PREGLOW PHENOMENON ORIGIN AND ITS SCALING FOR ECRIS

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Abstract

Preglow effect investigation is one of topical directions of ECR ion sources development at present. Preglow is of interest for efficient short-pulsed multicharged ion source creation. Particularly, such source of intense beams of shortliving radioactive isotopes multi-charged ions is one of key elements in "Beta-Beam" European project [1]. Use of Preglow-generating regime of an ECRIS operation is a promising way of pulsed high-intense multi-charged ion beams production with much shorter edges in comparison with usual operation regime. The first theoretical investigations of Preglow phenomenon were performed in references [2, 3]. Numerical simulations made with the updated theoretical model allow authors to propose more physical and intuitive explanation of Preglow phenomenon origins. Obtained dependences of Preglow characteristics on experimental conditions offer a scaling for a wide range of ECRISes.

INTRODUCTION

The preglow effect was first observed in experiments in LPSC (Grenoble, France) and later modeled theoretically in the works [2,3]. Theoretical model of ECR discharge development in a magnetic trap of an ECR MCI source, modified as compared to [2], allowed us to simulate the process of preglow peak more accurately and to assess dependence of its parameters on experimental conditions. The performed theoretical research and results of the numerical modeling give a new, more physical and clear insight into the nature of the preglow effect. We investigated preglow peak duration and intensity as a function of parameters controlled in experiments. Besides, we found a dimensionless parameter characterizing the regime of plasma confinement in the source trap that universally defines the preglow properties and may be used as scaling for a wide class of available and future experimental facilities. These results are also presented in the paper.

PHYSICAL INTERPRETATION OF PREGLOW

Theoretical research demonstrated that the condition necessary for the existence of multicharged ion current burst at the beginning of the pulse, i.e., preglow, is intense heating of electrons by microwave radiation at the initial stage of gas breakdown that must be sufficient for formation and maintaining for some time of superadiabatic energy electron distribution function (EEDF, see [3]). The EEDF form ensures efficient neutral gas ionization due to the presence of electrons in the energy region corresponding to maximum ionization cross-sections, on the one hand, and allows "storing" higher energy (compared to the maxwellian EEDF with the same mean energy) of "hot" electrons whose lifetime in the trap is large in comparison with the characteristic time of discharge evolution, on the other hand. Hereinafter, under plasma energy content we understand the quantity $w = \langle E \rangle * Ne$, where $\langle E \rangle$ is average electron energy over EEDF, and Ne is electron concentration.

With a definite combination of parameters of seed plasma, the concentration of neutral particles at the beginning of the discharge and characteristics of heating microwave radiation, there may occurs a situation when the energy stored at the initial stage of plasma breakdown is much higher than its energy content at the steady-state stage of discharge combustion. Fast withdrawal of this excess energy in the form of an intense flux of charged particles from the trap gives rise to a preglow peak. In other words, at the stage of avalanche-like growth of plasma concentration, when its magnitude reaches a high enough level, the energy stored in hot electrons as well as the energy of microwave radiation is expended on intense gas ionization. This energy reserve makes it possible in a short time to create plasma with concentration and temperature higher than those attainable by means of microwave radiation. A particle flux from the magnetic trap, too, may be much higher than the steady-state one. Note that, if the power of microwave radiation is so small that sufficient energy cannot be stored, there will be no preglow effect. Nor will it occur in the case of too large power, when all the electrons, even with total-lot gas ionization, are heated up to maximum energies.

The said above may be readily illustrated by means of numerical modeling of the evolution of ECR discharge within the framework of the considered theoretical model. Results of computation of the dynamics of plasma energy content, its concentration and density of particles flux from the trap at the initial stage of discharge are presented in fig. 1 for the following parameters: 28 GHz, 200 W/cm^2.

It is clearly seen from the time plots in fig. 1 that, by the time the particle flux from the trap starts to grow, the plasma energy content is almost an order of magnitude higher than the steady-state level and termination of the stored energy release exactly coincides with termination of the burst of particle flux, after which the discharge parameters take on steady-state values. The preglow current peak intensity (the ratio of the amplitude of peak current to a steady-state value) in this case is the larger, the higher the maximum plasma energy content was in comparison with the steady-state one.

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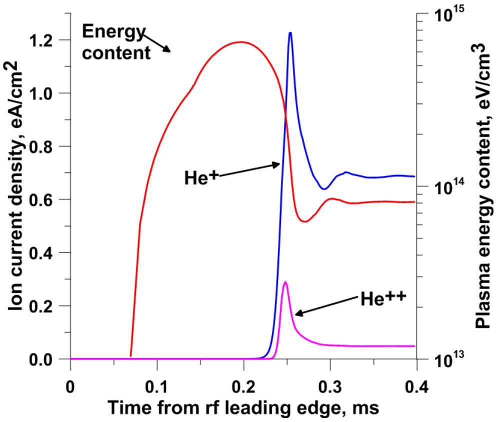

Figure 1: Plasma energy content & ion current density

Temporal parameters of preglow peak depend on how active neutral gas ionization is (i.e., on ionization rate, hence, on particle concentration) and on how fast the particles may withdraw "excess" stored energy from the trap, i.e., on their lifetime. As plasma lifetime, its concentration and temperature are interrelated quite intricately, it is very difficult to give a comprehensive analysis of the preglow effect without numerical simulation. In the next section we present results of simulations.

NUMERICAL SIMULATION

It is convenient to investigate preglow characteristics using the parameters based on Gaussian approximation of preglow peak [2]. *Imax* is maximum value of peak current (current density), *Time(Imax)* = *Tmax* is the time period from the beginning of heating pulse to attaining maximum current, *FWHM* is full width at half maximum.

Numerical simulation was performed using the code created by the authors on the basis of the model described in [3]. The variable parameters in the computations were the following: heating radiation frequency f, microwave radiation flux density p, and initial concentration of atoms N_{a0}. All the other parameters were constant: magnetic trap length L=20 cm, mirror ratio R=5, initial plasma concentration $N_{e0}=10^5$ cm^{-3}, initial electron temperature T_{e0} =1 eV. Frequency f was varied within the 28-60 GHz range corresponding to the frequencies of available and developed ECRIS. Power density p was varied in a wide range accessible to state-of-the-art ECRIS. The operating gas was helium.

We introduce parameter *RP* (stands for regime parameter) as ratio between gasdynamic and classical electron lifetime: $RP = \tau_{gd} / \tau_{cl}$ (see [3]). This parameter characterizes the regime of plasma confinement that is realized at a given moment of time. For *RP*>>1 the regime is collisional or quasi-gasdynamic, whereas for *RP*<<1 it is collisionless or classical regime of confinement. Initial conditions of ECR gas breakdown unambiguously determine the confinement regime at the steady-state stage of the discharge and, consequently, the magnitude of *RP*.

Preglow intensity *Int* (the ratio of peak current amplitude to current at the quasi-stationary stage of the discharge) as a function of RP at a steady-state stage of the discharge is plotted in fig. 2 for different power densities at the frequency of 28 GHz. The highest intensity of the 2nd ion preglow (solid lines in the graph) is attained at the power of 100-500 W/cm^2 with the initial density of atoms of 4-6*10^{12} cm^{-3}.

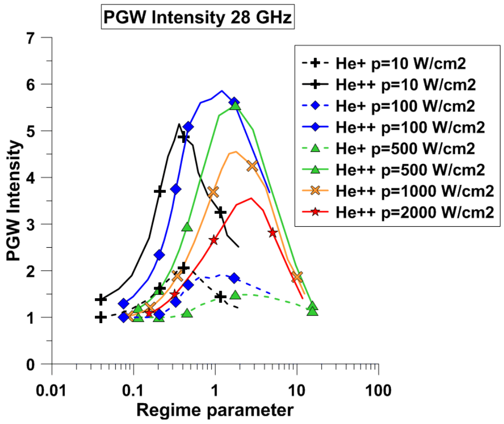

Figure 2: Preglow *Int*.

The curves for preglow intensities lie primarily in the region 0.1<*RP*<10 outside which the preglow effect is not observed (as follows from definition, *Int*=1 corresponds to the absence of preglow peak in current oscillogram). This means that a preglow peak is generated only in a plasma in the intermediate state in terms of confinement regime, i.e., when *RP*~1. At *RP*>>1, which corresponds to a fully filled loss cone and a strongly collisional plasma, preglow is not formed because of a small lifetime of particles – energy is not stored due to its intense withdrawal. In the opposite case, at *RP*<<1, energy is not stored either because of a small number of collisions and, as a consequence, insufficient ionization multiplication of electrons.

An oscillogram of current densities of the 1st and 2nd helium ions in the regime corresponding to maximum preglow intensity of the 2nd ion (p=100 W/cm^2, N_{a0}=5*10^{12} cm^{-3} -> *RR*=1.5) as well as the time dependence of plasma energy content are shown in fig. 1.

FWHM of the preglow peaks is plotted as a function of *RP* in fig. 3. Clearly, unlike fig. 2, where power greatly influences maximum intensity and to a lesser degree position of *RP* maxima, the curves in fig. 3 almost coincide. This is attributed to the fact that preglow *FWHM* is defined by plasma lifetime that is rigorously related to *RP*. It is apparent from figs. 2 and 3 that an intense preglow peak with a duration of several tens of microseconds may be generated.

Simulations showed that the increase in frequency has an insignificant impact on the preglow peak intensity. In the 20-100 GHz range, the preglow intensity of the 2nd ion increases by 12% only, and the preglow intensity of the1st ion remains almost unchanged. The insignificant growth of preglow intensity with increasing frequency

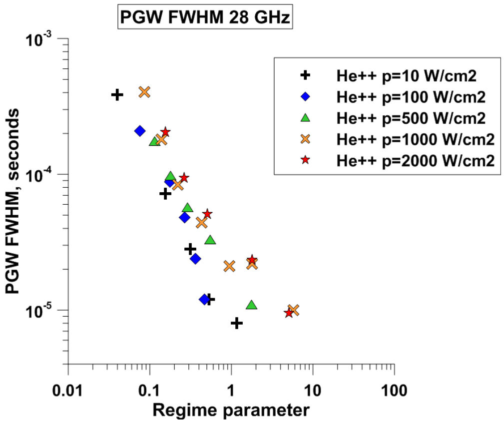

Figure 3: Preglow *FWHM*.

(other parameters being fixed) is explained by the fact that maximum possible electron energy in the superadiabatic regime is related to frequency by $E_{max}\sim f^{1/2}$ [3], hence, the energy average over EEDF that defines energy storage at the initial stage of the discharge also depends on frequency as $<E>\sim f^{1/2}$. Taking into consideration that preglow parameters weakly depend on the absolute magnitude of initial energy storage, we obtain a very weak dependence of these parameters on heating radiation frequency.

Note that, when the power of heating radiation is increased, for attaining intense preglow one has to increase the initial concentration of atoms too so as to maintain *RP* within the existence range of preglow, which in turn leads to increased plasma density that may exceed the cut-off density value for the used frequency. Preglow intensities as a function of steady-state plasma density are shown in fig. 4 for different values of power. The diagram was constructed for 60 GHz, but with allowance for the weak dependence of preglow parameters on frequency, it may be used for assessing preglow parameters at other frequencies also, if plasma density is lower than a critical one. The diagram also shows cut-off concentrations for some typical frequencies.

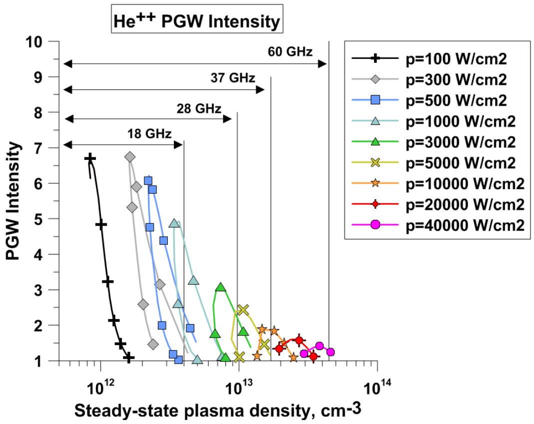

Figure 4: Preglow *Int*.

Besides preglow intensity and peak duration, an absolute value of current (current density in our case) is a parameter important for applications. As a supplement to fig. 4, fig. 5 gives a diagram of maximum current densities in the preglow peak.

It is clear from figs.4 & 5 that it is impossible to produce intense Preglow with current density higher than 1 eA/cm^2 using low power radiation sources at a frequency of 18 GHz and less.

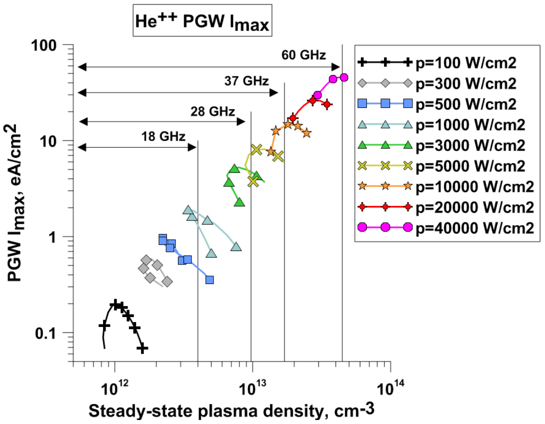

Figure 5: Preglow *Imax.*

CONCLUSION

The results presented provide an insight into the origin of the preglow effect and dependence of its principal parameters (intensity, half-width, and others) on the characteristics of microwave radiation and initial conditions of gas breakdown in a source trap. This effect may be observed in all ECR sources almost independent of characteristics of the used microwave radiation; a proper choice of gas pressure may ensure a regime of ion current burst at the beginning of the pulse. Results of the numerical simulation confirm that the preglow effect is promising for creating a short-pulse ECR source of multicharged particles. The proposed scaling demonstrates that an ECR source with plasma heating by radiation at a frequency of 37 GHz and higher seems to be the most effective in terms of currents, preglow intensity and mean ion charge.

ACKNOWLEDGMENTS

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[2] T. Thuillier et all. Rev. Scient. Instrum., 79, 02A314, 2008.
[3] I. Izotov et all. IEEE Trans. Plasma Sci.36, 1494, 2008.

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Russian Academy of Sciences

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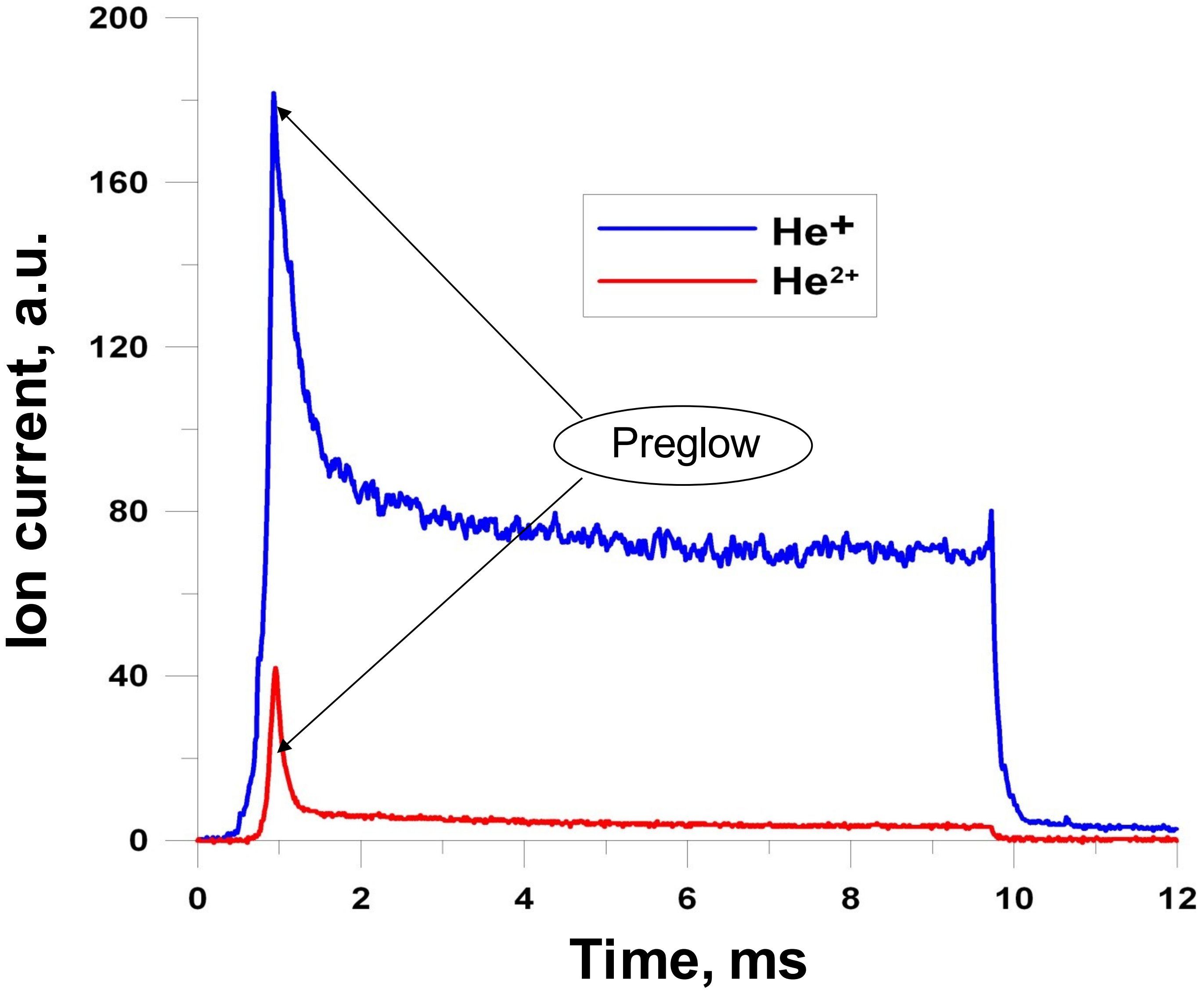
Outline

- Theoretical model and main equations
- Physical interpretation of Preglow phenomenon
- Numerical simulation: Preglow vs experimental conditions
- Universal parameter defining existence of Preglow
- Frequency scaling of Preglow

What is “Preglow”?



Theoretical model [1,2]

$$\begin{cases}
\dfrac{dN_i}{dt}=(k_{i-1,i}N_{i-1}-k_{i,i+1}N_i)\cdot N_e-\dfrac{N_i}{\tau_i} & \text{Ions} \\
\dfrac{dN_e}{dt}=N_e\cdot\sum\limits_{i=0}^{n-1}k_{i,i+1}N_i-\dfrac{N_e}{\tau_e} & \text{Electrons} \\
\dfrac{dN_0}{dt}=I(t)-k_{0,1}N_0N_e & \text{Neutrals} \\
\dfrac{1}{\tau_e}=\dfrac{1}{N_e}\sum\limits_{i=1}^{n}\dfrac{iN_i}{\tau_i} & \text{Condition of quasi-neutrality} \\
\dfrac{3}{2}\cdot\dfrac{d(N_e\cdot T_e)}{dt}=\dfrac{P}{L}-\dfrac{N_e}{\tau_e}\cdot\left(T_e+\varphi_0\right)-\sum\limits_{i=0}^{n-1}k_{i,i+1}\cdot N_e\cdot N_i\cdot E_i & \text{Balance of energy} \\
k=<\sigma v>=\dfrac{\int F(\varepsilon)\sigma(\varepsilon)v(\varepsilon)d\varepsilon}{\int F(\varepsilon)d\varepsilon} & \text{Ionization rate}
\end{cases}$$

Free parameters of the model:
- ***Gas density***
- ***Microwave absorption coefficient***

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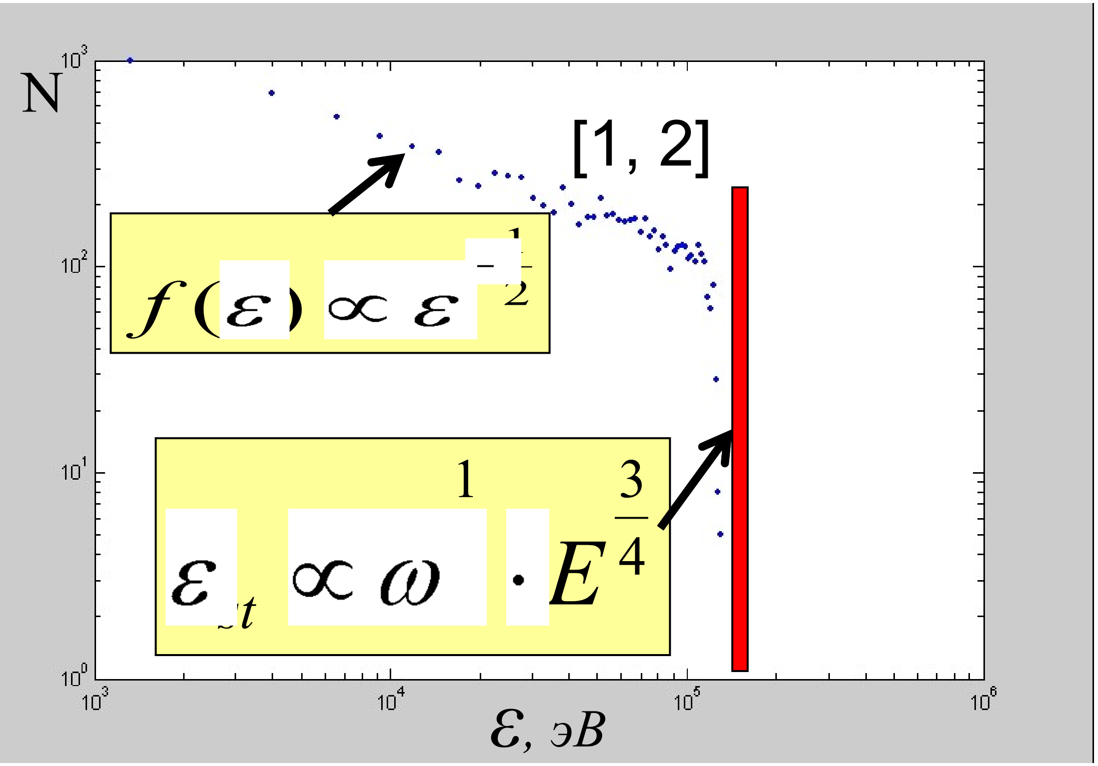
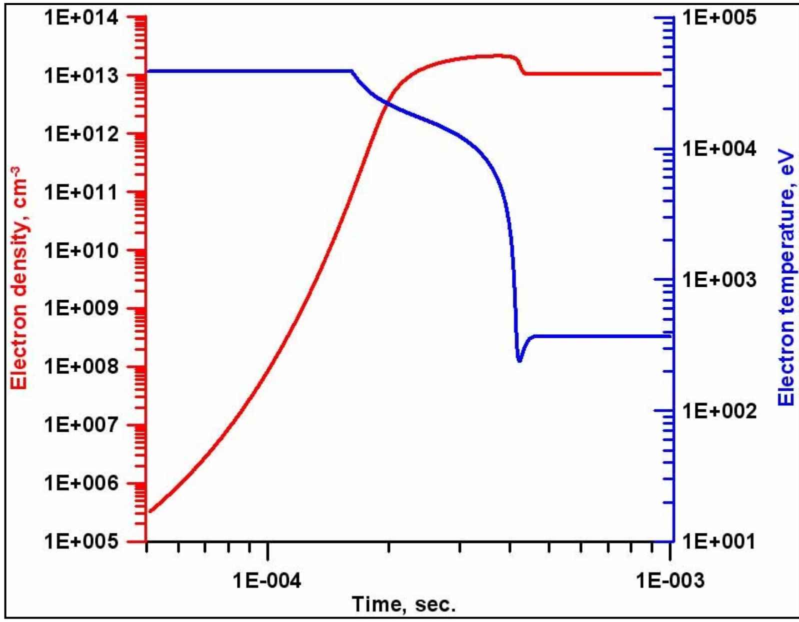
Superadiabacity effect



$$f(\varepsilon) \propto \varepsilon^{-\frac{1}{2}}$$

$$\varepsilon_{t} \propto \omega^{1} \cdot E^{\frac{3}{4}}$$

Non-maxwellian EEDF!



[1] E. V. Suvorov and M. D. Tokman, Sov. J. Plasma Phys. **15, 540 1989.**

[2] Edgell D.H. et all. Modeling of electron cyclotron resonance ion source plasmas. Proceedings of Particle Accelerator Conference, USA, 2001.

E_e - N_e plane [1]

Coulomb electron scattering into the loss-cone

$$\tau_e = \ln R/\nu_{ei}$$

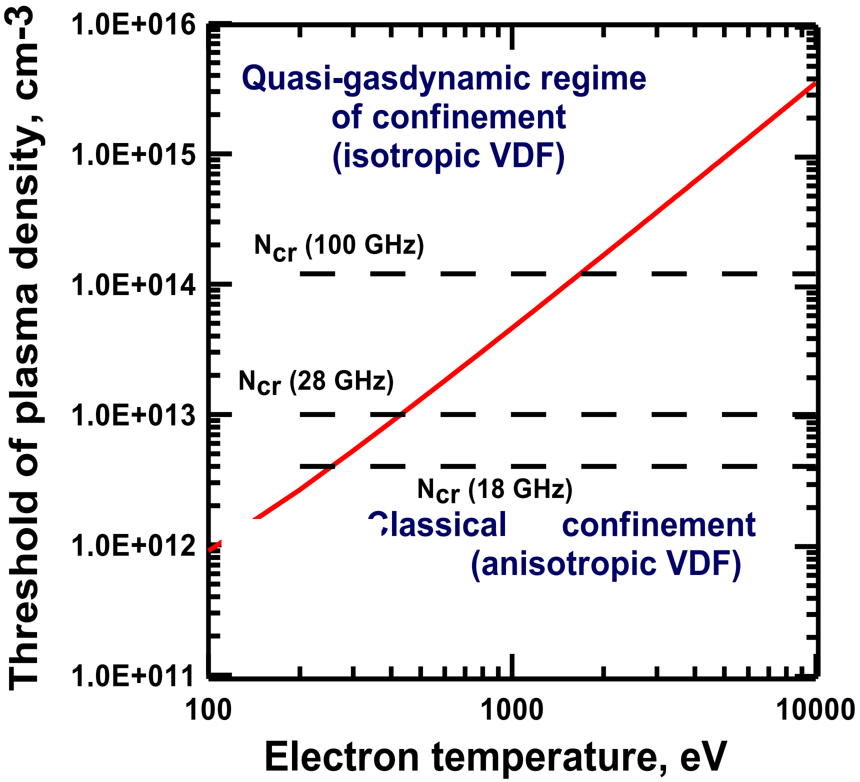
$\tau_e > \tau_g$ (collisionless)

$\tau_e < \tau_g$ (collisional)

Duration of plasma escape

$$\tau_g = L_{eff}/V_s$$

Doesn't depend on VDF

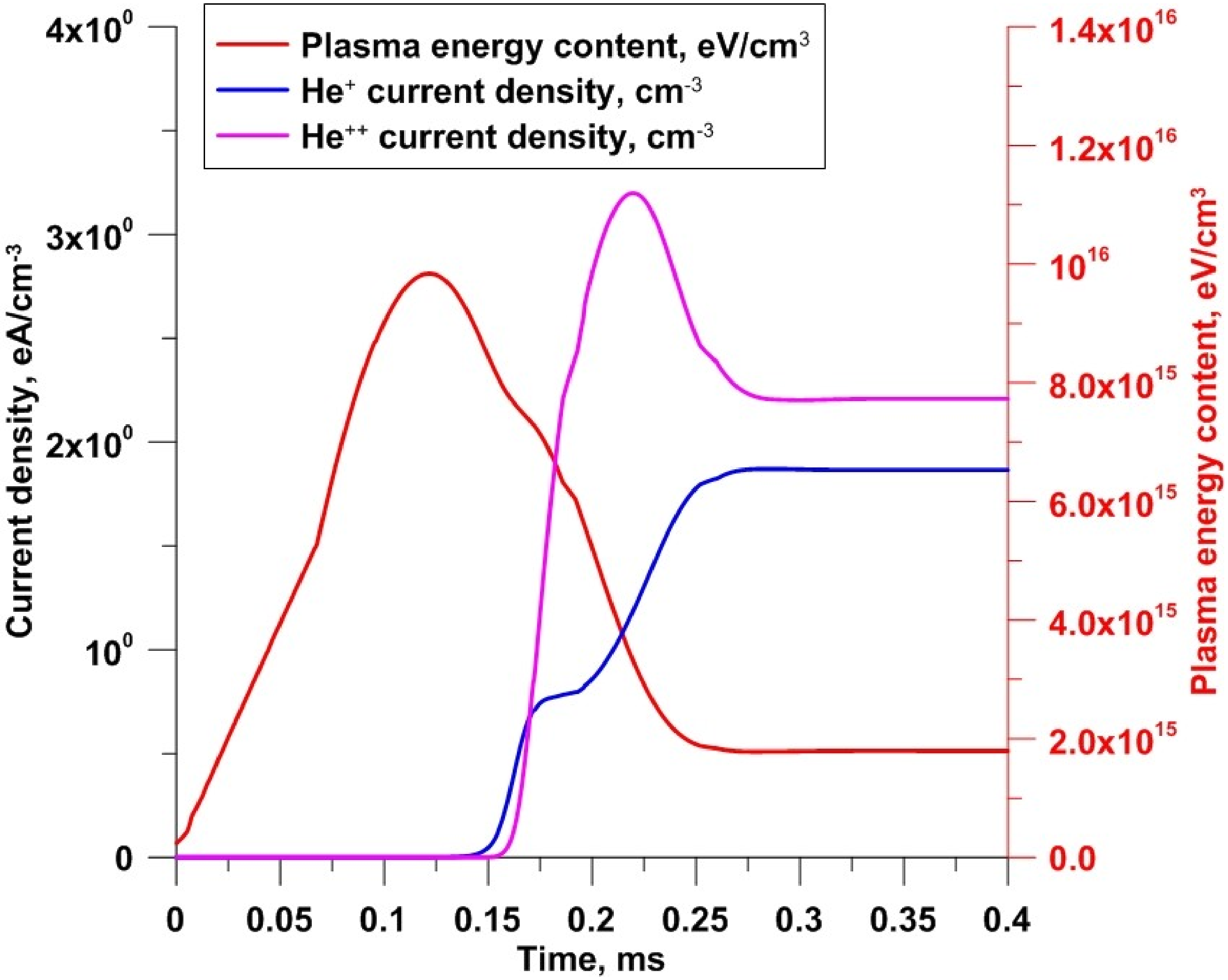


V_s – ion sound velocity

L_{eff} – effective trap length

[1] V. Semenov, V. Skalyga, A. Smirnov, V. Zorin. Review of Scientific Instruments. v. 73, #2, p. 635 – 637. 2002.

Physical interpretation of Preglow



Energy content:

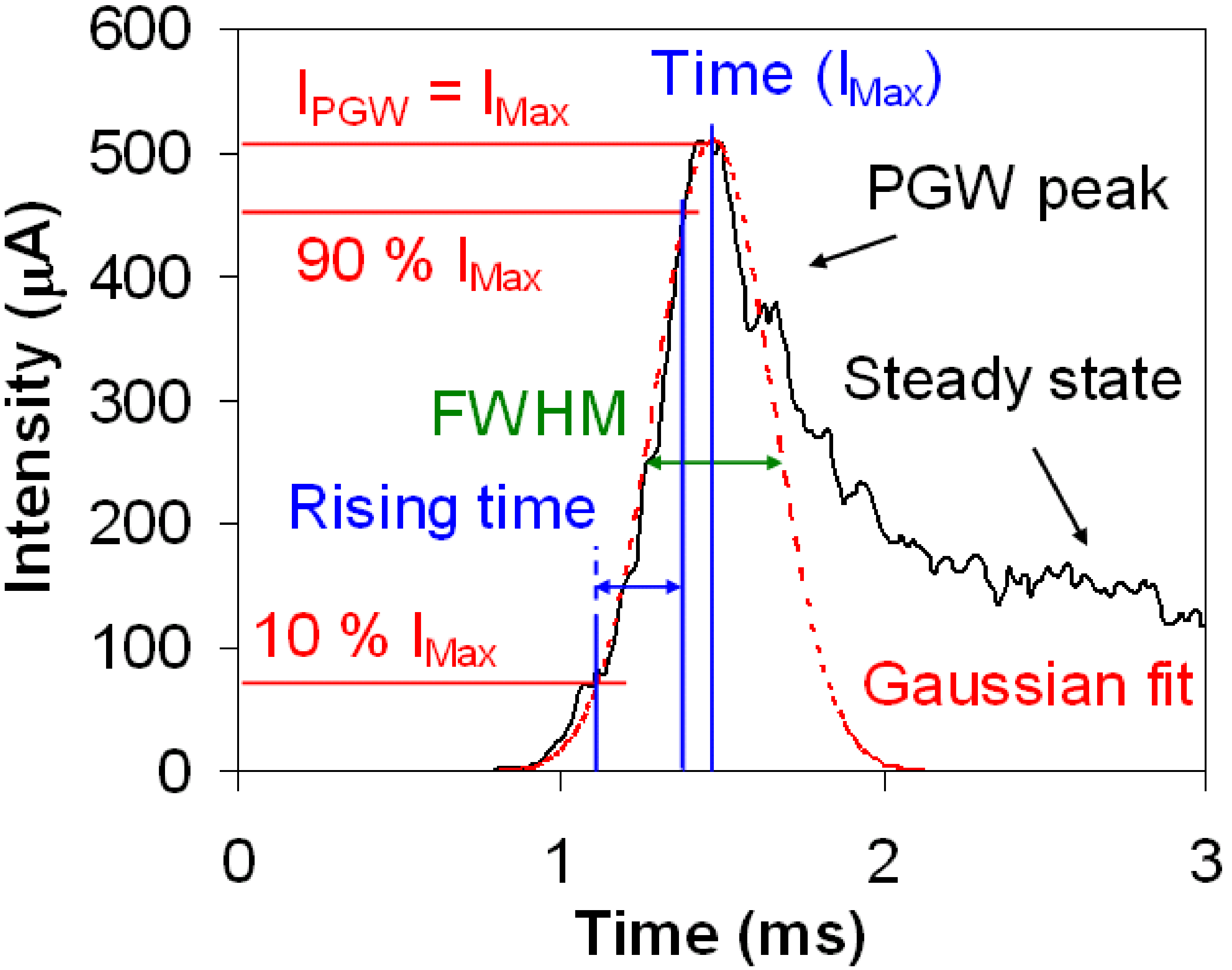
w=<E>*Ne

<E> - average electron energy over EEDF

Ne - electron concentration.

Plotted for:
SMIS`37
37.5 GHz
100 kW

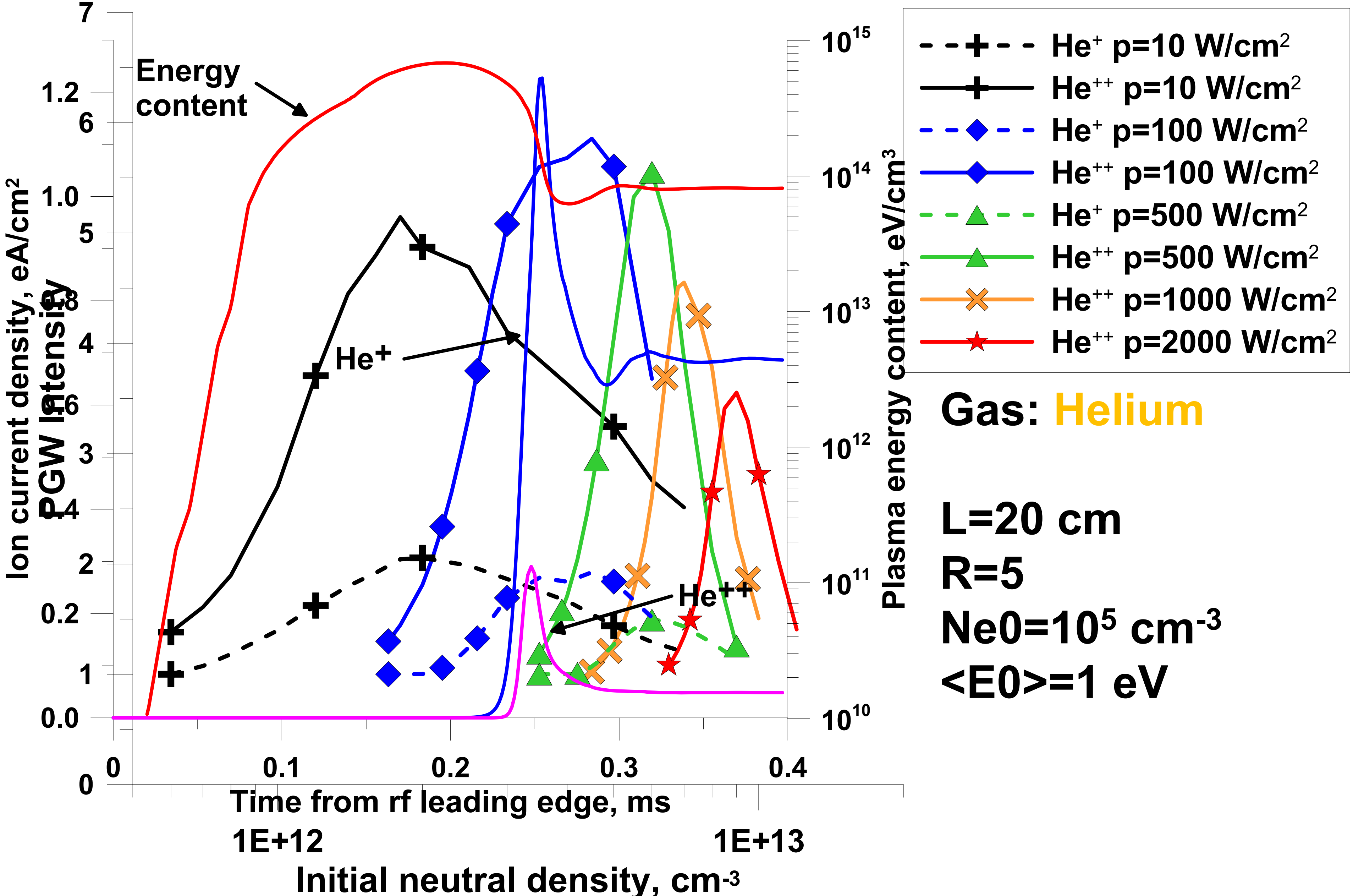
Preglow parameters definition



Intencity:
Int=Imax/
I(steaty-state)

T. Thuillier et all. R.S.I., 79, 02A314, 2008

PGW Intensity 28 GHz

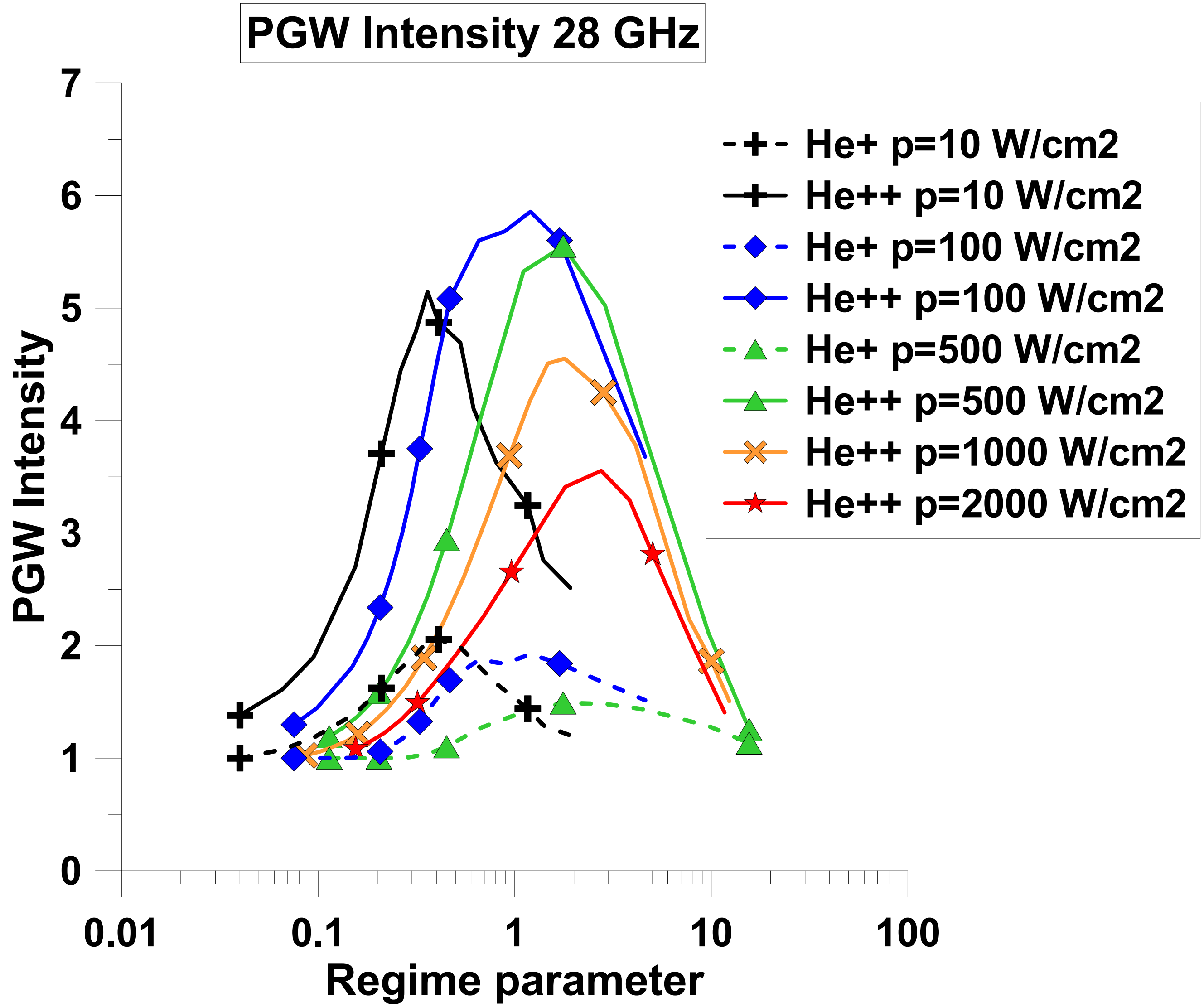


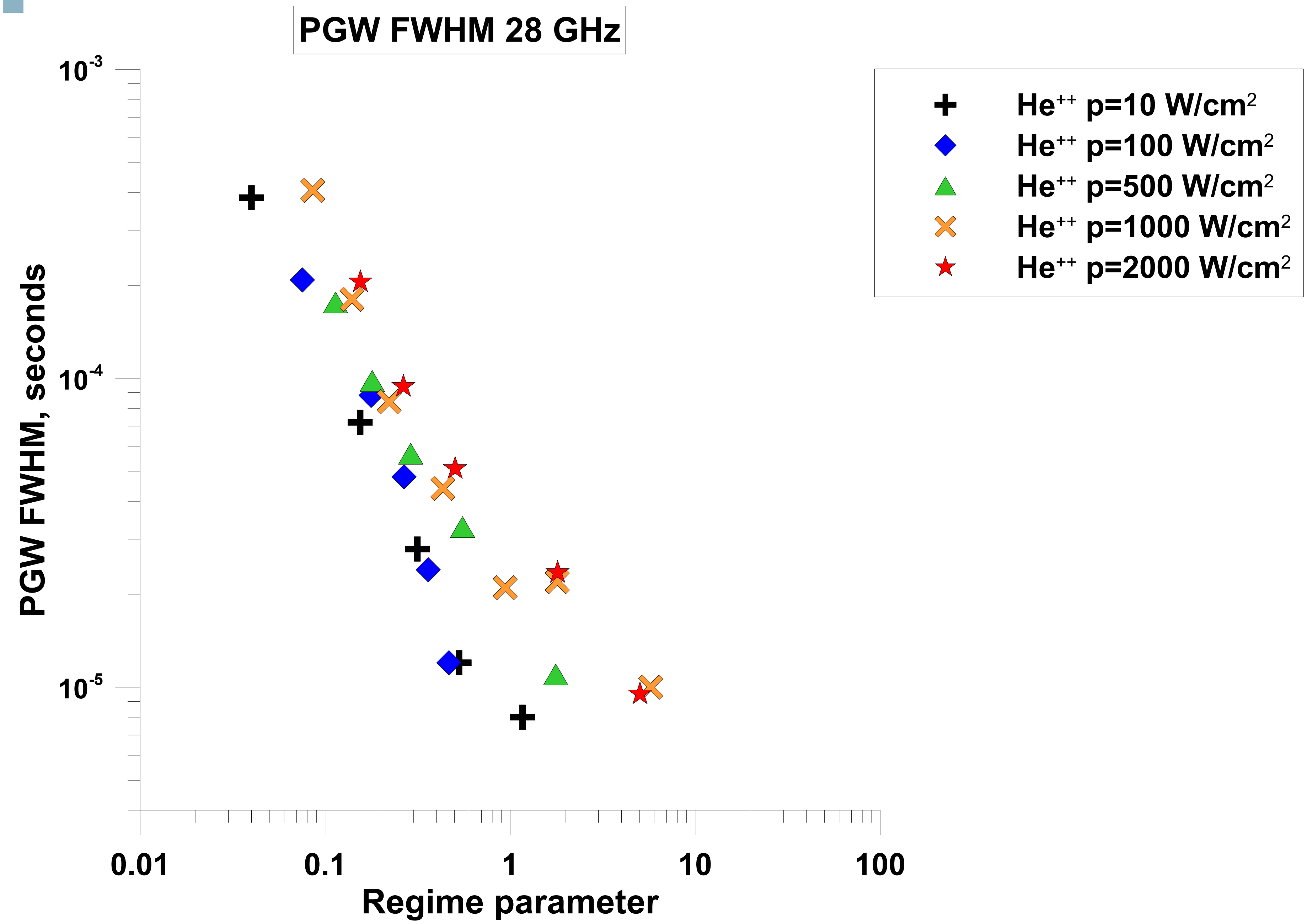
Gas: Helium

L=20 cm
R=5
Ne0=10^5 cm^{-3}
<E0>=1 eV

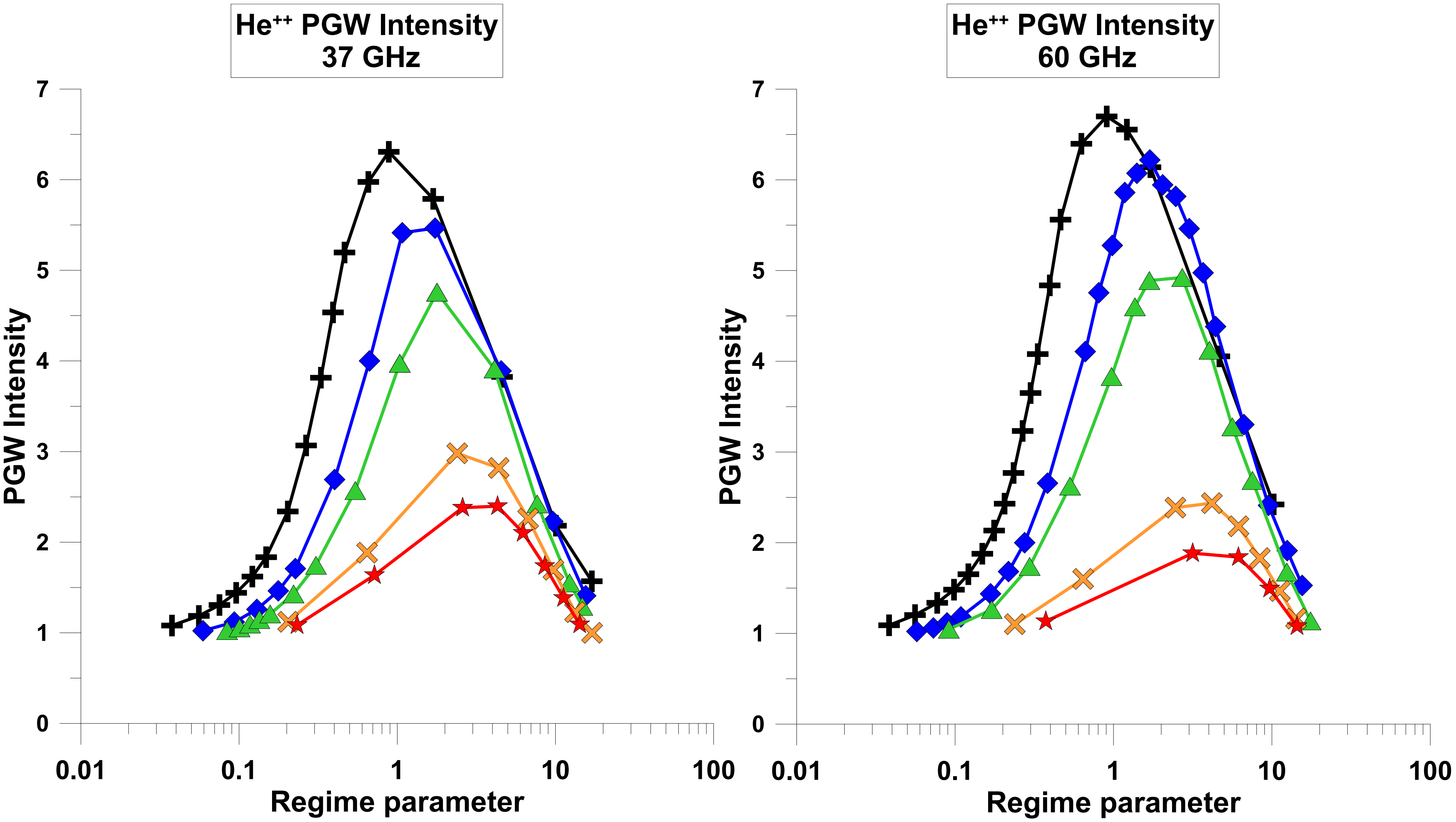
$RP \equiv \tau_g / \tau_s$

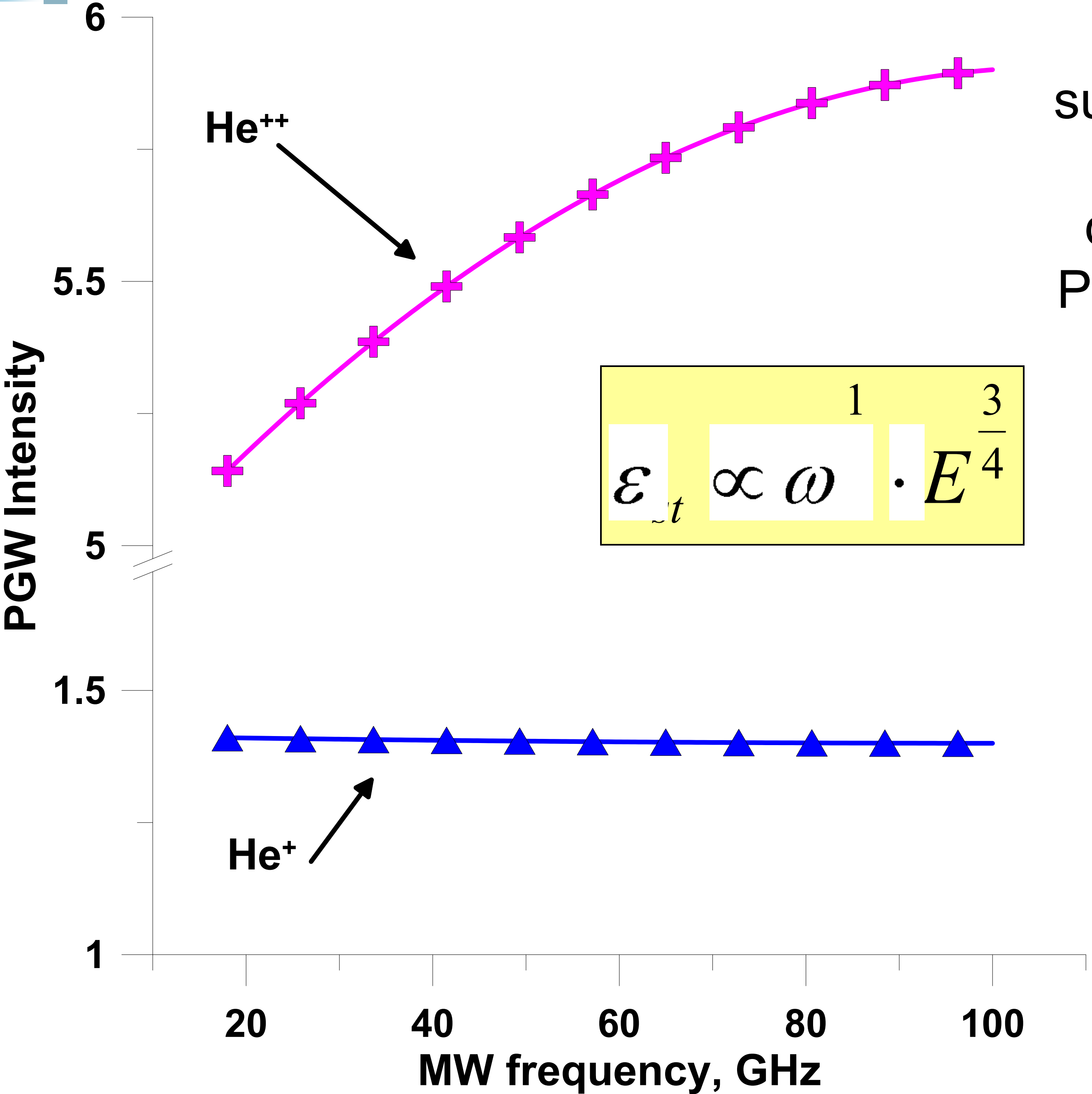
RP<<1 – classical confinement,
RP>>1 – gasdynamic confinement




PGW FWHM 28 GHz
PGW FWHM, seconds
10^{-3}
10^{-4}
10^{-5}
0.01
0.1
1
10
100
Regime parameter
He^{++} p=10 W/cm^2
He^{++} p=100 W/cm^2
He^{++} p=500 W/cm^2
He^{++} p=1000 W/cm^2
He^{++} p=2000 W/cm^2

Weak dependence of Preglow Int on Frequency





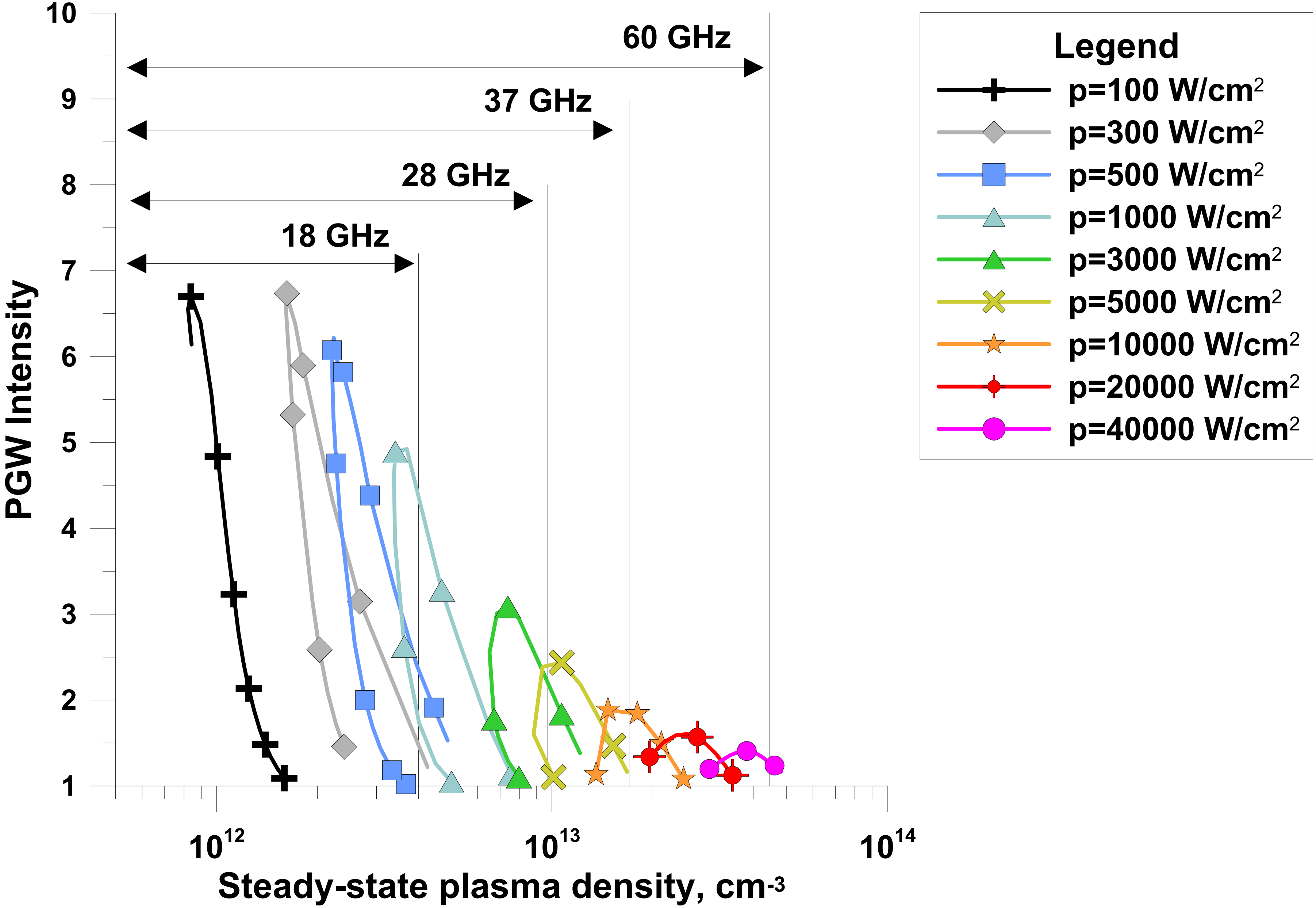
$$\varepsilon_{t} \propto \omega^{1} \cdot E^{\frac{3}{4}}$$

Stored at superadiabatic mode energy, which determines further Preglow, has a weak dependence on a heating frequency

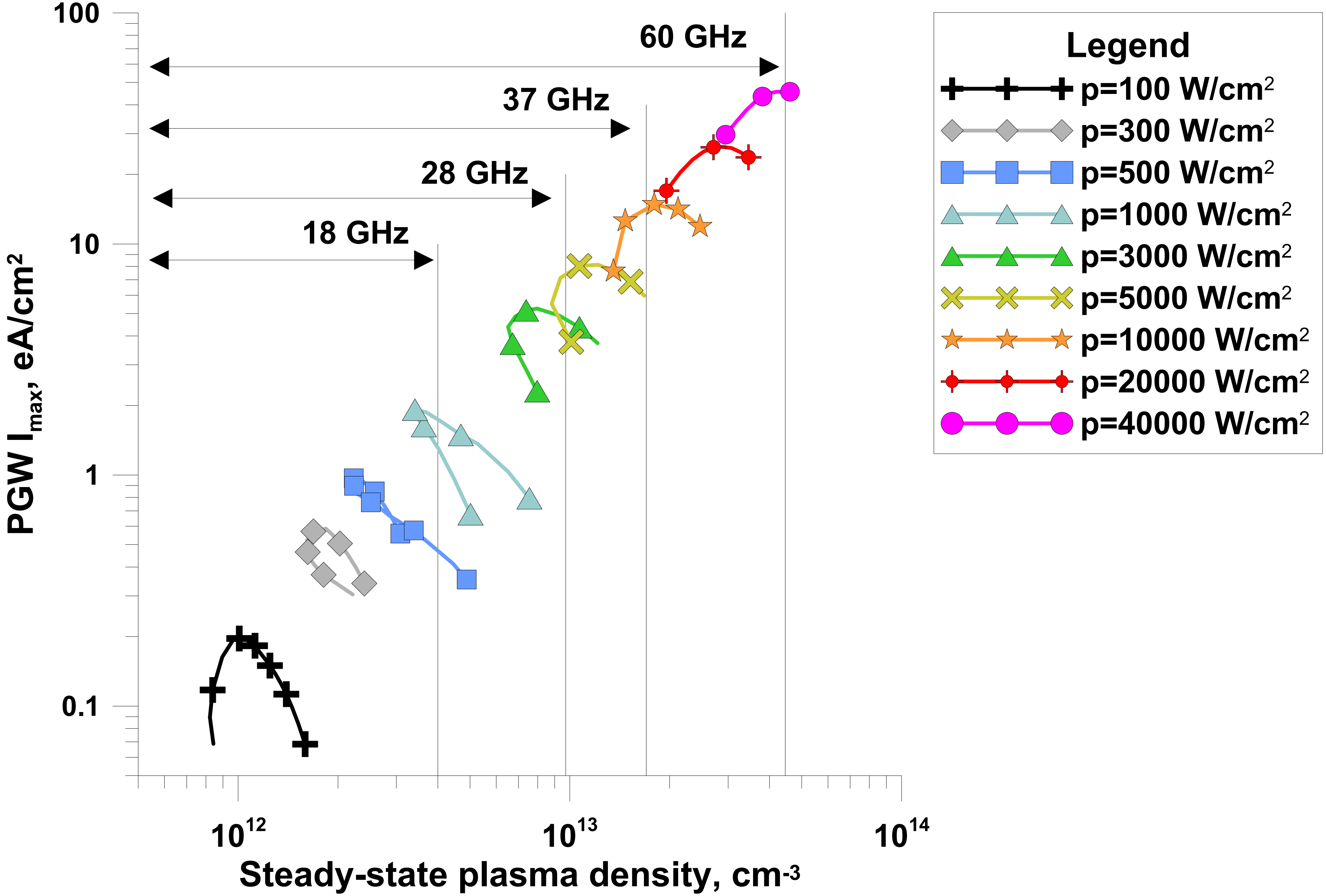
L=20 cm
R=5
Ne0=10^5 cm^{-3}
Te0=1 eV

RP=1.1
(Na0=5.5E11,
p=500W/cm^2)

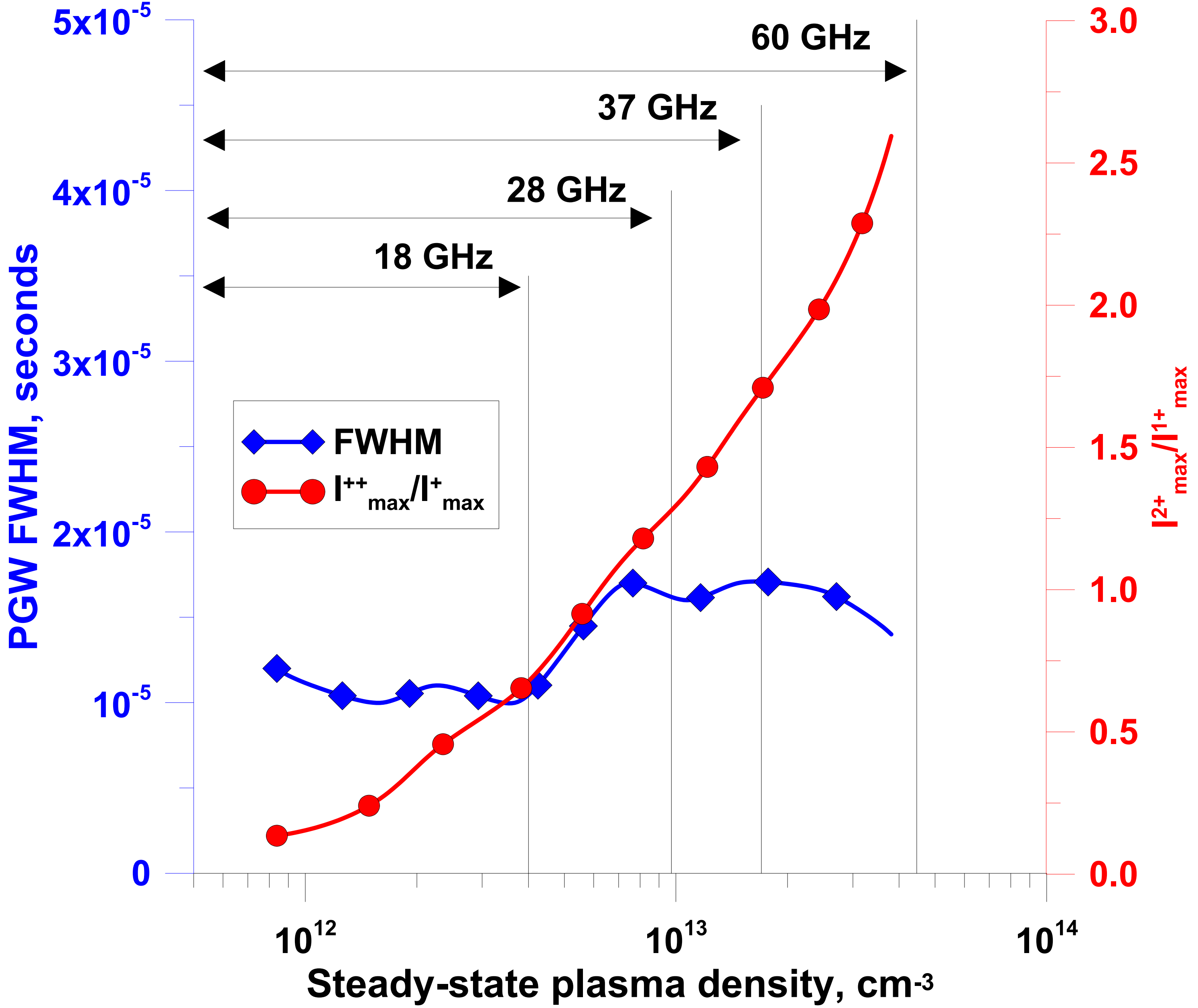
He^{++} PGW Intensity



He^{++} PGW I_{max}


PGW I_{max}, eA/cm^2
100
10
1
0.1
60 GHz
37 GHz
28 GHz
18 GHz
10^{12}
10^{13}
10^{14}
Steady-state plasma density, cm^{-3}
Legend
p=100 W/cm^2
p=300 W/cm^2
p=500 W/cm^2
p=1000 W/cm^2
p=3000 W/cm^2
p=5000 W/cm^2
p=10000 W/cm^2
p=20000 W/cm^2
p=40000 W/cm^2

FWHM & Current ratio



Conclusion

- New, more physical explanation of Preglow phenomenon is suggested.
- Provided results show dependence of Preglow principal parameters on experimental conditions.
- Preglow effect may be observed in almost every ECR source; a proper choice of initial conditions may ensure the phenomenon existence.
- The proposed scaling demonstrates that an ECR source with plasma heating by radiation at a high frequency (37 GHz and higher) seems to be the most effective to generate pulsed beams of multicharged ions with current density of several eA/cm2 and higher and duration less than 50 µs.
- The next step is experimental investigation of the preglow effect on the SMIS`37 facility with 37.5 GHz @ 100 kW pumping.