DENSE PLASMA HEATING BY 200KJ-ELECTRON BEAM AT THE GOL-3-II FACILITY

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Collective interaction of microsecond electron beam with a plasma and its fast heating is being investigated at the GOL-3-II facility [1]. In this facility the plasma column has a diameter 6cm and 12-m length, longitudinal magnetic field is up to 5T in the homogeneous part of the solenoid and up to 10T in its end mirrors. Plasma density can be varied in $10^{14}\div10^{17}$ cm^{-3} range. For the beam-plasma interaction experiments the high-power electron beam generator U-2 is used with possible beam energy content up to 0.3MJ [2].

In the paper recent results performed at this facility are presented.

It is experimentally shown that macroscopically stable transportation of a 200kJ-electron beam (1MeV, 30kA, 8μs) through the 12m-plasma column is possible under conditions close to total current neutralization. At injection of such beam into plasma with density $(1\div2)\times10^{15}$ cm^{-3} the very strong beam relaxation is observed. The efficiency deceleration of the beam electrons is 30÷40% according to measurements of their energy spectrum. Energy content of the plasma and its electron temperature increase with growth of the beam energy content. The measurement of distribution function of plasma electrons by Thomson scattering has shown that characteristic temperature of the electrons is ~2keV at density $(1\div2)\cdot10^{15}$ cm^{-3}. An anisotropy of the distribution function of hot plasma electrons is observed. The average energy of particle movement along the beam direction is few times higher than transverse one. Under these experimental conditions, the ion temperature is 20÷30eV.

For substantial increasing the ion temperature and obtaining plasma with $\beta\geq1$ the method of a two-stage heating of a dense plasma is developed [3]. New experiments in this direction are also started at the GOL-3-II facility. To do so, in the beginning of the 12-m device the deuterium cloud of a few meters length and with a density of up 10^{17} cm^{-3} is formed. On the rest of the device the density of the plasma is ~ 10^{15} cm^{-3}. In this case, the plasma with a ~10^{16} cm^{-3} density has the electron temperature of 300÷500eV, and the ion temperature increase up to 100÷200eV.

In order to improve parameters of a dense plasma it is planned not only to optimize the conditions of its heating but also to improve the dense plasma confinement. For this, the dense plasma bunch is placed in a short (~1m) region with lower magnetic field ("magnetic pit") where a dense plasma should be confined as in "gasdynamic" trap. As the calculations show under the conditions of the GOL-3-II facility it is possible to obtain the dense ($10^{16}\div10^{17}$ cm^{-3}) and hot (~1keV) plasma with $\beta\geq1$.

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D.C. HIGH POWER ELECTRON ACCELERATORS OF ELV SERIES: STATUS, DEVELOPMENT, APPLICATIONS

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Beginning from 1971, the Budker Institute of Nuclear Physics SB RAS develops and manufactures the electron accelerators of the ELV type for their applications in the industrial and research radiation-technological installations. At present, the Institute offers the electron accelerators of ELV-series covering he energy range from 0.2 to 2.5 MeV with the beam current of accelerated electrons up to 400 mA, and maximum power of up to 400 kW. By now, INP has delivered both inside of Russia and abroad over 70 accelerators of the ELV-series and their total operational time is of the order of 500 years.

The unification of the units and systems makes increasing the accelerator reliability and requires the minimum expenses for their adaptation for the specific requirements of the customer by the main parameters such as the energy range, beam power of accelerated electrons, length of extraction window, etc. The total accelerator efficiency is about 90%.

All the accelerators of this series are controlled by the unified control system based on the IBM-PC compatible computer and it offers the customer a possibility to arrange the operation of accelerator in technological line with the fully automated run without an operator.

ELV-accelerators can be equipped with the device for beam extraction into air through the foil window or through the system of holes in diaphragms. Device for beam extraction through the diaphragms contains magnetic lenses. It is used when high density of e. beam power is needed. Other extraction system of the concentrated beam uses the compression of beam by adiabaticaly increasing magnetic field. It has been used for the accelerators the power of which is over 500 kW.

ELV-accelerators with several kinds of beam extraction devices are used practically in all radiation processing where electron beam is needed.

SPECTRA OF LASER SCATTERING ON POWERFUL REB

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The pumping efficiency of electromagnetic waves in vacuum and plasma by powerful relativistic electron beams essentially depends on a velocity spread of the beam electrons. On this reason measurements of the electron distribution function have great importance for high-power beam physics. Such measurements on the base of CO_2-laser radiation scattering (λ=10.6 μm) on a high current ribbon beam with registration of scattered radiation spectra in an optical range, were discussed in the paper [1]. In this presentation we describe the experiment on CO_2-laser radiation scattering on the ribbon electron beam and results of computer simulations for these experimental conditions [2]. The experiments are carried out at the U-3 device [3] that has been specially modified for generation of the ribbon beam.

In the experiments the CO_2-laser radiation with total energy about 10 J at 100 ns pulse passes in a vacuum channel in the opposite direction to the relativistic ribbon electron beam. The typical value of the electron energy is E ~ 1MeV (γ ~3) and the linear current of the beam is about $I' = 0.5$ kA/cm. Back scattered laser radiation is analyzed by a spectral system.

Computer simulations of the scattered radiation spectra were made at various velocity distribution functions of the beam electrons. An angular spread of the beam electrons with the influence of self electric and magnetic fields of the beam were taken into account in these simulations. It was shown that a typical spectrum had a width about of 7 Å for the case of the Gauss distribution function at the angular spread 1^0 for the beam electrons with small current density and $\gamma = 3$. The effect of the self beam fields for high linear current ($I' = 0.5 \div 1$ kA/cm) led to the increase of the spectrum width up to a few tens of Angstrom. Moreover, it was possible to obtain the angular spread of the beam electrons and the values of the self beam fields separately by analysis of the width and the shape of spectrum. The last circumstance permitted to find the beam charge neutralization value and its time evolution in the experiment.

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RETRIEVAL OF REFRACTIVE INDEX DISTRIBUTION IN AN ANODE LAYER FROM FOURIER IMAGE OF PROBE LASER BEAM

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Quality of an intense ion beam generated in the ion diode sufficiently depends c characteristics of the anode plasma. One of the ways to study the anode layer is a refractiv index gradient diagnostics based on the record of deflection of a collimated laser beam [1-3 To retrieve a refractive index distribution across the layer by such a technique one needs t perform a number of measurements at different distances of the laser beam from the anoc surface. An alternative technique [4], which is usually used for detection of distant objects, retrieval of phase shift across a wide wave front that have passed through a gradient layer b solution of the inverse problem from two intensity measurements: intensity in the object plar and intensity in the Fourier plane.

An experimental technique which combines these methods and allows to record both laser beam deflection and Fourier-image of the beam have been implemented on COBR accelerator at Cornell University [3]. Dynamics of the refractive index distribution obtaine from laser beam deflection data was presented in papers [5] where experimental setup wa described in detail. In this paper we present the results obtained from streaks of intensit recorded in the Fourier plain by solving the inverse problem. In contrast to classic Gerchberg Saxton algorithm [6], instead of using in the iterative procedure two intensities, we use th intensity in the Fourier plane only: before plasma appearance, as a reference, and during th diode pulse. Refractive index as a function of distance from the anode (within the caustic of th laser beam), which is retrieved by this technique with accuracy up to a constant, was fitted t the refractive index distribution obtained by the deflection technique at three moments of th anode layer expansion. Results of both techniques are in a reasonable agreement, but a spatia resolution (~0.03 mm) of new method is ten times higher than of the deflection technique. Or can expect that with a broad probe laser beam a refractive index distribution with a high spac resolution can be obtained in a single diode shot.

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ATOMIC BEAM SOURCE FOR ION DIODE DIAGNOSTICS

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The quality of beams generated in Megavolt electron and ion diodes sensitively depends on processes in the diode acceleration gap. Although passive spectroscopy allows to study many of the details of light-ion diodes (see, e.g.[1]), ions suitable for spectroscopy are often not present in sufficient quantities. Active spectroscopy based on laser resonance excitation of an atomic beam injected into the diode has already been successfully applied in electron diodes [2] and may also be used as a diagnostic tool in ion diodes [3]. To provide reliable local measurements and to minimize the interference with diode operation a low density thin atomic beam needs to be injected. Typically, its density should be close to the background gas density i.e. 10^{-12}-10^{-13} cm^{-3}. Such an atomic beam with rectangular cross section can be formed by passing an expanding vapour cloud obtained by laser ablation from a remote solid target through a collimator.

In this paper we present results from an investigation on the laser atomic beam source. It is shown that with a laser pulse energy of 5 J and a pulse width of 3 ns one can obtain a planar atomic lithium beam with a density of about $5 \times 10^{-12} cm^{-3}$ at the diode. The design of an atomic beam source using a flashlamp pumped dye laser is described. Computer calculations of the lifetime of lithium atoms in the diode gap at different distances from the anode and for the KALIF pulse characteristic show that it exceeds the duration of the ion current pulse everywhere in the gap except in a narrow space very close to the emission boundary. Analysis of existing experimental data [1] on Stark splitting of lithium atoms in a strong electric field, estimation of field ionization limits [3], as well as the availability of suitable tuneable broadband lasers, lead to a selection of the 2s-2p-3d cascade transitions for the experiments on KALIF (1-4 MV/cm). These transitions should be populated to saturation by two dye lasers. The spontaneous emission from the 3d level split in the electric field has to be recorded with a polychromator and a detector system with high time, space, and wavelength resolution.

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TRIPLY-ACTIVE DIAGNOSTIC METHOD FOR THE STUDY OF ION BEAM DIODES

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A new approach to measuring several key parameters in an intense ion diode which we call Laser-driven Atomic-probe-beam Diagnostic (LAD) is presented. This method is a further development of the Active Stark Atomic Spectroscopy (ASAS) method [1], which was successfully applied to measurement of the local electric field in the accelerating gap of a microsecond electron beam diode U-1 [2]. Like the ASAS technique, the new diagnostic allows a determination of the electric field as a function of position and time, including the positions of anode and cathode plasma emission surfaces (in order to obtain the effective accelerating gap); the rate of neutral gas ionization in the gap (especially, near the anode emission surface), as well as the direction of the electric field vector. In addition, LAD enables measures of the potential as a function of position in the gap and a determination of the regions in the diode in which ion beam divergence is increased.

A slow atomic probe beam is injected into the diode before the voltage is applied. Since the probe atom density is less than the density of the background gas, this technique should not disturb the diode. A broadband dye-laser is used to populate (directly or stepwise) an atomic level of interest. The Stark splitting of a probe-atom spectral line enables a calculation of the electric field with high time and space resolution. In addition, a precisely-focused laser-beam is used to provide photoionization of probe atoms that are excited to any one of the upper levels of the atom. The extracted probe ions can be analyzed to give, for example, the electrostatic potential at the point of origin of the ion, or the ion divergence as a function of the point of its birth, with excellent spatial resolution. The latter might allow us to study the influence of conditions in the accelerating gap on the origin of ion divergence.

As possible probe beams, we suggest the use of lithium, sodium and, possibly, boron atoms. A laser intensity of a few kW/cm^{2}nm, which is needed to saturate the upper levels of alkali atoms, can be easy obtained with a flashlamp-pumped dye laser. To ionize the probe atoms for one nanosecond, a local laser intensity of 0.3-1.2 GW/cm^2, which can be easy obtained with ruby or excimer lasers, is sufficient for optimally selected excited states. With a ribbon-like atomic beam [3] one can generate approximately 10^7 probe ions in a volume of 0.2x0.2x0.2 mm^3. These small dimensions allow detection of the ions with a Thomson spectrometer having a wide input aperture. Because one can easily distinguish signal from noise by simply omitting the probe beam, tuning lasers away from resonance with transitions, or switching the ionizing laser on and off, a reliable measurement can be made with this ìtriply-activeî diagnostics.

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NON-VACUUM ELECTRON BEAM WELDING BY ELV-TYPE INDUSTRIAL ACCELERATORS.

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Beginning from 1976 manufactured in our Institute industrial accelerators of ELV-type were equipped by the differential pumping system for extraction of the high power concentrated electron beam into gas medium at atmospheric pressure.

The welding of metals by the electron beam with energy range of 0.8...1.5 MeV and beam power up to 60 kW was studied. The configuration and dimensions of melting zone was investigated as dependence of pressure and beam power for stainless steel, copper and aluminium alloys. The results of this experiments are given in table 1 as dependence of depth of melted zone from beam power and air pressure.

Table 1. Depth of melting zone, mm.

	Beam power, kW							
	Pressure $P = 2 \times 10^2$ Pa				Pressure $P = 2 \times 10^5$ Pa			
	10	25	40	75	10	25	40	75
Aluminium alloys	40	80	105	140	10	23	30	40
Copper	10	26	45	70	6	16	24	32
Stainless steel	17	42	66	105	8	20	27	37

The improvement of differential pumping system for non-vacuum welding of thick-walled oil-pipes was a next step of the investigation. The quality of weld as well as obtaining of good welding salience at inner pipe surface was the purpose of one. The possibility to make keyhole welding of steel was confirmed in case beam power density about 10^5 W/cm² at atmospheric gas pressure. The possible welding depth was varied from 5 to 20 mm in one pass. Welding speed reached 2.4 m/min and more. Maximum beam power in this experiments were 45 kW. The product of welding depth and welding speed as dependence of beam power density is given at Figure 1a. Melting zone profile as dependence of beam power density is given at Figure 1b.

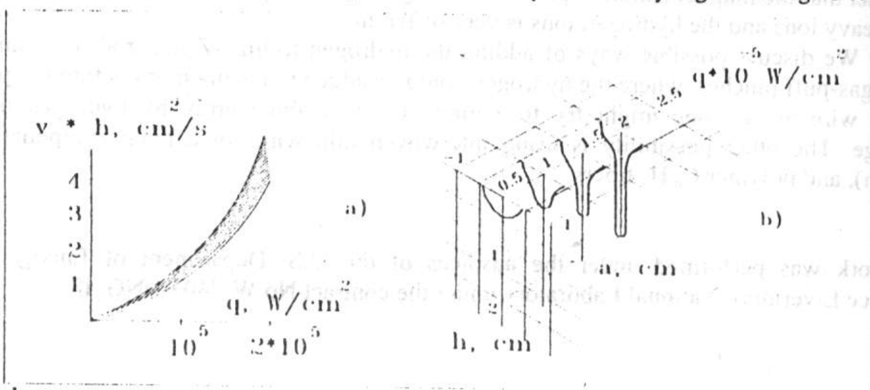

Fig. 1.

PROGRESS IN INVESTIGATIONS ON MICROWAVE FEL DRIVEN BY MICROSECOND SHEET BEAM

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Investigations on generation of microwave radiation on the scheme of Free Electron Laser driven by a high-current sheet electron beam are carried out at BINP. In the experiments with a passive undulator at the U-2 device this generator with the microsecond sheet beam produced 4 mm wavelength radiation with 200 J total energy content at pulse duration of a few microsecond [1]. Progress in these investigations will be presented in the paper.

The experiments were performed at the following beam parameters in the U-2 accelerator: E_e~1MeV, I_b~3kA, τ_b~5μs, S_b= 0.2x12cm. In differ from the previous experiments a new plane undulator allows us to vary the transverse magnetic field component from zero up to H_u=2 kG independently on a longitudinal one that is important for optimization of the generator. The another difference of the last series of the experiments is connected with RF-breakdown in generator which limits the pulse duration of the radiation as well as its energy content. In order to eliminate this effect we have connected the slit channel where the microwave radiation is produced, directly with a big size vacuum chamber that contains all measuring equipment. The results of the experiments at these conditions will be also discussed in the paper.

The further development of these microwave investigations is performed on the U-3 accelerator [2] specially modified for the ribbon beam experiments. The advantage of the experiments is possibility to keep the voltage invariable at the U-3 diode during the beam generation at 5 μs. Another advantage of these experiments is that we can vary the longitudinal velocity spread of the electron at the entrance of microwave generator and we have possibility to measure this spread by CO_2-laser scattering on the beam electrons. At these conditions one has opportunity to optimize the process of the 4mm power generation by the FEL driven by the sheet beam.

Perspectives to increase the energy content of the radiation pulse up to ten kJ are based on using a full-scale ribbon beam with the cross section 1x140cm at the beam current ~30kA. Such kind beam with the energy content on the level a few hundreds kJ has been also produced in the experiments at the U-2 accelerator [3]. The achievement of good coherence of the generated radiation can be provided by using the 2-D distributed feedback [1]. The problems of its realization are also discussed in the paper.

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FREE ELECTRON LASERS WITH SHEET ELECTRON BEAMS AND TWO-DIMENSIONAL PLANAR BRAGG RESONATORS

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For generation of super-power coherent microwave radiation in FELs driven by intense sheet relativistic electron beams the use of two-dimensional distributed feedback have been proposed [1]. This feedback can be realized in the planar Bragg resonators formed by two double-periodical corrugated metal plates. On this corrugation mutual scattering of e.m. energy fluxes propagating in forward, backward and transverse with the respect to electron beam directions takes place. These additional transverse electromagnetic energy fluxes synchronize radiation of the large size sheet electron beam. A project of super-power FEL (P ~ 20 GW) of millimeter wave range on the base of pulse accelerator *U-2* (INP RAS) was elaborated [2].

To design the project one should solve a problem of output for the transverse e.m. fluxes from the FEL. Using some additional units it is possible to turn these fluxes and to provide a single-directed output of radiation. However, it seems more simple to restrict the resonator by two metal mirrors on transverse sides and to consider the transversely closed scheme of the FEL.

Theoretical analysis of the planar two-dimensional Bragg resonator have been done for the case of side reflections of transverse e.m. fluxes. This reflections provided by side metal mirrors or «parasitic» reflections from the side walls of the vacuum beam transporting channel. It is shown that for the small reflections ($R \leq 0.3$) the eigenmodes frequencies, Q-factors and the resonator selective properties remain approximately the same as in the case of «open» resonator ($R = 0$). For this ideal case computer simulation demonstrates the possibility to provide spatial coherent radiation in the FEL with the planar 2-D Bragg resonator for the driving sheet beam width up to 1000 wavelengths.

Increase of side reflections leads to appearance of the new set of eigenmodes which corresponds to the eigenmodes of a two-mirror Fabri-Perrot resonator. Q-factors of these modes are approximately the same as the Q-factors of the fundamental mode of the resonator which related with the waves mutual scattering on the double-periodical Bragg structure. As a result selective properties of the «cold» resonator are getting worse. Nevertheless, computer simulation shows that if the beam width does not exceeds 50 - 100 wavelength the single-mode single frequency generation regime is still stable even for the side walls reflection coefficient close to 100%.

The analysis carried out confirmed the possibility to realize single mode operation regime in the new scheme of FEL . The current stage of the project is discussed.

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ON THE POSSIBILITY OF CONCRETE DESTRUCTION UNDER HIGH-POWER MICROWAVES GENERATED BY E-BEAM

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Creation of generators for microwave radiation with a few kJ energy in microsecond pulses on the base of high-power E-beams gives a possibility to propose new promising technologies. Cleaning and rehabilitation of concrete constructions polluted by radioactive and toxic wastes is one of them. Action on concrete surface by high-power microwave pulses seems a rather promising technology for cleaning the constructions. The advantages of such method, if it can be realized, are: the possibility of remote control over the cleaning process, excluding direct personal contact with radioactive or toxic pollution, relative safety concerning electromagnetic radiation and mobility of the installation. For these reasons we study the problem of action of the pulses of microwave radiation on the concrete surface. Results of these studies will be given in the paper.

The propagation of millimeter waves through concrete samples and their absorption have been studied experimentally. Test measurements have shown that about 75% of energy of the microwave radiation are absorbed by the concrete in a thin surface layer with the thickness of a few centimeters for a wavelength of 4mm and 8mm.

As a result of theoretical calculations it has been established that at the location of the energy deposition a shock wave is generated and fragmentation of the concrete surface layer occurs. The concrete surface destruction occurs because shear or hoop stresses of the material are exceeded. Concrete failure under tension takes place under the action by microwaves radiation pulses of energies of the order of 10 J/g at a duration of less than 1 μs. For an increase of the microwave pulse duration the energy deposition should be substantially increased. The boundary of the destruction region is essentially defined by the conducting layer and irradiation geometry. Estimations of the microwave energy that should achieve concrete surface failure by shearing, have been theoretically obtained.

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REQUIREMENTS AND OPPORTUNITIES FOR RIBBON MICROSECOND REB, GENERATED AT U-3 ACCELERATOR, TO BE USED FOR PRODUCTION OF HIGH-POWER COHERENT MILLIMETER WAVELENGTH RADIATION

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Since the efficiency of high frequency (HF) microwave radiation sources on the base of relativistic electron beams (REB) depends strictly upon the quality of the REB, it is necessary to pay serious consideration to the formation of the beam so that to have some of its critical parameters fixed.

The cyclotron autoresonance maser (CARM) [1] or undulator can be used to obtain short microwave generation. And low value of the spread in pitch angles of the electrons of the beam is essential for attaining high radiation output. So high-current REB with maximum current density at smaller angular spread of particles should be used for high-power coherent mm wavelength emission production.

The progress in high-current ribbon REB generation by means of explosive emission makes it promising to create high-power coherent microwave source on the base of ribbon REB particularly.

The successful experiments [2] with the emitters that made of fibrous carbon materials give a possibility of transition to quasi-Pierce geometry of the diode and to reduce substantially the angular spread of the electrons of the beam owing to that transition.

The geometry of the diode of the accelerator for generation of high-current REB with high current density (500 A/cm^2) and low angular spread determined mainly by unsteadiness of cathode plasma surface is presented. The calculations in stationary case show that optimal geometry can be find which provides the smallest angular spread. The actual realization of such diode at U-3 accelerator [3] are discussed.

The results of computations regarding a version of a kicker that gives nearly the same pitch angle to the electrons of the beam are also presented.

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HIGH-POWER ELECTRON GUN FOR AN 11.4 GHZ MAGNICON*

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A 500-kV, 210-A advanced Pierce gun is described for a high power, 11.4 GHz, 60% efficient, second-harmonic pulsed magnicon amplifier. This magnicon is being developed as a prototype RF source for future linear colliders by a collaboration of workers from Omega-P, Inc., the Naval Research Laboratory, and Litton Electron Devices Division. A small diameter electron beam is required to achieve high magnicon efficiency. The gun described in this paper has a computed beam diameter of 1.5 mm when matched into a 0.65-T magnetic field. The diameter of the cathode is 75 mm; hence, the beam area compression ratio is 2500:1. The beam current density is12 kA/cm2, the beam power density is 6 GW/cm2. The gun will be driven at 10 Hz with a 1-microsecond pulse length. Special means have been developed to decrease the beam emittance, in order to achieve this high area compression ratio. The paper will conclude with experimental beam test results.

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TECHNOLOGICAL APPLICATIONS OF INDUSTRIAL ELECTRON ACCELERATORS OF ELV SERIES.

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From 1983 in our institute is functioned set of equipment for developing new electron beam (EB) technologies on the base of ELV6 type accelerator. The energy range of electrons 1-1.5 Mev corresponds the penetration depth of electrons in the different materials 0.5-6 mm that is convenient for applications. Extraction EB into atmosphere is done through the foil window or through the system of diaphragms with holes about 1 mm diameter. Device for beam extraction through the diaphragms contains magnetic lenses and used when high concentration of power in the beam is needed.

Both low and high temperature EB technologies are developed. Low temperature technologies are: purification of waste water and flue gas, sterilisation of medicines, gels production from water solution of polyethylenoxide.

In high temperature radiation technologies promising results have been achieved in manufacturing wide class of ceramic materials. In particular EB have been used for manufacturing various types of cements. For this purpose was developed special stack type plant with water cooling walls and uniformly deposition of powder on the wide sintering zone under the beam. The top position of sintering zone stay unchanged due to descending bottom of the sinters material. Other conveyer type plant with water-cooling wall is applied for production of ceramic materials by melting of initial components. Quick cooling of molten faze in the plant is often used as drops into water.

For production of pure ultra-dispersion nanometer range powder used a plant with accompany the beam in magnetic field.

The processes of concentrated EB steel hardening and powder surfacing of many kind of materials was developed for various parts.