Kinetics of Neutral Beams in Fusion Plasmas: Charge-Exchange Recombination and Motional Stark Effect

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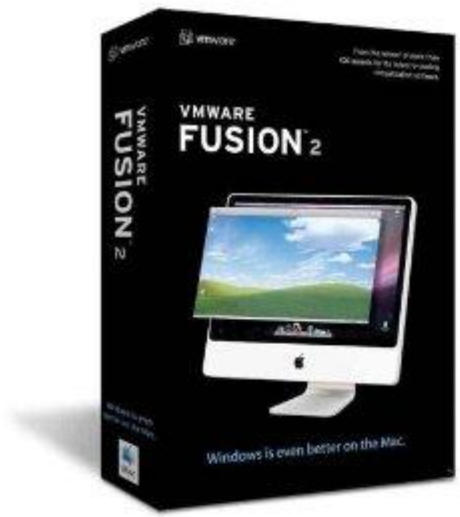
Fusion


VMWARE
FUSION 2
Windows is even better on the Mac.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Gates: 'Perfect Fusion' Made bin Laden Raid Succeed
By John D. Banusiewicz
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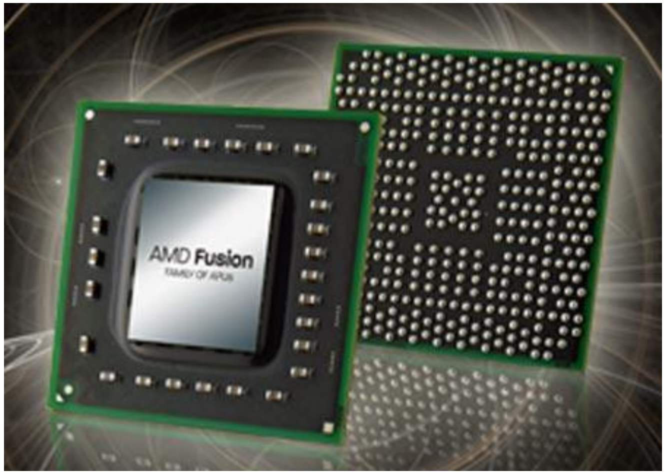
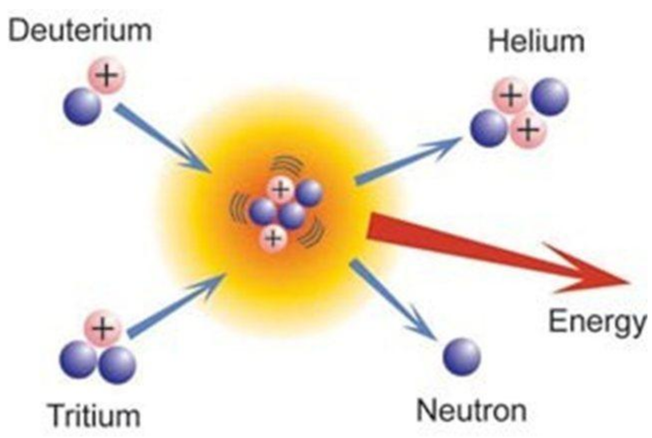
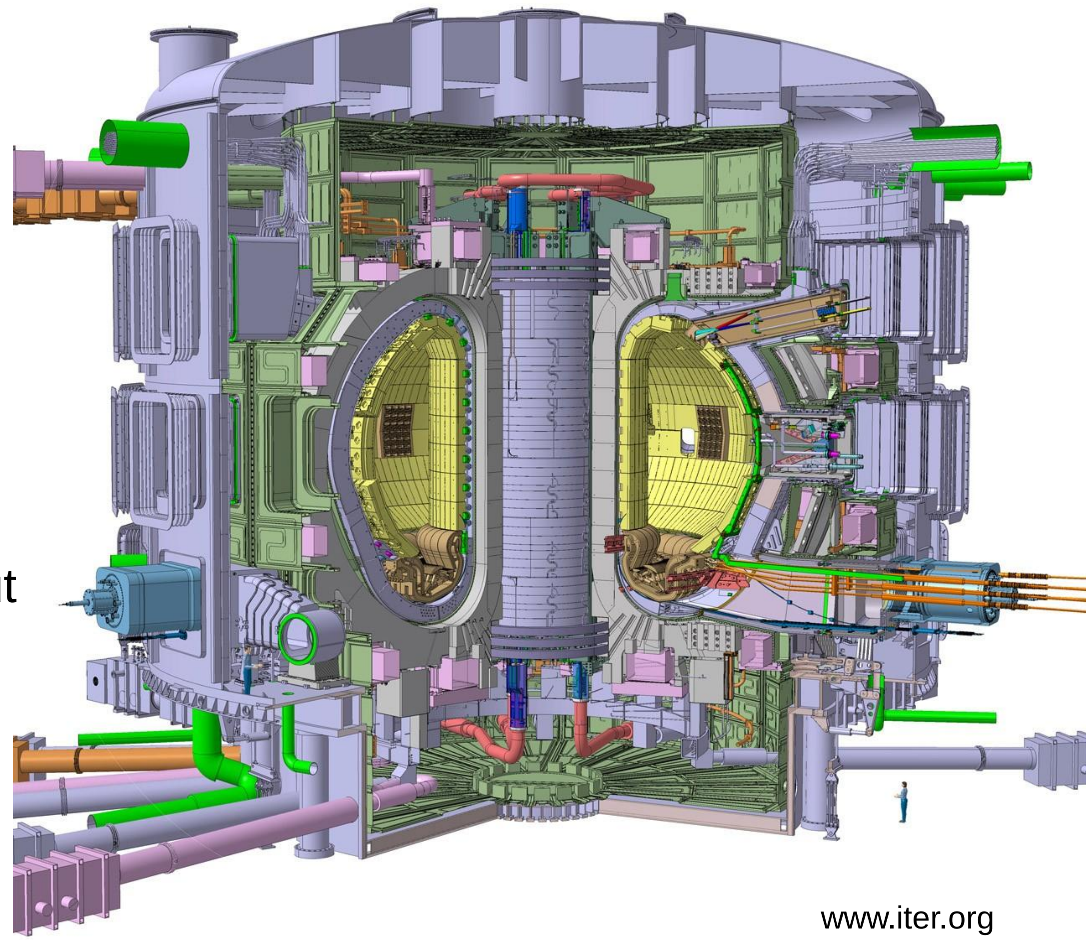

AMD Fusion

Nuclear Fusion



ITER: 50 MW input, 500 MW output

First plasma: 2019 (?)



www.iter.org

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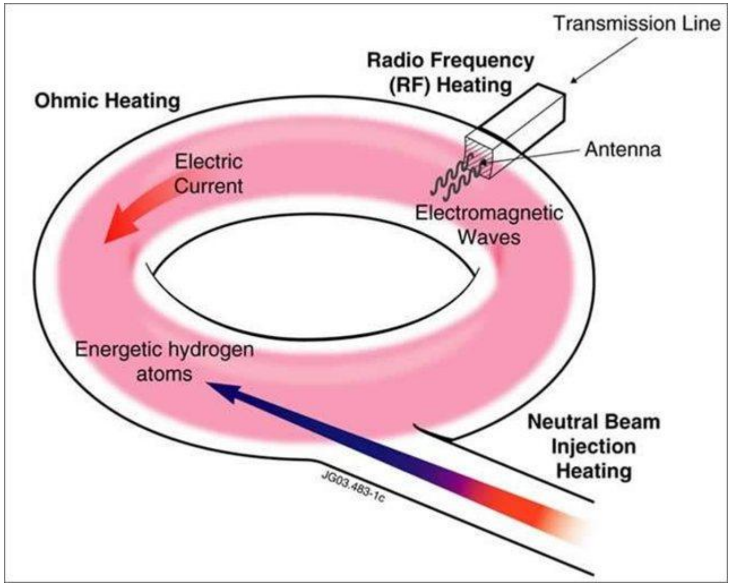
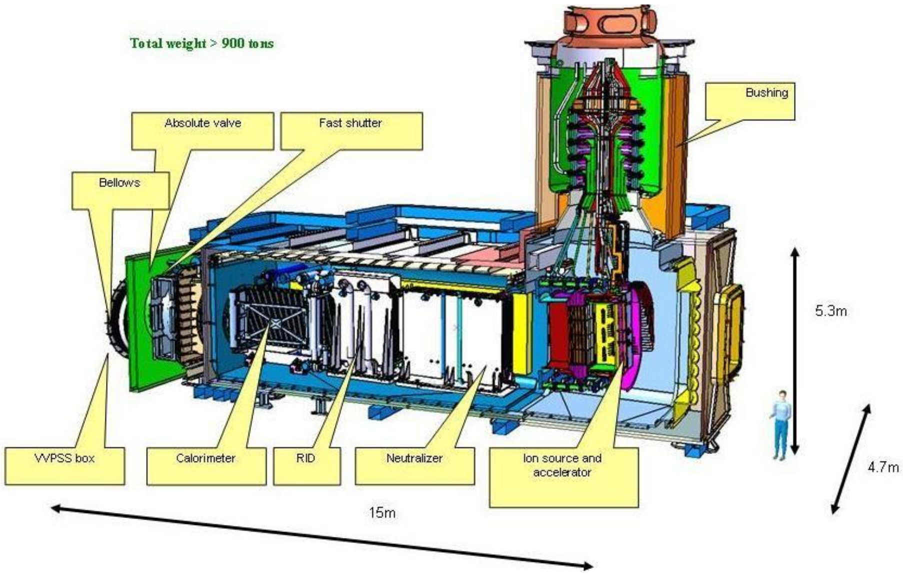
Plasma Heating for Fusion Devices





Heating beams
- ITER: 500 keV/amu
- JET: ~140 keV/amu

Diagnostic beams
- ITER: 100 keV/amu
- TEXTOR: 50-100 keV/amu

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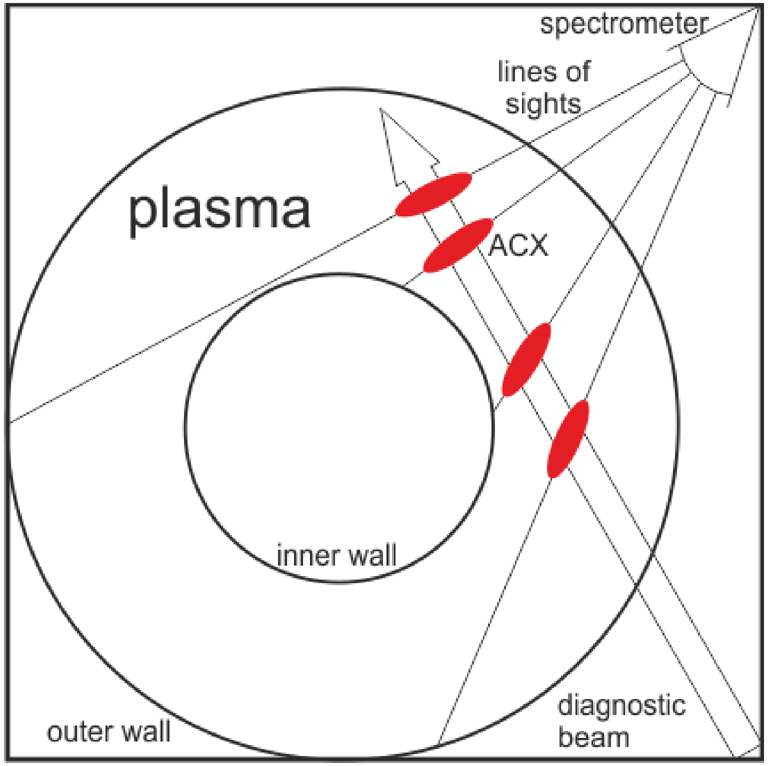
Neutral Beam Spectroscopy in Fusion Devices



Major reaction channels:

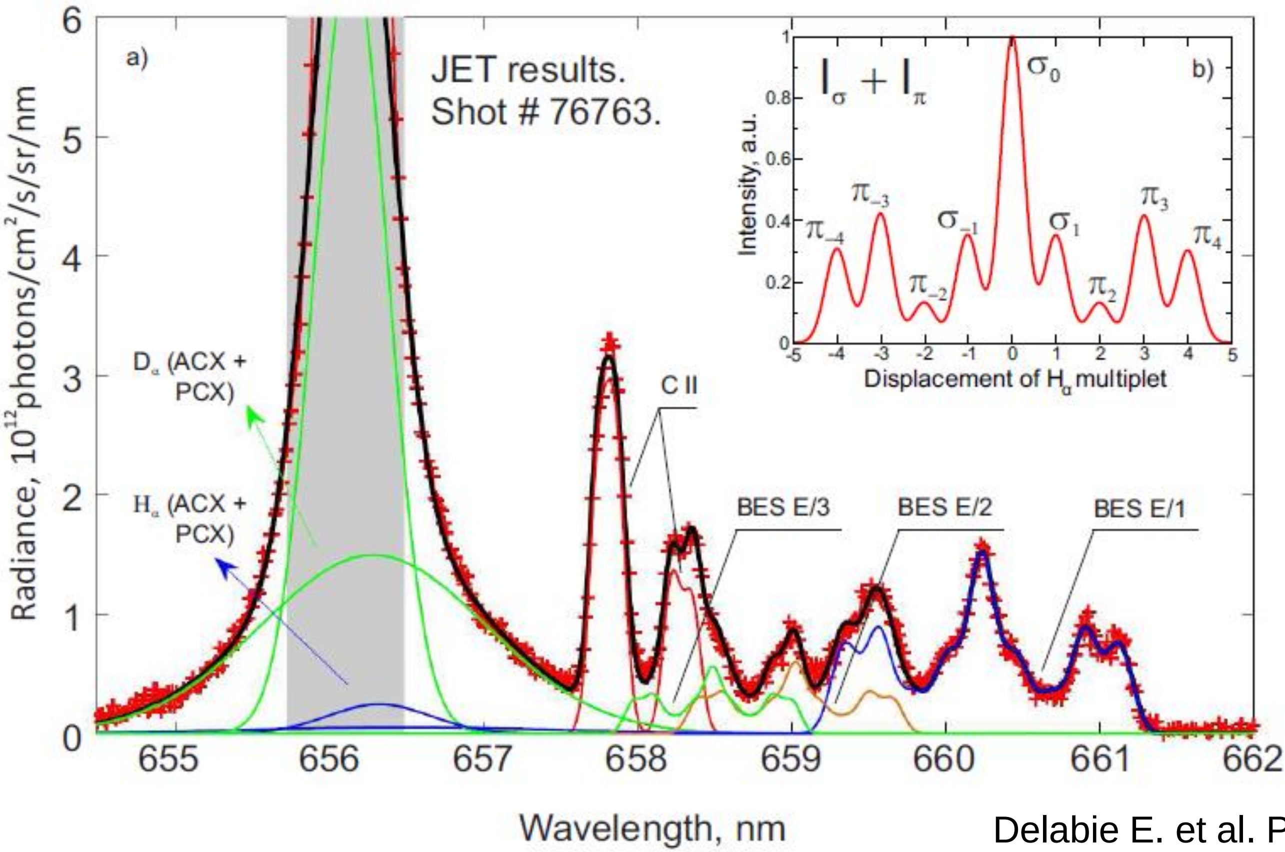
$$H_0 + \{e,H^+,X_z\} \rightarrow H^* + \{e,H^+,X_z\} \rightarrow \hbar\omega \quad (1)$$

$$H_0 + X_z \rightarrow H^+ + X^*_{z-1} \rightarrow \hbar\omega \quad (2)$$

$$H^+ + H_0 \rightarrow H^* + H^+ \rightarrow \hbar\omega \quad (3)$$

(1) beam-emission spectroscopy (BES) and motional Stark effect (MSE)
(2) Charge exchange on impurities (CXRS)
(3) CXRS of fast ion diagnostics and fuel ion ratio measurements (ACX: active charge exchange)

$H_\alpha(n=3 \rightarrow n=2)$ spectrum from the JET tokamak



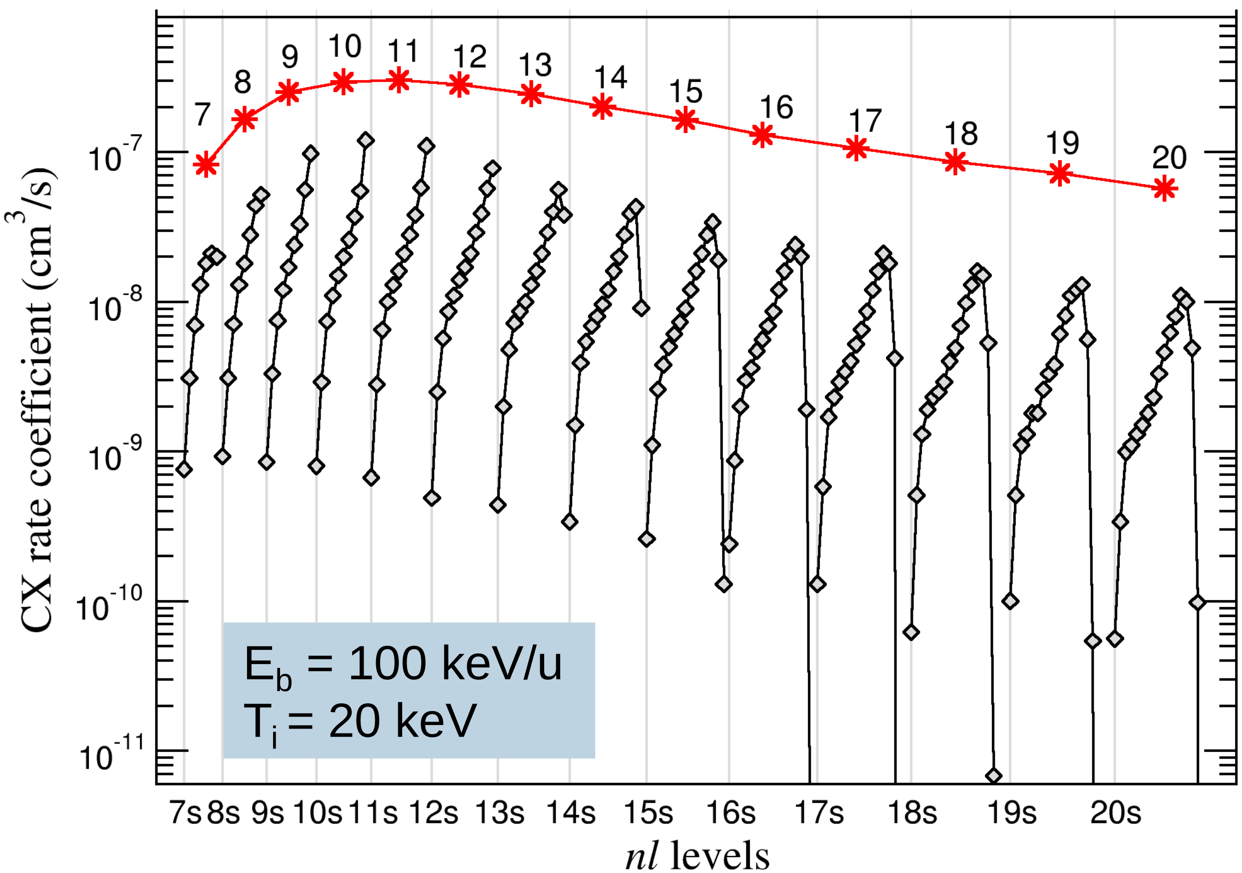
- Passive light from the edge
- Emission of thermal H^+ and D^+
- Cold components of CII Zeeman multiplet
- Overlapping components of MSE spectra (E, E/2, E/3)

Delabie E. et al. PPCF **52** 125008 (2010)

- Ratios among *π*- and *σ*- lines within the multiplet are well defined and should be constant.

Charge eXchange Recombination Spectroscopy (CXRS)

$Ar^{18+} + H \rightarrow Ar^{17+} + p$



Hung, Krstic and Schultz, CFADC-ORNL database

CX goes into high *n*'s:

$n \sim Z^{3/4}$

H-like Ar:

n=14-15 at 428 nm

n=15-16 at 523 nm

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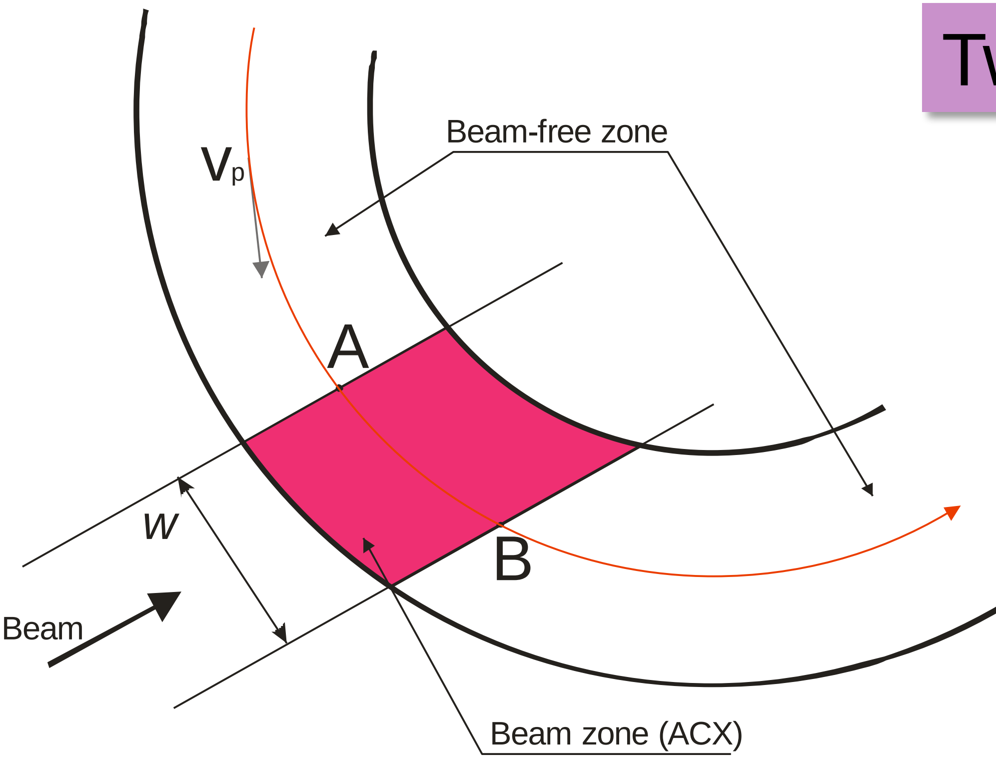
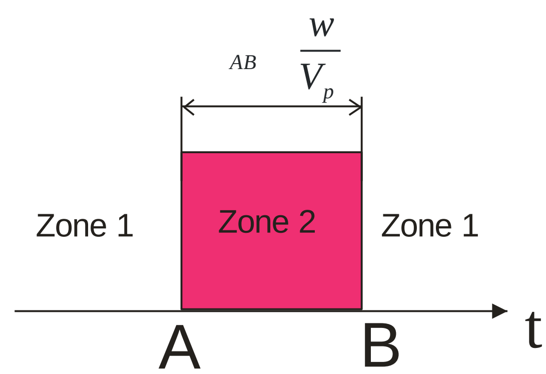
Two-zone model





V_p ~ 200 km/s

$t_{AB} \cong 4\ \mu s$

$t_{BA} \cong 40\ \mu s$

$\varepsilon = n_b/n;\ E_b$

Goal: **analyze time-dependent kinetics of Ar impurities under CXRS conditions**

Collisional-radiative model

- Atomic states
  - [Li] 14 terms $1s^2nl$ ^2L, $n \leq 5$
  - [He] 19 terms $1snl$ $^{1,3}L$, $n \leq 4$
  - [H] 210 nl terms, $n \leq 20$ and 30 n-bundled Rydberg states, $21 \leq n \leq 50$
- Radiative transitions
  - Cowan + FAC
- Radiative recombination
  - Rozsnyai & Jacobs (1988)
- Electron collisions
  - Flexible Atomic Code (FAC) for excitations from 1s
  - Van Regemorter
  - ATOM for [Li] and [He]
- Proton collisions
  - Impact-parameter method
    - agrees well with the available close-coupling results
- Charge exchange
  - Classical Trajectory Monte Carlo (Hung, Krstic & Schultz)

Time-dependent code NOMAD
Yu.Ralchenko and Y.Maron, JQSRT 71, 609 (2001)

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Strategy

- Steady-state condition w/ and w/o beam
- Time-dependent relaxation in a beam zone
- Complete time-dependent evolution

- TEXTOR
  - $n_e = 5\times10^{13}$ cm^{-3}, $T_e = 2$ keV
- ITER
  - $n_e = 10^{14}$ cm^{-3}, $T_e = 20$ keV

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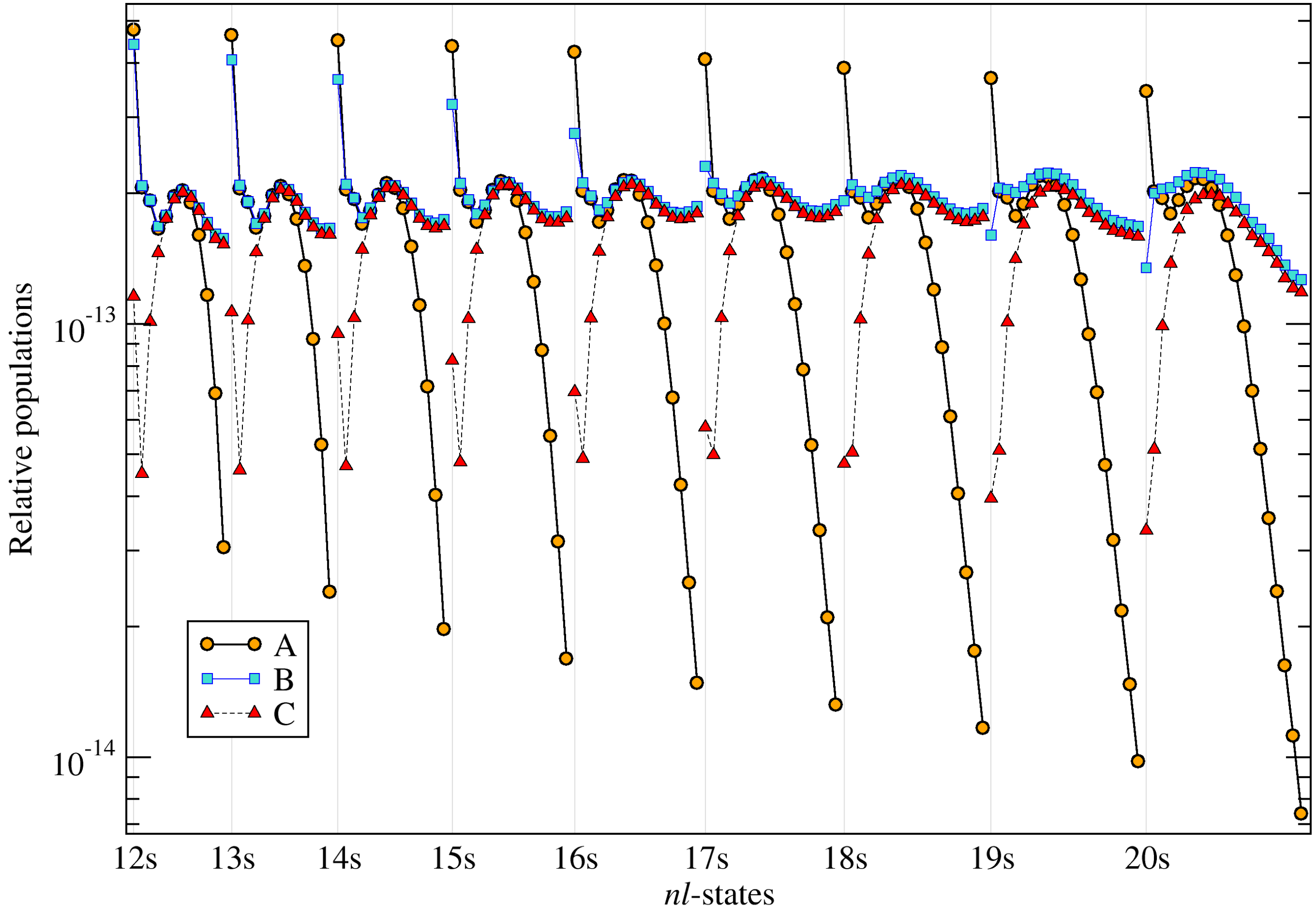
No beam: populations of high-n states



A. Only electrons
B. A + protons
C. B - excitations from other n's

5×10^{13} cm^{-3}/2 keV

proton collisions are responsible for redistribution among the *nl* excited states

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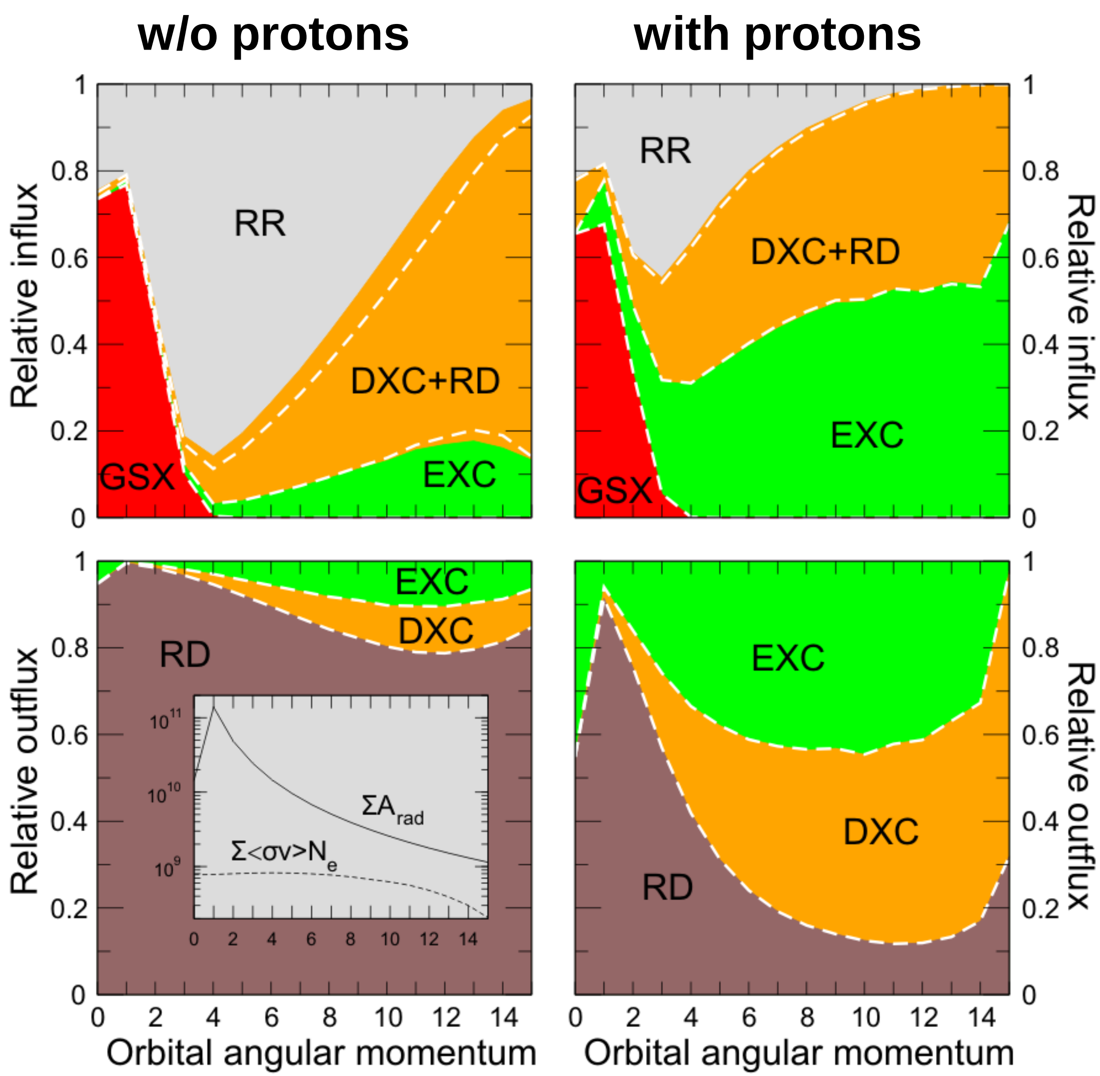
Population flux analysis



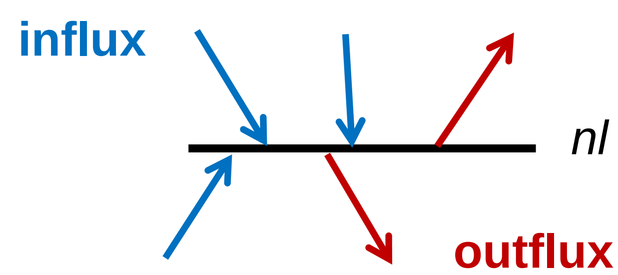
GS eXcitation

EXCitation

Radiative Decay

DeeXCitation

Radiative Recombination



T=2 keV, $N_e = 5 \cdot 10^{13}$ cm^{-3}

n=16

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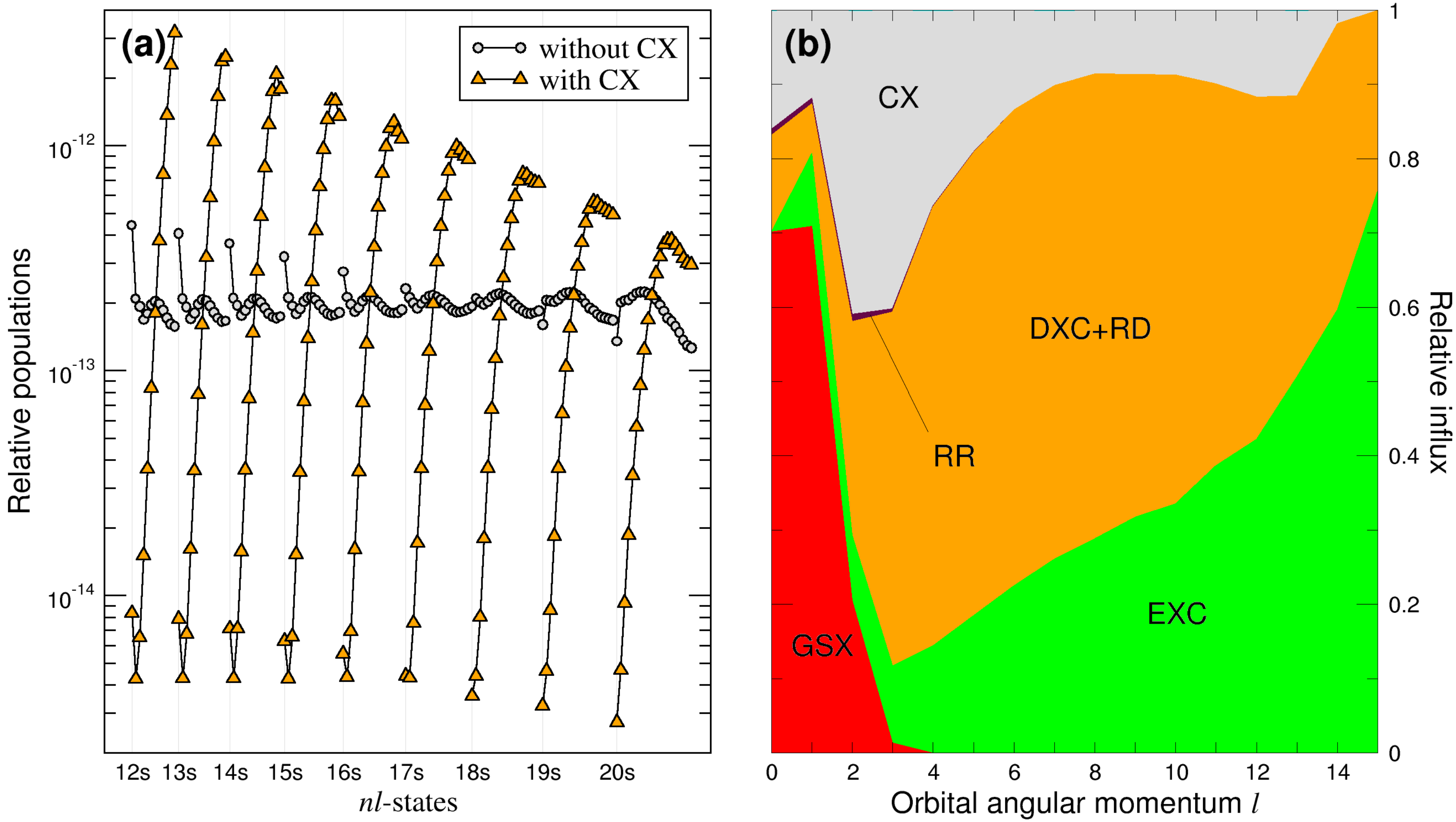
Steady state for the beam zone



w/o: T=2 keV, N_e =$5{\cdot}10^{13}$cm^{-3}

w/ CX: ε =$2{\cdot}10^{-5}$, E_b= 100 keV

- Substantial change in *nl* distribution in the beam zone.
- Proton collisions can not „wake up“ the high *l* sublevels
- Statistical equilibrium is not achieved
  - Charge exchange in the whole plasma

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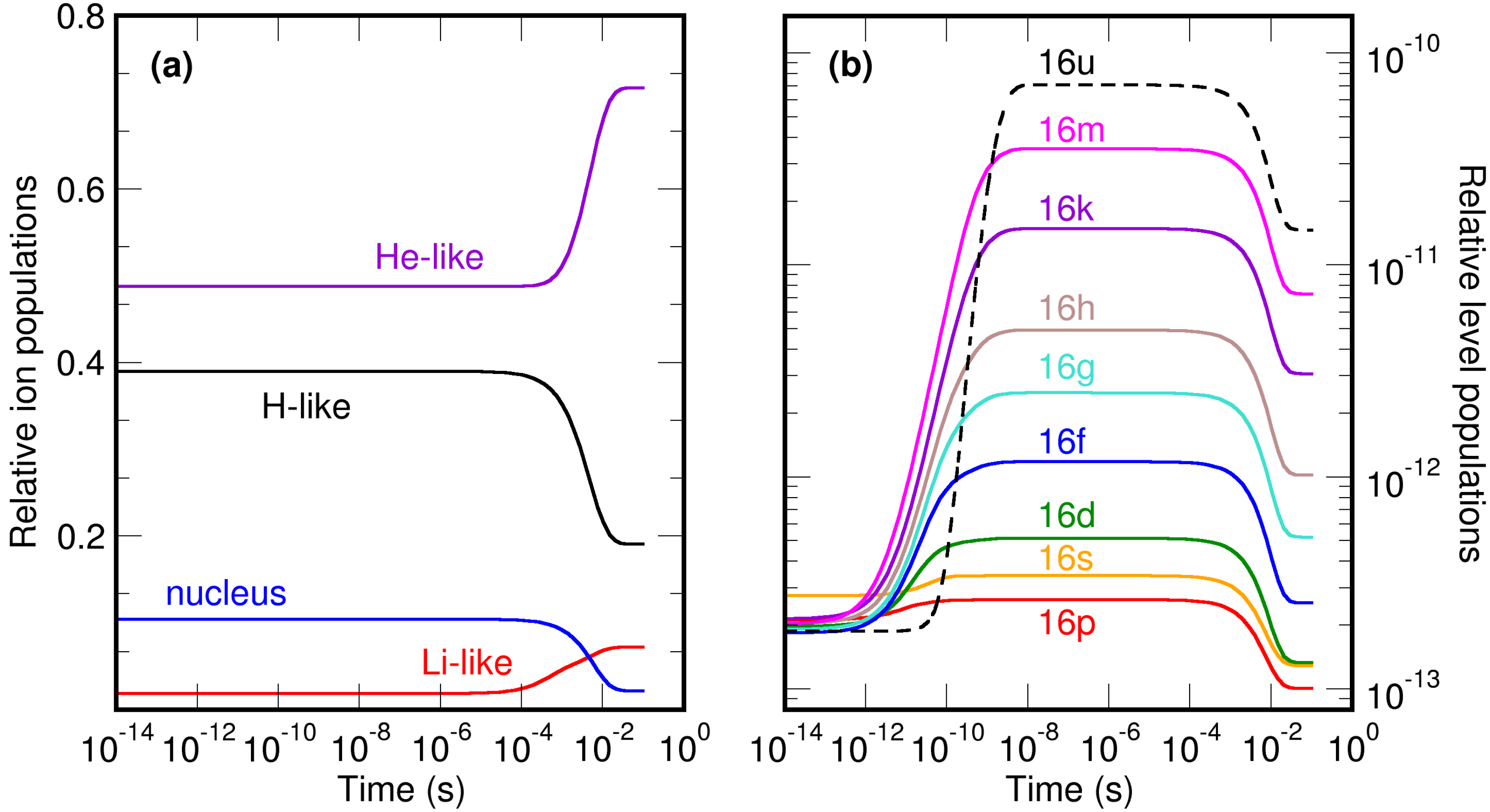
Time-dependent relaxation



- Very long relaxation time
- High-l equilibrate by collisions (16u)

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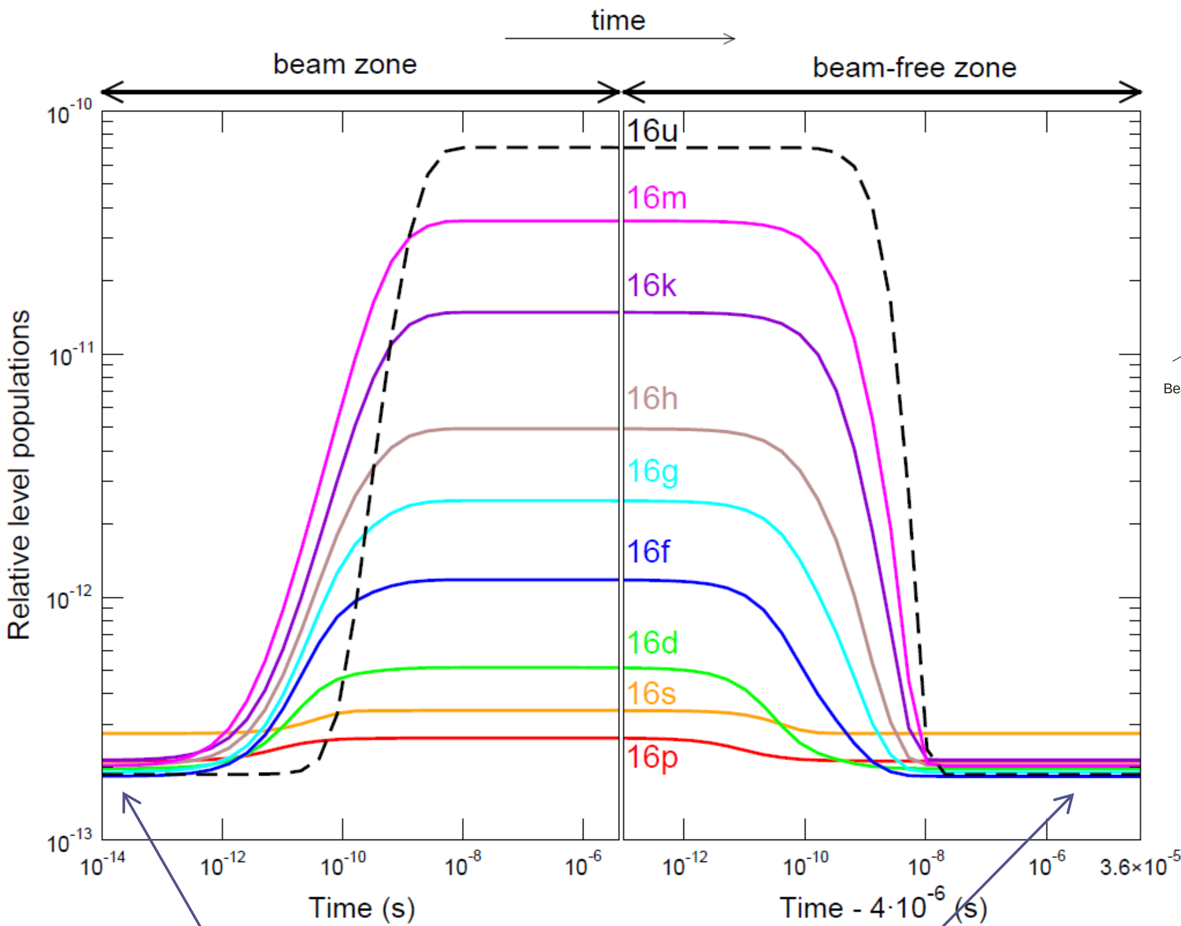
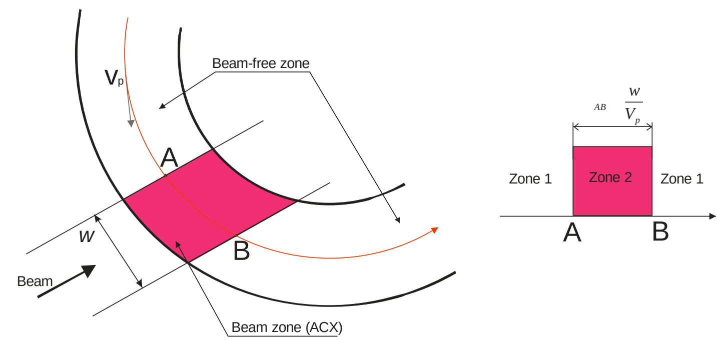
Impurity entering and leaving the beam zone





$$\frac{\delta N_n}{N_n} \approx R_{CX} \cdot \Delta t_{bz} - \left(R_{RR} + R_I\right)\Delta t_{bfz}$$

Populations are NOT the same

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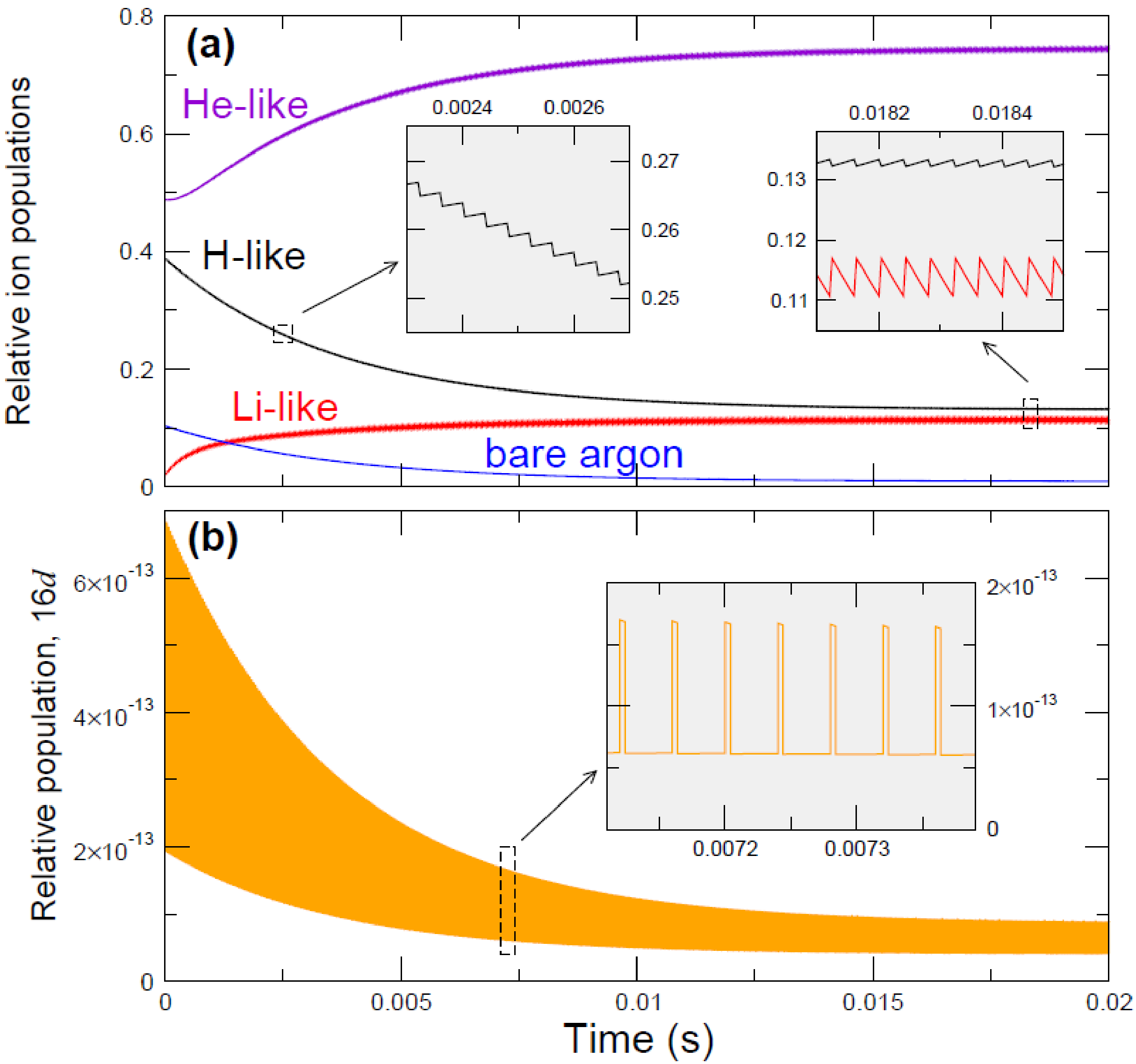
Full non-stationary model



1000 cycles of 4e-5 s

Equilibration time:

Ground states are slow

Excited states are very fast

Effective CX rescaled by:

$$\xi = \frac{\Delta t_{bz}}{\Delta t_{bz} + \Delta t_{bfz}}$$

20 steps of 0.002 s give the same ion populations

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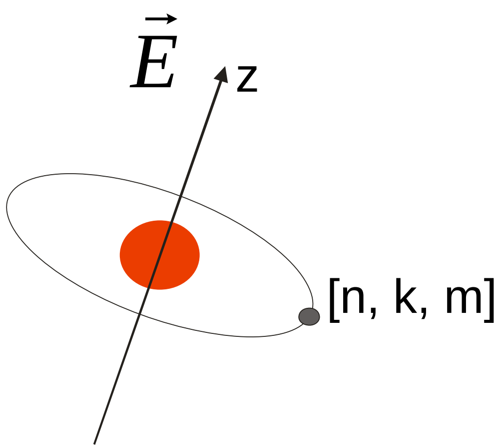
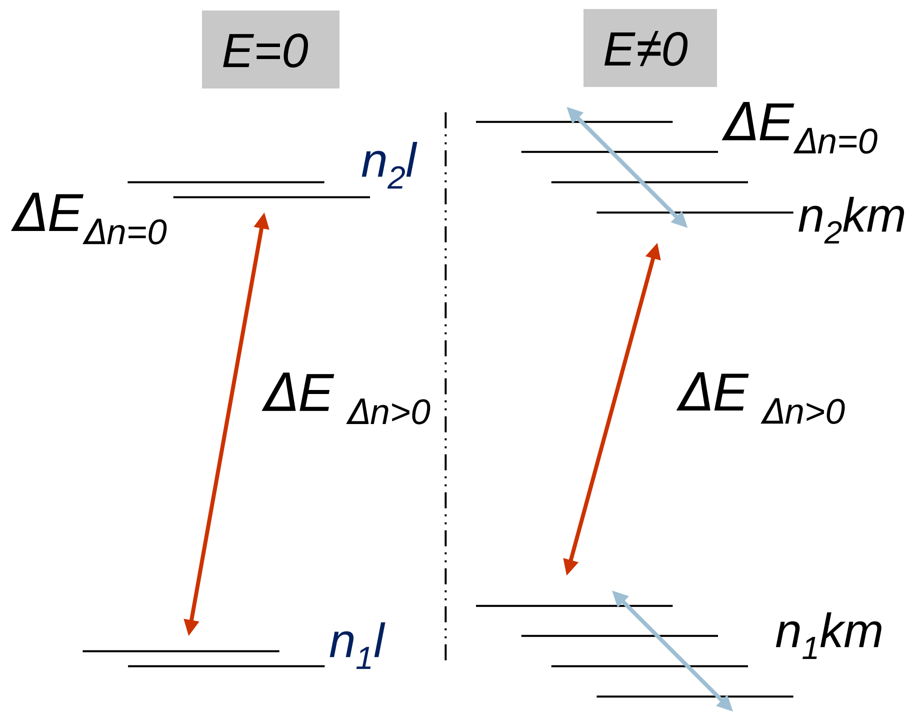
Motional Stark effect for H beam

- Hydrogen beam penetrates the plasma volume
- The induced electric field **E**=**v**×**B** mixes the spherical states and splits line multiplets

$\Delta E_{\Delta n=0,E=0} << \Delta E_{\Delta n=0,E\neq0} << \Delta E_{\Delta n>0}$ (*)





„Good“ quantum numbers

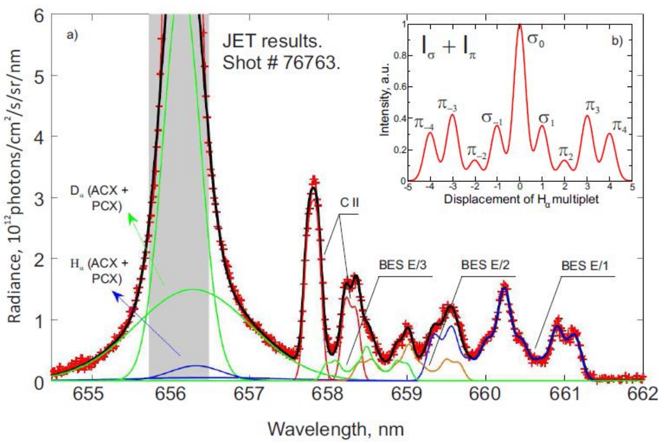
$n=n_1+n_2+|m|+1$, $n_1, n_2>0$ (parabolic states)

n – principal quantum number

$k=n_1-n_2$ – electric quantum number

m – z-projection of orbital momentum

Beam emission



Delabie E. et al. PPCF **52** 125008 (2010)

CR model for the H beam:

Major processes affecting level populations:

- Interaction with plasma electrons
- Interaction with plasma protons

•Can we do it for parabolic states?

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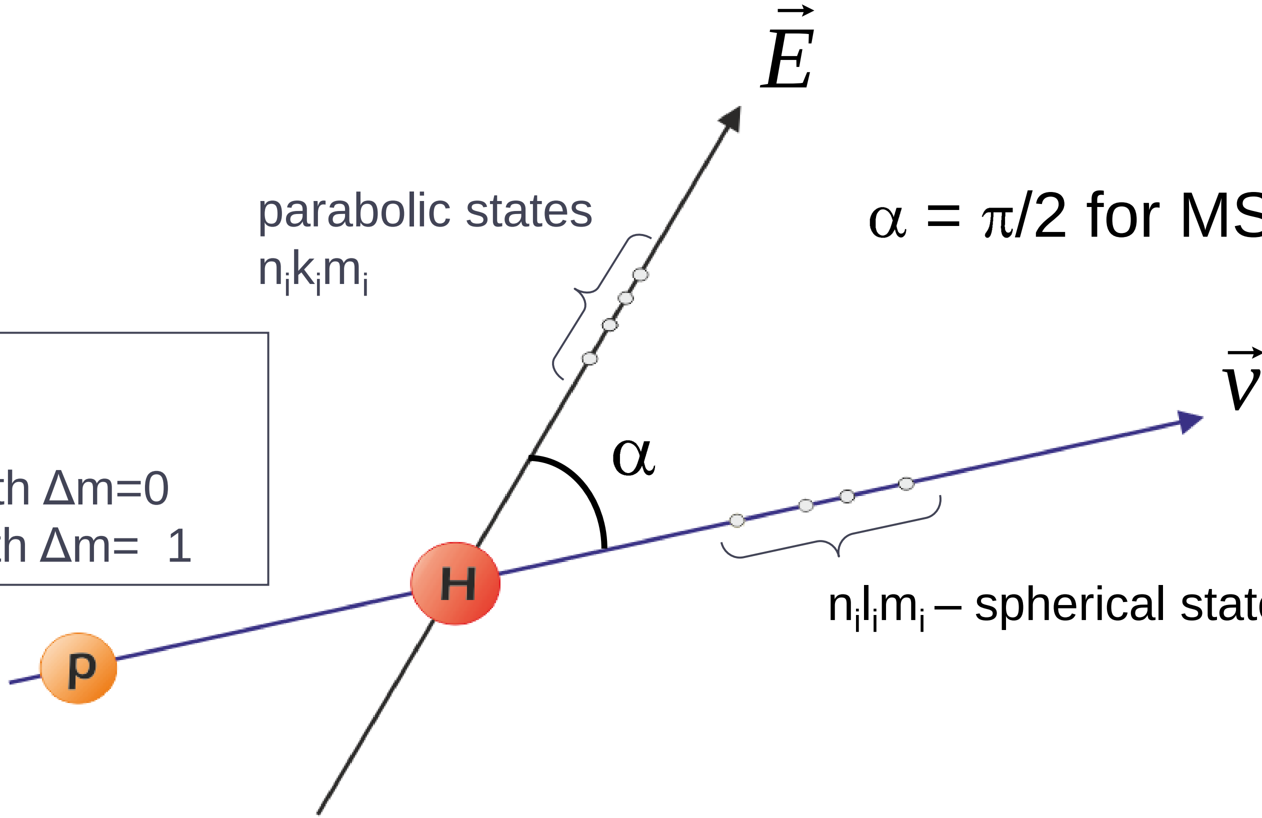
Cross sections for parabolic states, part I



Radiative channel
$n_i k_i m_i \rightarrow n_j k_j m_j$
π – components with Δm=0
σ – components with Δm= 1

Classical excitation: $n_i l_i m_i \rightarrow n_j l_j m_j$

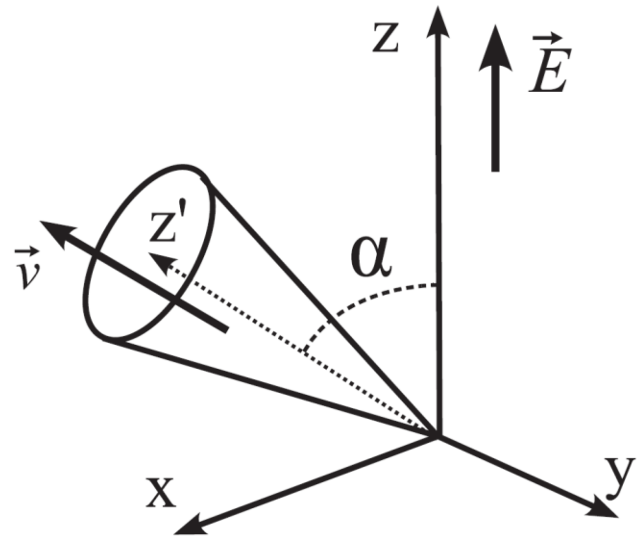
Only one axis: along projectile velocity

There is another axis: along the induced electric field **E**

Cross sections for parabolic states, part II

Scattering amplitude between parabolic states a ≡ (nkm)

$$F_{ba} = \langle \psi_b | \hat{\Gamma} | \psi_a \rangle$$



Transformation 1:
parabolic along z into spherical along z

$$\psi_{nkm} = \sum_{l=|m|}^{n-1} C^{lm}_{j_1\mu_1 j_2\mu_2} \varphi_{nlm}$$

Transformation 2:
spherical along z into spherical along z'

$$\varphi_{nlm} = \sum_{m'=-l}^{l} D^{(l)}_{m'm}(\alpha)\, \varphi_{nlm'}$$

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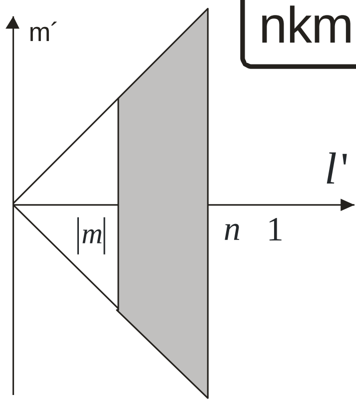
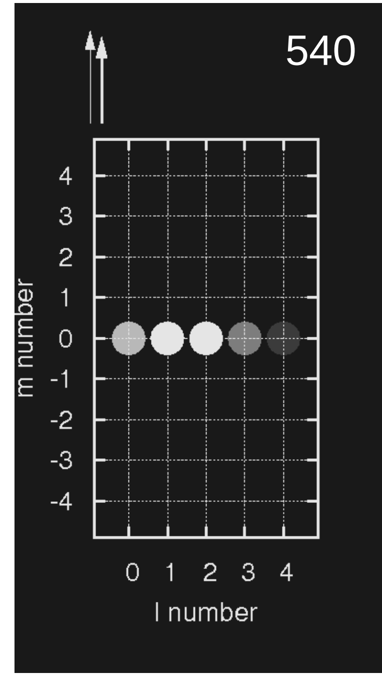
Transformation between the spherical and parabolic states

$$\psi_{nkm} = \sum_{i\in\Omega} c_i(\alpha)\,\varphi_{nlm'} \longrightarrow$$



nkm



Final cross section:

$$\sigma = \left|< n_i k_i m_i \,|\, \hat{\Gamma} \,|\, n_j k_j m_j >\right|^2 = \left|\sum_{\Delta m'=2-n_a-n_b} c_i c_j F_{a_i}^{b_j}(\vec{q})\right|^2 + \left|\sum_{\Delta m'=3-n_a-n_b} c_i c_j F_{a_i}^{b_j}(\vec{q})\right|^2 + \ldots$$

$$+\left|\sum_{\Delta m'=n_a+n_b-3} c_i c_j F_{a_i}^{b_j}(\vec{q})\right|^2 + \left|\sum_{\Delta m'=n_a+n_b-2} c_i c_j F_{a_i}^{b_j}(\vec{q})\right|^2$$

For excitation from the ground state the expressions are still simple:

$$\sigma_{2\pm10} = \frac{1}{2}\sigma_{2s0} + \frac{1}{2}\cos^2(\theta)\sigma_{2p0} + \frac{1}{2}\sin^2(\theta)\sigma_{2p1} \mp \cos(\theta)\boxed{Re(\rho_{2s0}^{2p0})}$$

$$\sigma_{20\pm1} = \frac{1}{2}\sin^2(\theta)\sigma_{2p0} + \sigma_{2p1}\left(1 - \frac{1}{2}\sin^2(\theta)\right)$$

Density matrix elements

$$\rho_{pq}^{rs} = \frac{k_f}{k_i}\int F_{pq}(\mathbf{q})F_{rs}{}^*(\mathbf{q})d\mathbf{q}$$

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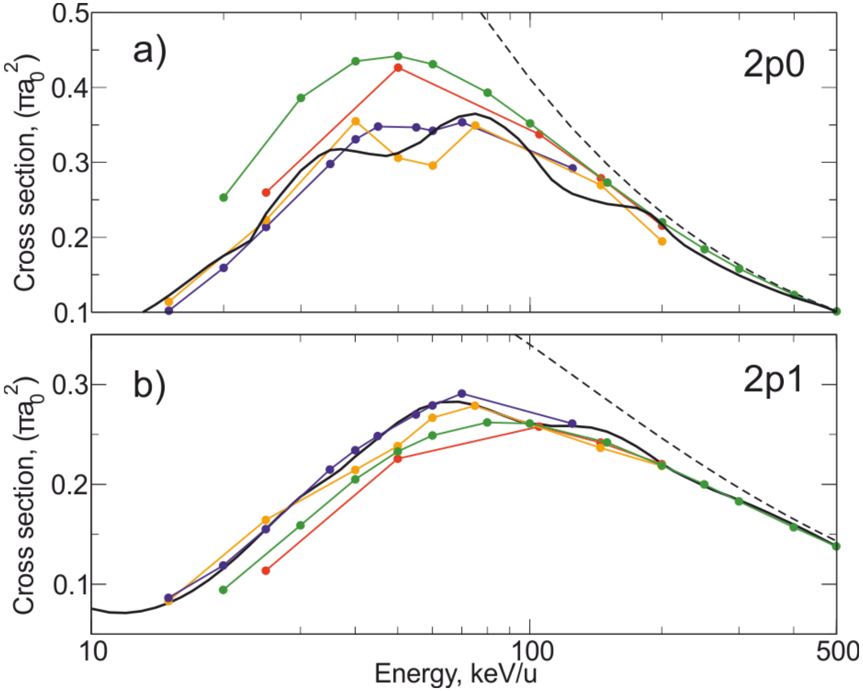
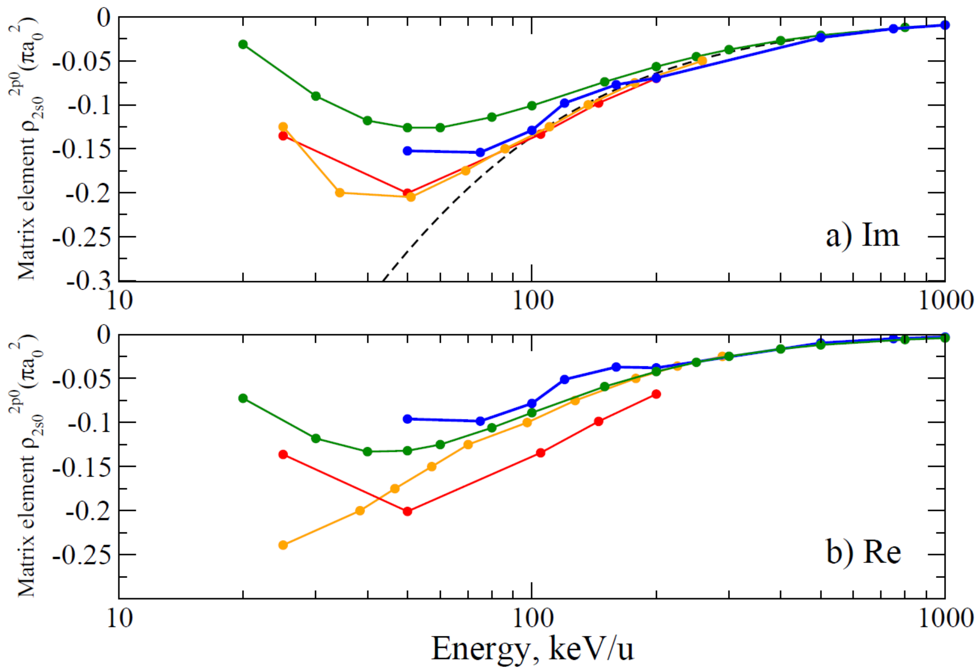
states (4)





black - AOCC (present results)

green - GA(present results)

dashed - Born approximation

blue - SAOCC Winter TG, Phys. Rev. A 2009 **80** 032701

orange - SAOCC Shakeshaft R Phys. Rev. A 1976 **18** 1930

red - EA Rodriguez VD and Miraglia JE J. Phys. B: At. Mol. Opt. Phys. 1992 **25** 2037

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green - GA (present results)

dashed - Born approximation

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red - EA Rodriguez VD and Miraglia JE J. Phys. B: At. Mol. Opt. Phys. 1992 **25** 2037

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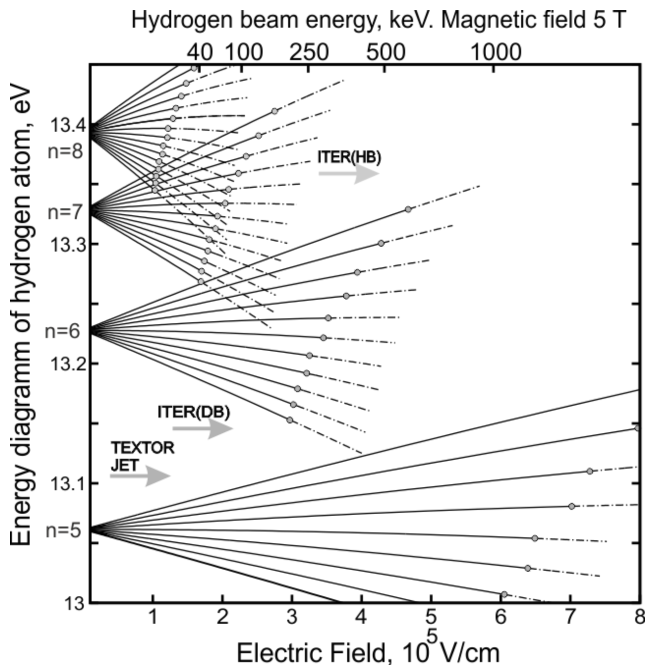
Collisional-Radiative Code NOMAD in parabolic states

- Time dependent collisional radiative model for non-Maxwellian plasma applied for studies at EBIT and spectroscopy of fusion plasmas

  Ralchenko Yu V and Maron Y 2001 *J. Quant. Spectr. Rad. Transf.* **71** 609
- Full non-statistical simulations in parabolic *m* resolved states
- The model is extended up to n=10 states including 220 magnetic levels.
- The cross sections are calculated up to Δm_{max}= 5 for first excited states with n<6 and Δm_{max}= 3 for other states. In total ~$5\cdot10^5$ cross sections where AOCC and GA data are used.
- Level-crossing and ionization induced by electric field are included for different values of electric field.
- Electron collisions are based on the Van-Regermorter formula with reccomended Gaunt factors (high precision is not required)
- Collisional ionization from m levels of the same principal quantum number is assumed to be the same



Time dependent solution
Quasi-steady state calculations

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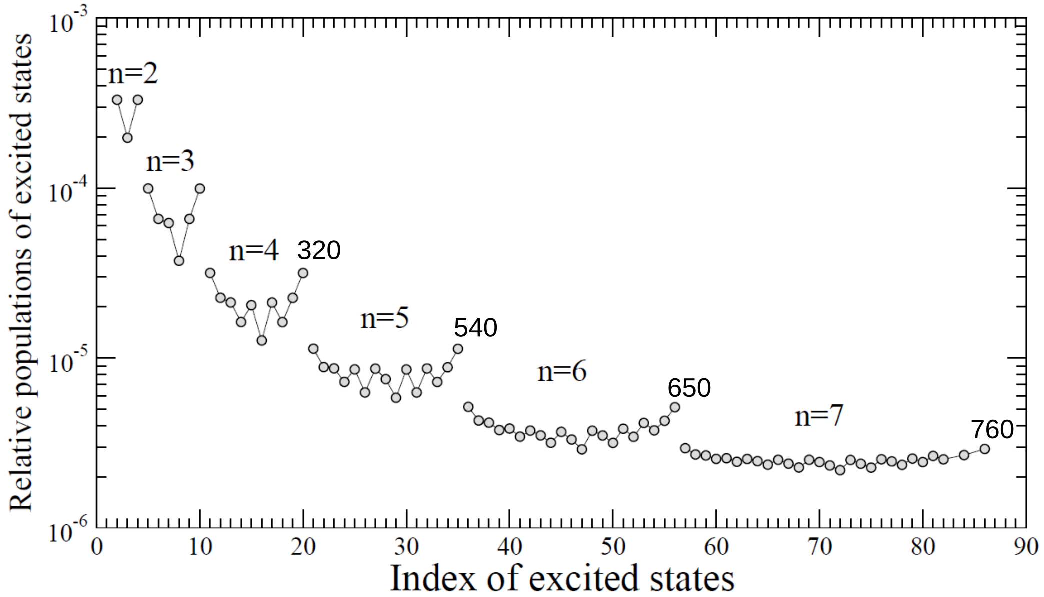
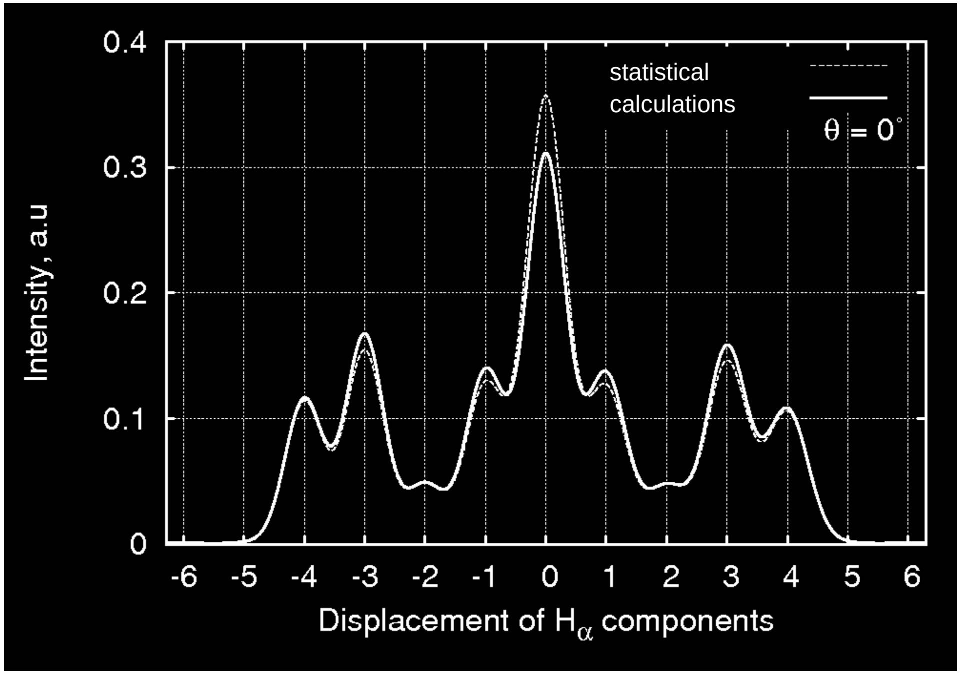
Populations of excited states





- Population of first excited states is much closer to the coronal than to the Boltzmann limit
- Only for n=6 and n=7 the populations approach statistical case
- The states with m=0 have the highest populations. The major channel of the population remains the excitation from the ground state and the cross sections with Δm=0,±1 are the strongest ones:

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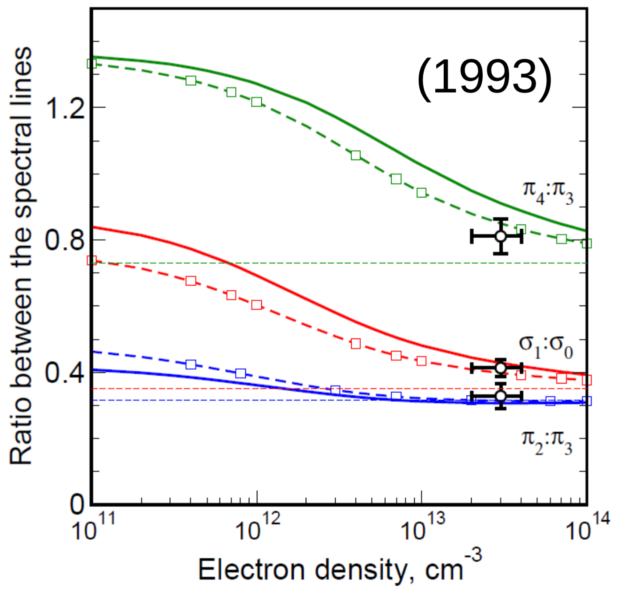
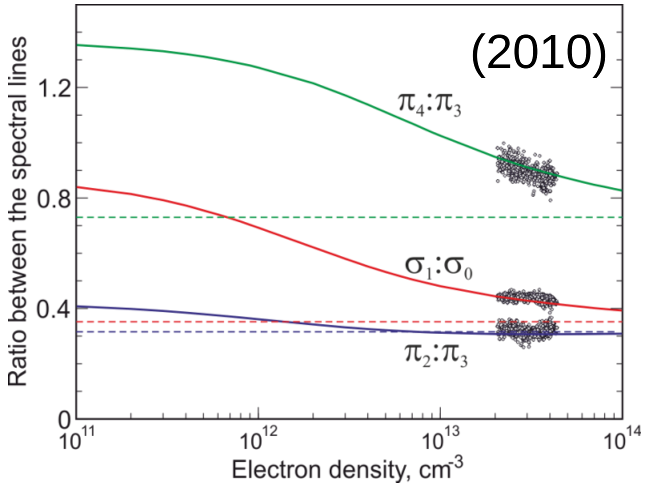
Theory vs Experiment



- Experiment 1993
- **W. Mandl et al. PPCF 35,1373 (1993)**
- Solid: $Z_{eff} = 1$
- Horizontal dashed: statistical limit
- Dashed w/ symbols: $Z_{eff} = 2$ (C^{6+})



- Experiment 2010
- **E. Delabie et al. PPCF 53, 125008 (2010)**
- Solid: $Z_{eff} = 1$
- Horizontal dashed: statistical limit
- Dashed w/ symbols: $Z_{eff} = 2$ (C^{6+})