2023

AWAKE: — We continued our participation in the AWAKE Collaboration, the quest to build the world's first proton-driven plasma wakefield accelerator for electrons at CERN [1]. We finished our comparison of plasma channel formation using on-resonant and off-resonant terawatt power laser pulses and published the results [2]. We concluded that on-resonant pulses (780 nm wavelength for the case of Rb vapor) are much more suitable for the creation of a long, homogeneous density plasma channel than off-resonant pulses. The main reason for this is the fact that resonant pulses are focused and channeled more efficiently by the vapor. We used schlieren imaging to investigate the plasma channel that is created by the pulses, and we designed a novel type of mask to place in the focal plane between the two lenses of the measurement setup. The mask is made up of two knife edges turned in opposite directions and it is much more suitable for the accurate measurement of the plasma channel transverse profile. This is because the new mask is free of the disturbing interference effects that limit the resolution of the measurements with a circular mask in the same setup. The new mask was tested in a series of measurements at CERN, in collaboration with Patric Muggli's group (Lucas Ranc and coworkers), using the new rubidium plasma source of the AWAKE Run2 device and the initial results are very promising. We started planning a slightly simpler version of the same measurement to probe the plasma profile that can be installed and run parallel with the proton beam modulation and electron acceleration experiments to serve as a permanent plasma diagnostic.

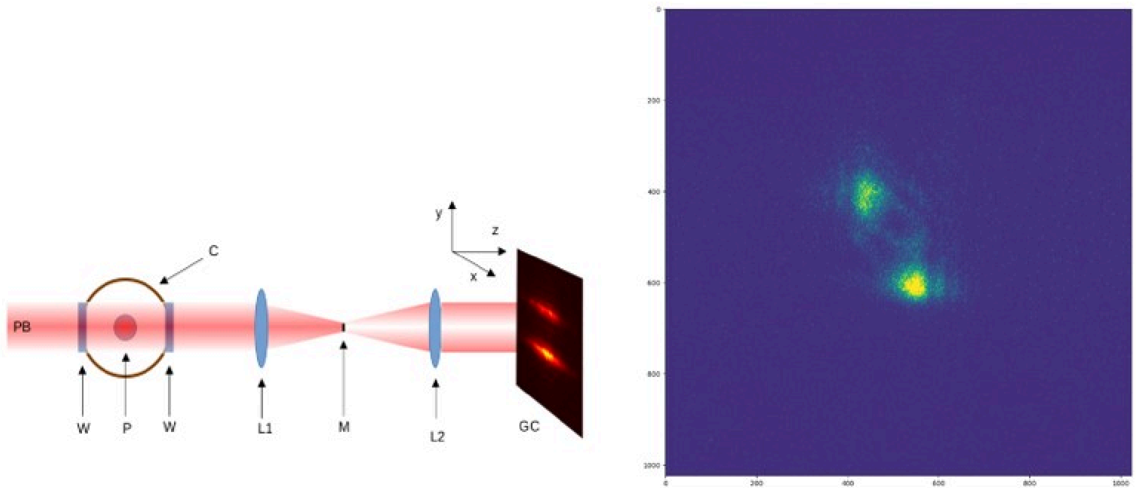


Figure 1. Schlieren imaging setup with the probe laser beam (left), and an example schlieren picture (right) taken with the new mask during the ionizing laser shot through the rubidium vapor.

Laser driven ion acceleration — We continued the evaluation of the experimental data taken in 2022 at the ELI-ALPS facility using the Sylos Experiment Alignment laser in cooperation with the National Laser Transmutation Laboratory of Szeged University. One of the main goals of these studies was the generation of accelerated positive and negative ion beams from gas cluster targets injected into the vacuum system. Although the highest laser intensity was generated at the shortest pulse duration of the laser (12 fs), we have observed that the highest maximum ion energies could be reached at longer pulse (i.e. lower intensity) settings. In Figure 2(a) the cut-off energy of Kr^+ ions can be seen as a function of the laser pulse group delay dispersion (GDD; the pulse length was minimum at 260 fs^2 and reached about 700 fs at -3000 fs^2). Similar observations were found with CO_2 molecular gas targets. Using CO_2 we also detected accelerated negative oxygen ion beams with maximum energy values in the range of 100-180 keV (see Figure 2 (b)).

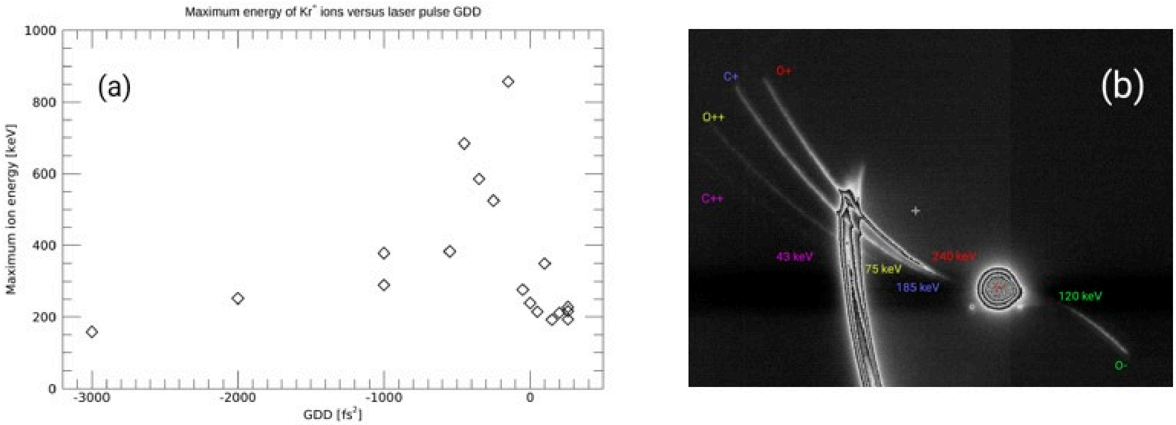
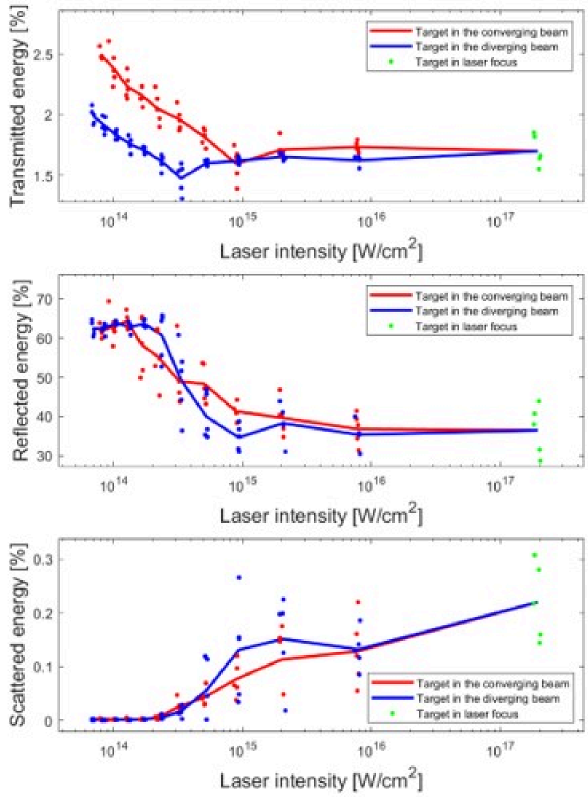


Figure 2. (a) Maximum energy of accelerated Kr^{+} ions versus laser pulse GDD (pulse duration). (b) Ion parabolas detected with CO_2 gas cluster targets showing the traces of positive ions as well as negative oxygen ions of 120 keV maximum energy.

NAPLIFE laser plasma studies — Femtosecond laser plasma studies were conducted in the framework of the Naplife project [3] in order to determine the energy absorption of the different targets and the propagation properties of the generated plume. The energy of the reflected, transmitted and scattered fractions of the incoming laser pulse were measured as a function of the laser intensity (spot size on the sample), varied by translating the focus position with respect to the target surface. Hydrocarbon polymer (UDMA) samples (undoped or doped with Au nanorods) were irradiated at 45 degrees incidence angle and the specular reflection, the transmission and the scattering (at 45 degrees above the incidence plane) were measured using laser energy meter heads. The results of one particular series of shots can be seen in Figure 3. At relatively low intensities most of the incoming energy is reflected as a result of the plasma mirror effect. When the target is in the beam focus, the specular reflection and the transmission decreases and the scattering increases, suggesting the increase of the energy absorption in the target material.

The plume propagation was measured using an intensified gated camera taking pictures with 10 ns exposure time in the direction parallel to the target surface (Figure 4) with different time delays after the laser pulse. By curve fitting calculations plume center-of-mass velocities in excess of 10^5 m/s were obtained. During a part of the experiment series the laser exhibited an unwanted pre-pulse at about 2.8 ns before the main pulse due to imperfect alignment. This pre-pulse can be suppressed by proper settings of the pulse slicer of the laser. As it can be seen in the figures, a significant difference in plume propagation can be observed between the cases when pre-pulses were or were not present. Without pre-pulses, the plume propagation is much more directional, and also the plume velocity is significantly higher.



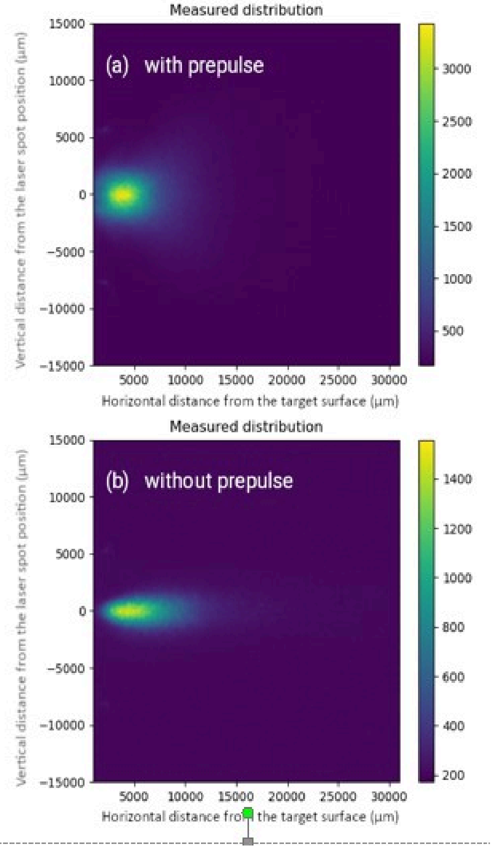
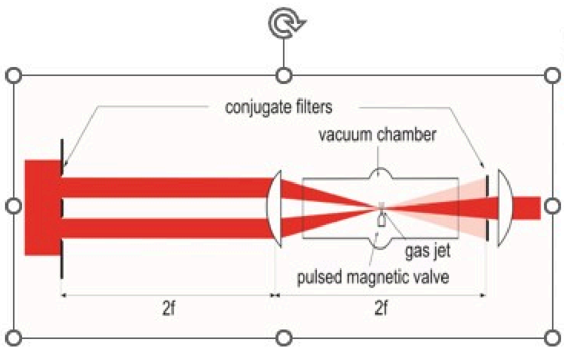


Figure 3. Specularly reflected, transmitted and scattered energy fraction vs. laser intensity at the target.Figure 4. Laser plume images taken at 50 ns time delay with (a) and without (b) pre-pulse before the main pulse.

EUROFUSION and Laser-plasma activity — Applicability of Fourier-filtering for the contrast improvement of CPA lasers. In the interactions of short pulse lasers with matter it is essential to have laser pulses free of prepulses and pedestals. A new method of nonlinear Fourier filtering in an ionized gas jet was developed and successfully applied earlier for the ultraviolet KrF laser in the University of Szeged by the group lead by Sándor Szatmári [4,5] with the participation of the Wigner RCP. Joint experiments – with the participation of Tamás Nagy from the Max Born Institute were now performed with our Hidra laser (30 mJ /40 fs). It was demonstrated that the method is applicable for the CPA Ti:sapphire system, and it is able to filter not only the ASE prepulses of several nanosecond duration but the picosecond pedestal originating from the incomplete compression, too. These preliminary experiments were carried out without optimizing the imaging, but still, ~3 orders of magnitude contrast improvement could be demonstrated. 4



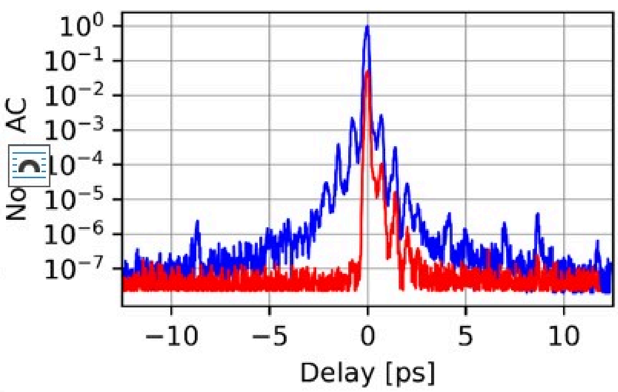


Figure 5. The experimental arrangement   Figure 6. Autocorrelator results show that the original (blue) curve has a 5 ps pedestal which disappears due to the Fourier filtering.

EuPRAXIA — The main goal of the EuPRAXIA Project is to build a novel particle accelerator for civil applications. After the successful foundation of the international consortium in 2022 the work went on in 2023. The Hun-Ren Wigner Research Centre for Physics is still active in different working groups planning the

EuPRAXIA facility. In the framework of the EuPRAXIA Doctoral Network the University of Pécs managed to hire an Argentinian PhD Student. He is going to investigate the questions of electron acceleration in THz fields both theoretically any experimantally as well. Our group continuously follows his activity and helps his professional career.

Laser-Matter Interaction — After a long-tem cooperation with the colleagues of the University of Szeged, University of Pécs and ELI-ALPS we manged to publish our results. We showed that with strong infrared laser pulses the energy levels and bound-lenght of a diatomic molecule can be changed with a dressed Morse potential [6]. We found analytic results for the energy shifts, the model was tested on the LiH and H_2 molecules. Figure 7 presents the relative energy shifts.

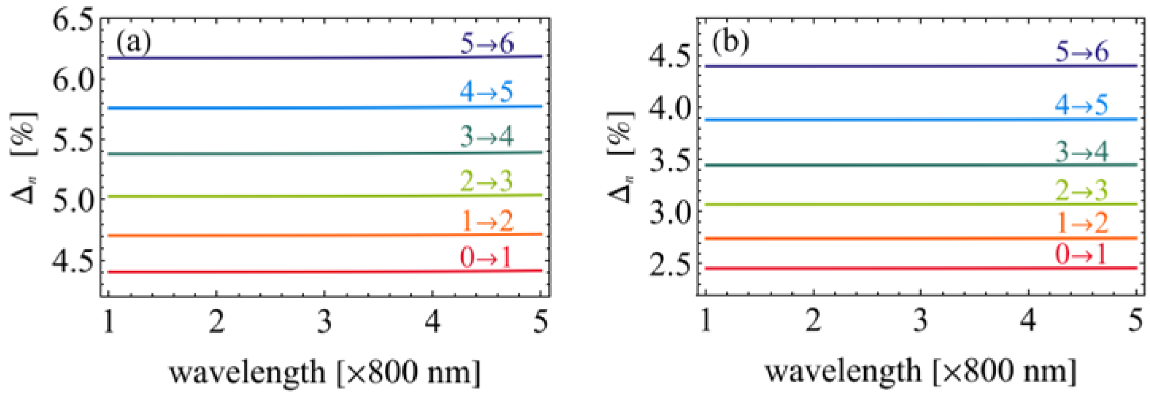


Figure 7 Relative shifts of vibrational transition frequency caused by the laser field for the first six energy levels for LiH (a) and for H_2 (b) as a function of laser wavelength in case of F_0 = 0.02 a.u. for LiH and F0 = 0.04 a.u. for H_2.

Mathematical physics — Our activity on the investigation of physically relevant analytic solutions of partial differential equations was continued in 2023. New results were published on regular diffusion [7], on non-linear reaction-diffusion equation [8] and about the dynamics of the rotating Euler-Poisson model [9] which is a candidate to understand dark matter in the Universe.

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2022

Laser-driven ion accelerator — Bursts of ions emitted from laser produced plasmas on solid-state surface or gas-jet targets have interesting characteristic and their possible application inspires our research. The velocity of the ions from laser plasma is related to the mechanism of the laser and matter interaction. The laser pulse is absorbed mainly by the 'hot' electrons in the skin depth of the solid target and the electron energy is transported to the ions by the target normal sheet acceleration (TNSA) process. Coulomb explosion phenomenon is relevant when intense laser pulse highly ionizes clusters in gas-jets. The clusters explode resulting in generation of multiply charged ions with large kinetic energy. The energy distribution of different ions accelerated from the laser illuminated targets is investigated by Thomson parabola ion spectrometer that combines magnetic and electric fields to separate ions by energy and specific charge.

An experimental device was built in our laser laboratory, in which ions can be generated and examined with ultra-short, sub-TW laser pulses focused on the surface of a target in the target chamber of the two-chamber vacuum system (Fig. 1. left). The mass and energy distribution of the ions passing through the Thomson parabola spectrometer arrangement placed in the detector chamber can be measured with a spatially resolved micro-channel plate (MCP) detector. The equipment can be used to study the efficiency of ion generation and the parameters of the ion beam depending on the material and structure of the target object and other conditions.

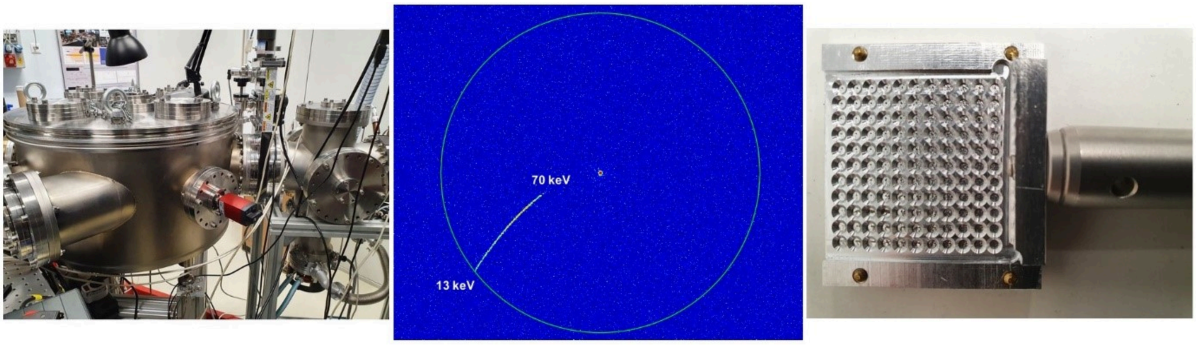

Figure 1. External view of the device to create and detect ion beams (left). Proton energy distribution on the Thomson parabola spectrometer (middle). A film in the target holder after the high-intensity laser shot (right). Tiny holes are visible in the holder's openings.

In 2022, our group had the opportunity to conduct laser-driven ion acceleration experiments with the SYLOS Experiment Alignment laser at ELI ALPS within the project. This is an appropriate laser for our experiments, its peak power can be slowly varied in the TW range and pulse duration can be stretched from 12 fs up to 200 fs by chirping the pulse. We examined the interaction the laser pulse with thin carbon nanotube foils and with 10 nm thin gold layer grown on the carbon nanotube targets in the case of TNSA ion acceleration. The preliminary results suggest that the thin gold layer enhances the 'hot' electron generation which increases the flux of the ions. For the investigation of the Coulomb explosion scheme, we used gas-jets created by different nozzles and with different gases, such as atomic argon, krypton and a molecular gas carbon dioxide. Experiments show that the spectrum of the ion energy depends on the atomic mass and the geometry of the nozzle and thereby the cluster size. As for the carbon dioxide, in addition of positive ions we detected negatively charged ions. This is an exciting result, because the electron capture mechanism is not completely clear.

AWAKE: The AWAKE Collaboration at CERN, in which we participate, aims to build a novel plasma wakefield particle accelerator device for electrons. We continued our investigations of plasma channel creation with ultrashort, terawatt laser pulses by evaluating the laser propagation experimental data that was taken for resonant (780 nm central wavelength) and off-resonant (810 nm) ionizing pulses. The data contained information on the energy and the transverse distribution of the transmitted laser pulses, as well as schlieren imaging measurement pictures for the plasma channel. We extracted information on the diameter of the plasma channel core from these images, as well as the width of the plasma sheath layer, the layer of partially ionized rubidium vapor between the fully ionized core and the unionized vapor. We showed, that resonant ionizing pulses create a more compact plasma channel with a much thinner sheath (i.e. a much sharper transition between plasma and vapor) than off-resonant ionizing pulses. As a result, resonant pulses lose less energy in creating a plasma channel of equal core radius than off-resonant pulses do, so they can be used to create longer plasma channels. Using the measurement data, we showed that the AWAKE laser system would easily be able to create a 0.5 mm core radius, 20 m long plasma channel with resonant pulses and is even close to being able to create a 1 mm core radius channel with the same length (Fig. 2). We developed a theory to describe the propagation of resonant and off-resonant pulses in the rubidium vapor in a unified way. The results of the corresponding computer simulations show very good qualitative agreement with the experimental data. While studying the schlieren measurements, we developed and tested novel, machine learning methods for estimating plasma channel parameters from the camera images [1]. We also took part in the proton bunch self-modulation experiments conducted at CERN [2].

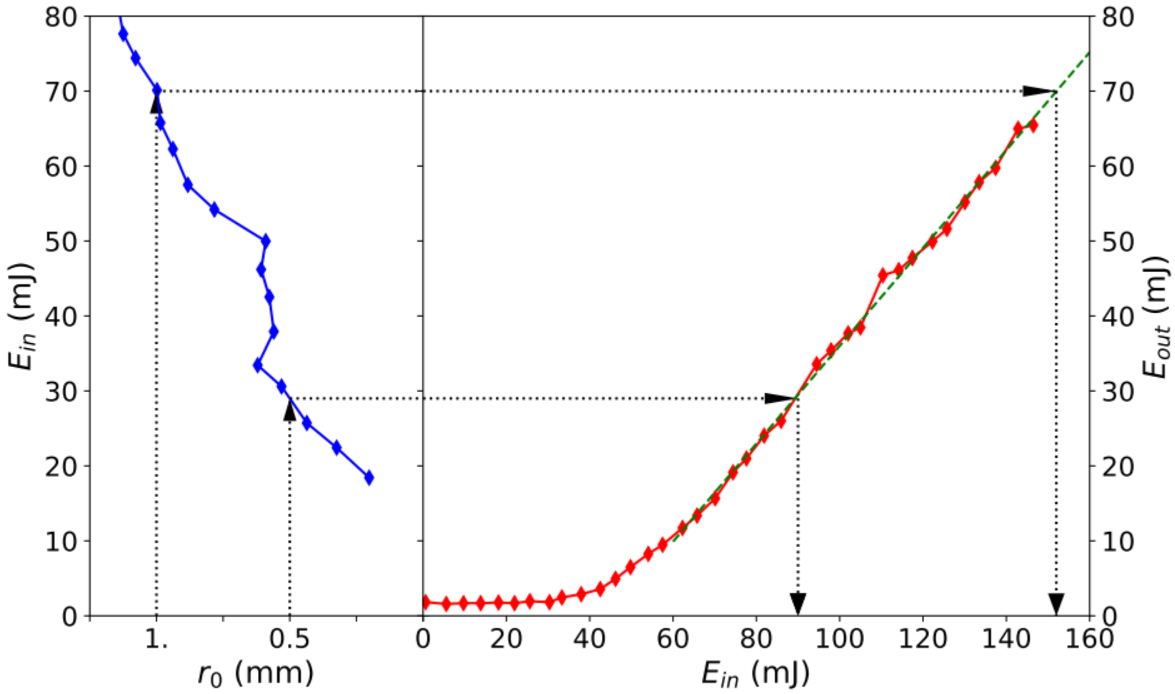

Figure 2. Transmitted pulse energy (right) and plasma channel core radius (left, rotated) as a function of initial energy for resonant ionizing pulses and 10 m vapor length. Arrows depict the method for estimating the energy requirement to create a 20-m-long plasma channel.

Eurofusion and laser-plasma activity — Simultaneous observation of Kα radiation from different emitters allows exact determination of hot electron temperature in laser-plasma interaction. A conical von Hamos spectrometer was prepared for simultaneous observation of Ni and Cu radiation [3], Fig. 3 illustrates the detection K-lines using cw x-ray source. Experiments are planned with the Frascati ABC laser using special sandwich-structured targets. We also designed a spectrometer for the large ELI-Beamlines facility for which simultaneous Cu and Ti emission is to be observed. In our recent experiments [4] large absorption and high acceleration of ablating material was observed in the laser-plasma interactions of 600 fs laser pulses on the 248 nm wavelength up to 10^{18} W/cm^2 intensity. The MULTI-fs hydrocode could well describe the observed velocity of the expanding plasma, but it underestimates the high absorption in case of the largest intensities. Further simulations with imporved equation of states are in progress.

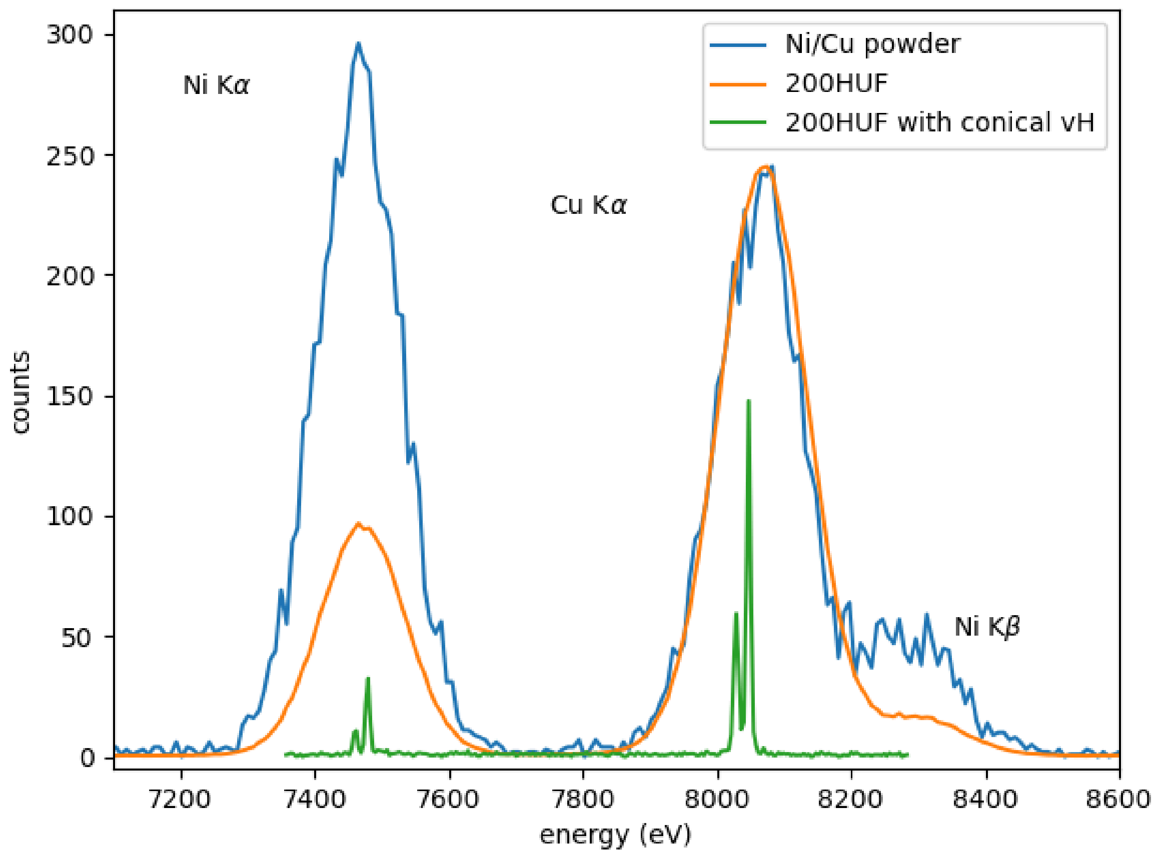

Figure 3. Cu and Ni K-shell spectrum. The resolution with our spectrometer is much higher than that of energy resolving solid state detectors.

EuPRAXIA — The main purpose of the EuPRAXIA Project is to develop and build a novel particle accelerator for civil applications. In 2022 the the final structure of the international consortium was formed and all members signed the document. The Wigner Research Centre for Physics joined the project in a close collaboration with the University of Pécs and University of Szeged, as a full member of the consortium. In the second half of 2022 the EuPRAXIA Doctoral Network also started to educate and train highly qualified personnel who will operate the EuPRAXIA accelerator infrastructure. In close collaboration with the Universit of Pécs, the Wigner RC can apply to host students to provide them a qualification such that they will be eligible to attend this innovative project.

Mathematical physics — The investigation of physicaly relevant analytic solutions of partial differential equations of flow systems was continued. Results were published on regular diffusion [5,6], water waves [7] and about the dynamics of dark fluid [8] which is a candidate to understand dark matter.

International collaborations: EUROFUSION, AWAKE, EuPRAXIA

2021

Laser-driven ion accelerator. — Ion and electron acceleration using ultrashort high intensity laser pulses is currently being widely investigated, but laser-plasma interactions as sources of high energy negative ion and neutral atom beams have not been investigated thoroughly yet. The laser acceleration of positive ions is possible through a number of processes (e.g. in the so-called Target-Normal-Sheath-Acceleration mechanism). The charge of a positively charged projectile can be reduced by capturing bound or free electrons, the strong neutralization can even generate negative ions if atoms have positive electron affinity. By irradiating clusters of CO_2, the interaction can form stable C and O negative ions. Our research work for developing of a laser-driven ion and atom accelerator in the frame of an NKP project. We would like to develop compact foil and gas cluster targets and a portable Thomson parabola spectrometer for the generation and characterization of ion and atom beams which can be applicable up to relativistic-intensity laser-plasma interactions. In the detection system the ions are deflected in static magnetic- and variable electric fields. The laser beam is focused into the target by a parabolic mirror. The arrangement can be seen in the Figure 1.

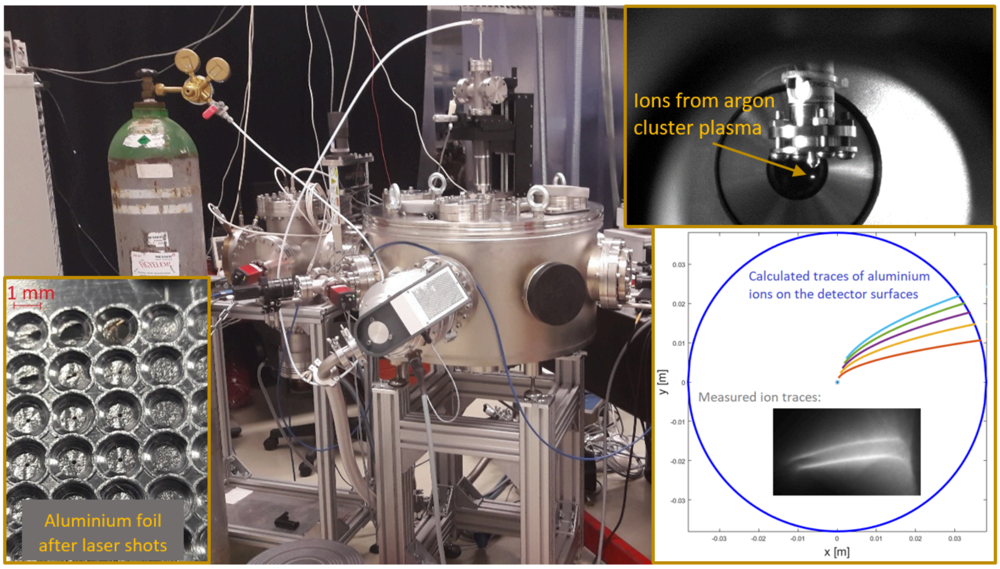

Figure 1. Compact laser-driven ion- and atom accelerator setup.

In 2021 we developed a high pressure gas injection system, with which Van-der-Waals-bonded clusters can be generated with a wide range of diameters. Cluster size was monitored by Rayleigh scattering of laser light. New sample holders for solid targets were designed and fabricated, which allow effective and economic usage of expensive foils. Ion generation was investigated from aluminum foil and argon clusters. For ions with different energies it is necessary to use different magnetic field strengths in a wide range, therefore we measured the magnetic field in case of several setups with yoke geometry. Calibration and testing of the Thomson parabola spectrometer was carried out with several targets which required the shielding of the detectors to avoid stray light.

AWAKE: Laser pulse propagation in rubidium vapor and plasma channel diagnostics. — As a member of the AWAKE Collaboration at CERN, aiming to build a novel plasma wakefield particle accelerator for electrons, we investigate the creation of a long plasma channel using ultra-short, terawatt laser pulses. At the AWAKE location in CERN we conducted laser pulse propagation experiments in a wide range of parameters (vapor density, pulse energy), measuring the transverse energy distribution and spectrum of the transmitted laser pulse. We investigated the difference between the propagation of a 780 nm wavelength 'resonant' pulse and that of an 810 nm wavelength 'non-resonant' pulse. Theory predicts the propagation properties of resonant and non-resonant pulses to be very different [1] and these experiments were aimed at probing these differences as the resulting plasma channel is also predicted to be quite different. We thus also measured the ionization of the rubidium vapor using a Schlieren imaging setup, in an attempt to quantify the width of the plasma channel. Processing of the experimental data has begun and its comparison with the most recent simulation results is expected to soon follow. We also took part in the experimental program of the collaboration by helping operate the laser system and plasma generation during the measurements of proton beam modulation and electron acceleration.

Relativistic electrons by THz radiation. — In previous experiments of the group with the University of Szeged [2] half cycle THz radiation was efficiently generated by Large Aperture Photoconductive Antennas (LAPCA). A new setup is proposed together with the University of Pécs which combines their Optical Rectification method in lithium-niobate with the LAPCA method. THz radiation from LAPCAs may result in bunching of the electrons, thus shaping the electron beam.

The conical con Hamos spectrometer. — The conical von Hamos spectrometer designed by our group was built together and tested. The tests were carried out together with the Femtosecond Spectroscopy and X-ray Spectroscopy Research Group. In the tests, radiation from a CW X-ray tube was focused on samples, and the fluorescent signal was investigated. Our spectrometer was compared with simple semiconductor detectors and also with a high-resolution, cylindrical von Hamos spectrometer. The measured spectrum proves that the arrangement now allows the simultaneous observation of Cu and Ni K-α radiation at 7.4 and 8.0 keV with a single CCD detector. The compression of the spectrum in size does not mean serious loss of the resolution, as the K-α doublets can be clearly distinguished in both cases. The spectral resolution in this range was better than 5 eV, in good agreement with ray tracing calculations. Thus, we started with designing experiments on high power laser facilities (ABC laser in Frascati and HILL KrF laser in Szeged) to investigate hot electron temperature using this spectrometer.

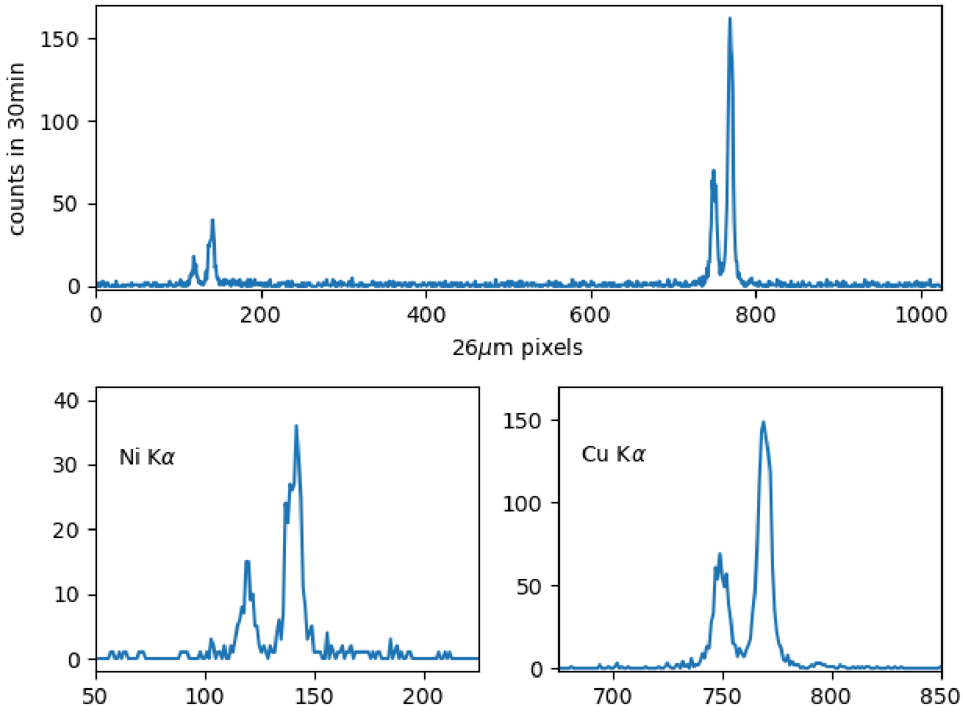

Figure 2. Fluorescent spectrum of the Cu and Ni K-shell spectrum. The lower curves show the Cu and Ni radiation in more detail

EuPRAXIA. — The goal of the EuPRAXIA Project is to develop and build a novel particle accelerator for civil applications. At the beginning of the year 2021, the EuPRAXIA Conceptual Design Report was published and became available online [3]. During the year, the final structure of international consortium has been formed. The Wigner Research Centre for Physics will join the project in a close collaboration with the University of Pécs and University of Szeged, as a full member of the consortium. The goal of the 2nd phase is to elaborate the Construction Design Report between October 2022 and September 2026.

The development, construction and running such an accelerator, and planning tailor-made accelerators in the future requires highly qualified personnel. Therefore, the EuPRAXIA Project applied for stipends via the Marie Skłodowska-Curie Actions. The Wigner Research Centre, in a close collaboration with the University of Pécs, also applied to host a Ph.D. student and give her/him a qualification such that she/he will be eligible to attend this innovative project.

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[1] G. Demeter, J. T. Moody, M. Á. Kedves, B. Ráczkevi, Aladi et al., Phys. Rev. A 104, 033506 (2021)

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International collaborations: EUROFUSION, AWAKE, EuPRAXIA

Selected journal papers:

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2. F. Batsch, … G. Demeter, ... AWAKE Collaboration: Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma, Phys. Rev. Lett. 126, 164802 (2021)

3. I.F. Barna and L. Mátyás: "Analytic solutions of a two-fluid hydrodynamic model", Mathematical Modeling and Analysis 26, (2021) 582, https://doi.org/10.3846/mma.2021.13637

4. Földes I.B., Tikhonchuk V.T.:Comment to the paper I. Papp et al.: Laser wake field collider [Phys. Lett. A 396 (2021) 127245]; PHYSICS LETTERS A 424 Paper: 127845 2 p. (2022)

2020

Ionizing laser pulse propagation in rubidium vapor — Our research group is a member of the AWAKE Collaboration at CERN, whose aim is to build a novel plasma wakefield particle accelerator for high-energy physics applications. We investigate the physical processes associated with the creation of a long plasma channel in rubidium vapor that serves as the proton bunch modulator and the energy exchange medium for acceleration, using high-intensity laser pulses. We have conducted experimental investigations of laser pulse propagation in Rb vapor at CERN using the AWAKE plasma chamber and laser system, by observing the transverse profile of the ionizing laser pulses after the chamber, as well as measuring transmitted energy and laser profiles in a virtual laser diagnostic line. Our analysis of the data revealed several interaction regimes depending on laser pulse energy, including a *sub-threshold* domain, a *breakthrough* domain and *confined beam* domain. These domains are characterized by distinctive changes in beam width, transmitted energy and transmitted pulse fluence. Experimental findings were also compared to extensive numerical simulations of a theoretical model derived by us earlier to describe the system. Qualitative predictions of the model were verified, quantitative differences between theory and experiment identified.

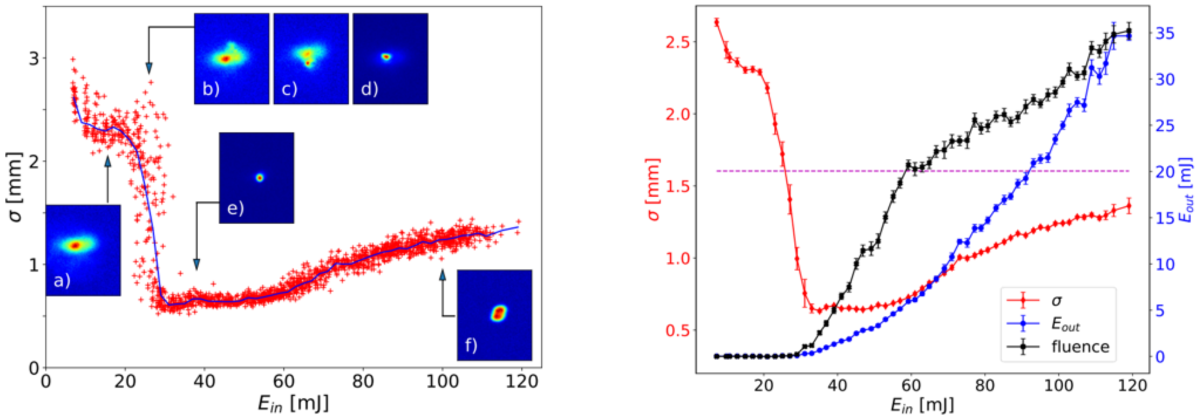

Figure 1. *Left: Laser pulse width after propagating across the chamber with selected pulse profiles displayed. Right: Transmitted pulse energy, peak fluence and pulse width.*

Compact laser-driven ion- and atom accelerator. — Our research group studies laser-plasma interactions as sources of high energy negative ion and neutral atom beams for a wide range of societal and industrial applications. Laser-field-accelerated particles can be obtained from thin-foil targets using high-intensity pulsed lasers. Our work for the building of a laser-driven ion and atom accelerator was initiated in September 2018 in the frame of an NKP project. We would like to develop compact target sources and detector systems for the generation and characterization of ion and atom beams which can be applicable both for moderate-intensity and relativistic-intensity laser-plasma interactions. The first task was the planning of an accelerator compatible vacuum system. A vibration isolated breadboard for laser optics was planned for avoiding the misalignment of the beams due to the pumping. The ion generation will be carried out from gas, liquid and solid targets. Using of solid foils needs a vacuum-compatible translation stage on the breadboard. The detection system is a Thomson parabola spectrometer. The ions will be deflected in static magnetic and variable electric field. The laser beam is focused into the target by parabolic mirror. In order to reach the optimum focus distribution, precise alignment of the mirror and measurement of the waist size and quality are required. The arrangement can be seen in the Figure 2.

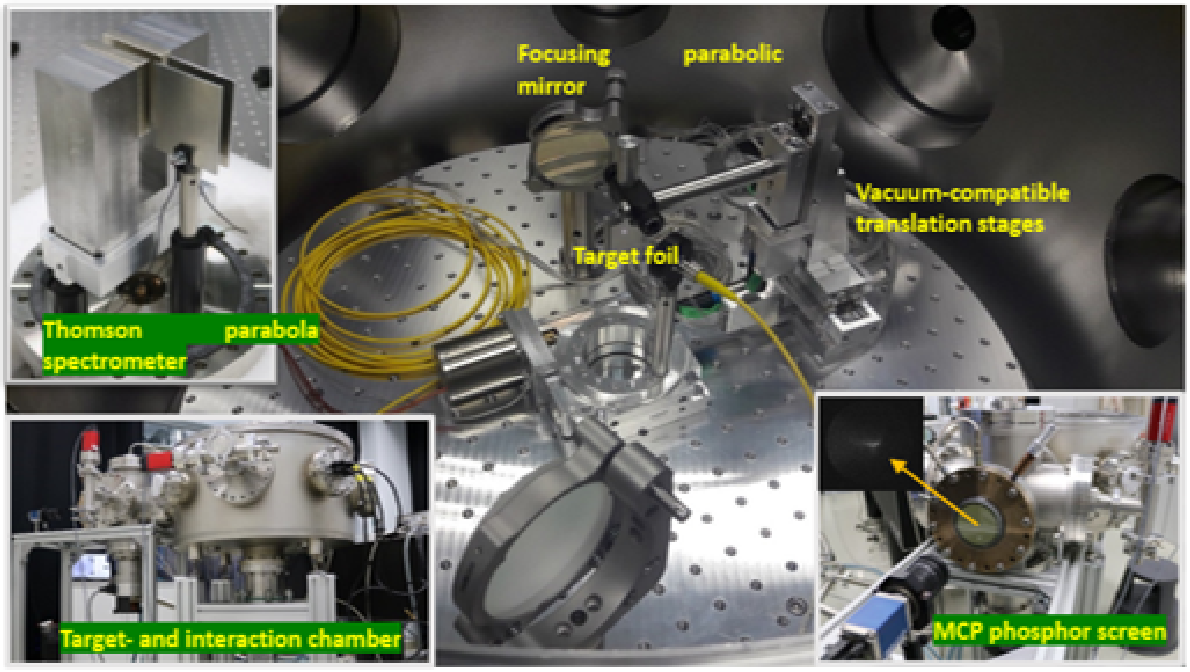

Figure 2. *Experimental setup for laser-driven ion- and atom beam generation and detection.*

Reflectivity and spectral shift of KrF laser pulses from plasmas on solid surfaces - The energy and spectrum of the reflected 248 nm radiation was studied from solid targets up to more than 10^{18} Wcm^{-2} intensity. The experiments used the 700 fs directly amplified pulses of the KrF system which was cleaned from prepulses with the new Fourier-filtering method providing 12 orders of magnitude temporal contrast. Increasing intensity from 10^{15} Wcm^{-2} results in increasing absorption both by high and low contrast pulses up to more than 90% above 10^{18} Wcm^{-2}. This is accompanied by increasing x-ray conversion exhibiting a less steep power law dependence for low-Z matter than for gold. Strong blue shift of the reflected radiation from the backward propagating plasma was observed. The velocity derived from the Doppler shift shows the effect of high-contrast, in which case a higher than previous velocity could be observed. The results show that radiation pressure inward motion and the **jxB** force is negligible. It is shown that in the case of KrF laser pulses of highest contrast, vacuum heating can be one of the dominant absorption mechanisms. The high absorption is probably a combined effect of collisional, resonance and Brunel-absorption.

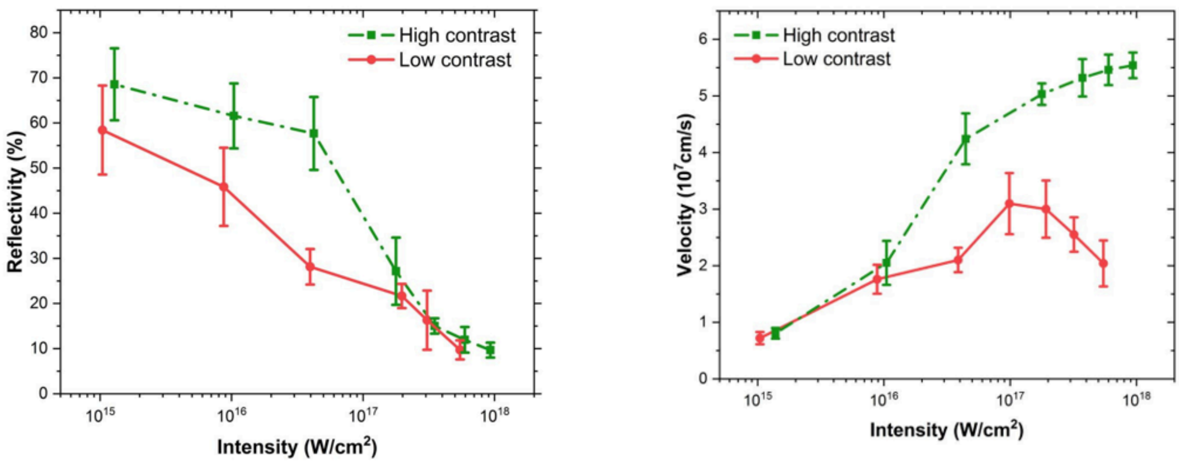

Figure 3. *Reflectivity of 248 nm laser pulse from solid B targets in case of high and low contrast laser pulses (left-hand-side). Velocity of the expanding plasma derived from the Doppler shift in the same case.*

Instrument design and development:
We designed a new **conical von Hamos spectrometer** for plasma diagnostics, which can simultaneously observe the Kα radiation from Ni and Cu microdots. In our design – assuming a target-detector distance of 800 mm - the distance between the Ni and Cu Kα lines will be only 17 mm in the detector plane, therefore it will be possible to use a streak camera for time-resolved measurements. Conical von Hamos spectrometers are used in some labs in the soft x-ray range, however – as far as we now – it is new in the multi keV range.
We built an **external compressor for the Coherent Hydra Ti:Sa laser system**. The system allows (via bypassing the built in internal compressor of the laser) the transport of the stretched, low intensity pulses for large

distances in air to optical tables in the laboratory and their compression just before the target. This avoids energy loss and pulse distortion due to nonlinear effects during propagation.

Rubidium ionization studies using ab-initio calculations – were conducted to examine the ionization probability and photoelectron spectrum of Rb atoms under irradiation by intensive laser pulses. In this description atom-laser interaction explicitly includes continuum states for the ejected electron. The results can be used to verify and improve the description of the simplified model used in the propagation calculations in the AWAKE project. We are also involved in investigations of analytical solutions of hydrodynamical equations.

Outreach - We also took part in the preparatory phase of the EuPRAXIA collaboration, which is a planned research infrastructure of the European Union. This device is to be a plasma wakefield accelerator to yield 5 GeV electrons for practical applications such as material science and biological experiments.

International collaborations: EUROFUSION, AWAKE, EuPRAXIA

Selected journal papers:

1. F. Braunmüller, et al., incl. M. Aladi, G. Demeter, G. P. Djotyan, M.Á. Kedves, B. Ráczkevi,: Proton Bunch Self-Modulation in Plasma with Density Gradient Phys. Rev. Lett. 125, 264801 (2020)

2. Z. Kovács, K. Bali, B. Gilicze, S. Szatmári, I.B. Földes: Reflectivity and spectral shift from laser plasmas generated by high-contrast high-intensity KrF laser pulses; Phil. Trans. Roy. Soc. A 378, 20200043. (2020) http://dx.doi.org/10.1098/rsta.2020.0043

3. M. Turner, et al. incl. M. Aladi, G. Demeter, G. P. Djotyan, M.Á. Kedves, B. Ráczkevi: Experimental study of wakefields driven by a self-modulating proton bunch in plasma Phys. Rev. Accel. And Beams 23, 081302 (2020),

4. A.A Gorn, et al. inc. M. Aladi, G. Demeter, G. P. Djotyan, M.Á. Kedves, B. Ráczkevi: Proton beam defocusing in AWAKE: comparison of simulations and measurements Plasma Phys. Control. Fusion 62 (2020) 125023,

5. Zs. Kovács, B. Gilicze, S. Szatmári & I.B. Földes: Large Spectral Shift of Reflected Radiation From Laser Plasmas Generated by High Contrast KrF Laser Pulses; Frontiers in Physics 8, 321 (2020) doi:10.3389/fphy.2020.00321

6. W. Assmann, M. Weikum., et al. incl I. Barna and M. Pocsai: EuPRAXIA Conceptual Design Report Eur. Phys. J. Special Topics 229, (2020) 3675-4284

7. I. F. Barna, G. Bognár, L. Mátyás, M. Guedda, and K. Hriczó Analytic Traveling-Wave Solutions of the Kardar-Parisi-Zhang Interface Growing Equation with Different Kind of Noise Terms Springer Proceedings in Mathematics & Statistics Series, Vol. 333 Differential and Difference Equations with Applications, Page 239 - 255

8. I.F. Barna, G. Bognár, M. Guedda, K. Hriczó and L. Mátyás Analytic self-similar solutions of the Kardar-Parisi-Zhang interface growing equation with various noise term Mathematical Modelling and Analysis 25, (2020) 241

9. I.F. Barna, L Mátyás and M.A. Pocsai Self-similar analysis of a viscous heated Oberbeck-Boussinesq flow system Fluid. Dyn. Res. 52, (2020) 015515