High energy density science with tabletop terawatt lasers

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Abstract. High energy density science (HEDS) addresses some of the most fundamental questions in contemporary research. Tabletop terawatt femtosecond lasers provide a robust platform for experiments in HEDS – on the one hand, they push the limits of ultrarapid excitation and on the other they provide a perfect complement to the experiments performed with high energy, longer pulse lasers. After a general introduction we consider results in a niche regime of these lasers, namely femtosecond dynamics. Specifically, we consider pump-probe experiments with relativistic intensity 30 fs, 10 Hz, 800 nm Ti: Sapphire laser pulses. The physical processes considered are the transport of hot electrons with their associated giant magnetic fields, the spatio-temporal evolution of these magnetic fields at target front and rear and ultrafast dynamics of the plasma critical surface.

In the last twenty years, the chirped pulse amplification scheme has revolutionized the production of high intensity light in two important ways - (a) pushing the upper limits of intensity more than a thousand fold and (b) reducing the foot print of high intensity lasers by a factor as large as 100 (with concomitant cost reduction). In doing so, it also democratized the participation of researchers by offering smaller groups with limited resources an opportunity to join the ranks and make effective contributions. This last aspect of ‘globalization’ has led to establishing more robust methods in the area.

This paper seeks to discuss some of these features in the area of high energy density science (HEDS). It is well known that HEDS addresses some of the most fundamental questions in science [1], with its emphasis on understanding the creation and behaviour of extreme states. It is further gratifying to note that table top, femtosecond lasers can play a key role in the creation of these states as the femtosecond nature of the pulses freezes out deleterious motions and couples energy at solid densities. While many interesting HEDS experiments are already being performed at the big facilities around the world and more will definitely be undertaken at the NIF, table top experiments can provide complimentary and unique perspectives in this area. High energy laser pulses from the big facilities are necessarily limited to a few shots per experiment and our colleagues address and attempt to overcome this limitation by increasing the versatility of diagnostics in the experiment and providing enough multiplicity and redundancy. The experiments are viewed in close conjunction with simulations and this all round effort has been pushing the frontiers for many years. It is obvious however that the field would benefit immensely by experiments in a more traditional mode, i.e. ease of operation, ready manipulation of beams, more repetitive collection of data in the establishment of systematic, calibration and cross checks by multiple labs with similar capabilities and possibilities for testing extended ideas with incremental efforts. Current tabletop lasers promise all these and more.
The big question in HEDS i.e. creation and evolution of extreme states under controlled conditions, is best met by high intensity laser pulses with the shortest possible duration, provided they are truly short. The latter implies that the pulses have to have increasing contrast with background simultaneously with increasing intensity. What make tabletop femtosecond lasers very attractive is the recent improvements in producing temporally leaner and cleaner pulses. Presently, laser systems operating at the 100 TW level offers an ASE contrast of better than $10^{-9}$ and a contrast of $10^{-8}$ at the 10-20 ps level [2]. At a peak intensity of $10^{21}$ W cm$^{-2}$, prepulse levels are only at the level of $10^{12-13}$ W cm$^{-2}$ at the nanosecond and picosecond levels. The second aspect is that of ever shortening duration. From the 100 fs level at which high intensity pulses were routinely produced a decade ago by a tabletop laser, we have advanced to the 10-20 femtosecond level and shorter few cycle pulses should be available at relativistic intensities in the near future. Some of the interesting consequences of this shrinking are the induction of nonadiabatic effects, higher levels of absorption in steeper, denser plasmas and associated physical effects. Absorption of as much as 80% of laser light has been observed with clean p-polarized 8 fs pulses in highly overdense plasma with a very steep gradient, possibly from mechanisms other than vacuum heating [3]. Similar experiments at ultrahigh intensities (close to $10^{21}$ W cm$^{-2}$) at Livermore also showed very high levels of coupling (upto 60% for normal and 85% for 45 degree incidence [4]. It is also well known now that femtosecond, high contrast pulses shining on ultrathin targets can produce the highest proton and ion energies (see for example, Maksimchuk et al., IFSA09 oral 3.4.3).

![Diagram](https://via.placeholder.com/150)

**Figure 1.** (a) Sketch of setup Pump-Probe studies. (b) (left) Magnetic fields measured at the front of an aluminium coated glass target and (right) the rear of a 100 micron fused silica target. (c) Spatially resolved magnetic field for 3 picosecond pump-probe delay at the critical surface at target front for an aluminium coated glass target. (d) Spatially resolved magnetic field at the critical surface of plasma at the rear of a 100 micron thick fused silica target at the same delay.
Let me now illustrate the power of the tabletop lasers in the realm of unravelling ultrafast dynamics for which they are uniquely positioned. A typical pump-probe set up that is used in our laboratory is depicted in Fig.1 (top, left). The measurement of the polarization state of the probe, reflected from its critical layer (polarimetry) gives a measure of the giant magnetic fields, depicted on the right. Magnetic fields as large as 65 MG at the front of an aluminium coated glass target and 15 MG at the back of a 100 micron fused silica target have been measured at intensities of $10^{18}$ - $10^{19}$ W cm$^{-2}$. These magnetic fields are caused by the hot electron currents in the target and their time evolution mirrors the electron transport process involving both forward and return currents. We have also captured spatial profiles of the magnetic fields at different instants, shown at the bottom of the figure (x-y profile of the magnetic field as captured by the CCD camera). These are the first ever measurements of the simultaneous space and time resolved giant magnetic field. The 2D profile of the magnetic field is not cylindrically symmetric but has a structure inside. This indicates that current distribution which is responsible for this magnetic field has filamentary behaviour. It is interesting to see that the field at the back has a hollow portion at the centre. Mapping of this magnetic field provides the insight of the transport of relativistic electrons in the solid dense plasma. These data are being further refined and analyzed in detail and will be published in details elsewhere along with appropriate modelling (for some details see Mondal et al., IFSA09 poster 3.10.038). Preliminary analysis reveals the signatures of magnetic turbulence in these plasmas. Our recent work has also shown that crucial transport information can be derived from the measurement of giant magnetic pulses [5-7].

![Figure 2](image.png)

Figure 2. Time resolved Doppler shifts in the probe beam reflected from plasma created by an 800 nm, 30 fs laser pulse at $5 \times 10^{18}$ W cm$^{-2}$. The target is Al coated glass.
Another aspect that is interesting to study is plasma motion on ultrafast timescales, specifically, the motion of the critical surface, which we show in Fig. 2. The Doppler shifts in probe spectra indicate that the critical surface moves into the denser plasma portion at initial times, and the motion reverses at later time [8]. These results are important for understanding mass and energy transport in the plasma at early times. For more details, please see Oral presentation 2.1.4, Lad et al. in these proceedings.

![Figure 3. Comparison of bremsstrahlung emission from polished copper (red) and copper nanorod coated targets (blue) at incident laser intensity of $10^{15} - 10^{16}$ W cm$^{-2}$. Inset shows the logarithmic plot of bremsstrahlung emission.](image)

We have also been interested in enhancing laser coupling to the target and enhancing hot electron production. One of the attractive ways to do this is to have nanostructuring on the target surface [9]. The structure enhances local electric fields and cause efficient absorption. We have recently studied surfaces coated with copper nanorods (150 nm diameter, 20-30 micron length, 100-150 nm spacing between rods) and obtained nearly 30 times enhancement in the hard x-ray emission caused by the hot electrons generated. The temperature of the hot electrons is increased by more than an order of magnitude (Fig. 3).

Before concluding, it is relevant to offer a few remarks about the increasing participation by the Indian community in this area. Recent Indian efforts are concentrated in HEDS, be it studying opacities, x-ray emission, shock wave propagation, hot electron generation and transport, giant magnetic fields, explosion of cluster targets, behaviour of nanostructures etc. The emphasis is on attempts to understand basic physics of the hot, dense matter that is created and applications in novel x-ray sources, particle acceleration and laser fusion, particularly fast ignition.
The experimental areas are being pursued mainly at the Tata Institute of Fundamental Research (TIFR), Mumbai (erstwhile Bombay), Raja Ramanna Centre for Advanced Technology (RRCAT), Indore and Bhaba Atomic Research Centre (BARC), Mumbai, apart from some universities. Theoretical work, including analytical aspects and simulations is driven by efforts at the Institute for Plasma Research (IPR), Gandhinagar, Indian Institute of Technology, Delhi and the BARC, Mumbai. Figure 4 shows a few of the major facilities at different laboratories. In 2010 two high contrast, 100 TW, ‘petawatt scale’ laser facilities will be installed at TIFR and RRCAT. A PW laser is slated to be developed by 2013. For a summary of these aspects, please see [10].

Conclusions
Tabletop terawatt, femtosecond lasers are enabling faster progress in high energy density science by virtue of the flexibility, robustness and repeatability they offer. Interesting efforts are being made by the HEDS community to search for and understand newer ways of coupling light to dense plasma, particle emissions and their dependence on various laser and target parameters, hot electron transport, giant magnetic field generation and similar plasma processes. The feasibility to unravel ultrafast dynamics carves out a niche area for the tabletop lasers and promises new understanding of plasma dynamics and their impact on target physics.

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