# Study of fast electron transport with femtosecond scale laser pulses

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To date, numerous studies of fast electron transport have been carried out with picosecond (ps) scale laser pulses [1–4]. As the number of femtosecond (fs) scale laser systems continues to grow, important questions are prompted about the pursuit of current avenues of fast electron transport research at these high intensities using short (sub-100 fs) pulses.

Initially motivated by the work of Tabak et al. in 1994 [5], there is significant interest in the transport of hot electrons through solid density materials, for applications ranging from the important role played in fast ignition fusion [6, 7], to ion acceleration [8], and the production of secondary x-ray sources [9] or warm dense matter states [10]. High intensity laser-solid interaction experiments have included several studies of pulse duration, ranging from long nanosecond (ns) scale pulses, through to the more typical ps scale, and further to fs scale pulses. More recently, novel pulse temporal profiles have been utilised in efforts to control the electron beam divergence [11].

The majority of studies of fast electron transport studies thus far have involved using ps pulse length Nd:glass laser systems. The proposed extension of current laser facilities to reach ultrahigh intensities may be achieved by either producing greater energies or shorter pulses. Currently, a major aspect of the development of future laser systems is focused on reaching these multi-PW intensity scale by shortening pulse length to the order of 30 fs, as higher energies are not easily achievable [12–15]. This is also motivated by the desire to move to higher repetition rates.

Detailed investigation of the composition and structure of the target material has yielded important information on how a materials lattice structure and detailed electrical resistivity profile strongly effects the transport of hot electrons in solid targets [16–19]. For these ps scale experiments, hybrid particle-in-cell (PIC) simulations have been shown to be a good indicator of the electron transport for ps length laser pulses. In this report we investigate fast electron transport as a function of laser pulse duration using hybrid-PIC simulations. The hybrid-PIC code Zephyros models the hot electron population within the target using a PIC component, with the remaining background electrons in a fluid background [20].

The combination of Ohm's and Faraday's law leads to the expression for the self generated magnetic field as

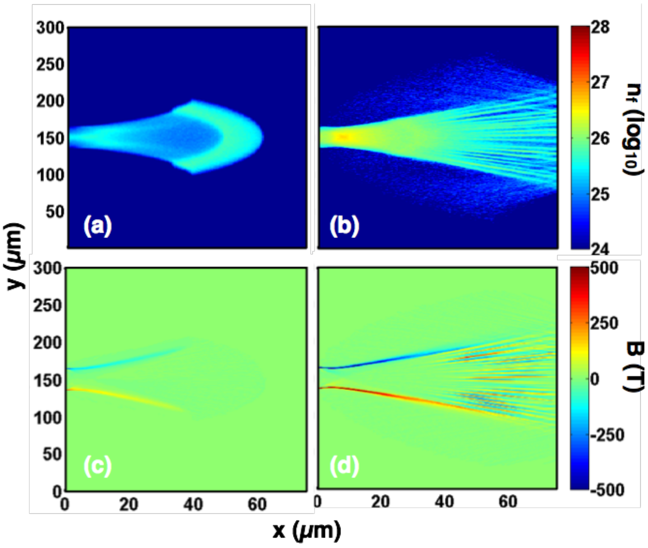


Figure 1: Zephyros simulation results showing the electron density m$^{-3}$ (log) for (a) 40 fs pulse and (b) 400 fs pulse, and the magnetic field in T for (c) 40 fs pulse and (d) 400 fs pulse - all for 75 um CH target with 15 J, 800 nm laser pulse incident on the centre of the left boundary.

$\partial B/\partial t = \eta\nabla \times \boldsymbol{j_f} + \nabla\eta \times \boldsymbol{j_f}$ where $B$, $\eta$ and $\boldsymbol{j_f}$ are the magnetic field, target resistivity, and fast electron current density respectively. The first and second terms in this well known equation represent the magnetic field pushing electrons into regions of high current density and high resistivity [16, 21]. The resistive filamentation instability as described by Gremillet et al. [22] is dependent on the pulse length. The growth rate of this resistive instability is given by the beam current, temperature and background target resistivity. For longer pulse durations the instability will therefore continue to grow, resulting in a higher probability of beam filamentation.

Magnetic field ($B_z$) plots shown in Figure 1 (c) and (d) show far more structure in the electron beam for a 400fs pulse than for one of 40fs of the same energy input (i.e. same total electron energy). Parameters here have been constrained to consider constant input laser energy, to highlight only the effects of changing pulse length. These and further pulse length simulations (not shown) indicate that this filamentation may not be spatially resolvable experimentally for pulse lengths less than 400fs.

To initially assess the extent of the growth of the magnetic fields in three common target materials, Figure 2 shows the maximum magnetic field in a series of similar simulations for Si, CH and Al targets (all of 75 $\mu$m thickness). The maximum magnetic field for all three materials is seen to increase with laser pulse duration, in agreement with the model of Bell et al. [23]. It is also seen for the three pulse durations modelled here that the greatest magnetic field generated occurs in Al, with Si and CH being comparable. The very different resistivity profiles for Al and Si gives rise to lower magnetic fields being generated in Si, even though they have a similar Z [23].

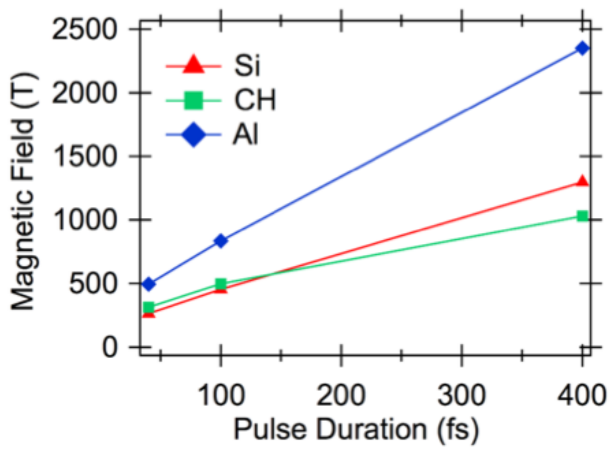


Figure 2: Maximum magnetic field strength generated in each target type increases with laser pulse duration (fixed energy)

Magnetic fields generated within targets such as these have been shown to strongly affect the transport of electrons. The presence of filamentation and other effects such as beam pinching (or collimation), or hollowing of the beam has also been observed [9]. The generation of strong magnetic fields, particularly in the case of a collimating field, can be very advantageous to applications such as fast ignition (FI) fusion, and as such the conditions needed to produce such fields are of great interest. The stronger magnetic field generation for greater pulse lengths indicates that this will be possible for longer pulse drives, in this case of the order of several hundred fs, as strong magnetic field structures are not seen here for shorter pulses. Figure 1 shows that for a 75 $\mu$m CH target, there is no visible filamentation for a 40fs laser drive and that the onset of a filamentation is visible for the 400 fs drive.

For short pulse interactions where the magnetic fields are relatively small, a collimating magnetic field is not generated. The conditions under which strong magnetic fields are generated are therefore important to understand as this will determine regimes where instabilities leading to beam filamentation become an issue, and perhaps what regimes can be used in FI fusion or other applications requiring a high energy but to some degree a collimated beam.

## Conclusion

The strong time dependence of the resistive filamentation instability and the growth rate of the magnetic field given by the combination of Ohm's and Faraday's formulae (as above), indicates that the use of shorter fs scale pulses will significantly change the fast electron transport physics. The work shows that the transport patterns observed with ps Vulcan-type lasers will be very different from fs Astra-Gemini type lasers due to the large differences in the pulse duration.

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