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Fyzika interakce intenzivního laserového záření s hmotou

Physics of interaction of intense laser radiation with matter

Summary

One of the unique features of laser radiation is its capability to deliver a relatively large amount of energy to an extremely small volume in an extremely short time. When this energy is absorbed by matter present in this volume, matter is heated to high temperature and multiply ionized hot plasma is formed.

This lecture is based on the author's participation in the research of laser interactions with dense targets for laser intensities high enough for ionization of the target surface layer. The first part of this lecture, devoted to the interactions of nanosecond laser pulses, summarizes mostly our research that is a part of the global effort towards laser application for inertial fusion for energy production (IFE). Various processes that influence the uniformity of absorbed laser energy and the uniformity of ablation pressure around spherical targets are studied theoretically and by numerical simulations. Experimental studies of laser interaction with low density foams that have been carried out on laser PALS in Prague under the author's leadership are presented. The observed foam structure effects have been explained by means of fluid simulations. Our numerical simulations aimed to interpretation of X-ray line emission from laser-irradiated targets and of laser-accelerated macroparticle impact experiments are also briefly mentioned.

The second part of the lecture is devoted to the theory and numerical simulations of femtosecond laser interactions with dense targets. When an intense laser beam is incident on the target, a significant part of the absorbed energy goes to very energetic electrons, penetrating deep into the target. Results of our one-dimensional (1D) relativistic particle-in-cell (PIC) simulations of laser interactions with solid targets are presented. These results are post-processed by our 3D time-resolved Monte-Carlo code that calculates characteristics of K-α emission from target. The impact of ionization processes and of elastic collisions on short-pulse laser-target interactions is demonstrated by means of our so far rare 1D PIC code that includes optical field ionization, collisional ionization and elastic collisions. Table-top ion acceleration is potentially an important application of femtosecond lasers and our 2D simulation results demonstrate advantages of mass-limited targets for this process.

At the end, link between research and education in the area of laser produced plasmas is briefly discussed in the context of their integration into the international research environment in Europe. Several selected examples are presented how our students benefit from the chances opened by the advancement of the research field at our faculty.

Souhrn

Jednou z unikátních vlastností laserového záření je jeho schopnost dopravit relativně velké množství energie do velmi malého objemu v extrémně krátkém čase. Absorpcí části této energie se hmota v dané oblasti zahřeje na vysokou teplotu a vznikne mnohonásobně ionizované plazma.

Tato přednáška vychází z autorových zkušeností získaných při výzkumu v oblasti interakcí laserového záření s hustými terči pro intenzity dostatečné k ionizaci povrchu terče. První část přednášky, věnovaná interakcím nano-sekundových laserových pulsů, většinou sumarizuje náš výzkum, který je součástí celosvětového úsilí směřujícího k využití laseru pro výrobu energie pomocí inerciální fúze (IFE). Teoreticky a pomocí numerických simulací jsme studovali různé procesy, které ovlivňují homogenitu rozložení absorbované energie a ablačního tlaku po povrchu sférických terčů. V přednášce jsou prezentovány výsledky experimentálních studií interakce laserového záření s pěnami o nízké střední hustotě, které byly pod autorovým vedením prováděny na laseru PALS v Praze. Pozorovaný vliv struktury pěny byl vysvětlen pomocí hydrodynamických simulací. Krátce jsou zmíněny i naše numerické simulace sloužící k interpretaci experimentů, zkoumajících vlastnosti čárové rentgenové emise z laserem ozářených terčů, a k vyhodnocení experimentů, studujících srážku laserem urychlené makročástice s masivním terčem.

Druhá část této přednášky je věnována teorii a numerickým simulacím interakce femtosekundových laserových pulsů s hustými terči. Při dopadu intenzivního laserového svazku na terč je značná část absorbované energie předána velmi rychlým elektronům, které pronikají hluboko do terče. Jsou uvedeny výsledky našich jednodimenzionálních (1D) relativistických simulací interakce laserového záření s pevnými terči metodou částice v buňce (PIC – Particle-in-Cell). Tyto výsledky pak slouží jako vstupní data pro náš 3D Monte Carlo kód s časovým rozlišením, který počítá charakteristiky K-α emise z terče. Vliv ionizačních procesů a pružných srážek na interakci krátkých pulsů s terči je studován pomocí našeho zatím ojedinělého 1D PIC kódu, který započítává ionizaci optickým polem, srážkovou ionizaci a elastické srážky. Naše 2D PIC simulace ukazují výhody terčů s omezenou hmotou pro urychlování iontů, které je velmi důležitou potenciální aplikací femtosekundových laserů.

V závěru přednášky je stručně diskutován vztah mezi výzkumem a vzděláváním v oblasti laserového plazmatu v kontextu jejich integrace do mezinárodní výzkumné infrastruktury v Evropě. Na několika vybraných příkladech je ukázáno, jak studenti využívají možnosti, které jim rozvoj oboru na naší fakultě přinesl.

Keywords

Laser-produced plasma, laser-target interaction, multiply ionized plasma, inertial confinement fusion, ablation pressure smoothing, low-density foam target, line X-ray emission, fluid simulations, short-pulse laser-target interaction, relativistic PIC simulations, optical field ionization, K-α emission, laser ion acceleration

Klíčová slova

Laserové plazma, interakce laserového záření s terči, mnohonásobně ionizované plazma, inerciální fúze, vyhlazování ablačního tlaku, terč z pěny o nízké hustotě, čárové rentgenové záření, hydrodynamické simulace, interakce ultrakrátkých laserových pulsů s terči, relativistické simulace metodou částice v buňce (PIC), ionizace optickým polem, K-α záření, urychlování iontů laserem

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1. INTRODUCTION

One of the unique features of laser radiation is its capability to deliver a relatively large amount of energy to an extremely small volume in an extremely short time. Extremely high power densities are thus reached in the focus of intense laser beams. When this energy is absorbed, matter is heated to a very high temperature and multiply ionized hot plasma is formed.

Soon after the construction of the first laser in 1961, the laser capability to achieve high energy densities was identified and the ignition of controlled nuclear fusion by laser was proposed [1]. Research of inertial confinement fusion (ICF) was the driving force for building large scale laser facilities in Soviet Union [2], Japan [3] and USA [4]. Linear and non-linear laser absorption in plasma on the surface of solid targets, transport of the absorbed energy into the target interior and shock wave formation were studied, the acquired knowledge led to scheme proposals for fusion ignition and for energy gain [5]. Pressures in the laser-induced shock waves are the highest pressures achieved on the earth with the exception of nuclear explosions. Thus, laser target interactions are often used to study the equation of state and the thermodynamic properties of materials under extreme conditions [6]. Laser-produced plasmas are often in a non-equilibrium state and a population inversion may arise between levels with a large energy difference of hundreds of eV. Thus, lasing in the soft X-ray region has been achieved [7] and extensively developed to a reliable system suitable for applications [8].

A new important stimulus for the research of laser-matter interactions was the discovery of chirped pulse amplification (CPA) [9] that ended up in the construction of high-power femtosecond lasers. Relatively small femtosecond lasers, table-top terawatt (T^3) lasers, achieve the same laser intensities as nanosecond lasers of national laboratory scale. Additional advantage of high-power femtosecond laser is a high repetition rate up to several kHz, as compared with one shot in several minutes or hours from high-power nanosecond lasers. Consequently, the application field of T^3 lasers is very broad. They are already extensively used as a laboratory tool [10] and many prospective applications are being intensively studied and developed [11]. When large amplifier chains are used inside CPA scheme, extreme powers are achieved. Petawatt project [12] used the amplifier chain of Nova laser [4] to reach power 1 PW and focused laser intensity 10^{21} W/cm^2, experiments at the same power and intensity level are now conducted at PW upgrades of Vulcan laser [13] in UK and GekkoXII laser [3] in Japan. Several other installations are now under construction; multi-petawatt lasers are now designed and construction of an exawatt laser has been already proposed [14]. High-power short-pulse lasers may be also used to ignite fuel compressed by long-pulse lasers in the ICF fast ignition scheme [15].

This lecture is based on the author's participation in the research of laser interactions with dense targets for the laser intensities high enough for ionization of the target surface layer. The first part of this lecture, devoted to the nanosecond laser pulses, summarizes mostly the research that is a part of the effort towards laser application for inertial fusion for the energy production (IFE). Various processes that influence the uniform distribution of the absorbed laser energy and of the ablation pressure around the spherical targets are studied theoretically and by numerical simulations. Using targets with outer layer made of low-density foam has a potential of a significant improvement of the ablation pressure uniformity. Experimental studies of laser interactions with low density foams are presented that have been carried out on laser PALS [16] in Prague under the author's leadership. The observed foam structure effects are explained by means of numerical fluid simulations. Our numerical simulations aimed to the interpretation of X-ray line emission and of laser-accelerated macroparticle impact experiments are also briefly mentioned.

The second part of the lecture is devoted to theory and to numerical simulations of femtosecond laser interactions with dense targets. When a very intense laser beam is absorbed at the target surface, a significant part of the absorbed energy goes to very energetic electrons, penetrating deep into the target. Results of our one- (1D) and two-dimensional (2D) relativistic PIC (particle-in-cell) simulations of laser interactions with solid targets are presented. These results were post-processed by our 3D time-resolved Monte Carlo code that calculated the characteristics of K-α emission from targets. K-α emission has already been used for X-ray crystallography with a subpicosecond resolution [17] and it can be applied for medical imaging [18]. Numerical simulations facilitate the search of optimum interaction conditions for the applications. The influence of ionization processes and elastic collisions on short-pulse laser-target interactions is demonstrated by means of our novel rare 1D PIC code that includes optical field ionization, collisional ionization and elastic collisions. Table-top ion acceleration [19] is potentially another important application of femtosecond lasers. Our 2D simulation results demonstrate advantages of mass-limited targets for this process. The most of the presented results have been obtained in a close international co-operation within several national and international research projects with a strong participation of our doctoral and master students.

At the end, link between research and education in the area of laser produced plasmas is briefly discussed in context of their integration into the international research environment in Europe.

2 INTERACTIONS OF NANOSECOND LASER PULSES WITH TARGETS

Interaction of intense nanosecond pulses with solid targets is a well-established topic studied experimentally and theoretically over 40 years. The surface of a solid target is evaporated and ionized well ahead of the laser pulse maximum.

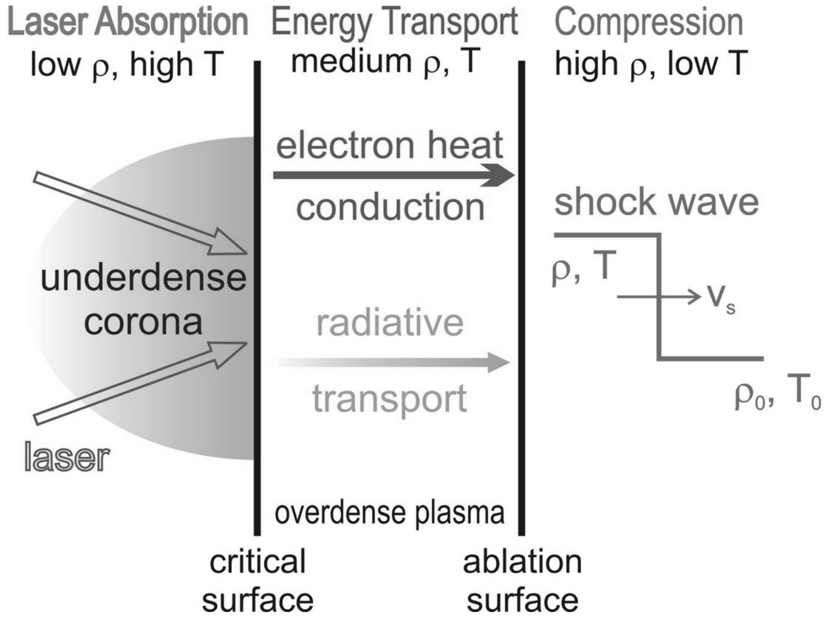

Fig. 1 A schematic description of laser interaction with a dense target; ρ_0, T_0 are the initial target density and temperature, respectively, v_s is the shock velocity.

While the typical intensities at the laser pulse maximum are above 10^{13} W/cm^2, the intensity of 10^{11} W/cm^2 is usually sufficient for plasma formation with the electron density n_e higher than the critical density n_c. The heated plasma expands perpendicularly to the target surface and laser radiation can penetrate only to the critical surface where it is reflected. At lower intensities, laser is predominantly absorbed in underdense plasma by collisional (inverse bremsstrahlung) absorption. For higher laser intensities, resonance absorption and non-linear absorption via parametric instabilities are also important. The typical density scale length of underdense plasma is 100 μm with some steepening by ponderomotive force in the critical surface neighborhood. The absorbed laser energy is transferred inwards into the target by the electron heat conduction and by the radiative transfer. The target material is evaporated at the ablation surface and a shock wave propagates into the target. A schematic description of laser-target interaction is presented in Fig. 1.

Numerical simulations are an important part of the laser interaction research. In experiment, it is usually impossible to measure an adequate set of data with a sufficient spatial and temporal resolution, and thus theory and simulations are vital for the experiment interpretation and for a physics insight into the complex interaction processes. Even when conclusive experimental results are obtained, theory and simulations are needed for an extrapolation of experimental results to previously unexplored parameter regions and for a search for the optimum targets and interaction regimes. Numerical simulations of laser target interactions are very difficult due to density and temperature variations over many orders of magnitude. While an ideal plasma with densities less than 10 mg/cm^3 and temperatures in keV (1 keV = 1.16×10^7 K) range is typical for the underdense corona, the overdense plasma near the ablation surface is strongly coupled and the material behind the shock wave has density higher than the solid density and temperature in eV range. Only fluid codes are capable to model the global situation in all the target regions. However, processes like nonlinear laser absorption and electron heat flux are included here only in a phenomenological way, and their description is often based on detail models of the particular region via kinetic Fokker-Planck codes or particle-in-cell codes.

In the first subsection, the essentials of laser-driven inertial fusion are presented together with the selected results of our theoretical and experimental research on topics important for the success of laser fusion. In the second subsection, our fluid simulations are used for the interpretation of experiments studying line X-ray emission and the impact of laser-accelerated macroparticles.

2.1 Laser-driven inertial confinement fusion

Inertial confinement fusion is essentially a microexplosion of the thermonuclear fuel. The fuel mass is limited by the energy that can be contained in a vacuum vessel. A crude estimate of this limit is 340 MJ [20] (equal to explosion of 75 kg of TNT) that is released in the fusion of 1 mg DT. In the inertial fusion, the confinement time $\tau_c \approx R/c_s$, where R is the fuel radius and c_s is the ion sound velocity. As the fusion reaction rate is proportional to the density square, the relative part Ψ of thermonuclear fuel burnt during confinement is a function of ρR. When burning efficiency $\Psi = 1/3$ is assumed, 3 mg of DT fuel have to be compressed to 200 g/cm^3 [20].

The basic inertial fusion scheme is based on proposal [5]. A thin spherical shell is filled with the DT fuel, preferentially in the form of cryogenic DT ice. The outer layer of the shell is heated and ablated by an energy driver. The un-evaporated part of the shell is accelerated by the reaction force to a very high velocity towards the target centre. The shell compresses DT fuel to a high density. If the compression symmetry is high enough, ion temperature rises in a small central region of the fuel to the ignition threshold of about 5 keV. Thus, a small spark is formed that initiates thermonuclear burn wave propagating out of the centre. This central spark ignition scheme is shown in Fig. 2.

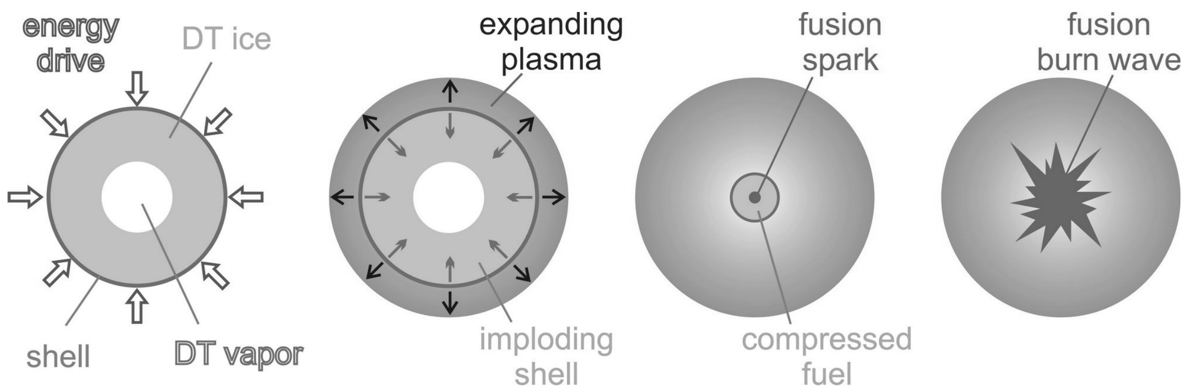

Fig. 2 Principle of inertial confinement fusion. Four stages of target dynamics are ablation; implosion; fuel compression and ignition; and fusion burn wave.

Fuel compression to the required densities thousand-time higher than DT ice density 0.2 g/cm^3 has been demonstrated on GekkoXII laser already in 1986 [21] by the direct laser acceleration of the shell (direct-drive ICF). However, the neutron yield was two orders of magnitude lower than predicted by a one-dimensional model as too high deviations from the spherical symmetry of the compression deteriorated the central temperature rise. The most serious challenge for the directly driven inertial fusion are hydrodynamic instabilities (Rayleigh-Taylor, Richtmeyer-Meshkov and Kelvin-Helmholtz) [22] growing during the shell acceleration and during the fuel compression. In order to improve the stability of shell compression, indirect-drive ICF was proposed [23] when the driver energy is transferred to X-ray radiation that performs the ablation and the compression of the shell target. X-ray driven ICF was successfully demonstrated in the classified Centurion-Halite experiment [24] using X-rays from an underground nuclear test explosion. Indirect-drive ICF is also preferred by the military research. Indirect drive uses hohlraum targets [25], where the shell target is situated inside a hollow cylinder with 2 side entrance holes for the laser beams (Fig. 3). It is the primary option for the presently built lasers NIF [26] in USA and LMJ [27] in France, both financed from the military budgets. These facilities will deliver around 2 MJ of energy at wavelength λ=351 nm (third harmonics of Nd-laser) in a shaped 10 ns pulse on the target and the predicted fusion energy gain is around 10 [27].

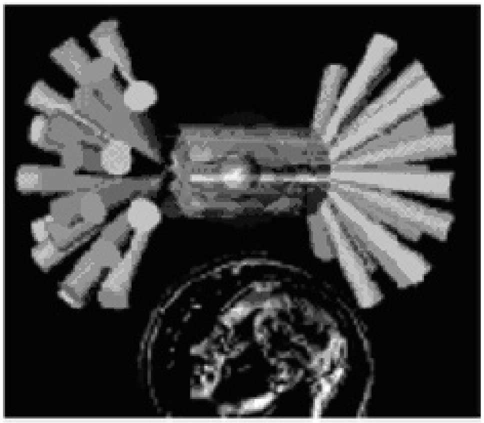

Fig. 3 Schematic view of NIF hohlraum target with incident laser beams. Scale depicted by one dollar coin.

Direct-drive inertial fusion is still a viable option for inertial fusion energy IFE (acronym IFE is now widely used to distinguish the peaceful energetic utilization from the military applications of ICF). Though directly-driven targets are less stable, the energy conversion from the laser energy to the kinetic energy of the accelerated shell (hydrodynamic efficiency) is significantly higher [28], and thus, the same energy gain may be achieved with less driver energy. Stringent requirements on target and ablation pressure symmetry apply for the success of directly driven fusion. It is technologically very difficult to achieve the required shell thickness and DT ice layer thickness variations below or around 1%, but it is possible [29]. A very high uniformity of the target irradiation or a very efficient smoothing of non-uniformities in the absorbed energy is needed for the required ablation pressure symmetry. Many laser beams with very smooth spatial profiles are required for the symmetric target irradiation. Spatial intensity profiles in the focus of high-energy solid-state lasers are very inhomogeneous with intense hot spots, and thus laser beam smoothing techniques have been developed. An efficient combination of these techniques has been implemented

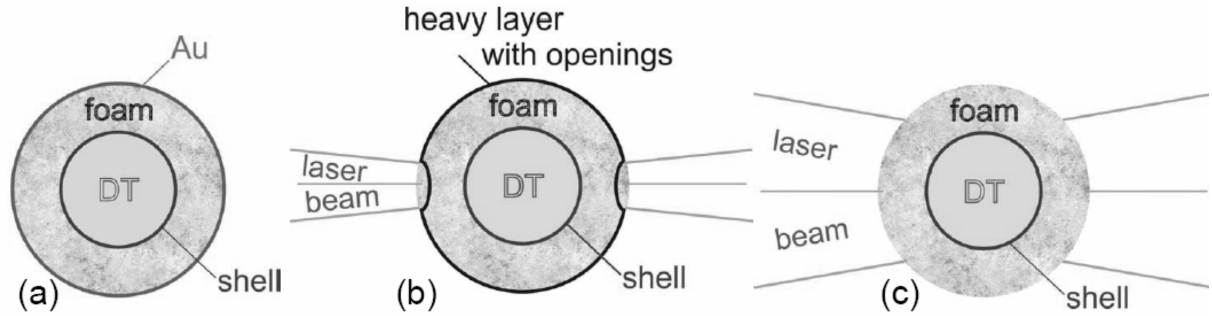

Fig. 4 Target for imprint smoothing [32] (a); closed (b), and open (c) variants of laser greenhouse target [34].

on the 60-beam laser Omega [30] at LLE, Univ. of Rochester, USA, serving now as a primary experimental tool for the direct drive ICF. However, the irradiation inhomogeneities are imprinted on the ablation surface very early at the rising edge of laser pulse [31]. The formed flow structures are usually preserved for the whole interaction time and the induced inhomogeneities in the shell acceleration are then enhanced by the Rayleigh-Taylor instability. As an efficient smoothing of the rising edge of laser pulse has not been developed yet, the smoothing of the absorbed laser energy in the target is very important. A special target (Fig. 4a) has been proposed [32] in order to suppress laser imprint. The front edge of the laser pulse is converted into X-rays in a very thin (~25 nm) outer gold layer; these X-rays are symmetrized in the low-density foam and they preheat the shell before intense ablation starts, and thus imprint is suppressed. The rest of the laser pulse is absorbed in the foam efficiently. A remarkable enhancement of the symmetry was achieved in spherical implosions of such targets [33]. However, the fuel compression was decreased due to the fuel preheat by the X-ray emission. In the same time, Soviet researchers [34] proposed laser greenhouse targets (Fig. 4b, 4c) in order to minimize number of laser beams irradiating the target with the aim to simplify the IFE reactor chamber design. In these targets, laser interacts directly with the low density foam that serves both for the enhancement of laser absorption and for smoothing out of the inhomogeneities in the absorbed energy by the lateral heat transport in a relatively thick layer of the heated foam. There are also other reasons for laser-foam interaction studies. Low density foam may serve as a dynamic phase plate for the smoothing of inhomogeneities inside the laser beams [35] and foam is also attractive as a hohlraum component in the indirect-drive systems [36].

I have been involved in the research of the smoothing of ablation pressure inhomogeneities for a long time. Theoretical analysis of transverse structures observed in corona of laser irradiated targets was presented in paper [37]. Our model calculations [38] including ion dynamics indicated that transient spatial growth of laser beam filamentation in corona may be much higher than in the stationary situation if the laser pulse is initiated abruptly. Possibility to enhance smoothing of ablation pressure by using of a suitable laser prepulse was studied experimentally [39] on the small iodine laser PERUN in Prague. I was involved in the interpretation and in numerical simulations of these experiments. Our

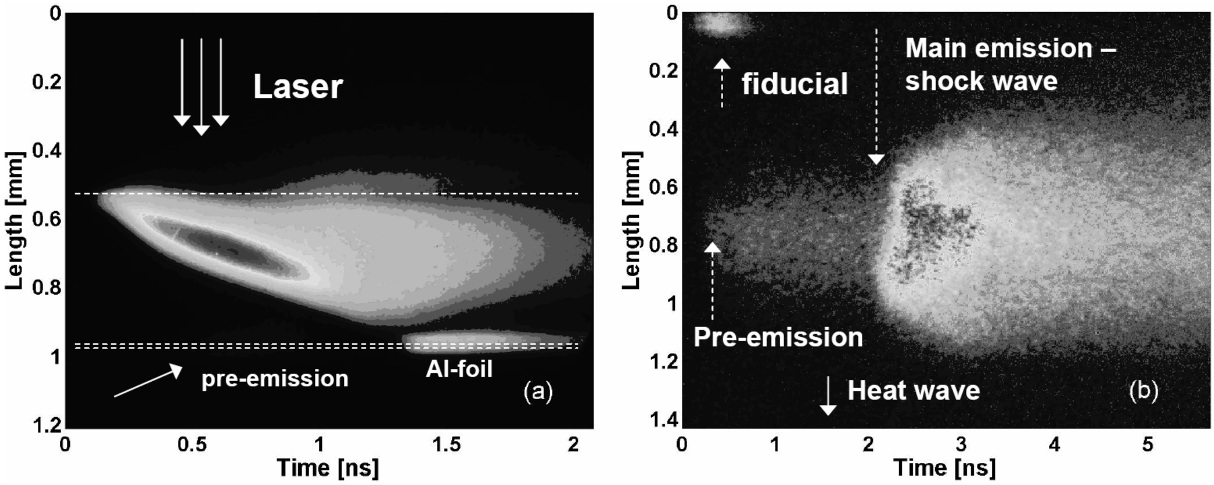

Fig. 5 Side-on X-ray slit image (a) and optical self-emission from the target rear side (b). Laser (λ=439 μm, 320 ps FWHM, 170 J, spot diameter 300 μm) is incident normally on 400 μm-thick TAC ($C_{12}H_{16}O_8$) foam of density 9.1 mg/cm^3, and pore diameter in range 0.5-3 μm with 5 μm Al-foil on the target rear side.

numerical analysis showed that the smoothing effect observed for suitable delays between the prepulse and the main pulse was basically due to the shift of laser absorption from the critical surface neighborhood to the more distant lower density corona [40]. However, this increase in the distance between the absorption region and the ablation surface decreased the hydrodynamic efficiency. Our two-dimensional fluid simulations also proved that even non-uniform prepulse may result in a decrease in the growth rate of the non-uniformities in the foil acceleration [40].

I served as the international coordinator of the project INTAS-01-0572 "Plasma creation, energy transport and smoothing of non-uniformities in volume-structured media irradiated by high-power laser pulses" in the period 2001-5. Within this project, laser interactions with low-density foams of various structure and chemical composition were studied at PALS laser in Prague. The unique feature of these experiments was the investigation of interactions of a relatively short 400 ps laser pulse with an underdense foam (the electron density n_{eh} of fully ionized homogenized foam is less than critical density n_c). We have observed a striking difference in energy transport in the foams with small and large pores. While 380 μm layer of underdense plastic TAC (cellulose triacetate) foam of density 4.5 mg/cm^3 ($n_{eh} \approx n_c/4$) with ~2 μm pores is heated before the laser maximum, laser energy is confined to 150 μm thick surface layer in plastic foam with ~70 μm pores and approximately the same density [41]. Laser penetration and energy transport slows down with foam density even for underdense foams with small pores. Side-on X-ray slit image of laser interaction with TAC foam of density 9.1 mg/cm^3 ($n_{eh} \approx n_c/2$) is presented in Fig. 5 together with the streaked image of optical self-emission from the foil at the target rear side taken during the same laser shot. Optical pre-emission from the target rear

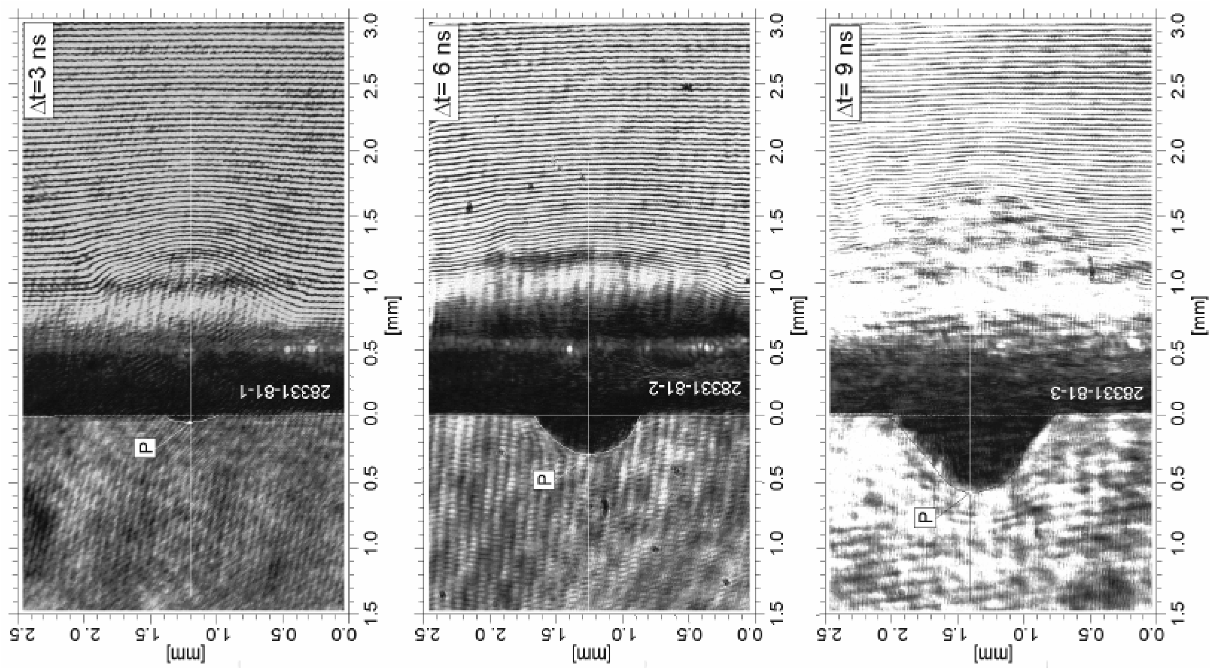

Fig. 6 Three-frame interferometry of laser (λ=439 nm, 320 ps FWHM, spot diameter 300 μm, 130 J) incident normally downwards on the plastic TMPTA ($C_{15}H_{20}O_6$) foam of density 10 mg/cm^3, thickness 480 μm, pore diameter ≤1 μm with 5 μm Al foil on the rear side. The delays Δt measured with respect to the laser pulse. Point P is the centre of the accelerated region on the target rear side.

side starts during the laser pulse (timing by the laser fiducial) and a weak X-ray pre-emission from Al-foil is observed simultaneously. The observed stronger pre-emission for foams with Cu addition supports the idea that pre-emission is due to Al-foil X-ray preheat [42]. It can be also due to laser preheat, as we have recently observed penetration of the laser pulse leading edge through transparent TAC foam before it is ionized and the transparency is blocked by overdense pore walls [43]. The laser-heated area deepens gradually and the heat wave penetration to the target rear-side is marked on the X-ray streak by a strong emission from the Al-foil after the laser pulse end. The heat wave penetration is not seen on optical streak where the main emission appears only later when the shock wave reaches the target rear side. Simultaneously, the acceleration of the target rear side is observed via 3-frame interferometry [44], a sequence of the interferometric pictures taken in one shot is presented in Fig. 6. The motion of the target rear side is found to start approximately at the same time when the main optical self-emission is observed at the streak. When the foam is modeled in the approximation of low density homogeneous media, the final velocity of the accelerated foil is reproduced, but the onset of the motion is significantly earlier than in the experiment [45]. Final foil velocities of order 10^7 cm/s are observed, and high hydrodynamic efficiencies of order 10% are deduced.

Detailed numerical modeling of the laser interaction with foam is very difficult due to the difference between the macroscopic experimental scale and the microscopic foam cell scale. Our 1D simulations show that laser can skin

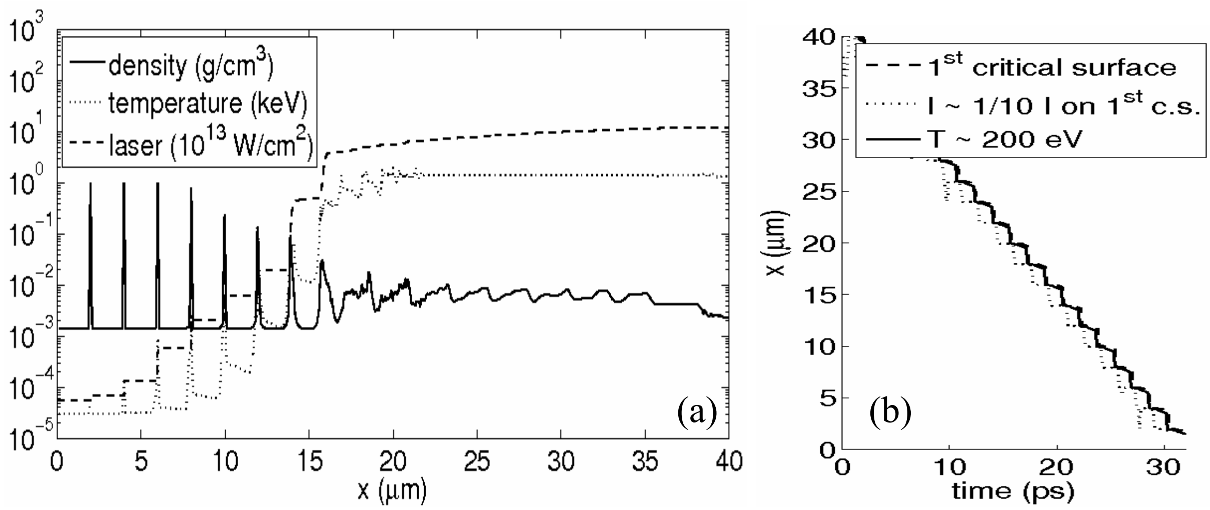

Fig. 7 (a) Density, temperature and laser (incident from the right) intensity profiles at time 20 ps for foam target of average density 5 mg/cm^3 and (b) laser penetration into this foam. Pore wall thickness 10 nm, the slab and void density 1 g/cm^3 and 1:43 mg/cm^3, respectively. Laser (λ =439 nm) intensity rises in 1 ps to constant maximum value 3.7×10^{14} W/cm^2.

through the thin cell walls and heat several cells simultaneously for low-density foams with small cells (Fig. 7a). In this situation, laser interacts with the wall in the exploding foil regime [46] and laser penetration is enhanced compared to the ablative acceleration of thicker pore walls in foams with large cells or of higher density. Laser penetration into the foam in the exploding foil regime is plotted in Fig. 7b). The laser skin depth behind the first critical surface is constant in time and the front of X-ray emission (T> 200 eV) practically coincides with the first critical surface. We have used our newly developed Arbitrary Lagrangian-Eulerian (ALE) code [47] to study the impact of the lateral heat flux on the laser penetration and on the energy transport into the foam layer (Fig. 8).

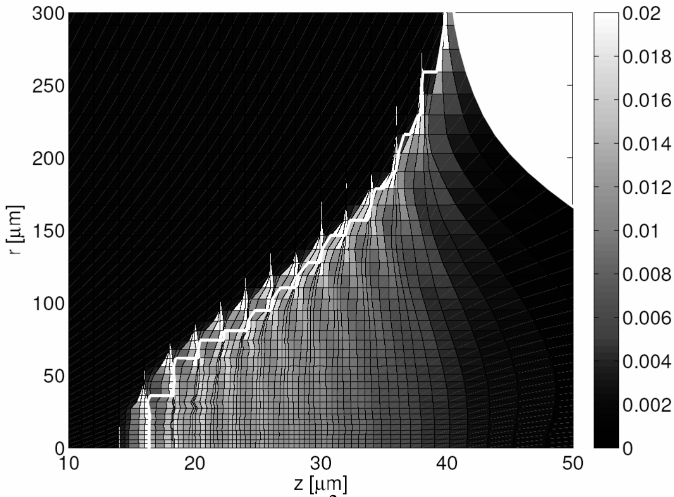

Fig. 8 Density (g/cm^3) colormap at 20 ps (simulations via 2D fluid ALE code). Laser (λ =439 nm) incident form the right, intensity 3.7×10^{14} W/cm^2, Gaussian laser spot of radius 125 μm, foam average density 10 mg/cm^3, pore wall thickness 20 nm. First critical surface is denoted by the white line.

2.2 Fluid simulations of X-ray emission and impact experiments

We have developed 1½D atomic physics post-processor [48] to 1D and 2D

Lagrangian hydrodynamic codes. The post-processor calculates K-shell line emission from high temperature plasmas. It was successfully used for the interpretation of X-ray spectroscopy with high spectral and spatial resolution on laser PALS [49]. We have used it also for the interpretation of an enhancement of the resonance line emission by a laser prepulse in the interactions of femtosecond pulses of moderate intensity with solid targets [50].

Lagrangian fluid codes are widely used for the modeling of laser-plasma interactions as the Lagrangian approach with a computational mesh moving together with the fluid suits better for compression and expansion regimes with moving boundaries. However, 2D and 3D Lagrangian meshes may be distorted by complex flows (typically due to shear). Arbitrary Lagrangian-Eulerian (ALE) method offers a possibility to avoid the distortions of moving Lagrangian meshes by mesh rezoning and conservative remapping of physical quantities. My colleagues have developed a modern 2D ALE code [47] and we have applied the cylindrical version of this code for modeling of the experiment [51] where a crater is formed at the surface of bulk target by the impact of a thin laser-accelerated disc. While the problem of the disc impact cannot be treated by Langrangian codes, we have found a good agreement of our simulation results with the experiment.

3 INTERACTIONS OF FEMTOSECOND LASER PULSES WITH TARGETS

The construction of the first high-power femtosecond lasers in 1989 opened a new previously unexplored regime of laser-target interaction, Small and relatively cheap femtosecond lasers, table-top terawatt (T^3) lasers, may be focused to a very small area of a few λ^2 and very high laser intensities are achieved. The additional advantage of high-power femtosecond lasers is their high repetition rate up to several kHz. Consequently, the application field of T^3 lasers is very broad. They are already extensively used as a laboratory tool [10] in chemistry and biology. High harmonics of the order several hundreds are generated in gases, and thus coherent XUV and soft X-ray emission is produced. As the different harmonics are phase locked, attosecond pulses are generated opening the way to attosecond physics [52]. Femtosecond lasers have been also used to pump table-top plasma transient X-ray lasers [53]

Focal intensity I of a small short-pulse laser may reach $I = 3.4\times10^{16}$ W/cm^2 when the laser electric field is equal to the field seen by electron on the first Bohr orbit in hydrogen atom. A few-terawatt femtosecond laser may reach the relativistic threshold $I\lambda^2 = 1.35\times10^{18}$ W/cm$^2\times\mu$m^2 when the momentum p_L of electron oscillating in the laser field is $p_L = eE_L/\omega_L = m_e c$, where E_L, ω_L are the amplitude and the angular frequency of the laser electric field and e, m_e are electron charge and rest mass, respectively. The dimensionless amplitude of the laser electric field $a_0 = p_L/m_e c$ characterizes the non-linearity of laser-plasma interaction. For the maximum presently achieved intensities of 10^{21} W/cm^2 at Nd-laser wavelength λ=1.05 μm, electron oscillations are ultrarelativistic with the gamma factor $\gamma \approx a_0 \approx 30$.

We shall consider laser-target interactions for conditions when high temperature plasma is generated at least at the target surface. The interaction physics and applications differ for the laser interactions with gas targets and for the interactions with high density solid or liquid targets [11]. Gas targets are used for the generation of high-current collimated electron beams that may be even monoenergetic [54] and thus, table-top electron accelerators may be developed. We shall concentrate here on laser interactions with high density targets that can be used as a unique X-ray source or for ion acceleration.

Section 3.1 is devoted to one-dimensional relativistic particle-in-cell (PIC) modeling of electron acceleration in the corona of dense targets. The PIC results are post-processed by 3D time-resolved Monte Carlo (MC) simulations of the electron transport into the solid bulk target and emitted K-α pulses are calculated. The impact of ionization and of the collisional processes on the electron acceleration is studied in section 3.2 by means of our unique PIC code including the above processes. Our newly developed two-dimensional PIC code is applied to ion acceleration in section 3.3.

3.1 Electron acceleration and K-α emission from solid targets

In the case of non-relativistic intensities, the laser energy transformation into fast electrons is most efficient for an obliquely incident p-polarized laser wave. Electrons are accelerated due to the collisionless resonance absorption. This is based on the tunneling of the laser field from the reflection surface to the critical surface, where the electric field component parallel to the density gradient resonantly excites the electron plasma wave. While the plasma wave is damped either by collisions in low-temperature plasma and or by Landau damping in high-temperature plasma with a long density profile, its energy is transformed here non-linearly to the energy of very energetic electrons via wavebreaking [55]. About 50% of the incident laser energy is absorbed by the resonance absorption for the optimum density scale length L given by the relation $(k_0 L)^{1/3} \sin\theta \simeq 1$ where k_0, θ are the laser wavevector and the incidence angle, respectively. For extremely short density scale lengths L shorter or comparable to the amplitude of electron oscillation in the laser field, this mechanism transforms to the "vacuum heating" [56] when electrons are accelerated to vacuum by the normal component of the laser electric field in one half of the laser period and they are returned to the target in the second laser half-period and they pass through the skin layer to the target interior. When a fast electron enters the dense cold target, it may collide with an electron bound in K-shell producing K-shell vacancy. This vacancy is filled in less than 10 fs, and either Auger electron or characteristic photon is produced. If the photon is produced by the transition of

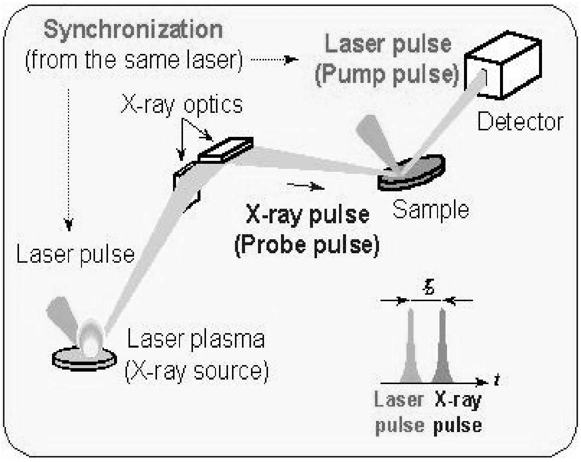

Fig. 9 The scheme of pulse-probe setup for X-ray diffraction measurements with high temporal resolution. Film is formed from various delays.

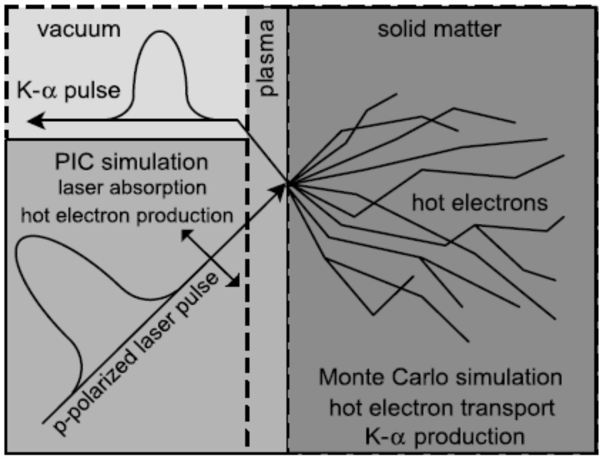

Fig. 10 Simulation is split into 2 regions. Surface hot plasma layer is modeled by 1D3V PIC code, electron transport in the cold interior is treated by 3D MC code.

L-shell electron to K-shell, K-α radiation is emitted. As the free path of K-α photon is typically 10 to 100 μm, only photons generated near to the target surface can escape to vacuum. As the fast electron transit time is typically of order 100 fs, very short X-ray pulses may be produced. Such K-α pulses have been already used for X-ray diffraction measurements with ps temporal and μm spatial resolution [17] in the pulse-probe set-up (Fig. 9). A small part of the laser energy excites the sample surface while the main part is used to generate K-α emission that is focused by X-ray optics on the sample and the diffracted X-ray emission is detected. The delay between the laser and the X-ray pulse can be varied easily and thus the sample dynamics may be followed. The best temporal resolution of 250 fs has been achieved when ultrafast melting was studied [57]. Even subtle effects may be measured with subpicosecond resolution when a laser with a high repetition rate of 1 kHz is employed [58]. K-α emission may be also used in medical applications [11, 18] and for the radiography of the compressed cores of spherical laser targets [59].

We have modeled K-α emission from Al and Cu targets [60] by splitting the simulation into two regions (Fig. 10). The surface layer is modeled by one-dimensional relativistic Particle-In-Cell (PIC) code including all three velocity components (1D3V). The problem is transformed relativisticly to the boosted frame where the laser is incident normally on plasma moving tangentially with the velocity $c\times\sin\theta$. Fast electrons reaching the rear boundary of the simulation box are substituted by thermal electrons forming the return current. The time of this event and all three velocity components of the fast electron are recorded and they are subsequently used as the input for our 3D time resolved MC code. Zero width of the transition layer between hot and cold region is assumed. Our MC code is tailored for the calculation of K-shell vacancy formation. The propagation of K-α photons in the target is treated by

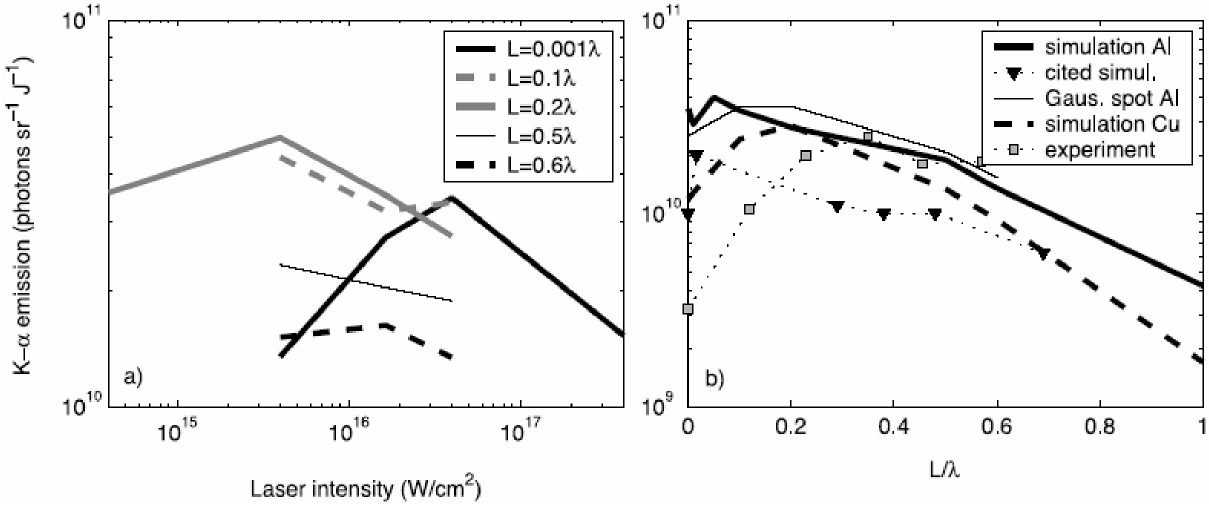

Fig. 11 a) The K-α emission normalized on the laser energy versus intensity of p-polarized laser obliquely incident at angle 30° for various density scale lengths L. b) The dependence of K-α emission on the density scale lengths L for the maximum laser intensity $I = 4\times10^{16}$ W/cm^2. The results of our simulations for Al and Cu and spatially constant laser intensity are compared with our results for a Gaussian laser beam (Al target) and also with the experimental and simulation data for SiO_2 targets taken from the article [61].

the Beer's law. We have shown that K-α pulses as short as 180 fs FWHM may be emitted normally from Al target irradiated by 120 fs Ti:Sapphire laser pulses of intensity 4×10^{16} W/cm^2. Fig. 11a) demonstrates the existence of an optimal intensity for each density scale length L. This optimal intensity is minimal for the optimum L for the resonance absorption and K-α energy is maximal for these conditions. The emitted energy is compared with the experiment and with the other simulation [61] in Fig. 11b). The calculated number of emitted photons is in a good quantitative agreement with the experiment but the simulations cannot reproduce the sharp decline of the emission yield for very small density scale lengths L. This difference may be partly relieved by the integration of the emitted energy over the laser intensity profile in the focus. The remaining difference may be caused by the PIC model that uses a constant time-averaged ion charge that is much higher than its real value at the rise of the main laser pulse. The simulations use exponential density profiles that may also differ from the experiment. On the other hand, one should note that the experimental density scale lengths are not measured but only deduced from the delay between the prepulse and the main laser pulse. The calculated maximum efficiency of the laser energy transformation into K-α emission was 2×10^{-5} for aluminum and 6×10^{-5} for copper.

3.2 Role of ionization and collisions in femtosecond interactions

Mean ion charge Z changes considerably during the interaction. Material evaporated due to an insufficient laser contrast or due to an intentional weak

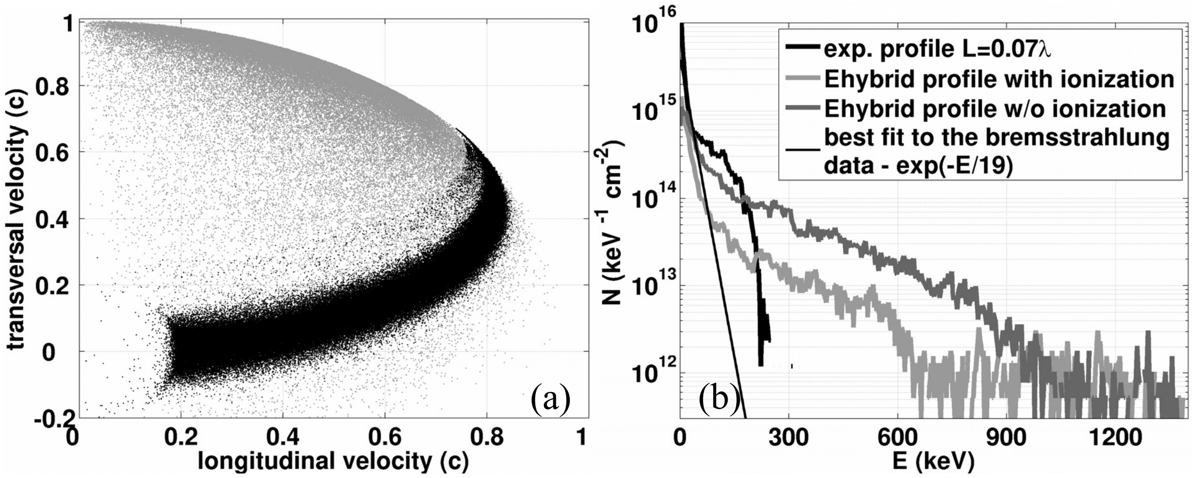

Fig. 12 (a) Directions of electrons (light grey) released by ionization near the laser pulse maximum are different from the other accelerated electrons (black) propagating into the target. (b) Energy spectra of fast electrons for exponential profile and profile from the simulation by Ehybrid code [69] with ionization processes switched off and on in the PIC code compared with the experimental bremsstrahlung spectrum (measured for energies ≤ 100 keV).

laser prepulse is lowly ionized with $Z \leq 1$ at the main pulse onset. Plasma is ionized mainly by optical field ionization during the rise of the main pulse. When the laser intensity exceeds the limit for ionization to a certain ion charge, ionization to this charge state proceeds in the time shorter than the laser period. The maximum ion charge achievable by the optical field ionization is controlled by the maximum intensity during the laser pulse. Collisional ionization dominates after the laser pulse maximum. While the mean ion charge may be usually calculated from equilibrium relations for nanosecond laser pulses, these relations are not applicable to the femtosecond laser interactions.

However, the majority of PIC codes used for simulations of short-pulse laser-target interactions are collisionless and they do not include ionization processes. The collisional and atomic processes are difficult to incorporate into the collisionless PIC model and moreover, the simulations with collisions are significantly more time-consuming. Originally, ionization was included into PIC code via an increase of the number of electrons represented by one macroparticle [62]. This methodology is not sufficient when the new electron is released by ionization in a different phase space position. In our code [63], ionization is treated by the addition of new macroparticles using Monte-Carlo probabilistic algorithm similarly to Kemp *et al*. [64]. We use the ADK tunneling ionization rate [65] since this is valid with the exception of a few cycle pulses where the critical field for barrier suppression ionization may be exceeded. Classical Lotz cross-section is used for collisional ionization. Elastic Coulomb collisions are included using probabilistic Takizuka-Abbe algorithm [66].

In Fig. 12a), the impact of ionization on the directions of fast electrons propagating into the target [63] is demonstrated for 45 fs p-polarized pulse of intensity 10^{19} W/cm^2 incident at the angle 45° on titanium plasma with the exponential profile of the density scale length L=4λ. Electrons (grey), released near the laser pulse maximum, propagate at large angles to the target normal, while the direction of the other fast electrons (black) agrees well with the classical formula derived from the energy and momentum conservation arguments [67]. This formula indicates that the non-relativistic fast electrons propagate normally to the target surface while the ultrarelativistic electrons fly in the direction of the incident laser wave. We have used our code for the interpretation of experiments [68] where K-α emission from copper foils irradiated by 45 fs pulses of 1 kHz Ti:Sapphire laser of intensity 10^{16} – 10^{17} W/cm^2 was measured. We were unable to reproduce experimental results when constant ion charge and exponential density profile was assumed. Fluid Ehybrid code [69] specialized on low intensity laser-solid interactions was used for the calculation of the plasma density profile formed by the amplified spontaneous emission. In Fig. 12b), electron energy spectra calculated for constant ionization and exponential profile and for the profile calculated by Ehybrid code. Only when PIC simulations include ionization processes and they start from the density profile taken from Ehybrid simulations, the calculated electron spectrum [70] agrees well with the experimental exponential spectrum with the hot electron temperature T_h = 19 keV obtained via bremsstrahlung measurement in the photon energy region below 100 keV [68]. In these simulations [70], the laser incidence angle 22° for which K-α emission is maximal, and the dependences of K-α emitted energies from the foil front and rear sides on the foil thickness agree well with the experiment.

3.3 Two-dimensional PIC simulations of ion acceleration

Ions are accelerated to very high energies in the short-pulse laser-target interactions. Up to now, the most successful scheme has been the transient normal sheath acceleration (TNSA) which is based on ion acceleration on the rear side of a thin foil target by a quasi-static electric field induced by the fast electrons penetrating through foil from the laser-irradiated side. Highly collimated ion beam is formed, and a success in the generation of monoenergetic ion beams has been announced [71]. Recently, interactions of femtosecond laser pulses with mass-limited targets (e.g. droplets, big clusters, small foil sections) have been studied experimentally [72]. Mass-limited targets reduce the undesirable energy spread from the primary particles interacting directly with laser to many secondary particles.

We have recently developed a two-dimensional relativistic PIC code including all three velocity components (2D3V) and we have used this code for simulations of ion acceleration in foil and droplet targets [73]. Special damping regions may be added to any combination of boundaries in our code in order to eliminate spurious reflection of electromagnetic waves from the simulation box boundaries. Three different options are available for the particles reaching the simulation box boundaries; they can be either reflected or substituted by thermal

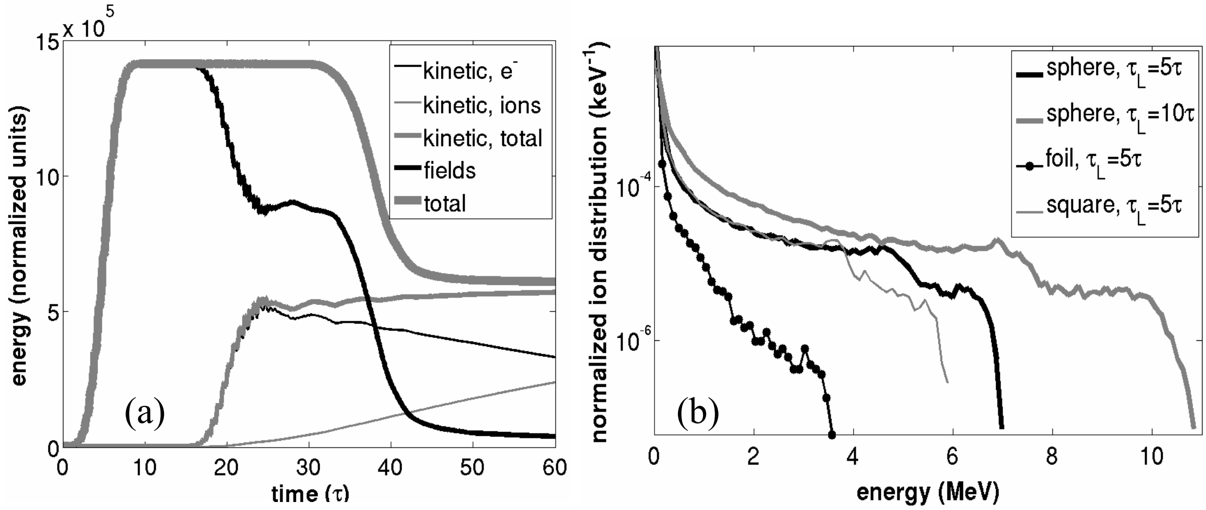

Fig. 13 (a) Energy balance in 2D simulations of laser interaction with water droplet target. Gaussian laser beam of width 4λ is incident on droplet of the same diameter and of electron density 4 n_c, laser amplitude a_0=10, pulse duration τ_L= 10 τ (τ=laser period). (b) Proton energy spectra for various targets and laser pulse durations τ_L.

particles or they can be captured at the boundary. Zigzag scheme is employed for the computation of the current densities in order to guarantee an automatic compliance with the continuity equation.

We have used our code for simulations of laser interactions with spherical droplet targets. The sphere is modeled in 2D by an infinite cylinder. Energy balance is plotted in Fig. 13a). For Ti:Sapphire laser with laser period 2.8 fs, the dimensionless amplitude a_0 = 10 corresponds to intensity 2×10^{20} W/cm^2. In the first 10 laser periods τ laser pulse enters the simulation box, at 15τ laser interaction with the water droplet starts, the electron kinetic energy rises fast, rapid oscillations in the electron kinetic and in the field energy are due to the electron oscillations in the laser field. Direct laser interaction with the droplet stops at about 25τ and then, slow oscillations in the kinetic and field energy are due to the fast electrons flying forth and back through the droplet. Electrons gradually transfer their energy to the ions in the electrostatic sheath around the droplet. Laser radiation starts to leave the simulation box at about 32 τ, the field energy at the simulation end is mostly the electrostatic sheath energy. Energy spectra of accelerated protons are plotted in Fig. 13b) for foil, foil section and droplet targets. The highest proton energy is achieved for the droplet due to the minimal transverse sheath dimension. Acceleration is also enhanced for longer laser pulses as more electrons form a thicker sheath with a higher electrostatic field.

4 RESEARCH AND EDUCATION IN THE AREA OF HIGH-POWER LASER-TARGET INTERACTIONS

Let me briefly comment on mutual relations of research and education in the area of high-power laser-target interactions. This research area includes experimental, theoretical and technological aspects. Department of Physical Electronics of FNSPE CTU educates master and doctoral students for research in all these areas. They are trained for experimental and technological research in the study program “Physical Electronics” and for theory and numerical simulations in the program “Information Science in Physics”. Our faculty now opens a new program “Physics and Technology of Nuclear Fusion” and we are preparing the part of the curriculum that concerns inertial fusion.

A very important aspect of the education in the area of high-power laser plasma interactions is its close link to our research. Although this research has a long tradition since 1970’s at our department, the last seven years were the most successful. The largest physics research infrastructure in the Czech Republic, PALS laboratory was opened in Prague in the year 2000, as a joint laboratory of the Institute of Physics and of the Institute of Plasma Physics of AS CR putting a new life into our existing collaboration with the AS CR. From the same year, our collaboration with PALS was supported in the frame of the research project “Laser Plasma Research Centre”, granted by the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic for years 2000-4. Our theoretical activities were incorporated into the international project INTAS-01-0233 coordinated by Professor Pegoraro, University of Pisa, Italy. I became the international coordinator of the project INTAS-01-0572, and within this project I started to plan, design and lead experiments at the PALS laser. Our group is presently also involved in 3 research projects supported by the Czech Science Foundation. In 2005, a new project “Laser Plasma Centre” has been granted by MEYS CR for the period 2005-9. Using the financial support of this project, our department has acquired a small high-power Ti: Sapphire femtosecond laser (12 mJ, 70 fs, 10 Hz) in 2006. This installation will enable our students to carry out research using an expensive up-to-date technology. This research will include technological aspects of high-power CPA laser systems, metrology of femtosecond pulses and experimental aspects of short-pulse laser-target interactions and diagnostics.

Our master and doctoral students have taken part in all our research projects. This participation have opened them way to research at the international level and also to a financial support. Consequently, our students have been able to participate actively at international conferences, and their articles have been published in international journals. For instance, we have published the results of two master theses in one article in the journal „Laser and Particle Beams” in 2004, and this article has already been 10 times independently cited. One of our PhD students spent several months in France with the support from COST project and he has already been offered post-doctoral positions in France and Japan. Another our PhD student is supervised jointly by me and French professor of CELIA laboratory at the University of Bordeaux. We also participate in the pedagogically oriented doctoral project „Advanced Topics in Physics and Chemistry of Plasmas” of the Czech Science Foundation where our students learn collaboration in team and get acquainted with research in related fields in the participating universities and institutes. We also encourage our students to submit projects to the CTU internal grant program and to the Czech Universities Development Fund. Most of our students succeed in these competitions and they gain valuable experience in the project management. As the standard PhD studentship is not sufficient to cover the living costs, an additional financial support of PhD students from various projects is vital. Otherwise, most of our PhD students would not be able to devote themselves fully to PhD study that according to my opinion has to be a full time occupation.

The close cooperation with the PALS laboratory is a great advantage also for our students. Some of them are directly supervised by the researchers from the institutes of AS CR. Several our graduates have found permanent positions at these institutes, some directly at PALS laboratory. However, even the other students profit from the international environment at PALS. PALS laboratory is a member of the consortium "LASERLAB-Europe", linking together the largest European laser facilities. Using the support of this consortium within the 6th EU Framework Program, many foreign researches are carrying out their research at PALS laboratory in Prague in collaboration with Czech researchers. Our students participate in these experiments and in the interpretation of experimental results. The unique opportunity of personal contacts with renowned European scientists is a great motivation for them.

I am convinced that our students will greatly benefit from the present stimulating international research environment at our department and in Prague.

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Doc. Ing. Jiří Limpouch, CSc.

CURRICULUM VITAE

Education and degrees

Ing. in Physical Engineering, 1978, Czech Technical University in Prague
CSc. in Applied Physics, 1984, Czech Technical University in Prague
Doc. in Applied Physics, 1999, Czech Technical University in Prague

Career/Employment

1983-4	Czech Technical University in Prague, technical associate
1984-91	Czech Technical University in Prague, research associate
1991-9	Czech Technical University in Prague, assistant professor
since 1999	Czech Technical University in Prague, associate professor
2000-5	PALS laboratory, AS CR, part-time project leader

Research visits

1983	6 months, Lebedev Physical Institute, Academy of Sciences of the USSR, Moscow,
1988	2 months, Rutherford Appleton Laboratory, Chilton, United Kingdom
2003	1 month, Utsunomiya University, Utsunomiya, Japan

Field of research

(i) **general interests**
numerical simulation and theory - laser target interactions; inertial confinement fusion; laser-produced plasmas; atomic physics of multiply ionized plasmas; short-pulse laser-target interactions
experiment - design and interpretation of interaction experiments

(ii) **current research interests**
laser interactions with low-density foams; line X-ray emission from laser produced plasmas; Particle-In-Cell simulations of short-pulse laser-target interactions; generation of ultrashort X-ray pulses; laser acceleration of charged particles

Publications and citations

Number of articles in refereed international journals:		55
Number of papers in proceedings of international conferences	over	60
Number of citations in ISI Web of Science (self-citations excluded)	over	100

Regular lectures

Fundamentals of plasma physics, FNSPE, summer term, 3+1 h, 1991 and since 1996
Numerical methods, FNSPE, summer term, 2+2 h, since 1993
Signal and data processing (with I. Procházka), FNSPE, winter term 2+1 h, 1992-2004
Computer applications I (with R. Liska), FT, summer term, 1+2 h, 1994-7
Introduction into physical kinetics, FNSPE, summer term, 1+1 h, 1993-5
Physical processes in laser-produced plasma, FNSPE, winter term, 2 h, 1990-1

Research projects

Project INTAS-01-0572 „Plasma creation, energy transport and smoothing of non-uniformities in volume-structured media irradiated by high-power laser pulses“, international coordinator, 2001-5
Project INTAS-01-0233 „Fast Ions in Laser-Plasma Interaction in the Relativistic Regime of Ultra-Short Ultra-Intense Pulses”, Czech team leader, 2001-5
Project HPRI-CT-2001-00163 „Bergen Computational Physics Laboratory“, leader of 2 subprojects (24 and 48), 2001-4
Projects LN00A100 “Laser Plasma Research Centre”, CTU team leader, 2003-4 and LC528 “Laser Plasma Centre”, CTU team leader 2005-9
Project GA202/06/001 of the Czech Science Foundation, principal investigator, 2006-8 and CTU team leader of other 4 CSF projects

Other scientific activities

External member of the Scientific Council of the Institute of Plasma Physics of the AS CR - since 2003
Project evaluator for INTAS – since 2006
Member of Program or Organizing Committees - 8 international conferences

Membership in Professional Societies

SPIE – since 2000
Union of Czech Mathematicians and Physicists – since 2005