Plasma Physics and
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PAPER • **OPEN ACCESS**

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To cite this article: Gregor Loisch *et al* 2026 *Plasma Phys. Control. Fusion* **68** 025007

IOP Publishing Plasma Phys. Control. Fusion 68 (2026) 025007 https://doi.org/10.1088/1361-6587/ae3ad6

Plasma Physics and Controlled Fusion

RECEIVED
22 October 2025

REVISED
10 December 2025

ACCEPTED FOR PUBLICATION
20 January 2026

PUBLISHED
4 February 2026

PAPER

Kilohertz repetition rate capillary discharge pulse modulator with energy recuperation and energy deposition monitoring

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Keywords: discharge plasma, plasma diagnostics, pulsed power

Abstract

Acceleration of electrons in plasma wakefields is one of the prime candidates for complementing or partially replacing conventional accelerator technology, due to its superior acceleration gradients. The plasma acceleration medium is often supplied independently of the acceleration process by e.g. electrical discharging an external current through a gas. Such discharge plasma sources are typically operated at several 10's of Hz but have also been operated at up to kHz repetition rate. Here, we present the design of a high voltage pulse modulator capable of supplying 10 kV, 400 A peak current pulses at 1 kHz repetition rate into a dynamic plasma load. The pulse circuit is based on a low-loss silicon carbide switch and passive pulse-recirculation, which allows reduction of the power consumption by up to 50% and also monitoring of the energy deposition in the plasma load.

1. Discharge plasmas for wakefield accelerators

Acceleration of particles in plasma wakefields, either driven by an intense laser [1] or another particle beam [2], is one of the most promising candidate technologies for future particle accelerators. Particle accelerators today are based on metallic resonators, which are limited in acceleration gradient due electrical breakdown [3]. In plasma, acceleration by multiple GeV over acceleration distances on a meter scale can be achieved [4, 5], which would allow to reduce the size and thereby cost of accelerator facilities significantly.

To supply the plasma acceleration medium [6–8], to guide the drive laser [9–11], to focus the highly-divergent, accelerated beams [12, 13], or to focus light [14] electrical discharges in various gases are used among other techniques. Advantages of such linear discharge plasmas are the simple setup of the plasma source, the inexpensive drive technology when compared to laser-based ionization techniques, and the good reproducibility of the produced plasmas. The repetition rate of these capillaries has mostly been in the few 10 Hz range with some setups reaching up to 1 kHz [15]. Future experiments and pilot user facilities require repetition rates in the 100's of Hz up to the 10 kHz range [16], which poses challenges for the drive electronics as well as the discharge cells. Here, we show a setup and the operation of an energy-recycling, kilohertz repetition rate, high voltage pulse circuits, which can save up to 50% of electrical power compared to non-recycling circuits and additionally allows to passively determine the amount of energy deposited in the plasma discharge. This parameter is critical for benchmarking plasma simulation models and thereby for dimensioning discharge plasma cells to meet the requirements of their individual application, and further developing such cells for e.g. high-average-power operation. Monitoring the energy flow of a discharge can potentially also contribute to the stable operation of discharge plasma cells as an input for active feedback systems.

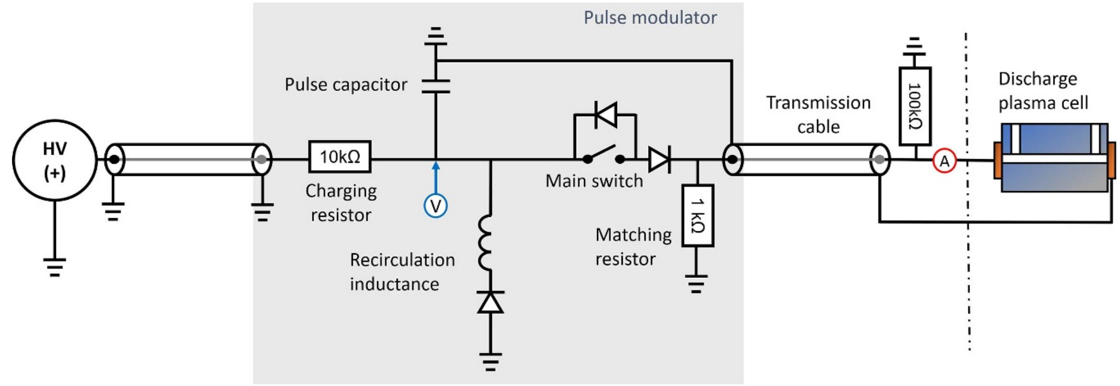

Figure 1. Sketch of the high voltage circuit of the kHz repetition rate discharge pulser. Blue and red circles mark the positions of voltage and current measurements, respectively.

2. Energy recuperation circuit

The high voltage pulse circuit is sketched in figure 1. It comprises a pulse capacitor of $6 \pm 0.35\,\mathrm{nF}$ which is charged to high voltage by a positive polarity high voltage capacitor charging power supply via a $10\,\mathrm{k\Omega}$ charging resistor. When triggered, the main pulse switch, which is built from an array of parallel and series silicon carbide MOSFET-switches and capable of withstanding a maximum voltage of 30 kV, closes the circuit to the discharge plasma cell. A parallel high-voltage diode protects the main switch from reverse polarity voltages and current flow in the reverse direction is prevented by a series high-voltage diode. The pulse voltage in the presented setup was limited by the maximum voltage rating of the recirculation inductance and the power of the high voltage power supply. Higher pulse voltages can be achieved by correspondingly dimensioning all components of the setup. Pulses from the modulator are transmitted to the vacuum tank, in which the plasma discharge cell is placed, via a 12 m long, $50\,\Omega$, coaxial cable. At the feedthroughs into the vacuum tank, a $100\,\mathrm{k\Omega}$ parallel resistor to ground prevents charging of the coaxial transmission line to high voltage and then parasitically discharging into the plasma cell due to leakage currents through the main switch in its open state. The parallel resistor upstream of the transmission cable is employed to better match the output of the pulser to the cable impedance.

Together with the parasitic inductance of the circuit, the pulse capacitor forms a resonant circuit and a current pulse with an approximately half-sine waveform runs through the plasma discharge. When the pulse current returns to zero, the capacitor is charged to opposite polarity with the remaining electrical energy. As negative polarity is reached, a second resonant circuit, consisting of the pulse capacitor and the recirculation inductance (ca. $800\,\mu\mathrm{H}$), is closed by the series diode in this circuit, allowing the capacitor energy to be charged back into positive polarity. The recirculation path is equipped with an inductance as the parasitic inductance of this path is otherwise very low and would result in a very fast recirculation. Recirculation should be significantly slower than the main discharge pulse (to avoid multiple plasma discharges while the main switch is closed) but be fast enough to allow for the maximum possible charging time by the high voltage power supply. Such energy recuperation with passive or active elements is used in various pulsed high voltage circuit, e.g. for fast pulsed magnets like septum and kicker magnets [17] or solenoids [18] but has so far not been applied in discharge plasma drive electronics.

The application of this circuit with the dynamic load of the plasma poses several additional challenges. As both the interruption of the current pulse due to opening of the main switch as well as due to quenching of the discharge plasma can lead to fast current fall rates and thereby large induced voltages in the parasitic inductance of the circuit, both cases must be avoided to protect the main switch from overvoltages. After a discharge pulse, the trigger for opening of the main switch has to be timed accurately. The switch has to be open before the polarity of the pulse capacitor reaches positive values again but may not be opened during the current pulse at maximum discharge ignition time delay.

These values have to be determined empirically during the commissioning of the system. Quenching of the plasma can especially happen when gases with a high electronegativity like oxygen are part of the gas mixture in the discharge cell. Therefore, the pulser is only operated with gases that are less prone to quenching like argon, nitrogen or hydrogen.

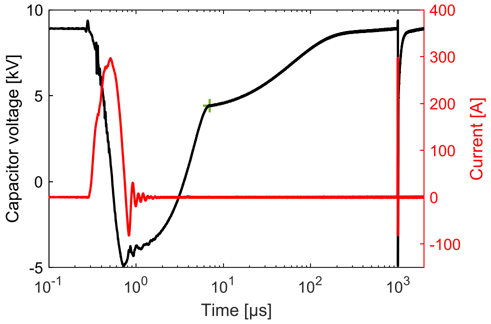

Figure 2. Load current and pulse capacitor voltage for a 5 Ω resistive load and 8 kV charging voltage. The green cross marks the voltage that is reached after energy recuperation through the recirculation inductance is finished, i.e. the voltage that is recuperated. At 1000 μs the next pulse at 1 kHz repetition rate can be seen.

Even when operated without load, i.e. in short circuit configuration, not all energy can be recuperated. Parasitic losses in the circuit are caused by the residual Ohmic resistance of the main switch, which is about 0.4 Ω, displacement currents in the high voltage diodes, the parallel matching resistor at the pulse modulator resistance of the cables, and by positive polarity charging of the capacitor when it is polarity is still reversed. The latter can be reduced by actively switching the capacitor charging power supply onto the capacitor when the pulse capacitor energy has been recuperated [18], which would also allow for a much lower charging resistance and hence faster capacitor charging.

Further optimization can possibly be achieved by integrating an equivalent model of the discharge into electrical simulations (see. e.g. [6, 19]), which has not been done for the present setup.

3. Measurements with resistive load

Before commissioning with a plasma discharge as a load, the pulse modulator was connected to various resistive loads. Figure 2 shows a measurement of the current pulse through a 5 Ω load and the corresponding pulse capacitor voltage. After the fast voltage drop to −5 kV during the discharge of the pulse capacitor, the voltage rises quickly again due to the recycling of energy through the recirculation inductance. The point that marks the end of this energy recuperation phase is marked by a drop of the voltage rise to zero for a few 10 ns. In this measurement a voltage of 4.4 kV is recuperated after ca. 7 μs.

Following the recuperation phase the pulse capacitor is slowly charged by the high voltage power supply until the original voltage is reached approximately after 1 ms. The next pulse at 1 kHz pulse repetition rate is also triggered at that time. Faster charging and hence a more stable voltage for the consecutive pulses can be achieved by using a lower charging resistor or—if the load requirements can still be met—by a lower pulse capacitance.

In figure 3 the amount of recuperated energy compared to the energy stored in the pulse capacitor before pulsing is shown in dependence of the load resistor. The error of the measurement is dominated by the uncertainty of the pulse capacitance of ±6% and could be further reduced by accurate measurement of the actual capacitances.

The power consumption of the high voltage power supply for varying repetition rate is shown in figure 4. To better represent the actual power consumed by the pulse circuit the power that is consumed without any voltage applied to the capacitor is subtracted.

A pulse repetition rate of 1 kHz could not be achieved without energy recuperation in the current pulse capacitor charging configuration with the employed high voltage power supply. The charging power should depend linearly on the energy fed into the pulse capacitor times the repetition rate. Therefore, the energy recuperation as shown in figure 3 does not suggest the factor of more than two in power consumption that can be seen in the data in figure 4. In the configuration without energy recuperation, the energy that is not deposited in the parasitic resistances nor the load is first stored in the pulse capacitor with reversed polarity. Without recirculation, this energy has to be discharged by the high voltage power supply. A power supply with even higher charging current capability would thus be required. This can be avoided by damping of the harmonic oscillation in the circuit either by a series [15] or—with less additional losses—a parallel [7] resistor. Therefore, compared to an operation without energy recuperation but with no reverse charging of the pulse capacitor, ca. 50% of energy at negligible load resistance can be saved with the circuit presented here according to the data shown in figure 3.

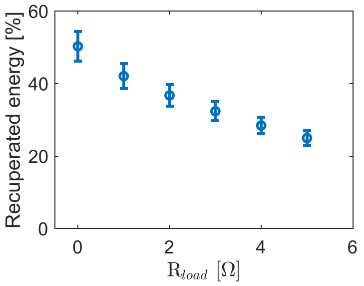

Figure 3. Recuperated energy divided by the energy stored in the pulse capacitor before it is discharged for varying load resistance.

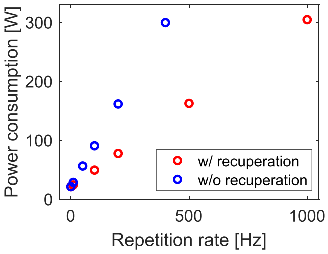

Figure 4. Energy consumed by the pulse circuit at varying pulse repetition rates for 8 kV charging voltage and a 5 Ω load resistance.

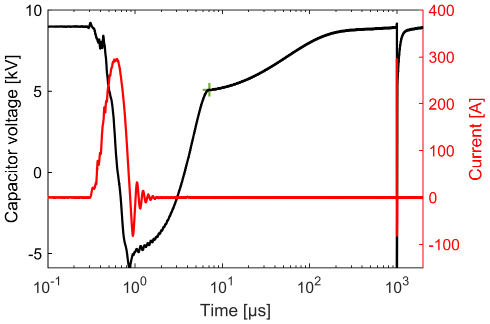

Figure 5. Plasma current and pulse capacitor voltage for 8 kV charging voltage and an argon plasma at a gas flow rate of 20 mln min^{-1}. The green cross marks the voltage that is reached after energy recuperation through the recirculation inductance is finished and also here the next pulse at 1 kHz repetition rate can be seen at 1000 μs.

Even though the pulse circuit can operate at 10 kV, a repetition rate of 1 kHz with recharging of the capacitor with a voltage deviation of $<0.1\%$ is only possible up to 8 kV. Measuring the dependence of the energy consumption for varying pulse capacitor charging voltage also revealed a linear dependency on the charging voltage, as expected.

4. Measurements with plasma dynamic load

To test the performance of the kHz pulser with an actual plasma load a 50 mm long, 1.5 mm diameter plasma cell with a similar geometry as described in [8] was used. This capillary was filled with either argon or hydrogen gas. Figure 5 shows the current pulse and capacitor voltage evolution at 1 kHz repetition rate for 2 pulses. Compared to figure 2 the current pulse and voltage drop are slightly delayed due to the initially high resistance and consequent breakdown of the plasma to a low resistance load. Continuous operation at 1 kHz with a plasma has been successfully tested but is currently limited to a few minutes operation by the heat load capacity of the plasma cells, which can be solved e.g. by water cooling [15].

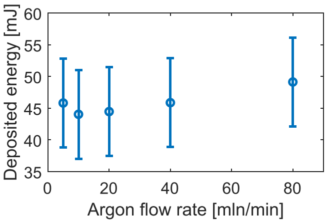

Figure 6. Energy deposited in an argon plasma for a pulse voltage of 8 kV and varying gas flow rate through the cell. The error is the systematic error due to the uncertainty of the pulse capacitance, relative errors between measurement points are <0.1%.

5. Plasma energy deposition measurement

It has been shown that nearly the full energy deposition into the discharge plasma is transferred to the surrounding plasma cell [19]. For high repetition rate operation, the heat load on the discharge plasma cell poses a significant threat to the integrity of the device. Therefore, the actual energy deposition into the plasma is a crucial parameter for the design of discharge plasma cells in future accelerator facilities, which are only competitive when operated at high repetition rate. While the energy deposition by the acceleration process, which depends on the exact acceleration parameters, can be paramount, the discharge pulse can contribute a significant and even comparable part of the overall energy deposition. So far, the discharge energy deposition could only be estimated through complex simulations and benchmark temperature measurements of the cell in continuous operation. Determining the energy deposition via voltage and current measurement at the plasma is technically challenging due to the setup of the discharge plasma cells discussed here. The cells are typically placed inside a large vacuum vessel and are moved with remote-controlled motors to align them with a light or particle beam. Voltage measurement—if placed inside of the vacuum—would significantly constrain movement and access to the cell for other diagnostics; measurement outside of the vacuum would introduce uncertainties to the measurement due to the parasitic inductance of the connections from the cell to the outside of the vacuum vessel.

Due to the energy recuperation and its clear signature in the voltage measured at the pulse capacitor in the pulse modulator circuit presented here, the difference of the recuperated energy with and without load (see also figure 3), i.e. the energy deposited in the load, can easily be determined.

This concept was applied to the plasma cell described in the previous section. In figure 6 the energy deposited in the plasma can be seen for varying gas flow rate through the plasma cell. The measured values correspond to a longitudinal energy density of a bit less than 1 J m^{-1} and therefore the power density at 1 kHz would be 1 kW m^{-1}. When assuming laminar flow, the density in the discharge channel should depend on the square root of the gas flow rate. The deposited energy is roughly depending linearly on this square root for gas flow rates of 10 mln min^{-1} or more as well. Why the energy deposition does not linearly depend on either the gas flow rate or its square root for a very low gas flow rate of 5 mln min^{-1} is beyond the scope of this study, but demonstrates the physics potential of the measurement technique presented here.

Figure 7 shows the same measurement for a hydrogen plasma at variable gas flow rate through the plasma cell. A similar dependence of the energy deposition is found for this gas, whereas due to the higher mobility of hydrogen the gas flow rates are significantly increased. Low gas flow rates, where a nonlinear energy deposition was observed in argon, could not be accessed with hydrogen as the discharge jitter becomes prohibitive for measurements under these conditions. The slight dependence of the deposited energy on the gas density in the cell means that the heat load on the plasma cell can be reduced by up to 10% in the parameter range shown here. In an application, the gas density and also the gas species can be constrained by other requirements, though [13, 20]. Finally, the dependence of the deposited energy from the pulse voltage was studied. The result for an argon plasma at a gas flow rate of 20 mln min^{-1} is shown in figure 8. The linear dependence allows to reduce the heat load on a plasma cell by reducing the pulse energy. This can either be achieved by reducing the pulse length or its peak value. The limit for such a reduction are again the physics requirements on the produced plasma, e.g. its density or ionization degree. Reduction of the pulse length would be especially interesting for a hydrogen plasma as due to the very fast recombination rates, significant recombination can already happen during the pulse. This can result in multiple ionizations of one hydrogen atom, which would probably not contribute to the physics requirements but only to the heat load on the plasma cell. In the circuit

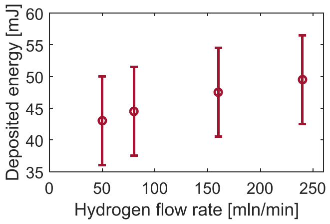

Figure 7. Energy deposited in a hydrogen plasma for a pulse voltage of 8 kV and varying gas flow rate through the cell. The error is the systematic error due to the uncertainty of the pulse capacitance, relative errors between measurement points are <0.1%.

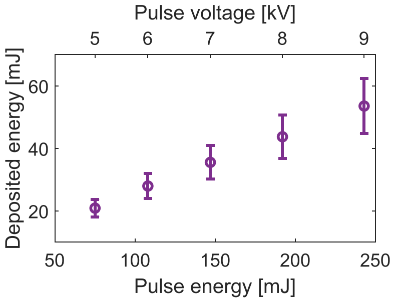

Figure 8. Energy deposited in an argon plasma for a gas flow rate of 20 mln min^{-1} and varying pulse energy. The error is the systematic error due to the uncertainty of the pulse capacitance, relative errors between measurement points are <0.1%.

presented here, the pulse length and amplitude can be influenced by the parasitic inductance of the circuit, the pulse capacitance and the charging voltage. Even though the benefits of reduced pulse energy on the wear of plasma sources has been demonstrated before [15], the possibility to actually measure the energy deposition would allow a much more detailed modeling and design of future devices.

6. Discussion

We have presented the design and operational data of a high voltage, kHz repetition rate pulse modulator with energy recuperation. This circuit can be used to drive linear discharge plasmas for accelerator applications like laser- and beam-driven plasma-wakefield acceleration, particle focusing, or guiding and focusing of light. It has been shown experimentally that up to 50% electrical power consumption of the pulse circuit can be saved with this circuit compared to a circuit without energy recuperation. Apart from the space that can be saved when less power has to be handled in the system, power saving can especially become critical when the application has a rather small footprint or when multiple discharge systems are required as in an optical setup [14]. Additionally, the energy recuperation allows to determine the difference in energy that can be recycled without load and with a plasma load, which corresponds to the energy that has been deposited in the plasma.

As the energy deposition in the plasma determines the heat load on the plasma source, measuring this value is crucial for benchmarking discharge plasma simulations, for further developing high duty cycle plasma sources, and—due to the measurement being fully parasitic—as an input for active feedbacks for the stable operation of such plasma sources.

Compared to modeling of the plasma [19, 21, 22], the presented measurement technique delivers immediate and accurate data about the operated discharge. As many electrical components can be reused in a circuit that employs energy recuperation, monitoring discharge performance via the energy deposition might often be enabled as an upgrade to an existing system. Initial measurements of the energy deposited in a plasma presented here give first insights into the dependencies of the deposited energy on gas density, gas species, and the high voltage pulse energy and showcase potential physics applications of this measurement technique.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors would like to thank K Ludwig and A Schleyermacher for preparing the discharge plasma cell for the measurements presented above as well as S Wesch and J Wood for allocating experimental time in the ADVANCE laboratory at DESY Hamburg to this study.

Author contributions

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Conceptualization (lead), Formal analysis (lead), Investigation (equal), Methodology (lead), Resources (supporting), Software (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Joachim Kahl
Resources (equal)

Frank Obier
Conceptualization (supporting), Resources (lead)

Jan Lukas Teichgräber
Investigation (equal), Resources (equal)

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