Available online at www.sciencedirect.com
ScienceDirect
MATTER AND RADIATION AT EXTREMES
Matter and Radiation at Extremes 1 (2016) 201−206
www.journals.elsevier.com/matter-and-radiation-at-extremes

Review Article

Review of high-power pulsed systems at the Institute of High Current Electronics

A.A. Kim*, B.M. Kovalchuk, V.A. Kokshenev, A.V. Shishlov, N.A. Ratakhin, V.I. Oreshkin, V.V. Rostov, V.I. Koshelev, V.F. Losev

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3 Academichesky Ave., Tomsk 634055, Russia

Received 23 May 2016; revised 27 June 2016; accepted 4 July 2016
Available online 18 August 2016

Abstract

In this paper, we give a review of some most powerful pulsed systems developed at the Institute of High Current Electronics (HCEI), Siberian Branch, Russian Academy of Sciences, and describe latest achievements of the teams dealing with these installations. Besides the presented high-power systems, HCEI performs numerous investigations using much less powerful generators. For instance, last year much attention was paying to the research and development of the intense low-energy (<200 kV) high-current electron and ion beam and plasma sources, and their application in the technology [1−3].

PACS codes: 84.60.Ve; 84.70.+p; 52.58.Lq; 89.20.Bb

Keywords: Energy storage systems; Z-pinch; High power microwaves; High power laser; Linear pulse transformer; Linear transformer driver

1. Introduction

The Institute of High Current Electronics (HCEI) was founded in 1977 upon the initiative of the Academician Gennady A. Mesyats, who was its first director. From the very beginning HCEI was an academic institute whose main purpose was development of high-power pulsed systems for different applications. For the achievements in these areas, the HCEI researchers have received numerous government prizes, and HCEI is often listed among the best institutions of the Siberian Branch of Russian Academy of Sciences. Currently HCEI collaborates with numerous scientific laboratories from Europe, Asia and America.

* Corresponding author.
E-mail address: kim@oit.hcei.tsc.ru (A.A. Kim).
Peer review under responsibility of Science and Technology Information Center, China Academy of Engineering Physics.

2. GIT-12 generator

The most powerful high-current generator of HCEI is called GIT-12 (Generator of Impulse Current, see Fig. 1). This generator was developed in 1996. GIT-12 consists of 12 modules, each of 9 parallel Marx generators with 12 series stages. The power pulses of the modules are delivered to the central part of the machine along 12 coaxial magnetically insulated transmission lines (MITLs). At 70 kV charge voltage the GIT-12 stores 5 MJ of energy [4].

All these years the GIT-12 has been used for the research of the inductive energy storage technology with various plasma opening switches (POSs). The goal of the research is to improve the energy coupling between the Marx generators and different radiating loads, and to provide desired output voltage (or current) amplitude depending on the load preferences [5−7].

Recently, the GIT-12 was used in Z-pinch experiments with deuterium gas puffs without POSs for the generation of fast

http://dx.doi.org/10.1016/j.mre.2016.08.001

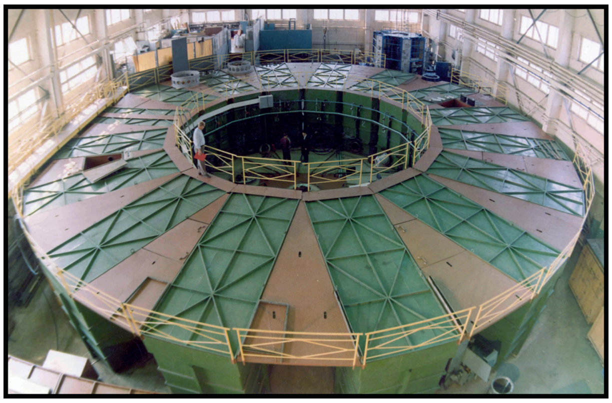

Fig. 1. GIT-12 pulsed power generator.

neutrons at ~3 MA current rising in ~700 ns (Fig. 2). A novel configuration of the deuterium Z-pinch load has been tested: a deuterium gas puff was surrounded by an outer hollow plasma shell consisting of hydrogen and carbon ions to form a homogeneous, uniform conducting layer at a large initial diameter of 35 cm. As a result of these tests, a neutron yield of 3.6×10^{12} at a high production efficiency of 6×10^{7} neutrons per joule of plasma energy was achieved at 2.7 MA current (Fig. 3) [8].

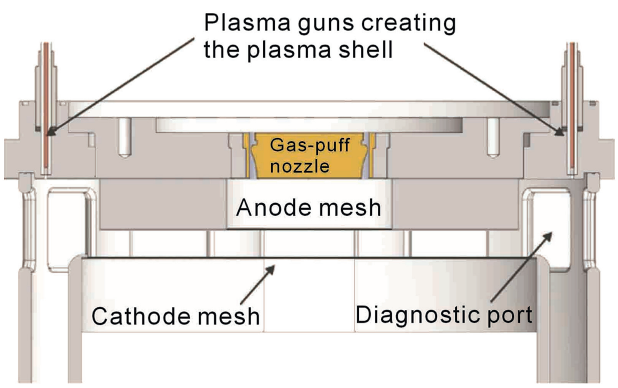

Fig. 2. Novel configuration of deuterium gas puffs with outer plasma shell.

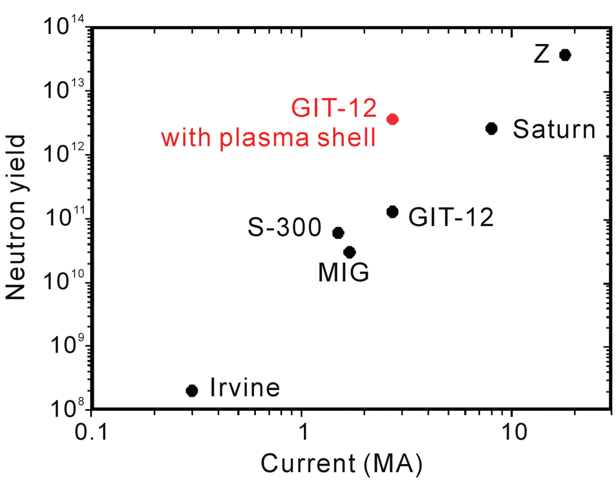

Fig. 3. Neutron yields from deuterium gas puff Z-pinches.

3. MIG generator

The team of the High Energy Density Department is involved in the research of the Z-pinch and high temperature dense plasma physics, as well as of the high-current relativistic e-beam diodes. For such multipurpose research, the high-power pulse generators in this department were developed using the Linear Pulse Transformer (LPT) Technology approach as a primary energy storage for charging the water filled pulse forming section of the generator.

One of such LPT-based generators is the 2.5-TW MIG (Fig. 4) [9]. The axial length of this generator is ~11 m, the length of its water filled section is 6 m. The water section includes two pulse forming lines and a transmission line, which delivers the power pulse to the water-vacuum interface. In vacuum the power pulse propagates along the conical MITL to the load. When loaded into the Z-pinch, the MIG generator with a load current multiplier currently produces a peak current of ~3 MA rising in 100 ns [10].

Before the upgrade in 1995, MIG generator was called the SNOP-3. SNOP-3 was used for the implosion of axially pre-magnetized gas puff Z-pinches, providing even higher convergence ratio [11] than what was reported recently [12].

Fig. 4. 2.5-TW MIG generator providing a Z-pinch current of ~3 MA rising in 100 ns.

4. High power microwaves

4.1. Coherent narrowband radiation

In the Department of Physical Electronics (DPE), a series of the pulse power generators operating at a high repetition rate called SINUS accelerators are developed. These accelerators are used for the generation of high-current relativistic electron beams for investigations in the field of high power coherent narrowband microwave radiation. All SINUS accelerators are based on Tesla transformers with ferromagnetic cores, which charge the secondary capacitance designed as an oil-filled coaxial pulse forming line. The SINUS accelerators are extremely reliable and provide electron energy of

0.2−2 MeV, e-beam current of 1−20 kA, pulse width of 40−130 ns, and reprate up to 1000 pulses per second (pps).

The most powerful of these accelerators is SINUS-7, which is used for testing of different Cherenkov type oscillators (Fig. 5) [13]. SINUS-7 is able to accelerate the electrons to a peak energy of 1 MeV, with a pulse width of 50 ns. At 1 MeV electron beam energy and 20 GW e-beam power, SINUS-7 typically operates in a single shot mode or at few pps. For high power microwave generation, the reprate of SINUS-7 is limited by the magnetic system, which is needed for the e-beam formation and its propagation inside the slow wave structure. The highest power efficiency of the microwave radiation of ~30% might be achieved at strong pulse magnetic fields of about 30 kG. At such fields, the microwave power up to 5 GW is realized on SINUS-7 in S- and K-bands [14,15]. Peak microwave energy per pulse is about 100 J.

To operate at high reprates, the development of microwave sources with reduced magnetic field strength of 5−7 kG was very important. For this purpose, a series of SINUS accelerators with reduced output voltage (500 kV) and e-beam current ($\leq$5 kA) were developed. An example of such installations is SINUS-500, which includes an 80-ns-length spiral line in series with a 26-ns-length coaxial pulse forming line thus allowing to increase the output pulse width to 106 ns. Currently, the SINUS-500 with optimized slow wave structure and magnetic field decompression drives the Relativistic Backward Wave Oscillator (RBWO) in a pulse-periodic mode, providing the 3-cm-wavelength radiation at 320 MW output power, 90 ns pulse width, 100 pps reprate, and beam-wave power efficiency of 30% (Fig. 6) [16].

Another important advance of the DPE team is the experimental validation of the theory predicting the possibility to control the phase of microwave coherent radiation in case the microwave source is driven by a voltage pulse with short enough rise time. It opens the way to multichannel microwave systems of oscillators with nanosecond pulse width. In the DPE, the two-channel microwave source is developed where the ferrite-filled nonlinear transmission lines are used to sharpen and shift the rise time of the driving voltage pulse (Fig. 7). This source radiates at 100 pps 2 × 0.3 GW, 2-ns-width pulses with a central frequency of 10 GHz, and produces the fourfold higher power density in the maximum of the interference pattern in the far zone than each single channel separately [17].

Fig. 5. SINUS-7 with S-band microwave oscillator.

Fig. 6. SINUS-500 with RBWO source operating at 100 pps.

4.2. Ultra-wideband (UWB) radiation

The UWB sources of microwaves with linear polarization have been intensively investigated for over 20 years. The figure-of-merit of such sources is the effective potential of the UWB radiation. In the Laboratory of Microwave Electronics (LME), the UWB source based on the bipolar voltage pulse driver and a 64-element antenna array is developed providing stable microwave radiation with a pulse reprate of 100 pps and

Fig. 7. Two-channel 2 × 0.3 GW source producing the fourfold power density in the maximum of the interference pattern in the far zone compared to that of each single channel.

Fig. 8. UWB source with linear polarization and a 64-element antenna array providing an effective potential of 4.3 MV.

effective potential of 4.3 MV (Fig. 8) [18]. This source is able to operate continuously in 10 min.

Compared to linear polarization, elliptical polarization of microwaves greatly increases the variety of objects feasible for identification. In the LME, a high power source of UWB radiation with elliptical polarization and a 4-element antenna array with an effective potential of 440 kV is developed, which is able to operate at a reprate of 100 pps during 1 h [19].

5. THL-100 laser system

In the Laboratory of Gas Lasers, the THL-100 multi-TW hybrid laser system of visible range is developed (Fig. 9). This system includes the START-480M Ti:Sa starting complex (Fig. 10), the prism stretcher, the XeF(C-A) photochemical amplifier, and the fused silica (quartz glass) compressor. The START-480M produces a 50-fs-width laser pulse with an energy up to 20 mJ at the second harmonic wavelength of 475 nm. This pulse is stretched by the prism stretcher to a width of 1580 fs, then enters the XeF(C-A) amplifier (Fig. 11). The active medium of this amplifier is created in the XeF_2/N_2 gas mixture by VUV radiation of Xe, which is excited by six e-beams. These e-beams are produced by six vacuum diodes that are powered by two drivers assembled of LTD cavities with air insulation. In the amplifier, the laser beam makes 33 passes, then leaves the amplifier and enters the fused silica compressor, where its width is compressed back to ~50 fs. At the output of the THL-100 system the power of the laser beam is 14 TW [20], which is above the power of any other laser system in the world operating in the visible spectrum [21]. Next goal of the THL-100 team is to increase this power to 40 TW [22].

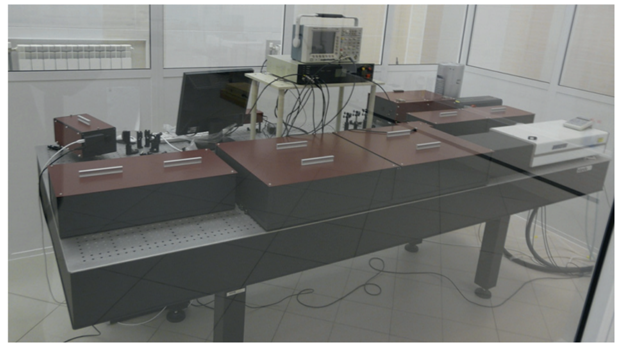

Fig. 10. START-480M Ti:Sapphire starting complex.

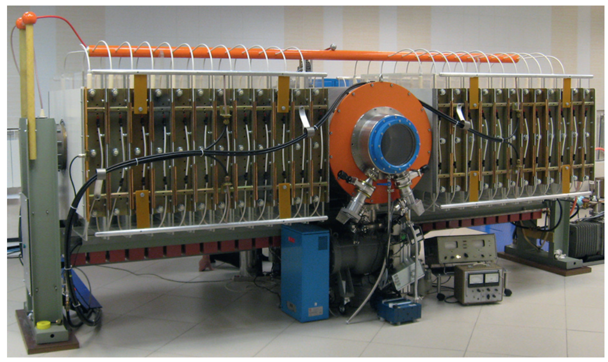

Fig. 11. XeF(C-A) amplifier with two air insulated LTD drivers.

6. Linear transformer drivers (LTDs)

Unlike in LPT (such as on MIG accelerator), where all transformer cores locate inside the same cavity, in LTD each transformer core locates inside its own cavity. Another important difference is the location of the storage capacitors: in LPT these capacitors locate outside the cavity and discharge around the cores along the high voltage cables, whereas in LTD the capacitors locate inside the cavity and discharge around the cores along the cavity walls. This design difference makes the LTD-based accelerators more compact, powerful, scaleable and flexible compared to that based on LPT.

First LTD cavities were designed in 1995−1997 by Boris M. Kovalchuk, the head of the HCEI Pulsed Power Department [23]. These were the cavities with 2 bricks, each brick consisting of one HAEFELY-TRENCH storage capacitor (90 kV, 3.95 μF, 10 nH, 13 mΩ) and the spark gap switch. The ~4 μF capacitance of HAEFELY-TRENCH capacitor determined the ~1 μs output pulse width of these first LTD cavities. Such kind of LTDs are used in the Sphinx generator at CEG, France (Fig. 12) [24].

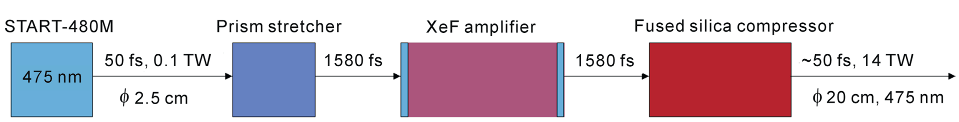

Fig. 9. THL-100 hybrid laser system.

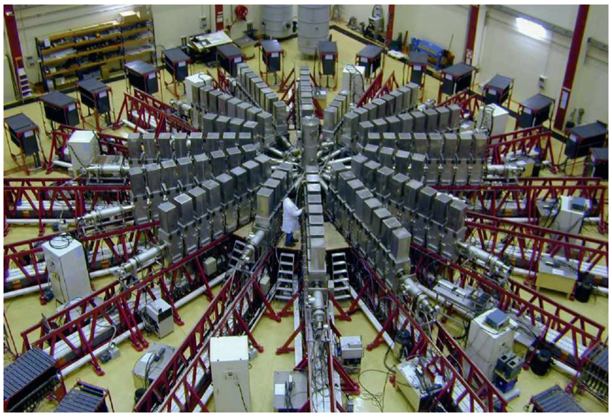

Fig. 12. Sphinx generator in 2004 at CEG, France.

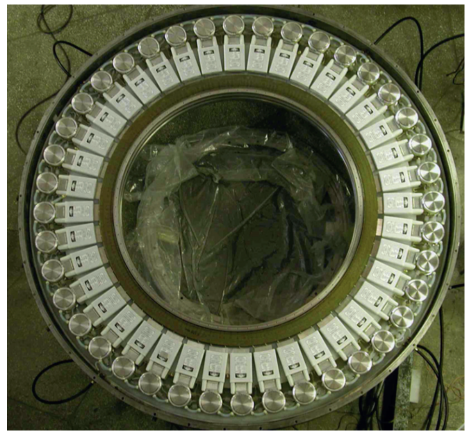

Fig. 14. 1-MA LTD cavity with transformer oil insulation.

Next step was the development of LTD cavities with ~100 ns output pulse width. To reduce the pulse width from ~1 μs to ~100 ns, numerous bricks with small capacitive storage capacitors, each with its own spark gap switch, were suggested to be applied in the LTD cavity. Total number of such bricks in the cavity is a function of the required output current.

Currently, two types of LTD cavity with ~100 ns pulse width are available at HCEI: one with atmospheric air insulation inside the cavity, and the other with transformer oil insulation. Air insulated LTDs are designed of the bricks with GA35426 (100 kV, 40 nF) double ended capacitors in plastic cases, which are sealed in pairs into the single epoxy body (Fig. 13) [25]. This body prevents the capacitors from flashing along the capacitor cases at 100 kV charging in atmospheric air, and has an additional cavity for the spark gap switch of 6 parallel channels, that operates in atmospheric air also. Each of these capacitors and a half of the switch of 3 parallel channels represent one single brick of the LTD cavity with air insulation. The air insulated LTDs are used in two e-beam drivers of the THL-100 laser system. Each of these drivers includes 12 series cavities, and each cavity consists of 8 parallel bricks [26]. The advantage of the air insulated LTD cavity is that it does not require to disassemble the whole driver to replace its damaged bricks.

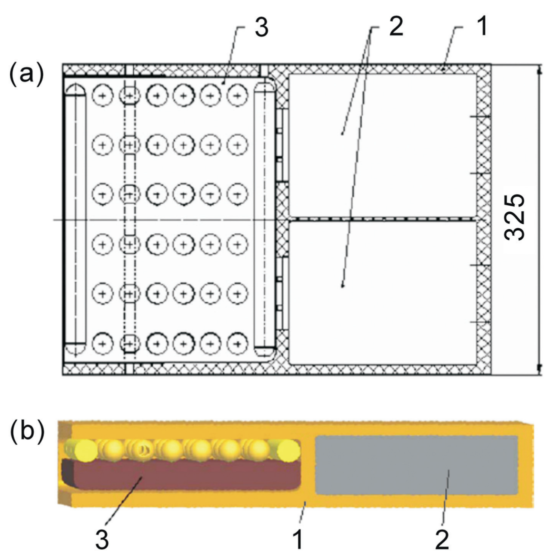

Fig. 13. Two parallel bricks of the air insulated LTD cavity in (a) top view and (b) side view: 1 − single epoxy body, 2 − two GA35426 storage capacitors sealed into the body, 3 − multigap, 6-channel spark gap switch.

The oil insulated LTDs are more powerful, compact and reliable but less comfortable in maintenance than those with air insulation, because they require to disassemble the driver for the replacement of the damaged bricks. The most powerful oil insulated LTD cavity produced and tested at HCEI is the 1-MA LTD cavity including 40 bricks, each of 2 series GA35426 storage capacitors and ±100 kV spark gap switch with corona discharge for voltage distribution (Fig. 14). The optimum load impedance of this cavity is 0.1 Ω, at ±100-kV charging it delivers to such load the 0.1-TW-power, 1-MA-current pulse. In 2007 the module of five 1-MA LTD cavities was tested at HCEI with the resistive and e-beam diode loads [27], and in 2008 ten such cavities were shipped to Sandia National Laboratory [28].

Spark gap switches, storage capacitors, and ferromagnetic cores are the most important components of the LTD cavities, their reliability determines the vitality of the whole LTD technology. Unlike the cores and the capacitors, the LTD switches are still in the developmental stage and are designed and built mainly by various laboratories. The best life time of more than 10^5 shots, prefire probability of ~(2−6) × 10^{-5}, and 1-σ jitter of ~2.2−4.5 ns was demonstrated recently in tests at ±100 kV charge voltage and 4.0 ata dry air pressure of the HCEI spark gap switches for oil insulated LTDs, which are using corona discharge for voltage distribution between the switch gaps [29], and also of the switches without any special voltage divider developed at the Northwest Institute of Nuclear Technology (China) [30].

7. Conclusion

The results described above, as well as the development of various low-energy high-current particle beam and plasma sources for technological application [1−3] demonstrate that the Institute of High Current Electronics is a progressive member of the modern world-wide pulsed power community. HCEI is open for collaboration within the most burning problems with other pulsed power laboratories. Last year, for example, we are working with the Chinese scientists in the designing of the LTD drivers for the Z-pinch ICF program [31].

Acknowledgements

The authors would like to thank their numerous HCEI colleagues for their input into the creation of the installations, and into the research described in this paper.

This work was supported in part by Russian Foundation for Basic Research (project No. 15-08-01324).

References

[1] S.P. Bugaev, S.D. Korovin, N.N. Koval, E.M. Oks, D.I. Proskurovsky, et al., Studies and application of intense low-energy electron and ion beams, in: Proc. KORUS 2003: 7th Korea-Russia Inter. Symp. on Science and Technology, vol. 1, 2003, pp. 1−6.

[2] N.S. Sochugov, A.A. Soloviev, A.V. Shipilova, S.V. Rabotkin, V.P. Rotshtein, et al., The effect of pulsed electron beam pretreatment of magnetron sputtered ZrO_2:Y_2O_3 films on the performance of IT-SOFC, Solid State Ionics 231 (2013) 11−17.

[3] N.N. Koval, Yu.F. Ivanov, I.V. Lopatin, Yh.H. Akhmadeev, V.V. Shugurov, et al., Generation of low-temperature gas discharge plasma in large vacuum volumes for plasma chemical processes, Russ. J. Gen. Chem. 85 (2015) 1326−1338.

[4] B.M. Kovalchuk, V.A. Kokshenev, A.A. Kim, N.E. Kurmaev, S.V. Loginov, et al., GIT16: state of project in 1995−1997, in: Proc. 11th Inter. Pulsed Power Conf., Baltimore, 1997, pp. 715−723.

[5] V.A. Kokshenev, F.I. Fursov, N.E. Kurmaev, A two-stage scheme of the current pulse sharpening on the GIT-12 generator with the use of the plasma opening switches, in: Proc. 14th Symp. High Current Electronics, Tomsk, 2006, pp. 328−331.

[6] V.A. Kokshenev, B.M. Kovalchuk, F.I. Fursov, N.E. Kurmaev, Cascade from power amplifier and current transformer for Z-pinch experiments on the GIT-12 generator, in: Proc. 15th Symp. High Current Electronics, Tomsk, 2008, pp. 269−273.

[7] V.A. Kokshenev, B.M. Kovalchuk, F.I. Fursov, N.E. Kurmaev, N.A. Ratakhin, et al., Adapting of a plasma opening switch with a load current multiplier in experiments on the GIT-12 generator, in: Proc. 16th Symp. High Current Electronics, Tomsk, 2010, pp. 273−277.

[8] D. Klir, A.V. Shishlov, V.A. Kokshenev, P. Kubes, A. Yu. Labetsky, et al., Efficient generation of fast neutrons in an optimized deuterium gas-puff Z-pinch, Plasma Phys. Contr. F. 57 (2015) 044005.

[9] A.V. Luchinskii, N.A. Ratakhin, V.F. Fedushchak, A.N. Shepelev, Multipurpose transformer-type pulse generator, Rus. Phys. J. 40 (1997) 1178−1184.

[10] S.A. Chaikovsky, A.S. Chuvatin, V.I. Oreshkin, A load current multiplier of the МИГ terawatt generator, Instrum. Exp. Tech. 55 (2012) 209−217.

[11] S.A. Sorokin, S.A. Chaikovsky, Imploding liner stabilization experiments, AIP Conf. Proc. 299 (1993) 83−92;
S.A. Sorokin, S.A. Chaikovsky, Highly stable radial implosion of plasma liners, Fizika plasmy, vol. 19, 1993, pp. 856−865.

[12] T.J. Awe, K.J. Peterson, E.P. Yu, R.D. McBridge, D.B. Sinars, et al., Experimental demonstration of the stabilizing effect of dielectric coatings on magnetically accelerated imploding metallic liners, Phys. Rev. Lett. 116 (2016) 065001.

[13] S.D. Korovin, V.V. Rostov, S.D. Polevin, I.V. Pegel, E. Schamiloglu, et al., Pulsed-power driven high power microwave sources, P. IEEE 92 (2004) 1082−1095.

[14] S.D. Korovin, V.V. Rostov, E.M. Tot'meninov, A relativistic backward wave oscillator with a modulating resonance reflector, Tech. Phys. Lett. 31 (2005) 411−413.

[15] A.I. Klimov, I.K. Kurkan, S.D. Polevin, V.V. Rostov, E.M. Tot'meninov, A multigigawatt X-band relativistic backward oscillator with a modulating resonant reflector, Tech. Phys. Lett. 34 (2008) 235−237.

[16] E.M. Tot'meninov, P.V. Vykhodtsev, A.V. Gunin, A.I. Klimov, V.V. Rostov, Increase in the energy efficiency of a pulsed-periodic relativistic backward oscillator with a modulating resonant reflector, Tech. Phys. 59 (2014) 428−433.

[17] V.V. Rostov, A.A. El'chaninov, A.I. Klimov, V.Yu. Konev, I.V. Romanchenko, et al., Phase control in parallel channels of shock-excited microwave nanosecond oscillators, IEEE Trans. Plasma Sci. 41 (2013) 2735−2741.

[18] A.M. Efremov, V.I. Koshelev, B.M. Kovalchuk, V.V. Plisko, K.N. Sukhushin, Generation and radiation of ultra-wideband electromagnetic pulses with high stability and effective potential, Laser Part. Beams 32 (2014) 413−418.

[19] Yu.A. Andreev, A.M. Efremov, V.I. Koshelev, B.M. Kovalchuk, V.V. Plisko, et al., Radiation of high-power ultra wideband pulses with elliptical polarization by four-element array of cylindrical helical antennas, Laser Part. Beams 33 (2015) 633−640.

[20] S.V. Alekseev, A.I. Aristov, N.G. Ivanov, B.M. Kovalchuk, V.F. Losev, et al., Multi - terawatt femtosecond laser system of visible range based on a photochemical XeF(C-A) amplifier, Laser Part. Beams 31 (2013) 17−21.

[21] T. Ozaki, J.-C. Kieffer, R. Toth, S. Fourmaux, H. Bandulet, Experimental prospects at the Canadian advanced laser light source facility, Laser Part. Beams 24 (2006) 101−106.

[22] S.V. Alekseev, M.V. Ivanov, N.G. Ivanov, V.F. Losev, G.A. Mesyats, et al., Parameters of the THL-100 hybrid femtosecond laser system after modification, Rus. Phys. J. 58 (2015) 1087−1092.

[23] B.M. Kovalchuk, V.A. Visir, A.A. Kim, E.V. Kumpyak, S.V. Loginov, et al., Fast primary storage device utilizing a linear pulse transformer, Rus. Phys. J. 40 (1997) 1142−1153.

[24] Ch. Mangeant, B. Roques, R. Cadiergues, F. Lassalle, F. Bayol, et al., Status on the Sphinx generator based on 1 microsecond rise time LTD stages, in: Proc. 13th Symp. High Current Electronics, Tomsk, 2004, pp. 111−114.

[25] B.M. Kovalchuk, A.V. Kharlov, V.B. Zorin, A.A. Zherlitsyn, A compact submicrosecond, high current generator, Rev. Sci. Instrum. 80 (2008) 083504.

[26] B.M. Kovalchuk, A.V. Kharlov, E.V. Kumpyak, A.A. Zherlitsyn, Pulse generators based on air-insulated linear-transformer-driver stages, Phys. Rev. STAB 16 (2013) 050401.

[27] A.A. Kim, M.G. Mazarakis, V.A. Sinebryukhov, B.M. Kovalchuk, V.A. Visir, et al., Development and tests of fast 1-MA linear transformer driver stages, Phys. Rev. STAB 12 (2009) 050402.

[28] SNL/ITHPP/HCEI contract #696243.

[29] A.A. Kim, M.G. Mazarakis, V.A. Sinebryukhov, S.N. Volkov, V.M. Alexeenko, et al., Lifetime of the HCEI spark gap switch for linear transformer drivers, in: Proc. 20th IEEE Inter. Pulsed Power Conf., Austin, 2015, pp. 196−199.

[30] Dr. Peitian Cong, Private Communication, 2016. The description of this switch is given in: Peitian Cong, Tieping Sun, Aici Qiu, Zhengzhong Zeng Analysis and enhancing of self-breakdown voltages of multistage gas switch, IEEE Trans. Plasma Sci. 41 (2013) 187−191.

[31] Zhou Lin, Li Zhenghong, Wang Zhen, Liang Chuan, Li Mingjia, et al., Design of a 5-MA linear-transformer-driver accelerator for wire array Z-pinch experiments, Phys. Rev. Accel. Beams 19 (2016) 030401.