

BEAM DYNAMICS STUDIES FOR PARTICLE DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENTS AT PITZ

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Abstract

The Photo Injector Test Facility at DESY, Zeuthen site (PITZ) is developing and optimizing high brightness electron sources for linac based free electron lasers such as FLASH and the European XFEL. The high quality of the 25 MeV electron beam together with the availability of a highly flexible photocathode laser system makes the PITZ injector a perfect facility for variety of experimental studies. Two approaches are of great interest for future applications in the context of particle driven plasma wakefield acceleration experiments: self-modulation and transformer ratio studies. In both cases a high density electron beam is interacting with a plasma which has a density of about 10^{15} cm^{-3} . ASTRA [1] simulations were done to study the e-beam density along the existing PITZ beamline, especially at two different possible longitudinal positions of the planned plasma cell, in order to reach the particle density required for occurrence of self-modulation. The results of the beam dynamics studies are presented and discussed in this paper.

MOTIVATION

Plasma is a promising medium for high gradient acceleration of charged particles. It can sustain orders of magnitude higher fields compared to conventional accelerators. Large amplitude plasma waves can be excited either by powerful lasers [2] or by charged particle beams [3]. In both cases either the pulse length of the intense laser or the temporal length of the particle beam should be in the order of the plasma wavelength. In a particle driven wakefield acceleration scheme, the fields generated by the drive bunch / bunches are used to accelerate a witness bunch. The transformer ratio $R \equiv W_w^+ / W_d^-$ (maximum energy gain of the witness bunch divided by maximum energy loss of the drive bunch) is an important parameter which in general is limited to two [4], except in special cases when the bunch has an asymmetric current profile [5]. The most successful experiment in concept of particle driven plasma wakefield acceleration was performed at Stanford Linear Accelerator Center (SLAC), by doubling the energy of an ultra-short (50fs) 42 GeV electron beam [6]. Although two order of magnitudes higher accelerating gradients compared to RF accelerators were demonstrated, the experimental results revealed the limitation of the transformer ratio. An other idea was to accelerate an electron beam up to hundreds of GeV by using high energy ultra-short proton beams as a

driver [7]. The plasma in this case will play the role of a medium, which transfers the energy of the protons to the energy of the electrons. As currently available high energy proton beams are tens of centimeters long, a self-modulated regime for long proton beams was afterwards suggested to excite large amplitude wakefields in plasma [8]. When a long particle beam (bunch length is long compared to the plasma wavelength) enters the plasma, it is radially modulated by the periodic focusing/defocusing forces and the beam density modulation provides a positive feedback for the instability to grow [9]. For the case of the CERN 450 GeV proton driver beam, simulations show that an injected 10 MeV witness electron beam can be accelerated to an energy of several hundred MeV after a few meters propagation in a $7 \cdot 10^{14} \text{ cm}^{-3}$ density plasma [10]. For beams which are longer than the plasma wave period, where self-modulation occurs, the wakefield properties are strongly affected by the drive beam dynamics [11]. PITZ is a known facility for generating and characterizing high brightness electron sources. Recently PITZ has become a very attractive facility for different challenging experiments due to the excellent transverse beam properties such as the transverse emittance which turned out to be unique over a wide range of bunch charges [12]. PITZ can make an important contribution to the questions related to self-modulation by measuring the longitudinal phase space properties of a relatively long 25 MeV electron beam after interaction with a 10^{15} cm^{-3} dense plasma. The basic observation would be to detect electron beam energy modulation $> 1\%$, which should be possible with the recently available PITZ diagnostics [13]. In this work two possible longitudinal positions of the planned plasma cell arranged into the PITZ linac are considered. Beam dynamics studies were done predicting the possibility of high beam densities required for the self-modulation process.

INTRODUCTION: BEAM PARAMETERS FOR SIMULATIONS

An overview of the current PITZ setup is shown in Fig. 1. The highly flexible laser system at PITZ, which was developed by the Max-Born institute, produces flat-top laser pulses with sharp rise and fall times [14]. High brightness electron beams are generated using a Cs_2Te photocathode and are accelerated in an L-band RF gun cavity up to 7 MeV (low energy section). The electron beam gets its final energy of about 25 MeV by the cut disc structure (CDS) booster cavity. A big dipole can be used to deflect the beam by 180° for different studies, particularly for the

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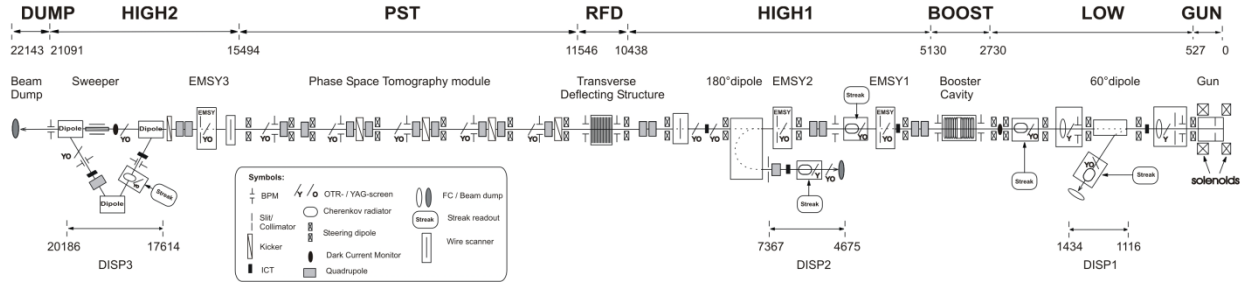


Figure 1: Schematic view of the current PITZ beamline. The electron beam propagates towards the left.

final beam energy measurements. Two pairs of identical quadrupole magnets are located between the booster cavity and the 180° dipole. The plasma cell should be inserted before the matching section for the phase space tomography module (PST) which starts at ~ 10 m from the cathode. The RF deflector (RFD) for measuring the longitudinal beam properties is situated right after the matching section. A Space charge TRacking Algorithm (ASTRA) was applied to track the electron beam to two possible central positions of the plasma chamber (which is assumed to be ~ 1 m long) either directly in front of or behind the 180° dipole, i.e. until the point where the beam will enter the ~ 30 cm long plasma. The goal in the simulations was to reach the highest possible electron beam density at the starting point of the beam-plasma interaction by smooth transverse focusing of the beam. In the simulation setup

tion in the high energy section (EMSY1 in Fig.1). Two pairs of quadrupoles are used to further focus the beam transversely. The simulations were carried out in two steps. Firstly, the electron beam was tracked to 5.1 m downstream of the cathode by using the 2D space charge routine in ASTRA. The quadrupole focusing was applied afterwards for the final beam transverse focusing by using the 3D space charge settings. The principal part of the simulation setup starting from the first quadrupole in the high section until the matching section is illustrated in Fig. 2. The components which should not be removed / replaced are colored in green. The yellow marked components can be removed / replaced. The plasma cell is presented in red. The numbers written on the components convey their distance in meters calculated from the cathode. Fig. 2 (a) shows the current situation. Two possible scenarios for the plasma cell ar-

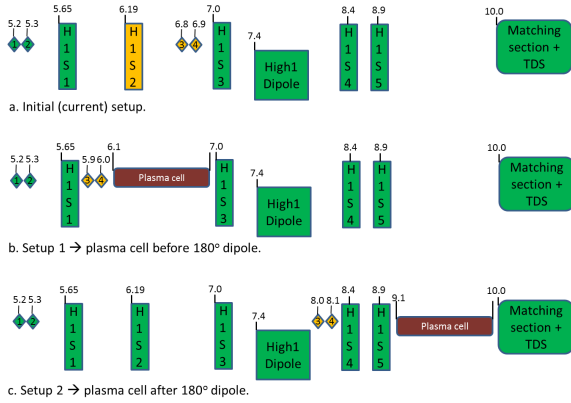


Figure 2: The scheme of possible scenarios for plasma cell insertion.

the photocathode laser temporal profile was considered a flat-top with 22 ps FWHM length and with 2 ps rise and fall times. The laser rms spot size at the cathode was chosen to be 0.3 mm for 100 pC bunch charge. The gradient of the RF gun was set to 61 MV/m corresponding to 7 MeV/c beam momentum after the gun. The peak field in the second accelerating module (CDS booster) was tuned to achieve a final beam momentum of 25 MeV/c. 0.5 Million macro-particles have been used for the simulations. In both cases the magnetic strength of the main solenoid was chosen for minimum beam spot size at the first screen sta-

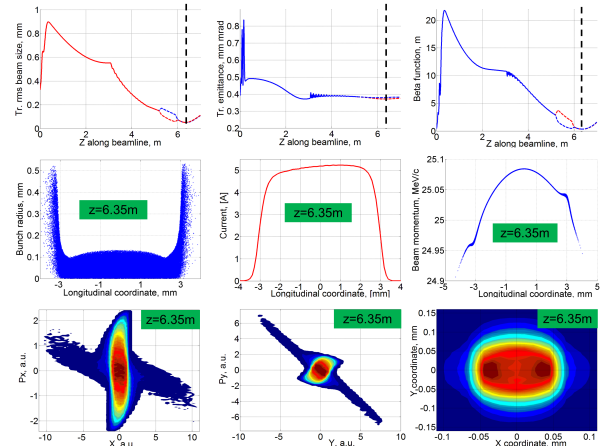


Figure 3: Beam transverse properties along the PITZ beamline and the beam overview at 6.35m downstream the cathode (setup1).

agement in the PITZ beamline are described as setup1 (b) and setup2 (c). The quadrupoles are introduced by numbers, from one to four as indicated in Fig. 2, and the screen stations are presented as H1S#, i.e. H1S1 being the first screen in the high section. The electron beam properties for the setup1 (b), where the plasma cell is situated before the 180° dipole are given in Fig. 3. The first line shows the electron beam transverse sizes, emittances as well as

the beta functions (different colors correspond to the parameters in horizontal and vertical planes) along the PITZ beamline. The bunch radius (assuming cylindrical symmetry), the charge distribution and the longitudinal momentum vs. the longitudinal coordinate are shown in the second row. Transverse phase spaces and the beam projection are presented in the last line. The transverse electron beam sizes along the beamline for the two different setups are shown in Fig. 4. The analysis of the beam overviews for the

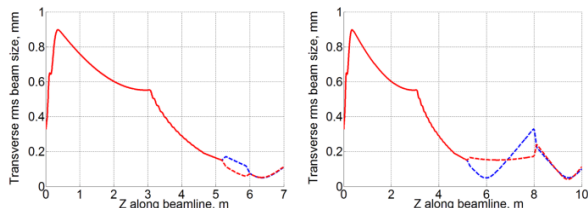


Figure 4: Transverse beam focusing for two different positions of the plasma cell. Different colors correspond to rms beam sizes in different transverse planes.

two cases (Tab.1) suggests the first setup (plasma cell before the 180° dipole) as a better candidate compared to the second case (plasma cell after the 180° dipole) which requires more complex transverse beam focusing. The peak beam density values in Tab.1 are calculated using a formula which assumes Gaussian shape of the electron beam.

Table 1: E-beam output parameters for two different z positions of the PITZ linac (before and after the 180° dipole).

Beam parameters	Before	After
Total charge, pC	100	100
Long. beam position, mm	6.35	9.45
Hor. rms beam size, μm	49.8	59.4
Ver. rms beam size, μm	51.2	59.4
Bunch length in FWHM, mm	5.92	5.92
Average kinetic energy, MeV	24.55	24.55
RMS energy spread, keV	27.5	27.8
Peak slice current, A	5.2	5.2
Hor. emittance, mm mrad	0.37	0.38
Ver. emittance, mm mrad	0.38	0.36
Long. emittance, keV mm	42.4	42.4
Beam density, 10^{12} cm^{-3}	9.1	6.6

SELF-MODULATION AT PITZ

The self-modulation instability is a result of a long particle beam (longer than the plasma wave period) interaction with the plasma. In this case different slices of the long beam sample different transversely focusing (defocusing) and longitudinally accelerating (decelerating) forces depending on their longitudinal position inside of the plasma. As a result both the charge density as well as energy of the long bunch are modulated with respect to its longitudinal coordinate. The period of such modulations is in the order

of the plasma wave period. The self-modulation instability grows exponentially with the N number of e-foldings $\sim \exp(N)$. For the PITZ beam parameters $N \approx 5$ and a beam energy modulation of $> 1\%$ are expected after a few centimeters propagation in 10^{15} cm^{-3} density plasma [15]. However, hosing instability [16] which is a result of the interaction of the beam and plasma sheath electrons remains a critical issue. The latter can lead to a position displacement of the beam centroid and therefore have an impact on the beam-plasma interaction efficiency. Ideally the sharp falling edge of the electron beam ($\sim 0.6 \text{ mm}$) will initiate significant fields in the plasma and suppress the effect of hosing instability. A precise beam density calculations should be performed by applying suitable distribution functions for longitudinal and transverse projections of the simulated electron beam outputs. Further simulations on the beam-plasma interactions, as e.g. in [17] are necessary for the case of the PITZ beam-plasma parameters to get a better understanding of the self-modulation process.

SUMMARY AND FUTURE PLANS

Beam dynamics simulations have been performed to transversely focus the electron beam at two different longitudinal positions of the PITZ beamline. In both cases an rms beam spot size of $\sim 50 \mu\text{m}$ was demonstrated for 100 pC bunch charge and for 24.55 MeV beam energy. The results are promising and meet the preliminary requirements on the electron beam for self-modulation studies. The transverse deflecting cavity, recently installed in the PITZ beamline, will make possible to accurately study the longitudinal beam properties before and during the planned self-modulation experiments. Installation of a bunch compressor for transformer ratio studies is also in the future schedule of the PITZ facility.

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