THE MODEL OF MICROWAVE PHASE INVERTER CONTROLLED BY A NEON PLASMA SOURCE

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In the wakefield accelerator for a separation of a long train of bunches to drive and accelerated ones, it is proposed to use a phase inverter of electromagnetic waves of the microwave frequency range. A change in the phase of the wave by 180° occurs when the microwave power is reflected from the resonator when the resonance is disrupted by igniting the plasma in a glass vessel placed in the resonator. A scheme for the implementation of a phase-inverter is proposed, for which a model version of the phase-inverter is assembled, and photomultiplier measurements of the radiation from a source of neon plasma are carried out. When a rectangular pulse of 0.2…1 μs duration, amplitude 250…800 V and current up to 1 A is supplied to the plasma source, the signal from the photomultiplier output has a rather "steep" rising edge (up to 58 ns) and a low-angle trailing edge (more than 100 μs). The duration of the decay (fall time) remains constant and does not change when the duration, frequency, and amplitude of the pulses applied to the plasma source change, and the duration of the rising edge decreases with increasing amplitude. Qualitative measurements on the phase invertor model showed that the waveforms of the reflected and transmitted waves have a similar shape as the signals from the photomultiplier output, but they have a flatter rising edge (200…500 ns) and the trailing edge (~ 400 μs). From the studies carried out it follows that the developed phase inverter can be used for a single (per pulse) separation of the bunch sequence relative to the wakefield wave.

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INTRODUCTION

Acceleration of charged particles by wakefields excited by a bunch or a train of bunches belongs to the two-beam acceleration method. In this scheme, the accelerated beam must be displaced relative to the generating beam by a certain distance (in a collinear scheme of acceleration by $s=(2n-1)\lambda/2$, λ – wavelength, n – integer). Usually, the same source of electrons is used to produce two beams. The required shift is achieved either by splitting the main laser pulse incident on the photocathode [1] or by dividing a single bunch in cross section by two by means of a notching device and manipulating it in the phase space [2, 3] or by elongation the path of the second beam part [4], deflected by rotary magnets, or by introducing a detuning between the bunch repetition frequency and the frequency of the resonance wave, as a result of which some parts of the beam are in the accelerating phase [5].

Disadvantages of the method [5] are the impossibility of obtaining a transformer ratio that exceeds the classical limit [6] and a large energy spread of the accelerated particles. This is due to the fact that each bunch of the train is at shifted wakefield phase relative to the preceding bunch. A charge of generating bunches and accelerated ones are equal, which also limits the maximum energy of accelerated particles. To avoid these drawbacks, we propose using a phase-inverter that will allow us to extract from a long sequence of bunches [5] a short train used for acceleration by the field of the preceding long train of drive bunches. In this case, both the drive and accelerated bunches can be at the same phase relative to the wave. The phase-inverter is located in waveguide transmission line between the magnetron and the accelerator klystron. The first part of the pulse of relativistic charged bunches, injected into the wakefield resonance structure, until the key fires, will excite the wakefield, all bunches will be at the retarding phase. After the change in the phase of the microwave oscillations at 180° applied to the klystron, the next bunches formed in the accelerator tract will be displaced relative to the preceding bunches by a distance that is a multiple of half the length of the wakefield. I.e. they will be in the accelerating phase.

Fast phase inverters with a rising edge $10^{-9}…10^{-11}$ s, used in modern microelectronics, are suitable for small power. To change the phase in sections of high-power microwave devices, several devices [7 - 11] have been proposed, the operation of which is based on the transmission of the microwave wave through the resonator. The microwave wave is reflected due to the detuning of the resonator when the dielectric constant (conductivity) of semiconductors in its volume changes [7], or when an electron beam is injected [8, 9], or when the plasma is ignited in the isolated part of the resonator (in a gas-discharge tube) [10, 11]. For the method [8, 9], pulsed high-current electron beams are required (an electron beam with a current of ~ 400 A, voltage U = 50…100 kV, duration 100 ns was used in [9]). To switch the reference signal from the driving generator to the accelerator klystron similar to described in [5], such large powers are not required, therefore, in the authors' opinion, it is more practical to use the plasma created in the resonator. The time of phase change in the resonator depends on the time of creation of the perturbation and the time when oscillations become steady-state [9]. For low-Q resonators in the microwave frequency range, the phase switching time is determined by the plasma creation time. Although the principle realizability of this method of switching the phase of the wave is shown in [10, 11], but the dependence of the phase switching time on the characteristics of the impulse voltage applied to the gas-discharge tube has not been investigated.

In this paper we consider a mock-up of a phase-inverter, the operation principle of which is based on the effect of the phase change of the microwave wave reflected from the resonator when disrupting the resonance. The disruption is carried out by igniting a neon plasma trapped in a glass vessel, which was located in the antinode of a standing H_{01} wave. Below are the results of measurements of the amplitudes of the reflected and transmitted microwave waves.

The design of the plasma switch in [10, 11] made it impossible to observe the behavior of the plasma, since it ignites in the resonator volume, and it was not possible to place the photomultiplier there. In this study, the time characteristics of the ionization and recombination of neon plasma were registered in a separate stand by the photomultiplier FEU-68. These measurements make it possible to evaluate the possibility of controlling the reflectivity of the phase invertor.

EXPERIMENTAL SCHEME AND TECHNIQUE

For the design of the phase inverter, the scheme shown in Fig. 1 is proposed.

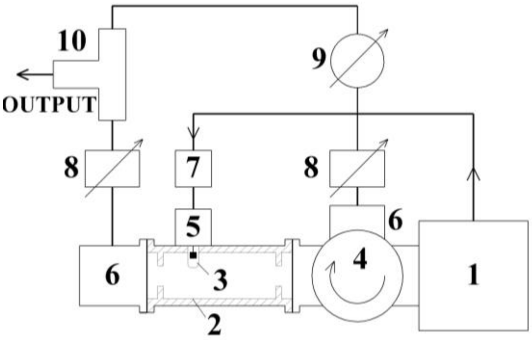

Fig. 1. Scheme of the developed plasma phase inverter: 1 – microwave generator; 2 – resonator; 3 – plasma source; 4 – circulator; 5 – the generator of rectangular impulses; 6 – waveguide-to-coaxial adapter; 7 – schematic diagram of triggering a rectangular pulse generator; 8 – attenuator; 9 – phase shifter; 10 – T-bend

The operation of the phase inverter is as follows. The microwave power from the generator 1 through the circulator 4 enters the resonator 3. At the same time, with the beginning of the microwave power generation pulse, a circuit 7 is started, which sets the switching delay, and can also provide the turning number of generator of rectangular pulses 5 required during the beam passage time.

Resonator 3 is a segment of a rectangular waveguide bounded by the input and output diaphragms. In the place of the maximum of the electric field in the resonator, a plasma source is installed. Initially the resonator is tuned to a generator frequency. If plasma source is off, then the noninverted microwave wave leaves the resonator and passes through the elements 6, 8, 10 to the output of the phase-inverter circuit. Then, when the rectangular pulse generator is started, the plasma source is turned on, the resonator is detuned, the microwave power is reflected and the inverted phase wave through the circuit having elements 6, 8, 9 and 10 is fed to the output.

To simulate the phase inverter operation, a model version of the device, presented in Fig. 2, was assembled.

As can be seen from Fig. 2, most of the elements of the circuit (positions 1-6) are the same as in Fig. 1. The reflected and transmitted signal from the generator 1 is fed to different inputs of the oscilloscope. For the model as a resonator, a section of the waveguide R32 with a transverse dimension of 34×72 mm and a length of 155 mm was chosen. The plasma source was a gas discharge in neon. The advantage of the neon discharge is that for its ignition, several hundred volts are sufficient for the voltage rather than kilovolts in the plasma source used in [10]. For the current experiments, a neon lamp TN-02, located at a distance of 1/6 of the length of the resonator, was the plasma source. As a microwave generator, the measuring generator G5-80 was used, which allows to operate at a frequency range from 2.56 to 4 GHz.

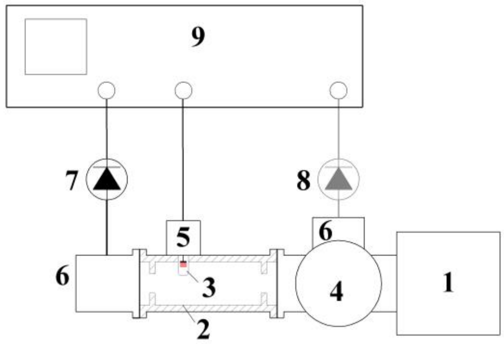

Fig. 2. Scheme of the model version of the plasma phase inverter: 1 – microwave generator; 2 – resonator; 3 – neon plasma source; 4 – circulator; 5 – generator of rectangular pulses (the scheme is shown in Fig. 3); 6 – coaxial-waveguide transition; 7 – incident power detector; 8 – reflected power detector; 9 – digital oscilloscope

Since the characteristics of the phase inverter depend to a large extent on the plasma source, we performed additional measurements of the excitation time of the neon plasma at a separate stand. The scheme of the stand is shown in Fig. 3.

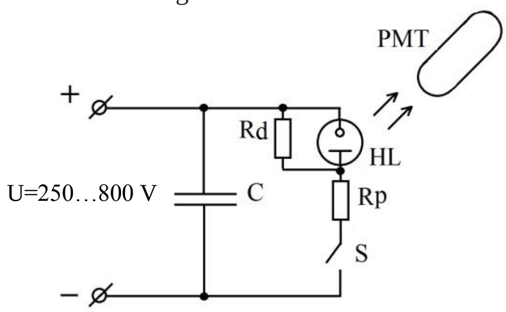

Fig. 3. Scheme of the stand for measuring the radiation of a neon plasma, where PMT is a FEU-68, HL is a neon lamp, U is the DC supply voltage of the circuit, C is a discharge capacitor, Rd is a discharge resistor, Rp is a protective resistor, S is a semiconductor switch

One of the main elements on which the speed of the circuit depends is the "S" key, which uses a "fast" MOSFET transistor with an on/off time of <7 ns. Elements of the discharge circuit C, Rp and the conductors connecting them are made with a minimum inductance. Resistor Rp serves to protect the MOS transistor from exceeding the permissible current. The control of the S key is carried out from the square-wave generator G5-54. Pulses from the generator to the key come through the optocoupler and the driver (not shown in the diagram). The optocoupler provides a galvanic isolation of the square-wave generator from the high-voltage circuit. This reduces the mutual influence of the circuits and the appearance of parasitic inducing when measuring the shape of voltages and currents and adjusting the circuit. The driver provides current amplification for quickly charge the parasitic capacitance of the gate of the

MOSFET transistor, thereby providing a fast-closing and opening of the transistor.

The generator with the pulse shaping circuit for creating the neon plasma provided the control of the pulse characteristics from the output of the photomultiplier in the following ranges: the pulse repetition rate (f) is 100 Hz…4 kHz, the pulse duration (τ) is 0.2…10 μs, the voltage amplitude (U) is 250…800 V.

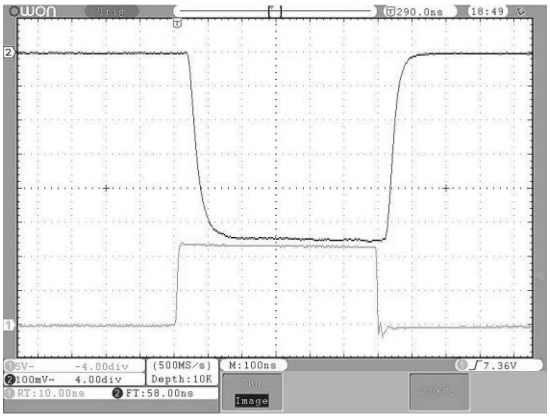

Fig. 4. Oscillograms of signals: the lower "beam" is the form of the voltage applied to the LED, the upper "beam" is the negative pulse from the output of the photomultiplier because of the LED radiation

The time dynamics of the produced plasma was investigated from the radiation intensity. To measure plasma radiation, PMT FEU-68 was used, powered by a 1200 V constant voltage source. The signal from the photomultiplier output came to a digital storage oscilloscope with a maximum sweep frequency of 100 MHz. For the correct display of pulses, additional capacitors were added to the FEU-68 circuit, according to [12].

The PMT with additional capacitors test was performed by measuring the radiation of a conventional signal LED, the results are shown in Fig. 4.

It is seen from Fig. 4 that the shape of the pulse from the photomultiplier output repeats quite well the form of the voltage supplied from the generator to the LED, that is required for our experiments.

RESULTS OF MEASUREMENTS

During studies of the neon plasma radiation carried out at the stand (see Fig. 3), oscillograms of the signal from the photomultiplier output were obtained. One of them is presented in Fig. 5.

A special feature of all the obtained oscillograms, as well as those shown in Fig. 5, is the presence of a high-frequency (b) c short spike in the front part of the pulse, and a low-frequency component with a smooth decay (a). The high-frequency part of the oscillogram from the output of the photomultiplier corresponds to the process of creating plasma, and the low-frequency part of the oscillogram is its relaxation. The high frequency has approximately the same duration as the pulse applied to the plasma source (lower beam 1), but has a smoother shape. The duration of the low-frequency component decay reaches 100 microseconds and remains practically constant when the amplitude, duration and frequency of the pulses applied to the neon plasma source change. A large plasma relaxation time does not allow inverting the phase many times during the microwave pulse in the proposed phase inverter. This is a shortcoming of the used plasma source.

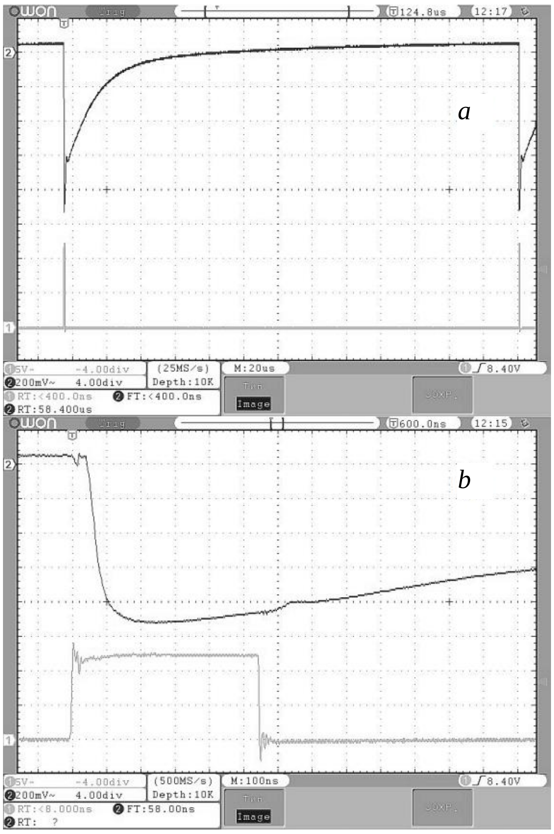

Fig. 5. Oscillogram of signal from the photomultiplier for scaling a) 20 μs/div and b) 100 ns/div (upper curves) at voltage on the neon plasma source equal to U = 800 V, duration τ = 0.5 μs and frequency f = 4 kHz. The lower curves are the form of the voltage applied to the LED

In the experiments, it was found that when the voltage decreases from 800 to 500 V, the amplitude and shape of the pulse remain practically unchanged. Further, with a decrease in voltage below 500 V, a decrease in the low-frequency part of the pulse is observed, and then, starting from 350 V and until the plasma extinction at 250 V, the amplitude and high-frequency part of the pulse falls off.

Fig. 6 shows the dependence of the rise time of the signal from the photomultiplier output on the voltage at the discharge for different values of the pulse durations and the repetition frequency.

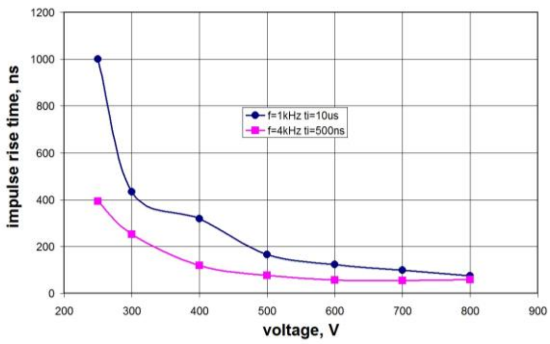

Fig. 6. Dependence of the duration of the pulse rise time (the rising edge of the signal) from the photomultiplier output on the voltage at the neon plasma source. The upper curve corresponds to f = 1 kHz and τ = 10 μs, the lower curve f = 4 kHz and τ = 500 ns

The minimum duration of the rise edge of the signal from the photomultiplier output obtained in the experiments is 58 ns and is observed near the maximum value of the voltage U = 800 V, regardless of the duration (τ) and the repetition rate (f) in the range of interest.

Thus, carried out experiments to study plasma characteristics allowed to optimize the operation of the circuit (see Fig. 3) and to obtain a plasma generation time of 58 ns, which makes it possible to detune the resonator fairly quickly in the model of the plasma microwave phase inverter (see Fig. 2). Using the parameters at which from the PMT output the shortest pulse rise time of 58 ns was obtained, oscillograms of the incident and reflected power on the phase inverter mode (see Fig. 2) were recorded. The results are shown in Fig. 7.

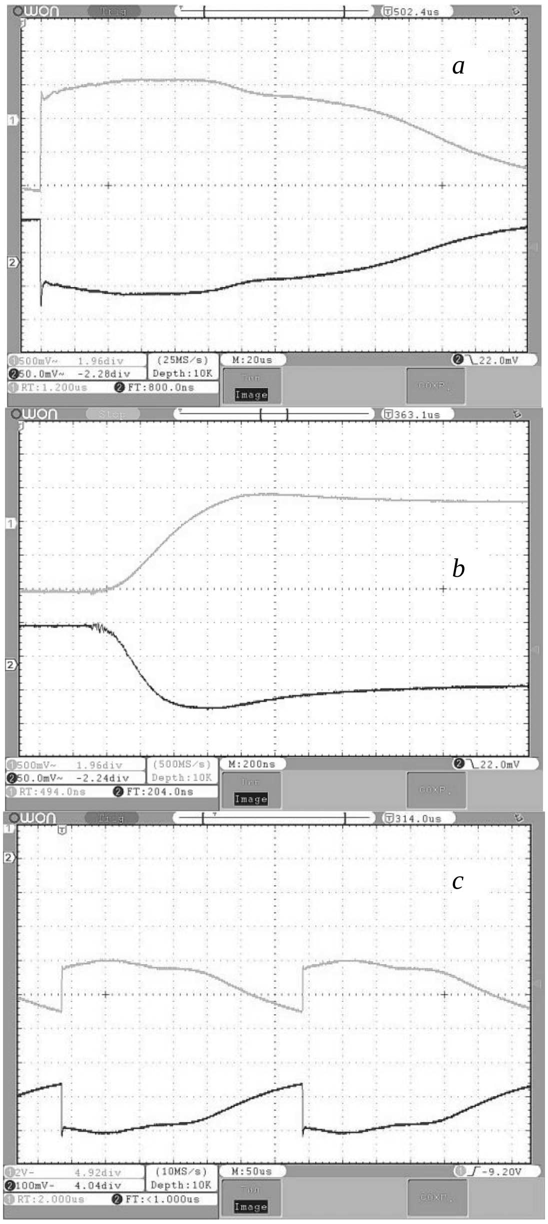

Fig. 7. The oscillograms of the incident (beam 1, upper curve) and the reflected (beam 2, lower curve) signals illustrating the shape (a), the front duration (b) and the amplitude (c) of the propagated signal. Time scaling is a) 20 μs/div; b) 200 ns/div and c) 50 μs/div. The generator parameters: U = 800 V, duration τ = 0.5 μs and frequency f = 4 kHz

As seen from Fig. 7,a, the pulse shapes from the incident (upper beam 1) and reflected (lower beam 2) pulses are similar to the pulse shape from the photomultiplier output (see upper beam 2 Fig. 5,a), but it has a slightly more gentle decline. Also, the rise time of the reflected and incident signals (see Fig. 7,b) are also several times larger than the pulse rise time from the photomultiplier and is 500 ns for the incident wave and 200 ns for the reflected wave. This may be due to measurement error, in particular, with a large nonlinearity in the characteristics of the detectors 7 and 8 of the model of the plasma phase inverter (see Fig. 2).

It is seen from Fig. 7,c that the magnitude of the signal difference from the reflected power detector and from the detector of transmitted power caused by the resonator detuning is about 20 and 30% of the total signal amplitude, respectively, which coincides with the results obtained by the authors in [9].

CONCLUSIONS

Studies of time characteristics of neon plasma produced by a generator of rectangular pulses showed that plasma relaxation time (trailing edge of radiation from the photomultiplier output) is sufficiently large (about 100 μs) compared with the duration of the voltage pulse (τ) applied to the plasma source and is not dependent on the amplitude of the voltage (U), duration (τ) and pulse repetition frequency f, in the range we were examining.

Minimum time of plasma generation, defined by rising edge pulse from the photomultiplier is 58 ns at a voltage obtained on discharge of 800 V. It was shown that at this voltage, it is independent of τ and f in the tested range.

Based on the results obtained in the model of the plasma phase inverter, one can state the possibility of creating on the basis of a microwave resonator a phase-inverter controlled by a neon plasma source, which can switch the phase from non-inverted to inverted in an electron accelerator with a beam duration time of 2…100 μs, but only one time.

It should be noted that the disadvantage of the described layout of the phase-inverter is a small detuning of the resonator (20…30%). This disadvantage can be eliminated by increasing the power of the plasma source, or by using several plasma sources located in the antinodes of the microwave electric field of the resonator.

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МАКЕТ СВЧ-ФАЗОИНВЕРТОРА, УПРАВЛЯЕМОГО ИСТОЧНИКОМ НЕОНОВОЙ ПЛАЗМЫ

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Для разделения в кильватерном ускорителе длинной цепочки сгустков на ведущие и ускоряемые предложено использовать фазоинвертор электромагнитных волн СВЧ-диапазона. Изменение фазы волны на 180° происходит при отражении СВЧ-мощности от резонатора при срыве резонанса путем зажигания плазмы в стеклянном сосуде, размещенном в резонаторе. Предложена схема реализации фазоинвертора, для исследования которой собран макетный вариант фазоинвертора, а также проведены измерения излучения источника неоновой плазмы, используемого в макете, с помощью ФЭУ. При подаче на источник плазмы прямоугольных импульсов длительностью 0,2…1 мкс, амплитудой 250…800 В и током до 1 А сигнал с выхода ФЭУ имеет достаточно «крутой» передний фронт (до 58 нс) и «пологий» спад (свыше 100 мкс). При этом длительность спада остается постоянной и не меняется при изменении длительности, частоты и амплитуды импульсов, подаваемых на источник плазмы, а длительность фронта уменьшается при увеличении амплитуды. Качественные измерения на макете фазоинвертора показали, что формы импульсов отраженной и проходящей волн имеют форму, подобную сигналам с выхода ФЭУ, однако имеют более пологий передний (200…500 нс) и задний (~400 мкс) фронты. Из выполненных исследований следует, что разработанный фазоинвертор можно использовать для однократного разделения последовательности сгустков относительно фазы кильватерной волны.

МАКЕТ НВЧ-ФАЗОІНВЕРТОРА, КЕРОВАНОГО ДЖЕРЕЛОМ НЕОНОВОЇ ПЛАЗМИ

Д.Ю. Залеський, Г.А. Кривоносов, Г.В. Сотніков

Для поділу в кільватерному прискорювачі довгого ланцюжка згустків на провідні й прискорюючі запропоновано використовувати фазоінвертор електромагнітних хвиль НВЧ-діапазону. Зміна фази хвилі на 180° відбувається при відбитті СВЧ-потужності від резонатора при зриві резонансу шляхом запалювання плазми в скляній посудині, розміщеній в резонаторі. Запропонована схема реалізації фазоінвертора, для дослідження якої зібраний макетний варіант фазоінвертора, а також проведені виміри випромінювання джерела неонової плазми, використовуваного в макеті, за допомогою ФЕП. При подачі на джерело плазми прямокутних імпульсів тривалістю 0,2…1 мкс, амплітудою 250…800 В и струмом до 1 А сигнал з виходу ФЕП має досить «крутий» передній фронт (до 58 нс) і «пологий» спад (понад 100 мкс). При цьому тривалість спаду залишається постійною й не міняється при зміні тривалості, частоти й амплітуди імпульсів, що подаються на джерело плазми, а тривалість фронту зменшується при збільшенні амплітуди. Якісні виміри на макеті фазоінвертора показали, що форми імпульсів відбитої й минаючої хвиль мають форму, подібну сигналам з виходу ФЕП, однак мають більш пологі передній (200…500 нс) і задній (~400 мкс) фронти. З виконаних досліджень випливає, що розроблений фазоінвертор можна використовувати для однократного поділу послідовності згустків щодо фази кільватерної хвилі.