Pulsed Strong Magnetic Field Generation by Laser and Application to Guided Electron Beam Transport

João Jorge Santos[1], M. Bailly-Grandvaux[1], L. Giuffrida[1], P. Forestier-Colleoni[1], S. Fujioka[2], Z. Zhang[2], R. Bouillaud[1], S. Dorard[3], D. Batani[1], M. Chevrot[3], J. Cross[4], R. Crowston[5], J.-L. Dubois[6], J. Gazave[6], G. Gregori[4], J.J. Honrubia[7], E. d'Humières[1], S. Hulin[1], K. Ishihara[2], S. Kojima[2], Ph. Korneev[1], E. Loyer[3], J.-R. Marqués[3], A. Morace[2], Ph. Nicolaï[1], O. Peyrusse[1], A. Poyé[1], D. Raffestin[6], J. Ribolzi[6], M. Roth[8], G. Schaumann[8], F. Serres[3], C. Spindloe[9], V.T. Tikhonchuk[1], Ph. Vacar[3], N. Woolsey[5]

[1] Univ. Bordeaux, CNRS, CEA, CELIA, UMR 5107, F-33405 Talence, France
[2] Institute of Laser Engineering, Osaka University, Osaka 565-0871, Japan
[3] LULI, Ecole Polytechnique, CNRS, CEA, UMR 7605, F-91128 Palaiseau, France
[4] Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK
[5] Department of Physics, Heslington, University of York, YO10 5DD, UK
[6] CEA/DAM/CESTA, BP 12, F-33405 Le Barp, France
[7] ETSI Aeronáuticos, Universidad Politécnica de Madrid, Madrid, Spain
[8] Institut für Kernphysik, Tech. Univ. Darmstadt, Germany
[9] Scitech Precision, Rutherford Appleton Laboratory, Chilton, Didcot, UK

We describe recent experimental results on strong magnetic-field (B-field) generation by laser, and its application to Relativistic Electron Beam (REB) transport. Laser irradiation conditions were 500 J, 1 ns focused to intensities up to 3×10^{17} Wcm^{-2} to generate the B-field in capacitor-coil targets, and 50 J, 1 ps focused to 3×10^{19} Wcm^{-2} to generate the REB in solid plastic (CH) targets. We demonstrated reproducible B-field with typical few ns duration and dipole-like spatial distribution over a ~1 mm^3-volume, with peak values of several hundreds Tesla. We have also measured a factor two pinching of the REB in magnetized targets, being the first clear effect of an exterior B-field imposed to REB transport to be observed experimentally.

1. Motivation

The presented research project aims at achieving a clear experimental observation of REB guided propagation by imposed kT B-fields in controlled target magnetization levels. This would have an extremely positive impact on the feasibility evaluation of the fast ignition (FI) scheme [1, 2], in magnetized inertial fusion in general [3] as well as on the development of many other applications built on high flux of energy through dense matter. Besides, the possibility of imposing externally strong and pulsed B-fields generated by laser to a variety of samples opens significant perspectives to many other researches, such as X-ray spectroscopy of strongly magnetized plasmas relevant for atomic physics in magnetized astronomic objects (crust of white dwarfs or neutron stars) [4], magnetic collimation of plasma jets [5], collision-less shock generation in magnetized plasma [6].

2. Experimental Methods and Main Results

The described experiments were carried out in two campaigns at the LULI pico 2000 laser facility (Ecole Polytechnique, France).

2.1 *Strong Magnetic-Field Generation by Laser*

We generated pulsed (ns-scale) B-fields with amplitude up to several hundreds Tesla, using capacitor-coil targets, irradiated by a 1.057 μm wavelength ($1\omega_0$), 500 J, 1 ns long-pulse laser beam (LP), focused to intensities up to $3\text{x}10^{17}$ W/cm^2. We followed the scheme initially proposed by Daido *et al.* [7], and more recently explored by Courtois *et al.* [8] and Fujioka *et al.* [9]: the capacitor formed by two disks is charged by the laser irradiation of one of the disks. The target then discharges through a current of intensity I, driven in a coil-shaped wire connecting the disks. The discharge generates a strong and pulsed B-field with maximum amplitude at the coil centre $B_0 \approx \mu_0 I/2a$, where a is the coil radius. The system is short-circuited when the plasma-generated plume, propagating at the plasma sound speed, reaches the non-irradiated disk, producing a drop in B-field amplitude. We tested different target materials.

Time-resolved measurements of the B-field were done using two B-dot probes (3 GHz bandwidth electronics). For targets with $a = 250$ μm, the measured B_0 reaches peak values of 700 ± 100, 500 ± 100 and 100 ± 50 T respectively for Cu, Ni and

Al targets [see Fig. 1-a)]. The B-field rising time is ≈ 1 ns, corresponding to the duration of the laser irradiation (system charging). For a majority of shots, the typical duration of the pulsed B-field is ≈ 3.5 ns. The results are confirmed by measurements of the rotation, by Faraday effect, of the linear polarization direction of a probe laser beam, propagating trough TGG crystals along the coil axis. Proton-deflectometry data, obtained with laser-accelerated proton beams of energy up to 20 MeV, shows the dipolar-like spatial distribution of the B-field, distributed over a ~1 mm^3 typical volume. Yet, quantified analysis of the proton deflections reveal the B-field generated by the target discharge through the connecting wire is *screened* by collective effects in plasma cumulating in the coil region.

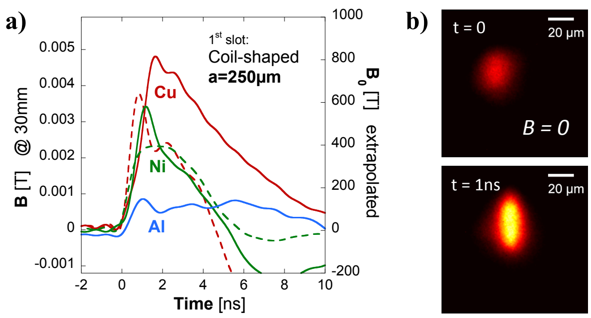

Fig.1. **a)** Sample results for B-dot probe measurements of B-field, at the probe position (left ordinate-axis) and extrapolated to the coil centre (right ordinate-axis). **b)** Sample CTR snapshots from the target rear surface, for different delays between the SP and LP laser pulses.

2.2 *Relativistic Electrons Transport with Imposed Axial Magnetic-Field*

Relativistic electrons were generated by focusing, along the coil axis, a short pulse laser beam (SP: 50 J, 1 ps, 3x10^{19} W/cm^2) into 50 µm thick CH targets, positioned at the vicinity of the coil (100 µm horizontal shift along the coil axis, 120 µm vertical shift relative to the coil axis). The REB spatial pattern was inspected by imaging the Coherent Transition Radiation (CTR) emission at $2\omega_0$ from the targets rear surface, for varying delay of the SP relative to the LP laser beam, $\tau_{SP/LP}$.

Sample CTR snapshots are shown in Fig. 1-b). Without B-field ($\tau_{SP/LP} = 0$) the REB shows a cylindrical pattern of about 20 µm diameter. For $\tau_{SP/LP} = 0.5$ ns, the pattern looks less symmetric but is roughly of the same dimensions and intensity level. For $\tau_{SP/LP} = 1$ ns the pattern is about two times narrower in the horizontal direction, and its yield is about two times higher than in the previous cases. The asymmetric CTR pattern, signature of horizontal magnetic pinching of the REB, is undoubtedly due to the target positioning and the local B-field asymmetry: the vertical component of the poloidal field around the coil rod and its gradient over the height of the target are indeed non-negligible at its position.

According to preliminary MHD simulations, 1 ns seems to be the needed time to fully magnetize the 50 µm thickness of CH. By simply considering the characteristic time for the B-field resistive diffusion, $\tau_B = \mu_0 L^2/\eta \approx 1$ ns over $L = 50$ µm, yields $\eta \approx 10^{-6}$ Ωm for the target resistivity, which is fairly reasonable for CH on the temperature range from a few eV to a few tens of eV. Such temperature could result from target pre-heating by the fast particles and hard X-rays emitted form the LP interaction region, and then from the electron currents induced by the B-field circulation when diffusing on the target.

3. Summary

The results obtained in our experiments show: i) a reproducible strong B-field generation by laser, with typical few ns duration and mm^3-volume, with peak values of several hundred Tesla; ii) a pinching of the REB over a magnetized 50 µm CH target, a clear effect of the imposed axial B-field.

We are presently working on a fully-consistent model for the target charging and discharging, responsible for the B-field generation, on the improvement of a MHD code for accurate prediction of target magnetization and on PIC-hybrid REB transport simulations in such magnetized propagation media.

The *screened* B-field probed by the protons is the remaining issue to be fully understood. For that, we are also performing large-scale 3D PIC simulations of the proton-beam propagation over strong B-fields.

The next experiment will be devoted to assess the robustness of the kT B-field guiding effects over the REB propagation, with a detailed characterization of target magnetization (for insulator and conductor materials) and a foreseen improved REB guided transport.

References

[1] M. Tabak *et al.*, Phys. Plasmas **1**, 1626 (1994).
[2] D.J. Strozzi *et al.*, Phys. Plasmas **19**, 072711 (2012).
[3] L.J. Perkins *et al.*, Phys. Plasmas **20**, 072708 (2013).
[4] B.N. Murdin *et al.*, Nature Comm. 4:1469 (2013).
[5] A. Ciardi *et al.*, Phys. Rev. Lett. **110**, 025002 (2013).
[6] Ph. Korneev *et al.*, Phys. Plasmas **21**, 022117 (2014).
[7] Daido *et al.*, Daido *et al.*, Phys. Rev. Lett. **56**, 846 (1986).
[8] C. Courtois *et al.*, Phys. of Plasmas **11**, 3386 (2004).
[9] S. Fujioka *et al.*, Scientific Reports **3**, 1170 (2013).