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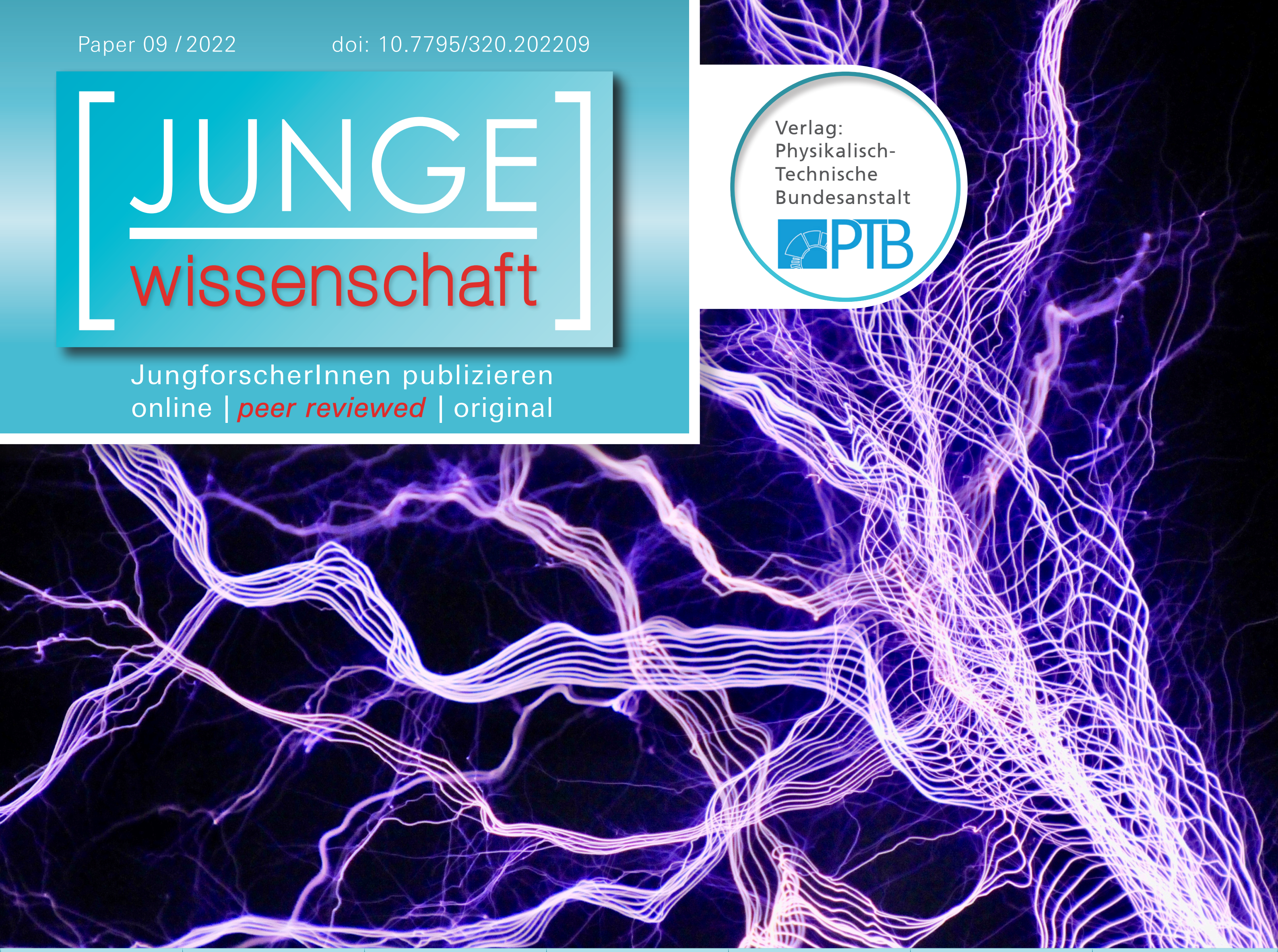

Physik

Making Music with Discharges

Development of an Audio Modulated Tesla Coil

A powerful high voltage generator was built that can produce discharges of about one meter. This high voltage transformer can be driven in such a way that audible pressure waves can be generated by the electrical discharges. Normal high-voltage measuring devices cannot be used for this sensitive system. Therefore, two measuring methods were developed.

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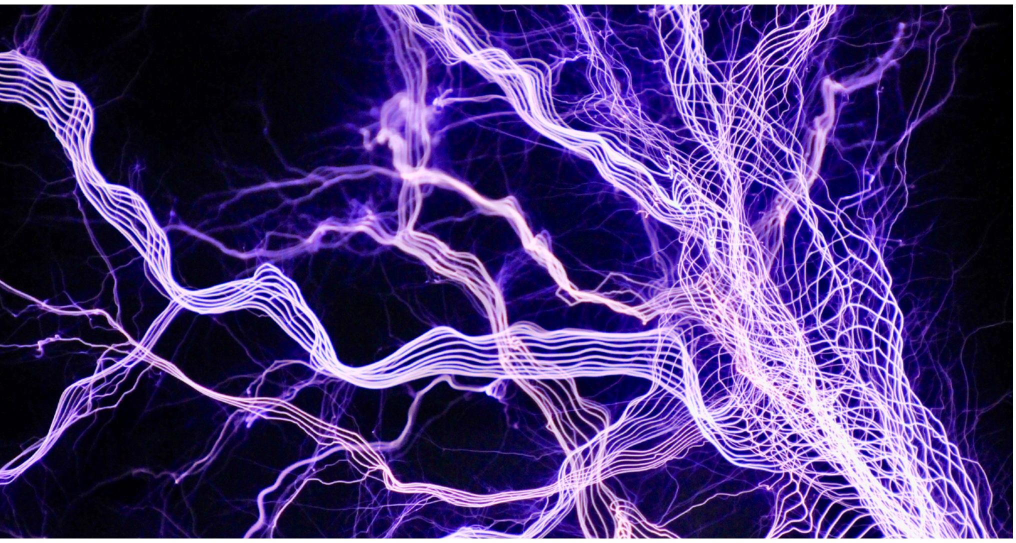


Making Music with Discharges

Development of an Audio Modulated Tesla Coil

1. Introduction

Nikola Tesla developed the first Tesla coil with the vision of providing the whole world with wireless electricity. This first Tesla coil is now known as Spark Gap Tesla Coil (SGTC) and is essentially a high-voltage transformer that generates impressive discharges through a physical spark gap and transmits energy through the air. As all wireless power transmission systems are subject to large losses, the Tesla coil had no future and was never used in industry or in the power grid. Today, the Tesla coil is mainly used for research purposes and as a display object. Due to the generated, impressive high voltage discharges as shown in Fig. 1, a community of electrical engineers and hobbyists formed, who constantly developed and improved the Tesla coil.

Today, there are various types of semiconductor-controlled Tesla coils that were developed in the 1980s. One of the first semiconductor controlled, rather low power Tesla coil is called Solid State Tesla Coil (SSTC). The SSTC has only one oscillating circuit. The electronics usually automatically adjust to the resonant frequency of the one resonant circuit. However, it was not until around 2005 that the development of the first Dual Resonant Solid State Tesla Coils (DRSSTC) enabled a similar performance to the original SGTC.

Unlike Nikola Tesla's SGTC, the DRSSTC can be driven very precisely and is controlled by high-precision and high-performance semiconductors. The special feature of DRSSTC is that their power electronics consist of two magnetically coupled resonant circuits, the primary and secondary resonant circuits, whose resonant frequencies are tuned to each other. The primary resonant circuit is set into forced oscillation, such that high AC currents flow through the primary coil at its resonant frequency. Due to the changing magnetic field in the primary coil, an energy exchange takes place to the secondary coil as given by Faraday's law of induction. This power transfer is adjusted such that it leads to high voltages in the secondary circuit, which result in discharges of this secondary voltage at the top load into the environment.

High-power transistors (Insulated Gate Bipolar Transistor (IGBT)) are used as switches. These semiconductor modules change from a blocking state to a conducting state to create a pulsed excitation. These voltage pulses created by an interrupter can be audio modulated due to the digital and very precise control of the semiconductors [1]. Further, the IGBTs can be driven in such a way that audible pressure waves, and thus music, are generated by the electrical discharges at the high-voltage electrode (Video 1).

The aim of this work was to investigate how a DRSSTC can be developed and built. In the following, the main modules important of the DRSSTC are introduced. After successful construction of the DRSSTC, it was of special interest to measure the electrical voltage of 200,000 V of the discharges, which changes sign more than 100,000 times per second. Two different measurement methods to determine this voltage were used and compared.

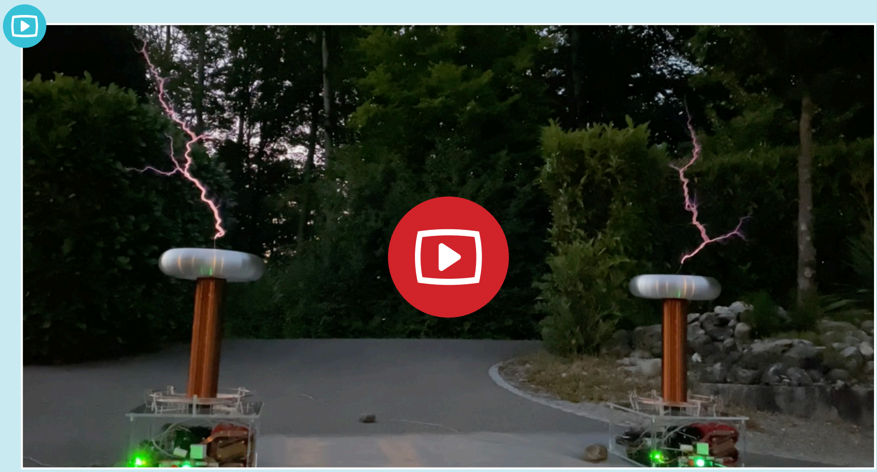
2. Operation of a DRSSTC

In the schematic diagram of a DRSSTC in Fig. 2, the power flow can be traced from the socket to the discharge. The input power control regulates the current flowing into the DC power supply. The DC power supply are electrolytic capacitors. The self-resonant driver (gate driver) is like a computer that monitors the whole system (with feedback transformers) and turns off the Tesla coil when needed. The self-resonant driver controls the switching circuit. The switching circuit is the transistors, which in turn switch the DC power supply at the resonant frequency of the Tesla coil via the primary resonant circuit.

3. Engineering Process

The most important components and considerations are explained to provide an overview of the development process of the self-constructed DRSSTC. The Tesla coil consists of different modules that all have to work together perfectly. Particularly, each module must be precisely matched to all the others and only then they can function optimally together as a whole in a system. In the following, the three most important modules and their interaction are explained. The completely constructed DRSSTC can be seen in Fig. 3.

All measurements in this paper utilized the Keysight's DSOX1204G, 200 MHz, 2 GSa/s oscilloscope. In addition, the signal generator of this oscilloscope was always used.



Vid. 1: The two Tesla coils play Badinerie (Suite No. 2 BWV 1067) by Bach in duet.

3.1 Gate Driver

The gate driver is the central control and monitoring unit of the DRSSTC. It controls the transistors, so that the primary resonant circuit can be set into oscillation. It is also responsible for monitoring the primary current and switches off the Tesla coil at a defined overcurrent [2].

Fig. 4 shows the basic operation of a gate driver. It measures the resonant frequency at the current transformer depicted in grey and delays the received signal through the buffer. Based on this input signal, the gate driver sends the control signal to the gates of the transistors and puts them either in the conducting or blocking state. When the interrupt signal ends or an overcurrent is detected, the gate driver turns off the transistors in the upcoming zero current crossing.

The most important step in the construction of a reliable and high-performance Tesla coil is a robust and well-functioning gate driver. The first DRSSTC driver was developed over 10 years ago by Steve Ward. It fulfills the key requirements for a gate driver and was implemented in the first circuit he called Universal Driver, or UD [2]. Its improved version, the UD1.3b, has established itself as a robust and reliable standard gate driver to this day, essentially displacing all other gate drivers. Over the years, the original gate driver has been continuously

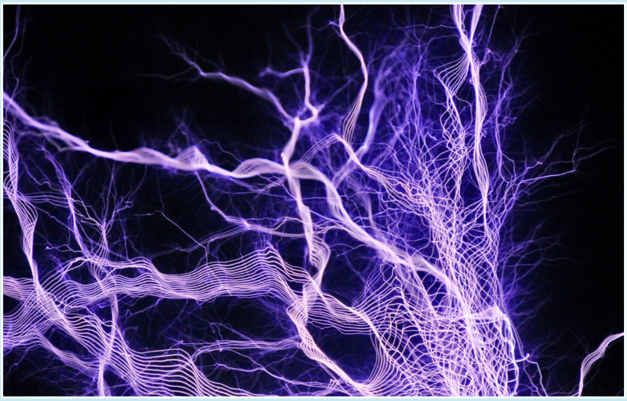


Fig. 1: Close-up of the discharges to be measured.

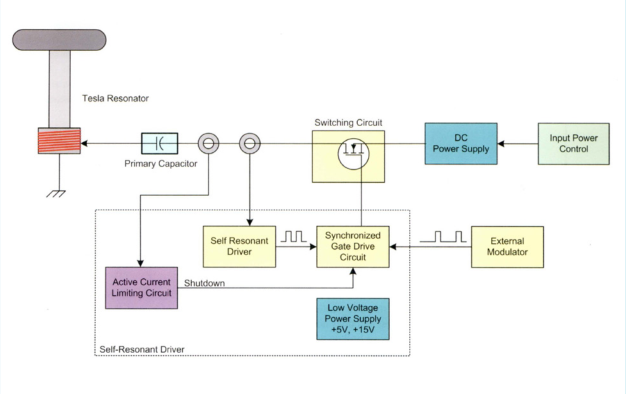


Fig. 2: Schematic representation of a DRSSTC. (source: [1], p. 195)

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Fig. 3: An audio modulated DRSSTC with medium power output and characteristic toroidal top load.

improved and developed by the Tesla coil community. The schematics and documentation of each gate driver are freely available [3].

Nowadays, the most popular and reliable version is the UD 2.7C by Gao Guangyan [3]. The UD 2.8 developed in this work represents a slightly modified version of the UD 2.7C. The logic and the basic structure of the circuit were retained. Only the smallest changes were made, such as the adjustment of individual resistors when slightly different components were used. The circuit diagram of the new UD 2.8 is shown in Fig. 5.

3.2 IGBT Module

The Insulated Gate Bipolar Transistors (IGBT) in a DRSSTC act as inverters and generate a square wave AC voltage for the primary resonant circuit.

For this DRSSTC, the CM300DY-24H IGBT half-bridge module from Powerex was used [4]. The CM300DY-24H has proven to be a reliable IGBT for DRSSTCs and was therefore chosen for this work [5]. Further, the CM300DY-24H is already an IGBT half-bridge module in which two individual IGBTs are installed. This compact form results in less parasitic inductances.

The IGBT half-bridge module can switch sustained currents of up to 300 A. However, this is a problem, because a DRSSTC requires currents of over 300 A to be quickly switched. Specifically, simulations of the Tesla coil have shown that currents of up to 3 kA can occur if the circuit is not limited. For this reason, the gate driver always switches the IGBTs at zero current. Thus, the CM300DY-24H IGBT can practically switch currents of up to 1 kA. The IGBT was mounted on a heat sink and connected to the rest of the components as shown in Fig. 6 [5].

3.3 Interrupter

When the IGBT half-bridge permanently sets the primary oscillating circuit into a forced oscillation, high currents are generated within a very short time. To prevent the components from being overloaded by excessive voltages and currents, the Tesla coil is not operated in a continuous wave mode but is continuously interrupted at a clock frequency. For this constant interruption, as implied by the name, the interrupter is responsible.

This external modulator sends short pulses to the gate driver, in which the coil should turn on and immediately turn off again. Such a switch-on sequence usually lasts between 30 and 300 µs. During this time, the primary resonant circuit is excited and power is transferred to the secondary resonant circuit. This results in a voltage overshoot at the toroidal top load, which consequently leads to a discharge. The length of these signals is defined as the so-called pulse width (Fig. 7). Depending on the system used,

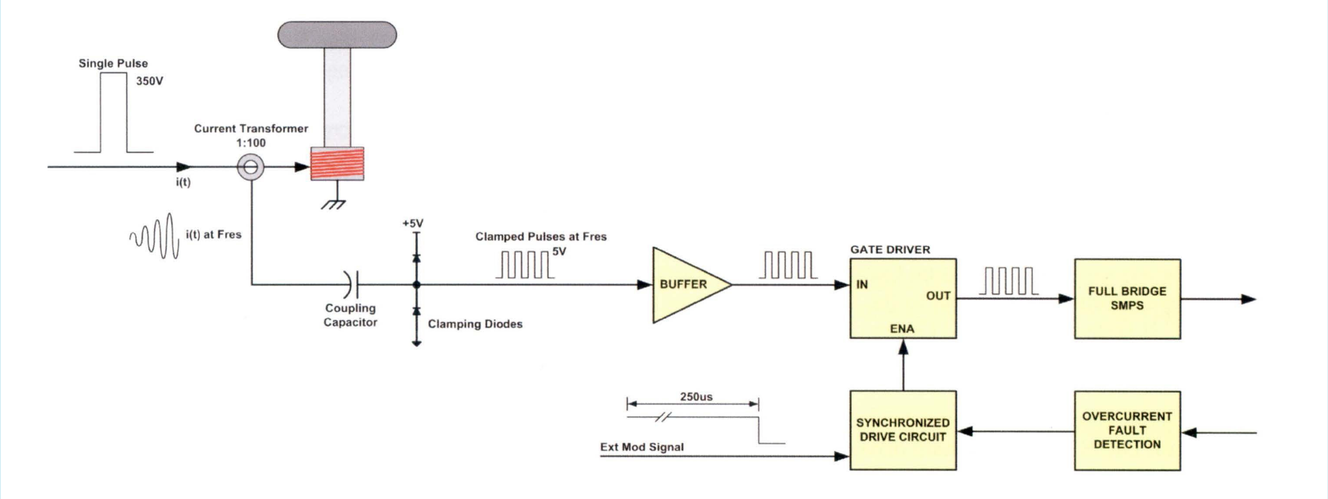

Fig. 4: Basic operation of the gate driver in schematic representation [source: [1], S.196)

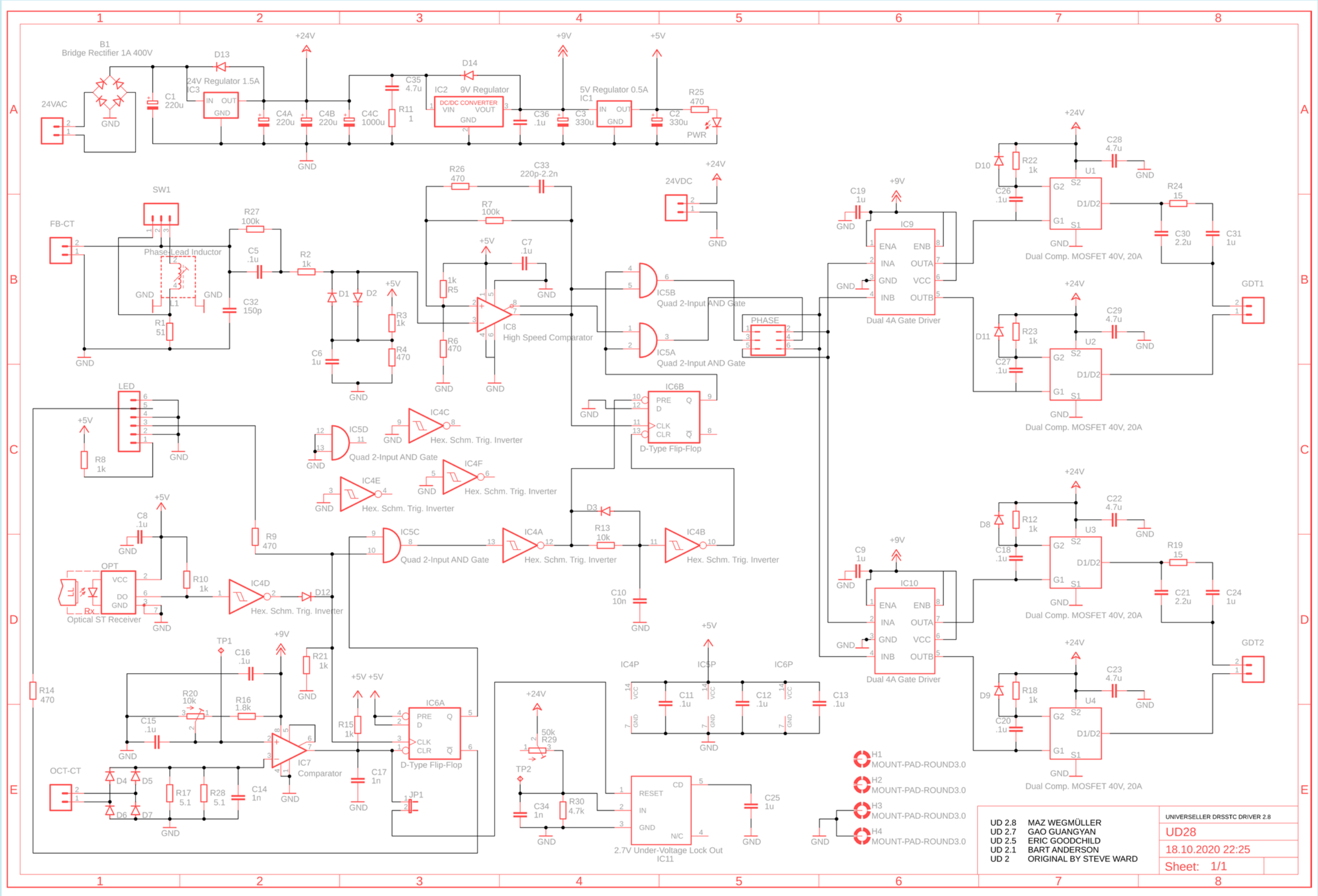

Fig. 5: The circuit diagram of the new UD 2.8, which is basically identical in construction to the UD 2.7 C.

the pulse width has an influence on the size and type of the discharges. A longer pulse width and thus a longer transient phase leads to a larger power transfer and thus to stronger and longer discharges. Overall, each pulse corresponds to a voltage discharge at the Tesla coil, which emits a characteristic and loud bang [6].

Now, several of these pulses can be sent to the DRSSTC in succession, which leads to regular discharges at the top load. If this happens in a periodically repeating process, we speak of a frequency. The discharges are therefore controlled at this pulse frequency. If this pulse frequency is between 20 Hz and 20,000 Hz, i.e. in the audible frequency range of humans, sounds can be played with the discharges. For example, if the pulse frequency is set to 440 Hz, 440 discharges per second are produced. At this frequency, the loud bangs of the individual discharges are perceived as sound. In this example, the concert pitch A (a′) will be heard [7, 8].

In summary, the interrupter is essentially an external pulse frequency and pulse width modulator. Fig. 7 illustrates the pulse width and pulse frequency. During the duration of the pulse width, the resonant frequency of the oscillating circuit is excited. Such signals are sent by the interrupter in the form of a light pulse through a fiber optic cable to the gate driver. Without the interrupter, it would not be possible to drive the Tesla coil. The interrupter controls the final signals for the discharges and thus represents the last control instance by the user of the DRSSTC [9].

4. Measurement of the Secondary Voltage

For measuring an electrical voltage of 200,000 V, which changes sign more than 100,000 times per second, two different approaches were followed.

Conventional high-voltage measuring instruments cannot be used for a Tesla coil, as an additional measuring probe on the top load increases the secondary capacitance and thus changes the resonant frequency of the sensitive system. Consequently, an incorrect voltage would be measured which does not correspond to the fine-tuned DRSSTC. For this reason, other approaches must be considered to measure the voltage accurately and without disturbing the system.

In the following sections, two fundamentally different measurement

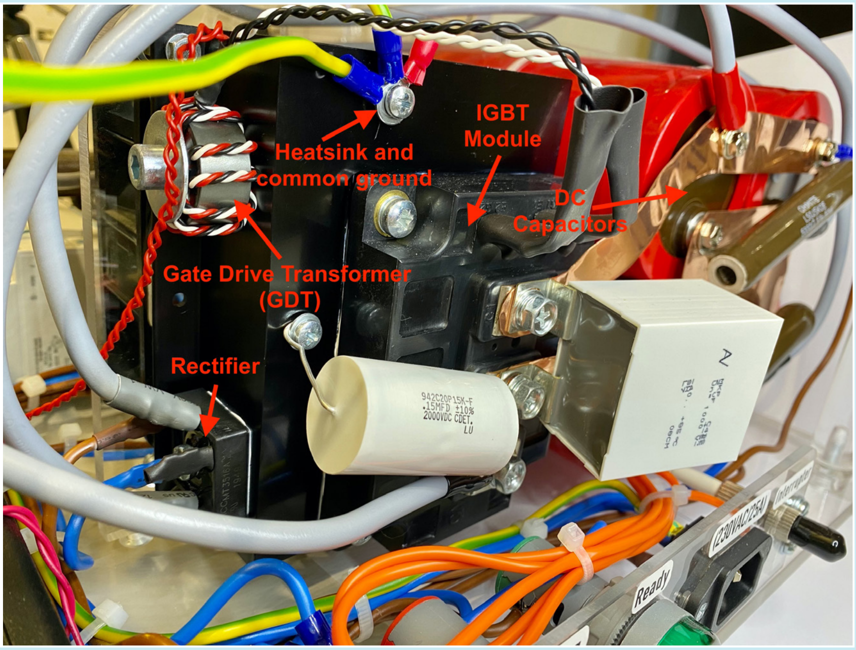

Fig. 6: The CM300DY-24H IGBT module mounted on the grounded heat sink.

methods for secondary voltage determination are presented. In the first approach, the secondary voltages were calculated via the measured secondary current. In the second experimental setup, the voltage was measured via the divider ratio using a self-developed measuring electrode.

4.1 Voltage Calculation via Secondary Current Measurement

An indirect way to determine the voltage of a Tesla coil is the secondary current measurement. Subsequently, the secondary voltage is calculated from the secondary current using the following formula [10]:

$$\hat{U}_2 = 2\pi f L_2 \hat{I}_2 \qquad (1)$$

where L_2 is the inductance of the coil in the secondary resonance circuit, f is the resonant frequency and $\hat{I}_2$ is the amplitude current of the secondary circuit.

L_2 was calculated as 63.58 mH using the specific dimensions of the coil. To measure the resonant frequency f and the secondary current $\hat{I}_2$, the Wide Band Current Transformer 411 from Pearson Electronics was connected to the ground of the Tesla coil as shown in Fig. 8. As long as the primary resonant circuit is not excited, no current flows through the ground. Thus, the measurement takes place exclusively when the voltage at the toroid discharges and the primary resonant circuit is excited.

The Tesla coil was operated at a pulse frequency of 300 Hz and a pulse width of approximately 60 µs. At a pulse width of more than 60 µs, the over current detection would be triggered by the gate driver. Depending on the shape and characteristics of the space in which the Tesla coil is operated, the secondary capacitance can change significantly. As a result, the resonant frequency may change and the transformer may no longer be accurately tuned. Therefore, the transformer was operated outdoors so that the environment would have as little influence as possible on the secondary capacitance.

The evaluation of the measurement results as seen in Fig. 9 shows that a secondary current $\hat{I}_2$ of 3.65 A flowed through the ground with a resonant frequency f of 130.38 kHz.

The secondary voltage can now be approximately calculated: Formula (2).

The amplitude voltage of the discharges is approximately $\hat{U}_2$ = 190 kV, which is a realistic value for a DRSSTC in this power category [10].

4.2 Voltage Measurement via Measuring Electrode

The voltage measurement via an electrode connected to an oscilloscope, which is placed some meters away from the Tesla coil, shows a fundamentally

$$\hat{U}_2 = 2\pi f L_2 \hat{I}_2 = 2\pi \cdot 130{,}380\ Hz \cdot 63.58 \cdot 10^{-3}\ H \cdot 3.65A = 190{,}109\ V$$

Formula (2)

$$|r| = \sqrt{\left(1+\frac{C_i}{C_k}\right)^2 + \left(\frac{1}{\omega R_i C_k}\right)^2} \approx 1+\frac{C_i}{C_k}, if\ \omega R_i C_k \gg 1$$

$$\measuredangle r = -arctan\left[\frac{\frac{1}{\omega R_i C_k}}{1+\frac{C_i}{C_k}}\right] \approx 0, if\ \omega R_i C_k \gg 1$$

Formula (3)

different measurement approach. The aim is to calculate the divider ratio r between the secondary voltage U_{sec} and the measured oscilloscope voltage U_{osc}. The divider ratio r can then be multiplied by the oscilloscope voltage U_{osc} to obtain the secondary voltage U_{sec}.

There are three major advantages of voltage measurement via a measuring electrode: First, there is no physical contact with the Tesla coil, such that significant interference with its operation is avoided. Second, the electrodes are cheap and easy to manufacture. Third, if the values and thus the divider ratio are correct, the measuring electrode offers a very precise and reliable method of measuring secondary voltages.

Fig. 10 shows a simulation of the experimental setup by *LTspice XVII from Analog Devices* [11]. The simulation was provided by Dr. Raphael Färber from ETH Zurich. Using the simulation, the quantities to be measured can be estimated and also the phase shift due to the coupling capacitance between the electrode and the Tesla coil C_k can be investigated.

The principle and operation of the measurement is relatively simple. The electrode is connected to the oscilloscope and consists only of a copper plate, which has a coupling capacitance C_k to the top load. The current I flowing through the impedance Z_{high} (impedance of the coupling capacitance C_k) and input impedance Z_{low} (R_i and C_i) of the oscilloscope is constant over the whole experimental setup. The constant current I now allows for the divider ratio r between the secondary voltage U_{sec} and the measured oscilloscope voltage U_{osc} to be calculated if the impedances Z_{low} and Z_{high} are known.

Fig. 11 shows the simulated oscilloscope voltage U_{osc} in blue and the phase shift $\measuredangle r$ as a green line in a frequency response plot. When inputting a secondary voltage of 200 kV, it is evident from the

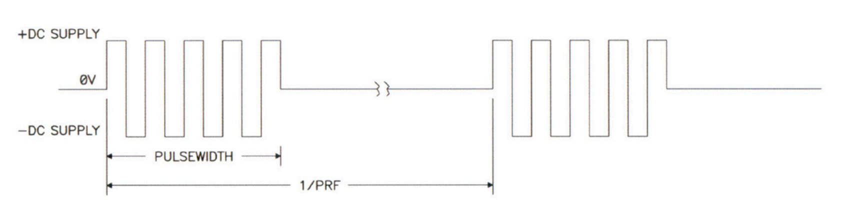

Fig. 7: During the pulse width of the interrupt signal, the bus voltage is switched via the primary oscillating circuit. (source: [1], p.104)

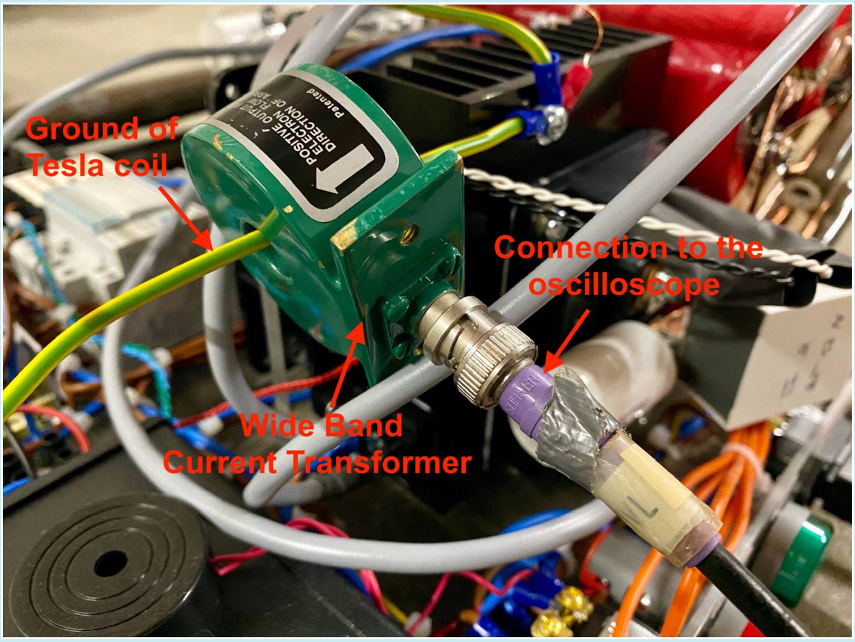

Fig. 8: A current transformer was used to measure the secondary currents $\hat{I}_2$ and the resonant frequency f at ground.

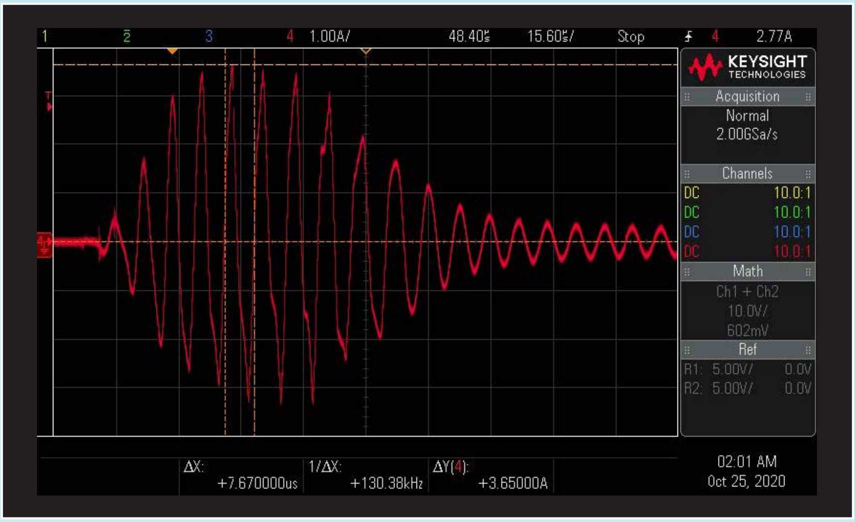

Fig. 9: Measurement result of the secondary current measurement.

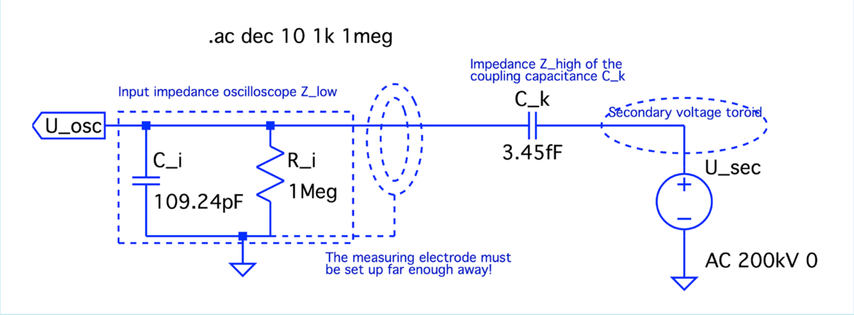

Fig. 10: Simple LTspice simulation of voltage measurement via a measuring electrode.

simulation result that the phase shift is negligible at a resonant frequency of 130 kHz and voltages of about 6.3 V can be expected.

The experimental setup is simple and mainly consists of the measuring electrode, the connecting cable and a small gas discharge tube to protect the oscilloscope. The complete experimental setup can be seen in Fig. 12. The Tesla coil is visible in the background at a safe distance from the measuring electrode. Specifically, the electrode was placed 3.5 m away and at the same height as the toroid. The measuring electrode was mounted on a camera tripod and connected to the oscilloscope via a coaxial cable. A gas discharge tube is soldered onto a PCB board, which was connected directly to the oscilloscope and the coaxial cable. The measured voltage is displayed on the oscilloscope.

The magnitude of the divider ratio $|r|$ and the phase shift $\measuredangle r$ can be derived from the coupling capacitance C_k, input capacitance C_i and input resistance R_i [10].

The magnitude $|r|$ and the phase shift $\measuredangle r$ are thereby: Formula (3).

Compared with the simulation from Fig. 10 and 11, the result agrees with the derivation of the divider ratio and the phase shift. At very high frequencies, the phase shift can be neglected.

The input resistance R_i of the oscilloscope was given in the technical specifications as 1 MΩ. Further, to determine the input capacitance C_i, the individual capacitances of the experimental setup must be added together. The individual capacitances are arranged in parallel from the measuring electrode to ground and can thus be added together to obtain the total input capacitance C_i. The oscilloscope had an input capacitance of 16 pF. The RG-174 coaxial cable had an inherent capacitance of about 101.97 pF per meter. Thus, the 91.44 cm long coaxial cable with BNC connector had a capacitance of 93.24 pF. Consequently, the input capacitance C_i was [12]:

$$C_i = C_{Cable} + C_{Osci} = 109.24\ \text{pF} \tag{4}$$

The coupling capacitance C_k can be estimated mathematically by an approximation of a spherical capacitor. The electric field constant is $\varepsilon_0 = 8.854 \cdot 10^{-12} \frac{As}{Vm}$, R_T is the radius of the toroid (corresponds to the inner sphere of the spherical capacitor) and R_M is the distance from the center of the toroid to the measuring electrode (corresponds to the radius of the outer sphere of a spherical capacitor). The capacitance of a spherical capacitor C is given by [11]:

$$C = \frac{4\pi\varepsilon_0}{\frac{1}{R_T} - \frac{1}{R_M}} \tag{5}$$

The surface of the outer sphere is given by:

$$A = 4\pi R_M^{\ 2} \tag{6}$$

The measuring electrode area A_M is a fraction of the large sphere area:

$$C_k = \frac{A_M}{4\pi R_M^{\ 2}} \cdot \frac{4\pi\varepsilon_0}{\frac{1}{R_T} - \frac{1}{R_M}} \tag{7}$$

The measuring electrode had a square size of 15 cm side length. The measuring electrode area was therefore $A_M = 0.0225\ \text{m}^2$. As mentioned in the experimental setup, the distance

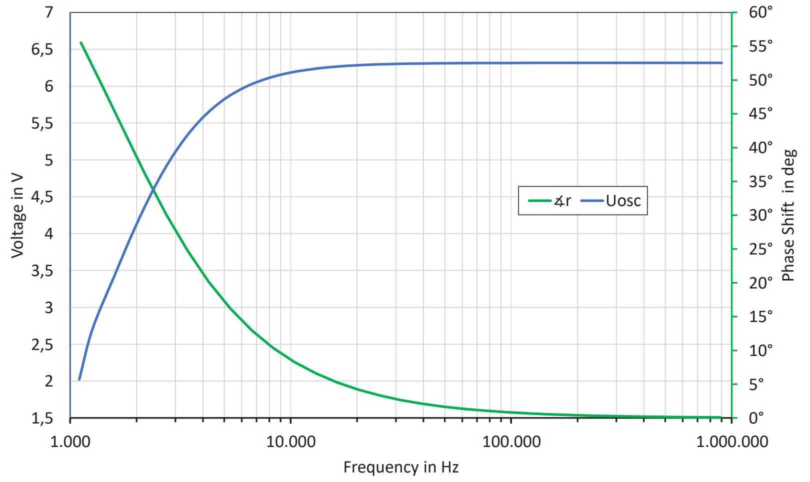

Fig. 11: The simulation result of the voltage measurement via a measuring electrode.

Fig. 12: The experimental setup of the voltage measurement via a measuring electrode.

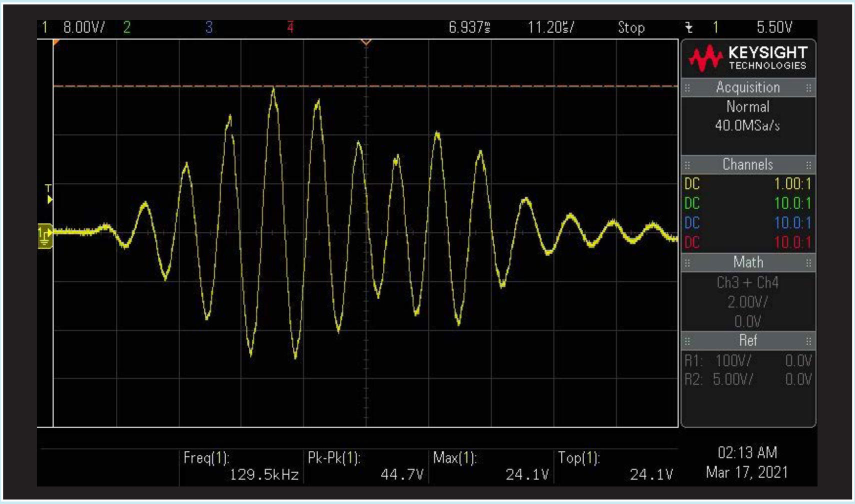

Fig. 13: The voltage measurement at the measuring electrode.

between the center of the toroid and the measuring electrode was R_M = 3.5 m. The toroid had a diameter of 40 cm, following is R_T = 0.2 m. Because the secondary capacitance is slightly increased by the discharges, this approximation assumes that the toroid is a sphere. Consequently, this corresponds to a coupling capacitance C_k of:

$$C_k \approx 3.450 \text{ fF} \tag{8}$$

The Tesla coil was operated using the same pulse frequency of 300 Hz and pulse width of about 60 µs as used for the determination of the voltage via secondary current measurement. As before, the Tesla coil was operated outdoors, so that the environment had as little influence as possible on the secondary capacitance.

The evaluation of the measurement result in Fig. 13 shows that the resonant frequency f is about 130 kHz and the measured voltage peaks of U_{osc} are about 24 V. The divider ratio $|r|$ can now be calculated from the calculated capacitances, the measured resonant frequency of 130 kHz and the input resistance R_i of 1 MΩ: Formula (9)

The secondary voltage U_{sec} is now given by multiplying the divider ratio $|r|$ by the oscilloscope voltage U_{osc}:

$$U_{sek} = |r| \cdot U_{osc} \approx 760{,}000 \text{ V}$$

With this measurement method, the calculated secondary voltage via divider ratio determination is U_{sec} = 760,000 V, which is a very high and rather unrealistic value for a DRSSTC of this size.

5. Discussion and Conclusion

A fully functional DRSSTC was constructed, whose main components include an adapted gate driver, an IGBT half-bridge module and an audio modulated interrupter.

Two fundamentally different methods were presented to measure the discharges of a Tesla coil, which change sign more than 100,000 times per second. The problem of not being able to use conventional high voltage measuring instruments due to their disruptive effect on the system has been solved by these methods. However, it is noticeable that the results differ greatly, as the secondary voltage was determined as about 200 kV via secondary current measurement, while the electrode-based method yielded a value of 760 kV.

A secondary voltage of 200 kV resulting from secondary current measurement can be considered realistic for the observed discharge lengths of about 1 m. Consequently, the calculated voltage based on the electrode measurement of 760 kV is far above a realistic voltage, which means that the calculated divider ratio |r| must be too high. The source of error probably lies in the assumed value of the coupling capacitance between toroid and measuring electrode, which was only able to be determined approximately within the scope of this work. As a solution to nonetheless use the measuring electrode for the voltage measurement, the divider ratio could be calibrated over the 200 kV. For an independent measurement method, the coupling capacitance would have to be determined with a 3D E-field simulation.

$$|r| = \sqrt{\left(1 + \frac{C_i}{C_k}\right)^2 + \left(\frac{1}{\omega R_i C_k}\right)^2} \approx 31{,}666.76$$

Formula (9)

However, apart from absolute voltage measurements, the measuring electrode can also be used to study relative voltage waveforms, which do not require absolute quantities. Overall, with the development and construction of these Dual Resonant Solid State Tesla Coils (DRSSTC) and the associated measurement technology, the foundation was laid for many other interesting investigations and measurements.

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Appendix

The appendix can be accessed digitally on the Internet via the following URL:

https://drive.google.com/drive/folders/1le4WvCgWcIhyMEIzKRgoVSQzY8EVamUY?usp=sharing.

There are more pictures, videos, measurements and the CAD drawings of the plexiglass parts stored on the Google Drive folder.

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In der Jungen Wissenschaft werden Forschungsarbeiten von SchülerInnen, die selbstständig, z. B. in einer Schule oder einem Schülerforschungszentrum, durchgeführt wurden, veröffentlicht. Die Arbeiten können auf Deutsch oder Englisch geschrieben sein.

Wer kann einreichen?

SchülerInnen, AbiturientInnen und Studierende ohne Abschluss, die nicht älter als 23 Jahre sind.

Was musst Du beim Einreichen beachten?

Lies die Richtlinien für Beiträge. Sie enthalten Hinweise, wie Deine Arbeit aufgebaut sein soll, wie lang sie sein darf, wie die Bilder einzureichen sind und welche weiteren Informationen wir benötigen. Solltest Du Fragen haben, dann wende Dich gern schon vor dem Einreichen an die Chefredakteurin Sabine Walter.

Lade die Erstveröffentlichungserklärung herunter, drucke und fülle sie aus und unterschreibe sie.

Dann sende Deine Arbeit und die Erstveröffentlichungserklärung per Post an:

Chefredaktion Junge Wissenschaft
Dr.-Ing. Sabine Walter
Paul-Ducros-Straße 7
30952 Ronnenberg
Tel: 05109 / 561508
Mail: sabine.walter@verlag-jungewissenschaft.de

Wie geht es nach dem Einreichen weiter?

Die Chefredakteurin sucht einen geeigneten Fachgutachter, der die inhaltliche Richtigkeit der eingereichten Arbeit überprüft und eine Empfehlung ausspricht, ob sie veröffentlicht werden kann (Peer-Review-Verfahren). Das Gutachten wird den Euch, den AutorInnen zugeschickt und Du erhältst gegebenenfalls die Möglichkeit, Hinweise des Fachgutachters einzuarbeiten.

Die Erfahrung zeigt, dass Arbeiten, die z. B. im Rahmen eines Wettbewerbs wie **Jugend forscht** die Endrunde erreicht haben, die besten Chancen haben, dieses Peer-Review-Verfahren zu bestehen.

Schließlich kommt die Arbeit in die Redaktion, wird für das Layout vorbereitet und als Open-Access-Beitrag veröffentlicht.

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Deine Forschungsarbeit ist nun in einer Gutachterzeitschrift (Peer-Review-Journal) veröffentlicht worden, d. h. Du kannst die Veröffentlichung in Deine wissenschaftliche Literaturliste aufnehmen. Deine Arbeit erhält als Open-Access-Veröffentlichung einen DOI (Data Object Identifier) und kann von entsprechenden Suchmaschinen (z. B. BASE) gefunden werden.

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Richtlinien für Beiträge

Für die meisten Autor/Inn/en ist dies die erste wissenschaftliche Veröffentlichung. Die Einhaltung der folgenden Richtlinien hilft allen – den Autor/innen/en und dem Redaktionsteam

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- Formulieren Sie eine eingängige Überschrift, um bei der Leserschaft Interesse für Ihre Arbeit zu wecken, sowie eine wissenschaftliche Überschrift.
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