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# Study of pulsed ECRIS plasma near breakdown: The Preglow

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**Abstract**: A careful study of pulsed mode operation of the PHOENIX ECR ion source has clearly demonstrated the reality of an unexpected transient current peak, occurring at the very beginning of the plasma breakdown. This regime was named the Preglow, as an explicit reference to the Afterglow occurring at the microwave pulse end. After the transient Preglow peak, the plasma regime relaxes to the classical steady state one. Argon Preglow experiments performed at LPSC are presented. A theoretical model of ECR gas breakdown in a magnetic trap, developed at IAP, showing satisfactory agreement with the experimental results is suggested.

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## Introduction

During pulsed mode operation in electron cyclotron ion sources (ECRIS), various plasma parameters regimes can be observed. Once these regimes are reproducible, they can be used for specific applications. One of them is the Afterglow mode (AFG) [1], occurring at the microwave pulse end. During the microwave power pulse application, in the case of 18 and 28 GHz microwave frequencies, a new regime has been identified: an unexpected transient current peak occurring at the very beginning of the gas breakdown called preglow mode (PGW)[2]. It has been observed in several gases. Argon was chosen for this paper because it is a reference gas for the ECRIS community. In argon, PGW is observed for low and medium charge states on a time scale lower than 1 ms. As for a standard ECR plasma tuning, PGW characteristics depend on the magnetic confinement, the microwave power and the pressure. This regime is stable from pulse to pulse. In this paper, after a quick recall of the experimental setup, two argon PGW discharges are presented: one at 18 GHz microwave frequency, the other at 28 GHz. A theoretical model showing encouraging preliminary agreement with the experimental results is suggested.

## Experimental setup

The experiments have been performed on the LPSC-PHOENIX test bench, previously presented [3]. The PHOENIX injection flange enables to inject either a 28 GHz heating frequency from a Gycom gyrotron [4], or a 18 GHz frequency from a 2 kW SAIREM klystron. In order to get a good beam transmission efficiency (>75%) throughout the 90° dipole to the analysis Faraday cup, the ion extraction voltage was adapted for each experiment between 30 and 40 kV. In this work, results include studies with 8 and 10 mm plasma electrode hole diameters respectively for 28 GHz and 18 GHz ECR plasma. The Repetition rate was 10 Hz and the microwave pulse duration was fixed to 10 ms.

## Experimental evidence of the Preglow

In order to avoid any mistake due to high voltage drop during pulsed mode, the experimental study is based on 3 dimensions (3D) ions spectra records. The 3 recorded datas being the dipole magnetic field, the measured ionic current and the time. A typical 3D argon PGW spectrum is shown in figure 1(a).

The X-coordinate is the magnetic field of the bending magnet, the Y-ordinate is the time and the colors represent the beam intensities. However, as shown in figure 1(b) which represents a zoom of the $Ar^{4+}$ pulse, the spectrum can show distortions due to high voltage variations: *V(t),* particularly when the total current collected is important. This effect is due to the limited internal capacity of usual CW high voltage power supply. The voltage variation leads to an ion energy change as a function of time. Consequently, the magnetic field *B* in the dipole necessary to select an ion with a specific charge over mass ration (Q/A) changes with time: *B=f(V(t))*. The *V(t)* law and the 3D spectra permit to straighten out individual pulses, as shown in figure 1(c), which can then be used for analysis. Figure 1(c) includes two reconstructed $Ar^{4+}$ pulses. The black pulse is obtained by making a projection of the distorted pulse on the time axis : the value kept for each time bin *t* is the maximum of *I(B)*. This first reconstruction is easy to make but intensity instability information is lost. The second plot (grey curve of figure 1(c)) is reconstructed using the *B=f(V(t))* dependence. This analysis is preferred because it keeps the information on the current noise. In order to study the PGW peak characteristics, several parameters have been introduced for convenience, based on the results of a Gaussian fit of the reconstructed PGW peaks. The PGW parameters, presented in figure 2, are as follows: $I_{max}$ is the peak maximum current, $\delta T$ is the peak full width at half-maximum (FWHM), and $T_{Imax}$ is the time to reach the maximum intensity (t=0 being microwave trigger). The evolution of multi-charged argon intensity for different charge states in the case of a 18 GHz microwave frequency is presented figure 3. The tuning was made to maximize the $Ar^{8+}$ current. The microwave power was 950 W. Figure 3 clearly shows PGW peaks for charge states 2+, 3+ and 4+. The $Ar^{6+}$ pulse seems to be a transitory pulse between PGW pulses at lower charge states and usual pulses, i.e. without PGW peak, at higher charge states. This is confirmed when analyzing the PGW parameters variations as a function of the charge state, as shown in figure 4. The FWHM is almost constant for charge states ranging from 2+ to 4+ and remains lower than 0.6 ms, while $T_{Imax}$ increases slowly. One can note a contrast, for charge states higher than 6+, where these parameters sharply increase: the transient PGW phenomenon is no more seen and the standard ECR plasma discharge is observed:  AFG is even present at the pulses end.

The same analysis was performed at a 28 GHz microwave frequency. The tuning was made to maximize the $Ar^{8+}$ peak, the microwave power was then 3600 W. The figure 5 represents the time evolution of multi-charged argon pulses for the different charge states. This figure clearly shows PGW peaks for charge states ranging from 2+ to 8+. The corresponding PGW parameters charge state dependence is shown figure 6. Here, the FWHM remains flat for all charge states ranging from 2+ to 8+, and lower than 0.6 ms. It is noticeable that $T_{Imax}$ evolves on ~0.5 ms from charge 3+ to 8+. A PGW intensity above 400 μA is obtained for the 8+ charge state. The comparison between the 18 and 28 GHz experiments show that the microwave frequency increase tends to support the production of PGW peaks at higher charge states. Since PHOENIX has a magnetic confinement suitable for 18 GHz ECR heating, the confinement for 28 GHz is poor, however medium charge states can be produced thanks to higher microwave power levels.

**Theoretical plasma model**

The following description of the PGW effect is based on calculations which have been made with the zero-dimension plasma confinement model in a magnetic trap, which is described in [5]. Main features will be mentioned further. It can be found that at the very beginning of the ECR breakdown, which means low plasma density and absence of electronic collisions, the electron energy distribution function (EEDF) is determined by a superadiabatic interaction of the electrons with the microwave. Such EEDF was analytically obtained in [6], and was later completely confirmed by numerical calculations as shown in figure 7. In the model, the EEDF at the very beginning of the discharge is similar to the plotted one in figure 7. With the further increase of the plasma density, more power is necessary to sustain such EEDF, and at some instant the absorbed microwave power becomes insufficient. At this moment we suggest that the EEDF turns into a Maxwellian one and then the electron temperature is calculated from an energy balance equation. The main characteristic of a superadiabatic EEDF is an extremely high average electron energy. Also, it is assumed that the electron velocity distribution function is strongly anisotropic, which means that the number of electrons in the velocity space loss cone is much lower than the total one, and these electrons weren't considered in the energy and ionization balance calculations. Electrons lifetime (defined as longitudinal lifetime) determined by electron-ion collision frequency $\nu_{ei}$ and mirror ratio *R*, was calculated as follows:

$$\tau_{\parallel}^{e} = \ln R / \nu_{ei} \qquad (1)$$

Ions lifetime was determined according to the quasi-neutrality condition, which also could be used to calculate an ambipolar potential profile [7]. Plasma losses determined by transversal diffusion in the magnetic field weren't calculated due to the complexity of a "Minimum-B" structure. Because they can significantly change quantitative PGW characteristics, transversal lifetime was included into calculations as a free parameter, as well as the initial neutrals density and the microwave radiation absorption coefficient. These free parameters were adjusted to provide the best agreement between experimental and calculated intensities for all charge states at the steady state of the discharge. The comparison between the calculated and the experimental result obtained for $Ar^{4+}$ (extracted from figure 6) is shown in figure 8. Free parameters appeared to be as follows: the absorption coefficient is 25 %, the initial density of neutrals is $2 \times 10^{11}$ $cm^{-3}$ and the upper limit for transversal lifetime is 600 μs. One can observe an over evaluation of the intensity during the steady state and a time shift of the PGW peak for $Ar^{4+}$, it could be explained as follow:

- the model doesn't take into account charge exchange effects as well as ionic pumping effect. These effects can significantly reduce the current of highly charged ions on a steady state.

The calculation of average electronic energy (<E>) is shown in figure 8 too. Fast falling of <E> for $t > 1.2$ ms is determined by the plasma density reaching the value where the EEDF transits from superadiabatic to Maxwellian. Longitudinal lifetime is decreasing as a result of the <E> dropping which provides fast plasma outflow from the ECRIS and formation of PGW peak.

**Acknowledgments**

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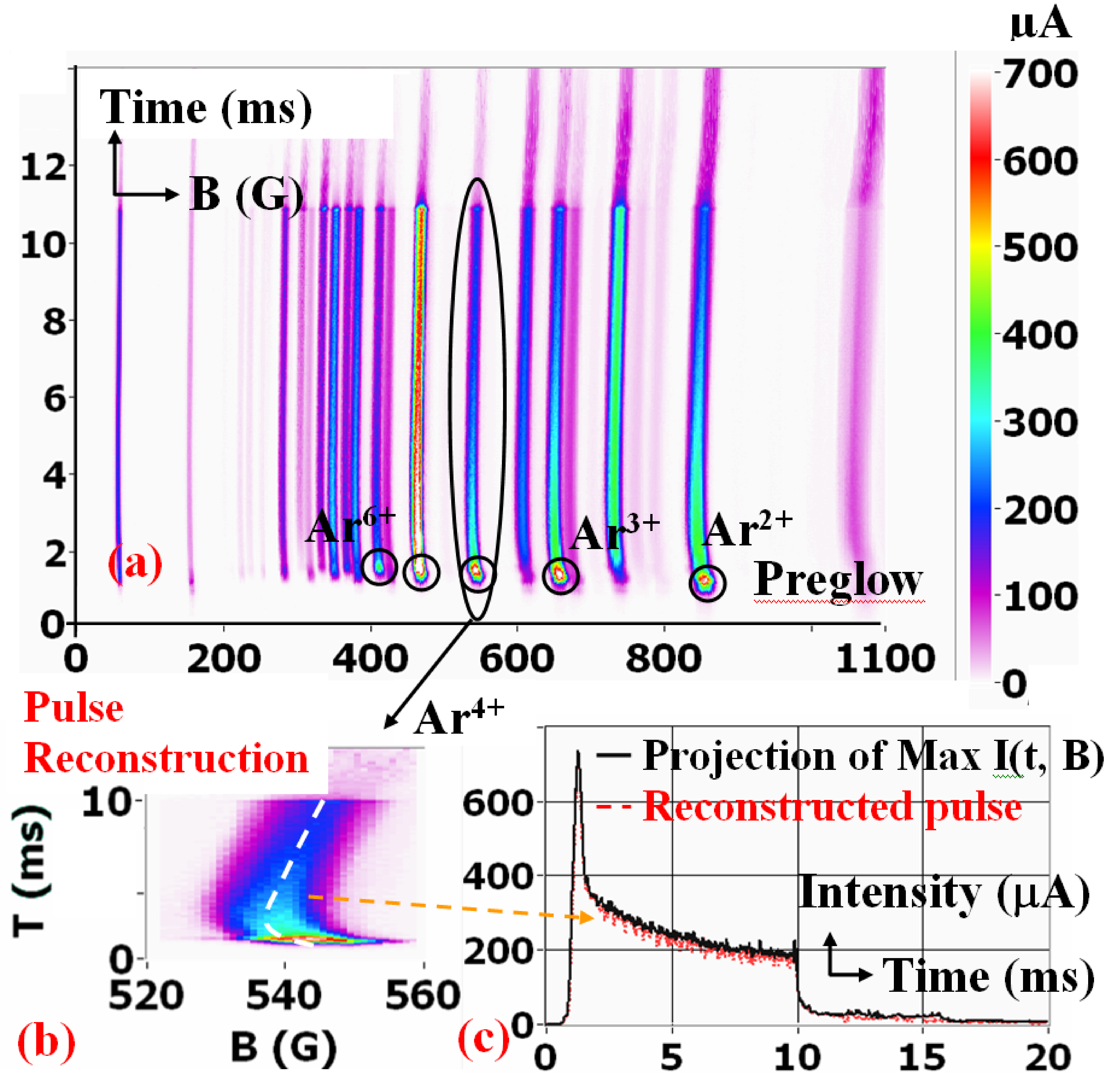
**List of figures**

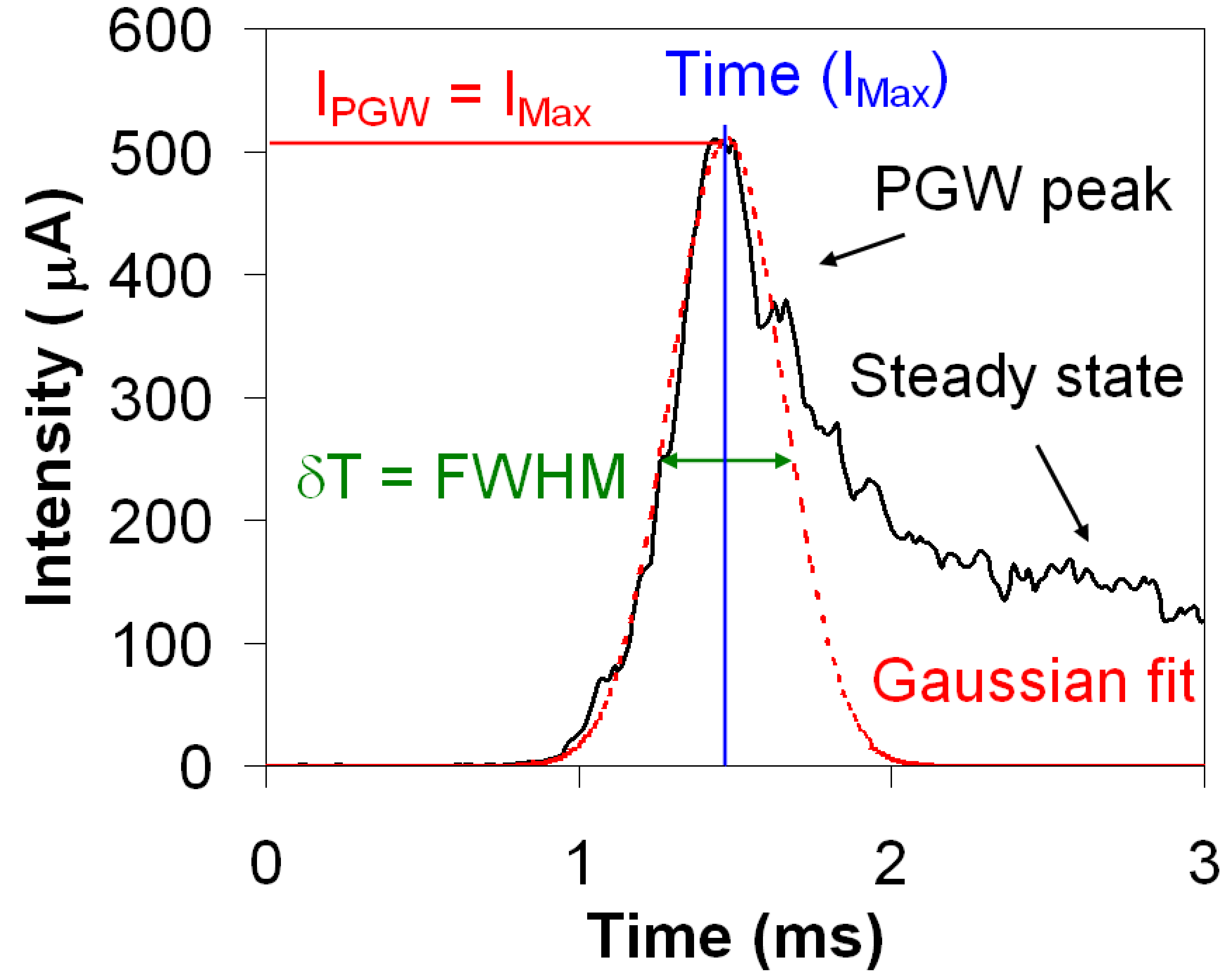
Figure 6. PGW parameters variations as a function of the charge state in argon for 28 GHz experiment.

Figure 7. Numerical Superadiabatic EEDF.

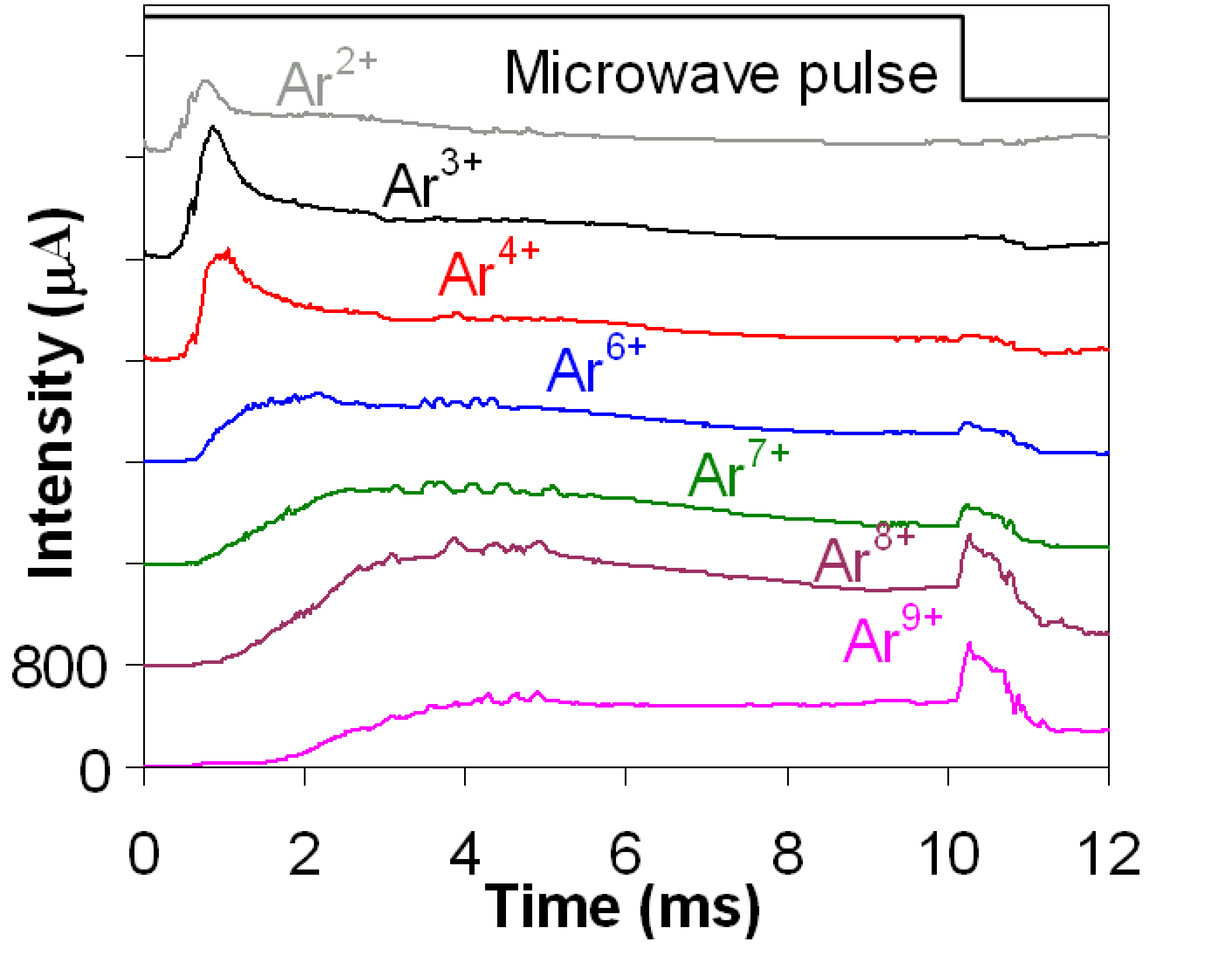
Figure 8. Experimental PGW pulse plotted with the simulated one.



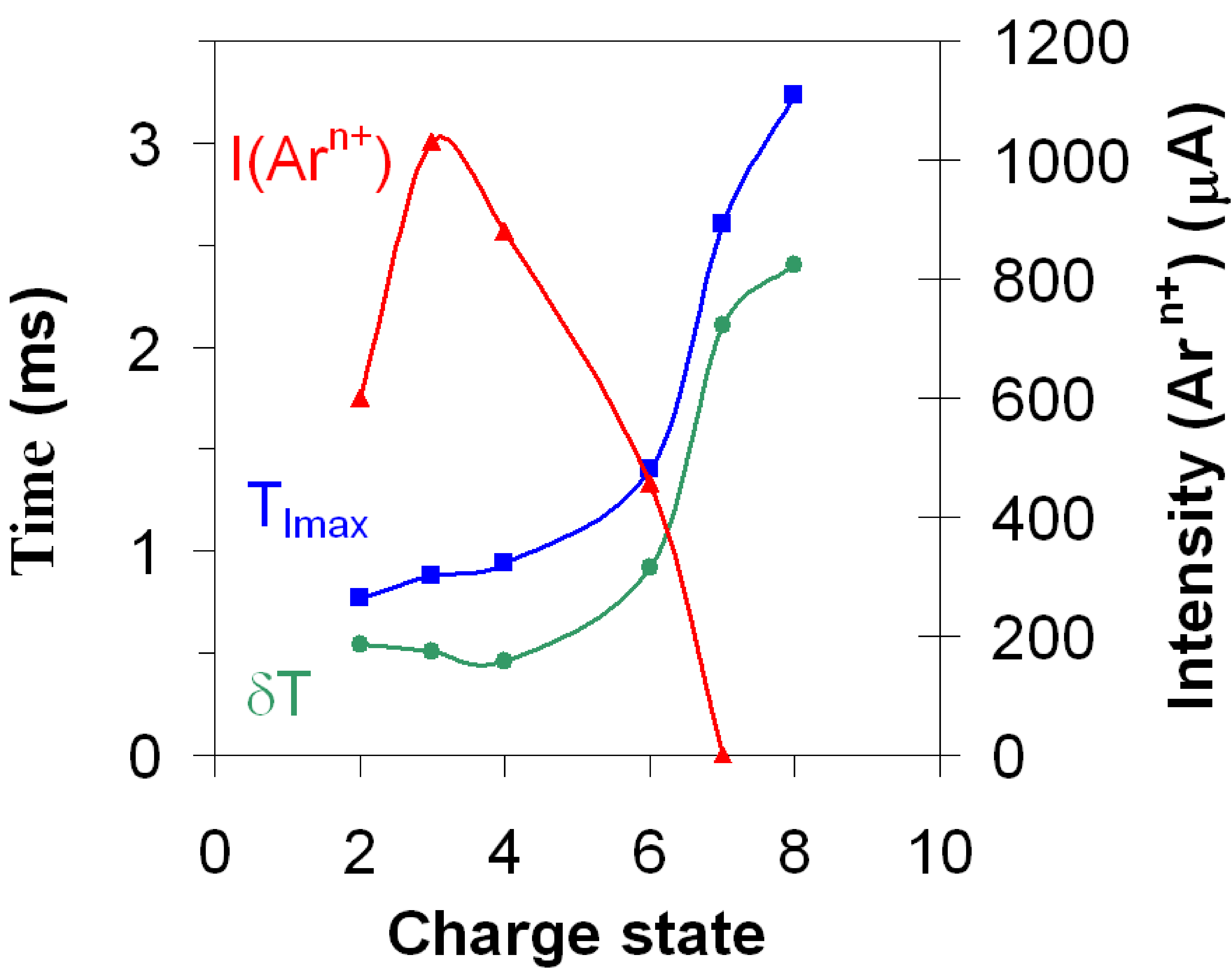
µA
Time (ms)
B (G)
Ar6+
Ar3+
Ar2+
Preglow
(a)
Pulse
Reconstruction
Ar4+
T (ms)
B (G)
(b)
Projection of Max I(t, B)
Reconstructed pulse
Intensity (µA)
Time (ms)
(c)



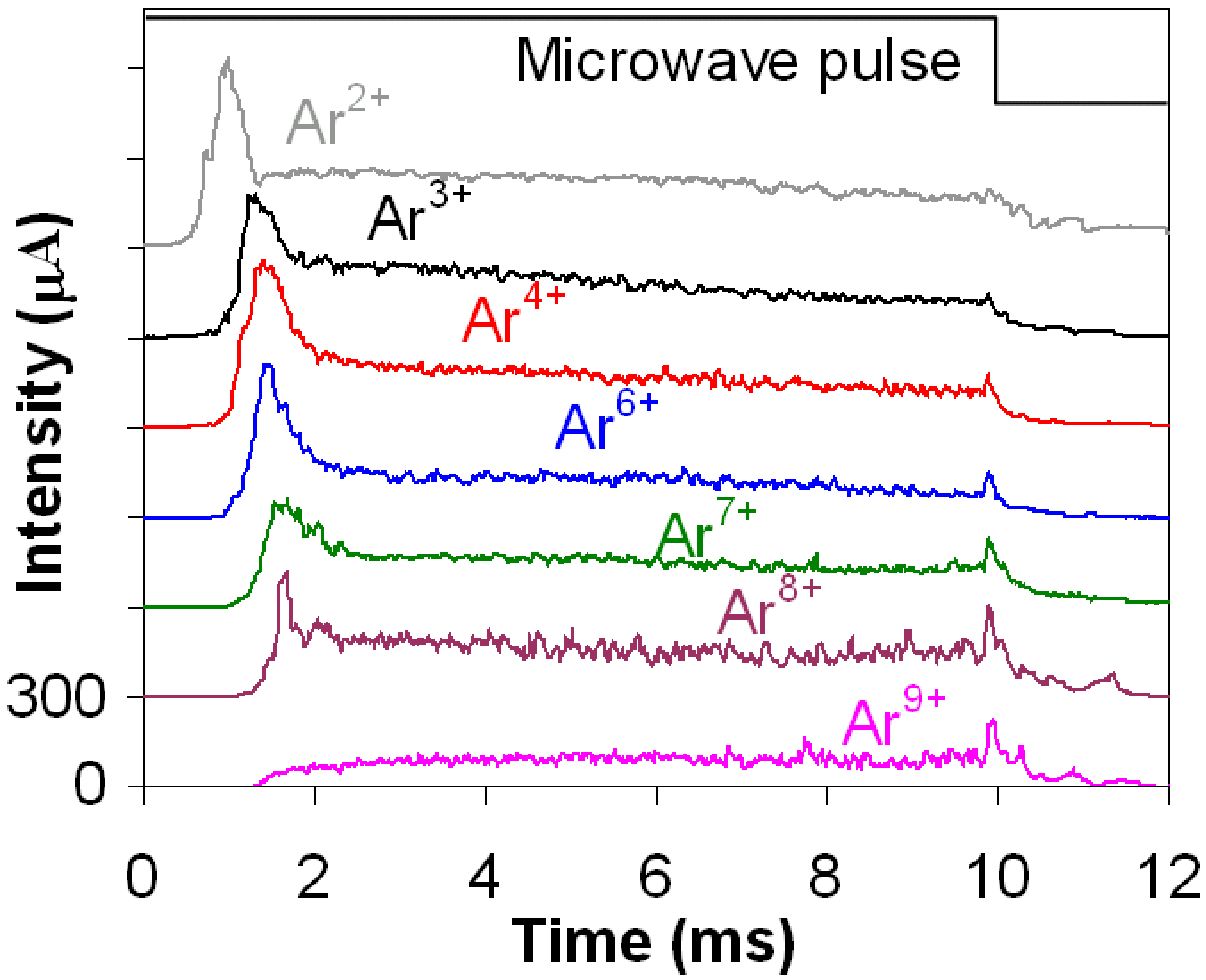
600
500
400
300
200
100
0
Intensity (μA)
I_PGW = I_Max
Time (I_Max)
PGW peak
Steady state
δT = FWHM
Gaussian fit
0
1
2
3
Time (ms)

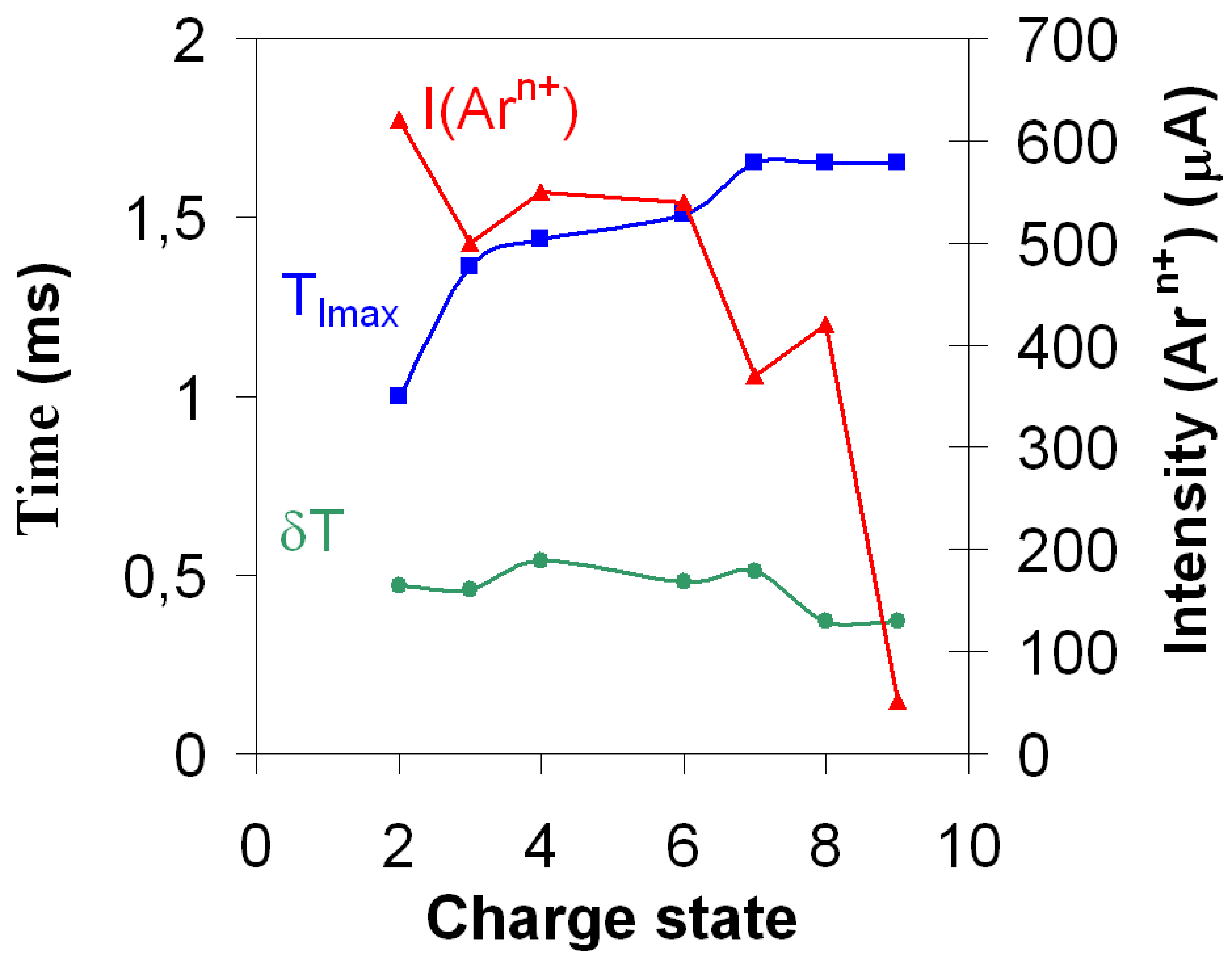


Microwave pulse
$Ar^{2+}$
$Ar^{3+}$
$Ar^{4+}$
$Ar^{6+}$
$Ar^{7+}$
$Ar^{8+}$
$Ar^{9+}$
Intensity (μA)
800
0
0
2
4
6
8
10
12
Time (ms)

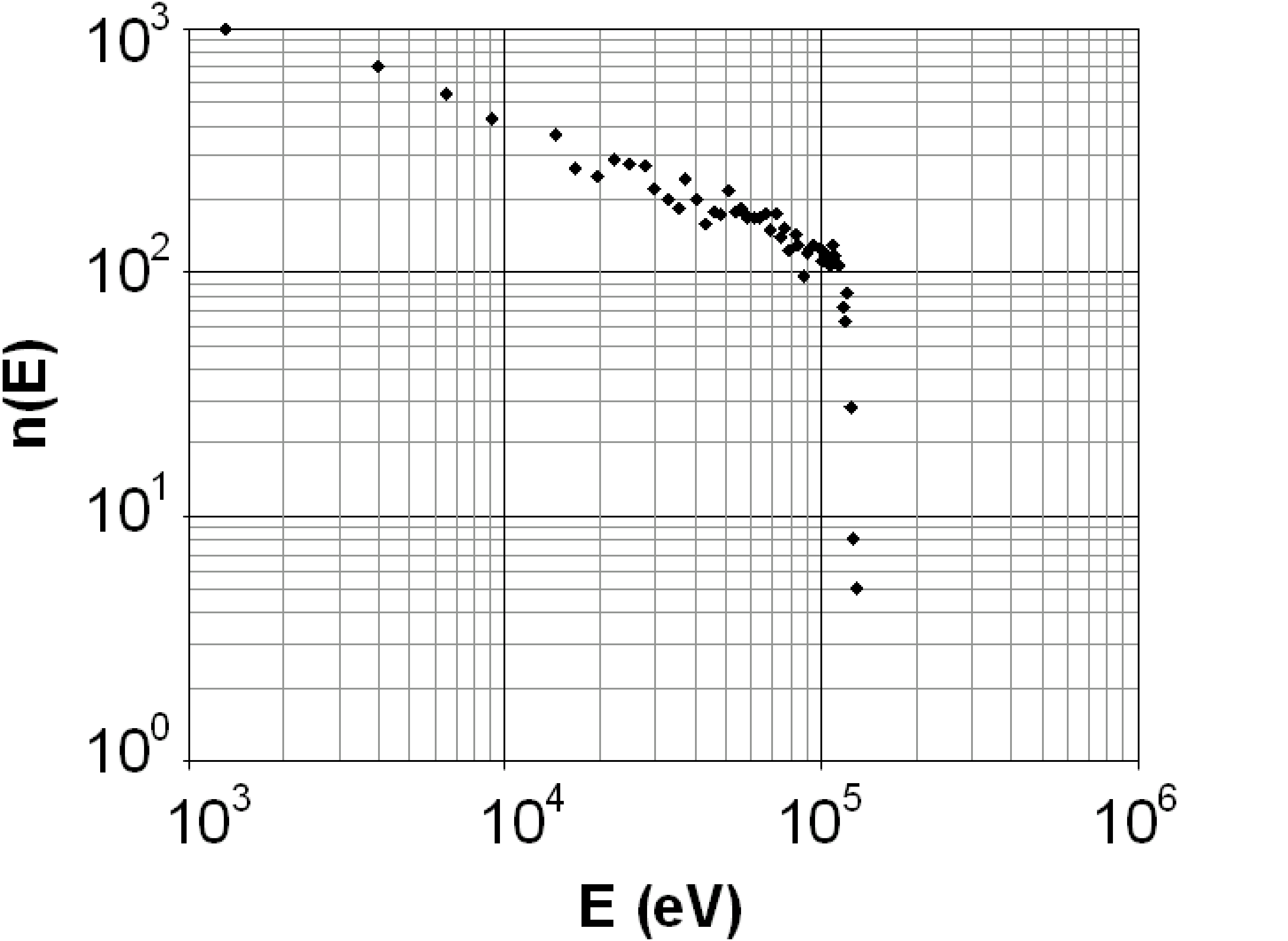


I(Ar^n+)
T_Imax
δT
Time (ms)
Intensity (Ar^n+) (μA)
Charge state
0
1
2
3
0
200
400
600
800
1000
1200
0
2
4
6
8
10

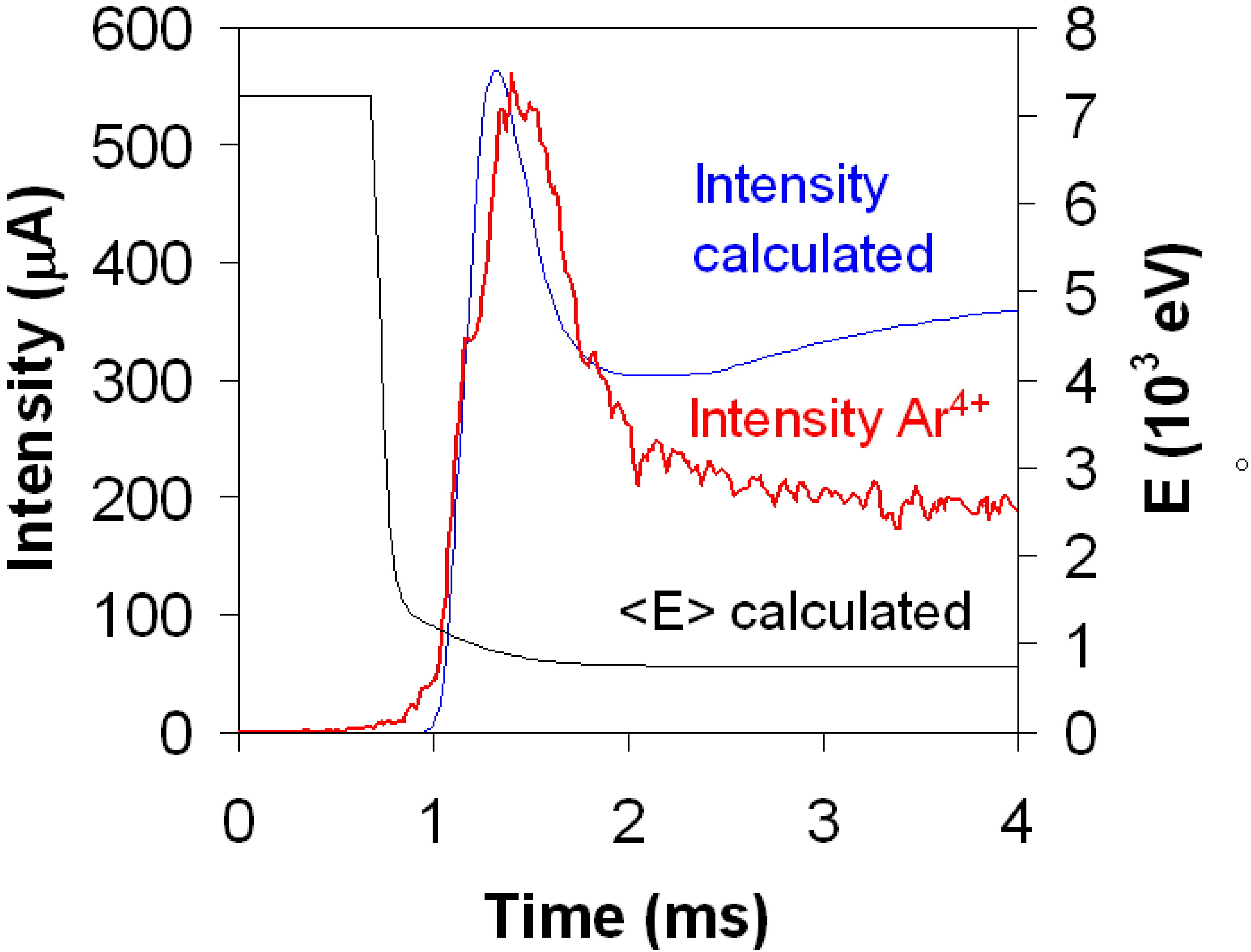

Microwave pulse
Ar2+
Ar3+
Ar4+
Ar6+
Ar7+
Ar8+
Ar9+
Intensity (μA)
300
0
0
2
4
6
8
10
12
Time (ms)



Time (ms)
Intensity ($Ar^{n+}$) (μA)
Charge state
$I(Ar^{n+})$
$T_{Imax}$
δT
0
0,5
1
1,5
2
0
100
200
300
400
500
600
700
0
2
4
6
8
10



$10^3$
$10^2$
$10^1$
$10^0$
n(E)
$10^3$
$10^4$
$10^5$
$10^6$
E (eV)



Intensity (μA)
600
500
400
300
200
100
0
Intensity calculated
Intensity Ar4+
<E> calculated
E (10³ eV)
8
7
6
5
4
3
2
1
0
0
1
2
3
4
Time (ms)