Physics
UNIVERSITY OF TORONTO

RAPPORT SUR LES TRAVAUX DE
Madame Maïmouna BOCOUM

EN VUE DE LA SOUTENANCE
D'UNE THESE DE DOCTORAT DEVANT
L'Ecole Doctorale
Ecole Polytechnique, Université de Paris-Saclay
Laboratoire d'Optique Appliquée, ENSTA-ParisTech, Palaiseau

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Le mémoire présenté par Madame Maïmouna BOCOUM est intitulé **«High-Order Harmonics and Electron Beams from Plasma Mirrors»**, écrit en anglais.

This dissertation presents an original and significant research contribution in an area of strong interest of physics, at the intersection of extreme nonlinear optics, relativistic laser-plasma physics and frontier ultrafast laser development. The thesis of this work is that there are strong connections between the relativistic laser-plasma physics which drives currents resulting in high-harmonic radiation from solid-density plasmas and the control of those currents to become streams of relativistic electrons released from the interaction zone. In my opinion the research has been conducted at a high level, and clearly establishes several important principles and relationships between fine optical control, harmonic generation from electrons driven inward, and fast electrons driven outward. The work has already generated four very-high-quality peer-reviewed publications in premier journals, two of them first-authored by the candidate — this represents broad acceptance and a high endorsement of the research by the community of active researchers, as normally expected of PhD research.

The dissertation is laid out in sections consisting of:

First, a very general introduction to the field, with a presentation of essential background theory.

Second, a detailed presentation of the sophisticated laser system which is the basis of almost all the research presented. This revolves around the 'Salle Noire' laser at LOA, a state-of-the-art carrier-envelope stabilized high-repetition-rate laser system to which Ms Bocoum has made significant contributions in development and running.

Third, experimental results in four groupings: foundation theory and experiments on HHG and attosecond pulses; foundation theory and experiments on the new method of Spatial Domain Interferometry; foundation theory on electron acceleration from laser

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plasmas and experiments in the relationship between such acceleration and the production of high harmonics; lastly, effects of electron acceleration in strong fields in vacuum.

The first, background section overall is adequately presented. The context of energetic particle and photon production are sketched, and some basic plasma physics context is given. The history of laser-plasma physics is laid out, and the history of intense ultrafast pulses is reviewed. Production of high harmonics is described from history, and energetic particle production too. This section has some minor weaknesses which can be easily addressed: parts of the history are presented inconsistently. For instance, the generally accepted definition of a plasma is not merely an ionized material, but one which meets the conditions for *collective behaviour*, such as electron plasma waves. In another, it's noted that Dawson proposed laser-driven fusion using Terawatt lasers, and that precisely such lasers were produced in the 1970s; Dawson actually proposed powers two orders of magnitude smaller, and the LLNL laser referred to actually generated gigawatt peak power. Modelocking of Ti:sapphire lasers was not produced in 1980 — Ti:sapphire lasers were demonstrated around 1982, but modelocking around 1989. In the discussion of changes from 10μm lasers to 1μm lasers to visible-light lasers, it would be very constructive to note the the universal scaling parameter $I\lambda^2$, and the role it plays in describing the energy of oscillating electrons; it explains how it was that a great deal of the current physics of the field was known several decades ago, for lasers of much lower intensity. For other corrections, a number of suggestions for this chapter have been noted directly on the PDF document for the dissertation, to be returned to the candidate.

Chapter 2 comes closer to the immediate expertise of the candidate, and describes laser absorption and Landau damping in a plasma. It's correct in this section that early researchers using CO_2 lasers in the 1970s identified the production of hot electrons and the relevant mechanisms, but these researchers (myself included) recognized that fast electrons would greatly disrupt the efficient coupling of energy for driving adiabatic compression — both decoupling the energy from the ablative surface but also pre-heating the interior of the target and shifting it to a less-efficient adiabat. This was long before Tabak's concept of fast ignition, which is the notion behind 'detonation' of the pellet discussed in Chapter 2. The descriptions of resonance absorption and Brunel absorption are good; I would suggest adding to the description of phase-wave acceleration of electrons in the density gradient. This section contains some very beautiful illustrations and descriptions of some complicated and subtle physics, including coherent-wakefield emission, and PIC simulations are elegant. Analytic or qualitative discussion of the nature of Landau damping would be an improvement, where there's currently dependence on PIC simulations — essentially numerical experiments, from which it is sometimes difficult to extract understanding of relationships.

Chapter 3 begins descriptions of work that exemplifies the candidate's actual direct mastery in the field. Figures, technical descriptions, and characterization of the laser and its many dependencies are authoritative and substantial. The analysis of pre-pulse production from nonlinear conversion of post-pulses is clear and detailed. It might be

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helpful to make the historical connection that before it was found in CPA laser amplification, it had been seen in saturated amplification of radio signals as well — a little like the way that the CPA technique used in lasers was shown first in the production of intense and precise radar. The level of simulation of laser effects in this section is impressive and is very well connected to hands-on improvements made to the laser once they are understood. This chapter begins to demonstrate the enormous level of detail which must be brought under control by the experimental team, before any experiments described could ever have been as successful as they have been shown.

Chapter 4 describes the physics of CWE, with expert analysis. The intuitive descriptions are very good. There is, in the field, some problem still with the notion of ascribing a time of emission to individual harmonics, since harmonics themselves are a phenomenon only as the result of periodic repetition of attosecond pulses at the laser frequency, and each attosecond pulse simply has a continuum of emission. Joint time-frequency analysis is a field which is pretty well developed, and misapplication has been fraught with error in the past, leading for instance to some notable misapprehensions in topics like faster-than light communication. In my opinion, the descriptions would benefit from a little more time taken carefully to outline the concepts used here informally, like time-of-emission of individual harmonics, and such as the measure of 'instantaneous periodicity' in terms of group and phase delay in more formal analysis. That said, the physics descriptions appear correct and comprehensive, and include some pretty sophisticated and far-ranging considerations. The attosecond chirp experiment concerns manipulation of the spatial chirp at beam focus — the experimental concept, the analytical description and the WFR characterization are all well-done and intriguing, with the comparison of modelling and experiment very satisfying. That said, I found the description given of why the 0° wedge case of experimental data is so spectrally broad (Fig. 4.19) only cursory, and the issues involved not clearly resolved. To say it indicates the femtosecond chirp was undervalued in the model seemed odd — perhaps it meant as stated that the model did not consider the femtosecond chirp sufficiently, or perhaps it was meant to say that the value of femtosecond chirp used was too small. But this doesn't seem obviously to fit with the experimental 70° image. Perhaps this can be better-explained.

Chapter 5 brings a very interesting and attractive approach to measuring the density gradient. The material surrounding the inversion problem and phase retrieval is pretty thorough and informative. The section included an intelligent discussion of how to give up redundancies in the regular symmetric positioning of probes, because symmetric disposal gives no additional information, and instead using asymmetric positioning to give much more useful information for uniqueness in inversion. These is a useful and important advance, and I'll watch attentively for reports of the experimental deployment.

Chapter 6 makes a review of the mechanisms of electron acceleration in laser-plasma interaction. In the case of resonance absorption an oversimplification has perhaps been made, asserting that acceleration comes from the normal component of the electric field at critical; more generally, the work of Albritton quoted in Ref. 74 I recall as saying that a phase wave appears in the density gradient around critical, owing to the natural de-

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phasing of local plasma waves — this phase wave is capable of trapping and accelerating the right part of the warm tail of the electron distribution, a bit like a surfer catching a wave by paddling. This phenomenon is not much present for ultrafast plasmas, but owing to the conceptual connection with CWE in the region above critical, it's useful physics to draw out at this point of the dissertation. The most critical physics of this work follows, bringing all subjects together to discuss the production of HHG *vis à vis* electron acceleration. As pointed out in the analysis of Brunel absorption, the phase relationship of electrons emitted from the plasma, like that of electron 'birth' in the Corkum model of HHG in atoms, controls the behaviour of electrons — moving inwards and generating CWE, or outwards to be swept up in net plasma + laser fields. Here, relativistic effects around space-charge or reflection lead to an unbalanced E-field appearing as a B-field to the relativistic electrons. The gyromagnetic effect results in a phase-delay of electrons relative to the laser field, and this can steer the electrons' fate, the competition then resulting in anticorrelation. The model, the experiments, and their analysis are all difficult and detailed, and here Ms Bocoum makes important and impressive contributions to understanding in the field. In the end, there are enough experimental results and enough analysis remaining to support at least a MSc dissertation in addition to meeting the requirements of the PhD.

Finally, Chapter 7 brings analysis of electron acceleration outside of the critical density surface. The description of ponderomotive acceleration is rather nice, and intuitively simple here. PIC-style illustration also gives a helpful illustration of the rise of electron expulsion. In the next section concerning non-ponderomotive acceleration, which depends on a spatial profile of intensity, the discussion surrounds a plane-wave approximation. As such, it would be useful — and academically more sound — to first introduce the Lawson-Woodward theorem, which concludes that a free electron in vacuum cannot gain net energy upon passage of an infinite plane wave. This would give a useful conceptual context from which to discuss the departures that permit acceleration in the real experimental case. In this section there is also a small mis-statement: that the B-field in laser-plasma interaction cannot do work. This is true for static B-fields, where the Lorentz force is perpendicular to the electron velocity, but the dissertation already discusses in an introductory historical section the Betatron accelerator — noting that acceleration there is produced by inductive effects in a rapidly changing B-field created by the primary coil. Since this section discussed JxB, and concerns itself directly with the physics involved in AC gyromagnetic motion, and other dynamic B-field effects are likely, it would be useful to review this part of the description of the relevant physics.

There are multiple minor comments and observations I have noted for correction directly on the PDF copy to return to the candidate (e.g., a number of very small English-language corrections, standard use of XFEL vs. X-FEL, likewise X-UV (a bit old-fashioned) vs. XUV in places, and some simple clarifications required in places).

I note that at UK universities, one goes through all such corrections with the candidate at the viva, sometimes taking over 5 hours; at Toronto, the practice is to identify corrections as those which either require the supervision of an examination sub-committee, or which are so minor they are easily resolved by the candidate and super-

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visor. None of my marked corrections or suggestions are more than minor, so I propose simply to review a marked copy of the dissertation together with the candidate, I hope shortly after the examination, if that's acceptable to the Doctoral School and to the committee.

In summary, and considering the whole dissertation, there is no question in my mind that this is a report which meets all requirements for a PhD, surely at any institution. It demonstrates new and significant science, argues articulately, proves both its theoretical and its experimental theses to a high degree of confidence, and surely will provoke interesting scientific discussions when published, or even at its defense.

In my opinion this dissertation establishes Maïmouna Bocoum as a well-qualified colleague in the field. I expressly recommend its acceptance in fulfillment of the conditions of the doctorate.

Sincerely,

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