A high power helicon discharge as a plasma cell for future plasma wakefield accelerators

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Plasma wakefield accelerators are a promising concept for future electron accelerators with output particle energies in the TeV range [1, 2]. The world's first experiment on proton-beam driven plasma wakefield acceleration is currently being prepared by CERN [3] within the framework of the international AWAKE collaboration [4], aiming at the demonstration of electron acceleration over a length of 10 meters.

In order to reach the envisaged accelerating electric fields on the order of a few GV/m, a plasma density in the range $10^{20} \ldots 10^{21}$ m^{-3} is required. Fundamental power balance calculations [5] suggest that a heating power of the order 50 kW is required to reach this density in a 1 meter long, 2 cm diameter plasma column assuming a flat-top density profile. This power density of $P/V \approx 160$ MW/m^3 poses a challenge to both the technical realization of the plasma cell and the employed plasma diagnostics.

While laser-ionized plasmas are limited in length by the available laser energy and dc discharges suffer from instabilities at higher currents, our approach using a helicon wave heated discharge is generally scalable to arbitrary lengths. Helicon waves are right-hand circularly polarized bounded low frequency whistler waves, which are excited by external antennas and dissipate their energy non-resonantly. The cold plasma solution of the helicon wave dispersion relation reads [6]

$$\frac{k_{\parallel}\, k}{\omega_{\mathrm{rf}}} = \frac{\mu_0\, e\, n_{\mathrm{e}}}{B_{\mathrm{z}}}, \tag{1}$$

where $k_{\parallel}$ and $k = \sqrt{k_{\parallel}^2 + k_{\perp}^2}$ are the wave vectors, ω_{rf} the excitation frequency, and B_{z} an axial magnetic field. It is commonly assumed that the wave vectors of the excited wave are imprinted by the experiment geometry, i.e. antenna length and the discharge radius. In this case, the plasma density scales linearly with the ambient magnetic field B_{z}. This scaling behaviour has been experimentally verified for a range of magnetic fields where ω_{rf} stays above the lower hybrid frequency (e.g. Ref. [7]). With the power balance yielding $n_e \propto P_{\mathrm{rf}}/V$, the rf heating power represents the second control parameter regulating the achievable plasma density.

The prototype high power helicon plasma cell for AWAKE employs a 1 meter long, 50 mm

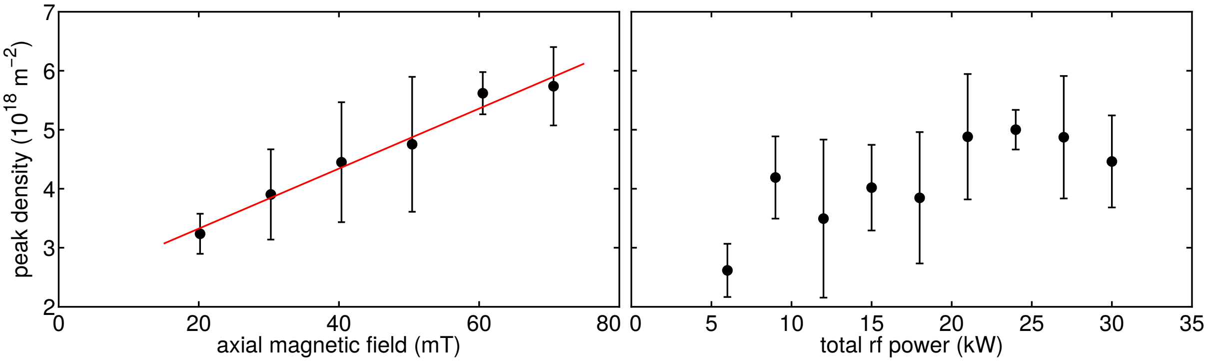

Figure 1: *Density scaling behaviour in the helicon plasma cell. Left: peak plasma densities at different magnetic field strengths; the solid line is a linear fit to the data. Right: peak plasma densities at different rf powers; each antenna contributes 1/3 of the total heating power.*

diameter quartz tube as discharge vessel, an axial magnetic field up to 100 mT on the discharge axis, and three rf-synchronized heating systems. Each of these systems consists of a 12 kW rf generator (TRUMPF Hüttinger RF3012), an L-type capacitive matching network, and a half-turn helical antenna with a length of 75mm. With this set-up, a total power of up to 33 kW (corresponding to a power density of 17 MW/m^3 in the tube, or more than 100 MW/m^3 in a plasma column of 1 cm radius) is coupled into the discharge. The plasma density is measured using a Michelson-type CO_2 interferometer at 10.6 nm wavelength, which is passing twice through the plasma in radial direction. The intensity calibration of the interferometer is provided by modulating the length of the reference leg over 15 μm.

The general scaling behaviour of the plasma density with applied magnetic field and rf power is shown in Fig. 1. The (line integrated) density shows a clear linear dependence on the magnetic field strength as suggested by the helicon wave dispersion relation. The dependence on the rf power is less pronounced, but there is a general trend $n_e \propto P_{rf}$ as suggested by power balance considerations for constant electron temperatures. For an evaluation of the local plasma density, however, the density profile along the interferometer's line of sight is required. Because Langmuir probe signals are difficult to interpret at these rf power levels, we relate the density profile to the emission profile of the 442.6 nm Ar II line. The emission of this line was recorded over one shot with a CCD camera at a frame rate of 27 kHz and a spatial resolution of approximately 1 mm. The line integrated density of 41 shots ($p_0 = 5$ Pa, $P_{rf} = 3 \times 9$ kW, $B_z = 56$ mT) and the emission profile evolution are shown in Fig. 2. While the density peaks around $t \approx 600$ μs, falls off until $t \approx 3$ ms and stays roughly constant until the end of the shot, the emission quickly develops into a centrally peaked profile with increasing central intensity towards the end of the shot.

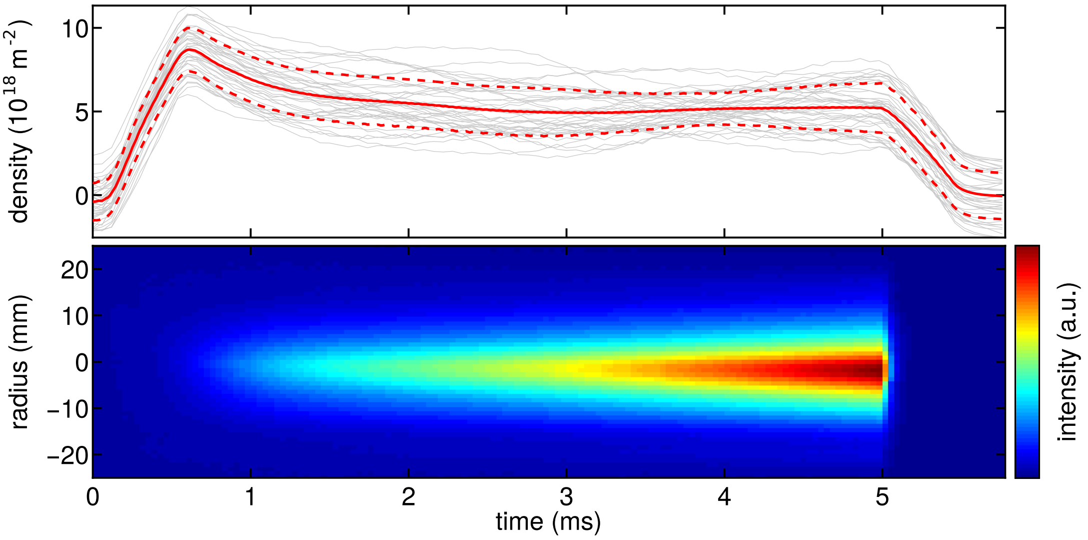

Figure 2: *Top: Temporal evolution of the line integrated plasma density of 41 individual shots (light grey). The red lines are the mean value (solid line) of all shots and a 1σ region around the mean value (dashed lines). Bottom: Argon II emission at 442.6 nm. The rf power is switched on at* $t = 0$ ms *with a rise time of 2* μs *and switched off at* $t = 5$ ms.

Using the emission profile at each time step as an estimate for the density profile, the line integrated density can be converted into the local density profiles shown in Fig. 3. The resulting time evolution of the peak plasma density is displayed in Fig. 4 (red curves). Densities of $n_e \approx 2.5 \cdot 10^{20}$ m^{-3} are measured at $t \approx 600$ μs, falling off to a plateau value of $n_e \approx 1.7 \cdot 10^{20}$ m^{-3}. Because the line intensity is a strong function of T_e, these values have to be interpreted as an upper limit of the local density. A lower limit is estimated by using a fixed width Gaussian density profile with $3\sigma = 25$ mm $= r_{\text{tube}}$, yielding a maximum density of $n_e \approx 1.7 \cdot 10^{20}$ m^{-3} that falls off to a value of $n_e \approx 1 \cdot 10^{20}$ m^{-3} (Fig. 4, blue lines). Comparing the two curves with the power balance for a 1 meter long, 10 mm radius plasma column with a flat-top density

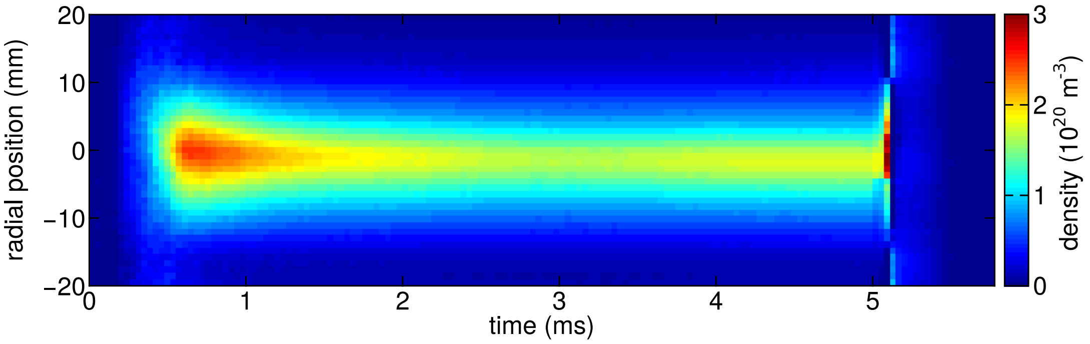

Figure 3: *Temporal evolution of the plasma density from interferometer measurements and emission profiles as an estimate for the radial density profile.*

profile, the measured values correspond to electron temperatures in the range $T_e = (2\ldots2.5)$ eV, which is typical for helicon discharges.

With this experiment we have demonstrated that plasma densities in the range relevant for AWAKE can be achieved in helicon discharges with heating power densities around $P/V = 100$ MW/m^3. The observed non-stationary temporal behaviour is likely due to neutral depletion (see e.g. Refs [8, 9]), an effect that will be accounted for by including a gas puffing system in the experiment.

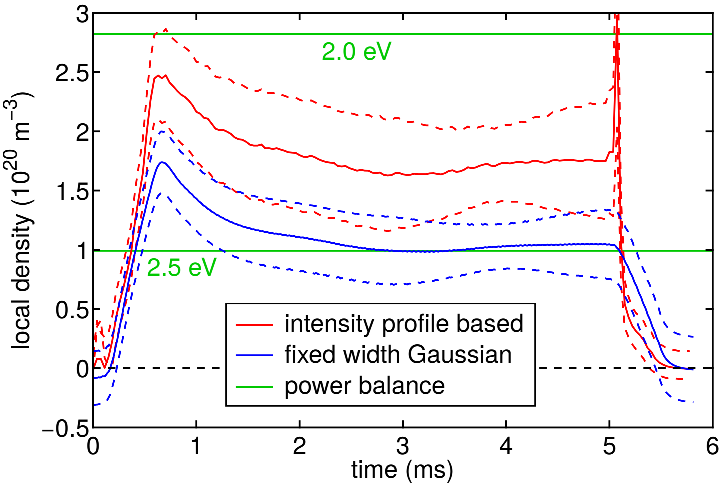

Figure 4: *Evolution of the local peak plasma density. Red curves: from emission profile; blue curves: from fixed-width Gaussian with* $3\sigma = 25$ *mm; green lines: expected densities from power balance with* $r_{pl} = 10$ *mm.*

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