DIAGNOSTICS SYSTEM FOR THE 67MJ, 50kV PULSE POWER CAPACITOR BANK


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Abstract
The diagnostics system described in the paper is for charging and discharging to the load of the large 67MJ and 50kV capacitor bank for the iodine laser pulse power of ISKRA-5 facility. Discharging diagnostics of the capacitor bank has used a technique to measure a sequence of times between representative discharge events for 665 discharge circuits of the bank. Benefits of the measurement techniques used are discussed.

Introduction
High-power laser facilities have been built in many countries for experimental research in laser fusion area. Among its subsystems every such facility has a pulse power system to supply flashlamps in the active medium pumping system of laser amplifiers. The pulse power system is built upon capacitor banks which are separated into individual modules. Each module is a bunch of capacitors which is discharged through a switched of the flashlamp an individual load.

High-power operating currents \( I_{\text{max}} \leq 300\, \text{kA} \) and voltage \( U_{\text{ch}} \leq 50\, \text{kV} \) are what determine failure probability for high-voltage components as \( P_{\text{fail}} = 10^{-4} - 10^{-5} \) per shot with the total number of component \( N_c \geq 10^4 \). Therefore, in each physics experiments there may be any kind of failure in the pulse power system, which has to be detected and eliminated. This is what the capacitor bank diagnostics system is intended for.

There are some considerations that make the diagnostics system development a difficult problem. First, it is electromagnetic compatibility requirement between the capacitor bank and diagnostics equipment at the bank discharge and associated high interference pulses. Next, it is requirement for multichannel measuring systems. Therefore, a measuring channel must have as simple design as possible to make equipment less expensive. Finally, efficient diagnostic technique must be provided physical measure to allow maximum possible detection of pulse power system failures and failure prediction techniques to be developed.

The paper presents diagnostics techniques for charging and discharging events in the large 67MJ, 50kV, capacitor bank of ISKRA-5 facility.

Capacitor bank description
The ISKRA-5 capacitor bank \([1]\) includes 665 capacitor modules. A module has its schematic diagram as shown in Fig.1. Its basic components are: a bunch of parallel-connected capacitors \( C_m \), a spark gap \( S_{w_m} \), cable connection lines \( K \) and series-parallel connected flashlamps \( L_1-L_4 \) as the load. Diagnostic signals during the module operation are to be produced by voltage dividers \( DV \) and pulse detectors \( D_{S_w}, D_{L_{1,2}} \).
Diagnostics technique for module discharge to the load

Reportedly [2], there is a diagnostics technique for capacitor module discharge to the load, which measures peak value of the discharge current carried through the flashlamp and switch. When a high-voltage component is broken down, this would cause variations in the discharge circuit 's RLC parameters and thus make the experimental peak current measurement different from expected value.

However, this technique to measure peak current value offers the following disadvantage. It can only state the occurrence of a high-voltage component breakdown while providing no preliminary information on the failure possibility. However, as shown in practice, module components such as the switch and flashlamp have the probability of shot delays increasing with running time, which is due to these components having different breakdown conditions in their gas spark gaps because of wear. With shot delays in high-voltage module components, there would be no variations in the circuit RLC parameters, therefore, significant changes in the peak current value cannot be detected until the switch or flashlamp breakdown.

The diagnostics implemented at the ISKRA-5 facility [3] is pulse-time technique. The idea of the proposed technique is as follows. Experimentally, the initial and terminal times were determined for the following major discharge events of the module: switch and flashlamp shot delays, current onset and zero-crossing in the load, simultaneity in trigger generator shots. These are times when specific detectors are used to generate diagnostic signals with representative time intervals to be measured between them, and these measurements would serve for performance evaluation of module components.

Fig.2 shows a timing diagram for direction of transients involved in the bank discharge to the flashlamps, together with times measured between start-stop signals ($t_4=t_1+t_2+t_3\leq 50\mu s$).

The pulse-time diagnostics allows detection of delays, misfires and prefires of the module switch and triggering generators. It can be also efficiently used to detect discharge failures which involve variations in the discharge current RLC parameters. These are such failures as connection line breakdown between the switch and the load. As this takes place,
the discharge current half-period varies in duration, thus being just detected as decrease in the interval $t_3$.

![Timing diagram of detector responses with the module discharge.](image)

**Fig. 2. Timing diagram of detector responses with the module discharge.**

Shot time measurements of high-voltage components provided an easy and efficient way to address major discharge diagnostics problems for the ISKRA-5 pulse power system.

The above-mentioned module discharge diagnostics is a technique that offers high interference immunity. This is primarily because detectors do not transmit analog signal to the diagnostics system, but a signal indicating the beginning or termination of any time interval, and thus requirement for nondistored signal transmission are not high. This allows efficient isolation between low-voltage diagnostics circuits and the high-voltage discharge circuit of the module.

This isolation is provided by using fast-response fiberoptic pulse communication units connected in between start-stop signal detectors and the equipment for time interval measurements.

With minimized number of measurements (one or two time intervals of a high-voltage components), the developments of diagnostics equipment was made much less expensive, while there was an opportunity to provide complete diagnostics for all the module components.

A great deal of data obtained from more than 10 000 experiments carried out on the ISKRA-5 facility during 1986-1996 proved the pulse-time diagnostics technique as highly efficient and important. During prelaunch adjustment operations, this technique allowed detection of about 5000 failure events of any kind in high-voltage module switches and trigger generations, and also application of performance prediction procedures for xenon flashlamps.

Similar diagnostics techniques may be designed into multiple pulse power systems operated with high-voltage modules having discharge events of microseconds duration.

**Charge diagnostics of the capacitor bank module**

For ISKRA-5 facility, the time to charge its 665 capacitor modules to 50kV voltage is 90-100s. During the whole of the capacitor bank charging cycle (fig.3), the module voltage is to be against the reference (at the power supply). Once a signal measurement goes beyond
$\pm \Delta V = 0.5 \text{kV}$, the module is indicated to have failed and then withdrawn from the experiment. In this way, breakdowns in charging lines and capacitors and switch prefires can be detected.

**Fig.3. Charge diagnostics of the ISKRA-5 capacitor bank module.**

For its detectors, the charge diagnostics system employs resistive voltage dividers with their interference immunity is achieved by no connection to exist between the “common points” of the module and the diagnostics system. For this purpose, the module has only a current control resistor with its signal to be transmitted via a cable (which is a shielded twisted pair, its shield and either wire connected only to the diagnostics “common point”) to the diagnostics circuit where the lower divider port is located.

This approach ensures reliable performance of the diagnostics system.

**Conclusions**

For the purpose of diagnostics of the ISKRA-5 capacitor bank modules for their switching performance to the load, measurement techniques have been put into operational use to determine time intervals that account for discharging of circuit operating in oscillatory mode.

As compared with techniques to measure peak discharge current in a circuit, the pulse-time diagnostics helps predict switch and flashlamp failures.


PFN-MARX PULSERS FOR HPM TESTING APPLICATION

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Abstract
This article deals with the development of fast compact systems applicable to the field of high power microwaves. Characteristics of a conventional Marx H.V. generator and two coaxial PFN-Marx pulser systems, operating up to 500 kV levels, are presented.

1. Conventional Marx: This type of generators are frequently used as the simulators of enhanced electromagnetic pulse effects. To drive HPM source, the voltage pulse should have a flat top of at least several 100 ns duration. At first glance, conventional Marx can meet this requirement. In zero order approximation, the output can be described as: \( V=V_0 e^{\frac{-t}{T}} \).

Here, \( \tau=RC \), \( R \) is the resistance of the load and \( C \) the erected capacitance (=capacitance of stage per number of stage). The energy delivered to the load as a function of time, \( t \) is:

\[
\text{energy} = \left[ V_0^2 \frac{\tau}{(2R)} \right] \left( 1-e^{\frac{-t}{\tau}} \right)
\]

If we allow a 10% drop in the voltage output (: i.e. \( e^{\frac{-\tau}{\tau}}=0.9 \)), we have that \( t/\tau =0.105 \) and \( e^{\frac{-t}{\tau}}=0.81 \). This suggests that for a 10% drop in the voltage, Marx generator has discharged only 19% of its energy. If at this instance, the system is short circuited by a crowbar switch, 81% of energy stored in the bank will be wasted. In some situation this is not important e.g. when one is developing high-power microwave sources where the width of the pulse is parameter in the investigation. This requires replacing a set of capacitors in the existing system with the set having longer time constant, \( \tau \) to achieve the pulses of longer duration. An alternative way is to employ an LC circuit to compensate for Marx generator drop as described by Crumley et al [1]. An example of using a diverter (crowbar) switch to get "square" pulse is given in Fig. 1.

2. PFN-Rim-Fire: In this system, attention was paid to the rise time characteristics. To achieve the steep rise in the voltage pulse, twelve UV-coupled spark gap switches are employed per each stage. Each switch has a sphere-ring geometry that is placed in the vicinity of the return current path. All attempts are made to minimize the discontinuities in the internal structure of the coaxial arrangement. The main difference between the Rim-Fire and the system described in Ref. [2] is that, here we have employed 12 switches per stage. A single switch per stage was used in Ref. [2].

The Rim-Fire has 40 stages, hence 480 switches. As in Ref. [2] the first stage is activated by a 50 kV, 10 ns rise-time trigger pulse and all the remaining (468) spark gap are U.V. coupled and activated by overvoltage applied in a sequential manner as demonstrated in Ref. [2]. During the discharge circle, an impression is created as if the rim is on fire (hence the name for the system: "Rim Fire"). The brightness of the spark channel does not vary from a spark gap to a spark gap in both the azimuthal- and longitudinal directions. To evaluate the system, a 100 \( \Omega \) transmission (diagnostic) line with its capacitive- and magnetic probes is attached to the output. To minimize the discontinuities, the peaking circuit described in Ref [2] was placed between the Rim-Fire and the 100 \( \Omega \) line. When the system is pressurized to 7 psi of \( \text{SF}_6 \), the rise time is 150 to 300 ps, depending on the charging voltage.

The pulse width is governed by the capacitance in the stage and by the finite dimensions (inductance) of the connecting
metallic plate (sandwiching six 2.7 nF, 40 kV Murata capacitors in each stage) with adjacent lead to the switch. Regardless how compact this geometrical combination is, the circuit can be represented by the LC section of the (co-axial) transmission line. L is the distributed inductance of all the leads, and C the lumped capacitance in the stage. We find that the duration of the pulse of 51 ns corresponds to $2(LC)^{1/2}$.

The reproducibility of output pulses is excellent, when viewed by both 602 A and 7250 digitizers (Fig. 2). The efficiency of the system defined as the ratio of the output voltage to 40 times the charging voltage (of 7 to 14 kV) is about 80%. No attempt was made to minimize the rise-time characteristics. If this would be necessary, the system should be placed in a metallic enclosure, so that the pressure could be raised from current 7 psi to 50 plus psi'. We need only to follow the path used in the electrical switch gears in gas-insulated apparatus. It is believed that, this system should be superior in respect to the rise-time characteristics to the system given in Ref. [3]. In the current form, the system could be used to power a high-current relativistic magnetron (Brasile et al [4]) or Backward-Wave Oscillator (Schamiloglu et al, [5]).

3. PFN Marx: To broaden the width of the pulse, the lumped LC networks are employed in each stage of Marx. We have introduced purposely the inductance between the individual capacitor to get a PFN. Some other arrangements of PFN (e.g. Guillemin type "C" network) are discussed by Crovey et al [6]. In our case we have used ten 2.7 nF, 40 kV Murata capacitors separated by a small inductance in each stage. This facilitates the duration of the pulse of 373 ns duration (Fig. 3). If longer pulse is required more LC stages could be

Fig. 1. Top: Photograph of the conventional six stage-12 capacitors (0.09 µF, 75 kV, each) Marx generator. A is the waveform at the beginning of the load. With capacitive probe, the rise-time is 1 ns at 300 to 500 kV. If the load is placed in a coaxial enclosure the rise-time falls to 0.4 ns. B is the waveform obtained using two resistors of 400 and 300 Ω connected in series. With the resistive probe, the voltage, B is measured across a 300 Ω. The resistor ahead of the probe acts as an antenna (that radiates high frequency components of the pulse), therefore, the rise-time "rises" from 1 ns to 7-12 ns. The waveform C was obtained as in B, but with a triggered-crowbar switch activated at 1.025 µs. The crowbar action can be applied in programable steps from 400 ns to 1 µs. A trigger pulse of 200 kV and 20 ns duration was used.
added. We find that the rise-time remains the same if more LC stages are added or if the PFN is reduced to a single stage.

The computer modeling of the performance of 8, 24 and 40-stage Marx generators were carried out using "PSpice" program. Internal PFN features: the characteristic impedance ($=(L/C)^{1/2}$) and the pulse width ($=2(LC)^{1/2}$) were considered. Also, we find that, the coupling capacitance between stages and switch characteristics must be taken into account in the computer simulation. The experimental results are well accounted for by a PSpice computer simulation as long as the experimental values of the formative time lag of the switch's breakdown were correctly observed. In zero order approximation, we get that, if the characteristic impedance of the stage is $Z_0=(L/C)^{1/2}$, then the output impedance of the system is $nZ_0$.

The pulse width of the system, $T$ is governed by a single stage: $T=(LC)^{1/2}$. "Smart gas mixture" used in the generator can contribute to minimizing the ripple at the flat portion of the pulse. However, this is a challenging task because: (a) it is rather difficult to produce a pure resistive load required to do the test covering the entire frequency range.

Fig. 2. Top: Photograph of forty-stage Rim-Fire. The system is enclosed in a 11" diameter plexiglas tube. 24 copper rods of 1/4" diameter are enclosed in 1" diameter plexiglas tubes to provide the return current path.

Waveforms: A, B and C of Rim-Fire at low (400 kV) output voltage into a 100 Ω load. A & B recorded with 602A digitizer. C recorded with 7250 digitizer (2 ns/div; 273 ps rise-time). The dip on the flat portion of the pulse at around 15 ns is due to imperfection of the resistive termination.
from d.c. to giga-Hertz and (b) it is difficult to construct a H.V. resistive probe that could be as fast as the capacitive probes. To simplify the engineering task, a single switch per stage was used in Fig. 3 resulting in the rise-time of 4 ns.

In all systems an effort was made to reduce the size and weight and to make the systems portable. The co-axial structure offers the possibility of combining the Rim Fire technology with the classical LC networks in order to achieve an ultra fast rise-time and long duration pulses. With inductive charging, the pulse repetition frequency of 10 Hz can be accomplished.

**Conclusions:** Conventional- and PFN Marx are applicable to the "Super-Reltron" tube described by Miller *et al* [7]. It is frequently stated that this tube has an extended frequency coverage, excellent efficiency (due to good electron bunching and small energy spread of the electrons in the bunches), and convenient output configuration. We are interested to understand the onset characteristics in the tube's modulating cavity using our pulsers. We want to appreciate the importance of the observations by Scarpetti *et al* [8] that, a full space-charge limited current is fully established at 400 kV/cm for velvet (cloth fiber) cathodes and the emitted current can follow the nano-seconds rise time of the applied voltage pulse.

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**References:**


**Fig. 3.** Top: Photograph of 8-stage-PFN-Marx. The system is enclosed in a 11" diameter plexiglas tube. Bottom: The pulse width of the waveform is 372.6 ns and rise-time about 4.2 ns. Reproducibility of the pulse is excellent.
Controlled Multiple Channel Switch

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Abstract.
The method of the energy switching in the two-electrode sharpening discharged switch gap, when voltage pulse with variable rise velocity (du/dt=10^{11}-10^{14} V/s) is applied to the between switch electrodes, is considered. The switch was set in the circuit with the inductive energy store and current switch (IGUR-3), that is used to switch of the energy to the accelerator tube. The switch gap change controls the voltage (current) pulse front in the range 15-250 ns. The switching current amplitude is ~ 80 kA with voltage up to ~ 7 MV.

Introduction.
The different duration pulses formation essentially extends the possibility of the IGUR-3 accelerator to research. To obtain the required duration of the pulse front the sharpening discharger switch gap must be changed. The switch operation in the all range of the rise velocity of the voltage pulse is provided by the gap change in the range from 20 mm to 150 mm. In this case the number of the energy switching channels change in the range from 1 to 5 (7 switching channels were obtained in the experiment with 5 high-voltage electrodes).

Experimental Setup and Results.
Circuits with the inductive energy store and the electrically exploding wires (EEW) switch of current is used to produce overvoltages and to form voltage pulse of required shape and duration. In the direct action IGUR-3 accelerator [1] the mentioned scheme (see fig. 1) is

![Fig.1]

Simplified circuit of IGUR-3 accelerator
C1,C2-capasitor stores (Marx generator); L1,L2-inductive stores;
EEW-exploding wires; AT-accelerator tube; S-sharpening discharged switch; S1-triggering discharged switch.

\footnote{The work was supported by ISTCprojekt #271}
used for the production of voltages up to $U = 7$ MV with their subsequent switching to the

Fig. 2.
Typical voltage waveform for EEW of IGUR-3 accelerator.

acceleration tube (AT). The typical voltage waveform for EEW of IGUR-3 accelerator is
represented in fig. 2.

The characteristic peculiarity of such pulse is the presence of pre-pulse of $\sim 1.7 \mu s$ duration

Fig. 3.
Schematic of the sharpening discharged switch.
1-high-voltage electrode; 2-high-voltage flange of AT.
and main (working) pulse with variable rise velocity in the du/dt range between $1 \cdot 10^{11}$ and $1 \cdot 10^{14}$ V/s.

To switch the energy for loading at the IGUR-3 accelerator usage is made of the oil two-electrode sharpening discharged switch, which can operate, under the certain conditions, in the mode of "controlled" multiple channel switching of energy. The switch design is given in fig. 3. High-voltage electrode consists of the cylinder 60 mm in diameter with the notch at its end. Second electrode is the plate high-voltage flange of acceleration tube. The electrodes are made of steel.

Conditions of the origin of the first discharge channels, the velocity of their propagation and the dynamics of overlapping by them of the oil discharge gap are essentially determined by the state of the surface of high-voltage electrode, by the value of electric field strength and by the voltage pulse rise velocity rise. Gap variation from 20 to 160 mm inside the switch allows its operation within the whole du/dt range. The increase of the gap in the switch leads to du/dt rise when switch comes into action and to realization of energy switching mode at a number of channels $n>1$. At increase of the gap (hp>30 mm) the velocity and the time of the development of primary channels don't permit to overlap the gap by one of them and the time of the process ($t<3$ ns) doesn't provide the conditions of primary channel transfer to leading one [2]. At significant du/dt rise, that leads to important increase of electric field strength at "the head" of the primary channels, the break-down along several channels takes place. With du/dt rise, a number of the energy switching channels in the switch gap increases. In fig. 4 the dependence

![Graph](image)

**Fig. 4.**
Voltage pulse front as a function of the number of switching channels.

of the front duration of voltage to AT on a number of switching channels is shown.
It is to note that the important role in the realization of multiple channel switching mode is played by the structure of high-voltage electrode surface. With polished electrode surface the mode of multiple channel switching isn't observed.

The conditions of the realization of "controlled" multiple channel switching mode are the following:
- voltage pulse with variable rise velocity (at $du/dt > 10^{12} \text{ V/s}$) is passed to high-voltage electrode of the sharpening discharged switch;
- discharger switch has to come into action along all $du/dt$ range of passed voltage pulse;
- multiple channel switching modes and the stability of the operation of pulse front reducing discharger in required mode is being achieved as a result of the forming of determined structure of high-voltage electrode surface.

**Conclusion.**

The proposed method of the pulses formation with the different front duration permits simply and without expense to control the pulses duration and one is widely used on IGUR-3 accelerator in carrying out of researches.

**References**
