Enhancement of fast electron energy deposition by external magnetic fields

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Abstract.
Recently, generation of external magnetic fields of a few kT has been reported [Fujioka et al. Scientific Reports 2013 3 1170]. These fields can be used in fast ignition to mitigate the large fast electron divergence. In this summary, two fast ignition applications are briefly outlined. The first one deals with electron guiding by external B-fields applied at the end of the shell implosion of a re-entrant cone target. Preliminary results show that the B-field strength at the time of peak ρR may be sufficiently high for fast electron guiding. The second application deals with guiding of fast electrons in magnetized wires surrounded by plasma. Results show a significant enhancement of electron energy deposition at the end of the wire, which is particularly important for low-Z wires.

1. Introduction
Recently, magnetic fields have been proposed for guiding fast electrons towards the compressed core of fast ignition targets [1]. B-fields of a few kT are required to guide fast electrons towards the dense fuel. Two approaches have been proposed so far for generating so strong magnetic fields: i) magnetic flux amplification [2] and ii) field generation by laser-driven external coils [3]. In the first approach, it has been reported that, after the flux amplification, fast electrons are guided towards the dense core by an increasing magnetic field resulting in a significant ‘backscattering’ of those electrons due to the mirroring effect [1]. The second approach is based upon generating B-fields by a laser-driven external single-turn coil [3] at a time close to the end of the target implosion and offers the possibility to generate the optimal field distribution for fast electron guiding. The main issue is to ensure magnetic field penetration up to the dense core over times of the order of a few nanoseconds.

2. Model for B-field penetration in plasma.
A model for resistive diffusion and amplification of external magnetic fields has been developed. This model is based on post-processing the data obtained from radiation-hydrodynamic codes. It does not account for the fields generated in the plasma. Instead, the model deals with the penetration of external...
B-fields in the plasma, which is important for fast electron transport and energy deposition. The following induction equation is solved for the B-field:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$$  (1)

where \(\mathbf{v}\) is the fluid velocity and \(\eta\) the plasma resistivity. The relative importance of each term is given by the magnetic Reynolds number \(R_m = \mu_0 L v / \eta\), where \(L\) is the typical flow scale-length. If \(R_m >> 1\), the advection term is dominant, whereas if \(R_m << 1\) the diffusion term prevails. Once \(\mathbf{B}\) is obtained from Eq. (1), the Ampère law provides the plasma current density induced in the plasma, from which ohmic heating, plasma temperature and resistivity are obtained. The induction equation is solved semi-implicitly by using a preconditioned bi-conjugate gradient solver algorithm for matrix inversion [4]. It has been applied to two different situations found in electron-driven fast ignition targets: i) fast electron propagation in cone-targets with external B-fields and ii) fast electrons guiding in magnetized wires.

3. Fast electron propagation in cone-targets with external magnetic fields.

The B-field diffusion model described above provides the distribution of the external B-field in the target at the time of the peak \(\rho R\), just when fast electrons are generated at the cone tip. The model target used in our calculations is sketched in Fig. 1, where a re-entrant cone is attached to the direct-drive ignition scale capsule shown in Fig. 2a. It contains a DT shell of 0.3 mg, which is imploded with a peak velocity of 160 km/s. The r-t flow diagram of the 1-D implosion is depicted in Fig. 2b, where the 24 ns pulse duration is remarkable. Note that most of the implosion takes place without external magnetic fields, which are turned on just 1 ns before the end of the implosion by a coil sited in the position shown in Fig. 1. This timing has been chosen in order to avoid B-field configurations that ‘backscatter’ fast electrons due to the mirroring effect. Ideally, it is assumed that the coil current is 5 MA during 1 ns, generating a 3 kT B-field at the cone tip placed 450 mm away from the coil.

![Figure 1](image1.png) **Figure 1.** Sketch of the cone target used in the simulations. The coil is sited at the left of the shell and separated from the plasma by a metallic plate.

![Figure 2](image2.png) **Figure 2.** Target and r-t diagram of the target used in simulations. Shell radii are shown at the right of the target sketch in mm. The target is illuminated by a 0.2 TW pre-pulse followed by the main pulse with a peak power of 40 TW.

The B-field in the target depends on the diffusion of the external B-field through the cone walls and the shell, and its amplification during the shell implosion. As shown in Eq. (1), high-resistivity materials should be used to ensure the diffusion of the B-field along the cone walls. Here, solid gold with an initial temperature of 10 eV has been chosen. The B-field distribution near the time of peak compression is shown in Fig. 3. Initially, the B-field diffuses along the cone and through the dense and cold part of the imploding shell, which has a relatively high resistivity. As the B-field is generated 1 ns before the time of peak \(\rho R\), its amplification is much lower than that
reported in [2]. However, there is a small but non-negligible amplification factor of 2-3. It is worth noting that the B-field peaks where fast electrons are generated, and its value near the axis is about 1 kT, that may be sufficient to reduce divergence or even guide fast electrons, depending on their energy. Note also the oscillations of the B-field near the axis, which may affect fast electron transport. Our preliminary simulations show that imposing external magnetic fields near the end of the implosion may enhance fast electron energy deposition and coupling efficiency. However, more detailed studies including fast electron transport are required to fully assess this possibility.

4. Fast electron guiding in wires.

The use of resistive wires to guide fast electrons along relatively large distances has been proposed recently [5,6]. It was extended to specially engineered targets by Cai et al. [7]. In the context of fast ignition, we have performed a study of electron transport in wires of different materials – diamond-like carbon (DLC) at 3 g/cm³, and aluminium, copper and gold at solid density– surrounded by an ideal imploded DT density distribution. The target used in our simulations is shown in Fig. 4, which is similar to that used by Solodov et al. [8] for fast electron divergence control. As beam collimation in wires is caused by radial resistivity gradients [5], high-Z materials should be more effective for fast electron transport between the cone tip and the compressed core. It is assumed that 1 ns before the time of peak $\rho R$, a laser-driven coil placed as shown in Fig. 1 generates a magnetic field, which diffuses resistively along the cone tip and the wire. The initial temperature of the cone and the wire is 10 eV, while that of the DT is 100 eV. Thus, the B-field penetration in the DT fuel is quite low due to its lower resistivity. At the maximum compression time, a fast electron beam is generated at the cone tip and guided towards the compressed core by the diffused B-field. It is assumed that fast electrons are generated by a laser beam with a peak intensity of $5.5\times10^{20}$ W/cm² and a wavelength of 0.525 µm. The beam has a 20 µm (FWHM) width super-Gaussian density distribution in radius of and the fast electron temperature is obtained by the ponderomotive scaling. The pulse length is 14 ps and the laser to fast electron conversion efficiency is 50%. The fast electron energy deposition is shown in Fig. 5. Without wire and external magnetic fields, it is dominated by the fast electron divergence and the coupling efficiency between electron beam and core is too low, as shown in Fig. 5a. Resistive wires enhance the energy deposition in the ignition region substantially due to the electron confinement.
within the wire [5], even for the low-Z DLC wire of Fig. 5b. However, the magnetic field induced at the DLC wire edge due to the resistivity gradient is not strong enough to trap all fast electrons in the wire, resulting in a significant loss of fast electrons, as shown in Fig. 5b. On the contrary, light materials are more effective for electron transport due to the lower electron energy deposition, scattering and ohmic heating. Assuming that a B-field is generated by a laser-driven coil similar to that described in [3], and that this field diffuses along the wire for 1 ns, Fig. 5c shows how the energy deposition in the ignition region and in the whole core is substantially enhanced due to the fast electron guiding by the imposed B-field.

The electron beam coupling efficiencies are shown in Fig. 6 for all the cases analysed. Note their enhancement due to the non-magnetized wire. When external magnetic fields are on, there is a substantial enhancement of the coupling efficiencies, especially for low-Z materials, for which the enhancement is similar to that produced by the wire itself. It is worth noting that coupling efficiencies higher than 20% can be achieved for DLC wires and B-fields of about 6 kT on target, which correspond to 10 MA current on the single-turn coil.

5. Conclusions

Regarding the fast electron transport in magnetized targets, the preliminary results shown motivate a more detailed study of the B-field penetration for a full assessment of the option proposed here. This study should include cone material selection, optimal time to apply the magnetic field and fast electron energy deposition in the magnetized imploded target.

Our results on fast electron guiding in magnetized wires show that external B-fields improve substantially the coupling efficiency, in particular for wires of low-Z materials. Note that this effect is more beneficial than it appears to be because lower electron beam energies mean, lower short pulse laser intensities, lower electron energies and shorter penetration range. The survival of the wire during the fuel compression is still an open question.

Future developments include the extension of the post-processor for B-field calculations and the implementation of a MHD model in radiation-hydrodynamic codes.

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