Study of the ion generation and acceleration in plasma produced by the PALS laser pulse

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OUTLOOK

1. **Introduction.**

2. **Studies of fast ion generation in by PALS laser radiation interracting with different targets.**

3. **Production of high-current heavy ion jets using the short-wavelength PALS laser pulse.**

4. **Influence of a pre-pulse plasma on ion emission from the laser-produced plasma.**

5. **Application of laser-generated Ge ions for implantation into SiO_2 substrates (production of Ge nanocrystals).**

6. **Summary.**

1. Introduction

- *General*
- *Ion diagnostics used in the PALS experiments*
- *A typical experimental arrangement.*

GENERAL

- Studies of *plasma produced with high-power laser* are directed towards the determination of *physical processes* in such a plasma as well as towards important application – among others *optimisation of laser fusion (*ICF).

- Generation of *intense ion beams* from high-intensity laser-plasma interaction is a rapidly *developing research area* stimulated by *a variety of potential applications* from the technological ones through nuclear medicine up to high energy-density physics and ICF.

- In the *long-wavelength laser-plasma interaction*, *the nonthermal processes (e.g. phenomena)* transfer a part of laser energy into the energy of *hot electrons*, which accelerate *fast ions*.

- There are also *nonlinear phenomena (e.g. ponderomotive forces, and self-focusing of the high intensity laser beam)*, which can lead to the fast ion production also in the case of the *short-wavelength laser-plasma interaction*.

GENERAL (contin.)

- In the selected PALS experiments, presented here we have studied the characteristics of laser-produced ions in dependence on *laser pulse parameters, illumination geometry and target material*.

- The careful *optimisation of irradiation conditions* of high-Z targets has been performed to generate *high intensity ion beams* using a short-wavelength PALS laser pulse.

- We investigated also the influence of the *laser focus position* with respect to the target surface on the characteristics of the expanding plasma, especially on the *ion beam angular distribution*.

- *A slab target of Ge* irradiated by the laser beam was used for generation of ion streams destined *for implantation into SiO_2 films* prepared on the surface of Si single-crystal substrates.

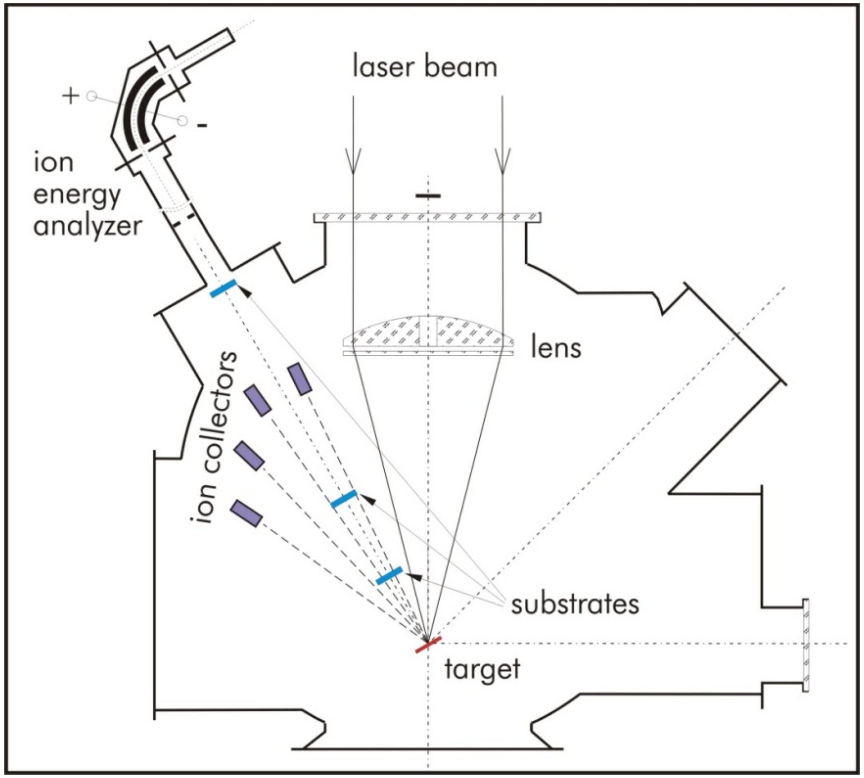
A TYPICAL EXPERIMENTAL ARRANGEMENT

The PALS laser parameters:

- **pulse duration: ~0.3 ns,**
- **minimal laser spot diameter: ~ 70 μm**
- **pulse energy:**

  at wavelength of 1315 nm (1 ω_0): < 750 J

  at wavelength of 438 nm (3 ω_0): < 250 J
- **power density – up to 10^{16} W/cm^2.**



The laser beam was focused onto a slab or foil targets by means of an aspherical lens at angles of 0º or 30º with respect to the target normal.

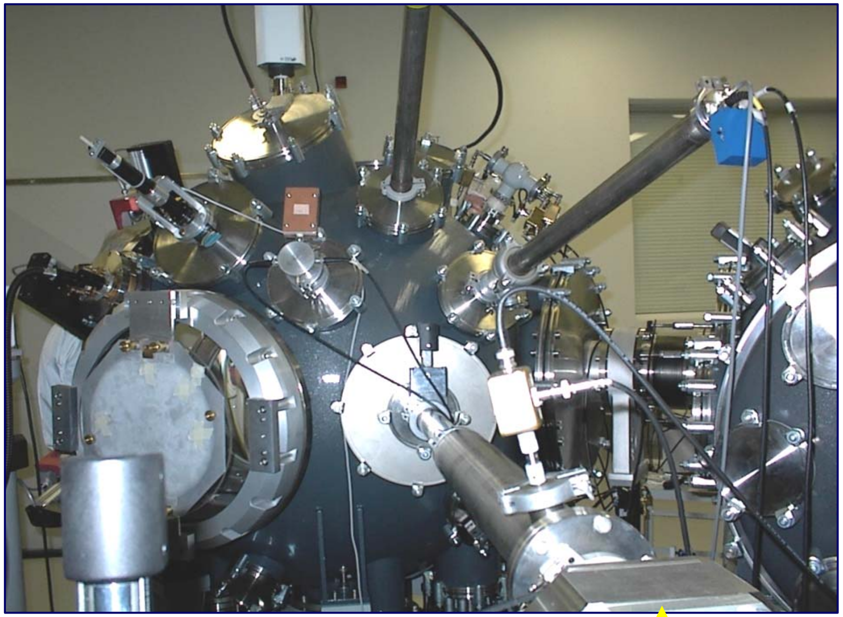
The characteristics of the *ion streams* were investigated using diagnostics based on the *time-of-flight method and trace detector.*

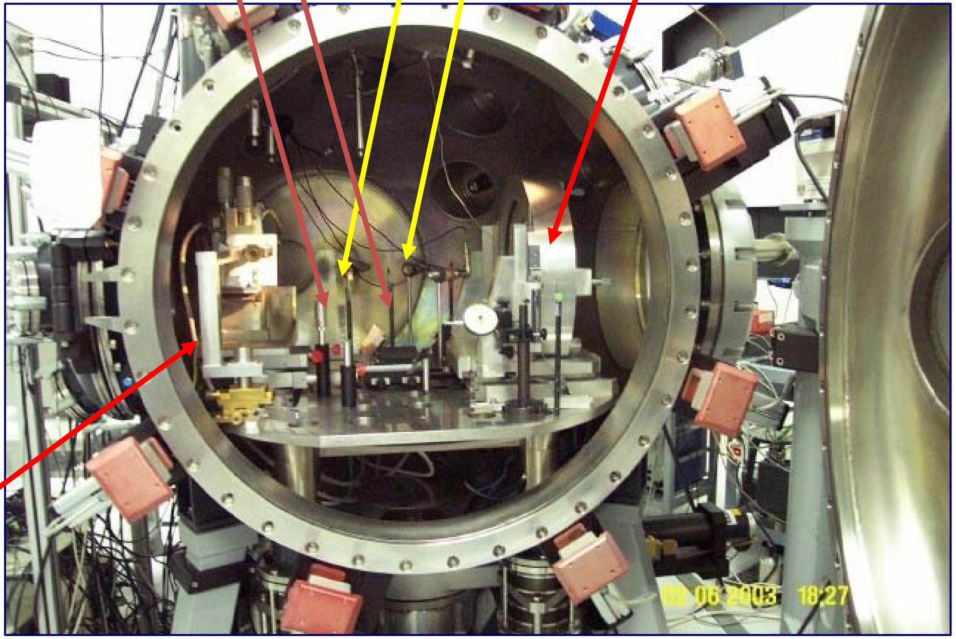
The x-ray emission was measured with the use of ***semiconductor detectors*****.**

In some experiments ***the crater dimensions were measured*****.**

The SiO_2 samples implanted with laser-produced Ge ions were placed at an angle of ~0º and *at different distances*.

EXPERIMENTAL ARRANGEMENT FOR STUDIES OF LASR-PRODUCED IONS USING PALS LASER SYSTEM





Ion collectors

Implanted samples

Focusing lens

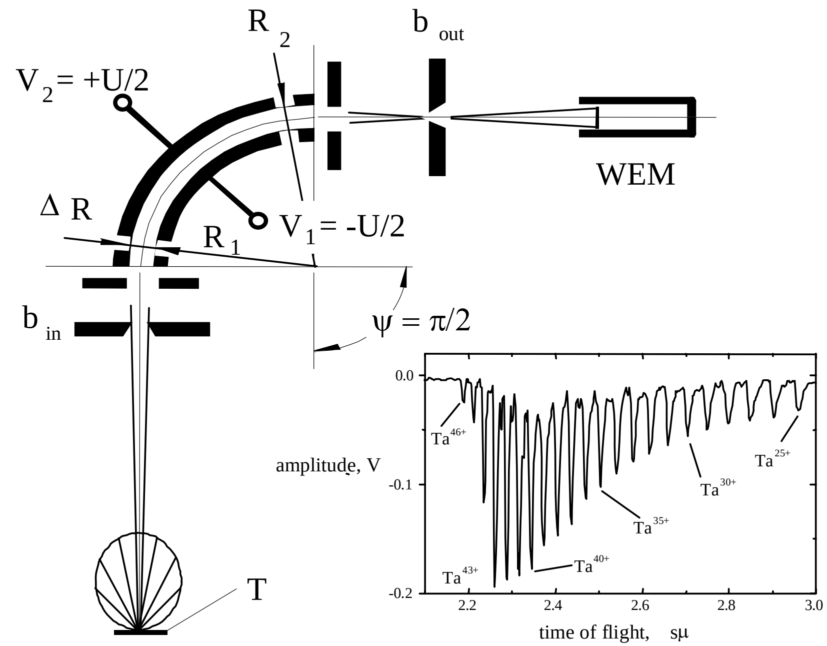
Ion energy analyser

Target holder

ION DIGNOSTICS BASED ON TIME-OF-FLIGHT METOD

An electrostatic ion energy analyzer (IEA)

Only ions with particular values of m_i/z can pass through the IEA and reach the detector (WEM).



From the equation of motion and time-of-flight of ions one can determine the essential parameters of particular ion species.

An ion collector (IC)

From the ion current or the time distribution of ion charge measured with the use of an ion collector one can obtain:

the temporal, dQ/dt, velocity, dQ/dv or energy dQ/dE_i distributions.

By integrating them it is possible to obtain: total charge, Q_T, total energy, E_T, carried by ions, mean energy of ions, $\langle E_i \rangle$.

2. Studies of fast ion generation by PALS laser radiation interracting with different targets.

The series of PALS experiments was devoted ***to optimise the processes of generation of the fast ions in dependence on illumination conditions and characteristics of targets.***

AN EXAMPLE OF ION COLLECTOR SIGNAL FOR Ta PLASMA

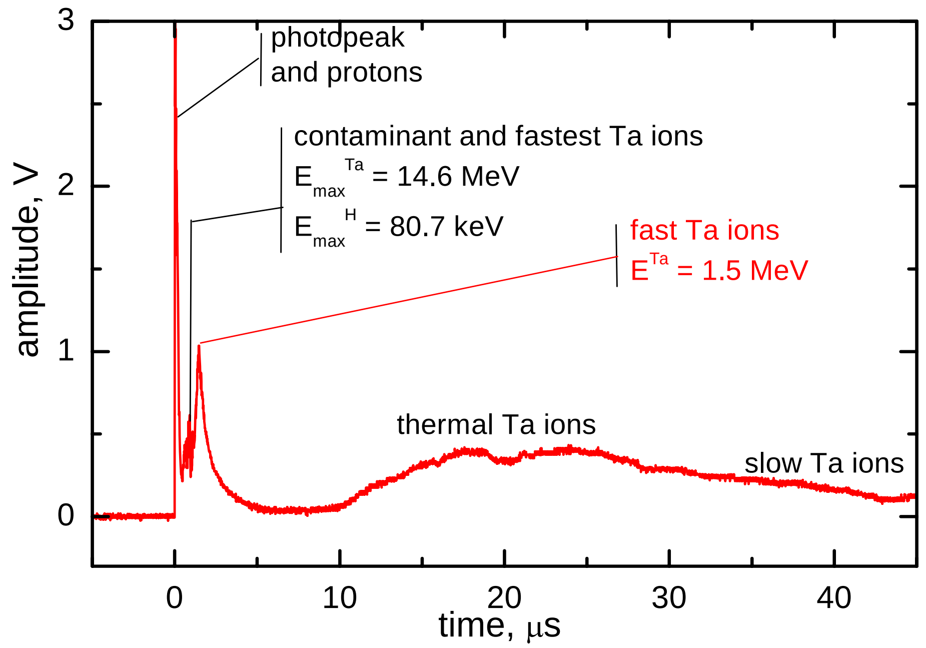
This IC signal was recorded along the target normal.
Ion collector signal shows the occurrence of *different group of ions* reaching the IC.

- **The *first* maximum represents *photopeak and contaminant ions* (mainly protons).**

- **The *second* ion group consists of *fast, high-Z ions.***

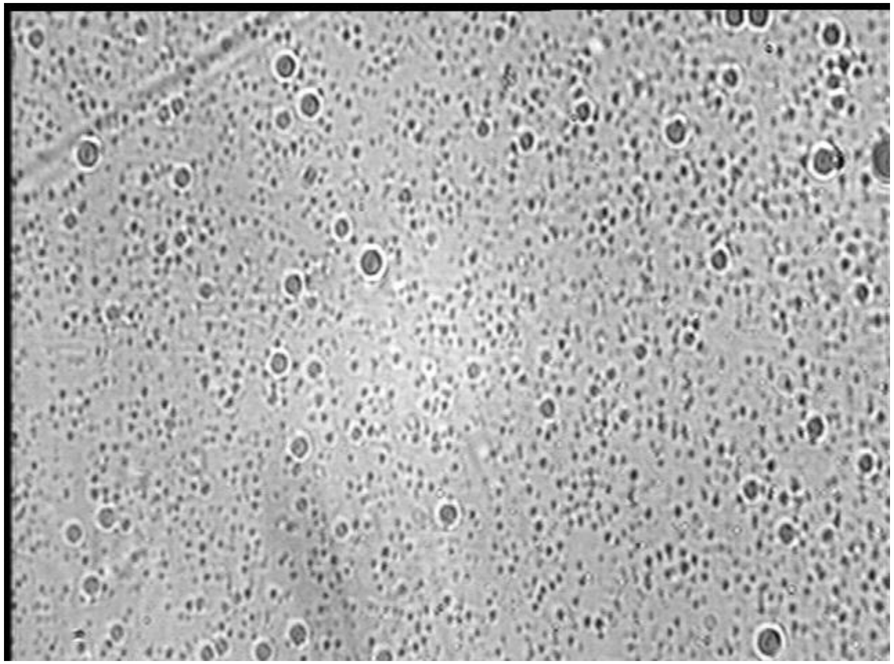
- **The *third* one corresponds to *thermal high-Z ions.***

- **The *forth* one consists of *slow high-Z ions* generated indirectly around the laser focus spot by the x-rays emitted from the hot plasma.**



MEASUREMENTS OF FAST IONS WITH THE USE OF SOLID STATE TRACK DETECTORS

- **Ion tracks were recorded on the PM-355 detector covered with** ***4 μm Al-foil filter*** **(three laser shots at $E_L \approx 80$ J).**
- ***The tracks of larger diameter*** **were inducted** ***by energetic (>22 MeV) Ta ions.***
- ***The small diameter tracks were produced by protons of energy >0.5 MeV.***
- **Track densities of >*10^7 tracks/cm^2* for Ta-ions were observed.**

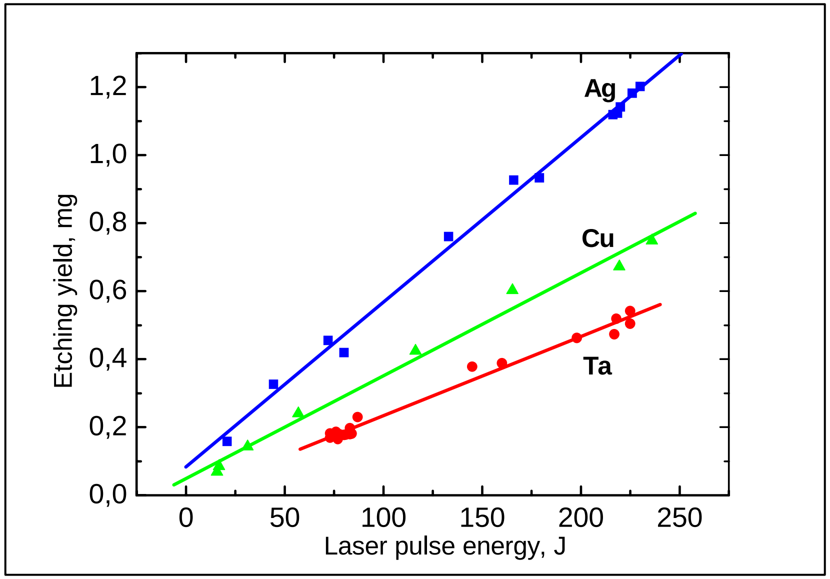


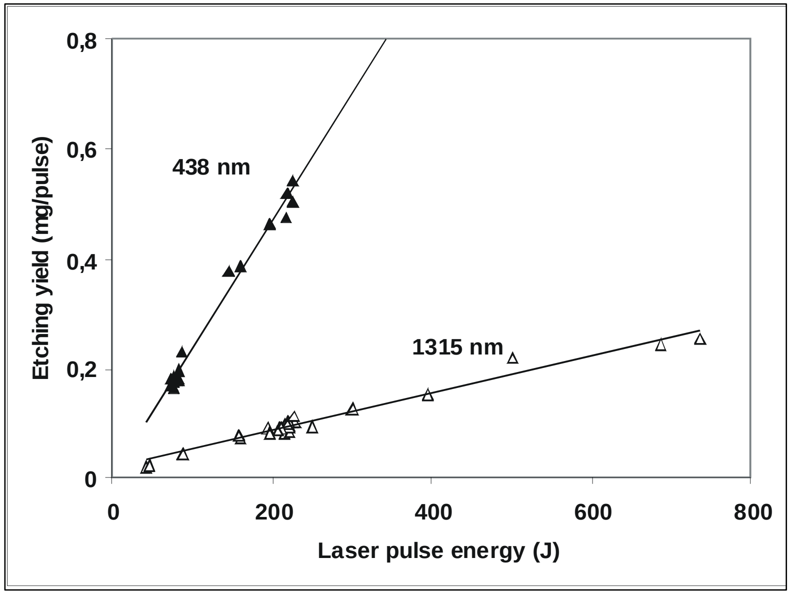
This result confirms the fact that Ta ions of energies > 20 MeV were emitted from the targets irradiated with the short-wavelength high-energy laser beam.

The Ta ion energies corresponded well to the maximum Ta ion energies determined from the ion collectors signals.

MEASUREMENTS OF ABLATION YIELD

A mass of material removed from the irradiated targets was calculated on the basis of the crater volume measurements.





The different etching yields demonstrated for Cu, Ag and Ta targets can be explained on the basis of their *different physical properties* (e.g. melting and boiling points, heat of evaporation and specific heat).

- **At *438 nm* significantly *higher ablation rates* were observed.**
- ***High ablation yields (maximum: ~ 0.55 mg per ~220-J pulse at 438 nm)* were measured as a function of the laser pulse energy at both the wavelengths.**

3. Production of high-current heavy ion jets using the short-wavelength PALS laser pulse.

In PALS experiment we investigated the influence of the *laser focus position* on the characteristics of the expanding plasma, especially *on generation of intense collimated ion beams* using a short-wavelength laser pulse.

EXPERIMENTAL ARRANGEMENT

Laser irradiation conditions:

The 3ω beam (λ_L= 0.438μm) of the PALS laser beam at *different energies* was focused onto Cu, Ta, Al or CH targets perpendicularly to the target surface.

Diagnostics:

- ***Ion collectors*** **placed at different angles,**
- ***X-ray detectors:*** **PIN Si detectors with different Al and Be filters to record both soft (~ 1keV) and hard (4 – 20 keV) X-ray signals,**

,

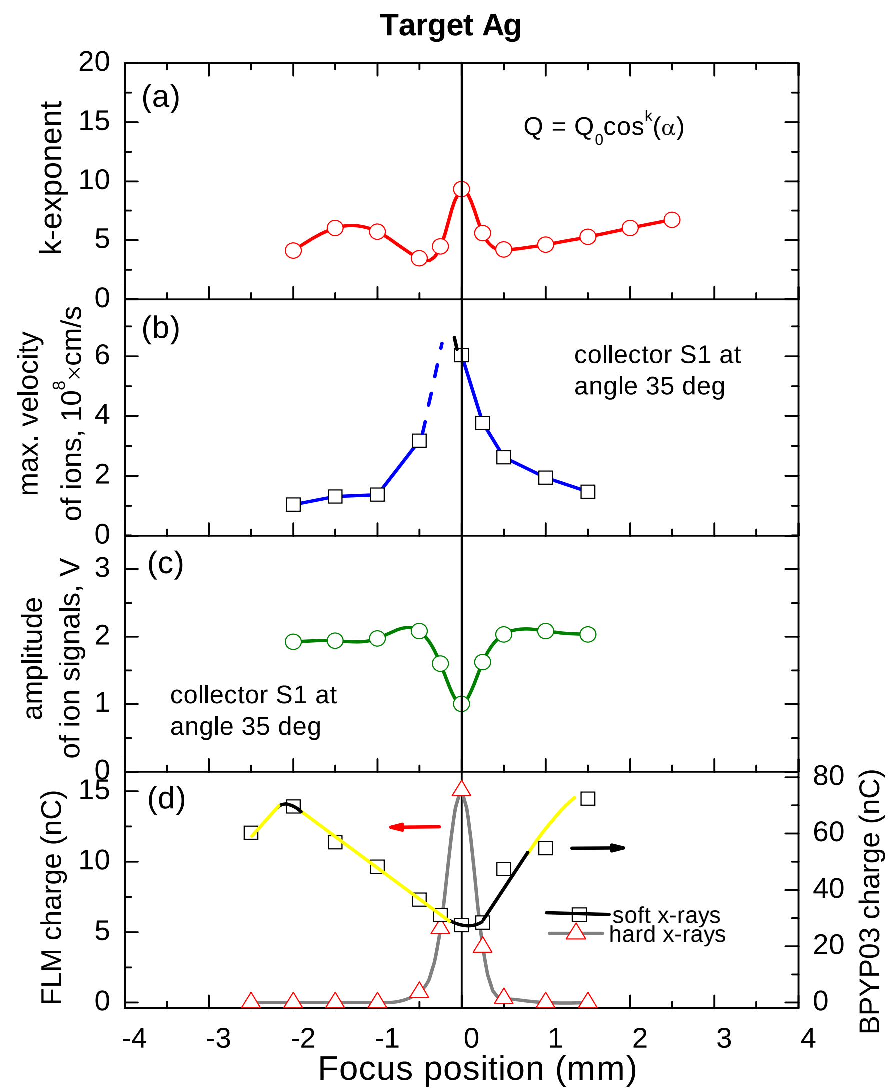
- ***A three-frame interferometric system*** **for time evolution of the plasma configuration.**

CHARACTERISTICS OF X-RAY AND ION EMISSION IN DEPENDENCE ON FOCUS POSITION (LASER INTENSITY)

The X ray emission in the soft channel is related to the volume of the plasma, which becomes the smallest just in the case of sharp focusing.

The peaking of the hard X-ray emission indicates the most intense production and then interaction of fast electrons with surrounding plasma and target material.

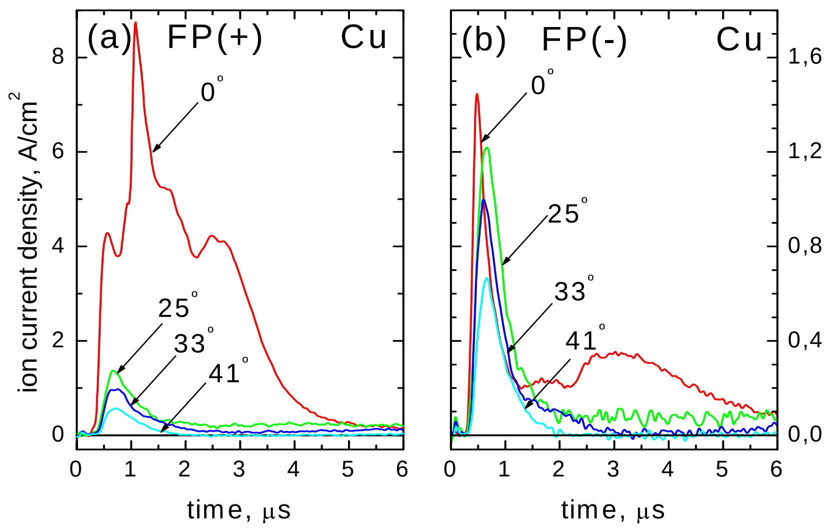
The hard x-rays are correlated with the fast ion emission at highest laser intensities.

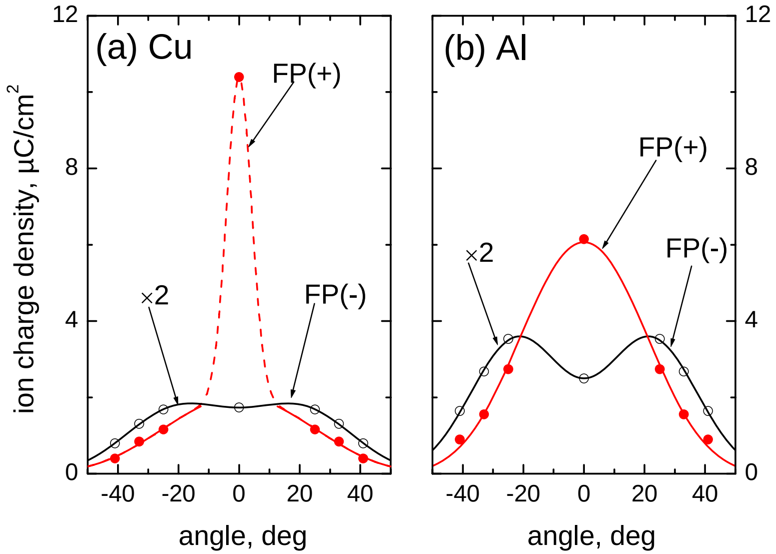


ANGULAR DISTRIBUTIONS OF ION CHARGE DENSITY MEASURED FOR TWO LASER FOCUS POSITIONS

Ion collector signals from Cu target recorded for different angles and two laser focus positions (+FP and –FP).

Angular distributions of the ion charge density for ions of velocities in the range (0.2-2) x10^{8}cm/s.





The generation of a highly collimated ion jet of very high ion current is possible when the laser beam interacts with the high-Z (Cu) target at FP(+) (the laser focus behind the target surface).

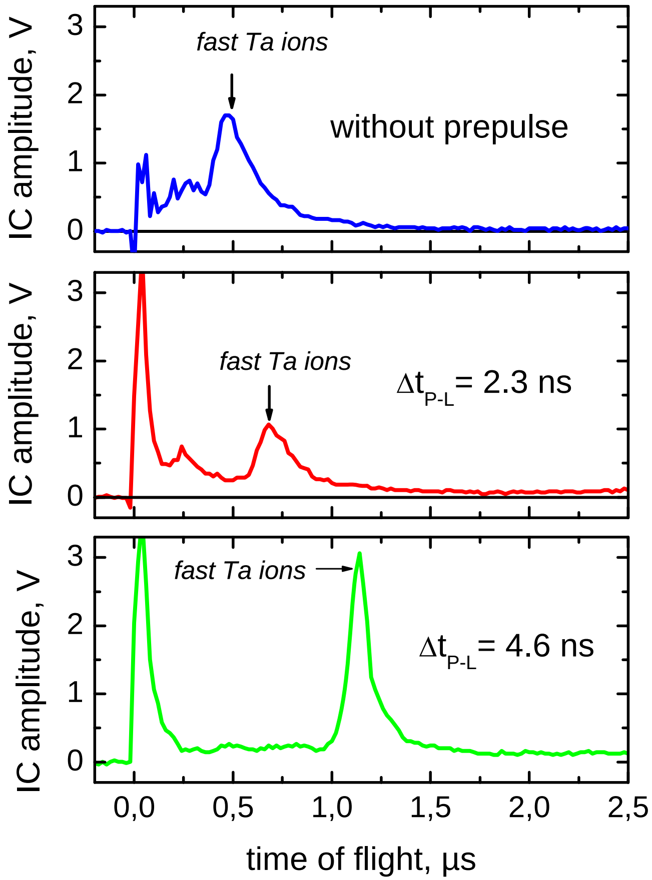
Generation of heavy ion (plasma) jets for +FP case was also observed using the interferometric measurements. Similar jets were observed for Ta plasma.

4. Influence of a pre-pulse plasma on ion emission from laser-produced plsma

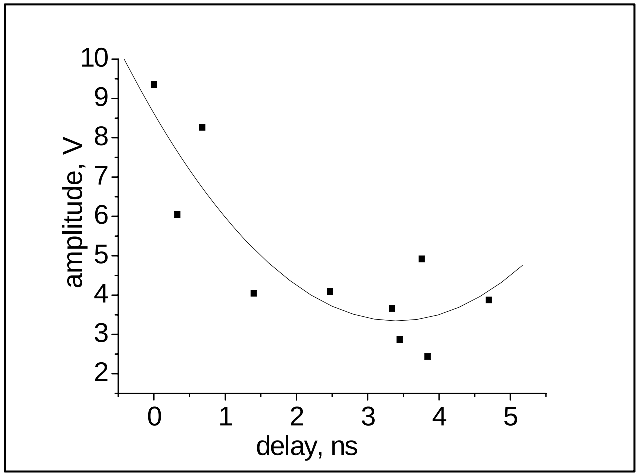
The dependence of *characteristics of of laser-produced ion strems* on plasma density distribution have been investigated using low intensity *laser pre-pulses to generate pre-plasmas*.

IC SIGNALS OF FAST Ta IONS RECORDED FOR DIFFERENT DELAY TIMES

The IC signals recorded at 0° for different delay times



The dependence of the amplitude of fast ion signal on the delay time



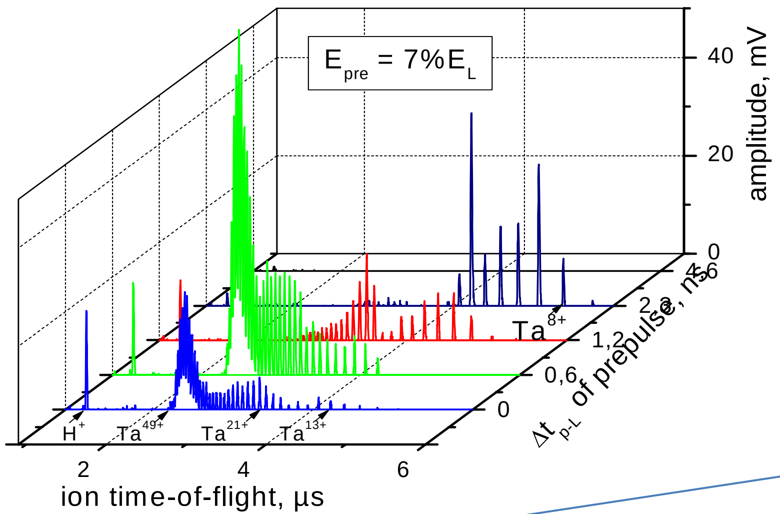
The maximum $E_{i,max}$ and peak energies $E_{i,p}$ of the fast Ta ions **attain a maximal values for** ***Δt_{p-L} <1 ns.***

$E_{i,max}$ and $E_{i,p}$ decrease for longer delay times **while** ***$j_{f,max}$*** **reaches high value also at** ***2.5 – 4.6 ns.***

The peak ion energy corresponds to the maximum of the fast ion collector signal.

THE IEA SPECTRA AS WELL AS HARD AND SOFT X RAYS OF FAST Ta IONS RECORDED FOR DIFFERENT DELAY TIMES

The IAE spectra

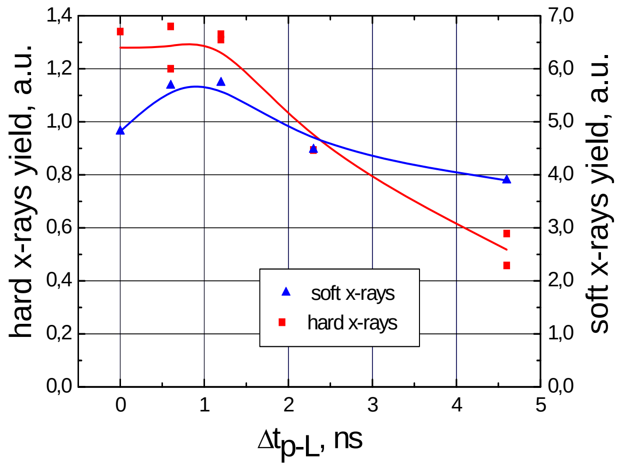


The maximum ion charge state depend significantly on the $\Delta t_{p\text{-}L}$:

$\Delta t_{p\text{-}L}$ ***= 0, 0.6 and 1.2 ns***	z_{max} ***~50+***
$\Delta t_{p\text{-}L}$ ***= 2.3 ns***	z_{max} ***~25+***
$\Delta t_{p\text{-}L}$ ***= 4.6 ns***	z_{max} ***~3+***

The relative abundance of different Ta ion species achievs maximum at the $\Delta t_{p\text{-}L}$ = 0.6 ns.

The amplitudes of X-ray signals



For measurements *of soft x-ray component* silicon photodiodes with active layer of ~2 µm a dead layer of about 0.15 µm were used.

For the measurement of *the harder x-ray component* the FLM photodiodes with 380-µm active-layer thickness were used.

5. Application of laser-generated Ge ions for implantation into SiO_2 substrates for production of Ge nanocrystals)

In the PALS experiments the laser-produced ions have been implanted into the following samples: ***polymers, C, Si and Ti*** **placed at different distances and angles.**

Here we present ***application of laser-produced Ge ions for implantation into SiO_2 substrates for production of Ge nanocrystals.***

EXPERIMENTAL ARRANGEMENT FOR INVESTIGATION OF IMPLANTATION OF LASER-PRODUCED Ge IONS

The *slab targets of Ge* irradiated by the laser beam was used for generation of ion streams destined *for implantation into SiO_2 films* prepared on the surface of Si single-crystal substrates.

Laser, target, samples

The PALS laser beam at was focused on the *Ge target* at the angle of 30^o with respect to the target normal.

The laser pulse energy was: *~17 J, ~35 J and ~51 J.*

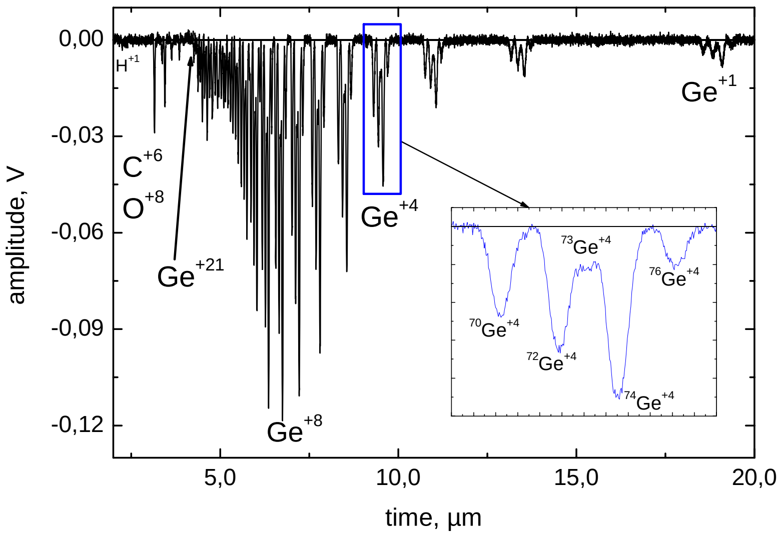
The *SiO_2 samples to be implanted* were placed at an angle of $\sim 0^o$ and at distances: *17, 31 and 83 cm.*

Diagnostics:

- ***Ion collectors* placed at different distances ,**
- ***An ion energy analyser* located at 0^0 to the target normal.**

THE CHARACTERISTICS OF STREAM OF LASER-PRODUCED Ge IONS

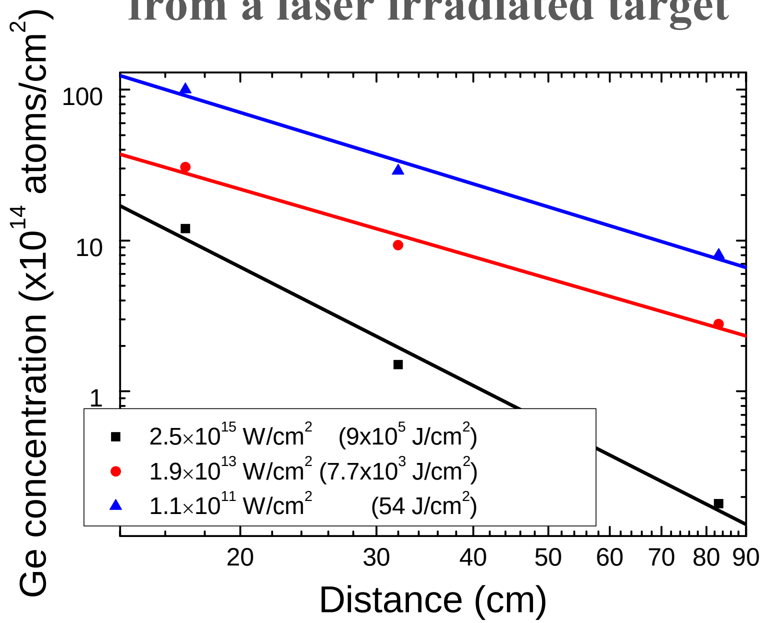
An examlpe of the ion energy analyzer (IAE) spectrum of Ge ions.



The maximum recorded Ge ion charge state is in this case ***+25.***

The insert in the figure shows a spectrum of ions of ***five Ge isotopes having charge z = 4+.***

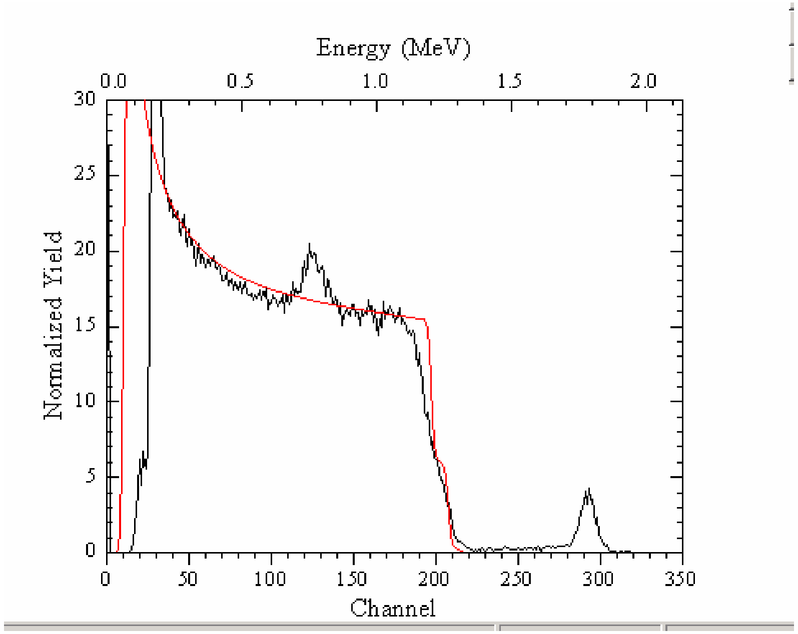
The dependence of Ge concentration in the SiO_2 sample on the distance of the sample from a laser irradiated target

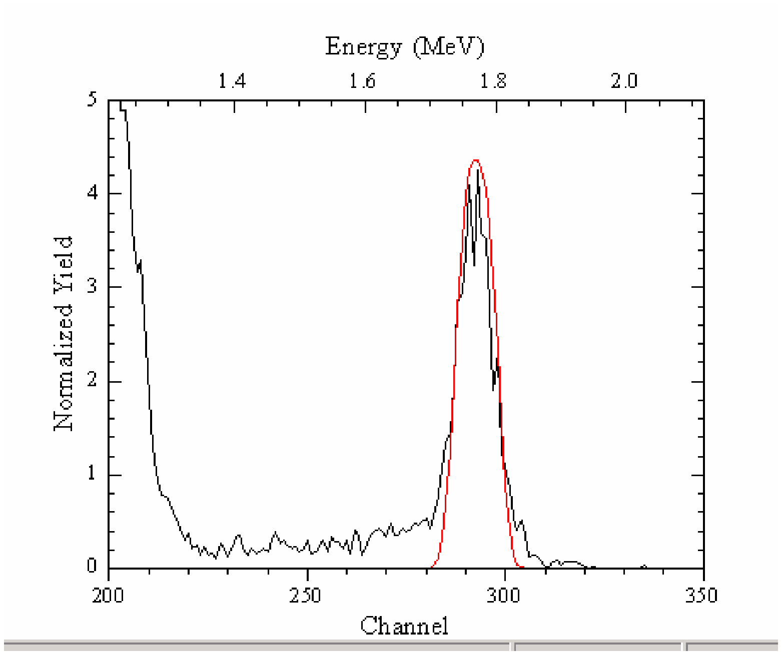


The concentration of implanted ***Ge ions higher than ~10^{15} atoms/cm^2*** **can be achieved using either high laser intensity (fluence)** ***>$2x10^{13}$ W/cm^2 ($8x10^3$ J/cm^2)*** **or by placing the sample closer to the illuminated target** ***at distance of <30 cm*****.**

AN EXAMPLE OF RBS SPECTRA FOR SAMPLE LOCATED AT THE DISTANCE OF 17 CM

laser pulse energy: ~51 J, laser spot diameter: ~11 mm, laser fluence: ~54 J/cm^2





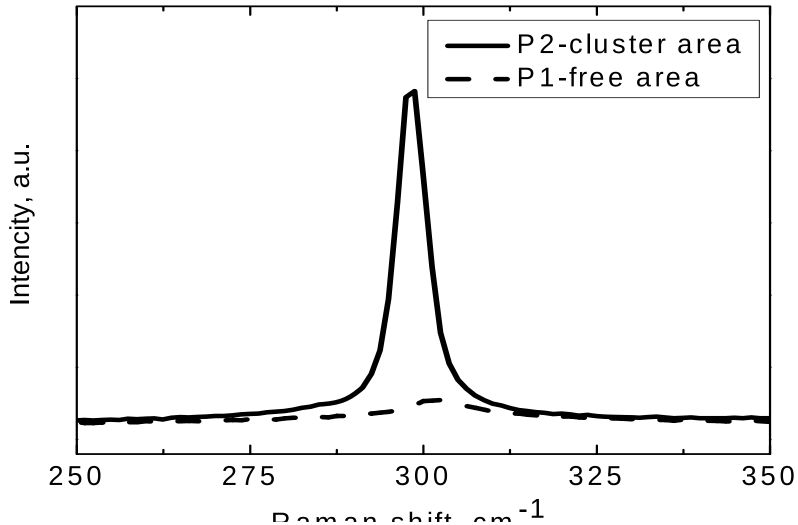
1.4x10^{16}cm^{-2} Ge implanted at 3000 A depth of SiO_2; E(Ge) = 500 keV

2.9x10^{14} cm^{-2} Ge implanted at 5000 A depth of SiO_2; E (Ge) = 0.8 MeV

THE RAMAN SPECTROSCOPY OF ANNEALED SiO_2 SAMPLES IMPLANTED WITH Ge IONS

The investigation of *annealed samples* implanted with Ge in the PALS experiment was performed in *METU in Ankara* with the use of *Raman spectroscopy*.

Sample properties: *206 nm layer of SiO_2* on the Si crystal, Ge ion stream of *~10^{16} cm^{-2}*, annealing temperature of *600^oC,* annealing time of 15 min.



The Raman spectrum of the *Ge crystalite structure* on the surface of the annealed PALS sample obtained using a *514.5 nm Ar^+ laser* excitation source.

SUMMARY

A careful *optimization of the conditions of irradiation of high-Z target* by a short-wavelength subns laser pulse enables generation of a collimated heavy ion beam of *current of > 100 A and a current density of > 1 A/cm^2 at 1m from the target.*

Such ion streams are produced with a high energy *conversion efficiency (~ 10%) at a moderate laser intensity(~10^{14}W/cm^2)* .

An efficient production of highly charged high-energy ions, by an *intense short-wavelength laser pulse* suggests that in this case besides of ambipolar acceleration also *ponderomotive forces and self-focusing* of laser radiation may contribute to *the acceleration of ions*.

SUMMARY (contin.)

The ion currrent density, maximum and mean energy of the fast ions, **as well as the yields of both hard and soft x-rays, attain their highest values for delay times in** ***the range of ~ 0 – 1.2 ns.***

The laser-produced Ge ions **were used for implantation into** SiO_2 **substrates for effective production of** ***Ge nanocrystals.***

<u>Foreseen goals of proposals to be prepared by IPPLM researchers for PALS experiments (supported by LASERLAB):</u>

1.Study of nonthermal processes in laser-produced plasma causing acceleration of fast particles.

2.Study of phenomena relevant to specific options of ignition of ICF target (proton FI, shock ignition and impact FI).

3.Improvement of laser-induced plasma jet generafion for simulation of space plasma phenomena.

Thank You for Your kind attention!