**Template for PhD project description**

**1. Project title.**

Instabilities and efficiencies in a beam-driven plasma wakefield accelerators.

**2. Main objective and summary of the project**. The beam-plasma hosing instability [1, 2, 3], similar to the transverse "beam-breakup instability" found in RF linacs, is seeded by transverse beam or plasma asymmetries, and is considered a major potential impediment for realising a plasma wakefield accelerator (PWFA) collider [19, 4, 5, 6]. Can high-gradient acceleration with high efficiency and good beam quality be achieved for a realistic machine, as opposed to a perfectly aligned machine? How strong transverse instabilities are, how well they can be mitigated, and the corresponding efficiency and tolerances are considered by the accelerator community to be paramount for answering whether a plasma collider is practically realisable [4, 5, 6].

The main objective of the PhD project is to understand and model transverse instabilities for beam driven plasma wakefield acceleration of electrons. The relation between instability and power efficiency have been much discussed recently. The project will aim to investigate if there are fundamental limitations to the power efficiency in PWFA’s due to the transverse beam break up instability in the accelerated beam. This PhD project aims to answer this question with a combination of theory, numerical simulations, and experiment.

**3. Project background and scientific basis**.

Propagating a beam of charged particle through a plasma source or shining a high-power laser on a plasma source disperses the charged particles in the plasma from the longitudinal axis of the beam via the coulomb force for the former and the pondermotive force for the latter. The plasma electrons are dispersed at a faster rate than the ions because of their much smaller mass. This creates an ion structure around the longitudinal axis often called a ‘bubble’, which attracts the dispersed electrons back to the beam axis. As the beam or laser propagates through the plasma several bubbles are formed with a high ion density on the beam axis which produces a strong electric field referred to as the ‘wakefield’. By inserting a beam of charged particles into this wakefield, one can accelerate particles with orders of magnitude larger accelerating gradient than in traditional accelerators. This project will focus on beam-driven plasma wakefield accelerators, where the initial wakefield is produced from a beam of charged particles propagating through the plasma source and will be referred to in this document as (PWFA’s). These accelerators have been shown to produce accelerating fields of the order of 10 GV/m [7]. This is several orders of magnitude higher than in traditional accelerators using radiofrequency cavities which have upper limits of around 100 MV/m due to electrical breakdown of the medium. Because of the high accelerating fields PWFA’s have the potential to act as cost-effective and compact colliders in experimental physics [19], as well as accelerators that can be applied to fields such as medicine in radiotherapy and material science as free-electron-lasers. The PWFA scheme has been shown to accelerate a significant amount of charge with high efficiency, low energy spread and an accelerating gradient of 4.4 GeV/m [8].

One of the major challenges in realizing this technology is maintaining good beam quality, as the accelerated particles traverse the beamline. The beam-breakup instability in plasma wakefield accelerators is a transverse instability that is produced from the wakefields of the accelerated particles. The particles in the accelerated bunch will produce transverse wakefields which depend on their offset from the longitudinal axis. The particles situated behind will then produce a wakefield which has a contribution from the leading particle [9]. This wakefield may exhibit resonance behaviour and its amplitude grows without bound which leads to the particles in the tail of the beam diverging from the longitudinal axis. This is a major issue because a stable beam with a compact beam size is required for most applications. Studies show that the size of this instability is related to the power transfer efficiency to the accelerated beam from the wakefield [6]. This relation means that more energy extracted from the wakefield to the accelerated beam produces more instabilities. Because of this relation, maintaining a high efficiency while reducing instabilities is a major obstacle when developing PWFA’s. Hence, it is essential to analyze this relation, develop methods that can be used to circumvent it. An example of a method that will be described more in detail below is operating the accelerator in different regimes which are described by how many electrons are repelled from the plasma. Analytical experiments have indicated that the efficiency-instability relation may not hold in certain regimes.

**4. Research questions and scientific challenges.**

If the efficiency-instability relation holds in all scenarios, there will be a fundamental limit to the efficiency that can be achieved in an ideal accelerator. This is a major challenge in the field as sufficient efficiency is necessary for the advantages of PWFA’s such as very high accelerating field and low construction cost.

**Research question 1.**

Can we inhibit transverse instabilities while maintaining sufficient efficiencies by operating in the quasi-linear regime? The instability-efficiency relation is derived while assuming acceleration is operated in the blow-out regime where the incident beam repels all the plasma electrons away and forms an ion bubble. The beam-breakup instability in the accelerated bunch has also been analyzed theoretically in the quasi-linear regime where only a fraction of the plasma electrons is repelled. In this regime the instability was shown to saturate at a much smaller level than previously predicted [10]. This saturation originates from a naturally occurring head-to-tail betatron frequency spread which mitigates the instability [10, 11, 12]. This is not viable in the blowout regime as the wakefield’s focusing force does not depend on the longitudinal axis. However, in the quasi-linear regime the focusing force varies as a function of the axis which naturally introduces a spread in the betatron frequency [10]. This was demonstrated in particle-in-cell simulations (PIC) carried out in the quasi-linear regime where the instability quickly saturated. We will examine if this is what we see in practice while operating a PWFA in the quasi-linear regime at the E302 experiment at FACET-II.

**Research question 2.**

Can we inhibit transverse instabilities with appropriate amounts of ion motion and initial beam distribution shaping? When the density of the incoming particle beams in the accelerator is much larger than the density of the plasma the coulomb forces repel the ions in the plasma enough to cause significant ion motion which produce focusing fields. Specific beam distributions have been shown to inhibit transverse instabilities in the blowout regime because of the non-linear focusing introduced from moderate ion motion [13]. This was shown analytically and holds for both the blowout and quasi-linear regime. Simulations were carried out in the quasi-linear regime using the PIC framework and were shown to be in good agreement from the analytical results where equilibrium distributions of the initial beam which preserves emittance and inhibits transverse instabilities were found [13]. We want to investigate if this method functions well in a real environment to inhibit transverse instabilities in the quasi-linear regime while maintaining high efficiency. This will be done at the E302 experiment.

**5. Scientific method.** There are two components to the project, one numerical/theoretical, and one experimental:

**Numerical/theoretical:** We will build numerical models to study the "beam-breakup instability” in the accelerated beam in the plasma accelerator, and to quantify the tolerances for accelerating a beam while preserving the beam quality. The numerical model which is called OPAL (optimizing plasma accelerators) was created by the particle acceleration group at UiO and will be a start-to-end beam-driven plasma wakefield accelerator built in python. This simulation will have a class system consisting of the various stages and components in a PWFA. I will contribute with design and implementation of concepts relevant to this PhD such as imaging of the accelerated particles and instabilities and efficiencies in beam. The code will be structured in a way to allow for variations in input parameters for the beam and beamline components such that the accelerator can be tuned to model the plasma and accelerated particles under various conditions. An example of this is introducing an initial offset in the beam in either the x or y axis. By doing this we can observe how the wakefield and position of the beam particles are impacted by an initial offset which leads to transverse instabilities as described in Section 3.

We will use established Particle-In-Cell (PIC) code to model the interaction of the particle beam and plasma in the detector which returns a wakefield that we can extract from the code. Additionally, this PIC code called HiPACE++ [14], will be used to test and validate the performance of our model by inserting our propagated beam into the code. We will for example be able to introduce an offset in the initial beam positions and observe if our start-to-end simulation produces the same transverse instabilities as the HiPACE++ code when the offset beam is inserted. We will use our simulation model and HiPACE++ to model the behaviour of the plasma wakefield and phasespace of the accelerated particles when transverse instabilities occur. We will also model how these instabilities relate to the power efficiency for the accelerated particles. Furthermore, this model will be used to obtain the prerequisite knowledge of beam-driven plasma wakefield acceleration, instabilities, and efficiencies before applying this information to run the E302 experiment at SLAC National Accelerator Laboratory in Stanford, California.

2) **Experimental:** to validate the theoretical models of the beam break-up instability, we will study transverse instabilities experimentally at FACET-II [15], a facility built for high energy plasma wakefield research, equipped with high energy (10 GeV), high-quality electron beams, and plasma sources of the scale required for a plasma collider [15]. The Oslo group have prepared for experiments at FACET-II on beam-plasma transverse instability studies [16]. This ensures we have full access to performing experiments. Transverse instabilities and their relation to power efficiency will be studied at the E302 experiment at FACET-II.

FACET-II is an upgrade of the previous facility used for studies on PWFA’s called FACET. The upgrade will have significantly improved beam quality with transverse beam emittances a factor of 10-100 times better [15]. Hence, this upgrade will provide an excellent facility for the study of transverse instabilities. Simulations have been carried out using the PIC code called Quickpic [17,18] that have shown that parameters of FACET-II can be used to significantly mitigate the instability growth in the plasma wakefields. An example of this is the chosen plasma gas which can be varied to employ a variation of ion masses to ensure focusing which inhibits the instabilities. Ideas for circumventing this relation such as non-linear focusing from ion motion [13] and operation in the quasi-linear regime will be investigated [10]. Using a rubidium heat pipe oven to create the plasma, the E302 experiment at FACET-II will have the capability to explore a range of PWFA regimes because of rubidium’s low ionization potential [15]. Hence, the experiment provides an excellent facility to investigate the efficiency-instability relation in the quasi-linear regime

**6. Expected impact.** The description should address the potential impact of your research on

1. your field of science

Maintaining good beam quality is essential for the application of PWFA’s in research and industry such as medical science (e.g., cancer treatment), particle colliders and free-electron lasers, where a stable and predictable beam distribution is needed. The power efficiency is essential for reaching high energies and producing accelerators in a cost-effective way.

1. Methodology

We will develop a complete start-to-end simulation of a beam-driven plasma wakefield accelerator, something which has not been done before. This may potentially be beneficial to the methodology used in the PWFA community.

1. environment

N/A

1. society

Developing PWFA’s such that they can be used in industry and research can provide immense benefit for society in several areas such as medicine, material science and particle physics research. Traditional particle accelerators are currently in use in these areas. Development of PWFA’s will provide accelerators that can probe new energies and reduce costs significantly such that they can be more widely used and potentially solve challenges currently faced in these fields.

**7. Ethics.** N/A

**8. Project timeline.** The project timeline will be used in connection with the third semester evaluation and must include verifiable milestones. Outline a research plan for EACH semester including (for example)

Spring 2023 (started end of December):

- MNSES9100 – Science, Ethics and Society, 5 credits

- FYS 9565 – Physics and Applications of Accelerators and Beams, 10 credits

- FYS 9620 – An Introduction to Plasma Physics, 10 credits

- STK9900 – Statistical Methods and Applications, 10 credits

- Build a simulation of an electron-driven PWFA with the FACET-II tracking lattice in Python.

- Learning about the experimental analysis required for operation of the E302 experiment.

Autumn 2023:

- Travel to SLAC and get introduced to the ongoing experiments relevant to the PhD

- Participate in relevant PWFA experiments at SLAC.

- Attend the (E)AAC conference and publish proceedings paper on experiment E302.

- Submit Journal publication related to modelling the instability-efficiency relation.

- Plan the E302 experiment on instabilities and efficiencies in an electron driven PWFA at the FACET-II facility.

Spring 2024:

- Start up the E302 experiment.

- Begin the experimental analysis for my project

- Attend 2024 IPAC conference and publish paper related to experimental progress on E302.

Autumn (2024):

- Finalize the E302 experiment.

- Complete most of the experiment analysis

Spring (2025):

- Finish the experimental analysis.

- Publish experimental results in a journal.

- Plan and start thesis.

autumn (2025):

- Attend EAAC conference and publish proceedings paper on E302.

- Writing thesis.

[16]

**11. Literature references.**

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[19] E. Adli. Towards a pwfa linear collider — opportunities and challenges.  
Journal of Instrumentation, 17(05):T05006, May 2022.

1[The guidelines of the National Committee for Research Ethics in Science and Technology](https://www.etikkom.no/en/ethical-guidelines-for-research/guidelines-for-research-ethics-in-science-and-technology/).

2[A guide to Internet Research Ethics](https://www.etikkom.no/en/ethical-guidelines-for-research/ethical-guidelines-for-internet-research/).

3[Data Protection Official for Research](https://eph-uio.uhad.no/ephorte/https:/nsd.no/nsd/english/pvo.html).

4[About the Nagoya Protocol](https://www.cbd.int/abs/about/)..

**Appendix: Checklist of potential ethical concerns for the PhD project**

This list is inspired by the Ethics list that is provided by the European Research Council grant applications. Please go through the list, and if any of the issues raised apply to your project, describe those and the necessary actions under element 7: Ethics in the project description.

1. HUMAN EMBRYOS/FOETUSES

* Does your research involve Human Embryonic Stem Cells (hESCs)?
* Does your research involve the use of human embryos?
* Does your research involve the use of human foetal tissues / cells?

2. HUMANS

* Does your research involve human participants?
* Does your research involve physical interventions on the study participants?

3. HUMAN CELLS / TISSUES

* Does your research involve human cells or tissues (other than from Human Embryos/ Foetuses, i.e. section 1)?

4. PERSONAL DATA

* Does your research involve personal data collection and/or processing?
* Does your research involve further processing of previously collected personal data (secondary use)?

5. ANIMALS

* Does your research involve animals?

6. THIRD COUNTRIES

* In case non-EU/EEC countries are involved, do the research related activities undertaken in these countries raise potential ethics issues?
* Do you plan to use local resources (e.g. animal and/or human tissue samples, genetic material, live animals, human remains, materials of historical value, endangered fauna or flora samples, etc.)?
* Do you plan to import any material - including personal data - from non-EU/EEC countries into the EU/EEC?
* Do you plan to export any material - including personal data - from the EU/EEC to non-EU/EEC countries?
* In case your research involves low and/or lower middle income countries, are any benefits-sharing actions planned?
* Could the situation in the country put the individuals taking part in the research at risk?

7. ENVIRONMENT & HEALTH and SAFETY

* Does your research involve the use of elements that may cause harm to the environment, to animals or plants?
* Does your research deal with endangered fauna and/or flora and/or protected areas?
* Does your research involve the use of elements that may cause harm to humans, including research staff?

8. DUAL USE

* Does your research involve dual-use items in the sense of Regulation 428/2009, or other items for which an authorisation is required?5

9. EXCLUSIVE FOCUS ON CIVIL APPLICATIONS

* Could your research raise concerns regarding the exclusive focus on civil applications?

10. MISUSE

* Does your research have the potential for misuse of research results?

11. OTHER ETHICS ISSUES

* Are there any other ethics issues that should be taken into consideration? If so, please specify in the project description.

5This point concerns research involving goods, software and technologies covered by the EU Export Control Regulation No 482/2009. These dual-use items are normally used for civilian purposes but may have military applications, or may contribute to the proliferation of weapons of mass destruction. Link to EU Export Control Regulation No 482/2009:

<https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1399888895034&uri=CELEX:02009R0428-20120615>.