# EFFICIENT TRAVELING-WAVE ACCELERATING STRUCTURE FOR LINEAR ACCELERATORS

Vitaly M. Pirozhenko*, Carlsbad, CA, USA


*Abstract*

The shaped traveling-wave (STW) structure contains periodic structure of cavities with optimal shape and magnetic coupling operating in the forward traveling-wave mode. The structure combines the advantages of conventional standing-wave (SW) and traveling-wave (TW) structures. It ensures high efficiency of the use of radio-frequency (RF) power for the particle acceleration inherent in the SW structures. Also it gives a possibility to vary output energy of the particles by changing the beam loading and provides for good matching with RF generator without application of special matching devices that is inherent in the TW structures. The STW structure is well suited for compact variable-energy electron linear accelerators used for radiation technologies.


## INTRODUCTION

The range of applications of particle accelerators is steadily extended. Now a demand arose for a variety of the electron linear accelerators for the radiation technologies. In particular, actual task is the development of compact self-shielded accelerators with variable energy of electron beam. They are used in medicine, industrial radiography, and X-ray cargo inspection. Main requirements for them are the following:

- Small sizes and high acceleration rate;
- Absence of magnetic devices for the beam focusing;
- High efficiency of use of radiofrequency (RF) power;
- Possibility to change electron energy in wide range.

In the electron linear accelerators, several types of accelerating structures with traveling wave (TW) and standing wave (SW) are applied [1-9].

The structure with shaped cavities and forward traveling-wave operation (STW) was initially suggested for the acceleration of protons [7]. Optimal choice of its parameters makes it possible to obtain high efficiency and apply the structure for compact variable-energy electron accelerators. The structure combines some features of the TW and SW structures.

## FEATURES OF TW AND SW ACCELERATING STRUCTURES

Conventional TW accelerator applies round disk-loaded waveguide as accelerating structure. Usually the phase shift per cell in the disk-loaded waveguide is $2\pi/3$ [1]. Coupling between the cells is executed by the electric field through the holes in the disks on the axis. The dispersion is positive, and directions of phase and group velocities are coincident.

The TW accelerating system provides for good matching with feeding RF generator and a possibility to vary the energy of accelerated electrons in wide range by changing the beam current.

Unfortunately, the disk-loaded waveguide has low efficiency. Besides, it requires application of a device with magnetic field of solenoid type to focus the electron beam during acceleration.

Conventional SW accelerator includes a bi-periodic structure of cavities with $\pi/2$-mode of operation [2,3]. Accelerating cavities of optimal shape alternate with coupling cavities, phase shift between adjacent cavities is $\pi/2$ and between the accelerating cavities is $\pi$. The cavity-to-cavity coupling is executed by the magnetic field via off-center windows, and the dispersion is negative.

The SW structures have high efficiency. The system can provide forming and acceleration of the electron bunches without use of a focusing solenoid [4,5]. However, the system can not provide good matching with feeding RF generator and requires application of special matching device such as a ferrite circulator. There are problems in the development of standing-wave single-section accelerator with variable energy because variation of the beam current causes changing the RF field in all the structure and affects conditions for forming bunches.

Some developers have applied the backward traveling-wave (BTW) mode in the accelerator with shaped cavities [6]. The RF generator was connected in the structure end. The phase shift per cavity was chosen $3\pi/4$ or $4\pi/5$. But the BTW structure is not appropriate for compact variable-energy accelerator because variation of the beam current causes large changing the RF field intensity in the structure beginning and deterioration of forming bunches.

The dispersion diagram for the periodic structure of cavities with magnetic coupling may be presented as shown in Fig. 1. The abscissa is the phase shift per cavity in the direction of moving electrons.

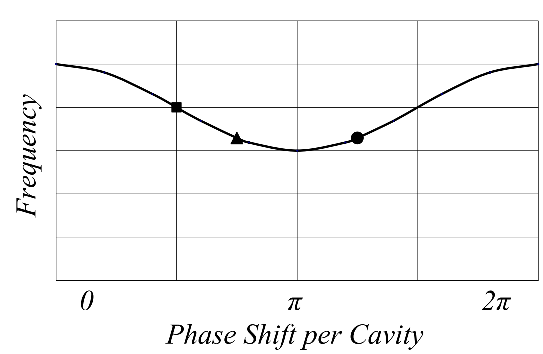


Figure 1: Dispersion diagram. Square – SW structure, triangle – BTW structure, circle – STW structure.

* E-mail: v_pirojenko@mail.ru

## CHARACTERISTICS OF STW STRUCTURE

The STW structure contains periodic structure of cavities with optimal shape and magnetic coupling. Due to special choice of phase shift per cavity and dimensions of cavities, it operates in the forward traveling-wave mode [7]. Unlike all other accelerating structures used in the electron linear accelerators, the STW structure has phase shift per cavity in the direction of moving electrons lying in the range from $\pi$ to $2\pi$.

Simplified scheme of the STW structure is shown in Fig. 2. Each cavity has windows for magnetic coupling with neighboring cavities. Usually two windows in each wall provide sufficient coupling. In order to better the field symmetry, the windows in adjacent walls may be displaced by 90° in azimuth. RF generator is connected to the first cavity, and matched load is connected to the last cavity.

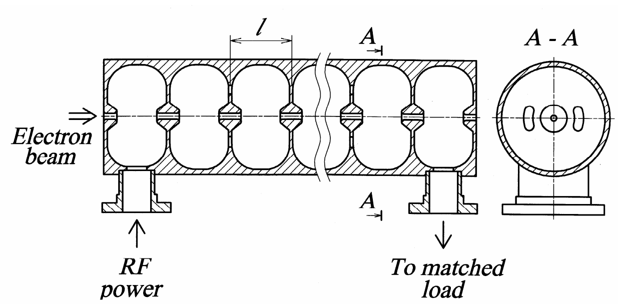


Figure 2: STW structure (front and side views).

Sometimes the matched load in the traveling-wave structure is developed as an internal load [9]. Such type load is made up as a thin layer of a material absorbing RF power that is applied in one or several last cavities.

In order to synchronize the movement of the wave and the electron bunch, the following relation between the structure period $l$, wavelength $\lambda$ and phase shift per cavity $\varphi$ should be fulfilled:

$$l = \beta \cdot \lambda \cdot \varphi \;/\; (2\pi),$$

where $\beta = v/c$ is relative velocity of electrons, $v$ is velocity of electrons, $c$ is speed of light.

Usually in the most part of the accelerating section, electrons have relative velocity $\beta \cong 1$. Here the period of the STW structure $l$ is in the range from $\lambda/2$ to $\lambda$.

Choice of the phase shift $\varphi$ determines the efficiency of the structure, achievable accelerating gradient, required coupling factor between the cavities, and sensitivity of the accelerating field to instabilities and errors.

A measure of the efficiency of an accelerating structure is effective shunt impedance

$$Z_e = E_a^2 \;/\; P_1,$$

where $E_a$ is accelerating gradient, $P_1$ is RF power loss per unit length without beam loading.

Accelerating gradient at given RF power flow $P$ is

$$E_a = (P \cdot Z_e \cdot 2\pi / \lambda)^{1/2} \cdot (v_g \cdot Q)^{-1/2},$$

where $v_g$ is group velocity, $Q$ is $Q$-factor of cavities.

The group velocity is determined by the angle of slope of the tangent to dispersion curve in the operating point (see Fig. 1). The group velocity is proportional to coupling factor between cavities.

Compact electron accelerator with output energy up to 10 MeV should have 10-15 cavities. Required relative group velocity $v_g/c$ and coupling factor are less than 1%.

The optimization of the structure parameters is made with due regard to the beam dynamics, accelerating gradient, coupling effect, and technology features.

Typical values of $Z_e$ are given in Fig. 3 for several structures operating in S-band.

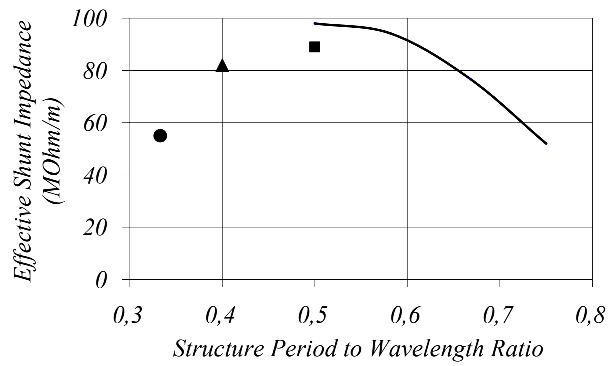


Figure 3: Effective shunt impedance. Curve - STW structure, square – SW structure, triangle- BTW structure, circle - disk-loaded waveguide.

The point $l/\lambda = 0.5$ corresponds to the case when the phase shift between the accelerating cavities is $\pi$. Usually SW structures operate in this point. The STW structure has some higher shunt impedance in this point because it does not contain coupling cells.

To obtain high efficiency of the STW structure, it is reasonable to select the phase shift close to $\pi$, for example, $\varphi = 6\pi/5$ ($l/\lambda = 0.6$). Here the shunt impedance of the STW structure approximately equals to that of the SW structure.

The distribution of accelerating gradient along the structure axis $z$ is determined by the distribution of group velocity. If the group velocity does not vary along the structure, the accelerating gradient as well as the power flow decreases with $z$. It is possible to keep the gradient constant while the RF power flow decreases, for this purpose the group velocity should monotone decrease with $z$. Change of the group velocity and coupling factor can be accomplished by changing dimensions of the coupling windows.

## COMBINED ACCELERATING SYSTEM

The STW structure may be effectively used in the combined accelerating system including SW bunching section and STW accelerating section [7]. In particular, the bunching section can be designed as a bi-periodic structure of cavities operating in the $\pi/2$-mode [8]. Scheme of the system is shown in Fig. 4.

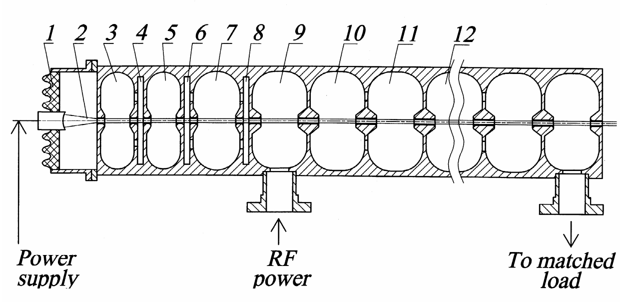


Figure 4: Combined accelerating system.

The system comprises following components:
- Injector 1 providing for electron beam 2;
- Bunching section including cavities 3…8;
- Accelerating section including cavities 9…12.

The bunching and accelerating sections are joined to integral design, coupled by electromagnetic field, and fed by RF generator through single waveguide. The waveguide is connected to the first cavity of the accelerating section. The bunching section is fed through coupling windows between this cavity and the last cavity of the bunching section.

The application of SW bunching section with $\pi/2$-mode of operation provides for a possibility to optimize dimensions of the cavities and field amplitudes therein so that bunching, focusing and preliminary acceleration of the beam is performed only by RF field, without use of focusing solenoid. Thorough optimization of characteristics of the bunching section makes it possible to obtain high current of accelerated beam [4].

As an example, in Table 1 are given some calculated characteristics of a version of combined system.

Table 1. Characteristics of accelerating system

| | |
|---|---|
| System length | 1 m |
| Operating frequency | 2856 MHz |
| Input RF power | 2.6 MW |
| Electron energy at low beam current | 10 MeV |
| Electron energy at 0,4 A beam current | 5 MeV |

The most convenient way for variation of the output energy is changing the beam loading. As the beam current changes, the field intensity in the system beginning is little affected, but the field intensity in the end cavities profoundly varies changing the output electron energy.

Fig. 5 shows effect of variation of the beam current on the values of the field intensity in the bunching section and the electron energy at the accelerator output.

Since the field intensity in the bunching section varies slightly, conditions for forming the beam bunches are not deteriorated. So, it is possible to vary the beam current and output energy in wide range without changing the beam dynamics. This is important distinction from the SW accelerating systems where the output electron energy varies proportionally with the field intensity.

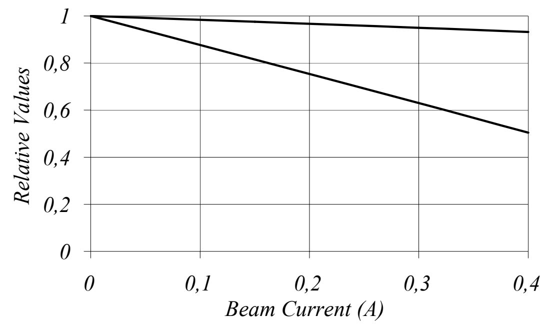


Figure 5: Field intensity in bunching section (upper line) and output electron energy (lower line) in relation to beam current.

## CONCLUSIONS

The STW accelerating structure ensures high efficiency of the acceleration inherent in SW structures and a possibility to vary output energy of the electron beam in wide range by changing the beam loading inherent in TW structures.

The combined system gives a possibility to develop compact accelerators with high efficiency and without application of magnetic focusing devices and special devices for matching with RF generator. The system is well suited for variable-energy electron linear accelerators, in particular, used for the radiation therapy, the industrial radiography, and X-ray cargo inspection.

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