Pulsed Plasma Generator as Laboratory Source of Axions or ALPs

Joachim Jacoby[1], *Christian Teske*[1], *Mary Tsagri*[2], *Konstantin Zioutas*[2,3]

[1]University of Frankfurt (Main), Germany
[2]University of Patras, Greece
[3]CERN, 1211 Geneve 23, Switzerland

DOI: http://dx.doi.org/10.3204/DESY-PROC-2008-02/jacobi_joachim

A lately investigated pulsed plasma source known as Low Frequency Inductively Coupled Plasma with power ratings of more than 1 MW is suggested as a novel source for exotic particles like axions. The apparatus uses high magnetic AC fields (∼1 T) with gradients of ∼1 T/cm and generates high power radiation with a significant percentage in the blue and UV range. Therefore the discharge could function as a catalyst for the emitted photons to become axions. These low cost and easy to handle devices could utilize CAST or other axion helioscopes as detectors in a parasitic way, i.e. while they are not tracking the Sun. The working principle and the performance of such an axion source we propose here for the first time.

Introduction Recently a low frequency inductively coupled plasma (LF ICP) has been introduced [1]. One of the principal advantages of this concept is the generation of high electron densities up to $10^{21}\mathrm{m}^{-3}$ which is well beyond the maximum limit of $10^{19}\mathrm{m}^{-3}$ for RF discharges [2]. The LF ICP device is a pulsed high density source which eliminates electrode contact by inductive coupling to the plasma. Inductively coupled pulsed plasmas are common in fusion research where they are known as θ-pinch devices. A relative new approach are LF ICPs which represent a compact design and can be seen as a linkage between conventional RF operated ICPs and the θ-pinch devices, which are to cumbersome for technical applications. One of the primary attractions of the LF ICP is the elimination of contact electrodes, which mitigates issues with material erosion while still achieving high pulsed power levels of more than 1 MW inside the plasma. Moreover the high magnetic AC fields involved in the discharge generation are in the Tesla range [1]. Therefore a research goal in conjunction with the CAST experiment would be to confirm a proposed axion production at the discharge edge, where the combination of photon intensity, magnetic field and magnetic field gradient culminate, making the generation of axions most likely.

Inductive Discharge Generation Generally in an ICP, the power is transferred from the induction coils to the plasma within a skin depth of scale length thickness δ by transformer action [2, 3]. In order to initiate and maintain an inductively coupled discharge for a given discharge volume there is a minimum requirement for the induced electric field $\mathbf{E}_{ind}$ [4]. Because of the nature of the induced electric field $\mathbf{E}_{ind}$, there being no space charge limit on its value, the ionization by collision in the volume of the gas can be increased by higher current densities [5].

The induced electromotoric force U_{emf}, required for dielectric breakdown is dependent on the gas pressure and the gas used and given by a modified version of the Paschen law [4]:

$$U_{emf} = \frac{C_2 p \Lambda}{\ln(C_1 p \Lambda^2)} \quad (1)$$

with the diffusion length Λ, the gas pressure p and two gas dependent constants C_1 and C_2. Analogous to the classical Paschen law, Eq. (1) can be derived from the diffusion equation though without the presence of electrode phenomena represented by the Townsend coefficient γ [4]. Numerical values and experimental data on C_1 and C_2 can be found in [4]. The measured electromotoric force for inductive discharge generation as a function of the gas pressure inside the spherical volume of the LF ICP setup described in [1] can be seen in Fig.1.

The measurements are consistent with the theory of dielectric breakdown at a gas pressure between 2 and 100 Pa showing a minimum current rise time at 4 Pa. It should be noted here that the law for dielectric breakdown represented by (1) does not include the effect of magnetic fields which give rise to a higher effective diffusion length of the charged particles if the discharge comes into the collisionless regime [2, 3]. In the current LF ICP setup, the induction fields of up to 0.6 T lead to a temporal magnetic confinement of the charged particles [1]. As a consequence of this the effective diffusion length for charged particles gets considerable larger, which should accord for the difference between the measured current rise time for discharge generation and the theoretical model of [4].

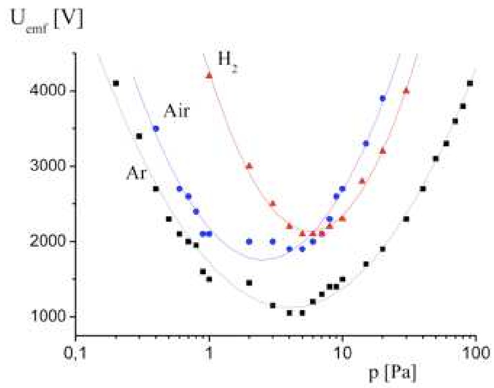

Figure 1: Electromotoric force necessary to initiate a dielectric breakdown as a function of gas pressure.

Measurements Experiments were performed to determine the electrical characteristics of the resonant circuit and the amplitude of the current flowing through the induction coils. The ohmic resistance of the induction coil R_0 was measured through the exponential damping of the current waveform without the plasma acting as a load. Further a fast photo diode was used to compare the electrical signals with the beginning of the discharge and to measure the discharge duration. The presence of a discharge plasma leads to a considerable enhancement of the damping of the circuit through transformer action. With the ohmic resistance of the coils being a known quantity the energy fraction dissipated in the coils during the discharge generation can be estimated. For an arbitrary current $I(t)$ the energy dissipated by the ohmic coil resistance is given by [1]:

$$W_c = R_0 \left[\int_0^{t_p} dt |I_1(t)|^2 + \int_{t_p}^{\infty} dt |I_2(t)|^2 \right] \quad (2)$$

Here t_p is the elapsed time period until discharge initiation starts, I_1 is the current waveform without the discharge plasma and I_2 is the current waveform with the discharge plasma acting as a transformer load. Subtracting W_c from the energy stored inside the capacitors gives the energy dissipated inside the Plasma W_p, leading to:

$$W_p = \frac{1}{2}CU_0^2 - W_c\,, \tag{3}$$

where U_0 is the load voltage of the capacitors and $I(t)$ is the current waveform measured with a Rogowski coil. By comparing the damping of the circuit with and without the presence of the plasma and using energy balance the coupling efficiency η between the primary and the plasma could be determined. Maximum current amplitudes of 4.2 kA were achieved during the ringing of the circuit. The measured results for η as a function of the gas pressure can be seen in Fig. 2.

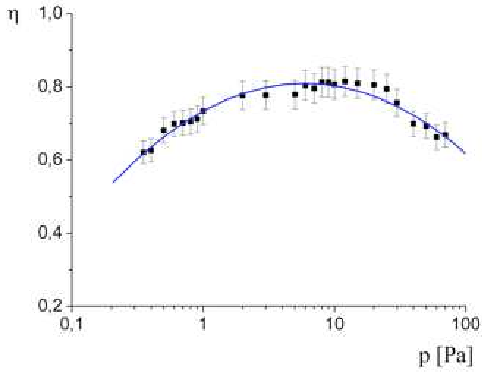

Figure 2: Energy transfer efficiency η of the coil-plasma configuration as a function of gas pressure p.

From the experimental data in Fig. 2, it is found that with maximum efficiency approximately 16% of the stored Energy is dissipated inside the induction coils and the transmission line including the stack assembly. Approximately 84% is dissipated inside the plasma due to the induced ohmic currents. This culminates to an energy transfer efficiency of 84% [1]. The vertical errors represent the uncertainty of the exponential fitting of the current waveform $I(t)$ and the measured coil resistance R_0. Energy transfer efficiency of the current experimental configuration varied between 0.61 up to 0.84. Maximum values were achieved at a gas pressure between 7 Pa and 15 Pa. With discharge duration of 120 μs and a stored energy of 100 J the transfer efficiency of 0.84 leads to a mean power dissipation of 680 kW inside the discharge. It should be noted that this is the integrated power dissipation over the damped discharge period. Peak values during the high intensity period could easily reach 1 MW of pulsed power. Beside the diagnostic of the electrical parameters the line intensities of the emitted spectra was measured. Due to the dynamic nature of the discharge the line intensities must be interpreted as time averaged quantities over a time scale of $\tau = 160\mu$s. Most of the emitted lines can be attributed to ArII. The dominant lines identified for the LF ICP where the ArII 488 nm, ArII 480 nm, ArII 461 nm and ArII 437 nm. This was also confirmed using the data obtained by the monochromator measurements. Emission lines from neutral Argon where scarce. At pressures between 8 Pa and 15 Pa, where maximum energy transfer efficiency was achieved, the UV ArII 359 nm line appeared at its maximum intensity. Higher power densities shift the emission spectra to the UV end. This was confirmed in [1] by comparing the relative intensity of the ArII 359 nm emission line with the most dominant emission lines between 437 nm and 488 nm. The broad band spectroscopic diagnosis was assisted by monochromator measurements for the accurate identification of the emission lines. For the density measurement the stark broadening of the H_β emission line was investigated as a function of the gas pressure. The monochromator measurements presented in this paper are averaged over the entire discharge duration period.

Applying VCS theory, the time averaged electron density could be determined from the spectroscopic data. According to Evans, Aeschliman and Hill [6] VCS (Vidal-Cooper-Smith) theory gives reliable results for the estimated density near $10^{21}\mathrm{m}^{-3}$. The resulting electron density achieved during the discharge generation is shown in Fig. 3. Maximum electron density correlates with the maximum energy transfer efficiency and the maximum line intensity. This is in agreement with the theory of inductive discharge generation which confirms a linear dependence between the electron density and the power density [2, 3]. In terms of achievable electron density the LF ICP is well beyond the limit of 10^{19}m^{-3} given by Lieberman as the current threshold for RF ICPs [3].

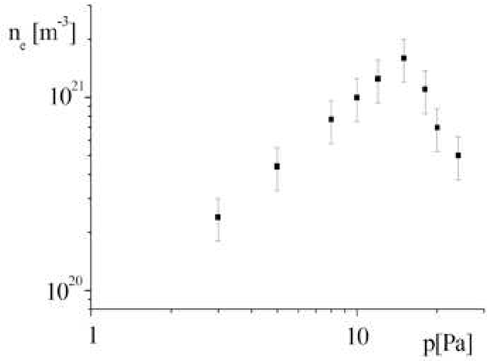

Figure 3: Time averaged electron density of the LF ICP.

Summary The experimental setup discussed in this publication can be seen as a linkage between conventional RF operated ICPs and the θ-pinch devices, which are too cumbersome for most applications. Compared to its high frequency pendant the LF ICP leads to some promising results in terms of achievable electron density and emitted light spectrum. Most of the emitted light was in the blue and violet wavelength with a considerable UV contribution and energy densities of 1 kW/cm^3. The maximum electron density achieved with the current experimental setup was in the range of 10^{21}m^{-3}, which is two orders of magnitude higher than the limit for RF ICPs [3]. Electron temperatures for the first experimental apparatus were 2 eV though more than 20 eV seems feasible with a more sophisticated device [1].

Summing up the principal advantages of the LF ICP concept, the setup should be suitable for the generation of axions in the laboratory. The strong magnetic AC fields generated at the edge of the discharge with field gradients of more than 1 T/cm would function as a catalyst for the emitted photons to become axions. A research goal involving the CAST experiment would be to confirm the proposed axion production at the discharge edge, where the combination of photon intensity and magnetic field (gradient) culminate, making the generation of axions most likely. It is also intended to use an optical resonator to increase the path length of the photons passing through the regions with a high magnetic field (gradient). This has the additional advantage that we can enhance accordingly also the potential axion emission towards the detector, e.g. the magnetic pipes of CAST. This resembles somehow the performance of a LASER. We also note here that the LF ICP provides a combination of strong magnetic fields ($\sim$1 T) and very strong magnetic field gradient ($\sim$1 T/cm), which is a promising new aspect of this proposed scheme. In summary the performance of such a device is characterized by its high pulsed power of more than 1MW with a measured energy conversion efficiency into photons of approximately 84%. Further a repetition rate up to 10 Hz seems feasible, while a cluster of several ($\sim$10) of such low cost devices is also possible.

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