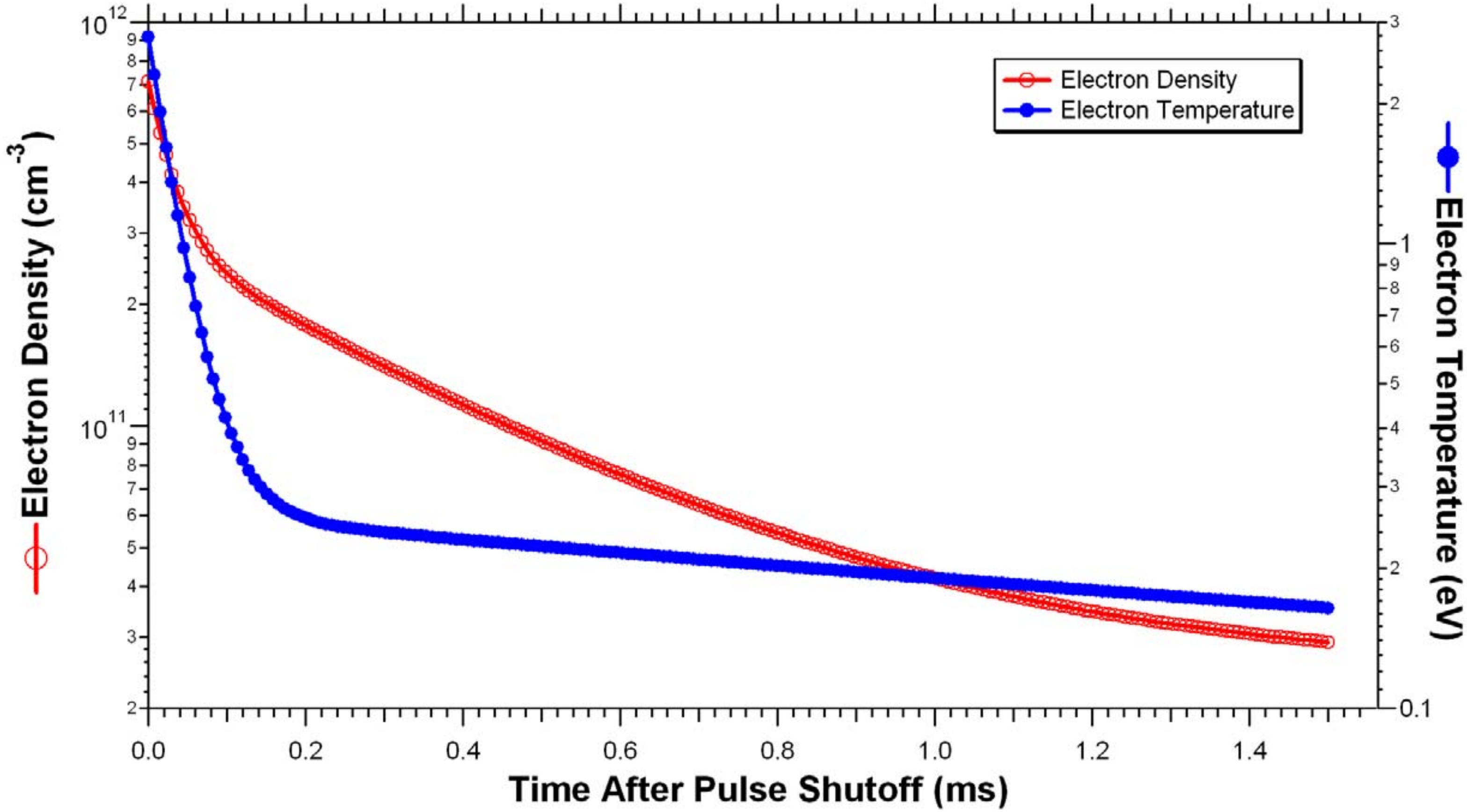
Non-Local Effects in a Bounded Afterglow Plasma with Fast Electrons

V. I. Demidov
UES, inc. and WVU
C. A. DeJoseph, Jr.
Air Force Research Lab
A. A. Kudryavtsev
St. Petersburg University

Introduction

- **The plasma which exists in the discharge volume after termination or significant reduction of the sustaining electric field, is commonly referred to as the afterglow plasma**
- **This type of plasma is a convenient medium for measurements of rate constants and cross-sections of some plasma reactions**
- **The afterglow plasma exists in all pulsed plasma sources, which are now widely used in technical applications, and therefore, its investigation is important for optimization and development of various plasma systems**

Electron Temperature and Density in the Afterglow (Post-Discharge)



UES

Plasma Models

- **Fluid (continuum) models**
- **Global (time-average) models**
- **Volume-averaged local kinetic models**
- **Self-consistent non-local kinetic models**

At low pressure, when the plasma scale L is less than electron energy relaxation length λ_ε, the EDF is non-local throughout the whole plasma volume. For noble gases $pL < 10$ cm Torr.

We will discuss here afterglow plasma *with fast electrons*.

Volume Production of Fast Electrons (examples)

Penning ionization of metastable atoms and molecules:

$$A^* + A^* \rightarrow A^+ + A + \vec{e} \quad (\varepsilon_f = 4.4...14.4eV) \qquad (1)$$

superelastic collisions of bulk electrons with metastable atoms and molecules:

$$A^* + e \rightarrow A + \vec{e} \quad (\varepsilon_f = 8.3...19.8eV) \qquad (2)$$

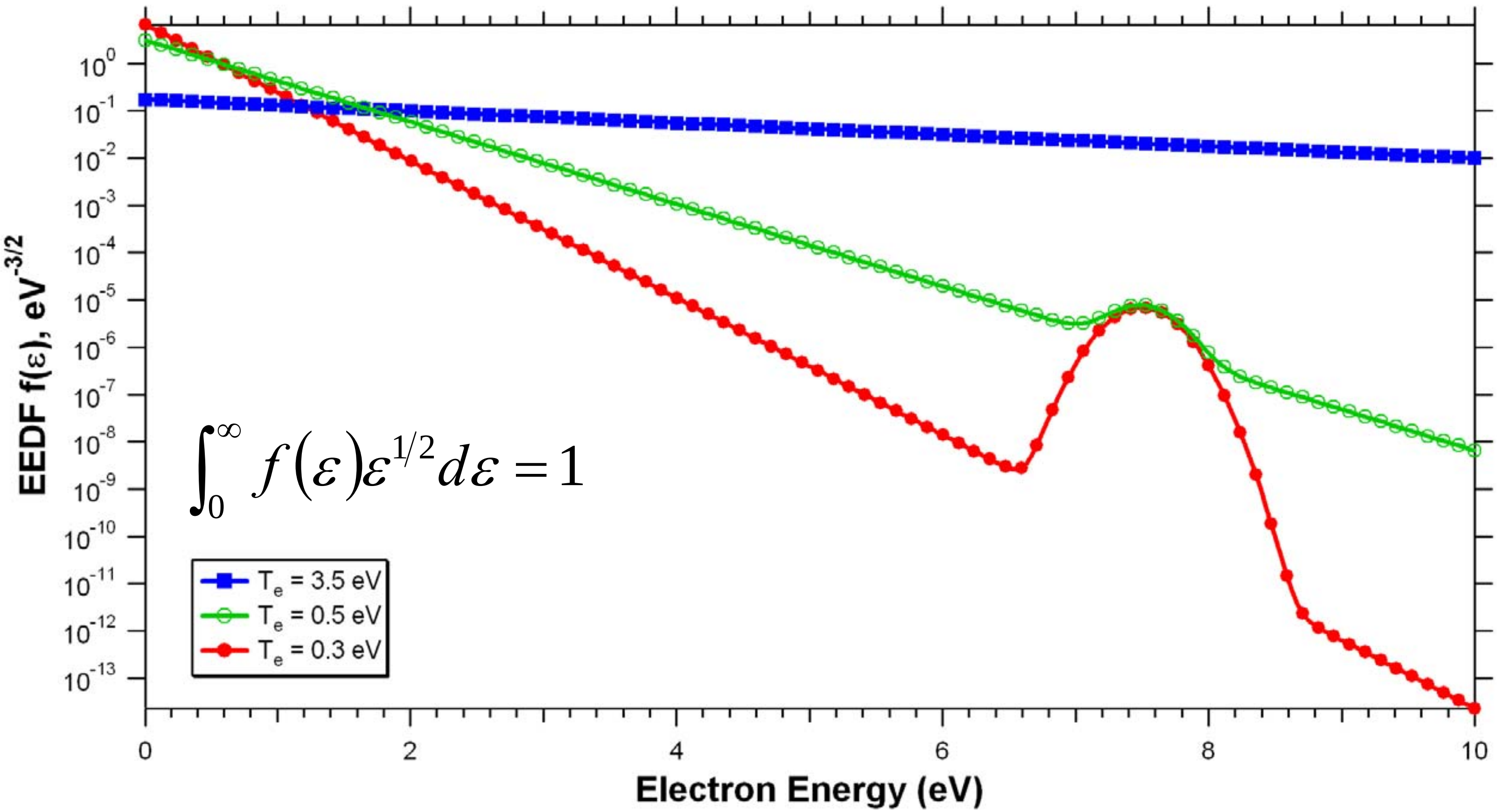
associative detachment of electrons from negative ions:

$$A^- + A \rightarrow A_2 + \vec{e} \quad (for\ O_2,\ \varepsilon_f = 3.6eV) \qquad (3)$$

monochromatic photons from external sources:

$$A\,(or\ A^*) + h\nu \rightarrow A^+ + \vec{e} \qquad (4)$$

Fast Electron Group has Little Effect on the Plasma unless Te<0.5 eV



Model EDF composed of a Boltzmann component at T_e plus a Gaussian of width 0.5 eV at an energy of 7.5 eV. Gaussian component represents 10^{-5} of the Boltzmann component. We assume: $T_e N_{eb} >> \varepsilon_f N_{ef}$

UES

Flux of fast electrons

Non-local fast electrons with energies $\varepsilon_{ef} >> e\Phi_w$ are produced in the volume by source term ΣI_j from reactions (1-4) and are lost to the walls. Their flux to the plasma boundary with area *S* can be found from their creation rate as

$$j_{ef} = \int_V \sum I_j dV \Big/ S$$

If the source terms I_j can be determined, the above equation lets one find the flux j_{ef}. For example, for argon, reaction (1), $I_p = \beta n_m^2$, where $\beta \sim 10^{-9} cm^3/s$ is the rate of (1) and n_m is density of the metastable atoms.

How Does Ambipolar Electric Field Depend on the Presence of Fast Electrons?

$$j_i + j_{eb} + j_{ef} = 0 \qquad (1)$$

Ion current in a plasma

$$j_i = N_i u_i = -D_i \nabla N_i + b_i E_a N_i \qquad (2)$$

Electron current

$$j_e = N_{eb} u_{eb} = (-D_{eb} \nabla N_{eb} + b_{eb} E_a N_{eb}) + (-D_{ef} \nabla N_{ef} + b_{ef} E_a N_{ef}) \qquad (3)$$

Then ambipolar electric field is $$E_a = -\frac{D_{eb} \nabla N_{eb} + D_{ef} \nabla N_{ef}}{b_{eb} N_{eb} + b_{ef} N_{ef}} \qquad (4)$$

Einstein's correlation $D_j/b_j=T_j$

Then $$D_{ef} \nabla N_{ef} / D_{eb} \nabla N_{eb} = \varepsilon_{ef} N_{ef} / T_e N_{eb} << 1 \qquad (5)$$

And, finally $$E_a = -\frac{T_e \nabla N_{eb}}{e N_{eb}} \qquad (6)$$

Fast electrons have no affect on ambipolar electric field

How Does Wall Potential Depend on the Presence of Fast Electrons?

$$j_i + j_{eb} + j_{ef} = 0 \quad (1)$$

The ion current to the wall

$$j_i = -D_a \nabla N_i / N_i \quad (2)$$

The electron current to the wall

$$j_{eb} = j_{eT} \exp(-e\Phi_w / T_e) \quad (3)$$

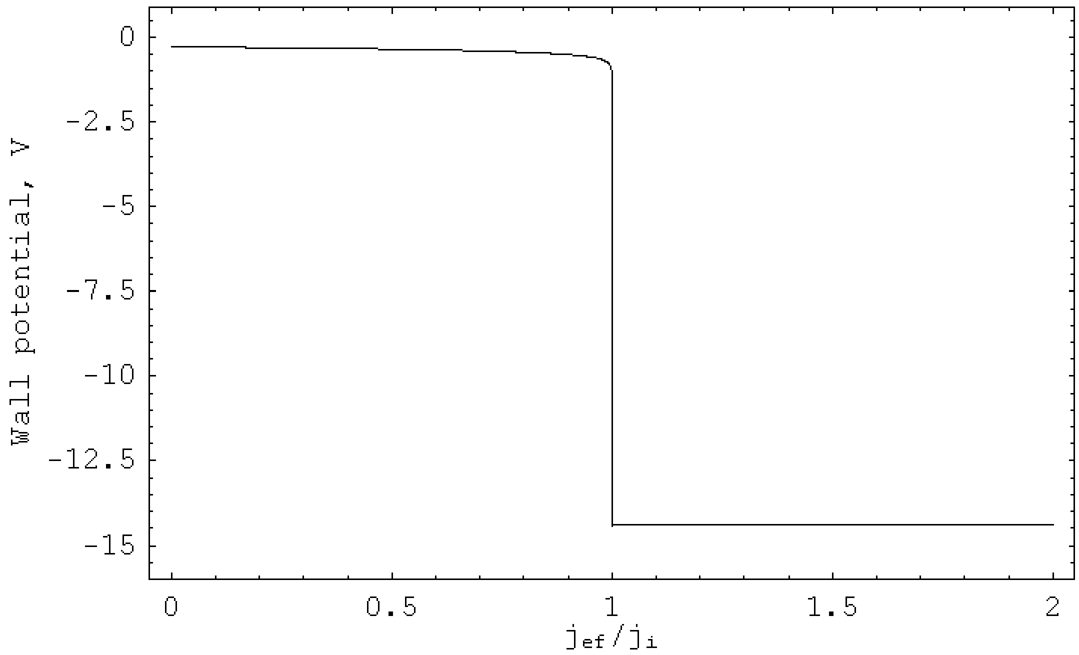
Then, wall potential is

$$e\Phi_w = \Phi_{wa} - T_e \ln\left(\frac{j_i}{j_i - j_{ef}}\right) \quad (4)$$

$$\Phi_{wa} = -\frac{T_e}{2} \ln\left(\frac{L}{\lambda_i} \frac{T_i}{T_e + T_i}\right) \quad (5)$$

Fast electrons can dramatically change wall potential

Wall Sheath in a Non-local Plasma with Fast Electrons



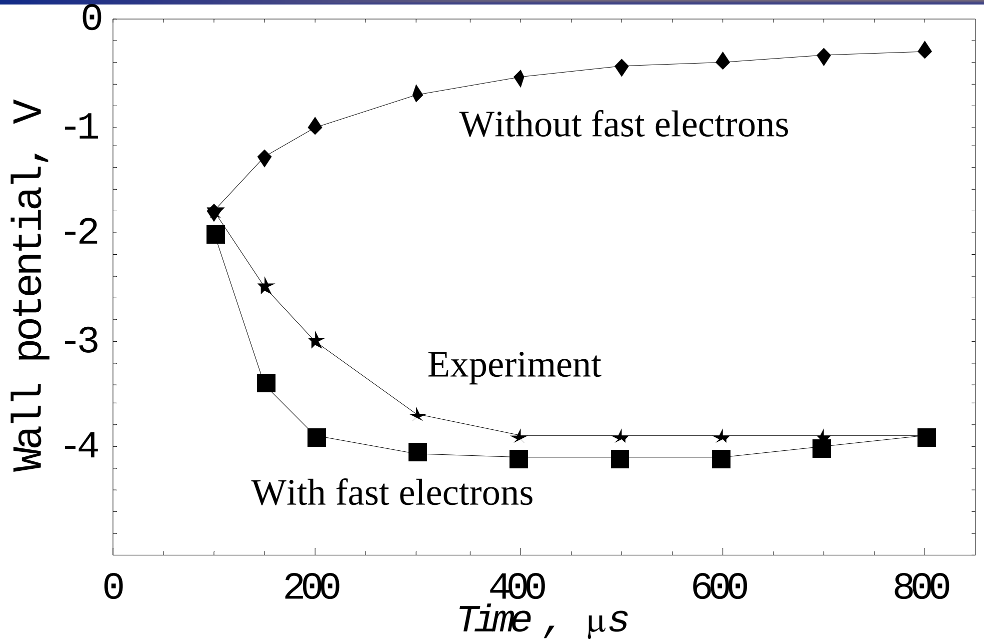
Consider the case for helium in reaction (1):

$$He^* + He^* \rightarrow He^+ + He + \vec{e}$$

where ε_{ef}=*14.4 eV*.

The presence of *fast electrons* causes the drop in the near-wall sheath to increase. This increase may be large even if the density $N_{ef} << N_i$ (say, 10^{-5} times).

Near-Wall Potential Drop in a Xe Afterglow Plasma



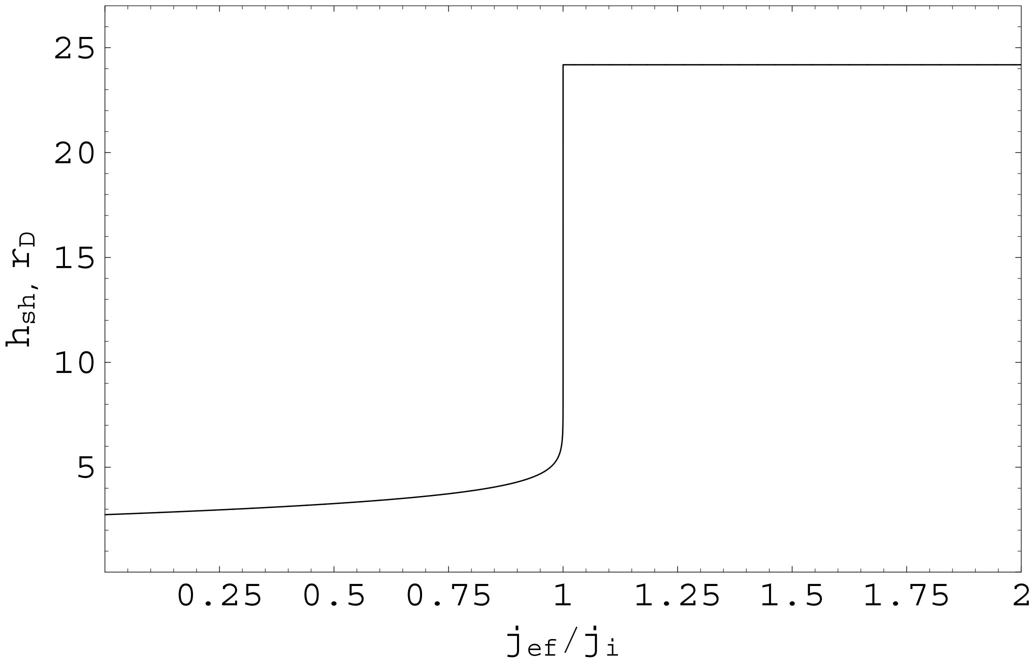
Both of the above cases (low and high Φ_w) can be realized in a decaying plasma. During this transition, the wall potential increases from ~0.1v to ~4v.

★ - Measurements

♦ - Calculations using: $\Phi_{wa} = \frac{T_e}{2e} \ln\left(\frac{M}{2\pi m}\right)$

■ - Calculations using: $\Phi_w = \Phi_{wa} + \frac{T_e}{e} \ln\left(\frac{j_i}{j_i - j_{ef}}\right)$

Sheath Thickness in a Non-local Plasma with Fast Electrons



The jump in sheath potential causes a jump in sheath thickness. Consider the case for argon in (1): ε_{ef} =7.3 eV. The sheath goes from a few r_D to 10's of r_D.

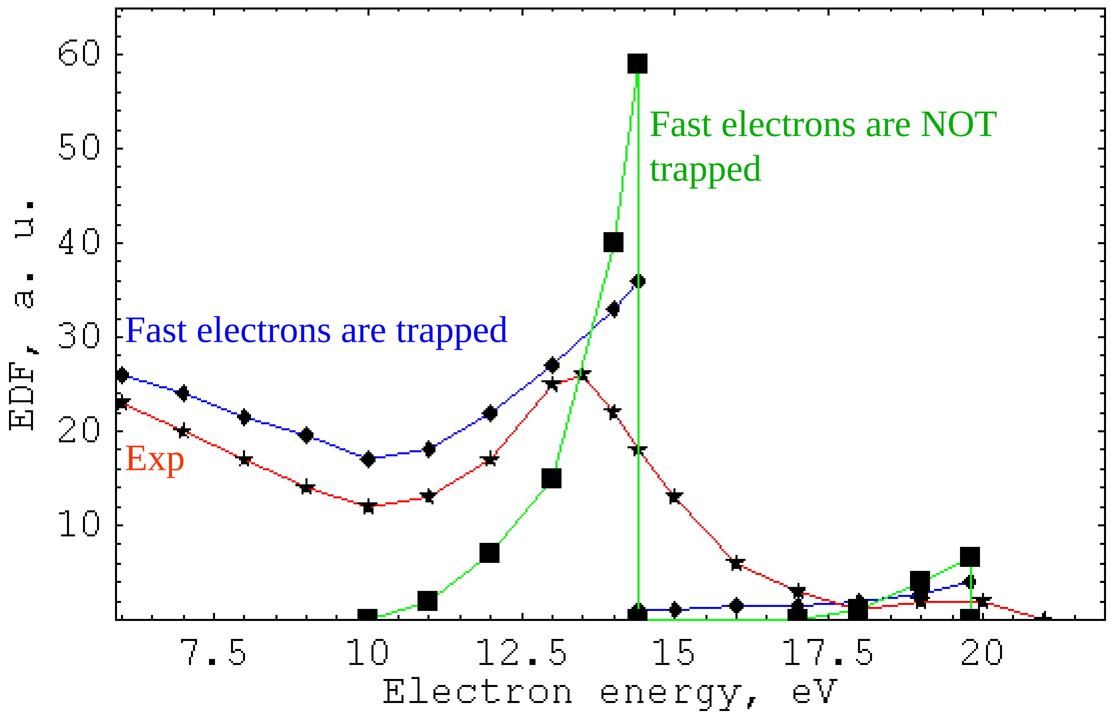
The above shows the calculated near-wall sheath thickness in an argon afterglow plasma with T_e =0.1 eV, which is typical for the afterglow. Here[1],

$$h_{sh} = \left[\left(\sqrt{2}/3\right)X^{3/2} + 2\sqrt{2}X^{1/2}\right]r_D \qquad X = \sqrt{1+2\left|\Phi_w\right|/T_e} - 2$$

UES

1. A. Kono, J. Phys. D: Appl. Phys. **37**, 1945 (2004).

Electron energy distribution in a helium afterglow

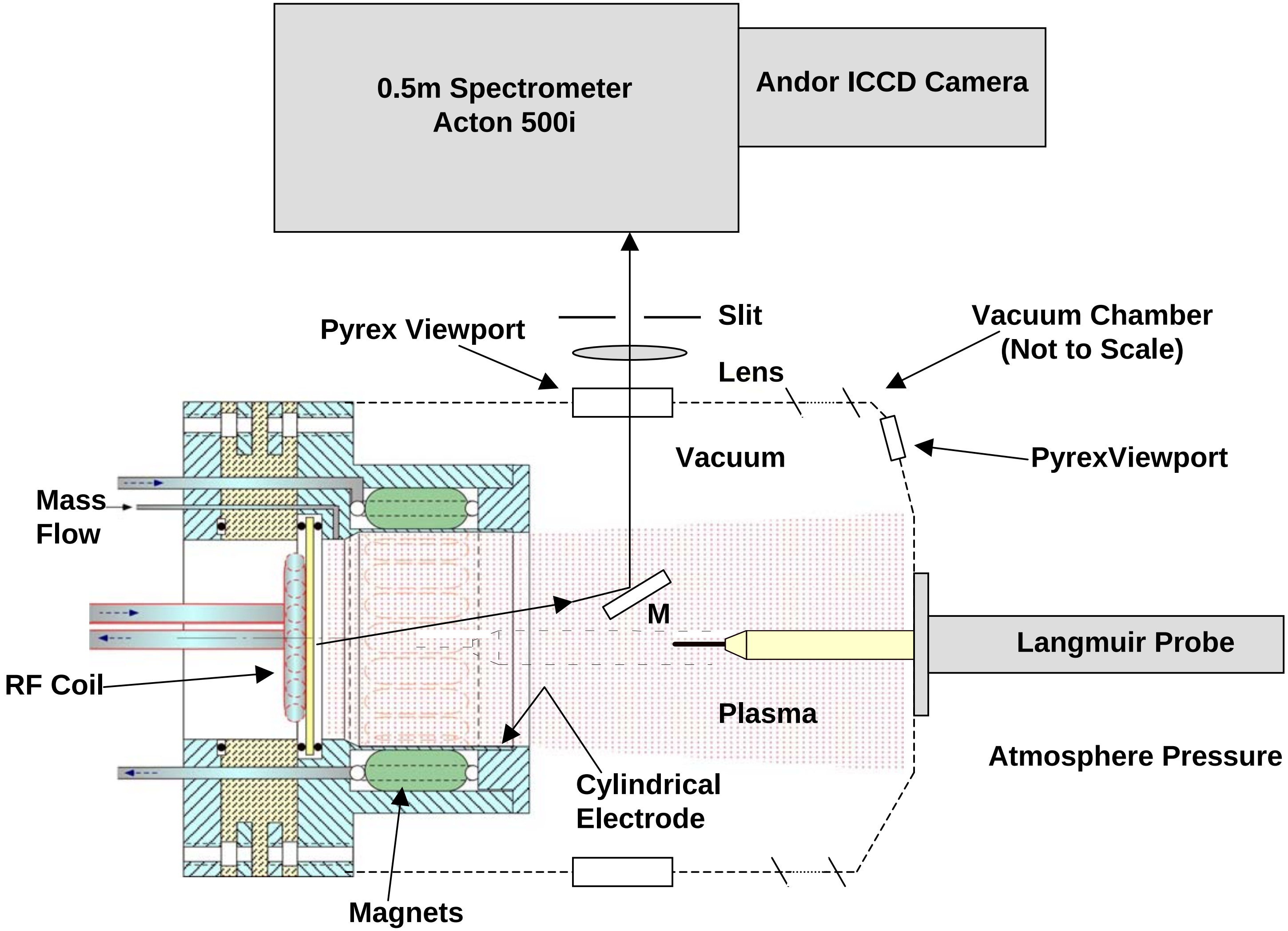


Changing of Plasma Properties

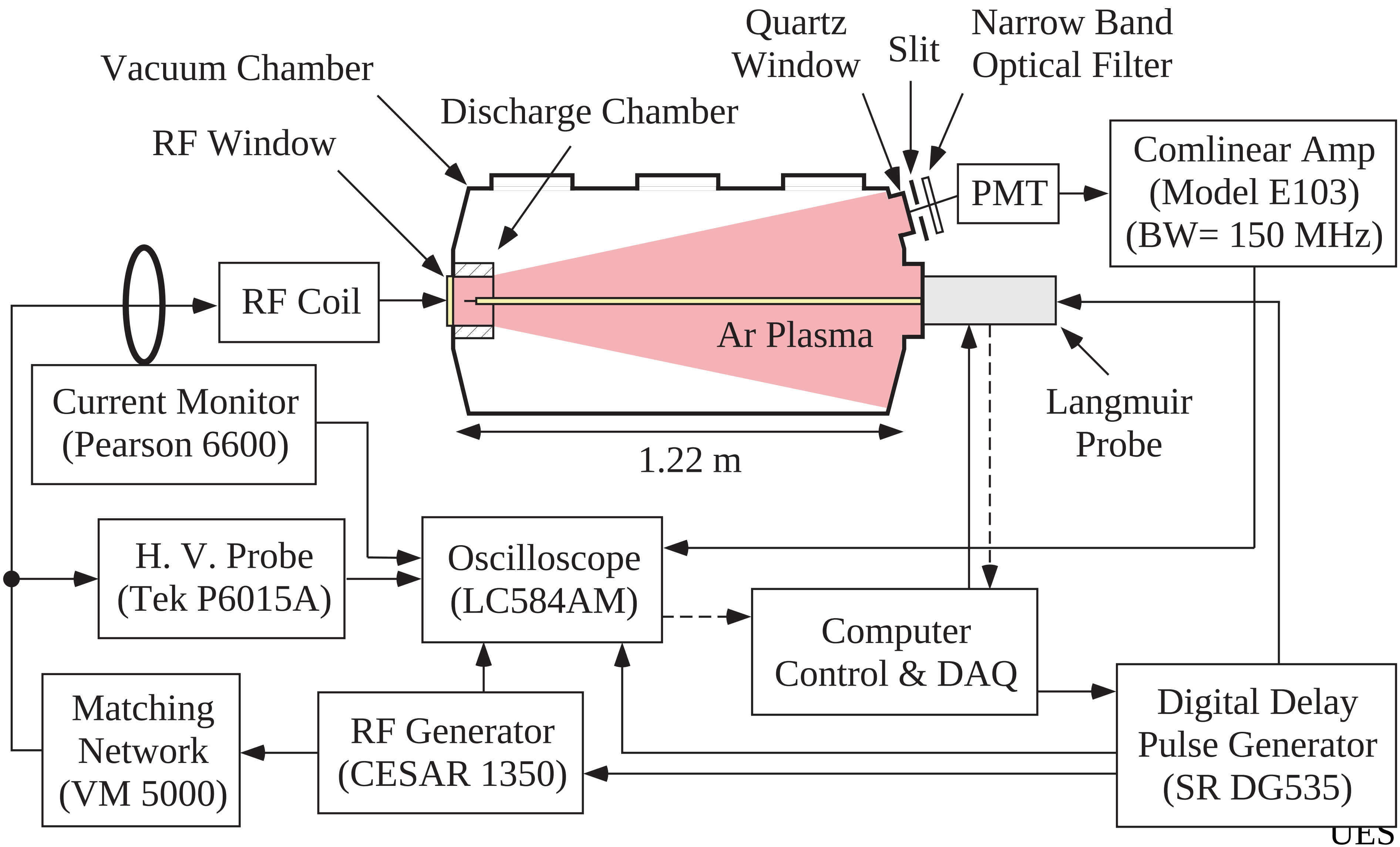
Changing the form of the EDF can change a number of plasma properties and should be taken into account in plasma modeling

- **Increasing of stepwise excitation**
- **Heating of slow electrons**
- **Absence of diffusion cooling of bulk electrons**

Schematic of the Experiment

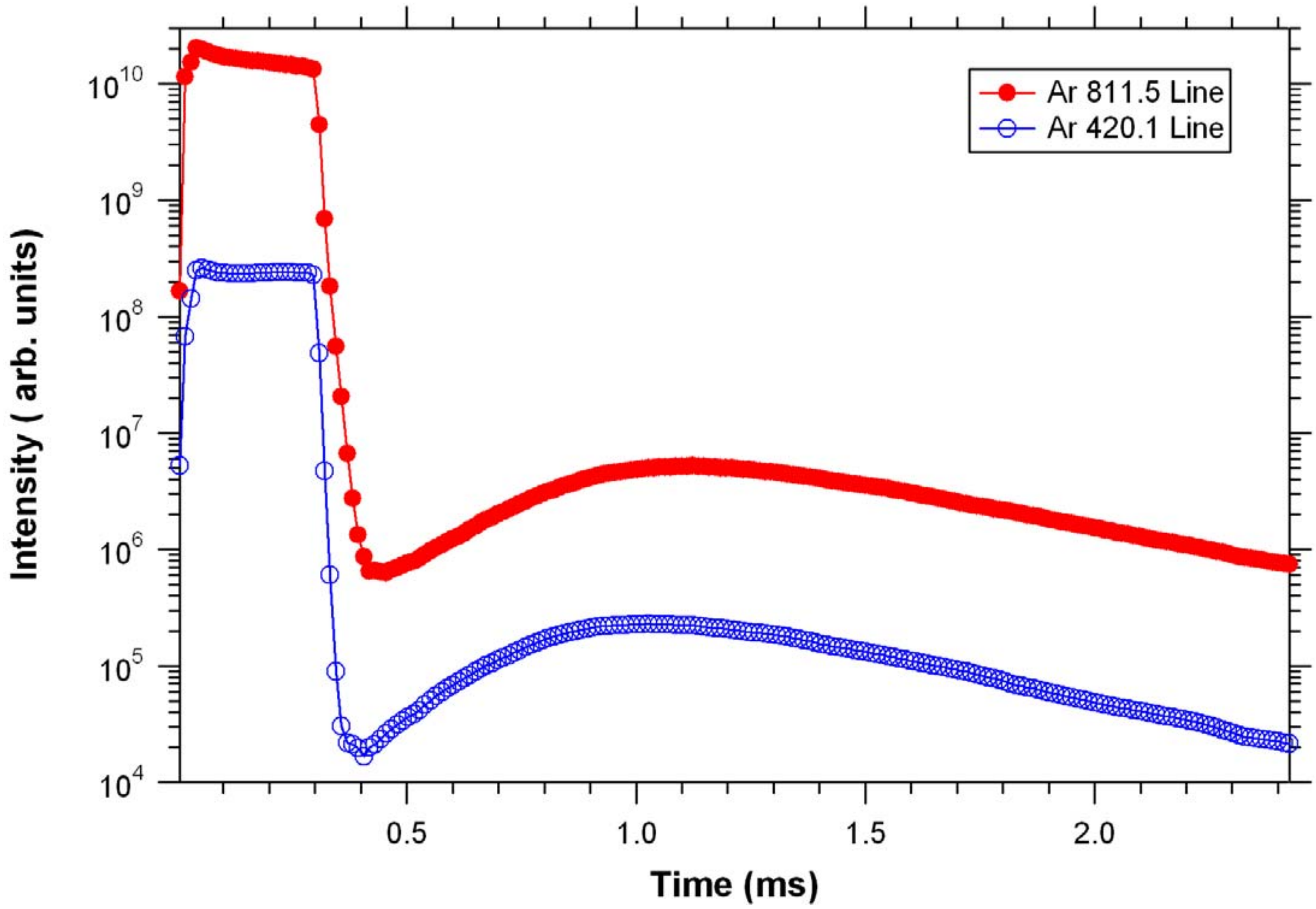


Details of Circuitry for Pulsed RF Operation

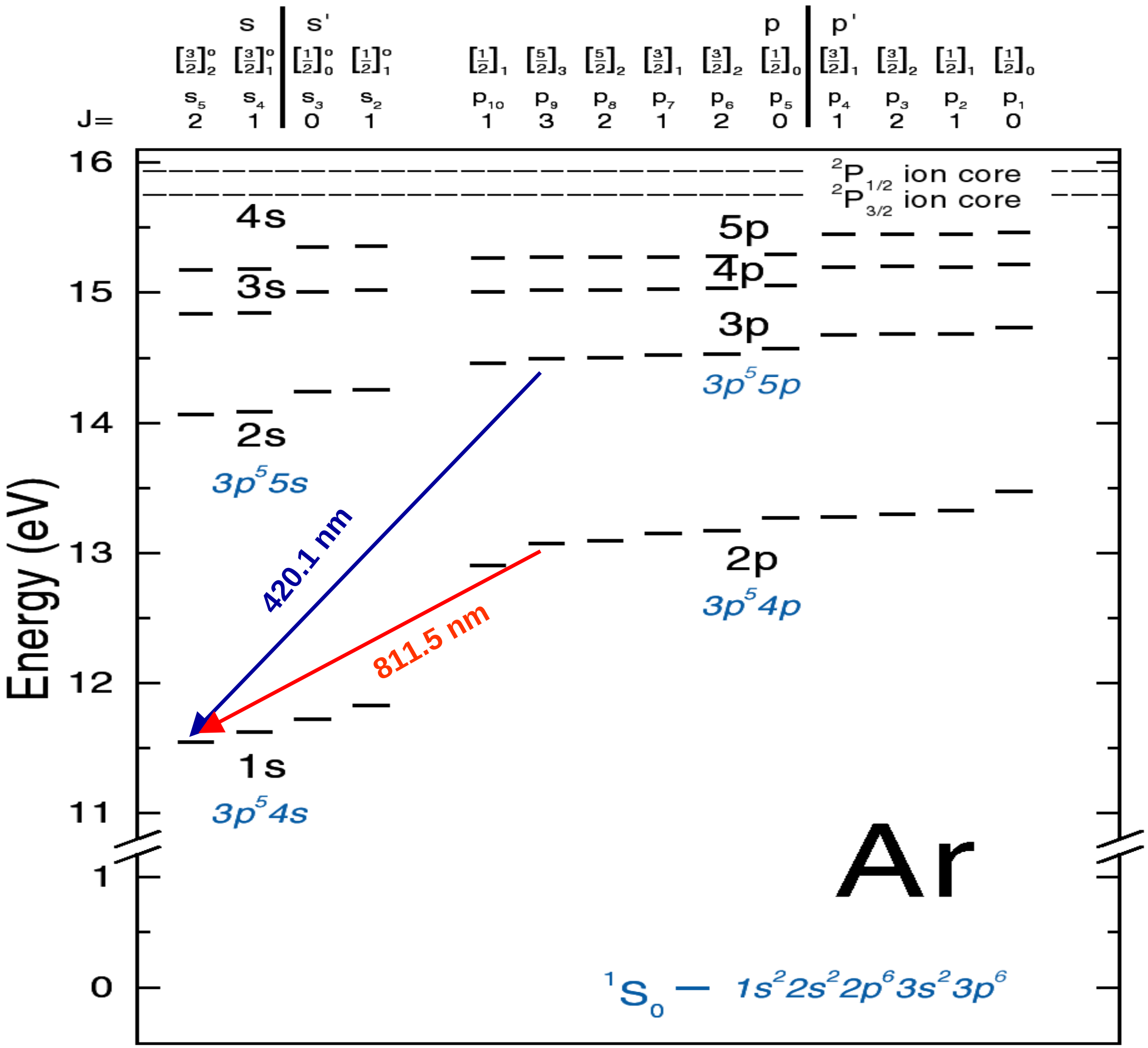


UES

Intensity of the Ar spectral lines 420.1 and 811.5 nm

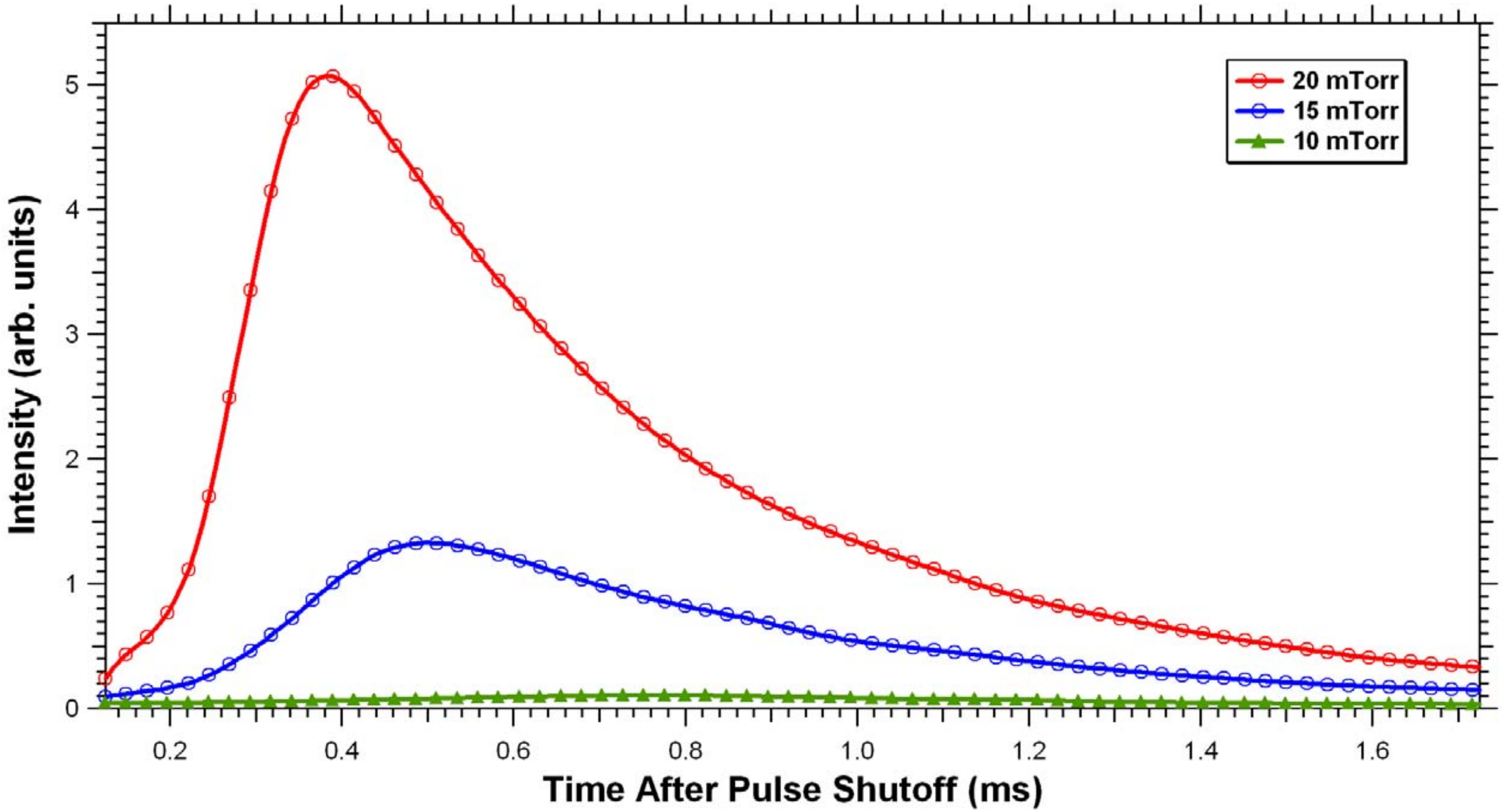


Two of the Transitions Studied in Argon



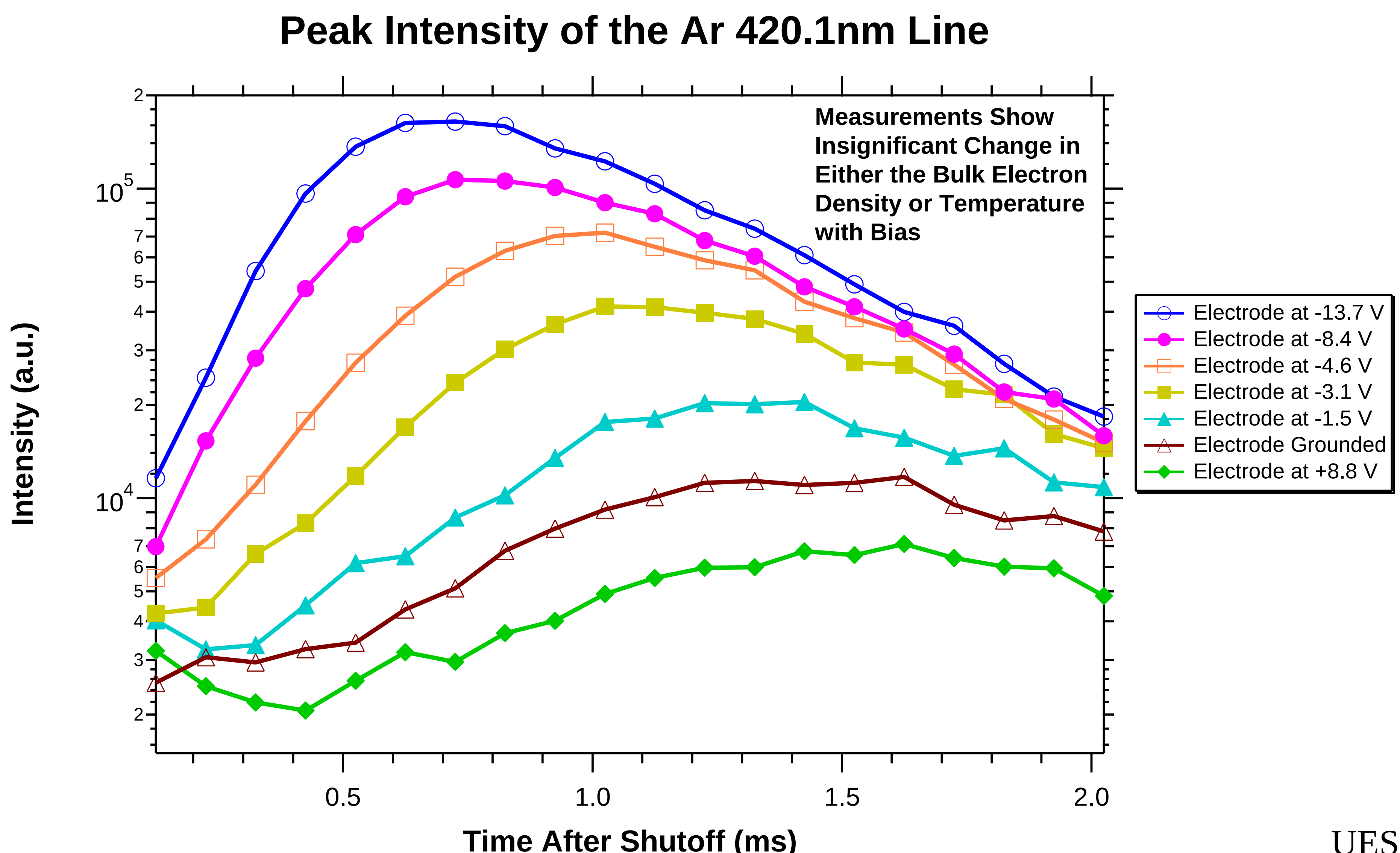
UES

Afterglow Emission Shows Strong Pressure Dependence



Time dependence of the emission from the Ar 420.1 nm line at various pressures. Both production of and trapping of fast electrons is effected by pressure.

Emission Line Intensities Vary Dramatically with Electrode Bias



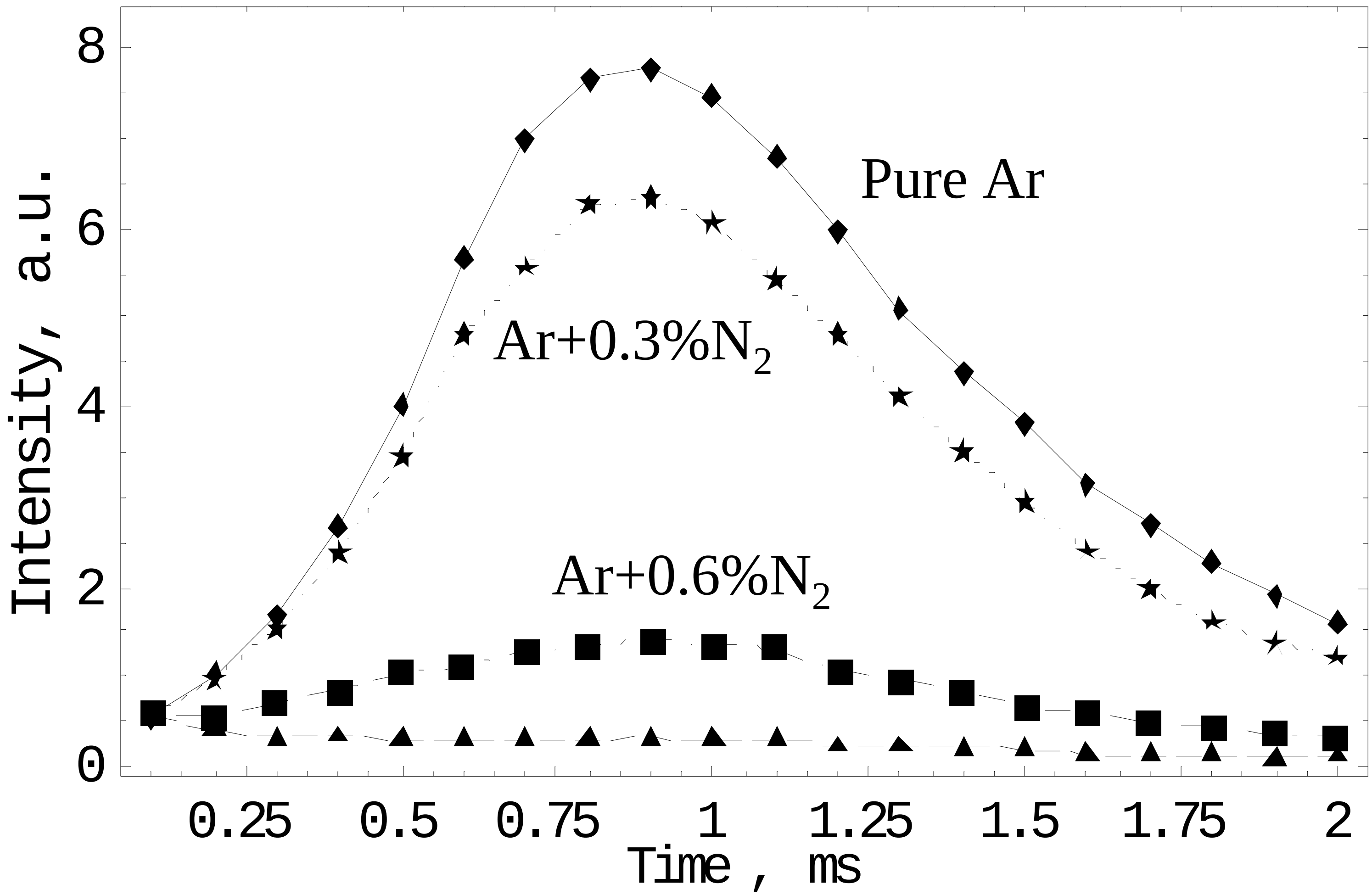
300 µs pulse, 400 Hz, 250 W

UES

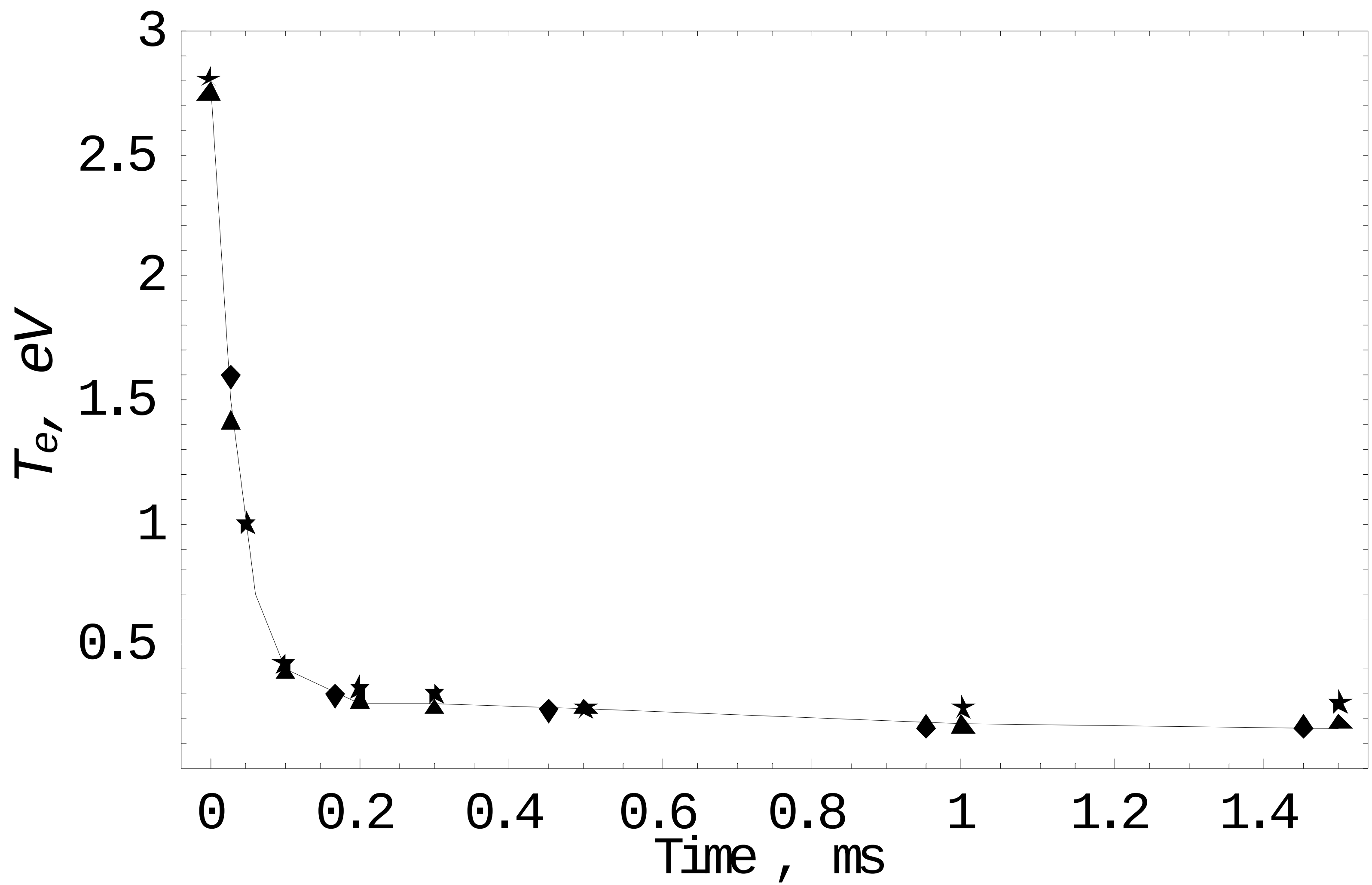
Summary and Conclusions

Effects, connected with non-locality of electron energy distribution in afterglow plasma with fast electrons, can lead to essential increasing (with compare to the bulk electron temperature) of near-wall potential drop even if density of fast electrons considerable much less than density of bulk electrons. This can change significantly near-wall electric fields and sheath thickness. When non-local fast electrons is partly trapped in the plasma volume, it can give noticeable heating of bulk electrons, gradual decrease (up to switching off) of their diffusion cooling and increasing of stepwise excitation rate.

Intensity of Ar spectral line 420.1 nm depends on nitrogen presence



Electron temperature in Ar afterglow



UES