# The impact of charge exchange and transport on $K_\alpha$–spectra of He-like argon

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and the TEXTOR-Team

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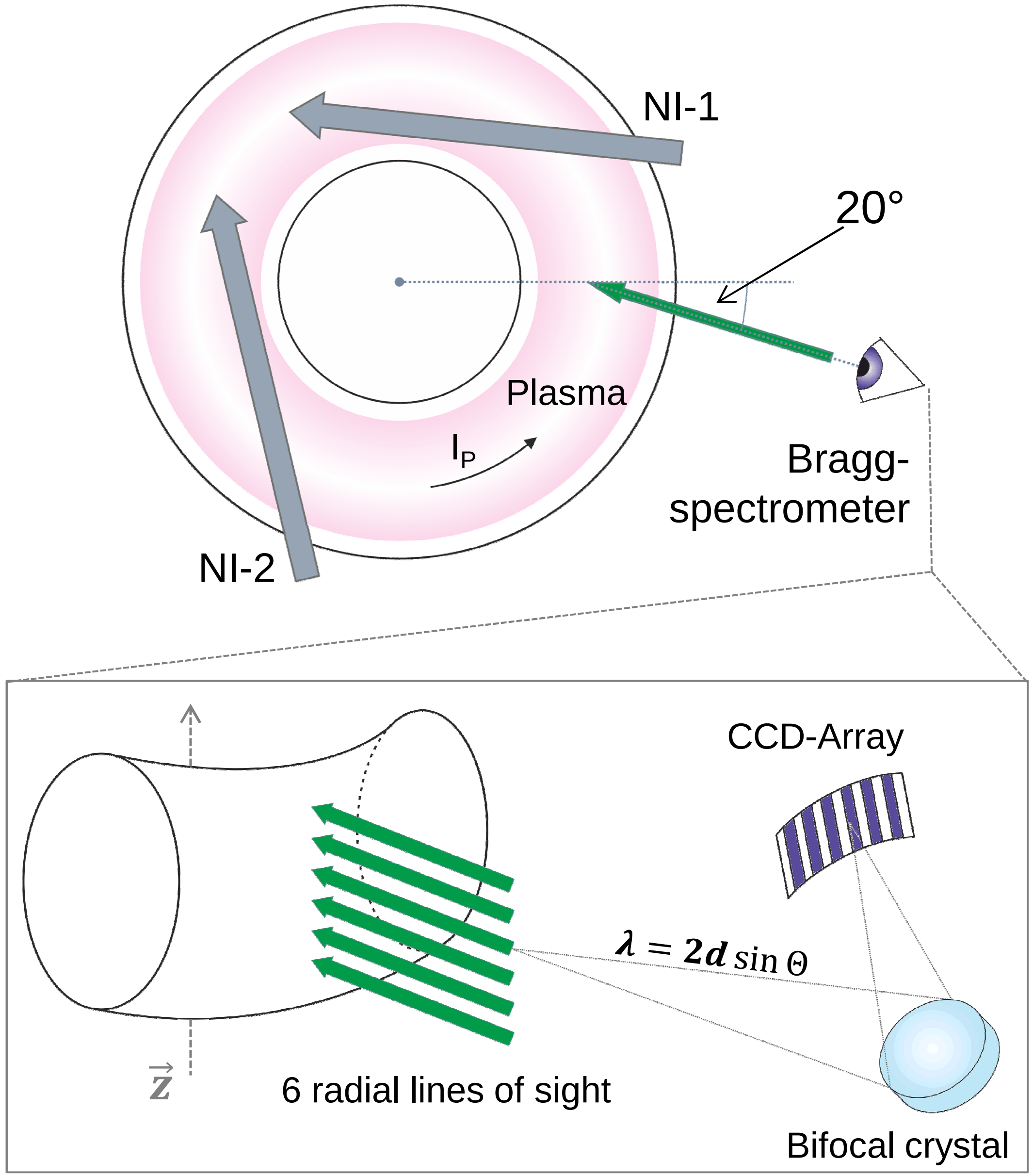
# Outline

- Multi channel Bragg-spectrometer for W7–X at TEXTOR
- $K_\alpha$ – spectrum of He-like Argon
  - The spectral lines
  - Discussion/Contradictions in literature
  - Radial scan of the $K_\alpha$ – spectrum
- $K_\alpha$ – spectroscopy as diagnostic for the neutral gas density in the plasma and for the radial transport.
- Experimental neutral gas density profiles and transport profiles from TEXTOR
- Conclusion / Outlook

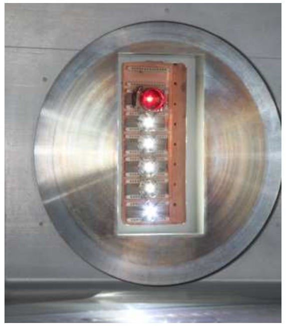
# Multi channel Bragg-spectrometer for W7–X at TEXTOR

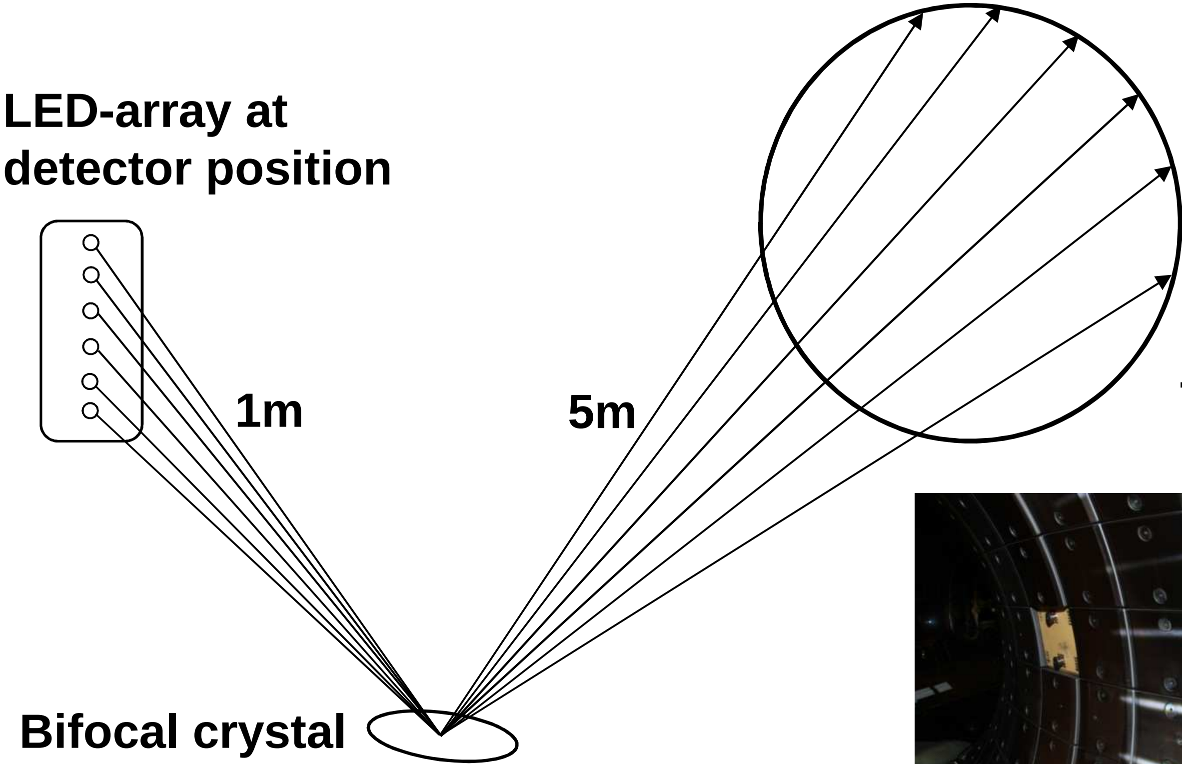
- Optimized for the $K_\alpha$ – spectrum (n=2 → n=1) of He-like Argon (ca. 4 Å)
- 6 Channels vertically distributed over the minor radius
- Radial profiles of
  - Ion temperature
  - Electron temperature
  - Toroidal plasma rotation
  - Argon ion ratios

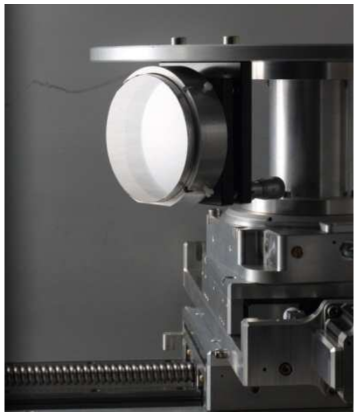
    (H-like : He-like, Li-like : He-like)



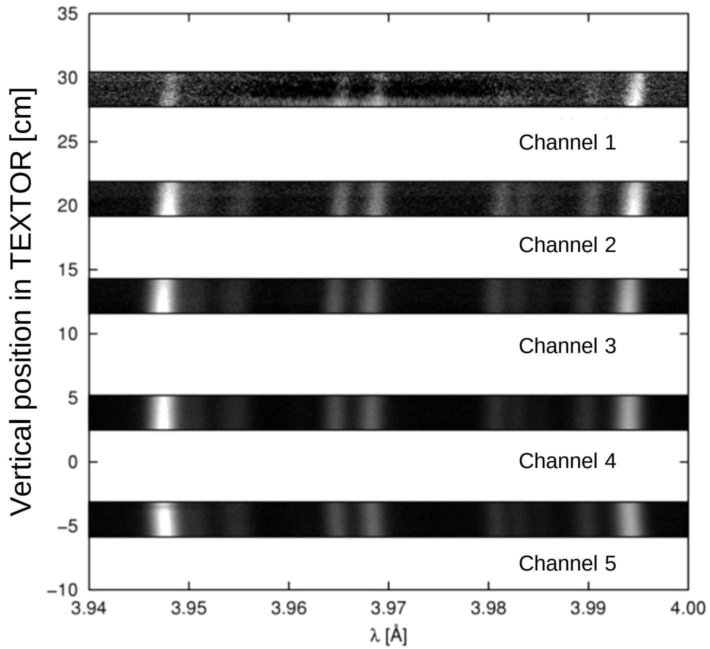
# Lines of sight



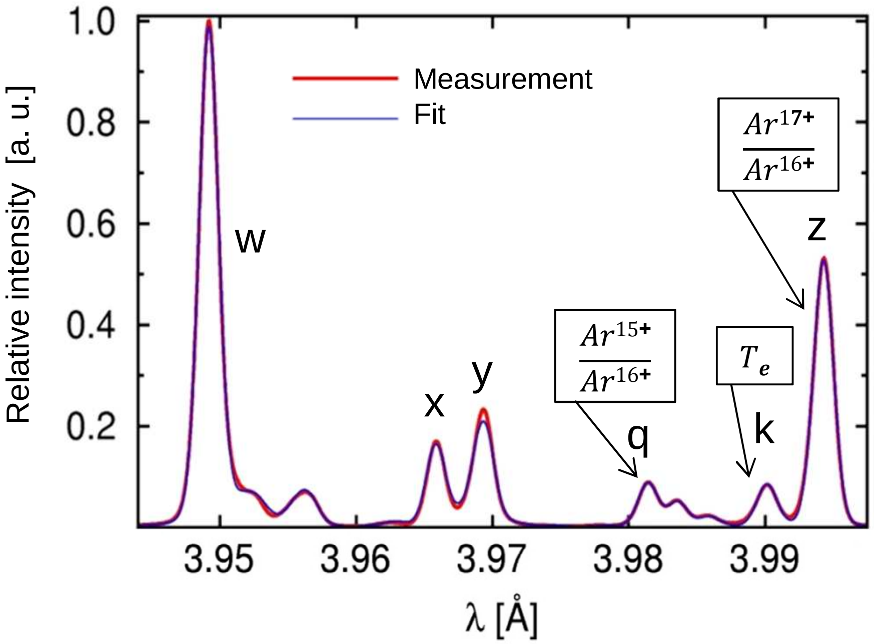


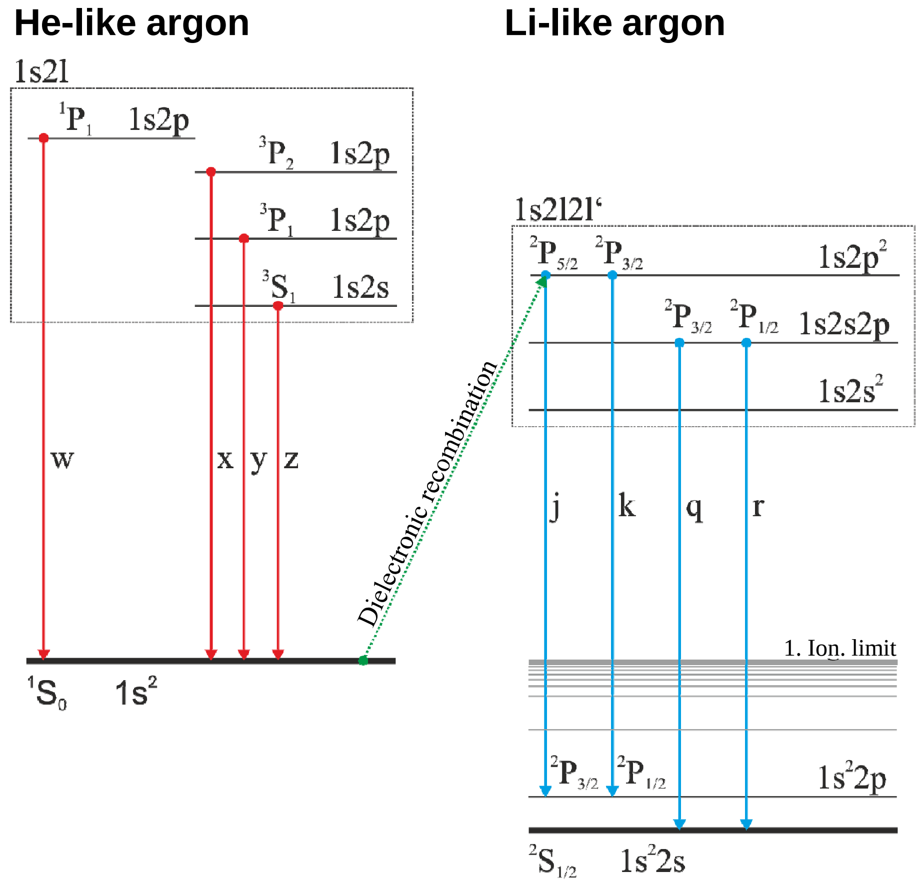



# Lines of sight



# The $K_\alpha$ – spectrum of He-like Argon



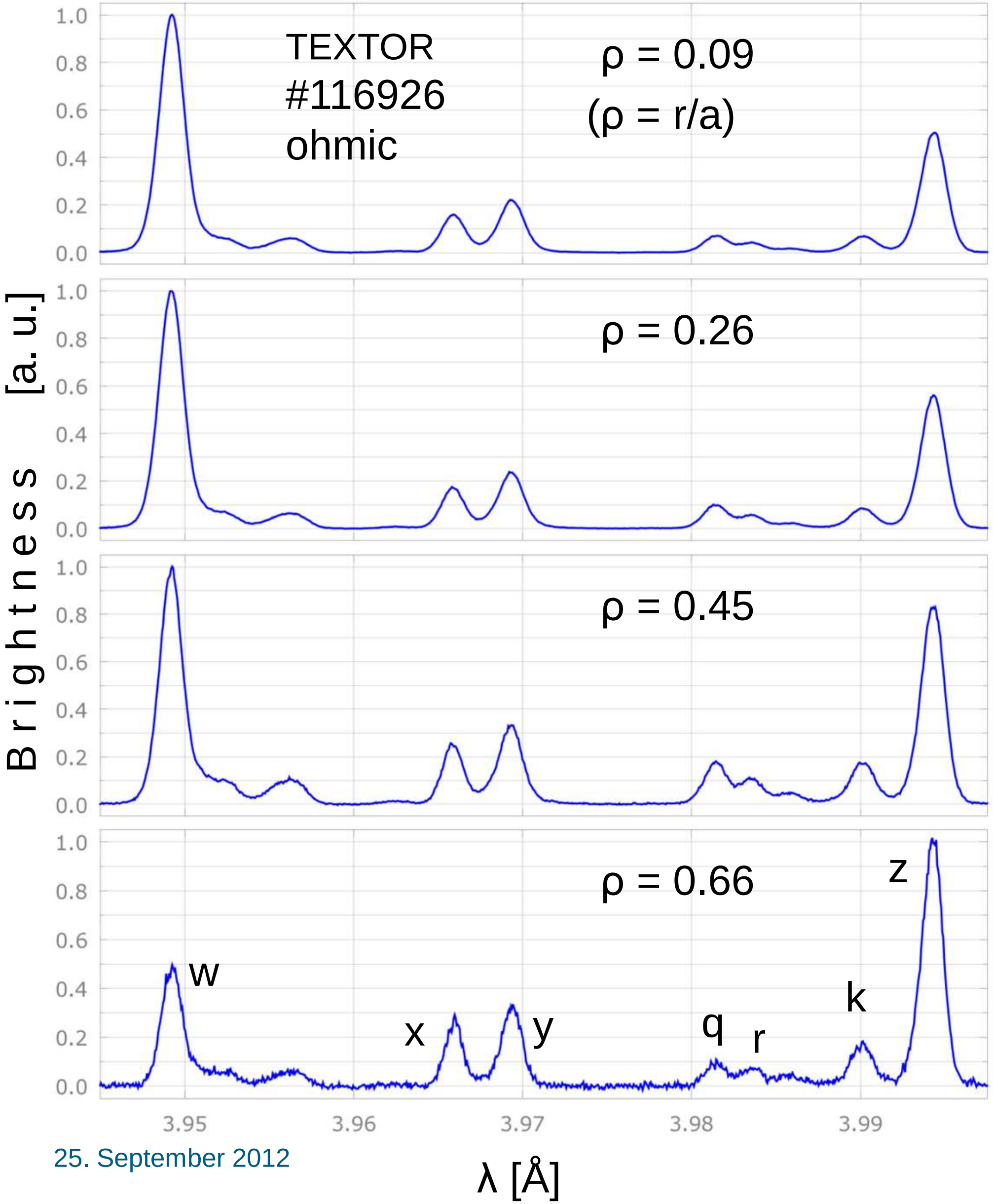

Atomic processes:

- Collisional excitation
- Radiative recombination
- Charge exchange
- Inner shell excitation
- Dielectronic recombination

$$\frac{I_q}{I_w} \approx \frac{\langle\sigma\cdot v\rangle_{iexc}(T_e)\cdot Ar^{15+}\cdot ne}{\langle\sigma\cdot v\rangle_{exc}(T_e)\cdot Ar^{16+}\cdot ne} = \frac{\langle\sigma\cdot v\rangle_{iexc}(Te)}{\langle\sigma\cdot v\rangle_{exc}(Te)}\cdot\frac{Ar^{15+}}{Ar^{16+}}$$

$$\frac{I_z}{I_w} \approx \frac{\langle\sigma\cdot v\rangle_{exc}(T_e) + \frac{Ar^{17+}}{Ar^{16+}}\cdot\left(\langle\sigma\cdot v\rangle_{rr}(T_e) + \langle\sigma\cdot v\rangle_{cx}(T_e)\cdot\frac{n_0}{n_e}\right)}{\langle\sigma\cdot v\rangle_{exc}(T_e)}$$

# $K_\alpha$ – spectrum of He-like Argon

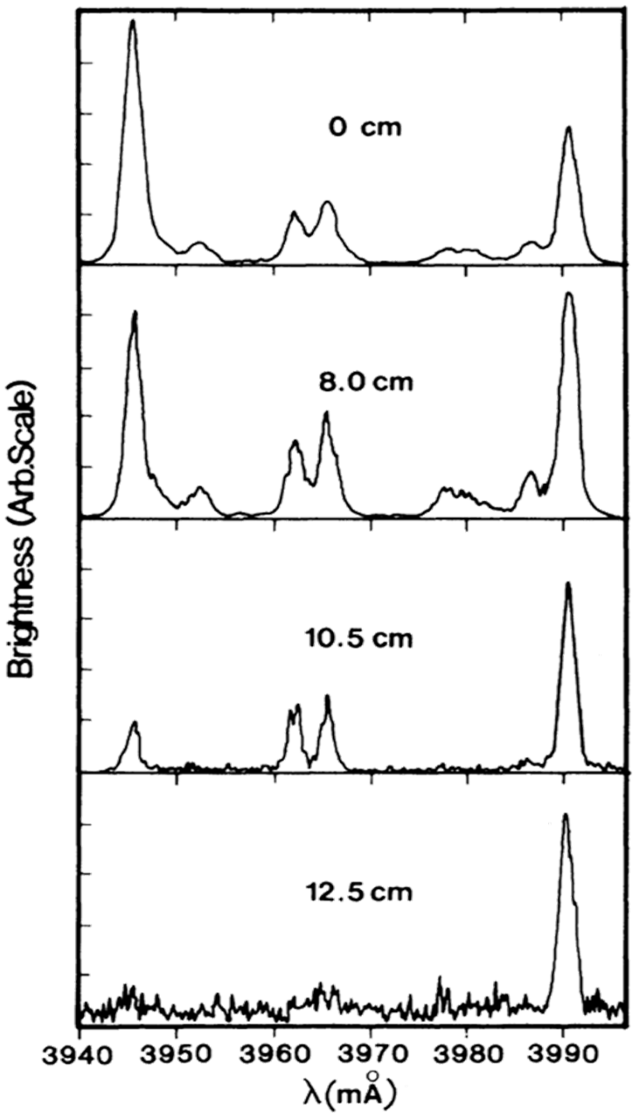



- Imaging X-ray spectrometry reveals increasing z-line towards the edge.
- Reason unresolved !
- Today two possible mechanisms are considered:
  - Charge exchange with neutral hydrogen

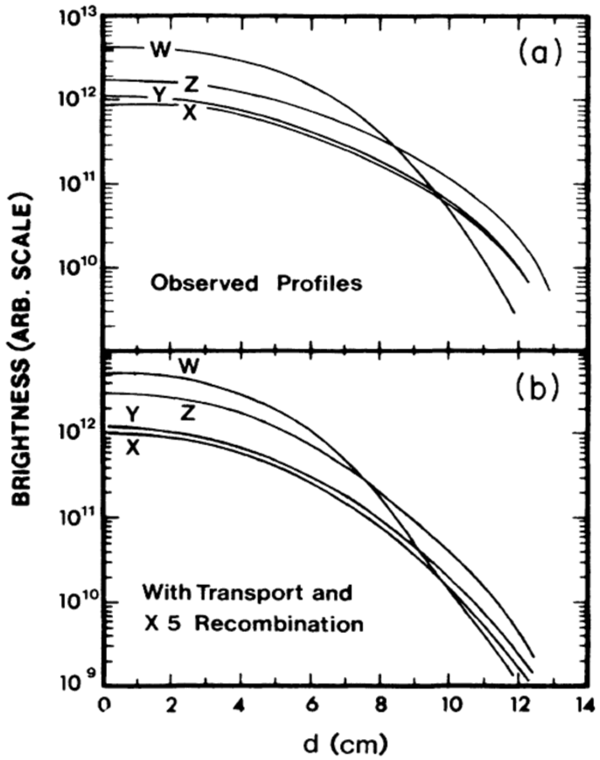
    $Ar^{17+} + H^0 \rightarrow Ar^{16+} + H^+$

    At lower $T_e$ $Ar^{17+}$ should not be abundant.
  - Transport

# $K_\alpha$ – spectra from ALCATOR-C




- [Rice – Phys. Rev. A, Vol. 35, No. 7, 1987]
- Rice could approximately describe the spectra with increased radiative recombination rates by factor of **five**.



# Former measurements at TEXTOR

**X-ray spectroscopy (1-dimensional, plasma center)**

- Rosmej et al.:

  Deviations from corona values:

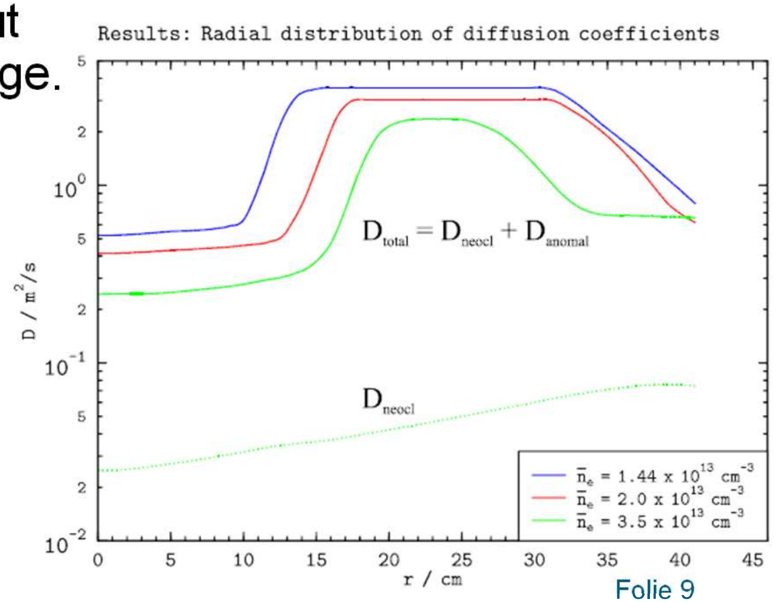
  - mainly charge exchange with neutral hydrogen
  - low transport coefficients needed

[Rosmej et al. – Plasma Phys. Control. Fusion, 41 (1999)]

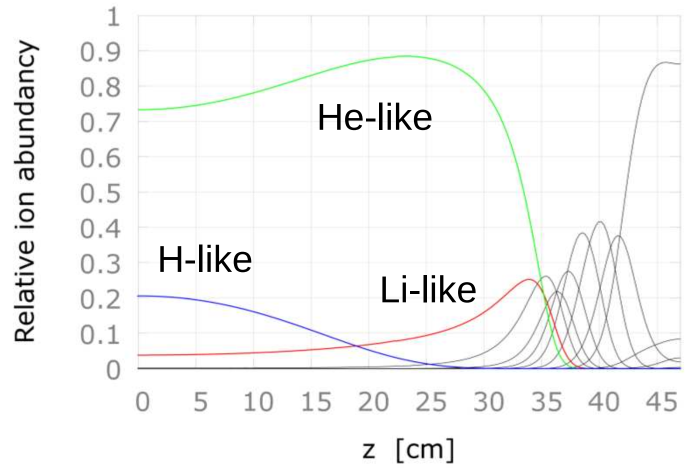
**VUV – spectroscopy (1-dimensional, plasma center)**

- Biel et al. could not describe VUV-spectra without high transport despite respecting charge exchange.
  [Biel, *ECA Vol.23 J (1999)*]
- High transport zone with very high diffusion coefficients was needed.
- Similar findings at Jet (L-mode) by Mattioli et al.
  [Mattioli et al. - Nucl. Fusion 38 (1998)]

→ Contradicting results!



# Fitting the $K_\alpha$ – spectrum

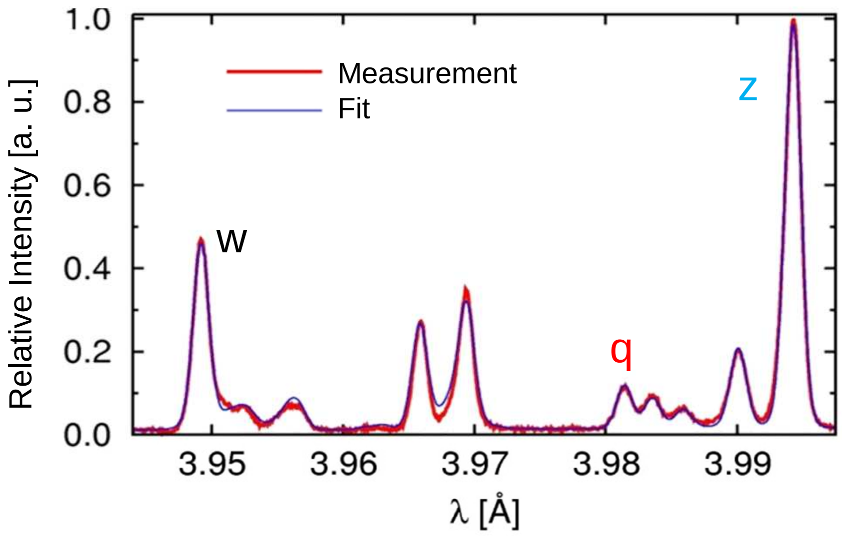



- For the interpretation of the $K_\alpha$ – spectra only the H-, He-, and Li-like argon states are considered.
- For the intensity of each line the following general equation applies:

$$I(\lambda) \propto \int_0^1 n_e \cdot ArH_e \cdot \left(\alpha_{He}(\varrho) + \left(\alpha_{H(\varrho)} + \alpha_{cx(\varrho)} \cdot \frac{n_0}{n_e}\right) \cdot \frac{Ar_H}{Ar_{He}} + \alpha_{Li}(\varrho) \cdot \frac{Ar_{Li}}{Ar_{He}}\right) d\varrho$$

- Theoretical description of the spectra is based on the theoretical cross sections for the atomic processes.
- Fit parameter: $T_e$, $T_i$, $n_0$, $Ar_H : Ar_{He}$ and $Ar_{Li} : Ar_{He}$
- To respect the line integrated signals, the fit routine integrates over the radial profiles for plasma density, temperature and neutral gas density given as input data. (→ **Emission profiles**)

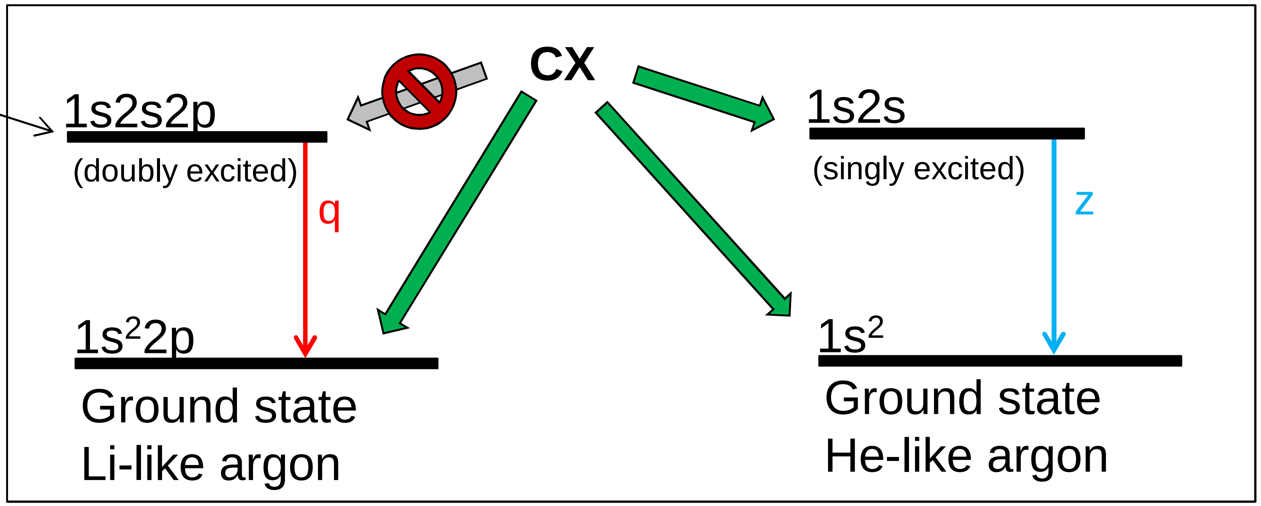
# Distinguishing between transport and CX




- Transport only affects the ground states of the argon ions.
- The z-line is affected by CX in two ways:
  - Cascade contributions
  - Ground state
- The q-satellite is affected by CX only via the ground state. (low density limit)

→ Transport and charge exchange are discriminable !

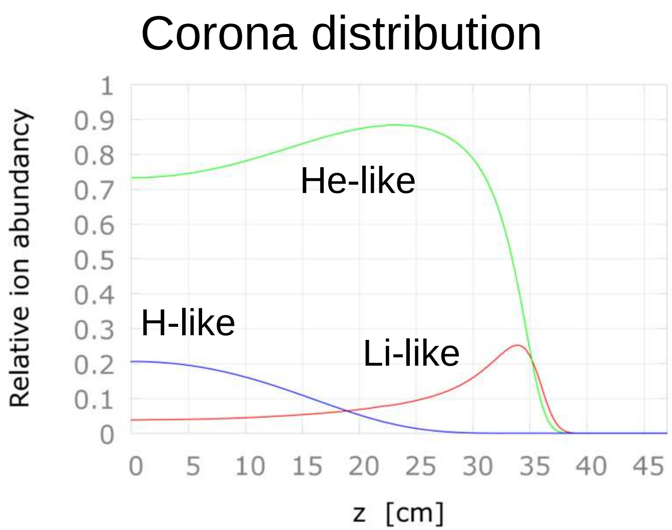
The q-satellite is not directly affected by CX !

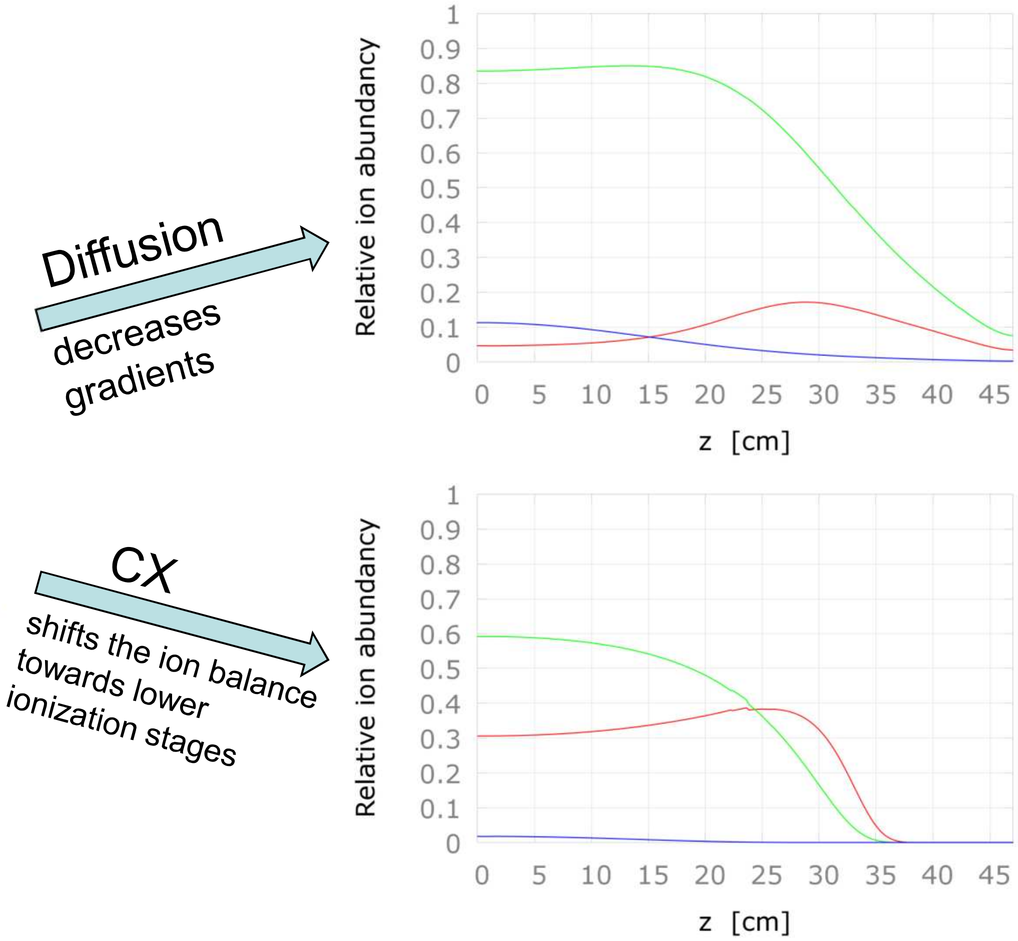


# Including transport and charge exchange

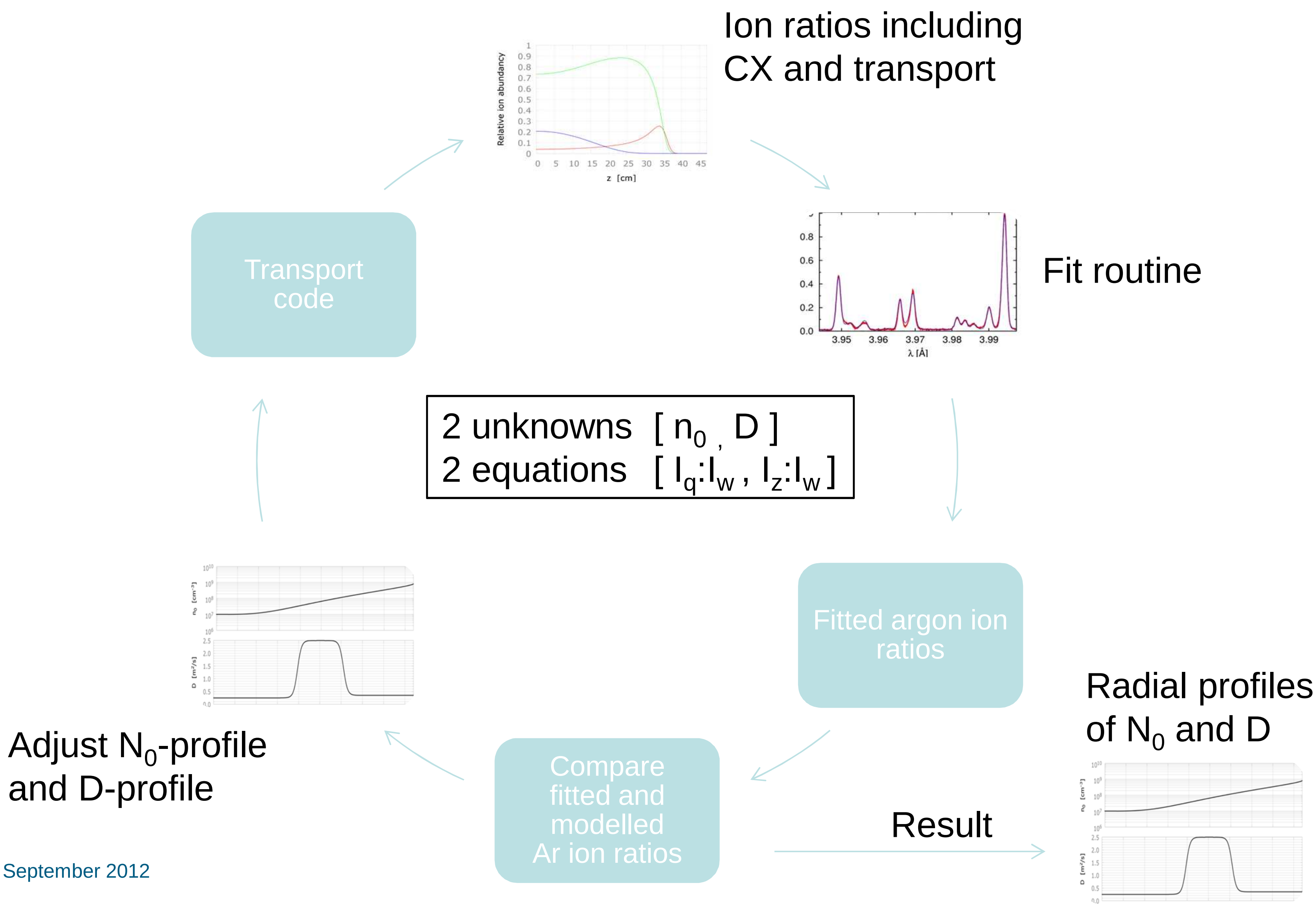
- The fit routine uses radial profiles of the argon ions given as input data.
- To include transport and charge exchange a simple transport code is used solving the system of steady state transport equations for $Ar^0 - Ar^{18+}$.

[Tokar – Plasma Phys. and Contr. Fusion, Vol. 36, No. 11, 1994]
[Dux – STRAHL – Code user manual]



# Self consistent approach



# Atomic Data

**Data fits:**

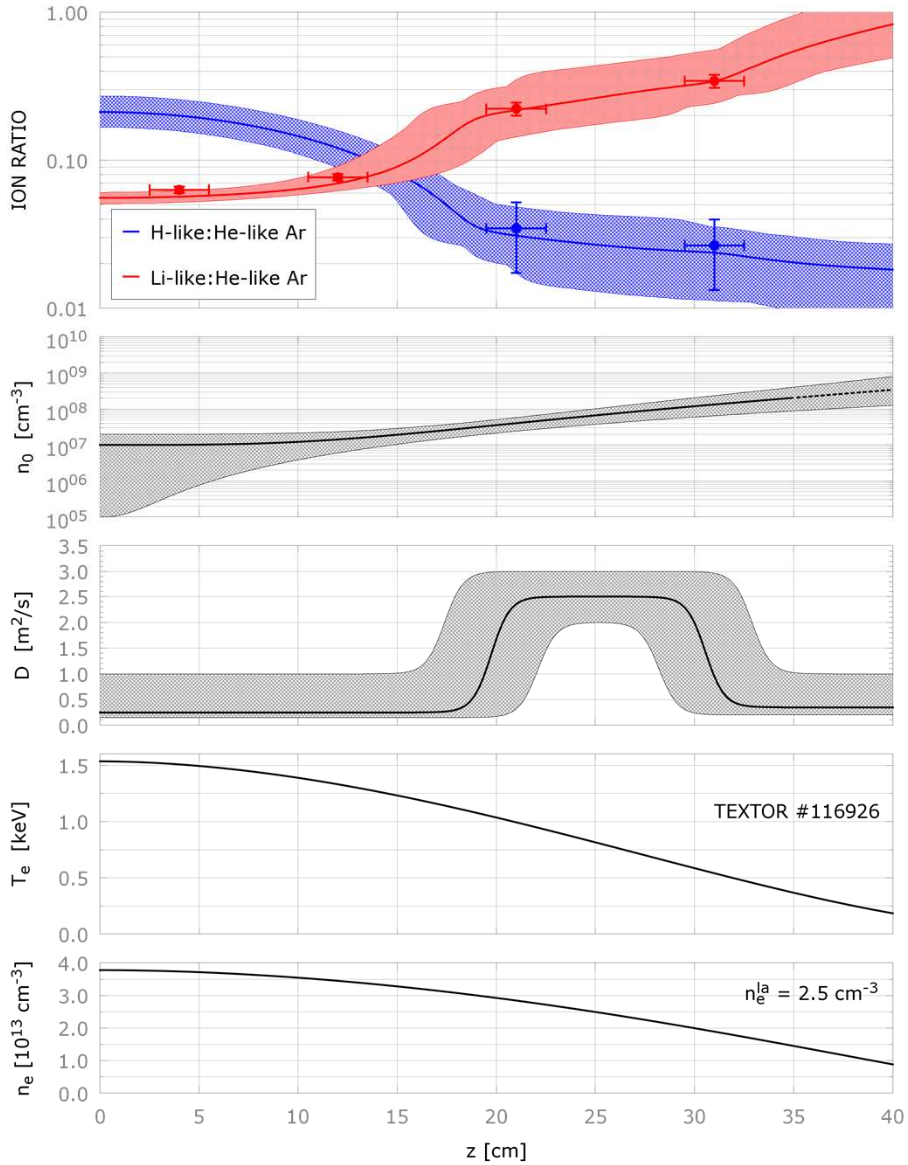
- Energies, wavelengths, oscillator strengths: WXYZ – fully relativistic **[Plante, Johnson, Sapierstein – Phys. Rev. A 49 3519 – 1994]**
  Satellites – MZ
- Radiative recombination – ATOM-Code [urnov….]
- Collisional excitation – ATOM-Code / R-Matrix incl. cascades up to n=4, extrapolated for n>4 **[Whiteford et al. – J. Phys. B: At. Mol. Opt. Phys. 34 3179 – 2001]**
- Inner shell excitation – ATOM-Code / R-Matrix
- Ion excitation – Impact parameter **[Sampson, Proc. Phys. Soc. 79 1105 – 1962]**
- Dielectronic recombination – Autostructure
- Charge exchange – CTMC, ACC **[Schultz et al. – J. Phys. B: At. Mol. Opt. Phys. 43 144002 – 2010]**

**Transport code:**

- Radiative recombination – **[Verner et al. – Astrophys. J. 456 487 – 1996]** updated by Badnell, Ferland et al.
- Ionization – **[Arnaud, Rothenflug – Astron. Astrophys. Suppl. 60, 425 – 1985]**
- Inner shell ionization – ATOM Code
- Dielectronic recombination – Autostructure
- Charge exchange – CTMC, ACC **[Schultz et al. – J. Phys. B: At. Mol. Opt. Phys. 43 144002 – 2010]**

**["Modeling of He-like spectra measured at the tokamaks TEXTOR and TORE SUPRA", Diss. O. Marchuk - 2004]**
**[Marchuk, Bertschinger, Kunze, Badnell, Fritzsche - J. Phys. B: At. Mol. Opt. Phys. 37 1951 - 2004]**

# Experimental neutral gas density profiles from TEXTOR




- TEXTOR discharge #116926
  ($n_{e,la}$ = 2.5·$10^{13}$$cm^{-3}$, ohmic)

**Results:**

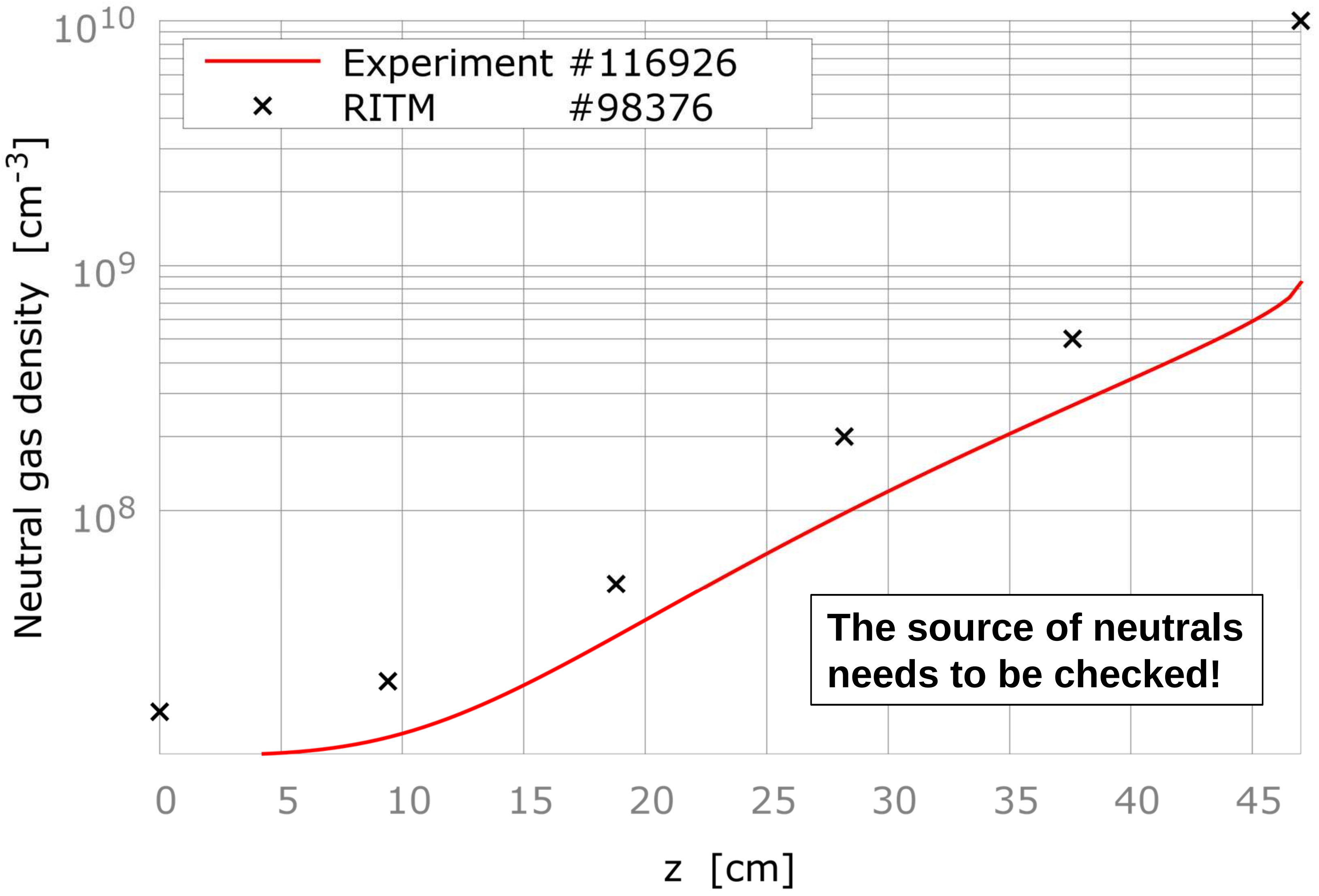
- No consistent description of all channels without a high transport region !
- Neutrals are needed to describe Li-like and H-like argon consistently !
- Transport is the dominant mechanism !

Errors:

- In the intermediate region the neutral gas density can be determined by a factor of 2.
- In the plasma center only a maximum neutral density can be obtained.
- Evaluation of the **2D information** from the detectors chip gives gradients at each radial point.

  → significant increase of accuracy

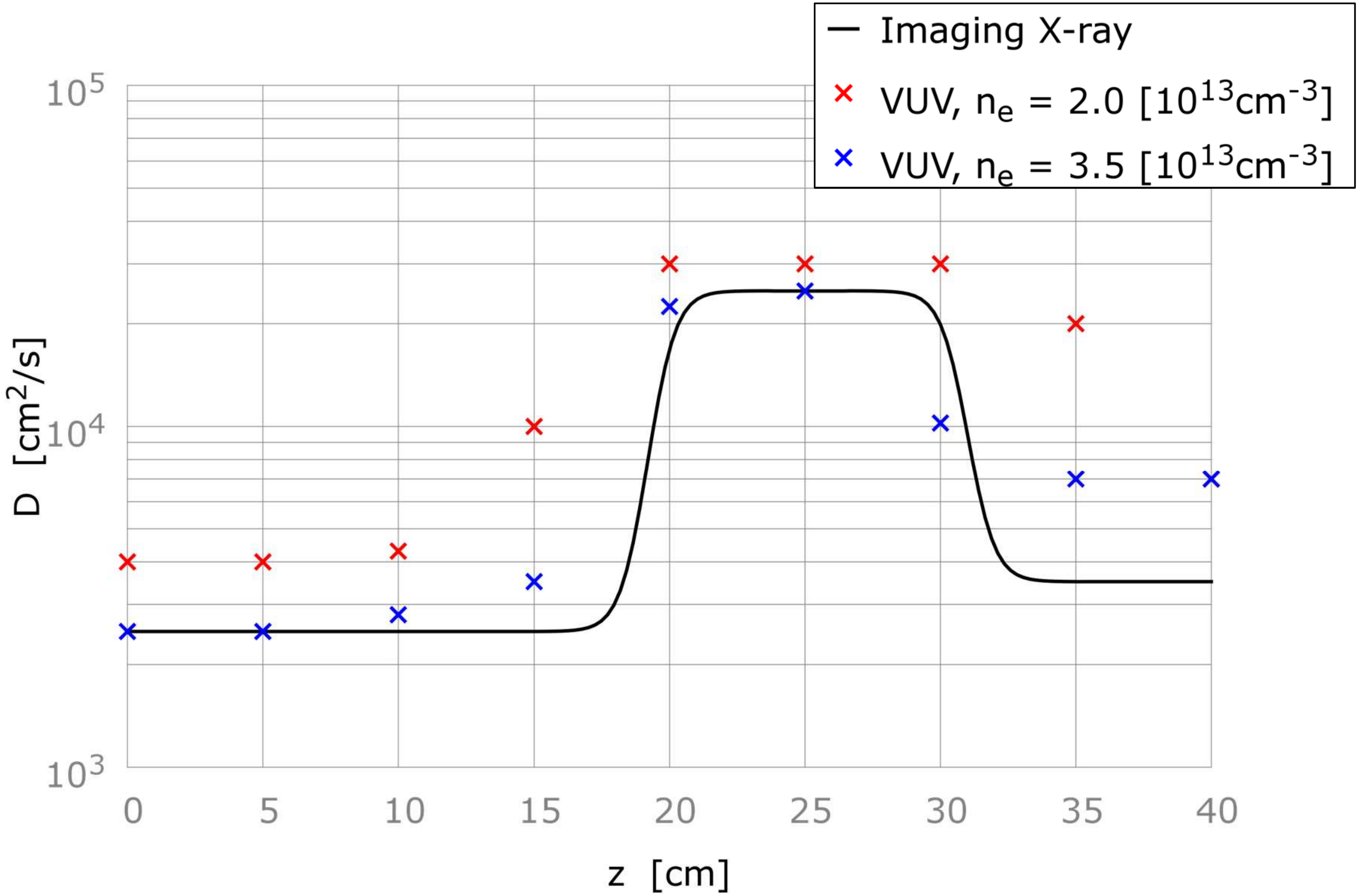
# Neutral gas density






[Marchuk et al. - Plasma Phys. Control. Fusion **48,** 2006]

# Diffusion coefficient




[Biel et al. - 28. EPS Conf. on Contr. Fusion and Plasma Phys., Funchal, 2001]

# Conclusion

- Measurements of He-like argon spectra in TEXTOR using new imaging Xray-spectrometer.
- Study of influence of charge exchange and radial transport on the argon ionization balance in TEXTOR based on these spectra:
  - Clear distinction between impact of charge exchange and transport on the line intensities.
  - Diffusive transport is the most important mechanism.
  - Significant charge exchange contributions are needed towards the edge.
  - Radial profiles for the neutral gas density and the diffusion coefficent have been obtained, showing a high transport region.
- Imaging Xray – spectroscopy is a suitable plasma diagnostic for neutral gas density and for radial transport.

# Outlook

- Evaluation of the 2D – information from the CCD – detector chips.
  → Gradients for each data point
  → Higher precision
- Further analysis of:
  - *Density dependency for ohmic discharges*
  - *Ohmic discharges in He-plasma*
  - *Neutral beam heated discharges*
- Modelling of VUV spectra with obtained D- and $N_0$-profiles
- Comparison of neutral density profiles with theoretical data.

# Thank you for your attention !

# Including transport and charge exchange

- The fit routine uses radial profiles of the argon ions given as input data.
- To include transport and charge exchange a simple transport code is used solving a system of steady state equations:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_{\perp}) = \mathrm{Sz} \qquad \text{for} \quad \mathrm{z} = 1 \ldots 19 \; (\mathrm{Ar}^{0} \ldots \mathrm{Ar}^{18+})$$

$$with$$

$$S_z = k_{ion}^{z-1} \cdot n_e \cdot Ar^{z-1}$$
$$+\left(\left(k_{rr}^{z+1} + k_{dr}^{z+1}\right) \cdot n_e + k_{cx}^{z+1} \cdot n_0\right) \cdot Ar^{z+1}$$
$$-\left(\left(k_{ion}^{z} + k_{rr}^{z} + k_{dr}^{z}\right) \cdot n_e + k_{cx}^{z} \cdot n_0\right) \cdot Ar^{z}$$

$$\Gamma_{\perp} = -D \cdot \frac{\partial n_z}{\partial r} + V_{\perp} \cdot n_z$$

[Tokar – Plasma Phys. and Contr. Fusion, Vol. 36, No. 11, 1994]
[Dux – STRAHL – Code user manual]

# The argon ion ratios

## $Ar_{Li}$ : $Ar_{He}$

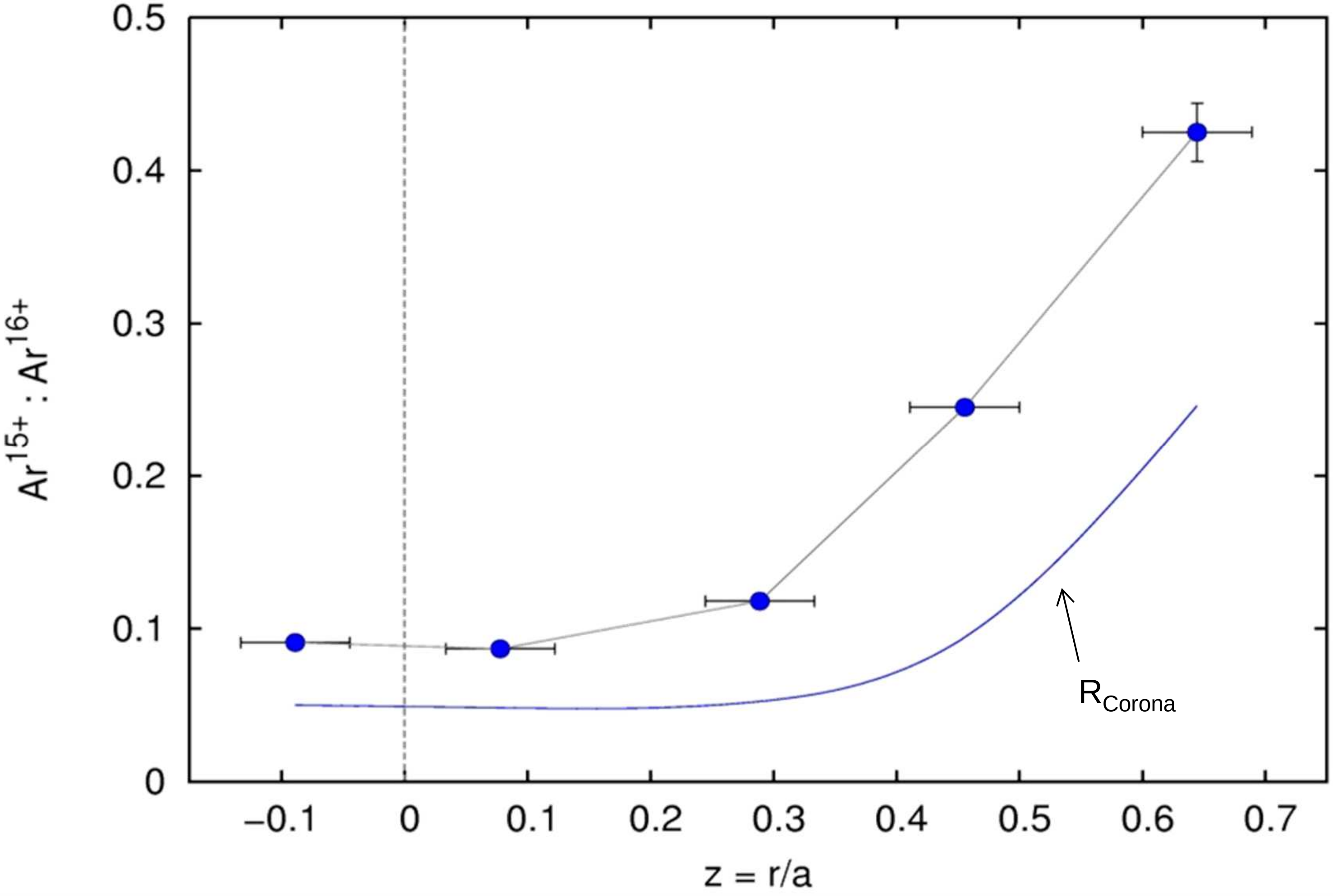
- q-satellite: 1s2s2p – 1s²2p (Li-like doubly excited state)

$$\frac{I_q}{I_w} \approx \frac{\langle\sigma\cdot\nu\rangle_{iexc(T_e)}\cdot Ar^{15+}\cdot ne}{\langle\sigma\cdot\nu\rangle_{exc(T_e)}\cdot Ar^{16+}\cdot ne} = \frac{\langle\sigma\cdot\nu\rangle_{iexc}(Te)}{\langle\sigma\cdot\nu\rangle_{exc}(Te)}\cdot\frac{Ar^{15+}}{Ar^{16+}}$$

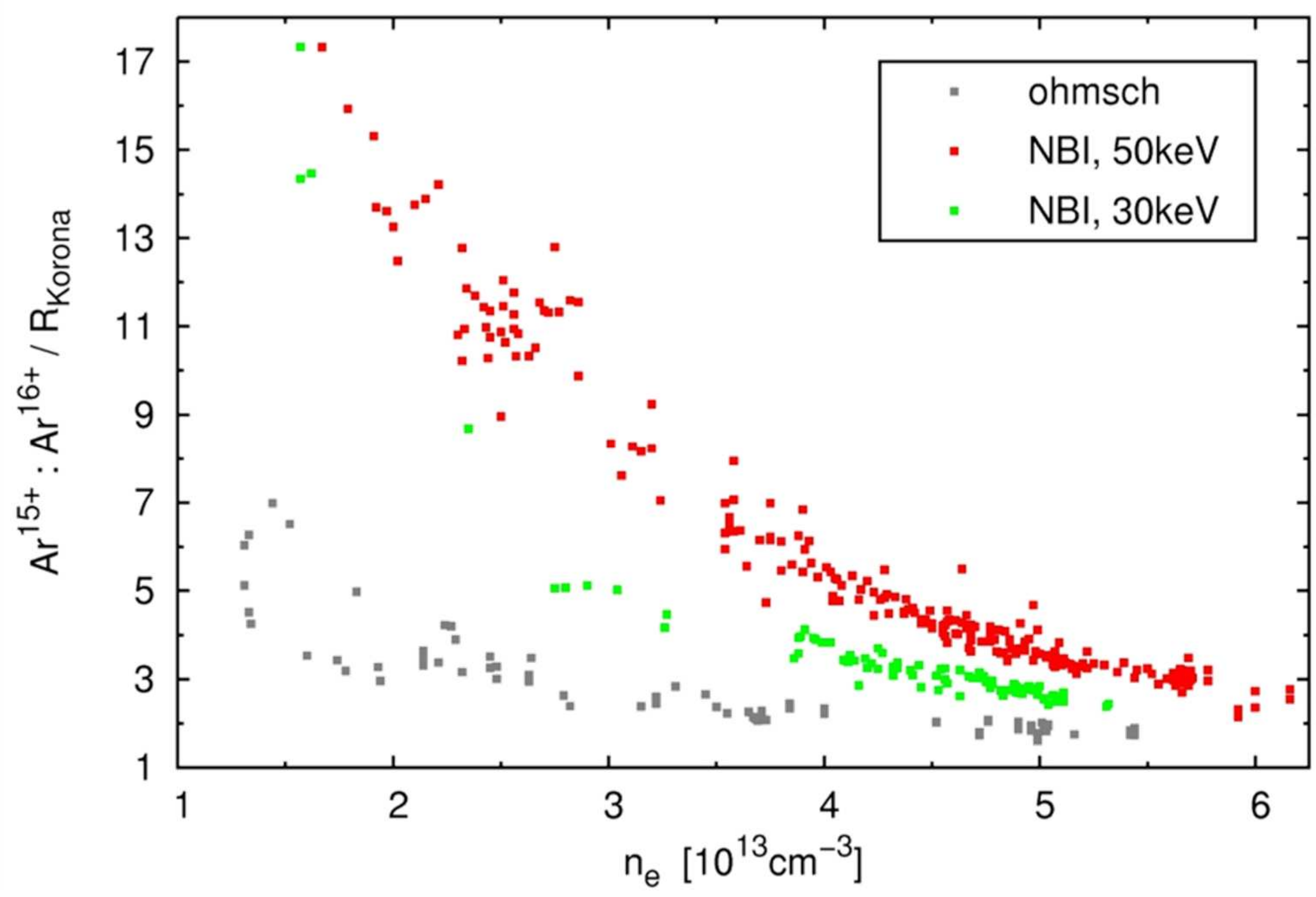
## $Ar_{H}$ : $Ar_{He}$

- Z-line: 1s2s – 1s² (He-like singly excited state)

$$\frac{I_z}{I_w} \approx \frac{\langle\sigma\cdot\nu\rangle_{exc}(T_e) + \frac{Ar^{17+}}{Ar^{16+}}\cdot\left(\langle\sigma\cdot\nu\rangle_{rr}(T_e) + \langle\sigma\cdot\nu\rangle_{cx}(T_e)\cdot\frac{n_0}{n_e}\right)}{\langle\sigma\cdot\nu\rangle_{exc}(T_e)}$$



0.5
0.4
0.3
0.2
0.1
0
$Ar^{15+} : Ar^{16+}$
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
z = r/a
$R_{Corona}$



ohmsch
NBI, 50keV
NBI, 30keV
$Ar^{15+} : Ar^{16+} / R_{Korona}$
$n_e$ [$10^{13}cm^{-3}$]
1
3
5
7
9
11
13
15
17
1
2
3
4
5
6

# $K_\alpha$ – spectroscopy as diagnostic for the neutral gas density

- Advantage of $K_\alpha$ - X-ray spectroscopy compared to other spectroscopic methods:

  Two spectral lines: q-satellite and z-line
  one sees cx-contribution one does not!
  Liver for distinguishing between diffusion and CX via N0!!

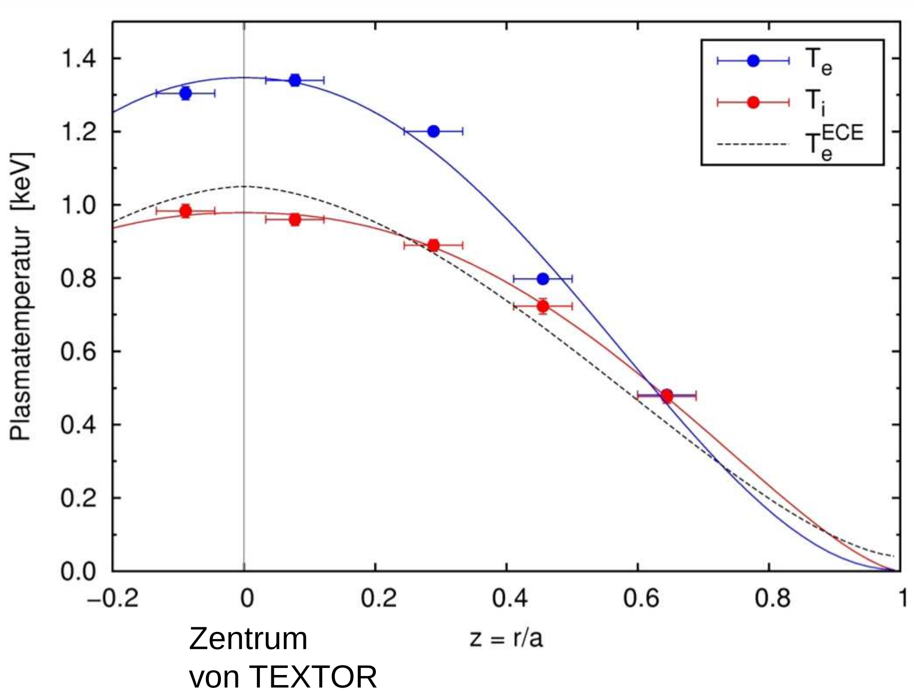
- q-satellite: ground state transition from double excited Li-like 1s…

$$I_q \propto \langle \sigma \cdot \nu \rangle_{iexc} \cdot Ar^{15+} \cdot n_e$$

- Z-line: ground state transition from single excited He-like 1s…

$$I_Z \propto \langle \sigma \cdot \nu \rangle_{exc} \cdot Ar^{16+} \cdot ne + \left( \langle \sigma \cdot \nu \rangle_{rr} + \langle \sigma \cdot \nu \rangle_{cx} \cdot \frac{n_0}{n_e} \right) \cdot Ar^{16+} \cdot ne$$

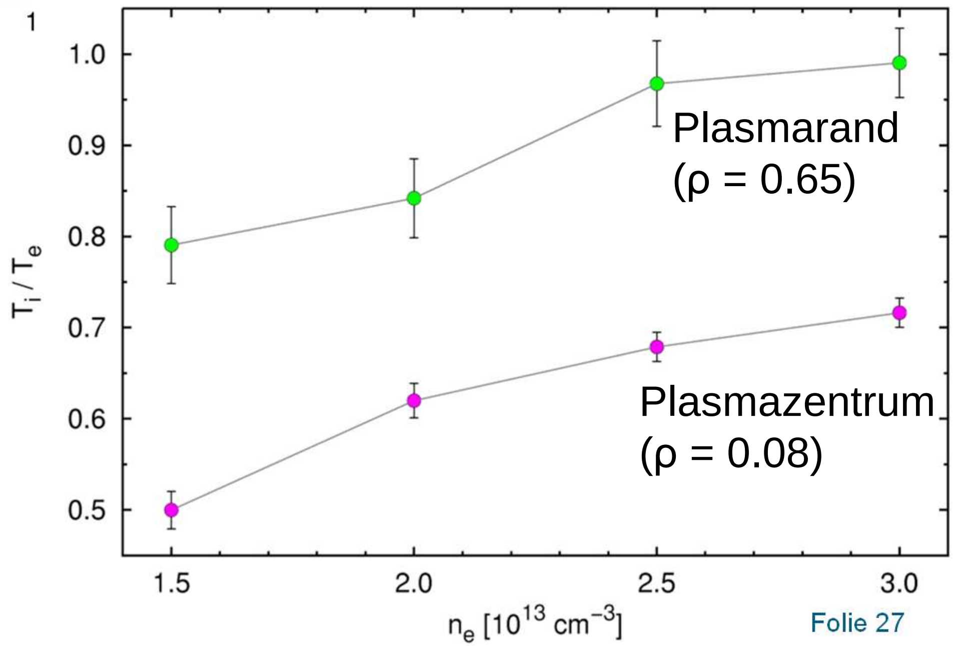
# Temperaturprofile von TEXTOR




Entladung #116925
ohmisch
$n_e = 3.0 \cdot 10^{13}\ cm^{-3}$

Thermische Kopplung:

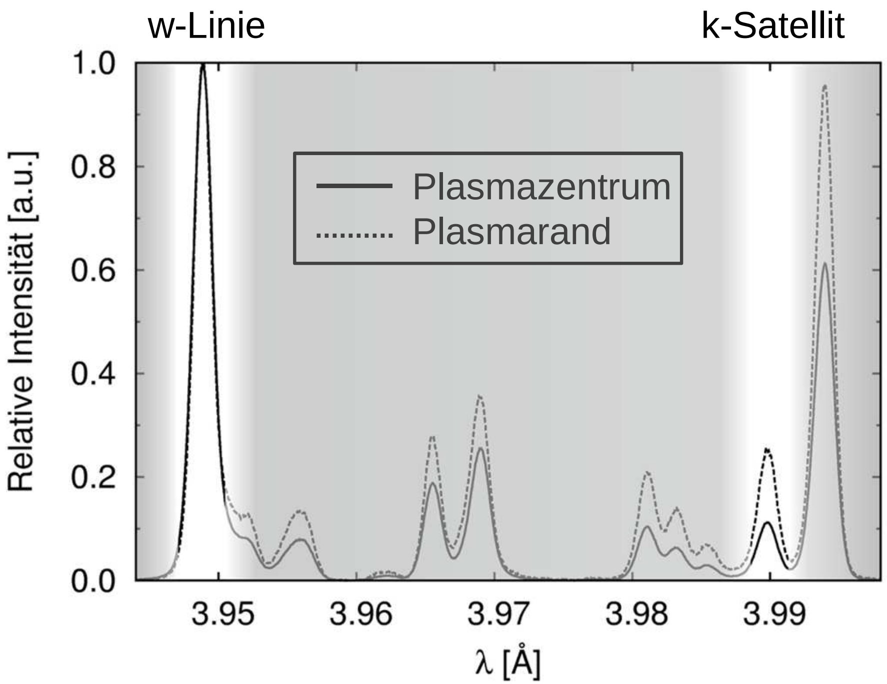
$$\nu_{ie} \propto n_e \cdot T^{-3/2}$$

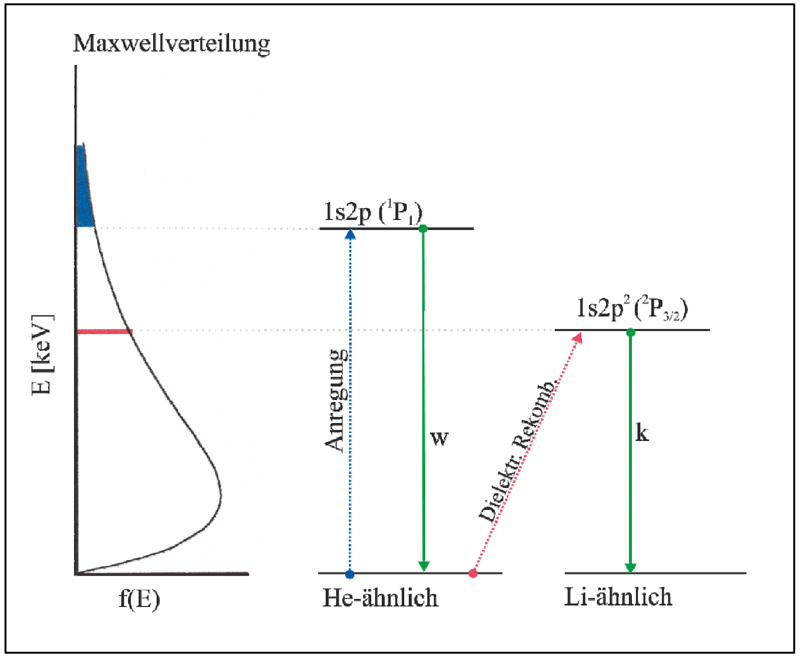



Simultane Messung der Temperaturen:

- Elektronentemperatur (Linienintensitäten)
- Ionentemperatur (Linienbreiten)

# Temperaturprofile von TEXTOR – $T_e$



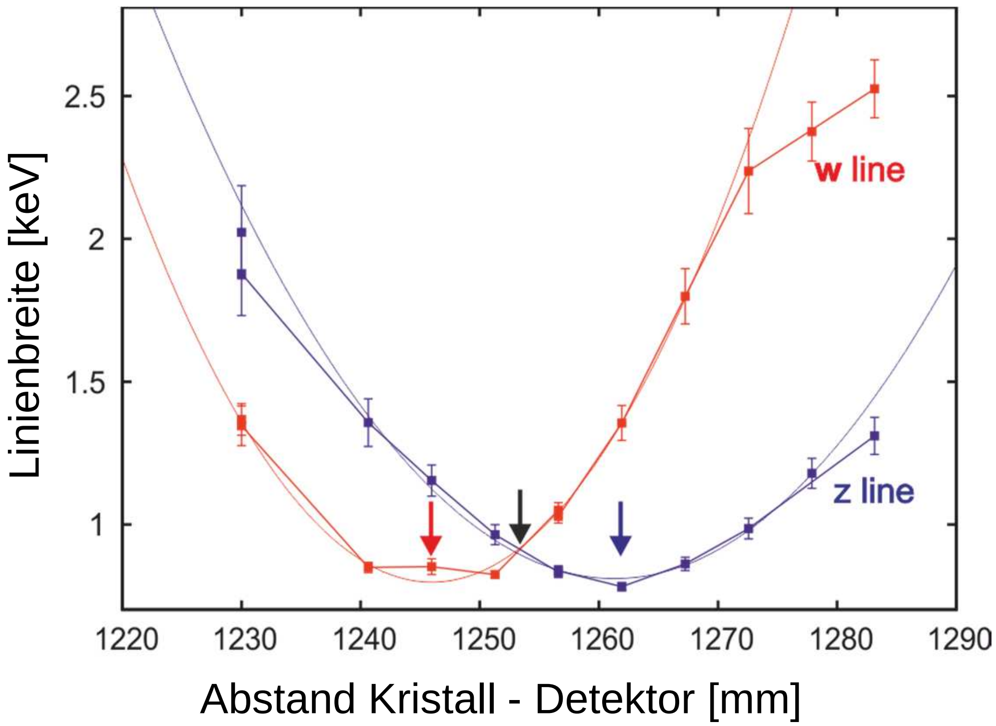



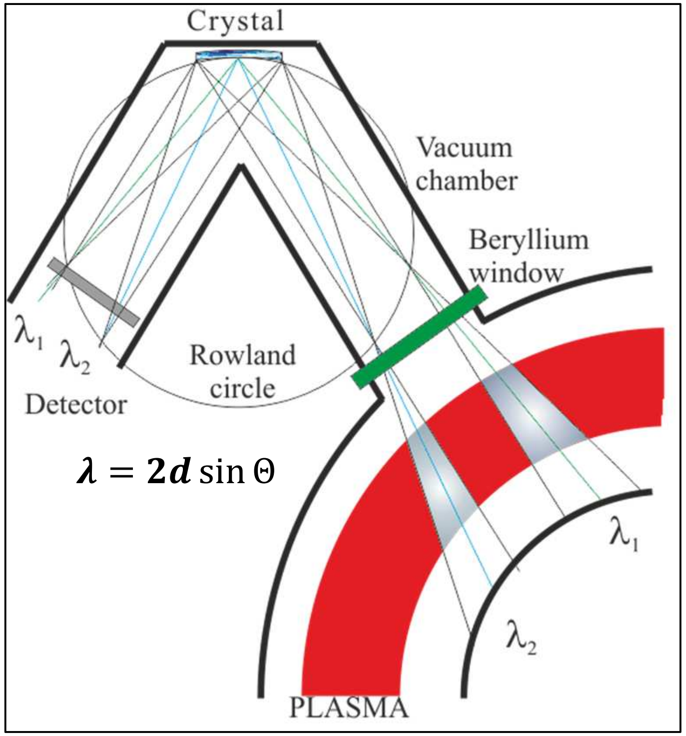

$$\frac{I_k}{I_w} = \frac{\langle\sigma\cdot v\rangle_{dr(T_e)}\cdot Ar^{16^{+}}\cdot n_e}{\langle\sigma\cdot v\rangle_{exc(T_e)}\cdot Ar^{16^{+}}\cdot n_e} = \frac{\langle\sigma\cdot v\rangle_{dr(T_e)}}{\langle\sigma\cdot v\rangle_{exc(T_e)}} \approx \frac{const}{T_e}$$

Vermessung der Maxwellverteilung der Elektronen

→ **Absolute Temperaturmessung**

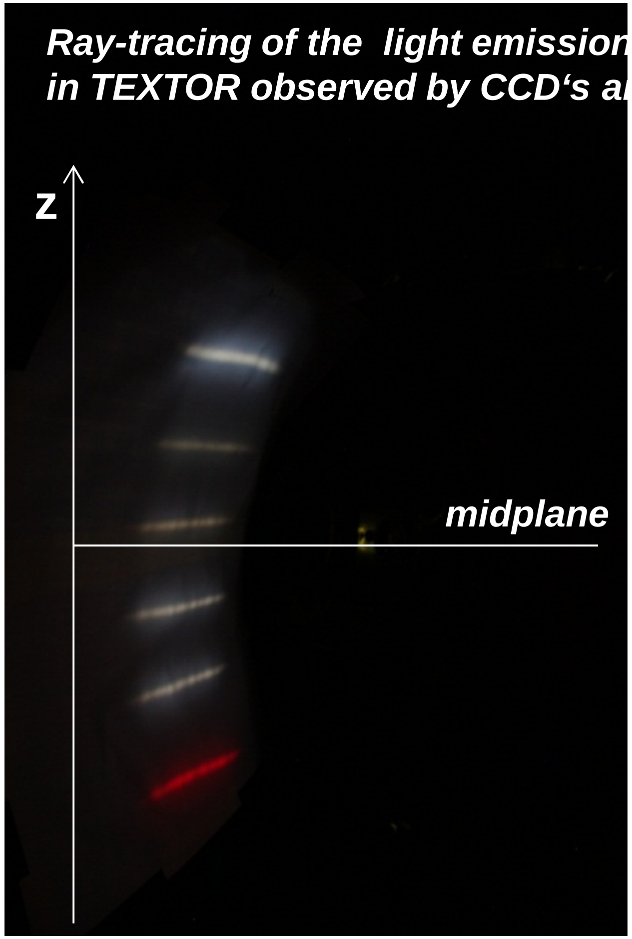
# Temperaturprofile von TEXTOR – $T_i$




- Aufgrund der unterschiedlichen Wellenlängen lassen sich nicht alle Linien zugleich fokussieren!
- Gezielte Defokussierung von w- und z-Linie führt zu homogenen Linienbreiten und ermöglicht einen konsistenten Fit der Spektren

→ $T_i$(w) und $T_i$(z) stimmen im Rahmen von 15% überein




**Illumination from CCD's position**

| | | | | |
|---|---|---|---|---|
| w | : | $1s2p\ (^1P_1)$ | $\rightarrow$ | $1s^2\ (^1S_0)$ |
| x | : | $1s2p\ (^3P_2)$ | $\rightarrow$ | $1s^2\ (^1S_0)$ |
| y | : | $1s2p\ (^3P_1)$ | $\rightarrow$ | $1s^2\ (^1S_0)$ |
| z | : | $1s2s\ (^3S_1)$ | $\rightarrow$ | $1s^2\ (^1S_0)$ |
| a | : | $1s2p^2\ (^2P_{3/2})$ | $\rightarrow$ | $1s^22p\ (^2P_{3/2})$ |
| k | : | $1s2p^2\ (^2D_{3/2})$ | $\rightarrow$ | $1s^22p\ (^2P_{1/2})$ |
| q | : | $1s2s2p\ (^2P_{3/2})$ | $\rightarrow$ | $1s^22s\ (^2S_{1/2})$ |
| r | : | $1s2p^2\ (^2P_{1/2})$ | $\rightarrow$ | $1s^22p\ (^2S_{1/2})$ |