Nanosecond pulsed streamer discharges
Part I: Generation, source-plasma interaction and energy-efficiency optimization

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Abstract
Streamer discharges generated by nanosecond high-voltage pulses have gained attraction for a variety of reasons, but mainly because they are very efficient for a number of plasma-processing applications. More specifically, researchers have noted that the pulse duration and the rise time of the applied high-voltage pulse have a significant influence on the radical yield of the transient plasmas generated with these pulses; shorter pulses result in higher yields. With the need to study transient plasmas generated by these short pulses comes the need to understand how to generate those pulses and to understand the interaction between the pulse source and the discharge. In this topical review, we will explore the different methods with which to generate nanosecond high-voltage pulses, how the interaction between the pulse source and the discharge may influence the source and the discharge and how to optimize the energy transfer from the pulse source to the discharge.

Keywords: pulsed discharge, plasma processing, nanosecond pulses, pulsed power technology

1. Introduction
Transient plasmas generated by high-voltage pulses have been widely studied and used for industrial and environmental applications for more than 100 years [1, 2]. Due to the fast electrons that are generated by these non-thermal plasmas, they are very efficient in producing highly reactive radical species and energetic photons [1, 3, 4]. These products can consequently react with, for instance, particles in gas streams (for example, pollutants, odor and dust), contamination in water, biological tissue, and material surfaces [1, 5, 6].

Research has shown that transient plasmas generated by short nanosecond high-voltage pulses are very efficient for a variety of applications [7–15]. More specifically, some researchers have noted that the pulse duration and the rise time of the applied high-voltage pulse have a significant influence on the radical yield of the transient plasmas generated with these pulses; shorter pulses result in higher yields [7–9, 13, 15]. With the need to study transient plasmas generated by these short pulses comes the need to understand how to generate those pulses and to understand the interaction between the pulse source and the plasma. In this topical review, we will explore the different methods with which to generate nanosecond high-voltage pulses, how the interaction between the pulse source and the plasma may influence the source and the plasma and how to optimize the energy transfer from the pulse source to the discharge.

A nanosecond pulse source is often thought of as just a tool to generate a discharge. In principle, this is true. But the...
way in which such a source is constructed or connected to the plasma reactor can greatly influence the discharge. In fact, even if two different type of pulse sources produce exactly the same voltage pulse into a matched load, the discharges they produce may be significantly different because of differences in output impedance, stored energy, manner of connection, etc.

There are various reasons why source-plasma interaction is important:

- Energy efficiency. If the plasma is used for industrial applications, it is imperative that all electrical energy is used as efficiently as possible, which can be realized by transferring all energy from the nanosecond pulse source to the plasma as efficiently as possible.
- Pulse shape integrity. If a pulse is applied to a plasma reactor and the plasma reactor is unable to dissipate all energy immediately (which is almost always the case) then pulse reflections (outside and inside the plasma reactor) will distort the pulse that is applied to the plasma reactor. The rise time, pulse duration and in extreme cases even the polarity of the pulse may be altered by such reflections.
- Equipment safety. When pulse reflections occur, voltages in the system (comprising e.g. the pulse source, cables, sensors, plasma reactor and all interfaces) may locally double in amplitude. This increased stress could potentially damage components in the system.
- The properties of the source determines the development of the discharge. This seems a rather obvious statement; anyone who is familiar with literature on nanosecond pulsed discharges will tell you that pulse duration, rise time, amplitude and polarity have a significant effect on the inception and propagation of discharges. It is therefore not the aim of this paper to give a complete overview of these effects (only where it concerns the energy efficiency). However, also the output impedance of a pulse source can have an effect on the discharge.

For the first three points, the ideal solution would be that all energy goes into the plasma immediately and that no reflections occur. This will only happen when the load of the pulse source is perfectly matched to the output impedance of the pulse source (or of the transmission line that connects the pulse source to the plasma reactor). Therefore, we call the process of optimizing this energy transfer ‘increasing matching’. Of the last point we will also see some examples in this paper.

For many fundamental studies, energy efficiency is not important and only a certain pulse shape is required (often rectangular). In such cases, matching the load (discharge) to the pulse source can often be done with matching resistors, of which we will see examples in this paper. Based on these fundamental studies, a desired pulse waveform can be identified that results in the desired effect that a discharge has for practical application (e.g. air purification, surface treatment, decontamination, etc). Subsequently, a nanosecond pulse generation method can be chosen that generates the required pulse waveforms and results in the best energy efficiencies. This paper reviews many such pulse generation methods and energy-efficiency optimization possibilities.

This paper is divided into several sections. Section 2 describes the different methods to generate nanosecond pulses. In sections 3–5 we explore energy optimization in a nanosecond pulsed plasma system from different angles. Section 6 then summarizes these results with two generalized tables which may be used as a guideline to optimize the energy transfer in any nanosecond pulsed plasma system. Finally, section 7 shows some examples of where source-plasma interaction is important in fundamental discharge studies, followed by a short summary in section 8.

2. Generating high-voltage nanosecond pulses

Considerable literature exists on the generation of nanosecond pulses. Some is specific to certain types of pulse source while other literature gives a broader overview of the field. Good examples of this last category are the works by, e.g. Martin [17] and Mankowski et al [18] for a quick overview and Smith [19], Bluhm [20], Mesyats [21] and more recently Akiyama et al [22], chapter 2 for a detailed overview.

This section presents the most common methods of generating nanosecond pulses. Some are simple in concept and straightforward to realize, while others are more complex. Some can be made with components you find lying around the lab, while others require more serious design and engineering or can be commercially acquired. The aim of this section is to show the most important of these pulse sources and discuss advantages and disadvantages of each, specifically for generating discharges.

2.1. General concept of nanosecond pulse sources

Figure 1 shows the general concept of a nanosecond pulse source, which most pulse source designs are based on. Besides the different options for charging, the heart of the concept is the nanosecond pulse generation block. It consists of an energy storage element (the pulse-forming network (PFN)) a (high-voltage) switch and the load.

2.1.1. The PFN. The PFN serves three important functions, the first of which is to temporarily store energy. Energy is stored in the PFN through a charging circuit. An important property for a PFN for nanosecond pulse generation is that it can release its energy rapidly. For instance, if a pulse is required with a 1-ns rise time, then this is also the time scale within which the energy must be available from the PFN. This requires a low-inductance PFN, which often means that PFNs for nanosecond pulse generation are capacitors or transmission lines. The second function of the PFN is impedance matching. By matching the impedance of the PFN to the load, perfect energy transfer of the PFN to the load can be realized. If the PFN is mismatched, i.e. the impedance of the PFN is unequal to the impedance of the load the pulse
will partially reflect off the load and not all energy is transmitted to the load (immediately). This concept will prove important for pulse-forming line pulse sources in section 2.3, where it will also be further explained. The same concept is also critical for optimizing the energy transfer of (sub) nanosecond pulses to a pulsed corona discharge (section 2.3). Finally, the third function of the PFN is to give shape to the pulse waveform.

2.1.2. The high-voltage switch. When dealing with high-voltage nanosecond pulse source design, one is often tempted to say that each component in the circuit is the critical component. However, this holds especially true for the high-voltage switch. It has to hold off the full charge voltage of the PFN and then nanoseconds later has to switch at powers that can exceed hundreds of MW. Then ideally, it is compact, robust, triggerable, light, reliable, cheap, easy to operate, low-maintenance, capable of high repetition rates, etc. It is therefore not surprising that the perfect high-voltage switch does not exist. For every type and even subtype of pulse source, a different switch might be best suited. In the next sections, we will see many of such different switches. Some are commercially available, some have to be custom made. These switches fall into two categories: spark gaps and solid-state switches.

Spark-gap switches exist in many different configurations, but all rely on a conducting channel being formed in an electrode system [23, 24]. In its simplest form, a spark gap consists of two opposing electrodes placed in a gas (or liquid) medium. Once the voltage across the electrodes exceeds a certain threshold voltage a discharge is initiated in the gap. If this results in the complete breakdown of the gap a conducting channel is formed and the spark-gap switch is switched ‘on’. Once the conducting channel is quenched (when the voltage across the electrodes and the current through the channel fall below a certain threshold) the spark-gap switch is switched ‘off’ again. The advantage of such switches is that they are capable of switching (extremely) high voltages at (extremely) high currents and in special configurations with subnanosecond rise times. The disadvantage of the spark gap is that it typically requires maintenance (the electrodes erode), that an auxiliary gas- or liquid flushing and filtering system is required for high power operation and that the achievable repetition rates are limited because the medium in the gap has to recover before it can hold off the full voltage again.

Solid-state switches are either magnetic switches or semiconductor switches. These switches have low maintenance (they have no moving components or discharge medium elements), can operate at high repetition rates and when regular semiconductor switches are used they can be switched off on command. The disadvantage of magnetic switches is that designing them is complicated, that they are typically not very energy efficient and that very fast rise times (several nanoseconds to subnanoseconds) are difficult to achieve. The disadvantage of semiconductor switches is that they have to be stacked to achieve high-voltage switching, that they are sensitive to over voltages, that the switching current is typically low (as compared to the spark-gap switch) and that they can be expensive.

In general, one can say that if high peak powers are required the spark gap switch is the best option. Also when switching with subnanosecond (or several ns) rise times is required spark-gap switches typically are preferred (an exception are the diodes discussed in section 2.9). However, when the peak powers are not that high and pulse waveform flexibility (does not hold for the magnetic switch), low maintenance and high repetition rates are required then solid-state switches are probably best to use.

Both the pulse forming network and the switch are often high-voltage components, imposing certain challenges and limitations to their design and use. For example: a PFN has to be compact to reduce inductance and thereby the possible rise time of the circuit, but to avoid high-voltage breakdown sufficient space is required between high-voltage connections and ground, which imposes a trade-off. In some nanosecond pulse sources the high-voltage stress of one or both of these components is divided over many smaller units, such as in the Marx generator, the linear transformer driver (LTD), the Impedance-matched Marx Generator (IMG) or the diode recovery pulse sources (sections 2.5–2.7 and 2.9).

2.1.3. PFN charging. Charging a PFN can be done in different ways (see figure 1). A simple and straightforward approach is

\[V_{DC} \rightarrow \text{PFN} \rightarrow \text{Switch} \rightarrow \text{Load}\]

Figure 1. The general concept of generating nanosecond pulses. The heart of the concept is the nanosecond pulse generation block, which consists of a pulse-forming network (charged by a charging circuit from the primary energy storage) a (high-voltage) switch and the load.
way of charging a PFN is with a HV DC power supply and a
resistor of high value (an example will be shown in
section 2.2). The advantage is that it requires a minimum of
components and that the PFN can be directly charged with
high-voltage. The disadvantage is that the resistor typically
dissipates as much energy as is stored in the PFN—so it is
not energy-efficient—and that the pulse repetition rate is
limited by the maximum power dissipation of the charging resistor
and the current rating of the DC power supply (often resulting
in repetition rates of at most tens of Hz). However, for
fundamental studies of pulsed discharges, these disadvantages
are typically not important and PFN charging with a HV DC
power supply is often employed. If energy efficiency is
important (e.g. for industrial applications) and/or if high
repetition rates are required (>100 Hz) other PFN charging
methods are required. One such method is to use an inductor
as the charging impedance (instead of a resistor). For low
frequencies this inductor forms a low impedance, but for the
pulse (which has high-frequency components) it forms a high
impedance and therefore it protects the HV power supply
from damage from the pulse. The advantage of using an
inductor is that no energy is lost in the inductor. A
disadvantage is that circuits with capacitors and inductors
can be underdamped, which can result in unwanted
oscillations.

Another method to energy-efficiently charge a PFN is
with a dedicated capacitor charger. These can either be
developed or can be commercially obtained (for large
capacitors). Typically, energy is first stored at low voltage
(<1000 V) in a primary energy storage element, such as a
capacitor, after which this energy is transferred to the PFN via
e.g.a high-voltage transformer [25–28] or a Marx generator
[29, 30]. The operating principles of such charging mechan-
isms is beyond the scope of this paper, though some will
appear in the next sections.

2.2. Simple capacitive-storage pulse sources

The most straightforward (and often most easy to construct)
nanosecond pulse source is the simple capacitive-storage
pulse source as shown in figure 2. In this example circuit, the
PFN is a capacitor, which is charged via a resistor and a DC
power supply. The resistor is typically of high impedance to
limit the capacitor charging current and to protect the DC
power supply from transients from the high-voltage pulse.
When the capacitor is charged, switch S switches either
spontaneously (e.g. when S is an untriggered spark gap or a
magnetic switch) or when it is triggered (e.g. when S is a
triggered spark gap or some semiconductor switch). At this
point a pulse is formed when the capacitor discharges into the
load (a simple resistor in this example). The shape of this
pulse depends on the circuit parameters. Some of these
parameters are parasitic, such as the inductance of the loop in
which the capacitor, load and switch are connected. Other
parasitic parameters are the capacitance and inductance of the
load and the switch. In this example, we will only consider
the parasitic loop inductance.

\[ V_{load} = A e^{(-\alpha + \sqrt{\alpha^2 - \omega^2}) t} - A e^{(-\alpha - \sqrt{\alpha^2 - \omega^2}) t}, \]

where

\[ \omega = \frac{1}{\sqrt{LC}}, \]

\[ \alpha = \frac{R_{load}}{2L}, \]

\[ A = \frac{V_0}{2L\sqrt{\alpha^2 - \omega^2}}. \]

Figure 2(b) shows some calculated example waveforms
for a typical capacitor value of 1 nF and a load of 50 Ω. As
can be seen, a fast rising pulse is only ensured when the
parasitic loop inductance is small (because \( \alpha \) will be high
then). Therefore, fast nanosecond pulse circuits always have
to be compact to minimize the parasitic inductance. Another
way to ensure a fast rising pulse is to keep \( R_{load} \) large. When
such a circuit is used to drive a nanosecond discharge, the
parasitic inductance typically remains relatively constant.
However, the load impedance will vary with time. When the
discharge has just initiated, the impedance is high and will
typically decrease with time when more energy is dissipated
in the discharge. We will go into more detail on load
matching in sections 3–5, but for now it suffices to remember
that the pulse waveform from the simple capacitive circuit

will not be as ideal as the calculated waveforms and will be dependent on the load.

A real-world example where the simple capacitive-storage pulse source is used to generate a discharge is shown in figure 3(a) [31]. This circuit is built slightly different from the example in figure 2(a). The main difference is the position of the switch in the circuit, which is now connected to ground. This can be an advantage, because now the switch is not on a floating potential; in the circuit of figure 3(a) a triggered spark-gap switch is used, but in another implementation, a triggered semiconductor switch was used, which is easier to operate from ground potential [32]. Additional components in the circuit are $R_2$, which limits the current through the switch (important when semiconductor switches are used) and $R_3$ which is placed parallel to the discharge setup and helps to shape the pulse so that the pulse shape is less dependent on the time-varying discharge impedance. Figure 3(b) shows an example waveform from this circuit. The dip in the peak of the voltage waveform is caused by the discharge, which is at its most intense at this time (and therefore has a very low impedance).

As mentioned before, when fast-rising pulses are required, the circuit has to be compact to avoid excessive parasitic inductance. However, this is not always possible or practical. For instance, in industrial applications, conditions might necessitate placing the pulse source at a distance from the plasma reactor. A solution is to connect the plasma reactor with a coaxial cable or other transmission-line structure. If the pulses are fast, the coaxial cable will act as a transmission line. Therefore, the only inductance we have to worry about is the inductance of the pulse source connection to the coaxial cable and the inductance of the cable connection to the plasma reactor. Because the coaxial cable then effectively decouples the pulse source from the plasma reactor for the circuit analysis. An example is shown in figure 4(a) [15, 33].

The circuit to the left of the (50 Ω) coaxial cable is a classic simple capacitive-storage pulse source. Figure 4(b) shows an example waveform measured over a 50-Ω load that is connected to the output of the coaxial cable. As can be seen, the rise time is quite short ($\approx 6\,\text{ns}$). This is purely because the inductance in the circuit before and after the coaxial cable was kept low due to a compact connection. The cable itself can be several meters or even tens of meters long without influencing the pulse shape (when losses in the cable may be neglected). However, there are also disadvantages. First, the impedance of the cable is fixed and therefore the output current (to the reactor) is limited. Since commercially available cables are almost always 50 Ω, this is typically the limiting impedance in a system with a cable. If a very large plasma reactor has to be energized, this impedance could be too high. A solution is to build a custom transmission-line structure, as we will see in section 2.4. A second disadvantage, is that when the load is not perfectly matched (transmission-line impedance = load impedance), pulse reflections will occur. This phenomena will be treated in more detail in sections 4 and 5, but an example can already be seen in figure 4(c) where we see the actual load voltage when a corona plasma reactor is used [15]. Instead of the pulse shape being the exponential decay that we saw in figure 4(b), we see a series of pulses. This effect is caused by the pulse partially reflecting off the not-perfectly-matched and time-varying impedance of the plasma reactor and reflecting back and forth over the cable. Resistor $R_1$ partially absorbs this reflecting pulse to ensure a decay of the load voltage within a reasonable time.

The downside of the simple capacitive pulse source is that its output waveform typically has a rather long tail, which might have unwanted effects on a discharge, such as gas heating. A slightly more complicated pulse source circuit that solves this issue employs a second switch to rapidly discharge the main capacitor. An example of such a circuit is shown in figure 5 [34, 35]. In this circuit, a high voltage pulse of around 20 kV is applied to a DBD gap with the main spark gap. After a short time, the second, smaller spark gap is charged and switches, which short-circuits the DBD gap and thereby limits the pulse duration, as can be seen in figure 5(b). A 20-ns pulse is generated in this way.

While many examples of simple capacitive-storage pulse sources employ spark-gap switches, it is also possible to use solid-state switches [32, 36–43]. Because solid-state switches can be switched off during the pulse, square pulses can be generated when they are used, while capacitive-storage circuits with spark gaps often only produce exponentially decaying pulses.

Finally, where it can still take some engineering to implement a simple capacitive-storage pulse source from separate components (even if a semiconductor switch is used), it is also possible to use a commercially available switch that

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**Figure 3.** (a) Real-world example of a capacitive-storage pulse source. It is built slightly different from the basic example in figure 2 so that the high-voltage switch is ground-referenced and not floating. (b) An example output waveform from the circuit in (a). Reproduced from [31].
has all the components built in. It only needs to be powered by a HV DC power supply and triggered by low-voltage pulses \[45–49\]. An example waveform generated with such a system is shown in figure 6. As can be seen, the pulse duration can be changed at will.

In this section, we saw the simple capacitive-storage pulse source, from a basic circuit to more complex implementations. Later, we will see even more complex implementations of this circuit, such as circuits using a transmission-line transformer (TLT) in section 2.4, but also the Marx generator in section 2.5. Even if such circuits look complex, at their heart is the most simple concept in pulsed power technology: discharging a capacitor into a load.

2.3. Pulse-forming line pulse sources

When constructed compactly and equipped with a fast switch, the simple capacitive pulse sources presented in the previous section may reach nanosecond rise time pulses. However, their pulse waveform is typically not square and sub-nanosecond rise times will be difficult, if not impossible, to achieve. What we need for fast rise times is a compact circuit geometry and distributed energy storage. This last requirement is also necessary for square pulse forming. A class of pulse sources that satisfies these requirements is the class of pulse-forming line (PFL) pulse sources.

2.3.1. Single-line pulse source. The most basic PFL pulse source is the single-line pulse source. The PFN in this type of source is a transmission line. In high-voltage PFL pulse sources, the transmission line that forms the PFN is often a coaxial cable, because these cables are commercially available up to high voltage ratings. Figure 7 shows the operating principle of the single-line pulse source. The PFL has a characteristic impedance of \(Z_0\) and is first charged to a voltage \(V_0\). Then at \(t = 0\) switch \(S\) closes. At the moment of switch closure, two waves are generated which propagate in opposite directions from the switch. Under the condition that...
\(Z_0 = R_{\text{load}}\) a wave with an amplitude of \(V_0/2\) propagates into the load and an equal, but opposite polarity wave propagates back into the transmission line. This last wave propagates to the end of the line, partially discharging the line. Once it reaches the end of the line, it encounters the charging resistor \(R_{ch}\). If \(R_{ch} \gg Z_0\) the wave sees the impedance of \(R_{ch}\) as an open end, and the wave completely reflects off the end of the line (see section 2.3.2 for the equation), further discharging the line until it reaches the load. The duration of the pulse that is generated this way is determined by the length of the PFL and is twice the propagation time \(T_0\) of the wave through the line. This propagation time is given by

\[
T_0 = \frac{l_{\text{PFL}}}{c} \sqrt{\mu_{\text{rel}} \varepsilon_{\text{rel}}},
\]  

where \(l_{\text{PFL}}\) is the length of the PFL, \(c\) is the speed of light in vacuum and \(\mu_{\text{rel}}\) and \(\varepsilon_{\text{rel}}\) are the relative permeability and relative permittivity of the insulating medium of the PFL, respectively. For commercially available coaxial cables \(Z_0\) is almost always 50 \(\Omega\) and the propagation speed of waves through those cables is typically around 5 ns m\(^{-1}\).

If the switch, transmission line and load are ideal and the load is matched to the transmission line \((Z_0 = R_{\text{load}})\) a perfect square pulse can be generated, as shown in figure 7. In reality however, switches and transmission lines are not ideal and the load may be a plasma reactor, which is often far from matched to the transmission line. In such cases, reflections will occur at the load and the voltage waveform over the load is a complex series of pulses. For a more mathematical and in-depth analysis of transmission lines and the pulse sources that can be made with these elements we refer to [20], chapter 5 and [19], chapter 3.

Fast pulse sources based on the single-line circuit have been around for some time and have amongst others been used to study nanosecond discharges [50–57]. We will see some examples in this section.

At Eindhoven University of Technology we developed a very fast nanosecond single-line pulse source for studying corona plasma discharges for air purification [55, 59, 60]. The requirements for the pulses were a square shape, subnanosecond rise time and an adjustable pulse duration, voltage amplitude and polarity. We implemented a single-line pulse source with a very fast oil spark gap to achieve these parameters. The basic circuit is shown in figure 8. The concept of this circuit is the same as that of figure 7 only now the load has been replaced by a cable, which acts as a matched
transmission line to transmit the pulses from the pulse source to the plasma reactor. This shows another big advantage of PFL pulse sources: connecting a cable to transmit the pulses to a load is very straightforward. This was necessary in our application to be able to integrate sensors on the cable and to delay the pulses to synchronize iCCD imaging [56, 58, 61].

Another difference with the concept in figure 7 is that rather than a DC power supply and a charging resistor, the PFL is charged by a custom-built high-repetition rate charger [25].

Figure 9 shows the implementation of the basic circuit of figure 8 [55]. It is a coaxially symmetric structure, with the PFL to the left, the spark gap in the middle and the cable connection and cable to the right. The entire structure is designed to be 50 Ω along its length to avoid any reflections due to mismatch. The spark gap is operated in pressurized transformer oil which is flushed through the gap via a secondary oil system with a filter and a pump. Using the spark gap in such a way, constructing it very compact and as much as possible as a 50-Ω structure ensures that the rise time of the pulses are around 200 ps. The pulse duration can be changed by adding or removing PFL sections. In this way a pulse-duration range of 0.5–10 ns is achieved. Additionally, the voltage amplitude can be changed (up to 50 kV) by adjusting the charging voltage and the spark-gap distance and the voltage polarity can be changed by reversing the charging voltage polarity. Depending on the output voltage, the pulse source can be operated up to several hundred Hz at full output voltage to 1 kHz at medium output voltages. Figure 10 shows example waveforms from the nanosecond pulse source.

A second example of a fast single-line pulse source is shown in figure 11(a) [53]. It consists of a short coaxial PFL which is charged by a Marx generator (see section 2.5) and discharged by a hydrogen spark gap. To produce the example output waveform of figure 11(b), this spark gap was pressurized to 55 bar. While the pulse duration of this generator is perhaps too short (600 ps and optionally 1.5 ns) to generate most discharges, it shows that the basic concept of the single-line pulse generator can be used to generate very fast pulses. Additionally, even such short pulses can be used to generate discharges if the voltage is sufficiently high (and the discharge arrangement used ensures a sufficiently high electric field) [54, 62–64].

Typically, single-line pulse sources are used up to a pulse duration of several hundred nanoseconds, because to generate a 100-ns pulse, a typical coaxial cable already needs to be 10 m long. Therefore, generating longer pulses with coaxial
cables as transmission lines quickly becomes unpractical. An alternative is to build the PFL out of capacitors and inductors, as described in detail in [20], Chapter 5.

2.3.2. Blumlein-line pulse source. A disadvantage of the single-line pulse source is that the output voltage is only half the charging voltage. A slightly more complicated pulse-forming line pulse source that solves this issue is the Blumlein-line pulse source [65], shown in figure 12. It utilizes two PFLs instead of one and the load is floating between the lines. Additionally, the load impedance now has to be twice as high as the characteristic impedance of the cable for proper pulse forming. Both lines are charged via a high impedance to a voltage of $V_0$. This connection is drawn in figure 12 on the right PFL, but it can also be connected to the inner conductor of the left PFL.

At $t = 0$ switch $S$ closes. Since this switch switches to ground, a wave with amplitude $-V_0$ propagates through the right PFL towards the load. Once this wave arrives at the load, it encounters a mismatch. In general when a wave propagates through a transmission line with impedance $Z_0$ and it encounters another line or a load with impedance $Z_L$, the part of the pulse that is reflected back into the original transmission line is determined by the reflection coefficient $R$. This coefficient is given by

$$R = \frac{Z_L - Z_0}{Z_L + Z_0}.$$  \hfill (6)

Likewise, the part of the wave that is transmitted into the load (or line) is given by the transmission coefficient $T$:

$$T = \frac{2Z_L}{Z_L + Z_0}.$$  \hfill (7)

In the case of the Blumlein-line pulse source, the wave that travels through the right PFL towards the load, encounters a series connection of $R_{\text{load}}$ and $Z_0$. Thus, $R$ is given by $[(R_{\text{load}} + Z_0) - Z_0]/[(R_{\text{load}} + Z_0) + Z_0]$ which is 0.5, given that $R_{\text{load}} = 2Z_0$. Using (6) and (7) the whole chain

Figure 11. (a) The PFL and spark gap of the Pau University nanosecond pulse generator (coaxially symmetric). (b) Output voltage of the Pau University pulse source. The rise time is 68 ps and the peak voltage 26 kV at a pulse duration of 600 ps. Reproduced from [53].

Figure 12. Concept of the Blumlein-line pulse source. See main text for details. The top circuit shows the Blumlein-line pulse source circuit and the five panels below it show the voltage in the system (related to the position in the circuit) for different moments in time (as explained in the main text). The bottom two panels show the output voltage and current waveforms.
of events can be analyzed, which is graphically presented in figure 12. In the end, the pulse that is formed over the load will start after a delay of $T_0$ and will have a duration of $2T_0$ and an amplitude of $V_0$. Therefore, while implementing the Blumlein-line pulse source is generally more complicated, the big advantage is that the output voltage is equal to the charging voltage. The disadvantage is that the switch current is twice that of the single-line pulse source and that due to its more complex construction a subnanosecond rise time is difficult to achieve. Table 1 gives a side-by-side comparison between the single-line and Blumlein-line pulse source.

Figure 13(a) shows a circuit where a Blumlein-line pulse source is used to drive a streamer discharge [66]. The basic concept is the same as that of figure 12. The main difference is that the load is connected in the ground connection of the lines, rather than in the center-conductor connection. The advantage of using the Blumlein this way is that the load is not floating with respect to ground. The circuit of figure 13(a) was used for fundamental research on streamer propagation, which is why the researchers chose to place a 100Ω resistor in parallel to their plasma reactor. Most of the energy will be dissipated in this resistor, but it serves to define the waveform, which is shown in figure 13(b). Without the resistor, the waveform would consist of a succession of multiple square pulses (caused by reflections), defined by the impedance of the plasma reactor. As stated in the introduction, for fundamental discharge studies, having a well-defined high-voltage waveform is often worth the loss of energy in a pulse-shaping resistor (for high-repetition rate studies this will bring its own challenges, like power dissipation in the resistor). As can be seen in the output waveform, the total load of the Blumlein-line pulse source is relatively well-matched. Only a reflection at around 250 ns is visible, which is caused by the mismatch of the plasma reactor (which impedance will initially be largely capacitive).

Another thing to notice about the circuit in figure 13 is the use of a multiple-gap spark gap switch [67]. This is a regular spark-gap switch, but with the gap divided into multiple smaller gaps with additional electrodes. If a fast rise time is important, such a switch is highly recommended to use, since it typically switches faster (at the same voltage) as a spark gap with a single gap, as can be seen in figure 14. In the circuit in figure 13 it results in a rise time of 10 ns.

![Figure 15](image3.png)

**Figure 15.** (a) A second example of a Blumlein-line pulse source implementation. It follows the basic design of figure 12, but includes a transformer to increase the output voltage. The pulse duration from this pulse source is 100 ns, as determined by the length of the coaxial cables and the typical delay time for the 50-Ω RG-213 cable that was used ($2 \times 10 \text{ m} \times 5 \text{ ns} \cdot \text{m}^{-1}$). The 1:3 pulse transformer not only transforms the voltage, it also transforms the impedance by a factor of $N^2$, where $N$ is the winding ratio of the transformer. Therefore, a matched load for this pulse circuit is $2 \times 50 \Omega \times 3^2 = 900 \Omega$. A small plasma reactor, as is used as a load with this circuit, often has a high impedance and therefore using a transformer is a good choice. However, as stated before, a plasma reactor is not a constant perfect load. Therefore, reflections can be seen on the output waveform, as shown in figure 15(b). If this is unwanted, a 900Ω resistor could be placed in parallel to the plasma reactor to match the load to the source (as was done in the example in figure 13).

A disadvantage of the Blumlein-line pulse source as compared to the single-line pulse source is that it is typically a more complex and less compact circuit, resulting in longer rise times. A type of Blumlein-line pulse source that partially negates this disadvantage is the triaxial Blumlein-line pulse source [10, 26, 69–71]. With such pulse sources, rise times of just several nanoseconds are achievable.
are required, the Blumlein-line pulse source can be equipped with some form of peaking switch [72], though more often the single-line pulse source is used for subnanosecond rise time pulse generation. In the triaxial Blumlein-line pulse source, the two transmission lines of the basic concept in figure 12 are integrated in one triaxial structure, where the inner electrode of one line forms the outer electrode of the second line.

Researchers at Kumamoto University have used the triaxial Blumlein-line pulse sources extensively for discharge generation [8, 10, 70, 73, 74]. The schematic of this triaxial Blumlein pulse source is shown in figure 16. The middle conductor is charged with respect to the outer conductor and the inner conductor. Therefore, the connection of the load is similar to the example in figure 13 where the load was also connected in the ground connection. An inductor (not shown) is placed between the inner and outer conductor in the triaxial Blumlein line to provide a charging path to the inner conductor. The inductance has a low impedance for the low-frequency charging current, but a high impedance for the nanosecond pulse and will therefore not disturb the pulse-forming process. The triaxial Blumlein line is followed by a matched transmission line (50-Ω characteristic impedance). The switch in the pulse source is a pressurized SF$_6$ spark-gap switch. SF$_6$ is used here for its excellent high-voltage insulation properties, allowing the spark gap to be as compact as possible and still hold off a high voltage (up to 90 kV). Figure 16 further shows the plasma reactor, which is a corona reactor with ceramic inlay for a DC-bias voltage [73] (shown in more detail in figure 50). The pulse voltage and current are measured with a capacitive voltage divider (CVD) and a Bergoz current transformer, respectively. Figure 17 shows an example waveform in this setup. The pulse duration is determined by the length of the Blumlein-line and is around 7 ns.

Besides its compactness and short output pulses, the advantage of the triaxial Blumlein-line pulse source as implemented in Kumamoto is that it is capable of operating at high repetition rates of up to 1000 Hz. Therefore, this pulse source can be used for both fundamental discharge studies, as well as industrial applications. To accommodate these high repetition rates, the charging of the pulse-forming line is not done via a DC power supply and a charging resistor, but with an efficient high repetition rate resonant charger that utilizes a pulse transformer [70].

The downside of both the single-line and the Blumlein-line pulse sources is that the output impedance is fixed and determined by the impedance of the transmission lines that are used. Depending on the type and volume of the to-be-generated discharge (see sections 3 and 4) this fixed impedance might be (much) higher or lower than the discharge impedance (which is, as mentioned before, time-dependent anyway), with pulse reflections and distortions as a result. We already saw one example of increasing the fixed output impedance of a line pulse source in figure 15. Another solution was to add a fixed resistor to the output of the pulse source (e.g. as in figure 13), but then this resistor will dissipate most of the energy, which might be undesired for
some applications. Two other ways of changing the output impedance of a line source are by using a TLT (see next section) or by using a configuration of multiple lines. Figure 18 shows an example of this last method [75]. By placing two lines in parallel on both sides of the load, the characteristic output impedance of this Blumlein-line pulse source is now $Z_0$ instead of $2 \times Z_0$. If $N$ lines are used in parallel in each branch of the Blumlein-line, the output impedance becomes $\frac{2Z_0}{N}$.

In principle, with the single-line and Blumlein-line pulse sources, all kinds of configurations are possible with parallel lines, lines in series, multiple switches, etc [69, 75]. Another such example is shown in figure 19(a), which shows a Blumlein-line generator with six lines [14]. On the primary side, these lines are connected in parallel (think of the ‘open end’ sides of the Blumlein-line as in parallel as well), but on the load side they are connected in series. This interesting arrangement results in an output impedance of $300\Omega$. Figure 19(b) shows the output voltage of the Blumlein-line pulse source with six lines, where on the primary side the lines are placed in parallel and in series on the load side. (b) Output voltage for different lengths of line with a corona plasma reactor as a load. Reproduced from [14].
pulse source for different lengths of line with a corona plasma reactor as a load.

Finally, while we have mainly seen line pulse sources with coaxial cables in this section, it is also possible to use other transmission-line configurations, such as the strip line. Some nice examples are given in [76, 77], where such strip lines are implemented on printed circuit boards (PCBs) in a Blumlein-line configuration. By stacking such implementations, voltages of several kV to as much as 10 kV or higher are achievable. The advantage of these implementations is that impedances can be chosen freely by the parameters of the strip lines (width and thickness).

### 2.4. Transmission-line transformer

Transmission-line transformers (TLTs) have been around for some time [78, 79] and have since been used in pulsed power systems [28, 80–82]. Basically, TLTs are multiple transmission lines connected differently (in parallel or in series) at the primary side than at the secondary side. This results in voltage, current and impedance transformation. In sections 3–5 we will discuss the interaction between the pulse source and a plasma load, where the output impedance of the pulse source has a big influence. By using a TLT, we can influence this impedance. In this section, we will explore the basic concept, limitations of TLTs and show some examples of pulse source implementations with TLTs.

#### 2.4.1. The basic concept

Let’s consider an ideal transmission line with a source at its input and a load \( Z \) at its output, as shown in figure 20. The voltage \( V_0 \) at any point \( x \) in the transmission line is given by the superposition of a wave traveling towards the load \( (V^+) \) and a wave traveling towards the source \( (V^-) \):\[ V_0(x) = V^+(x) + V^-(x). \] Likewise, the current \( I_0 \) at any point \( x \) in the transmission line is given by \[ I_0(x) = \frac{V^+(x) - V^-(x)}{Z_0}. \] Combining these two equations yields \[ V_0(x) = 2V^+(x) - I_0(x)Z_0. \] Assuming that the transmission line is excited by a pulse \( V_p \) then we can use (10) to define a simple equivalent model of the output of the transmission line, shown in figure 21. It is important to stress that we can only use this equivalent model to analyze the output of a transmission line.

Figure 22(a) shows an example of a two-stage TLT. The input voltage of the TLT is \( V_p \) and the input impedance is simply determined by the parallel-connection of the transmission lines (shown in the figure). On the output side of the TLT we can analyze the voltages and impedances (shown in the figure) with the equivalent model of figure 21. Figure 22(b) shows the equivalent model for the TLT of figure 22(a). Here we assume a matched load. A total of \( 4V_p \) is applied over a voltage divider of \( 2 \times Z_0 \) with the load (also \( 2Z_0 \)). Therefore, in this ideal case a voltage multiplication of the amount of lines that is used can be achieved.

Figure 23 shows two additional examples. Figure 23(a) shows a TLT for a voltage multiplication of a factor of four, while figure 23(b) shows an option where the output impedance can be maintained at \( Z_0 \), but at a voltage duplication.
2.4.2. Secondary-mode impedance and TLT length. In reality, TLTs are not as ideal as described before. An effect that reduces the ideal output voltage of a TLT is the secondary-mode impedance. It is the wave impedance associated with the possible current path from the output of a lower transmission line to the shield of an upper transmission line. In addition, a TLT should have a minimum length to function properly (for a given pulse duration). The secondary-mode impedance, the effect on the output pulse, solutions to minimize this impedance and TLT-length considerations are described in detail in the appendix.

2.4.3. Examples. Figure 24 shows three examples of pulse sources employing a TLT to drive a plasma reactor. These examples illustrate the flexibility of the TLT. First, figure 24(a) shows a single-line pulse source with a TLT [84]. The full circuit, including details on the efficient high-frequency resonant charger and the triggered spark gap, can be found in [83]. The advantage of using a TLT with a single-line pulse source is that the output voltage is now equal to the charging voltage, rather than half the charging voltage, as is the case with the basic single-line pulse source. To match the input impedance of the TLT and maintain proper pulse-forming in the single-line pulse source (as in figure 7), the input line also consists of two parallel-connected transmission lines. Although not drawn in the circuit, magnetic material was placed over the top transmission line in the TLT to increase the secondary-mode impedance (see appendix).

Figure 24(b) shows that a TLT can also be used to increase the output voltage of a simple capacitive pulse source [31]. Finally, figure 24(c) shows that even a combination of a single-line pulse forming line and a capacitive-storage pulse source is possible [85]. The capacitor was added to this pulse source to add some extra energy to the pulses and the pulse-forming line is connected in parallel to itself to match it to the input of the TLT and ensure proper pulse forming (as in figure 7).

A final note on TLTs is that care must be taken with energy losses in the transmission lines for high-power applications. If these become excessive, the lines and magnetic material may overheat. In addition, for high-power systems, the switching current may become excessive, leading to increased electrode erosion if spark gap switches are used. Examples of how high-power TLTs can be constructed and how the switch duty may be shared across multiple switches can be found in [28, 86, 87].

2.5. Marx generators

The pulse sources we saw so far in this part on nanosecond pulse generation were almost all custom made by research labs. Some were more complex than others, but in principle, most of these sources could be constructed in any lab with some basic (and sometimes more advanced) electrical engineering (and mechanical engineering) know-how. The sources that will be presented in the remaining sections of this nanosecond pulse generation part will be more complex, some in their basic concept, some in their construction and some in both. These sections are less to encourage budding plasma physicists to build such sources themselves but rather to give a complete overview of nanosecond pulse generation techniques and discuss some advantages and disadvantages of these sources for discharge generation. Many of these sources are also commercially available. The first source we treat here is the Marx generator.

The Marx generator was developed in 1924 by Erwin Otto Marx [29]. The basic principle of this circuit is shown in figure 25. It consists of $N$ stages with capacitors as PFN. First, all capacitors are charged in parallel by the DC voltage source to $V_{in}$ via the $R_a$ and $R_p$ resistors (figure 25(a)). Then, when the switches are switched on, all capacitors are discharged in series (figure 25(b)). The peak output voltage is then equal to $N \times V_{in}$, which is one of the biggest advantages of using a Marx generator: with a relatively low charging voltage, very high voltages can be achieved (>$MV$). Of course, in the real world the voltage will be less than the ideal output voltage due to parasitic effects.
Around the world, many classical high-voltage laboratories have large spark-gap switched Marx generators, from several hundred kV to MV output voltage. Typically, these Marx Generators are configured to generate standardized lightning impulses (1.2 μs rise time and 50 μs fall time) and are used to stress-test HV components, such as transformers, underground power cables, etc. They are also used to test the EMC (electromagnetic compatibility) behavior of (large) components and systems and as charging stages (or final stages) in large pulsed power machines that drive high-energy physics experiments. While impressive to behold, such generators are not used to generate nanosecond pulsed discharges.
because they typically have a $>1 \mu s$ rise time and even longer fall time\(^4\). Even though they can be configured to achieve slightly shorter rise times, nanosecond pulse generation is typically not possible with such large Marx generators due to their large inherent inductance. Additionally, these are single-shot devices that can operate at best every couple of seconds or tens of seconds. However, this does not mean that Marx generators have no place in nanosecond pulse generation. They are often used as a charging stage for faster pulse circuits, but can also be used as stand-alone nanosecond pulses in some configurations. Three types of Marx generator are typically capable of generating nanosecond pulses: the compact spark-gap switched Marx generator, the semiconductor Marx generator using MOSFET or IGBT switches, and the avalanche transistor Marx generator. Each have their unique features for nanosecond discharge generation.

2.5.1. Compact spark-gap switched Marx generators. A Marx generator that is able to produce nanosecond pulses at $>100$ kV output voltages is the coaxial Marx generator, first reported by Kubota et al [90]. Later, the same group and other researchers developed this type of pulse source further [91–93], even reaching voltages of 2 MV [94], all at pulse durations of hundreds of nanoseconds or less. In principle, the coaxial Marx generator is able to reach rise times of just several nanoseconds (depending on the size of the generator) because of its coaxial layout and distributed capacitive storage. Later, this type of pulse source was adapted even more so that with careful construction and spark-gap arrangement, a rise time of even less than a nanosecond was possible [95]. Furthermore a repetition rate of tens of Hz can be reached [96] and for systems at lower pulse energies even hundreds of Hz repetition rate is possible.

Two other good examples of low-inductance compact Marx generators are the one developed by Lassalle et al [97] and Neuber et al [98]. Lassalle et al developed a 400-kV output voltage, 5-ns rise time Marx generator with LC PFNs instead of capacitors as the storage element for each Marx stage. This resulted in a square pulse of 85 ns duration (an example waveform is shown in figure 26). It is able to operate at 100 Hz repetition rate (in burst mode). Neuber et al developed a 500-kV output voltage, 50-ns rise time, 200-ns pulse duration Marx generator capable of operating at 10-Hz repetition rate.

The main advantage of the compact Marx generator over other nanosecond pulse sources is its high output voltage of hundreds of kV to several MV. In principle, such voltages could also be achieved with line pulse sources or the simple capacitive pulse source, but the charging voltage for such systems would be excessive, while for the compact Marx generator the charge voltage is only a fraction of the output voltage. A disadvantage of the compact Marx generator for discharge generation is that the repetition rate is typically low, even though some moderately-sized systems can reach a hundred Hz.

2.5.2. Semiconductor Marx generators. A type of fast Marx generator that is extremely suitable for discharge generation is the solid-state Marx generator [99–104]. This is a classical Marx generator implemented with solid-state switches, such as MOSFETs or IGBTs. The output voltage (and power) of such a Marx generator is typically much lower than the Marx generators we saw so far. The output voltage is generally only several tens of kV, since Marx stages with MOSFETs or IGBTs are normally only 1 kV each. In principle, the output voltage can also be higher than 100 kV, but this is challenging [100].

The big advantage of the semiconductor Marx generator is that the switches can be flexibly turned on and off and that high repetition rates are possible. The control over the switches means that large capacitors can be used in the Marx stages, which do not have to be fully discharged each pulse, as is the case with the classical spark-gap switched Marx generator. This allows for the generation of square pulses (if the capacitors are large enough). Additionally, the pulse duration of such generators can be flexibly controlled with the turn-off time of the semiconductor switches. Finally, when MOSFETs are used as switches, rise times of tens of nanoseconds is possible.

Figure 27 shows an example circuit of a generalized Marx generator implemented with IGBT switches [102]. Because each stage of the Marx has six switches, the discharge polarity of the capacitors can be varied (from shot to shot), allowing for unipolar positive, unipolar negative or bipolar operation. Figure 28 shows the output waveform of a five-stage prototype operated in the bipolar mode. While this example shows microsecond pulses, the same circuit was also implemented with MOSFETs, which allowed for 10-kV, 100-ns duration pulses [105]. Recently, this circuit was extended to 15 stages and operated with a plasma reactor for efficient ozone generation [99].

\[^4\] That is not to say that they are not used for discharge generation at all. For instance, in [88, 89] a classic Marx generator was used to fundamentally study streamer discharges generated with a 1 MV pulse.

\[\text{Figure 26. Simulated and measured output waveform of a compact Marx generator. It can operate at a repetition rate of 100 Hz in burst mode. Reproduced from [97].}\]
2.5.3. Avalanche transistor Marx generators. The final type of Marx generator capable of generating nanosecond pulses is the avalanche transistor Marx generator [106–109]. In this type of Marx generator, special bipolar junction transistors (BJTs) are used as switches for the Marx stages. These BJTs are capable of operating in the avalanche regime, a regime in which the voltage over a device drops very fast due to an overvoltage, but without being damaged. As the voltage drops, the device comes into conduction very rapidly, allowing for fast current and voltage rise times. A good (yet not complete) overview of different implementations of the avalanche transistor Marx generator published in literature was presented recently in [110].

The most general circuit of the avalanche transistor Marx generator is shown in figure 29 [109]. Between pulses, the capacitors are charged via the resistors. Then, when the first transistor is triggered by a trigger pulse, an overvoltage occurs over the other transistors, which then break down one by one in the avalanche mode. Figure 30 shows a 16-stage implementation of this circuit, with the output voltage pulse shown in figure 31. These type of circuits are typically very compact and can generate several nanoseconds rise time pulses (in some cases subnanosecond) pulses of typically up to 2–3 kV amplitude and a pulse duration of several tens of nanoseconds.

A downside of the avalanche transistor Marx generator is that one circuit typically only delivers several kV output voltage, which is often too low for driving a discharge, especially since the pulse duration is so short. However, by building the circuit up in an alternative way [108] or by adding pulses from multiple circuits with transmission lines an output voltage of up to 8 kV was achieved [111, 112]. Furthermore, these circuits typically can achieve repetition rates of tens of kHz. These circuits are therefore ideal for nanosecond pulsed micro plasma applications.

2.6. Linear transformer drivers

As mentioned in the previous section, large Marx generators are used extensively in large pulsed power machines for high-energy physics, such as the Z-machine at Sandia National laboratory [113, 114]. With its 300 TW x-ray production capability it is perhaps the most impressive pulsed power machine.
Currently in operation. However, the quest for even higher powers is never-ending. The Z-machine is set up in a circular arrangement with a diameter of around 33 m, so to achieve even higher power levels, the physical size of the new generation of Z-machines becomes a limiting factor. A class of pulse source that will increase the energy density is the Linear Transformer Driver (LTD) [115–117]. The LTD consists of multiple (magnetically coupled) cavities stacked in series. Each cavity is filled with multiple parallel-connected capacitors and spark-gap switches. Each cavity, or LTD stage, typically outputs 100-kV pulses of just several hundreds of nanoseconds and by stacking the cavities, output voltages of several MV are possible. In this way the pulse forming process is done in just one step. In the current Z-machine this pulse-forming process consists of multiple steps, involving 36 5.4 MV Marx generators, intermediate storage transmission lines, 6 MV laser-triggered spark-gaps, water switches and many more. These could potentially all be replaced by many parallel-connected LTDs. While the figures of merit of the Z-machine and LTDs are highly impressive, at first glance they bear little relation to repetitive nanosecond pulsed discharges. However, there is one exception: the solid-state LTD.

At Nagaoke University of Technology, Jiang et al implemented an LTD in solid state at much lower power levels as the ones intended for high-energy physics. They started with a single stage, using 24 parallel-connected MOSFETs to share the current [118]. Later, multiple stages were stacked in series to obtain an output voltage of 30 kV [119–121].

The basic schematic of the solid-state LTD is shown in figure 32 and the actual implementation in figure 33. As can be seen in figure 32, each stage consists of many parallel-connected circuits, each with a switch and capacitors. These can be seen in figure 33(a) placed (24 times) in a circle on a PCB. In the center of the PCB a magnetic core is placed. This magnetic core ensures coupling from the primary circuit (the single LTD stage) to the secondary circuit (the output winding, running through the center of the LTD stage). By stacking 30 of these stages, the full solid-state LTD is currently in operation. However, the quest for even higher powers is never-ending. The Z-machine is set up in a circular arrangement with a diameter of around 33 m, so to achieve even higher power levels, the physical size of the new generation of Z-machines becomes a limiting factor. A class of pulse source that will increase the energy density is the Linear Transformer Driver (LTD) [115–117]. The LTD consists of multiple (magnetically coupled) cavities stacked in series. Each cavity is filled with multiple parallel-connected capacitors and spark-gap switches. Each cavity, or LTD stage, typically outputs 100-kV pulses of just several hundreds of nanoseconds and by stacking the cavities, output voltages of several MV are possible. In this way the pulse forming process is done in just one step. In the current Z-machine this pulse-forming process consists of multiple steps, involving 36 5.4 MV Marx generators, intermediate storage transmission lines, 6 MV laser-triggered spark-gaps, water switches and many more. These could potentially all be replaced by many parallel-connected LTDs. While the figures of merit of the Z-machine and LTDs are highly impressive, at first glance they bear little relation to repetitive nanosecond pulsed discharges. However, there is one exception: the solid-state LTD.

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assembled, as seen in the schematic in figure 32 and the actual implementation in figure 33(b).

The big advantage of the solid-state LTD can be seen in figure 34: arbitrary pulses can be generated. Each individual LTD stage can add at any moment (programmed by the user) to the output voltage, making it possible to vary pulse duration and the waveform shape, as well as the output voltage amplitude (with the charge voltage). Furthermore, since MOSFETs are used as semiconductor switch and the topology inherently has a relatively low inductance, the rise time that can be achieved with the solid-state LTD is several tens of nanoseconds. This also ensures that the minimum pulse duration is as short as around 80 ns. For discharge generation, this means that the pulse shape can be optimized for certain discharge properties. Figure 35 shows an example of this. Here, the LTD waveform was optimized for an as constant as possible discharge current, which was achieved for figure 35(d). For instance, in figure 35(b) it looks like the discharge is changing to a secondary streamer regime. By temporarily decreasing the voltage at that time, it appears that this can be prevented. Additionally, the solid-state LTD can operate at high repetition rates, making it an interesting candidate for both fundamental plasma research as well as industrial applications (for which it was developed).

2.7. Impedance-matched Marx generator

Recently, we introduced a new nanosecond pulse source concept: the solid-state Impedance-matched Marx Generator (IMG) [122]. It is a solid-state implementation of the general IMG concept that was proposed as an alternative for the LTD [123]. The solid-state IMG consists of fast semiconductor switch modules (FSSM) that are placed in parallel into stages. These stages are connected in series to increase the output voltage. Figure 36 shows a sketch of the solid-state IMG. For slow pulses, the solid-state IMG works as a regular solid-state Marx generator, but if the FSSMs can generate fast pulses, a fast high-voltage output pulse can be generated if all the stages are carefully impedance-matched. When this impedance-matching is done correctly, all the pulses from the FSSMs and stages add perfectly to the output pulse without internal pulse reflections. More detail on the exact operation can be found in [122].
The advantage of the solid-state IMG over the solid-state LTD is that no magnetic material is required and that extremely fast pulses are possible with the solid-state IMG (our aim is a 1-ns rise time). In fact, the rise time of the pulses is only limited by the rise time of each FSSM. In other words: the inductance of the pulse source structure plays no role, because the structure consists of transmission lines. At this moment, only a five-stage prototype was tested, of which the results are shown in figure 37. In the prototype, the rise time of the FSSMs is around 3 ns, which results in an output pulse with a rise time of around 5 ns (the increase in rise time is due to synchronization issues between the stages and individual FSSMs). Since this rise time is still relatively long and the IMG structure of the prototype relatively small, pulse reflections do not affect the output pulse significantly and therefore also flexible waveform pulses are possible (by choosing which stage to switch), as is shown in figure 37(b). Currently, we are developing a 30-kV, 1-ns rise time solid-state IMG for corona discharge generation.

2.8. Magnetic pulse compression (MPC) pulse sources

The final two types of pulse source we treat here are MPC pulse sources and fast diode opening switch pulse sources. While their detailed principle of operation and full review of the state-of-the art is beyond the scope of this paper, it is worthwhile to briefly discuss these sources, because they are often at the heart of commercially available pulse sources. A good overview of these sources is given in [124].

The key ingredient in MPC pulse sources is the magnetic switch [125]. Such a switch is a saturable inductor, i.e. an inductor wound on a magnetic core. When a small current flows through such an inductor, the magnetic core is unsaturated. In other words: the flux density \( B \) in the core will vary proportional to the magnetic field intensity \( H \) that is produced by the current through the inductor. The proportionality factor between \( B \) and \( H \) is the total permeability \( \mu \) of the magnetic material of the core:

\[
B = \mu H = \mu_r \mu_0 H. \tag{11}
\]

Here, \( \mu \) is the product of the permeability of vacuum \( \mu_0 \) and the relative permeability of the magnetic material \( \mu_r \). In ideal circuits, \( \mu_r \) is taken as a constant, but in reality \( B \) saturates when \( H \) is increased beyond a certain value, giving name to the well-known \( B-H \) curve of magnetic materials. In other words, the relative permeability of magnetic materials is dependent on \( H \) (and therefore on the current) and will suddenly approach 1 beyond a certain point. Since the impedance of an inductor wound on magnetic material is proportional to \( \mu_r \), this means that after a certain current threshold, this impedance will decrease with a factor of almost \( \mu_r \) which can be in the order of \( 10^3 \). This drastic drop in impedance once the magnetic core saturates is the working principle of the magnetic switch. Therefore a magnetic switch is ‘switched on’ when it saturates and is ‘switched off’ in its unsaturated state. In MPC pulse sources, this principle is used both in single circuit elements as well as in pulse transformers that can saturate [126–129].
The name ‘MPC pulse source’ originates from the typical use of the magnetic switch in such pulse sources: to compress the pulse. A simple example of this principle is shown in figure 38. All inductors are saturable and saturate once the current through them reaches a certain threshold. In the example, a small current starts to flow from the first capacitor once the switch switches. This current quickly saturates the first inductor, which results in a resonant charging of the second capacitor. If all inductors and magnetic cores are sized correctly (the main complexity in such pulse sources), the small current that was also flowing through the second inductor saturates this inductor and then the third capacitor is resonantly charged from the second capacitor, etc. With each stage the pulse is compressed in time, making it possible to achieve very short pulses. The magnetic switch in the final stage in figure 38 discharges the final capacitor into the load.

To achieve voltage multiplication as well as pulse compression, MPC circuits often use saturable pulse transformers, as is shown in the example of figure 39(a) [127]. The operation of this circuit can be divided into four time phases (refer to figure 39(b)):

- $t_0$ to $t_1$: The primary capacitor $C_{pri}$ is charged with a resonant charger (the pulse transformer was first brought into a saturated state, so that the secondary side of the transformer is uncoupled during the charging phase).
- $t_1$ to $t_2$: The transformer unsaturates and switch $S$ switches to discharge $C_{pri}$ and pulse charge $C_{sec,1}$ and $C_{sec,2}$ through the transformer. The capacitors are charged with opposite polarity. During this phase, the magnetic switch $MS$ was kept saturated (with an external circuit). It unsaturates due to the charging current.
- $t_2$ to $t_3$: The transformer is dimensioned such that it saturates at $t_2$, which resonantly inverts the polarity of $C_{sec,2}$. Now the secondary capacitor voltages add.
2.9. Fast diode opening switch pulse sources

The final type of pulse source that we treat here is the fast diode opening switch pulse source. It is a pulse source that uses inductive storage, rather than capacitive storage (all sources we saw up to this point were capacitive-storage pulse sources) in combination with a special type of diode: the semiconductor opening switch (SOS) diode or the drift-step recovery diode (DSRD) [130, 131]. An excellent overview of these devices is given in [131]. The operating principle of this type of pulse source is that the recovery process of these diodes can interrupt a current flowing through an inductor very rapidly, inducing a voltage spike over the inductor. The main difference between SOS diodes and DSRD diodes is that the mechanism with which a SOS diode interrupts the current is different from the DSRD diode, allowing for higher switched powers with SOS diodes [131]. These type of pulse sources have been demonstrated from several kV output voltage [132] up to MV output voltage [124], where the diodes are used in stacks to increase the output voltage. Some implementations of pulse sources using the fast recovery of diodes can be found in [132–136].

Figure 40(a) shows an example of a SOS pulse source [134]. The operation of this circuit can be divided into four time phases (refer to figure 40(b)):

- $t_0$–$t_2$ Now that the secondary capacitor voltages add, a current flows through $MS$ towards the load, which saturates the switch and the secondary capacitors are discharged over the load.

More detail on this pulse source can be found in [127]. It produces up to 65-kV pulses with a pulse duration of just over 50 ns, a rise time of 17 ns and can operate at 20-kHz repetition rate at an output voltage of around 65 kV (see figure 39(c)).

The main challenge with MPC pulse sources is that the design of the magnetic switches can be complex. The advantage is that they can operate at high repetition rates and are completely solid-state. This makes them ideal for nanosecond discharge generation for industrial processes, because they can operate at high average powers (high peak power combined with high repetition rates) and are practically maintenance free because they are solid-state. The disadvantage for industrial applications is that the energy efficiency of MPC pulse sources are typically lower than 75%. Additionally, pulse parameters such as pulse duration and voltage amplitude (and polarity) are typically not well adjustable, which can make them less suitable for fundamental discharge studies.

![Image](image.png)

Figure 40. (a) Example of a SOS pulse source. It uses a saturable pulse transformer and a SOS diode. (b) Waveforms in the SOS pulse source circuit (see main text for details). (c) The output voltage of the SOS pulse source. Reproduced from [134].

More detail on this pulse source can be found in [134]. It produces 11-kV negative pulses with a pulse duration of just over 100 ns, a rise time of around 20 ns and can operate at several kHz repetition rate (see figure 40(c)).

Just like MPC pulse sources, designing and implementing a SOS or DSRD pulse source is complex and often requires magnetic switches. However, when properly done, these pulse sources can deliver incredibly short pulses, even down to several nanoseconds [124]. Similar advantages and disadvantages as with the MPC pulse sources hold for SOS and DSRD pulse sources: they are solid-state and can operate at high repetition rates at very high peak powers, making them suitable for industrial discharge applications.
However, pulse parameters such as pulse duration and voltage amplitude (and polarity) are again typically not well adjustable, which can make them less suitable for fundamental discharge studies. In addition, SOS diodes and DSRDs are not standard components, which makes them expensive and sometimes difficult to source. SOS and DSRD pulse sources can typically be found in commercially available power supplies.

3. Optimizing pulsed corona efficiency: voltage waveform and reactor conditions

In this section we will explore ‘matching’, or the optimization of the energy transfer from the pulse source to the plasma, as a function of the parameters of the voltage pulse and the discharge arrangement (geometry and conditions), which we will call the ‘reactor’.

3.1. Background

For industrial plasma applications such as large-scale air purification, it is important to generate a large-volume plasma. The pulsed corona discharge is especially suited for this purpose, because it is a type of discharge that operates well at atmospheric pressure and can consist of many parallel discharge channels (streamers) [3]. Furthermore, pulsed operation ensures that no spark-transition occurs. The pulsed corona discharge is often generated in either a wire-plate or a wire-cylinder arrangement. Both electrodes are metal and unlike in a DBD arrangement they are uncovered by a dielectric.

When high-voltage is applied to the corona reactor, a high electric field is generated around the wire electrode. If this electric field is sufficiently high, an avalanche discharge is generated, which transits into a streamer discharge if the space charge of the avalanche discharge is sufficiently high [3]. A streamer is an ionized channel with a space charge layer at its head. The streamer can propagate under the influence of the applied electric field, as well as under the influence of its own electric field due to the space charge layer. A sufficient number of free electrons has to be available in front of the streamer head to generate new ionization, thereby allowing the streamer to propagate. In the negative streamer, these electrons can drift from the ionized channel. This is not possible for the positive streamer due to the direction of the electric field. For positive streamers, photo-ionisation is one of the dominant mechanism for the generation of new electrons [66]. In this process, an excited nitrogen molecule emits a UV photon, which is then able to ionize an oxygen molecule some distance away (including the region in front of the streamer head).

When a streamer propagates between two electrodes, the electric field generated by the streamer accelerates electrons near the streamer head to high energy levels. These electrons (as well as excited molecules) are also able to dissociate or excite molecules upon collision. As a result of this dissociation, highly reactive species are formed. These reactive species, are then able to react with other molecules, such as pollutants. As a result, these pollutants can be converted into less harmful substances, which is why the pulsed corona is so useful for industrial non-thermal plasma air purification [137–141]. In long corona reactors, multiple streamers will develop along the wire electrode, thereby forming a large-volume discharge.

If a streamer crosses the gap between the electrodes, it leaves behind an ionized channel. At this point, a large current can flow through this channel if the high-voltage source that generates the external electric field is powerful enough. As a result, the channel heats up, and eventually, a full breakdown can occur. The period in which the streamer is crossing the inter-electrode gap is called the primary streamer phase, whereas the period after crossing—but before a full breakdown—is called the secondary streamer phase. When nanosecond high-voltage pulses are used to generate the electric field, the electric field is only applied to the electrodes during the first phases (primary and/or early secondary streamer phase) of plasma generation, which prevents spark breakdown and significant heating of the discharge channel and the background gas. Consequently, the loss of energy due to these thermal processes is avoided.

An energy transfer efficiency of 100% from the pulse source to the plasma is only possible if the plasma is a perfectly matched load. However, the reality is much more complex. A distinction is made between a slow voltage pulse and a fast voltage pulse. Here ‘slow’ is defined by the rise time of the pulse and the length of the reactor. If the transit time of an electromagnetic wave through the reactor is not significant compared to the rise time of the pulse then the pulse can be considered slow. If the pulse rise time is much shorter, the pulse is considered as fast and the reactor can be treated as a transmission line. For example, in a 1-m long reactor, the transit time of a pulse is several nanoseconds. A pulse with a rise time of 50 ns applied to this reactor could be considered slow, while a 1-ns rise time pulse is fast for this reactor. Please note that this distinction between slow and fast is quite a simplification: in reality pulses often fall somewhere in between fast and slow and the matching optimization could be approached both ways. Additionally, general matching results and rules for slow pulses are typically valid for fast pulses too.

3.2. Slow rising pulses and general rules

When a slow pulse is first applied to a corona plasma reactor, the reactor behaves predominantly as a capacitor (and slightly as an inductor). During the charging of this capacitor by the voltage pulse, streamers can initiate. Since the streamers have a resistive character, the load of the high-voltage pulse now becomes partly dissipative. However, the resistive part of the streamers is only between the high-voltage wire and the streamer head. Between the streamer head and the reactor wall only a displacement current can flow. The streamer can therefore be seen as a time-varying resistor with a time-varying capacitor in series. These first streamers are the
primary streamers. When the streamers bridge the gap, they form a predominantly resistive load and reach the secondary streamer phase. The result of this streamer development in time is that the plasma load undergoes three phases (shown in figure 41) in which it is successively (1) mainly capacitive, (2) partly capacitive, slightly inductive and partly resistive and (3) mainly resistive. Therefore, the plasma load is a very dynamic and complex load. Achieving good matching in the primary streamer phase (partly capacitive and partly resistive) is challenging.

The simple truth is: a plasma is never a perfect resistive load even if at some point it can behave resistive, so perfect matching is not possible. However, we can strive to make the plasma as ‘resistive as possible’ (while maintaining good plasma-processing conditions). Typically, the plasma reactor (with the discharge inside) has a higher impedance than the output impedance of the nanosecond pulse source. Therefore, the resistive part of the plasma should be decreased as much as possible to obtain good matching. If we consider the streamers in the reactor as the resistive elements then there are several ways to decrease their ‘resistance’ (or the resistance of the reactor as a whole):

- Generate thicker streamers.
- Increase the conductivity of the streamers.
- Generate streamers that transition faster into the secondary streamer phase, i.e. generate streamers with a high propagation velocity.
- Generate more streamers in parallel.

3.3. Pulse waveform design to improve matching

Two crucial parameters to manipulate streamer development and propagation are the applied electric field $E$ and the density of the gas $n$. It is known that the gas density has a strong influence on the development of streamers, because the mean free path between collisions is inversely proportional to the gas density. The mean free path determines how much energy an electron can gain as it is accelerated in the applied electric field before it collides with a background gas molecule. Sufficient energy gain is important to initiate and sustain a discharge. Therefore, streamer parameters (e.g. velocity, diameter, branching, etc) are often displayed as functions of the reduced electric field $E/n$. The electric field can be changed with the applied voltage pulse or with the design of the reactor. We first focus on the effect of the voltage pulse and how it affects matching. Here, we define matching $\eta$ as

$$\eta = \frac{E_{\text{plasma}}}{E_{\text{total}}},$$

where $E_{\text{plasma}}$ is the energy dissipated in the plasma reactor and $E_{\text{total}}$ is the total energy available in the pulse. A matching of 1 would mean perfect matching and a 100% energy transfer from the pulse to the plasma.

3.3.1. Voltage amplitude. Four aspects of the voltage waveform are important for matching: amplitude, polarity, duration and rise time. Of these four aspects, the voltage amplitude has a very significant effect on matching. Increasing the applied voltage (and therefore increasing the applied electric field) increases matching, irrespective of amplitude, rise time or polarity. Figure 42 shows an example [142]. In this figure, the pressure is the pressure of the SF$_6$ spark gap in the Blumlein pulse source described in section 2.3.2. This pressure axis corresponds to a voltage of around 20 kV to 75 kV. As can be seen, the matching increases with the voltage, both for positive and for negative polarity pulses. This voltage amplitude effect on matching is seen consistently literature, both for wire-cylinder and wire-plate reactors [143–147]. The effect is also seen later in e.g. figures 45(a)–47 and 49.

The reasons why an increased voltage amplitude increases matching is the result of a higher applied electric field (and therefore a higher $E/n$). A higher electric field increases the streamer conductivity, diameter and velocity [84] and also the number of streamers can be increased at higher voltages [148], as shown in figure 43; in other words:
all the effects we would expect to lower the total plasma reactor impedance.

If voltage and current are measured at the beginning of a plasma reactor (and the capacitive current is subtracted from the total current) the plasma reactor impedance can be estimated from these parameters, as is done in [143] and shown in figure 44(a). As can be seen from figure 44(b), increasing the voltage decreases the plasma reactor impedance to the point where it is almost equal to the output impedance of the pulse source (100 Ω in this case), indicating that very good matching is possible for high voltages.

In conclusion we can state that if you want to increase the energy transfer efficiency of the pulse source to the plasma reactor, increasing the voltage is almost guaranteed to achieve this. (Of course, at some increased voltage amplitude spark or even arc discharges might occur, which will degrade the chemical efficiency of the process and/or possibly destroy the reactor.)

3.3.2. DC bias voltage. Another way of increasing the peak voltage is by adding a DC-bias voltage to the pulsed voltage [138, 143, 145, 149–151]. An important advantage of this strategy is that because of the increased peak voltage the energy dissipation in the plasma (and therefore the matching) increases [143, 145, 151], examples of which are shown in figure 45. The reason this energy dissipation increases is twofold: first, because of the effects described in the previous subsection and second because the DC voltage will also be applied to the high-voltage wire between pulses. This generates some additional ionization around the wire, which will decrease the inception voltage of the discharge when the pulse is applied.

An additional benefit of adding a DC bias is that the plasma reactor will act as an electrostatic precipitator in addition to a regular pulsed corona reactor. If such a system is used to treat e.g. exhaust gases that contain fine particles (dust, soot, etc) then the corona system targets both these particles and the pollution compounds (SO₂, NO, NO₂, etc).

Another advantage is that the DC bias can generally be added at a low cost and therefore offers a cheap method to vary the plasma behavior. Finally, the DC bias offers a simple way to add energy to the plasma without the complexities of switching a high current and a high voltage. The downside to the DC-bias method is that the DC voltage has to be decoupled from the pulse voltage by a decoupling network, which can have an adverse effect on the properties of the pulse. Later we will see a method to add a DC bias voltage to the pulse voltage of a nanosecond pulse source without these adverse effects by changing the plasma reactor [73].

3.3.3. Pulse polarity. Voltage polarity is usually an important parameter in optimizing matching. Most studies find that positive pulses match significantly better to a plasma reactor
We already saw one example where positive streamers have a higher energy efficiency in figure 42. Another example is shown in figure 46. One of the reasons for the polarity effect on matching is that negative streamers generally initiate at a higher voltage than positive streamers [84, 143, 152] and therefore for similar voltage amplitude, positive streamers will develop better than negative streamers. Furthermore, almost all studies on positive and negative streamer propagation show that streamers generated by positive pulses propagate faster than those generated by negative pulses [9, 84, 148, 153–157]. Faster propagating streamers will reach the secondary streamer regime more quickly, thereby entering the ‘resistive’ phase sooner and dissipating more energy.

If the rise time of the voltage pulse becomes very short (subnanosecond), the polarity effect seems to disappear, which was shown both experimentally [147] and theoretically [158]. This can be observed in figure 47 where a 200-ps rise time pulse with different pulse durations was applied to reactors with different length.

3.3.4. Pulse duration. A parameter that also has a significant effect on matching is the pulse duration. Given two different pulses with equal rise time, polarity and amplitude, the pulse with the longest duration will result in better matching. This is not a great surprise, given that if the electric field is applied longer, streamers will become more ‘resistive’, possibly even reaching the secondary streamer phase. An example of the effect of the pulse duration on matching was already shown in figure 47, where we can see that applying longer pulses results in better matching (for both positive and negative pulses) [147]. Furthermore, for the pulsed corona system of Winands et al of which some results were already presented in figures 43–45(a) and 46 an increase in pulse duration from 40 to 200 ns resulted in an increase in matching of 84% for positive pulses [159, chapter 4]. Additionally, for negative pulses an increase in pulse duration from 50 to 100 ns resulted in an increase in matching of 50%, showing that also for slower pulses the matching increases for longer pulses for both polarities. In the case of these results, this increase was explained by the fact that streamers can reach the secondary streamer regime for longer pulses (confirmed by iCCD imaging).

It should be noted that ‘matching’ only refers to the electrical energy efficiency, not to the chemical efficiency. For instance, in the pulsed corona system of Winands et al the chemical efficiency (oxygen radical yield) was significantly higher for a plasma with only primary streamers as compared to a plasma with secondary streamers, even though the matching was better for the latter [7]. As a result, the overall efficiency of the system was better for the primary-
streamer discharge. In contrast, for the pulses used in [147] the chemical efficiency in ozone production (amount of ozone produced as a function of the plasma energy) was roughly equal for different pulse durations, but because longer pulses were able to deposit more energy into the plasma, the overall efficiency of those longer pulses was higher.

3.3.5. Voltage rise time. Finally, also the voltage rise time has a significant influence on matching. In general a shorter rise time increases the energy dissipation in the plasma. An example is seen in figure 48 which shows matching as a function of the rise time of a 9-ns pulse with the system of [147]. In that specific example, the pulse reflections in the reactor also play an important role (see section 4). However, in experiments as well as in modeling it was shown that a shorter rise time increases the velocity of streamers (both positive and negative) for a range of different nanosecond pulse parameters [56, 148, 156, 160–163]. Additionally, a shorter rise time increases the streamer diameter, as was shown in [31, 161] as well as [164, chapter 7]. Both of these effects (faster and thicker streamers) will decrease the impedance of the plasma and therefore will increase matching. In [156] this impedance was measured and was found to almost halve when the rise time of the pulses decreased from 64 ns to 20 ns (for both positive and negative pulses).

The reason that a shorter rise time results in faster and thicker streamers is likely that the electron density in the streamers can become higher for shorter rise-time pulses. In the first stage of the discharge the electron density can grow to a higher value when the external electric field is applied in a shorter time (as compared to a slower rise-time pulse) [158, 162]. The electron density in the generated streamers will consequently also be higher, which means that the conductivity of the streamer is higher, resulting in faster and lower-impedance streamers. For example, in [161] modeling shows that the electron density at the center of the discharge is almost three times higher for a 0.5-ns rise time pulse as compared to a 50-ns rise time pulse.

3.4. Reactor design to improve matching

Besides the applied voltage, the dimensions of the plasma reactor determine the applied electric field. So another way to vary $E/n$ is to change the reactor design, which will be discussed here. Certain reactor parameters, such as the capacitance of the reactor or the vacuum impedance of the reactor can be optimized to receive the pulse energy as efficiently as possible. These parameters will be discussed in sections 4 and 5. Simple reactor parameters that can be changed are the HV-wire to ground distance and the reactor length.

When the distance from the HV wire to ground (either a plate or a cylinder wall) is decreased, the electric field increases and as a result the conductivity of the streamers and their velocity will increase. As a consequence, the impedance of the plasma reactor decreases and matching increases (also because the secondary streamer regime is reached at an earlier time) [143, 165]. An example is shown in figure 49. In this example a decrease in wire-plate distance from 9.3 to 5.3 cm increases the matching by a factor of almost three. Of course,
Figure 49. Matching as a function of wire-plate distance in the pulsed corona system of Winands et al. Reproduced from [143].

Figure 50. Cross-section of the DC-bias voltage corona plasma reactor. A DC bias voltage can be applied to the tertiary electrodes to increase matching. Reproduced from [73].

actual plasma processing experiments would have to show whether all this extra energy is also being efficiently used in the plasma process (or that this energy just goes to heat), but from an electrical-efficiency point of view increasing the electric field with the electrode distance will result in a more efficient system.

Another way to increase matching with the reactor design is to increase the length of the reactor. This will generate more streamers in parallel and thereby decrease the impedance of the reactor [144, 147]. An example was already shown in figure 47 where the matching increased roughly by a factor of 1.5–2 when the corona reactor length was increased from 0.25 m to 1 m. This effect was also observed by Matsumoto et al. in [144] where increasing the reactor length from 0.2 m to 1 m increased the matching by a factor of 2–3 when using 60–80-kV, 5-ns pulses in a cylinder-wire reactor.

As we saw before, adding a DC bias to the pulse voltage can increase matching. In order to add this DC bias to the pulse circuit, a coupling network has to be installed. However, for very fast pulses, such a network might deteriorate the pulse waveform or even cause reflections and losses. Therefore, we devised a type of corona plasma reactor with integrated bias electrodes placed on a dielectric layer [73]. The cross-section of this coaxial reactor is shown in figure 50. It is also shown in figure 16, because it was used with the 5-ns pulse source that was developed in Kumamoto. The advantage of this reactor is that a DC bias can be added to the pulse without a coupling network. More specifically, a DC bias electric field is added to the pulsed electric field. The total electric field at the high-voltage wire will consist of the pulsed electric field minus the DC bias field (because the wire is grounded for low frequencies with the charging inductor of the pulse source). Therefore, to add the DC bias, a DC voltage with opposite polarity to the pulse is used. For pulsed voltage of around 40 kV the matching increases with around 25% for a DC voltage of −15 kV [73].

3.5. Temperature and pressure effects on matching

As we discussed before, the reduced electric field $E/n$ is an important parameter for matching: the higher the reduced electric field the higher typically the energy dissipated in the plasma. Therefore, besides the electric field, also, the gas density $n$ has an important influence on matching. Here $n$ is defined by the ideal gas law as

$$n = \frac{p}{k_B T},$$

where $k_B$ is the Boltzmann constant and $p$ and $T$ are the pressure and temperature, respectively.

When looking at the effect of pressure, an extensive study by Briels et al. [84] shows that the streamer velocity increases nearly linearly with the applied $E/p \times (E/n)$. In addition, streamers become thicker with decreasing pressure (so increasing $E/n$). This same trend was also observed in [66, 166] and many others and is also true for streamers in a DBD. Pancheshnyi et al. also reported on the streamer conduction current, which increased significantly for lower pressures [166]. Faster and thicker streamers at lower pressures as well as a higher conduction current all indicate a lower-impedance discharge and therefore it is not surprising that the dissipated plasma energy whenever reported is always higher for low pressures. So in other words: to increase matching you can operate your plasma at a lower pressure (though this might not be so appealing for industrial plasma processing).

In 1984 Aleksandrov et al. performed experiments on positive streamers in a 46.5 cm long gap for different temperatures [167]. They found that the breakdown voltage of the gap decreased with increasing temperatures and that the conduction of the plasma channel increased such that the transferred charge through the streamer channel after reaching the cathode was 100 times higher at 900 K as compared to room temperature. In comparison, they only found a 5 times increase in transferred charge when they reduced the air density by decreasing the pressure at room temperature to a value corresponding to 900 K. Similar experiments were done.
In recent years, new research has been performed on the behavior of streamers in plasma, particularly in biogas systems. Experiments with biogas systems have shown that the plasma energy increases with a decrease in gas density, where an additional temperature effect can be observed.

As stated in the introduction, the application of nanosecond pulses for plasma processing seems to become more chemically efficient when short, fast rising pulses are applied [7–9, 13, 15]. However, with these short pulses comes a challenge: optimizing the energy efficiency of the system. For fast-rising pulses, the plasma reactor efficiency decreases with increased pressure or temperature, which normally would mean that the energy efficiency of the entire system might benefit from this improved matching. For instance, elevated temperatures have a significant effect on chemical processes (e.g., ozone production is hardly possible at high temperatures).

4. Optimizing pulsed corona efficiency: reactor as a transmission line

Figure 51 shows an example of their results, where we observe a noticeable increase in plasma energy for increased $E/n$. In both studies, the plasma energy increases with a decrease in gas density, where an additional temperature effect can be observed.

In conclusion, the reported results all show that a decreased pressure or an increased temperature will increase the plasma energy dissipation and therefore the matching. While this might explain the results up to 1000 K, Ono et al argue that this cannot explain the results at higher temperatures because the decomposition rates of the dominant cluster ion $O_4^+$ becomes almost constant in the temperature range over which they performed their experiments above 1000 K [170].

In both the works of Ono et al and [85] there is a noticeable temperature effect, i.e., also in these results the discharge dissipates more energy when the temperature is increased (even though the corresponding pressure data points are at the same $E/n$). This effect is due to the decomposition of cluster ions ($O_4^+$ and $N_2^+$) at high temperatures, which normally would form a significant source of electron loss at low temperatures [172]. While this might explain the results up to 1000 K, Ono et al argue that this cannot explain the results at higher temperatures because the decomposition rates of the dominant cluster ion $O_4^+$ becomes almost constant in the temperature range over which they performed their experiments above 1000 K [170].

The results of Aleksandrov et al and Allen et al were all obtained in relatively long gaps and long pulse durations, so in recent years, new research has been performed on the subject [85, 151, 170, 171]. In [85] we performed pulsed corona plasma experiments with 80-ns positive pulses at different temperatures (303–773 K) and pressures and clearly showed that increasing $E/n$ either with pressure or temperature increases the energy dissipation in the plasma (and therefore the matching). Figure 51(a) shows these results. Even more recently, Ono et al performed similar studies in more detail on a point-plane discharge over a larger temperature range (up to 1438 K) [170, 171]. Figure 51(b) shows an example of their results, where we also clearly see an increase in plasma energy for increased $E/n$. In both the works of Ono et al and [85] there is a noticeable temperature effect, i.e., also in these results the discharge dissipates more energy when the temperature is increased (even though the corresponding pressure data points are at the same $E/n$). This effect is due to the decomposition of cluster ions ($O_4^+$ and $N_2^+$) at high temperatures, which normally would form a significant source of electron loss at low temperatures [172]. While this might explain the results up to 1000 K, Ono et al argue that this cannot explain the results at higher temperatures because the decomposition rates of the dominant cluster ion $O_4^+$ becomes almost constant in the temperature range over which they performed their experiments above 1000 K [170].

In conclusion, the reported results all show that a decreased pressure or an increased temperature will increase the plasma energy dissipation and therefore the matching. While a lower-than-atmospheric-pressure industrial plasma processing system might not be feasible, a high-temperature system is definitely possible in industrial systems, where exhaust gases can have elevated temperatures, for instance in biogas systems [173]. Just as with pulse duration, we make the note that improving matching (in this case by decreasing $n$) does not necessarily mean that the energy efficiency of the entire system might benefit from this improved matching. For instance, elevated temperatures have a significant effect on chemical processes (e.g., ozone production is hardly possible at high temperatures).
system to identify some of the challenges in optimizing the energy transfer from a nanosecond pulse source to a plasma reactor when such transmission-line effects dominate the behavior of the system. The full report on this research can be found in [147].

We should note that most of the results from the previous section on matching also hold true for matching (sub)nanosecond pulses (where transmission-line effects become important). The reduced electric field in the plasma reactor is still important for the discharge. So also here a high voltage, long pulse duration, high temperature, etc. result in better matching.

4.1. A case study: matching (sub)nanosecond pulses to a pulsed corona reactor

The nanosecond pulse source used in most of the examples of this section was already shown in figures 8 and 9, which is capable of generating the waveforms of figure 10. It is a single-line pulse source which is attached to the plasma reactor with a long cable. The plasma reactor is a cylinder-wire plasma reactor of 1 m (unless noted otherwise). Figure 52 shows an example of a measured waveform in the nanosecond pulse source system, where we first focus on the red trace (the original measured waveform). This measurement is taken in the cable, 1.7 m before the plasma reactor with a D-dot sensor mounted on the cable [61]. At around 21 ns the pulse passes the sensor position, originating from the pulse source. Then at around 37 ns another, smaller pulse is measured. This is the reflection from the plasma reactor. It is the part of the pulses that did not enter the plasma reactor, because when the pulse encounters a change in impedance, it is partly reflected and partly transmitted, a process which is governed by the reflection and transmission coefficient, R and T, respectively:

\[ R(t) = \frac{Z_i(t) - Z_{\text{cable}}}{Z_i(t) + Z_{\text{cable}}} \]
\[ T(t) = \frac{2Z_r(t)}{Z_i(t) + Z_{\text{cable}}} \]

Here, \( Z_i(t) \) is the transmission-line impedance of the plasma reactor and \( Z_{\text{cable}} \) is the transmission-line impedance of the cable. The static (no plasma) transmission-line impedance of the plasma reactor is determined by its geometry and is given by

\[ Z_{r,\text{static}} = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} \ln \frac{d_o}{d_i}, \]

where \( \mu_0 \) and \( \epsilon_0 \) are the permeability and permittivity of vacuum, respectively, \( d_o \) is the 50-mm inner diameter of the outer conductor of the reactor and \( d_i \) is the diameter of the wire electrode of the reactor. This reactor impedance will be higher than the cable impedance, so the reflected pulse will be positive. However, when plasma is generated in the reactor the impedance of the reactor \( Z_{r,\text{static}} \) changes. First, the plasma has the effect that the inner conductor diameter \( d_i \) in (16) increases artificially since a cloud of highly ionized plasma is generated around it. Second, the discharge consumes energy and will therefore get a more resistive character. Both of these effects result in a lower reactor impedance. Therefore, the reactor impedance is time-dependent, which is why (14) and (15) were given as time-dependent parameters (unlike (6) and (7)).

We can calculate \( R(t) \) from measured waveforms such as figure 52(a) by dividing the reflected pulse by the incident pulse (the two black traces between \( t_c-t_d \) and \( t_a-t_b \) in figure 52(a), respectively), as

\[ R(t) = \frac{V_i(t)}{V_r(t)} \]

where \( V_i(t) \) and \( V_r(t) \) are the incident and reflected pulse, respectively. With \( R(t) \) we can now calculate \( Z_r(t) \) as

\[ Z_r(t) = \frac{[1 + R(t)]Z_c}{R(t) - 1} \]

Figure 52(b) shows the calculated plasma-reactor impedance from the reflection. It starts out close to the calculated 281 Ω—from (16)—and then drops gradually during the pulse.
as the discharge develops. So by placing the sensor not at the plasma reactor interface but slightly before it, it becomes possible to calculate the plasma reactor impedance during the pulse. However, we can see from figure 52(b) that the reactor impedance is still far from the impedance of the cable and therefore a significant part of the energy does not even enter the reactor. This energy is not lost. The reflected pulse will travel back to the pulse source, reflect and then come back to the plasma reactor, where it again partly reflects, etc. On average, 20%–30% of the energy that is dissipated in the discharge for each pulse event is delivered by these later reflections. Of course, the shorter the cable is, the faster these reflections will be reapplied. It is still a question whether the energy supplied by these later reflections is as effectively used by the discharge in generating radicals as that first pulse, but we want to avoid these reflections because energy is lost through dissipation in the cable and the spark gap in the pulse source as these reflections bounce up and down the system. There is another reason as well why we want the pulse to completely enter the reactor the first time: at the reactor interface and over a short part before the reactor interface, the reflected pulse will overlap with the incident pulse. The voltages of these pulses add (and the currents subtract) so locally, the voltage will be significantly higher than the incident pulse, causing extra high-voltage stress in that part of the system. Interestingly, we can also calculate the transmitted pulse into the reactor \( V(t) \) as

\[
V(t) = V_i(t) T(t) .
\]  

For the example in figure 52(a) this transmitted pulse is also shown. As we can see, this transmitted pulse has a significantly higher amplitude than the incident pulse. In other words, we think we apply a pulse of around 26 kV to the reactor, but in reality over 40 kV is applied inside the reactor. This is another reason why being aware of these effects is important. We will see later that this 40-kV pulse will be attenuated quickly once the discharge develops. In fact, with such short pulses the voltage in the reactor is highly location and time dependent.

Figure 47 already showed that matching increases with the voltage amplitude and pulse duration. With the new insight in reactor impedance we can now also explain why this happens. Figure 53 shows the time-dependent impedance of the plasma reactor for different voltage amplitudes for a 5-ns, positive pulse. The plasma reactor impedance decreases with time and with voltage amplitude. In other words: increasing voltage amplitude in this system will increase matching not only because \( E/n \) increases, but additionally the pulse reflection at the reactor interface decreases (i.e. more energy goes into the plasma reactor). Similarly: for long pulses the reactor impedance achieves a lower end value, again also because the streamers reach farther into the reactor (even bridging the gap), but also because of the decreased pulse reflection at the interface.

So the challenge for energy optimization in a system with very fast pulses comes down to two things: first, all the matching effects we already saw in the previous section and second, minimizing pulse reflections at the plasma-reactor interface. Of course, we could opt to not use a cable at all between the nanosecond pulse source and the plasma reactor (or a much shorter one). However, in that case, the reflections will follow each other so quickly that it has the effect to ‘spread out’ the pulse, basically elongating the pulse. So even for such a system, minimizing pulse reflections is a priority.

Ideally, the plasma reactor would have an impedance of 50 \( \Omega \), but if we follow (16) that would mean a HV-wire of 15-mm in diameter, which will not produce the high electric fields required to generate a streamer discharge. A solution is to use a multiple-wire electrode system, as shown in figure 54 and which we introduced in [147]. In these configurations not one, but \( N_w \) thin wires are used as HV electrodes (they are electrically connected), arranged in a cylinder. It has the effect of drastically reducing the transmission-line impedance, but at the same time the thin wires are spaced far enough apart that the electric field around them is high enough to initiate a streamer discharge.

Figure 55 shows the results with the multiple-wire reactor configurations. In figure 55(a) we see an significant increase in matching, which can be explained by the decreased reactor impedance, as shown in figure 55(b). Additionally, we measured ozone yields for all these experiments and found that the multiple-wire reactors performed equal to the single-wire reactors. In other words: all energy dissipated in the discharge was converted to ozone with more or less the same efficiency. Therefore, in absolute terms the multiple-wire reactors produced more ozone due to the increased matching. More recently, we undertook a large parametric (theoretical and experimental) study with multiple-wire electrodes to boost the efficiency of a nanosecond pulsed corona plasma system. There we were able to double the efficiency of the entire system with a multiple-wire electrode (as compared to a single electrode) [174].

4.2. Electrical model of the pulsed corona plasma

In order to better understand the transmission-line effects and the streamer development in the nanosecond pulsed plasma
system, we developed a SPICE model (in LTspice [175]) of the reactor. The model we developed is a simple transmission line model with dissipative components to approximate the dissipation by the streamers. Therefore, this model is not meant as an accurate discharge model, but rather as a simple electrical equivalent model of the reactor and the streamers. It will allow us to derive an approximation of the voltage waveforms in the reactor to understand what transmission-line effects will be relevant for the streamer development. For a more complete model, methods such are used in e.g. [176] or [177] could be implemented. For a complete description of the model and the results achieved with it, see [56]. Here we will give a brief overview.

The SPICE model of the coaxial (wire-cylinder) corona-plasma reactor is shown in figure 56. It consists of \( N \) identical sections (we used \( N = 128 \) per meter of reactor) with lumped elements that make up the transmission line elements of the reactor. Each section contains a distributed capacitance \( C \) and a distributed inductance \( L \). The distributed resistance of the wire in the reactor is represented by \( R \) in the SPICE model. The distributed components \( C, L \) and \( R \) are the classical parameters of a transmission line (with losses in the dielectric neglected) [178]. We added a resistive load \( R_p \) to model the dissipation of the streamers in the reactor (with an inductor in series to model a time-dependency). Finally, the Zener diodes model the inception voltage of the discharges. More detail on the model can be found in [56].

Figure 57 shows a measured and simulated voltage waveform measured with the sensors that are positioned on the cable 1.7 m from the corona-plasma reactor (in the real system, as well as in the simulation). Naturally, the incoming pulse (at \( t = 10 \) ns) is modeled properly, since the first part of the measured pulse is the input of the model. Then the pulse reflects on the cable-reactor interface and reappears at the sensors at \( t = 25 \) ns. The results show that the reflected pulse and therefore the impedance of the reactor is properly modeled (for at least the duration of the pulse). After the reflected pulse, the model still shows good agreement for 6.5 ns longer. Consequently, the modeled and measured results show a good agreement for a total time of \( t_c \) (indicated in figure 57). After that time, the modeled results and the measured results start to deviate due to the complexity of the discharge behavior and the modeling with a fixed value for \( R_p \). After \( t = 38 \) ns the measured result shows a severely dispersed pulse, which is not correctly predicted by the SPICE model. The time window \( t_c \) is similar for the 9-ns pulses.

Figure 58 shows an example of the simulated voltage profiles in the reactor as a function of time and position. When the pulse enters the reactor it increases in voltage due to mismatch \((V_{12})\). It attenuates as it propagates through the reactor and finally reflects off the end of the reactor \((V_{128})\). Here it adds to the incoming pulse, causing a doubling of the
voltage. As the pulse propagates back towards the boundary of the transmission line and the reactor, it continues to add to the incoming wave until it reaches the boundary. In the real reactor, the pulse will already be very dispersed at this point and therefore these later stages of pulse reflections in the SPICE results will not be so significant.

A similar SPICE model of a plasma reactor was presented in [179, section 5.3], with the advantage of modeling the resistance of the plasma as a time-dependent parameter to more faithfully model the dissipation in the plasma.

From a matching point of view it is perhaps not so interesting to model the plasma reactor in so much detail, but for a general understanding of source-plasma interaction it is very insightful. For instance, the fact that the voltage is not constant in each part of the plasma reactor for such short pulses has a significant influence on the streamer development, as we will see. From a more practical perspective, the fact that the voltage nearly doubles at the end of the reactor is also useful to know, because it means that care should be taken with how the plasma reactor is designed at that end. In practice, this is where we see spark discharges when we increase the voltage too much.

In [56] we show the streamer development in our plasma reactor as a function of time and position in the reactor. We were able to achieve these results with an elaborate computer-controlled, automated iCCD imaging setup which captures thousands of single shot images at different points in the reactor and compiles these into averaged, full-length iCCD images of the reactor with 1-ns time resolution [58]. It also calculates quantitatively how far streamers propagate in each part of the reactor as a function of time. Two such examples are shown in figure 59 for 5-ns and 9-ns pulses. The beginning of the reactor (where the pulses enter) is at \( x = 100 \text{ cm} \).

For the 9-ns pulses in figure 59(b), the streamers seem pretty homogeneously distributed over the entire reactor length (i.e. they propagate towards the reactor wall relatively independently from the position in the reactor). However, with the 5-ns pulses, the streamers towards the end of the reactor (at \( x = 0 \text{ cm} \)) propagate significantly farther than in the beginning of the reactor. Qualitatively we can understand this by considering that the pulse inside the plasma reactor reflects at the end of the reactor and then adds to itself (i.e. the incident and reflected pulses add), resulting in a higher voltage at the end of the reactor. Why this is not the same for 9-ns pulses is that the 9-ns pulses are so long compared to the reactor length that this ‘adding to itself’ is true for most of the reactor, while for the 5-ns pulses this is mainly true for the second half of the reactor. Quantitatively, we can simulate this with the SPICE model. The results are shown in figure 60, which confirm that the voltage differences (amplitude and duration) are more significant for the 5-ns pulses.

Perhaps not surprisingly, this transmission-line effect becomes even more significant for a 2-m long reactor. In such a reactor the streamers are most active towards the end and at the beginning of the reactor, because there the voltage is highest [56].

In conclusion, matching (sub)nanosecond pulses to a plasma reactor (i.e. optimizing the energy efficiency) is governed by the same rules as slower pulses, but with the addition of transmission-line effects such as reflections off the
reactor that can become dominant. Additionally, for short pulses the voltage and therefore the electric field in the reactor can become highly position and time-dependent, which is why it can be worthwhile to develop an electrical simulation model of the plasma reactor to model these voltages.

5. Matching nanosecond pulse sources to pulsed corona plasma

In the previous sections the focus was on source-load interaction and how to optimize energy transfer to a pulsed corona plasma. In this section, we will discuss how the pulse sources of section 2 fit into this picture (if not already discussed in the previous sections).
5.1. Capacitive pulse sources without TLT or transmission line

In this subsection we consider pulse sources that make use of capacitive storage, but have no TLT or other transmission line at their output. In this situation, matching is not influenced by transmission-like effects (which we saw in the previous section), unless the reactor is very long with respect to the duration and rise time of the pulses (which in reality is almost never the case with capacitive-storage pulse sources). In principle, here we consider any pulse source which has a capacitor (or aggregation of capacitors) for storage, followed by a switch. Such sources include the simple capacitive storage pulse source (a capacitor, followed by a switch), but also the Marx generator (which is a series connection of capacitors and switches) and most MPC pulse sources (where the switch is a magnetic switch). While each of these sources works differently and can have spark-gap switches, semiconductor switches or magnetic switches the principle is the same: a capacitor discharges into the load (the plasma reactor).

In any system where a pulse source connects to a plasma reactor an inductance is present between the capacitor in the pulse source and the plasma (this inductance can be parasitic). This is the case when a pulse source is connected to a plasma reactor and the connecting wires are long or not compactly connected. Another example is a MPC pulse source, where the magnetic switch itself still has an inductance when switched on. Such a system then becomes a resonant system. If a TLT or transmission line of sufficient length is used for the connection and the connection to that TLT or transmission line is made compactly, the inductance may be neglected and the situation of section 5.2 holds. If only a short TLT or transmission line is used (short with respect to the pulse rise time), which is then connected by wires to a pulse source or plasma reactor, this may introduce a parasitic inductance high enough to warrant treatment as a resonant circuit again.

An equivalent circuit of the resonant circuit is given in figure 61. In this figure, \( C_p \) is the equivalent capacitance in the pulse source, \( C_t \) is the capacitance of the plasma reactor, \( L \) is the discussed parasitic inductance between these two capacitances and \( S \) is an ideal switch, representing the switch (or combination of switches) in the pulse source. If we first consider this system without losses and plasma (and therefore without a dissipative component), it is an undamped system. The current through this system \( I \) and the voltages over the capacitors are given by

\[
I = I_0 \sin(\omega t),
\]

\[
V_{C_p} = \frac{C_{eq}}{C_p} (V\_{C_p,0} - V\_{C_t,0}) [\cos(\omega t) - 1] + V\_{C_p,0},
\]

\[
V_{C_t} = \frac{C_{eq}}{C_t} (V\_{C_p,0} - V\_{C_t,0}) [1 - \cos(\omega t)] + V\_{C_t,0},
\]

with

\[
\omega = \frac{1}{\sqrt{L C_{eq}}},
\]

\[
I_0 = \frac{V\_{C_p,0} - V\_{C_t,0}}{\omega L},
\]

\[
C_{eq} = \frac{C_p C_t}{C_p + C_t}.
\]

Here \( C_{eq} \) is the equivalent capacitance of the circuit (series connection of \( C_p \) and \( C_t \)), \( \omega \) is the resonance frequency, \( V\_{C_p,0} \) is the initial voltage on \( C_p \), \( V\_{C_t,0} \) is the initial voltage on \( C_t \) and \( I_0 \) is the peak current through the circuit.

Figure 62 shows the calculated results for three different combinations of \( C_p \) and \( C_t \), where \( T \) is the resonance period given by

\[
T = \frac{2\pi}{\omega} = 2\pi \sqrt{\frac{L C_{eq}}{C_p C_t}}.
\]

Three situations can be distinguished:

(i) \( C_p > C_t \): Not all energy from \( C_p \) is transferred to \( C_t \). The advantage is that the voltage on \( C_t \) is higher (almost
energy is left in this, it might be desired, but what may be undesirable is that voltage increase over the plasma reactor. To some extent, the discharge ignites before the maximum energy is used completely. In reality, a reactor will be designed such that the discharge ignites before the maximum energy transfer to the discharge or in other components. Extra dissipation in the system, the energy left in C_p, will influence the pulse-forming process of the next pulse, which is typically undesirable.

In situation (ii), in an ideal world, all energy is transferred to C_p perfectly, at which point the discharge ignites and all energy is used completely. In reality, a reactor will be designed such that the discharge ignites before the maximum peak voltage (otherwise only a small amount of energy from the source will be dissipated and used in a useful plasma process). When the discharge ignites, it will have the effect of increasing the capacitance of the plasma reactor. A very thorough theoretical treatise by Uhm et al on this subject can be found in [180]. They found that choosing C_p around three times higher than C_r results in the best energy transfer efficiency because the equivalent capacitance of the reactor will increase to around three times the value of the static capacitance of the plasma reactor.

The advantage of situation (i) is that we achieve a voltage increase over the plasma reactor. To some extent, this might be desired, but what may be undesirable is that energy is left in C_p. If the switch in a the pulse source is a spark gap, it will be switched on until the spark in the gap is extinguished and this will typically only happen when all the energy is dissipated in the system. In this case, the energy that was left in C_p will find a way to be dissipated, either in the discharge or in other components. Extra dissipation in the discharge might be desirable, but then again, it might also result in gas temperature increase, etc. So it depends on the plasma process and the system whether situation (i) is useful. Additionally, when the pulse source is a MPC pulse source, the energy left in C_p will influence the pulse-forming process of the next pulse, which is typically undesirable.

Figure 63. (a) Solid line: calculated energy transfer efficiency from the pulse source capacitance C_p to the static (before plasma inception) capacitance of the reactor C_{R0}. Choosing C_p around three times higher than the static reactor capacitance results in the optimum energy transfer. The dots represent measured results (in a wire-plate reactor) and show good agreement with the trend. (b) The ratio of the instantaneous reactor capacitance C_r over the static capacitance as a function of time (calculated from voltage and current waveforms). This figure shows that the reactor capacitance increases in time. Both figures reproduced from [181].

A final note is on systems with a small plasma reactor. In such systems, the capacitance of the plasma reactor is also small and situation (i) is almost always the case. In such systems, charging the capacitance of the reactor is therefore achieved very quickly. However, due to the stray inductance and the fact that it takes some time for the discharge to form, oscillations on the output voltage might occur before the discharge can damp these oscillations. In other words, the resonant charging of the reactor becomes more like a fast oscillation on top of the voltage peak. Such a situation might result in double for large inequalities in capacitance values) than the charge voltage on C_p, but the disadvantage is that not all energy from C_p is transferred.

(ii) C_p = C_r: All energy from C_p is transferred to C_r. The voltage across C_r is equal to the charge voltage on C_p.

(iii) C_p < C_r: All energy from C_p is transferred to C_r (but some is also transferred back). However, the voltage across C_r is lower than the charge voltage on C_p. Also, the voltage across C_p swings negative. For large inequalities in capacitance, the voltage across C_r is only a fraction of the charge voltage.

If we analyze these situations, we can immediately conclude that situation (iii) is unwanted. Even if the components in the pulse source can handle the negative voltage on C_p, the voltage over the plasma reactor is lower than intended.

Experimental results by Mok et al later confirmed this factor of three in their system [181]. Figure 63(a) also shows the theoretical curve calculated by Uhm et al: Mok et al additionally calculated the increase in reactor capacitance as a function of time and also there confirmed the factor of three in their system (figure 63(b)). Therefore, as a general rule, choosing C_p = C_r is a good starting point, but experimentation will have to reveal what sizing of capacitance values results in maximum energy transfer to the discharge (and whether this energy is used effectively for the plasma process in question). Often, choosing C_p larger than C_r gives the best results. Another example of such an optimization process is given in [146], where the capacitance of the MPC pulse source was fixed and the capacitance of the plasma reactor was varied.
occur when a semiconductor Marx generator (with large capacitances) is connected to a small plasma reactor, as in [99]. Since the reactor capacitance is small, the peak voltage on the reactor will be higher than the applied voltage from the generator. This might be used as an advantage (to ignite the discharge), but it can also result in switch failure if the switch is a semiconductor switch which is sensitive to overvoltage.

5.2. Capacitive-storage pulse sources with TLT or transmission line

When a capacitive-storage pulse source is connected to a plasma reactor with a TLT or a transmission line, optimizing the energy transfer to the plasma becomes less straightforward. Because of the use of lines the circuit can typically not be analyzed with the resonant circuit approach. Here we have to differentiate between two cases:

(i) The rise time of the pulses is long with respect to the used transmission line. In this case, the transmission line will not behave like a transmission line, but like a capacitor. The value of this capacitor may be added to the capacitance of the plasma reactor.

(ii) The rise time of the pulses is short with respect to the used transmission line or TLT. In this case, for analysis we may decouple the input side of the transmission line or TLT from the output side and replace the TLT or line with the equivalent model of figure 21. In case a TLT is used, the equivalent model has to be adapted, such as in figure A3.

If you are dealing with case (i), then the resonant-circuit approach from the previous section may be used. For case (ii), Yan et al [182, chapter 4], [183] and Winands et al [159, chapter 4], [143] reported extensively on optimizing the energy transfer to a plasma reactor. Additionally, if transmission-line effects of the plasma reactor itself become important, the effects described in section 4 may become significant as well.

Yan focussed on two type of pulse sources. The first pulse source was a capacitive-storage pulse source connected to a wire-plate plasma reactor with a TLT, as shown in figure 64. The capacitors \(C_{in}\) and \(C_{end}\) are placed in the system to compensate for stray inductance in the TLT. The effect of these capacitances is shown in figure 65, where the voltage waveform on a matched load is shown with and without these capacitances. Adding the capacitances results in less reflections from the stray inductance in the system and therefore in an increased energy transfer efficiency, because these reflections will cause additional losses in the TLT.

Several phases that the plasma reactor undergoes are identified: before corona inception, during corona plasma generation and after corona plasma quenching. For each of these regimes, equivalent electrical circuits are given and energy optimization criteria are determined. We will not go through all of these criteria and just show a couple of examples. The complete and very detailed work can be found in [182, chapter 4].

5.2.1. Before plasma generation. The plasma reactor before inception can be modeled as a capacitor, as shown in figure 66. As noted before, the pulse source and TLT are modeled simply as a transmission line with a characteristic
The energy transfer efficiency (before plasma generation) is then calculated by dividing the amount of energy delivered to $C_r$ by the amount of energy that would be dissipated in a matched resistive load for the same voltage pulse. It is then assumed that the streamers are generated at $t = \tau$, where $\tau$ is the rise time of the voltage pulse at the input side of the TLT. The calculations show that an optimal energy transfer efficiency before plasma generation of around 97% is obtained when the following condition is satisfied:

$$\tau = 2Z_0C_r. \quad (27)$$

Winands et al later extended the calculations to where streamers can generate at an arbitrary time and to incorporate the DC-bias circuit they used (to improve matching, see section 3.3.2). This circuit is shown in figure 67(a). As can be seen in the figure, thePFN of this pulse source is a PFL and not a capacitor. However, because the pulse rises sufficiently fast, also here everything before the TLT may be modeled as a voltage source, as can be seen in figure 67(b), where a slightly more complex equivalent circuit is used.

Now, the parameter $\lambda_1$ is introduced, which is given by

$$\lambda_1 = \frac{\tau}{Z_0C^*}, \quad (28)$$

where $C^*$ is the series connection of $C_{DC}$ and $C_r$ (Yan had no $C_{DC}$ in his first circuit and simply used $C_r$ in the equation). The parameter $\lambda_1$ therefore is a measure for how the time constant of the system compares to the rise time of the pulse. It was shown that $\lambda_1 = 2$ results in the best energy transfer before streamer inception, which is where (27) comes from. To include the arbitrary time before streamer inception,
Simulated energy transfer efficiency under certain conditions and for different capacitors is the same for the curves with energy efficiency to the plasma reactor before plasma generation as a function of when the streamers initiate (at time $t$), the pulse rise time (through $\lambda_1$) and the output impedance of the source and the plasma reactor capacitance. In this simulation $C_{DC} \gg C_t$. The results show that under certain conditions an efficiency of 97% can be achieved. (b) Simulated energy transfer efficiency as a function of $\lambda_1$ and different capacitor ratios, showing that if $C_{DC}$ is not large enough with respect to $C_t$, the efficiency decreases. Reproduced from [143].

Winands et al introduced a second parameter $\lambda_2$, given by

$$\lambda_2 = \frac{t}{Z_0 C_t^{\frac{1}{2}}}$$

where $t$ is now the time of streamer inception. Figure 68(a) shows the effect of these parameters on the energy transfer efficiency (before plasma generation). The maximum in the curves is the same for the curves with $\lambda_1 \geq 2$. For lower values of $\lambda_1$ (fast rise time or large $Z_0$ and/or large $C_t$) the maximum obtainable energy transfer efficiency is lower. What these results show is that if $C_{DC} \gg C_t$ and $\lambda_1 \geq 2$ an energy transfer efficiency of 97% before streamer generation can be obtained when the streamers are ignited at the moment the energy transfer efficiency reaches this maximum value. So

5.2.2. During plasma generation. The plasma reactor during plasma generation can be modeled as a resistor, as seen in figure 69. From what we already saw in section 4 it is straightforward to see that ideal energy transfer in this model is achieved when the resistor is matched to the impedance of the transmission line, i.e. $Z_0 = R$. In reality however, the plasma reactor is not simply a resistor when the discharge forms. Even while at some point the plasma may be seen ‘as a resistor’ (in the secondary streamer phase, see section 3), this resistance is not constant in time.

Figure 70 shows the theoretical efficiency and measured efficiency for different plasma reactors [183]. The results show indeed that the best efficiency is realized when $Z_0 = R$. For the experimental results, this resistance was calculated from the peak of the measured voltage and current waveforms.

Winands et al used a slightly more complicated model for the plasma reactor (figure 67(b)) which recognizes that the plasma impedance is time-varying and that also the capacitance (and inductance) of the reactor still plays a role during plasma generation. However, no exact electrical modeling of this effect was undertaken. Instead, a model was used in which at time $t = \theta$ the switch closes and a fixed $R$ was placed in parallel to the reactor. For this situation, they calculated the maximum energy transfer efficiency, an example of which is shown in figure 71 (here, $\lambda_1 = 4$). What this shows is that as long as the streamer discharge is ignited before the arrow, the energy efficiency into the plasma reactor reaches its maximum (they show that this is true for any value of $\lambda_1$). So as long as the plasma ignites quickly, the ratio between the rise time and $Z_0$ and $C_t$ is not so important. In reality the 100% modeled efficiency is not reached, because at some point the voltage will drop below the threshold for which the discharge can still dissipate and therefore some energy will remain in $C_t$. Also, in reality losses will occur in the TLT and spark-gap.

The experimental results of Winands et al showed that in reality a good transfer efficiency to the plasma reactor can be obtained, as we already saw in section 3 in e.g. figures 44, 45(a), 46 and 49.

In conclusion, matching the pulse source to the plasma reactor during plasma generation will come down to trying to get the plasma impedance as close as possible to the pulse source impedance, which can be done by all the tools we already saw in section 3: applying a high enough voltage, using a DC bias, applying positive pulses, etc. If it is not possible to achieve this with one plasma reactor, it is even possible to place many plasma reactors in parallel (as done in
It should also be noted that one should take the design rules for the ‘before plasma generation’ part not too strictly, which is also observed by Winands et al: ‘However, the efficiency before plasma generation is not of particularly great interest since the purpose of the system is to generate a streamer discharge, not to charge a capacitor.’ [143]. In the end, experimentation is the only sure method to verify the design of a system.

On a final note, Yan also considered energy optimization to a system with a DC bias in his second system in [182, chapter 4]. There he also describes equivalent electrical circuits and many other design rules for each phase of the plasma generation.

6. Total energy-optimization strategy for pulsed corona systems

In sections 3–5 we explored energy optimization in a nano-second pulsed plasma system from different angles. Here an attempt is made to generalize these results, though it should be noted that almost every nanosecond pulsed plasma system is different.

In section 3 we discussed matching, or the optimization of the energy transfer from the pulse source to the plasma, as a function of the parameters of the voltage pulse and the reactor (geometry and conditions). The main parameter that seems to affect matching is $E/n$, or the reduced electric field. A higher reduced electric field results in electrons that can be more easily accelerated in the gas (and over longer distances), thereby reaching higher energies. This results in a higher degree of ionization in the streamer and faster and wider streamers. All of these effects eventually promote more energy dissipation in the streamer, increasing matching.

Table 2 summarizes the result of section 3. These results seem to hold for all pulsed plasma systems, from very fast sub-nanosecond pulses to longer pulses.

Table 3 summarizes the results of sections 4 and 5 and divides the pulse source systems in three different categories, each with a different approach to optimizing the energy transfer to the plasma reactor. It can already be seen from the table that the boundaries between these different categories are quite fluid and not always as clear-cut. However, it offers a quick overview of the different systems and can be used as a starting point to new system designers.
7. Examples of source-plasma interaction for fundamental studies

In this final section we will briefly explore source-plasma interaction in nanosecond pulse source systems that have the purpose of fundamental study. In such systems, optimizing the energy transfer to the discharge is typically not important and the results presented in the previous sections might not be so interesting. However, also in fundamental studies, source-plasma interaction can be important. In this section we will give some examples of such instances.

7.1. Source impedance

Briels et al performed experiments on streamer discharges in a point-plane gap using different power supplies [31]: the capacitive pulse source from figure 3 and the TLT pulse source from figure 24(b). For each source, they had the possibility to add a resistor \( R_2 \) between the discharge chamber and the pulse source. The resistor limited the current during streamer formation and the rise time of the pulse was doubled. As a result, the generated streamers were thinner and carried less current.

Because of the internal resistance of the capacitive source, the situation where no resistor was present with this source was comparable (in terms of output impedance of the source) with the situation where they used the TLT source with the resistor in place. Each of these configurations produced pulses with similar rise times and voltage amplitudes and the streamers they imaged were very comparable in pattern. Additionally, the measured currents were also similar. They concluded that ‘power supplies will create similar streamer patterns if their voltage rise time, peak voltage and internal resistance are similar, and that the internal resistance plays a decisive role’ [31]. In other words, as stated in the introduction, even if two different type of pulse sources produce exactly the same voltage pulse into a matched load, the discharges they produce may be significantly different because of differences in output impedance.

7.2. Reflections

While studying streamer discharges for fundamental studies, one would ideally like a perfectly square pulse to be applied to their system. Often such a system is a point-plane arrangement so that the discharge can be easily imaged for instance. Since a point-plane reactor only generates a single (branched) discharge, it typically does not dissipate all the energy that might be available in a pulse. If this is the case and a transmission line is used to connect the pulse source to the reactor, part of the pulse will reflect. For slow pulses (with respect to the length of the transmission line) these reflections will appear as oscillations on the rising edge of the pulse and might not be so disturbing. For short pulses however, such reflections might seriously distort the pulse waveform. A simple solution to counter this problem is to add a resistor in parallel to the plasma reactor, as was done in the system of figure 13.

For very fast pulses, adding an external resistor might not always be easily possible, as it will introduce too much inductance. One such a system is the system of figure 8. Here the entire system is a coaxial system and approached as transmission lines. For one experiment, we removed the corona plasma reactor and replaced it with a coaxial DBD arrangement with a sharp tip as a central electrode to see if such short pulses could ignite a streamer discharge in a DBD reactor [184]. As it turned out, the short pulse was too short to initiate and sustain a streamer discharge in a DBD arrangement, but an interesting discovery was that the reflections of the pulse (which occurred around every 230 ns after the main pulse) were able to step-by-step evolve a discharge, resulting in quite an interesting discharge pattern over time as shown in figure 72. So here we have a case where unwanted source-plasma interaction actually resulted in an unforeseen but interesting discharge.

Another example of where these reflections were important was shown in figure 4. Here a mismatch with the plasma reactor caused reflections to travel up and down the coax cable connecting the pulse source with the plasma reactor, resulting in dips in the voltage waveform. As a result, instead of the capacitive waveform that was expected, a series of short pulses appears across the reactor. While in that particular example the reactor was a corona plasma reactor for plasma processing, a similar phenomenon also happens when the reactor would be a point-plane reactor. In that case placing a matched resistor in parallel to the reactor might again be a good solution to remove or at least reduce the reflections.

For fundamental studies of pulse discharges, it is possible to use the reflected pulses to obtain additional information about the processes in the discharge. To do this, a nanosecond voltage pulse from the generator is transmitted over a long cable, the electrical length of which is greater than the pulse duration. The cable contains probes, such as a reverse current shunt or B-dot and D-dot sensors, which detect the initial pulse and the reflected pulse from the discharge reactor. From the shape of the reflected pulse, not only the behavior of the discharge impedance can be calculated (as we saw already in section 4), but also the absorbed energy in the electric

### Table 2. General results for energy optimization in a nanosecond pulsed plasma system. A ↑ indicates that matching increases if the corresponding parameter increases (and decreases for a ↓).

| Parameter         | Matching increased by |
|-------------------|-----------------------|
| \( E/n \) (voltage pulse) | Voltage amplitude ↑     |
| DC bias voltage    | ↑                      |
| Temperature       | ↑                      |
| Pressure          | ↑                      |
| \( E/n \) (reactor conditions) | Pressure ↓              |
| Pressure          | ↓                      |
| Electrode distance| ↓                      |
| Reactor length    | ↑                      |

- \( P \): More power is available in the plasma reactor.
- \( V \): More voltage is available in the plasma reactor.
- \( t \): The pulse duration increases.
- \( \Delta \): The plasma reactor length increases.
Table 3. Overview of different pulse source systems and the corresponding energy-optimization approach. Here a reasonable length plasma reactor of around 1 m is assumed. The parameters $\tau$, $l_r$, $l_{TL}$ and $l_{TLT}$ are the rise time of the pulse, the length of the reactor, the length of the connecting transmission line and the length of the connecting TLT, respectively.

| System | I | II | III |
|--------|---|----|-----|
| Characteristics | Short $\tau$ compared to $l_r$. Connection with TLT or TL | Short $\tau$ compared to $l_{TLT}$ or $l_{TL}$. Connection with TLT or TL | Capacitive storage No TLT or TL |
| PFN | PFL | PFL | C |
| | C (if very compact) | C | |
| Sources | Blumlein-line | Blumlein-line | C-source |
| | Single-line | Single-line | Marx generator |
| | Compact C-source | C-source | Solid-state LTD |
| | Compact Marx | Marx generator | MPC source |
| | Solid-state IMG | Solid-state LTD | |
| | SOS/DSRD source | MPC source | |
| | | Solid-state IMG | |
| | | SOS/DSRD source | |
| Approach | Section 4 | Sections 4 and 5.2 | Section 5.1 |
| | Table 2 | Table 2 | Table 2 |
discharge, which is equal to the energy difference between the initial and reflected pulses [147, 185].

8. Summary

With the need to study transient plasmas generated by nanosecond high-voltage pulses comes the need to understand how to generate those pulses and to understand the interaction between the pulse source and the plasma. In this paper, we first explored the different methods with which to generate nanosecond high-voltage pulses, from the relatively simple capacitive-storage pulse sources to more complicated sources. Then we discussed matching, or the optimization of the energy transfer from the pulse source to the plasma, as a function of the parameters of the voltage pulse and the reactor (geometry and conditions). The main parameter that seems to affect matching is $E/n$ (the reduced electric field). A higher reduced electric field eventually promotes more energy dissipation in the streamer, increasing matching. Table 2 summarized these results, which seem to hold for all pulsed plasma systems, from very fast subnanosecond pulses to longer pulses.

Next, we focused on the interaction between the pulse source and the plasma reactor, both with subnanosecond pulses and more general pulse sources. Table 3 summarized the results and divides the pulse source systems in three different categories, each with a different approach to optimizing the energy transfer to the plasma reactor. These categories ranged from fast pulsed operation, where the plasma reactor has to be treated as a transmission line, to slower systems where the plasma reactor may be treated as a capacitor.

In the accompanying Part II colleagues from Kumamoto University describe the aspects of ‘physics, discharge characterization and plasma processing’ of nanosecond pulsed discharges. Here they predominantly focus on the great amount of work they performed at Kumamoto University on the subject [16].

Appendix

In section 2.4 we introduced the TLT. In reality, such TLTs are not ideal. An effect that reduces the ideal output voltage of a TLT is the secondary-mode impedance. It is the wave impedance associated with the possible current path from the output of a lower transmission line to the shield of an upper transmission line, as shown in figure A1(a). This current path has an impedance $Z_s$ associated with it. Figure A1(b) shows this impedance in the equivalent circuit. For systems with more than two lines, more secondary-mode impedances could be present (e.g. three in figure 23(a) and one in figure 23(b)). So what effect does this have on the output voltage?

Figure A2 shows the calculated voltage over a matched load (taking $Z_s$ into account) as a function of the number of transmission lines in a TLT, where the transmission lines are configured as in figure 23(a). Ideally, the output voltage for an $N$-stage TLT would be $N$ times the input voltage, but due to the secondary-mode impedance, the output voltage is lower. The output voltage is especially low when the secondary-mode impedance is relatively low compared to $Z_0$ of the transmission lines in the TLT.

A solution to the secondary-mode issue is to increase $Z_s$ by placing magnetic material over all transmission lines with a secondary-mode impedance [28, 86, 186], as shown in figure A3. The magnetic material on the transmission line forms no impedance for the balanced current flowing through the transmission line and therefore does not impede the primary pulse. However, the secondary-mode current flowing through the shield of the transmission line is

\[\text{Figure A1. (a) Illustration of the current that is associated with the secondary-mode impedance in a two-stage TLT. (b) The secondary-mode impedance placed in the equivalent model of the output of the two-stage TLT.}\]

\[\text{Figure A2. Simulated TLT voltage amplification as a function of the number of lines in the TLT and the value of the secondary-mode impedance. As can be seen, the secondary-mode impedance has to be as high as possible to obtain the highest voltage amplification with a TLT, especially for TLTs with a large number of lines.}\]
unbalanced and is enclosed by the magnetic material. The magnetic material significantly increases the impedance of this path and therefore decreases the secondary-mode current and increases the secondary-mode impedance. More detail on magnetic material, sizing of the magnetic material and loss evaluation of magnetic material can be found in [182, section 3.6].

Another solution to decrease the secondary-mode impedance is to construct a parallel-plate TLT, as discussed in [187], though at present this TLT was only experimentally verified for low voltages and powers.

It should be noted that TLTS only work for short pulses. For long pulses, the TLT is a short circuit from both the input as well as the output because typically at least one inner conductor of a transmission line is connected to ground. A general rule of thumb of how long a TLT should be for a given pulse duration is to delay the pulse experiences as it travels once through the transmission line. So for a 100-ns pulse, with a transmission line that has a delay of 5 ns m⁻¹, the TLT has to be at least 10 m long. Any shorter and the secondary-mode wave travels in the transmission line that has a delay of 5 ns m⁻¹.

Figure A3. (a) Placing magnetic material (black in the figure) around the upper transmission line will impose an extra impedance on the (unbalanced) secondary-mode current, thereby increasing the secondary-mode impedance, as also illustrated in (b) in the equivalent TLT model of the output.

The full expression of what length of a TLT should have for a given pulse duration is given by:

\[ l_{\text{TLT}} \geq \frac{1}{2} \Delta T \sqrt{\mu_r \varepsilon_r}, \]

where \( c \) is the speed of light in a vacuum and \( \mu_r \) and \( \varepsilon_r \) are the relative permeability and permittivity of the material through which the secondary-mode wave travels, respectively [182], section 3.6. If no magnetic material is placed around the upper lines of a TLT, then \( \mu_r \) and \( \varepsilon_r \) are both 1. If magnetic material is used, this becomes the material through which the secondary-mode wave travels (in a simple approximation). Therefore, in the 100-ns pulse example, when magnetic material is used with e.g. \( \mu_r = 100 \) along the whole transmission line, the minimum TLT length is only 1 m instead of 10 m, which shows another important benefit of using magnetic material: the TLT can be much more compact.

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