TOWARDS INTEGRATED DIAGNOSTICS FOR MULTI-STAGE DIELECTRIC LASER ACCELERATION: A CONCEPTUAL STUDY

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Abstract

Dielectric laser acceleration (DLA) enables compact, chip-scale accelerators. Recent demonstrations of multi-stage acceleration, alternating-phase focusing and interaction length in the millimeter range in dielectric nanostructures have verified the scalability of DLA concepts but the compactness places extreme demands on beam diagnostics due to submicron apertures, sub-fs bunch lengths and strong non-linear dynamics. To support the development of multi-stage structures and precise matching between stages, we explore diagnostic concepts that use the dielectric structures themselves. Tailored gratings can encode beam properties—such as bunch length—into emitted radiation, providing compact, high-resolution, on-chip diagnostics. Additionally to these hardware approaches, we propose to apply a machine-learning–based virtual diagnostic for DLA experiments. A neural network trained on 6D tracking simulations reconstructs key interaction parameters from the post-DLA electron beam and intermediate diagnostics and enables real-time optimization even in strongly non-linear regimes. Combining integrated dielectric diagnostics with ML-based reconstruction provides a scalable strategy for precise characterization and control of next-generation dielectric laser accelerators.

INTRODUCTION

Dielectric laser acceleration (DLA) has emerged as a promising route to compact, chip-scale electron accelerators by exploiting optical near-fields in dielectric nanostructures to reach gradients in the GV/m regime [1–3]. Recent experimental advances have demonstrated beam confinement by alternating-phase focusing, laser pulse shaping, and interaction lengths in the millimeter range, confirming the scalability of DLA concepts beyond single-stage proof-of-principle experiments [4–6]. However, the extreme compactness and submicron apertures of DLA structures impose stringent demands on the electron beam, including sub-femtosecond bunch durations, submicron-level transverse beam sizes, and tight tolerances on arrival time and phase stability [7, 8].

In this regime, conventional accelerator diagnostics, such as transverse deflecting cavities [9] or bunch compressor monitors [10] to measure the bunch length, reach their limits. Direct access to the interaction region is restricted by nanometer-scale vacuum gaps, and inserting invasive diagnostics between closely spaced stages risks disrupting the beam or breaking the compact integration that makes DLA attractive. Moreover, the strong non-linear dynamics in the optical near-field coupling and in the mapping from interaction region to downstream spectrometers complicate straightforward reconstruction of beam and laser parameters. To support the development of multi-stage DLAs and precise matching between stages, there is a need for diagnostics that are both integrated into the dielectric structures and capable of resolving the ultrafast, non-linear beam dynamics.

This contribution outlines a strategy “towards integrated diagnostics for multi-stage dielectric laser acceleration” by combining two complementary approaches. First, tailored dielectric structures are used as compact sources of radiation in the THz to optical range, encoding beam properties such as bunch length or arrival time into the emitted spectrum and angular distribution. Second, a machine-learning–based virtual diagnostic, previously developed for laser pulse shape reconstruction [11], is extended conceptually to multi-stage configurations and electron beam diagnostics, using a digital twin of the interaction to reconstruct key parameters from the post-DLA electron beam. Together, these approaches provide a scalable path towards precise, on-chip characterization and control of future multi-stage DLA setups.

DIAGNOSTIC REQUIREMENTS

Multi-stage DLA structures impose tight constraints on both beam quality and diagnostics. Submicron vacuum channels and high-gradient optical modes require transverse beam sizes well below the aperture in the submicron to few-micron range and trajectory alignment at the tens-of-nanometers level to avoid beam scraping and to maintain high transmission. At the same time, efficient energy gain over many optical periods demands synchronization between the laser field and the electron beam at the level of a small fraction of the optical cycle, corresponding to sub-femtosecond arrival time jitter and tight control of the DLA phase (see Table 1).

Diagnostics must therefore resolve longitudinal properties such as arrival time, phase relative to the drive laser, and bunch length at sub-femtosecond down to tens-of-attoseconds scales, while being compatible with the limited space available between stages. Conventional RF deflecting structures and large spectrometers are difficult to integrate into a chip-scale environment and often require large drift lengths or macroscopic components that break the compactness of DLA-based systems. Furthermore, strong non-linearities in the interaction — arising from the optical near-field, phase slippage, and transverse–longitudinal coupling — mean that simple linear reconstruction methods based on a few projections are insufficient, especially when aiming for single-shot, shot-to-shot–resolved diagnostics in the presence of fluctuations.

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These considerations lead to two key requirements for future DLA diagnostics. First, the measurement principle should be integrable into or directly adjacent to the dielectric structures, minimizing additional hardware and preserving the overall footprint. Second, the diagnostic must either directly encode the relevant ultrafast properties into an accessible observable, such as emitted radiation or energy spectrum, or be coupled to a reconstruction framework that can invert the non-linear response of the system. The concepts discussed in the following sections address these points: THz generation in tailored gratings provides a hardware-embedded observable, while the virtual diagnostic approach uses a machine-learning–assisted inversion of a high-fidelity tracking model.

Table 1: Resolution Requirements

Beam Property	**Range**
Optical cycle (λ = 2-10 μm)	~7-33 fs
Bunch length	~10-100 as
Max timing jitter	~100 as
Aperture / beam size	~1 μm
Transverse alignment	~100 nm
Energy spread	<0.1 %
Bunch charge	~1 fC
Current	~1 nA

VIRTUAL DIAGNOSTICS

The virtual diagnostic concept treats the DLA interaction region together with downstream beamline elements as a non-linear measurement device that maps laser and beam parameters onto the measured electron energy spectrum (cf. Fig. 1). A six-dimensional symplectic tracking code (DLAtrack6D) [12] acts as a digital twin of the experiment, simulating the DLA near-field interaction and transport to the spectrometer for a wide range of input parameters. Synthetic datasets generated by this forward model are then used to train a neural network that approximates the inverse mapping: given a measured spectrum, the network estimates the underlying interaction parameters.

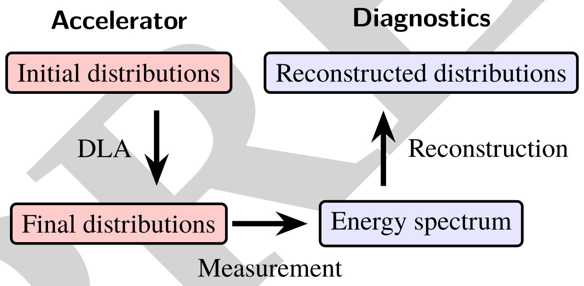

Figure 1: Workflow of the virtual diagnostics.

In the recently submitted study by the authors [11], this approach was applied to a planned DLA experiment at the ARES linac at DESY. The trained network was shown to reconstruct pulse front tilt angles with an accuracy of about 1° and phase offsets with a root-mean-square error of about 0.36 rad, corresponding to an arrival-time precision on the order of 0.4 fs. An example of reconstructed phase offset between laser beam and electron bunch compared to the initial value is shown in Fig. 2. Importantly, training with synthetic spectra that include realistic spectrometer noise improved the robustness of the reconstruction, and the evaluation time of the surrogate model was found to be in the millisecond range, making shot-to-shot parameter estimation compatible with the 50 Hz repetition rate of ARES. This effectively turns the DLA interaction region into a virtual in situ diagnostic for otherwise inaccessible laser–beam parameters. For this conceptual study, the model was also expanded to allow for the reconstruction of electron beam parameters given known laser beam parameters.

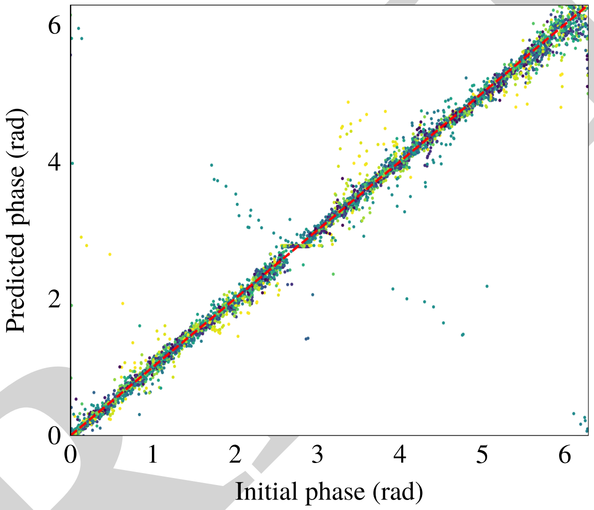

Figure 2: Reconstruction accuracy of phase offset (taken from [11]) between laser beam and electron bunch on independent test datasets (5000 samples).

For multi-stage DLA, the same principle can be extended conceptually by augmenting the digital twin to include multiple stages, intermediate optics, and integrated diagnostics such as compact spectrometers or THz emitters. The neural network can then be trained to infer not only single-stage parameters but also stage-to-stage phase relationships, matching conditions, and cumulative effects such as energy spread growth or emittance dilution. Intermediate measurements can be incorporated as additional inputs to the network, improving identifiability and allowing the model to disentangle correlated parameters. In this way, the virtual diagnostic becomes a flexible reconstruction layer that translates sparse, compact measurements into a high-dimensional description of the multi-stage DLA system.

THZ-BASED DIAGNOSTICS

As a complementary, hardware-based diagnostic, tailored dielectric structures can be used to generate THz radiation from the electron bunch, with the emitted spectrum and angular distribution encoding key beam properties such as bunch length and arrival time. In many accelerator facilities, coherent THz radiation — produced for example by transition radiation [13] or diffraction radiation [14] — has been established as a sensitive probe of ultrashort bunches, where the spectral cutoff or spectral modulation is directly linked to the longitudinal form factor. Translating this principle to DLA involves designing on-chip gratings or dielectric waveguides that couple the transient fields of the passing electron bunch into propagating THz modes, known as coherent Smith-Purcell radiation (SPR) [15] (cf. Fig. 3), that can be extracted to a detector. This is a well-known emission mechanism using periodic metallic gratings [14, 16].

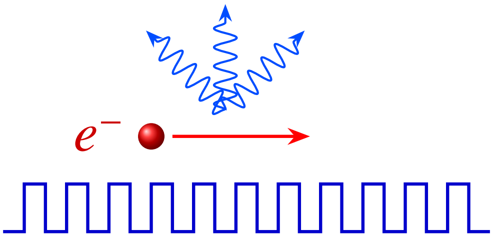

Figure 3: Schematic of Smith-Purcell radiation emitted from an electron passing by a periodic grating.

The compactness of DLA structures offers several opportunities for integration. First, the same lithographic techniques or 3D-printing used to fabricate accelerating gratings can be employed to realize dispersive structures for THz emission [17], enabling tight alignment and repeated patterning along a multi-stage sequence. Second, by varying the period and optimizing the structure or coupling geometry of the THz-generating gratings, the spectral sensitivity of the diagnostic can be tuned to target specific bunch length ranges or to emphasize arrival-time–dependent features [18]. In the context of multi-stage operation, different sections of the DLA chip could host distinct THz emitters, each optimized for a particular energy or phase space region, providing a distributed, stage-resolved view of the beam evolution.

To extract quantitative information, the measured THz signal is compared to simulated spectra from a model that includes both the beam dynamics and the electromagnetic response of the dielectric structures. This can be done either through direct fitting of the form factor or, more powerfully, by embedding the THz emission model into the same digital-twin framework used for the virtual diagnostic. In the first case, the functional dependencies of the analytical model for metallic structures [19] can be applied for evaluation. First studies using the electromagnetic simulation software CST [20] and varying the bunch charge and length have confirmed the validity of these models also for dielectric structures (see Fig. 4). However, adding further parameters to the model — such as the energy width of the bunch, the transverse dimensions, and the distance to the grating — would significantly complicate the model and make it difficult to analyze, if analysis were even possible at all. In the latter case, the THz diagnostics provide an additional observable that constrains the reconstruction of the beam parameters, especially the longitudinal parameters such as bunch length and sub-femtosecond timing jitter, without requiring the complete analytical model of the emission mechanism, invasive diagnostics or macroscopic spectrometers. Such integrated THz diagnostics would thus complement the virtual diagnostic and provide a hardware anchor for the reconstruction in multi-stage configurations.

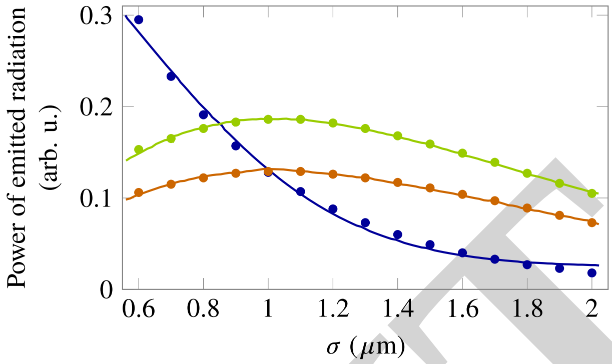

Figure 4: Emitted SPR power as function of the bunch length at a 2 μm grating: the blue curve with fixed bunch charge clearly shows coherent radiation, orange and green curves with constant peak currents. The simulations (dots) follow the analytical fits (lines).

CONCLUSION

Multi-stage dielectric laser accelerators require a new generation of diagnostics that can operate on sub-femtosecond time scales, within submicron apertures, and in the presence of strong non-linear dynamics. This contribution has outlined a conceptual approach towards integrated diagnostics for such systems, combining a machine-learning–based virtual diagnostic with THz-generating dielectric structures that act as compact, on-chip sources of diagnostic radiation. The virtual diagnostic uses a digital twin of the DLA interaction to invert measured energy spectra and reconstruct otherwise inaccessible interaction parameters with femtosecond-level precision, and its underlying framework can naturally be extended to multi-stage configurations.

At the same time, tailored gratings can encode bunch properties into emitted THz radiation, providing a hardware-based observable that is compatible with the tight spatial constraints of DLA and directly sensitive to the bunch length and arrival time. The combination of these approaches offers a scalable path towards precise characterization and control of multi-stage DLAs: integrated dielectric structures supply localized, compact observables, while the virtual diagnostic interprets these signals. Future work will focus on joint optimization of the DLA and diagnostic structures, experimental validation in single- and multi-stage setups, and integration of the reconstruction into real-time feedback loops for beam and laser control.

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