ANALYSIS OF 400 kV PULSE GENERATOR OPERATION

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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. The results of the high-voltage pulse generator operation analysis which have been done with the aim of pulse repetition rate increasing up to 100 *Hz* are given. Special attention is paid to operation of the multi-cascade capacitance-diode discriminator with inductances.

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INTRODUCTION

The INR linac proton injector provides at the accelerating tube exit a hydrogen ion beam with the following parameters: ion energy 400 *keV*; energy (pulse amplitude of accelerating voltage) stability ±0.1%; pulse top duration 200 μs, pulse repetition rate 50 *Hz*; pulsed ion current 100 *mA*; normalized transverse emittance 0.15 π $cm \cdot mrad$ for 90% of beam current. PRR of the injector has been doubling with goal of linac average beam current increasing [1].

The abbreviations made in the text:

HVPG	- high-voltage pulse generator;
PRR	- pulse repetition rate;
HV	- high voltage;
MD	- multi-cascade capacitance-diode discriminator with inductances;
PTSCS	- pulse top slope compensation system;
PFN	- pulse forming network;
PT-400	- 400 kV pulse transformer.

Currently, a project of increasing of proton linac average beam current is realized now by PRR doubling [2]. This requires a corresponding increasing of the proton injector PRR. However, 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).

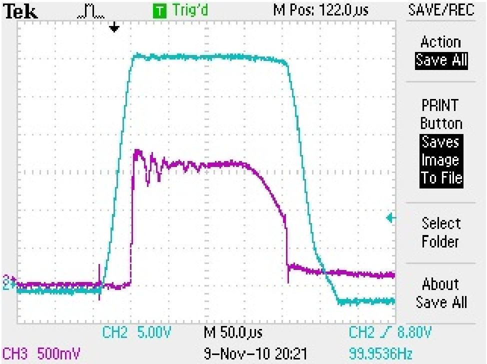

Fig.1. *Oscillogram of the HVPG pulse at 100 Hz PRR (the pulse with smaller amplitude is the top of the HV pulse on a larger scale)*

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.

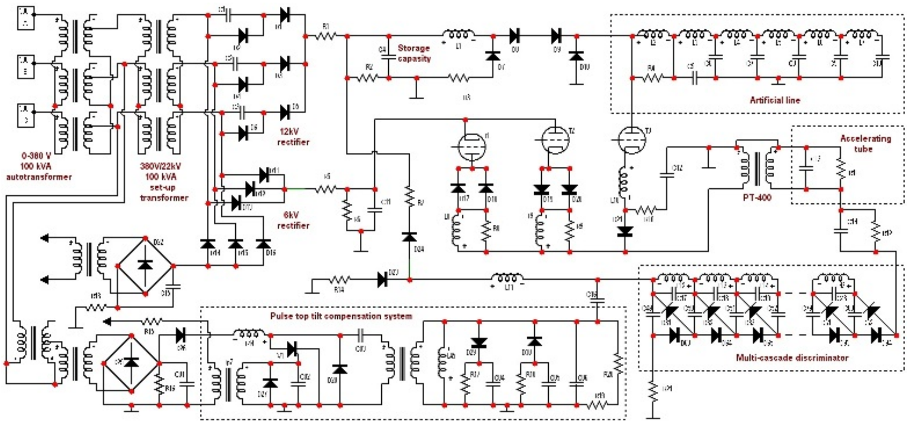

Fig.2. *The proton injector HVPG electrical circuit*

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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 article contains, basically, the information relating to achievement of desired HV pulse shape. The HVPG circuit diagram is shown in Fig.2.

The HVPG consists of: the PT-400; the MD, which stabilizes amplitude of HV pulses; the submodulator providing pulses with amplitude up to 20 kV to the PT-400 primary winding and made on the PFN basis. 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 50 Hz power supply slow changes and the PTSCS system. HVPG voltage pulse is measured using the precision capacitive voltage divider embedded in the PT-400. Switching of sub-modulator voltage pulses is carried out with HV thyratrons.

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 PFN capacitors are charged in a quasiresonant way from C_4 storage capacitor through 8 H choke to a voltage of about 1.6 U_{C_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.

200 μs HV pulse top 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 $C_5 \ldots C_{10}$ capacitors (0.15 μF), $L_2 \ldots L_7$ inductivities (2.5 mH) and amount of the PFN cells (6) are selected so as to provide the required 200 μs pulse top duration.

The MD stabilizes HVPG pulse top as follows: when HV pulse is supplied to the MD and providing that the PT-400 pulse voltage amplitude exceeds $C_{49} \ldots C_{80}$ capacitors sum voltage, $D_{31} \ldots D_{62}$ diodes are opened and $C_{49} \ldots C_{80}$ capacitors are connected in series, giving the stable (as a first approximation) 400 kV total voltage. During the HV pulse top there is a current in the MD. It is limited by inner HVPG impedance and proportional to difference between the PT-400 secondary winding open-circuit voltage and the MD voltage. But: current passage charges the capacitors. The MD voltage increasing is determined during the pulse flattop by the relation:

$$U_{MD} \sim \sum_{j=1}^{32} (I_j T)/C_{MD}, \qquad (1)$$

where j — the MD cascade number (amount of cascades equals to 32), I_j – capacitor current in j-th cascade, T — HV pulse flattop duration ($T = 200$ μs), C_{MD} – capacity of cascade capacitor ($C_{MD} =$ 0.5 μF).

The MD voltage rise that has been occurred during pulse flattop is compensated by the PTSCS which represents decreasing sawtooth voltage generator [5]. The amplitude of sawtooth voltage is chosen for the most complete MD voltage rise compensation.

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

$$I_{Ci} = (U_{Ci} \Delta T)/L_{MD}, \qquad (2)$$

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:

- $D_{31} \ldots D_{62}$ diodes are closed, $D_{63} \ldots D_{94}$ diodes are opened and serial connection of $C_{49} \ldots C_{80}$ 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.

Reactive energy stored during the pulse top in $C_{49} \ldots C_{80}$ capacitors and $L_{12} \ldots L_{43}$ chokes at 10. . . 100 Hz PRR does not have time to recur between pulses to C_4 storage capacitance due to the MD discharge time constant which is exceeding 100 ms. So at the beginning of a new pulse there is a current in the most part of the MD chokes. It is associated with energy recuperation from previous pulses. As a result, at higher PRR the chokes average current is increased.

Advanced analysis of the HVPG circuit has been performed with the software package Micro-Cap 9.0 [6]. 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 $C_{65} \ldots C_{80}$ capacitors ("upper" MD capacitors) decreases relative to the middle MD capacitor voltage, while voltage of $C_{49} \ldots C_{64}$ capacitors ("lower" MD capacitors) increases. C_{49} capacitor voltage reaches 18 kV amplitude at 100 Hz PRR, while C_{80} capacitor voltage is about 7 kV. I.e., the non-uniformity of the capacitors voltage distribution reaches a significant value. The MD element's voltages/currents non-uniform distribution leads to a redistribution of the MD total current between capacitor and choke in each cascade so that the MD capacitors current decreases as we move from the "upper" cascades to the "lower" ones during the pulse flattop. This process can lead to failure of the MD normal operation if "lower" cascades capacitor current has been vanished before the end of 200 μs pulse top duration.

After tuning of the Micro-Cap model at the 4-core CPU, 3.8 GHz, 8 GB RAM personal computer with 64-bit Win7 OS the standard account times are as follows: the conventional operating mode release schedule takes up to 30 minutes and the process of obtaining of results (for example, a HV pulse waveform) when a single key circuit element parameter is changed – up to 3 minutes.

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.

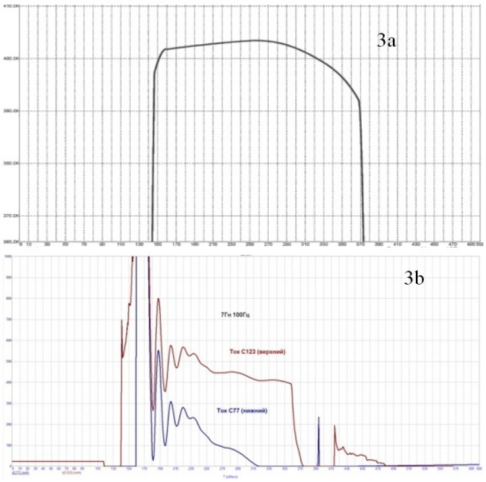

Fig.3. *Simulation results for HV pulse top (3a) and for "upper" and "lower" MD capacitors current shape (3b upper and lower curve, respectively)*

From the HVPG simulation results for 100 Hz PRR and 7 H choke inductivity it follows that at the end of pulse flattop there is a "decline" with a voltage difference of about 10 kV. This decline begins at ≈ 160-th microsecond of the 200 μs pulse flattop duration (Fig.3, a). At this moment the "lower" capacitor current is vanished to zero. It means closure of the corresponding "direct" diode and failure of the MD normal operation. That leads to appearance of HVPG pulse flattop "decline". But we do not observe the HVPG pulse flat-top "decline" (Fig.4, a) as well as vanishing of the MD "lower" capacitor current (Fig.4, b) when increasing choke inductivity up to 20 H.

In Fig.4 – similar curves for 20 H choke inductivity (PTSCS system is "OFF" in those simulation variants).

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

The MD chokes were replaced by the new ones (Fig.5) which have parameters as follows: L = 20 H; operating voltage — 25 kV; magnetic core – type of PL40x45-120; core material – cold-rolled 3408 electro-technical steel of 0.3 mm thick; coil body material – caprolon (PA6), the number of turns – 6000 for two coils (one choke); copper wire – ⊘ 0.67 mm.

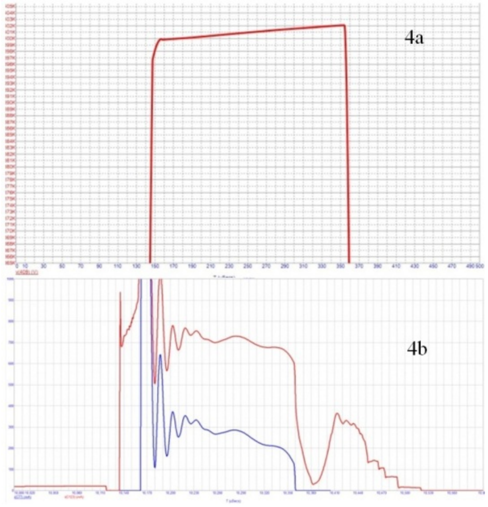

Fig.4. *Simulation results with choke inductivity of 20 H*

Fig.5. *General view of two installed MD cascades with the new chokes*

The HVPG tests have been carried out at 100 Hz PRR after installing the new MD chokes. The HV pulse oscillograms are shown in Fig.6. From the tests conducted it follows that the changes have improved the stability during HV pulse flattop at 100 Hz PRR to a desired value of ±0.1%.

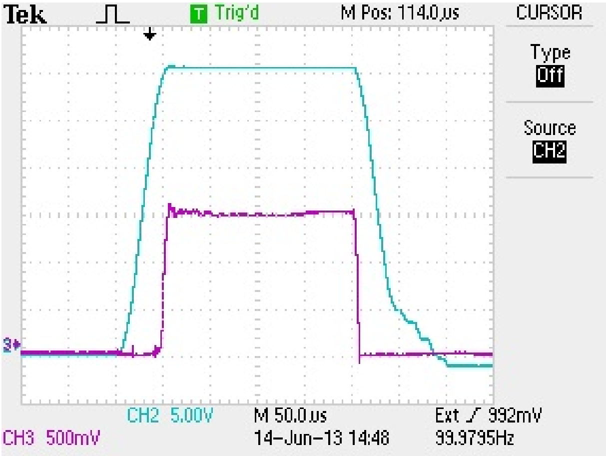

Fig.6. *The HVPG pulse oscillograms at 100 Hz PRR and the MD 20 H chokes (pulse with smaller amplitude - HV pulse waveform on a larger scale, the PTSCS system is ”ON“)*

CONCLUSIONS

The model of the high-voltage pulse generator is developed. We have achieved satisfying accuracy and reliability of simulation results. Simulation allows us to get information about processes in the HVPG which is difficult to obtain by direct measurements.

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

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References

1. A. N. Drugakov, A. V. Feschenko, A. I. Kvasha, A. N. Naboka, V. L. Serov. Investigation of INR DTL RF system operation of 100 Hz repetition rate // *Proc. of RuPAC-2012, St. Peterburg, Russia, September 24-28*, p.296.

2. A. V. Feschenko, A. I. Kvasha, V. L. Serov. Some peculiarities of the INR DTL RF system operation at doubling of average RF power level // *PAST. Series ”Nuclear Physics Investigations”*. 2014, N3(91), p.32.

3. V. I. Derbilov, S. K. Esin, E. S. Nikulin, O. T. Frolov, V. P. Yakushev. Average proton beam current increasing at the MMFL injector // *PAST. Series ”Nuclear Physics Investigations”*. 2004, N1(42), p.13.

4. Yu. V. Belov et al. // *Proc. of VIII All-Union Conference on charged particle accelerators,* Dubna, 1983, v.2, p.159 (in Russian).

5. V. N. Zubetz, V. I. Derbilov, S. K. Esin, E. S. Nikulin, O. T. Frolov, V. P. Yakushev. The stabilization system of 400...750 kV pulsed accelerating voltage // *PAST. Series ”Nuclear Physics Investigations”*. 1999, N3(34), p.52.

6. Micro-Cap 9.0, Electronic Circuit Analysis Program. Spectrum Software. 1021, South Wolfe Road, Sunnyvale, CA, 94086, www.spectrum-soft.com.

АНАЛИЗ РАБОТЫ ГЕНЕРАТОРА С АМПЛИТУДОЙ ИМПУЛЬСОВ 400 кВ

Е. С. Никулин, А. С. Белов, О. Т. Фролов, Л. П. Нечаева, А. В. Турбабин, В. Н. Зубец

Инжектор снабжает линейный ускоритель протонами с энергией 400 кэВ, стабильностью энергии ±0, 1%, длительностью импульсов 200 мкс и частотой повторения 50 Гц. Приводятся результаты анализа работы генератора высоковольтных импульсов, проведённого с целью повышения частоты следования импульсов до 100 Гц. Особое внимание уделено работе многокаскадного ёмкостно-диодного дискриминатора с индуктивностями.

АНАЛІЗ РОБОТИ ГЕНЕРАТОРА З АМПЛІТУДОЮ ІМПУЛЬСІВ 400 кВ

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Інжектор постачає лінійний прискорювач протонами з енергією 400 кеВ, стабільністю енергії ±0, 1%, тривалістю імпульсів 200 мкс і частотою повторення 50 Гц. Приводяться результати аналізу роботи генератора високовольтних імпульсів, проведеного з метою підвищення частоти проходження імпульсів до 100 Гц. Особлива увага приділена роботі багатокаскадного ємкістно-діодного дискримінатора з індуктивностями.