Tailoring the injected electron beam space charge to minimize the beam loading effect in laser wakefield accelerators.

1 State-of-the-art & motivation

Plasma-wave based accelerators are considered as next generation high-energy charged particle accelerators. The plasma wave is usualy created in the wake of the plasma-travelling laser pulse or particle (electron or proton) bunch. An accelerating longitudinal electric field associated with the plasma wave can reach much larger values (GV/cm) than in conventional radiofrequency accelerators (MV/cm), ~~given by~~ accelerating cavity-wall break-down. Such high accelerating fields imply that the new accelerators can be made more compact, which is in the context of future high-energy particle accelerators - ILC (30 km, 1 TeV) and FCC (100 km, 100 TeV) - an important feature; similar advantages of such compact (also called table-top) accelerators can be also found in other applications such as biology, chemistry, medicine, material sciences, and industry.

1.1 Laser wakefield acceleration in the bubble regime

Nowadays, the most effective way of the laser wakefield accelerator operation rely on the nonlinear plasma wave called bubble.

In order to optimize the performance of such ~~the laser wakefield~~ accelerator, the laser pulse duration is required to match the plasma period.

The efficiency of an LWFA also depends on the detailed shape of the plasma-wave driving laser pulse [1]

1.2 Electron beam injection

A plenty of various injection schemes (self-injection, ionization injection, optical injection) was proposed within the last few decades attempting to generate high-quality electron beams and to reach high energies. All of these schemes can be divided into several groups; dealing with a collection volume of plasma electrons - transversal or longitudinal injection according the position of plasma with respect to laser and plasma-wave axis. The most simple injection scheme is represented by self-injection; although a laser-and-plasma-parameter window of LWFA relatively stable operation was found, the nonlinear nature of self-injection makes the self-injection hardly contollable. Nonetheless, there are attempts to control the self-injection by manipulation of laser pulse temporal shape, in particular by the second and third order dispersion, or plasma parameters (density up-ramp or down-ramp).

~~There are several attempts how to control self-injection as laser pulse temporal profile modification by means of higher-oders of dispersion~~

The underlying physics of the plasma electron bunch injection relies on the plasma electrons dephasing from their fluid motion. To be dephased, plasma electrons have to obtain additional momentum. This can be done either by a space charge at the end of the bubble, by additional laser pulse, or by the density up-ramp or down-ramp (bubble shape evolution). Usually several above mentioned phenomena act together.

Although, many various injection schemes were proposed; none of them led to the injection of the electron beam with parameters corresponding to high-quality parameters of conventional radiofrequency accelerators. On the other hand, every proposed injection scheme gave us a clue for that what to do to obtain high-quality electron beams.

The electron beam injection can be divided into three main processes: bunch trapping, beam loading, and acceleration.

The most simple and used injection scheme relies on the self-injection when the only one laser pulse is used. However, this scheme due to its nonlinear nature is hardly controlled; thus the properties of the injected electron bunches usually fluctuate shot-to-shot. On the other hand there can be found a set of parameters where the self-injection become more stable.

The quality of the resulting electron beam depends on the interaction of the electrons with the wakefields.

The alternative injection schemes rely also on the dephasing of the plasma electrons. The density down-ramp uses a sudden drop in the plasma density to prolong the bubble in a controlled manner to trigger the wave-breaking. Optical injection use an additional injection laser pulse to influence the plasma electron motion in order to trap the electrons in the wakefield. Ionization injection use a high-Z admixture in helium gas; the electrons from inner shells are ionized only when the laser pulse intensity overcome a certain threshold. Such electrons can be pre-accelerated within the plasma bubble an thus trapped.

The electron beam injection into the accelerating plasma wave is based on the plasma electron dephasing from their (fluid) motion.

1.2.1 Electron bunch trapping

The first phase of electron beam injection in to the plasma wave is represented by an electron bunch trapping process. Plasma electrons complying with certain conditions as a proper momentum can be trapped into the plasma wave. Electron bunch trapping plays a role

1.2.2 Electron beam loading

Beam loading is a phenomenon limiting the charge and the beam quality in plasma-wave-based accelerators.

The experimental signatures of the beam loading, under an assumption that the beam would be injected into the same phase of the accelerating plasma wave, is the decrease of the beam energy, dark current reduction, and the increase of the energy spread for large beam charges. Trapped electron bunch generates decelerating electric field per unit of charge of the order of 1 GV/m/pC. Such an effect was experimentally studied via colliding pulse injection [2,3]. The beam loading reduces the energy of traling bunch electrons, because they experience the field perturbation generated by leading electrons; therefore, the electron bunch energy is correlated with the load.

These beam loading observations imply the technical requirements, which have to be considered, for the future plasma-wave-based accelerators. The longitudinal phase space volume evolution, which is tightly related to the beam energy spread, is influenced mainly by collection volume and beam loading, and their mutual interplay.

There is a certain magnitude of space charge which corresponds to an optimal load when the plasma-wave electric field get flattened. For the beam charge being below such an optimal load, the increasing injection volume results in a larger energy spread. For the charges above the optimal load, the accelerating electric field is inverted; thus, the energy spread increases.

The beam loading sets a limit on the bunch charge above which the energy spread will grow. For the further increase of the charge, which can be loaded, the higher laser intensity has to be used [4]; the optimal longitudinal density of the bunch scales as a_0^2. Furthermore, it is also necessary to control the injection/collection volume in order to avoid the irreducible energy spread increase.

The longer electron beams can be loaded with higher charge. The beam loading effect can be reduced also by downsizing the collection volume. Another option how to deal with the beam loading is the plasma density recudtion, i.e. to prolong the plasma period and thus the longer electron beams can be loaded.

1.2.3 Electron beam acceleration

Electron beam energy reduces with increasing beam charge, indicating the influence of beam loading.

The wakefield accelerator performance can be further optimized by modification of the second [5–11] but also of third order [12] of dispersion of plasma-wave-driving pulse. This modification can be relatively easily adjusted by acusto-optic programmable filter DAZZLER usualy located at laser front-end. Such adjustment modify not only the spectral chirp but also the temporal shape of the drive pulse, which significatly affects the plasma wakefield growth. Moreover, the laser pulse self-steepening in the plasma can be affected by the spectral phase modification; thus, the self-steepening can be in certain way controlled as well. This can substantialy influence the final electron beam properties.

1.3 Laser wakefield acceleration in plasma channels and near linear regime

2 Highlights of this project

This project deals with two of the important issues emerging in plasma-wave-based accelerators being beam trapping and beam loading. Another importaint issue faced by this project is stabilization of the acceleration process itself. All the mentioned challenges will be studied both experimentally and theoretically by means of numerical particle-in-cell simulations. The particular goals of the project are:

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3 PROJECT description

This project aims at the understanding of underlying physics of electron bunch injection i.e. trapping and beam loading. These both effects together with the role of so called collection/injection volume represent the fundamental issues of the generation of electron beams with parameters approaching to the classical radiofrequency accelerator electron beam parameters (i.e. mainly transversal and longitudinal emittance). The various injection schemes, which plenty of them was proposed up to now, provide indications of the nature of dephasing plasma electrons being later trapped into the accelerating plasma wave.

The project is also focused on the production of , to keep a term from LWFA Nature papers, "dream" beam with comparable parameters to classical rafiofrequency parameters, low transversal and longitudinal emittance and high charge,

3.1 Particle-in-cell study

The basic objective of this project will be a theoretical investigation by means of particle-in-cell simulations of the electron trapping and beam loading. This is intended by manipulation of the plasma electron injection volume in order to reach electron bunches with as small as emittance. The injection volume can be controlled e.g. by counterpropagating laser pulse with a special beam profile, additional ionization injection laser pulse (examination of transversal and longitudinal injection). The longitudinal and transversal beam emittance can be affected by modification of the electric field distribution inside the bubble.

The beam loading can be mitigated when the spatial charge density is minimized. Nonetheless, the minimal longitudinal emittance can be reached when the electron beam density is modified in such a way that the electric field is flattend on the electron bunch location. The beam loading effect can be minimized when ultrashort electron bunch is generated.

3.2 Experimental part

3.3 Injection schemes

Two, recently proposed, injection schemes, which represent a somehow complicated case of the electron beam injection because of two or three different collection volume locations, see Figure **??**. The space charge of individual, initial bunchlets influences both properties of the other bunchelets and electric field distribution inside the bubble. Figure **??** indicated tht the emittances of the bunchlets evolve quite rapidly according to the mutual bunchlet influence until the bunchlets merge and the bunch is created and accelerated; after that the beam emittance evolves steadily.

(a) EPchirp1.png

(b) EPchirp2.png

Fig. 1: Quasi-energy surfaces ($E_{\pm}(\omega, \varepsilon_0)$) on the plane of

3.4 Acceleration in plasma channels

4 Project timeschedule, milestones & deliverables

5 Risk assessment

6 Competency of the applicant's laboratory and experimental and theoretical team

6.1 The Ti:sapphire laser laboratory and theory at the Institute of Plasma Physics

The *Ti:sapphire laser laboratory* is located at *PALS Research Infrastructure* being part of Institute of Plasma Physics and as a joint laboratory together with Institute of Physics of the Czech Academy of Sciences. The Ti:sapphire laser system is *routinely operated for almost 15 years*; within last two years, it was *upgraded* by installation of the acousto-optic modulator *DAZZLER* which enables the spectrum and spectral-phase modification and thus, the laser pulse temporal profile shaping, and also generation of multiple laser pulses. The Ti:sapphire laser system is *routinely used for both for laser wakefield acceleration, and plasma-based XUV lasers and high harmonics generation (HHG).*

Theoretical team:

Vojtěch Horný (1983) – 40% is a young scientist graduated from Faculty of Nuclear Sciences and Physical Engineering (FNSPE) in laser-plasma physics (Ph.D.) and nuclear physics (MSc.). He specializes on electron beam laser acceleration and laser-based X-ray pulses and on electron and photon diagnostics. His focus in this project will use his experience obtained in electron spectrometry (knowledge obtained in electron spectrometer KATRIN and electron acceleration experiments at PALS, ELI-Beamlines, LOA Paris, APRI GIST, Gwangju, Korea and INFN Frascati, Italy) and XUV spectrometry (experience obtained at PALS); moreover, he will coordinate and manage the whole project. In 2017, he was awarded by Czech Academy of Sciences by Otto Wichterle Award for young and perspective scientists. Nowadays, he is a head of Laser Plasma Department at Institute of Plasma Physics; he is a (co-)author of 158 papers with 9903 citations, h-index 60.

Dominika Mašlárová – 30% is, currently, master degree student at FNSPE. His duty in this project will be experimental work on the laser system and XUV pulse fundamental parameters (chirp, length, etc.) characterization. He is skilled in optical system design framework Zemax and electron and ion optics framework SIMION. This knowledge will be useful in the design of the laser pulse stretcher and XUV focusing optics and XUV pulse diagnostics design.

Václav Petržílka – 20% is, currently, master degree student at FNSPE. His duty in this project will be experimental work on the laser system and XUV pulse fundamental parameters (chirp, length, etc.) characterization. He is skilled in optical system design framework Zemax and electron and ion optics framework SIMION. This knowledge will be useful in the design of the laser pulse stretcher and XUV focusing optics and XUV pulse diagnostics design.

Experimental team:

Miroslav Krůs (1983) – 20% is a young scientist graduated from Faculty of Nuclear Sciences and Physical Engineering (FNSPE) in laser-plasma physics (Ph.D.) and nuclear physics (MSc.). He specializes on electron beam laser acceleration and laser-based X-ray pulses and on electron and photon diagnostics. His focus in this project will use his experience obtained in electron spectrometry (knowledge obtained in electron spectrometer KATRIN and electron acceleration experiments at PALS, ELI-Beamlines, LOA Paris, APRI

GIST, Gwangju, Korea and INFN Frascati, Italy) and XUV spectrometry (experience obtained at PALS); moreover, he will coordinate and manage the whole project. In 2017, he was awarded by Czech Academy of Sciences by Otto Wichterle Award for young and perspective scientists. Nowadays, he is a head of Laser Plasma Department at Institute of Plasma Physics; he is a (co-)author of 158 papers with 9903 citations, h-index 60.

Michaela Kozlová – (1973) – 20% is an expert in XUV and soft X-ray coherent radiation generation and detection. She got a postdoc position in LOA, Paris, her shope was amplification of HHG in OFI XUV laser amplifier. She is an inventor of double Lloyd interferometer what was also the topic of her PhD thesis. Within the project, she will run experiments; she will be responsible for XUV generation and detection. She is a (co-)author of 116 papers with 596 citations, h-index 14.

Jan Hřebíček (1983) – 30% is an expert in femtosecond Ti:sapphire lasers; currently, he is responsible for local Ti:sapphire laser system R&D and operation. In the project, he will be responsible for laser system issues like laser amplification chain stabilization and the laser pulse parameter characterization. He is (co-) author of 24 papers with 67 citations, h-index 6.

Pavel Gajdoš – 20% is, currently, master degree student at FNSPE. His duty in this project will be experimental work on the laser system and XUV pulse fundamental parameters (chirp, length, etc.) characterization. He is skilled in optical system design framework Zemax and electron and ion optics framework SIMION. This knowledge will be useful in the design of the laser pulse stretcher and XUV focusing optics and XUV pulse diagnostics design.

David Grund – 30% is, currently, master degree student at FNSPE. His duty in this project will be experimental work on the laser system and XUV pulse fundamental parameters (chirp, length, etc.) characterization. He is skilled in optical system design framework Zemax and electron and ion optics framework SIMION. This knowledge will be useful in the design of the laser pulse stretcher and XUV focusing optics and XUV pulse diagnostics design.

Jan Batysta – 10% is, nowadays, bachelor degree student at FNSPE. He will be responsible mainly for the laser system stabilization and the data analysis.

7 Community connection of the project and collaborations

Particle-in-cell simulation will be performed with the EPOCH code, the basic (2D) simulations will be run on the National Grid MetaCentrum and basic 3D simulations on the Czech supercomputer IT4Innovation where almost 2 million CPU hours is dedicated to the team. (V. Horný and D. Mašlárová obtained support from IT4Innovation.)

8 Community connection of the project and collaborations

The proposed project deals with the fundamental issues emerging in the plasma-wave-based accelerators either driven by laser pulses or particle (electron or proton) bunches. The project follow the demands assigned by both European project EUPRAXIA and US DoE roadmap for a development of compact plasma-wave-based particle accelerator being demonstrated in 2035.

8.1 Experimantal and theoretical collaborations

All the members of the research group are in the contact with the international community and partner laboratories. The collaborations were already established and the contact is keeped with the following institutions: LOA (Paris, France), FZ Julich and HZDR (Dresden, both Germany), University of Strathclyde (Glasgow, United Kingdom), Weizmann Institute (Rehovot, Israel), CoReLS (Gwangju, Korea), ILIL INO (Pisa, Italy), CLPU (Salamanca, Spain).

8.2 Collaboration with Forschungzentrum Jülich

The Julich team will ensure the main theoretical part of the project. They will perform large – CPU-hour demanding – simulations. Besides particle-in-cell simulations, the Czech team will focus on the experimental – proof-of-principle – realization of the proposed schemes by numerical simulations. The German team will participate in these experimental campaigns. The knowledge obtained during joined experiments will be utilized during the construction of the laser wakefield accelerator which is being constructed in FZ Jülich but working on kHz repetition rate (compared to 0.1Hz repetition rate of Pragues group laser system).

9 Societal impact

Nowadays, more than 30,000 accelerators is installed and in operation around the world. The largest accelerators are used as colliders for high-energy particle physics; others serves as synchrotron light sources for various applications in solid state physics, biology or chemistry. Smaller particle accelerators are used in industry as ion implanters for semiconductor production, surface hardening, medicine for cancer therapy, production of radioisotopes for medical diagnostics, cargo inspection, food sterilization etc.

Laser-driven plasma-wave-based accelerators offer a revolutionary path to compact – table-top – and thus cost-effective new generation of accelerators.

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