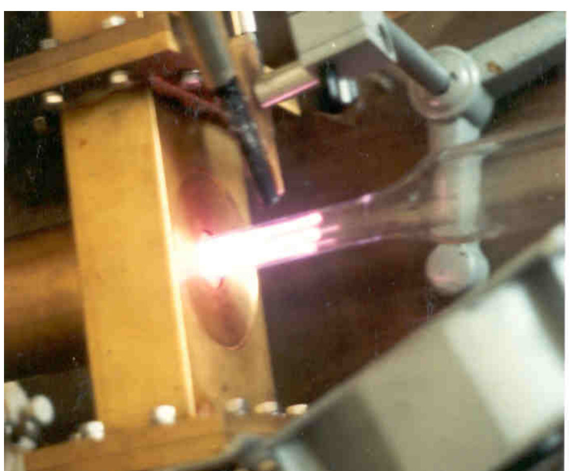


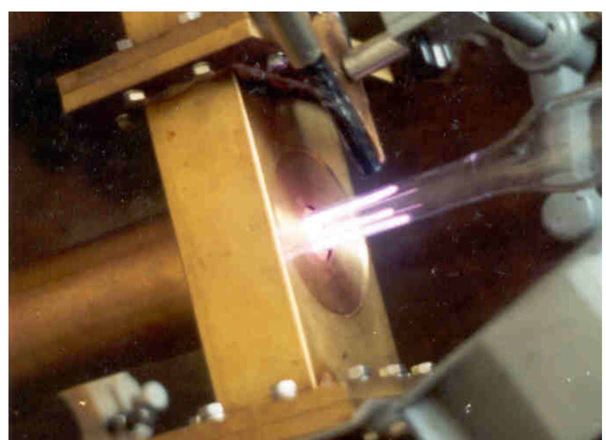
Filamentation of the discharge

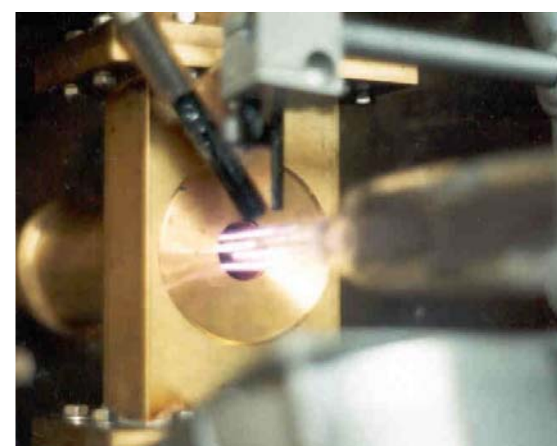
Djermanova N, Grozev D, Kirov K, Makasheva K, Shivarova A and Tsvetkov Ts 1999 *J. Appl. Phys.* **86** 737-745











Diagnostics methods for plasma parameters

- **Probe diagnostics**
- **Microwave and Radiophysics methods**
- **Optical spectroscopy methods**
- **Without any perturbation of both - plasma and wave**
- **Profile, broadening and shift of the emitted spectral lines - information about the plasma parameters and interactions emitter-perturbers (charged and neutral particles).**
- **The methods based on the broadening of the lines emitted by the gas under investigation are seldom used for diagnostics of SWDs.**

Spectroscopy diagnostics – broadenings

Aim: Experimental and theoretical investigation of broadening of spectral lines, suitable for electron density and gas temperature diagnostics of SWDs in the pressure range between 1-200 Torr and 1 atm.

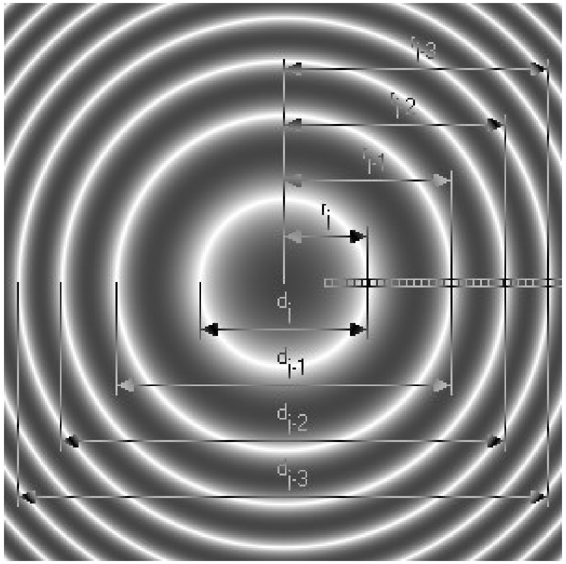
Goals:

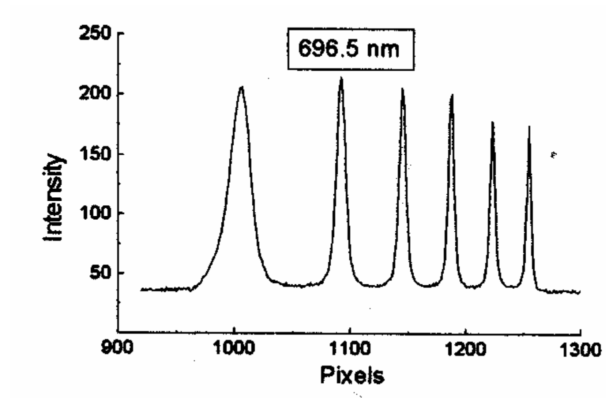
- **Nonstationary regimes of SWDs - Experiment**
- **Stationary regime under atmospheric pressure - Experiment**
- **Modelling the pressure broadenings of Ar I lines:**

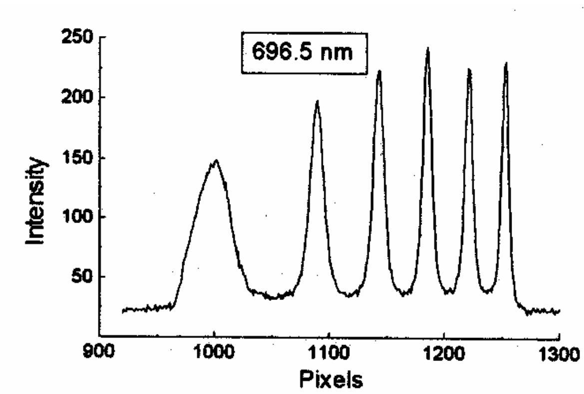
  a) Calculations of Stark broadening parameters

  b) Calculations of neutral broadening using different potentials of interaction.

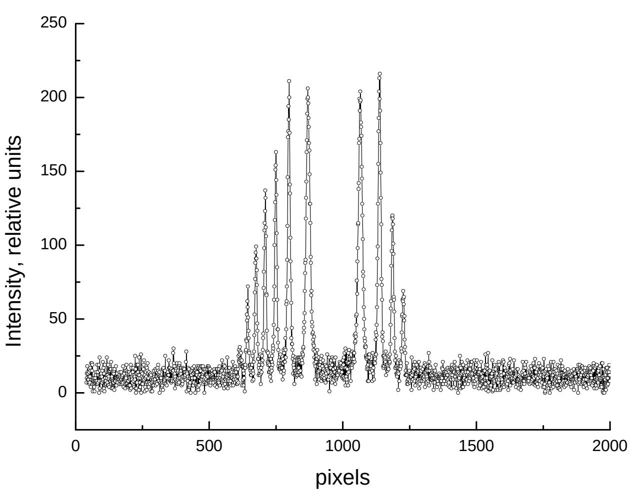
Nonstationary regimes of SWDs - Experiment

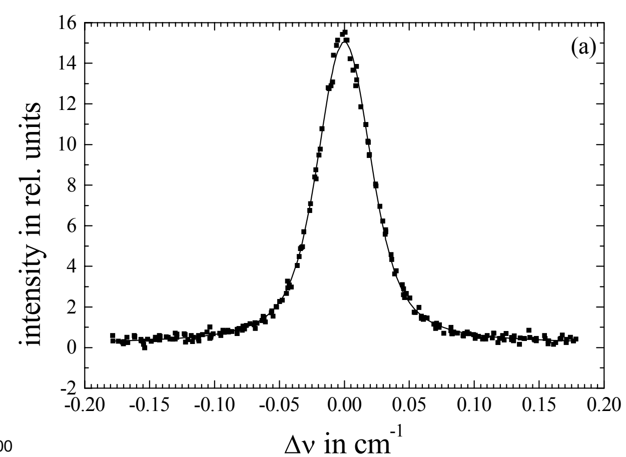




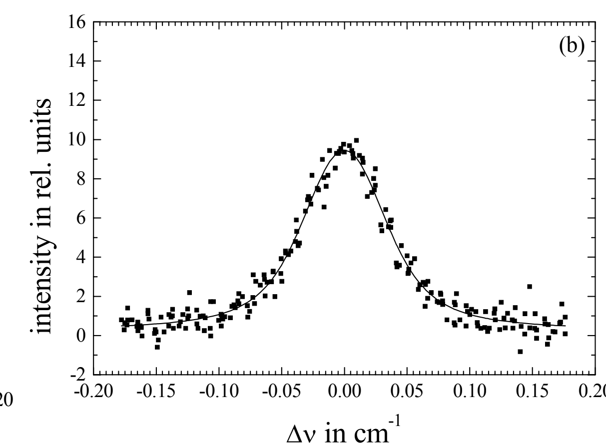


Ar I 696.5 nm



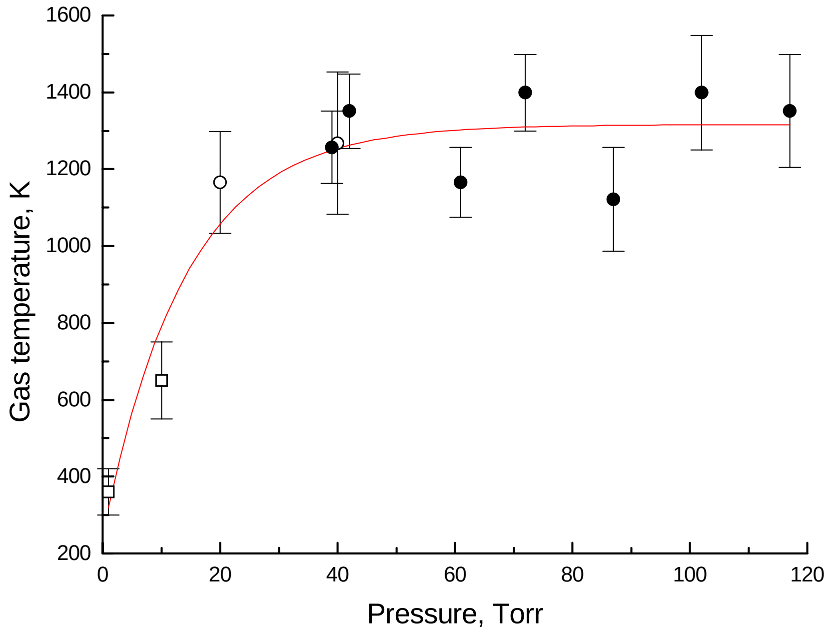


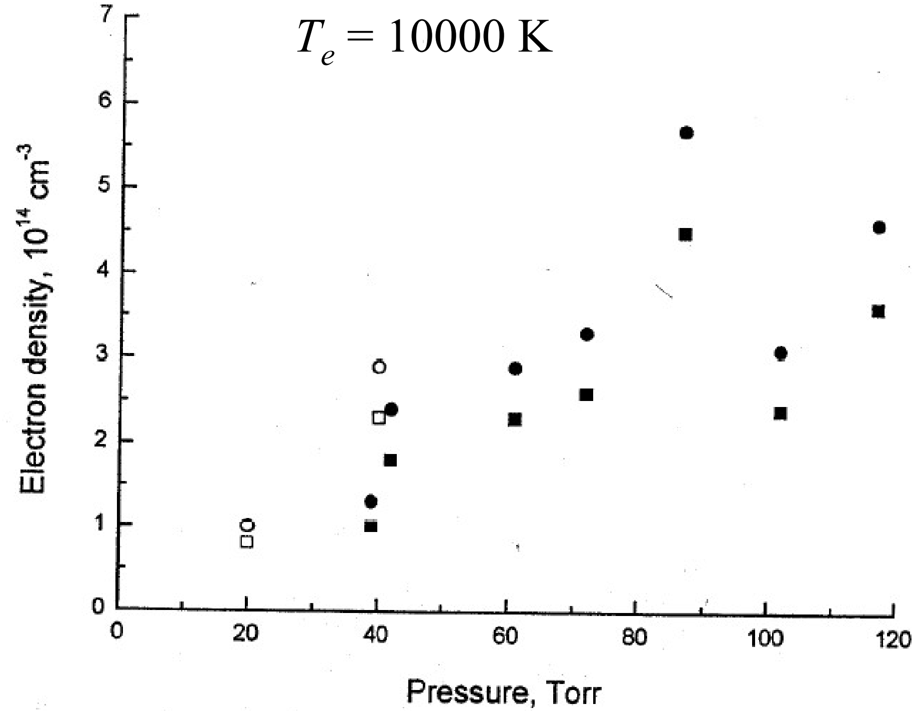
***p* = 1 Torr**



***p* = 104 Torr**

Experimental results: Gas temperature and electron density



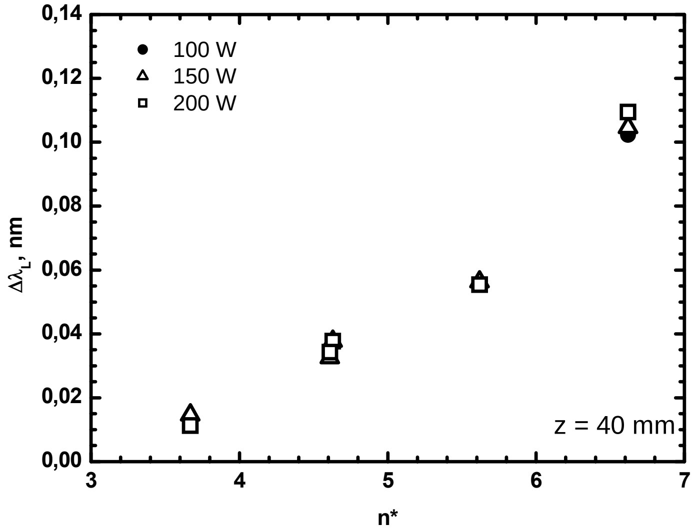


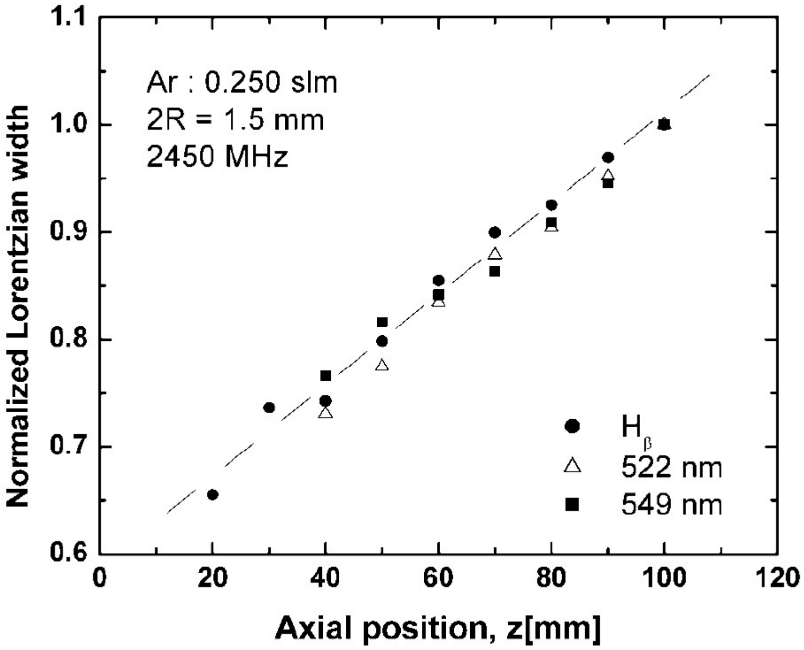
(□) p = 1 Torr и 10 Torr
(📫) at p = 20 и 40 Torr
(📪) at p = 35-117 Torr

✏ Griem's data 1962
📪 Pellerin formula 1996

Christova M, Gagov V and Koleva I, "Analysis of the profiles of the Argon 696,5 nm spectral line excited in nonstationary waveguided discharges" *Spectrochemica Acta B* (2000) **55** 815 - 822

Experimental results at 1 atm





λ (nm)	Transition	E_u (cm^{-1})	E_l (cm^{-1})	*n**
737.2	$3p^54d–3p^54p$	119024	105463	3.68
641.6	$3p^56s–3p^54p$	119683	104102	3.84
591.2	$3p^54d'–3p^54p$	121012	104102	3.81
560.7	$3p^55d–3p^54p$	121933	104102	4.60
603.2	$3p^55d–3p^54p$	122036	105463	4.65
518.8	$3p^55d'–3p^54p$	123373	104102	4.61
549.6	$3p^56d–3p^54p$	123653	105463	5.63
522.1	$3p^57d–3p^54p$	124610	105463	6.62

Christova M, Castaños-Martinez E, Calzada M D, Kabouzi Y, Luque J M and Moisan M
2004 *Applied Spectroscopy* **58** №9
1032 – 1037

Theoretical results for Stark broadening parameters of argon lines

⇒ To obtain Stark broadening parameters

522.1, 549.6, 518.8, 560.7, 603.2 и 696.5 nm
visible optical Ar I линии

Semi-classical theory of Sahal-Bréchot within impact approximation

Investigating the influence of:

1) Spin-orbital interaction

2) Coupling scheme

3) Oscillator strengths

Sahal-Bréshot theory

$$W = 2n_e \int_0^{\infty} \mathrm{v} f(\mathrm{v}) d\mathrm{v} \left[\sum_{i' \neq i} \sigma_{ii'}(\mathrm{v}) + \sum_{f' \neq f} \sigma_{ff'}(\mathrm{v}) + \sigma_{el} \right]$$

$$d = n_e \int_0^{\infty} \mathrm{v} f(\mathrm{v}) d\mathrm{v} \int_{\rho_3}^{\rho_d} 2\pi\rho d\rho \sin 2\varphi_p$$

Input data
n_e, T, λ, m_i, m_p
E_{ion}, B, Z_p, E_i, E_f,
l_i, l_f, $E_{i'}$, $E_{f'}$, $l_{i'}$, $l_{f'}$, f_{if}

$\Rightarrow$

Using cataloge
Topbase ***LS*** **(E, f_{ij})**
Kurucz ***j-L*** **(E, f_{ij})**
NIST ***j-L*** **(E)**
f_{ij} Beits and Damgaard

$\Downarrow$

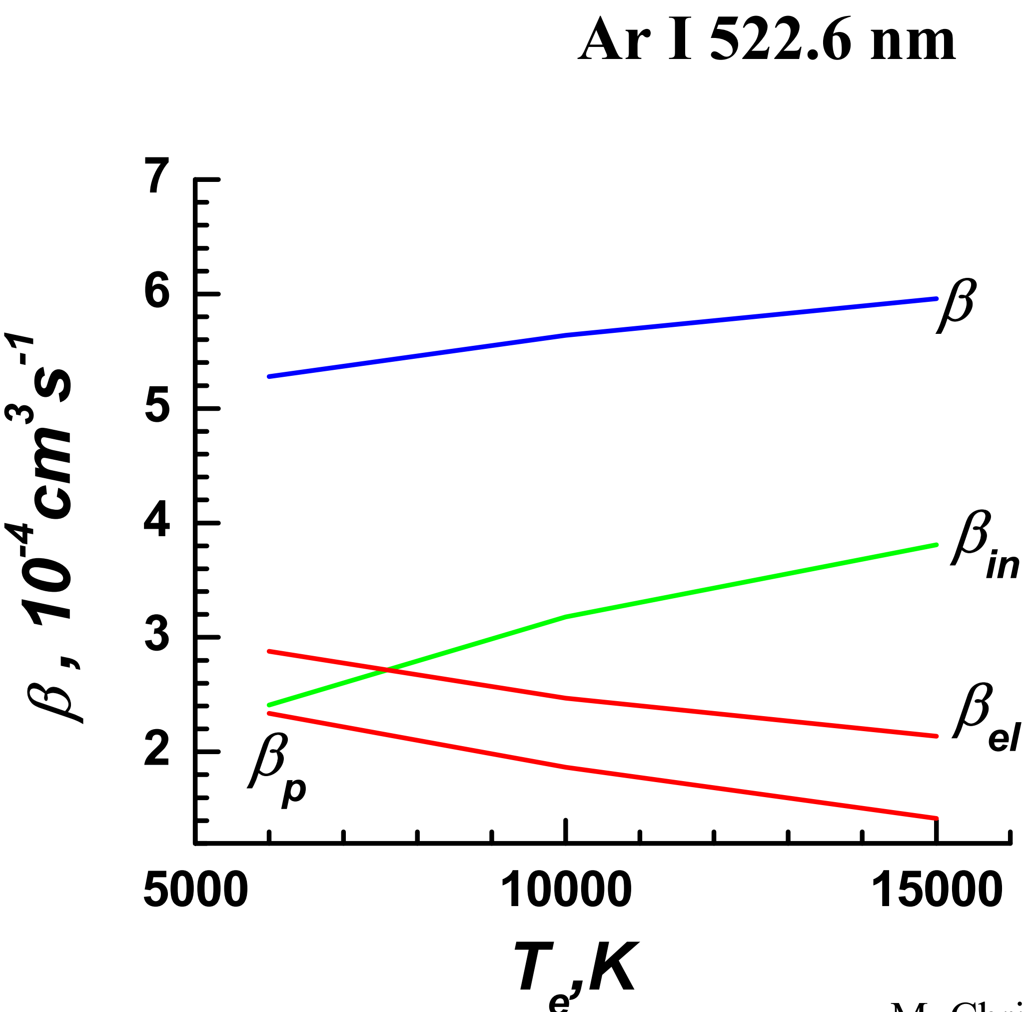
Output data
W_e, d_e, W_i, d_i, W_p, d_p
W_{str}, d_{str}, W_{el}, W_{in}, d_{in}
W_q, d_q, A

$$W = W_{in} + W_{el}$$

$$W_{in} = W_{in}^{str} + W_{in}^{w}$$

$$W_{el} = W_{el}^{str} + W_{el}^{w}$$

Temperature dependence of Stark broadening



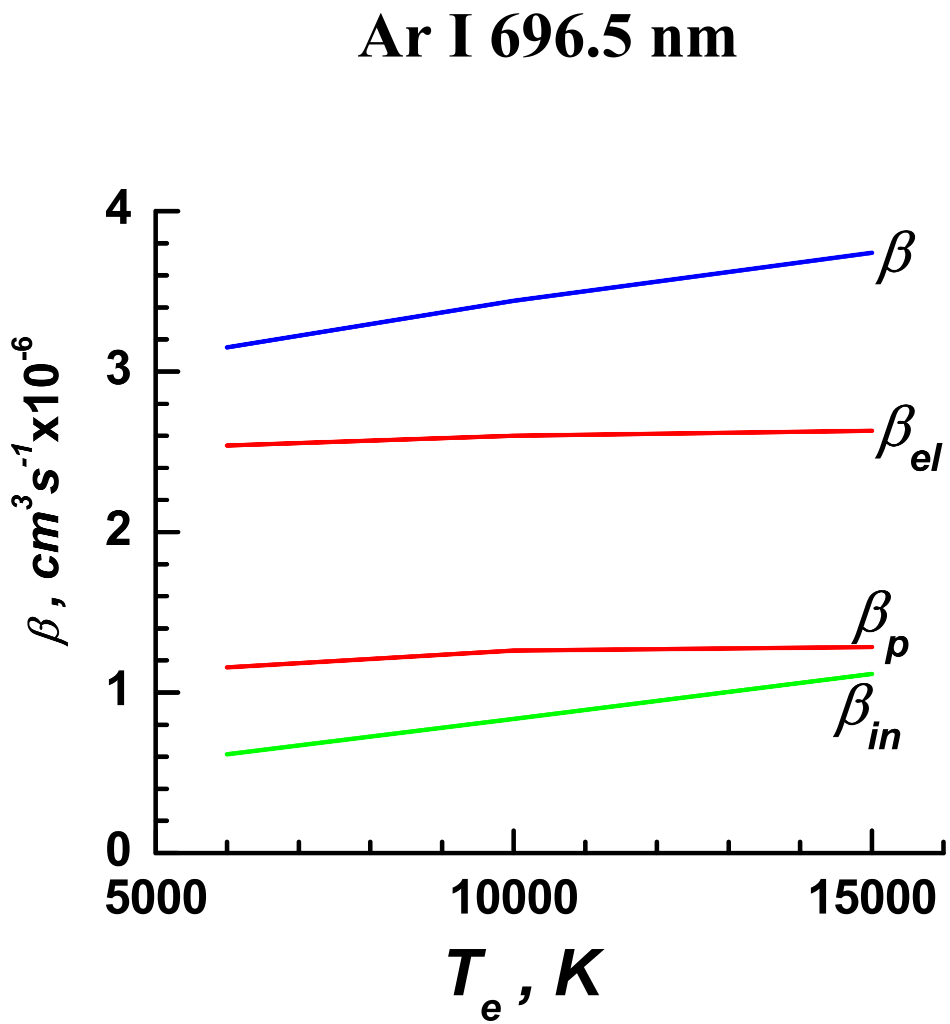
$$\beta = \frac{\gamma}{n}$$

$$\beta = \beta_{in} + \beta_{el}$$

$$\beta_{el} = \beta_{el}^{p} + \beta_{el}^{q}$$

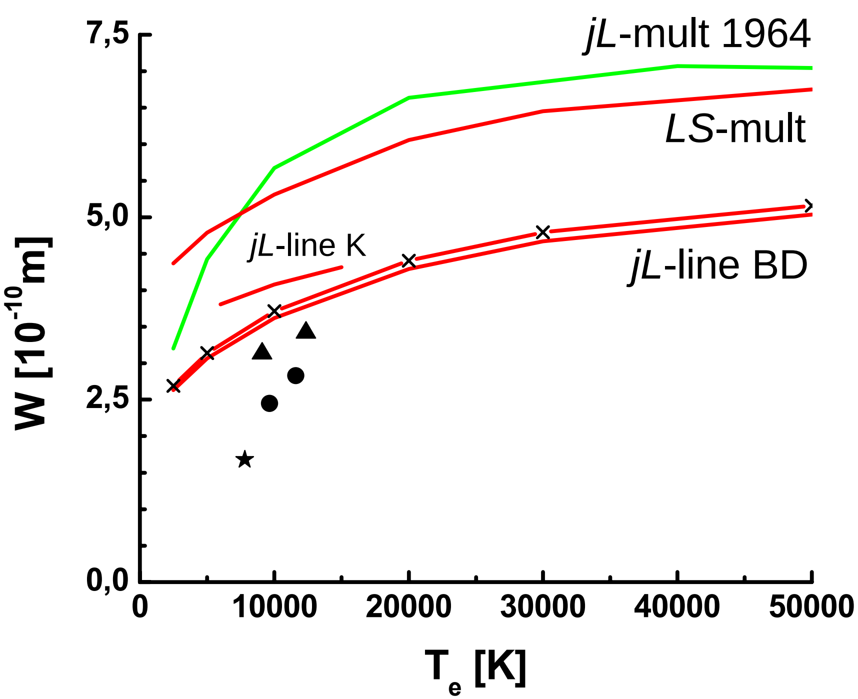
M. Christova, S. Sahal-Bréchot and N. Allard
GD 2004, **K9**, Sept. 5 – 10, Toulouse, France.

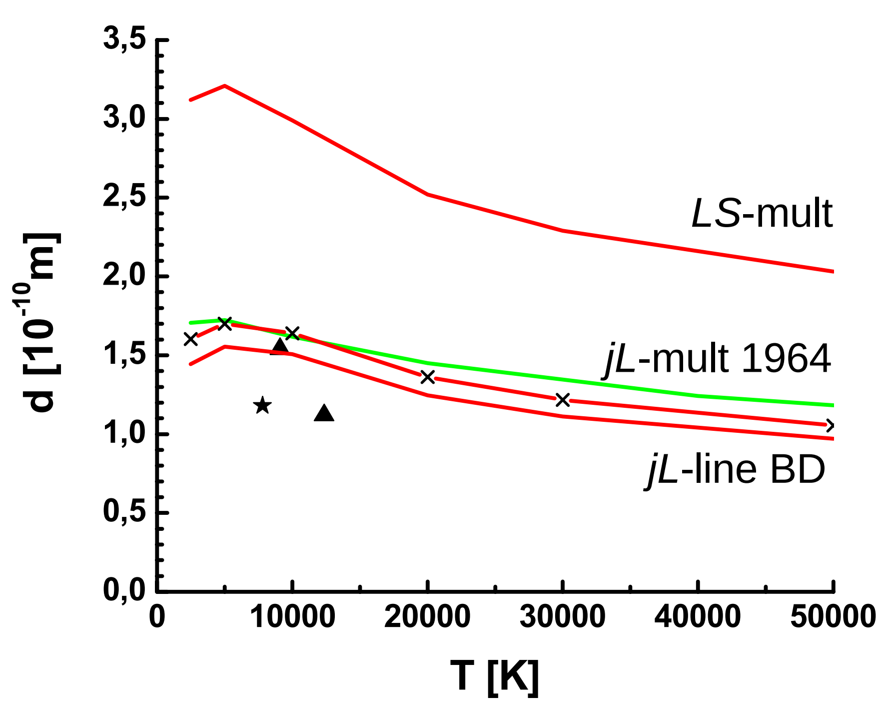
Temperature dependence of Stark broadening



Comparison with experimental and theoretical results by other authors

Ar I 549.6 nm





Dimitrijević M S, Christova M and Sahal-Bréchot S, “Stark broadening of visible Ar I spectral lines”, *Phys. Scripta* (2007) **75** 809-819

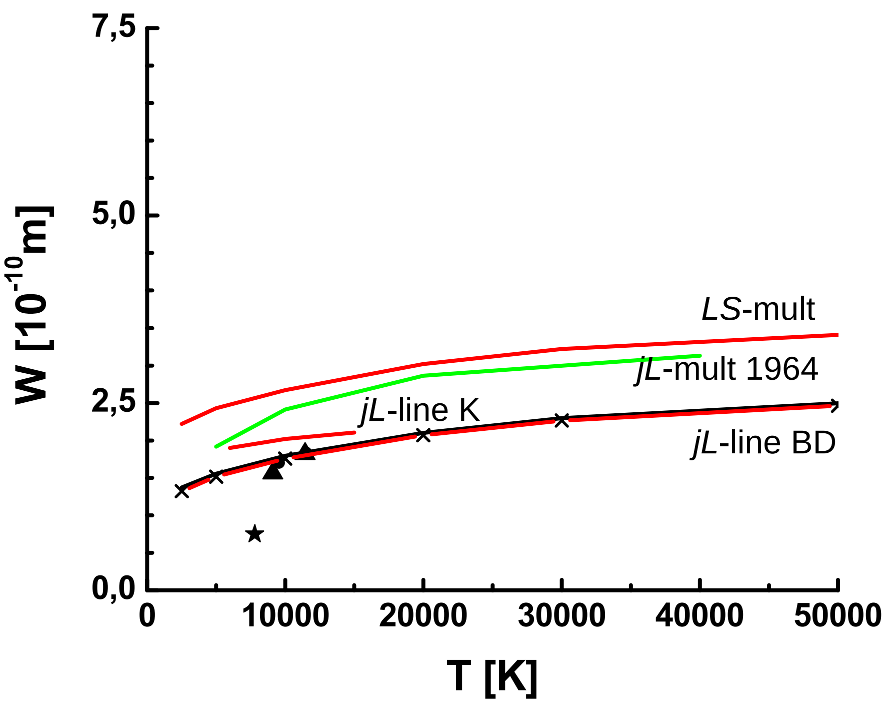
Griem 1974

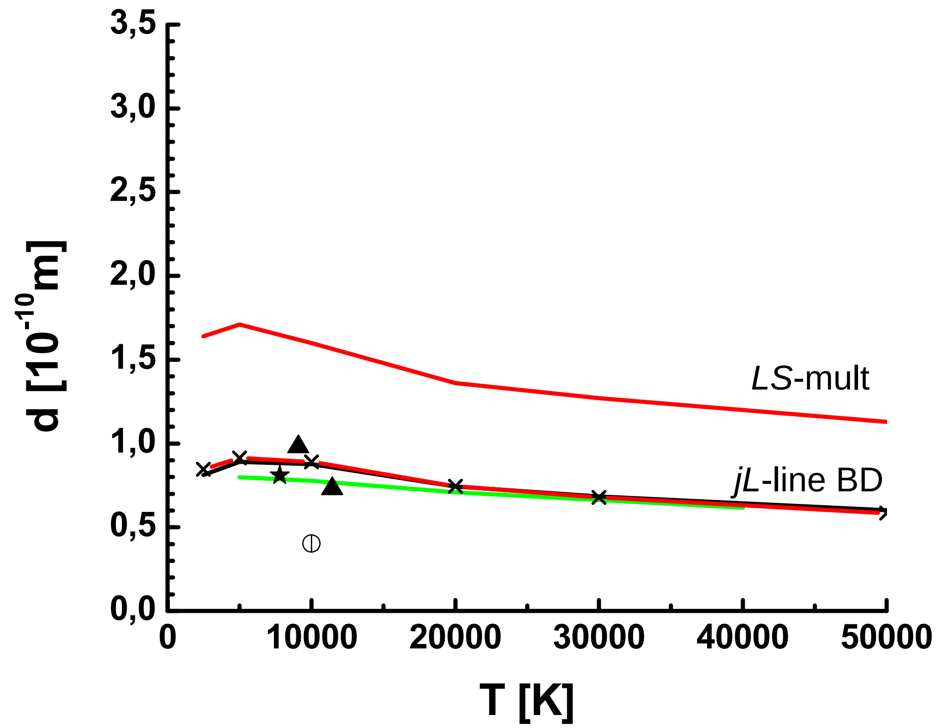
Sahal-Bréchot ❾❺❾ quasistatic ions

●Schulz 1968; ▲ Bues 1969; ☒Ranson 1974

Comparison with experimental and theoretical results by other authors

Ar I 603.2 nm



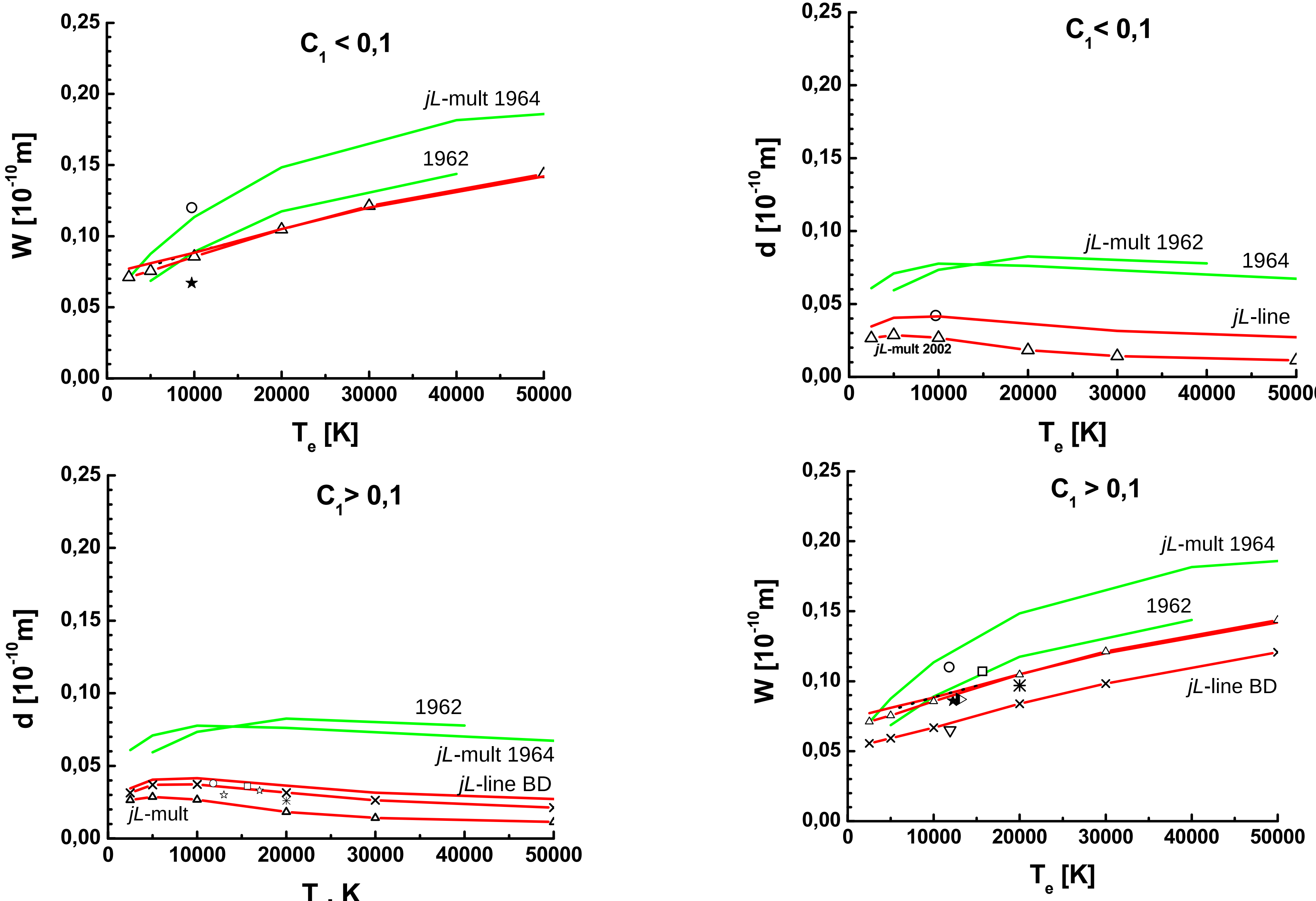


Griem 1974

Sahal-Bréchot ❾❺❾ quasistatic ions

●Schulz 1968; ▲ Bues 1969; ☒Ranson 1974; ♦ Kasakov 1981

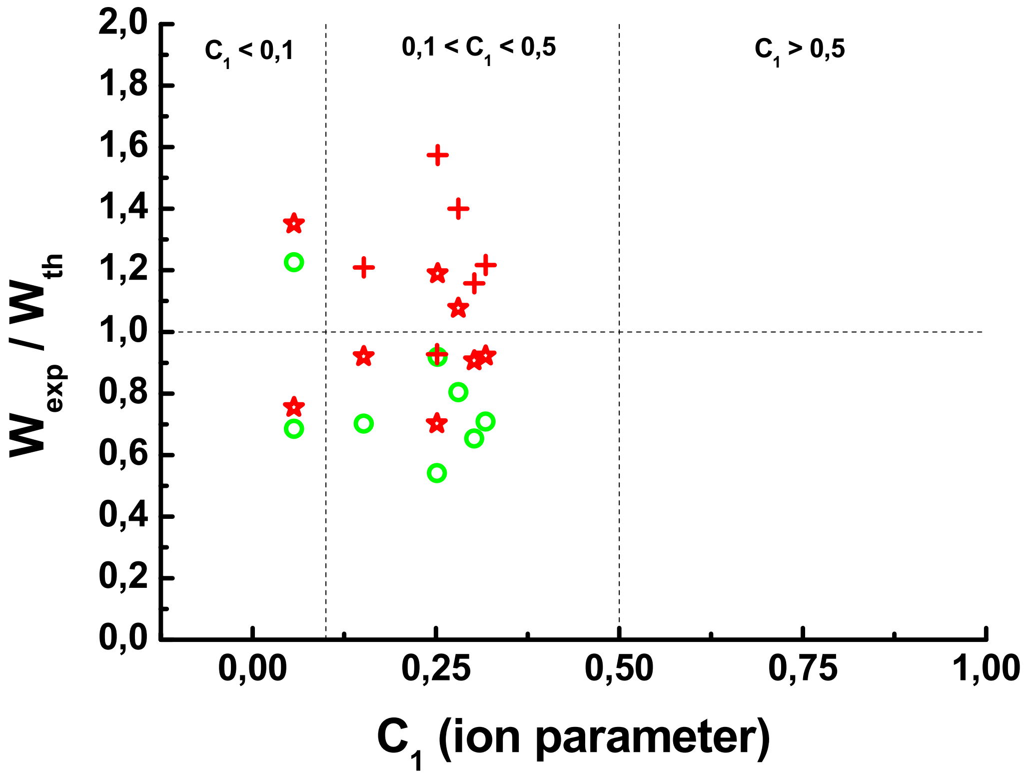
Ar I 696.5 nm



Griem 1962; 1964; ❾∆❾Sahal-Bréchot 2002 ❾❺❾ quasist. ions; Popenoe; Tonejc; ☒Ranson; Bakshi Djenize; ❻ Aparicio; ● Dimitrijevic ✂ Dzierzega

Criteria for impact approximation C_1 – transitional range

Ar I 696.5 nm



$$C_1 = \tau^* W_{str} << 1$$

Griem

Sahal-Bréchot – impact ions

Sahal-Bréchot – quasistatic ions

Theoretical results for broadening of argon lines by neutral atoms

$\Rightarrow$ **Potentials of interactions: Van der Waals, Lennard-Jones and Kaulakys**

Axial variation of n_e in capillary discharge at p = 1 atm by the pressure broadenings of Ar I lines, using the theoretical results

Potentials of emitter-atom interactions in ground state

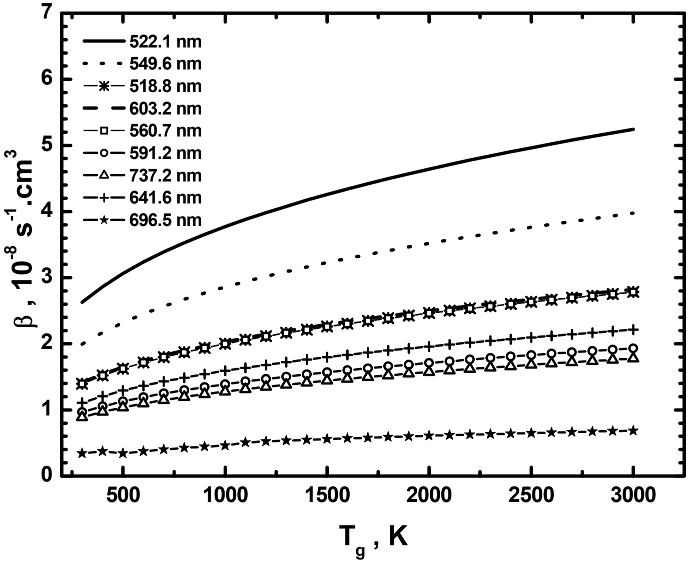
- **Van der Waals** $V(R) = -C_6 R^{-6}$
- **Lennard-Jones** $V(R) = C_{12} R^{-12} - C_6 R^{-6}$
- **Kaulakys** $V(\vec{R},\vec{r}) = V_c(\vec{R}) + V_{ce}(\vec{R},\vec{r}) + V_e(\vec{r}-\vec{R}) \quad |\vec{R}-\vec{r}| > r_0$

$$V_e(\vec{r}-\vec{R}) = 2\pi L \delta(\vec{r}-\vec{R})$$

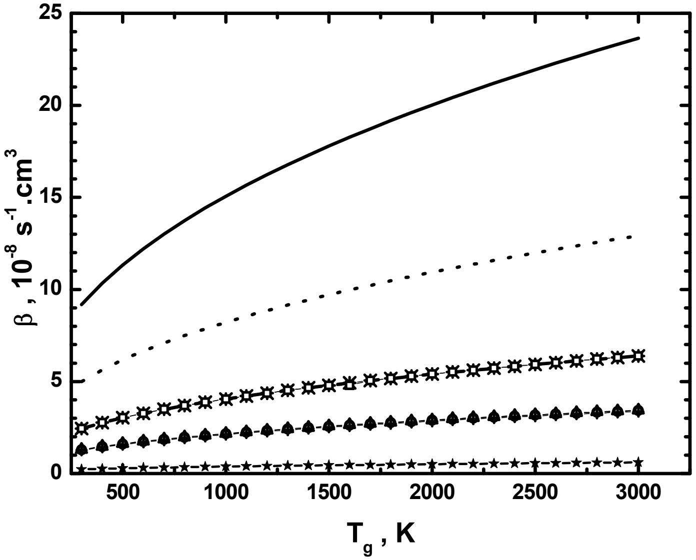
$$V(R) \Rightarrow \sigma(\mathrm{v}) \Rightarrow \gamma = \beta n$$

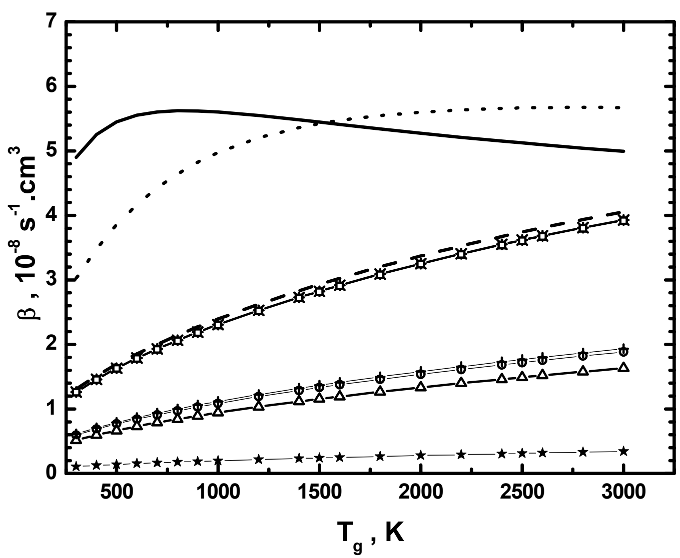
λ nm	Legend
522.1	❾
549.6	♋
603.2	❿❿
518.8	❾❻❾
560.7	❾✂❾
591.2	❾📫❾
737.1	❾🖱❾
641.6	❾❹❾
696.5	❾☒❾

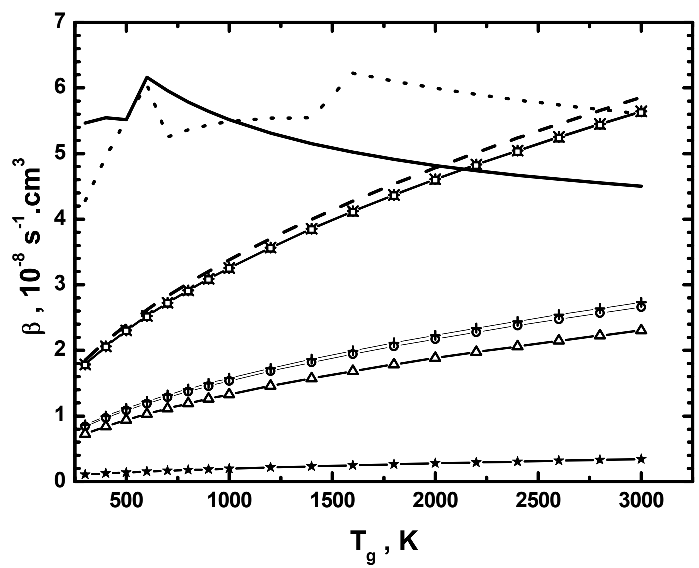
Van der Waals



Lennard-Jones





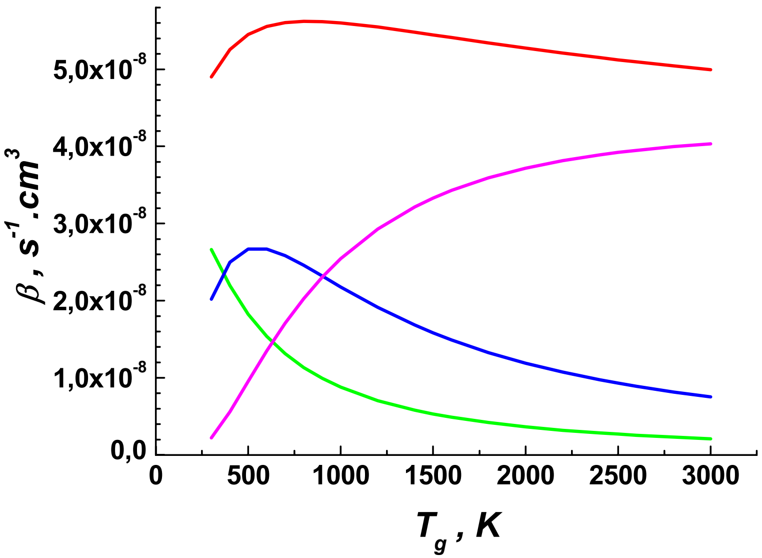


Kaulakys

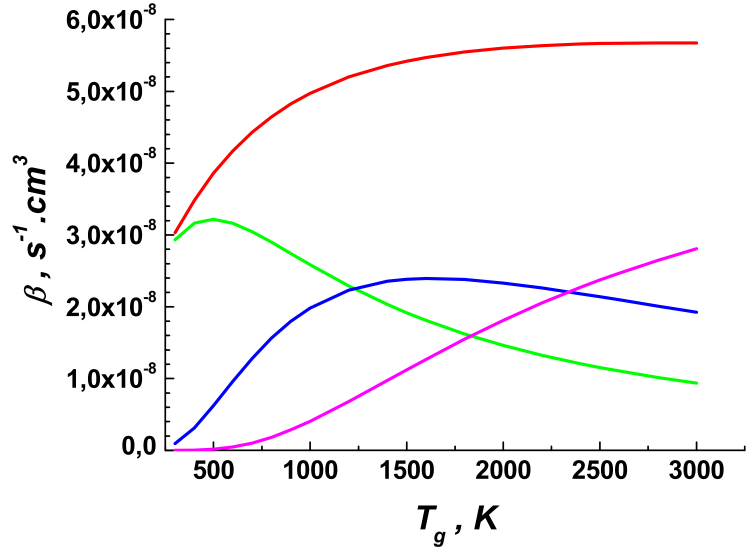
$$\beta = 2\bar{v}\sigma_v'(\bar{v})$$

$$\beta = 2\langle v\sigma'(v)\rangle$$

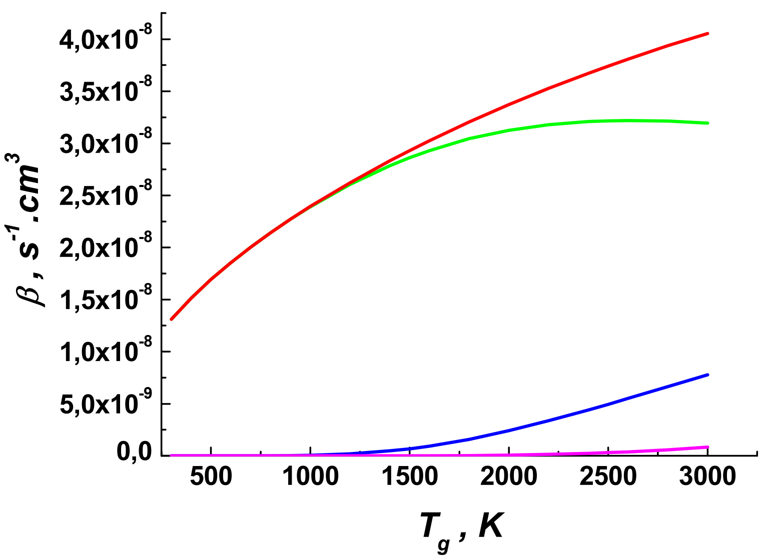
Ar I 522.1 nm



Ar I 549.6 nm



Ar I 603.2 nm



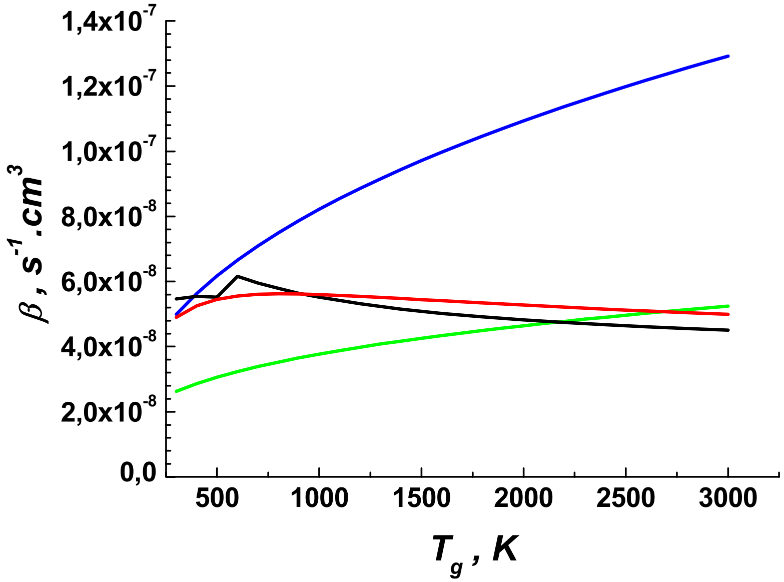
β_1; β_2; β_3; β

1600 K

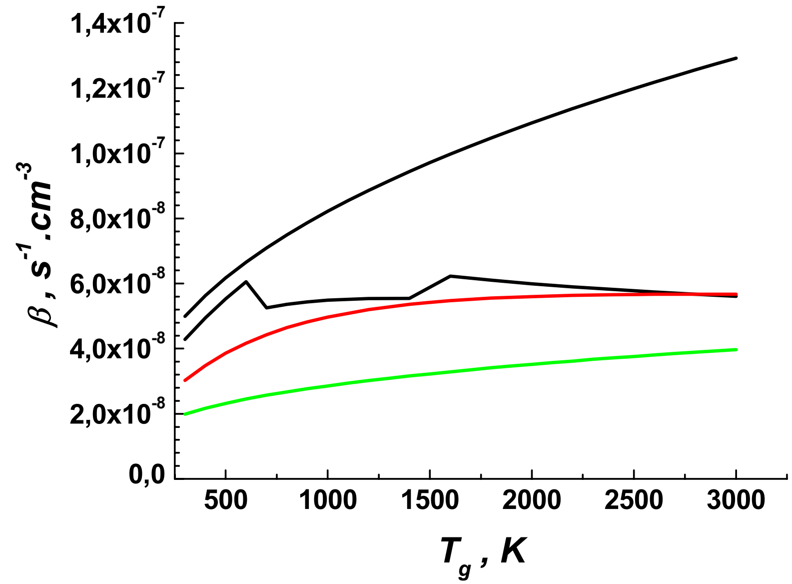
1atm

L= -1.6a$_0$

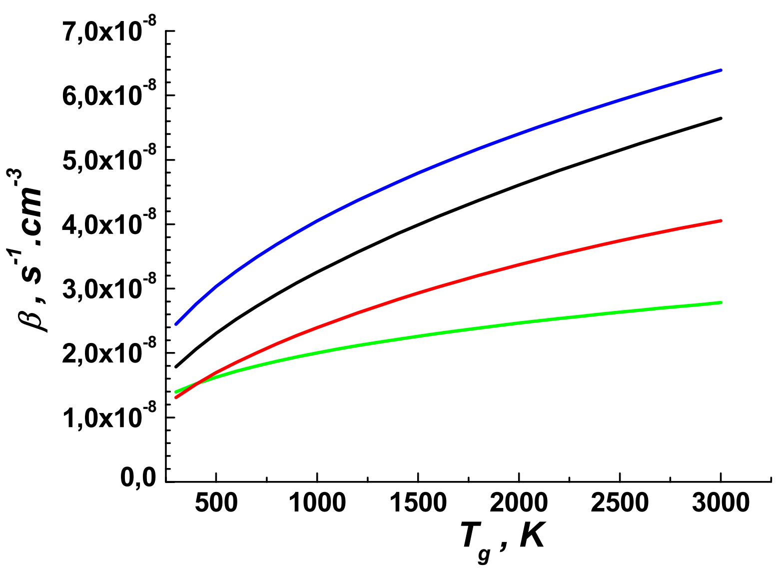
Ar I 522.1 nm



Ar I 549.6 nm

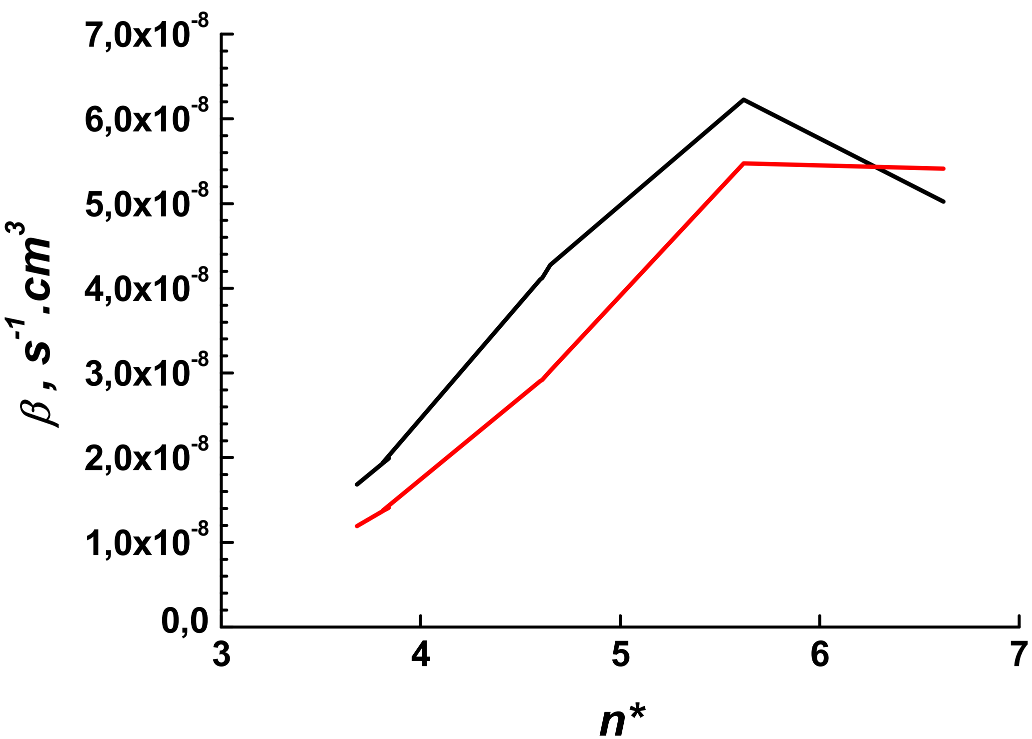


Ar I 603.2 nm



- Van der Waals
- Lennard-Jones
- Kaulakys
- Kaulakys $\bar{v}$

Influence of Maxwellian averaging of the broadening cross section on the *n**-dependence of the broadening coefficient

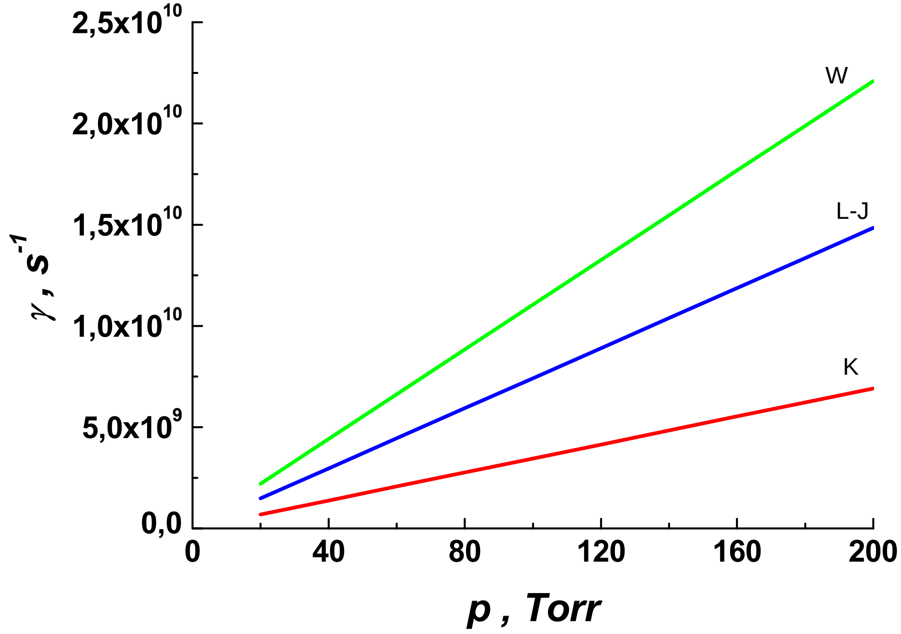


❾ $$\beta = 2\overline{\mathrm{v}}\sigma_{\mathrm{v}}'\left(\overline{\mathrm{v}}\right)$$

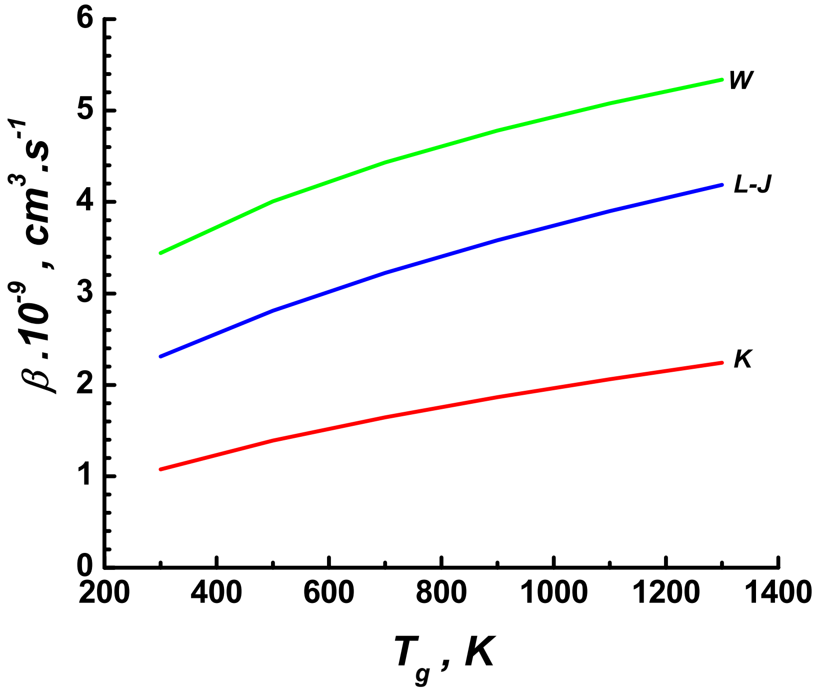
❾ $$\beta = 2\left\langle v\sigma'(v)\right\rangle$$

Christova M *Journal of Physics: Conference Series* 2007 **63** 012012

Pressure and gas temperature dependence of the broadening of Ar I 696.5 nm

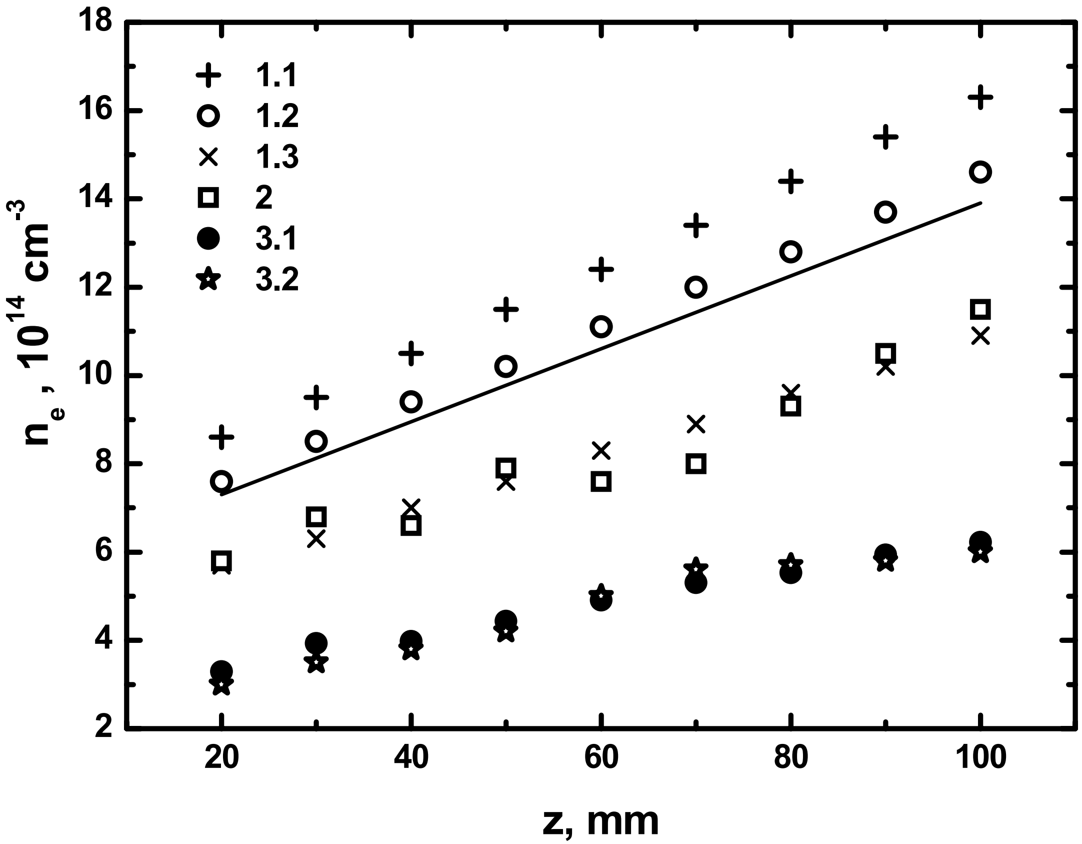


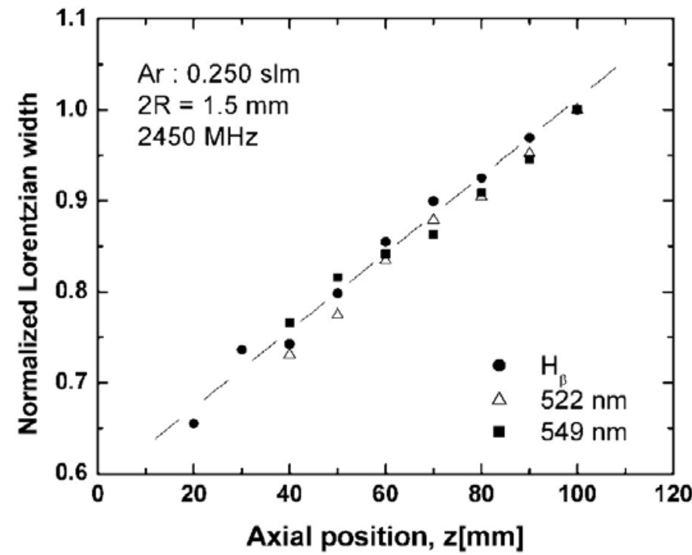
$T_g = 300$ K



p = 50 Torr

Axial variation of the electron density





$$\Delta\lambda_{St} \propto n_e \qquad \Delta\lambda_{St} \propto n_e^{2/3}$$

p **= 1 atm,** ***Tg*** **= 1600 K**

Ar I 1.1 522.1, 1.2 549.6 и 1.3 603.2 nm

n_e **3 Ar I lines**

2 Ar I 549.6 nm; Hβ 3.1 Griem, 3.2 Gigosos

λ nm	**g 10^{-14} Åcm^3**	**grad$_z n_e$ 10^{13} cm^{-4}**
522.1	0.07	9.7
549.6	0.04	8.7
603.2	0.02	6.5

Hvala