A High-Voltage Nanosecond Opening Switch Based on TVS Diodes

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Pulsed Power for Kicker Systems 2023 workshop
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Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Outline

Section I – Introduction

Section II – SOS diodes

Section III – TVS diodes

Section IV – Conclusion

Section I

INTRODUCTION

1. Introduction

Solid State Pulsed Power

Semiconductor Opening Switch*
(SOS diodes)

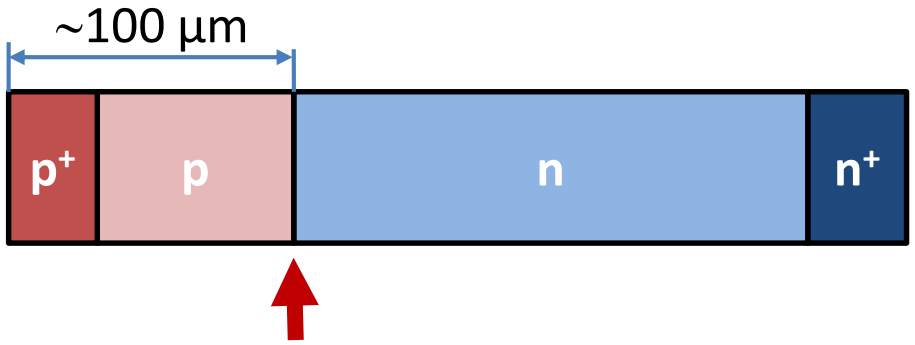
Impact Ionization Closing Switch*
(high-voltage thyristors)**

1. Introduction

1.1 Comparison of DSRD and SOS diodes

Drift **S**tep **R**ecovery **D**iodes

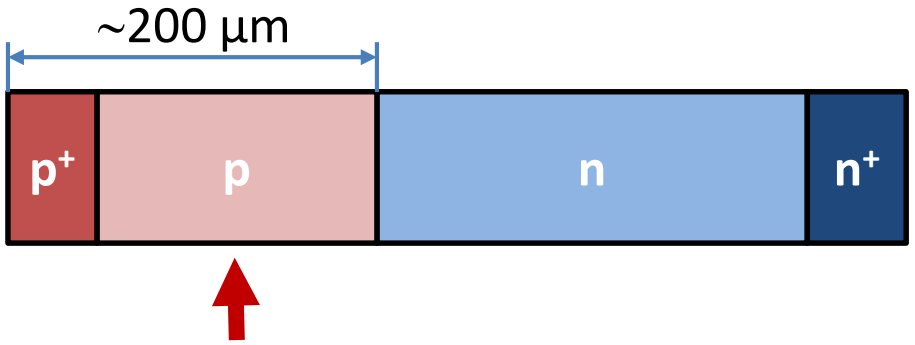
Dr. Grekhov *et al.*, 1980s



Current cut-off

Semiconductor **O**pening **S**witch,

Dr. Rukin *et al.*, 1990s



Current cut-off

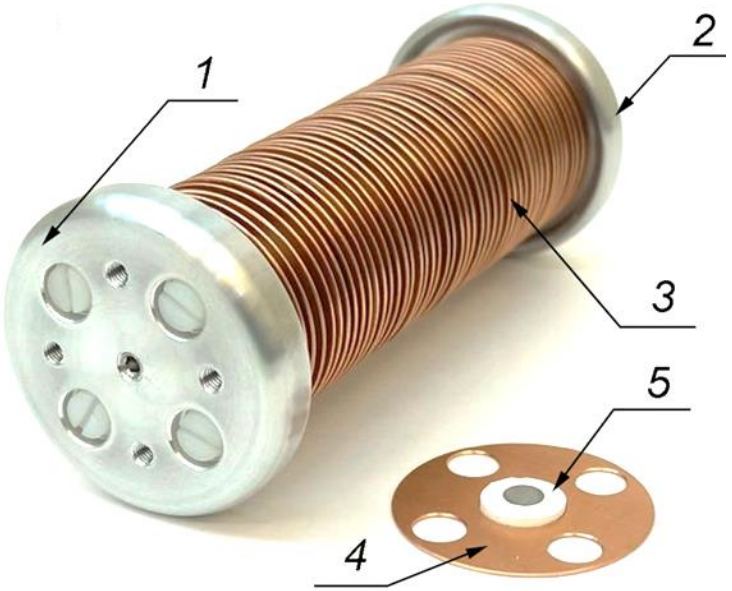
DSRD	Attainable Parameters	SOS diodes
0.2 – 0.3	Current density, kA/cm²	2 – 10
0. 1	Peak power, GW	10

[1] I. V Grekhov and G. A. Mesyats, “Nanosecond semiconductor diodes for pulsed power switching,” Physics-Uspekhi, vol. 48, no. 7, pp. 703–712, 2005.

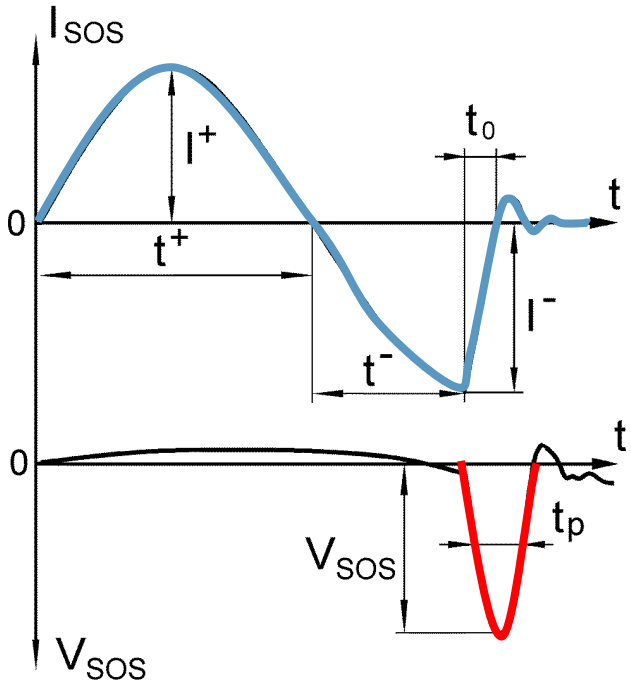
1. Introduction

1.2 SOS diode technology

IEP UB RAS



SOS-200-8 diode: peak voltage – **200 kV**, cutoff current – **8 kA**, length – 156 mm, mass – 760 g.



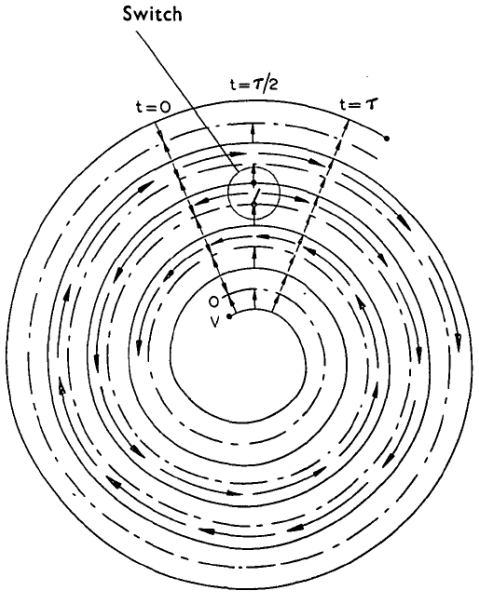
Typical waveforms of the **current** (top) via SOS and the output **voltage** across it (bottom).

Parameter	SM-2N
Output peak voltage	100–200 kV
Pulse current	0.2–0.4 kA
Peak power	30–50 MW
Pulse duration (FWHM)	25–40 ns
Continuous pulse repetition frequency	1 kHz
Burst pulse repetition frequency	5 kHz
Case length	0.62 m
Mass with transformer oil	~50 kg

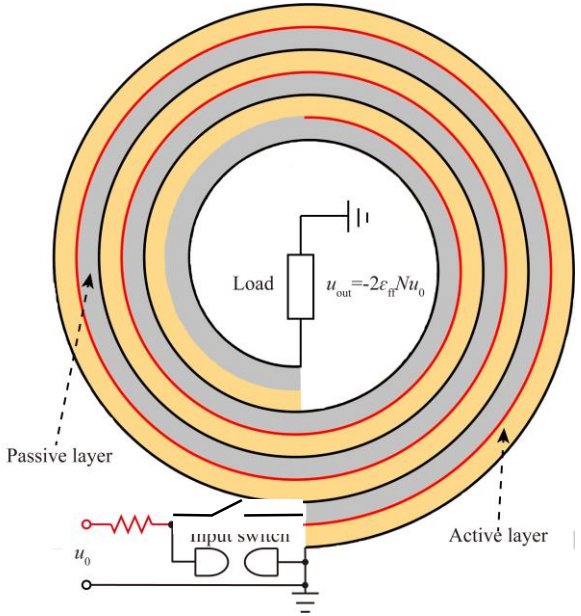
[2] S. Rukin, “Pulsed power technology based on semiconductor opening switches: A review,” Rev. Sci. Instrum., vol. 91, no. 1, p. 011501, 2020.

1. Introduction

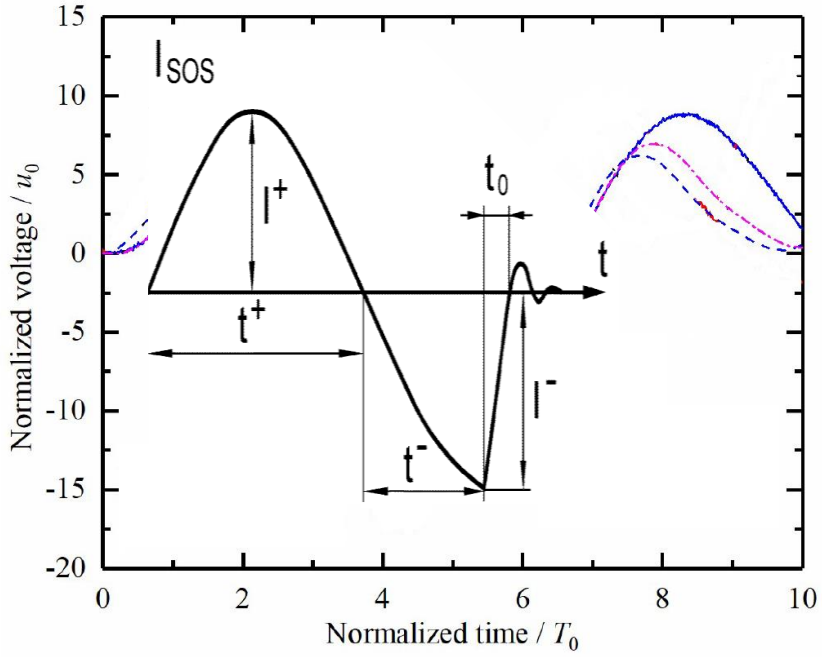
1.3 Spiral Generator (SG) a.k.a. Vector Inversion Generator (VIG)



Spiral generator diagram **[Fitch 1964]**



Spiral generator diagram **[Bland 2021]**



Output voltage of the spiral generator **[Bland 2021]**

[3] R. Fitch and V. Howell, “Novel principle of transient high-voltage generation,” in IEE Science and general, 1964, vol. 111, pp. 849–855.

[4] J. Yan, S. Parker, and S. Bland, “An Investigation Into High-Voltage Spiral Generators Utilizing Thyristor Input Switches,” IEEE Trans. Power Electron., vol. 36, no. 9, pp. 10005–10019, Sep. 2021.

1. Introduction

1.4 Motivation

1. Can we use SGs as a pumping circuit for the SOS diodes?

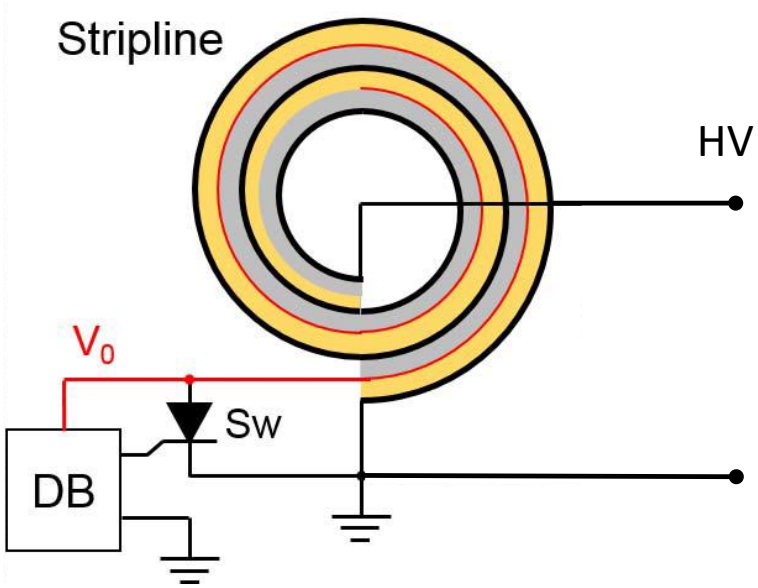
2. Can we replace SOS diodes by TVS diodes?

Section II

SOS DIODES

2. SOS diodes

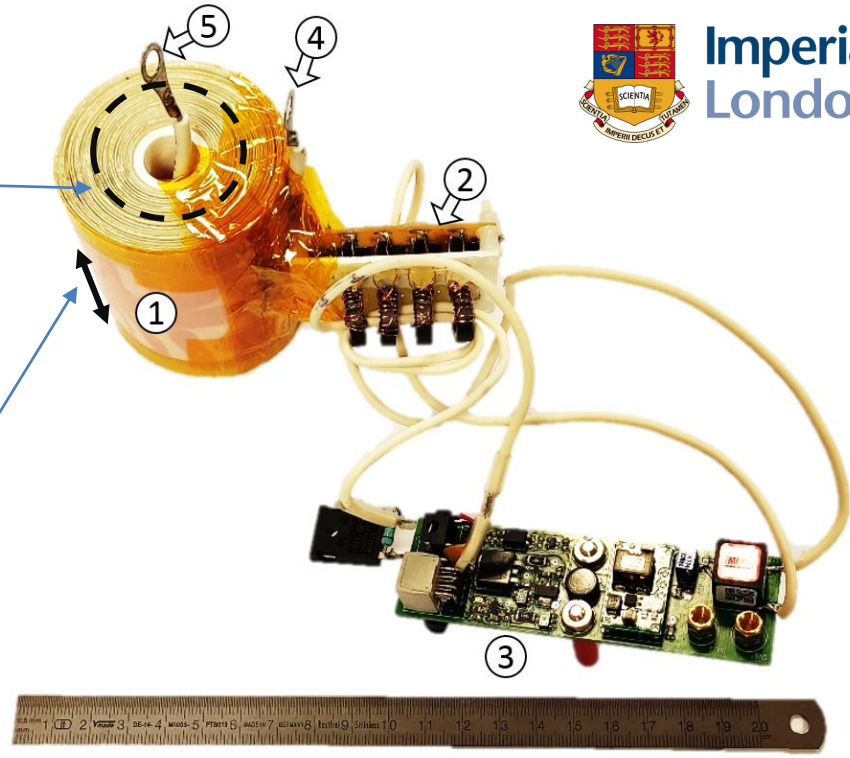
2.1 Spiral generator SG-40/50



Circuit diagram of the SG-40/50 generator: Stripline – schematic cross section of the spiral pulse forming line, DB – driver board, Sw – solid-state switch.

Mean diameter
D_M = 40 mm

Copper width
L_C = 50 mm



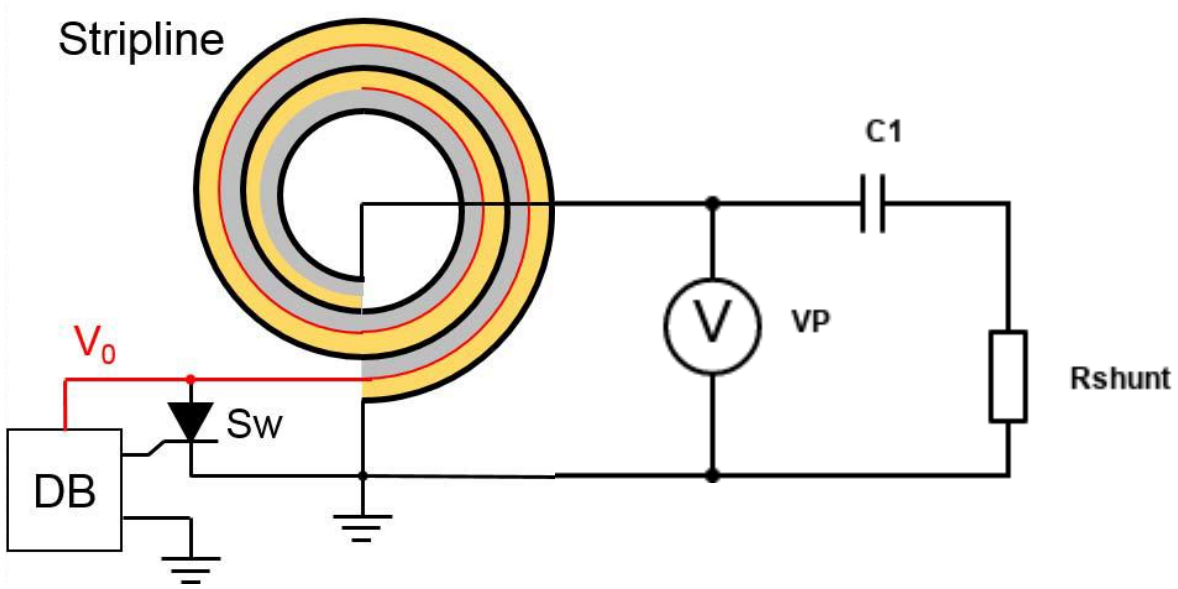
SG-40/50 generator: 1 – spiral stripline, 2 – solid-state switch, 3 – driver board, 4 – ground terminal, 5 – high-voltage terminal.

[4] J. Yan, S. Parker, and S. Bland, "An Investigation Into High-Voltage Spiral Generators Utilizing Thyristor Input Switches," IEEE Trans. Power Electron., vol. 36, no. 9, pp. 10005–10019, Sep. 2021.

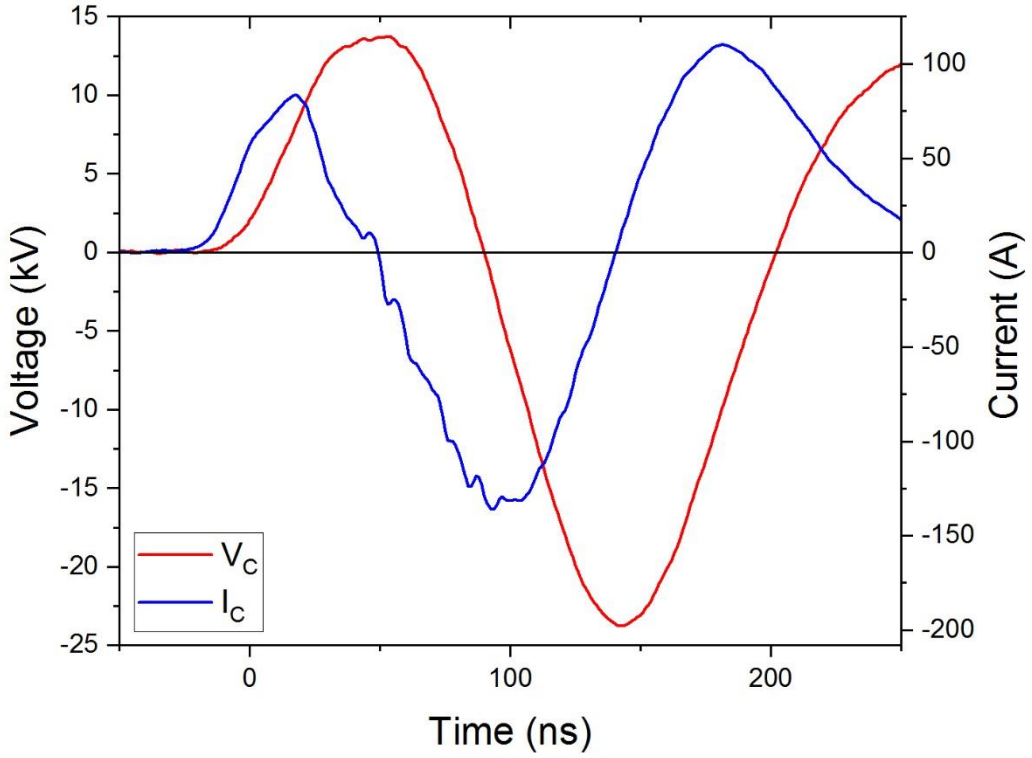
[5] I. Lavrinovich *et al.*, "2-kV Thyristor Triggered in Impact-Ionization Wave Mode by a Solid-State Spiral Generator," IEEE Trans. Plasma Sci., pp. 1–9, 2022.

2. SOS diodes

2.1 Spiral generator SG-40/50



Circuit diagram of the SG-40/50 generator: Stripline – schematic cross section of the spiral pulse forming line, DB – driver board, Sw – solid-state switch, VP – voltage probe, C1 – load capacitor, R_{shunt} – resistive shunt.

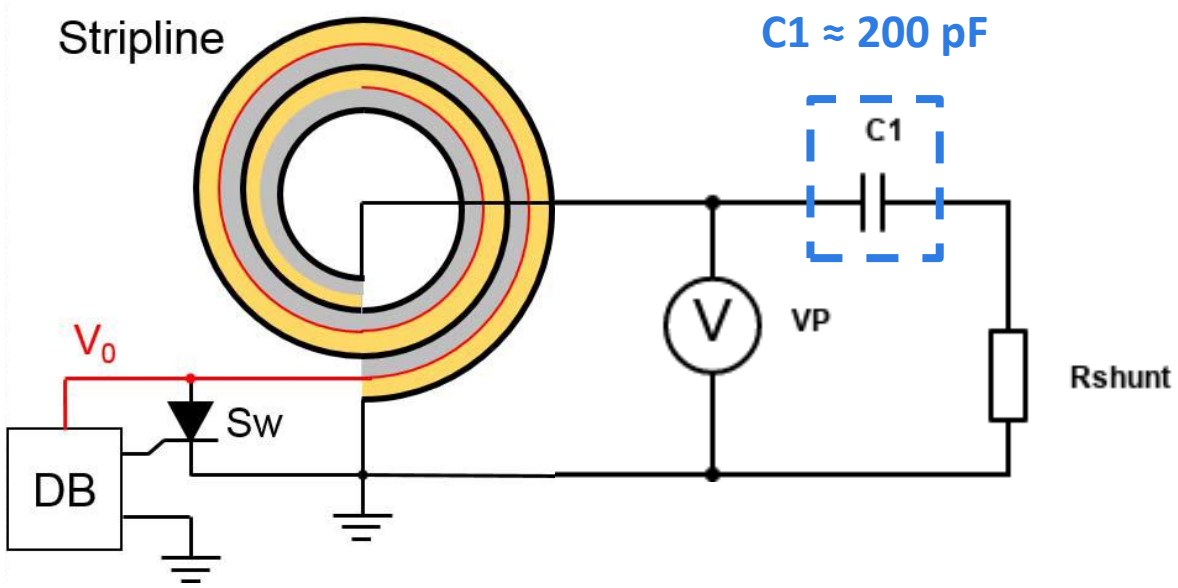


Output **voltage** (red) and **current** (blue) of the SG-40/50 spiral generator operated to a capacitive load C1=175 pF.

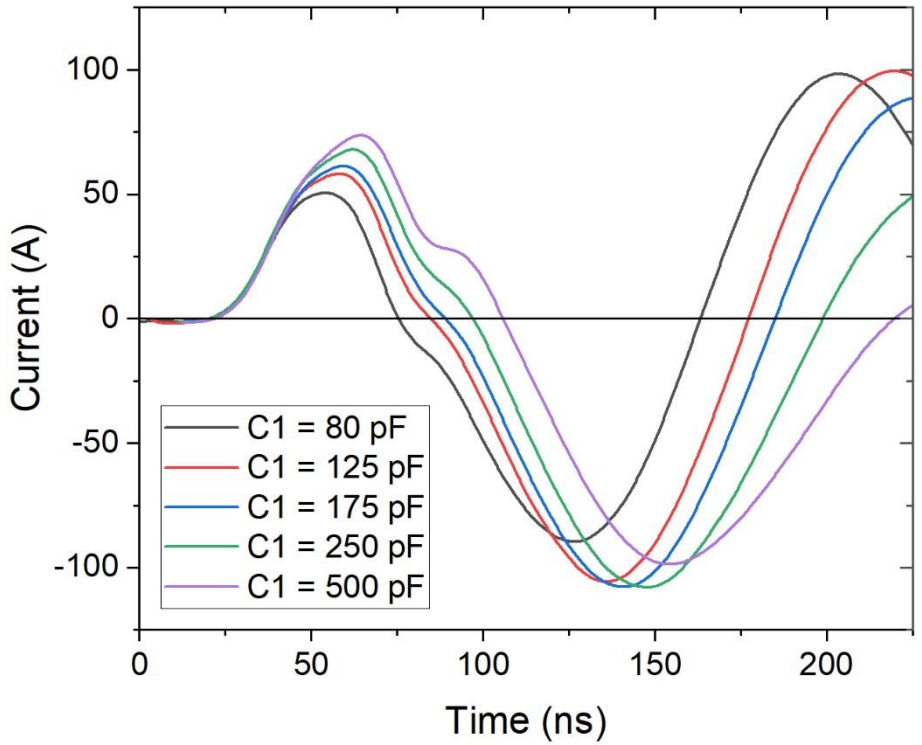
[5] I. Lavrinovich *et al.*, "2-kV Thyristor Triggered in Impact-Ionization Wave Mode by a Solid-State Spiral Generator," IEEE Trans. Plasma Sci., pp. 1–9, 2022.

2. SOS diodes

2.1 Spiral generator SG-40/50



Circuit diagram of the SG-40/50 generator: Stripline – schematic cross section of the spiral pulse forming line, DB – driver board, Sw – solid-state switch, VP – voltage probe, C1 – load capacitor, R_{shunt} – resistive shunt.

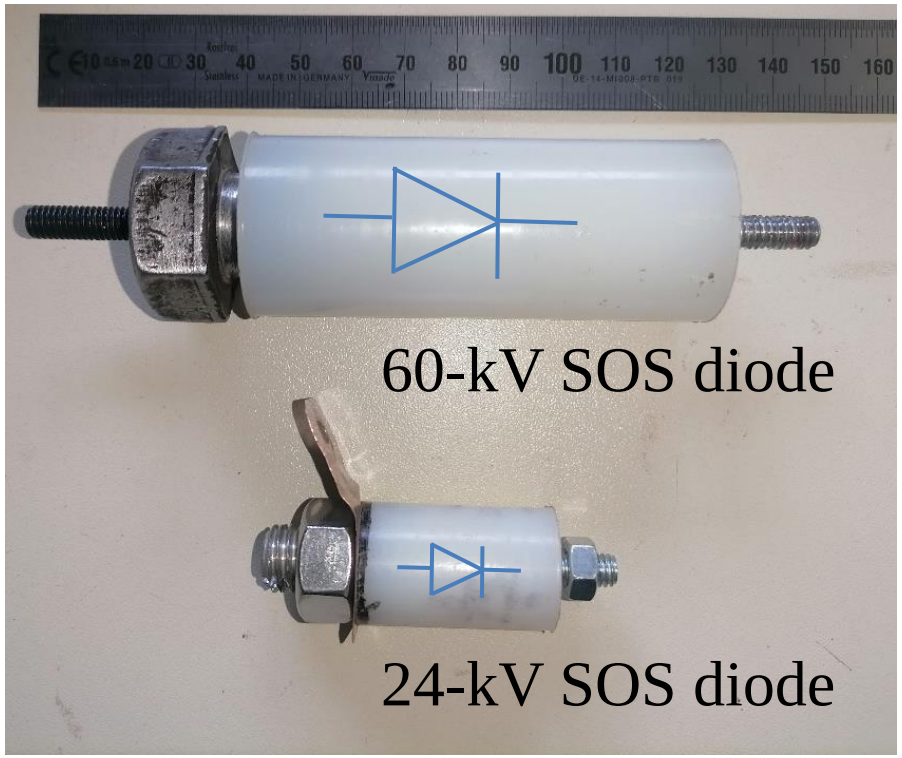


Output current of the SG-40/50 spiral generator at the different capacitive load C1.

[5] I. Lavrinovich *et al.*, "2-kV Thyristor Triggered in Impact-Ionization Wave Mode by a Solid-State Spiral Generator," IEEE Trans. Plasma Sci., pp. 1–9, 2022.

2. SOS diodes

2.2 SOS diodes under test



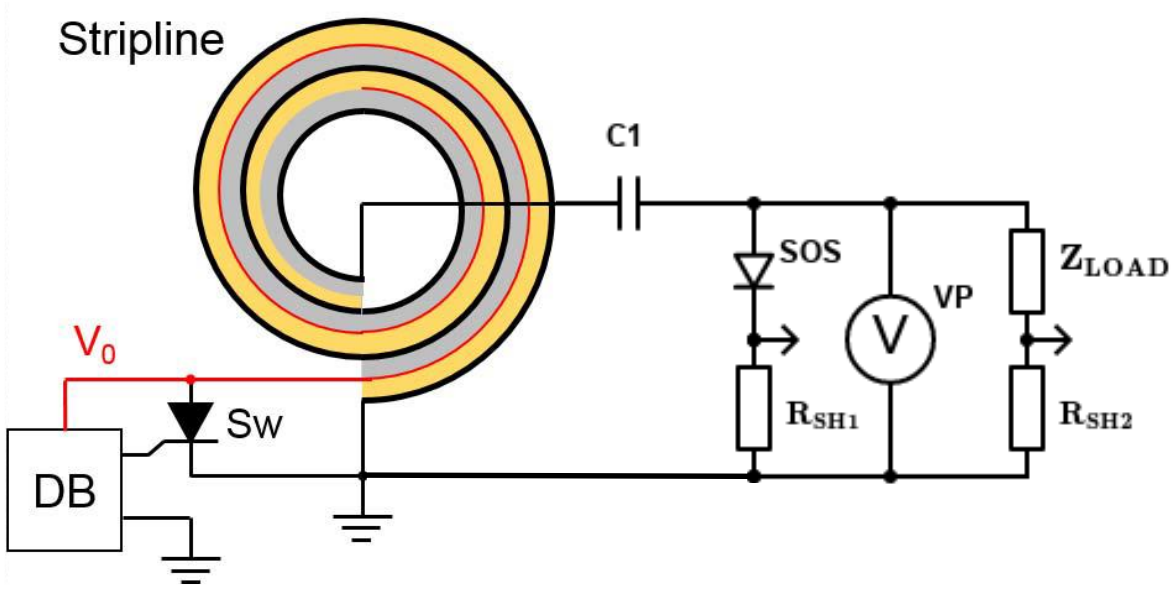
SOS-60-4 (top) – stack of 20 diodes connected in series with an area of 1 cm²; **SOS-24-1 (bottom)** – stack of 8 diodes connected in series with an area of 0.25 cm².

- Forward current density: $j^+ = 0.4 - 0.8$ kA/cm²
- Reverse current density: $j^- = 1 - 4$ kA/cm²
- Forward pumping time: $t^+ = 100 - 500$ ns
- Reverse pumping time: $t^- = 40 - 100$ ns
- Blocking voltage $V \approx 3$ kV

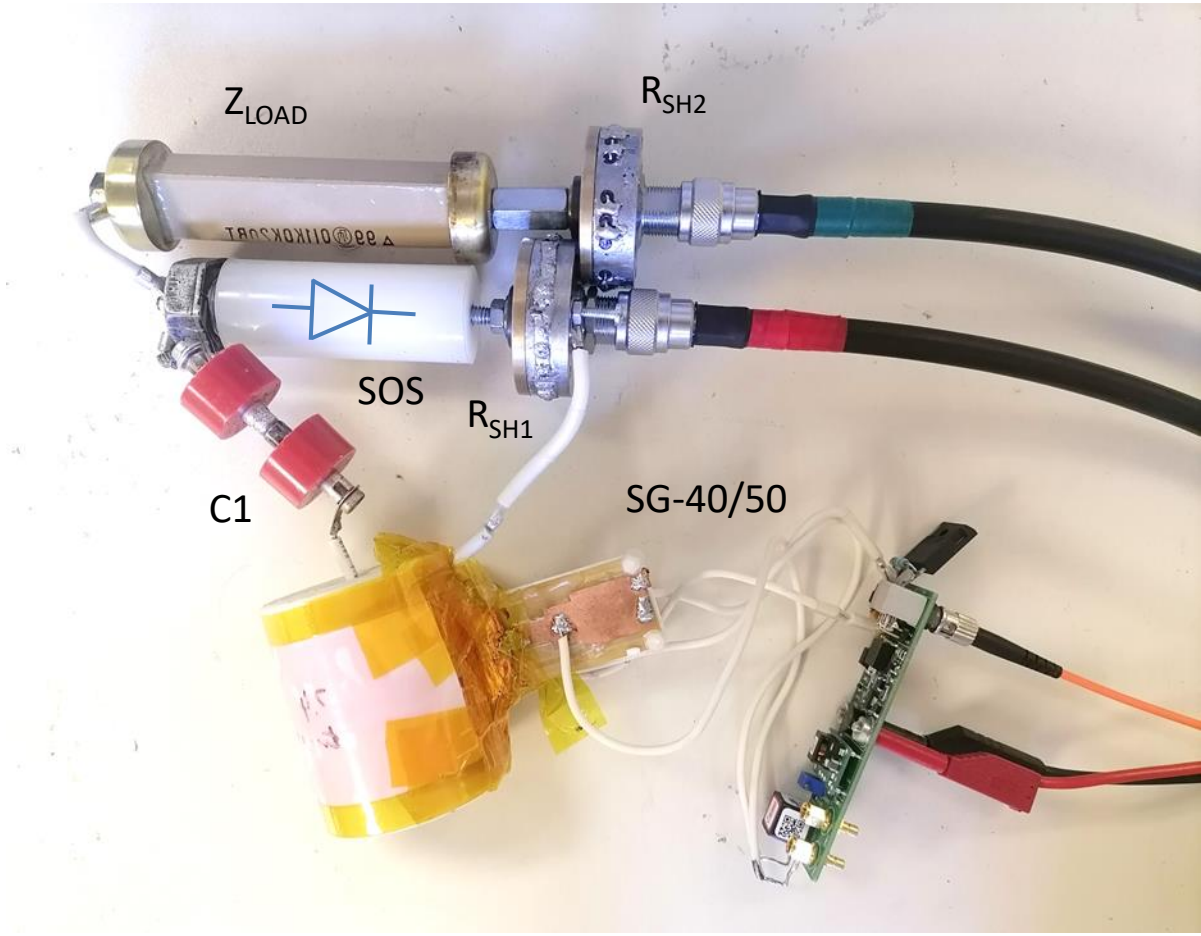
Elementary SOS diode with an area of 0.25cm² (top) and its typical parameters (bottom) provided by the manufacturer – Institute of Electrophysics.

2. SOS diodes

2.3 SG-SOS generator



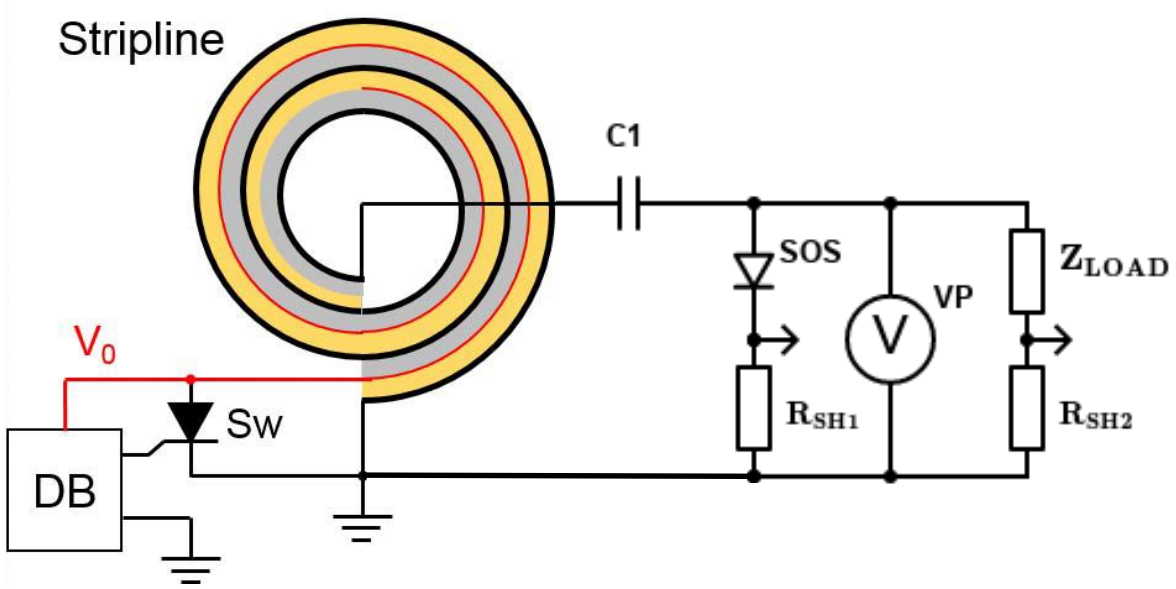
Circuit diagram of the SG-SOS generator: Stripline – schematic cross section of the spiral pulse forming line, DB – driver board, Sw – solid-state switch, C1 – pumping capacitor, SOS – semiconductor opening switch, Z_{LOAD} – resistive load, VP – voltage probe, R_{SH1} and R_{SH2} – resistive shunts.



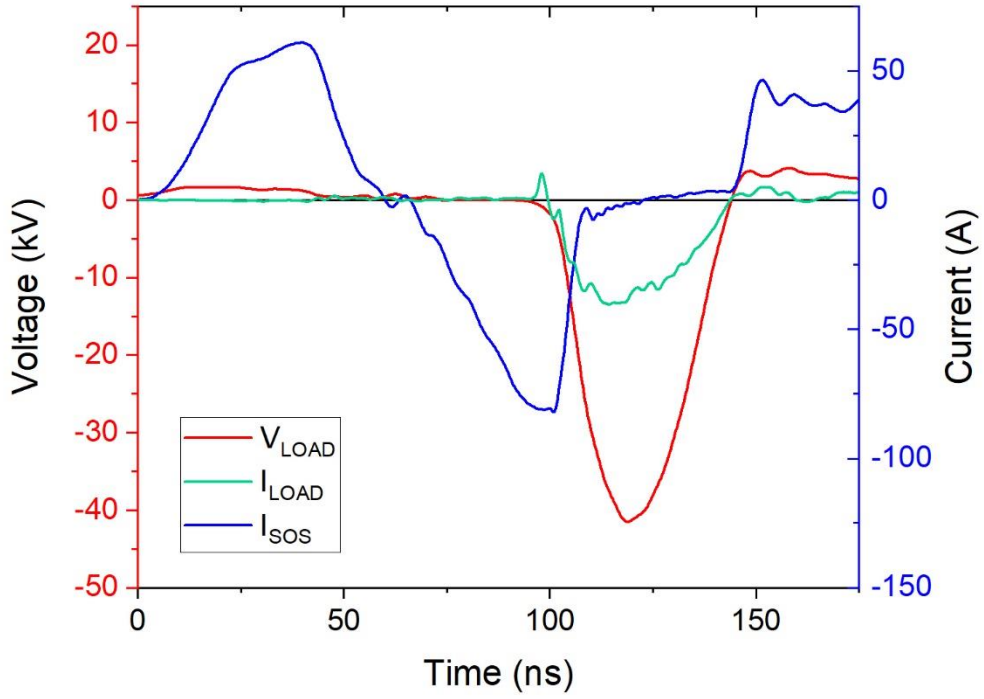
SG-SOS generator: SG-40/50 – spiral generator, C1 – pumping capacitor, SOS – semiconductor opening switch, Z_{LOAD} – 1 kΩ resistive load, R_{SH1} and R_{SH2} – diode and load resistive shunts, respectively.

2. SOS diodes

2.3 SG-SOS generator



Circuit diagram of the SG-SOS generator: Stripline – schematic cross section of the spiral pulse forming line, DB – driver board, Sw – solid-state switch, C1 – pumping capacitor, SOS – semiconductor opening switch, Z_{LOAD} – resistive load, VP – voltage probe, R_{SH1} and R_{SH2} – resistive shunts.



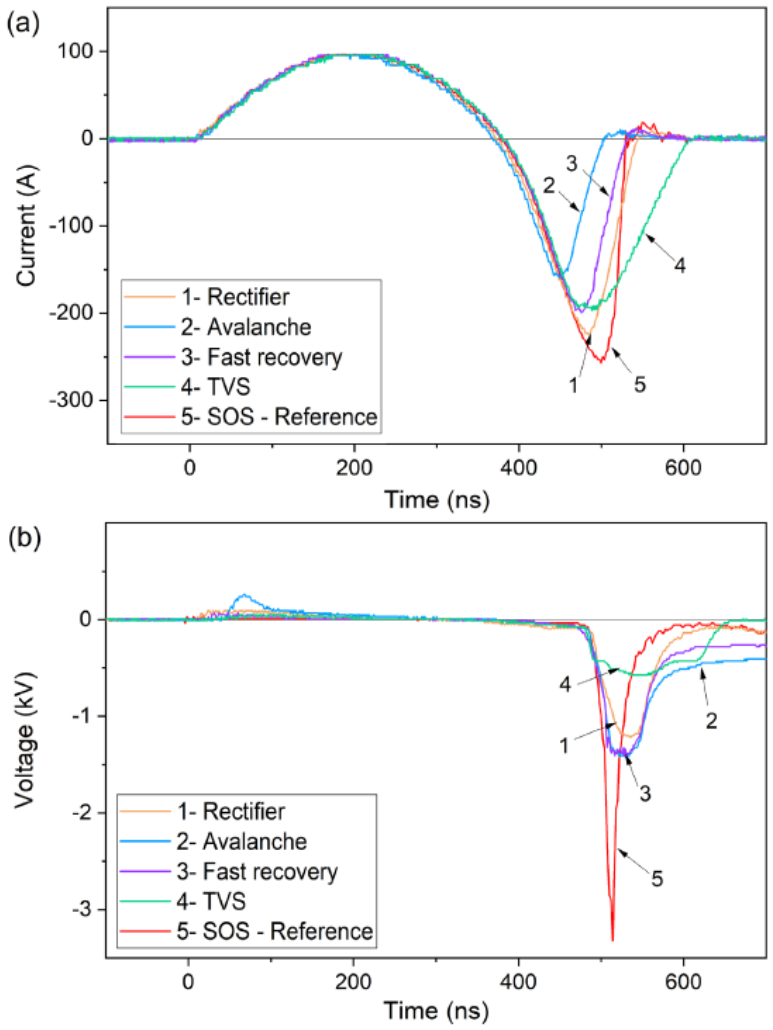
Typical waveforms of the SOS diode current (blue), load voltage (red) and load current (green) at the **1 kΩ load** captured by Tektronix TDS7704B 7 GHz oscilloscope.

Section III

TVS DIODES

3. TVS diodes

3.1 First experiments



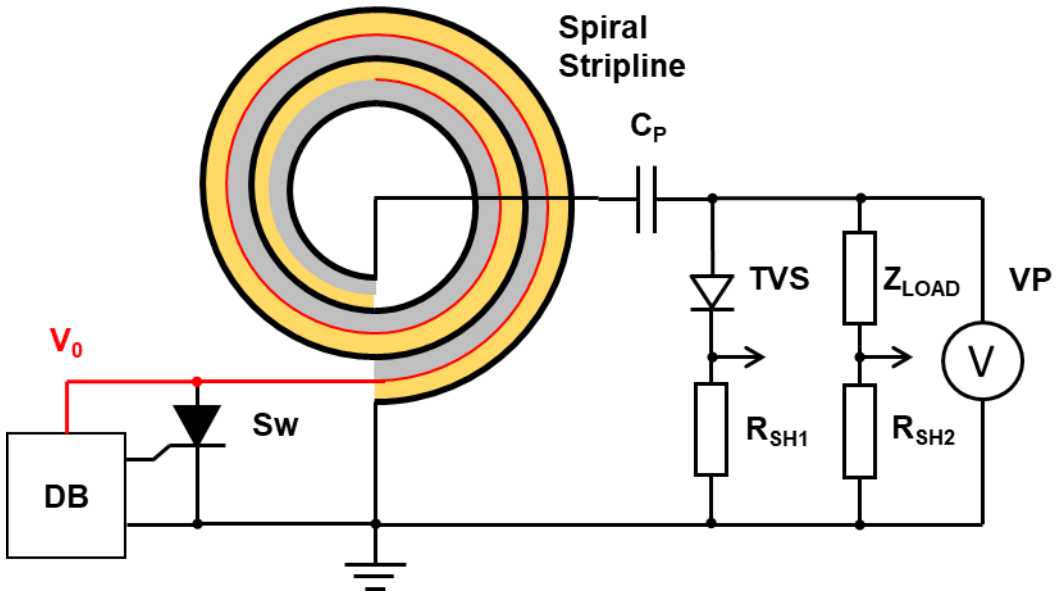
ITHPP ALCEN → ITOPP ALCEN

Diode type	Connections		V_R	T_r (ns)	FWHM
	Series	Parallel	(kV)	(10-90%)	(ns)
Rectifier	2	2	1.85	21.2	40
Avalanche	2	20	1.96	22.4	38
Fast recovery	2	1	2.54	27.1	28
TVS	7	3	1.83	13.2	45
SOS (Ref.)	1	1	3.35	19.5	16

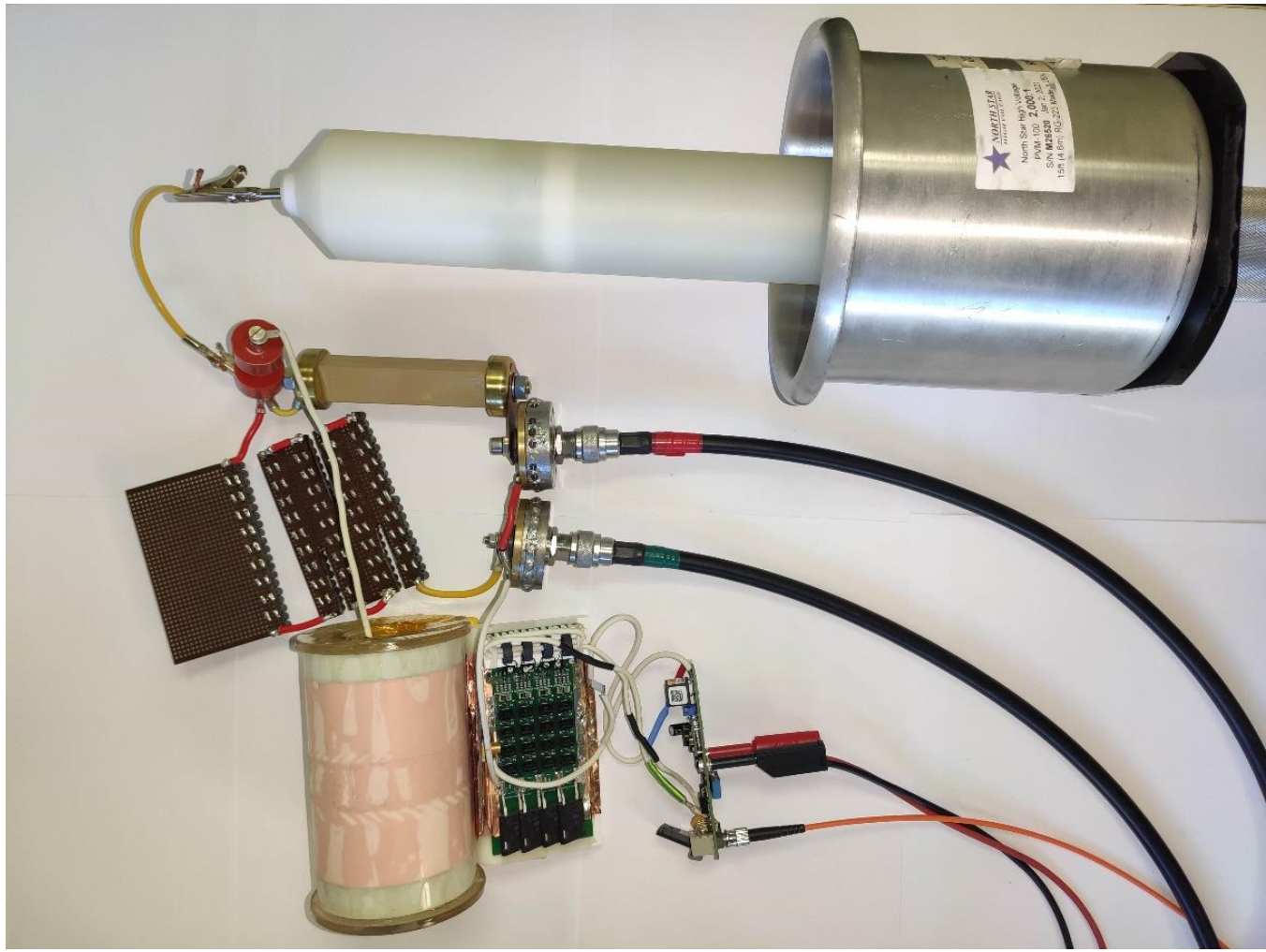
[6] M. R. Degnon et al., "Off-the-Shelf Diodes as High-Voltage Opening Switches," IEEE Trans. Plasma Sci., vol. 50, no. 10, pp. 3384–3392, 2022.

3. TVS diodes

3.2 SG-TVS generator circuit



Circuit diagram of the SG-TVS generator: Spiral Stripline – schematic cross section of the spiral pulse forming line, DB – driver board, Sw – solid-state switch, C_P – pumping capacitor, TVS – semiconductor opening switch, Z_{LOAD} – resistive load, VP – voltage probe, R_{SH1} and R_{SH2} – resistive shunts.

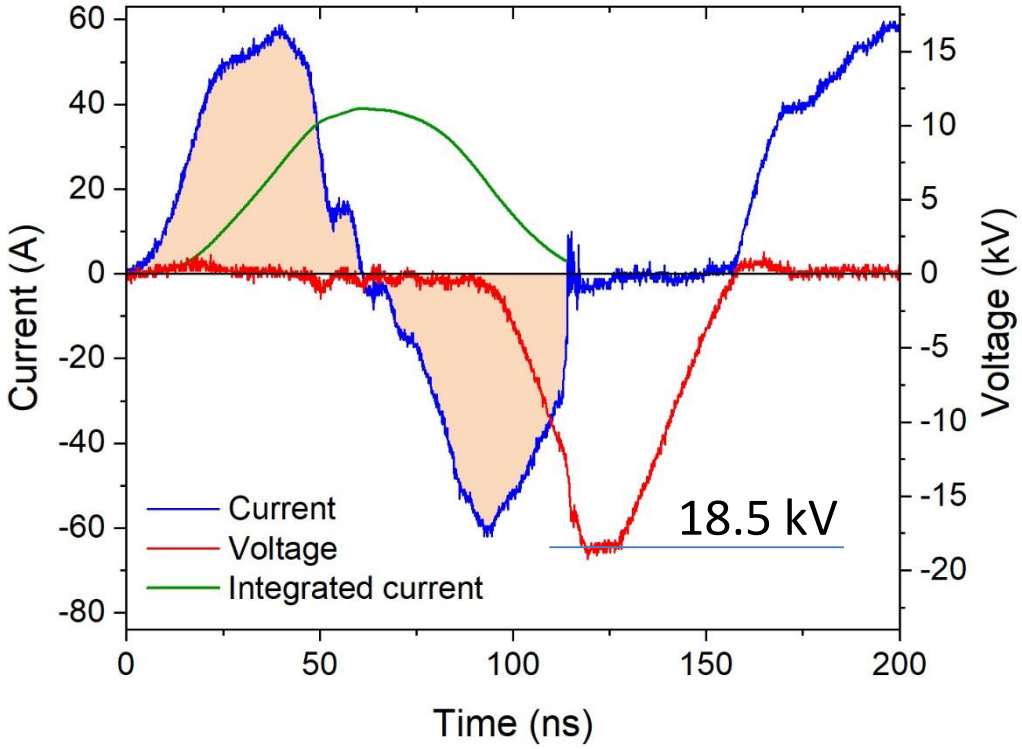


3. TVS diodes

3.3 Comparison of TVS-540 and TVS-600

TVS-540, 25x1, 267 Ω

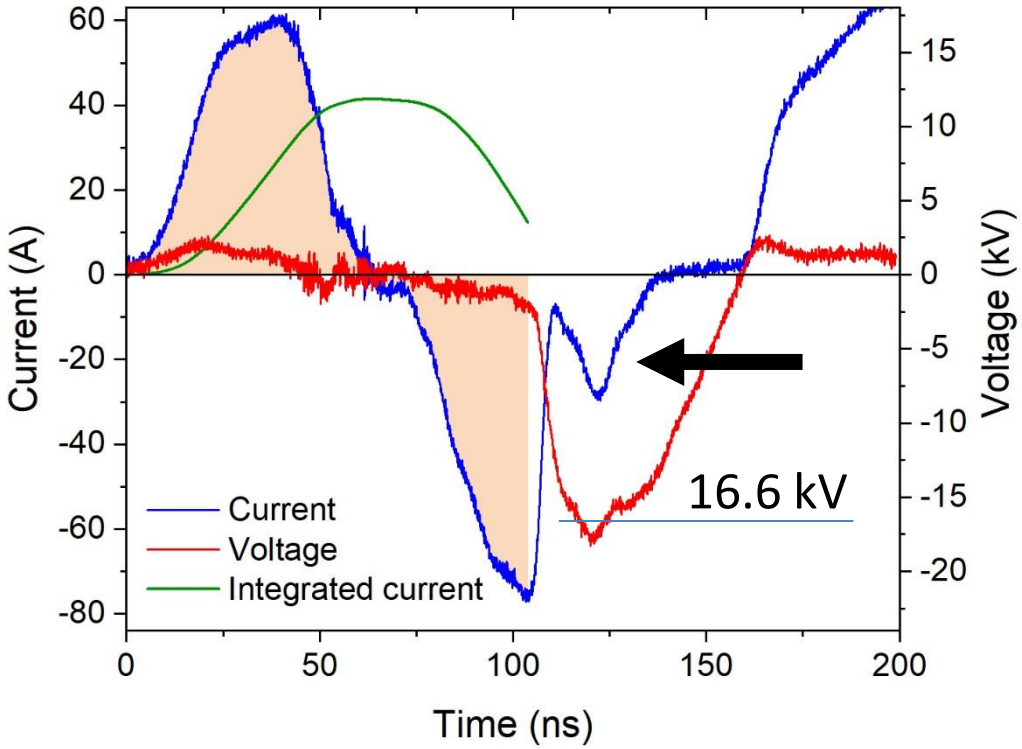
V_c x 25 = 18.5 kV



DSRD mode - ?

TVS-600, 20x1, 267 Ω

V_c x 20 = 16.6 kV



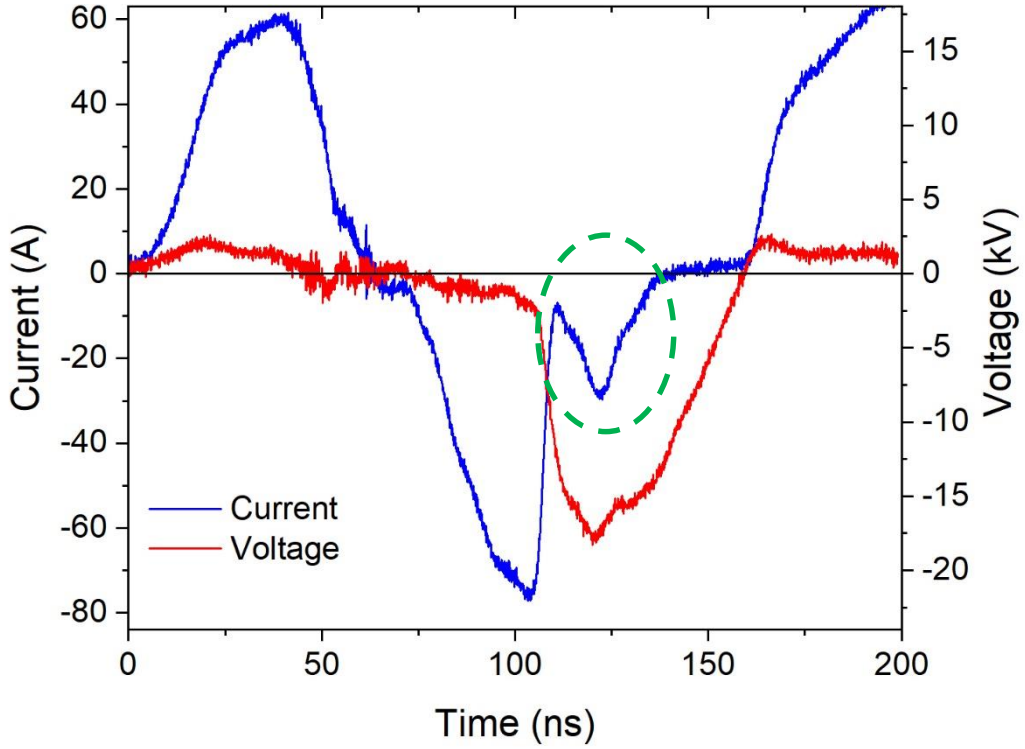
SOS mode - ?

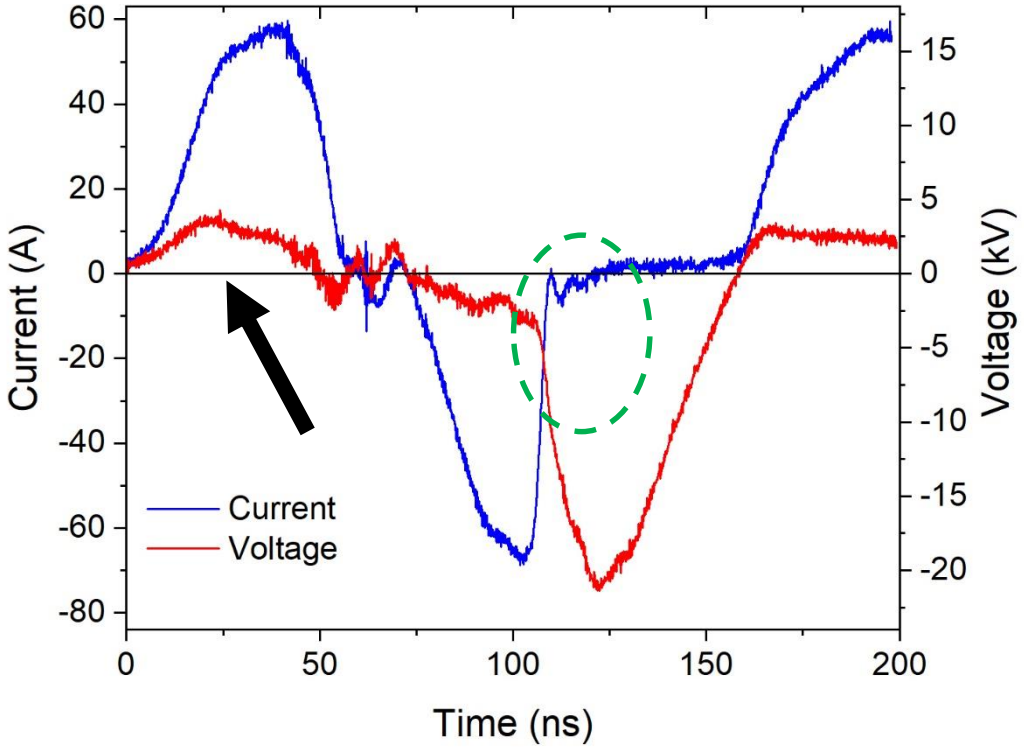
3. TVS diodes

3.4 Series connection of TVS-600

TVS-600, **20x1**, 267 Ω
V_c x 20 = 16.6 kV

TVS-600, **40x1**, 267 Ω
V_c x 40 = 33.1 kV

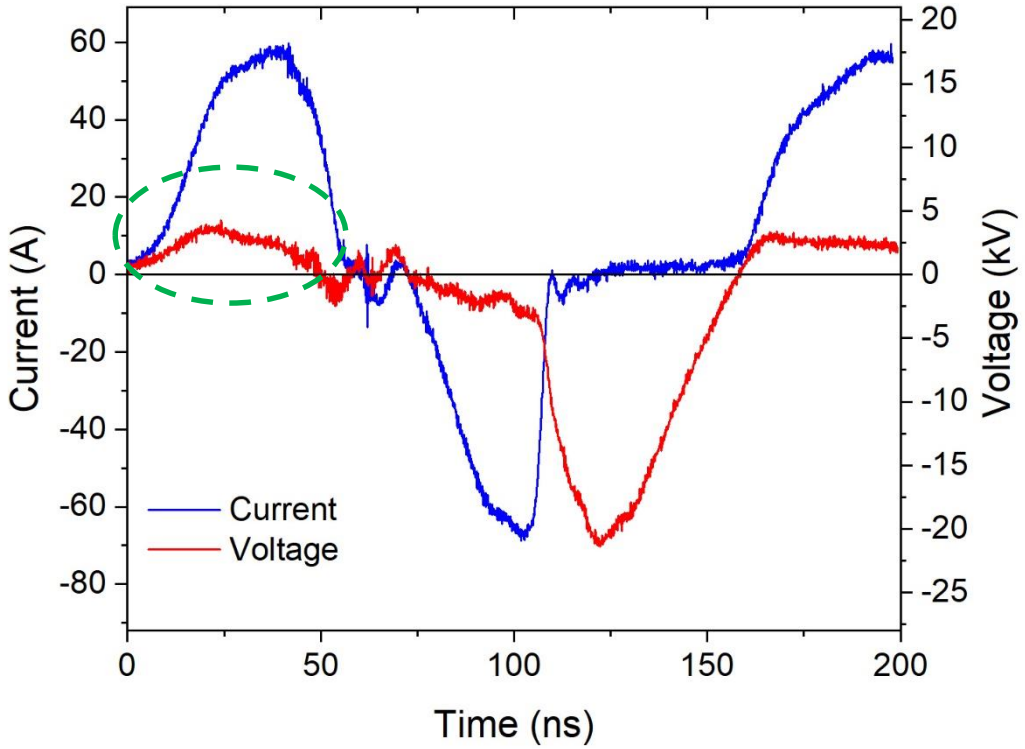




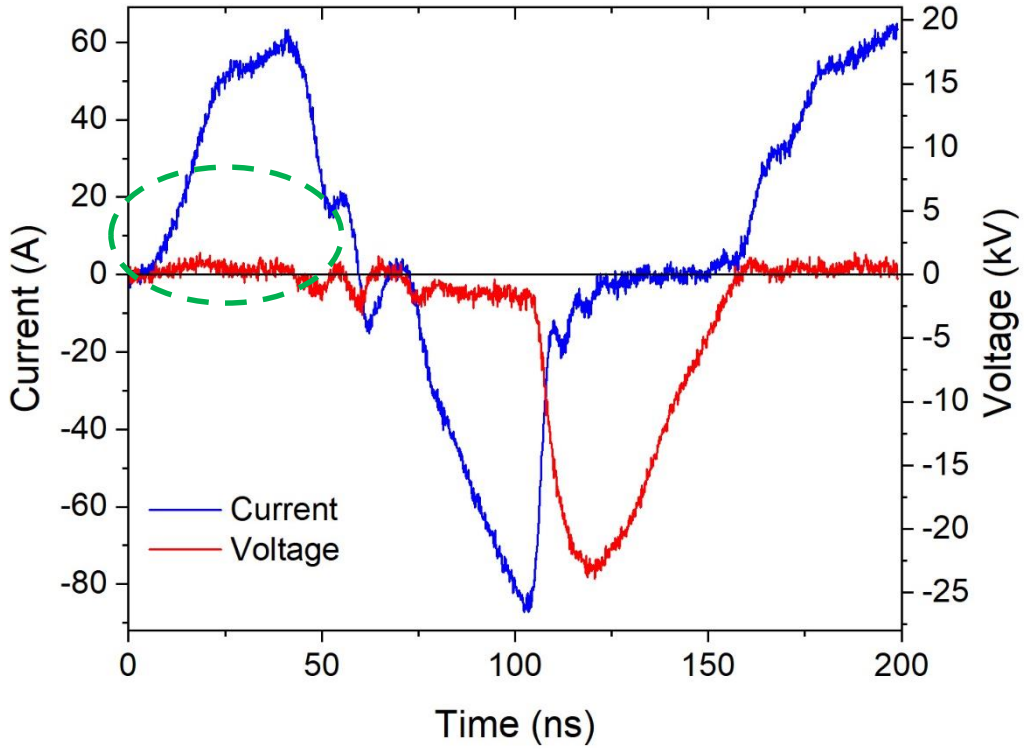
3. TVS diodes

3.5 Parallel connection of TVS-600

TVS-600, **40x1**, 267 Ω
V_c x 40 = 33.1 kV



TVS-600, **40x4**, 267 Ω
V_c x 40 = 33.1 kV

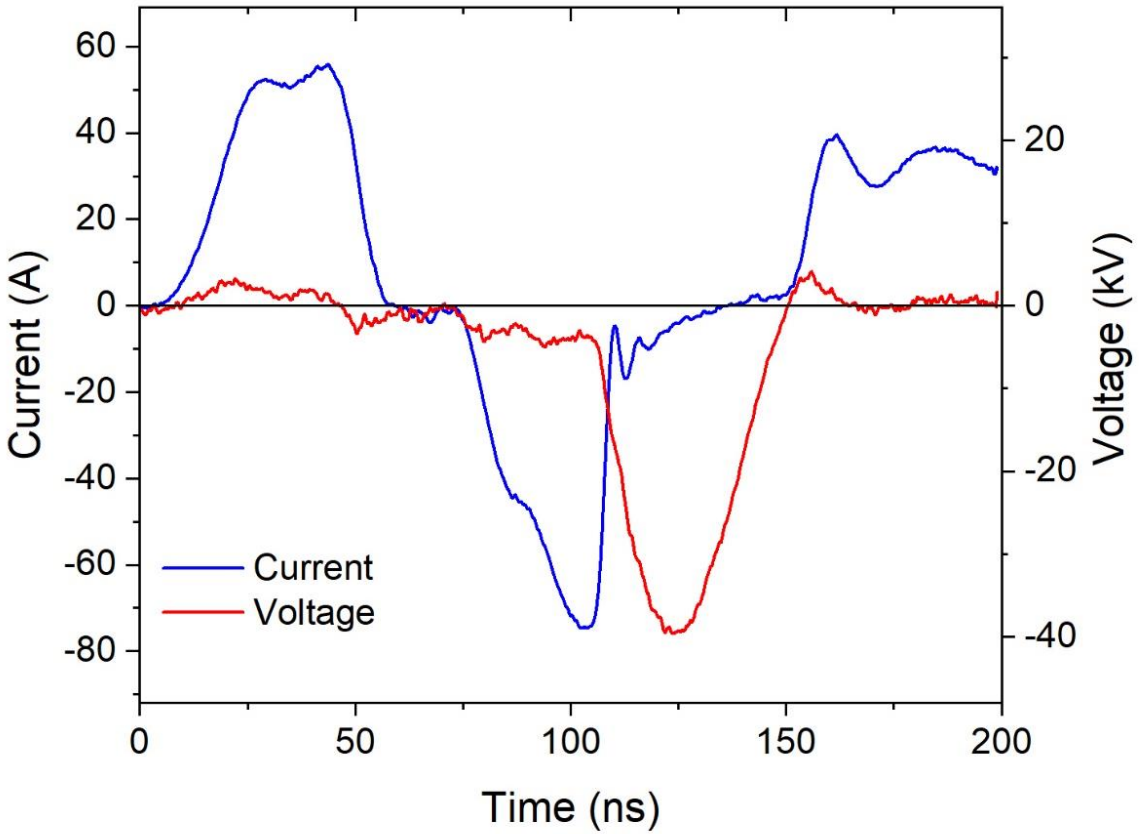


3. TVS diodes

3.6 Series-parallel connection of TVS-600

TVS-600, **80x2**, 1 kΩ

V_c x 80 = 66.2 kV



Parameter	1 kΩ	
Diode type	**TVS-600, 80x2**	**SOS-60-4**
Voltage, kV	40	44
Voltage rise time, ns	13	10
FWHM, ns	25	26
Cut-off time, ns	3.4	3.2
t^+, ns	53	53
I^+, A	56	63
t^-, ns	30	32
I^-, A	75	85

Section IV

CONCLUSIONS

4. Conclusion

In this work

- **Novel SOS pumping circuit based on the spiral generator** has been demonstrated
- **Nanosecond high-voltage generator based on TVS diodes** has been tested
- The following pulses have been obtained on **the resistive load 1 kΩ:**

voltage / rise time / FWHM / cut-off

- **SOS-60-4** **44 kV / 10 ns / 26 ns / 3.4 ns**
- **TVS-600** **40 kV / 13 ns / 25 ns / 3.2 ns**

On the way ahead

- Testing of **high-current spiral generators**
- **TVS diode array scaling** and voltage/current distribution measurement
- **Lifetime validation** of TVS diodes
- **Discussion with manufacturers**: doping profile, die area and package of TVS diodes

A High-Voltage Nanosecond Opening Switch Based on TVS Diodes

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