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**Final Report Task Order Number B239641 between The
Regents of The University of California and Institute of
Experimental Physics Task 1: Conceptual Design**

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RUSSIAN FEDERAL NUCLEAR CENTER - VNIIEF
INSTITUTE OF EXPERIMENTAL PHYSICS

FINAL REPORT

TASK ORDER NUMBER B239641

between

THE REGENTS OF THE UNIVERSITY OF CALIFORNIA

and

INSTITUTE OF EXPERIMENTAL PHYSICS

Task 1: Conceptual Design

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1. HIGH POWER LASERS AND PUMPING SYSTEMS FOR LASER IGNITION FACILITIES: CURRENT DEVELOPMENT STATUS.

The primary objective of the current laser fusion (LF) research efforts is to achieve the DT-mixture fusion ignition, i.e. the conditions where the thermonuclear reaction energy output will be in excess of the energy input to DT fuel. As shown by the calculations and irradiative UGT experiments, the threshold ignition energy should be about 1MJ [1].

The exact lower energy level is uncertain and depends on the target design and quality, illumination symmetry and pulse shape.

Many world's leading countries such as USA, UK, Japan, France, Russia are running LF research. The US Livermore Lawrence National Laboratory has designed and developed the world's most powerful Nd-glass laser system NOVA of 70kJ energy output at wavelength $\lambda=1.06\mu\text{m}$ and 30kJ energy output at wavelength $\lambda=0.35\mu\text{m}$. There is a Nd laser facility GEKKO-12 in Japan having 10kJ output energy at $\lambda=0.53\mu\text{m}$ and 7kJ at $\lambda=0.35\mu\text{m}$. In Russia, the largest laser facilities have been developed at VNIIEF, such as ISKRA-5 ($E=30\text{kJ}$, $P=120\text{TW}$, $\lambda=1.315\mu\text{m}$) and ISKRA-4 ($E=1\text{kJ}$, $P=3\text{TW}$, $\lambda=0.66\mu\text{m}$). These facilities have their working media pumped by flashlamps or electric discharge sources with power supply from high-power capacitor banks.

Currently, design concepts are underway for a new generation of facilities with laser energy output 1 or 2MJ.

It should be noted, that to develop the facility such as these is a challenging science and technology problem requiring accomplishment of a wide range of research, design and development, and installation efforts.

In view of the potential sophistication and expensiveness of laser ignition facilities, it would be expedient that before any preferential course of activities is taken, the candidate design approaches be considered both for the facility as a whole, and for its components. This, we believe, would be reasonable to be done at the design study stage considering the recent decade's advances in high-power laser development.

It is over this decade, that new high-performance laser devices and new laser designs for ignition applications have been developed. In term of this, of special interest is the collaborative work of VNIIEF and LLNL under Task Order B239720 addressing the feasibility of 10MJ laser system build around iodine photodissociation laser pumped by HE shock front light. Basically, the concept has been suggested relying on the experimental efforts to develop the monopulse version of this laser, as carried out at VNIIEF in 1983 through 1987. These experiments generated 6kJ of single beam energy output for nanosecond pulse durations [2], though the output achieved is not the ultimate level, for the generation was by far not optimized in the mixture composition, pumping conditions and input signal. Therefore, it would be quite reasonable to expect that, provided these conditions are optimized the energy output may be as high as 20kJ in a single beam. This makes it absolutely realistic the development of a multibeam laser system of 1MJ output energy.

The attractiveness of this concept lies in the pumping system having simple design and low cost, inexpensive and easy to operate capacitive energy storage system, reusability of the most important equipment such as target chamber and diagnostics package. The disadvantage of this laser design is

its single-shot operation. However, the ignition facility design using explosion-driven laser may be of interest as applied to demonstration LF experiments.

The same single-shot disadvantage also features another type of high-power laser devices using nuclear explosion radiation for pumping purposes. Thus, the research results are given in [3,4] for single-pass conic excimer traveling-wave laser pumped by nuclear explosion gammas. The following lasing characteristics have been observed-700J in a

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beam, 1.4×10^{10} W power and 3% of energy deposition efficiency. However, despite the existing capabilities to improve the lasing parameters, the applicability of these lasers in LF research is unlikely to be much promising due to both insufficient development status of this laser design and potential banning of underground nuclear testing in the future.

Worth mentioning is the next new laser type, such as nuclear-pumped lasers many world's leading research centers have been focused on - VNIIEF and VNIITF in Russia, LLNL, Sandia and NASA Langley Research Center in the US, etc. These lasers use pulsed nuclear reactors as pumping system. The comprehensive discussions of the issues on NPL topics took place at the Conference "PHYSICS OF NUCLEAR INDUCED PLASMAS AND PROBLEMS OF NUCLEAR PUMPED LASERS" held in Obninsk, 1992. The presentations were given to suggest various types of nuclear-to-laser energy conversion systems. The experimental data were reported on lasing for various active media. The available devices of this kind represent laboratory energy laser models to be used to study experimentally and validate the nuclear pumping concepts [5]. As shown by the presentations, there is a great deal of problems and limitations across the development path of high-power nuclear-pumped lasers. Therefore, it seems questionable that these can be used in LF research facilities.

Thus, it can be concluded from this brief survey of high-power laser developments involving various pumping techniques, that

- among new laser designs developed over the recent 10 years, it is the iodine photodissociation laser with its complete development and output characteristics that may be applicable in the ignition facility,

- flashlamp-excited Nd laser has an advantage over other designs due to its higher laser energy characteristics, reusability and components availability. Therefore, quite justified is the preference given to this by LLNL as to the use in the ignition facility.

We have examined the pulsed power system requirements for the National Ignition Facility (NIF) based on Nd laser, as specified in the Task Order B239641. According to these, the pulsed power system is to be responsible for supplying electric power to pulsed xenon lamps making up the lamp amplifiers pumping system. The power conditioning has the following general characteristics:

- total energy to lamps -300MJ;
- number of lamps -10700;
- charging time -60s;
- discharging time -380 μ s;
- shot rate -1/30min.

Note, that this system has energy capacity 10 times that of similar systems used by the available LF physics facilities, representing capacitive-type energy storage (CES).

Therefore, it would be very useful and practical that the design study stage should involve considerations of

energy storage designs using alternative physical concepts. This is quite essential, because the recent decade saw notable advances in various pulsed power areas.

Basically, the following sources can be useful to generate high pulsed powers:

- chemical (batteries);
- mechanical energy storage;
- inductive energy storage;
- HE energy storage - explosive magnetic generators (EMG)

- capacitive energy storage.

The choice of any energy storage depends on the given experimental requirements. The basic specifications for various energy storage systems are given in Table 1.1.

The requirement for as high-rate energy input to lamps

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as 10s, results in reducing the range of energy storage choice for lamp-pumped lasers to the three types:

- explosive-magnetic generators;
- inductive storage;
- capacitive storage.

EMG applications in high-power laser systems are subject to the following limitations:

- single-shot operation, and hence, difficulty to achieve the desired experiments rate;
- explosive storage type produces undesirable shaking of optical components, while its removal results in large energy transmission losses. These are the major reasons making EMG [6] undesirable for use as pulsed power system of laser ignition facilities, despite their availability and inexpensiveness.

To develop a high-power inductive energy storage with

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10s energy input to the load has been until now a difficult engineering problem. This is primarily due to the necessity to create fast current opening switches which operation involves overvoltages, arcing and considerable energy losses, etc. The inductive storage circuit switching is difficult due to stringent requirements on fast transients. The circuit opening time should be 1/10 to 1/100 as much as for the discharge to the load, otherwise a considerable portion of the stored energy may be lost in the switch [7,8]. Considering that the opening-switched currents can be thus made as high as hundreds or thousands kiloamperes, and the switch voltage - tens kilovolts [7,10], one may realize how difficult it is to provide effective inductive load switching. However, most recently there have been certain advances in addressing this issue.

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The tiristor devices have been developed having 10 or

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10s switching time. They can efficiently operate at currents 10-20kA and voltage about 10kV. Their applicability in large inductive loads is due to their high performance in bunch operation [14]. By using additional components to match currents and voltages, reliable operation of the switch as a whole can be achieved.

Considerable advance has been also made in the development of switches having movable contacts surrounded by high vacuum or SF6 media and actuated by a special drive

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[10,11,12]. The switch fast response achieved is 10s. These are frequently used as first-stage switches with the current further to be transferred to the fast closing switches of

Basic characteristics of energy storages. Table 1.1.

Energy storage type	Energy per volume unit	Maximum power	Power per volume unit	Time of energy delivery
	MJ/m ³	W	W/m ³	s
Chemical	200-500	⁶ 10 - ⁷ 10	⁷ 10	1-10
Mechanical	100	⁷ 10 - ⁸ 10	⁸ 10	0.1-10
Inductive	10-40	⁸ 10 - ⁹ 10	⁹ 10	⁻³ 10
Explosive magnetic generator	⁴ 10	¹¹ 10	-	⁻⁵ 10 ⁻⁶ -10
Capacitive	0.1-0.5	¹² 10 ¹³ -10	¹¹ 10	⁻⁴ 10 ⁻⁸ -10

the following parallel stages.

Very attractive for inductive load switching circuits are magnetically controlled spark gap switches with intercrossing electric and magnetic fields. These switches have their operation principle based on the spark gap conductivity changing as the magnetic field is applied to bend the path of the charged particles' motion induced by the electric field.

Artatrone [14] is what may serve as an example of magnetically controlled switch. This incorporates cylindrical coaxial anode and cathode with vacuum gap therebetween as large as about the electron free length for the conditions available. The applied voltage induces radial electric field in between the anode and the cathode. A suitable inductor is to produce longitudinal magnetic field having induction B . For $B=0$ and $E = 0$, few electrons move through the gap radially from the cathode to the anode, with no collisions, no discharge and circuit opened. When the inductor is on and the induction B produced, the electrons begin drifting through the crossed electric and magnetic fields. The electric path acquires considerable tangential contribution to become longer than free length. As they collide with and ionize the gap neutral gas molecules, the electrons produce a glow discharge to close the circuit. With the inductor off, the discharge collapses and thus the circuit opens. The current range to be off using this switch: 100-500kA,

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switching time 10s. The use of magnetically controlled switches is very promising, though large efforts are still to be made to optimize the performance and manage batch production of these devices.

Considerable success has been achieved in overconductor switch development [15]. A representative overconductor switch design includes a thin strip of overconducting material, such as NbTi. The corrugated strip is compactly packed and wrapped around by the control winding.

As the temperature decreases, the strip goes into superconducting state to become a shorted jumper. When a current pulse is applied to the control winding (i.e. by an ancillary capacitor) and magnetic induction produced in the strip, which is higher than critical, then the strip change over to its normal, or nonsuperconducting state, its resistance increasing stepwise and resulting in the sought current redistribution in the inductive storage.

These switches are featured by rather fast response

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which is 10-10s [10]. The switches like these are undergoing the developmental experimentation phase. It would be practical to use them in the superconducting inductive storage circuits with the switching unit placed into the same cryostat as the inductive storage.

Very encouraging results have been obtained during the development works on explosive-type switches with the circuit opening by rapid rupture of the current-carrying jumper [13]. This switch is designed as a tube serving as jumper. The tube encloses an HE charge surrounded by paraffin layer. On the outside, the tube is adjoined by a set of annular spacers with metal annular knives embedded therein. The electric detonator operation produces the detonation wave inside the tube, which travels along the axis and outwards radially, and breaks the tube, thereby opening the current circuit. It is spacers that make the tube breakdown produce series connected gaps the paraffin decomposition products will be streaming to, thus providing efficient arc quenching. These switch

types are capable of opening currents as high as 10A in 10s.

The major disadvantage of explosive opening switches is their single-shot use, for each shot is to be followed by switch replacement.

However, it can be stated that this design is undoubtedly reliable and can be used in the development of high-power energy storage systems.

During the recent decade the keys to inductive storage charging problems have been found. If the prime electric power is generated by ac generator or mains supplied, this requires the use of transformer-rectifier system. Independent power supply of inductive storage uses chemical sources and dc generators (chemical, unipolar, magneto-gasdynamics, etc.).

The choice of any charging device type depends on the applications [16,17].

The methodology has been developed to estimate the engineering and economic qualities of the facilities using inductive storage devices. These facilities involving inductive storage must be developed in terms of the systems approach, i.e. considering performance and characteristics for not only inductive storage devices, but also their associated components of the prime power supply, cooling system, switches and others. Otherwise, there would be a risk to come to irrational engineering designs [18].

Although the energy stored by the state-of-the-art inductive storage devices is as high as 900MJ [19], and the available switches have considerably fast response, while the facility may be less expensive than other storage types, the inductive storage devices have not yet found applications in LF facilities. This is due to the following considerations:

- ultimate carefulness in the load selection and constancy requirements;
- certain researches' conservatism;
- lack of experience in operating these devices (these size and scale).

However, it should be emphasized that inductive storage devices may be found useful to design power supplies for future LF facilities to operate in stationary conditions.

To summarize the development status of alternative designs of high-power energy storage, we can state that to date considerable advances have been made in designing inductive energy storage devices for modern CF systems, with

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900MJ output energy, 10 opening switch response,
4 5
switched currents 10 to 10A.

However, currently their use as power supplies for laser ignition facilities shows no promise.

Therefore the LLNL decision to use the capacitive energy storage to pump lasers of the ignition facility appears appropriate and, we believe, quite reasonable.

2. DESIGN PHILOSOPHIES OF PULSED POWER SYSTEMS FOR LF RESEARCH FACILITIES.

Pulsed power systems (PPS) have been commonly used for power conditioning of laser pumping sources in LF facilities and to date is no other alternative than this. This has been shown by the pulsed studies and the experience in developing large laser systems in different countries.

When PPS are designed and developed the critical aspects to be considered then include: performance, costs, and safe and reliable operation. The choice of optimum PPS

design provides for these interdependent and contradictory requirements being reasonably satisfied.

PPS reliable operation largely contributes to the good performance of the facility as a whole. Therefore, the major emphasis throughout the development phases is the reliability of large pulsed power systems.

Let us consider the design philosophies of the two PPSs similar in their outputs as used by the most powerful laser facilities NOVA in the USA and ISKRA-5 in Russia.

2.1. High-power PPS design concept.

Generally, the PPSs of LF facilities are designed as shown by the schematic of fig.2.1. Consider the basic PPS subsystems and their interaction algorithm.

The capacitor bank (CB) is intended for electric energy storage using capacitors. The charging system (CS) is used to charge the capacitors to a definite voltage. The switching system (SS) is designed to isolate the load (L) and CB during charging or connect the load to the capacitors during discharging. The energy is transmitted from the CB to the load by the switching units and transmission cable lines (TL). To provide the CB safe and reliable operation, the control, lockout and warning system (CLW) is used. The diagnostic package (DP) is responsible for monitoring the switching, power line and load performance during the discharging. The switches are operated by the triggering system (TS).

Thus, it is the operation principle for the PPSs used by the existing laser facilities, and Table 2.1 below summarizes their performance data.

Most LF facilities are Nd-glass designs, and it is but ISKRA-4, ISKRA-5 and ASTERIX-4 that have been built around iodine lasers and are almost by a factor of 15 different in laser pumping time from the neodymium systems.

One can see from the comparison of the performance data, that development of the pulsed power system for ISKRA-5 has been as much a challenge as that of the PPS for Nd facilities. Therefore, the background in PPS design, installation and operation for iodine laser pumping applications may help pick the design approach to pulsed power systems for advanced laser systems such as ignition facilities.

2.2. Capacitor bank design.

Capacitor banks have modular design. Each module includes a definite number of capacitors, a triggered switch, a pulse - forming network (inductance) and a load (flashlamp). The CB modules also incorporate high-voltage switching devices (relays) which provide, on commands from the control system, either connection of the CB modules to the charging system or removal of an electric charge therefrom and further short-circuiting of the capacitors.

NOVA facility has 110 such modules, and ISKRA-5 - 665.

Their modules are significantly different in the capacitor discharge time: for NOVA, the discharge time is 500 μ s, and for ISKRA-5 - 35 μ s.

This difference has required, that the NOVA discharging circuit incorporate a suitable pulse-forming inductance to increase the discharge time, and for ISKRA-5, that special features be used to reduce the discharging circuit inductance (such as low-inductance capacitors and switches, cables connected in parallel to transmit the stored energy from the

Fig.2.1. The schematic diagram of PPS.

PPS parameters of LF facilities.

Table 2.1

Facility	Store energy MJ	Operation voltage kV	Discharge time μs	Number of light sources	Number of switches	Switch type
NOVETTA USA	11	20	500	884	50	ignitron
SHIVA US	25	20	500	1212	69	ignitron
NOVA USA	60	20	500	1827	234	ignitron
GEKKO-XII Japan	21	25	300	2000	88	ignitron
DELFIN Russia	10	5	600	700	30	ignitron
ASTERIX-4 Germany	1,3	40	2,5-5	-	-	-
ISKRA-4 Russia	7,5	50	35	144	72	high pressure spark gap
ISKRA-5 Russia	67	50	10-35	1099	665	high pressure spark gap

capacitors to the load, etc.).

In both cases the pumping time for lasers has been selected on the basis of inverted population buildup by the laser medium. For Nd-lasers within 300-500 μ s at flashlamp temperature $T=10000K$, and for iodine machines - 10-30 μ s with $T = 30000K$.

One of the major problems with the development of large pulsed power systems is increased capacity of the capacitors and reliable operation of the capacitor bank during a specified service time (i.e. number of shots required).

Clearly, most capacitor types have comparatively low³ specific stored energy, which is 0,1MJ/m³, this being the major disadvantage of PPS as compared with other energy storage types. The ways to increase the specific energy are well understood and involve the use of advanced polymeric film materials featured by higher dielectric strength and good capacitivity. There have been good achievements in developing capacitors using a combination of film-paper and film insulation, the film being polyethyleneterephthalate with specific liquid infiltration.

Currently, by using paper-film and film insulations one can make capacitors having high specific energy density,

³0,5MJ/m³. Great advances in this area have been, made by US scientists who have designed for SHIVA and NOVA facilities a family of capacitors of 14.5, 29 and 52 μ F rated capacities.

The capacitors offer a unique combination of high specific stored energy density, high reliability and long⁶ operation life (as many as 10 shots).

The most recent capacitor modification has been operated high-duty conditions, and thus the number of shots⁶ has decreased, though it is still rather high, 0,3*10 shots.

Thus, the approach taken by the US colleagues to designing large PPS, which is based on reduced number of PPS components and their improved reliability, has been consistently pursued in any development stage.

It should be noted, that there are different capacitor ratings used by NOVA, which include those available from other programs and specifically developed ones ($C = 52 \mu$ F), all being optimized as required by LF applications. The use of "older" capacitors merely results from economic considerations.

The whole of the NOVA capacitor bank is broken into capacitor assemblies having 18, 25, 37.5 and 50 kJ stored energy. The most numerous are high-energy assemblies 37.5 kJ located in the final stages. The further increase in the assembly stored energy is hardly desirable because of high ignition risk following the breakdown of one out of the parallelly connected capacitors included in the assembly.

It is also worth noting, that as the capacitors were developed and improved the cost of their specific stored energy was going down (from 200 to 60-120 cent per joule), this being essential in designing high-power PPS as consideration which may reduce the total cost of the laser facility.

The following is the way the ISKRA-5 PPS has been designed and developed.

There have been no dedicated capacitor developments for ISKRA-5 because of short time and limited resources. To construct the capacitor bank, commercially produced pulsed

capacitors MK 50-3 type were used, characterized by charge⁴ voltage 50 kV, low inductance - 40 nH, operation life 3*10 shots for 200 kA switched current. The whole bank includes 665 modules with 105 kJ of stored energy each.

To improve PPS reliability, careful acceptance testing of the capacitors was performed before they were installed in sections.

MK 50-3 capacitors were tested on a dedicated testbench using a specific procedure including the following steps :

1. Charge capacitors to 1.1 $U_0=55\text{kV}$ and then hold for 1 minute.

2. Test capacitors by 50 "charge-discharge" cycles at $U_0=50\text{kV}$ and discharge current 50kA (5 times the operating current).

3. Again charge capacitors to 1.1 U_0 voltage to hold for 1 minute,

About 20000 capacitioris have been tested using these techniques. Approximately 2 % were rejected for different reasons. A failure distribution curve has been plotted in terms of the capacitor testing steps, defects nature, and manufacturing dates.

During installation and initial operation, 0,11 % or 20 more capacitors were rejected. Initially, the iodine laser

operation has the capacitor failure rate 10⁻⁴. Under service

conditions, this number proved significantly smaller 10⁻⁵. However, there are features used in the CB which help avoid the capacitor failure affecting the performance of the CB in any given shot.

Note, that currently the Russian capacitor industry has already started the production of capacitors having much higher specific energy density than those used by ISKRA-5 facility.

2.4. Power switches.

Switches are used to deliver the power stored by the bank capacitors to the load.

State-of-the-art switches must meet the following requirements:

- wide range of operating voltages (10 - 50 kV);
- transmit high current (100 - 500 kA) and quantities of electricity (100 C and higher);
- short switch time with minimum jitter;
- operation life as long as 10⁵ - 10⁶ shots;
- current and structural stability;
- low energy for triggering - 0,1-1J;
- minimum weight and size;
- operability in any disposition over broad temperature range, fire and explosive safety;
- environmentally friendly production and operation;
- retalively low cost.

No currently existing switch can fully satisfy the above requirements. The diversity of switch types is what accounts for their purpose, performance, switching conditions and the necessity to meet these requirements at least in part.

The most widely accepted for LF facilities are ignitron and spark-gap switches. Thus, NOVA facility uses 117 switches including 234 ignitrons size "D". A single switch can have a whole amplifier connected thereto, thereby

allowing its independent operation as required.

Ignitrons have the following advantages: broad operating voltage, small weight and size, reasonably high switched currents (of the order of hundreds kiloamperes) and quantities of electricity (up to 100 C).

The limitations of these switches to be mentioned are: narrow range of operating temperatures, vibration sensitivity and positioning in space being strictly specified. There is another major limitation which has lately become topical and is the use of mercury, and this is what requires the compliance with special regulations in production, careful handling in operation, specific mercury reclamation procedures and is likely to result in dangerous consequences caused by the device damage. Like all switch types, the ignitron also tends to prefires, thus needing early rejection by acceptance testing. Each two series-connected ignitrons in operation undergo performance check by periodic high-voltage testing at 25 kV AC.

Most likely, these measures are not sufficient to provide the operation reliability, because the prefire risk is yet probable; so, for its detection each switch is provided with a voltage meter connected via optical fibers to the monitoring system, which would help locate and replace the defective ignitron.

There is one more kind of ignitron failure, i.e. ignitor damage. For NOVA, each ignitron has a trigger signal coming to its ignitor in any shot, and this trigger signal is to be followed by the current transformer. These triggering data are also transmitted via optical fibers to the monitoring system to be then analysed, so that the defect will be timely located and removed.

ISKRA-5 uses high-pressure gas switches that are the most high-voltage and current devices capable of operating at

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10 - 10 V voltages. They feature short switching time (0,1 μ S) and small jitter. The limitations they have are the generation of strong shock waves which damage structural components, discharge plasma reacting chemically with the electrode material, high-voltage triggering and gas supply requirement, low deionization rate and small operating voltage range.

Basically, these switch designs are built around the main spark gap having air insulation pressurized to 5 atmospheres and coaxial cylindrical electrodes. The triggering electrode is made as a ring axially aligned with the main electrodes.

The coaxially annular electrodes of the switch makes all the electrode and insulation surface wear more uniformly than in other designs. Moreover, the electrode portions contacting the spark gap are made of selected erosionproof steels.

Spark gaps use polyethylene insulation. Testing the switch at 50 kV operating voltage and 120 kV triggering voltage pulse with 0,1 μ s risetime, has shown the following switching performance:

maximum switched current	- 300 kA
operation life	- 5000 shots
electric strength margin	- 2 (Ustr = 100 kV)
switch time	- 0,1 μ s
jitter	- 0,03 μ s

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The switch prefire probability is 10 . Currently, the most frequent switch limitation is still shot delays more

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than $3\mu\text{s}$ with the probability $5 \cdot 10^{-3}$. However insignificant the delay effects on the laser beamline output, efforts are taken to fully eliminate this deficiency or reduce its effects upon the laser performance.

In total, there are 665 switches operated at a time in ISKRA-5, with the tolerable jitter $0.03\mu\text{s}$ or less.

As one may point out, although both ignitron and high-pressure gas switches have limitations, their use by NOVA and ISKRA-5 facilities is justifiable. However, some operation difficulties do exist. This is why new switch types have to be developed, that would be avoid these limitations. These include large triggered vacuum switches (sealed-off type) (TVS) and reverse switched dinistors (RSD).

A detailed summary TVS and RSD studies has been included into the dedicated report under this Task Order.

2.5. Load

NOVA facility uses xenon lamps as PPS load, while ISKRA-5 has for this purpose both xenon lamps - for initial amplification stages, and electric-discharge sources (EDS) - for final stages. The EDS operation is based on the sliding spark produced over the dielectric surface by capacitive units.

The electric-discharge source 2m long with 14mm spark gap can be safely initiated by applying a high-voltage pulse of 70 kV and $0.1\mu\text{s}$ risetime. The EDS has about 0,25 - $0.4\mu\text{s}$ shot time.

The source lifetime is about 150 shots of a PPS module of 105 kJ stored energy. Toward the end of this lifetime, the source shot time would increase to $1\mu\text{s}$, thus indicating the need for timely replacing this.

Both lamps and electric-discharge sources are functionally pulsed power system components, while in the design embodiment they are part of the laser system. In this situation, the load becomes of critical importance both in terms of the laser beam performance it should provide and the reliability of the laser system as a whole, because the lamp explosion may often result in the laser optics damages. But this event is undesirable and even unacceptable. Therefore, there is an evident need for more reliable load operation, particularly for Nd-lasers with lamps closely packed.

Consider how there problems are solved in NOVA and ISKRA-5 cases.

The critical consideration in the reliability problem for large glass laser systems is normal operation of the numerous flashlamps. The NOVA background in this aspect is of great value for LF system designers.

There have been the following basic consideration the flashlamp reliability problem: production process, multistep acceptance testing, correct performance control, and diagnostics in operation.

The production process involves high-precision fabrication of the flashlamp sealed high-voltage leads, high-voltage cable wire being securely soldered to the flashlamp electrode conductor, prevention of air leakage into the flashlamp bulb, and the flashlamps being carefully mounted in arrays inside the illuminator, etc.

The acceptance testing steps would proceed as follows:

1. Flashlamp inspection for defects such as cracks, scratches and others.
2. Post-solder testing of high-voltage cable and flashlamp sealed leads at 40-60 kV voltage.
3. Dynamic testing of the flashlamp array by 25 shots

under heavy-duty conditions with energy deposition about 40 % of outdoors explosion.

4. Testing of flashlamps following their mounting into the reflector at full-scale energy.

The correct performance control requires that normal operation conditions be provided, most particularly, preionization. This is done by applying voltage into between the control electrode and reflector.

As a result, there occurs an overvoltage of 30 kV which during 50 μ s produced a streamer running from the triggering electrode to the wall. Then, this streamer travels along the inside wall until it reaches the opposite electrode, and following this the arc expands radially to fill the whole flashlamp light diameter.

Importantly, this also involves looking at the switching circuit transients, there by making it possible to detect overvoltages of some components and take adequate measures to ensure their electric strength.

NOVA facility is provided with diagnostics for correct operation of each flashlamp switching circuit. For the purpose of detecting and locating any prefire event, each switch has a voltage meter connected to the monitoring system via fiber optic. A current transformer is used to control the ignitor correct operation. There is a large current transformer on the switch, used for control over the current flowing through the energy grounding terminal of each flashlamp switch circuit. The current transformer outputs are also transmitted by fiber-optical lines to the monitoring system.

ISKRA-5 facility has less stringent requirements set for pumping sources (flashlamps and electric-discharge sources), than NOVA. Electric-discharge sources are rather distantly spaced from each other and from the laser metal wall (50 mm), so that any of these being damaged would have insignificant effects on the others performance. Electric-discharge sources are simple designs easy in operation, inexpensive in fabrication, and functionally independent from each other. They need no special testing prior to their insulation into the laser structure.

As shown by the studies, the EDS degradation during operation results in its shot time increasing by more than 1 - 2 μ s.

The EDS misfire may produce a long high-voltage pulse (about 0.1ms) in the cable line, which affects the cable terminations and thus causes a surface breakdown where the cables has been connected to the switch. The energy released at the breakdown location, would damage the cable shield and conductor, and result in the need for repairs.

The EDS performance is assessed and their lifetime predicted from their fire time stability. For this purpose, the fire times of all pumping sources are measured simultaneously by 576 channels using a specifically designed pulsed diagnostics package (PDP).

The xenon lamps of the smaller amplifiers have their fire times showing the similar behavior.

Thus, timely detection and replacement of defective EDS in ISKRA-5 facility has been the most important ways to improve the pumping system reliability given its components having comparably short operation life.

This approach may be recommended in designing sophisticated power conditioning for the next-generation facilities.

2.6. PPS charging system.

The PPS charging system is responsible for converting supply line energy to the power for charging the capacitors. The system uses rectifiers to provide the transformation and rectification of single or three-phase line voltage to the CB operating voltages.

Basic requirements for the charging system are 1) charging voltages as specified, 2) voltage stable and accurately controlled, and 3) minimum charging time.

No less important is the charging equipment should be made as inexpensive as possible. This is a significant consideration for every facility which largely determined the preferences for engineering approaches.

Specifically, ISKRA-5 has the charging system including 12 commercial three-phase thyristor controls and high-voltage rectifiers, which allow charging the CB to 50kV and 70kV in 90s time. No development of the newer equipment was undertaken, for it would increase the costs for power facilities and the time of the PPS initial operational capability.

For LLNL facilities, suitable charging sources have been developed using a unique circuit of transformer-based voltage doubler combined with silicon thyristor stabilizer. These power sources can provide both highly accurate setting of the charging voltage and repeatability which is essential for LF facilities. They allow charging the capacitor bank to 15 - 25kV in 30 - 120s with 0,1 % accuracy. As shown by the operation of charging devices, they are easy and safe to operate, and offer a cost-effective charging method for large capacitor banks.

Thus, the approach to charging large PPS may be either based on commercially available equipment or using suitable system development.

2.7. Triggering system.

The triggering system is to provide timed power transmission from capacitor banks to laser pumping sources by firing the switches and pumping sources as specified by the functional algorithm of the facility as a whole.

Generally, any triggering system used by large PPS is multichannel high-voltage pulse generator, which is intended to simultaneously fire the CB power switches and trigger the pumping sources (when necessary).

Therefore, the design concepts of the NOVA and ISKRA-5 triggering systems are similar, while having particular engineering approaches substantially different.

For NOVA, 234 switches are triggered at a time. While the time for switching the stored energy to the load is comparatively long (500 μ s), there may be about 1 μ s jitter in switch fires, and this can be readily achieved by applying high-voltage pulsed of several kilovolts to the switches. It is quite possible to create such a triggering system, provided its functioning is made reliable.

The major difficulty in developing the triggering system for ISKRA-5 was the way to achieve simultaneous firing of 665 spark-gap switches and 576 electric-discharge sources with the jitter less than 1,0 μ s.

It has been shown by the studies, that this can be achieved by generating high-voltage pulses of 120kV with 0,1-0,3 μ s risetime, each for every switch in the CB module. Creating a 665 - channel generator to produce high-voltage pulses having about 0,1 μ s voltage risetime was a difficult problem due to stray L and C of the circuit affecting the

output performance. Therefore, the ISKRA-5 triggering system has been built upon series-parallel circuit and represents a system of high-voltage pulse generators.

There are higher reliability and noise resistance standards set for the triggering system equipment. In view of this, high-voltage triggering generator were developed with special emphasis laid on the optimization of their componentry.

The generators employ low-inductance specifically designed capacitor and two spark-gap types, including commercial (designated PY-65) and specific switch designs, similar to the modular power switches but rated for 70kV operating voltage.

The triggering generators are connected to both the module switches and EDS via cable lines as long as 100m using a suitable high-voltage cable type.

The noise resistance standards are made especially high for low-voltage triggering system units. To comply with these, special measures have been taken to provide the grounding network, reduce stray coupling and use any types of decoupling for low-voltage circuit.

To date there have been several thousands of shots of the PPS triggering system with no more than 2 % of these showing abnormal performance, and this indicates, that the technical decisions made have proved effective.

The development background of the ISKRA-5 triggering system may be helpful for the design and development of ignition facilities that would involve many more modules and higher stored energies than their operational analogs.

2.8. Pulsed diagnostics package for PPS.

It is an important may to improve the reliability of multimodular PPS using timely and efficient diagnostics for high-voltage components, which includes immediate detection and removal of faults in the CB modules to prevent emergency situations.

For charging operation, both NOVA and ISKRA-5 use the customary measurement techniques for charging currents or voltages. Should they deviate from the rated values (or a few modules fail), the experimental procedure can be modified.

During PPS discharging to the load, the processes are very fast to occur, thus making it impossible to intervene in the PPS operation and prevent the component failures. However, with the diagnostics used for certain behaviors involved, one can locate defective components, explore the causes of high-voltage breakdowns, predict the performance of components in the follow-on experiments to measure the deviation of the parameters of interest from the rated values, and timely run maintenance operations.

Let us look at how this methodology has been implemented in the ISKRA-5 case. Ideologically, the methods are as follows. The initiation and termination times of the following PPS transients are determined: switch and triggering system firing, current generating and crossing the zero in the load, i. e. laser pumping sources. At these times, special generators are used to produce diagnostic pulses with the representative time intervals therebetween measured to evaluate the performance of PPS components.

Using time-to-amplitude converters, these time intervals are converted to the slow-falling voltage amplitudes which are to be held for a long time by capacitive storage cells. Following the experiment, when there is no electromagnetic interference from PPS discharge any longer,

all the information signals are coded, filed and entered to computer magnetic disk.

Later, the applied software is used to load this information into the physics experiment database, and the data are processed by specified algorithms.

The database stores informations about every PPS module, indicating their firing times, defect codes and component failures in experiments over several years of operation.

In general, PDP system has the following specifications: time intervals measured : 0,1-5 and 1-50 μ s , maximum measurement channels - up to 6000.

The PDP performance has been testing in actual installation and operation environments of ISKRA-5 facility by a large series of experiments (about 10,000).

The PDP measurements have helped identify the many PPS component failures, such as delayed switch fire, switch prefire, switch and light source misfires, breakdowns in high-voltage cables and connectors, triggering system malfunctions, etc.

The following general conclusions may be made from the implementation of the PDP system :

1. High noise resistance has been provided for PDP hardware mainly by using fiberoptical lines which help keep the package operational under high-voltage breakdowns in the measurement cables.

2. The PDP characteristics allow to detect credibly almost PPS faults possible during the discharge to the pumping sources.

3. The time interval measurements has helped speed-up the installation, adjustment and repair operations for CB modules due to substantially reduced troubleshooting time for PPS. In addition, timely locating the defective high-voltage component would prevent severe accidents, because the shot following may cause more severe consequences to recover by repairs.

4. Highly automated PDP performance has provided the physics experiment database and prediction of PPS components performance in subsequent experiments.

5. The pulsed diagnostics principles are applicable to various PPS types.

3. CONCEPTUAL DESIGN OF THE FACILITY PULSED POWER SYSTEM.

The design philosophies of large pulsed power systems for existing LF facilities have been examined and compared, and this is what serves as a basis to define the basic design concepts for next-generation system of the kind. Let us consider some of these.

3.1. Capacitor bank.

Capacitor bank represents one of the most critical and expensive subsystems in multibeam laser facilities. Therefore, throughout the development stages the ideas are always sought that would provide the most cost-effective way to meet the specified requirement.

On this basis, the following questions should be addressed in the conceptual design stage :

1. Capacitor bank operation conditions?
2. CB layout and module stored energy?
3. Module componentry?

4. How installation and preshot operations proceed?

The background in operating large laser facilities suggests the necessity to make the laser operational under the following conditions :

1. All beamlines operate simultaneously (12 beamlines are envisaged for NIF).

2. Any of the 12 beamlines operates alone.

3. Any beamline portion operates. For definiteness, one may take the 1/16 beam fraction allowing pumping for a single "beamlet".

No doubt, the capacitor bank will be designed on a modular bases as making any operational conditions of the facility readily achievable and matching well the distributed load, i.e. the flashlamp array.

Selection of the module stored energy (module size) depends on the laser construction layout on the one hand, and on the switch efficiency on the other.

Consider the CB design which includes 192 modules (suitable as applied to the candidate laser schematic). Then each module will have stored energy 1,6 MJ, thereby allowing to pump a single "beamlet" with 56 flashlamps.

Each flashlamp will operate under rated energy and current conditions ($E = 28\text{kJ}$, $I_{pk} = 12\text{kA}$, - see p.3.3). Then the total switched current in this module will be 670kA, and the charge - 140C.

Currently, there are no reliably operating switches that would offer such performance. What may be the way out is the use of lower-power switches and reduced stored energy of the module, or several switches operating simultaneously in a single module.

Given the switch rating, one can define the module size and number for the entire facility. The calculated numbers are summarized in Table 3.1.

Basically important in creating large PPS is selection of the PPS module stored energy value. We believe, it would be expedient to take the module of 0,4 MJ stored energy, for this would allow switching with commercially produced vacuum switches TVS-40m or well-explored ignitrons size "D".

Another argument in favor of this idea is reduced energy loss in laser pumping if module failure occurs for any reason (the lower module stored energy, the less its effects on the laser output).

The weaknesses of this approach are large number of modules and difficulty to achieve simultaneous triggering of 900 switches.

In our view, they can well be overcome. This is evidenced by many-years operation practice of the ISKRA-5 PPS having triggering system requirements more stringent than for NOVA facility.

But to develop a switch for $I = 600\text{kA}$ current implies avoiding the physical limitations existing in switching this high currents as current contraction effect, and thus will need many efforts and expenditures to solve this problem.

Semiconductor RSD-based switches are very much promising for the development of high-current switches having ultimate current rating and highly reliable operation. What currently restrains one from recommending its use in NIF application, is lack of data on its performance in groups (of as many as several hundreds of switches) and under voltage surge conditions typical of switching circuits with flashlamps as load.

What capacitor type should be chosen is an important point in the PPS module development. Clearly, capacitors are one of the major contributions to the costs of the laser

PPS structure for differ switch type.

Table 3.1

N	Switch type (switched current)	Module energy kJ	Number of circuites in module	Number of modules in bank	Number of modules in one channel
1.	Expect (I=600 kA)	1600	57	192	16
2.	Ignitron size "D" (I=140kA)	336	12	890	74
3.	Vacuum switch TVS-40 (I=140 kA)	336	12	890	74
4.	RSD-based switch (I=240 kA)	560	20	535	45

facility. To reduce their costs, LLNL have made large efforts increasing the capacitor stored energy density.

As a result, a whole range of capacitors of above 10kJ stored energy have been development. In our opinion, the most suitable in stored energy density, number of shots and costs is 12,5kJ capacitor, and this is what may serve as the basis for the module design. Making this number go beyond 30kJ is hardly reasonable, since the capacitor breakdown its energy releasing will inevitably result in its destruction and high risks of fire, whatever safety measures are taken.

Worth special consideration is the selection of the module circuit diagram. Analytically, we have looked at the module circuit options shown in figs. 3.1 and 3.2. For all their likeness, there are certain differences between them, particularly, the circuit of fig.3.2 has less auxiliary components (charging and discharging resistors, high-voltage fuses) and higher reliability in the module operation in case the capacitor breakdown occurs. Clearly, our opinion on this point may not be indisputably correct, however, it would be desirable to continue this discussion.

For the purpose of easier installation and operation, the CB modules should be mounted as individual structural units, thereby readily providing maintenance and repair.

Typically, there are several steps in installation and preoperation testing of large PPS that proceed as follows:

1. Acceptance testing of components (switches, capacitors, cables, flashlamps) using specific testbenches.
2. Testing of CB modules using testbenches.
3. Testing of one channel.
4. Testing of the overall system.

This is the procedure by which the power conditioning systems for NOVA [22,23] and ISKRA-5 have been built. The advantage of this approach is thoroughly performed preliminary testing of components and individual subsystems, thus helping avoid the risks in starting up the whole facility.

However, the sequence of activities such as this would appear more expensive and time-consuming. It should be noted, that preliminary testing of a module, however, carefully done, cannot ensure its reliable operation as part of the CB, because after it has been positioned in the rack certain postmounting operations follow.

Based on these considerations, the preoperation procedure may be changed and involve :

1. Acceptance testing for capacitors and high-voltage cables only.
2. Installation of power lines concurrently with pulsed diagnostics package (to measure firing times of switches and pumping sources, and circuit switched current pulse length).
3. Simultaneous testing of several lines for equivalent load involving pulsed diagnostics package.

It has been shown by the previous practice, that 10 - 15 test shots may be sufficient to reject defective components or remove the mounting faults in the modules and the CB as a whole, i. e. eliminate the infant mortality problem.

The advantage offered by this approach is significantly reduced time and costs of the operations. Its value increases with largescale pulsed power systems.

3.2 Switches.

The following specifications for the switches of the ignition facility project have been defined in the statement of work on the conceptual design : peak current - 400kA,

Fig.3.1. The scheme of module with the switch between the capacitors and the ground point.

Fig.3.2. The scheme of module with the switch between the capacitors and the load.

charge transfer - 150C, operating voltage - 25kV, operation life - 10,000 shots, and minimum prefire probability.

For comparison, the performance parameters of size "D" ignitron used by NOVA facility are as follows : peak current - 140kA, charge transfer - 70C and operating voltage 22kV.

As is clear from the comparison, that PPS designers in LLNL are seeking to have large modules in the system, and thus reduce their number and improve the PPS operation reliability.

Based on the experience we have in the development of large pulsed power systems, we do not share the US colleagues desire to enlarge the module this much.

It is known, that there are two contradictory problems to be addressed in the development of high-power switches : high reliability and high switching efficiency in current and energy. Physically, the reason for discharge current limitation lies in that higher switched currents in the switch may result in the space charge change-over to channeling caused by contraction (pinching) with cathode and anode spots forming, which are typical of channeled burning patterns and cause the electrodes damage with their materials scattering at the discharge chamber insulation. The higher the switches current and charge, the more severe the damage. The negative consequences of this scattering are shorter operation life and reliability degradation of the switch.

Another aspect of this problem is the switch failure consequences and effects on the laser output. Clearly, large PPS module failure would severely degrade the laser beam quality.

Therefore, one may conclude that currently vacuum switches type TVS-40m, reverse switched diodes (RSD) and size "D" ignitrons can be used as CB switches for NIF project. The tests of TVS-40m switches conducted under this Task Order, have proved their reliable operation under the following conditions : current - 140kA, voltage - 15-20kV and current pulse - 500 μ s.

Reliable operation of the module at 25kV voltage requires that an assembly of two series-connected switches should be used to test their performance under these conditions. Simultaneous firing of 900 switches will be achievable without great difficulties using the available componentry.

Recently, new high-power RSD-based semiconductor switches have been developed, with their electrodes remarkably combining energy switching and control functions. This combination provides for opposite polarities of switched and control currents.

For the purpose of looking at RSD applicability in large pulsed power systems for high-power Nd-laser pumping, they have been testing at the UNIEF tailored testbench at 25kV voltage, 200kA switched current and 500 μ s switched current pulse.

The switch is designed as 15 individual elements packed to make up a column with suitable techniques used to allow proper contacts therebetween.

As shown by the testing, RSD of 80mm diameter can switch current as high as 200kA.

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The RSD operation life is expected 10 shots or more, though it seems impossible to prove this due to the limited lifetime of the testbench components. By extrapolating the resulting data one can conclude the possibility to increase the switched currents to 300kA making the individual RSD elements larger in diameter, though having the costs growing

with the area.

Making a decision conceptually as to the use RSD as energy switch for NIF project requires continuing work to develop simultaneous circuit for firing 200 switches operating in bunch.

Thus, encouraging though the test results are for TVS and RSD in high-current environment, it would prematurely to recommend them for NIF switches.

Therefore, it is ignitrons that are the most probable candidates to serve as these switches. The following arguments can be used in favor of this preference :

1. Large amount of data on the NOVA ignitron bunch operation are available.

2. Previous engineering approaches can be used, which have been proof-tested at the operational facilities, thus saving time for design paperworks, and fabrication, installation and adjustment of individual subsystems and the facility as a whole.

As the size and cost of the pulsed power system grow, stronger will become the effects of ignitron faults (prefire, misfire, and fire delay) on the facility performance.

To increase the operation reliability, the control over ignitron fire delays against their operating age is suggested.

It is our opinion, by measuring the peak current in each discharge circuit one cannot judge the initial degradation of switches, but faces the accomplished fact, such as generation of defect.

Our experience in operating about 700 spark gap switches at ISKRA-5 facility suggests, that switch fire delays are 10 times more frequent, than other operational abnormalities, while the switch degradation with time and shots would primarily affect the shot time, other effects being less significant.

Therefore, with the shot time measured, predictions can be made for switch failures, thus providing timely measures to repair or replace these.

3.3. Load.

The PPS load to be used by NIF facility will be flashlamps of 2m length and 2,5cm inner diameter, filled with Xe pressurized to 200torr. The flashlamp size has been selected based on the operational requirements for the laser amplifiers.

Flashlamps serve as nonlinear resistive load with two impedance states, and this is what should be taken into account in selecting the CB cell parameters to achieve a critical discharge for maximum energy deposition.

Based on the statement of work, the following are the load requirements:

1. Flashlamp input energy to range within 0,15 and 0,25 Ex, where Ex is flashlamp explosion energy in a single shot, while $E = 0,25 E_x$ accounts for 300MJ energy input to all of the flashlamps.

2. Pulse length $T = 380\mu s$ (T is defined as $3(LoCo)^{1/2}$, where Lo and Co are the inductance and capacitance of the discharge circuit, respectively).

3. Current pulse shape to have near-critical decay for maximum energy,

4. Total number $N = 10,700$ flashlamps.

To develop the PPS module, the discharge circuit parameters should be determined.

To this end, let us calculate the flashlamp explosion

energy:

$$Ex = 2 \cdot 10^4 \cdot l \cdot d \cdot t^{1/3} = 112 \text{ kJ}, \text{ where } t = (Lo/Co)^{1/2}$$

The nominal energy input to each flashlamp is found from the relationship:

$$E = (0.15-0.25) Ex = 17-28 \text{ kJ}.$$

For $E = 0.25 Ex$, the discharge is to have critical decay, with the decay factor:

$$a = K / (Uo Zo)^{1/2} = 0.75$$

The coefficient K is related only to the flashlamp parameters:

$$K = Ko \cdot l / d = 93.6,$$

$$\text{where } Ko = 1.36 (Px / 450)^{0.18} = 1.17 \text{ (for } Px = 200 \text{ torr)}$$

Now, consider the discharge circuit capacitance to be discharged to a single flashlamp:

$$Co = (2 \cdot E \cdot a^2 \cdot t^2 \cdot l^2 / K^2)^{1/3} = 155 \mu\text{F}$$

Calculate the circuit inductance and wave resistance:

$$Lo = t^2 / Co = 103.6 \mu\text{H},$$

$$Zo = (Lo/Co)^{1/2} = 0.82 \text{ Ohms},$$

The capacitor charge voltage is evaluated from the relationship:

$$Uo = (2E/Co)^{1/2} = 19 \text{ kV}$$

The peak current per single flashlamp is evaluated from the relationship:

$$Ipk = Uo / Zo \cdot \exp(-0.87a) = 12 \text{ kA}.$$

As one can see from the results, that PPS discharge circuits for NIF and NOVA facilities have their parameters comparably close in magnitudes.

Therefore, the available methodology for flashlamp safe and reliable operation should be also applied to the newer facility.

We do appreciate the acceptance testing developments and high-voltage techniques for flashlamp rejection, however we would like to invite our US colleagues to look at the capabilities of early predicting flashlamp failures using firing time measurements, that have been successfully implemented for ISKRA-5.

Actually, during preamplifier development, the acute problem we faced was the design of pumping lamps for

heavy-duty operation, i.e. for specific power input 0.5 MJ/cm^2 . Efforts were made to develop vacuumized quartz Xe lamps 25 and 50mm in diameter having discharge of 1m length, which can withstand 1000 or more shots.

The pulse diagnostics package was used to observe the flashlamp firing times changing with their operation age.

Illustrative for this case is ageing dynamic of the amplifier flashlamps of one ISKRA-5 beamline during 1990 - 1993 period. Fig.3.3 shows the history of the amplifier flashlamp firing delays.

Earlier 100 shots show sporadically small ($< 0.5 \mu\text{s}$) firing delays having no effects on the amplifier performance. Following 150 or 160 shots, there is a sharp increase in the occurrence frequency of the flashlamp firing delays about 2 to $5 \mu\text{s}$, and thus the amplifier degrades in its performance.

This is normally followed by the decision to replace the flashlamps before their damage.

Actually, specialized studies are needed to gain the

Fig.3.3. The diagram of flashlamp firing delays change in ISKRA-5 amplifier.

Fig.3.4. The scheme of series triggering of lamps.

confidence that the use of early failure prediction techniques for flashlamps will be desirable for NIF facility.

3.4. Preionization system.

Basically, a flashlamp preionization system is designed to make a breakdown stable in time, improve the pumping light spectral composition and flashlamp luminous efficiency.

By the statement of work, the preionization system must deliver to each flashlamp about 0,3J of energy per sq.cm of its inner surface, and any preionization pulse must be applied to the flashlamp 100 - 500 μ s before the main pulse.

Operation conditions : concurrently with discharging the whole of the CB during the shot, or independently without the main power system discharge.

The latter is most frequently used for quality testing of sealed-off flashlamp design with their bulbs likely to unseal as a result of high dynamic loading induced by discharges.

While considering the flashlamp preionization system, the following questions should be addressed :

1. Stored energy for the whole system ?
2. Circuit selected the preionization system cell ?
3. Efficiency of flashlamp control and testing using preionization system ?

The CB energy for flashlamp preionization was found from the equation

$$E_p = E_i \cdot N = 5.5 \text{ MJ},$$

where N is the total number of pumping flashlamps (10,700), E_i - preionization energy per flashlamp (500J).

The CB energy used for flashlamp preionization system accounts for 1,8 % of all of the PPS energy.

Various preionization circuit designs have been considered to identify the configuration of the flashlamp preionization system, including series initiation circuit, parallel initiation circuit and externally initiated circuit (see fig.3.4-3.6).

The better circuit to meet the statement of work's specifications is parallel flashlamp initiation like that used by NOVA. A supplementary capacitor bank used for preionization is charged to a negative voltage - 15kV. It is switched to the PPS module using a suitable switch.

As one can see from the analysis of transients occurring therewith, there is a negative voltage wave of about 50kV peak generated in the cable line which is then applied to the flashlamp to cause its preionization.

Since the main CB module has significantly larger capacitance than the preionization bank section, it has its charge unchanged when the preionization pulse is generated.

The circuit advantageously features simple design, reliability, using main discharge circuit components for source-to-lamp transmission of preionization pulse, low charging voltage.

The analysis has been made which helped define the switch requirements : operating voltage - 40kV, peak current - 75kA, switched energy - 10kJ, current pulse - 35 μ s.

Feasibility of the preionization system depends on the main CB module design. Most likely, they must be made to function independently of each other, so that the module components would avoid over voltages.

While the PPS modules are isolated from each other, it would be desirable to have the preionization system split into separate modules operated to fire bunches of flashlamps

Fig.3.5. The scheme of parallel triggering of lamps.

Fig.3.6. The scheme of external triggering of lamps.

switched by a single power switch.

This implies, that the main PPS must have as many modules as there are in the preionization system.

Then it would be possible to apply the preionization pulse to the power switch loading electrode, thus saving substantially both the length and number of cable lines.

Quality control over sealed-off lamps is possible by measuring the preionization current through the lamp and comparing it with the rated value. However, the flashlamp diagnostics for early degradation would be more efficient if added by measurements of their firing delays in terms of the operation age.

3.5 Triggering system.

The purpose of the NIF triggering system (TS) is to provide simultaneous firing of numerous (200 - 900) parallel-operated switches, this being of critical importance from the point of view of both the efficient use and safe operation of the capacitor bank.

Additionally, there is a requirement that preionization of flashlamps be achieved 100 - 500 μ s before the entire capacitor bank discharges.

The following description of the facility is essential for the triggering system development :

1. Operation algorithm.
2. Overall PPS configuration.
3. Switch types and trigger signal characterization.
4. Number of switches.

These data are used as a basis to select the schematic design of TS and develop specifications for its major subsystems.

Simultaneous firing of very many power switches is among the most difficult problems involved in the development of TS.

Reliable simultaneity in the switch operations can be achieved given independent triggering.

For this purpose, the switches may be triggering each by its respective generation, or by isolating them in time using long connection cables.

In this case, it is essential to know the switch fire time as a function of the triggering voltage. Simultaneous operation of the switches with the firing time t and its rms deviation s as a function of voltage being clearly pronounced may be achieved given: $2 \cdot l/v > 2 \cdot T_a \cdot s$, where l is the cable length, v - electromagnetic wave velocity through the cable, T_a - two-sided confidence interval associated with the firing reliability a within the delay $2 \cdot l/v$. The value a is found from the consideration that the acceptable misfire

probability for any switch in the capacitor bank is $P = 1 - a^n$, where n is the number parallel-connected switches. Thus, the required isolation in time depends on the switch statistical characterization $F(s)$, number and reliability in parallel operation specified [31].

As shown by estimates, to make 100 switches operate in parallel for $s=20$ ns, about 150ns (150m cable) delay is required with the switch misfire probability 0,05. With the switches increasing in number, the cables should be longer, and this may add to the cost of the capacitor.

For switches with s not strongly related to the voltage (such as vacuum switches), the above isolation requirement is not rigid. As our practice shows, their simultaneous actuation can be done with high reliability for $s=100$ ns.

Fig.3.7. Circuit diagram of the multichannel PPS triggering system.

Basic units and functions:

- 1.CBTU - CB triggering unit;
- 2.CBTD - CB triggering delay unit;
- 3.CT - channel triggering unit;
- 4.STPG - switch trigger pulse generator;
- 5.PCT - preionization channel triggering;
- 6.PSTG - preionization switch triggerig generator.

Another challenge in the development of triggering system for large PPS is multichannel generator to produce high-voltage pulse for firing the switches.

Clearly, the switch operation stability is the higher, the shorter is the risetime of the triggering voltage. When the number of channel is large (100 - 1000), there is a physical limitation on generation of signal having short voltage risetime, due to spurious inductance L_s and capacitance C_s existing in the discharge circuit of the high-voltage generator. As a consequence, it is virtually impossible to develop the multichannel generator to trigger 100 - 1000 switches. There is a way out from this situation, which is to develop the triggering system based on the parallel-series circuit with the approximate form as shown by fig.3.7.

Operation reliability of the triggering system is the point of special consideration. With the succession in PPS performance being provided as specified, its misfire or prefire must be made almost impossible, other wise this may result in either unsuccessful experiment or emergency. Therefore, the operation reliability problem for TS is to be addressed using the familiar methods :

1. Selection of correct circuit design.
2. Careful acceptance testing of critical components.
3. Operation of critical components under conditions below rated values.
4. Providing noise stability for critical components and all of the system.
5. Performance control over critical subsystems, failure prediction, timely replacement of rejected parts.

If RSD design is used as power switch, then the triggering system would have to be more complicated, and thus a special study would be needed to develop it.

3.6. Charging system.

Charging system configuration is largely dependent on laser requirements. Both NOVA and ISKRA-5 facilities have their power sourced grouped by amplified rather than beamlines, thus allowing to charge one and the same amplification stage for all of the beamlines at a time.

While the NIF facility is going to have a "beamlet" as its elemental constituent with the amplifier flashlamps to be provided with equal power, the following charging system configuration may be considered :

Configuration A. Each "beamlet" has its capacitor bank ($E_s = 1.6\text{MJ}$) charged by its respective power supply.

Then the charging system will include 192 identical power supplies. For 60s charging time, the SHIVA - dedicated power supplies 100kVA may be used as these rectifiers.

One should point out the major issues arising from this charging system idea.

1. Large number of power supplies used makes one set higher reliability standards for them.

Normally, the high-voltage portion of the power supply must have insulation provided with substantial strength margin (the breakdown voltage should be at least 1.5 times the operation), because the power supply breakdown is typically associated with long delays in experimentation.

The general requirement for the power supply failure rate is that it must be lower than that of any CB component.

The power supply failure rate as calculated from the

available data on the NOVETTA operation [24], has too high a value (1.1×10 failures/shot), i.e. for 200 power supplies having failure rate like this, there will be failures occurring every five shots (MTBF=5), therefore actions need be developed to improve the power supply reliability.

2. Power supplies 100kVA are intended for installation inside the capacitor bank room. This would considerably decrease the space to take up by the capacitors, thus making it desirable that power supplies be located outside the CB room.

This charging system configuration offers the following advantages :

1. Each power supply is loaded by the CB of equal capacitance. This levels off the charging time and makes the control and monitoring easier.

2. No need for specialized high-voltage switches that should exist to connect several CBs to a single power supply.

3. Prior to experiment, easy changes in the charging voltage at specified points.

Configuration B. Each beamline to be charged its respective power supply.

In this case, 2MVA power supplies development for NOVA can be used, overall number - 12.

The advantages include :

1. Less expensive than configuration A in terms of power supplies (2MVA power supply costs \$160,000 , 12 * \$160,000 = \$1,920,000 ; 100kVA = \$15,000 , 192 * \$15,000 = \$2,880,000).

Additionally, NOVA facility currently uses 6 2MVA power supplies, i.e. 50% of the number required by configuration B, and 8 100kVA power supplies, i.e. 4% of that required by configuration A.

2. The power supplies 2MVA are meant for location outside the facility building.

Major problems involved in this configuration :

1. Reliability. When a power supply fails, the whole of the beamline will go out of the experiment, and thus the experiment will no doubt break down. For failure rate 1.1×10 and 12 power supplies used, MTBF=75 which is not adequate to the system reliability required (MTBF=100).

2. The beamline CB is all charged to the same voltage.

3. If single-"beamlet" operation is required, the CBs of the other 15 "beamlets" must be disconnected from the power supplies, i.e. there is a need for suitable high-voltage switches included in the CB charging circuits.

Configuration A would make the facility more flexible in operation. However, in terms of cost and reliability considerations the configuration B seems more preferable.

We would like to mention the difference in the approaches to the power supply designs for LLNL and VNIIEF facilities.

We use commercial three-phase bridge uncontrolled rectifiers, with the voltage in the transformer primary coil controlled by relevant tiristor devices commercial as well using phase control technique. Unlike voltage doubler, this circuit allows the use of transformer of lower peak power. We have optimized rather well the output current control under the load short-circuiting conditions, so that the ISKRA-5 charging system of 12 rectifiers has been operating reliability over the 5 years facility operation, causing no problems in its pulsed power system.

3.7. General activities to improve PPS package reliability.

Reliability is one of the critical problems to overcome in creating large PPS system. For pulsed systems of more than hundreds megajoules stored energy, it is the emergency safety problem that is particularly important.

Even when capacitor bank components are highly reliable, any weakness may still occur and pose the risk of failures during charging. Moreover, the release of stored energy through the breakdown point may result in an emergency and thereby failure of the experiment.

The familiar efforts to improve PPS reliability include:

1. Detection of defective components during installation by means of acceptance testing.
2. Confinement of failures, and disconnection of failed components from the system during the experiment.
3. Prediction of emergencies, and preventive measures.

While the acceptance testing of components is quite understandable, there is no need to justify this. Therefore, we will consider in more detail the confinement of failures, that may result from the breakdown of one capacitor of the many thousands used by the facility.

As shown by the ISKRA-5 test experience, this kind of emergency can be effectively confined by immediately disconnecting the PPS module where a breakdown in cable, capacitor or switch has occurred, using a high-voltage fuse positioned between the common charging line and the module components connected thereto.

In this case the unaffected performance of other PPS modules and charging system could be provided by sufficiency quick disconnection of the damaged module from these systems. In doing so, the PPS stored energy will not have enough time to charge significantly, while its power supply current from the charging system will be insufficient to make operate the safety features provided for its cutting from the power line in emergency.

The study of the above technique to disconnect the PPS module, with the characterization of transient behaviors occurring with this disconnection and also high-voltage fuse performance, are all detailed in [27].

Quick disconnection of failed modules in PPS under charging being achieved, this has made it possible to experiment, given individual module failures.

Clearly, any module failure in this case would result in disabling the respective group of flashlamps.

In terms of this, undoubtedly critical is the question: what are the PPS stages, where the module disconnection would be allowable? For ISKRA-5, this may be allowed in the final stages only.

This is attributed to the fact, that it is these stages where the laser output loss is smaller, and the risk of capacitor breakdown is very high because of many capacitors used.

The efficiency of this approach was evaluated by comparing the PPS operation reliability for the ideal (no failures) and real case with failure accepted for any but one module in the final stages of any of the 12 ISKRA-5 beamlines.

It has been shown both numerically and experimentally, that the probability of no component failure in the experiment is 0,15, and increases to 0,96 for the case with allowance for the disconnection of 1 or 2 modules during the shot.

Possible disconnection of a few modules allowed during the experiment raises the PPS repairability problem, repair being one of the ways to make the PPS usable for further experiments in a reasonably short time.

Repairability implies capabilities for detection of damaged modules, elimination of damage effects, and making them operable through repair.

Basically, repairability is one of the critical PPS requirements and involves permanent maintenance to make PPS available for an experiment.

Of special concern in operating large PPS systems is the module fire hazard following the insulation breakdown of any high-voltage component. The more important this problem is when the module failure is allowable during charging for the experiment continuing.

Generally, ignition in the high-voltage module equipment is to be initiated by an electric arc with its possible causes as following :

- a) electric insulation breakdown of the module components;
- b) electric circuit opened structurally during voltage buildup;
- c) arcing at the switch contact during switching.

There may be two approaches in principle to the fire safety problem :

1. Avoid electric arcing as the cause for ignition.
2. Provide conditions to quench the arc before ignition, i.e. make individual ignition events allowable with the following immediate self-quenching.

Clearly, the first is more preferable, though calling for more expenses to improve certain components and subsystems in terms of safety. However, it would be impossible to eliminate completely any kinds of electric breakdowns in this case either.

The other approach would require investigating the performance of the various CB module components in abnormal environments in terms of their fire safety and the ways to make it better.

As concerns fire hazards, it is capacitor which is the most riskful module component. It may ignite following its can being depressurized by the electrohydraulic shock caused therein by the breakdown.

Thus makes it clear that the energy stored by the module and released within the capacitor must be limited.

In so doing, what must be taken into account is the contribution of capacitors, parallel connection, i.e. how inductance and ohmic resistance would influence the energy redistribution among the circuit components.

During the design and development of the ISKRA-5 PPS system containing 665 modules, there was a special comprehensive study carried out for the above-mentioned range of issues.

Fire safety studies of the PPS cell allowing for all of the capacitor breakdown considerations, also together with cable and other components failures, make up an extremely difficult problem requiring a great deal of time and resources. Its detailed description is beyond the scope of works under this contract.

However, the problem we have just touched upon, is of great concern, therefore, we believe, it would be relevant to reflect at least the most significant efforts made for ISKRA-5.

Our studies show, paper-oil insulation ignites as a result of the capacitor can depressurization caused by the

electrohydraulic shock at the breakdown location, and the castor oil spilling out to the damaged point. Moreover, the fire is sustained due to a wick effect without significant intensification.

Basically, it has been shown and realized the capability to limit the broken capacitor energy by connecting thereto a suitable resistor including several nichrome wires. Simulation testing has been conducted for capacitor breakdown due to the insulation being deliberately damaged, this showing using this wire resistor with specified parameters can limit the energy input to the broken capacitor to the value where no can depressurization would occur. Also, the energy lost in the resistors during the module discharging would not exceed 5%.

For the conditions needed to minimize the risk of fire in the PPS module as results from the capacitor breakdown involving this safety resistor, essentially important is its properly selected design with the account for its positioning in the module, minimum effects on the module reliability under operating conditions and cost-effectiveness.

Thus, the ISKRA-5 PPS has used the double confinement procedure for capacitor breakdown, i.e. by disconnecting the broken capacitor-containing module from the rest of the CB and the charging system and then making most of the module energy dissipate into a suitable resistor, rather than at the breakdown point, included into the main charging circuit.

We have chosen this way to limit the energy at the breakdown point, because the fuse series-connected to the capacitor with the operating voltage being 50kV would make a cumbersome structure, thereby increasing the module self-inductance, while we considered it very important to minimize the inductance. For 25kV operating voltage, we believe, it would be more reasonable to use the fuse to disconnect wholly the broken down capacitor from the rest, thus making it possible to continue the experiment with slight loss of the module- stored energy.

We have an inexpensive and high-performance fuse design already developed.

However, we believe, this work should be started with numerical and experimental simulations of the given abnormal situation (capacitor breakdown) for the actual module circuit of the NIF capacitor bank, in order to define the abnormal currents and possible overvoltages in the discharge circuit.

Then, the requirements can be established for this fuse and its breakdown made as applied to the design already available.

4. CONCLUSIONS.

1. The analysis of the development progress in high-power laser technology over the past 10-15 years shows, that flashlamp-pumped neodymium laser is advantageous over other technologies for its high beam output, reusability and componentry availability. Therefore, this technology as a preference for the NIF project is quite justified.

2. The review of various energy storages types for pulsed power pumping systems of large lasers has been made. It is shown, that despite the achievements made in designing inductance power systems, the LLNL decision to use capacitance pulsed power system for laser pumping in NIF facility is well reasonable.

3. The design philosophies of pulsed power systems for

the largest state-of-the-art LF facilities NOVA and ISKRA-5 have been discussed.

As is shown, there is much in common in their development methodology :

3.1. The circuit configuration allows the operation of any individual beamline ; one or more amplifiers in different beamlines; all the beamlines simultaneously.

3.2. Broad uses of engineering approaches developed and tested for previous facilities.

3.3. Use of commercially available high-voltage components (capacitors, switches, cables, etc.).

3.4. Testbed capability under development for acceptance testing of high-voltage components independently of their post-production tests.

3.5. The same installation and adjustment procedures.

3.6. Diagnostic capabilities under development for PPS charging, discharging and post-discharging conditions.

4. The existence of specific differences in these facilities design concepts are also mentioned.

4.1. During the NOVA PPS development, emphasis has been laid on the design of newer capacitor bank components (capacitors, resistors, rectifiers, etc.) featuring high stored energy density. The advances were the greatest in designing high-energy capacitors using the latest dielectric materials, which can operate under nearcritical electric intensity conditions.

4.2. The ISKRA-5 PPS was designed involving no new high energy density components, but using the earlier commercially developed products. This helped reduce the time and costs of development, though required that failure-free operation problem be solved for the facility.

5. Based on the available experience and literature survey, the basic concepts for the pulsed power system design of the NIF facility have been defined. Given below are some of these :

5.1. NIF facility should have its PPS configured in general terms similar to that of NOVA with its modular design preserved.

5.2. There is a suggestion that the module stored energy be taken about 400 kJ, with careful acceptance testing using specialized techniques and testbenches.

5.3. PPS should be provided with pulse diagnostics package to measure firing times of power switches and flashlamps, and used in adjustment operation simultaneously for several beamlines, thus reducing time for these operations.

5.4. Ignitrons are more preferable as power switches at present. A fire delay measurement system is desirable to control and predict their performance.

Other advanced switch types not studied enough to recommend their use in the NIF capacitor bank.

5.5. Flashlamps may be one of the "bottlenecks" for the facility. However, careful the technologies for their production, pretesting, and mounting into the amplifiers, their failure probability is still quite realistic. To reduce this, it is desirable that the facility be equipped with early prediction capabilities for flashlamp degradation, using measurement of flashlamp discharge delays to provide timely replacements.

We consider it appropriate to conduct a specialized study on this subject.

5.6. Flashlamp preionization system also should have

modular design. In this case, each module would fire an array of flashlamps switched by a single power switch, and thus the CB module can be designed smaller in size.

5.7. The facility triggering system should be designed around series-parallel pattern, so that to create a multichannel high-voltage generator of short-risetime output, with special measures taken to ensure reliable operation.

5.8. For PPS charging, 12 power supplies should be used 2MVA of power each, this allowing to use partly the available devices, thus reducing the cost of the charging system as a whole.

5.9. What should be included in the procedures to keep the PPS operable is the following :

a) making failures allowable for one or two modules in a single CB channel, which would have no significant effects on the laser output ;

b) confining failure locations within an individual module to be disconnected from the whole facility during the experiment.

c) PPS operation control during charging and discharging, data collection and processing to predict individual components, failures and provide replacement.

6. This report has summarized the basic concept embodied and proof-tested at the operational facilities NOVA and ISKRA-5. Together with the similarity between these, there are also differences that can be attributed to different views of their designers at the problem, available components, funding and time considerations.

Some ideas we suggest are debatable issues that need be jointly discussed, including whether or not the stored energy of some components should be increased to specified limits, CB diagnostics during charging, module circuit and energy density to be selected, etc.

The NIF facility to be developed will be an advance both in LF research and in pulsed power technology for large lasers. We trust, the data described in this report will be a useful contribution to this challenging problem of physics.

References.

1. Basov N.G., Kirillov G.A. et al. "Monopulse photodissociation laser with 1-2MJ energy" /Preprint FIAN, Moscow, 1992.

2. Y.V. Dolgoplov, G.A. Kirillov, G.G. Kochemasov, S.M. Kulikov, V.M. Murugov, S.N. Pevny, S.A. Sukharev. "High-power nanosecond pulse iodine laser provided with SBS mirror", presented at: SPIE OE/LASER-91 Symposium on High Power Lasers., 1991, Los Angeles, SA.

3. Jacob J.H., Rokni M., Klinowstein R.E., Singer S. /Appl. Phys. Lett., 1986, v.48, N5, p.318-320.

4. Alechin B.V., Bonjuchkin E.K. et al. / Inter. Conf. "PHYSICS OF NUCLEAR INDUCED PLASMAS AND PROBLEMS OF NUCLEAR PUMPED LASERS" Obninsk, 1992, p.172

5. Zrodnikov A.V. / Inter. Conf. "PHYSICS OF NUCLEAR INDUCED PLASMAS AND PROBLEMS OF NUCLEAR PUMPED LASERS" Obninsk, 1992, p.21

6. Protasov M.S., Chernyshev V.K. et al. in "High-power magnetic fields", editors Titov V.M. and Shvetcov G.A., Moscow, Nauka, 1984, p.26-28. .
7. "High density energy storage and switching" editors W.Bostic and V.Nardi, Moscow, Mir, 1979.
8. "Energy pulse sources based on inductive storages", Preprint B-0299, NIIEFA, 1976.
9. "Electrotechnical hand-book" v.2, Moscow, Energoatomizdat, 1986.
10. Komin A.V., Kutchinskii V.G. "High pulse power supplies" , Preprint OK-21, NIIEFA, 1978.
11. Azizov E.A., Achmerov N.A., Godonjuk V.A. / 4th Conf. of termonuclear reactors engineering, Leningrad, 1986, v.3.
12. Larionov B.A., Michailov N.A. / 4th Conf. of termonuclear reactors engineering, Leningrad, 1986, v.3
13. Atachkov M.M., Bokoskritov Y.I. et al. / 4th Conf. of termonuclear reactors engineering, Leningrad, 1986, v.3
14. Vichnevskii A.I., Rudenko V.S., Platonov A.P. "High power semiconductor devices" Moscow, Vischaja chkola, 1975.
15. Koljadin N.P. et al. / 4th Conf. of termonuclear reactors engineering, Leningrad, 1986, v.3
16. H.Knoepfel "Pulsed high magnetic fields", Moscow, Mir, 1972.
17. But D.A. /Elektrichestvo, 1987, 7.
18. But D.A., Alievskii B.L., Mizjurin S.R. "Energy storages" Moscow, Atomizdat, 1991.
19. Drughinin A.S., Larionov B.A. et al./ 5th Conf. of termonuclear reactors engineering, Leningrad, 1990.
20. William L.Gagnon "Glass Laser Power Conditioning Report", 1975.
21. Holloway R.W., Whitham K., Merritt B.T., Gritton D.G., Oicles J.A. "NOVA Pulse Power System Description and Status", UCRL-85720, 1981.
22. Whitham K., Merritt B.T., Gritton D.G., Holloway R.W. "Design and Construction of Large Capacitor Banks". UCRL-88669, 1983. Presented on 4th IEEE International Pulsed Power Conference, Albuquerque, NM, 1983.
23. Whitham K., Larson D., Merritt B.T., Christie D. "NOVA Pulse Power System Design and Operational Experience". UCRL-95051, 1987, Presented on SPIE Optoelectronics and Laser Applications, 1987.
24. Whitham K., Merritt B.T., Gritton D., Smart A.J., Holloway R.W., Oicles J.A. "NOVA Power System: Status and Operating Experience". UCRL-89546, 1983, Presented on 10th

Symposium on Fusion Engineering, Philadelphia, PA, December 1983.

25. Bezuglov V.G., Galakhov I.V., Gasheev A.S., Murugov V.M. et al. / Pribori i tehnika eksperimenta (PTE), 6, 1981.

26. Bezuglov V.G., Galakhov I.V., Gasheev A.S., Murugov V.M. et al. / PTE, 3, 1982.

27. Gasheev A.S., Kuzmichev Yu.P., Kucherov A.I., Murugov V.M. / PTE, 5, 1981.

28. Antipov S.I., Galakhov I.V., Gasheev A.S., Murugov V.M. et al. / PTE, 5, 1990.

29. Bezuglov V.G., Galakhov I.V., Gasheev A.S., Murugov V.M. et al. / PTE, 3, 1991.

30. Tuchkevich V.M., Grehov I.V. "New principles of high power switching by semiconductor devices" Leningrad, Nauka, 1988.

31. Efimov B.V., Zaienc S.L. et al. / Elektrotehnika, 1, 1981.