CONTINUOUS-WAVE ELECTRON LINEAR ACCELERATORS FOR INDUSTRIAL APPLICATIONS

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Abstract

Based on SINP MSU experience in developing continuous wave (CW) normal conducting (NC) electron linacs, we propose an optimal design for such accelerators with beam energy of up to 10 MeV and average beam power of up to several hundred kW. As an example of such design, we discuss the 1 MeV industrial CW linac with maximum beam power of 25 kW, which was recently commissioned at SINP MSU.

INTRODUCTION

Rapid progress in the area of superconducting RF accelerating structures (AS) technology, which began in the mid 80-s, made it a standard practice to use SRF AS to obtain continuous high-energy beams with relatively low average current, as well as for high current ERLs. However, CW linacs can provide not only high-precision beams for scientific research, but also beams with high average power for industrial applications.

If the power of an accelerated beam is significantly greater than the power loss in the AS walls, use of NC AS is not only expedient, but it also has a number of advantages over SRF AS. In particular, design of NC AS is much more simple, they do not require a cryostat nor a refrigerator, and the reasonable loss of beam current does not have any serious consequences for the AS operation. NC CW electron linacs can generate electron beams with energy in the range of 1 to 10 MeV and with power of tens and hundreds kilowatt.

Pioneering work in the area of NC CW electron linac development was done at Chalk River Laboratory in the 70-s [1, 2]. A significant contribution to the research of operation of NC AS in the CW mode was made during construction of microtrons cascade MAMI [3], as well as during design of SINP MSU race-track microtron [4].

Since the 90-s, SINP MSU has been developing high-power S-band CW electron linacs for industrial applications [5, 6]. Based on our work in this area, we discuss main features of devices of this type, and point out solutions to reduce size of such facilities and to make their operation more simple.

SPECIFIC FEATURES OF NORMAL CONDUCTING CW AS

Specific features of NC AS operation in CW mode are connected primarily with two factors. The first is high thermal loads, which causes significant changes in electro-dynamic characteristics of the AS, such as shift in resonance frequency, appearance or change of the stop-band in the dispersion characteristic, decreasing of the effective shunt impedance due to increased resistance of the wall material. The second factor is low accelerating field, which results in a low pace of energy gain by the particles, which in turn causes electrons to remain non-relativistic for a substantial part of the AS.

Thermal Loads

High thermal loads of the AS operating in CW mode result in its mean temperature increase, as well as in appearance of the temperature gradient and related strains.

Typical RF power loss in the walls of the AS is about 20 kW/m in the wavelength range of 12 cm (2450 MHz), which ensures accelerating gradient of about 1 MeV/m. The maximum accelerating gradient for NC AS is limited by achieving a material yield point due to temperature gradient or by local boiling of the coolant. Experimentally proven limit of RF losses per unit length is 210 kW/m [7], which corresponds to the accelerating gradient of about 3.5 MeV/m. This accelerating gradient makes it possible to build compact industrial CW linac with beam energy up to 10 MeV and average beam power of MW level.

Heating of the AS operating in CW mode by RF power results in significant shift of the operating frequency. In some cases, frequency shift in transitioning from cold state to a state with rated field level can be up to several widths of the resonance curve. RF system should automatically maintain resonance conditions between the RF power source and the AS.

SINP MSU studied several arrangements for automatic frequency control for klystron based RF systems.

Constant Frequency of the Master Oscillator (MO). This method can be used in both single-section and multi-section linacs. Adjustment of resonance frequency of the AS to the frequency of the MO is maintained by change in temperature of the coolant. Prior to RF power input, electric heating elements heat the coolant to the temperature that ensures resonance of the AS with the MO. As the RF power is input, the temperature is lowered by the automatic frequency control (AFC) system, which includes phase detector and the electric heating elements control unit. The range of AS frequency adjustment is limited by the allowable range of the coolant temperature change.

Adjustable Frequency of the MO. It is the most common method where output signal of the phase detector is received by the MO frequency control unit. The MO frequency is adjusted to ensure the resonance conditions. This method is fast, however, it can only be used in single-section accelerators, since as a rule resonance frequencies of different sections behave differently with RF power.

Self-Oscillations Method. This method of klystron operation with an AS in the feedback loop is simple and reliable for CW mode. It works well for accelerators with high beam power and with high accelerating gradients, when significant changes of the operating frequency are possible. With additional stabilization circuits, the method can be used also to get high-precision electron beams.

In this method, a low-power RF signal from a coupling loop installed in one of the accelerating cells of the AS is directed to the klystron input through a feedback circuit, which includes adjustable attenuator and phase shifter, as well as a ferrite isolator. Conditions for self-oscillation at operating mode frequency are meet through selection of the feedback loop attenuation and phase shift values. Self-oscillation frequency automatically follows the resonance frequency of the structure, which changes due to thermal processes. If RF discharges occur in the structure or in the waveguide, the conditions for self-oscillations are broken, and they discontinue. Thus, when operating in CW self-oscillations mode, amount of RF power reflected from the AS is determined by its matching with the waveguide; if matching is optimal, klystron can operate with high Q loads without circulator between klystron and AS. Elimination of the circulator makes the accelerator cheaper and smaller in size, and allows connecting flanges of the klystron and of the AS directly, using vacuum window of the klystron for vacuum insulation of the AS.

Self-oscillation method can also be used for a multi-section accelerator, provided that stability requirements for relative phases of the field are not rigid. In particular, such arrangement was used for a two-section accelerator with beam energy of 1.2 MeV and average beam power 60 kW [8]. If accelerated beam current is high, fields of separate sections can be automatically synchronized with the field of the first section, where accelerated bunches are formed, with phases required for acceleration, provided there is certain correlation between beam current and frequency deviation [9].

Beam Dynamics

Distinctive characteristics of a NC CW linac beam dynamics are determined by the low accelerating gradient. At the characteristic value of the accelerating gradient of 1 MeV/m and frequency of 2450 MHz, energy gain per one cell of the AS changes from 30 to 60 keV, as a particle energy is increased. This is why injected several tens keV electrons remain nonrelativistic for a substantial part of the structure, and their velocity changes significantly as they are accelerated.

Since length of an accelerating cell for a standing wave AS cannot be made appreciably smaller than quarter of the wavelength, as a rule to meet synchronism conditions the injection energy is set to be high, about 100 keV, which corresponds to $\beta = 0.548$ (where β is a relative velocity of the particle).

AS with cell length increasing in proportion to velocity of the particles has low capture efficiency; that is when continuous beam in injected into the structure, only about 30% of the particles are captured, whereas the remaining particles leave the structure with the energy close to the energy of injection, or are absorbed by the beam channel walls. To get beams with high monochromaticity and small losses of current, a chopper and a buncher are used. At that, the buncher is adjusted to achieve minimum length of the bunch in the first accelerating cell. To avoid ungrouping of bunches during their further acceleration, modulation of the beam energy by buncher should be significantly less than the energy gain per cell (as a rule, the modulation is ±2-3 keV), which increases drift space, where bunching occurs, to ~1m. Installation of a separate bunching resonator to increase capture efficiency noticeably complicates the RF system and the accelerator design, and increases its dimensions.

Solution to the problem was found in significant lowering of the injection energy (to 15 keV), which allowed integrating the bunching cavity into the AS, as well as in incorporating a booster resonator, which would increase beam energy for further conventional acceleration [10-11],

Figure 1 shows schematics of the AS that ensures bunching and accelerating of an electron beam with low injection energy in CW mode. Accelerating cell 1 is a bunching cavity that ensures velocity modulation of a continuous electron flow. Electron bunches are formed in the drift region L_g, and their energy is increased by the booster cavity (cell 2) to make it sufficient for further acceleration by cells 3, 4 ….N. Presence of the drift region L_g makes it possible to form a booster cavity with high effective shunt impedance and to ensure significant increase of the beam energy with low RF power consumption.

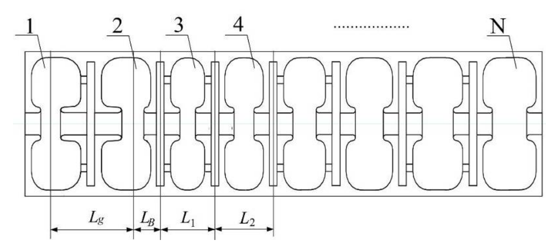

Figure 1: CW AS with low injection energy.

Utilization of the above approach resulted in the injection energy decrease to 15 keV with capture efficiency of over 50%.

1 MEV INDUSTRIAL CW LINAC

Considering the experience gained, SINP MSU designed a compact 1 MeV industrial CW electron linac with maximum beam power of 25 kW [12]. The following methods were utilized in this accelerator to achieve compactness and to simplify its operation and maintenance: bunching and capturing are done in the first few accelerating cells of the AS; self-oscillations operation of the RF system; absence of the circulator between klystron and AS. Besides, low injection energy of 15 keV made it possible to supply the electron gun and the klystron from

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the same HV power supply (high voltage of the multi-beam klystron KU-399a [13] used in this linac is 15 kV).

An external view of the accelerator is shown in Fig. 2, and its main characteristics are given in Table 1.

Figure 2: External view of 1 MeV accelerator.

Table 1: Design Parameters of the Accelerator

Beam energy	1 MeV
Beam current	0-25 mA
Maximum beam power	25 kW
Gun /Klystron high voltage	15 kV
Operating frequency	2450 MHz
Klystron power	50 kW
Efficiency	~33%
Dimensions	500x900x1400 mm^3

Commissioning works were performed at the accelerator in 2013 [12], and now it is used to study radiation degradation of solar cells, to treat hard-alloy cutting tools [14] and for other applications.

The applications require various beam-loading conditions and therefore we develop an adjustable coupler with a wide range of coupling factor tuning. One can find an example of such a system in [15].

CONCLUSION

At present, industry utilizes primarily DC accelerators in the energy range of 1-2 MeV. Having high efficiency, they at the same time are bulky and heavy, require construction of special premises, and use of expensive insulating gas under high pressure. Experience gained at SINP MSU makes it possible to design compact easy-to-operate and easy-to-maintain industrial continuous-wave electron accelerators with beam power of tens of kilowatts in this energy range.

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