Project Description

Doctoral Program in Accelerator Physics,
Department of Physics, University of Oslo

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Supervisor:
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Co-supervisors:
— Dr. Spencer J. Gessner (Stanford University and SLAC National Accelerator Lab, USA)
— Dr. Jonathan C. Wood (Deutsches Elektronen-Synchrotron DESY, Germany)

1 Main objective and summary

Conventional radio-frequency (RF) particle accelerators are growing large and expensive due to their limited electric field. Plasma-wakefield acceleration (PWFA) have proven capable of sustaining electric fields that are more than 1000 times stronger than the limit in RF accelerators, promising significantly more compact and affordable accelerator facilities. There are, however, several challenges in realizing this technology for high-energy physics applications.

The main objective of this PhD project is to contribute to the design of a high-energy, multistage plasma accelerator for a near-term application; a stepping stone toward the more ambitious high-energy physics facilities such as linear colliders. This means performing research on how we can produce stable high-energy beams with realistic-looking parameters. In order to do so, experimental verification is crucial. During my time as a PhD candidate, I will:

1. Do experimental research at the Stanford Linear Accelerator Center (SLAC) in California, USA, where my supervisor and others in the accelerator group have previously had extended research stays. The experiments aim to measure the effects of transverse instabilities in a plasma-wakefield accelerator, and attempt to mitigate them.

2. Analyse data recently retrieved from a plasma-accelerator facility at DESY in Hamburg, Germany. Here, I will attempt to verify the effects of *ion motion* in the plasma accelerator; this is an important but yet unobserved effect that forms the basis of the instability mitigation. The analysis will be complemented by particle-in-cell (PIC) simulations, performed on the supercomputer LUMI (Finland), in an attempt to reproduce the analysed result.

3. In parallel to the above, work on a conceptual design for an demonstrator facility for a stabile, multistage plasma accelerator that is capable of performing world-leaving experiment in strong-field quantum electrodynamics (SFQED).

The start date was 7 Aug 2024, with a four-year duration (i.e., until 7 Aug 2028), with a 25% teaching load.

2 Project background and scientific basis

Particle accelerators have long been a tool for particle physics, allowing us to probe the structure of the universe through colliding accelerated particles. These particle collisions have gotten more and more energetic through the years, revealing the existence of previously undiscovered particles. The increase in collision energy has required larger, and therefore more expensive, particle accelerators. Plasma-based acceleration has proved to sustain electric fields of more than 100 GV/m [1, 2, 3], several orders of magnitude greater than those in conventional RF accelerators [4, 5]. This means that a plasma-based linear accelerator (linac) can be significantly shorter than one based on RF technology.

Plasma-based accelerators work by injecting a driver into the plasma. This driver expels the plasma electrons transversely, and can be a bunch of charged particles or an intense laser pulse. In the wake of this driver, the ions remain relatively immobile, due to them being several orders of magnitude heavier than electrons. The size of such a wake, or “bubble”, is dependent on the plasma density, but is typically on the order of hundreds of microns. Such a small bubble imposes tight restrictions on e.g. transverse offsets and beam focusing [6], which can be challenging to achieve in practice.

Although PWFA is a promising field of research, plasma-based accelerators currently cannot deliver the high-quality beams required for many applications. In order to realize such an “useful” plasma accelerator, more research and technological maturation is required. To achieve this, we need to build a medium-scale PWFA-based facility, which again requires a scenario where PWFA outperforms conventional accelerators. This is where the SPARTA project (Staging of Plasma Accelerators for Realizing Timely Applications) comes in. SPARTA is a project funded by the European Research Council (ERC), and spearheaded by my supervisor, Carl A. Lindstrøm. The project aims to fill the gap between current PWFA technology and a large-scale plasma-based collider, by developing plasma-based accelerators suitable for use in a SFQED experiment; here the objective is to observe nonlinear effects in the interaction of high-energy electrons and a very strong electromagnetic field such as that of a petawatt laser. This particular application does not have the as challenging beam requirements as a particle collider, but does require a stable and high-energy electron beam: with the necessary advancements, plasma-based accelerators might soon be able to perform this experiment at significantly reduced cost.

3 Personal contributions

My contributions will include work on instabilities, both in the transverse and the longitudinal planes, the effects of ion motion, and driver distribution in a multi-stage PWFA facility. In practice, this means working on experimental data analysis, hands-on experimentation at SLAC and/or DESY, as well as simulations using the start-to-end framework ABEL recently developed by our group. In the end, I aim at making significant contributions to the development of an accelerator suitable for SF-QED experiments.

4 Research questions and scientific challenges

Research question 1: How can we experimentally measure and mitigate transverse instabilities?

Transverse wakefields are generated by the beam itself, where each particle is affected by the ones in front of it. This can create a resonating transverse force on the particles in the back of the bunch, rapidly and drastically reducing the quality of the beam. This resonance can be mitigated by introducing a focusing force that either is different for each particle or non-harmonic; detuning the resonance. This would require: (1) non-linear focusing, i.e. focusing that is not linear in the radius (distance from the transverse center of the bubble); or (2) an induced energy spread—known as BNS damping. Both these methods will also tested as a mitigation mechanism.

This will be investigated as part of the E302 experiment [7] at the FACET-II facility at SLAC.

Research question 2; Can we experimentally confirm the existence of strong ion motion in a plasma-based accelerator?

Ion motion has been experimentally confirmed to occur, but only on longer timescales and not in a way that has significantly affected the accelerating beam. Ion motion induces non-linear focusing, as mentioned above, which can help mitigate transverse instabilities.

Preliminary findings from the FLASHForward experiment have indicated proof of this effect. A recently gathered, complex set of data will be analysed and compared to PIC simulations.

Research question 3; Can self-corrections mechanism in the longitudinal plane correct for the energy spreads and offsets in fully consistent machine?

My supervisor, Carl A. Lindstrøm, has proposed a stabilization mechanism [8], which provides stability in the longitudinal phase space (i.e., stable energy). This new concept is important in the conceptual design of an SFQED machine, and needs to be understood in more detail; while it has been proven to work in simple simulations, does it work in a more complex and detailed setup?

I touched briefly on this topic in my previous work as a Master's student. If time permits, I would also like to numerically investigate if induced BNS damping in earlier stages can be corrected at later stages using the longitudinal self-correction. I showed in my master thesis that longitudinal self-correction automatically loads the trailing bunch in a manner that corrects for energy spread induced by betatron radiation. But is it possible to also correct for previously induced energy spread. This will likely depend on the amount of energy spread that is induced, and will be decided by how much energy spread is actually required in the BNS damping.

Research question 4; How can the drive beams be distributed in a functional and compact manner?

For each accelerator stage, a driver will need to be injected into the plasma, so that it can deposit its energy and subsequently be extracted. These beams must somehow be distributed and adequately delayed in time to be synchronized with the accelerating beam. While this topic has been briefly worked on by others in the past [9], it will be crucial for the conceptual design of an SFQED machine to come up with a detailed design of such a distribution system.

5 Scientific method

The two main methods of my research will be: (1) planning, performing and analysing experiments; and (2) performing PIC simulations.

Experiments (part 1): As mentioned, I will carry on the E302 experiments at SLAC after University of Oslo PhD student Ole Gunnar Finnerud has completed his stay at the facility. There will be an overlap between our stays in order to optimize the flow of information related to the experiment. The goal of the experiment is to measure the amplitude growth of the oscillating particles inside the plasma wake, and then measure the subsequent effect on the overall efficiency of the accelerator [7]. My contribution to the experiment will depend on the progress made at my time of arrival (around February 2025).

Experiments (part 2): In parallel, I will analyse data obtained at the FLASHForward facility at DESY by my supervisor in 2021. I will analyse the data in order to figure out if the beam in question has been affected by non-linear focusing forces. I will also use the measurements to extract the parameters of the beam and use these parameters to run an accurate simulation in HiPACE++ [10] on the LUMI supercomputer. HiPACE++ is a PIC code used to simulate plasma accelerators with high accuracy using GPU-enabled parallelization.

Simulations: Using HiPACE++, I will run accurate simulations with the beam parameters extracted in the data analysis. I will compare the results with and without the effect of ion motion, and compare the results with the experimental data.

In addition to the ion motion data, I will use simplified simulations in the ABEL framework. ABEL is a simplified start-to-end simulation framework designed to research plasma accelerators in a more holistic setting, i.e. with more components (each simulated with its own code). My end goal is to develop a conceptual design of an entire SFQED experimental facility, and this requires a complete and accurate simulation, taking into account the results on transverse instabilities (wrt. beam quality and efficiency) and mitigation, interstages and longitudinal stabilization, and driver injections and extractions.

6 Expected impact

No matter the results of the E302 experiment at SLAC, the impact on our field will be significant. If the results should agree with numerical simulations and current theory, we can proceed with mitigation experiments. If the beam-breakup instability should not occur as we expect, this is also a very interesting results, because it means we have learned something new (this has happened several times before in the field of plasma acceleration).

The impact of the ion-motion data analysis will also be significant, should I be able to demonstrate for the first time the effects of the non-linear focusing, as this was already theorized 20 years ago [11]. Further, should the result of the experimentation disagree with my subsequent simulation, this would also be interesting.

Finally, were I to complete a conceptual design of a SF-QED acceleration facility, this would greatly impact on the PWFA community, as well as the particle-physics community (on the path to a plasma-based collider). More directly, being able to do experiments at several factors higher than the Schwinger limit [12] is of great interest to the high-energy-density community.

7 Ethics

There are no direct ethical concerns related to this PhD project. There are no biological, no nuclear experimentation/research (beyond some generating short-lived radiation in the particle accelerators; an issue that is already tightly controlled and monitored at the respective accelerator labs), nor does it contain any psychological elements. No part of the project takes place in a third country, nor are there dangers of misuse of the research results.

8 Project timeline

Fall 2024:

1. Courses (20–25 ECTS): MAT-MEK9270 (10 ECTS) and FYS9110 (10 ECTS). Attending CERN Accelerator School in Advanced Accelerators (potentially 5 ECTS).
2. Starting experimental data analysis (ion motion).
3. Teaching (50% load).

Spring 2025:

1. Extended SLAC stay, USA (continue E302 experiment).
2. No teaching.

Fall 2025:

1. Finish data analysis (ion motion), start work on publication (Paper #1).
2. Start data analysis (SLAC), joining beam times at SLAC.

3. Courses: MNSES (5 ECTS).
4. Teaching (50% load).

Spring 2026:

1. Extended SLAC stay/beam times.
2. Start SFQED machine conceptual design.
3. No teaching

Fall 2026:

1. Continue SLAC data analysis, start work on publication (Paper #2).
2. Continue SFQED machine conceptual design
3. Teaching (25–50%).

Spring 2027:

1. Finish SLAC data analysis and publication (Paper #2).
2. Finish SFQED machine conceptual design, start work on publication (Paper #3).
3. Teaching (25–50%).

Fall 2027:

1. Finish SFQED publication (Paper #3)
2. Finish other papers/contingency.
3. Start writing thesis.
4. Teaching (25%).

Spring 2028:

1. Thesis writing.
2. No teaching (contingency 25% load).

9 Project organisation and cooperation

The PhD project is part of the ERC funded project SPARTA (Grant Number 101116161) "Staging of Plasma Accelerators for Realizing Timely Applications." The team consists of the me, the PhD candidate, a post-doc, master students, and the PI, Carl A. Lindstrøm. In addition, two additional post-docs will be hired on the project at a later stage. This team is embedded as part of the larger accelerator group at the Department of Physics. Dr. Lindstrøm will be my main supervisor, while the co-supervisors will be Spencer J. Gessner at Stanford University and SLAC National Accelerator Lab, and Jonathan C. Wood at DESY.

10 Cooperation with external parties

I will have two stays at SLAC, at six months each. The research stay is funded by the ERC prjoect and the candiate is hosted by his co-supervisor, Spencer J. Gessner. I will also cooperate with DESY on matters of the ion motion data.

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Signatures

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