POWERFUL ACCELERATORS FOR BREMSSTRAHLUNG AND ELECTRON BEAMS GENERATION ON THE BASIS OF INDUCTIVE ENERGY-STORAGE ELEMENTS*.

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Summary

The report summarizes RFNC - VNIITF activities from 1963 till 1995 devoted to the development of pulsed electron accelerators on the basis of inductive energy storage with electroexplosive wires. The name of these accelerators is IGUR. These activities resulted in the development of a series of generators of powerful radiation being cheap and easy in manufacturing and servicing. Accelerators enabled followind maximum parameters:

- the diode voltage	up to 6 MV;
- the diode current	up to 80 kA;
- current of the extracted electron beam	30 kA;
- density of the extracted electron beam energy	500 J/cm^2;
- bremsstrahlung dose	250 000 Rads;
- bremsstrahlung dose rate	10^{13} Rads/sec.

Introduction

In the beginning of the 60s there was a necessity in determining resistance of electronic equipment and components to ionizing radiation. That's why the problem of developing equipment for investigating and testing of resistance to gamma-radiation appeared.

A team of VNIITF physicists addressed to this problem. They proposed an original circuit of high voltage source to supply energy to the diode where it was planned to have high voltage due to overvoltage arising on the inductor in the case of break in the current circuit. Electric explosive wires were proposed as a switch.

A special testing equipment was created for investigation of wire electroexplosion process. The first stage was devoted to experimental development of the switch. Wires of various materials, such as copper and aluminium were investigated. Wires were exploded in different media (air, oil, sand). This effort resulted in the development of the switch consists from copper wires. Best results were obtained when copper wires were exploded in the air.

Released power in the load in the modes of capacitive and inductive storages were subjected to comparative analysis. It demonstrated the mode of inductive storages to ensure significant gain in the amount of released energy.

Facility of IGUR type

The high-voltage source consists from Marx generator, point inductance and electrical explosive wires was created by the beginning of 1967. The diode was

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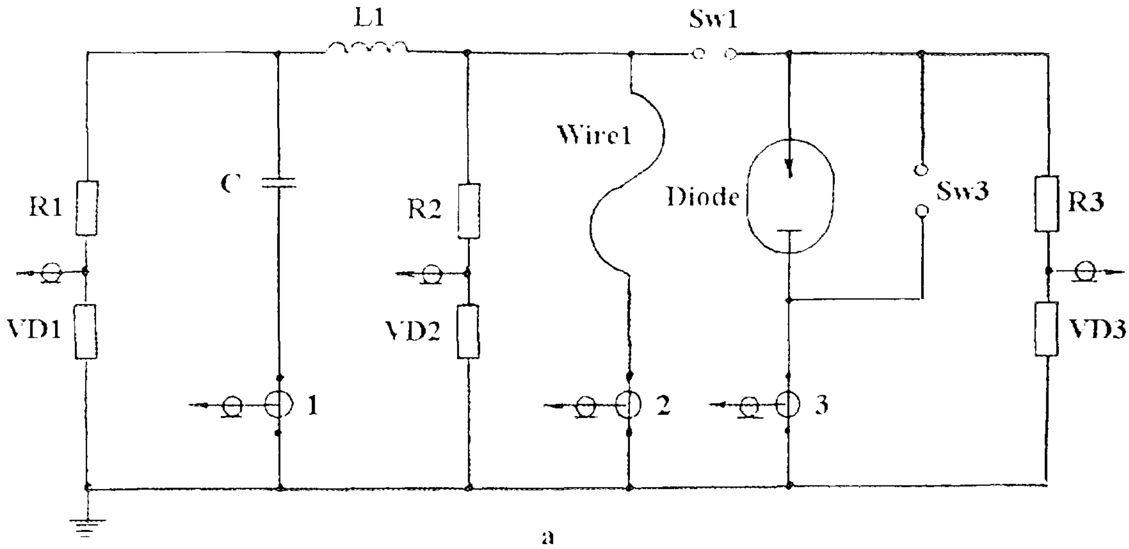
designed and manufactured by the end of 1968. The electron accelerator was put



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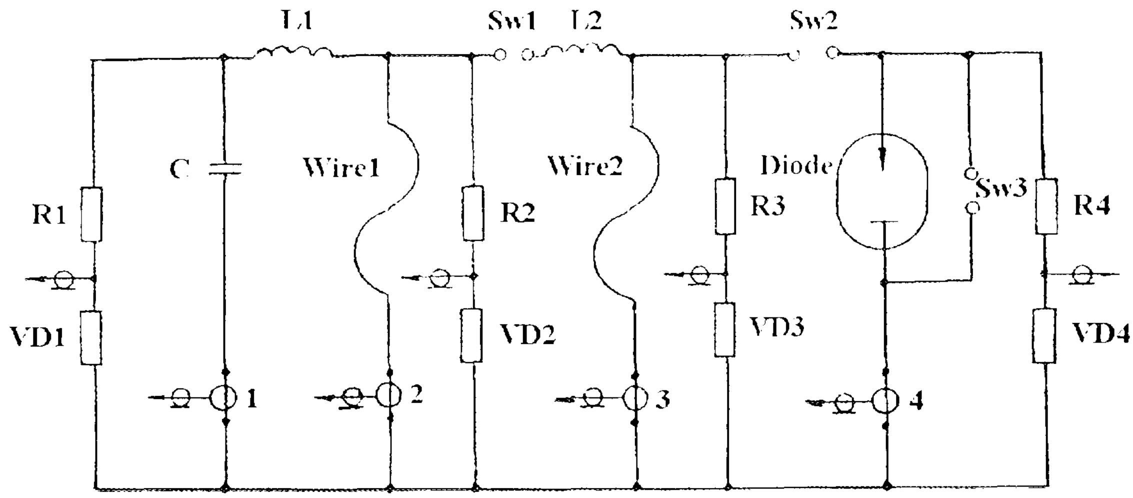

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Fig 1. Curcuit diagramm of accelerators
a) IGUR-1; b) IGUR-2
C - capacitance
L1, L2 - inductance of the 1st and 2nd cascades
Wire1, Wire2 - electric explosive wires of the 1st and 2nd cascades
Diode - acceleration tube
R1-VD1, R2-VD2, R3-VD3, R4-VD4 - voltage dividers
Sw1, Sw2, Sw3 - commutators in accelerator
1, 2, 3, 4 - "Rogovsky belt" to measure current in accelerator circuit

into operation and was named IGUR-1 (Radiation pulse gamma-ray facility) [1]. This facility development and manufacture costed 60,000 USD.

Fig.1a gives the simplified electric circuit of the accelerator. This accelerator has been used during 15 years.

Operation of the inductive storage with electric explosive wires (EEW) was studied on the "Sigma" test bench. It was used to investigate cascade switching on of inductive storages [2]. Voltage multiplication coefficient of 15 was obtained in the case with two cascades of electric explosive wires. Voltage of 600 kV was obtained at the output of the second cascade with the 40 kV input voltage. The dependence between the multiplication coefficient and energy loaded rate into EEW has been shown.

When results on "Sigma" test bench have been obfained it was decided to develop IGUR-2 electron accelerator. IGUR-2 high - voltage power source consisted from Marx generator and two cascades of the inductive storage with electric explosive wires. Fig. 1b gives the picture of the IGUR-2 simplified electric circuit.

IGUR-2 accelerator was the largest facility where the air insulation of high-voltage units was used. It also used the diode with a sectioned insulator.

The diode was operated in three modes:

- bremsstrahlung generation mode;
- mode of operation with the electron beam, extracted into atmosphere;
- mode of operation with the electron beam propagation in the diode

Main parameters for IGUR-1 and IGUR-2 accelerators are given in Table 1.

Table 1. Main parameters of IGUR-1 and IGUR-2 Facilities.

Main characteristics	IGUR-1	IGUR-2
Stored energy, kJ	135	300
Marx generator output capacitance, μF	0.29	0.15
Marx generator output voltage , MV	0.96	2
Inductance of the first cascade, μ Gn	36	28
Inductance of the secont cascade, μ Gn	-	3
The first cascade voltage, MV	3.1/5*	3.7/7*
The secont cascade voltage, MV	-	4.5/12*
Diode inductance, μ H	2	3.7
Diode voltage,MV	2.8	3.7
Diode current, kA	44	70
Bremsstrahlung pulse duration, μ sec	0.1 - 0.5	0.1 - 0.5
Bremsstrahlung pulse rate on 1 m, Rads/sec	$5 \cdot 10^8$	$2 \cdot 10^9$
Density of electron beam energy, J/cm^2	300	300/2500**

* Data refer to the loadfree (open circuit) operation mode.

** Measurements in vacuum at the anode plane.

Using of air insulation in order to reach voltages of megavolt range results in the increasing volume of the facility and therefore to the increasing of inductance of the circuit units. As a result the maximum of output power of accelerator is limited. A new generator IGUR-3 with units deposition in transformer oil has been developed in order to avoid this limitation.

IGUR-3 facility

For the designing of IGUR-3 accelerator the following developments and investigations were necessary:

- selection of the low-inductance design of the accelerator; [4]
- development of the low-inductivity diode;
- study of electric energy commutation in transformer oil;
- study of electric explosion of wires in various media; this enabled the development of a simple and easily servicing electrical explosive wire unit;
- development of a gas switch for 100 kV and 250 kA to switch Marx generator.

This work was done on specially designed test bench. Theoretical studying and numerical simulation of EEW behaviour under different application conditions were performed at the same time with experiments.

A.V.Luchinsky and Yu.D.Bakulin have developed MHD code for one-and two cascade electric explosion of wires on the basis of equations of state for copper and aluminium obtained at VNIITF [5].

Simple similarity relations, which enabed quick and rather accurate practical determination of EEW main parameters in the maximum power mode were developed for engineering designing.

Experimental research and numerical simulation efforts resulted in the development of IGUR-3 electron accelerator which was manufactured and put into operation in the end of 1978. The accelerator design is given in Fig.5.

High-voltage pulse is formed by inductive storage with the switch based on electroexplosive wires. The primary storage consists of 1.4 MV two Marx generators. Total stored energy is 300 kJ. Marx generator is located in a tank with 1.2 m in height and 7.5 m in diameter. Its axis coincides with the axis of a container with 8.5 m in height and 2 m in diameter. This container incorporates an inductive storage, a wire explosion unit, an oil discharge shaping switch to decrease the pulse front and diode. The wire explosion unit consists of 15 tubes with 110 mm in diameter. The diode insulator has a sectioned design. It has 1.3 m in height and 0.9 m in diameter. Insulation rings are manufactured from kaprolon and the "gradient" rings are made from aluminum AMG alloy. All accelerator components are situated in the transformer oil.

Up to 7MV voltage pulse is formed when IGUR-3 accelerator inductive storage current is switched. Varying steepness of voltage increasing of 10^{11} V/s up to 10^{14} V/s is the particularity of this pulse. It enables the current (voltage) pulse front to be formed in 15...200 ns range on the diode due to the breakdown of the two-electrode shaping switch at different $\frac{du}{dt}$ [6]. Voltage pulse decay is formed due to the voltage pulse cut-off on EEW in EEW circuit and is controlled within 25...200

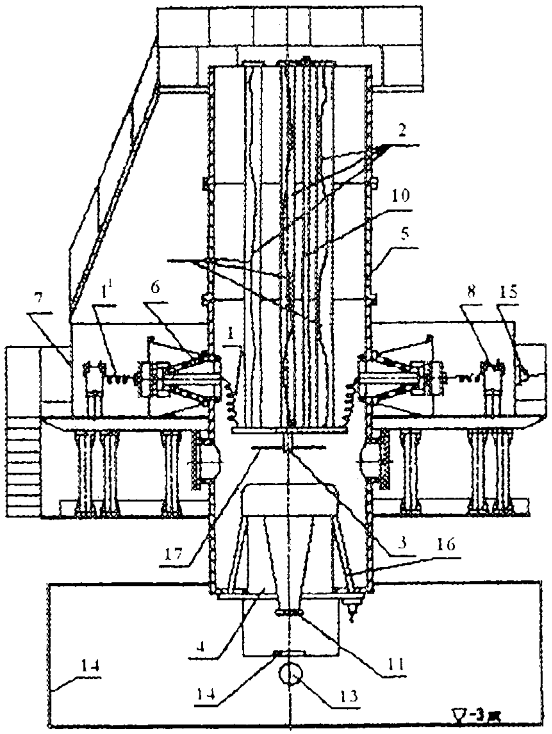

Fig 2. Accelerator IGUR-3 schematic design

1. Inductive storage; 2. Elecrically exploding wires; 3. Sharping discharged switch; 4. Accelerator tube (AT); 5. Pulse forming system tank; 6. Parfision insulator; 7. Matrix generator tank; 8. Matrix generator module; 9. Polyethylene tubes; 10. Electrically exploding wire voltage divider; 11. AT cathode; 12. AT anode; 13. Tested object; 14. Shielded box; 15. Grounding blocking; 16. AT capacitive - resistive voltage divider; 17. Shield.

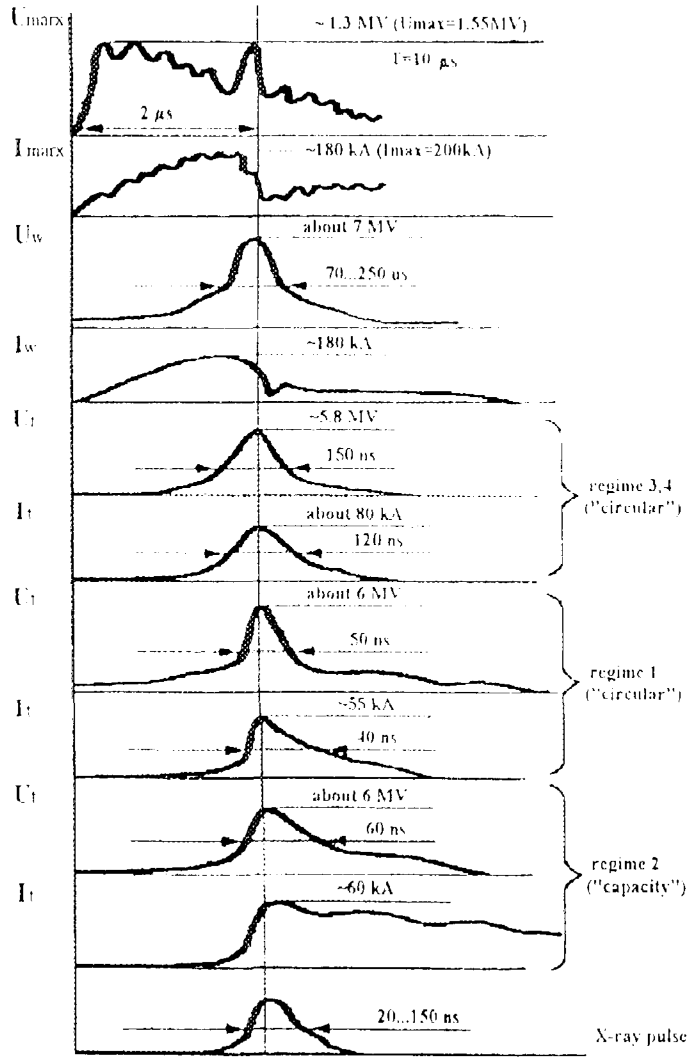

Fig 3. Typical wavefronts for the IGUR-3 accelerator electric circuit

ns range [7]. Processes of current (voltage) decay and rise shaping on the acceleration tube are interconnected. This ultimately enables shaping of bremsstrahlung pulses in $\tau/2$ ~ 15...150 ns duration range and electron beam pulses in $\tau/2$ ~20...400 ns duration range on the diode due to the gap change in the shaping switch. Main parameters for modes of bremsstrahlung pulse and electron beam pulse shaping selected for operation are given in Table 2. The Table gives seven bremsstrahlung producing modes and one electron beam producing mode.

Modes used to generate bremsstrahlung pulses of complicated shape and two series of pulses are possible due to the accelerator circuit reconstraction. One day is required to perform this reconstraction.

The mode for generating bremsstrahlung pulses of microsecond duration at $\tau/2 \leq 4$ mcsec was developed for the case when the diode is connected to Marx generator outlets. Fig.3 shows typical oscillograms for the first four operation modes (see Table 2).

Table 2. Main characteristics of the IGUR-3 accelerator exploitation regimes

Regime	Marx Storage Energy	X - ray Pulse Duration	Accelerator Tube Voltage	Accelerator Tube Current	Radiation Dose Power, Anode	Radiation Dose Power, R=1 m
	kJ	ns	MV	kA	R/s	R/s
1	300	25	5,8	55	4.10^{11} (S=300 cm^2)	10^{10}-maximum 7.10^3 - work regime
2	300	25	6	60	10^{13}-maximum 7.10^{12}-work regime (S=1,5 cm^2)	2.10^9
3	300	80	5,8	80	$2,5.10^{12}$ (S=6 cm^2)	3.10^9
4	300	80	5,8	70	4.10^{11} (S=300 cm^2)	7.10^9
5	300	about 4 μs	1	30	10^{10}	10^7
6		Regime of the "complex-form-pulse" generation 20-50->300-1000				
7		Regime of the "successire-two-pulse" generation 150-220 + 15-60			about 3.10^{10}+3.10^{10}	about 10^8 + 10^8

Electron beams:

Electron beams:	pulse duration	- 20...400 ns
	beam current	- about 30 kA
	maximum energy density profile of the beam	- about 500 J/cm^2
	total beam energy	- about 10^4 J
	mean electrons energy	- 2,5 MeV

EMIR - M facility

EMIR - M facility is a combination of two pulse high-voltage devices. The first one is the electron accelerator consists from Marx generator, the inductive storage, the current switch on EEW, the commutator unit and the diode. The second one- is the pulse high-voltage generator and the field-generating system (FGS) designed to generate the electromagnetic field. The devices are combined in the way, that the

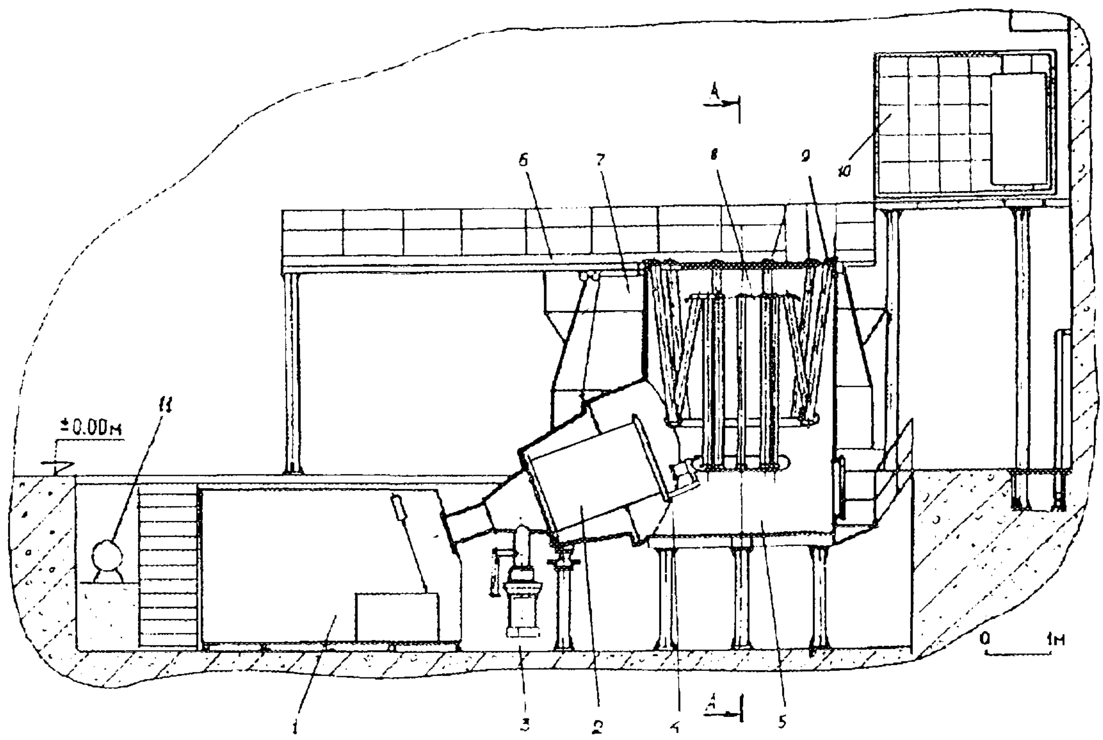

Fig 4. EMIR-M facility.
1. Testing box; 2. Acceleration tube; 3. Vacuum pump; 4. Acceleration tube commutator; 5. Container of wire explosion unit; 6. Technological platform; 7. Container of modulis unit; 8. Wire explosion unit; 9. Polyethylene tubes to place explosive wires; 10. Screened box with recording and measuring instruments; 11. Motor - generator of independent power supply.

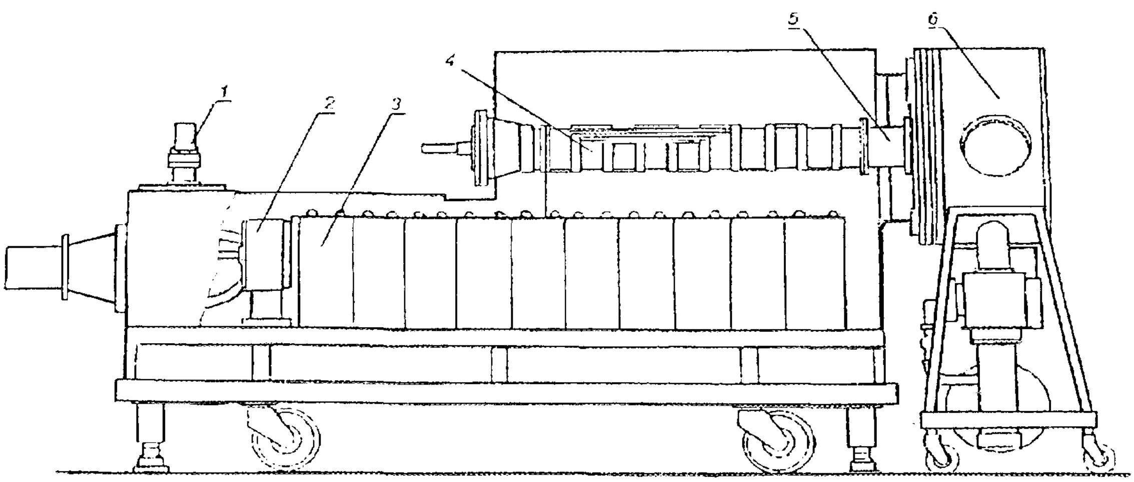

Fig 5. "Signal-20" accelerator.
1. Interlock; 2. Commutating discharger; 3. Capasitor bank; 4. Pulse generator system; 5. Discharger reducing a pulse front; 6. Laser vessel.

pulsed gamma-ray yield or electrons flow and the electromagnetic field can be generated in the testing zone simultaneously or independently.

In addition, Marx generator design and its configuration in the form of independent units enable the generation of two pulses with controlled time interval using one diode. Fig.4 gives the common view of EMIR-M facility.

Accelerator output characteristics were experimentally investigated depending on the following parameters:

- EEW (length, diameter, number);
- diode commutator;
- cathode-anode design.

When joint radiation and electromagnetic actions are performed on the tested ofjects, the time interval between these actions may be controlled in wide range.

Main characteristics of operation modes for EMIR-M facility are given in Table3.

Table 3. Main characteristics of operation modes for EMIR-M facility.

1. Bremsstrahlung pulse generation mode:	
Marx generator-stored energy	580 kJ
dose rate near the target	$2 \cdot 10^{12}$ rad/s
dose rate at 1 m distance from the target	$3 \cdot 10^{9}$ rad/s
radiation pulse duration	60 ns
average energy of γ-ray	$\cong$ 1 MeV
2. Extracted electron beam mode:	
Marx generator-stored energy	290 kJ
energy density of extracted beam	300 J/cm^2
duration of beam current pulse	$\leq$ 100 ns
beam current	up to 20 kA
3. Electromagnetic field-generation mode:	
the electromagnetic radiation generator stored energy	up to 1.5 kJ
electric field strength	$\leq$ 400 kV/m
magnetic field strength	$\leq$ 1.2 kA/m
pulse front duration	$\cong$ 40 ns
pulse duration	$\cong$ 1 mcs
4. Joint action of γ-ray pulse and electromagnetic radiation pulse mode has parameters mentioned for modes 1 and 3.	

SIGNAL facility

The technology developed for IGUR type accelerators was used as the basis for the development of low-impedance accelerators with low-inductive energy storages and electric explosive wires.

The first low-impedance generator SIGNAL-20 (High-Current Pulse Laser Pumping Generator for 20 kJ) was developed in the beginning of 80 s. It was specially developed to pump eximer laser by the electron beam. The common view of the fasility is given in Fig.5. The primary energy storage consists from capacitor bank of 4 μF capacity and 0.25 μH inductance which in switched by the gas switch.

The capacitor bank is discharged into the stored capacitor through the coaxial system of electric explosive wires. The pulse shaped on the inductor is applied to the coaxial diode with the blade-like cathode and the cylindrical anode of 50 mm thickness titanium foil through the shaping gas switch. The anode is used as a one wall of the laser vessel. Energy release density of 0.2 J/cm^2 for the electron beam having ±20% ununiformity at the edges was obtained in the laser vessel with 31 cm length and 4 cm diameter. The diode with the plane anode was used in the modes for producing the extracted electron beam and the bremsstrahlung. In this case, electron current pulses up to 80 kA with electron energy 400 keV and up to 100 ns pulse duration were generated. The accelerator is 3.3 x 0.7 x 1.6 m^3 in size and has a movable design.

The same technological scheme was used for the creation of SIGNAL-24 accelerator which is designed for radiation investigation of electronic components and materials.

At present time SIGNAL-24 accelerator has been upgraded. Plasma opening switch is used as the interruptor instead of electric explosive wires. The accelerator is used to investigate Z-pinch on wire. Current higher than 200 kA with rate up to 10^{13} A/s is loaded into Z-pinch. Those facilities are easily available physical laboratories due to their small size and relatively low cost. A small-scale accelerator with megaamps current in a load is being currently developed on the basis of prinsiples and technical solutions used in SIGNAL-type facilities.

Conclusion

The idea is conceived in VNIITF in early 60 th years, on the generation of the powerful pulses of electron beams by the accelerators with an inductive storage of energy and commutation by the electroexplosive wires, was developed into a new direction of pulse high-current high-voltage electronics. Fruitful work on accelerators development for many years made by Institute staff permited to create, on this basis, the generators for radiation investigations, having wide range of output parameters.

Main advantages of developed accelerators are the following:

- high density of energy and therefore the small dimension;
- higher power output compare to capacity storage;
- large range of output parameters, obtained at one accelerator;
- posibility of variation of output pulse duration in large time range /20ns-400 ns/ without changing accelerator design;
- simple manufacture technology and relatively low cost.

At present time the experience of work with inductive storage and electric-explosive wires is of a great importance and it can be used in investigations of plasma switches.

It should be noted a major contribution of Zysin,Yu.A., Luchinsky,A.V. and Martynov ,V.I. to the formation of this direction in accelerating technology.

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