FUSION SCIENCE CENTER MEETING ON ELECTRON DIVERGENCE IN FAST IGNITION

AUGUST 5-6, 2010

LAWRENCE LIVERMORE NATIONAL LABORATORY

SUMMARY AND CONCLUSIONS

by

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SUMMARY

The FSC meeting on electron divergence in fast ignition took place on August 5-6 in the conference room of Building 481 at Lawrence Livermore National Laboratory. In addition to FSC members from UR, UCLA, UNR, LLNL, MIT, OSU, UCSD, GA and ILSA, a number of guests from the United States, Japan and Europe attended the meeting. About fifty attendees participated to the meeting and discussion sessions. The agenda of the meeting is shown in Appendix A and the slides of the presentations can be found on the FSC web site at http://fsc.lle.rochester.edu.

A set of relevant questions was formulated to identify a path forward with respect to the issue of electron divergence in fast ignition. The questions are listed below:

- What is and what causes the divergence of the electron source?
- What is the divergence of the source for a 100kJ pulse?
- Is there experimental evidence for self-generated collimating resistive magnetic fields?
- Are these magnetic fields generated at the beginning of the pulse and then frozen into the plasma?
- Do B-fields generated by resistivity gradients persist at ignition scale energy?
- Are self-generated fields enough to improve the collimation or new ideas - like external B-fields - are needed?
- What is a possible path forward?

During the first day of the meeting, assessments and reviews of past and current experimental and simulation results were followed by specialized talks on the latest experiments, on integrated simulations of ignition targets and on the use of materials with resistivity gradients. The morning of the second day was devoted to code verification. Different codes were used to simulate a set of problems addressing basic issues related to fast electron generation and transport:

The results of the Verification Session indicated a good qualitative and general quantitative agreement between codes (LSP, PICLS, PSC, PETRA). The details of this exercise are described in a separate report to be posted on the FSC website.

Both first and second afternoons featured lengthy discussions on the current measurements and understanding of the electron divergence in high-intensity laser-matter interaction. In the LLNL simulations by A. Kemp [1], the divergence seems to approach a steady state value after a few picoseconds thus making these simulations and current experiments relevant for longer ignition pulses. More importantly, after only 2 ps, the electron spectrum in the presence of a pre-plasma approaches the no-pre-plasma case. Divergence experiments used different diagnostics from K-α imaging to Coherent-Transition-Radiation (CTR) emission and hard x-ray emission.

Detailed 3D simulations [1] of the electron divergence were carried out by A. Kemp (LLNL) showing a steady-state energy-integrated divergence full-angle of 94^0. The simulations were carried out for an intensity of $1.4{\cdot}10^{20}$ Wcm^{-2} and show a hot electron temperature of about 7MeV. The CTR measurements of Storm et al. [2,3] on MTW show a smaller divergence angle (full angle ~ 32^0) measured at different distances from the sources and consistent with the measurements reported by Green et al [4]. However, any measurement of the divergence carried out deep into a solid target must account for the collimating effects of the resistive magnetic fields. Such fields can significantly reduce the electron divergence during the e-beam propagation in the target (see Solodov's simulations with LSP in Ref. [3]). Using the LSP code to simulate the CTR measurements of Storm, the source divergence required to explain the measurements [3] is about 110^0 (in general agreement with Kemp's simulations). This result is also consistent with Honrubia's simulations of the experiments in Green's article. Honrubia reported [5] that a source divergence of about 100^{o} is required to reproduce Green's results. Similar results were also reported in OSIRIS simulations by Ren [6] where an angular spread of 48^{o} half angle was inferred. Results from recent LSP simulations from D. Schumaker (OSU) [7] also reported a similarly large divergence. Such LSP simulations used a postprocessor to infer the Cu K-α emission and indicated that the divergence inferred from K-α emission is generally higher than the actual electron divergence when refluxing effects become important. Results from recent experiments on electron divergence were also reported at this meeting. Recent Titan experiments by OSU using K-α emission (L. Van Woerkom [8]) and by LLNL using bremsstrahlung X-ray emissions in Al+Ag targets (C. Chen [9]) also indicate an electron divergence in the ~ 100^{o} range (it was somewhat less in the OSU experiments, ~80^{o}). Such a divergence angle is also consistent with the warm-dense-matter (WDM) experiments in shocked foam by the GA/UCSD group (R. Stephens [10]). Those experiments use Cu K-α emission and show a ~100^{o} divergence in the presence of a plasma medium (a layer of shocked foam). The size of the K-α emission region is significantly reduced when the electron propagation medium is solid CH. This can be explained through the generation of collimating magnetic fields in solid CH. Because of the higher initial resistivity, it is easier to induce collimating resistive fields in solid CH than in CH plasmas. This can be verified through hybrid simulations. These conclusions are also consistent with the latest experiments from the UCSD group on OMEGA EP [11].

Using the electron source from the LLNL code PSC (with a ~100^{0} angle and a two-temperature distribution function to approximate the PSC output), D. Strozzi (LLNL) [12] used LSP to study the transport of the fast electrons in an ignition-scale target simulated with HYDRA. The simulations indicate that even with a dense core in direct contact with the cone tip (i.e. optimum implosion), the electron coupling to the core is weak. In addition to the large divergence, another major detrimental factor is the hot electron temperature (or mean energy). The electron temperature can be reduced by using green light (instead of red). But even with green light, the electron beam energy required for ignition is about 185kJ thus requiring a PW laser of 400-500kJ.

While there is significant experimental and theoretical evidence that the electron divergence is large (about 100^o full angle), there are still significant questions about the validity and accuracy of past and current experiments. Divergence experiments must be designed to minimize the effect of refluxing (the shocked-foam UCSD/GA experiments were correctly designed with a large get-lost plasma). Furthermore, measurements based on Cu K-α emission can be significantly affected by the low energy component of the electron spectrum.

Two action items on the subject of electron divergence were identified:

(a) The need for hybrid simulations of the UCSD WDM experiments on divergence to determine if a source divergence of $\sim 100^o$ and the presence of collimating magnetic fields can explain the difference in K- α emission in solid CH and shocked CH foam [10]. [Tasks for A. Solodov (LLE) and Y. Sentoku (UNR)]

(b) The need for PIC/hybrid simulations of Chen's experiments in Al targets with a 500-µm Ag layer. [Tasks for J. Honrubia (UPM) and D. Schumaker (OSU)]

In the afternoon of the first day, A. Robinson (RAL) [13] described the recent idea about improving the electron collimation by using materials with different resistivities. The resistivity gradients at the interface between the two materials can generate a large collimating field. The B-field collimation is effective only if the electrons propagate through the material with the higher resistivity. This theoretical prediction has been confirmed by recent experiments at RAL [14] (not shown at the meeting). The applicability of this scheme to fast ignition depends on two factors:

(a) The collimating B-fields need to persist during the entire ignition pulse. In an ignition pulse, the material along the path of the electron propagation is heated to KeV temperatures. At such high temperatures, the resistivity of such material will be less than the resistivity of the surrounding plasma and the resistivity gradients are inverted. The question to be address is whether or not the inverted resistivity gradients cause a B-field reversal from collimating to de-collimating.

(b) The high resistivity path must survive the compression resulting from the implosion.

The first question was addressed as a part of the code verification exercise [15] using multiple codes and simulating the propagation of a highly divergent electron beam in a Cu wire surrounded by a D_2 plasma. The answer to (a) is that the collimating B-field will persist in an ignition pulse even if the resistivity gradients are reversed. This occurs because the collimating field has two components: one generated by the resistivity gradients and the other by the return current gradients. Initially, the collimating B-fields are generated by the resistivity gradients. The resulting collimation causes large current density gradients that enhance the collimating fields. The current density gradients offset the effects of the reversal of the resistivity gradients thus supporting a large saturated collimating B-field.

The second question was not addressed at the meeting but it was noted that it may be difficult to maintain a clean high-resistivity path to the dense core at the time of peak compression in an imploding capsule.

Two action items on the subject of resistivity gradients were identified:

(a) Hydro simulations of cone-in-shell target implosions with a Cu-wire are needed. One can start with a simple 1D simulation of a capsule imploding on a tiny copper sphere to determine the compressed copper-wire conditions. These simple 1D simulations should identify the Cu-plasma properties at the multi-Gbar pressures typical of ICF implosions. [Tasks for K. Anderson (LLE), P. Amendt (LLNL)]

(b) Design the cone-in-shell target implosion (without Cu wire) to assemble a high resistivity channel without Cu wire. This idea was proposed by J. Honrubia (UPM) in [16].

During the afternoon of the second day, the discussion focused on the fundamental physics at the root of the electron divergence problem. There are still outstanding questions with regard to the physics mechanism causing the electron divergence and the laser absorption. The belief is that the laser absorption also creates light filaments which in turn create narrow channels for hot electrons via relativistic LPI and their associated return currents and inevitable rippling of the plasma. The filamentary structure as the cause of the electron divergence is also discussed in Ref. [17]. These current channels cause the spreading or geometric character of the concomitant transport. There are three relevant questions: (1) What is the absorption mechanism into hot electrons and how can the hot electron spectrum be controlled? (2) How can we control the filamentary channels of light and hot electrons and their geometry? (3) How can we make sure that the ultimate current channels that the system settles into after a couple of ps (which must still work for another ~10ps), are the kind of channels that we want, i.e. the ones that deliver a large fraction of energy in hot electrons in the 1 MeV range (and not 7 MeV for instance)?

R. Evans (Imperial) and B. Afeyan (Polymath) proposed to investigate the use of multiple resonance points created in the plasma simultaneously (or thereabouts) which means the incoming light should be a superposition of discrete lines separated by significant fractions so as to make the various resonance points close enough to interfere with each others' behavior in terms of momentum, density perturbations, channel interconnection, B field re-accommodation, but not so close that two points look like one with twice the energy. Two laser lines (or N laser lines) drive must make the behavior of the plasma driven by only one laser at either of the two frequencies at twice the energy (or N times the energy, for any N>1) much different or else the spacings are wrong. This can be estimated on general grounds or based on specific electron acceleration processes/wave breaking/relativistic, warm plasma, etc., or from collective effects such as resonance absorption like plasma surface interaction, ponderomotive denting of the plasma, and their scaling. .

CONCLUSIONS

With regard to the relevant questions on page 1, the experimental and/or theoretical evidence presented at the meeting lead to the following conclusions:

- **What is and what causes the divergence of the electron source? About 100^o full angle (from experiments and simulations). The divergence is likely caused by the multiple narrow channels created by the light filaments observed in the simulations. A more fundamental understanding is required.**
- **What is the divergence of the source for a 100kJ pulse? The divergence reaches a steady state after a few ps (from Kemp's simulations). There is no measurement confirming this prediction.**
- **Is there experimental evidence for self-generated collimating resistive magnetic fields? The CTR emission experiments of Storm can be explained with a divergence of 100^o together with collimating B-fields of ~ 10MG (from LSP simulations of Solodov). Experiments by P. Norreys et al (not presented at this meeting) seem to confirm the generation of collimating fields. There are no direct measurements of the fields.**

- **Are these magnetic fields generated at the beginning of the pulse and then frozen into the plasma?** **This is observed in the simulations with LSP by Solodov and PICLS by Sentoku. There are no direct measurements confirming this prediction.**

- **Do B-fields generated by resistivity gradients survive at ignition scale energy?** **Yes. The current density gradients offset the effects of the reversal of the resistivity gradients thus supporting large saturated collimating B-fields.**

- **Are self-generated fields enough to improve the collimation or new ideas - like external B-fields - are needed?** **The self generated field from the resistivity gradients may be sufficient to improve the collimation in ignition scale targets. However, serious questions remain about the feasibility of such a scheme in ignition-scale imploding targets. Hydrodynamic simulations of cone-in-shell target with Cu-wire should clarify this point. New ideas concerning innovative target designs to generate high resistivity path (without wires) to the dense core should be explored**.

- **What is a possible path forward?** **While there is significant evidence (both theory and experimental) that the electron divergence is large (about 100^0), there are still doubts about the accuracy of the measurements. A well diagnosed experiment should be designed and fielded to accurately measure the divergence. Such an experiment should minimize both the electron refluxing and the effect of the low energy portion of the electron spectrum (if a Cu K-α diagnostic is used).**

It should be noted that in addition to the large divergence, another major detrimental factor is the high electron temperature (several MeVs). High energy electrons would propagate through the dense core without depositing their energy (unless some form of anomalous stopping is present). Strozzi's LSP simulations [12] of an ignition target use a dense core in close proximity of the electron source thus minimizing the detrimental effects of electron divergence. These simulations show that the ignition e-beam energy required for ignition is hundreds of kJs. The electron temperature can be reduced by using green light (instead of red). But even with green light, the e-beam energy required for ignition is about 185kJ thus requiring a PW laser of 400-500kJ. This represents a very serious issue that needs further investigation.

ACKNOWLEDGMENTS

Thanks to B. Afeyan, D. Strozzi, C. Ren and J. Honrubia for reviewing this document and providing input.

REFERENCES

[1] A. Kemp, FSC Meeting, presentation available at http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

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[3] M. Storm, A. Solodov et al, Phys. Rev. Lett. 102, 235004 (2009)

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[5] J. Honrubia et al, Plasma Phys. Cont. Fus. 51, 014008 (2009)

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[8] L. Van Woerkom, FSC Meeting, presentation available at http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

[9] C. Chen, FSC Meeting, presentation available at http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

[10] R. Stephens, FSC Meeting, presentation available at http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

[11] F. Beg, private communications

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[12] D. Strozzi, FSC Meeting, presentation available at
http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

[13] A. Robinson, FSC Meeting, presentation available at
http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

[14] P. Norreys, presentation at the OMEGA Laser User Facility Group workshop April 28-30, 2010, Rochester NY

[15] A. Solodov, Report on Code Verification Session, FSC Meeting, to appear on the FSC web site (in preparation)

[16] J. Honrubia, FSC Meeting, presentation available at
http://fsc.lle.rochester.edu/meetings/livermore2010/livermore2010.php

[17] A. Debayle, J. J. Honrubia, E. d' Humieres, and V. T. Tikhonchuk, “Divergence of laser-driven relativistic electron beams,” Phys. Rev. E (in press)

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APPENDIX A

MEETING AGENDA

9th ANNUAL MEETING FUSION SCIENCE CENTER FOR EXTREME STATES OF

SPECIAL MEETING ON ELECTRON DIVERGENCE

Lawrence Livermore National Laboratory
B481 R2005

AUGUST 5

8:45	Welcome	D. Correll/C. Keane (LLNL)
8:50	Goals of the Meeting	R. Betti (LLE)
	Invited Talks:	
9:00	Review of the Measurements on Fast Electron Divergence	M. Storm (OSU)
9:45	Review of PIC Simulations of Electron Divergence in Fast Ignition	A. Kemp (LLNL)
10:15	Break	
10:25	The Effects of Electron Divergence on the Point Design	D. Strozzi
10:50	Effects of Electron Divergence on Minimum Energy required for Ignition	J. Honrubia (UPM)
11:30	NIF Tour – Group A (1/2 the group)	
12:30	NIF Tour – Group B (1/2 the group)	
11:30-1:30	One Hour Lunch when not touring NIF	
1:30	Update on the National Ignition Campaign	B. MacGowan (LLNL)
2:10	Electron Collimation by Resistivity Gradients	A. Robinson (RAL)
2:35	The Effects of Self-generated Magnetic Fields	A. Solodov (LLE)

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2:45	Preliminary Results on Recent Titan Experiments on Electron Divergence	L. Van Woerkom (OSU)
3:05-6:00	**Discussion**	

AUGUST 6

8:45	Session on Code Verification Goals of the Session	A. Solodov (LLE)
	Results from the Test Problems and Discussion	
9:00	LLE Results on the Test Problems	
9:20	LLNL Results on the Test Problems	
9:40	UCSD/UNR Results on the Test Problems	
10:00	Break	
10:15	TBC – UCLA Results on the Test Problems	
10:35	OSU Results on the Test Problems	
10:55	Others?	
11:15	**Discussion** Moderators: Solodov (asol@lle.rochester.edu) and Strozzi (strozzi2@**llnl.gov)**	
12:15	Lunch	
1:30-4:00	**Discussion**	
4:00	Summary of the Meeting	R. Betti (LLE)
4:30	Adjourn	

List of registered attendees

Akli, Kramer

Anderson, Kenneth

Bartal, Teresa

Beg, Farhat

Bellei, Claudio

Betti, Riccardo

Chen, Cliff

Chrisman, Brian

Cohen, Bruce

Correll, Donald

Evans, Roger

Fiuza, Frederico

Freeman, Richard

Higginson, Drew

Ho, Darwin

Hohenberger, Matthias

Honrubia, Javier

Jozaki, Tomoyuki

Kemp, Andreas

Kemp, Gregory

King, Frank

Krygier, Andrew

Larson, David

Lasinski, Barbara

Li, Chikang

Link, Anthony

Ma, Tammy

May, Joshua

McLean, Harry

Meeker, Donald
Meyerhofer, David
Mori, Warren
Morrison, John
Nilson, Philip
Ovchinnikov, Vladimir
Paradjar, Bhooshan
Patel, Pravesh
Perkins, John
Poole, Patrick
Ren, Chuang
Ridgers, Christopher
Robinson, Alexander
Sawada, Hiroshi
Schumacher, Douglass
Sentoku, Yasuhiko
Shay, Henry
Solodov, Andrey
Stephens, Richard
Storm, Michael
Strozzi, David
Theobald, Wolfgang
Tonge, John
Van Woerkom, Linn
Wertephy, Douglass
Willis, Christopher
Yabuuchi, Toshinori