

TRANSFORMER TYPE ACCELERATORS FOR INTENSE ELECTRON BEAMS

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Summary

The principles and designs of transformer accelerators (TA) generating intense beams of charged particles over energy ranges 0.5-5 Mev are described. Pulse electron accelerators with pulse length of 10^{-8} to 10^{-5} sec are investigated (some of them have a repetition rate of several hundreds pps) as well as one-phase and three-phase 50-cps transformers.

The most models' power conversion efficiency is in the range of 60-95%, the averaged beam power comes up to or exceeds 10 kW and is in excess of 150 kW for one of the last models. The design of a 5 Mev single-pulse TA with peak current of 30 kA at pulse length of 40 nsec and of 1,2 Mev proton TA with average beam power of 10 kW are described.

The features of main components of high voltage transformers and of intense current acceleration tubes are discussed.

Introduction

Among systems based on known dc principles of charged particle acceleration, the most effective ones seem to be those using high voltage transformers. Having power conversion efficiencies close to 100%, the transforming power capacity of these systems has in principle no limit. Systems working at 50/60 Hz may be operated from industrial mains at conventional voltages. Others, working at higher frequencies, are considerably more compact but demand auxiliary converters and have smaller power conversion efficiencies.

One of the main questions in accelerators designed on the transformer principle is rectification of the accelerating voltage. In ICT each of the multiple secondaries is insulated from the others and has its own rectifiers. In a transformer accelerator (TA)¹ the only rectifying element is the acceleration

tube itself, with the high voltage being kept constant automatically by beam current modulation. In a resonance transformer² the desired energy homogeneity of the accelerated beam is obtained by adjusting the pulse length. This method can be also used in pulse accelerators-transformers¹.

In addition to many questions involving the high voltage transformer design itself, e.g. high voltage insulation and rectification, there are other problems which are associated directly with the acceleration tube, such as questions of the tube electric strength and electron optics of intense beams. The analysis of the processes in the acceleration tube is complicated and it is difficult to work out the optimum optical arrangement for the acceleration of intense beams. Significant progress is likely in achievement of high currents through use of inclined electrodes to provide a short acceleration path and use of strongly focusing systems in the beam tube³.

This report reviews the activity in designing of powerful TA's as well as some portable TA's for special needs. Main attention is given to electron accelerators with energies in the range of 0.5-3 Mev and average beam power of several tens kilowatts. Two directions of accelerator design and development are observable, namely, low frequency 50-60 Hz and pulse accelerators. The natural frequencies of the latter are tens of kilohertz. The main pulsed TA models are designed for a high repetition rate so that average powers of beam outputs are also high enough. Also a single pulse TA generating intense bursts of electron current has been designed on the pulsed transformer principle. An industrial frequency accelerator which generates an intense beam of hydrogen ions at more than 1 Mev has been built and operated successfully.

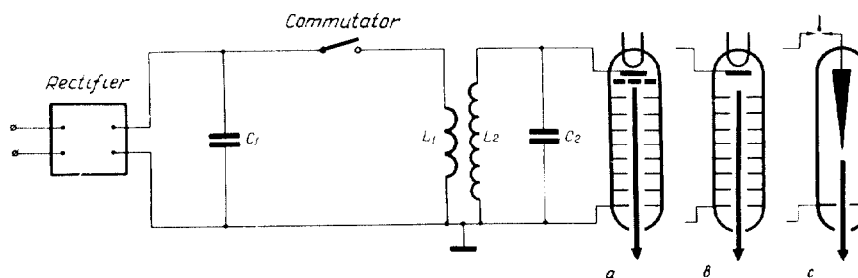


Fig.1. Equivalent circuit of pulsed accelerators.

C_1 - primary circuit capacitor, C_2 - self capacitance of the secondary circuit, L_1 , L_2 - inductances of the transformer circuits.

TA operating principles

Pulsed TA. In this case transformers with shock excitation are used as voltage supplies (Fig.1)⁴. The natural frequencies of the primary and secondary circuits of the transformers are equal: $C_1 L_1 = C_2 L_2$ where C_1 is a primary circuit capacitor charged by a rectifier before the operating pulse, C_2 is distributed capacitance of the transformer secondary circuit and L_1 and L_2 are the inductances. After switching the capacitor C_1 to the primary winding, the energy stored in C_1 is transferred to C_2 . The higher the Q-factors of the circuits (Q_1 and Q_2) and the coupling coefficient K are the fewer is the number of oscillations required to reach the maximum C_2 voltage. In the case $K = 0.6$ the secondary voltage already reaches its maximum at the second half-wave of oscillations (Fig.2).

$$U_2 = U_{01} \sqrt{\frac{L_2}{L_1}} e^{-\frac{t}{\tau}} \left\{ \sin \frac{\omega}{2} \left(\frac{1}{\sqrt{1-K}} + \frac{1}{\sqrt{1+K}} \right) t + \sin \frac{\omega}{2} \left(\frac{1}{\sqrt{1-K}} - \frac{1}{\sqrt{1+K}} \right) t \right\}$$

where U_{01} - initial voltage on capacitor C_1
 ω - natural frequency on both circuits
 τ - the time constant of damping

$$\tau = \frac{4}{\omega} \frac{Q_1 Q_2}{Q_1 + Q_2} (1 - K^2)$$

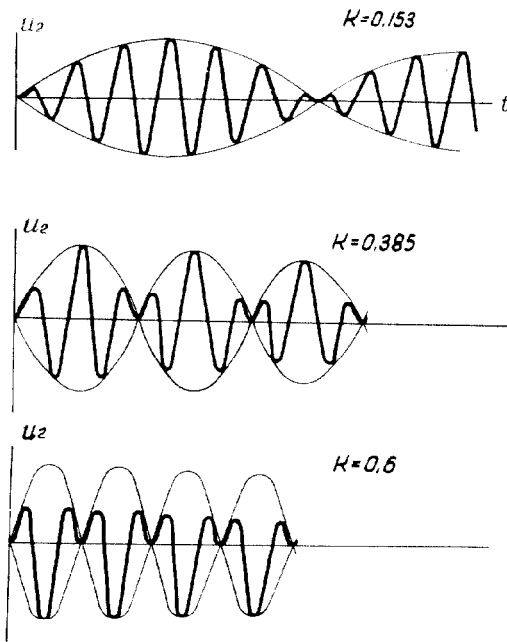


Fig.2. Time variation of secondary circuit voltage for different coupling coefficients.

The maximum value U_2 is reached in particular cases when $K=0.6$; 0.385 ; 0.285 . The part of the energy transferred from capacitor C_1 is

$$\alpha = \frac{C_2 U_{2max}^2}{C_1 U_{01}^2}$$

This ratio is shown in Fig.3.

plotted against the quantity $Q=2 \frac{Q_1 Q_2}{Q_1 + Q_2} (1-K)^2$.

In all pulsed TA which have been developed by us natural frequencies of transformer circuits amount to several tens of kHz and the time interval from the moment of switching the commutator to the moment when U_{2max} is reached is in the range $10-20 \mu\text{sec}$. The U_{01} voltage is usually chosen to be in range $10-50$ kV, and the voltage transformation ratio reaches $100-150$. An acceleration tube often is connected directly to the secondary winding (types *a* and *b* of Fig.1). In the case of *a*-type systems the moment of switching on the current and the pulse length can be regulated by the control grid of the injector. The switching on of the injector is usually performed close to U_{2max} (Fig.4), the pulse length can be varied over the range of 10^{-8} to $2-5 \cdot 10^{-6}$ sec, and the amplitude of the electron current i_e amounts to tens of amperes. The energy carried off in a beam reaches $50-70\%$ of the energy stored in C_2 .

After an operating pulse the remaining energy is stored again in C_1 at the time t_{11} . In a great number of models a commutator of the primary circuit is switched off just at the moment t_{11} so that no current passes through the commutator and the energy returned to C_1 is held for the following pulse.

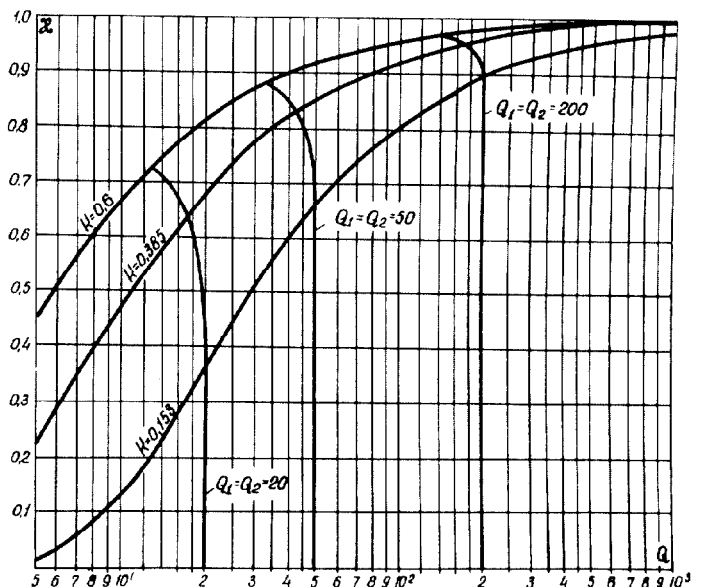


Fig.3. Energy transformation ratio α versus conventional Q-factor of the system.

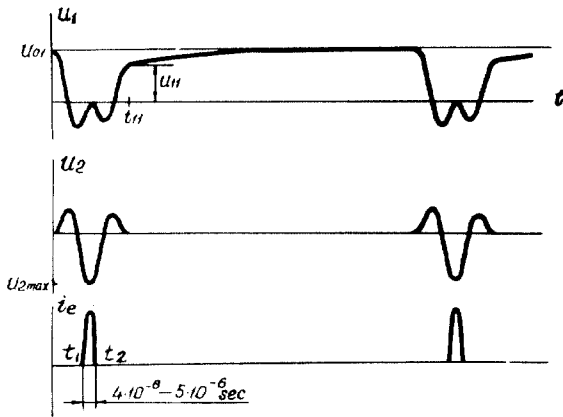


Fig. 4. Operation diagram pulsed TA with energy recuperation.

After C_1 is again charged to U_{01} (Fig. 4) the system is ready for the next operating pulse. The circuits in the cases considered have employed standard hydrogen thyratrons with rated voltage of 20-35 kV. The repetition rate may reach several hundreds Hz and the power conversion efficiency is in the range 60-70%.

In the remainder of this report, we shall continue to use the term efficiency to mean the ratio of the beam power to the power which is being taken from the main by the TA including power loss in the rectifier as well, if we are treating a pulsed TA.

In a-type TA's it is possible to get wide current pulses with an energy spread smaller than 1-2% by changing the tube current i_e in a specific way. The waveform $i_e(t)$ is found by solving the following set of two coupled circuit equations for the time interval during which the current pulse i_e is produced ($t_1 < t < t_2$) keeping U_2 constant:

$$U_1 = L_1 \frac{di_1}{dt} + M \frac{di_e}{dt}, \quad U_2 = L_2 \frac{di_e}{dt} + M \frac{di_1}{dt} = \text{const},$$

$$i_1 = C_1 \frac{dU_1}{dt}$$

where U_1 , U_2 and i_1, i_2 are the voltages and the currents in the primary and secondary transformer windings respectively. During the entire time of acceleration, $i_e = i_2$ as U_2 is constant and the electrical energy stored in capacitance C_2 does not change. The solution of the set of equations shows that the current should decrease approximately linearly throughout the pulse duration. Under this operating condition the output beam energy may amount to 70% of the full energy of the system.

The diode tubes (Fig. 1b) are used in TA's intended for certain applications such as high energy X-ray industrial radiography and radiation processing of materials. The absence of a grid and of a grid control circuit simplifies the machine considerably although it results in the presence of full the energy spectrum of accelerated particles. A transformer with a shock excitation may also be used for charging the high voltage capacitor C_2 which is subsequently connected

to the tube with a field emission cathode (Fig. 1c)⁶. In such installations an air gap is used as a primary circuit commutator.

Industrial frequency TA. In this type of TA the primary circuit is directly supplied by a 50/60 Hz main at 220/380 V (Fig. 5). The number of secondary winding turns w_2 and the geometrical dimensions of a machine are chosen in such a way that the natural transformer frequency is about 50 Hz. The reduction of the energy spread in the accelerated beam is achieved by modulating the beam current as is shown in Fig. 6⁷.

The required current-time variation during the pulse can be found for a simplified case (the transformer loss is assumed negligibly small and $\frac{1}{2\sqrt{LC_2}} = 50 \text{ Hz}$)⁸ from the equation:

$$i_e = \frac{U_{2m}}{L_s} [(k^2 + \theta) \cos \omega t - \alpha \omega (k^2 + \theta) (t - t_1) - k^2 \cos \omega t]$$

where U_{1m} and U_{2m} are the amplitudes of the primary and secondary voltages, respectively,

$$k = \frac{w_1}{w_2}; \quad \alpha = \frac{U_2}{U_{2m}} = \sin \omega t_1; \quad \theta = \frac{L_s}{L}$$

To maintain constant voltage at the accelerating tube in the machine now in operation⁸ feedback circuits are usually used which automatically regulate the current in the tube.

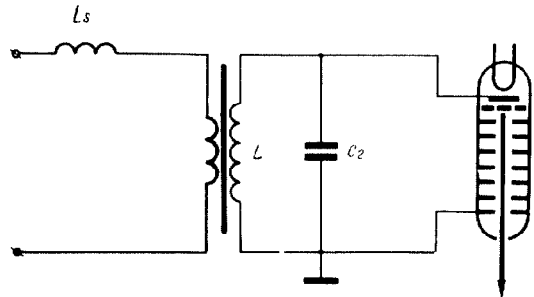


Fig. 5. Equivalent circuit of a single-phase TA. L - transformer inductance, L_s - stray inductance, C_2 - self (distributed) direct-to-ground capacitance of the secondary circuit.

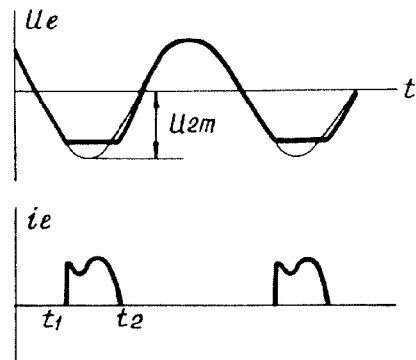


Fig. 6. Voltage and current in a single-phase TA acceleration tube.

The pulse length $t_2 - t_1$ may be changed over the range from zero (open circuit conditions) to 6-7 msec. Only the instant of control circuit switching on (t_1) is given from the control board, and after that the system works automatically. The maximum pulse length is determined by the value of allowed inverse tube voltage U_{2m} which, with $t_2 - t_1 = 6-7$ msec, exceeds by 15-20% the tube voltage during a pulse. This has a little practical effect on the electrical strength of the accelerator for the tube can withstand higher voltage when the absence of beam and associated radiation are off. In the long pulse operating condition the ratio of peak current and power to the average values is approximately 6. The uniformity of the energy of the accelerated particles depends on the care taken in the control system and the energy may be kept constant to within $\pm 0.1\%$. It is possible to attain the desired time variation $U_e(t)$ by setting up a program in the grid control system.

For accelerating beams of hundreds and thousands of kW, the utilisation of 3-phase TA is indicated. One of these types under current development has the equivalent electrical circuit shown in Fig.7. The transformer primary is supplied by a conventional 3-phase 50/60 cps main. The ripple of the tube voltage is in the range $\pm 3\%$. The current in the rectifiers is 120% of the tube beam and the rectifiers inverse voltage exceeds by 5% the tube voltage. Parameters of the first model are: tube voltage 1.2 MV, beam power 150 kW. Compact electric vacuum diodes developed by us have the desired performance (allowed inverse voltage 1.26 MV, peak current 150 mA) and are now undergoing operating tests.

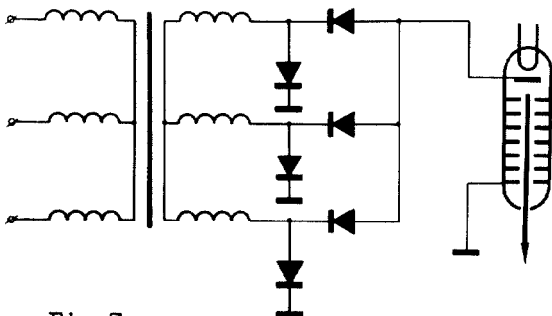


Fig.7.
Equivalent circuit of 3-phase TA.

Transformer design

Pulsed TA. The designs of pulsed TA's are remarkable for their relative simplicity. The primary and secondary windings are arranged coaxially (2 and 3 in Fig.8). The secondary terminates at the high potential terminals 5 and 5a. The accelerator is housed in a tank filled with a high electric strength medium - mostly SF_6 or a mixture of SF_6 and nitrogen.

The conical shape of the primary consisted of several turns improves the coupling coefficient K. To increase K the high potential terminal 5 is made transparent to the main magnetic field B which changes with a frequency of tens of kilohertz. Electrode 5 is a profiled insulator ring covered loosely by

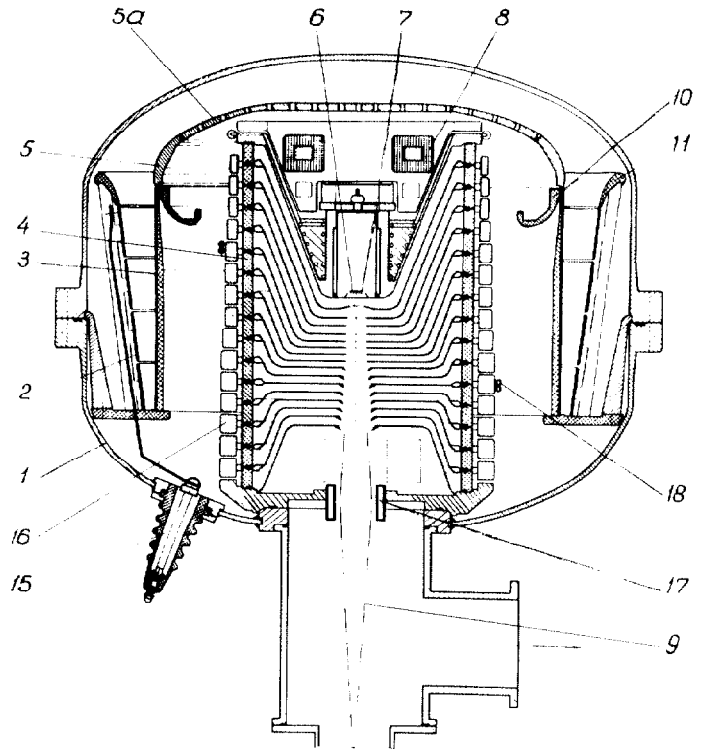


Fig.8. Design of ELITA-1,5. Parts denoted on Figs.8,9,10: 1-tank, 2-primary winding, 3-secondary winding, 4-acceleration tube, 5,5a-high potential terminal, 6-cathode, 7-cathode grid, 8-injector control system, 9-electron beam, 10-protecting screen, 11-ring which screens the edge of primary, 12, 12a, 12b, 12c-components of outer magnetic circuit, 13-conical core, 14-screen of the secondary, 15-input of primary, 16-rings which equalize electrode-to-electrode capacitances, 17-focusing lens, 18-cooling, 19-triggering gap, B-magnetic field.

separate turns of thin wire. There is no ferromagnetic yoke. The secondary winding has several hundred single-layer turns. The operating interturn voltage produced between layers of the secondary winding is 1-3 kV, and the potential gradient along the winding is in the range of 3-5 MV/m. To decrease the secondary winding voltage during breakdown, the screen 10 is installed. It produces an additional capacitance between the head end turns and terminal 5. In operation the pulse repetition rate of a transformer is limited mainly by the capability of the transformer cooling system.

Installation ELITA-1,5 shown in Fig.8 accelerates electrons up to 1.5 Mev. Maximum current is 100 A, pulse length can be varied from 50 nsec up to 3 μ sec at pulse repetition rates from single pulses up to 100 Hz. The acceleration tube 4 is assembled by epoxy rings tightened to the electrodes by rubber gaskets, and the electrodes are compressed along the tube axis. A LaB_6 30 mm diameter cathode with grid is used as injector. The acceleration channel length is 23 cm, the diameter 7 cm. Power for cathode heating and for the injector control system 8 (about 1 kW)

is supplied through the secondary winding 3 which consists of two layers. Rings 16 are mounted between the electrodes to equalize capacitances; the ring-to-ring clearances produce additional capacitances so that the pulsed voltage is distributed uniformly along the tube. After leaving the tube the beam 9 is focused by magnetic lens 17 and then strikes the object which is to be irradiated. Tube pumping is performed by an oil-diffusion pump with a liquid nitrogen trap. Cooling of components near the injector at high potential is provided by oil circulating through insulating pipes 18. The apparatus may be operated either in vertical or in a horizontal position. The weight of the accelerator itself (without radiation shielding, power supply and control systems) is about 500 kg.

In single pulse TA's the high potential terminal 5 is extended (fig.9). The capacity formed by this electrode and the tank is charged by the transformer and the terminal is then connected to the tube with a cold cathode.

On the installation RIUS-5 shown in Fig.9 an electron beam up to 30 kA with the energy of 5 Mev is obtained and the pulse length is about 40 nsec⁶. Natural frequencies of the primary and secondary windings are 32 kHz, the coupling coefficient is $K=0.45$ and capacitance to ground of the high potential terminal 5 is 220 pF. The number of primary turns is 4 and the secondary has 500 turns. The primary voltage being 50 kV the secondary voltage is $U_{2max} = 7$ MV. Such a voltage is actually obtained by filling the tank with a gas mixture of half SF₆ and half N₂. When the high voltage gap is triggered, up to 40% of the energy stored in C₂ (about 2.5 kJ) is converted into electron beam energy. Focusing of the beam by magnetic fields is employed in many experiments. The magnetic field near the cathode is about 1 kG and increases to about 4 kG near the anode, which may be quite far from the cathode. The beam dimension at the anode can be regulated¹⁰.

In a single pulse TA (Fig.1c) interesting new opportunities are presented by filling the tanks with water purified by special techniques. The electrical strength of water when the pulse length is in the range 10⁻⁷-10⁻⁶ sec can reach 500 kV/cm^{11,12}. The energy density amounts then to 1 megajoule/m³ and the wave impedance and power delivery time may be quite small.

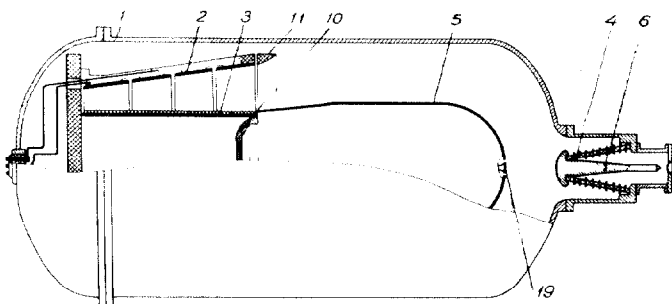


Fig.9. Design of RIUS-5. See Fig.8 for key to parts.

Industrial frequency transformers

The distinguishing feature of the low frequency transformer is the presence of a ferromagnetic yoke (Fig.10)^{8,13}. The yoke consists of several separate components: 1) an outer magnetic circuit parts 12, 12a and 12b, 2) a high potential terminal 5 and 5a and 3) central column cores 13. The secondary winding sections 3 are electrically connected with cores 13. The potential of the central column pieces changes from the ground potential up to the full secondary voltage U₂.

The core to core gas gaps are equal to 5 mm in the case of a typical model and are designed for an operating voltage of 70-80 kV. The primary 2 is mounted within the outer magnetic circuit component 12. The acceleration tube 4 and the injector control system 8 are placed within the central column. All is contained inside a steel tank 1.

The sections of the secondary 3 are the most critical components of the transformer. Parameters and the production quality of these sections determine to a great extent the size and reliability of the TA. The total number of turns in the secondary winding amounts to many tens of thousands; the number of turns in each section 3 is 8000. Every layer of a section is a plain spiral wound of a wire 0.55 mm in diameter (Fig.10). The layers are put one above the other and are connected in series. A spiral is glued from both sides by good insulating paper. Several tens of layers to form one section 3, after having been assembled, are placed in a special container where they are evacuated, dried

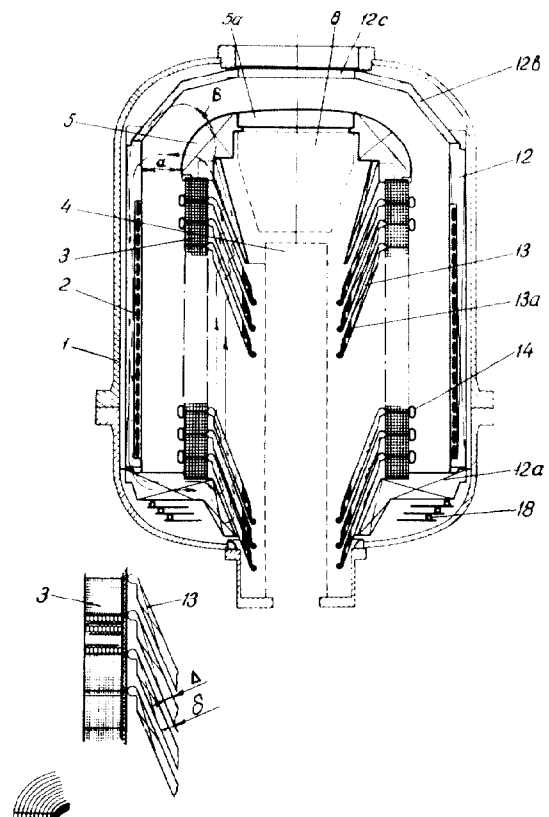


Fig.10. Design of industrial frequency single-phase TA.

and then impregnated by epoxy resin under a pressure of 40 atm. The result is a monolithic section with high electric and mechanical strength. The potential gradient along the secondary winding is 2-3 MV/m. The longitudinal secondary winding capacitance of such a design is much greater than that of a pulsed TA and so the breakdown overvoltages are not high. To preserve the sections when accidental discharges through the gas take place special metallic rings with an azimuthal cut are provided.

The components of a magnetic circuit are assembled out of radially oriented lamina of a conventional transformer steel of thickness 0.35 or 0.5 mm. The conical shape of the cores increases the longitudinal capacitance of the secondary winding and decreases the reluctance.

Dimensions of the transformer are chosen in such a way that its natural frequency is near 50 Hz. The coupling between the primary and secondary is high enough ($K=0.8-0.9$) so that keeping on resonance does not play as important role as it does in General Electric resonance transformers² and in pulsed TA's (Fig.1). But here too operating under resonance conditions gives some advantages: the power factor increases, transformer loss decreases (because the reactive power due to the stray capacitance to ground of the central column circulates only in the secondary circuit), and, lastly, the requirements for a unit to adjust the input voltage to the primary circuit are relaxed. A relatively high open circuit Q-factor of the transformer is $Q=60-70$.

The TA design provides a replacing of a control system 8, of an injector and of an acceleration tube without disassembling the tank. For tank filling the same gas mixtures and equipment for gas conservation are used as in the pulsed TA case.

To accelerate the beam while it is confined to a small diameter, permanent magnet lenses are employed in the acceleration tube^{3,8}. For accelerators ELT-1 and ELT-2 (see table) the beam current is 70-120 mA. The beam diameter is about 6 mm. Focusing channels consisting of axially-symmetric permanent magnetic, quadrupole permanent magnetic and quadrupole electrostatic lenses have been treated. These are all suitable for electron as well as for proton beams. Methods of matching focusing systems with input beam parameters at the beam source have been developed¹⁴. To show the capabilities of such lens systems, we shall give here the results of calculation of axially-symmetric magnetic lens optics for accelerating electron beams to 50 A (Fig.11)¹⁵. Each of the first three lenses is two thin rings magnetized oppositely and placed in a common screen-housing. Other lenses in the chain are single type and are unshielded. The inner diameters of the first three lenses are 14 mm, those of the others are 17 mm and the structure period length is 38.5 mm. The boundary particle motion in this case is described by

$$y'' + y' \frac{d \ln p}{ds} + \left[\frac{b^2(s)}{4\phi(2+\phi)} + \frac{1+\phi}{2\phi(2+\phi)} \phi'' \right] y = \frac{2J}{p^3} \frac{1}{\sqrt{y}}$$

where P , ϕ and J are beam longitudinal momentum, energy and the beam current, $b(s)$ is the longitudinal magnetic induction on the

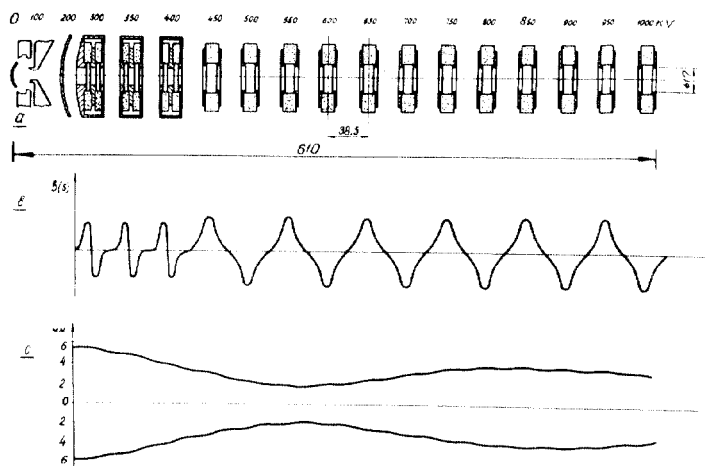


Fig.11. Electron acceleration through a chain of axially symmetric magnetic lenses: a-focusing channel, b-magnetic induction on the channel axis, c-beam envelopes.

channel axis (Fig.11b). The maximum beam diameter here is about 72 mm.

The possibility of confining intense beams of heavy particles in the same way was investigated experimentally on accelerator PRT. A hydrogen beam (50% H_1^+ , 30% H_2^+ , 20% H_3^+) of 1.2 Mev and 10 kw average power was obtained; the maximum current was 80 mA^{16,17}. A special control system installed in the high potential terminal regulated the beam current to stabilize the accelerating voltage on the tube. This system is similar to that used in ELT type accelerator. The beam confinement in acceleration tube was provided by quadrupole electrostatic lenses. Potentials on lens poles are supplied directly from the accelerating tube electrodes (Fig.12). The high energy gain per period of the system requires resort to numerical calculation¹⁷. The focusing lenses alternate with defocusing lenses (FODO system). The period length is 154 mm. All the lenses but the first five are of 25mm length and of 46 mm aperture. Because of the short length of the lenses the actual potential gradient distribution found in the electrolytic bath was taken into account in the calculations. The first five lenses are to match the input beam with the chain and their parameters are chosen by a random search method to provide the best conditions for beam passage through the tube and also to form the output beam cross section to a desired shape (usually round). The results for a PRT are:

lens N	1	2	3	4	5	6 and all the others
aperture (mm)	55	46	46	55	55	46
length of the lens (mm)	25	45	45	30	30	25

A channel of 1100 mm length consisting of a chain of 14 lenses is shown in Fig.12. According to calculation of the full channel voltage of 1.2 MV an electron beam of 65 ma equivalent current and phase volume of $2.2 \cdot 10^{-4}$ cm.rad may be passed through the channel. The concept of equivalent current

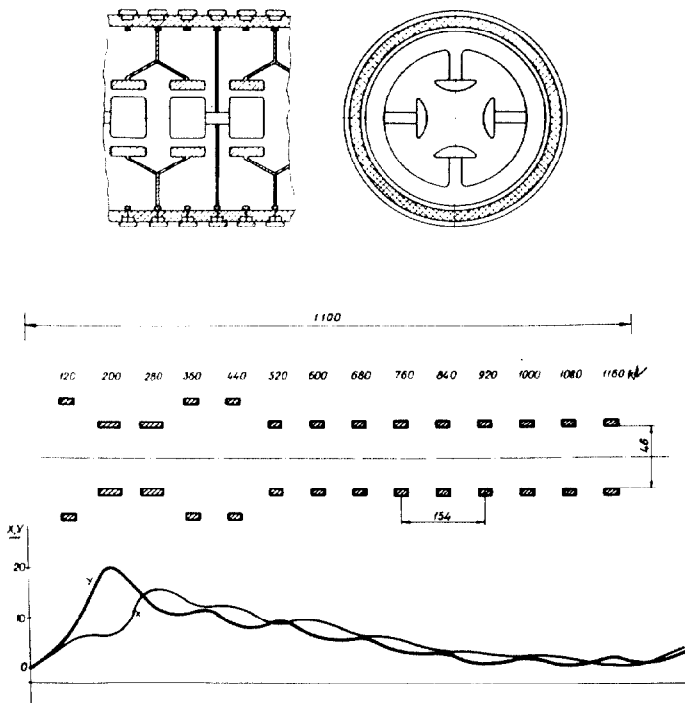


Fig. 12. Acceleration of heavy particle beams through a chain of electrostatic quadrupole lenses.

is introduced so as to take account of the presence of different components in the beam¹⁶:

$$i_{eq} = i_{H_1^+} + \sqrt{2}i_{H_2^+} + \sqrt{3}i_{H_3^+}$$

The value $i_{eq} = 65$ ma was calculated for the beam obtained in an experimental proton accelerator containing 50% H_1^+ , 30% H_2^+ and 20% H_3^+ . The beam envelopes are shown in Fig. 12.

The main purpose of reducing the apertures in the acceleration tube is to limit the processes causing breakdowns. It is known that these processes include acceleration and multiplication of secondary particles and initiation of electron-photon avalanches. As verified by experiment reduction of beam path length increases the electric strength of a tube essentially. Other effective measures taken to reduce acceleration of secondary particles in a tube are a choice of a particular electrode inclination and superposition of weak transverse magnetic fields. It is also known that there is a direct connection between the mean free path of the secondary particles and the tube's electric strength. In connection with investigations of strong focusing systems for acceleration tubes the ability of the systems to remove accidental particles from the channel has been analysed¹⁸. By means of a random number generator the appearance in a tube of 100-900 eV electrons with randomly directed velocities was simulated. The trajectory of each electron was calculated up to the moment of impingement on electrodes or of leaving the tube. The secondary-electron characteristics of three types of focusing systems equivalent in focusing the main beam (magnetic quadrupoles,

electrostatic quadrupoles and axially-symmetric magnetic lenses) have been studied. The smallest mean free path of secondary particles and hence the highest electric strength is provided by systems employing magnetic quadrupole lenses. It is possible to design channels with quadrupole lenses in which the path of the majority of the secondary particles is less than the structure period length.

The accelerator design which is based on three phase rectifier is shown schematically in Fig. 13. The transformer yoke is grounded. Three primary windings 2 are placed on yokes; secondary windings consist of many sections 3 similar in design to those of ELT-1 and ELT-2 (Fig. 10). The distances of sections 3 to the yoke and to the tank walls are designs to withstand full transformer voltage. The shapes of the components provide the necessary strength for supporting the electric fields at the ends of the secondaries. The construction and positions of valves 6 also avoid dangerous values of electric fields. At an operating voltage of 1.2 MV the maximum gradients inside the system do not exceed 210 kV/cm. As in other TA's the tank is filled with a SF_6 and N_2 mixture. The acceleration tube 7 may be placed separate from the transformer or as shown in Fig. 13 attached to the tank 1.

The main parameters of typical models are listed in the accompanying table.

Future prospects

The performance parameters of the models listed in table are by no means the upper limits for TA type accelerators. The most interesting directions of TA development are: extending the energy of accelerated particles, extending the power (pulsed and average), reducing the dimensions increasing the reliability, simplification of designs and of maintenance, and acceleration of heavy particles.

The energy is limited mostly by the electric strength of the acceleration tube and of the secondary winding and by the high voltage gap. In the tube of the latest design the potential gradients are close to 3 MV/m. Finer sectionalization of the tube insulator, use of insulators with smaller dielectric coefficient, strong focusing of the beams to permit reduction of the main channel diameter, and more careful selection of the tube electrode material appear to provide for increasing potential gradients up to 3.5-4 MV/m. To withstand a high voltage pulse length of 10^{-7} - 10^{-8} sec the tube insulator even today may be rated at 8 MV/m.

The potential gradient along the secondary winding of the pulsed TA reaches 3-5 MV/m and of the industrial frequency TA reaches 2 MV/m and higher. The limiting potential gradient at the high voltage gap when the tank is filled with SF_6 at 20 atm is also close to 0,5 MV/m. In the pulsed TA filled with water, for a pulse length of 10^{-7} - 10^{-8} sec, the highest supportable potential gradients are also about 0,5 MV/m. The average potential gradients in the high voltage gap are 1,5-2 times smaller than the maximum first of all because of a significant difference in the radii of curvature of the high voltage potential ter-

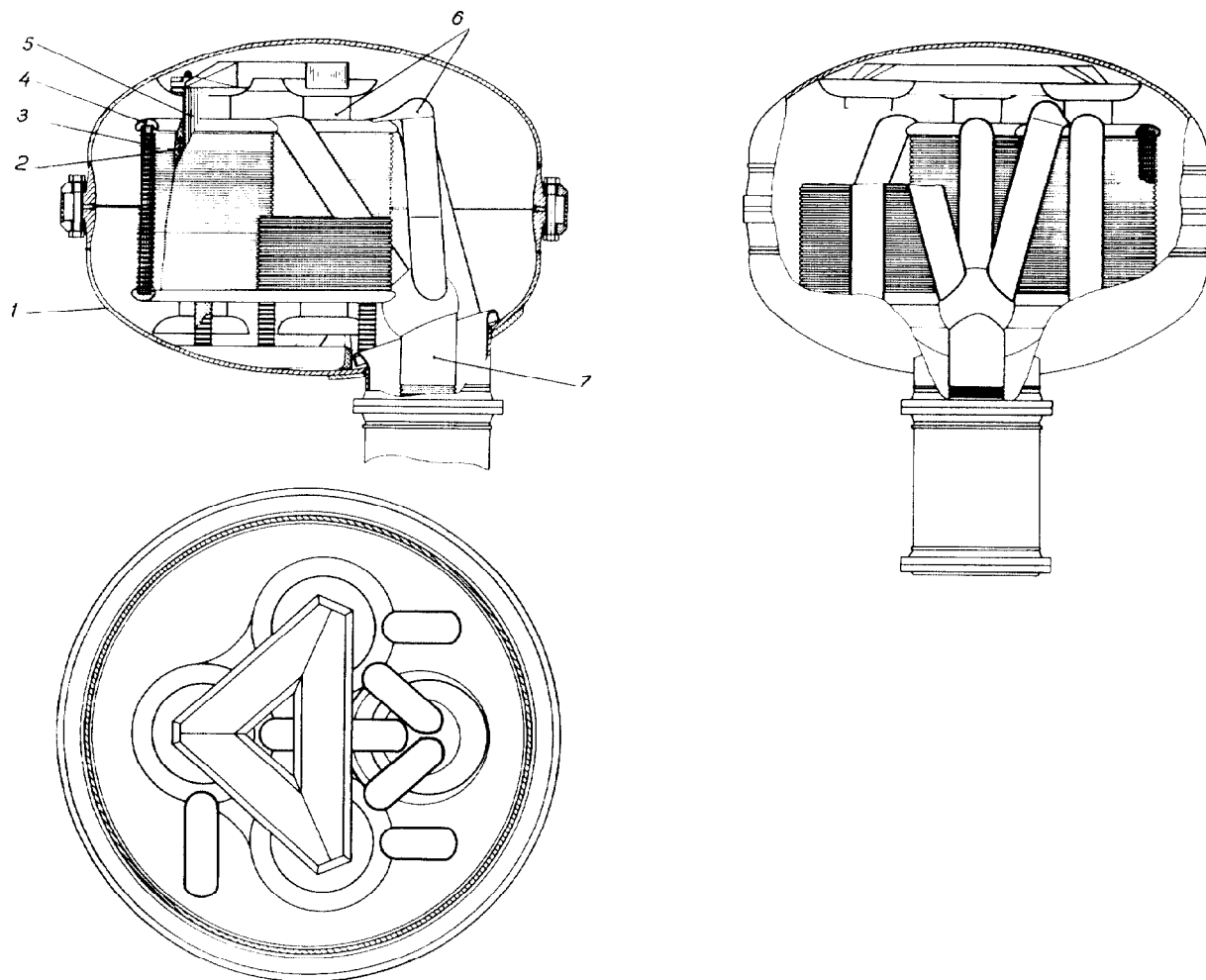


Fig.13. Three-phase TA TEUS-1,5: 1 - tank, 2 - primary winding, 3 - secondary, 4 - screen of secondary winding, 5 - magnetic circuit, 6 - valves, 7 - acceleration tube.

Main parameters of typical models

	ELITA-500	ELITA-1	ELITA-1,5	ELITA-3	EIT-1	ELT-2	PRT	TEUS-1,5	RIUS-5
Maximum energy, MeV	0.5	1	1.5	2.5(3)	1,3	1.8	1.2	1.2	5
Average power, kW	1	8	2	10(20)	15	25	10	150	
Maximum current, A	1.5	10(15)	100	20(40)	0.07	0.1-0.12	0.08	0,125	30000
Pulse length, μ sec	5	4	0.05-3	10	$6 \cdot 10^3$	$6 \cdot 10^3$	$5 \cdot 10^3$		0.04
Pulse power, kW	$7 \cdot 10^2$	10^4	$1,5 \cdot 10^5$	$4 \cdot 10^4$ (10^5)	90	215	95		$1,5 \cdot 10^8$
Maximum pulse repetition rate, pps	300	300	100	100(300)	50	50	50		one pulse per 2-5 min
Power conversion efficiency	70	70	60	60	90-95	90	70	95	30
Sizes of accelerator (ejection devices not taken into account)									
length, m	0.5	0.55	0.8	1.3	1.3	2.4	2,4	2,5	5.5
diameter, m	0.3	0.4	1.0	1	1	1,3	1,3	2	2
Accelerator weight (power supply system not taken into account), ton	0.04	0.12	0.5	0.8	2.5	7	7	4	5.5

minal and of the tank. A drastic increase of the potential gradient withstood in the high voltage gap will be obtained only by passing to qualitatively new insulators such as a solid dielectric. Manufacture of a solid insulator withstanding several MV and having the necessarily complicated shape and voltage spacing faces us with considerable technical difficulties today, however. On the whole, construction of a TA up to energies of 10 MeV and higher with the potential gradients mentioned is technically realizable. Tandems for heavy particle acceleration may be developed from the TA's currently designed. The average power of a pulsed TA is increased first of all by increasing the repetition rate. The energy imparted to the beam per pulse increases when the capacitance C_2 and voltage drive of the secondary circuit are increased. The two factors pulse length and injector current must provide then for extracting a great deal of energy.

It is supposed also to improve the performance of existing machines with single pulses. It is possible to increase their power conversion efficiency and to reduce the pulse-to-pulse interval. The former may be achieved by improving the high voltage gap breakdown conditions at the moment of voltage supply to the tube. For this purpose it is necessary to have a wide spark channel reducing the spark resistance in the gas and the accompanying energy loss. The most promising way to increase the width of the spark channel is to fire the gap with a wide auxiliary 0,5-1 MeV electron beam. This beam may be produced by a compact single pulse TA built in the high voltage electrode. A train of two or more pulses with short pulse-to-pulse intervals is possible if there are several separate capacitor banks in the primary circuit. The pulse-to-pulse time is determined by the combination of the post-pulse recovery of the tube vacuum and the recovery of the high voltage gap electric strength.

The power of a single phase TA can be increased by the same means used in ordinary power distribution transformers. A decrease in dimensions is provided by increasing the frequency up to 400 Hz. At higher powers 3-phase TA's are most practical. Their power, in principle, is not limited and the only limiting elements are the high voltage rectifiers and the acceleration tubes. Development of high voltage rectifiers have proved the possibility to provide electrovacuum rectifiers rated at several MV and at currents of tens of amperes which will provide rectification of several thousands of kW. Acceleration tubes with electron beams of thousands and of tens of thousands of kW can seemingly also be manufactured.

The minimum particle impingement of the tube electrodes is obtained by increasing the focusing properties of the system, by suppression of secondary particle acceleration and by vacuum improvement. The power conversion coefficients of high power 3-phase TA's should exceed 95%.

One way to reduce the dimensions of a pulsed TA with gas insulation is to decrease the high voltage acting time. In machines of small dimensions the natural frequencies may

exceed 1 MHz. The increase of electric strength to pulses permits increasing the potential gradients both inside the transformer and inside the acceleration tube and reduction of the TA dimensions. For short pulses it may turn out to be reasonable to use liquid insulation. The pulsed TA design is extremely simple, but these machines have rectifiers, commutators and power supply components. Industrial frequency accelerators are supplied directly from industrial mains, but their designs are more complicated. The pulsed accelerators are advantageous when it is necessary to have a compact TA with as high energy as possible. Industrial frequency TA's are advantageous when it is necessary to have high power and high power conversion efficiency.

The transformers described can be used without any changes for heavy particle acceleration. The main difficulties are connected with focusing in the acceleration tube and with providing compact ion sources and power supply to them. Successful operation of experimental proton accelerator PRT demonstrates the possibility of making accelerators for intense beams of heavy particles.

We would like to point out in conclusion that with the creation of high voltage electron accelerators at 1 MeV and higher it becomes possible to design equipment to provide an intense electron beam extracted into air with a density of 10-20 kW/mm² without spreading. A concentrated beam of electrons extracted into air may be used for welding of metals, cutting rock samples etc. The achievement of transportable TA's will allow wide application of electron-ray techniques for such purposes. Effective extraction of stationary intense beams of chosen density from vacuum is now a feasible project.

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