A helicon plasma source as a prototype for a proton-driven plasma wakefield accelerator

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Exploiting the large electric fields that can be generated in the wake of a plasma density perturbation has been proposed as a promising scheme for particle acceleration already in the 1970s [1]. The AWAKE project [2] aims at the construction of a proton driven plasma wakefield accelerator (PDPWA) [3], using high-energy proton bunches to modulate the plasma density in order to achieve electric field gradients in the GV/m range.

One of the key parameters for a PDPWA is the plasma density. Simulations indicate that plasma densities on the order of $n_e \approx 10^{21}$ m^{-3} are required with high homogeneity [3]. Current plasma sources for plasma based particle accelerators, which use high power laser beams (e.g., Refs. [4, 5]) or field ionization in the driving particle bunch (e.g., Refs. [6, 7]) to generate the plasma, are not scalable and thus the achievable particle acceleration is limited.

The experiment presented in this contribution applies an RF wave-heated (helicon) plasma as an alternative concept. Helicon plasmas have been shown to be very efficient in producing high plasma densities. Since external helical antennas are used, the heating power can be spatially distributed, allowing for arbitrary plasma lengths.

The helicon wave is a right-hand circularly polarized low-frequency whistler wave propagating in a frequency regime between the lower hybrid and the electron cyclotron frequency, following the dispersion relation [8]

$$kk_z = \frac{e\mu_0 n_0 \omega}{B_0} \tag{1}$$

where k and k_z are the absolute value and the axial component of the wave vector, e is the elementary charge, μ_0 the vacuum permeability, n_0 the plasma density, ω the driving angular frequency (typically $2\pi \cdot 13.56\,MHz$) and B_0 the externally applied axial magnetic field. Equation 1 shows that there is no intrinsic limit for the plasma density (unlike in other RF discharge regimes), although for high densities (and correspondingly high axial magnetic fields) it is unclear if and how the helicon wave propagation is modified close to the lower hybrid frequency.

A one meter long helicon plasma cell is currently being developed as a prototype for a PDPWA plasma source. Basic power balance calculations [9] indicate that unparalleled power

densities are needed for the required plasma density of $n_e = 7 \times 10^{20}$ m^{-3} for the AWAKE experiment. Studies of the dependence of plasma density on operational parameters are presented. Special attention is paid to key accelerator issues as peak plasma density and axial homogeneity.

A sketch of the experimental and diagnostics setup is shown in figure 1. A cylindrical quartz tube of 1 m length and 5 cm outer diameter is used as discharge vessel. A set of six water-cooled copper coils (not shown in the figure) is used to provide an axial magnetic field of up to 56 mT. The helicon wave is excited by means of presently one $m = +1$ helical antenna with a length of roughly 15 cm, connected to a 12 kW RF power supply via a capacitive matching network. Two more power supplies are available and will be installed in the near future, increasing the RF power to 36 kW using then three distributed antennas.
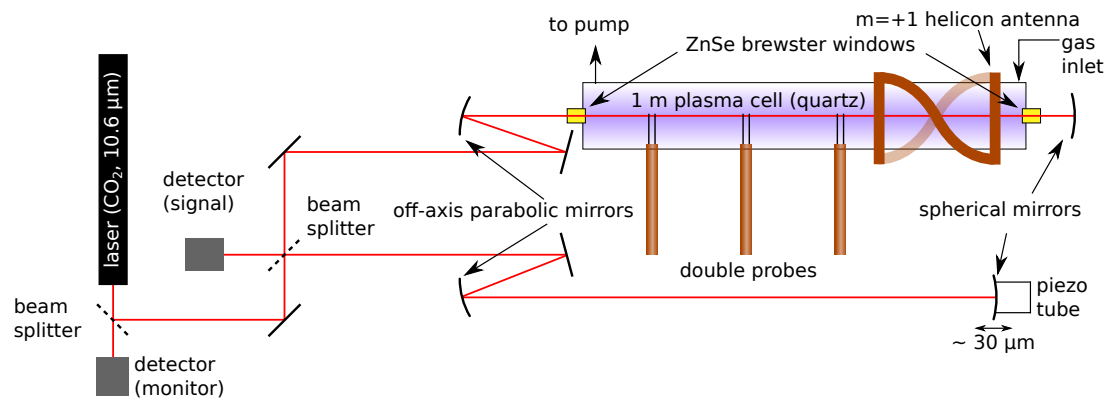

Figure 1: *Experimental setup showing schematically the helicon discharge and the interferometer setup.*

The chief diagnostic tool is a CO$_2$ laser interferometer measuring the line-integrated electron density. The interferometer is operated in a classical Michelson configuration (see figure 1), measuring along the discharge axis. Axial density profile measurements are obtained by a set of three double Langmuir probes, placed close to the discharge axis and axially spaced by approximately 20 cm.

Power balance calculations [9] based on the rate coefficients for ionization and recombination as well as coulomb collisions and inelastic electron-neutral and electron-ion collisions are used to estimate the RF power needed to sustain a discharge with the nominal density of 7×10^{20} m^{-3}. Because of the sensitivity of the involved atomic processes on the electron temperature, the required RF power levels depend on the electron temperature. Figure 2 shows the results of the calculations for Helium, Argon and Xenon plasmas at different neutral gas pressures. Argon clearly shows the highest densities of the gases, at relatively low electron temperatures of $T_e \approx (1 \ldots 2)$ eV. In this temperature range, a heating power of $P_{rf} \approx (40 \ldots 60)$ kW is required for the nominal density.
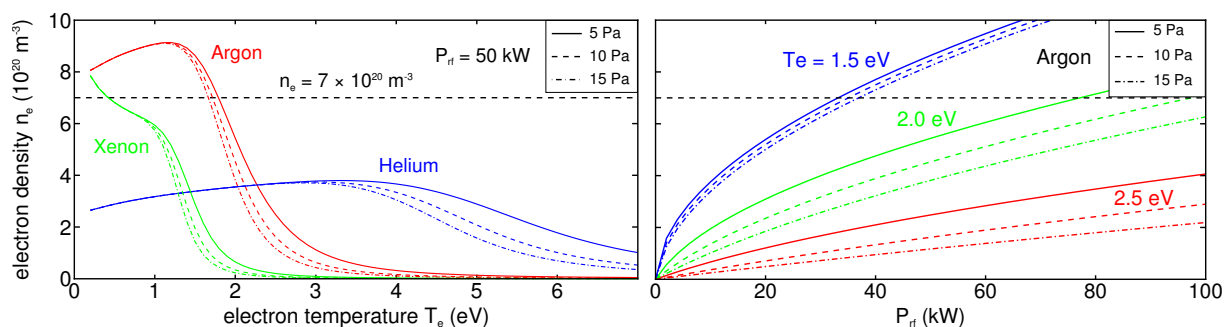
Figure 2: *Results of power balance calculations for different gases. Depicted are the dependence on neutral gas pressure (left) and electron temperature (right).*
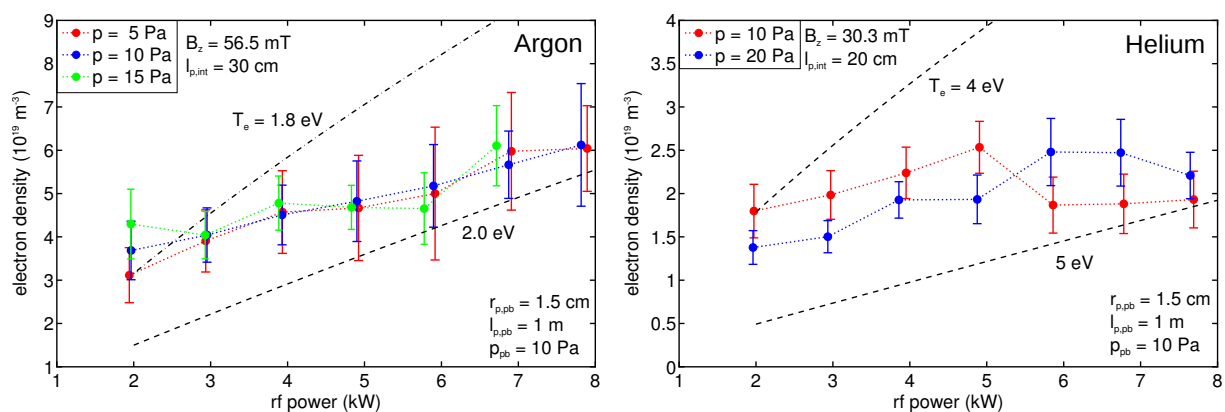

Figure 3: *Measured plasma densities in Argon (with axial magnetic field $B_z = 56.5$ mT) and Helium ($B_z = 30.3$ mT) for different gas pressures. Black dashed lines indicate densities from the power balance calculations.*

Plasma density measurements in Argon and Helium at RF powers up to 8 kW are shown in Figure 3, along with results of the power balance calculations (black dashed lines). Since these data are taken using the interferometer and thus are axially line-integrated, an effective plasma length has to be assumed to calculate absolute densities. Simultaneous measurements using the three double Langmuir probes along the discharge axis suggest a plasma length between 20 cm and 30 cm (see Figure 4), which is employed in the calculation of the densities in Fig. 3. All
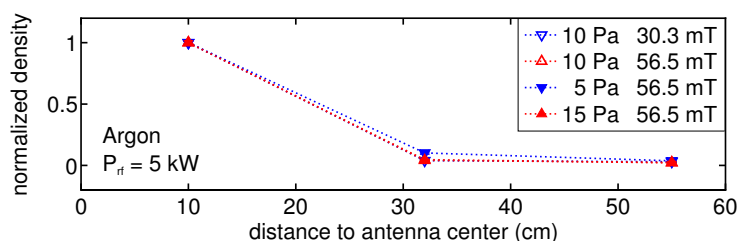

Figure 4: *Axial density measurements using the set of three double probes.*

measurements show a scaling of plasma density with RF power, but with a smaller slope than expected from power balance calculations. For Argon, the measured densities match the pre-

dicted densities assuming an electron temperature of $(1.8\ldots 2)$ eV, whereas in Helium the temperature has to be adjusted to $(4\ldots 5)$ eV to match the power balance predictions.

A straightforward interpretation of the measured less steep density increase with increasing RF power levels when compared to power balance calculations is a simultaneous increase of the the electron temperature. This might be a result of neutral gas depletion as previously suggested for high density helicon discharges [10] which would lead to a lower energy transfer from the electrons to the neutral gas and thus leaving the electrons at a higher overall temperature. For a more detailed analysis, additional diagnostics are currently implemented to measure the electron temperature inside the discharge.

To summarize, an experimental setup is presented that aims to investigate if helicon wave heated gas discharges are suitable as plasma cell element in future PDPWAs. Power balance calculations suggest that 50 kW of RF power per meter should suffice to generate a plasma with the required density. Actual plasma density measurements show good agreement with power balance estimates, but deviate for higher RF power levels most likely due to an increase of the electron temperature caused by neutral gas depletion. This trend will be studied in more detail, while the RF power is increased to 36 kW and a system of three antennas is employed to couple the power into the plasma. In that final setup, gas puffing will be implemented to gain control over the neutral gas inventory.

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