Wigner 121
Scientific Symposium

Wigner Research Centre for Physics
Institute for Particle and Nuclear Physics
Department of High Energy Physics
Laser Particle Accelerator Technology Research Group

Introduction

The Laser Particle Accelerator Technology Research Group participates in the development of novel particle acceleration technologies where ultra-short, high-intensity laser pulses play a dominant role.

We take part in the AWAKE (Advanced Proton Driven Plasma Wakefield Acceleration Experiment) Collaboration at CERN where laser pulses create the plasma that acts as an accelerating medium. In this framework we study the properties of the plasma as well as the propagation of the ionizing laser light that is in resonance with the atoms of the original neutral vapor. Besides, we took part in some of the data taking campaigns of the proton beam modulation experiments (→ AWAKE Plasma Studies).

Direct laser acceleration of ions is investigated by irradiating different target materials by high intensity femtosecond laser pulses in our laboratory, as well as at the ELI-ALPS laser facility in collaboration with the NLTL group in Szeged. Besides studying the acceleration from solid target foils of different structures we explore the generation of high energy beams of positive and negative ions or neutral atoms in pulsed gas cluster clouds or liquid vapors (→ Laser Particle Acceleration).

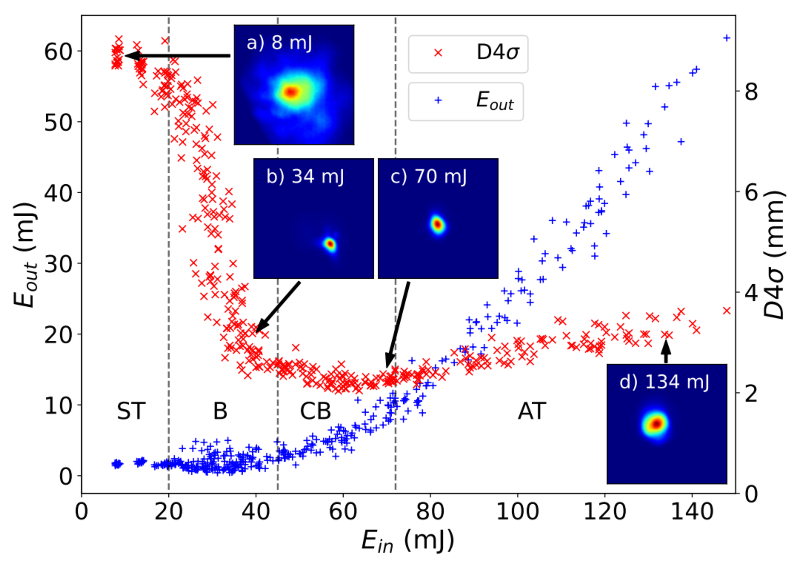
We are participating in the enabling research activity on „Advancing shock ignition for direct drive inertial fusion" of the Eurofusion, in which we are contributing to the temperature measurements of hot electrons with a new method (→ Inertial Fusion Energy).

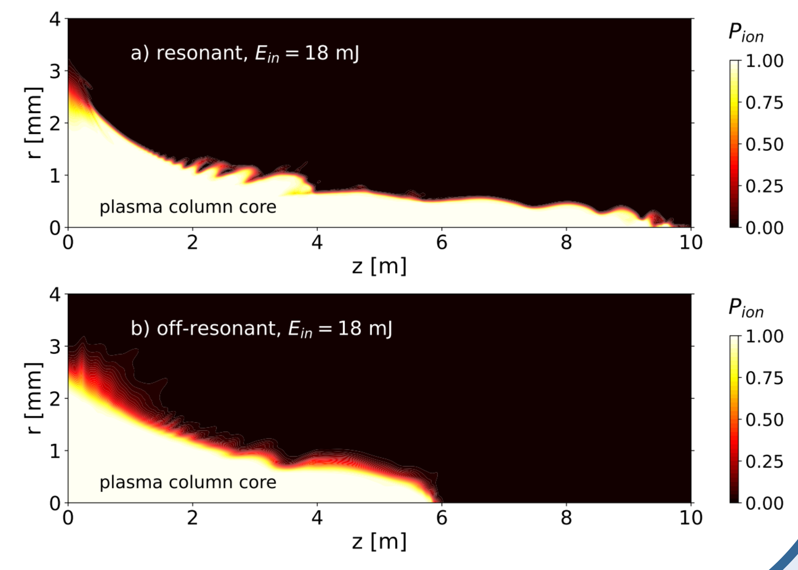
In the last decade Imre Ferenc Barna and coworker investigated physically relevant non-linear partial differential equations with the traveling wave and with the self-similar Ansatz. With this method numerous new and physically important solutions can be derived with analytic means (→ Self-similar Studies).

Members of the Laser Particle Accelerator Technology Research Group: Márk Aladi, Imre F. Barna, Gábor Demeter, Gagik Dzsotján, István B Földes, Miklós Á. Kedves, Béla Ráczkevi, Zsuzsa Simon

AWAKE Plasma Studies

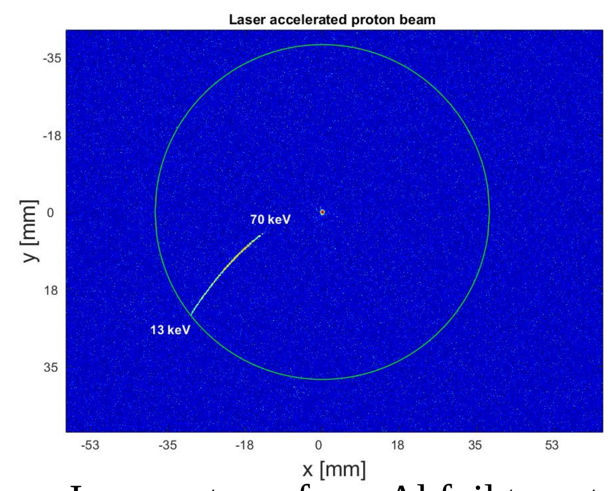
Our participation in the AWAKE Collaboration entails studying the propagation of the ionizing laser pulse that creates plasma in the accelerator device, as well as the properties of the plasma column it creates. We measured the properties of the pulse before and after propagation along the 10-m-long vapor source as a function of pulse energy. We conducted experiments with both resonant and off-resonant wavelengths and identified several distinct regimes of interaction. We also measured properties of the plasma profile close to the end of the vapor source using schlieren imaging. We showed that resonant ionizing pulses create plasma columns that are wider and more sharply bounded due to the strong nonlinear interaction of the resonant transitions. They therefore use energy much more efficiently to create the plasma and can thus create longer plasma columns for a given input energy. We also derived a theory that we used in computer simulations to investigate pulse propagation in the presence of the resonant nonlinearity. We found that the predictions of the theory are in good qualitative agreement with experimental observations.



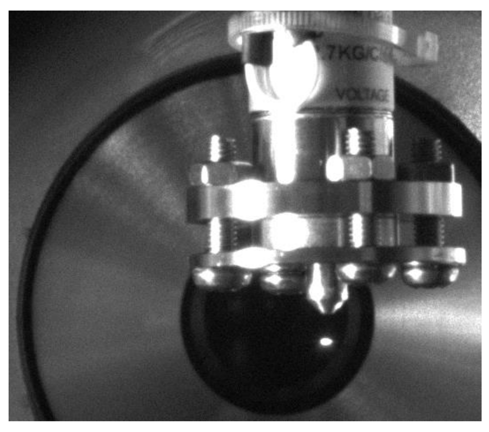


Laser Particle Acceleration

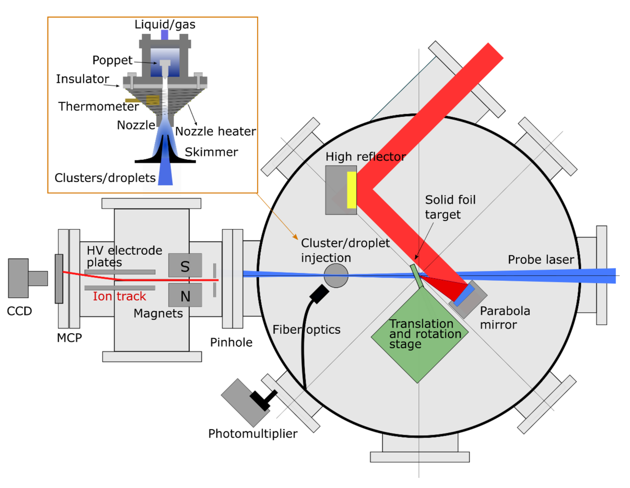
The Ti-sapphire laser pulses were focused onto the targets by a parabolic mirror and Thomson Parabola Spectrometers were used for the analysis of the generated ions. Different solid foils (Al, carbon nanotube, C nanotube with Au layer) as well as gas jets forming clusters (Kr, CO_2, Xe, Ar) were irradiated.



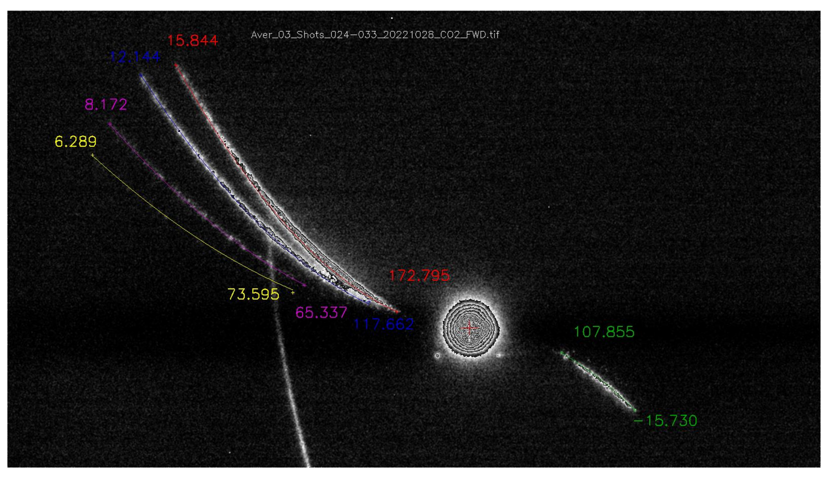
Ion spectrum from Al foil target measured at Wigner RCP.



Gas cluster nanoplasma.



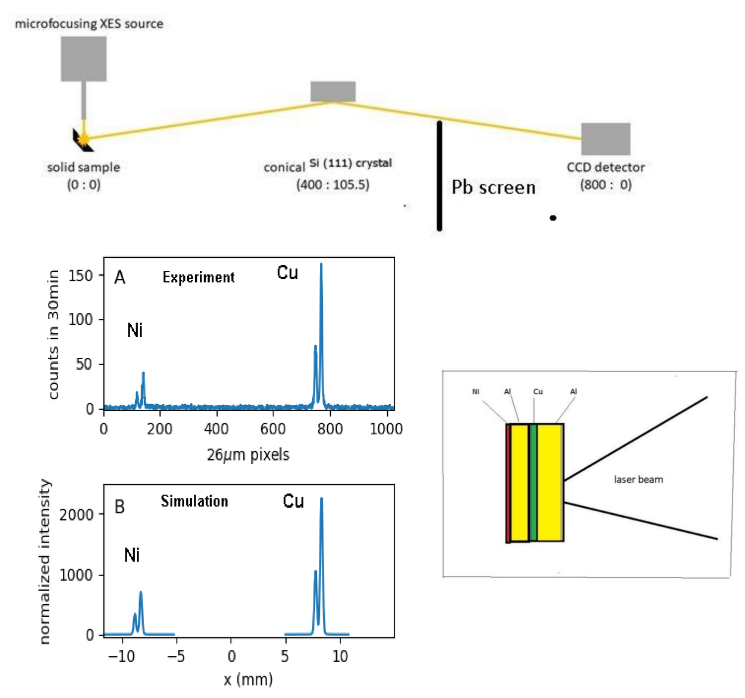
Experimental arrangement.



Ion spectrum from CO_2 clusters obtained with the SEA laser at ELI-ALPS. Negative oxigen ions with energies over 100 keV have been observed.

Inertial Fusion Energy

Energy production by clean nuclear energy which may come out of fusion was also a dream of Eugene Wigner and Edward Teller. The positive energy output obtained by the NIF laser opens the possibility to restart European Inertial Fusion Energy (IFE) activities. The proposal of Hiper+ is a fully civilian initiation for direct drive fusion. A laser pulse of several nanosecond duration compresses the fuel slowly, and a short pulse driven shock wave should ignite it. In the short pulse laser-plasma interactions hot electrons are also generated, the temperature of which is a crucial factor of ignition. Our group developed a new spectrometer which allows simultaneous or time-resolved observation of lines from two different emitters with high resolution.



The preliminary results are encouraging showing both the detailed structure of Cu and Ni Kα radiation. We designed an experiment at the ABC laser facility in Frascati which aims to demonstrate the applicability of the arrangement to observe the radiation from hot-electron heated emitters from different depths of low-Z targets. The method allows accurate determination of hot-electron temperature. The joint experiments are scheduled for the second half of this October.

Self-similar Studies

We have recently investigated the diffusion equation [6,7]. With our Ansatz we found additional solutions which are much beyond the classical and well known Gaussian curve. These solutions have a much more complicated structure, contains Gaussian times the Kummer's M and Kummer's U functions the later even have quadratic arguments. For one Cartersian space coordinate and time-dependent concentration C(x,t) the solution can be given:

$$C(x,t) = \frac{1}{t^{\alpha}}\left(\frac{x}{t^{1/2}} \cdot e^{-\frac{x^2}{4Dt}} \left(c_1 M\left[1-\alpha, \frac{3}{2}, \frac{x^2}{4Dt}\right] + c_2 U\left[1-\alpha, \frac{3}{2}, \frac{x^2}{4Dt}\right]\right)\right)$$

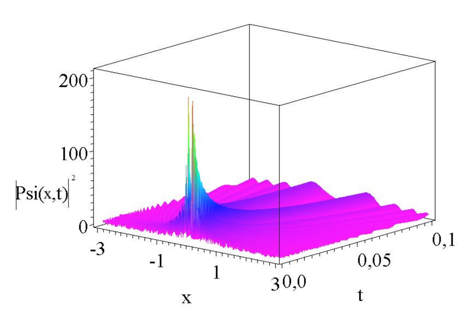
where D is the diffusion coefficient c_1 and c_2 are integral constants, and alpha is the free self-similar exponent ([6,7]).

Even more interesting results can be derived if we consider the free Schrödinger equation as a complex diffusion equation (again for one Cartestian space dimension) the time-dependent wave function can be given in the form of:

$$\Psi(x,t) = \frac{1}{t^{\alpha}}\left(c_1 M\left[\alpha+\frac{1}{2}, \frac{3}{2}, \frac{ix^2}{4t\hat{D}}\right]\frac{x}{t^{1/2}} + c_2 U\left[\alpha+\frac{1}{2}, \frac{3}{2}, \frac{ix^2}{4t\hat{D}}\right]\frac{x}{t^{1/2}}\right)$$

where the diffusion coefficient is: $\hat{D} = \hbar/2m$ with the Dirac's constant and the particle mass m.

Kummer's M and Kummer's U functions with complex quadratic arguments have interesting not so well-known properties.
For some alpha parameter the wave function fulfills the L^2 norm and the results can be interpreted as electon probability density, such a solution is presented on the Figure for unit parameters.
Further work is in progress.



Publications of the group

[1] *Long-range propagation of ultrafast ionizing laser pulses in a resonant nonlinear medium*, Demeter, J. T. Moody, M. Á. Kedves, M. Aladi, B. Ráczkevi et. al., Phys. Rev. A **104**, 033506 (2021)

[2] *Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma*, L. Verra, G. Zevi Della Porta, J. Pucek, T. Nechaeva, S. Wyler, M. Bergamaschi, E. Senes, E. Guran, J. T. Moody, M. Á. Kedves, E. Gschwendtner, and P. Muggli, (AWAKE Collaboration), Phys. Rev. Letters **129**, 024802 (2022)

[3] *Machine learning methods for schlieren imaging of a plasma channel in tenuous atomic vapor*, G. Bíró, M. Pocsai, I. F. Barna, G. G. Barnaföldi, J. T. Moody and G. Demeter, Optics & Laser Technology **159**, 108948 (2023)

[4] *Generation of 10-m-lengthscale plasma columns by resonant and off-resonant laser pulses*, G. Demeter, J. T. Moody, M. Á. Kedves et. al., Optics & Laser Technology **168**, 109921 (2024)

[5] *Multicolor single-analyzer high-energy-resolution XES spectrometer for simultaneous examination of different elements*, A. Mikeházi, J. El Guettioui, I. B. Földes, G. Vankó and Z. Németh:; J. Synchrotron Rad. **29**, 1216-1222 (2022)

[6] *Advanced Analytic Self-Similar Solutions of Regular and Irregular Diffusion Equations*, I. F. Barna and L. Mátyás, Mathematics **10**, 3281 (2022)

[7] *Even and Odd Self-Similar Solutions of the Diffusion Equation for Infinite Horizon*, L. Mátyás and I. F. Barna, Universe **9**, 264 (2023)

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