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HIGH-VOLTAGE PULSER TO PRODUCE PLASMAS INSIDE GAS-FILLED DISCHARGE CAPILLARIES

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Abstract

Plasma-based acceleration is leading towards compact accelerator machines able to produce accelerating gradients in the GV/m scale. Within this context, the plasma formation process represents a crucial point to control the plasma properties, which, in turn, can affect the electron beam dynamics. In this regard, at SPARC_LAB test-facility, in order to produce plasma channels that have lengths up to tens of centimeters, a gas-filled capillary plasma source is used, for which the gas ionization is produced through a high-voltage pulse applied to the electrodes at the ends of the capillary. Also, the electric circuit that is used to produce the high voltage pulse represents a strategic point to reach the appropriate properties of the plasma; therefore, in this work, this circuit will be described by taking into account two different versions, a classic scheme, that can reach lower values of the current pulses around 240 A, and a new prototype able to produce current discharges up to 1120 A.

1. Introduction

The overall apparatus we need to use in order to create, confine and characterize plasmas for plasma-based accelerators [1,2] is shown in figure 1. Inside of a cylindrical hydrogen-discharge plasma capillary, the neutral gas will be ionized by using a high-voltage discharge applied by mean of two copper electrodes. The capillary's channel that we are using at SPARC_LAB test facility goes from 10 to 100 mm in length and from 0.25 to 1 mm in radius. In this work, to test the discharge circuits, a capillary of 30 mm in length and 0.5 mm in radius has been used.

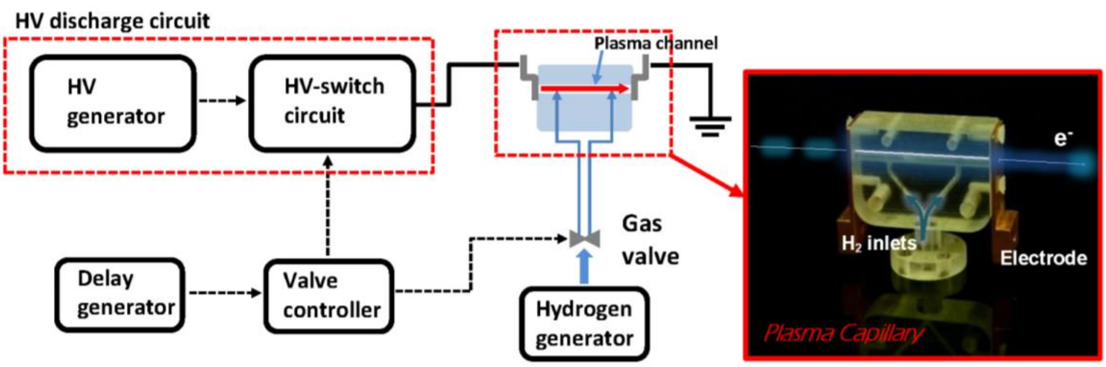


Figure 1 Scheme of the plasma module for plasma-based accelerators used at SPARC_LAB test-facility for which the plasma source is a gas-filled discharge capillary.

In this capillary, two gas inlets of 0.3 mm in radius feed the channel with hydrogen gas. The discharge circuit provides the power supply to produce the current discharge within the capillary by means of a high-voltage switch and a delay generator (Stanford Research DG535) to synchronize all events: gas injection, plasma diagnostics, and supplying high-voltage to produce the gas ionization [3]. The timing we use to produce the plasma inside the capillary is described in the following. The electronic gas valve is kept open for 3 ms to inject the hydrogen gas inside the capillary's channel and subsequently, 1.3 ms from the rising time, while the gas valve is still open, the high-voltage pulse is applied to the electrodes to ionize the gas and create the plasma in the channel. The high-voltage discharge circuit has been developed at LNF (Laboratori Nazionali di Frascati) and, in this work, it will be presented an analysis of its properties by comparing two different schemes about the plasma current pulse that they can produce.

2. Classic scheme of the high-voltage pulser circuit

Figure 2 represents the first version of the high-voltage discharge circuit we have assembled at SPARC_LAB to ionize H_2 gas in the capillary (Table 1). In general, such a circuit is composed of two parts: an external high voltage generator that supplies a switch circuit based on the charging and discharging of a capacitor through the plasma capillary; also, the solid state switch circuit, together with the electronic gas valve, controls the repetition rate of the plasma formation within the capillary.

In our applications, the typical repetition rate goes from 1 to 10 Hz. For this classic circuit diagram, the maximum plasma current that it is possible to reach is around 240 A when the generator voltage is 20 kV (Table 2). The current pulse behaviour produced by this circuit is shown in figure 3a. It should be noted the irregular behaviour is caused by the higher frequencies oscillations that are overlapped to the current profile. These oscillations are produced during the gas ionization and correspond to different frequency ranges: around 6 MHz and 67 MHz, also in the range between 80 and 140 MHz (see Fig. 3b).

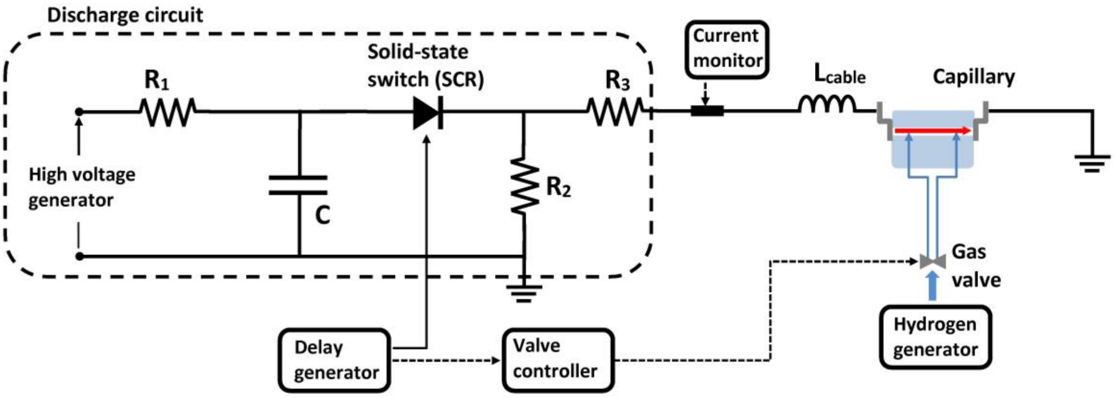


Figure 2 Classic scheme of the high voltage discharge circuit for plasma-based accelerators used at SPARC_LAB test-facility to create plasmas inside our discharge capillaries.

The natural frequency of a current pulse with duration of 1 μs is around 1 MHz. Such a ripple affects the plasma properties as the timing jitter of the discharge, the plasma stability and the uniformity of electron density along the longitudinal dimension of the capillary; as a consequence, also the beam dynamics could be degraded by this plasma behaviour.

Table 1 – Circuit parameters of a classic scheme of the high voltage circuit

Circuit component	**Value**
Generator voltage	0 – 40 *kV*
R_1	10 *kΩ*
R_2	100 *kΩ*
R_3	38 *Ω*
C	10.8 *nF*
R_{SCR}	17 *Ω*
L_{cable}	3 *μH*

Table 2 – Correspondence between generator voltages and plasma current pulses

Generator voltage (kV)	**Plasma current pulse (A)**
9	110
12	140
15	180
18	215
20	240

For this circuit, we have to also note the negative peaks (around -20 A) at the beginning of the current discharge, which are the responsible to damage the SCR switch, mainly when the current pulse goes over 350-400 A. Finally, the current pulse width is around 600 ns FWHM.

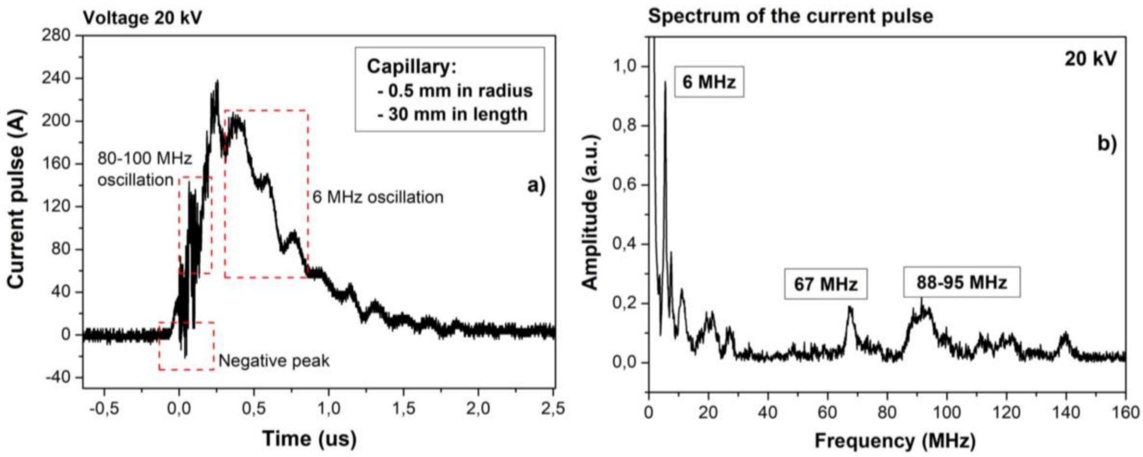


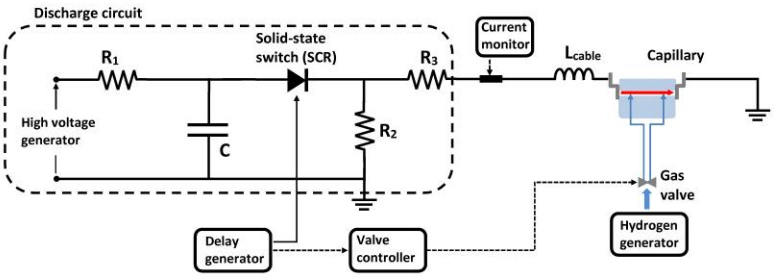
Figure 3 Plasma current profile (a) and its spectrum (b) that have been measured by using the classic version of the discharge circuit when the generator voltage was 20 kV.

With the purpose of improving the current profile and, at the same time, increasing the plasma current by maintaining the applied voltage range upon the capillary, a new discharge circuit has been developed. In the following, the improvements made to the circuit will be described together with some results obtained about the current pulse behavior produced during the gas ionization. All tests on the new version of the circuit have been done by using the same capillary composed of two inlets of 0.3 mm in radius, a capillary's channel of 30 mm in length and 0.5 mm in radius. Also the tests on the first version of the circuit have been done by using this kind of the capillary.

3. A new prototype of the high voltage pulser circuit

The possibility to use a capillary plasma discharge to accelerate and to focus an electron beam and, at the same time, preserving the beam quality is related to the capability to reach high values of the peak current. In fact, both the ionization degree and the radial uniformity of the plasma electron density depend on the plasma temperature that can be reached inside the capillary's channel [4,5], which in turn depends on the plasma current produced during the plasma creation. In particular, the temperature inside the channel play a crucial role for the application of active plasma lens, because it can affect the nonlinearity produced on the magnetic field, which in turn can determine an emittance degradation [6,7].

For these reasons, a new version of the discharge circuit has been developed. The mainly obstacle to reach higher values of the current pulse is represented by the negative peaks shown in Fig. 3, that can reach many tens of amperes for plasma currents exceeding 350 A. By using the first version of the circuit, without any protection on the SCR switch, such negative peaks cause an inverse current pulse through the SCR diode strong enough to break it. For the new version of the circuit, the protection diode D_{1p} is able to bypass negative pulse up to 1 kA (see Fig. 4). Such a precaution allows us to change the resistor R_3 and the inductance L_{cable} to increase the current pulse: R_3 has been decreased to 1 Ω and the HVcables, which connect the discharge circuit to the capillary, have been reduced to 70 cm (with respect 240 cm of the first circuit) to obtain a lower value of the inductance, L_{cable}, around 1 μH (with respect to 3 μH of the previous pulser circuit). The maximum peak current that has



Circuit component	Value
Generator voltage	0 – 40 *kV*
R_1	10 *kΩ*
R_2	100 *kΩ*
R_3	1 *Ω*
C	15.2 *nF*
R_{SCR}	17 *Ω*
L_{cable}	1 *μH*
C_p	2 *nF*
R_p	4 *Ω*
D_{p1}-D_{p2}	*Fast diode*

Table 4 – Correspondence between generator voltages and plasma current pulses

Generator voltage (kV)	Plasma current pulse (A)
9	320
12	480
15	630
18	800
20	910
25	1120

The circuit branch composed of the protection diode D_{2p} and the resistor R_p is used to prevent any negative overshoot of the current at the end of the pulse. Finally, the capacitor C_p introduces a low-pass filter to cut the high-frequency oscillations, with a cut frequency around 40 MHz. Figure 5 shows the current profiles corresponding to the two different pulser circuits that have been considered here, when the generator voltage is 20 kV. It should be noted the clear improvement of the current profile in terms of high-frequency oscillations overlapped to current pulse and the strong growth of the current peak, that goes from 220 A for the first version of the circuit to around 900 A for the new one. Also, the latter allow us to maintain the negative peak below 30 A, despite the current pulse exceeds 1kA.

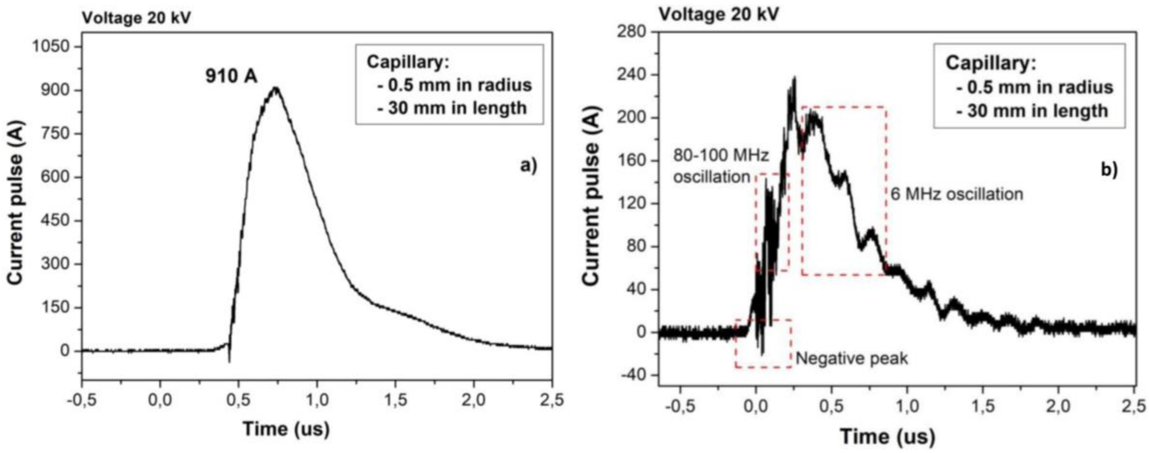


Figure 5 Comparison of measured current pulses between new (a) and first (b) versions of the high-voltage pulser circuit when the applied voltage is 20 kV; for the new version of the circuit, the peak current at different voltages has been reported in Table 4.

Finally, in Figure 6 is reported a comparison between two different operating conditions for which the new pulser circuit has been tested: when the load impedance is the resistance of the plasma created inside a 3 cm-long capillary and when the load impedance is a short circuit.

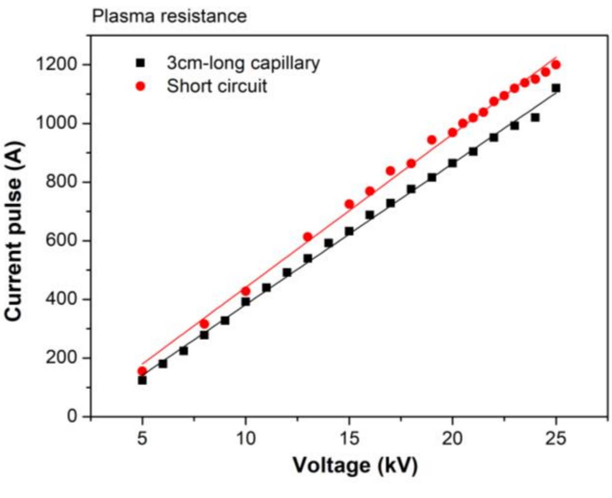


Figure 6 Measured current peaks for the new pulser circuit concerning two different operating conditions: load impedance equal to the plasma resistance of a 3 cm-long capillary and equal to a short circuit.

The difference between the slopes of the two measurements give us an estimation of the plasma resistance, that also depends on the geometric parameters of the capillary, as length and radius of the channel, and plasma properties as pressure and temperature. For a 3 cm-long capillary, 0.5 mm in radius and 30-40 mbar of the neutral gas pressure (before the ionization), we have measured an average resistance of the plasma around 2 Ω.

4. Conclusions

In this work, we present a new design of the high-voltage pulser to produce plasmas inside gas-filled discharge capillaries. The new circuit present several advantages with respect to the previous one as regards the maximum achievable current and reliability and safety of the circuit. First of all, it is possible to reach very high values of the peak current, around 1120 A (it was around 240 A for the old circuit), thanks to the use of a protection fast diode, which is mounted in parallel to the SCR switch. Also, by using a low pass filter, mounted with another protection diode in parallel to the capillary, the high-frequency oscillations of the plasma current, overlapped to the main pulse, have been strongly reduced.

Acknowledgements

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