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Final Report Task Order Number B239641 between The Regents of The University of California and Institute of Experimental Physics Task 2: Switch Development

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FINAL REPORT

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CONTENTS.

1. INTRODUCTION

The available in LLNL project of the pulsed power system for the National Ignition Facility (NIF) requires a switch with the following operating parameters: peak current of 400kA, the transferred charge of 150C, operating voltage of 25kV, and reliable operating life of 10 000 shots.

Besides, the switch during its life must survive without a change in the performance 5 emergency shots with a peak current of 1,2MA and transmitted charge 450C.

It has been known that development of a high-current switch meeting these requirement is an extremely complex problem, and large teams of scientists in many countries of the world are working on the solution of this problem.

The difficulty that the scientists face in this work are conflicting requirement in one design: high energy switched on the one hand and high reliability and long operating life on the other hand.

In this report we carry out an analysis of literature on high-current switches, the constructions of which better satisfy the formulated problem. Special attention has been given to Russian developments which can be or have already been put into production.

The analysis shows that in recent years a number of promising switches have been developed which can be used in the NIF pulsed power system. Our conclusion needs experimental verification.

To this end, the switches should be tested at 25kV, and transmitted current and charge as highest as possible for the selected switches under these conditions (the current pulse duration at the level of 0,1Im = 500μs).

This work has been performed by as on a specially designed and built high-voltage testbench. We have investigated prototypes developed and made according to our task on sealed-off vacuum and semiconductor switches based on reverse switched dinistors.

The aim of tests was to determine limiting modes of operation, develop methods for diagnosing the main parameters and formulate criteria which can be used in assessing the operating ability of switches.

Work intended to determine reliability of switches, to our great regret, could not be completed because of limited funding and shortage of time.

We think that the results given in the present report, a greater part of which has been obtained for the first time, can be of great interest for developers of high-power pulsed energy systems.

2. A REVIEW OF HIGH-POWER SWITCHES.

Two types of switches are usually used to solve the problems of pulsed energy switching : spark gap and semiconductor switches.

We shall not consider here switches with hard isolation (usually polymer films) of the main discharge gap which makes the usage of a great number of such switches very complicated.

Spark gap switches, in their turn, can be subdivided into high-pressure and low-pressure switches depending on gas pressure used for isolation of the main discharge gap .

High-pressure switches or spark gap switches operate under gas pressure (air, nitrogen, hydrogen, SF6 et al.) of 1 atm. and more.

The well-known constructions of such switches [1,2,3] make possible their operation in a broad range of voltages (up to several MV) and currents (up to units of MA), they have short fire times with a small jitter (up to units of nanoseconds) which makes successful simultaneous triggering of a great number of switches.

However, they have several shortcomings. To provide low probability of prefires such switches must have high electric strength i.e., the ratio Ub/Uo must considerably exceed 1. Here Ub is the breakdown voltage of the main discharge gap and Uo is the operation voltage across it.

It can be shown that in most cases at Ub/Uo=2.0 the prefire probability of this switch will be within $10^{-4} - 10^{-5}$. However our experience shows that this value of probability remains only when the gas is replaced in due time after the switch fire, especially upon transmission of a large charge through it. Thus the switches should be provided with a proper gasfeed system, no doubt that this complicates and raises the cost of their usage.

Another difficulty being the result of high electrical strength is their high ignition voltage. Only under this condition a small jitter of the switch fire time can be achieved.

A serious drawback of spark gap switches is electrode erosion appearing in the phase of arc discharge. With the growth of transmitted energy by the switch erosion increases, the operating life of the switch becomes shorter either due to the increasing probability of prefires or due to the appearance of large delays and misfires.

Attempts made to avoid this drawback by using electrode materials having a higher erosion resistance were not effective. This is confirmed by experience of work with switches ST-4198 and ST-300 [4] and the spark gap switch of the ISKRA-5 capacitor bank [5].

Their main parameters are given in Table 1.1. The first two switches use the erosion-resistant graphite as an electrode material, and the third one uses the heat resistant steel.

Table 1.1 shows that the switch of the ISKRA-5 capacitor bank has a higher operating life.

This is probably due to a considerably lower charge transmitted in one shot. The typical operating life of spark gap switches transmitting, the charge of 500C is several hundreds of fires.

These results show that spark gap switches are not promising for the NIF pulsed power system.

Low pressure spark gap switches can also be subdivided into several modifications. They are: hydrogen thyratrons and pseudospark switches with discharge in hydrogen under pressure of 0.01mm Hg; ignitrons with discharge in mercury vapor serving as a cathode; and triggered vacuum switches with vacuum under pressure of 10^{-5} mm Hg serving as isolation for the main discharge gap with discharge in the vapor of hard cold cathode material.

Thyratrons are not promising in solving the problems of high-energy switching due to high-energy release in them as for constructions of pseudospark switches, they are presently within the frames of laboratory model switches [6] .

Russian developments of ignitrons have not reached the parameters required for the project NIF. The most powerful of Russian commercial ignitrons is ИРТ-4 transmitting current up to 200kA at operating voltage up to 50kV, but when it

Characteristics of some spark gap switches.

Table 2.1.

		Parameter		
Name		ST-4198	ST-300	ISKRA-5
Operational voltage	kV	0-55	0-55	25-50
Operational current	kA	до 850	до 500	300
Charge transfer	C	700	700	40 *
Lifetime	C	90,000	150,000 **	240,000

* - per one shot

** - measured value 24,000Кл.

Characteristics of American (EGG и MPD) and Russian triggered vacuum switches.

Table 2.2.

		Parameter				
Name		GVP-7013	GVP-6313	ZR-7516	ZR-7512	TVS-40
Operational voltage	kV	0.3-32	0.3-80	0.3-25	0.3-40	0.3-25
Maximum voltage *	kV	-	-	35	55	40
Current**	kA	20	60	40	50	100
Maximum current	kA	-	-	-	-	180
Charge transfer A*s/shot		0.3	0.5	0.6	0.7	100
Lifetime, shots		-	-	-	-	*** 20 000
Fire time	μs	-	-	<1	<1	1
Length	mm	76	187	140	216	220
Diameter	mm	76	111	108	108	150

* - where occasional prefire is acceptable

** - at greatly reduced switch life

*** - at 50kA, 50A*s/shot

transmits charge of 23C at current of 200kA, its operating life is only 100 fires [7].

From literature known to us about ignitrons of the size "E" [8] we can conclude that they do not meet the requirements of the NIF too. With the current increase up to 400kA and the charge up to 300-400C the operating life of these ignitrons does not exceed several hundreds of fires.

It should be noted that in the ignitron under study dimensions of the main discharge gap are decreased with the aim to reduce energy release and they have been tested under pressure of 8,5kV.

Well-known difficulties are caused by the use of mercury in ignitrons.

During the phase of developing the ISKRA-5 capacitor bank we refused from ignitrons because of ecological reasons and because of a difficulty one is faced when triggering a great number of ignitrons with the required jitter.

Nevertheless, taking into consideration a rich experience of LLNL in work with ignitrons we consider them to be the most probable candidates for the use in the NIF capacitor bank.

Triggered vacuum switches have been for a sufficiently long time used for solving the problems of transmitting high energies [9]. Initially these were constructions demanding the discharge chamber [10,11] be evacuated constantly.

It is evident that this complicated their usage especially in big facilities with a great number of switches. In 1960s as a result of a large research work at a number of firms and in the first place of "General Electric", USA [12], the problem of preserving a sufficiently low pressure of residual gases (less than 0,001 mm Hg) during all operating life of the switch was solved and there appeared constructions of sealed-off vacuum switches.

However, they were not widely used in the first place due to a limited operating life of the triggering electrode construction. Fabrication of these switches was limited as a rule it was in the form of laboratory specimens.

In the early 1980s Russia also began works on development of a controlled vacuum switch of a sealed-off construction. As a result there appeared several types of such switches.

Comparison of characteristics of one of them with the available in USA industrial specimens [13] is given in Table 1.2. One can see that the switch of such a type TVS-40 sufficiently exceeds other switches in transmitted current and charge at the same time having an acceptable operating life (10 000 000C in all shots).

Switches TVS-40 are produced in small series at a number of plants in Russia [14].

We think that switches of this modification have good prospects for usage in high-power capacitor banks including the NIF capacitor bank. The main task to be solved at the present moment for such switches is high probability of prefires the feature which is intrinsic to all types of triggered vacuum switches.

Semiconductor switches in recent years became more competitive with the spark gap switches surpassing them in operating life and stability of operation. The possibility to operate in series and parallel connections allows to use semiconductor switches in a wide range of operating currents and voltages and solve successfully many problems for pulse power systems [15,16,17].

Efficient use of the operating area of the semiconductor device upon switching is the main factor determined the threshold transmitted power. It is well-known that the most convenient and widely used semiconductor switch of a microsecond range is a high-power silicon tiristor.

The drawback of devices of such a type is localization of switching at the controlled electrode in the region with a characteristic width of 0,1-0,2mm and a relatively slow (0,05 - 0,01 mm/μs) propagation of conducting state over the area of tiristor structure.

This, naturally, strongly limits the permissible value and the rate of transmitted current rise. During the last 10 years semiconductor devices of a new type were developed that is reverse switched dinistors (RSD), when switching them uniform and simultaneous triggering of the whole semiconductor operating area is realized [18].

Such mode of operation allows to transmit considerably higher currents than when using tiristors.

Production of RSD has been organized by a number of plants in Russia, but the production and wide use of these devices holds some what back, the reason of this is a complex circuitry of RSD switching.

However, we believe that this switch can become very promising for the use in high power capacitor banks, even in spite of the main drawback of semiconductor devices that is sensitivity to overvoltages causing their irreversible damage.

Thus, in spite of a great variety of available switch constructions not all of them can be used at the facilities like the NIF. In our mind, sealed-off vacuum switches and RSD-based switches have the greatest potential abilities. To confirm this, special investigations have been conducted.

3. VACUUM SWITCHES : INVESTIGATION OF MAIN PARAMETERS.

We have investigated the operating capability of switch TVS-40 and some of its modifications under conditions, required for the NIF capacitor bank and compared the obtained results with the test results of this switch, obtained by other investigations [13,14,19,20].

3.1. CONSTRUCTION OF THE SWITCH OF THE TVS-40m TYPE

The TVS-40m switch is a controlled vacuum switch of a sealed-off construction with alternating (interlacing) rod electrodes.

Such electrode system offered by specialists of "General Electric" [14] has a higher switching capability (as to the transferred charge) per unit chamber volume if compared with the traditional parallel-plate system.

This advantage is obtained owing to the optimal use of the chamber operating volume, influence on the discharge arc of its intrinsic magnetic field under which low voltage drop across arc and uniform electrode wear are provided.

The switches are made using electron-vacuum technology which includes long-term heating under 450 C and constant oil less pumping. Before being unsoldered from the vacuum station the gap electrodes are exposed to pulsed arc treatment and training by voltage breakdown.

As a result of good clearing of the gap inner surfaces and usage of getters and materials with low gas content, the pressure of residual gases in the gap is below 10^{-4} Pa during all its life (10 years).

The gap construction is given in Fig.3.1. The case consists of two ceramic cylinders 1 connected through feat copper seal 2 which also serves as a holder of central

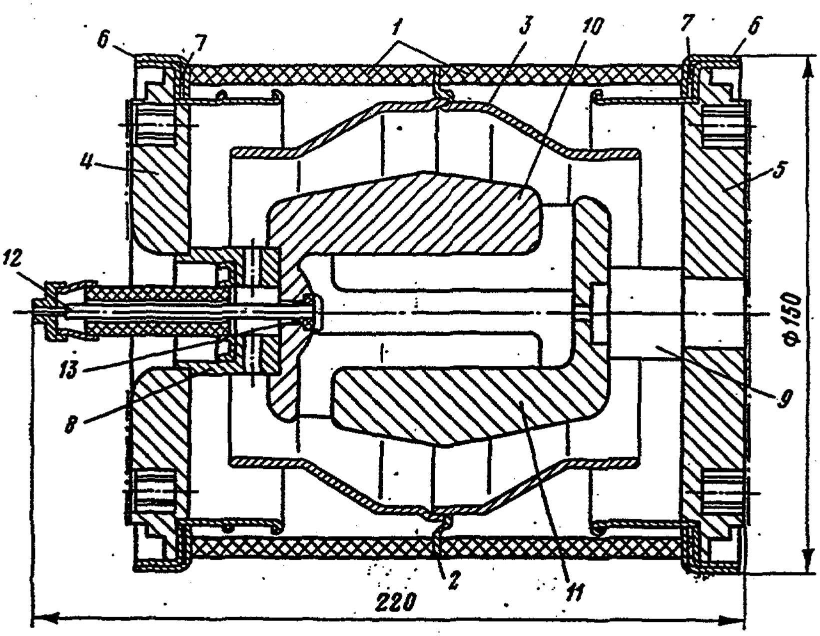


Fig.3.1. Construction of vacuum switch TVS-40.

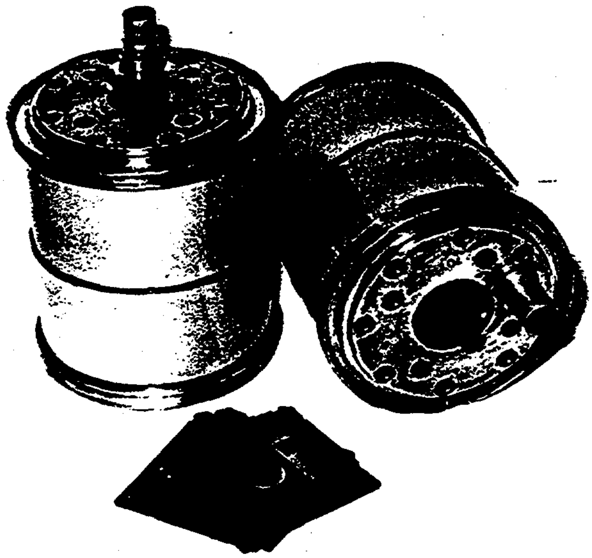


Fig.3.2. Photography of vacuum switches TVS-40m.

isolated copper screen 3 and two copper flanges 4,5 connected with ceramic cylinders through copper 0-ring seals.

To prevent damaging of vacuum-tight junction of the ceramic cylinders with end 0-ring seals under temperature variations, compensators 7 are used made of a metal having suitable temperature of thermal expansion.

Inside the case the current leads 8,9 from copper are located to which the electrode system 10,11 is attached. Each of the main electrodes is made in the form of three parallel rods so that rods of opposite electrodes at placed of overlapping form six parallel arc gaps.

Minimal interelectrode spacing is 6 mm. Electrodes are made from copper obtained by vacuum melting. The ignitor, consisting of triggering electrode 12 and dielectric 13 (aluminum-oxide ceramic) insulating the main electrode from the triggering electrode, is located in one of the main electrodes.

Initiating breakdown is realized over the side surface of cylindrical dielectric. The length of igniting gap is 1mm. The photograph of the switch is shown in Fig.3.2.

In 1993-1994 two modifications of the switch TVS-40 were developed. The first modification is TVS-40m in which the ignition circuitry was changed, as for the main electrode system it remained unchanged. The second modification is TVS-49 which underwent more series changes in its construction aimed to reduce its dimensions and weight and to simplify the electrode system, as a result a more technologically effective switch was obtained.

The TVS capability to operate was studies by various teams of investigators in various regimes including also regimes considerably exceeding the passport data. We shall consider the obtained data on the most important switch parameters.

3.2. INVESTIGATION OF THE ELECTRICAL STRENGTH.

Usually the electrical strength of inner and outer insulations is studies. In Ref.14 distribution functions are presented for the electrical strength of the TVS switch inner and outer insulations which were obtained as a result of measuring the electrical strength by applying slowly rising voltage of commercial frequency (50Hz). These data are given in Fig.3.3 where experimental points were applied on the probability coordinate grid in which the normal distribution low is shown by a straight line. Curve 2 of the inner electrical strength has been plotted by 20 measurement points during the switch life test through each 1000 fires over the period of 20 000 fires.

From Fig.3.3 one can see that the curves sufficiently closely follow the normal law and the outer insulation electrical strength considerably exceeds the inside insulation electrical strength and is more stable which provides safe operation of the switch avoiding overlapping.

As a rule, the TVS switches can withstand the static voltage up 35-40kV. Thus, one of the research groups [20] has studies 150 TVS-40 switches under the voltage of 35kV during a minute and all the switches have passed this test without fires.

We have studies 7 switches of various modifications: four TVS-40 switches, two TVS-40m switches and one TVS-49 switch. The test scheme is given in Fig.3.4.

A slowly rising (0,5 kV/s) rectifiered voltage was applied across the switch, the breakdown voltage was recorded at the moment of fast voltage drop across the capacity.

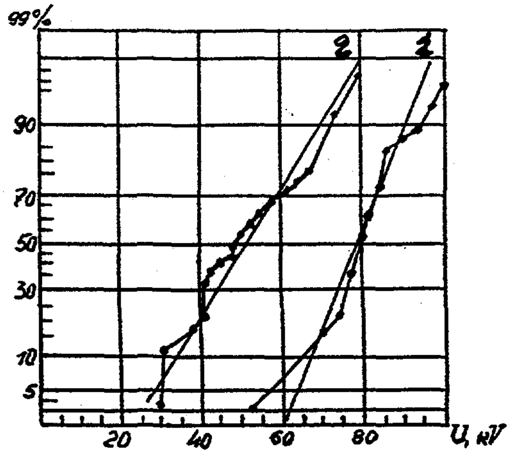


Fig.3.3. Distribution functions for the electrical strength of TVS-40 switch outer (curve 1) and inner (curve 2) insulations.

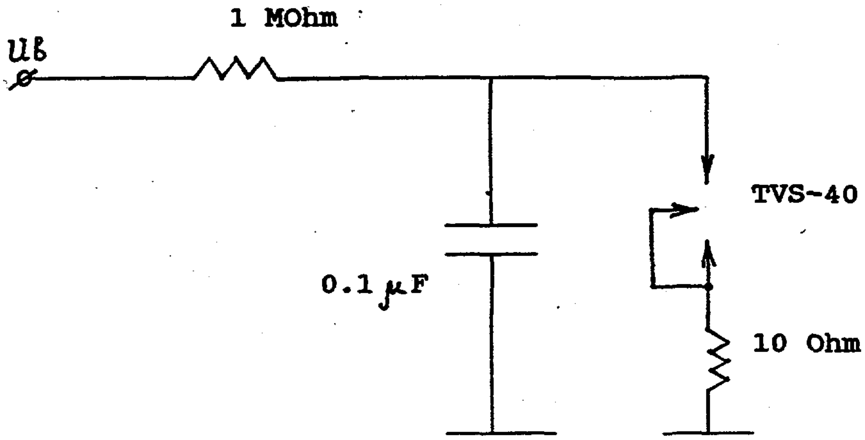


Fig.3.4. Circuit diagram of breakdown voltage measurements for vacuum switch TVS-40.

The current switched through the gap at breakdown was not above 5 kA. Each switch passed 30 charging cycles (up to breakdown). This study revealed a feature typical of all tested switch modifications: during the first 10-15 cycles the breakdown voltage rises from 20 to 40kV for the switches TVS-40 and TVS-49 and from 40 to 50kV for the switches TVS-40m, then remaining practically constant, i.e., a certain kind of electrode training occurs, increasing the switch electrical strength.,

Individual specimens have voltage surges, that is nonuniform fall of the breakdown voltage by 10-15 kV and the strength recovery during the subsequent fire. This can be seen in Fig.3.5, where the test results are presented for three various switches TVS-40. The switches with voltage surges have a higher probability of prefires and they should be rejected. Thus, using this technique the switches can be checked and trained prior to the cycle of in-service fires.

3.3. INVESTIGATION OF THE SWITCH LIFETIME DEPENDENCE ON THE VALUE OF SWITCHED CURRENT.

The value of operating current has a considerable influence on the switch parameters, in the first place, the prefires probability, growing with the current rise and the charge transferred, and on lifetime which for the given switches is also determined by an abrupt decrease in the electrical strength.

As has been shown in Ref.14 the lifetime is determined by the ouset of the metallic film pieces separation from copper screen 3 (see fig.3.1) formed as a result of electrode erosion.

Thus, the erosion intensity is directly connected with the switch lifetime.

It is known [12] that in triggered vacuum switches there exist two modes of discharge: diffusion when plasma practically isotropically fulfills all the discharge gap and constricted when plasma is constricted into a comparatively low channel.

In diffusion mode erosion is of a vapor character and its intensity is small. In the constricted mode erosion becomes dropwise, its intensity sharply increases, especially anode erosion increases because of the characteristic for this mode formation of anode spots.

The threshold of vacuum arc transition into the constricted mode and formation of anode spots depends on electrode material, geometry of vacuum gap, current value and duration. TVS switch tests have shown [14,19] that for switches of this modification up to 100 kA there exists the diffusion discharge mode and at high currents it goes into the constricted mode and the lifetime reaches about 20,000 shots.

Lifetime tests were performed in the following modes: at currents of 50kA and charge of 50C (pulse width at half maximum is 1 ms) [14] the lifetime of 20,000 fires was obtained, and at the current of 150 kA and charge of 100C (pulse width at the level of 0.1Im is 2 ms) [19] the lifetime of not less than 2000 fires was obtained.

In Ref.19 the switch test result are given under current in the form of a dumped sinusoid with the first half-wave current amplitude of 200kA, oscillation period of 600μs, and charge per shot of 75C. The authors note that this mode is the most severe for the switches of this modification, electrode erosion is the most intensive, and the tests have been stopped at the 749th shot because of

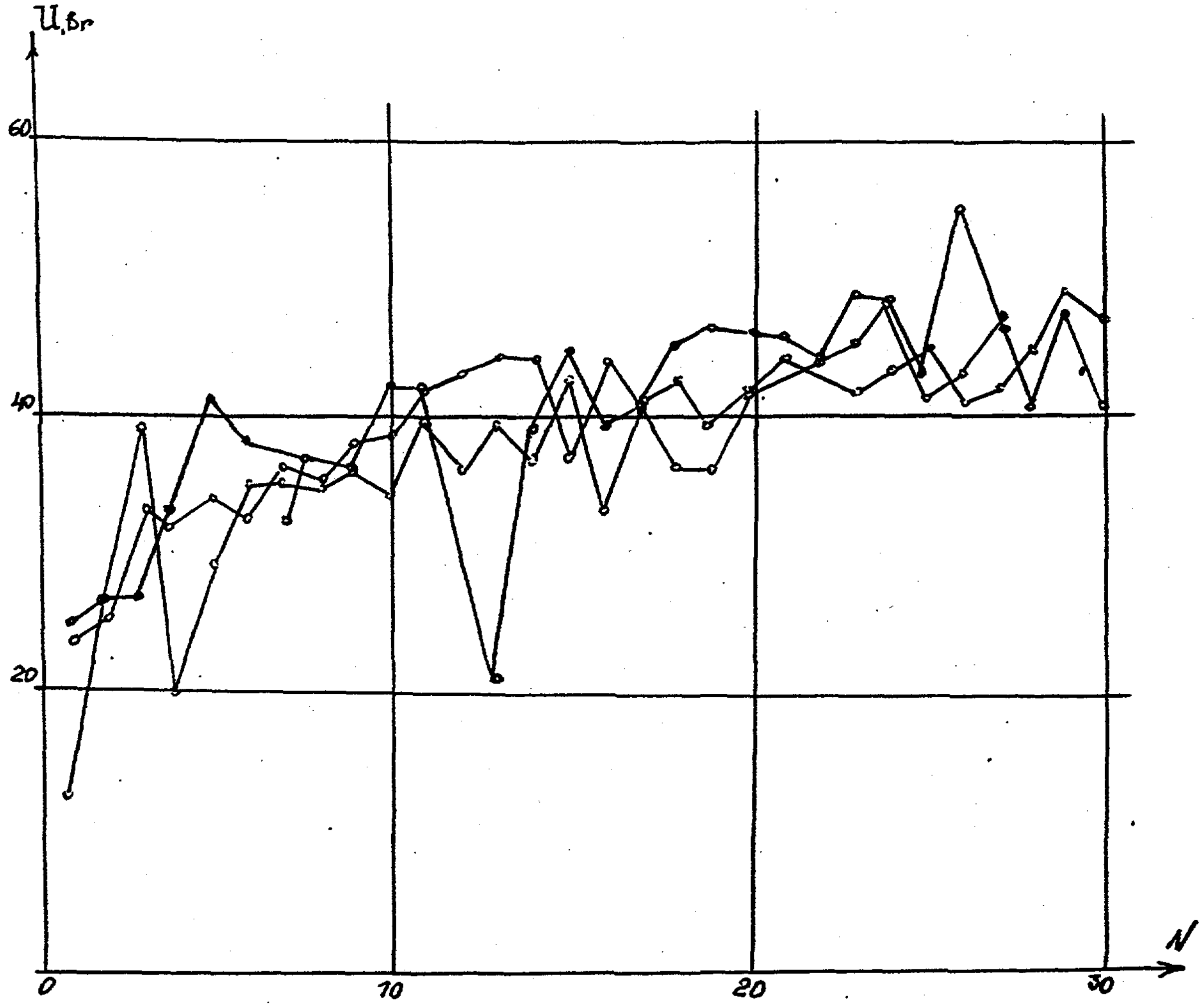


Fig.3.5. Diagram of breakdown voltage changing for three switches TVS-40.

nonrecovered short triggering gap.

Study has been performed on the ability of the switch TVS-40m to switch current in the range of 350 - 400kA. It shows that these currents give rise to electrodynamic forces causing compression of electrodes and their short circuiting. In designing the switch TVS-49 attempts have been made to avoid this phenomenon.

Thus, we can consider that this switch modification is quite suitable to switch currents with the amplitude of 100 - 150kA and charge of moreover the switch lifetime is not less than 2000 shots. Nevertheless, we think that it is necessary to conduct lifetime tests under conditions close to those required for the NIF. We have not been able to do this because of the limited funding of the Task Order.

3.4. STUDY OF PREFIRE RATE.

Experience of work with vacuum switches shows that they have a high prefire probability. Especially this is characteristic of sealed-off switches in which the erosion products deposit on the inner surface of the discharge chamber and can be pulled into the discharge gap by electrical field upon subsequent charge.

We have tested switches of specified modifications of the testbench with the operating voltage of 25kV and revealed that up to 20kV the failure of these switches is a very rare event (this is also confirmed by data of other investigators) and in the region of 20-25kV the prefire probability is 0.01 failures/shot. Such rate of prefires is very high to use them in a high-power capacitor bank where operation of several hundred of switches is required.

Tests of the switch TVS-49 which has a shorter interelectrode spacing and a shorter distance from electrodes to the screen if compared to TVS-40 and TVS-40m, have shown that its prefire probability is severalfold higher than that of TVS-40m, that is the optimal construction of this switch has been reached yet.

The reduced prefire probability can be achieved by using instead of copper as the electrode material more erosion resistant materials (such as compositions of copper-molybdenum and copper-chrome, molybdenum and some kinds of bronze). As a result of their usage, the size of particles, formed due to erosion and sucked into the discharge gap, diminishes and the rate of prefires decreases, but from data of Ref.14 it can be seen that simultaneously with the achieved above advantages the lifetime of these switches becomes shorter.

It is very likely that a more reliable way to reduce the prefire probability is to use a pack of several switches in series connections for switching operations.

However in this case a more complicated firing system is required, to optimize it additional investigations should be performed.

3.5. INVESTIGATION OF THE SWITCH SHOT AND TRIGGER TIME.

A peculiar feature of vacuum switches is their high shot stability upon properly selected trigger parameters, curves of shot time dependencies td on the trigger current It are given in Ref.14 together with the empirical formula for the shot time: $td = 7*10^{-5}*It^{-0.5}$. Here the current is given in A and time in sec. Similar dependencies can be found in works of other investigators.

It is noted [14] that the shot time at the selected value of trigger current does not depend on the operating voltage at the switch anode. However, according to our data and data of other investigators [20], with the charge of anode voltage in the range of 5 - 25 kV and constant trigger current the shot time decreases approximately by a factor of 2 and at 25kV it is 1.1 ± 0.2μs (the trigger current is 2kA) for all the tested switches modifications.

The shot time is a criterion of the switch trigger unit operation. We determine it as the time interval between the onset of trigger current and the moment of time when the rate of current rise of the main discharge reaches the maximum value.

We used the switch trigger mode when the trigger unit is at the cathode. The trigger function becomes easier and the current can be decreased down to a value of 0.5-1.0kA [13].

The trigger voltage amplitude lies within 5-10kV the width of the current first half-wave is about 2 μs. When the switch is used in the mode of trigger on the anode the trigger current must be increased up to 2.5 - 3.5kA.

The triggering electrode construction used in the switch TVS-40 has a considerable drawback : short circuiting of the firing gap when current above 100kA is switched by a metallic film formed as a result of electrode erosion. As a rule, it can be removed through a firing gap of a capacitor of large capacity (we used in these cases a 200 μF capacitor charged to 3kV). The same was done by the authors in Ref.19, but this, no doubt, is inconvenient under service conditions.

In constructions of the switches TVS-40m and TVS-49 the triggering electrode construction was changed and during their life tests under 140 kA short circuiting of the firing gap was not observed during 5500 shots.

It is not difficult to do the triggering system for these switches at showed above the current and voltage parameters. Usual schemes can be used for capacitor discharge by selecting suitable tiristors.

3.6. CONCLUSIONS TO CHAPTER 3.

1. The possible candidates for the NIF bank are sealed-off vacuum switches. Performance of the most powerful of them according to the current and charge transferred of the type TVS-40 presently is being investigated by various groups of investigators for various purposes.

2. We have investigated performance of the switch *TVS-40m developed and manufactured according to our task in* modes typical of the neodymium laser power system. The switch has a considerably more reliable unit if compared to TVS-40. It successfully switches currents with the amplitude of 150kA under operating voltage to 20kV and has the lifetime about 10,000,000C during all the shots under operating voltage of 25kV the rate of prefires rises.

According to our estimates, in the present construction it amounts about 0.01 failures/shot. To reduce the prefire rate it is expedient to use these switches in series connections. Operation of such a pack needs to be additionally investigated.

3. The increase of the switched current to 300 - 400kA is limited by discharge transition to the constricted phase and abrupt decrease of the switch life due to intensive trickling electrode erosion. Physical nature of plasma instabilities leading to a constricted discharge is insufficiently studied so as to work out concrete measures to

avoid them. However it is possible to use in the vacuum switches intended for current of 300 - 400kA achievements of vacuum arc quenching chamber operating at such currents and considerably longer discharge durations.

4. SEMICONDUCTOR SWITCHES: STUDY OF BASIC CHARACTERISTICS.

Unlike vacuum switches, there is little knowledge of the operation of switch designs based on reverse switched dinistors (RSD). Only two publications are available [21,22] where RSD monopulse operation is described.

It is shown in [21], that RSD of $20cm^2$ operating area can repeatedly switch current pulses 20kA high, half-period pulse length 30μs and current rise rate 30 kA/μs or less.

What has been studied in [22] is the operation of an assembly of three RSDs having $40cm^2$ operating area at 7.5kV voltage. As it is shown, this assembly can switch operating currents as high as 300kA with square pulse length 100μs.

The data reported can not be used as reasonable grounds to decide whether or not RSD-based switches are suitable for the NIF pulsed power system. Specific studies of these switches' basic characteristics have been carried out in the environments close to their operation by the pulsed power system of high-power glass laser. Given below are the results of these studies.

4.1. RSD AND RSD SWITCH DESIGNS.

RSD is designed [22] to include several dozens of thousands of alternating tiristor and transistor elements with their size smaller than the thickness of the wide (about 0.3mm) n-base of the device (see fig.4.1). The elements have common collector junction which holds the external voltage of the polarity as indicated in fig.4.1. They have also common upper n+ -p emitter junction. RSD is uniformly switched by applying a short reverse voltage pulse Up. As a result, there occurs a breakdown in the low-voltage n+ -p junction and a charge of excess carriers is injected into the base regions of the structure, with its quantity determined by the pulse height and length of the reverse current (pumping current). Thus, RSD has the tiristor control electrode replaced by an areally uniform control plasma layer, thereby allowing generation of the plasma current conduction channel for main discharge current having the same area as the silicon plate.

With the operation of RSD through anodes, one can easily pack these RSD in series columns without using complex transformer triggering circuits typical of similar tiristor packs. A column of series connected RSD only requires leveling static voltage between individual units. In most cases, virtually instantaneous RSD switching makes it unnecessary to level off the column voltage dynamically using RC-circuits, though this should be determined for an actual discharge circuit. The above-mentioned switch [22] rated for 7.5kV has been made of three RSD each enclosed in its case. However, having a case for every RSD significantly increases the switch weight, size and cost (see fig.4.2). Therefore, we have had a switch prototype КРД-25 developed to our specifications, and its design is illustrated by fig.4.3. As fig.4.3 shows, this switch includes 15 commercially manufactured RSDs 10 removed from cases and clamped between suitably selected copper plates 9. Some efforts were taken to

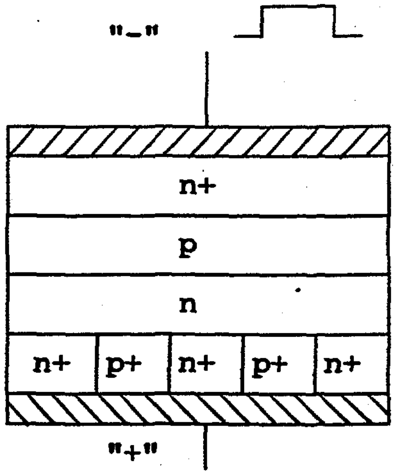
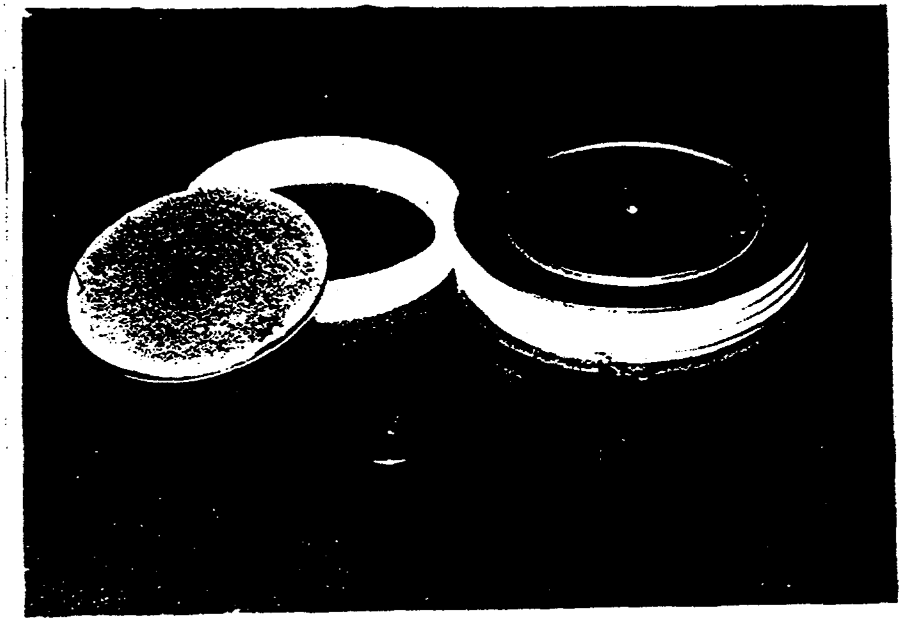


Fig.4.1. Scheme of RSD semiconductor structure.



(50cm^2)

Fig.4.2. Photography of RSD with 80mm diameter. Left -RSD without the case, right - RSD in the case.

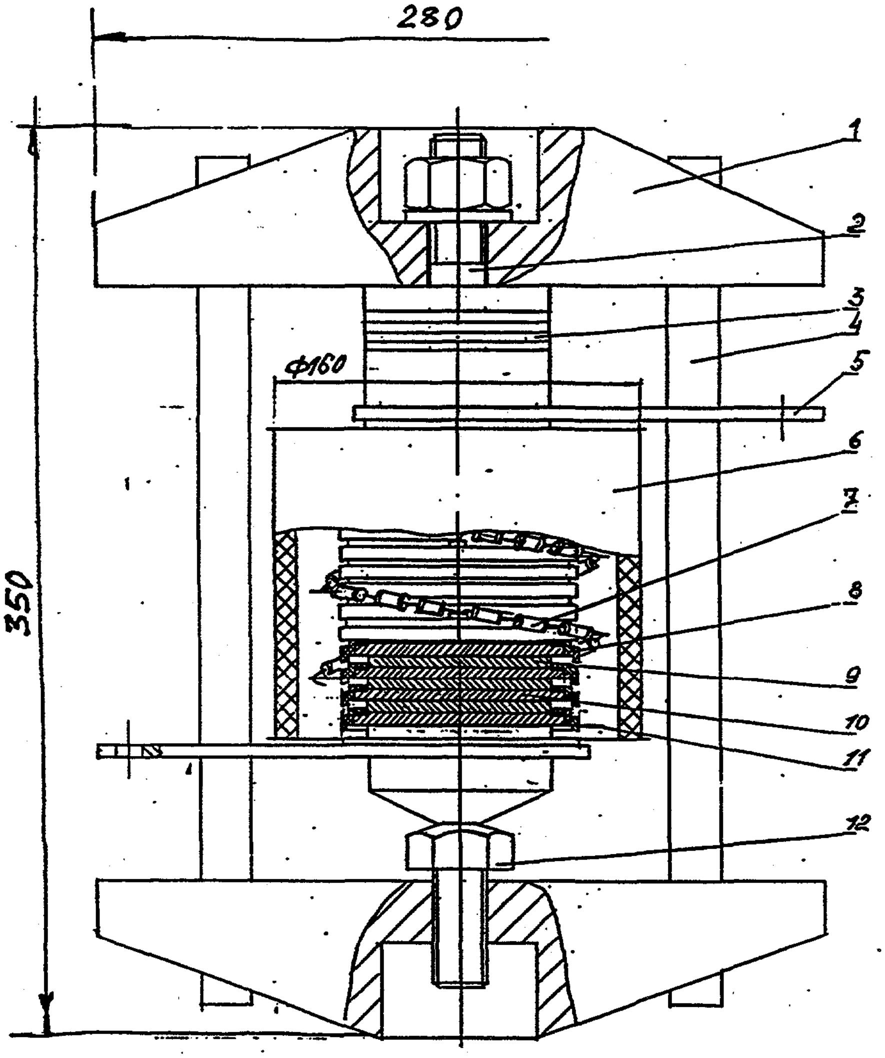


Fig.4.3. Construction of RSD-based switch КРД-25.

ensure good contact between the plates and RSDs, which is very important to achieve the pack operation life as required. Fluoroplastic insulators 8 are used to prevent a potential breakdown occurring in between any unit and the case 5 which is formed in this prototype by four larger-diameter tiristor cases.This houses an ohmic divider 7 to level off the RSD potentials. Switching high currents successfully requires a substantial force to clamp the units of the columns together. This force is achieved by specifically designed tie rods 1. The general view of КРД-25 switch is shown in fig.4.4.

4.2. STUDY OF ULTIMATE SWITCHED CURRENTS.

According to the existing phenomenology of monopulse RSD operation [23], peak pulsed current transmitted by RSD before its thermal breakdown is formulated as follows:

$$Imax<K*S/f*tp^{1/3} ,$$

where S is the RSD area in cm^2,

tp - current pulse length (over the base) in seconds,

f - form factor of the current curve ranging from 1 for square pulses to 0.66 for half-period,

K - coefficient, related to RSD structural parameters.

K value is inversely proportional to the RSD base thickness which determines its operating voltage. For 2kV operating voltage it is:

$$K=210\ A*s^{1/3}/\ cm^2 .$$

The Russian industry has run the production of RSD having maximum area $50cm^2$ (and $75cm^2$ RSD design is on the way to production status). It would be easy to figure out that switched current peak for these RSD will not exceed 200kA (and 300kA for $75cm^2$ RSD) when half-period current pulse is 500µs long.

Note, that there are some limitations on the use of the above formula. It is pointed in [23] that the phenomenological theory has been developed for current pulse length shorter than 100µs. The pulse length being increased to 500µs may modify the expression for peak current case due to the effects not considered by this work (such as thermal diffusion, etc.). Therefore, solution of the application problem for RSD as pulsed power system switches in glass lasers requires investigations of the ultimate switched current capabilities of RSD having the largest operating area.

We have conducted these studies using techniques like those described in [21]. The testbench is schematically shown in fig.4.5. Single RSD units having $50cm^2$ operating area were tested by transmitting the current therethrough, with its amplitude varied between 100-300kA by respective variations of the capacitor bank charge voltage, while the current pulse length remained unchanged.

A vacuum switch was used to isolate the RSD pumping and switching events in time, moreover there had been no voltage across RSD before the switch operated. This was done with the purpose to make the pumping current pulse height and length unchangeable with the variations of the charge voltage

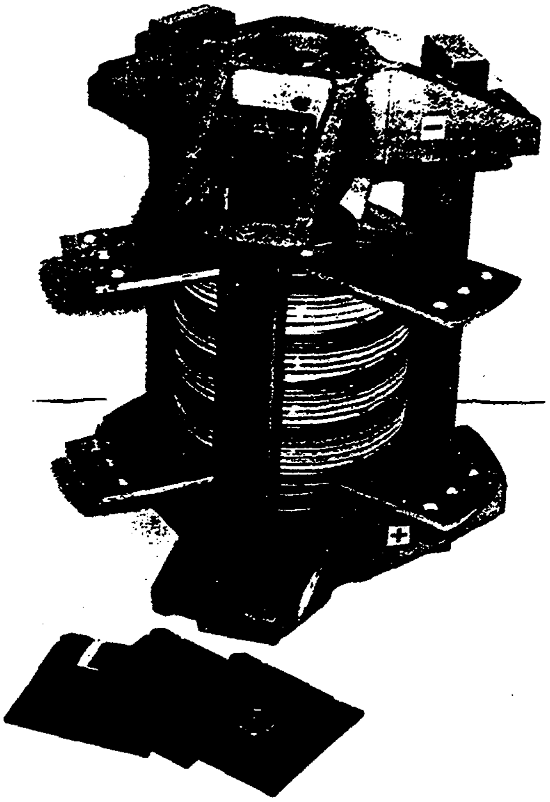


Fig.4.4. Photography of RSD-based switch КРД-25.

across the basic switched capacitance (C2), and also to avoid heating the RSD structure due to leak currents in charging, so that identical initial conditions would be provided for RSD heating by the current pulse.

As many as 17 RSDs of 50cm^2 area manufactured by standard process techniques have been tested. Measurements were made for switched current and voltage drop across RSD. The typical oscilloscope patterns are given in fig.4.6.

RSD overheating which may result in the RSD thermal breakdown was indicated by the limited voltage drop across RSD and specific dynamic voltage rise (see fig.4.6). For every RSD tested, the voltage rise had not been observed before the current through RSD reached 220-230kA, moreover 4 units had this rise not observed until 260kA (further current increases were limited by the testbench capabilities); and only two units were broken down at current ranging within 230-250kA. Shot intervals were 15 minutes or longer.

It may be thus concluded that for RSD of 50cm area switching currents as high as 200kA (of about 500μs pulse length at the level 0.1Imax), there will be no overheating that may result in the device failure. But currents 250kA and higher having the same pulse length are capable of causing the RSD thermal breakdown. Note, that the observation has insignificant difference from the theory.

The test technique used also allows to evaluate the ultimate current for a pack of series connected RSD. We expected the ultimate current for this case to be somewhat lower than for single RSD case due to different heating conditions between the central and extreme RSDs of the pack.

To reduce the risk of damage for the whole pack, special cautions were used. Initially, we tested a pack of three RSDs with its design absolutely equivalent to КРД-25 switch. The units (RSD) making up to pack were previously tested each individually, these tests showing no voltage rise until 230kA. Then, the pack was tested, and again there was no voltage rise observed at currents until 230kA, that would indicate the structure overheating. Thus, there is no reduction in the maximum tolerable operating current with changing from a single RSD case over to a pack connected RSDs. This is also proved by testing the pack of 15 RSDs (КРД-25 type), where no dynamic voltage rise was observed at currents up to 230kA either.

Following these tests, we tested the above packs for their normal operation in the discharge circuit as shown by fig.4.7. These tests involved the capacitor bank operating voltage being applied to RSD, thereby simulating real operation conditions for RSD as a switch. A pack of three RSDs was rated for up to 6kV voltage, 15 RSDs for up to 30kV operating voltage. Testing involved the following circuit characteristics: for three RSDs - up to 4.8kV voltage Uo, up to 230kA current, current pulse length at 0.1Imax level - 500 μs, capacitance C1=16 000μF, RSD charge in a shot - about 70C; for 15 RSDs (КРД-25) - voltage Uo up to 25kV, operating current up to 200kA with the pulse length 500μs at the level 0.1Imax (the discharge current shape is given by the oscillogram of fig.4.8), main discharge capacitance C1=1950μF (about 50C charge through a switch per shot).

As shown by voltage drop measurements for both switches transmitting currents within the above range, these switches operate without excessive overheating of RSD structure (no voltage rise at the pulse trailing edge).

Therefore, КРД-25 type switch is suitable to switch current pulses up to 200kA high and up to 500μs long at the

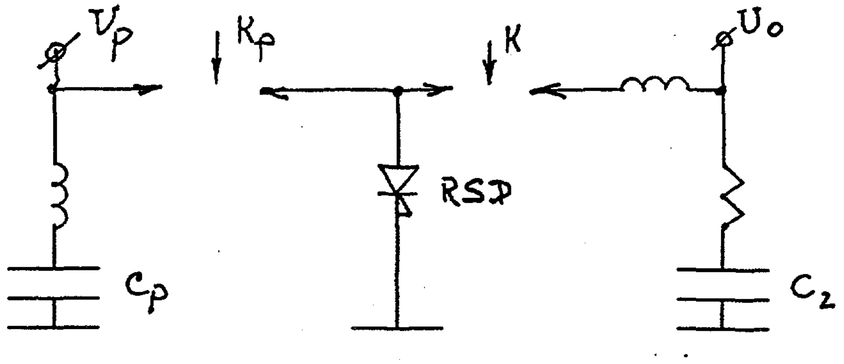


Fig.4.5. Circuit diagram of 5kV testbench.

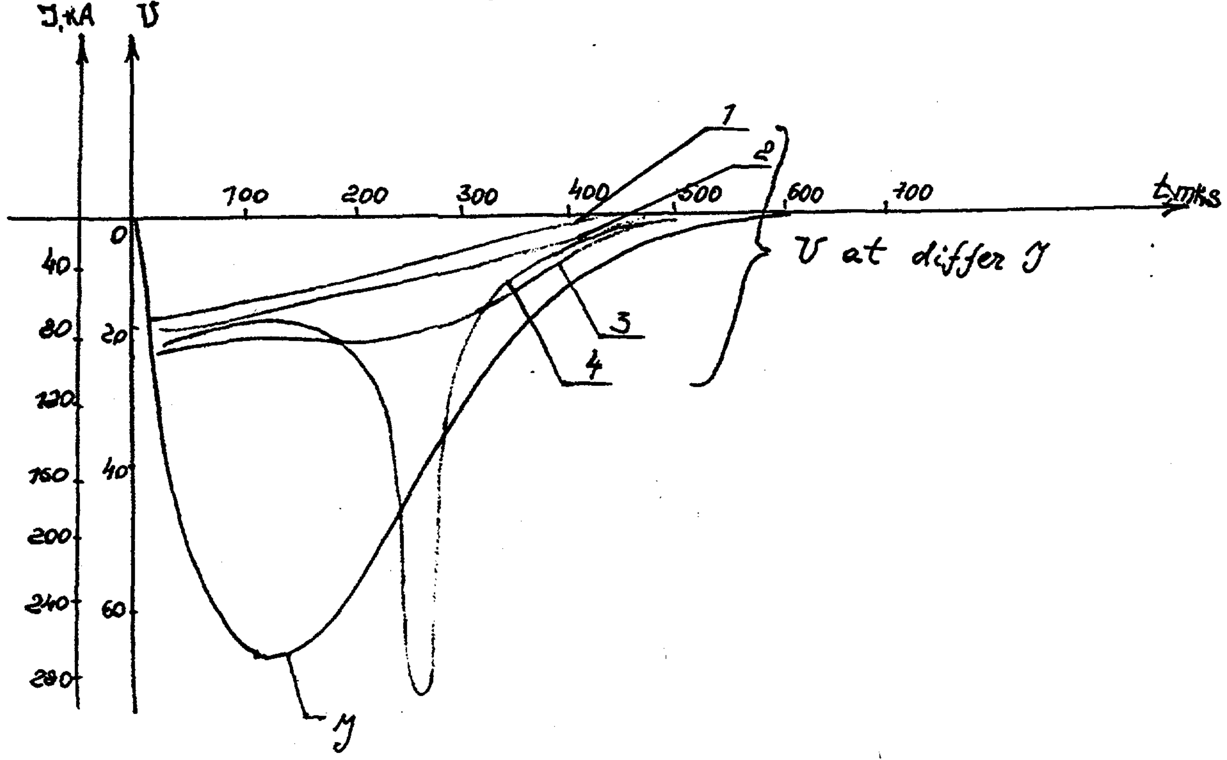


Fig.4.6. Oscillscope patterns of voltage drop on RSD and current across RSD.

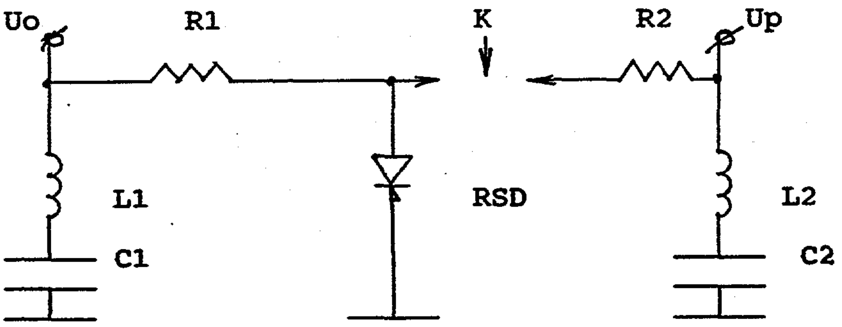


Fig.4.7. Circuit diagram of RSD-based array testing.

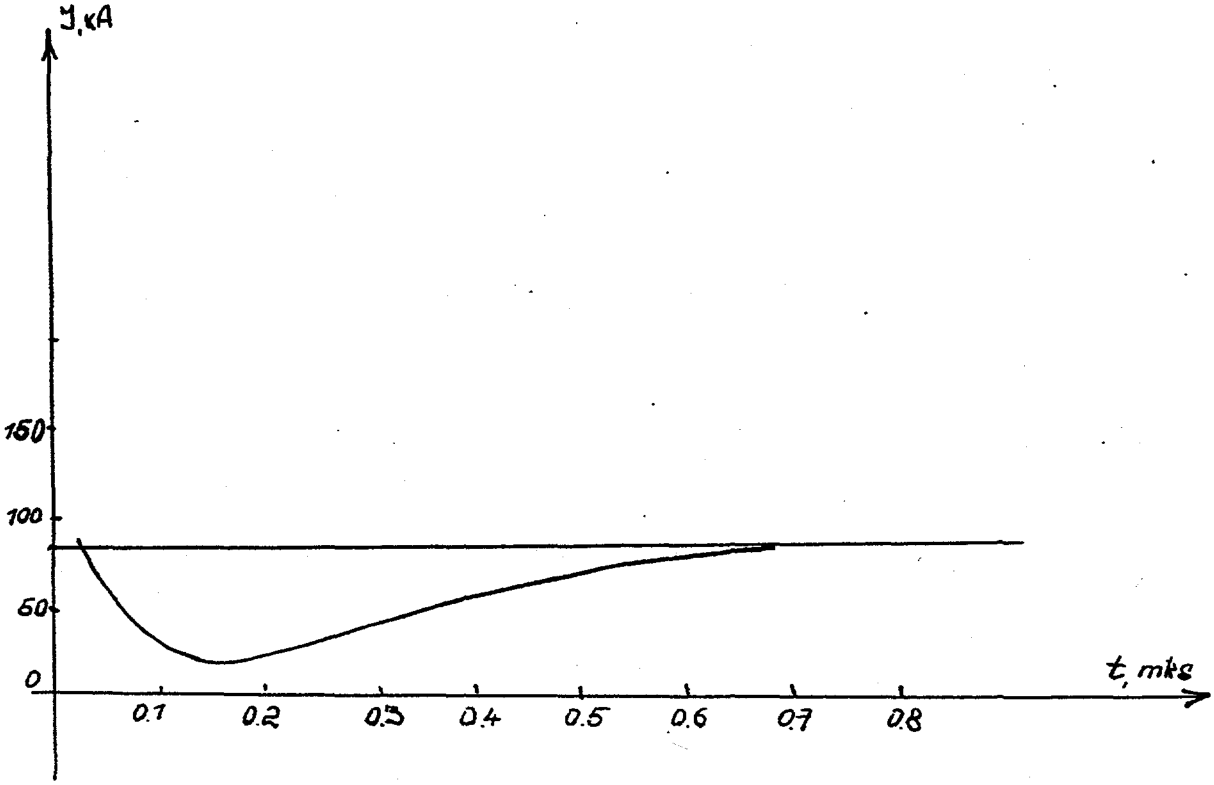


Fig.4.8. Oscilloscope pattern of the switched current on 25kV testbench (current at voltage Uo=10kV).

base level with the operating voltage up to 25kV. Should the same design use RSDs of 75cm^2 operating area, the increase of the current to 300kA may be expected for the same ultimate pulse length.

4.3. STUDY OF КРД-25 SWITCH PUMPING CIRCUIT.

As it has been noted earlier, switching of RSD occurs when a definite charge of excess carriers is injected into the base region of the RSD structure, and the main RSD-switched current will be distributed uniformly given the initiation charge at each point of the structure being significantly above some critical value. In so doing, the quasidiode switching mode for RSD is achieved, where control plasma layer exists [22] which serves as cathode emitter.

In terms of these quasidiode switching conditions, the critical charge value is to be found for the charge injected into RSD by pumping. According to [22], the critical charge Qcr is:

$$Qcr=3.4*10^{-14}\ dJ/dt,\ C$$

where J(t) is the discharge current density in the primary circuit. For RSD of 50cm^2 operating area and current rising in the primary circuit as $dI/dt=4*10^{9}$ A/s, the latter representing discharging conditions for glass lasers, we obtain the critical charge value Qcr=2.72 C.

We expect that with pumping current 2kA and 2μs risetime to peak, the injected charge (about 2mC for half-period) will be enough to pump RSD efficiently, though this point needs special experimental evidence.

Several candidate RSD pumping circuits have been considered. The basic RSD pumping circuit [21] used by many authors is given in fig.4.9. This involves the use of a saturated throttle to isolate the main discharge and pumping circuits. This makes the pumping circuit design much more simple. However, this throttle must be rated for the full operating current and operating voltage of the main circuit. Designing this throttle makes up another separate challenge.

That is why we looked at pumping circuits using no throttle. We were able to do this due to the main circuit having rather high inductance. Fig.4.10 shows a circuit having a supplementary power supply in the pumping section. Here, the K switch closing is to be followed by the RSD voltage polarity reversal, and this is when pumping current will flow through RSD. This will be possible given that:

$$Up - (Up+Ub)*Lp/Lp+Lb>=0,$$

where Up is the pumping circuit voltage,
Ub - voltage of the main discharge circuit,
Lp - pumping circuit inductance,
Lb - main discharge circuit inductance.

Using this equation, it would be easy to obtain the limiting voltage value in the pumping circuit:

$$Upmin=Ub*Lp/Lb.$$

For the pumping circuit voltage below Upmin, RSD pumping is impossible. The voltages Up and Ub have opposite polarities, therefore the switch K must withstand the voltage Uk=Up+Ub. Thus, it is clear that the K switch requirements must be made less stringent by reducing the pumping circuit inductance.

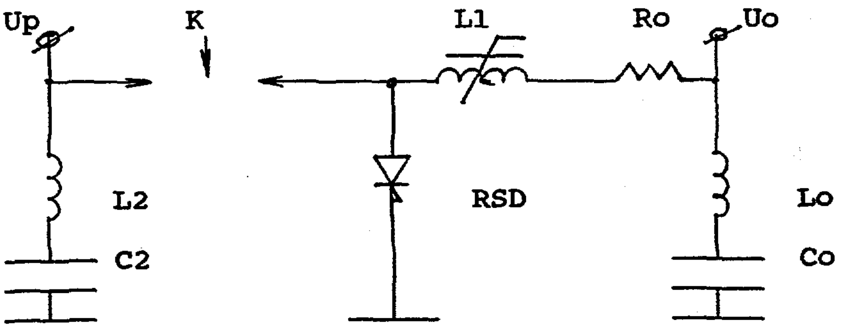


Fig.4.9.. Circuit diagram of RSD pumping with a saturated throttle.

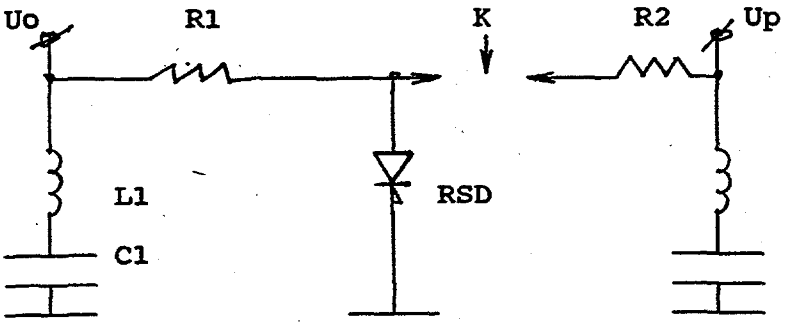


Fig.4.10. Circuit diagram of RSD pumping with a supplementary power supply in the pumping section.

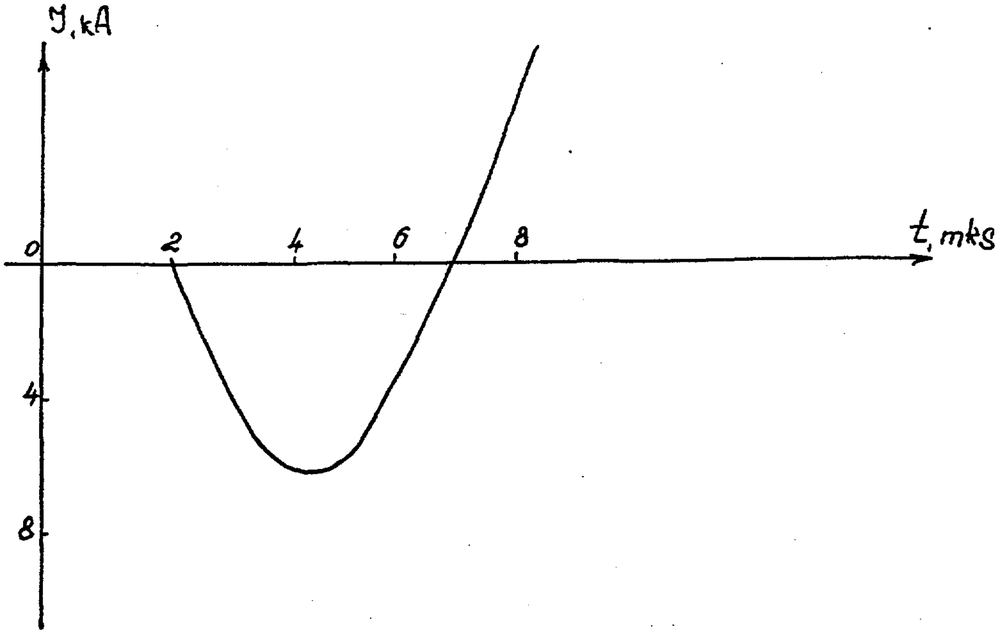


Fig.4.11. Oscillscope pattern of current across RSD at pumping circuit using a supplementary power supply in pumping section.

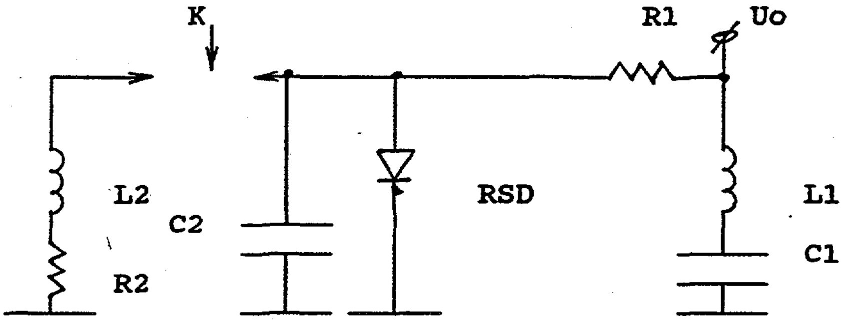


Fig.4.12. Circuit diagram of RSD pumping without a supplementary power supply in pumping section.

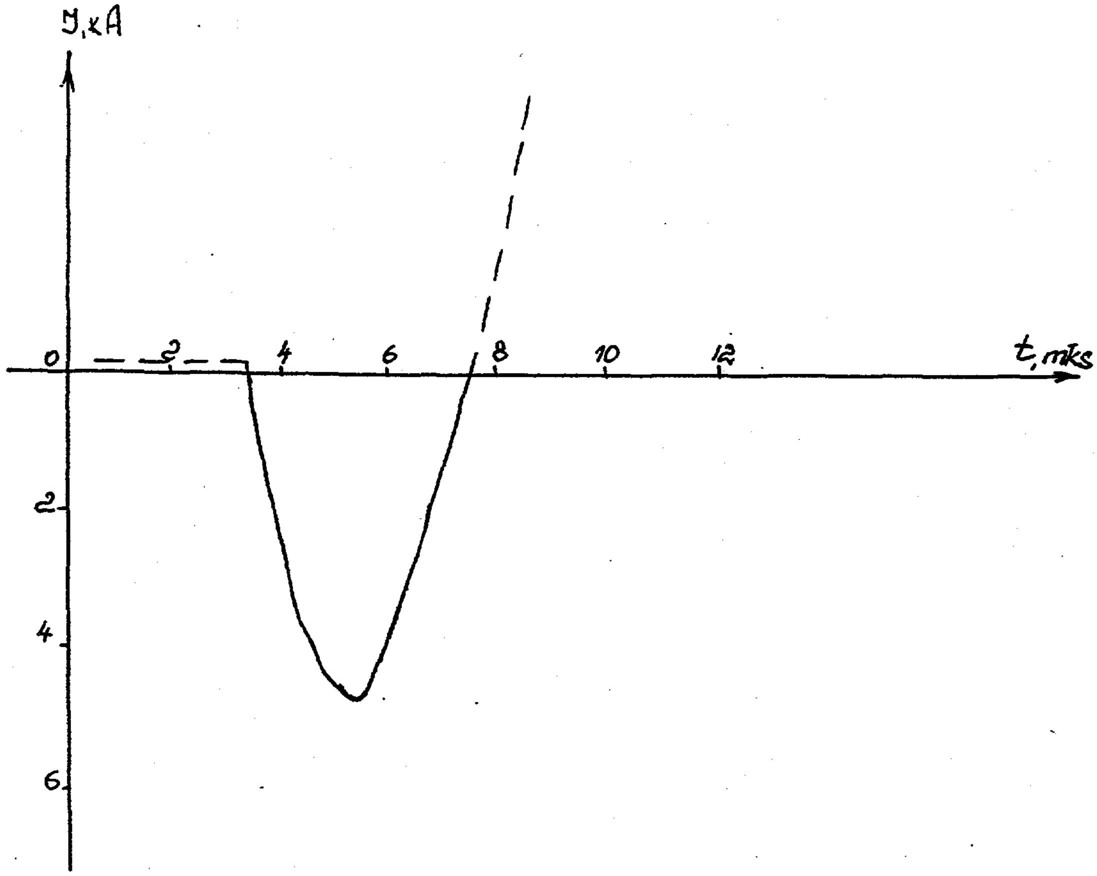


Fig.4.13. Oscilloscope pattern of current across RSD at pumping circuit without a supplementary power supply in pumping section.

For the 25kV testbench, we used the pumping circuit characterized as follows: Up=20kV, Cp=3μF, Lp - about 2.0 μH, to generate thereby the pumping current about 3kA with the pumping pulse length about 3 μs. Fig.4.11 shows a representative oscillographic pattern of RSD current at pumping and main discharge initiation.

The disadvantage of this circuit in addition to the switch high operating voltage, is that it uses a dedicated power supply for the pumping circuit. RSD can be pumped using the same power supply as for the basic circuit. The circuit design is illustrated by fig.4.12.

The capacitance C2 is charged to Ub, and it is to discharge when K switch operates, thus the second half-wave of the discharge current serves as pumping current pulse for RSD. The advantage of this circuit, together with using a single power supply and lower voltage across the pumping circuit switch (which is equal to that of the basic circuit), is that it has lower pumping capacitance. However, the disadvantage here is that there are many components in the pumping circuit connected in parallel to the basic circuit capacitors. For the 25kV testbench, we have used this circuit having the following pumping circuit characteristics:C2=0.5μF, Lp - about 3μH, and thus the pumping current through RSD had the pulse shape as shown in fig.4.13.

As become clear from comparing the oscillograms of fig.4.11 and 4.13, the circuit having an additional power supply provides a slightly larger charge to be injected into RSD through pumping, therefore this pumping circuit is what we used in most КРД-25 experiments.

We would like to note a few points not investigated by now.

1. Ultimate switched current amplitudes have not been evaluated for КРД-25 switch made of 15 RSD connected in series. This testing involves the risk of irreversible switch damage.

2. Minimum permissible values have not been determined for pumping current and charge making switching possible. The current and pumping time values we have mentioned above are predetermined as higher than minimum permissible ones, thus resulting in larger pumping circuit size and expenses. These investigations are also associated with the switch damage risk and would require additional funding.

4.4. CONCLUSIONS TO CHAPTER 4.

1. We have tested reverse switched dinistors of 50cm^2 operating area and a prototype of the switch type КРД-25 initially developed and fabricated to our specifications. This switch is a pack of 15 RSD having 50cm^2 operating area connected in series and enclosed in a single case.

2. In monopulse operation, RSD are capable of switching currents up to 250kA with about 500μs pulse length at the base level. For currents above 250kA, there occurs RSD dynamic overheating to cause the structure thermal breakdown.

3. Two RSD packs were tested under single-pulse conditions: one having three RSDs and the other - 15 RSDs (КРД-25) connected in series. As it was shown, for the given current pulse length there is no decrease in the critical switched current (before dynamic overheating occurs) from that in testing single RSD units.

4. КРД-25 switch was tested under switching conditions with the discharge circuit characteristics as follows: 25kV

operating voltage, 200kA operating current, current pulse length at 0.1Im level - 500μs. There was no indications of the structure overheating, this allowing these conditions to be regarded as suitable for КРД-25 operation.

5. A variety of candidate triggering circuits for КРД-25 switch have been tested using the discharge circuit of the 25kV testbench. Switch triggering circuits were developed having no throttle in the basic discharge circuit, but which had not been used in RSD circuitry before. A triggering circuit has been selected which provides reliable RSD switching. No optimization of the circuit has been performed for this would pose the risk of the switch damage.

6. The performance diagnostics of RSD-based switches is different from that of vacuum and spark-gap switches. The basic parameters which is determinant for RSD performance is pulsed voltage across RSD when operating current is flowing therethrough. Also, what must be established is performance criteria for RSD to check its operation under normal conditions.

7. At least two issues should be investigated to decide upon the applicability of КРД-25 type switch in the NIF capacitor bank under development: The switch operational capability in a circuit having actual flashlamp load and actual pulsed overvoltages at transients, because semiconductor switches are very sensitive to voltage overloading; and simultaneous triggering of a large number of these switches in view of the triggering circuitry being unique. These investigations go beyond the scope of this work.

5. CONCLUSIONS.

The following conclusions can be made from the studies carried out:

1. Currently, there exist no switch designs fully satisfying the LLNL requirements.

2. As shown by the review of publications on gas spark-gap switches and the integrated data on the performance of spark-gap switches used by ISKRA-5 facility. this switch type can not be recommended for use by the NIF pulsed power system. Spark-gap switches are featured by heavy electrode erosion which degrades the switch performance stability. Measures against erosion are not efficient enough.

3. Large experience in ignitron operation techniques existing in LLNL would make this switch type most suitable for use. However, there is no ignitron type among the Russian developments having its characteristics suitable for NIF applications.

4. Possible candidates for use in the NIF capacitor bank are sealed-off vacuum switches. Many research teams are now studying the performance of TVS-40 type switches having the highest switched current and charge.

5. We have tested sealed-off triggered vacuum switches types TVS-40, TVS-40m and TVS-49 to show their stability under the following operating conditions: voltage up to 20kV, current up to 150kA, and current pulse length 500μs.

To provide reliable operation of the NIF pulsed power system modules at the voltage about 25kV, it would be assembly of two series connected switches. Special testing should be carried out to prove the reliable operation of this assembly.

6. Reverse switched dinistors (RSD) are currently most powerful semiconductor (silicon) devices showing promise in addressing many high pulsed power problems. Unlike tiristors where switching is achieved by creating a narrow plasma channel near the control electrode, RSD has switching performed by generating a control plasma layer over the entire anode surface, thus significantly improving the switching performance of RSD as compared with tiristors having the same operating area.

7. We have tested for the first time reverse switched dinistors of 50cm^2 operating area in a single-pulse mode. They were tested for capability of switching currents 200-300kA high with 500μs pulse length. The test results have proved that RSD can operate under these conditions. It has been shown, that currents about 250kA make RSD operate under near dynamic overheating conditions, and this is what may result in the structure thermal breakdown.

8. For the first time the operation testing was performed for КРД-25 switch including 15 series connected RSD of 50cm^2 operating area. The tests were conducted for 25kV voltage, 200kA current and 500μs pulse length. The test assembly showed no indications of RSD dynamic overheating, this demonstrating the capabilities of these switches. We expect that with similar switch design incorporating 75cm^2 RSDs the operating current can be increased to 300kA.

9. However, positive the test results for vacuum and RSD-based semiconductor switches, they are not sufficient to make a final choice of the switches for the NIF pulsed power system. This requires switch testing in bunch operation involving real flashlamp load.

REFERENCES.

1. "Technique of high pulse currents and magnetic fields", editor Komelkov V.S., Moscow, Energiya, 1972.

2. Kiselev Yu.V., Vasiliev V.P., Cherepanov V.P. "Spark gap switches", Moscow, Sovetskoe radio, 1979.

3.Gundersen M.A. "Gas-phase pulsed power switches"/ IEEE Trans.Plasma Sci., 1991, v.19, N6, pp.1123-1131.

4. Warren F.T., Bhasavanich D., Curry J., Hammon H.G., Hitchcock S., Naff J.T. "Development and miniaturization of high-current transfer switches and high-current pulse shaping inductors" /8th Inter.Pulsed Power Conf.- San Diego, June 1991, p.p.63-67.

5. Bezuglov V.G.,Borisov R.K., Galakhov I.V. et al./ Pribori i tekhnika eksperimenta, 6, 1981, p.105-108.

6. Frank K., Almen O., Christiansen J. et al."Pseudospark switches for high repetition rates and high current applications" /8th Inter.Pulsed Power Conf.- San

Diego, June 1991, pp.472-477.

7. Khromoi Yu.D., Andropova V.P., Antokhin R.G. et al. Pribori i tekhnika eksperimenta, 2, 1978, p.195-1987.

8. Spikings C.R., Oxley C.M., Beacham J.R. "High current evaluation of the new size E ignitrons with a ringing waveform" /8th Inter.Pulsed Power Conf.- San Diego, June 1991, p.p.495-499.

9. Lafferty J.M. //Proc.of IEEE, 1966, v.54, N1, pp.23-32.

10. Dashuk P.N., Zaienc S.L., Kichaeva G.S. et al./ Izv.AN USSR, Energetica i transport, 1977,N6, p.32-42.

11. Pavlovskii A.I., Smirnov E.N., Latich V.Ia. et al. Pribori i tekhnika eksperimenta, 1, 1974, p.122-126.

12."Vacuum arc. Theory and application", editor Lafferty J.M., Moscow, Mir, 1982.

13. Dethlefsen R., Sidorov V.A., Vozdvijenskii V.A. /8th Inter.Pulsed Power Conf.- San Diego, June 1991, p.p.511-514.

14. Alferov D.F., Vozdvijenskii V.A., Sibiriak I.O., Sidorov V.A./ Pribori i tekhnika eksperimenta, 5, 1990, p.139-142.

15. Thelen R.F.,Price J.N. "Power electronics in the 9 Megajoule EM range gun system" /8th Inter.Pulsed Power Conf.San Diego, June 1991, pp.146-149.

16. Nowee J.,Kaanders M. "The counter-pulse semiconductor opening switch of the Kapitza facility" /8th Inter.Pulsed Power Conf.- San Diego, June 1991, pp.213-216.

17. Zotkin R.P., Kapitonov V.A., Koidan V.S. et al./ VANT, 1, 1990, p.50-54.

18. Grekhov I.V./ Elektrotechnika, 3, 1984, p.21-25.

19. Bogdanov B.S., Borisov B.A., Golochapov V.I., Lavrinovich V.A./ Pribori i tekhnika eksperimenta, 2, 1992, p.163-166.

20. Emelin P.Yu., Rutberg F.G., Sergeev V.D., Fridman B.E. in "Electrical power pulse generators", Leningrad, VNIIelektromach, 1990, p.106-116.

21. Grekhov I.V., Korotkov S.V,, Iakovchuk N.S. / Elektrotechnika, 3, 1986, p.44-46.

22. Tuchkevich V.M., Grekhov I.V. " New principals of high power switching by semiconductor devices", Leningrad, Nauka, 1988.

23. Gorbatiuk A.V., Panaiotti I.E./ GTF, 60, 5, 1990,p.129-135.