USSR ACADEMY OF SCIENCES
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preprint

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Summary

MeV direct transformer type accelerators are revewed. Units generating electron beams of mean power of dozens of kw and machines with pulse power of $10^8 - 10^9$ W and frequency of several dozens of cps are described. The efficiency of the first type accelerators is 90-95 %, that of the second type is up to 80-90%. Type designs and strong-focussing accelerating tubes are concerned. The main parameters of several accelerators are given. Possibilities of increasing of the highest energies of such devices, intensive proton beams acceleration and other problems are discussed.

Various methods of charged particles acceleration based on transformer principle are known. Althouth from the energetical point of view it is always desirable that the beam power is considerably higher than losses in yoke and windings, this is not realised in every type of accelerators. In betatrons e.g. the limitation of current and beam power is connected with the difficulty of keeping a large space charge in the initial time of the acceleration. Although ways of designing betatrons with high efficiency are possible to imagine, that is increasing the injection energy /1/, special regimes of charge accumulating at the initial time of the acceleration (for example /2/), installating of several cameras on the yoke etc, such accelerators do not exist as yet. On the other hand direct acceleration transformer type machines are capable to accelerate intensive beams of charged particles with an efficiency near to 100% already at present.

Problems of developing betatrons and number of other accelerator type based on transform principle will not be concerned here. We shall restrict only on possibilities of transformer accelerators (TA) which appeared in the last years /3,4/ and which are not well known. Such accelerators combine some features of resonance transformers /5/ and Insulating-Core Transformers /6/ with a number of new elements. Some modification of the TA used for generating accelerated electron beams of high mean power ,generating large pulse currents and for acceleration of intensive proton beams are described in a number of papers /7,8,9/. We shall remind in short of their operation principles.

Operation of transformer accelerators

The electrical circuits of the described accelerators are shown in Fig.1a and 2a. The secondary of the transformer is loaded in both cases on the accelerating tube with current can be controlled . In the first case the primary is connected to 50(60) cps power system or to another low-frequency voltage source ; in the second case it is an impact excitation transformer (Tesla transformer) the primary circuit of wich is charged from a rectifier. The base frequencies of the secondary circuits are equal to the voltage frequency of the primaries.In the second case it is necessary as in usual Tesla transformers. In the first one the resonance with the supply voltage frequency has some advantages; $Cos\varphi$ is near to 1, losses in the transformer are reduced as the reactive power conditioned by a capacity between the high-voltage winding and ground is present only in the secondary circuit and the like.

The losses of the transformer in the first case are considerably low if it is designed availably and the voltage U_1 of the power system is practically devided between the dissipation inductance L_s of the transformer and the accelerating tube . It is clear that there is a law of electron current time changing according to that the tube voltage remains constant when current passes (Fig.1b)/7/. The needed current shape of accelerated particles is provided by the control grid (or by the electrode) of the injector and by the control system that determines the potential of the control grid. The mean current value in the accelerating tube is 5-6 or more times lower than the amplitude value depending on the pulse width. Monochromatization of the par-

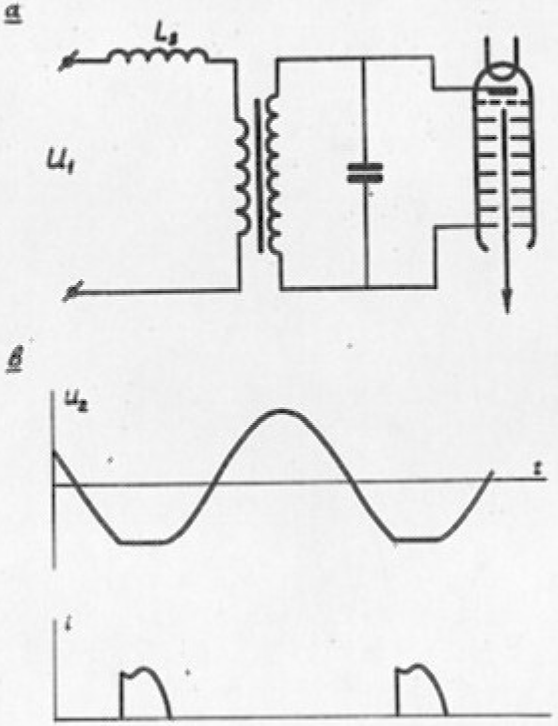

Fig.1. Electrical circuit of the accelerator, voltage U_2 and current i of the tube.

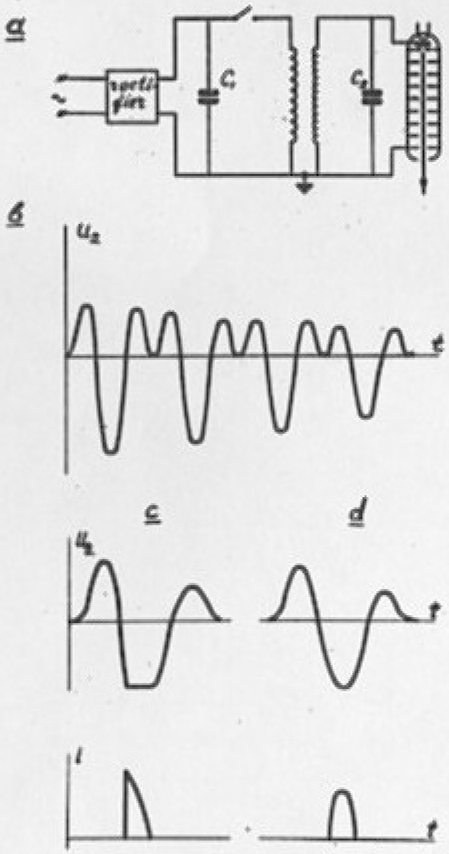

Fig.2. Electrical circuit of the pulse accelerator ,voltage U_2 and current i of the tube.

ticles can be provided in the range of 0,02-0,04%. Energy error of 2,5%, in many cases even of 10-15% is sufficient for electron accelerators used for applied purposes. Thus the stabilization of the accelerating voltage is realized by means of the accelerated beam itself without any rectifiers that essentially simplifies the apparatus. If necessary,the electron energy is not to be constant and can be changed during the pulse according to a given law. The power transferred into the load is more than 90% of the power supplied to the primary as specific losses of copper and steel are roughly equal to those of a usual transformer and the power used by the injector and the control system is not very high.

The impact excitation transformer shown in Fig.2a is used in the first line for accelerating of high currents in short pulses /8/. At sufficient high coupling coefficient k=0,6 between the primary and the secondary the energy accumulated in the capacitor C_1 of the primary circuit is transferred to the capacity C_2 of the secondary already in the first oscillation period (Fig.2b). The injector is switched on near the high voltage maximum.

Beam out energy can be 40% and more of the energy accumulated in the primary circuit capacitor before the cycle. This takes place in the case of operating with wide current pulses of 1/4 - 1/6 oscillation period. In the case C,Fig.2 , the accelerated particle current changes according to the given law and as a result of this the tube voltage remains constant during the acceleration . And about 70-75% of the system energy is transmitted into the beam. The injector is switched on for a given time at regime and energy instability of the particles depends on current and pulse width. After a cycle the rest of the energy is reset to the capacitor C_1 (instant t_1 in Fig.3). Switching out the circuit by commutator the energy can be kept in the capacitor for the next operation cycle. Between the pulses the capacitor C_1 is charged up to the rated voltage. Such operation using energy recuperation allows to increase the efficiency of the apparatus.

The described circuits can be used for acceleration of

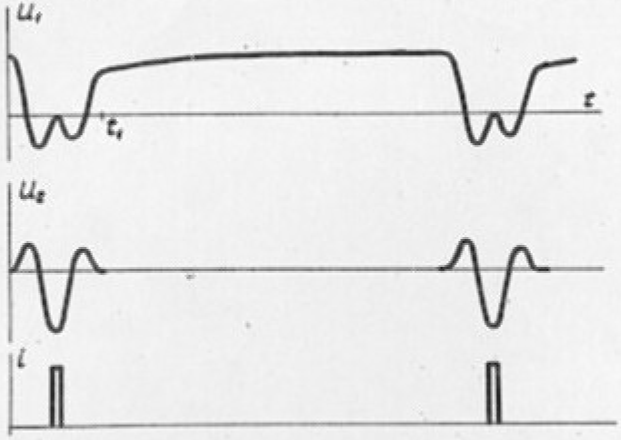

Fig.3. Operation regime of the pulse accelerator with energy recuperation, primary capacitor voltage U_1, tube voltage U_2 and current i.

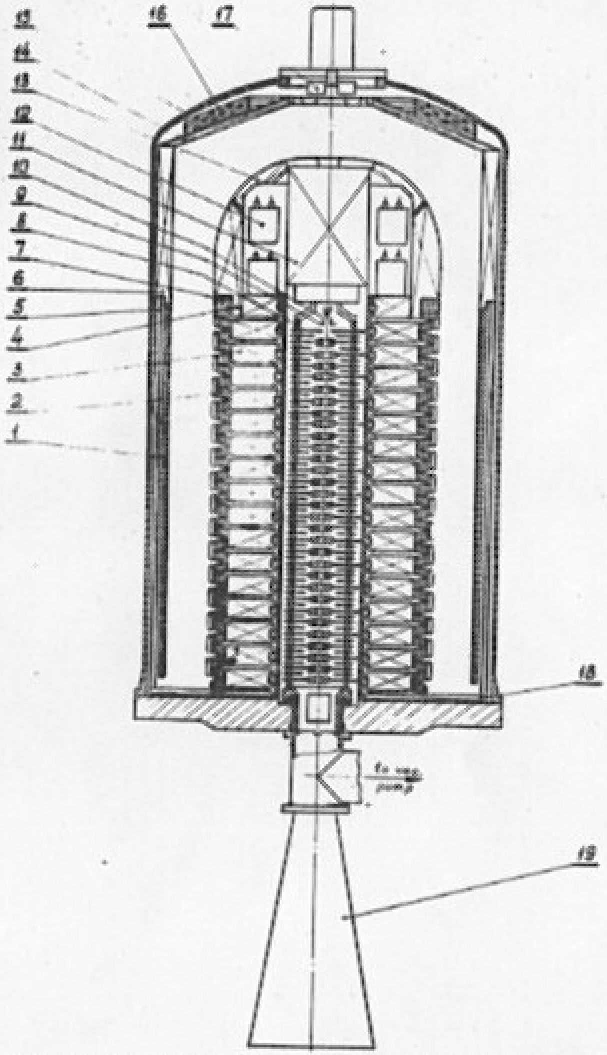

Fig.4. Constructive diagram of the ELT-1,5 accelerator. 1-primary winding of the transformer; 2-sections of the secondary winding ; 3-core disk; 4-high-voltage part of the core (head); 5,6,14,18-core components; 7-head coil ; 8-accelerating tube ;9-controle electrode ; 10-injector ; 11-control system ;12-capacitor ; 13-capacity giver of the head; 15-tank ; 16-heat exchanger ; 17-ventilator ; 19-bell with the output-window.

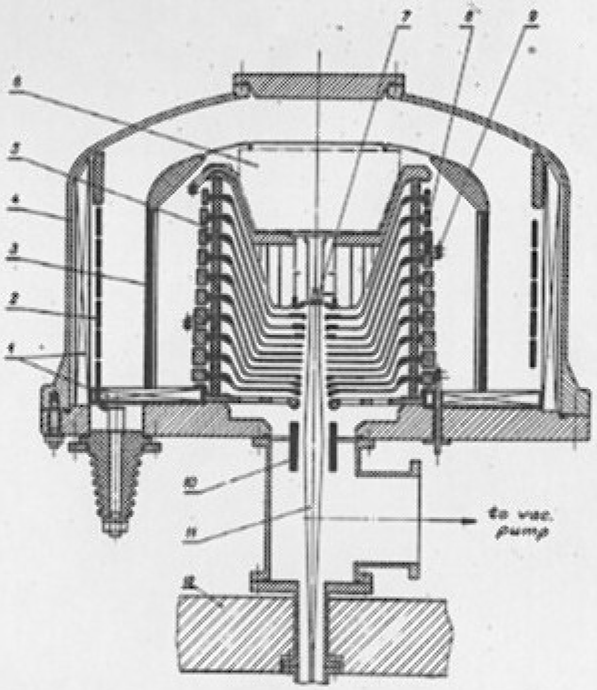

Fig.5. Constructive diagram of the ElIT-1 accelerator. 1-core yokes ; 2-primary winding of the transformer ;3-secondary winding ; 4-tank ; 5-accelerating tube ; 6-control system ;7-injector ; 8-capacity divider ; 9-oil cooling tubes; 10-focussing lens ; 11-electron beam ; 12-protection.

both electrons and other particles.

At the present time we have developed electron accelerators based on the both methods and now we make ready a machine for proton acceleration based on the first method . These sets are called electron transformer ElT (Fig.1a),electron impulse transformer ElIT (Fig.2a), proton transformer PrT (Fig.1a) resp .

Design diagrams

The design diagrams of described devices are shown in Fig.4 and 5. The transformer with low-frequency voltage of the primary (circuit in the Fig.1a) have a steel core, the central column of wich is partitioned into separate insulating disks 3(Fig.4). The primary and the secondary windings 1 and 2 are placed coaxial and have roughly equal height. The secondary consists ot many series connected sections. Each two sections are mounted on the disk of the central core and the middle point of section pair is electrically connected to the disk. The number of the turns of the secondary and the sizes of the accelerator are determined so that the base frequency of the circuit consisting of the inductance and distributed capacity of the secondary is equal to the supply voltage frequency. It is suitable to design the accelerator for a common power system of 50 or 60 cps. In this case the core is made of usual transformer iron ,thickness 0,5 mm e.g. At the high-voltage terminal is mounted a condencer battery connected to a part of turns of the secondary to provide more uniform gradient of the electrical field strength along the central column (s./7/ in detail). The accelerating tube is built inside the transformer and has contacts with disks 3 to provide a constant voltage gradient along it. The voltage is transmitted to the cathode and control electrode from the control circuit placed in the upper part of the column. The control circuit is supplied from a part of the secondary.

One of the most serious problems,passing an intensive electron beam through the tube, is solved by means of strong focussing system inside the tube with constant magnets /10/. The device is placed in electrical strong gas pressure up to 16 kg/cm^2.

The design of the pulse accelerator is similar to that described above. One of the essential features of it is the fact that there is no core central column that is not necessary here because the coupling coefficient k-0,6 is achieved without it.

Particle acceleration in short pulses allows to supply the voltage to the secondary 2 and to the accelerating tube 5 respectively for a short time ,therefore the base frequencies of the primary and the secondary circuits can reach several dozens or hundreds of kilocycles. According to this the number of turns of the secondary is two or three orders lower than that in the device described above. The secondary is wound with double wire to power the high voltage part of the tube for heating cathode etc. The electrical gradient along the secondary and the tube insulator reaches 25 - 30 kV/cm and between the accelerating electrodes of the tube in vacuum reaches 50- 70 kV/cm. This fact provides high densities of cathode current and promotes passing the beam throgh the tube. To provide a constant voltage gradient along the tube there are installed rings 8 on the electrodes that equalize capacities between the electrodes. The transformer and the tube are placed in tank 4 designed for 8 atm. Between the target and the accelerator there is a radiation protection 12. A high coupling coefficient between the windings(k=0,6 or k=0,39) as well as the fact that the injector current is controlled allow to get the ratio of the beam power to the primary capacitor power up to 0,4-0,7. Using the recuperation and an economic method of charging of the capacitor C_1 it is possible to increase the efficiency up to get 90%. The cycle frequency can run to dozens or hundreds cps and depends on commutator , thermal conditions and electric strength of the tube with a high mean-power of the beam. The latter circumstance cannot be estimated precisely and will be experimentally investigated in detail. The beam parameters achieved by means of such accelerators are given below.

Parameters of electron accelerators

At present are produced and tested two accelerator models; ElT-1,5 accelerating electrons up to 1,5 MeV with the mean power of the beam of 25 kw and ElIT-1 accelerating electons up to the energy of 1MeV in pulses in the range between $1{,}5\cdot10^{-6}$ and $3\cdot10^{-8}$ sec and current amplitude of between 20 and 100 a respectively. The accelerators ElT-2,5 and ElIT-3 are now mounted and adjusted. The main data of the above mentioned machines are given in the table.

Table of main parameters of the accelerators

Type of accelerators	ElT-1,5	ElT-2,5	ElIT-1	ElIT-3
Energy	300KeV- 1,5 MeV	600 KeV- 2,5 MeV	300 KeV- 1 MeV	600 KeV- 3 MeV
Mean power with highest energy	25 kw	40 kw	1-3 kw	10-20 kw
Pulse power	130 kw	200 kw	up to 10^{8} W	up to 10^{9} W
Maximum pulse frequency	50 cps	50 cps	25 cps	100 cps
Efficiency	90%	90%	up to 70%	up to 80 %
Sizes without ouput assembly height	2,4 m	4,3 m	0,7 m	2,4 m
diameter	1,3 m	1,82 m	1 m	1,3 m

The diameter of the electron beam at the output of the ElT-1,5 is about 5 mm. There are mutually perpendicular magnetic scannings to put out the beam through foil.
About the concentrated beam output will be said beneath.
A sertain disadvantage of the ElT accelerator is the fact that the pulse current is considerably higher than the mean current. But it is of no importance for radiation processes when

the needed dose is accumulated during many pulses. As to the tube the strong focussing systems allow to transfer necessary currents without essential decreasing of tube electric strength.

The mean power of the ElIT-1 of 3 kw is achieved with the pulse frequency of 50 cps and the beam energy of 60 joule.These data are not the highest for the accelerator. At present attempts are made in order to increase its pulse and mean power.

The parameters of the ElT-2,5 and ElIT-3 accelerators are given conditionally because they will be finally ascertained after the adjustment will have been finished.

Outlook on heavy particle acceleration

Acceleration of such powerfull beams of protons or other heavy particles by means of the described methods is exceedingly desirable. The most serious problem is to create an accelerating tube that could keep its electric strength when an intensive ion beam passes through it. It is also necessary to elaborate a small ion source with controlled current and needed beam parameters,to provide vacuum pumping on the high-voltage terminal and to solve a number of other technical problems.

Consideration of possibilities of strong focussing systems installed inside the accelerating tube shows that the keeping of proton current of 100 ma and more with the beam diameter of about 2 cm is quite real with a gradient along the tube of 1,2 MeV/m /9/. If proton energy amounts to several MeV it is reasonable to use electrostatic quadrupole focussing lenses supplied directly from the secondary winding taps /9/. The quadrupole lenses make also electrons and other random secondary particles difficult to pass through the tube.

As a proton injector is considered a source with oscillation of electrons in magnetic field with current controlled by the potential of the anticathode. Application of duoplasmotron is also examined. Thus the gas consumption of a powerful source is high it is difficult to provide the vacuum pumping at the ground terminal of the tube even using pulse gas input and so additional high-vacuum pump is istalled at the high-voltage terminal of the tube. Powering the high-voltage assemblies causes no serious difficulties. So in the accelerators shown in Fig. 1a the power is taken off from a part of the winding at the high-voltage terminal of the secondary. Cooling of the high-voltage assemblies is secured by means of forced gas convection in a tank or by means of oil circulating from ground to the high-voltage electrode through an insulated spiral tube.

It is known that the beam of ion source contains ions of various kind. So a proton source with electron oscillation as described above contains about 70% of protons,the rest are H_2^+ and H_3^+ . It is easy to prove that the ion separation at the input of the accelearting tube is not necessary as the presence of heavy components does not essentially increase the proton beam dimensions in the tube /9/. It is not excepted however that separator will be installed for some investigations.

As it is to conclude from the account given above ,possibilities of the proton acceleration are concerned for the accelerator types similar to ElT-1,5 or ElT-2,5 . At present several parts of the PrT-1,5 proton accelerator with energy and power of beam close to that of the ElT-1,5 electron accelerator are adjusted on the test stands.

In this accelerator it is suggested to provide the proton monochromatisation better than 0,1%. The acceleration of heavy ions in strong-focussing tubes will demand an essential increasing the gradient of the focussing lenses and probably using electromagnets. The supply of every electromagnetic lens will be provided from several transformer turns having the lense potential. Besides of the axialsymmetric lenses and quadrupoles a stronger nonlinear focussing system consisting of lenses with four or more pole numbers can be used (e.g./11/). Application of high current ion sources in pulse accelerators is also possible ; on principle there are no limitations of generating beams with high pulse and mean power.

Possible modification

On the basis of a proton transformer it is possible to build a tandem (Fig.6). In such an accelerator the magnetic

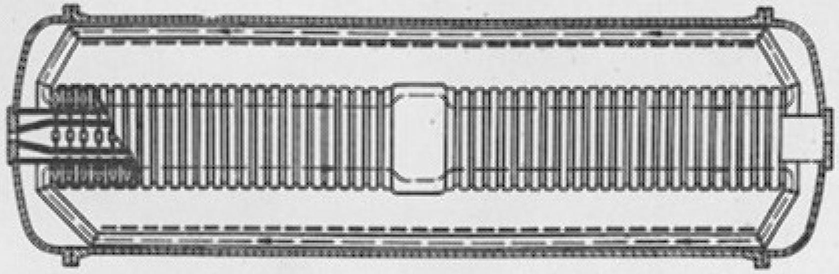

Fig.6. Tandem based on EIT type accelerators.

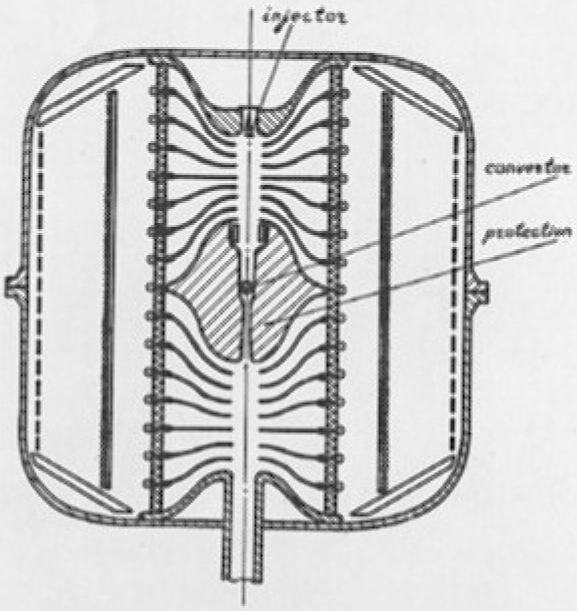

Fig.7. Device based on the pulse TA used for generation of accelerated positrons.

flow passes through the central column without falling out the high-voltage gap. The turns of the secondary are wound on both parts of the column in mutual opposite directions. Unlike the tandems based on electrostatic accelerators the current can be here two or three orders higher as there are no limitations caused by a mechanical transporter. As pointed out at the beginning of the paper , the energy stability in such transformers can amount to 0,02-0,04 % which is not worse than in modern electrostatic tandems. The application of strong focussing in the tube will probably allow to produce higher than it is possible in known tandems based on the ICT.

A futher development of this modification is heavy-ion accelerator with multiple recharging the operation of which is described in /12/ . Accelerating and decelerating sections alternate in this model. After accelerating sections targets of low tightness are installed and after the decelerating sections tighter ones respectively. In consequence of this fact the degree of ion ionization is at the average higher during the acceleration than during the deceleration. On account of the charge difference an energy accumulation takes place. Such a design allows to accelerate multicharget heavy ions up to hundreds of MeV with the maximum potential in the system of some MV. Creating of an accelerator with the multiple recharging becomes more real thanks to a possibility of transferring and acceleration of intensive proton beams that has appeared.

An accelerator design as a tandem based on the pulse transformer (Fig.7) can be used powerful source of accelerated positrons. In this case the potential of the high-voltage electrode must run to several MV and a convertor is to be placed inside the electrode. The electron current in the first part of the accelerator can amount to some hundreds amperes. A portion of the postrons flying out from the convertor at a small angle to the machine axis is accelerated in the tube in second part of the accelerator.

One of the main problems of the development of the concerned accelerators is the achievement of highest energy and power of beams . The highest energy of the particles in any accelerator of this kind is limited by the electrical strength of the gas gap and the accelerating tube like any other DC accelerator. The operation regime of the gas gap is not harder in transformer accelerators than in usual electrostatic generators and the tolerant gradient of the potential can amount to 150 -200 kv/cm. The gradient of the electric potential along the accelerating tubes in the accelerators which exist are 13 kv/cm in ELT-1,5 and 25 kv/cm (along the insulator) in ELIT-1 resp. Thus they correspond to the gradients of the known accelerators, e.g./13/. So predicting the highest energies which can be possibly achieved in the accelerators based on the described designs we can go out of the possibilities of the electrostatic accelerators. And if the voltage value of 10-15 MV on the high-voltage electrode is the reality to-day, it is quite possible to design accelerators with energy of several dozens of MeV.

To increase the power of transformer accelerators it is necessary,first, to transfer the needed power to the secondary and , second, to provide in the tube a current capable of carrying out this power. It is not very difficult to create a transformer designed for high powers. For the given machine dimensions the power can be increased by means of supplying of 400 cps or by means of other technical ways.As to the possibilities of the accelerating tubes we can not yet achieve the highest current which can pass through the strong focussing system insyde the tube. In /14/ there are concerned systems for currents that are some orders higher then these the ELT-1,5.

As stated above pulse transformer accelerators can sustain frequencies of hundreds of cps. Now it is difficult to reveale the highest frequencies. But we hope that in the next years electron pulse accelerators can operate with frequencies of the 200-400 cps with considerable energy carried out by the beam in pulse. Probably it is available to use cathodes with autoelectronic emission in such accelerators.

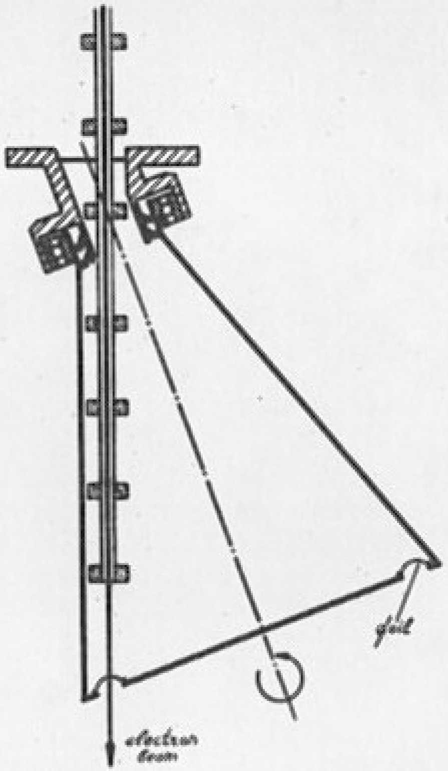

Fig.8. Arrangement serving for passing a concentrated electron beam through the rotating foil.

Some aspects of beam application

Detailed review of application field of powerful electron and ion beams is not dealed with in this paper. We shall concern only some aspects of accelerated electron application. There are three methods of influence on substance by means of electron accelerators.

I. direct bombarding materials with electrons for radiation influence;

2. application of concentrated beam as an energy carrier for the thermal influence on material ,e.g. for melting and welding metals;

3. beam converting into gamma-radiation for fault detection or radiation of massive objects. As a rule in the first two cases it is reasonable to carry the beam out of high vacuum volume in which acceleration took place as it will entail great difficulties to put the object to be processed into the vacuum; sometimes it is not possible at all. Passing a beam of electrons accelerated up to many hundreds of keV out of the vacuum through foil offers no difficulty in the presence of a preliminary magnetic scanning. More complicated is the second case when it is necessary to put out a beam with energy concentration of dozens of kw/cm^2. Besides of differential pumping windows /15/ we dealed with rotating foil devices.In the device shown in Fig.8 the rotation axis of cone with foil is inclined to the beam direction. Thanks to this angular velocity of the foil rotation is considerably higher than in rubber tightening region. The focussing path extends on to the radius of which can be sufficient reduced. This allows to apply very thin foils and to provide small electron dissipation at the output. In similar way the beam can also come into a vessel being under pressure.

To generate an intensive γ-radiation flow speedly rotating targets being in vacuum or in smalted-metal targets are used. Energy carry-out from surface of the latter is secured by evaporation of metal.

Conclusion

The developments stated above concern to achievements of TA research that was made by a number of collaborators of Institute of Nuclear Physics /Novosibirsk/ during the last 3-4 years and is on principle an initial result of this work.Considerations of possibilities of such accelerators are largely conditioned and can change in the future.

But we can confidently suppose that transformer acceleration methods and those described above in particular are one of the most promissing ways of creating powerful and low-cost accelerators. Numerous technological applications of the machines stimulated development of low energy sets /16/. If necessary the energies can be essentially increased. As stated above there are also ways to increase considerably beam powers.

In conclusion the author seizes the opportunity to express his thanks to G.Budker for a steady interest for my work,V.Gaponov,S.Vasserman and V.Vecheslavov for creation of described accelerators done in common.

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