# Preplasma effect on the hot electron generation at the action of sub-relativistic laser pulse onto the surface of solid targets

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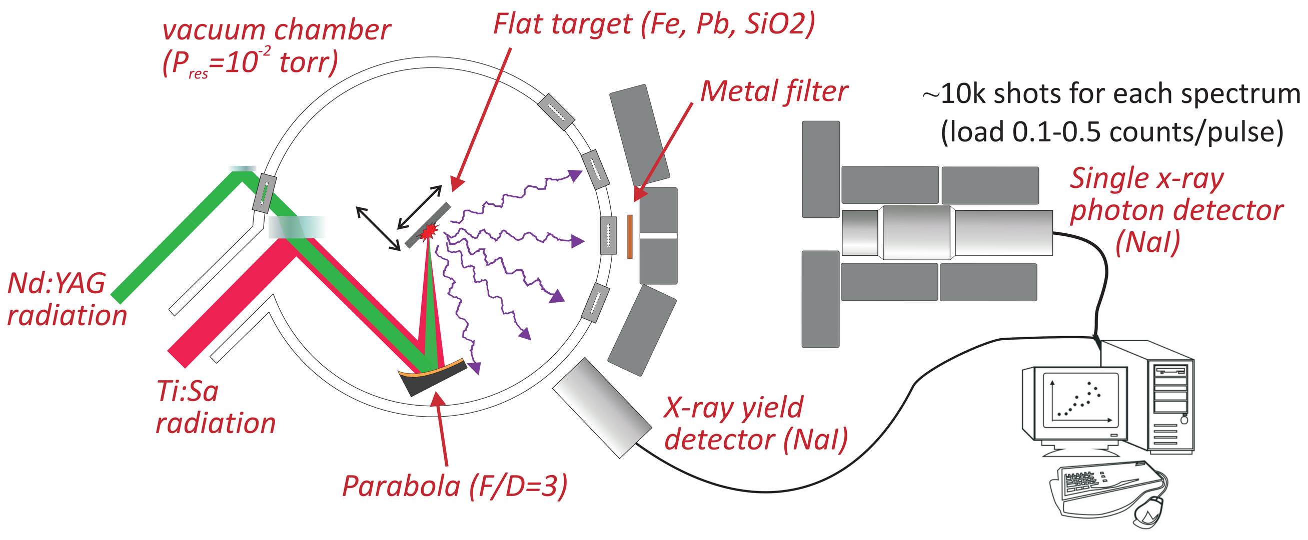
## INTRODUCTION

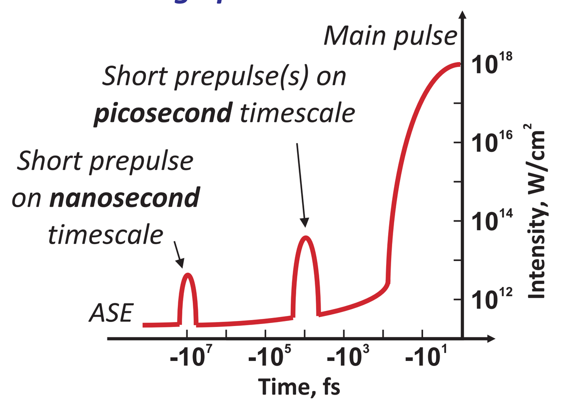
**The influence of different regimes of preplasma formation on the hot electron acceleration is studied at the action onto the surface of solid targets of a sub-relativistic femtosecond laser pulse with varied prepulse temporal and amplitude structure.**

**The generation of hot electron component with temperature higher than 1 MeV is observed for long scale warm preplasma due to excitation of relativistic effects in subcritical density region. The experimental results are supported by PIC simulations and optical shadowgraphy of preplasma cloud.**

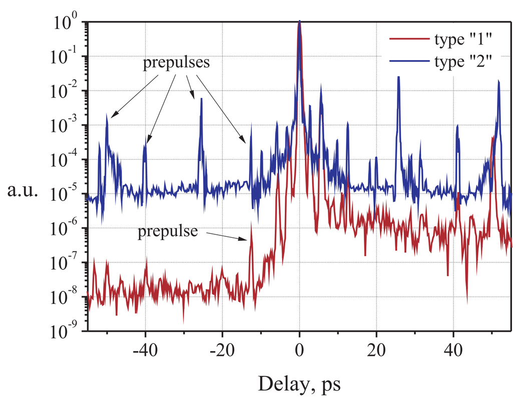
## EXPERIMENTAL SETUP & PULSE TEMPORAL STRUCTURE




*Rough pulse structure*




*3rd order correlation functions of type "1" & "2" pulses (see below)*




**Laser pulse (Ti:Sa) parameters:**
- pulse duration – **45-400 fs**;
- wavelength – **0,8 μm**;
- energy on target – **5-15 mJ**;
- **peak intensity - 0.5-50x10$^{17}$ W/cm$^2$**

**Nd:YAG pulse parameters:**
- pulse duration – **13 ns**;
- wavelength – **0,532 μm**;
- energy on target – **30 mJ**;
- intensity – **10$^{12}$ W/cm$^2$**

***Origins of prepulses in high power lasers:***

*- The origin the short prepulse on **nanosecond** timescale is the leakage of the radiation through the Pockells cell based contrast cleaner.*

*- The short prepulses on **picosecond** timescale come form the reflections and nonlinear transformation in the stretcher-amplifier-compressor system.*

*- The **ASE pedestal** arrives from the mismatched pump injection in the Ti:Sa crystal of the amplifier.*

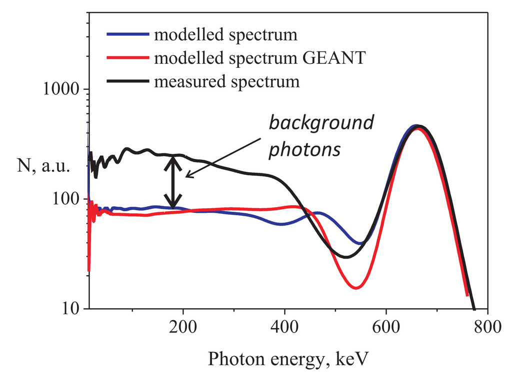
In our experiments we used 3 different target material: **Fe**, **Pb** and **SiO2**. This allowed us to elucidate the peculiarities of the plasma, formed onto the targets with different ionization thresholds.
By adjusting the amplification system of the laser we could obtain pulses with two different level of ASE. Detuning the Pockells cell in the amplifier the short prepulse at nanosecond time scale could be introduced. Finally, we also used the radiation of an additional Nd:YAG laser with controlled time delay to the main femtosecond pulse to study in detail the influence of the preplasma on the hot electron generation.

We also increased the pulse duration from **45** to **350 fs** with ***constant fluence*** to study the hot electron component behavior at approximately the same preplasma scalelength, which is mainly defined by the ASE and prepulses.

## INITIAL X-RAY SPECTRA RECONSTRUCTION MODEL

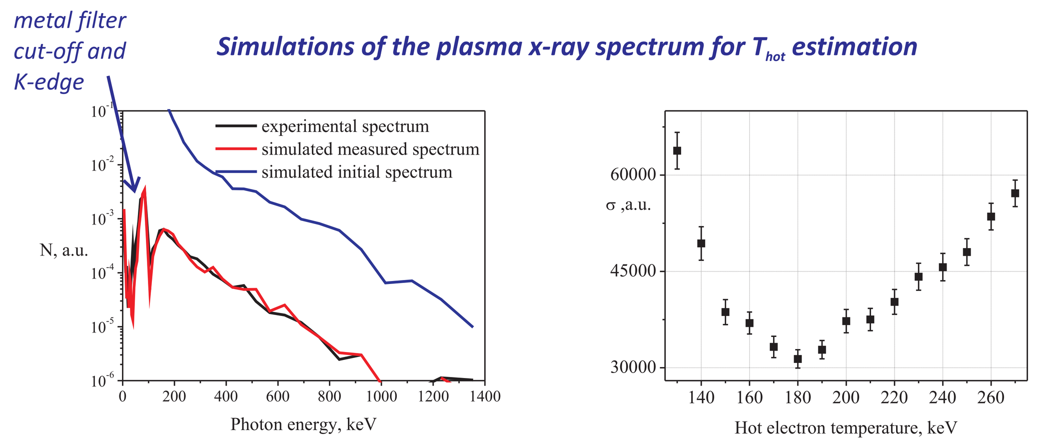
The initial x-ray spectra of plasma were reconstructed by using the original Monte-Carlo code for simulation of the interaction of x-ray photons with scintillating medium.

*Cs-137 X-ray spectrum*

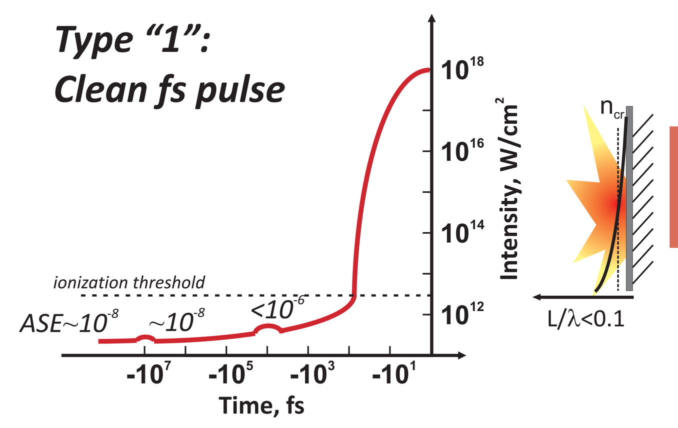



The hot electron temperature was estimated by finding the minimum deviation of the modelled spectrum from the experimentally measured. The error of the $T_{hot}$ value was assumed as the interval of $T_{hot}$ within which the excess of the deviation is less than 10% from the minimal value.

*Simulations of the plasma x-ray spectrum for $T_{hot}$ estimation*

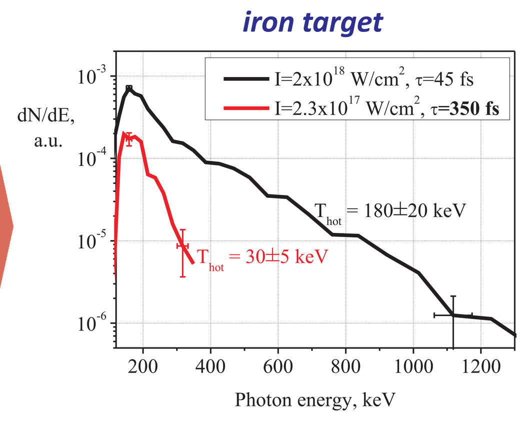



## RESULTS FOR VARIED TYPES OF PULSE CONTRAST




*Prepulses intensity is kept below the ionization threshold*

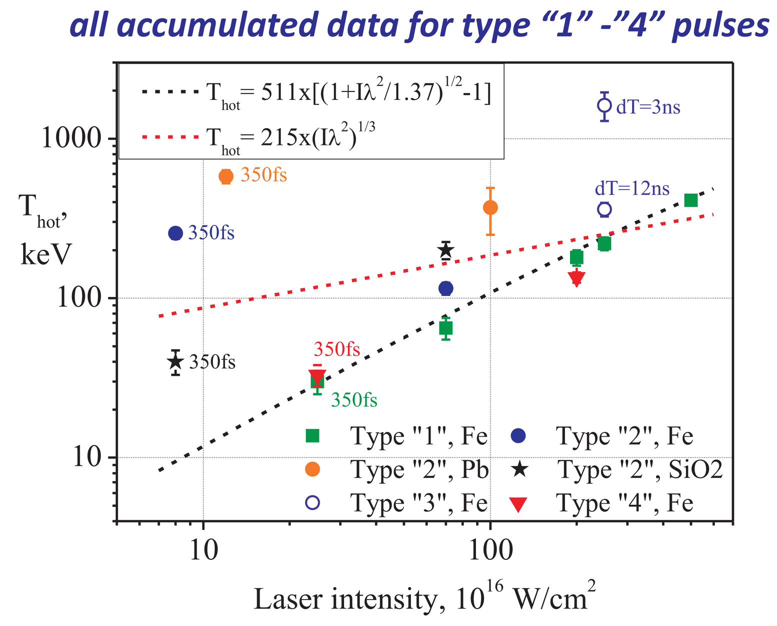
*iron target*

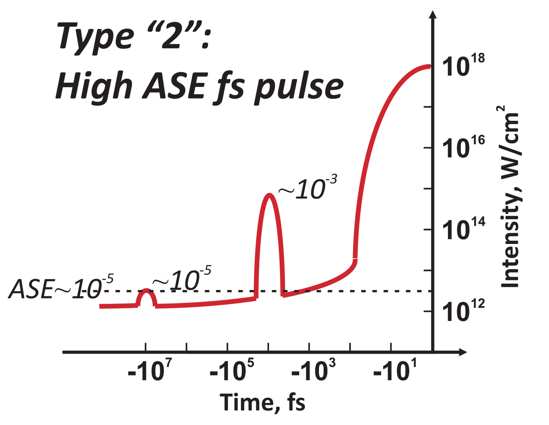



**Hot electron temperature scaling consistent with the ponderomotive heating**

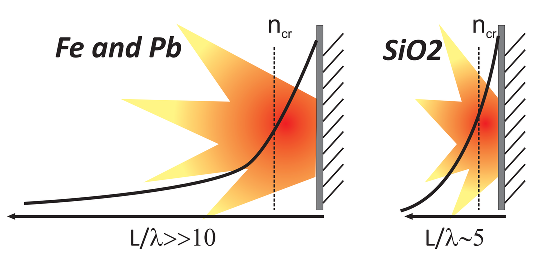
The hot electron temperature scaling fits well with the ponderomotive heating mechanism acting in the case of sharp plasma-vacuum interface. At increased pulse duration the electron temperature decreases according to the intensity reduction.

*all accumulated data for type "1" -"4" pulses*



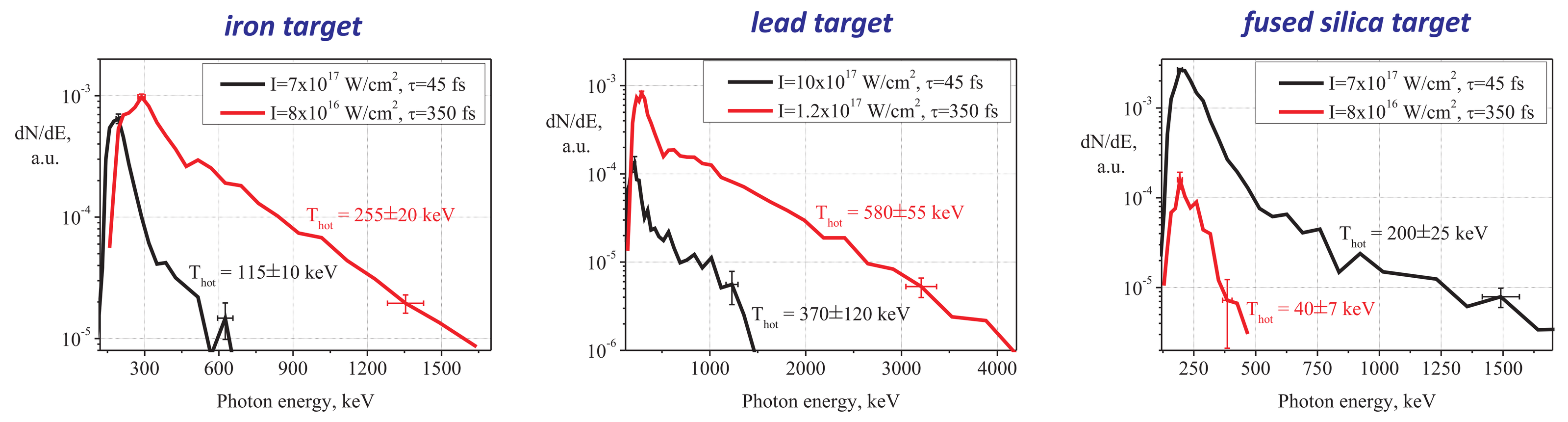




The spectra behavior indicates, that the hot electron generation mechanism is dependent on plasma scalelength, pulse intensity and duration. For metal targets the $T_{hot}$ scaling is not consistent with resonant heating. Two possible effect may be involved: **parametric plasma wave excitation** near 1/4 critical density (TPD and SRS) and **stochastic heating** in cross-propagating waves of incident and reflected laser radiation. The results for long pulse are **independent on chirp sign**.




*Due to higher ionization threshold the preplasma at dielectric target surface is less extended for the same prepulse parameters.*

*iron target* / *lead target* / *fused silica target*



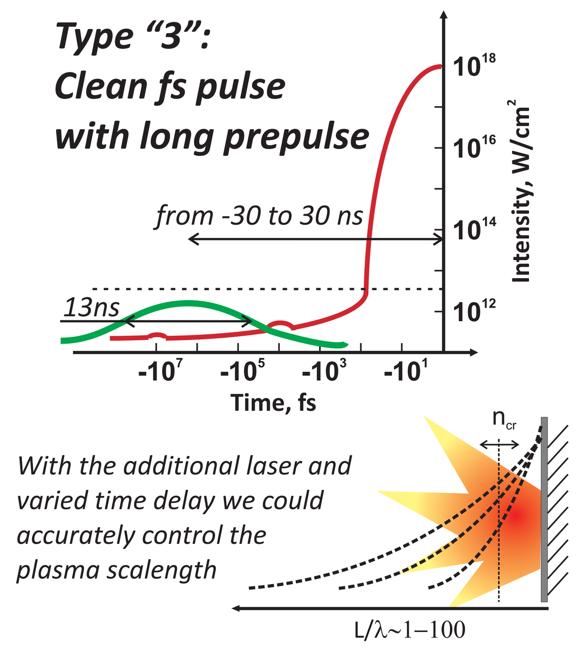

**Emission of 3/2ω is observed**

**Parametric instabilities in long scale preplasma of metal targets**

**Strong dependence on pulse duration**

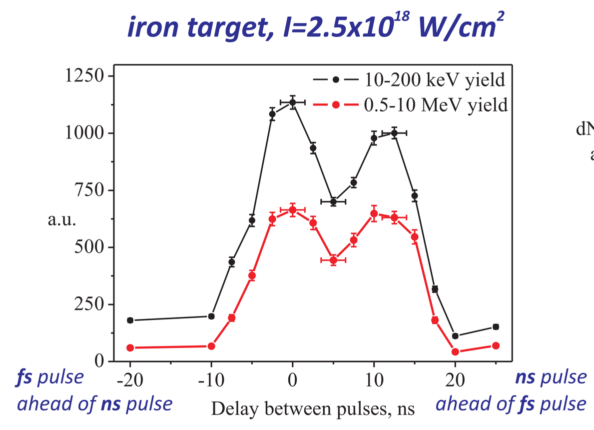
**Much higher ionization threshold for SiO2**

**No "pulse duration" effect, "regular" resonant heating at slightly blurred plasma-vacuum boundary.**




*With the additional laser and varied time delay we could accurately control the plasma scalelength*

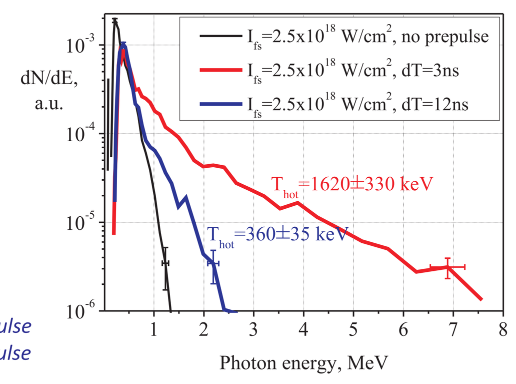
*iron target, I=2.5x10$^{18}$ W/cm$^2$*



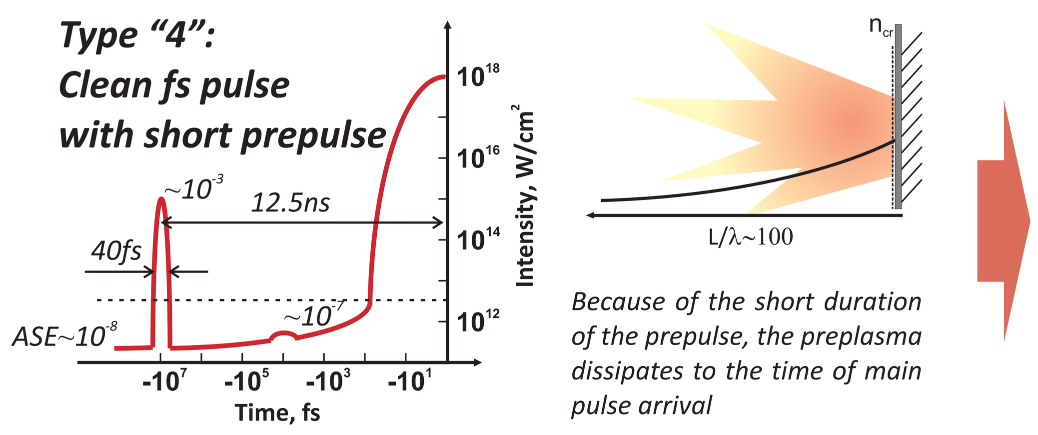

**Two maxima of x-ray emission**

**Two different mechanisms of hot electron acceleration**

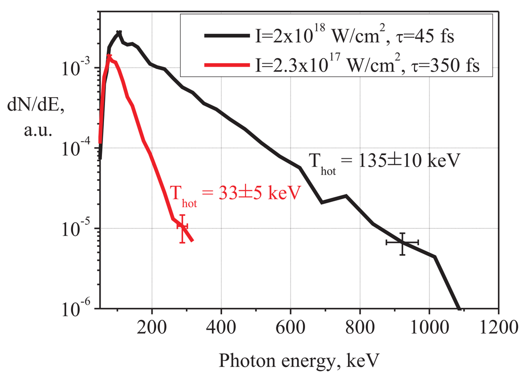
*iron target*




Two different mechanism of hot electron generation may be acting at different preplasma configuration. The first, at a delay of ~0 ns acts at higher density and temperature of plasma, when it is maximally heated by the long ns prepulse. The second, at a delay of ~12 ns play a role in a extended preplasma profile with subcritical density (TPD and SRS). The lower hot electron temperature at ~12 ns may be attributed to the low femtosecond pulse duration (45 fs, as for the case of type "2"), as the TPD process is not saturated and the plasma wave rises substantially, when the pulse duration is increased.




*Because of the short duration of the prepulse, the preplasma dissipates to the time of main pulse arrival*




**Dissipation of laser energy in low density cloud of matter**

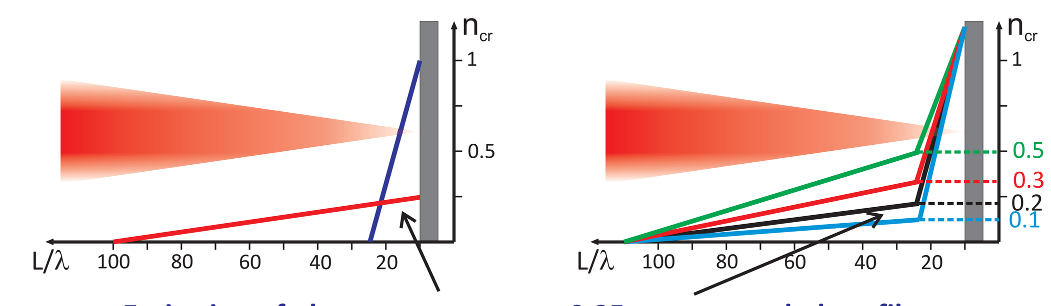
After 12.5ns of the short prepulse action the density of the preplasma and its temperature are already low, and the growth of relativistic effects is not observed. The energy of the main pulse is dissipated in the cloud of matter. For increased pulse duration the hot electron temperature decreases according to the lowering of the intensity.

## 2D PIC SIMULATION OF LASER-PLASMA INTERACTION

To support our experimental results we simulated the laser-plasma interaction using fully relativistic 3D3V PIC code "**Mandor**". The preplasma was modeled as a sum of two profiles with different slopes. The cases of only low density and sharp profiles were also simulated. The simulation was two-dimensional.

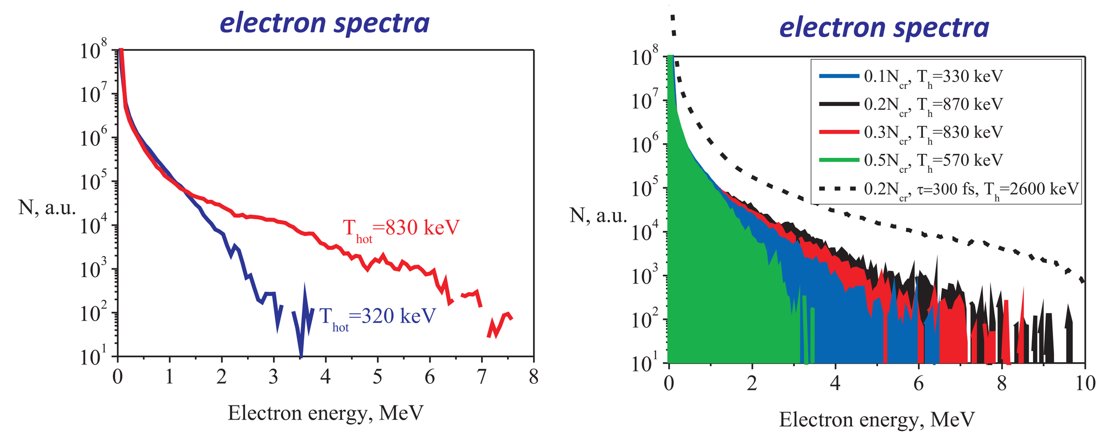
***Laser pulse parameters:***
*pulse duration - **50 or 300 fs**; polarization - **p**; wavelength - **1 μm**; peak intensity - **10$^{18}$ W/cm$^2$**; focal spot diameter - **5 μm**.*

***Target parameters:***
*thickness - **5 μm**; density - **5 $n_{cr}$**.*




**Excitation of plasma wave near n=0.25 $n_{cr}$ at extended profile**

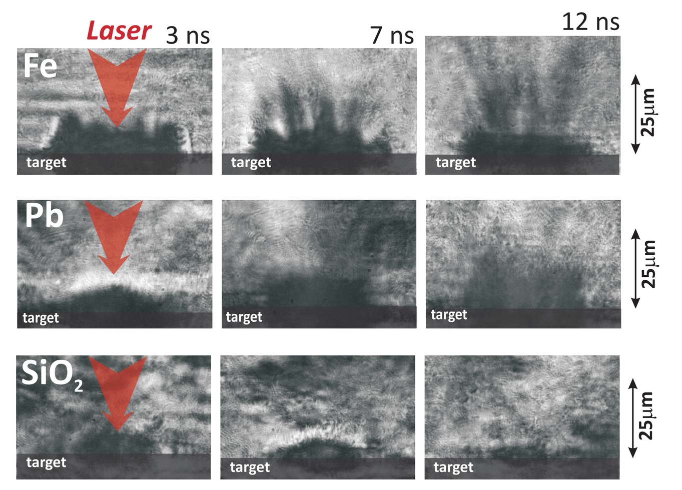
*electron spectra* / *electron spectra*




For extended profile the propagation of the laser pulse near the **1/4 critical density region** leads to the formation of high energetic tail in the electron distribution due to **plasma wave excitation** by the parametric instabilities in plasma. When this point is near the sharp profile ("**0.2-0.3N$_{cr}$**") with high reflectivity, the plasma wave is fueled by the incident and reflected laser radiation, increasing the hot electron temperature. At **300fs the tail temperature is much higher** due to increased plasma wave growth rate, which is consistent with our experimental results. The movement of the 1/4 $n_{cr}$ point toward the tail of the plasma slope (case "0.5N$_{cr}$") approximates the situation to the case of sharp density profile, when the wave excitation is not observed.

## SHADOWGRAPHY OF PREPLASMA

The pictures of the preplasma evolution, formed onto the surface of Fe, Pb and SiO2 targets by the action of a femtosecond laser pulse with an intensity around **10$^{15}$ W/cm$^2$**, were obtained. The **type "4"** pulse temporal structure was simulated.




A huge cloud of preplasma is formed onto the surface of metal targets, which almost dissipates at a delay of 12 ns, which proves the assumption of the high density long scale corona presence necessity for growth of relativistic effect of electron acceleration. Due to high ionization threshold the preplasma extension onto SiO2 target is reduced.

## CONCLUSIONS

**It is demonstrated that the formation of a dense long scale-length warm preplasma by the action of long prepulse or high level ASE pedestal onto the surface of metal targets leads to generation of electron with energies up to a few MeV. The effect may be connected with growth of parametric instabilities near ¼ critical density (TPD and SRS). At the same time the temperature rises when the main pulse duration is increased up to a few hundreds of femtoseconds with constant laser fluence. Such behavior is not observed for low density large preplasma and also for high ablation and ionization threshold material, with much less extended profile.**