INR RAS LINAC PROTON INJECTOR 100 Hz PRR OPERATION MODE

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Abstract

The injector provides linac by 400 keV protons with energy stability ±0.1%, pulsed ion current – up to 100 mA, 50 Hz pulse repetition rate (PRR) with 200 µs duration. PRR of the injector has been doubling with goal of linac average beam current increasing [1, 2]. Main stages and results of the injector modernization are presented.

Tests conducted earlier [3] have shown that pulse shape of the accelerating voltage produced by the high-voltage pulse generator (HVPG) at 100 Hz PRR has been distorted (Fig. 1).

It is seen that the high voltage (HV) value change in last forty microseconds of pulse duration is approximately 3% of the total pulse amplitude. This is unacceptable because the specified voltage change during pulse for the proton injector is ±0.1%.

Besides achieving a desired shape of HV pulse at 100 Hz PRR we have revealed two additional problems to be solved: first - instability of pulse amplitude and shape, associated with presence of a second 50 Hz series of pulses ("doubling of pulses") and second - overheating of the HVPG individual components and elements. This report contains, basically, the information relating to achievement of desired HV pulse shape. The HVPG circuit diagram is shown in Fig. 2.

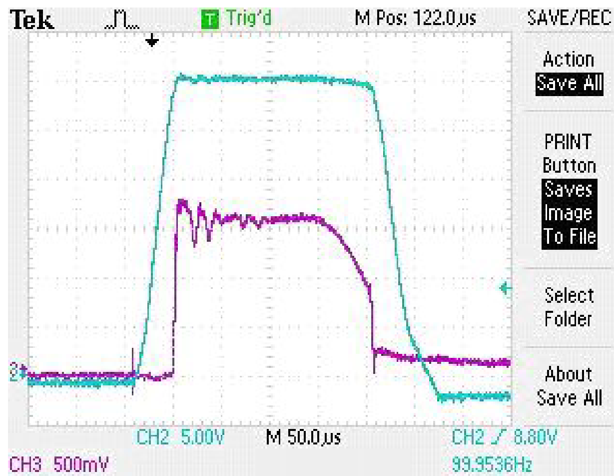

Figure 1: Oscillogram of the HVPG pulse at 100 Hz PRR (the pulse with smaller amplitude is the top of the HV pulse on a larger scale).

The HVPG consists of: 400 kV pulse transformer (PT-400), multi-cascade discriminator (MD) which stabilizes amplitude of HV pulses, sub-modulator that provides pulses with amplitude up to 20 kV to the PT-400 primary winding. The HVPG structure also includes three-phase 0 ÷ 380 V, 100 kVA auto transformer; step-up 380 V / 22 kV, 100 kVA transformer; the stabilization system of accelerating voltage which is intended to compensate the HVPG power supply slow changes, and the pulse top tilt compensation system.

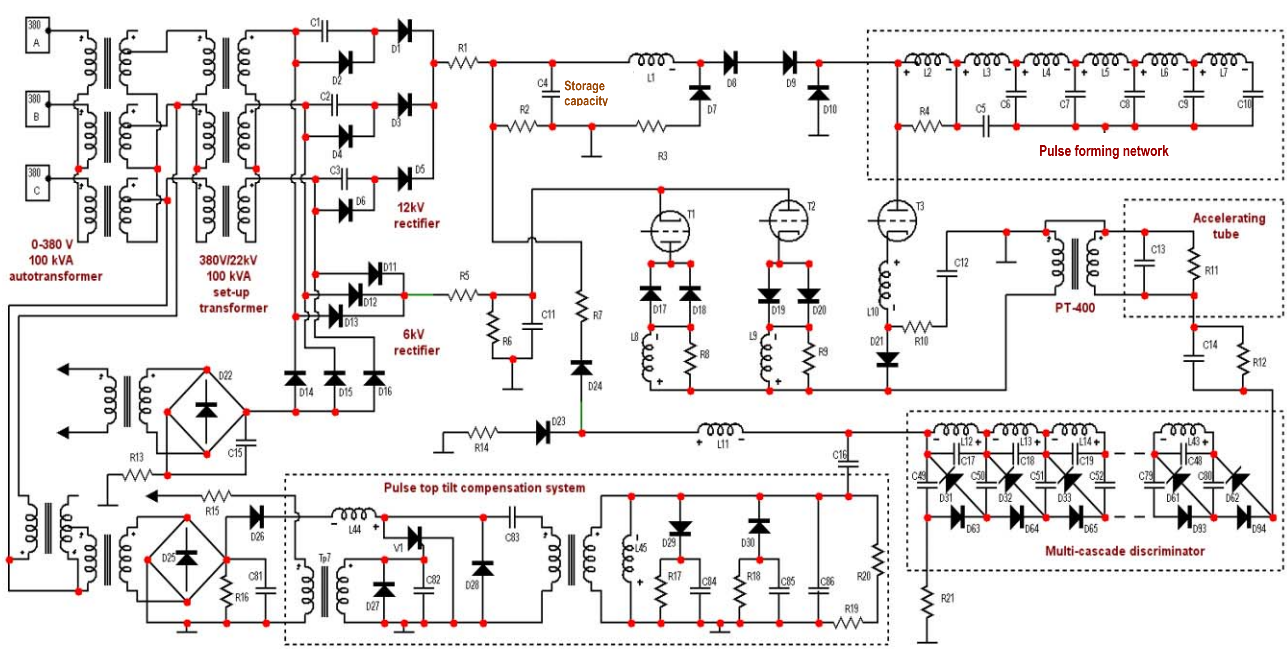

Figure 2: The proton injector HVPG electrical circuit.

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HVPG voltage pulse is measured using the precision capacitive voltage divider embedded in the PT-400. Switching of the sub-modulator voltage pulses is carried out with high-voltage thyratrons.

The HVPG is developed in the 1970's at the D.V. Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA, St. Petersburg) [4].

The HVPG operates as follows: C_4 storage capacitor of 11 μF is charged up to 12.5 kV by full-wave doubler. C_{11} leading edge shaper storage capacitor of 2.5 μF is charged up to 6 kV by six phase rectifier.

The pulse forming network (PFN) capacitors are charged in a quasiresonant way from C_4 storage capacitor through 8 H choke to a voltage of about 1.6 Uc_4.

When T_2 thyratron is opened then C_{11} capacitor is discharged through D_{19}, D_{20} diodes and L_9, R_9 buffer circuit to the PT-400 primary winding. As a result, the forced charge of constructive capacitance connected with the PT-400 secondary winding is occurred and the pulse leading edge of 40 μs base duration and of 400 kV amplitude is formed.

The trailing edge of pulse is formed by T_1 thyratron triggering. The charge which is stored in the constructive capacitance of the injector equipment is recurred in C_{11} capacity.

HV pulse voltage is applied to the accelerating tube which has the capacitive-resistive (water) voltage divider (R_{11} and C_{13}) as well as to the MD via R_{12} resistor and C_{14} capacitor.

The top of 200 μs HV pulse is formed during the PFN discharge to the PT-400 primary winding through T_3 thyratron, L_{10} choke and D_{21} diode assembly. Parameters of $C_5 \div C_{10}$ capacitors and $L_2 \div L_7$ inductances and the amount of the PFN cells are selected so as to provide the required 200 μs discharge current pulse duration.

Let us assume that HV pulse is supplied to the MD. If amplitude of the PT-400 open-circuit pulse voltage exceeds sum voltage of $C_{49} \div C_{80}$ capacitors, then $D_{31} \div D_{62}$ diodes are opened and $C_{49} \div C_{80}$ capacitors are connected in series, giving the stable (as a first approximation) 400 kV total voltage during HV pulse top. Current via the MD is limited by inner HVPG impedance and is proportional to difference between the PT-400 secondary winding open-circuit voltage and the MD voltage. This current charges the capacitors and the MD voltage slightly increases during the pulse.

$L_{12} \div L_{43}$ series-connected chokes are connected in parallel to $C_{49} \div C_{80}$ capacitors during the pulse top. Choke currents increase under influence of the U_{Ci} pulse voltage, which value is determined by relation:

$$I_{Ci} = (U_{Ci}\, \Delta T) / L_{MD}$$

where: I_{Ci} - current change in the i^{th} MD choke during the pulse, ΔT- pulse duration, L_{MD} - choke inductivity.

Between pulses MD state is changed:

- $D_{31} \div D_{62}$ diodes are closed, $D_{63} \div D_{94}$ diodes are opened and serial connection of $C_{49} \div C_{80}$ capacitors during pulse top is switched into PFN type circuit.
- an energy stored during pulse top in the MD chokes and capacitors is recurred to C_4 storage capacitor. Herewith some energy is lost, mainly in R_7 resistor.

Advanced analysis of the HVPG circuit has been performed with the software package Micro-Cap 9.0 [5]. It makes possible to receive information about processes in the HVPG which is not available by means of direct measurements when using the real HV equipment.

In particular it has been found that voltage of the MD capacitors is redistributed during a pulse: voltage of $C_{65} \div C_{80}$ capacitors ("upper" MD capacitors) decreases relative to the middle MD capacitor voltage, while voltage of $C_{49} \div C_{64}$ capacitors ("lower" MD capacitors) increases. Calculations show that C_{49} capacitor voltage reaches 18 kV, while C_{80} capacitor voltage is about 7 kV. I.e., the non-uniformity of the capacitors voltage distribution reaches a significant value. It leads to a redistribution of total current between capacitor and choke in each cascade. "Lower" choke currents reach higher values during pulse than "upper" choke currents and currents through cascade capacitors are changed in contrary. This can result in disruption of normal operation of the MD if any "lower" cascade capacitor current decreases to zero value before the end of 200 μs pulse top duration.

A cascade capacitor voltage has been decreased to the C_4 capacitor voltage value if transition processes are ending before next HV pulse beginning. The example of simulation at 100 Hz PRR with 7 H choke inductivity is shown in Fig. 3.

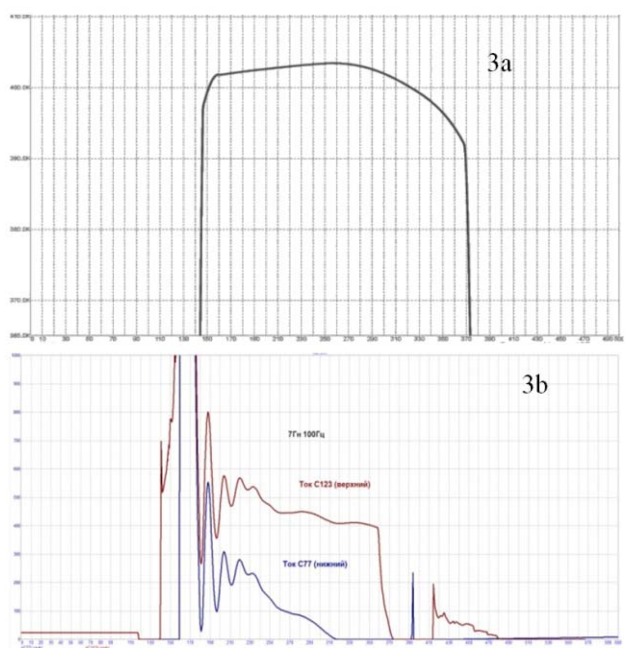

Figure 3: Simulation results for HV pulse top (3a) and for "upper" and "lower" MD capacitors current shape (3b, upper and lower curve, respectively).

Simulation results show that when the HVPG operates at 100 Hz PRR with 7 H choke inductivity then there is a "decline" with a voltage difference of about 10 kV. It begins at 115^{th} μs. The current of "lower" MD capacitor

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decreases to zero value at 155th µs in such a way (Fig. 3b): between 115th and 155th µs the zero current of capacitor signifies a closure of corresponding "direct" diode and violation of normal MD operation, which leads to appearance of "decline".

Fig. 4 shows similar curves for 20 H choke inductivity.

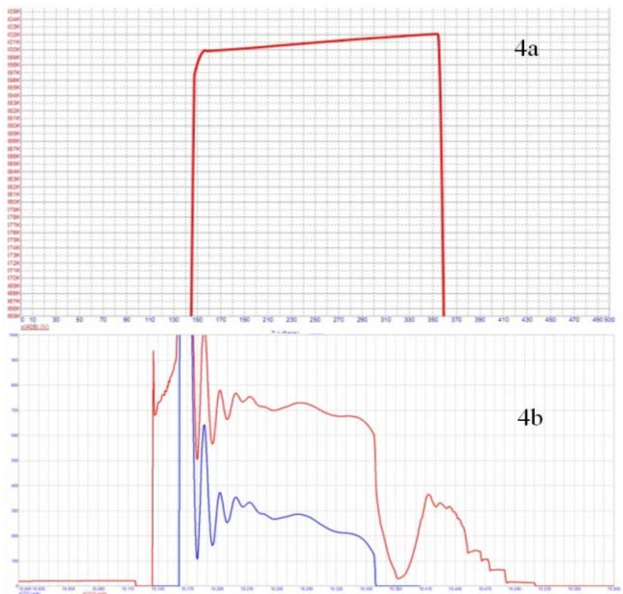

Figure 4: Simulation results with choke inductivity of 20 H.

We do not observe the HVPG pulse top "decline" (Fig. 4a) as well as vanishing of the MD "lower" capacitor current (Fig. 4b) when increasing choke inductivity up to 20 H.

The MD chokes were replaced by the new ones which have parameters as follows: L = 20 H, operating voltage – 25 kV, magnetic core - type of PL40h45-120.

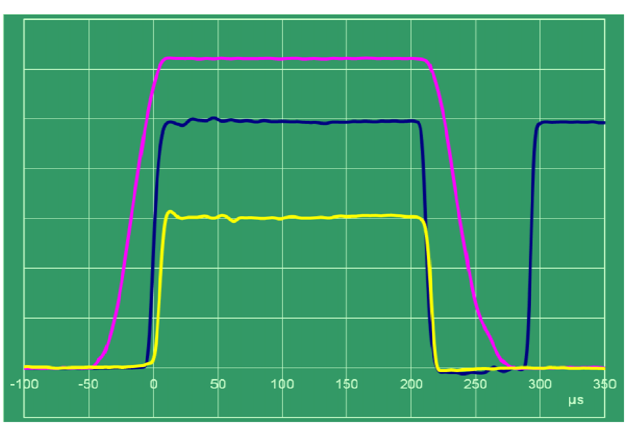

Figure 5: Oscillograms of the HVPG pulse at 100 Hz PRR (the yellow pulse with smaller amplitude is the top of HV pulse on a larger scale). Also there are (dark blue) the beam current curve and 100 mA calibrator pulse (on the right).

The oscillogram of HV pulse at 100 Hz PRR is shown in Fig. 5. From the tests carried out it follows that the changes have improved stability during HV pulse flattop at 100 Hz PRR to a desired value of ±0.1%.

CONCLUSION

The model of the high-voltage pulse generator is developed. We have achieved the satisfying accuracy and reliability of the simulation results.

The analysis has identified a number of necessary HVPG constructive changes. Its realization has allowed us to get 100 Hz PRR proton injector operation mode with 200 µs pulse duration, energy instability less than ±0.1% and ion beam current up to 100 mA.

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