Plasma diagnostics and simulations

Electrical diagnostics

Why to use electrical diagnostics in low temperature plasma physics?

Although the electrical diagnostics of discharges generating low temperature plasma can usually deliver only macroscopic and approximative results, some modern concepts can be very helpful for e.g. investigation of coronas or barrier discharges :

- novel current probes reach high sensitivity and time resolution at the same time » counting electrons and ions
- estimation of internal macroscopic plasma parameters using equivalent circuit models - dissipated energy and power, mean electric field, conductivity, mean electron density
- counting the electrons and ions with novel sensitive current probes
- enabled analysis of memory effects using the statistical analysis

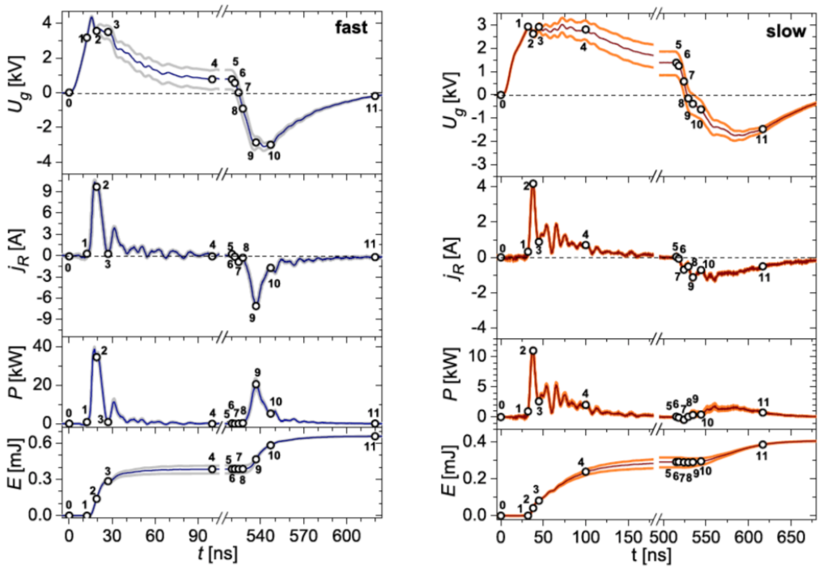

Figure 1: Determination of instantaneous parameters of nanosecond pulsed barrier discharge (faster and slower voltage slopes) in lower pressure argon using precise electrical measurements and equivalent circuit model. For clarification see further in the text. Taken from [1].

High-resolution and high-sensitivity current measurements

Electrical measurement of discharge current and voltage waveforms is a classical and sometimes the easiest way to access the dissipated energy or estimate the electron density in the generated plasma [6]. In the case of streamer-initiated discharges however, the temporal time-scales go to the sub-nanosecond level and the current amplitude in some pre-breakdown phenomena is in the order of few units of micro-amperes. For this task, we briefly describe some enhanced methodology and techniques we applied as supportive means which can confirm spectroscopically obtained results.

The first problem, as noted above, is the design of the proper setup which is able to detect low and fast changing signals. We adopted the methodology proposed in [7, 8] where a so-called coaxial design of the current probe was used. Similar experiments were done also in [9] or [10] where it was further improved with the statistical analysis. The coaxial setup minimizes the noise and oscillations in the signal due to the external influences. Only such an enhanced setup combined with high-tech oscilloscopes with sufficient bandwidth can lead to results capturing the fine features of the current signal under investigation. Such a setup was applied in our experiments also, during the investigation of both coronas [11], and barrier discharges [12]. The step at the leading edge of the current pulse of negative corona Trichel discharges in atmospheric pressure air can be resolved, which is a sign of well adjusted electrical measurements [11]. Study of this extremely fast feature of the current pulse enabled a deeper analysis of the fundamental mechanism of the Trichel pulse [13]. We correlated the current measurements with sub-nanosecond optical recordings and electric field development for the first time in [11] and contributed to the experimental understanding of the Trichel pulse corona discharge.

Comparision of commonly used current probes and coaxial probe

Most commonly used current probes are current transformers or Rogowski coils. Such probes measure derivation of the magnetic field surrounding the conductor induced by the current change.

The current transformer has a primary winding, an (iron) core, and a secondary winding. The advantage is that the output voltage is directly proportional to the current. The disadvantage is low sensitivity which comes hand to hand with the increased noise. Also, each transformer has a range of frequencies where it provides correct results and outside this range, you obtain incorrect amplitude and artificial phase shift. Last main disadvantage is the saturation of probe when the core becomes fully magnetized.

Rogowski coil has no core (eg. only rubber band) thus avoiding some of the current transformer problems at cost of making new ones. The main advantage is that Rogowski coil is easy application as you can just wind the coil wire around the conductor without the need of disconnecting the device. However as it has no core it requires the integration unit, which makes it difficult to use at high frequencies and adds up significant noise.

Above mentioned probes are based on the principle of a transformer of a kind, so they are principally unable to measure DC currents. The third option is to measure the current directly by introducing 'shunt' resistor and measuring the voltage drop on it. This approach has many benefits: it is cheap, have high sensitivity and low noise, can measure DC currents. BUT in case of over-voltage can easily burn down the oscilloscope, which is usually a much more expensive device.

Each design has advantages and disadvantages. In our recent work, we have analyzed two current transformer probes and coaxial design shunt probe using vector network analyzer Rohde&Schwarz ZVL13 to obtain frequency response and phase shift in 10 kHz to 1 GHz range.

Pearson current monitor is probably one of the most used current probes today. The important parameters here are the sensitivity of 1 Volt/Ampere and stated frequency range of 300 Hz-200 MHz. Tektronix CT-1 probe is an alternative to Pearson current monitor which allows going into higher frequencies with the sensitivity of 5 Volt/Ampere and stated frequency range of 20 kHz-1 GHz. Last is the coaxial design probe which is basically smartly designed **shunt**. In electronics, a **shunt** is a device which allows the electric current to pass around another point in the circuit by creating a low resistance path. We can measure voltage drop on this element and if we know the resistance of the shunt we can easily calculate the current as $I = U/R$.

The frequency responses for Pearson current monitor, Tektronics CT-1 current probe, coaxial design probe and 1 m long coaxial cable, which connected probes to the oscilloscope, were recorded and are shown in Fig. 2.

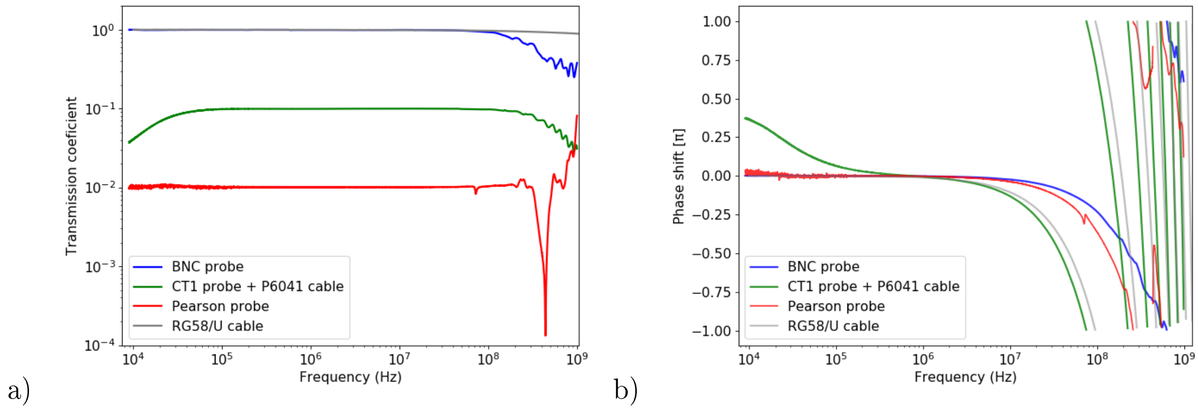

Figure 2: Transmission coefficient a) and phase-shift b) for each probe measured using network analyser. Note that CT1 probe which was hard-wired to P6041 cable, show similar response as *RG58/U cable.*

As seen from the graph the coaxial design probe has the highest transmission over the whole frequency range which provides the best signal to noise ratio. The transmission of the CT-1 probe is one order of magnitude lower and Pearson current monitor is two orders of magnitude lower than the coaxial design probe. This corresponds to the noise levels of the probes.

Coaxial design probe has flat frequency response up to 80 MHz where transmission starts to drop reaching approximately 30% of the maximum value at 1 GHz. CT-1 probe has the optimal transmission in the range from 40 kHz to 200 MHz. This may be an issue for measurements of the signal under 40 kHz range as the capacity currents in this region may be undervalued. Pearson current monitor results are in agreement with a user manual with optimal transmission coefficient in the range up to 200 MHz. For higher frequencies probe starts to behave rather erratically as there is sharp transmission coefficient drop at 0.45 GHz which we suppose corresponds to the resonant frequency of the Pearson probe internal circuitry.

Another part of the frequency analysis is the phase shift of the signal. Phase shift θ is an important parameter for determination of the absorbed power in discharge by multiplying current and voltage waveforms. Even a small change of phase-shift can severely change the resulting power calculation, especially for nanosecond pulsed discharges. In the high-frequency range, the phase-shift can affect even the pulse profile. Both Pearson current monitor and CT-1 probe act as inductances which is most notable in the low-frequency range. Pearson current monitor has small inductive phase-shift up to 10 MHz frequency. Again, in close vicinity of 0.45 GHz there is a rapid change where the signal undergoes phase-shift oscillation due to the resonance. The CT-1 probe measurement shows that it has over $\pi/4$ inductive phase-shift up to the frequency of several MHz as it could be expected from amplitude response. This may lead to incorrect capacitive current measurements and complicates analysis results for frequencies which are not in close range of 1 MHz. The coaxial design probe gives most steady results providing zero phase-shift up to 20 MHz. All probes show phase shift due to the dispersion towards higher frequencies, this contributes to delay of the pulse and causes effective broadening of the pulse. It is worth noting that a small part of the transmission and large part of phase shift changes at higher frequencies are due to the BNC cable distortion.

In principle each current pulse can be transformed from time domain to frequency space using Fourier transform and represented as an array of complex numbers (each half of the array is complex conjugate of the other half as we are performing Fourier transform on real numbers), where each value in the array determine amplitude and phase shift for given frequency. Given the calibration (known frequency and phase response of the probe) from network analyser presented

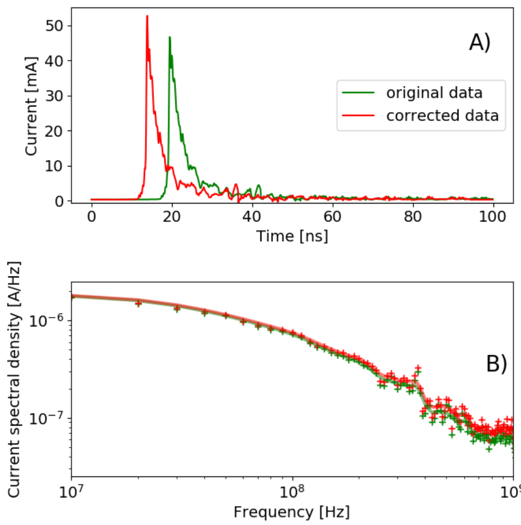

Figure 3: Original and corrected pulse signal a) and respective Fourier transformation amplitude b).

before we can correct the measured pulse by performing inverse Fourier transform. As we measure the signal using both probe and cable the equation was used as follows:

$$FT[f_{real}(\omega)] = \frac{FT[f_{meas}(\omega)]}{\sigma_{cable}(\omega)\sigma_{probe}(\omega)} \tag{1}$$

where $FT[f_{meas}(\omega)]$ and $FT[f_{real}(\omega)]$ are Fourier transformations of measured and real signal and $\sigma_{cable}(\omega)$ and $\sigma_{probe}(\omega)$ are frequency responses of *RG58/U cable* and probe.

As an example, we have carried out this operation for the results of the coaxial design probe measurement. For low-frequency part (capacitive currents) the changes were limited to a time shift of the whole data by approximately 6 ns back in time. This is due to Speed of light in vacuum is approx. $3{\cdot}10^8$ m/s while in *RG58/U cable* it is approx. $1.5{\cdot}10^8$ m/s this itself makes al least 6 ns. What is more important, however, mentioned delay is not counting in a signal dispersion which causes higher frequencies to propagate even more slowly. This can be seen on changes of current pulses (see Fig. 3) where the final shift is around 7 ns. Also, after the correction, the frequency dispersion of the pulse is removed, reducing the FWHM to 2.0 ns from 2.8 ns. The change of the integral over the pulse nevertheless, which gives the charge transfer during the discharge, was negligible.

By performing this correction of the current pulse the original current signal is obtained, i.e. as it entered and at the time it entered the probe. This fact is of great importance when operating with results of electrical measurement for power determination or synchronizing these measurements with results of other highly temporally resolved techniques (optical emission, absorption or laser spectroscopy).

Mutliple channel measurements

Most of the oscilloscopes use analog/digital converters which are in 8-10 (12[1]) bit range. This means that most information can be gathered by matching the signal maximum to maximum of the converter. A large part of the information about capacitive currents or low current discharges becomes lost or obscured by the readout and intrinsic noise. To counter this we can perform

[1] This usually utilizes some intricate internal post-processing as interpolation which may not be desired as beneficial in all cases.

simultaneous measurement of probe signal in two different ranges on two oscilloscope channels with different gain - eg. one range optimized for high current pulses and second optimized for low current pulses and capacitive current. One should be careful to prevent long term input overload as it might result in signal saturation or oscilloscope damage. The are two issues here; a) we have to be certain that we don't over-saturate the channel with high gain (eg. make sure that it returns to normal value immediately after discharge pulse), b) we have to match the overall impedance to impedance of the probe (eg. if we use two channels in parallel and the probe expects 50Ω we use the 1MΩ impedance of the first channel and 50Ω on second.)

Finally, such measurement of both channels can be then merged into one data stream while it is necessary to correct the delay between each input cable lengths.

Equivalent circuit for barrier discharges: the simplest one

In the case of electrical characterization of barrier discharges, one has to deal with the capacitive nature of the system. The current and voltage measured in the external circuit are not the real values physically present in the gas gap [2, 3]. This makes the analysis more complex in comparison to the corona or spark discharges where the electrodes are in direct electrical contact with the plasma. Typically, an equivalent circuit has to be applied using the Kirchhoff equations to decouple the net discharge characteristics from the recorded signals [3, 4, 5]. The net discharge current, gas gap voltage, net transferred charge, and instantaneous power can be obtained. The gas gap voltage is of special importance, as it gives the temporal development of the value of the average electric field in the gas gap if divided by the gap size. The scheme of the equivalent circuit discussed by Pipa et al. [5] is shown in figure 4.

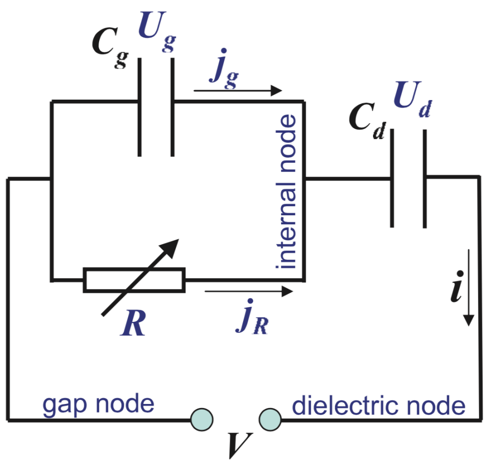

Figure 4: Scheme of the simplest equivalent circuit as investigated by Pipa et al. in [5]. Taken from [1].

The computations then give following equations for internal net discharge current, transferred charge and gap voltage on the plasma:

$$j_R(t) = \frac{1}{1 - C_{cell}/C_d}\left[i(t) - \frac{\mathrm{d}V(t)}{\mathrm{d}t}C_{cell}\right] \tag{2}$$

$$q(t) = \frac{1}{1 - C_{cell}/C_d}\left[Q(t) - C_{cell}V(t)\right] \tag{3}$$

$$U_g(t) = V(t) - \frac{Q(t)}{C_d} \tag{4}$$

where $j_R(t)$, $q(t)$ and $U_g(t)$ are the net discharge current, transferred charge and gap voltage, which are of interest. The C_{cell} and C_d are characteristic capacitances of electrode cell arrangement and of dielectric, respectively. $V(t)$, $i(t)$ and $Q(t)$ are voltage, current and charge (integrated current) measured in the external circuit. For exact description see in figure 4 and in [5].

Experiments

In the following two experiments, the student will deal with two issues connected to the modern electrical diagnostics of barrier discharge plasma. The first one is related to the test of the different types of current probes themselves and to compare their advantages and disadvantages.

The second issue will be the application of the electrical probes onto the volume barrier discharge in ambient air. The aim is then to record the precise waveforms of electrical current and voltage for a few voltage amplitudes for further analysis using the equivalent circuit model. The exact implementation of the below-given points will be carried out under the supervision of the specialist.

The resulting report from these investigations should contain relevant short introduction based on the student individual literature research, data evaluation based on the recommendations and literature given by the supervisor and commented results and their discussion.

Tests and performance of the electrical probes

1. Use frequency generator to produce different voltage shapes and evaluate the probe response (eg. sine waveforms at different frequencies, short rectangular pulses, ...)
2. Use the multi-channel measurement on DBD discharge to record simultaneously data in different gain ranges
3. Merge the data into one dataset

Plasma properties of the volume barrier discharge

1. Recording of the electrical current and voltage signal for volume barrier discharge in atmospheric air for few voltage amplitudes. Application of the know-how obtained in the first part of this task for precise current measurements.
2. Analysis of the recorded data using the simplest equivalent circuit model [1, 3, 14, 5] and determination of intrinsic discharge parameters of the investigated system.
3. Discussion of the applicability of the simplest equivalent circuit under given conditions and comparison with the more complex yet more exact model of Peeters et al. [15]. The discussion should consider the macroscopic and the microscopic approaches to the problem.

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