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Review of the Doctoral Thesis

"Development of gas targets for laser-driven electron acceleration "
written by Ing. Sebastian Lorenz

In his doctoral thesis Ing. Sebastian Lorenz discusses his researches in the design, development and manufacturing of gas targets for Laser Wakefield Acceleration (LWFA) of electrons. LWFA allows lower the costs of production of ultra-short ultra-relativistic electron beams, enables development of compact secondary sources of ionising radiation having variety of applications in material science, diagnostics and radiotherapy. The gas targets are the core part of the accelerator defining the injection and acceleration processes, and have to be matched to the specific laser beam parameters of interest. In the thesis, the main problems of the targets as gas flow stability, gas load into the vacuum chamber, technological requirements and scalability are evaluated. In the simulation of the spatial distribution of gas density, both Computational Fluid Dynamics (CFD) and Direct Simulation Monte-Carlo (DSMC) methods for rarefied gas are used. Advanced interferometric methods and 3D tomographic reconstruction algorithms were implemented for the experimental characterisation of the target prototypes. To increase the sensitivity of the diagnostics, a novel 4-pass interferometry, and Filtered Algebraic Reconstruction Method (FARM) algorithm were developed. In the experimental part of the thesis, the ultra-fast optical probe diagnostics implementing Compression after Compressor Approach (CafCA) was investigated. During an experiment with the J-KAREN-P laser, the improved the probe-to-self-emission intensity ratio and imaging of plasma microstructures with the compressed probe pulse of 18 fs was achieved. The developed gas targets were tested on the commissioning experiments of ALFA and ELBA of ELI-Beamlines.

The doctoral thesis written in English consists of six chapters in 102 pages. The first chapter is focuses on the physics of LWFA acceleration, second one describes the state-of-the-art technology used for building the gas target for electron acceleration, the third chapter discusses the methods of target development. In fourth chapter, the laser-plasma interaction experiments with ultra-fast optical probe diagnostics are presented, the fifth chapter introduces particular LWFA gas targets developed, and, in the last chapter, the results of recent commissioning experiments of two LWFA beamlines accommodated in ELI-Beamlines are discussed. Finally, the full gas target development process and the implementation are summarized. The thesis contains 105 references, the author has published three papers as a first author and two papers as a co-author in reviewed journals, and contributed to two conference proceedings.

The thesis comprises the research and development of gas targets implemented in two main classes of present lasers – kHz class lasers with pulse energy of tens to hundreds of millijoules and multi-joules Petawatt class lasers with substantially longer acceleration distance and higher challenges of gas load. The presented simulation and design methods of gas targets are of high practical value and present significant interest for laser accelerator community.

I have the following comments and questions for the author to discuss:

The major questions the Candidate may like to address are:

1. Comment: In DSMC simulations, quite a small nozzle with a 100 μm slit length, 30 μm exhaust width, and throat diameter of 10 μm was evaluated. How the simulation of this nozzle can be upscaled to the real experimental dimensions? Is there any specific type of boundaries you mentioned (e.g., specular surfaces, thermal walls, fluxing reservoirs) that could be applied for the estimation of the impact of wall roughness? (p.30 – 31).
2. Comment: What is the actual spatial resolution of the designed four-pass setup for interferometric gas target measurement and FARM algorithm? Is the resolution of 100 px ×13.2 μm = 1.32 mm enough for the reproducing of the shock wave thickness of the gas with concentration of ~ $10^{19}cm^{-3}$? (p. 14, p. 42)
3. Comment: How the maximal allowed average roughness depends on the dimensions of nozzle profile? What is the minimal dimensions of the nozzle for the R_a < 1.5 μm indicated in the thesis (R_a defined in ISO 4287:1997 standard) (p. 56) ?
4. Comment: What is the maximal intensity, f/d ratio and quality of the laser beam for the successful operation of the proposed design of the Dual-stage target for reduced gas load (p. 63) ?
5. Comment: In the description of ALPHA and ELBA experiments only the laser pulse energy and power inside the interaction chamber is mentioned. What was the laser intensity and corresponding laser strength parameter a_0 on the target? The actual laser intensity on the target is an essential parameter in the design of the nozzles (p. 66-74) ?
6. Comment: Could you estimate the percentage of laser beam energy and fluence at the nozzle frame of the beam caused by the second-order focal spots ? Is the nozzle affected only by the increased temperature or also by plasma ablation effects? (p. 79) ?
7. Comment: Author could consider to include into the conclusions of the process of development of gas targets the importance of resistance of the nozzle materials, allowed fluence, focusing angle and quality of the laser beam (p. 80).

Minor remarks:

1. "Motivated by these exceptional results, efforts have focused on translating the electron sources into practical applications." Suggestion: "efforts have been focused" (p.1)
2. Figure 1.1. The distribution of the background electrons is a bit misleading. Actually, the electrons are pushed out by ponderomotive force of the centre forming an ion cavity (p.3).
3. The blowout regime is usually discussed at higher laser beam intensities than bubble regime, for example: S. Gordienko et al. http://dx.doi.org/10.1063/1.1884126 . You write: "The bubble regime describes a singular non-linear wake driven by laser pulse with $a_0 \geq 2\omega_0/\omega_p$. The blowout regime then describes a periodic non-linear wake driven by a laser pulse with $2 \leq a_0 \leq 2\omega_0/\omega_p$ (p.8)
4. It is worth to mention why the gas propagates at supersonic speed in the vacuum in the case of subsonic nozzle. "The gas reaches $M_a = 1$ at the exit of the nozzle and then it propagates at supersonic speed inside the vacuum chamber". (p.15)
5. "The plasma channel is composed of fully ionized gas (usually hydrogen), thus the laser does not suffer from why the laser does not suffer from de-focusing". Actually, the

reason of beam propagation is the formation of the parabolic concentration profile leading to the waveguiding of the beam. (p. 17).

6. ISO 4287:1997 standard was replaced by ISO 21920-2:2021 Geometrical product specifications (GPS) standard (p. 56).

Summarizing all said above, it is to conclude, that the drawbacks outlined by the reviewer do not diminish the importance of the performed work. Doctoral thesis "Development of gas targets for laser-driven electron acceleration" written by Ing. Sebastian Lorenz complies with the requirements of the Doctoral thesis and I recommend to the committee accept this thesis.

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