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ABSTRACT

In the field of beam driven acceleration of particles in plasma wakefields (PWFA), the source of the plasma medium is a crucial part of the accelerator setup. Gas discharges have proven to be a reliable and simple type of a plasma source in past experiments. Nevertheless, especially in plasma cells that aim for peak density in the range of $10^{15}\,\mathrm{cm}^{-3}$, physical apertures around 10 mm, and lengths of up to several meters, the stability of the discharge ignition and the pulse current waveform is limiting the applicability. We show successful mitigation of these jitters in a 0.1 m argon gas discharge cell, operating at maximum densities of $\leq 10^{16}\,\mathrm{cm}^{-3}$ by optimisation of the cell design and the discharge current pulse circuit.

I. INTRODUCTION

The acceleration of particles in wakefields driven in a plasma by either laser pulses [laser wakefield acceleration (LWFA)][1] or relativistic charged particle bunches (PWFA)[2] has drawn significant attention throughout the past years due to the prospects of high gradient, small size accelerators for free electron laser[3–5] or high energy physics applications.[6,7]

Plasma cells as source of the acceleration medium are being used or considered in most experiments in the field, as a pre-ionised plasma has several advantages over the ionisation by the driver, such as guiding of laser pulses[8] or mitigation of driver head erosion.[9] If the driver head does not produce sufficiently high field strengths for ionisation, preformation of a plasma is even inevitable, which is often the case in PWFA. Therefore, the investigation of suitable plasma sources has become a major part of the development of plasma accelerators. Whereas many experiments aim for plasma densities of $10^{16}\,\mathrm{cm}^{-3}$ or higher[10–12] to reach maximum acceleration gradients, some experiments demand densities below $10^{15}\,\mathrm{cm}^{-3}$. This is especially the case for proton-driven PWFA in the scope of the Advanced Wakefield Experiment (AWAKE)[13] and experiments without bunch compressor.[14] For both experiments, pulsed, linear, low density argon gas discharges have been proposed as possible plasma sources for their simplicity and also for their scalability to lengths of up to several meters. In these cells, which are operated near the minimum of the gas breakdown potential (often referred to as the Paschen-minimum), gas pressures are typically around 1 mbar up to a few mbar, physical apertures around 10 mm, and plasma lengths between 0.1 m and 10 m. The gas is ionised by current pulses of several hundred ampere and several microseconds length. It has been found experimentally at the Photoinjector Test facility at DESY, Zeuthen site (PITZ) and in prototypes built for the AWAKE at CERN[15] that such cells can exhibit discharge initiation time jitters on the μs scale and current waveform jitters of the discharge pulse of more than 10%. These jitters are assumed to result from lower yields of secondary electrons at the cathode by ion impact during the build-up of the high current arc discharge plasma compared to higher density gas discharge media. With such uncertainties in the plasma formation—and consecutively the plasma density at a fixed beam arrival time—reproducible interaction, like wakefield acceleration, is not possible.

In this publication, we present the design of a low density, 0.1 m long argon discharge cell and means of mitigating discharge current pulse jitters by optimising the electrical discharge circuit and the plasma cell design. Successful jitter mitigation is confirmed by electronic discharge monitoring and via the stability of wakefield interaction of a relativistic electron beam with the produced plasma.

II. DESIGN OF THE LOW DENSITY GAS DISCHARGE CELL

A schematic of the gas discharge cell used at PITZ is shown in Fig. 1. It consists of two copper electrodes (dark brown) with central apertures for electron beam passage, positioned at the ends of a 0.1 m long discharge vessel (blue/purple). Supporting structures and insulators (dotted lines, light brown) stabilise the cell and make vacuum connection to the accelerator beamline (gray). The cell gas atmosphere is separated from the beamline vacuum by metallized polyethylene therephthalate (PET) foils (blue) of 1–2 μs thickness that serve as electron beam windows.[16] By applying a current limited, negative high voltage between the electrodes, a glow discharge is established. On trigger, a high voltage pulse is applied to the electrodes that leads to arc formation and ionisation of a high percentage of the cell gas. The electrodes are connected to the inner (cathode) and outer (anode) conductor of coaxial pulse cables (Fig. 1, red lines) that conduct the negative high voltage ($\leq$3 kV) and high current ($\leq$1 kA) pulse supplied by a pulse circuit (Fig. 1, bottom right). To prevent discharges to the beamline components, the beamline connection on the high voltage (cathode) side, including the foil window mount, is kept on floating potential. A constant gas flow is established through the cell to exchange the gas on a minute timescale.

The pulse network was designed to supply the DC pre-ionisation current of a few mA and the negative, μs current pulses at repetition rates up to 10 Hz. Length and amplitude of the pulses were determined by calculation of the achieved density under one-dimensional, idealised conditions via calculating the plasma resistivity (due to electron-atom and electron-ion collisions), Ohmic heating of the cell gas, and the Saha-equation self-consistently.[17] Even though the calculation assumes local thermal equilibrium, homogeneous current, and electron distribution and excludes effects like the decay of plasma density (by, e.g., recombination), diffusion, radiation-induced cooling, or cooling at the cell walls, a rough estimate of the final density can be achieved, which was confirmed by spectroscopic and wakefield-based density measurements.[18,19] The results of such a calculation are shown in Fig. 2.

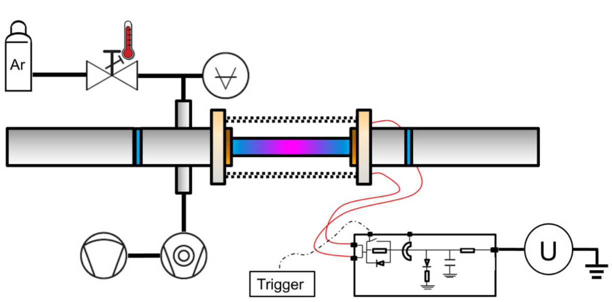

FIG. 1. Layout of the PITZ argon gas discharge plasma cell.

III. DISCHARGE IGNITION TIME AND CURRENT JITTER

As stated above, plasma sources with similar dimensions and parameters as described in Secs. I and II have shown different forms of discharge jitter, like time jitter of the discharge ignition, current amplitude, or waveform jitters, which influence the parameters of the plasma witnessed by a particle bunch that is synchronised to the plasma source trigger. Capillary discharge cells in contrast, which typically operate in the several ten to several hundred millibar gas pressure range, usually exhibit discharge initiation jitters of only a few nanoseconds.[21–23] This might be caused by the considerably higher pressures in such capillary discharges, which enhances secondary charge emission through ion impact and collisional ionisation in the avalanche formation by reducing the mean free path length. Furthermore, the higher electric fields due to shorter length and higher voltage as well as the smaller electrode surfaces could contribute to lower discharge initiation time jitters.

Figure 3 shows a representative set of consequent discharge current waveforms, measured with a Rogowski coil[24] at the high voltage current lead from the discharge capacitors

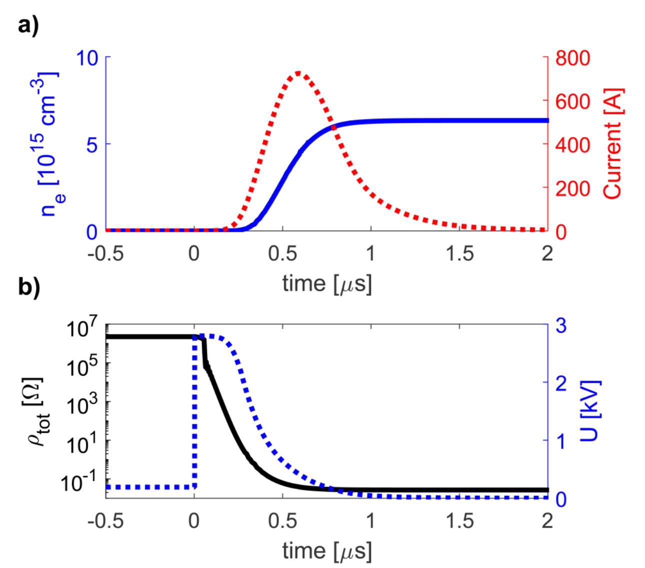

FIG. 2. Simulated current pulse (SPICE[20]) and corresponding plasma electron density n_e calculated using one-dimensional theory (a). The simulated voltage U across the plasma and the plasma resistance (ρ_{tot}) is plotted in (b). The discharge switch is closed at 0 μs and the capacitor charging voltage is 2.8 kV.

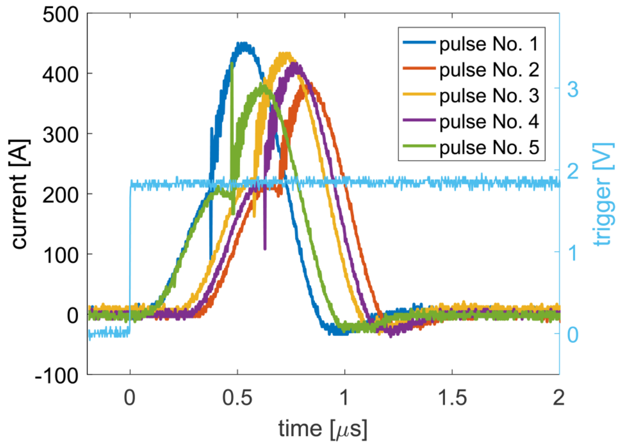

FIG. 3. Trigger signal and current of 5 consequent discharge pulses exhibiting strong ignition time and current waveform jitter.

to the plasma cell described above (half circle in Fig. 1, lower right). The time jitter of several hundred ns between the ignition times of the discharges is clearly visible. Also, the change of the current waveform is obvious: although pulse number 1 shows a nearly undisturbed damped capacitor discharge, the other pulses show changing current rise rates at the front of the pulse, separated from the sine-like part of the pulse by a sharp transition. Current amplitudes and ignition times also differ between these current-limited pulses.

Operation of the cell without gas exchange showed a significant increase of the discharge jitter with time. Simultaneously, an increase of the hydrogen spectral line intensity was measured: whereas upon filling of the discharge vessel, hydrogen lines are only weakly visible in the spectrum of the discharge, the spectrum is dominated by the H_α line after some time of operation. This is shown in Fig. 4, where the strongest emission lines of the discharge for singly ionised argon (750.4 nm)

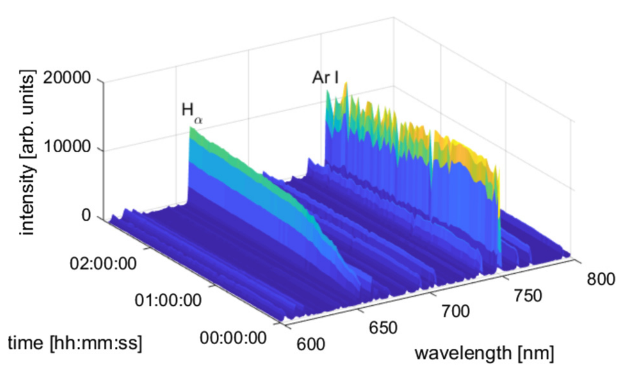

FIG. 4. Time evolution of the Ar gas discharge spectrum during 10 Hz pulse operation without gas flow.

and hydrogen (H_α, 656.3 nm) are visible. Discharge jitters already increase after ca. one hour of operation, when the hydrogen line is clearly visible but not yet dominant. This change of the emission spectrum was observed during pulsed operation as well as with a glow discharge only and is attributed to the release of gas from the cell surfaces due to bombardment by high temperature argon ions. Especially, the amorphous quartz-glass stores large amounts of hydrogen, which could not be reduced significantly by conditioning (via discharge exposure for $\geq$12 h) or baking.

IV. JITTER MITIGATION

To avoid the effects of the change of discharge gas composition, the cell is operated with a constant gas exchange, as mentioned before. Another significant reduction of discharge jitter was achieved by using pure copper electrodes. Despite the fact that charge carriers in the pulsed arc discharge are mainly supplied by the (copper) cathode,[25–27] an anode made of 1.4429 electroslag remelted (ESR) stainless steel was identified as the main source of the current-limited pulse rise times shown in Fig. 3. Corrosion-like layers have been observed on this material after exposure to the plasma discharge, whereas their composition and origin are not fully understood.

Even though the presence of the pre-ionisation glow discharge has a major influence on the discharge jitter, the current of the glow discharge does not seem to affect it much further. Whereas a reduction in root mean square (RMS) ignition time jitter $\geq$50% by applying pre-ionisation was observed for some parameters, higher pre-ionisation current at constant pulse parameters did not have measurable influence, which is supported by the fact that a change in initial density in the calculations shown in Fig. 2 has no considerable effect on the density evolution. The availability of some initial free charges seems to be sufficient for stable discharge formation.

To study the impact of the arc discharge parameters on the plasma source performance, inductance L (mainly given by number and length of transmission line cables, Fig. 1, red lines) and capacitance C (given by pulse capacitor, Fig. 1, bottom right) in the pulse circuit were varied. As the LC product determines pulse duration and also pulse rise time, the factor by which this product is reduced from initial conditions L_0C_0 is used as figure of merit. For every LC value, the pressure in the plasma cell was scanned and the RMS jitter of the delay between discharge current and trigger pulse for 100 consequent discharges was measured. The jitters measured at two constant pressures and the minimum jitter for every electronics configuration are plotted in Fig. 5. All measurements were taken during continuous 5 Hz pulse operation. The discharge voltage of 1.6 kV was kept constant for all measurements, whereas due to different values of C and L, the maximum current differs between different measurements. No dependence of discharge jitter on the maximum current was found and no significant correlation between LC configuration and gas pressure could be observed. For fixed LC values, the pressure of the gas has a strong influence on the discharge performance, though.

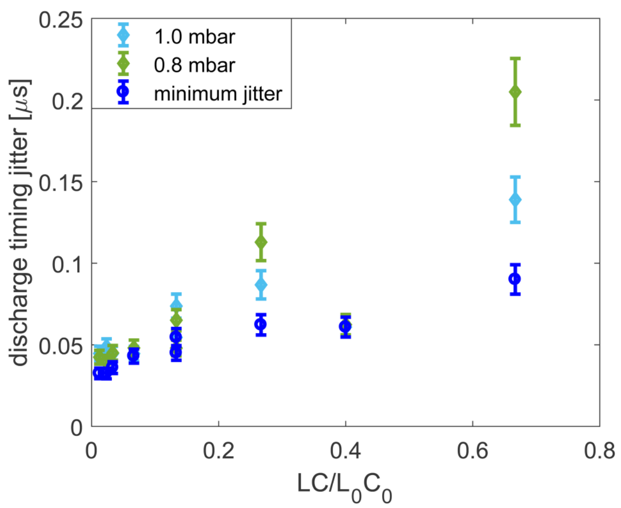

FIG. 5. RMS jitters of discharge ignition from mean delay in 100 discharges for different configurations of inductance L times capacitance C in the pulse circuit of the plasma cell. Minimum jitters and jitter values for two exemplary constant gas pressures are shown.

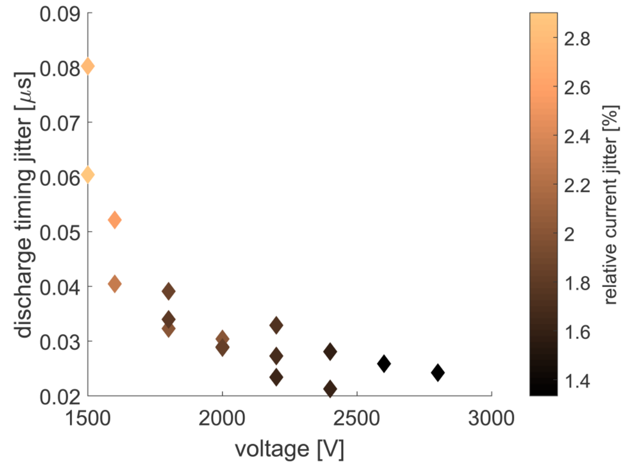

FIG. 6. Dependence of RMS discharge initiation time jitter and maximum current amplitude jitter on the capacitor charging voltage.

The reduction of ignition time jitter is attributed to an increased period of high voltage applied between the electrodes: due to the high initial resistance of the glow discharge, the voltage between the electrodes directly after closing of the pulse switch corresponds to the maximum capacitor voltage [Fig. 2(b)]. As the plasma current rises with increased voltage and decreasing plasma resistance, the voltage between the electrodes decreases. This voltage decrease is delayed by several 10 s to 100 s of nanoseconds for lower values of LC, as revealed by SPICE[20] simulations of the dynamic discharge resistance. The "Equal-area Criterion," known from high voltage engineering, predicts a constant time integral for the voltage at the electrodes from the time of application of the voltage until breakdown, i.e., full build-up of an arc discharge.[28] Accordingly, a delayed voltage decrease between the electrodes corresponds to shorter breakdown delays and thus also to smaller breakdown time jitters. Further jitter reduction by lowering the LC value is limited by parasitic impedances as well as the minimum energy needed to form an arc discharge, i.e., a minimum current density in the plasma.

Consistently, a similar result can be achieved by increasing the voltage at the capacitors as shown in Fig. 6. In contrast to the previous method, the voltage can be increased further and it is reasonable to assume the discharge jitter is also dropping further. This assumption is again based on the Equal-area Criterion. An initial higher voltage reduces the time delay until the integral voltage has reached the constant area and thus also the jitter is reduced. Even though increasing the voltage is a valid and far more common way of reducing discharge ignition jitters, it can quickly turn into major effort in terms of insulation, power supply, and electronics equipment. The previously applied means rather result in simplification and reduction of components.

The minimum achieved jitter is 21 ns at a pulse duration of 1 μs FWHM, as plotted in Fig. 6. As the variation of the plasma density due to discharge initiation jitter depends on the actual plasma density, temperature, and the ionisation degree, no general relationship between time jitter and density variation can be presented. Spectroscopic density measurements imply that the measured minimum time jitter corresponds to a plasma electron density jitter below 0.5% directly after the discharge current termination,[19] which translates into a plasma wavelength jitter lower than 0.25%. The corresponding set of 100 consecutive discharge current waveforms measured in the optimised cell is shown in Fig. 7. Deviations of individual current waveforms at the start of the high current half wave are attributed to electronic noise, caused by high frequency oscillations in the electronics during discharge formation and are hence considered irrelevant for the plasma reproducibility. Further studies were conducted regarding the impact of pulse repetition rate. Changing the repetition rate might alter the local temperature distribution on the cathode due to different time periods of heat transfer from the hot spots of charge emission between discharges. This could have significant influence on the arc discharge formation due to enhanced thermal emission. Also other factors like gas attached to the electrode surfaces might influence discharge behavior and change with repetition rate. Nevertheless, no measurable influence on the arc discharge jitter was found between 1 Hz and 10 Hz. A change in discharge performance during continuous pulse operation was not evident neither. The amplification of the cathode field by a virtual anode also did not improve the discharge jitter, whereas this might become significant at higher electrode distances, i.e., lower cathode fields.

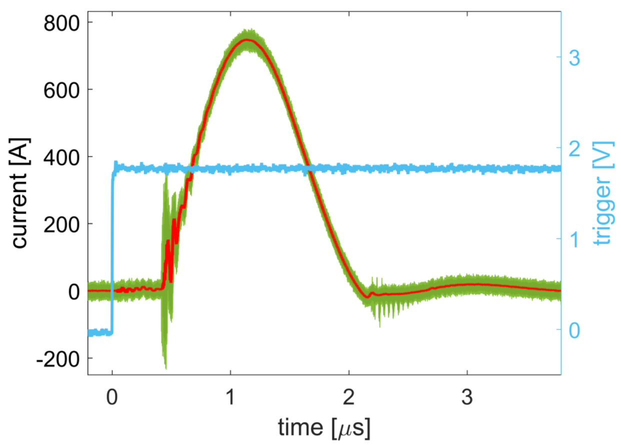

FIG. 7. Trigger signal (blue) and current (green) of 100 consequent discharge pulses in the optimised cell. The mean current waveform is shown in red.

V. WAKEFIELD BASED JITTER EVALUATION

To validate the electronically measured jitter of the discharge and the deduced density uncertainty, a direct measure for the electron density jitter is necessary. As the cell was built to be used for PWFA experiments, a method based on the wakefield interaction seems natural. Bunches that are longer than the plasma wavelength can be subject to the self-modulation instability (SMI) when they interact with a plasma.[29–31] The periodicity of such a self-modulated electron bunch directly depends on the plasma density[30] and thus can be taken as a measure for the discharge stability. Even though the suitability of this parameter for absolute density measurements is discussed elsewhere,[19] a change in plasma density affects the periodicity of the bunchlets of a self-modulated bunch, due to changed length between focusing and defocusing regions and thus changed dynamics in the plasma wake. The bunch arrival time jitter, which is on a ps-scale, can be neglected as the plasma density evolves on a time scale at least four orders of magnitude longer.

Figure 8 shows the longitudinal projection of a 22.5 MeV, 1 nC flat-top electron beam without and with plasma interaction at a delay between discharge current termination and bunch arrival of 60 μs. The longitudinal profile is measured using a transverse deflecting structure (TDS) and a scintillator screen. To achieve the highest possible measurement resolution, the delay between the first and the last resolvable microbunch in the self-modulated bunch is measured. The RMS deviation of 10 measurements was found to be 0.05 ps in the shown case, whereas the resolution given by the pixelsize of the measurement screen's camera was 0.08 ps. Taking the average microbunch distance as a rough measure of the plasma wavelength, this translates into an approximate density jitter of 0.6% and 1%, respectively.

Measurements at different plasma densities, i.e., different plasma ignition-bunch arrival delays, showed similar results. Even though the measurement resolution is not sufficient to confirm the electronic jitter measurements, the stability of the beam-plasma interaction also excludes negative influence of, e.g., plasma instabilities.

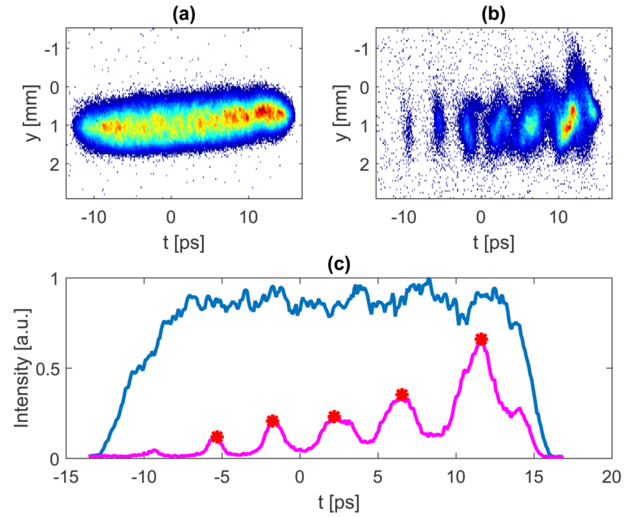

FIG. 8. Time resolved bunch t-y-projections without (a) and with (b) interaction with the cell plasma. (c) The corresponding bunch profiles (blue without and purple with plasma interaction) and the microbunches that are taken into account (red asterisks).

VI. CONCLUSION

In the presented studies, a stable plasma source operation for a cell with parameters as needed for low to medium density PWFA experiments is demonstrated for the first time. Typical jitters that have been observed on such plasma sources were mitigated by introducing a constant gas flow through the cell and optimising the plasma cell and driving electronics setup: capacitance and inductance in the pulse electronics are reduced to delay the voltage drop due to the rising plasma current during the build-up of the arc discharge in the cell. In accordance with the Equal-area Criterion by Kind, which is well established in the field of high voltage engineering, this leads to a significant reduction of delay and hence jitter of the arc discharge. The final jitter of the plasma density at fixed bunch arrival timing was shown to be less than 0.5 % by electronic measurements. Discharge stability was also confirmed by the interaction of a long relativistic electron beam with the plasma via the self-modulation instability. The presented plasma cell has now in total been operated for more than 60 h at 10 Hz, which corresponds to roughly 2×10^6 pulses. No further stability issues and no electrode surface degradation have been observed so far. The results already gave way to successful PWFA experiments at PITZ[19,32] and also provide the basis for the development of stable, low complexity, low density plasma sources for future experiments, as, e.g., AWAKE in the planned run 2,[13] where the main challenge will be the achievement of similar performance at cell lengths up to several meters.

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