INCREASE OF EFFICIENCY OF ACCELERATION OF THE TEST ELECTRON BUNCH BY SEQUENCE OF ELECTRON BUNCHES IN THE DIELECTRIC RESONATOR

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Results of numerical simulation of the test bunch acceleration by relativistic electron bunch sequence in the cylindrical dielectric resonator of terahertz frequency range are provided. If the bunch spacing equals to the electromagnetic field wavelength in structure and the test bunch follows the last bunch of sequence, the step energy growth of the accelerated test bunch with increase in number of drive bunches is observed. To approach step dependence to linear and, thus, to avoid cases when the increase in drive bunches number does not lead to energy growth of test bunch, it is necessary to arrange bunches of sequence at distance not smaller resonator lengths. Bunch repetition period has to be multiple of the inverse to resonant frequency of structure.

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INTRODUCTION

For obtaining high rates of charged particles wakefield acceleration it is necessary to use single drive bunch with great charge [1].

Another way of the wakefield accelerating amplitude increasing is using of periodic drive bunches sequence with smaller charge [2-7].

During studying of test bunch acceleration at changing of bunch number of drive sequence in the dielectric resonator we have found out that the step growth of energy of the accelerated test bunch is observed [8]. Each step is characterized by two stages: 1) linear energy growth of the accelerated test bunch when increasing in bunch number of drive sequence, which follows; 2) practically, invariable value of test bunch energy at changing number of drive bunches. At that the distance between bunches of drive sequence equaled to the wavelength of electromagnetic field in the structure, and the test bunch followed the last bunch of sequence.

To reduce a step length by shorten its 2nd stage, we investigated influence of multiple increase in distance between bunches of drive sequence at the invariable bunch duration on acceleration of the test bunch.

It should be noted that for finding of coherent addition conditions of the electromagnetic fields excited in the dielectric resonator by profiled charged bunches and also increase in transformation ratio rare injection was used in works [9, 10].

STATEMENT OF THE PROBLEM

The dielectric tube with an inner radius a and dielectric constant ε is inserted into a cylindrical metal waveguide of radius b. Length of a metal waveguide L coincides with length of a dielectric tube. The input and output end faces of a resonator are closed by the metal grid transparent for electron bunches. The sequence of electron bunches is injected into the resonator. After the certain delay time t_{del} relative to the last drive bunch the test electron bunch is injected in the system. The studied system is schematically shown in Fig. 1.

We investigated change of energy of test bunch electrons at the output end face of resonator during it motion in the electromagnetic fields created by drive sequence depending on number of bunches in the sequence.

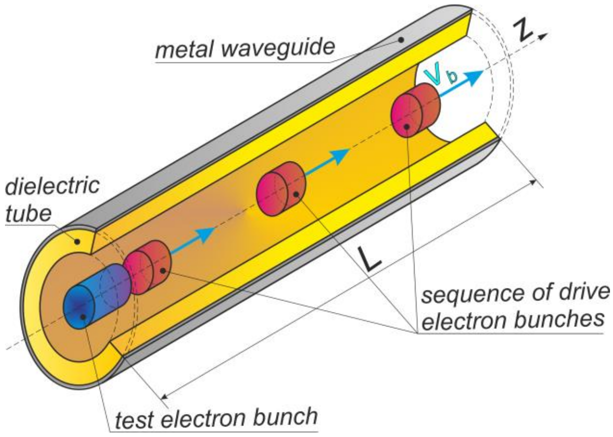

Fig. 1. Schematic view of the dielectric structure, excited by sequence of electron bunches. Into a metal cylindrical waveguide of length L the dielectric plug is inserted (yellow color). Drive electron bunches (pink color) move along a cylinder axis from left to right. Blue cylinder shows test electron bunch

In Table the parameter of resonator, driver and witness bunches used in calculation are given.

Parameters used in calculation

Inner radius of dielectric tube *a*, mm	0.5
Outer radius of dielectric tube *b*, mm	0.6
Operating frequency *f*, GHz	297.4
Waveguide length *L*, mm	5.05 (5λ)
Relative dielectric constant ε,	3.75 (quartz)
Bunch energy E_0, GeV	5
Total drive bunch charge, nC	3
Total test bunch charge, nC	0.3
Bunch diameter $2r_b$, mm	0.9
Drive bunch axial RMS dimension 2σ (Gaussian charge distribution), mm	0.1
Full drive bunch length used in PIC simulation, mm	0.2
Number of bunches in drive sequence,	1…50
Test bunch length (homogeneous charge distribution), mm	0.4
Delay injection time of test bunch relative to the rising edge of last drive bunch t_{del}, ps	1.315

TECHNIQUE OF CALCULATIONS PERFORMANCE

The analysis of test electron bunch acceleration by drive bunch sequence was carried out by us by means of 2.5-dimensional numerical code in the following way:

1. The given number N_{db} of drive bunches was injected into the investigated structure.
2. Later on the delay time t_{del} after the rising edge of beginning of the last drive bunch injection the test bunch was injected and moved up to the system output end in the electromagnetic field created by drive bunches.
3. From the calculated values of electrons energies of the test bunch, which was near output end face of the structure, maximum energy was determined. Difference between this energy and initial energy E_0 was taken as test bunch acceleration ΔE_w.
4. Having done the actions described above in items 1–3 for different N_{db}, the dependence of test bunch electrons energy gain on number of drive bunches obtained $\Delta E_w(N_{db})$.
5. Further we increased distance between drive bunches with the invariable duration of bunches so that it remained multiple to the wavelength λ of electromagnetic field in the resonator and calculated dependence $\Delta E_w(N_{db})$ again.

RESULTS OF 2.5D-PIC CODE SIMULATION

At first we will consider case, when distance between drive bunches is equal to wavelength λ.

In Fig. 2 dependences $\Delta E_w(N_{db})$ for two resonators with lengths $L=5\lambda$ (blue curve) and $L=10\lambda$ (red curve), and also for the waveguides of the length $L=5\lambda$ (green curve) and $L=10\lambda$ (purple curve) are shown. Charts clearly demonstrate that the stepwise behavior of the accelerated test bunch energy at change of number of drive bunches sequence is observed only in the resonator case. At the 1st stage the linear growth of energy of the accelerated test bunch with increase in number of drive bunches sequence is observed. At the 2nd stage test bunch energy practically does not change at change of drive bunch number.

For explanation of step behavior $\Delta E_w(N_{db})$ we will analyze structure of longitudinal field $E_z(z)$ depending on number of the injected drive bunches. Dependences of longitudinal force $F_z(z,N_{db})=-|e|E_z(z,N_{db})$ in the form of surface (Fig. 3,a) and color maps (Fig. 3,b) for the resonator of the length $L=5\lambda$ at $r=0.5$ mm are given in Fig. 3. The $F_z(z)$ dependences are given for the time when the test bunch completely enters the resonator.

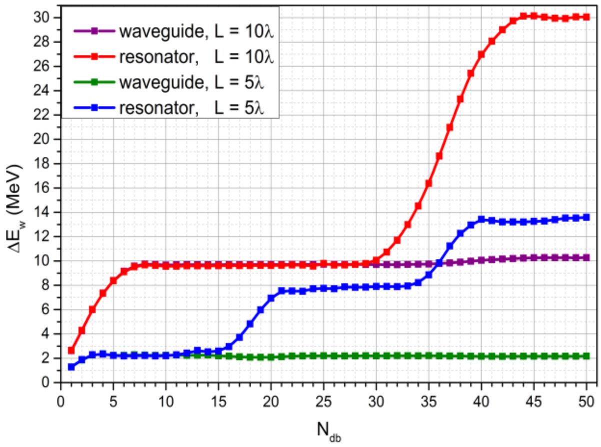

Fig. 2. Dependence of electron energy gain of test bunch on number of injected drive bunches for two resonators with lengths $L=5\lambda$ (blue curve) and $L=10\lambda$ (red curve), and also for the waveguides of the length $L=5\lambda$ (green curve) and $L=10\lambda$ (purple curve)

At any given time it can be no more than $N^s_{db}=L/\lambda$ bunches in the studied structure. Respectively, for the resonator of the length $L=5\lambda$ we obtain $N^s_{db}=5$, and for the resonator of the length $L=10\lambda$ we had $N^s_{db}=10$. In linear approach at N_{db} change from one to N^s_{db} fields after the last drive bunch summarize and linearly increase depending on N_{db}. However, the self-consistent numerical simulation performed by us has shown that the increase in fields is observed only for the first $N^s_{db}-2$ bunches, i.e. for the 3rd in the resonator of the length $L=5\lambda$ and for the 8th in the resonator of the length $L=10\lambda$. We believe that it is connected with that in linear single-mode approximation the field of transient radiation is not considered.

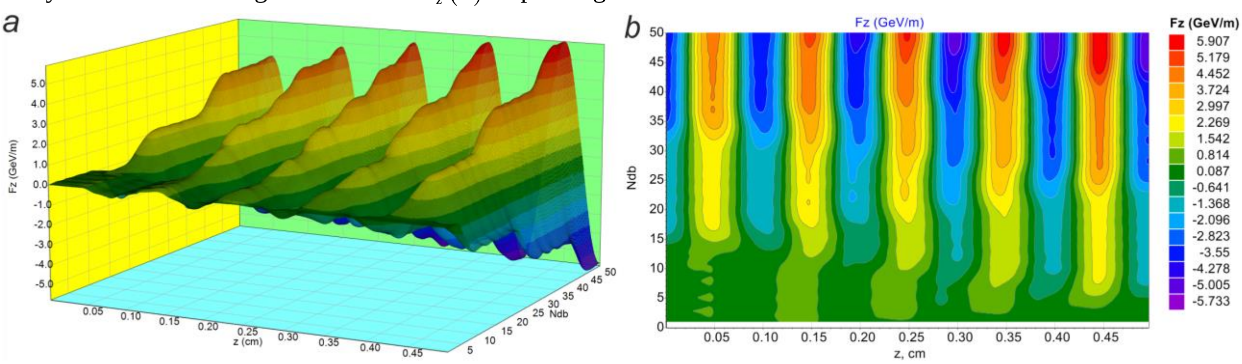

Fig. 3. The longitudinal force $F_z(z)$ at r = 0.5 mm, depending on number of the injected drive bunches N_{db} in the form of surface (a) and color map (b) at distance between drive bunches equal to λ

After the drive bunch leaves the resonator from output end face of the resonator the wakefield is reflected and moves to its input end face. Group speed of the principal mode is $v_g = 0.53c$, where c – light speed. Therefore for the resonator of the length $L = 5\lambda$ through time, equal to $10\,T_r$, where T_r is the drive bunch repetition period, the backward wave will reach input end face of the resonator. Respectively, in the resonator of the length $L = 10\lambda$ the backward wave will reach the resonator input end face after the time $20\,T_r$.

Thus, for the resonator of the length $L = 5\lambda$ at injection of the 16th drive bunch the wakefield created by bunch adds with the wave reflected from input end face of the resonator. This wave affects test bunch electrons, additionally accelerating them that is observed in the form of the growing stage of step dependence in Fig. 2. Respectively, for the resonator of the length $L = 10\lambda$ the growing phase of step function will begin at $N_{db} = 31$.

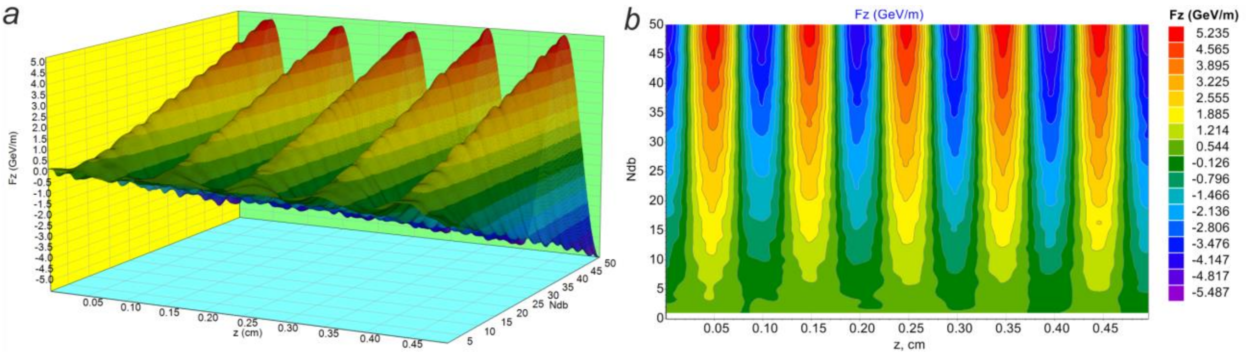

Fig. 4. The same that in Fig. 3 when the distance between drive bunches equal to 5λ

For step length reduction we, at the constant bunches duration, increased distance between drive bunches so that it is kept multiple to the electromagnetic field wavelength λ in the resonator, and calculated dependence of test bunch acceleration $\Delta E_w(N_{db})$ again.

Dependences $F_z(z, N_{db})$ in the case when the distance between drive bunches equal to 5λ are given in Fig. 4. Comparing Fig. 2 with Fig. 4, we see that at increase in distance between bunches the increment and height of steps are reduced that has to lead to the same effect on $\Delta E_w(N_{db})$ dependence.

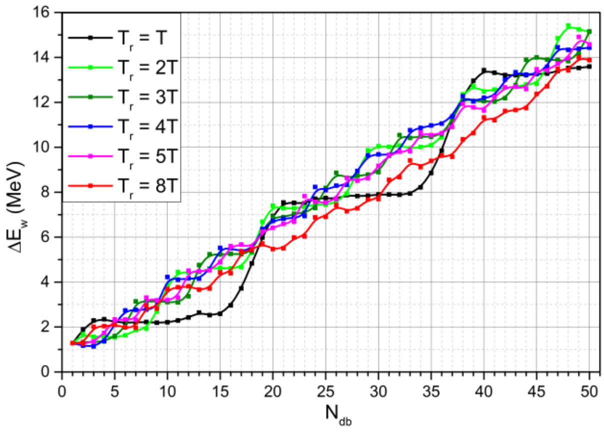

Fig. 5. Energy dependence of the accelerated test bunch when changing the number of drive bunches for the different T_r

In Fig. 5 $\Delta E_w(N_{db})$ dependences are shown for the resonator of the length $L = 5\lambda$ when the distance between drive bunches equaled λ, 2λ, 3λ, 4λ, 5λ and 8λ that corresponds to change T_r from T to $8T$, where T is the resonant period of structure. As appears from Fig. 5, when increasing distance between drive bunches sequence the duration and the height of steps on curves $\Delta E_w(N_{db})$ decreases. At 5th, 8th multiple increase in distance between drive bunches the test bunch acceleration dependence becomes almost linear.

CONCLUSIONS

At study of test bunch acceleration in the field of drive bunches sequence we have found out that when bunch number change the step energy growth of the accelerated test bunch is observed.

To reduce step length on test bunch acceleration dependence we multiple increased the distance between drive bunches retaining the invariable bunch duration.

In the cases of 2, 3 and 4-fold increases in distance between drive bunches on the curve of accelerated test bunch energy dependence as function of bunch number the steps duration and height decreases, and at 5, 8-fold increase in distance between drive bunches the dependence becomes almost linear.

Thus, we have shown that to avoid case when the increase in number of drive bunches injected in resonator does not lead to test bunch energy growth it should inject bunches with the repetition period multiple 5 and more inverse resonance frequency of the structure.

In other words, the optimum distance between drive bunches is equal to $L + n\lambda$, where n is positive integer.

It should be noted that at injection of large number of drive bunches energy of the accelerated test electrons weakly depends on T_r (see Fig. 5). Therefore the considered optimization is reasonable at rather small number of bunches $N_{db} < (10…20)\, L/\lambda$.

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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ УСКОРЕНИЯ ТЕСТОВОГО ЭЛЕКТРОННОГО СГУСТКА ПОСЛЕДОВАТЕЛЬНОСТЬЮ ЭЛЕКТРОННЫХ СГУСТКОВ В ДИЭЛЕКТРИЧЕСКОМ РЕЗОНАТОРЕ

П.И. Марков, И.Н. Онищенко, Г.В. Сотников

Представлены результаты численного моделирования ускорения тестового сгустка последовательностью релятивистских электронных сгустков в цилиндрическом диэлектрическом резонаторе терагерцового частотного диапазона. Если расстояние между сгустками последовательности равняется длине волны электромагнитного поля в структуре и тестовый сгусток следует за последним сгустком последовательности, наблюдается ступенчатый рост энергии ускоренного тестового сгустка с увеличением количества сгустков драйверной последовательности. Для того чтобы приблизить ступенчатую зависимость к линейной и, таким образом, избежать случаев, когда увеличение количества драйверных сгустков не приводит к росту энергии тестового сгустка, следует располагать сгустки последовательности на расстоянии не меньшем длины резонатора. Период повторения сгустков должен быть кратным обратной резонансной частоте структуры.

ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ПРИСКОРЕННЯ ТЕСТОВОГО ЕЛЕКТРОННОГО ЗГУСТКА ПОСЛІДОВНІСТЮ ЕЛЕКТРОННИХ ЗГУСТКІВ У ДІЕЛЕКТРИЧНОМУ РЕЗОНАТОРІ

П.І. Марков, І.М. Оніщенко, Г.В. Сотніков

Представлено результати чисельного моделювання прискорення тестового згустка послідовністю релятивістських електронних згустків у циліндричному діелектричному резонаторі терагерцового частотного діапазону. Якщо відстань між згустками послідовності дорівнює довжині хвилі електромагнітного поля в структурі й тестовий згусток іде за останнім згустком послідовності, спостерігається східчасте зростання енергії прискореного тестового згустка зі збільшенням кількості згустків драйверної послідовності. Для того щоб наблизити східчасту залежність до лінійної й, таким чином, уникнути випадків, коли збільшення кількості драйверних згустків не призводить до зростання енергії тестового згустка, слід розташовувати згустки послідовності на відстані не меншій, ніж довжина резонатора. Період повторення згустків повинен бути кратним до зворотної резонансної частоти структури.