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ORIGINAL PAPER

Technical setup and physical properties of a gas-liner pinch

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Abstract The present technical status and physical properties of the gas-liner pinch device in Bochum are presented and discussed. This comprises spectroscopic as well as diagnostic achievements. A short review on the measurements performed at this light source will also be given.

Key words lineshapes • spectroscopy • Z-pinch

Introduction

Noteworthy progress in understanding spectral line broadening by plasmas was made in the last decades. On the one hand, theoretical approaches on plasma radiator interaction were improved as well as simulations of the plasma particles itself and their interaction with (charged) radiators. On the other hand, the validity and applicability of these theoretical predictions had to be verified by data of various experiments (preferably taken over a large density range). For line broadening measurements arcs and pinch plasmas were applied with its respective advantages and disadvantages. The crux of the gas-liner pinch is that it combines the advantages of the arc like high accuracy line measurements with the high density of a pinch plasma. The disadvantages of both are avoided which are mainly the low temperature of the arc allowing for only very few ionisation stages and those of usual pinches as optical thickness and inhomogeneities. Therefore, the gas-liner pinch provided important data which became possible due to its outstanding properties concerning spectroscopic features as well as its independent diagnostic in a mediate to high density range and a mediate temperature regime.

In 1980, the year of the conception of the gas-liner pinch [17–20], Stark broadening studies were mainly limited to low ionization stages of atoms, and the gas-liner pinch opened up the possibility to extend experimental studies to higher ionisation stages and to force respective theoretical investigations. With its setup, a Z-pinch with two independently acting gas-inlet valves, it was optimal for spectroscopic investigations with low optical thickness at high densities. It was thought that the pinch was able to reach densities in the range between 1×10^{18} to 1×10^{20} cm^{-3} at temperatures of a

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few eV to some keV [18]. Although the highest density reached so far is 1×10^{19} cm^{-3} the properties concerning homogeneity, absence of cold boundary layers as well as low to negligible optical thickness were proven to be true. With the setup of a laser-light scattering system the gas-liner pinch became one of the rare experimental devices operating in this density regime with an independent diagnostic. This was important for the theoretical understanding of Stark broadening as well as the application of theoretical predictions to highest density plasmas ($n_e > 1\times10^{21}$ cm^{-3}) since the data up to that time had been scaled from densities lower than 1×10^{16} cm^{-3}.

Experimental setup

The gas-liner pinch is from its principles a large aspect-ratio Z-pinch. The diameter of the electrodes is 18 cm and their distance is 5 cm; both are not variable. A drawing true to scale is given in Fig. 1. The energy is stored in 6 parallel capacitors (Maxwell, model 32003) of 1.85 µF each. The capacitors are usually charged to minus 25–42 kV providing an energy of 3.5–9.8 kJ; in principle, they can be charged up to 60 kV. The circuit is switched by a rail-gap-switch (Maxwell, model 40100) consisting of two of halfcircled alloy rods (35 cm in length) at a distance of 9 mm. A trigger electrode made of CuWoDur (copper, tungsten, duraluminum) is positioned at a ratio of 1:2 near to the negatively charged electrode. This switch is floated with a mixture of SF_6 in Ar and has an inductivity of 20 nH. The trigger pulse of about 60 kV is supplied by an usual Marx-generator (2 times 50 nF). With this trigger the rise time becomes 5 kV/ns where the time-jitter is about 2 ns. The rail-gap delivers the negative voltage of the main capacitor bank via 32 circular mounted coax-cables to the lower electrode of the pinch. The symmetry of the feeding cables keeps the inductivity low. The time development of the pinch current is monitored by a Rogowski-coil giving the time periode of the pinch to 6.2 μs. The inductivity of the whole circuit is approximately given by $L=T^2/(4\pi^2 C) = 88$ nH.

The upper electrode has a Laval-type nozzle in its center and a circular orifice near the wall through which the gases are injected. In order to achieve a better symmetry the lower electrode also has a hole of 2 cm in diameter in its center. In addition, a central circle of 6 cm in diameter as well as an outer ring of 3 cm in the lower electrode is drilled. These holes (1 mm in diameter) reduce reflections of gas particles, improve the pumping and allow for preionization. The upper electrode is made of aluminum whereby the ring near the glass wall and the Laval-nozzle is made of CuWoDur. The lower electrode is completely made of CuWoDur. The gas is injected into the vacuum chamber (2×10^{-3} Pa) by means of two independent gas inlet systems, which are powered by two fast electromagnetic valves. There is one valve for the outer gas, so-called the driver gas, and the second for the axially injected gas, which will be spectroscopically investigated and is, therefore, named the test-gas. The electromagnetic valves are described in detail in Ref. [36]. The piston of each valve has a circular groove of 120 mm^3 at its end containing the gas. The number of injected gas particles is varied by the pressure of the gas. The piston is accelerated by the eddy current of a 1.8 kV pulse originating from a 100 µF capacitor and is pneumatically damped. This results in an opening duration of about 50 µs. It takes rather 1 ms for the gas to reach the discharge vessel. The driver gas is injected near the glass wall of the discharge and is preionized by means of 50 needles mounted 2 mm below the lower electrode on a diameter of 15 cm. A 50 nF capacitor charged to minus 30 kV drives a discharge between the needles and the lower electrode. The homogeneity of the preionization discharge is ensured by 2 kΩ resistors arranged in series with each needle. The ionization of the driver gas between the electrodes of the pinch is by UV-radiation and electrons passing through the holes of the lower electrode. The ionization rate is less than 1%, but the preionization is indispensable for an azimuthally homogeneous collapsing pinch, because it keeps the initial amplitude of Rayleigh-Taylor instabilities small.

Spectroscopic and diagnostic setup

The plasma radiation is accessible through 4 ports and 4

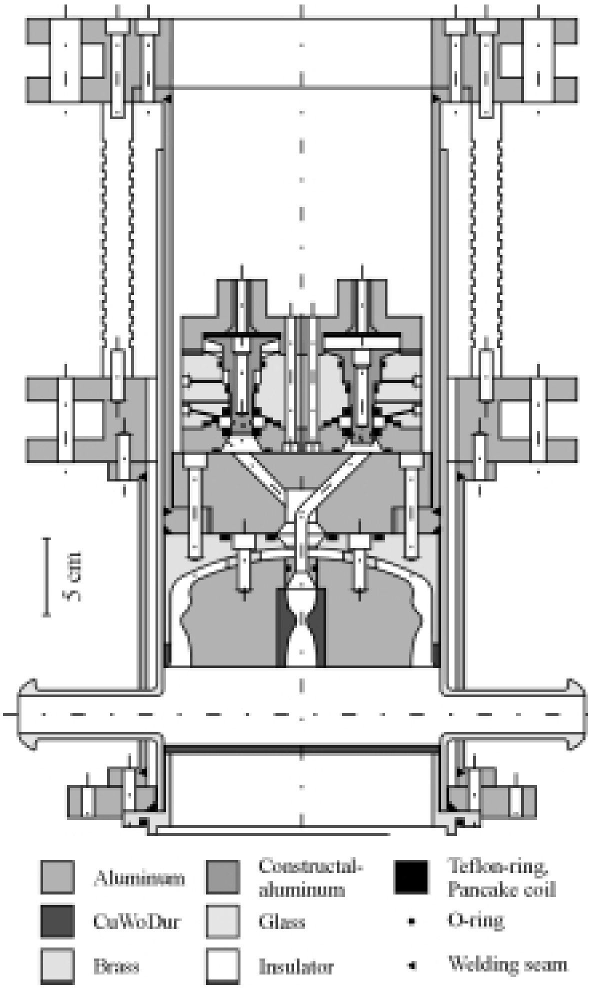

Fig. 1. Drawing true to scale of the discharge vessel together with the electromagnetic valves.

holes drilled in the current conductor towards the lower electrode (see sketch in Fig. 2). Two ports are closed with plane quartz windows and used for spectroscopy and diagnostics. The two other ports serve for the passage of the laser beam. Through one of the 4 holes the plasma monitor collects the plasma radiation at 520 nm imaged via a f = 150 mm lens (f/3) onto a 1/4 m monochromator (ISA, Jobin Yvon) and a photomultiplier (RCA 1P28) connected to an oscilloscope (Gould, DSO 4094). It gives estimates of life and rise time of the plasma to 1 μs and 200 ns, respectively, where the life time of the high density plasma is 300 ns.

The diagnostic of the plasma is carried out by a Q-switched ruby-laser system (Korad K1-Q, 50 MW, 25 ns pulse duration (FWHM)). The laser beam of a diameter of 1.6 cm passes a system of lenses and diaphragms and is finally focused by means of a f = 666 mm lens in the center of the pinch vessel onto a spot of 0.6 mm in diameter. The light dump of the laser beam consists of a blue glass filter as beam divider and additional absorber. The time evolution of the laser pulse is measured by a fast photodiode (FND 100) mounted behind the resonator mirror. The spectral width of the laser is less than 6 pm and given by an etalon which serves also as exit mirror of the resonator (reflectivity 40%). The scattered radiation is 1:1 imaged onto the entrance slit of a 1 m spectrograph (Spex, model 1704, f/8) by two plano-convex f/10 quartz lenses. The image of the scattering volume is rotated by means of two mirrors (see [59, 60]). The measure of the vertical slit determines the size of the scattering volume to 50 μm in height and the length can be varied from 2.5 to 25 mm. The depth of the scattering volume is given by the laser diameter to 0.6 mm. The spectrograph is fitted with a 1200 lines/mm grating, blazed at 1000 nm. With an OMA-system (EG&G, model 1456B-990G) or an ICCD-camera (Princeton Instruments, 384×579 pixels) at the exit plane the linear reciprocal dispersion is 6.3 pm/pixel in second order and the apparatus profile becomes 3 pixels (FWHM). With the ICCD-camera the spectra are radially resolved. In order to improve the signal-to-noise ratio a polarizer and a red filter are employed. The Thomson scattering profiles are fitted according to the form factor of Evans [16]. The procedure as well as the calibration via scattering on propane is described in detail in Ref. [62]. In order to measure the plasma parameters off-axis, the laser and the imaging optics can be shifted in the midplane of the vessel.

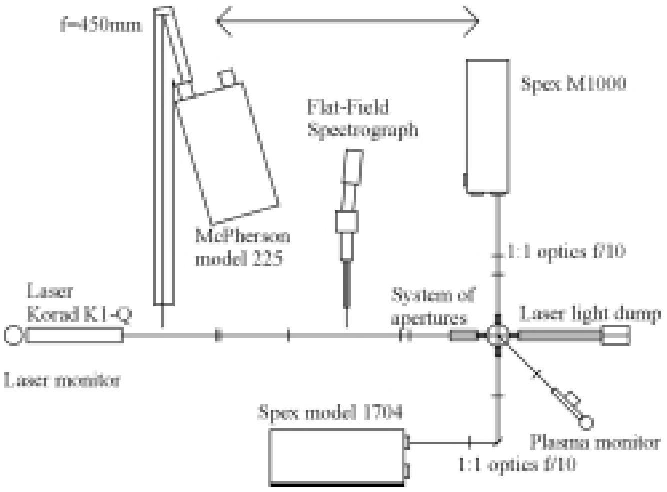

Fig. 2. Onview on the device.

For axially resolved Thomson scattering the laser beam enters the vacuum vessel 50 cm below the lower electrode, is directed along the axis via a mirror into a focus at the center of the discharge. False light is reduced by an additional aperture and the gas inlet system of the inner valve acts as light dump. The scattered radiation is collected with the second 1 m spectrograph (Spex model M1000, corrected Czerny-Turner-Mounting, f/8) by 1:1 imaging f/10 quartz optics. The spectrograph is fitted with the above mentioned grating resulting in the same dispersion and apparatus profile.

Spectroscopic investigations are performed simultaneously with the respective other spectrograph. Each spectrograph can be fitted with several different gratings optimized for the specific spectral range. In addition, the second 1 m spectrograph can be replaced by a 1 m VUV spectrograph (McPherson, model 225, 1200 lines/mm grating) to cover the vacuum-ultraviolet spectral range from 30 to 200 nm or a flat-field spectrograph with a curved grating (variable line spacing 1095–1450 lines/mm) from 3 to 30 nm [41].

Short overview of measurements

There are three main topics of the measurements performed at the gas-liner pinch device. First, Thomson scattering and improvement in the application of this diagnostic. Second, the investigation of line-profiles of hydrogen or hydrogen-like ions and, third, measurements of the Stark width of transitions in multiply ionized ions and corresponding sequences along spectroscopic charge number Z. Spectroscopy is carried out in both the visible and UV spectral range. In addition, there are some measurements providing atomic data. Some results were summarized in Refs. [43, 44, 53, 57, 58, 63].

The Thomson scattering diagnostic with its calibration on propane (see, e.g. [42, 62]) is a reliable, independent technique applicable in a large density range [46, 47]. It was established as standard diagnostic at the gas-liner pinch [22] and used for all following measurements. The diagnostic was refined when the effect of impurity ions on the measured scattering profile was investigated [15]. Also the theoretical predicted asymmetry of the form factor due to electron-proton drifts was measured [33, 62]. The last development concerning diagnostic is that the plasma parameters are determined radially [54] and axially [59, 61] resolved with a resolution of 60 μm. Both measurements unambiguously prove the homogeneity of the pinch plasma and the localization of the test-gas ions in the central homogeneous part of the plasma which was shown only indirectly so far. The results were finally summarized in Ref. [60].

The investigation of atomic hydrogen or hydrogen-like ions was and still is an important topic at the gas liner pinch [1, 48]. One purpose was the verification of an empirical formular for a handy density diagnostic [21, 22] which was finally slightly corrected [12]. Shift, width [6] and structures [7] on the line-shape of H_α line of hydrogen were investigated as well as structures on the L_α line [50]. The H_α line of HeII was also measured axially resolved with the help of an argon floated spectrograph for the visible spectral range [13, 14].

The largest effort went into the investigation of line-profiles of non-hydrogen-like ions (Z<9). Several lines were measured in lithium-like ions of carbon and nitrogen [10] and the dependence of the Stark width on Z along the sequence was investigated [9]. The investigation of the Z-dependence of the sequence was extended to oxygen and neon [30]. The measured Z-dependence along the lithium-like, the beryllium-like [5, 55] as well as the boron-like sequence [25] show systematical discrepancies from the theoretically expected Z^{-2} scaling. These investigations are helpful to improve theories regarding the contribution of strong collisions and of the quadrupole term. In addition, the LS-coupling scheme was checked but no significant violation of the validity became obvious [28].

Stark widths of lithium-like n = 3–4 transitions were investigated [35] and agreement of n = 4–5 transitions of this sequence with theory accounting for ion-dynamics was proven [32]. Stark width of other transitions (either overlapping or isolated) were measured and compared with various theories; many for mediately (3<Z<5) ionized carbon and nitrogen [1, 22, 24, 29, 51], some for neon and fluorine [31, 52, 64]. Furthermore, theories were compared with experimental data of argon [39, 40], krypton [2, 3], some lowly ionized species (Z<3) [49] and atomic helium transitions [11]. All these data were employed to improve theoretical calculations.

It has been shown in Ref. [8] that the gas-liner pinch can also be used as a blackbody limited radiating source in the VUV spectral range which can be used as radiative normal. In another study the radiative energy loss coefficients were determined for Ne, Ar and Xe [5]. Optically thin measurements of the resonance transition in BIII disagree with quantum-mechanical calculations [27] by a factor of two and stimulated recent discussions [4, 23, 37, 38]. Measurements of the resonance transition in CIV indicate that turbulent broadening might play a role also for the BIII widths (see discussion in Ref. [56]). Driving the device under some extreme conditions as high test-gas concentration and high voltage, population inversion was observed for some upper levels in OVI and FVII. The transition was investigated end-on and side-on showing a gain-length product of 4.5 in the XUV spectral range [26, 34, 45]. For future studies a surface injector will be installed instead of the fast electromagnetic valve in order to make ions of solids accessible for spectroscopic investigations.

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