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Novel high-energy physics studies using intense lasers and plasmas

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Accomplishments:

Summary of the project: In the framework of the project "Novel high-energy physics studies using intense lasers and plasmas" we conducted the study of ion acceleration and "flying mirrors" with high intensity lasers. We focused on the two mechanisms of ion acceleration from near critical density plasma and from thin solid density foils in the radiation pressure acceleration (RPA) regime. First, the optimization of the RPA regime through the laser pulse matching to the target to ensure maximum energy transfer from the pulse to the ions was carried out. We showed that proper tailoring of the laser pulse will lead to a significant reduction of acceleration distance leading to more compact laser ion accelerator designs, requiring less energy to operate. In the course of this study we found that there are several factors that may limit the maximum attainable ion energy in the RPA regime. These factors are related to the fact that the RPA regime requires high laser intensities to operate, which can only be achieved by tightly focusing the laser pulse. As a result the laser pulse group velocity is smaller than the vacuum light speed and the target experiences the transverse expansion under the action of a tightly focused laser. We showed that these factors may significantly limit the maximum attainable ion energy. However we proposed a new target design, i.e., a composite target consisting of a thin solid density foil attached to a front surface of a near critical density slab. Such targets offer a way of compensating the transverse expansion and group velocity effects and enhancing the maximum attainable ion energy.

We studied the ion acceleration from near critical density targets in order to determine the principal design for the laser driven ion source for different applications, in particular for the hadron therapy of oncological diseases. Though the previous theoretical studies showed that the PW-class lasers would be able to generate ion beams with the required properties and the experiments were able to generate ~100 MeV maximum energy proton beams, the generation of a laser based ion source that would meet the maximum energy, energy spread, number of particles per bunch, and repetition rate requirements simultaneously is still a challenge both theoretically and experimentally. Moreover most of the theoretical and experimental studies on laser driven ion acceleration towards possible application for hadron therapy are performed with hydrogen or carbon ions. We instead proposed to consider different species of ions, which optimize a laser driven ion source. Though the idea to use helium instead of hydrogen may sound easy and obvious, it is derived from the understanding that not only the effectiveness of laser ion acceleration, maximum attainable ion energy, and the properties of an ion beam, but also the therapeutic properties of the beam, such as side scattering, relative biological effectiveness, and linear energy transfer should be taken into account when designing laser driven ion source. Thus our research gives a whole new dimension to the studies of laser ion acceleration with the application towards radiation therapy. We expect our results to open a new field of study of ion acceleration: the acceleration of different ion species. Given the intrinsic flexibility of laser ion acceleration, we expect a lot of interest in this field.

The development of sources of intense ultra-short electromagnetic (EM) pulses, X-rays, and even γ-rays is an important potential application of intense laser-matter interactions. One of the potential mechanism is the "flying mirror" concept, when an EM pulse is reflected by such a mirror the radiation frequency up-shift is proportional to the square of the mirror Lorentz factor, making the scheme very attractive for the generation of high frequency pulses. Such relativistic mirrors, which can generate ultra-short high-frequency EM pulses by reflection of EM radiation, can be formed in the regimes of laser–thin foil interaction previously considered in regard with the ion acceleration. Thus during the development of a new theoretical model for the interaction of an intense laser pulse with a thin foil we considered a broad range of problems, such as frequency upshifting by "flying mirrors", high order harmonic generation, and high energy ion acceleration. In the framework of this model we were able to calculate the spectrum of reflected by "flying mirror" radiation and study its properties.

The second part of the proposal was devoted to the laser-based positron creation and capture. Since it was proposed to study the positron creation by the high energy electron beam interacting with a solid density foil, we considered first the generation of such electron beams. Since the quality of the electron beams is very important for the laser plasma acceleration we studied the transverse emittance of an electron beam, which is injected in the accelerating field through the ionization of background plasma ions. We showed that ultra-low emittance beams can be generated in such interaction. We also provided theoretical support for the on-going experiments at BELLA facility at LBNL, where a record electron energy of 4.25 GeV was obtained. Such high energy of electrons as well as the high intensity of the laser pulses may in principle allow for the experiments on the radiation reaction. In this regime the electrons radiate away a significant amount of their energy in a form of high frequency radiation. This completely changes the behavior of charged particles in electromagnetic fields. In order to address this problem we studied the fundamental properties of the electron interaction with high intensity laser pulses in two cases: (i) moderate intensity, low electron energy, (ii) high intensity, high electron energy. We found that the radiation reaction effects can be detected in the first case by the clever choice of the parameters of interaction. In the second case we found that the interaction of a high-energy electron beam with an intense laser pulse leads to the subsequent production of photons and electron positron pairs. We showed that charged particles in the strong electromagnetic field experience multiple emissions of photons, leading to the fast depletion of particle energy. Such interaction can be used for the generation of positron beams if the laser intensity is high enough to trigger the prolific electron-positron pair production.

We initially proposed to study different schemes of laser ion acceleration, in particular, from solid density targets and from near critical density targets, in order to develop sources of ion beams for different applications. Since some schemes of laser ion acceleration are also considered a good source of "flying mirrors", we proposed to investigate the mechanisms of "mirror" formation. As a result we were able to study the laser ion acceleration from thin foils and near critical density targets. We identified several fundamental factors limiting the acceleration in the RPA regime and proposed the target design to compensate these limitations. In the case of near critical density targets, we developed a concept for the laser driven ion source for the hadron therapy. Also we studied the mechanism of "flying mirror" generation during the intense laser interaction with thin solid density targets. As for the laser-based positron creation and capture we initially proposed to study different regimes of positron beam generation and positron beam cooling. Since the for some of these schemes a good quality electron beam is required, we studied the generation of ultra-low emittance electron beams. In order to understand the fundamental physics of high energy electron beam interaction with high intensity laser pulses, which may affect the efficient generation of positron beams, we studied the radiation reaction effects.

In what follows we give a brief description of the papers published or submitted, which were written as a part of the "novel high-energy physics studies using intense lasers and plasmas" project:

1. Ion acceleration and "flying mirrors" with high intensity lasers

1) **"*Optimized laser pulse profile for efficient radiation pressure acceleration of ions*", S. S. Bulanov, et al., PoP 19, 093112 (2012); *ibid*., AIP Conf. Proc. 1507, 785 (2012):** The radiation pressure acceleration regime of laser ion acceleration requires high intensity laser pulses to function efficiently. Moreover, the foil should be opaque for incident radiation during the interaction to ensure maximum momentum transfer from the pulse to the foil, which requires proper matching of the target to the laser pulse. However, in the ultrarelativistic regime, this leads to large acceleration distances, over which the high laser intensity for a Gaussian laser pulse must be maintained. It is shown that proper tailoring of the laser pulse profile can significantly reduce the acceleration distance, leading to a compact laser ion accelerator, requiring less energy to operate.
2) **"*Ion acceleration from thin foil and extended plasma targets by slow electromagnetic wave and related ion-ion beam instability*", S. V. Bulanov, et al., PoP 19, 103105 (2012):** When ions are accelerated by the radiation pressure of a laser pulse, their velocity cannot exceed the pulse group velocity which can be considerably smaller than the speed of light in vacuum. This is demonstrated in two cases corresponding to a thin foil target irradiated by high intensity laser light and to the hole boring produced in an extended plasma by the laser pulse. It is found that the beams of accelerated ions are unstable against Buneman-like and Weibel-like instabilities which results in the broadening of the ion energy spectrum.
3) **"*Strong field electrodynamics of a thin foil*", S. V. Bulanov, et al., PoP 20, 123114 (2013):** Exact solutions describing the nonlinear electrodynamics of a thin double layer foil are presented. These

solutions correspond to a broad range of problems of interest for the interaction of high intensity laser pulses with overdense plasmas, such as frequency upshifting, high order harmonic generation, and high energy ion acceleration.

4) **"*Advanced geometries and regimes*", S. S. Bulanov, et al., AIP Conference Proceedings 1546, 9 (2013):** We review and discuss different schemes of laser ion acceleration as well as advanced target geometries in connection with the development of the laser-driven proton source for hadron therapy of oncological diseases, which is a part of the ELIMED project.
5) **"*Enhancement of maximum attainable ion energy in the radiation pressure acceleration regime using a guiding structure*", S. S. Bulanov, et al., Phys. Rev. Lett. 114, 105003 (2015); *ibid., Proc. SPIE 9514, 95140G (2015)*:** Radiation Pressure Acceleration is a highly efficient mechanism of laser driven ion acceleration, with the laser energy almost totally transferrable to the ions in the relativistic regime. There is a fundamental limit on the maximum attainable ion energy, which is determined by the group velocity of the laser. In the case of a tightly focused laser pulses, which are utilized to get the highest intensity, another factor limiting the maximum ion energy comes into play, the transverse expansion of the target. It makes the target transparent for radiation, thus reducing the effectiveness of acceleration. Utilization of an external guiding structure for the accelerating laser pulse may provide a way of compensating for the group velocity and transverse expansion effects.
6) **"Enhancing proton acceleration by using composite targets", S. S. Bulanov, et al., submitted to Phys. Rev. ST-AB:** Efficient laser ion acceleration requires high laser intensities, which can only be obtained by tightly focusing laser radiation. For Radiation Pressure Acceleration the tightly focused laser driver leads to the appearance of the fundamental limit for the maximum attainable ion energy corresponding to the laser pulse group velocity as well as to another limit connected with the transverse expansion of the accelerated foil and consequent onset of the foil transparency. These limits can be relaxed by using composite targets, consisting of a thin foil followed by a near critical density target. Such targets provide guiding of a laser pulse inside a self-generated channel and background electrons, being snowplowed by the pulse, compensate for the transverse expansion. The use of composite targets results in a significant maximum ion energy increase, compared to a single foil target case.
7) **"*Helium-3 and Helium-4 acceleration by high power laser pulses for hadron therapy*", S. S. Bulanov, et al., Phys. Rev. ST-AB 18, 061302 (2015):** The laser driven acceleration of ions is considered a promising candidate for an ion source for hadron therapy of oncological diseases. Helium ions with the same energy per nucleon as protons, delivering larger biological damage to cancer cells, have the same penetration depth unlike other heavier ions. Two mechanisms (Magnetic Vortex Acceleration and hole-boring Radiation Pressure Acceleration) of PW-class laser driven ion acceleration from liquid and gaseous helium targets are studied with the goal of producing 250 MeV per nucleon helium ion beams that meet the hadron therapy requirements. We show that He^3 ions, having almost the same penetration depth as He^4 with the same energy per nucleon, require less laser power to be accelerated to the required energy for the hadron therapy.

2. Compact laser-based positron creation, capture.

1) **"*Thermal emittance from ionization-induced trapping in plasma accelerators*", C. B. Schroeder, et al., Phys. Rev. ST-AB Phys. Rev. ST-AB 17, 101301 (2014); *ibid., Proc. SPIE 9514, 951408 (2015)*:** The minimum obtainable transverse emittance (thermal emittance) of electron beams generated and trapped in plasma-based accelerators using ionization injection is examined. The initial transverse phase space distribution following ionization and passage through the laser is derived, and expressions for the normalized transverse beam emittance, both along and orthogonal to the laser polarization, are presented. Results are compared to particle-in-cell simulations. Ultra-low emittance beams can be generated using laser ionization injection into plasma accelerators.
2) **"Multi-GeV electron beams from capillary-discharge-guided sub-petawatt laser pulses in the self-trapping regime", W. P. Leemans, et al., Phys. Rev. Lett. 113, 245002 (2014):** Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms

divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}$ cm^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. A detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.

3) **"*Detecting radiation reaction at moderate laser intensities*", T. Heinzl, et al., Phys. Rev. E 91, 023207 (2015):** We propose a new method of detecting radiation reaction effects in the motion of particles subjected to laser pulses of moderate intensity and long duration. The effect becomes sizeable for particles that gain almost no energy through the interaction with the laser pulse.
4) **"*Generation and pointing stabilization of multi-GeV electron beams from a laser plasma accelerator driven in a pre-formed plasma waveguide*", A. J. Gonsalves, et al., Phys. Plasmas 22, 056703 (2015):** Laser pulses with peak power 0.3 PW were used to generate electron beams with energy **>** 4 GeV within a 9 cm-long capillary discharge waveguide operated with a plasma density of 7×10^{17} cm^{-3}. Simulations showed that the super-Gaussian near-field laser profile that is typical of high-power femtosecond laser systems reduces the efficacy of guiding in parabolic plasma channels compared with the Gaussian laser pulses that are typically simulated. In the experiments, this was mitigated by increasing the plasma density and hence the contribution of self-guiding. This allowed for the generation of multi-GeV electron beams, but these had angular fluctuation >2 mrad rms. Mitigation of capillary damage and more accurate alignment allowed for stable beams to be produced with energy 2.7 ± 0.1 GeV. The pointing fluctuation was 0.6 mrad rms, which was less than the beam divergence of <1 mrad full-width-half-maximum.
5) **"*High-Energy Electron Beam Collision with Intense Laser Pulse: the Electromagnetic Cascade*", S. S. Bulanov, et al., to appear in AIP Conf. Proc.**: The interaction of a high-energy electron beam with an intense laser pulse with subsequent production of photons, and electron positron pairs is studied. It is shown that charged particles in the strong electromagnetic field experience multiple emissions of photons, leading to the fast depletion of particle energy. The final distributions of electrons, positrons, and photons are calculated for the case of a high-energy e-beam interacting with a counterstreaming, short intense laser pulse.

<u>Collaborations established:</u>

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