Investigation of acoustic resonances in high power lamps

M Kettlitz ¹, J Rarbach ² and J Zalach ¹

¹ Leibniz Institute for Plasma Science and Technology , 17489 Greifswald, Germany

E-mail: kettlitz@inp-greifswald.de

² Diez Elektromaschinenbau, 73265 Dettingen-Teck, Germany

E-mail: J.Rarbach@vorschaltgeraete.de

Abstract. High power, medium pressure, mercury containing lamps are used as UV sources for many industrial applications. Lamps investigated in this paper are driven with an electronic ballast with a non-sinusoidal current waveform at a fixed frequency of 20 kHz and a maximum power output of 35 kW. Instabilities can occur if the input power is reduced below 50%. The reason is identified as acoustic resonances in the lamp. Comparison of calculated and measured resonance frequencies shows a good agreement and explains the observed lamp behavior. This led to a development of a new ballast prototype which is able to avoid instabilities by changing the driving frequency in dependence on the applied power.

PACS numbers: 52.35.Dm, 52.77.Fv, 52.80.-s, 51.50.+v, 52.80.Mg

Keywords : light source, acoustic resonances, photo diode, high power lamp

1. Introduction

Plasma light sources are widely used in industry as ultraviolet radiators for UV curing of ink, varnish and plastics, for water purification and for the interlacing of adhesives. The UV radiation initiates the chemical reactions for these processes, and a high radiation output is needed for an effective production process. In many cases, high- and medium-pressure mercury lamps are used for these purposes because of their good performance, high luminous flux and efficiency.

Generally, inductive ballasts are used to drive these lamps, but in the last years there was a change towards electronic ballasts. In order to keep them compact and small in size medium working frequencies are preferred. For both types of power supply, a good match of lamp and ballast is important to guarantee a stable and secure operation. The performance of plasma lamps can be reduced by several effects. One of them is an instability of the lamp plasma caused by acoustic resonances, which limits the parameter space for secure lamp operation. Instabilities are a potential safety risk and can destroy the lamp. Some less annoying but also unwanted effects which may occur are light flickering, color change and a reduced lifetime.

High power lamps are often designed to operate at one fixed power and frequency. Of course, it is desirable to extend the working parameters and, for instance, to reduce the lamp power without the risk of lamp destruction. Unfortunately, changing the lamp power will change temperature profiles in the plasma and therefore its properties. The transition between two applied electric power levels may pass the lamp's specific region of acoustic resonances which can lead to arc instability. There are several ways to omit instabilities which are already described in literature [1–8]. First, do not change the power, just operate the lamp at the fixed, stable power level. Second, change the lamp geometry to suppress the development of acoustic resonances, and third, adjust the electronic ballast to avoid the region of acoustic resonances during the change of operating parameters.

Actually the electric ballast has been identified as a very important factor to avoid acoustic resonances [1]. Therefore electronic ballast engineering has become increasingly important for the development of new lamps and lamp systems. Other possibilities to avoid acoustic resonances are the variation of the lamp tube geometry as described in [2].

In this work, acoustic resonances in high power lamps are investigated. With 35 kW lamp types this was done for the first time. In contrast to most other experiments the current waveform was non-sinusoidal with values of roughly 30 A at 35 kW. Another challenging aspect of this work was the combination of plasma diagnostics, namely optical emission spectroscopy and acoustic resonance diagnostics represented by the Fourier transform of the light fluctuation spectrum, which together delivered data for the computation of resonance frequencies.

The purpose of this work is not to develop a new strategy to avoid acoustic resonances. But to analyze already described methods of changing the driving frequency

for its applicability on real ballast driving a particular type of high power lamp.

2. Acoustic Resonances

Acoustic resonances, like all instabilities, are problematic because they can lead to several unwanted effects. When established, the obvious symmetry of the straight, symmetric arc is broken and flickering, color change, acoustic noise, traveling arc structures and arc bending can be observed. In the last case the deflected arc can locally heat the wall, increasing its temperature and weaken its mechanical stability. This can result in lamp destruction due to deformation or a structural break of the glass body. Which of these effects occur and at which intensities depends on the lamp type used. In contrast to this, acoustic resonances can also exhibit advantageous aspects. By intentionally inducing well defined modes it is possible to reduce demixing effects and straighten the arc as demonstrated by Stockwald [9]. Furthermore, acoustic resonances can be used as a diagnostic tool to estimate the total gas pressure inside the discharge vessel [10]

The mechanism of acoustic waves occurring in lamps has already been described for example in [2–4,7–9,11] and is shortly summarized here.

Plasma light sources are often designed as glass or ceramic tubes. Gas filled cylinders define geometrical boundary conditions for pressure waves. An excitation mechanism is always included in form of alternating current at the electrodes. This leads to a periodical power input to the plasma.

Witting [3] computed the resonance frequencies analogously to standing pressure waves in cylinders (organ pipes) using the lamp length l , inner radius r and the speed of sound v_s as parameters:

$$\omega_i = \pi i \frac{v_s}{l} \quad (\text{longitudinal mode}) \quad (1)$$

$$\omega_{mn} = a_{mn} \frac{v_s}{r} \quad (\text{transversal modes}) \quad (2)$$

$$\omega_{mni}^2 = \omega_{mn}^2 + \omega_i^2 \quad (\text{mixed resonance}) \quad (3)$$

$$v_s = \sqrt{\gamma \frac{RT}{m}} \quad (4)$$

The variables have the usual meaning – gas constant R , mass m , temperature T and coefficients a_{mn} which are derived from the Bessel function by applying boundary conditions. For the numerical values of a_{mn} Witting refers to Rayleigh [12], they are also given in more recent publications, for example by Jahnke et al [13]. The term transversal modes means all wave modes propagating perpendicular to the arc. Spatial fluctuation pattern for several modes are graphically shown i.e. in [14]. The speed of sound v_s is usually calculated for a mean gas temperature with $\gamma = \frac{5}{3}$ for monoatomic gases used as filling in lamps analyzed in this work.

This model of standing pressure waves ignores all complex interactions of gas properties. Particularly, it takes not into account the radial temperature profile $T(r)$ as it occurs in lamps. In this case an average temperature is considered. The temperature profile affects of course the speed of sound as well as other relevant plasma and gas properties, for example viscosity, convection, heat transfer, collision frequencies and electrical conductivity. This means that acoustic resonances are a complex phenomenon. Also, it can be seen in the fact that the observed hysteresis as a characteristic behavior can not be explained within the picture of standing pressure waves [4].

This complexity has obvious consequences for lamp operation. An intentional change of the power input affects the temperature profile and therefore many plasma and gas properties along the discharge tube and along the inner radius which in turn change the temperature dependent resonance frequencies — the lamp can become unstable. These properties effectively limit the parameter region of safe lamp operation.

A more detailed look at the pulsating power input mentioned above leads to the electrodes. During a power cycle the electrodes become alternatively an anode or cathode - in dependence on the phase. The change between anode and cathode results in a periodical occurrence of a hot spot, which locally heats the gas. This corresponds to a recurring small 'gas explosion', which travels along the discharge tube as a pressure fluctuation. Usually, the electrode region is the origin of the instability as shown in figure 1.

Figure 1. Stable and unstable arc near the electrode of a high power lamp. The fluctuations are concentrated at the electrode region and in most cases instabilities began there.

Geometrical boundary conditions given by the shape of the discharge volume define the tube specific resonance frequencies and give rise to the possibility of standing pressure waves. The pressure wave amplitude can grow if the frequency of the fluctuations is in phase with the frequency of the power input and lies close to a resonance frequency of the tube. The resonance frequencies are defined not only by the lamp geometry, but also by the temperature profile $T(r)$ and gas type. Increasing amplitude of pressure waves can disturb the discharge path and its shape, the whole set of discharge parameters may change and strong instability with the above mentioned effects can occur.

The instability grows on time scales of 0.01-1 s, which is much longer than the period of power input. This means that the acoustic resonance generating conditions have to last for a relatively long time compared to the duration of one HF cycle to

make growing of the pressure wave amplitude possible. Otherwise the arc can still be stable despite the presence of all ingredients for acoustic resonance [2, 6]. This property was used by Wada [2] to suppress acoustic resonances by inducing a high frequency component to the driving voltage which distorted the growing process. A good example of the different time scales was given by Olsen [15], where a driving frequency of 60 Hz produced an acoustic resonance at 24 kHz. Furthermore, not all acoustic modes are in the same way sensitive to the excitation level, some need much stronger stimulation to develop than others [4]. An example of a non-destructive acoustic resonance occurrence is shown in figure 2. The initial stage of a not fully developed instability can be seen in figure 1.

Figure 2. Distorted arc of a high power lamp during unstable operation caused by acoustic resonances.

An ideal electronic ballast should suppress the growth of acoustic resonances i.e. by changing the driving frequency in dependence on the applied power, in order to avoid the region of acoustic resonance frequencies.

3. Setup

The investigated medium pressure high power lamps were horizontally operated by a digital high-speed power supply with a control cycle below 10 ms (Teck-Tiger, Diez). It used a non-sinusoidal fixed frequency of 20 kHz with a maximum power output of 35 kW. Current and voltage values reached levels of roughly 30 A and 1 kV respectively. Some current waveforms for different power levels are shown in figure 3.

The used waveform is responsible for very low electromagnetic interference (EMI) and fulfills the CE (Conformité Européenne) specifications. Together with a total mass of about 80 kg, which lies greatly below typical weights of inductive ballasts, it was easy to integrate the compact device into the experimental setup, which was placed on an optical workbench shown in figure 4.

The lamps were cylindrically shaped, quartz made, without outer bulb and with tungsten coil electrodes. The inner diameter ranged between 18 and 25 mm and the length between 1.1 and 1.7 m. The filling consisted of some mg of Hg and about 20 mbar Ar as ignition gas. Figure 5 shows the end part of such a lamp.

Forced air cooling was necessary during lamp operation. In contrast to their industrial application a special lamp housing was used allowing good access for

Figure 3. Current waveform of the power supply (Teck-Tiger) for different power levels at a fixed frequency of 20 kHz.

Figure 4. Experimental setup for high power lamp diagnostics. The electronic ballast was integrated into the setup.

Figure 5. One of the analysed lamps — quartz glass tube ending with electrode, electrical connection and infrared reflection coating.

diagnostics and good thermal and UV radiation shielding. For diagnostic purposes special windows for the IR (ZnSe) and UV (sapphire) spectral range were inserted into the housing.

Spectroscopic plasma diagnostic measurements [16, 17] were carried out in the middle of the lamp with a 0.5 m-spectrograph (SpectraPro 500i, Acton) combined with a 2048x2048 CCD-camera (Pixis, Roper). Two different gratings with 600 l/mm and 2400 l/mm were used in order to obtain overview spectra and high resolution line-shapes necessary for optical temperature measurements. The plasma temperature was determined with the Bartels method [18, 19, 20] from the radiance of the self-reversed maxima of the optically thick Hg spectral line at 546 nm. The electrodes and the lamp ending were observed in the visible and infrared spectral range. Especially the use of a fast 12 bit camera (SensiCam, PCO) with a minimal exposure time of 1 μs allowed phase resolved observations of the arc attachment mode on the electrode (figure 7) as well as the movement of the arc near the electrode region. The arc in the middle of the lamp was observed with a 8 bit camera (FlashCam, PCO) (figure 2).

Additionally, the electrode region was imaged using a simple optical system. At the image plane a photo diode (IPL-10531, IPL) with external low noise power supply was installed and the optical signal from different positions around the electrode was recorded and analyzed with a fast spectrum analyzer (FSEA20, Rohde&Schwarz) to detect plasma fluctuations. With this method introduced by Olsen [15] the resonance frequencies of the lamp for a given power could be recorded at a glance.

A photo diode measurement produces a signal caused by the integrated effect of the light flux originating from its line of sight. Spatial information about the fluctuation intensities which are coupled to the local temperature of the radial profile $T(r)$ is lost.

So it was not possible to distinguish from which radial position the signal came from. Measurements using acoustic detection methods (eg. microphones) as suggested by Stromberg and Schaefer [6] were not possible due to strong vibrations and high noise level caused by the air cooling of the lamp.

4. Results and Discussion

Measurements on high power lamps for varying input power were performed on standard lamps used in industrial applications as well as on a limited number of specially prepared lamps with changed geometry and filling. All lamps operate stably at the nominal power of 35 kW, but a reduction of the input power by 50% (or less) leads in most cases to arc constriction and instability. In these cases arc distortion occurred combined with flickering and arc rotation. This was easily observable as increasing light flickering and arc deflection when the operating parameter approaches the unstable region.

The observed instabilities were identified to be caused by acoustic resonances because of its typical hysteresis which is not present i.e. in helical instabilities [21, 22] exhibiting a similar appearance. Also the local magnetic field induced at the electrodes by currents of up to 30 A for maximum lamp power seem not to play a dominant role

as the arc is stable at such high currents. The observed instabilities occurred at much smaller currents than its maximal value.

Plasma temperature profiles were measured in the middle of the lamp with temperature values ranging from 5500 K to 7000 K in the plasma core.

The temperature profile can be retraced in the high temperature central region of the arc where the self absorption of the optically thick line results in a self reversion. By assuming a parabolic like shape a corresponding profile can be fitted using:

$$T_{parabolic}(r) = T(0) - (T(0) - T_{wall}(R)) \left(\frac{r}{R} \right)^m \quad (5)$$

Here $T(0)$ is the arc core temperature, R the inner radius of the discharge volume and $T_{wall}(R)$ the glass wall temperature. It should be mentioned that a true parabolic profile is obtained only for an exponent value $m = 2$ which is not necessarily the best fit parameter for a given profile. Usually values around 2 are found to give best profile fits. With the temperature profile a mean gas temperature can be computed using

$$\langle T_{mean} \rangle = \frac{\int T(r) r dr}{\int r dr}. \quad (6)$$

Resonance frequencies were computed for every lamp as shown exemplarily for the reference lamp (1400 mm length) in figure 9. This figure also shows measured values for comparison which were taken from photo diode measurements presented in figure 6.

Figure 6. Measured light fluctuation spectrum at two different positions in the reference lamp driven with 25 kW. The strongest peaks correspond to the frequency of power input and its harmonics. The peak at 20 kHz lies close to a computed resonance frequency in the corresponding temperature region.

The measurements were carried out with the photo diode near the electrode and in the lamp center. A Fourier analysis of its signal delivered a light 'fluctuation spectrum' which reveals the resonance frequencies at a glance as described by Olsen [15]. Furthermore, in figure 6 it is evident that the light fluctuation amplitudes are not homogeneously distributed along the lamp axis.

The measured spectrum reflects also the spectrum of the driving signal. The prominent peak at 40 kHz is situated at the double driving frequency which corresponds to the frequency of power input. The peak at 20 kHz corresponds to the frequency of mode switching at the electrode (compare with figure 7). In our case the change between cathode and anode at low powers also showed a change of the arc attachment mode which alternated between a spot- and diffuse mode. This can be seen in figure 7 for one electrode observed during different phases of a current period. Due to horizontal lamp operation heat convection along the lamp axis was obviated leading to expected identical thermal conditions at the electrodes. For this reason the second electrode was not observed and is expected to behave the same, similar to observations in high pressure mercury lamps [23].

Figure 7. Phase resolved measurements of the arc attachment at the electrode of a high power lamp. The anode phase is shown on the left, the cathode phase on the right-hand side. The working frequency of 20 kHz corresponds to a period of 50 μ s. The images were taken with an exposure time of 10 μ s at 15 kW input power.

The lamp observed in figure 6 was driven with 25 kW power. This assured always a stable operation. Any increase of input power increased the temperature, any decrease could lead to instability. In this sense the lamp was operated near the borderline between the regions of stability and instability. Once an instability was established, it was not possible to get rid of it by further decreasing the power due to a strong hysteresis as shown in figure 8. Only a jump to much higher input power eliminated the instability.

Figure 8. Hysteresis of the 35 kW reference lamp.

A computation of resonance frequencies in dependence on temperature should agree with the measured peaks found in figure 6 and hence help to understand the lamp behavior with respect to stability. A comparison of measurement and computation is presented in figure 9. In this diagram the resonance frequencies are calculated using equations (1-4) for the reference lamp as a function of the temperature. Applying Gaussian error propagation to equations 1 and 2 the sensitivity between frequency and

temperature in terms of relative errors can be derived giving $\Delta^{rel} f = C \cdot 0.5 \cdot \Delta^{rel} T^{0.5}$, with C being a constant for longitudinal or transversal modes respectively. However, the more relevant source of uncertainty is the steep slope of the curves in the diagram.

The measured resonance frequencies in figure 9 are indicated by vertical lines. The slope of the calculated curves for different modes depends on the frequency - it is steep at low frequencies and becomes flat as the frequency increases. Due to the strong slope of the first resonance curve around 8 kHz the corresponding temperature interval is initially broad but it becomes relatively narrow if combined with the temperature intervals defined by the slope of the following resonance curves. Wall temperature measurements delivered values within an interval from 700 K to 1000 K leading to a mean temperature ranging from 3300 K to 3500 K.

Longitudinal resonances are located at much lower frequencies than transversal resonances of the same mode number. The first computed longitudinal mode starts at roughly 180 Hz at the corresponding mean temperature, whereas the transversal modes begin above several kHz. For this reason the longitudinal modes are not included in the diagram. This huge frequency spread between longitudinal and transversal modes is caused by the aspect ratio of this lamp type as the length and inner radius determine the frequencies in equation 1 and 2. Longitudinal modes seem to be dominant in the low frequency region which is consistent with the observation of lamps operated at 50 and 60 Hz, where the arc was stable in the first case and unstable in the second case as the slightly higher driving frequency or its harmonics were able to excite a resonance. On the other hand transversal resonances become important when the driving waveform contains a significant high frequency part [5].

For every intersection point between a measured resonance and the computed resonance curve a hysteresis of ± 500 Hz was assumed. This value is justified by experience operating HID lamps where a typical hysteresis had a width of roughly 1 kHz. Usually the hysteresis was much higher near strong resonances. With the assumed hysteresis a temperature interval linked to the respective resonance was defined. For subsequent resonance modes along the frequency axis the width of this temperature interval was successively reduced due to the decreasing slope of the resonance curves. Consequently, a narrow temperature interval with a mean temperature of about 3450 K was found which corresponds to an assumed wall temperature of 920 K.

On the other hand, if one would like to determine the mean temperature and therefore the pressure in the lamp it is useful to take more than one frequency for a precise calculation.

Many of the measured resonances were found to be located in the marked mean temperature interval calculated from the measured temperature profile. Ovals indicate measured frequency peaks for which such a computed resonance can not be found in the corresponding temperature interval. Beside the possibility of electrical distortions coupled to the signal a more satisfactory explanation can be given if wave coupling is taken into account, as a coupling of two waves can transfer energy to other frequencies [24]. In this case the missing correlation between measurement and computation

Figure 9. Calculated resonance frequencies compared with measured ones for the reference lamp at 25 kW. The resonance frequencies taken from figure 6 are indicated by the dotted vertical lines. Two mean temperatures result from two wall temperatures of 700 K and 1000 K respectively. A hysteresis of ± 500 Hz is assumed for the intersection points of calculated and measured frequencies at the mean temperature.

disappears if the driving frequency and its harmonics couple to the first transversal resonance mode. Within the relevant temperature interval its frequency lies roughly at 12 kHz. A coupling of the 20 kHz driving frequency leads to beat tones at the difference and sum frequencies with values of 8 kHz and 32 kHz respectively. The further coupling of the harmonics at 40 kHz and 60 kHz with the same mode leads to beat tones at 28, 52, 48 and 72 kHz covering all missing consistency.

The important finding for lamp operation is a computed resonance for $T = 3450$ K situated very near to the 20 kHz driving frequency. This is the main factor for lamp distortion and explains the observed behavior of flickering. The hysteresis in the lamp dysfunction as shown in figure 8 might be explained in such a way, that an increase of input power pushes the mean temperature upward increasing the distance to the resonance curve assuring stable operation. Reducing the input power lowers the mean temperature and the resonance approaches the driving frequency. For this particular lamp geometry this resonance curve is always crossed at the same input power (mean temperature) marking the transition between the regions of stable and unstable operation.

For the sake of completeness the formal possibility to correlate all measured peaks to resonance curves calculated for a much lower temperature T_{low} of roughly 1270 K should be mentioned. For this temperature all observed peaks in the measured spectrum could be assigned, neglecting wave coupling. However, the required colder mantel around the

hot central plasma, to allow the modes to exist, cannot be assumed as it would lead to an unrealistically low pressure for the particular lamp volume, mean temperature and fill.

5. Conclusion

The influence of length, inner radius and filling was investigated for high power lamps concerning their stable operation under power variation. All lamps behaved in a way corresponding to the picture of standing pressure waves. Best results were obtained with lamps of reduced inner radius. In this case the number of possible radial modes was effectively reduced and therefore the region of stable lamp operation considerably extended.

Peaks extracted from the measured light fluctuation spectra correspond well with transversal standing waves computed for the mean gas temperature. Considering wave coupling between the first transversal mode with the driving frequency and its harmonics beat tones occur which explain all additional measured peaks well.

Arc instability starts usually at the electrodes and is amplified when the resonance condition is reached, the excitation extends a certain level and lasts long enough to allow growth of the instability amplitude. In frequency space the resonance exhibit a Lorentzian profile [25, 26] with side bands which in principle allow a coupling of the resonance to distant excitation frequencies. This means that a lamp should be operated in a region far away from its acoustic resonances.

Our calculations revealed a resonance free window for frequencies below 20 kHz. This encouraged us to develop a new electronic ballast which should be able to vary the driving frequency in order to omit the lamp specific acoustic resonance frequencies. Consequently such a ballast (DIMAC, Diez) was built. With this prototype the driving frequency can be varied between 10 and 20 kHz with a maximum output power of 13 kW. Much higher driving frequencies in the range of some 100 kHz at which acoustic resonances should not occur [2, 27] were not considered as well as frequencies below the frequency of the lowest transversal mode due to special electrical properties of the ballast. Its high efficiency is optimized for the used frequency band.

First experiments with the new ballast are promising. Even though the development is not finished yet, it shows a good matching with the lamp and is able to avoid instabilities by changing the driving frequency.

Despite these good results it should be reminded that both the ballast and the lamp shape have to be adjusted in order to effectively avoid acoustic resonances as already stated in [2, 28].

Finally, our approach of looking for 'resonance free windows' seems to be a handy tool to estimate actual lamp behavior with respect to stability. The correlation between computed resonance frequencies, the mean temperature and geometry can be checked easily and adjusted in such a way, that acoustic resonances are not excited. This was successfully tested in additional experiments on different commercial 150 W type HID

lamps, where acoustic resonances were intentionally established or avoided.

Acknowledgments

We would like to thank the neoplas GmbH for all support and the good collaboration. This work was promoted within the PRO INNO II project of the Federal Ministry of Economics and Technology.

References

- [1] Bhosle S, Aubes M, Cristea M 2004 *Proc. of the LS-10*, Toulouse 2004, France, 35-40
- [2] Wada S, Okada A, Morii S 1987 *J.Ill.Engin.Soc.* 162-175
- [3] Witting HL 1978 *J. Appl. Phys.* **49** (5) 2680-2683
- [4] Bhosle S, Dalla C, Alonso JM, Lopes E, Calleja AJ, Ribas J 2005
Fourtieth Industry Applications Conference Annual Meeting, Conference Record
- [5] Jongerius MJ, Ras AJMJ, Vrehn QHF 1984 *J. Appl. Phys.* **55** (7) 2685-2692
- [6] Schäfer R, Stormberg HP 1982 *J. Appl. Phys.* **53** (5) 3476-3480
- [7] Davenport JM, Petti RJ 1985 *J.Ill.Eng.Soc.* **14** 633-643
- [8] Stromberg HP, Schäfer R 1983 *Light.Res.Technol.* **15** 127
- [9] Stockwald K, Kästle H, Weiss H 2008 *35. IEEE ICOPS*, Karlsruhe
- [10] Käning M, Schalk B, Hartel G, Hitzschke L 2004 *Proc. of the LS-10*, Toulouse, France, 405-406
- [11] de Groot JJ, van Vliet JAJM 1986
The high-pressure sodium lamp, Kluwer Technische Boeken B.V.
- [12] Strutt J W (Baron Rayleigh) 1896 *The Theory of Sound* MacMillan, London
- [13] Jahnke E, Emde F, Lösch F 1966 *Tafeln höherer Funktionen* Teubner Studienbücher, 7. Auflage
- [14] Collatz L 1990 *Differentialgleichungen* Teubner Studienbücher, Band 1, 7. Auflage
- [15] Olsen J, Moskowitz WP 1998 *IEEE IAS, St.Louis*, 2111-2115
- [16] Hartel G, Schöpp H, Hess H *et al* 1999 *J. Appl. Phys.* **85** 7076
- [17] Kettlitz M, Grossjohann R 2002 *J. Phys. D: Appl. Phys.* **35** 1702
- [18] Bartels H 1950 *Z. Phys.* **127** 243-273
- [19] Bartels H 1950 *Z. Phys.* **128** 546-574
- [20] Franke S, Schneidenbach H 2008 *J. Phys. D: Appl. Phys.* **41** 144016
- [21] Mentel J, Hülsmann HG 1987 *Phys. Fluids* **30** (7) 2266-2273
- [22] Stoffels WW, F. van den Hout, Kroesen GMW, Haverlag M, Keijser R 2006
Applied Physics Letters **99**
- [23] Böttcher R, Kettlitz M 2006 *J. Phys. D: Appl. Phys.* **39** 2715
- [24] Ritz Ch, Powers E, Bengtson R 1989 *Phys. Fluids B* **1** (1) 153-163
- [25] Baumann B, Wolff M, Hirsch J, Antonis P 2009 *J. Phys. D: Appl. Phys.* **42**
- [26] Hirsch J, Baumann B, Wolff M, Bhosle S, Barrientos RV 2010 *J. Phys. D: Appl. Phys.* **43**
- [27] Siessegger B, Guenther K, Gueldner H, Hirschmann G 2007
Proc. of the LS-11, Shanghai 2007, China, 389-390
- [28] Kettlitz M, Rarbach J, Zalach J 2008
IEEE Industry Applications Society Annual Meeting, Edmonton, Canada