Sub-MeV ion generation by standing wave excitation of ionized gases

Sz. Turnár[1], Z. Tibai [1], M. I. Mechler[1], L. Pálfalvi[1], G. Almási[1,3] and J. Hebling[1,2,3]

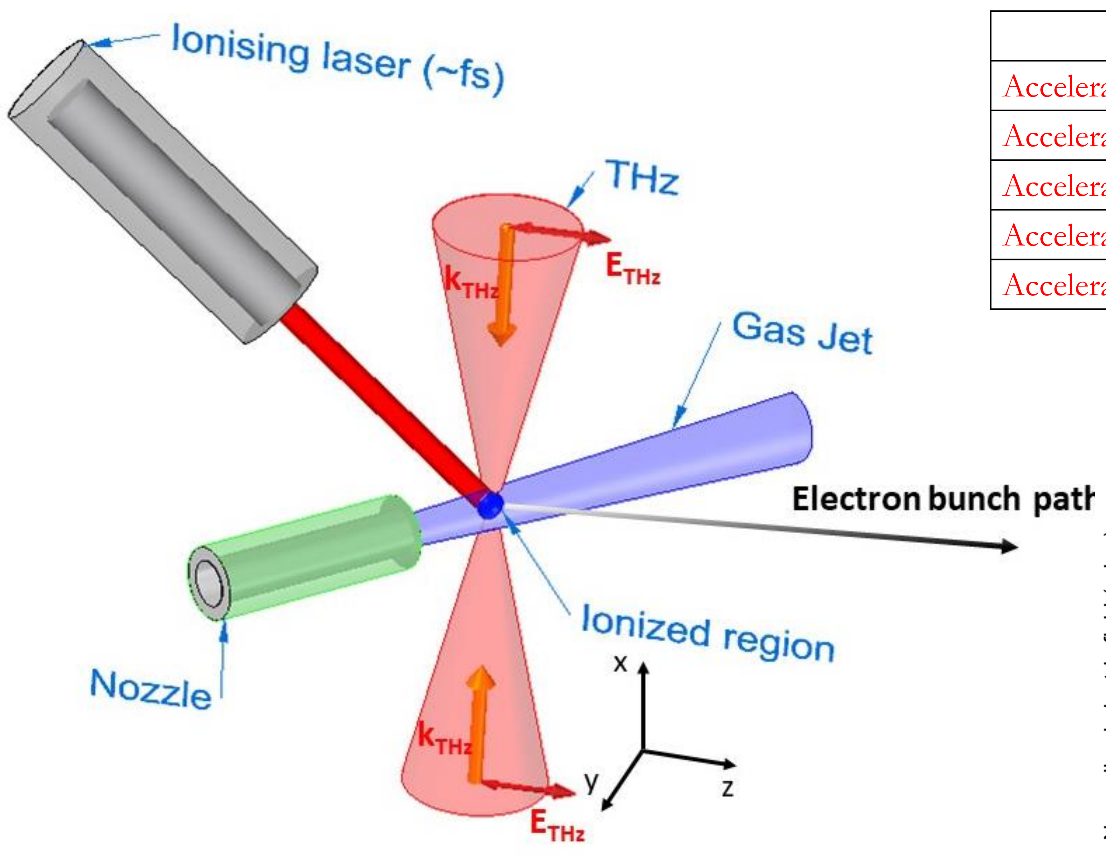
1. Institute of Physics, University of Pécs, Ifjúság street 6, 7624 Pécs, Hungary
2. MTA-PTE High Field Terahertz Research Group, Ifjúság street 6, 7624 Pécs, Hungary
3. Szentágothai Research Centre, University of Pécs, 7624 Pécs, Hungary

Introduction

- The Laser driven ion acceleration is a hot topic of laser plasma physics [1]. In the last two decades several ion acceleration mechanisms have been suggested and extensively studied, e.g. the target normal sheath acceleration (TNSA), the collisionless electrostatic shock acceleration (CESA), the radiation pressure acceleration (RPA), and the Coulomb explosion acceleration (CEA) [1]. Although rather successful CESA acceleration of ions in gas plasma was demonstrated [2], in most laser-ion acceleration experiments thin metal or plastic foil targets are used.
- The other exception is the CEA mechanism. This was most extensively investigated in cluster plasmas [3,4]. If other mechanisms are not significant, CEA in clusters result spherically symmetric acceleration. This do not cause any problem for example in case of neutron generation by DD fusion in deuterium (D) clusters [5].
- We have been working on a new scalable and controllable particle (ion) accelerator setup by CEA in gas plasma instead of cluster one. Our simulations based on the recently proposed RNLS [6], which predicts 11 mJ THz pulse energy with up to 40MV/cm peak electri field.

Proposed setup

- We numerically investigated the ion acceleration by Coulomb explosion following ripping the electrons from gas plasmas by high energy ultrafast standing waves. Few years before this technique was used to simulate electron acceleration from gas plasma [7].
- We simulated a tabletop accelerator setup using THz pulses. For the numerical simulations of the particle acceleration, EPOCH and GPT codes were used [8].
- Injection of particles is accomplished by ionizing atoms in a gas jet with a short laser pulse. We examined the effects of standing waves concerning the efficiency of the particle acceleration.
- On the other hand, we investigated the effects of the different initial bunch charges, initial bunch shapes (different dimensions), and the number of THz sources with respect to the final kinetic energies and final dimensions of the bunch. After the acceleration stage around **0.1 MeV peak ion** - and higher than **0.6 MeV electron energy** can be achieved using the optimized setups. Generating with 0.7 % efficiency of sub-MeV energy protons and ~ 0.4 MeV electrons, both with 1.1 nC bunch charge is predicted.



I. Laser Parameters

Parameter	Value
Accelerator THz pulse frequency	0.3 THz
Accelerator THz pulse beam waist	1000 μm (λ)
Accelerator THz energy/pulse	33.55 mJ
Accelerator THz pulse electric field	20 MV/cm
Accelerator THz pulse FWHM	2.025 ps

II. Bunch parameters (deuteron/proton)

Parameters (**long cylinder**)	Value
E-beam energy (γ_0)	0 – 4 eV
E-beam length (L)	250 μm
E-beam diameter (d)	25 μm
E-beam charge (total pulse)	0.7 nC

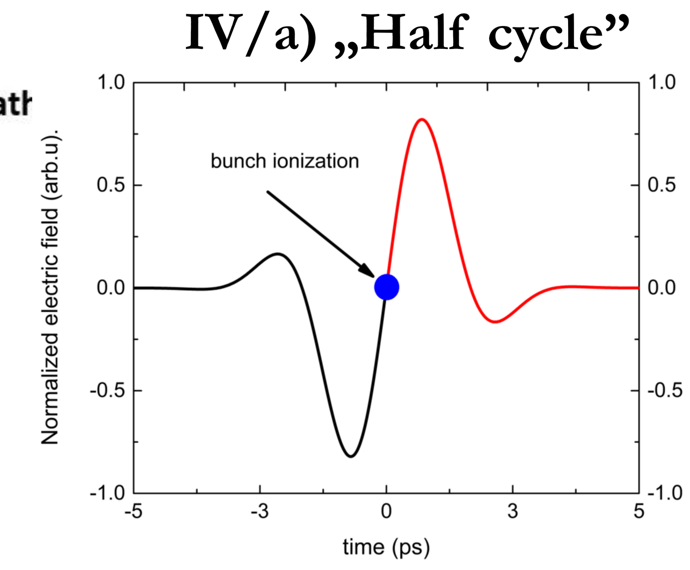
Parameters (**„disk”**)	Value
E-beam energy (γ_0)	0 – 4 eV
E-beam length (L)	12.5 μm
E-beam diameter (d)	250 μm
E-beam charge (total pulse)	1.1 nC

III. Bunch parameters (electron)

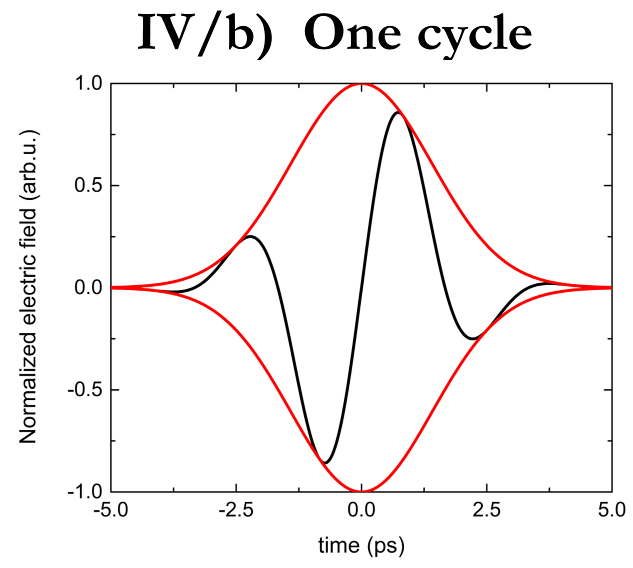
Parameters (**short cylinder**)	Value
E-beam energy (γ_0)	0 – 4 eV
E-beam length (L)	75 μm
E-beam diameter (d)	46 μm
E-beam charge (total pulse)	10-300 pC

IV. Pulse shapes

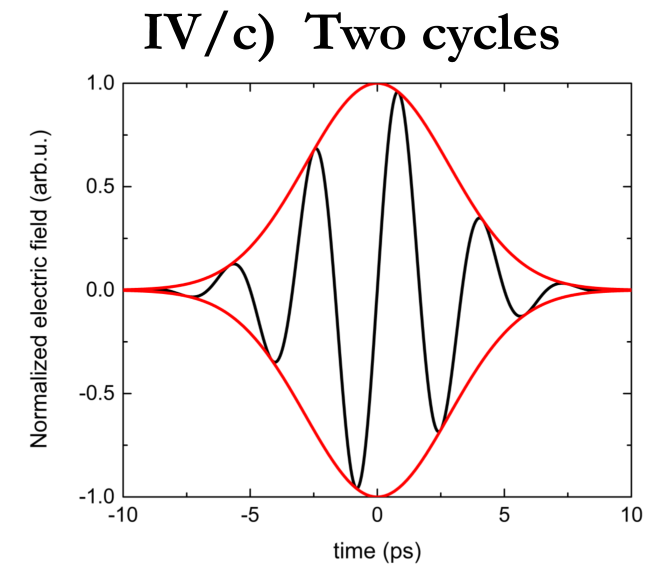
IV/a) „Half cycle”



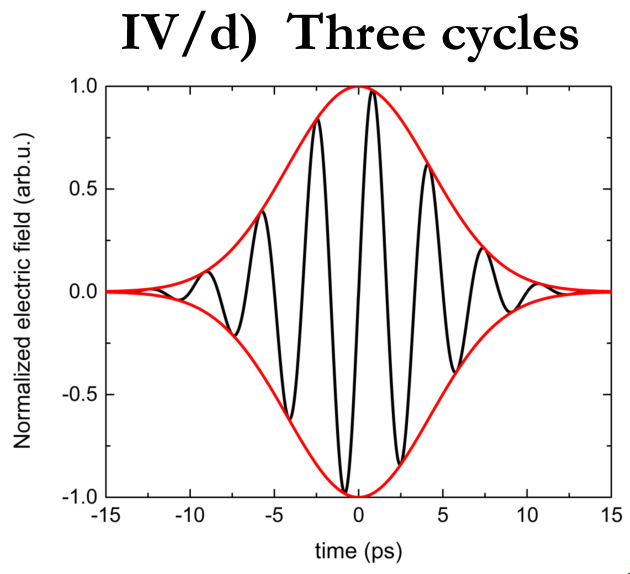
IV/b) One cycle



IV/c) Two cycles

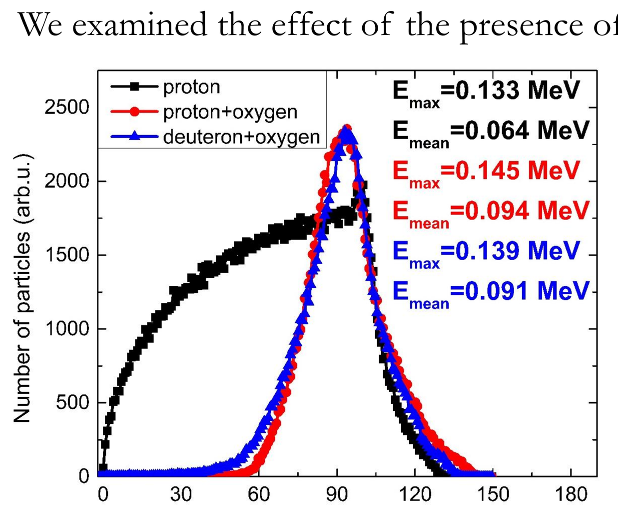


IV/d) Three cycles

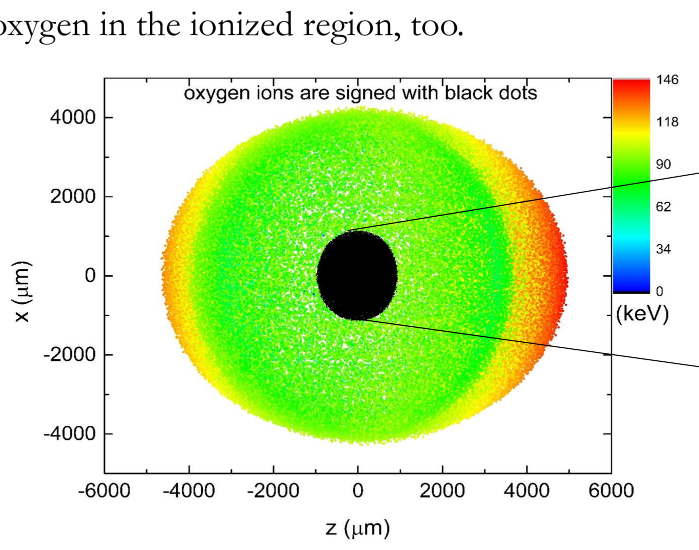


Positive ion (deuteron/proton) acceleration

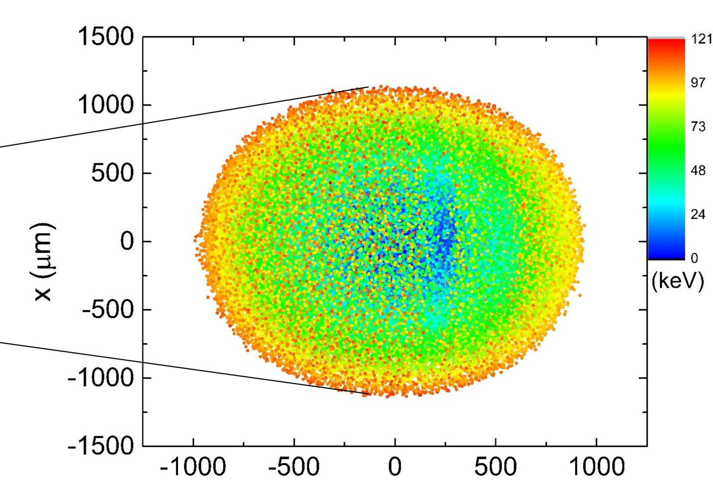
- We simulated standing wave with 0.3 THz mean frequency to accelerate the particles (Fig IV/a). Two counter propagating THz pulses accelerate the particles. We simulated the THz pulses with the conditions in table I. We had simulated the ionized region with two different shapes („long cylinder", "disk", see in table II), and we investigated its effects.
- Using a proper synchronization (**IV/a**), we can eliminate the positive (decelerating) part of the THz pulses, thereby achieved higher kinetic energies.
- We examined the effect of the presence of oxygen in the ionized region, too.



Deuteron and **proton** energy spectra for plasma containing and not containing oxygen ions („**disk**” as an initial bunch shape is simulated)



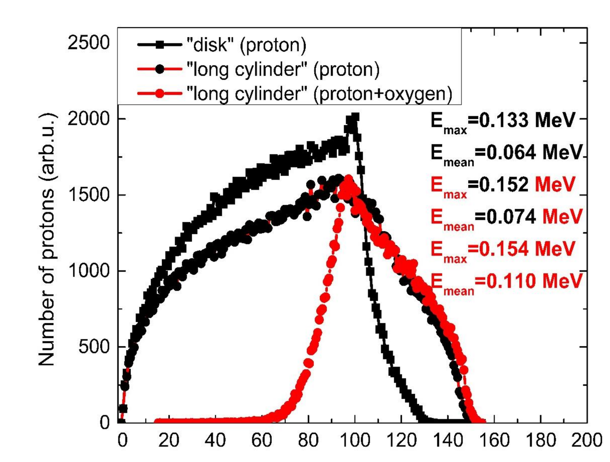
The spatial distribution of **protons** in the z-x plane (colormap scaling depends on the energies of **protons**)



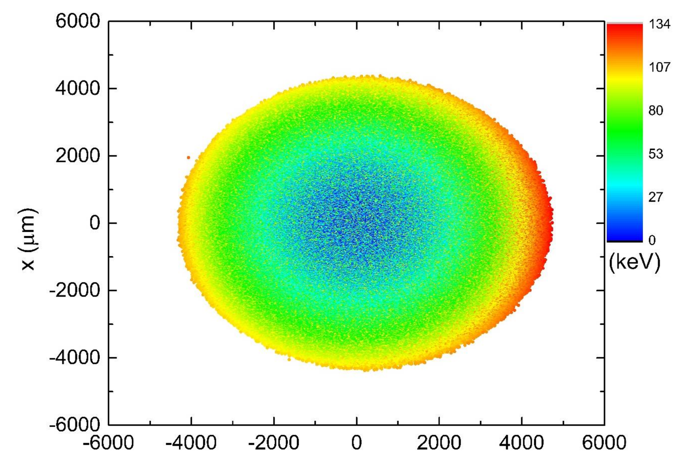
The spatial distribution of **oxygen ions** in the z-x plane (colormap scaling depends on the energies of **oxygens**)

Dependence from the initial shape of the bunch

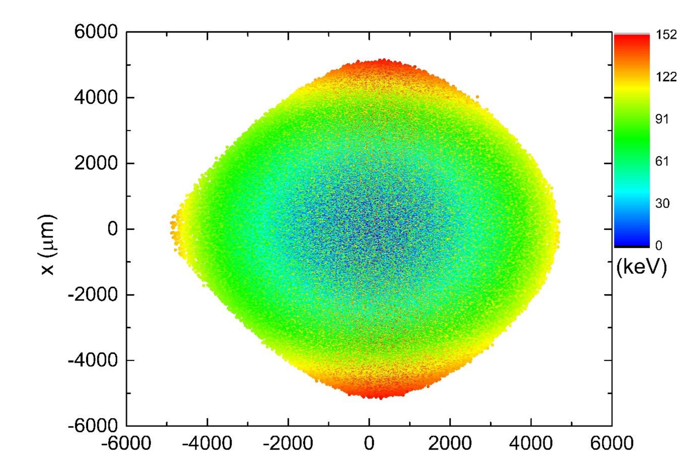
- Different initial bunch shapes cause different limitations in case of the bunch charge and thereby in their energy spectra.
- We take into account the achievable maximum bunch charges in case of the different bunch shapes (Table II).
- The spatial distribution of the deuteron bunches are different. „**Disk**”: huge percentage of the deuterons propagate in the polarization direction (z- plane). Long cylinder: huge percentage of the deuterons propagate perpendicular to the polarization direction (z- plane).
- Using tilted pulses, the „**long cylinder**” initial bunch shape also could be appropriate for further applications.



Energy spectra depend on different initial bunch shapes (**protons**)



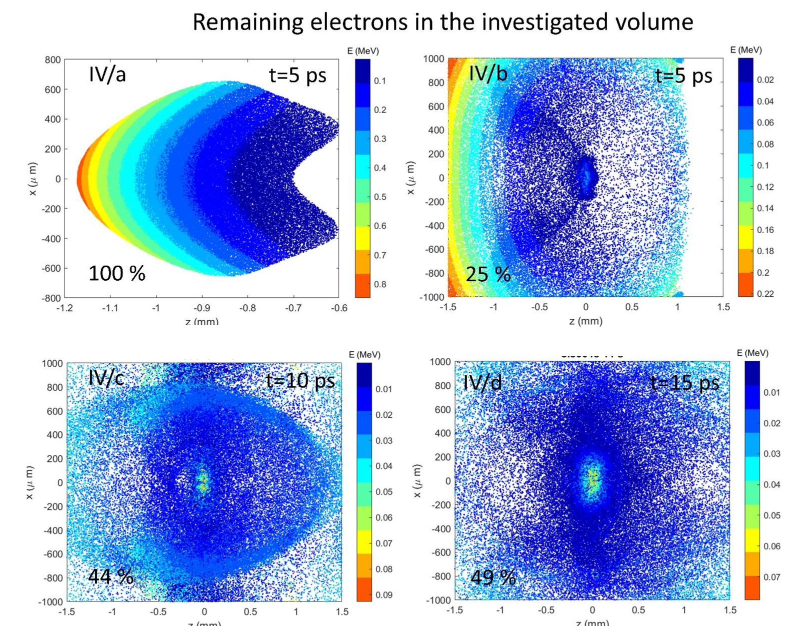
The spatial distribution of the deuterons in the z-x („**disk**”, colormap scaling depends on the energies of **protons**)



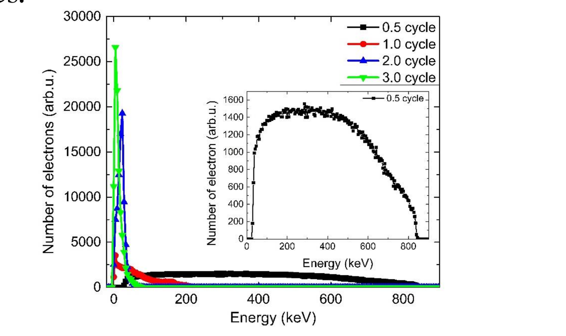
The spatial distribution of the deuterons in the z-x plane („**long cylinder**”, colormap scaling depends on the energies of **protons**)

Electron acceleration

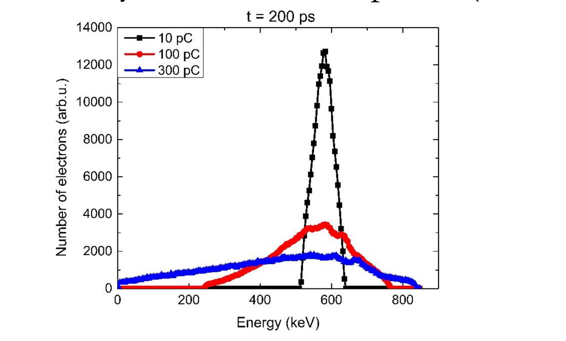
- We have examined the importance of the **number of cycles** concerning both the final spatial distribution and final energy spectra.
- We simulated 0.5 -3.0 cycle(s) **standing** waves using **two THz** pulses to accelerate the particles („disk”)*.
- We optimized the shape of the initial ionized region (short cylinder as an initial bunch shape is simulated) and investigated the effect of different initial bunch charges.



Spatial distributions achieved **by „half cycle”** (top left), **by one cycle** (top right), **by 2 cycle**s (bottom left), **by 3 cycles** (bottom right), after the THz pulses leave the interaction volume („disk”)



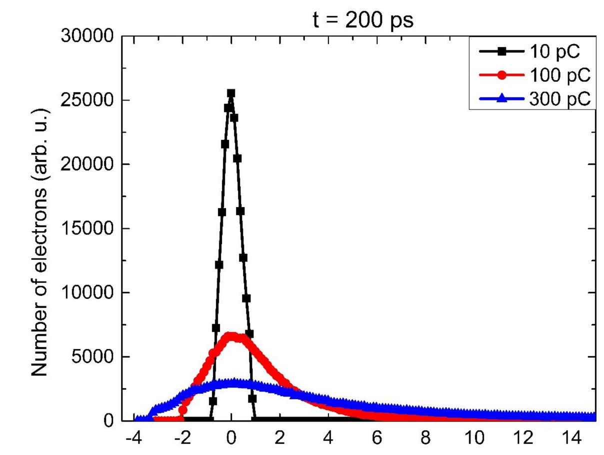
Electron energy spectra depending on the number of cycles of the THz pulses (**„disk”**)



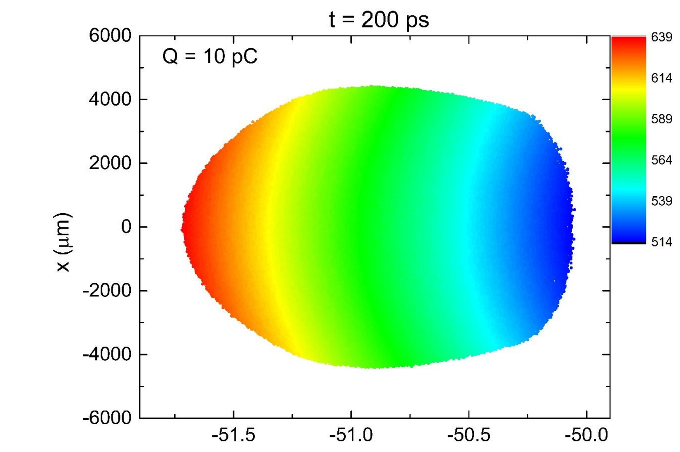
Electron energy spectra with different initial bunch charges (**„short cylinder”**)

Spatial distribution – „0.5 cycle THz” ; short cylinder

- The electrons could achieve from rest to around 600 keV final kinetic energy.
- The smaller the initial bunch charge is, the narrower both the spatial distribution and energy spread is.



The spatial distribution of the **electrons** depending on the initial bunch charge (**„short cylinder”**).



The spatial distribution of the **electrons** in the z-x plane (colormap scaling depends on the energies of electrons)

Conclusion

- Ion acceleration to 0.1 MeV energy by focused THz pulses have been investigated.
- The proposed setup, as an electron gun, can emit electron bunches with up to 300 pC charge and **0.6 MeV** energy .
- We simulated a **new controllable** ion source which enables to use gas plasmas instead of the nanoscaled solid-state as an initial particle source.
- We present a **scalable technique** from few μm to few thousands of μm driving wavelengths, thereby also could be possible to generate **ultrashort (few ps) neutron bunches.**

References

[1] J. Badziak et al., IOP Conf. Series: J Phys: Conf. Series **959,** 012001 (2018).

[2] D. Haberberger at al., N. Phys. **8,** 95-99 (2018)

[3] T. Ditmire et al., Nature **386,** 54-56 (1997).

[4] M. Murakami and K. Mima, Phys. of Plasmas **16,** 103108 (2009).

[5] T. Ditmire et al., Nature **398,** 489-492 (1999).

[6] Gy. Tóth et al., Opt. Express **27,** 30681-30691 (2019).

[7] Z Tibai et al, J. Phys. B, **51**,134004 (2018)

[8] http://www.pulsar.nl/gpt.

Acknowledgement

The project has been supported by the European Union, co-financed by the European Social Fund Grant no.: EFOP-3.6.2-16-2017-00005 entitled by Ultrafast physical processes in atoms, molecules, nanostructures and biology structures. The project has been supported by Hungarian Scientific Research Fund (OTKA) (125808 and 129134). Supported by the ÚNKP-20-3 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.