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Simulation of traveling-wave high-gradient accelerating structures driven by nanosecond Ka-band pulses

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Abstract. Short microwave pulses with nanosecond or sub-nanosecond duration and sub-GW power are promising for particle acceleration since they allow increasing the breakdown threshold and thus raising the acceleration gradient. To leverage the advantages of short pulses with large spectrum bandwidth, the accelerating structures with small frequency dispersion are needed, and the traveling-wave structures fit well for this purpose. In this work, three variants of the traveling-wave structures are considered for the high-gradient electron acceleration, namely, dielectric-lined waveguide and circular waveguides with sinusoidal and rectangular corrugation. In the simulations, structures were powered by 100–200 MW Ka-band pulses with 2 ns duration that corresponds to parameters demonstrated earlier for relativistic backward wave oscillator driven by compact RADAN accelerator. Simulations show that the proposed table-top device makes it possible to increase the electron energies from 300 keV to 8–23 MeV at the distances of 10–20 cm.

Keywords: microwaves, high-gradient particle acceleration, accelerating structures, traveling wave, short pulses.

1. Introduction

The increase of the acceleration gradient over 1 MV/cm level is an urgent task in accelerator physics since it could pave the way to new generation of compact facilities. Decrease of the microwave pulse duration to nanosecond or sub-nanosecond level allows increasing the microwave breakdown threshold on a structure wall and thus is currently considered as a promising method for raising the acceleration gradient [1]. However, sub-gigawatt radiation power is needed to achieve high electric fields in an accelerating structure powered by pulse as short as hundreds or dozens of microwave periods. Currently, there is a number of approaches to producing and application of high-power short pulses for particle acceleration, including wakefield generation in periodic structures [1, 2], pulse chopping and compression [3, 4], etc. We suppose that the high-power microwave generators based on the high-current electron beams, such as relativistic backward-wave oscillators (RBWO), are natural sources of pulses with required parameters. Recently, the Ka-band pulse produced by superradiant RBWO was used for acceleration of electrons from 300 keV to 1.25 MeV in 0.5-cell structure (cell length is 4 mm) with peak gradient of 500 MV/m [5].

Multi-MeV electron acceleration requires structures with large length. A short microwave pulse with a wide spectrum is not suitable for powering multi-cell resonant standing-wave accelerating structures (like a chain of coupled resonators with a π-type operating mode). Indeed, in a long chain of coupled cavities the mode spectrum is very dense close near a stop-band edge, so a short pulse with a wide spectrum cannot selectively excite only one axial mode. In addition, the Q-factor of the π-type mode increases rapidly with the increase of cell number, and the resonance curve width correspondingly decreases. Therefore, short high-power pulses can be used to feed only a small number of coupled cells that hinders prolonged acceleration and high total energy gain.

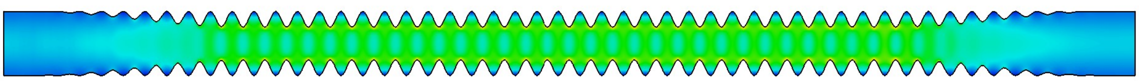
An effective scheme of short-pulse acceleration can utilize traveling-wave structures rather than standing-wave mode. Some examples of such structures are chains of coupled cavities with a relatively low external quality factor (operating at the mode far from π-point), corrugated metal waveguides, and smooth waveguides with partial dielectric filling. The traveling-wave structures with coupled cavities are widely used in conventional accelerators, and two other types of structures are being actively developed for wakefield acceleration techniques. The use of traveling-wave structures with low dispersion allows to maintain a synchronism between electrons and the electric field of a short pulse over a long distance and thereby to obtain a significant increase in particle energy, as well as provides the possibility of more complete transfer of the microwave pulse energy to electrons. The acceleration length increases with the duration of the microwave pulse and decreases with the difference between pulse group and phase velocities.

2. Simulation of structures for short pulse acceleration

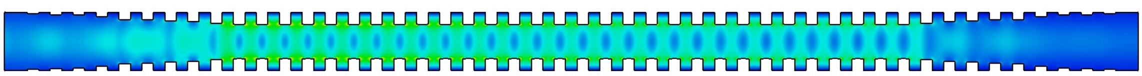
In this work, we simulated the electron acceleration in traveling-wave structures powered by Ka-band pulse generated by compact RBWO driven by RADAN accelerator [6]. The accelerating structures in the form of a cylindrical waveguide with partial dielectric filling [7] and two variants of circular corrugated waveguides (with smooth corrugation and iris-like corrugation) are considered. All the structures operate at the TM_{01} mode. In the calculations, a microwave pulse with a frequency of 38 GHz, a power of 200 MW and a total duration of 2.7 ns is assumed (the duration of the part of the pulse with constant power is 1.2 ns). The initial electron energy was assumed to be 300 keV that corresponds to electron beam generated by RADAN accelerator. In simulations, the axial magnetic field of 5 T was applied to provide beam formation and guiding. The electron current of 0.1 A was assumed in most simulation runs; however, current increase up to 10 A does not result in noticeable decrease of total electron energy gain.

In the first simulated variant with a circular waveguide with smooth sinusoidal corrugation (Fig. 1a), the operating point corresponding to group velocity about of 0.1 *c* was chosen (*c* is a light speed). The maximal electric field on the surface of the wall was about of 500 MV/m, and the accelerating field magnitude on the waveguide axis was up to 210 MV/m. This structure demonstrates energy gain up to 10 MeV in simulations (Fig. 2). The second structure was an iris-like corrugated structure (Fig. 1b) with a little higher amplitude of electric field at the axis, about of 270 MV/m. The slightly lower energy gain in this structure (8.5 MeV) can be explained by lower group velocity resulting in shorter effective acceleration distance. For both corrugated structures, the microwave input couplers were designed in a form of smooth corrugation tapers that eliminate reflections and emergence of longitudinal modes. The third structure is a capillary fused quartz tube with outer wall metalized, i.e., circular waveguide with partial dielectric filling (Fig. 1c). For waveguide with group velocity about of 0.25 *c* at the operating frequency of 38 GHz, the magnitude of the electric field on the walls was 150 MV/m, with accelerating gradient at the axis of 125 MV/m. Despite of twice lower maximal electric field on axis in comparison with corrugated waveguides, simulations predict similar average acceleration rate for these cases. That can be explained by the low axial electric filed magnitude at iris position for periodically corrugated waveguides, while for uniform capillary structure on-axis field does not depend on the axial coordinate, see Fig. 1. According to simulations, the electrons with initial energy of 300 keV can be accelerated up to 24 MeV at the 20 cm length.

(a)



(b)



(c)

Fig. 1. Electric field amplitude distribution in (a) smooth-corrugated waveguide structure (maximum field amplitude on the walls surface is 250 MV/m), (b) rectangular-corrugated waveguide structure (maximal field on wall is 300 MV/m), and (c) capillary waveguide structure (field amplitude is 150 MV/m on the waveguide surface and 125 MV/cm on the waveguide axis).

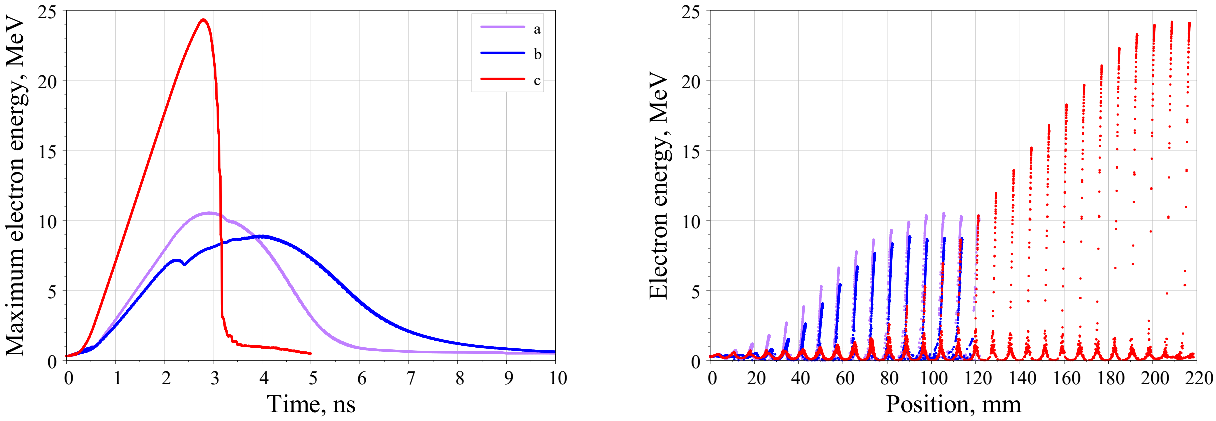


Fig. 2. Maximum electron energy gain vs. time (left) and electron energy distribution in space (right) in different accelerating structures: a) smooth corrugated structure, b) rectangular-corrugated structure, and c) capillary structure.

3. Conclusion

Three types of traveling-wave accelerating structures with TM_{01} operating mode were numerically studied, namely circular waveguides with rectangular and smooth corrugation, and circular waveguide with dielectric layer. Simulations show that each structure with wave group velocity of 0.1–0.25 *c* allows high-gradient electron acceleration by 2 ns pulse at long distance and to raise the particle energy from 300 keV to 8–20 MeV in a waveguide of 10–20 cm length.

Acknowledgement

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4. References

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