SYSTEMS OF BEAM ACCELERATION OF POWERFUL HIGH-VOLTAGE ELECTRON ACCELERATORS

E.I.Gerasimov, M.P.Svinjin, N.G.Tolstun

D.V.Efremov Scientific Research Institute of Electrophysical Apparatus, 189631 Leningrad, USSR

Possible use of traditional axisymmetric electron-optic system of highvoltage accelerators used in radiation--technological apparatus are being studied. The boundaries of such accelerating systems with the beams of small cross-section applicability are defined by analytical and numerical simulations and their optimal criteria are worked out. Acceleration of significantly more powerful electron beams is shown to be possible with such acceleration systems without modification of their design.

Power of the most of modern high-voltage accelerators used in radiation-technological complexes is 10-100 KW in the energy range 0.15 - 4 MeV. Possibilities to obtain and accelerate such beams are well studied. Nowadays the problem of significantly more powerful systems up to 1 MW and higher becomes vital for the whole series of applications (flue gases treatment, liquid wastes purification etc.). While solving the abovesaid problem the superpowerful electron beams should be obtained and the question of their acceleration should be decided.

As a rule, at energies exceeding 0.3 MeV, electron-optical system of highvoltage accelerator is a multisectional accelerating tube. This permits to exclude possible breakdown of an accelerating gap, inevitably accompanied with accelerator switch off and technological apparatus shut down.

Accelerating tubes of different machines are similar in design. Usually, at energies higher than 1 MeV their outer diameter is 20-30 cm, aperture-several centimeters what corresponds to the optimal geometry of high--voltage accelerator and permits to ensure sufficiently high vacuum in the electrons source region. The accelerating voltage operating gradient of the most of such class machines is 0.7 - 1.5 MV/m. Practically, different electric

Practically, different electric potential distributions at the accelerating tube electrodes are used. In the sumpliest system the field is constant over the whole accelerating length beginning from the cathode. The cathode operates under the mode of complete current extraction. Due to influence of space charges, maximum at the initial part of the acceleration length, the beam envelope in the tube is close to parabola in the given case. The accelerating system of such type may evidently be used at comparatively small tube lengths and small cathode transverse dimensions comparatively to its aperture.

comparatively to its aperture. To increase the current of the beam, passing through the tube, the space charge should be compensated. It can be achieved due to variable gradient in the initial acceleration (injection) region or over the whole accelerating tube length. The beam convergence at the outlet of the near-to-the--cathode region of the tube or its constant diameter over the whole tube length is provided.

The beam hydrodynamic model, sufficiently completely described by the boundary particle trajectory is used as an approximation for the maximum current evaluations.

Some definite angle of the injected boundary particle α_M , at which the inlet and outlet beam diameters are equal, corresponds to the highest current I_M flowing through the accelerating tube with the constant field gradient. Varying this angle α , the maximum current I_M which may flow through the tube without the beam at its electrodes may be defined.

Fig.1 shows $I(\alpha)$ -dependencies for the beam with the initial radius $\tau_0 = 1 \text{ cm}$ and different $E_{\mathbb{Z}}$ -values at accelerating voltage 1 MV and injection energy $W_0=30$ keV. Fig.2 gives the beam envelopes for two accelerating voltages with the constant length of the accelerating tube $L_T = 1 \text{ m}$

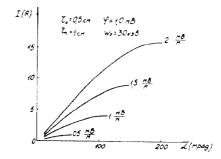


Fig.1. Ultimate current variation depending upon an angle of electron injection into the tube

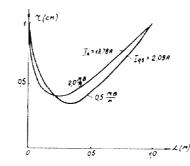


Fig.2. Ultimate current envelopes at different accelerating voltages with the constant accelerating tube length The maximum current $I_{\mathcal{M}}$ flowing through the accelerating tube of any length and aperture at different injection energies and field strengths $E_{\mathbf{Z}}$ may be defined. The range of E =0.5-2 NV/m and accelerating voltages U up to 4 NV, typical for the most accelerators of considered type, is of practical interest. The limit of injection energy variation for single-gap electron sources is 10-50 keV. Fig.3 shows the maximum current $I_{\mathcal{M}}$ dependencies upon electric field $E_{\mathbf{Z}}$ at $T_{\mathbf{C}}$ =1 cm and different accelerating voltages and injection energies $W_{\mathbf{C}}$.

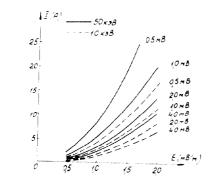


Fig.3. The beam ultimate current change depending upon the electric field strength variation for the different accelerating voltages and injection energies 10 and 50 keV for the tube with a conventional aperture 20 mm

From the given above data the conclusion can be drawn - that all abovesaid dependencies are sufficiently exactly approximated by the curve of the view:

$$I_{M} = K_{M} E^{2} \tag{1}$$

where K_M - is a coefficient defined by the accelerating voltage, beam radius at the tube inlet and injection energy. $K_M(U)$ - dependency for 7_0 equal to 0.5, 0.75 and 1 cm are given on Fig.4.

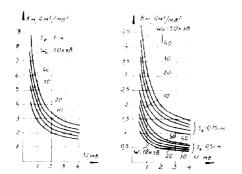


Fig.4. K_{M} - coefficient dependence upon the accelerating voltage at different beam initial radii and injection energies

Relationships defining I_{M} - magnitude and character of its variation depending on E_{Z} , U, 7_{o} , W_{o} are obtained on the assumption that the electron beam has a sharp boundary and current density over its cross-section is constant. As for the real systems, the beam peripheral regions blurring and halo appearing are typical. For taking the space charge into account this phenomenon is insignificant, as there is only minor part of the total current in the halo region. However the situation is changed if there should be no accelerated particles at the electrodes, the indispensable condition for the system electric strength and operation reliability. In this case the beam radius should be less than that of a channel, formed by the accelerating tube electrodes Z_{TP} . The required T_{TP}/T_n ratio may be estimated assuming T_n to be an effective radius of Gauss distribution characterizing the current density over the beam cross-section what is testified by the experimental data:

$$j = j_o \exp\left[-\frac{\tau^2}{\tau_n^2}\right] \qquad (2)$$

The ratio of current I_n passing through the circle with radius γ_n to the current on the accelerating system electrodes I_3 at $I_n \gg I_3$ equals to:

$$\frac{I_n}{I_3} = -\frac{\int_{o}^{2\tau_p} dI}{\int_{z_{\tau_p}}^{\infty} dI} = \frac{1 - exp\left[-\frac{\tau_p^2}{\tau_p}/\frac{\tau_n^2}{\tau_n}\right]}{exp\left[-\frac{\tau_p^2}{\tau_p}/\frac{\tau_n^2}{\tau_n}\right]} = exp\left[\frac{\tau_p^2}{\tau_p}/\frac{\tau_n^2}{\tau_n^2}\right]$$

Setting the permissible I_n and I_2 magnitudes, the required $\gamma_{\tau p}/\gamma_n$ ratio can be defined. So, for example, assuming that current to the electrodes shouldn't exceed 10^{-6} we find that at T 100 m/s

 10^{-6} A, we find that at $I_n = 100$ mA $\gamma_{1p}/\gamma_n \ge 3.4$ and at $I_n = 1$ A, $\gamma_{1p}/\gamma_n \ge 3.7$ The maximum aperture of the present-day machines accelerating system is known to be 10 cm. Taking $I_n / I_2 > 10^{-6}$ we find the maximum beam radius to be 13.5 mm in this case. From given above estimations it is seen that at achieved nowadays field

strength E = 1 LV/m, the maximum current passing through the tube with such an aperture is several amperes, whereas it is not more than 0.1 A in the most powerful modern accelerators.

The second version of the accelerating system when the constant beam diameter is provided due to accelerating voltage non--uniform distribution over the whole accelerating tube length results in relationship similar to (1). However, the coefficient K_M appears to be several times less in this case and necessary longitudinal dimension of the accelerating system is enlarged.

Thus, considered previously system with the homogeneous field may be thought to have high electro-optical characteristics without additional focusing devices at acceleration section and permits to accelerate continuous electron beams with the current up to several amperes on condition of formation of the beam with optimal convergence ange at this system inlet and outlet. So it may be recommended to be used in high-voltage electron accelerators with the beam power many times as high as that achieved nowadays. In obtained relationships possible beam blurring due to electron elastic interaction with the atoms and molecules in the accelerating system vacuum volume $(1019 \text{ } 1/\text{m} \text{ at } 10^{-1} \text{ } Pa \text{ pressure in } 10^{-1} \text{ } Pa \text{ } P$ glue-bonded tubes) isn't taken into consideration. The source of these particles is gas desorption from the outlet window, tube surface and cathode. As the tests results have shown, at beam currents up to 100 mA and aperture 35 mm it may be consedered justified. However when the beam currents are increased electron-neutral particle interaction may be the limiting factor. The most radical way to eliminate this pheno-menon is reduction of the accelerating system residual pressure. For example, using of the tubes made by diffusion welding permits to reduce gas release from the tube surface by a factor not less than 10. At effective pumping out of the scanning device chamber, this also corresponds to 10-fold reduction of the pressure in the tube. Now the welded tubes with an insulator inner diameter up to 180 mm and aperture maximum dimension about 100 mm are produced. The accelerating tube module made by diffusion welding - DA method is given on Fig.5.

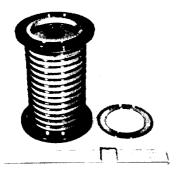


Fig.5. Accelerating tube module made by DW method

Thus, the beam formation with an optimal convergence angle at the inlet to the homogeneous field region by means of nearto-the-chathode lens or special source of electrons permits to rise the beam ultimate current in the accelerating system up to units or tens of amperes. In this case the maximum current dependency upon the accelerating field gradient is close to the square one and the proportionality coefficient is defined by electrons initial and final energy and also by the beam permissible dimensions at the tube inlet and outlet.

The beat current magnitude of the most of the accelerators applied nowadays in industry is known to be tens of miliamperes Basing on the given above calculations, the conclusion can be drawn that the accelerating systems of such machines can accelerate more powerful electron beams without significant design modification.

Application of the accelerating tubes made by diffusion welding eliminates the limitations resulted from the residual gas in an accelerating system.