Atomic processes in the afterglow of noble gas plasmas

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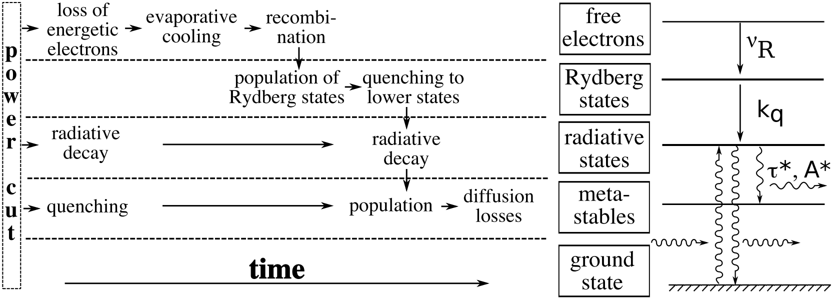
Overview

RUB

Afterglow of low-temperature plasmas

- Gas: Ar
- Electron densities: $n_e \sim 10^{17}$ m^{-3} → low ionization degrees
- Electron temperatures: $T_e \sim 0.1 - 5$ eV → singly ionized ions
- Species: ArI, ArII
- Magnetic fields: No

Atomic processes in the afterglow



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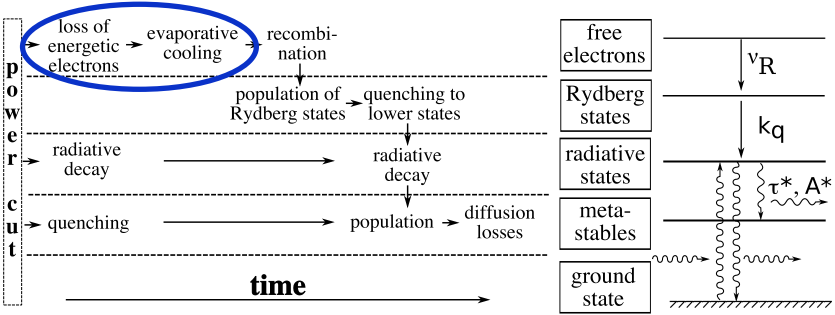

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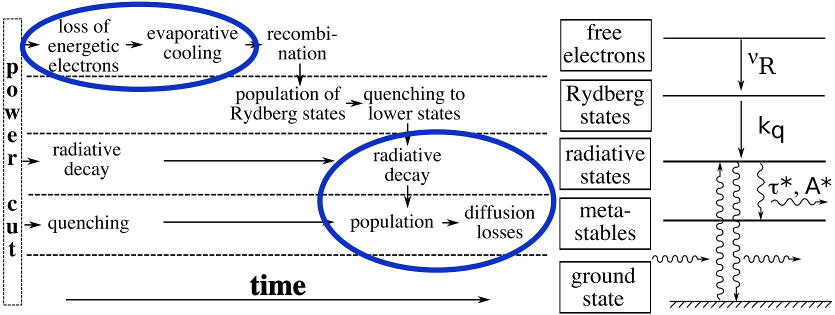

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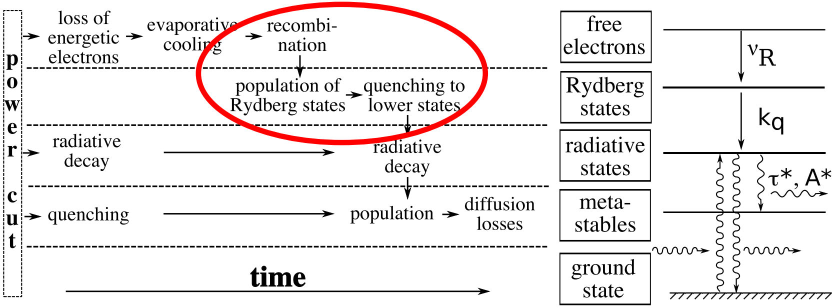
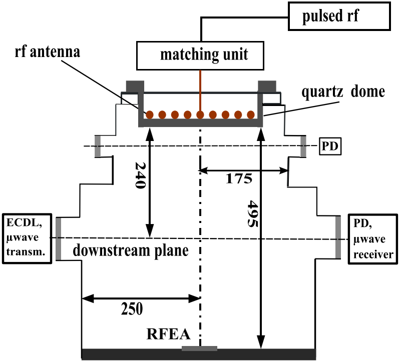


Experimental setup



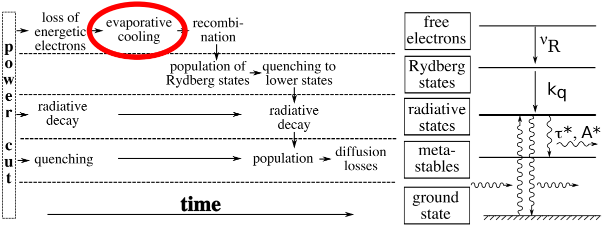
Experimental conditions

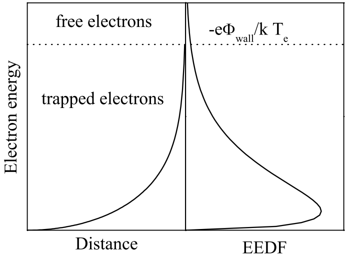
Chamber height:	0.5 m
Chamber diameter:	0.35 m (up)
	0.5 m (down)
Gas:	Argon
Pressure:	1 Pa
Frequency:	13.56 MHz
Power:	50 – 1000 W
Pulse frequency:	5–20 Hz
Duty cycle:	85%

Diagnostics

- Langmuir Probe (steady state)
- Microwave Interferometer (MWI)
- Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- Retarding Field Energy Analyser (RFEA)
- Optical emission spectroscopy (OES)

Evaporative (diffusion) cooling





- Loss of only high-energy electrons
- Self-adjusting energy barrier

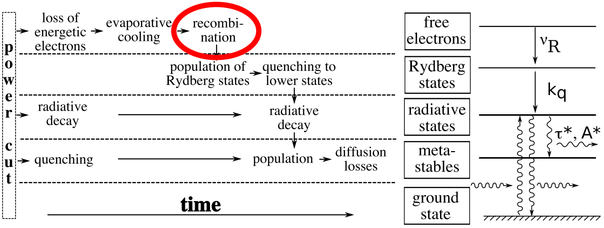
  $\rightarrow$ Effective energy loss mechanism
- Analytical theory[1]: $n_\mathrm{e}(t) \propto [T_\mathrm{e}(t)]^\gamma$

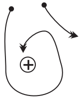
  $T_\mathrm{e} > T_\mathrm{g}$: $\gamma \sim 0.1$

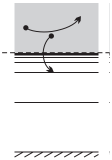
  $T_\mathrm{e} < T_\mathrm{g}$: $\gamma = 5/2$

[1] Y. Celik, Ts. V. Tsankov, M. Aramaki, S. Yoshimura, D. Luggenhölscher, U. Czarnetzki, *Phys Rev* E 85 (2012) 046407

Three-body recombination







Analytical theory of Thomson[2]

- Ionization rate constant β_p:

$$\beta_p = \frac{8\sqrt{2\pi}a_0^2}{\sqrt{m_\mathrm{e}}}\frac{R_\infty^2}{I_p\sqrt{\kappa T_\mathrm{e}}}\mathrm{e}^{-x_p}\left[1 - x_p \mathrm{e}^{x_p}\mathrm{E}_1\left(x_p\right)\right]$$

- Recombination rate constant α_p:

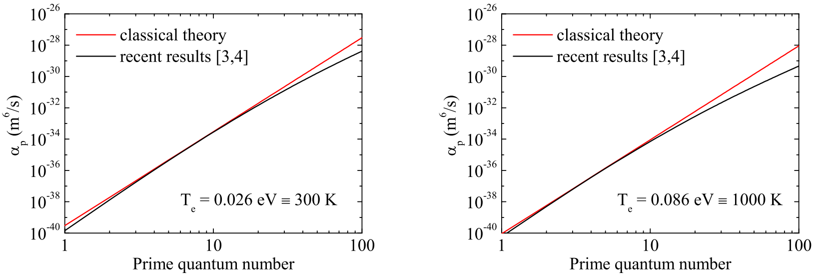
$$\alpha_p = \frac{2}{\pi}\frac{h^3 a_0^2}{m_\mathrm{e}^2}\frac{g_p}{g_\mathrm{i}}\left(\frac{R_\infty}{I_p}\right)^2\frac{I_p}{\left(\kappa T_\mathrm{e}\right)^2}\left[1 - x_p \mathrm{e}^{x_p}\mathrm{E}_1\left(x_p\right)\right]$$

[2] J. J. Thomson, *Philos. Mag.* **23** (1912) 449; *ibid* **47** (1924) 337;

Three-body recombination

- With $x_p = I_p/\kappa T_\mathrm{e} \gg 1$ and $I_p = R_\infty/p^2$: $\alpha_p = \frac{4}{\pi}\frac{h^3 a_0^2}{m_\mathrm{e}^2}\frac{p^6}{\kappa T_\mathrm{e}}$
- For comparison [3,4]

$$\alpha_p = \frac{4}{\pi}\frac{h^3 a_0^2}{m_\mathrm{e}^2}\frac{p^6}{\kappa T_\mathrm{e}}\frac{11}{\sqrt{8\pi}}\frac{x_p^2}{x_p^{7/3} + 4.38 x_p^{1.72} + 1.32 x_p}$$



[3] L. Vriens, A. H. M. Smeets, *Phys Rev* A **22** (1980) 940

[4] T. Pohl, D. Vrinceanu, H. R. Sadeghpour, *Phys Rev Lett* **100** (2008) 223201

Three-body recombination

Recombination rate

$$\nu_{\mathrm{r}} = n_{\mathrm{e}}^2 \sum_{p=1}^{p_{\mathrm{m}}} \alpha_p \approx \frac{C'}{T_{\mathrm{e}}} n_{\mathrm{e}}^2 \int_1^{p_{\mathrm{m}}} p^6 \mathrm{d}p \approx \frac{C'}{7T_{\mathrm{e}}} n_{\mathrm{e}}^2 p_{\mathrm{m}}^7 .$$

Thomson result – cut-off by re-ionization:

$$p_{\mathrm{m}} = \sqrt{\frac{E_{\mathrm{i}}}{\kappa T_{\mathrm{e}}}} \;\rightarrow\; \nu_{\mathrm{r}} = A \frac{n_{\mathrm{e}}^2}{(\kappa T_{\mathrm{e}})^{9/2}}$$

Micro-field limited cut-off:

$$p_{\mathrm{m}} = p_{\mathrm{IT}} = (n_{\mathrm{IT}}/n_{\mathrm{e}})^{2/15}$$

$$n_{\mathrm{IT}} = 10^{29.19}\ \mathrm{m}^{-3}$$

Modified formula – micro-field limited AND re-ionization:

$$\frac{E_{\mathrm{i}}}{p_{\mathrm{m}}^2} = \frac{E_{\mathrm{i}}}{p_{\mathrm{IT}}^2} + \eta \kappa T_{\mathrm{e}}, \qquad \psi_{\mathrm{IT}} = \frac{E_{\mathrm{i}}}{\eta \kappa T_{\mathrm{e}}} \left(\frac{n_{\mathrm{e}}}{n_{\mathrm{IT}}} \right)^{4/15}$$

$$\nu_{\mathrm{r}} = \frac{A}{\eta^{7/2}} \frac{n_{\mathrm{e}}^2}{(\kappa T_{\mathrm{e}})^{9/2}} \frac{1}{(1+\psi_{\mathrm{IT}})^{7/2}}$$

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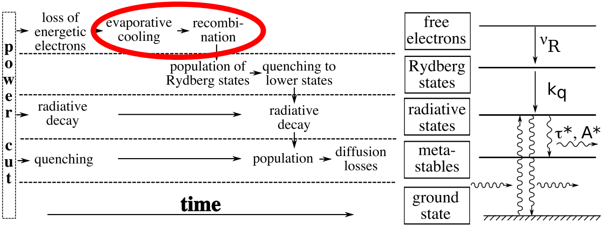
Evolution of the electron density

Evaporative cooling and recombination



Evaporative cooling: $T_e - n_e$ relation → recombination rate

$$\nu_r = \frac{A}{\eta^{7/2}} \frac{n_e^2}{\left(\delta n_e^{2/5}\right)^{9/2}} \frac{1}{\left(1 + \hat{\psi}_{IT}\right)^{7/2}} = \rho \frac{n_e^{1/5}}{\left(1 + \hat{\psi}_{IT}\right)^{7/2}}$$

$$\hat{\psi}_{IT} = \frac{E_i}{\eta \delta n_{IT}^{4/15}} \frac{1}{n_e^{2/15}}, \qquad \nu_r = f(n_e)$$

Evolution of the electron density

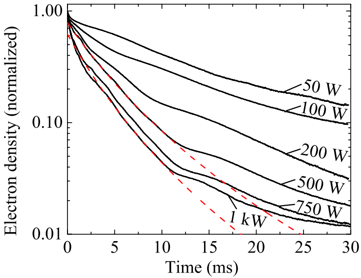
Two limiting cases:

- $\hat{\psi}_{\mathrm{IT}} \ll 1$: $\nu_{\mathrm{r}} \propto n_{\mathrm{e}}^{1/5}$
- $\hat{\psi}_{\mathrm{IT}} \gg 1$: $\nu_{\mathrm{r}} \propto n_{\mathrm{e}}^{2/3}$

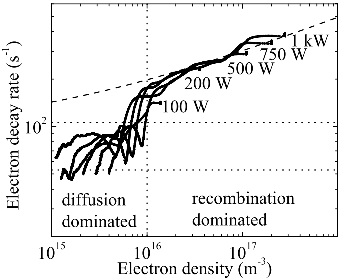
At our experimental conditions[5] $\hat{\psi}_{\mathrm{IT}} \simeq 0.1 \ll 1$

$$\Rightarrow \nu_{\mathrm{r}} = \rho n_{\mathrm{e}}^{1/5}$$

Normalized electron density

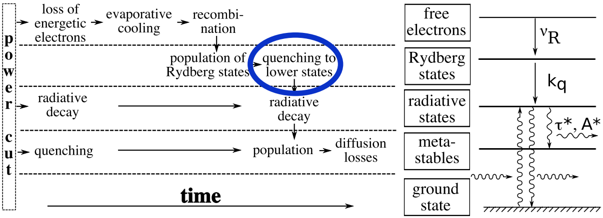


Density decay rate

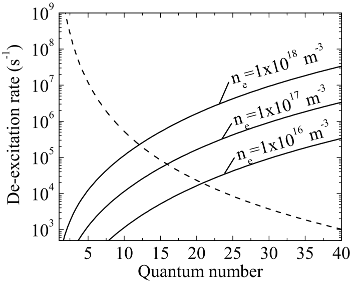


[5] Y. Celik, Ts. V. Tsankov, M. Aramaki, S. Yoshimura, D. Luggenhölscher, U. Czarnetzki, *Phys Rev* E 85 (2012) 056401

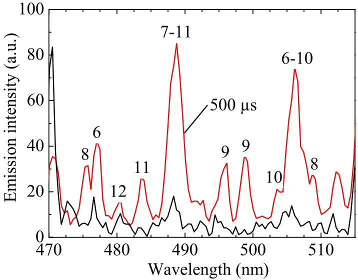
Light intensity



De-excitation “bottleneck”[6]



Light spectrum



[6] S. Byron, R. C. Stabler, P. I. Bortz, *Phys Rev Lett* 8 (1962) 376

Light intensity

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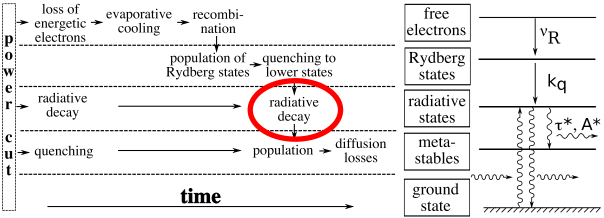

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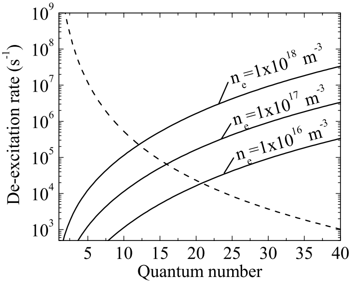

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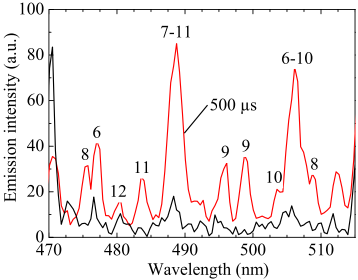
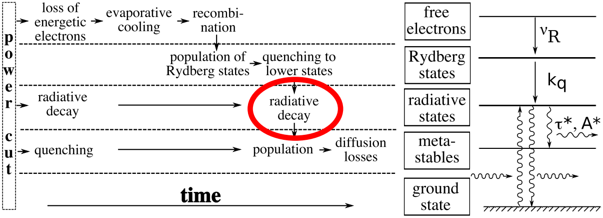
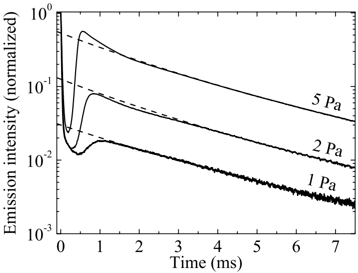


[6] S. Byron, R. C. Stabler, P. I. Bortz, *Phys Rev Lett* 8 (1962) 376

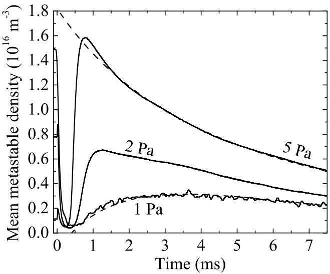
Light intensity and metastables



Emission evolution



Metastables evolution



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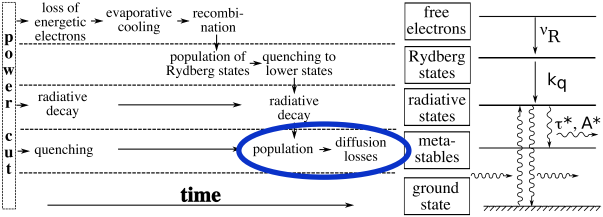

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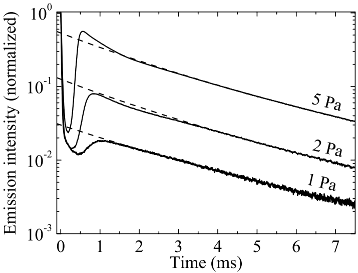

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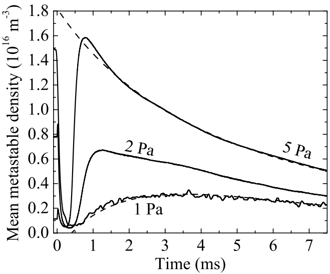
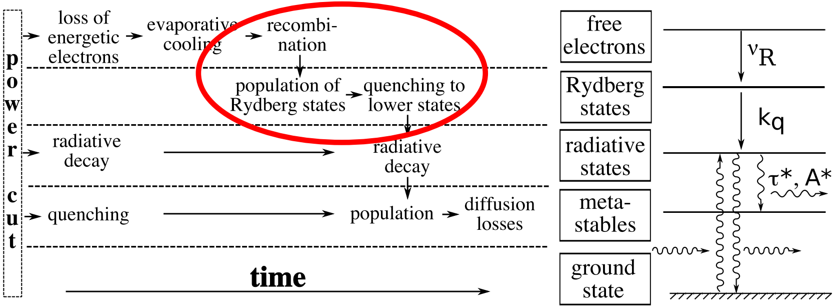


Open problems



- Angular momentum distribution of the recombined states
- Interaction of the $j = 3/2$ and $j = 1/2$ subsystems
- Rates for collisional and radiative transitions
- Heavy-particle collisions (?)

Summary and Outlook

- Unified description of low-pressure afterglows
- Importance of the atomic processes
- Population from "above"
- Quantitative description requires collision rates of "high" states
- Collisional-radiative model for recombining plasmas

Thank you!

RESEARCH DEPARTMENT
Plasmas with Complex Interactions

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