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Electron heating and ion acceleration in ultrarelativistic laser-solid interactions

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State-of-the-art high power lasers are reaching ever-higher focal intensities, enabling discoveries in high-field science. One key application is the generation of high energy particles, which will lead to the establishment of ultra-high gradient compact particle accelerators. It is important to experimentally explore the behaviour of particle acceleration mechanisms at the high-intensity frontier.

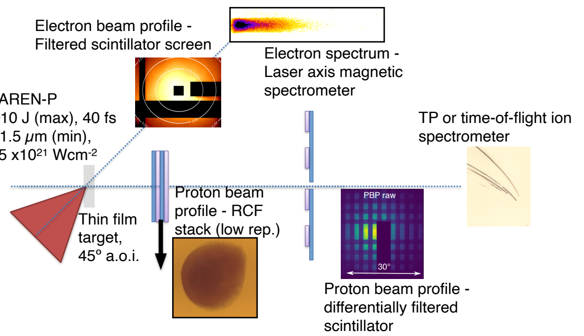

Fig. 1. Schematic of typical experiment on J-KAREN-P for measuring accelerated ion and electron beams

We have therefore investigated the scaling of electron and ion acceleration from laser-solid interaction up to an ultra-high intensity of ≈5x10^{21} W/cm^2 [1], using the ≈10 J PW-class J-KAREN-P laser facility at Kansai Photon Science Institute, QST, Japan [2]. A simplified experiment schematic is shown in Fig. 1. We have developed a repetitive target and diagnostic system to acquire statistically significant datasets of the LPI including both spectral and spatial measurements of the accelerated electron [3] and proton beams [4].

The accelerated electron beam parameters were found to be strongly dependent on focal spot size, not just laser intensity, resulting in a suppression of electron temperature at highest intensities compared to the expected scaling laws, reaching a temperature of ~15 MeV at maximum intensity. The electron temperature is suppressed due to insufficient acceleration length in the tightly focused spot. At the same time, the electron beam divergence decreases with smaller focal spot size due to strong magnetic field generation in the preplasma down to ~30° full-width-half-maximum [1]. The spot size is also shown to be important for the energy scaling of protons accelerated by the so-called Target Normal Sheath Acceleration mechanism, with only a modest improvement by using very small focal spot sizes. We suggest a new acceleration model resulting from an increase in acceleration time due to electron recirculation in the foil [1].

We subsequently explored the proton maximum energy scaling up to a higher laser energy, ~15 J, and demonstrated the establishment of an energetic proton source at 0.1 Hz with energies up to 40 MeV by using a reeled 5 μm steel tape target [5]. We used this repetitive system to investigate the stability of the sources and its behaviour with laser focus spot size. We also show that by using even thinner, single-shot targets, higher maximum energies >50 MeV are achievable from sheath acceleration, with a drive laser energy ≈10 J on target.

Finally, we investigated energetic ion acceleration in a different interaction regime, where the foil thickness is so thin that the target becomes relativistically transparent to the laser. We show that, even without a contrast-enhancing plasma mirror, we can generate high flux, high energy ion beams from ~100 nm plastic targets. There is a dramatic increase in proton and ion energies at the optimum target thickness, with the highest energy ions originating from the densest part of the target during transparency. The beam spatial properties vary considerably from sheath acceleration, with the most energetic ions being observed along the laser axis.

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