ANOMALOUS DOPPLER EFFECT AT INTERACTION OF ELECTRO-MAGNETIC WAVES WITH ELECTRON BEAMS: EXPERIMENTAL RE-SEARCHES AND OPPORTUNITIES FOR APPLICATION

B.I. Ivanov

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: ivanovbi@kipt.kharkov.ua

The anomalous Doppler effect (ADE) in systems consisting of an electron beam and slow wave structure in longitudinal magnetic field is considered. Resonance condition for amplifiers and generators based on ADE enables resonance maintaining in case of wave phase velocity or beam velocity changing (acceleration of ions at ADE, reception of high efficiency at microwave generation). Essential advantages can be reached at combination of ADE and normal Doppler effect. The review of experimental studies of ADE is presented: amplification and generation of microwaves, energetic relations, excitation of accelerating IH-structures, development of ion acceleration.
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1. INTRODUCTION

Investigations of the anomalous Doppler effect (ADE) [-] in the case of an oscillator velocity larger than wave phase velocity is of importance for many fields of physics such as interaction of high-energy particles with media, channeling of charge particles in crystals, high-energy particle acceleration, microwave generation, plasma-beam interaction and collective methods of acceleration, polarization of electrons using microwave pumping at ADE and normal Doppler effect (NDE), instabilities at ADE in hydrodynamics and aerodynamics, pendulum radiation of diffracted electrons, etc [-]. Theoretical studies of the ADE are published in many papers, reviews and monographs. Unfortunately, it is difficult to say the same about the experimental works related to this matter. There are elsewhere only a few experimental works devoted to ADE in the case of electron beam interaction with slow electromagnetic waves.

In this work the main attention is paid to experimental investigations of the ADE at the electron cyclotron frequency in a systems consisted of an electron beam and slow wave structure (helical or interdigital periodic ones) placed in the longitudinal resonance magnetic field. In this case the slow cyclotron waves (SCW) in the beam and eigen modes in the structure can be excited (e.g., [,]). As it is known, the resonance condition for the conventional amplifier and oscillator based on Cherenkov effect can be written as $\omega=k_z(z)v_e(z)$; for the amplifier and oscillator based on the ADE it can be written as follows:

$$\omega=k_z(z)v_e(z)-\omega_c(z), \qquad (1)$$

where ω is the wave frequency, ω_c is the electron cyclotron frequency, v_e is the electron beam velocity, k_z is the wave number, z is the longitudinal coordinate. One can see, that in the case of ADE we have the additional term $\omega_c(z)$ that can take additional possibilities, in particular, to support the resonance conditions in case of phase velocity or beam velocity changing. This property can give some opportunities, e.g., for acceleration of ions at ADE [,,] or reception of very high efficiency at microwave generation, e.g., []. The essential advantages can be reached at a combination of ADE and NDE: alternation of ions acceleration at ADE and NDE [,], increase of generation efficiency at a double resonance at

ADE and NDE [], polarization of electrons at alternating of a microwave pumping n ADE and NDE []. In this work it is presented a brief review of the experimental works, in the main, carried out at the KIPT: amplification and generation of microwave oscillations in case of ADE, energetic relations, excitation of accelerating IH-structures at ADE, development of ion accelerators with accelerating and focusing fields excited at ADE. Now it is considered experimental possibilities of ADE investigation in the case of electron channeling in crystals.

2. RF AMPLIFICATION AT ADE OF AXISYMMETRICAL WAVES

The case of symmetrical waves excitation (the mode m=0) is very interesting due to its possible using in the autoresonant accelerator where the symmetric, charge density slow cyclotron wave (SCW) with longitudinal electric field component may be excited and used for ions acceleration [,14,23]. For this case the first experiments were made in [,] (see Fig. 1).
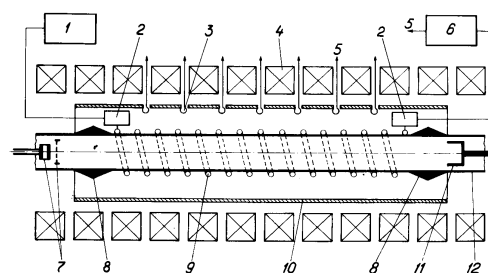
Fig. 1. *Experimental set-up. 1 - RF generator, 2 - matching section, 3 - RF probe (a loop), 4 - solenoid, 5 - RF cable (to oscilloscope), 6 - matched attenuator, 7 - electron gun, 8 - RF absorber, 9 - helix, 10 - shield, 11 - collector, 12 - glass tube*

In Fig. 1 the electron beam was produced by a diode gun *7* with the LaB$_6$ cathode of 3 cm diameter and mesh anode. Beam parameters: energy up to 60 keV, current up to 50 A, pulse length 30 μs. Gas pressure 10^{-6} Torr. The beam was passed through a slow wave structure - single wire helix *9* in conducting shield *10*. Helix length 80 cm, step 0.9 cm, average diameter 7.5 cm, shield diameter 14 cm. There were sections *2* on the both ends of the helical waveguide, matching it with coaxial feeders. In the frequency range of 100-500 MHz, the standing wave ratio was less than 1.5.

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The dispersion characteristics were measured using a perturbation method. Here the phase velocity was about 10^9 cm/s and the anomalous Doppler effect condition (the phase velocity less than the velocity of oscillating electrons) may be fulfilled in the range of 100 to 500 MHz for the beam energy greater than 400 eV. The helix waveguide was placed into the homogeneous magnetic field. The ADE instability is difficult to observe in the presence of a stronger instabilities unless to take some special precautions. These ones include following: a) the measurements were carried out in the regime of resonance amplification of a RF traveling wave with sufficiently large initial level (however, until non-linear effects appear); b) by connecting the matched attenuators *6* to the ends and using RF absorbers *8* the feedback coefficient was decreased while the threshold and rise time of undesirable instabilities were increased; c) the operating conditions of the gun were chosen to form the current pulse with a steep front of order 1 µs (see Fig. 2, trace 2), in this case, the resonance amplification conditions were fulfilled and the measurements were carried on immediately after the current front (see Fig. 2, trace 3: RF wave envelope at slow sweep, and trace 4: RF wave at fast sweep), thus other instabilities had no time to achieve an appreciable level. The typical operating conditions were: resonance value of electron energy W_e =30 keV, electron current I_e=4 A, resonance value of magnetic field H=580 Oe. The measurements were performed in the following way: the continuous RF signal from the generator *1* (power about 100 W, frequency 150 MHz) was passed through the matched attenuator and matching section *2* on the helix *9*, in which the traveling wave was propagated. Then the signal was received at the tube of high speed oscillograph through the matching section *2* and the matched attenuator *6*. In the case of wave and beam propagation in the same direction, under fulfillment of the ADE resonance condition, a wave amplification was observed.
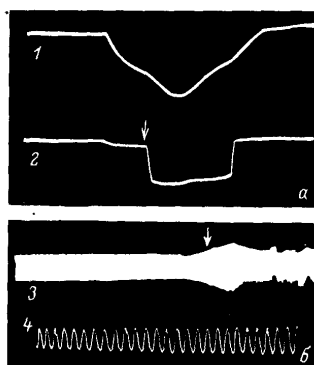

Fig. 2

In the case of opposite beam and wave propagation and the fulfillment of the resonance condition for the NDE, a wave absorption was observed. As it is follows from the sinusoidal form of the oscillations, any nonlinear effects do not take place. By switching an oscillograph in sequence to the RF probes *3*, one can see the amplification or absorption increase along the system.

In Fig. 3 are shown the resonance curves of wave amplification and wave absorption for the ADE and NDE versus the magnetic field intensity (the calculated

resonance values are shown for ADE by the up arrow, and for the NDE by the down arrow). The relatively large half-width of these resonances may be explained,
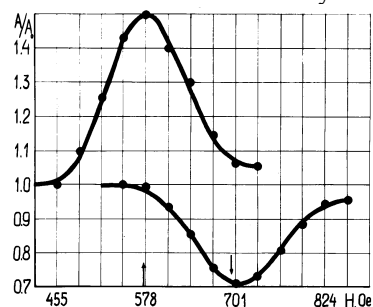

Fig. 3

evidently, by scattering of the experiment parameters in measurements from pulse to pulse. The observed amplitude amplification is up to 2 times within the length of 80 cm and corresponds to the power amplification up to 7.5 dB/m or to the time growth rate $10^7\,s^{-1}$. The ratio of the growth rate to the plasma beam frequency is about 10^{-2}, in agreement with the theory []. It is worth noting, that variation of RF power at the input of the helix in the range of 10-100 W did not influences the growth rate, that is evidence of the linear regime.

3. RF GENERATION AT ADE (ABSOLUTE INSTABILITY AND ENERGY RELATIONS)

In this part we discuss the absolute ADE instability at electron beam - helix interaction (in case of $m = -1$ mode) []. In ADE experiments, to avoid an other instabilities' competition, it is convenient to employ high-order axial modes of a cavity with a helical slow wave structure. In this case we may separate the ADE instability and, for example, Cherenkov one due to additional boundary resonance conditions: $k_z L = \pi q$, where q is an integer for the ADE only, k_z is the wave number, and L is the resonator length. In this situation the ADE instability would be excited but the Cherenkov one would not. The measurements were performed on the same device but now the helical resonator was used instead of the helical waveguide (see Fig. 4).
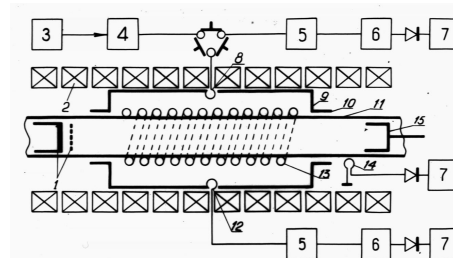

Fig. 4. *Measurement scheme: 1) electron gun; 2) solenoid; 3) RF generator; 4) ferrite insulator; 5) step attenuator; 6) wavemeter; 7) oscilloscope; 8, 12) connected loops; 9) resonator; 10) limiting waveguides; 11) quartz tube; 13) helix; 14) inductive pick-up loop; 15) beam collector*

The helix was made by turn to turn winding of a thin RF cable (without a shield) onto a quartz tube. Helix length is 28 cm, step is 0.46 cm, average diameter 3.5 cm, wire diameter 0.07 cm, right winding. A type of oscillation was determined by a perturbation

method; numbers of field half-wave length variations are: on the azimuthal direction $m=1$, on the radial one $p=1$, on the axial one $q = 16$-22. For the main mode we have: $f=1727$ MHz, $q=18$, $v_{ph}=5.53 \cdot 10^9$ cm/sec, $k_z=1.96$ cm^{-1}. Parameters of the experiments: $W_e=15$-30 keV, $I_e=0.1$-1 A, pulse length 100 μs, beam diameter 1 cm, intensity of magnetic field 200-600 Oe. In Fig. 5 we represent the ω-k_z diagram in which we have drawn lines corresponding to SCW for beam energy 20 keV (straight line) and the wave in the spiral resonator with azimuthal number m= -1. The dispersion relations correspond to the absolute instability and ADE generation. We had seen that calculated dispersion curve and measured data were in a rather good agreement. As it was experimentally shown, the ADE generation take place (e.g., see Fig. 6), if a beam velocity and magnetic field intensity are varied according to the ADE resonance condition. In Fig. 7 it is shown how the resonance value of electron velocity depends on the strength of the external magnetic field for the ADE. Here the solid line represents the theoretical dependence, the dots are experimental data.
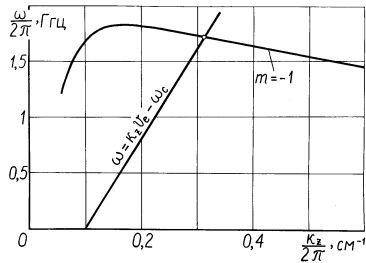

Fig. 5

In the case of ADE generation, according to Ref. [2], the energy of the directed motion of oscillators is expended both on a RF emission and increasing of the internal energy (i.e. the energy of the transverse motion of the electrons). The energy relations for cyclotron waves have the form [,]:

$$\left| P_{scw,fcw} \right| \Big/ \Delta P_\perp = P_{RF} \Big/ \left(\pm \Delta P_\perp \right) =$$
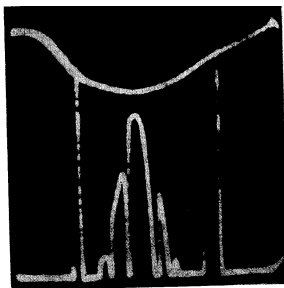$$= \omega \Big/ \omega_c = v_{ph} \Big/ \left(v_e - v_{ph} \right) \tag{2}$$

Fig. 6. *Oscillograms: upper curve shows the accelerating voltage on the gun; lower curve shows the envelope of the RF signal excited in the pick-up loop (14) due to ADE. Sweep duration is 250 mcsec. Generation is visible at frequencies of 1675, 1702, and 1727 MHz corresponded to the resonator eigenmodes*

where $P_{scw,\,fcw}$ is the power of slow or fast cyclotron wave, P_{RF} is the radiated RF power, $\Delta P_\perp$ is the change in the power (energy flux) associated with the trans-

verse motion of the electrons ("+" for the SCW and "-" for the FCW), v_{ph} is the phase velocity of the wave.
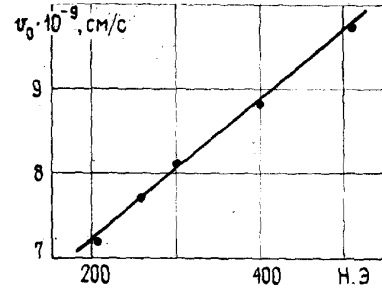

Fig. 7

In accordance with (2), in the case of the ADE and SCW (or slow plasma wave) excitation, the longitudinal kinetic energy is converted into the radiation energy and "internal" energy, i.e., energy of electrons' rotation (or their longitudinal oscillatory motion).

The energy relations were investigated experimentally in [28,29]. The absolute value of the RF power generated by the beam in the structure was measured using calibrated coupling loops and detecting unit. The increase of the transverse components of the electron velocities at the ADE resonance was recorded with an axial (a small diameter) Faraday cup, and with a transverse (a plate aligned with the beam axis) electron collectors [,]. The RF signals generated by the ADE correlate with the decreasing of electron current onto the coaxial collector and increasing onto transverse one. This circumstance is explained by the transverse components of the electron velocities and electron Larmour radii increasing under the resonance RF radiation. Fig. 8 shows the ratio $P_{RF} / \Delta P_\perp$ measured as a function of ω/ω_c which is in a good agreement with the energy relations (2) shown by dot line. Similar relations were measured in the case of the ADE at the electron Langmuir (plasma) frequency where the slow plasma waves excited by the electron beam interaction with the 1st harmonic of the spatially periodic slow wave structure of π-type [,].
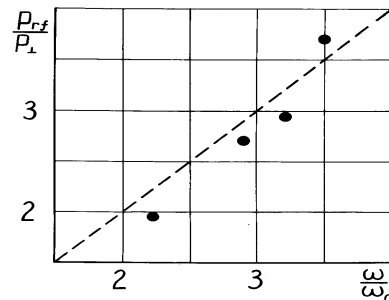

Fig. 8. *Measuring of energy relations at ADE*

4. RF FIELD EXCITATION AT ADE IN H-RESONATORS WITH SPATIALLY PERIODIC SLOW WAVE STRUCTURES

The H-resonator with spatially periodic slow wave structure of π-type (so named interdigital, i.e., IH-resonator) is used in some ion linear accelerators. In Refs [,] IH-resonators were proposed for RF fields generation under ADE conditions. The main advantage of this method is opportunity for exciting of intense axisim-

metrical slow waves favorable for high current ion beam acceleration. First experiments [] were carried out with the scheme shown in Fig. 9.
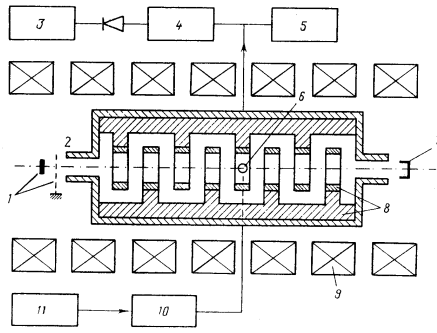
Fig. 9. *Measuring scheme: 1) electron gun; 2) IH-resonator; 3) oscilloscope; 4, 10) microwave attenuators; 5) frequency-meter; 6) microwave coupling loop; 7) beam collector; 8) drift tubes with opposed comb suspenders; 9) solenoid; 11) generator of standard signals*

The electron gun, IH-resonator, and beam collector were placed in the uniform magnetic field with intensity up to 1 kOe. IH- resonator was excited at the main mode (with frequency 630 MHz) by the generator *11* or by an electron beam (energy W= 10-30 keV, current I = 10-100 mA, diameter 1 cm). Vacuum corresponded to $1 \cdot 10^{-6}$ Torr. In the first turn, it was studied excitation of RF oscillations at the main mode by the electron beam where the beam velocity and magnetic field intensity were varied. It was found excitation of RF oscillations (with power of 1-10 W) at parameters of ADE conditions:

$$\omega = (k_0 \pm k_z)v_0 - \omega_c \; ; k_0 = 2\pi / l ; k_z \approx \pi / L , \quad (3)$$

where ω is the oscillation frequency, ω_c is the electron cyclotron frequency, v_0 is the velocity of the electrons, l is the space period of the structure, L is the structure length. In Fig. 10a the dependence of RF generation (lower traces) versus the gun voltage (upper traces) are shown. The magnetic field intensity was constant and the gun voltage was raised from upper to lower oscillograms. In this case the RF generation envelope bifurcated, left and right RF generation pulses go away one from another because the resonance values of the electron velocity were moved to left and to right from the maximum value of the gun voltage, see middle and bottom oscillograms. Now in Fig. 10b the dependence of RF generation (lower traces) versus magnetic field intensity (upper traces) are shown. In this case the gun voltage was constant and the magnetic field intensity was decreased from upper to lower oscillograms. The RF generation envelope bifurcated, left and right RF generation pulses go away one from another because the similar reason, see middle and bottom oscillograms. Parameters of both experiments corresponded to the ADE conditions. The power of the RF oscillations was depended on the magnetic field intensity by resonance manner, see Fig. 11 (parameters: W_0=28 keV, I=250 mA; values of the resonance magnetic field intensity was 214 Oe from the theory and 236 Oe ±15 % from the experiment; the resonance half-width was 0.08). In Fig. 12 the dot line presents the function:

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$$\omega + \omega_c = k_\| v_0$$, where $k_\| = k_0 \pm k_z$, $\quad (4)$
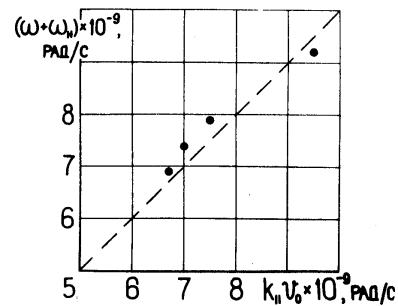
and experimental dots correspond to excitation of oscillations that depend from the magnetic field intensity by resonance manner. Evidently, excitation of oscillations corresponds to the ADE conditions.

Рис. I.   Рис. 2.
a   b
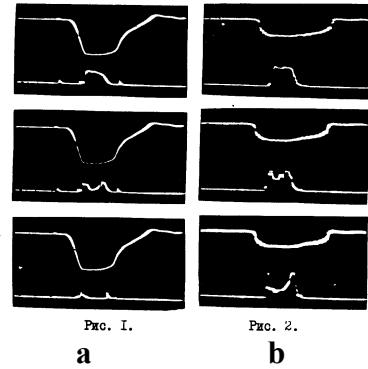
Fig. 10
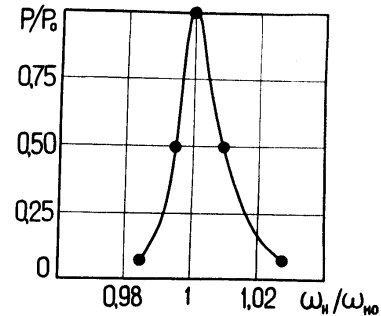
Fig. 11

Fig. 12

The excitation of the symmetric SCW at ADE in a high-current electron beam had an important step in the development of the autoresonant ion accelerator with very high parameters of accelerated ion beams (see also parts 2 and 5). The SCW with longitudinal electric field intensity E_z ~100 kV/cm and duration ~50 ns were obtained in Ref. [] where it was amplified by high-current electron beam in helical waveguide section, similar to one in part 2. In Ref. [] it were carried out experiments on the excitation of symmetric SCW of microsecond duration due to interaction at ADE of a high-current electron beam with a resonator of IH type like described here (this work was realized in the Moscow Radio-Technical Institute with participation of the author). The experimental scheme is shown in Fig. 13. Experimental parameters were as follows. Electron beam energy 150 - 500 keV, current 0.5-1.5 kA, pulse

duration 4-12 mcs, radius 5-17 mm. The distance from the cathode to the anode was 2 m, the external magnetic field 3-15 kOe. The IH-resonator was a copper cylinder of 14 cm diameter and 33 cm length, inside of which were 15 drift tubes of 4 cm diameter mounted on "interdigital" rods. The resonator excitation by the E-beam and symmetric SCW generation had occurred at a
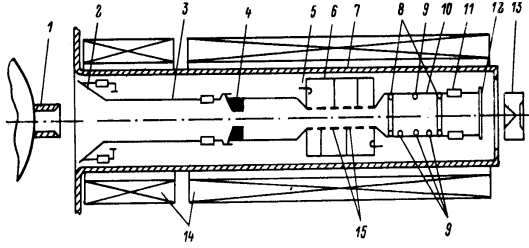
Fig. 13. *The experimental scheme: 1) cathode, 2) anode, 3) liner 4) diaphragm, 5) coupling loop, 6) resonator, 7) vacuum chamber 8) inductive pick-up, 9) magnetic probes, 10) diagnostic section, 11) return-current shunt, 12) collector, 13) pinhole camera, 14) solenoid, 15) drift tubes*

frequency of 670 MHz, this mode had four field variations along the resonator length. The SCW generation duration was 0.4-1.0 mcs; the power of the resistive losses in the resonator walls reached 0.5 MW; the electric field intensity between the drift tubes was 100-300 kV/cm. Simultaneously, the signal from the pinhole camera showed that the transverse dimensions of the E-beam were increasing that corresponds to ADE. The oscillation breakeoff was due to electric breakedown between the drift tubes.

The SCW wavelength was measured by means of two magnetic probes separated on distance of 12 cm and connected into an interferometer scheme. The sum signal from the probes had the maxima corresponding to integer number of wavelength in base length. Then, it was possible to determine the SCW length versus magnetic field intensity, and to compare its value with theoretical one, see Fig. 14.
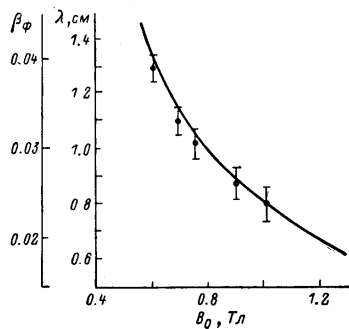
Fig. 14. *Phase velocity and wavelength of the SCW versus the magnetic field intensity (the solid line represents the calculated function)*

So, the good experimental results were obtained in the ADE interactions of electron beams with slow wave interdigital periodic structures of π-type (with short drift tubes on the meeting suspenders) in the IH-type resonators [,]. In the work [] the axisymmetric SCW with the amplitude of order of 100 kV/cm, pulse length ~1 μs, controlled phase velocity 0.02-0.05 c were excited by

intense electron beam interaction with such IH-type resonator.

5. DEVELOPMENT OF THE ION ACCELERATOR WITH RF FIELD EXCITATION AT ADE

On the basis of the experimental and theoretical results, a proton accelerator with accelerating and focusing RF fields excited at the ADE is being developed at the KIPT to ground a new type of advanced linear accelerators with ion energies and currents of order of 10-100 MeV, 1-10 A [23,,]. As it is known, the main condition of resonance ion acceleration is:

$$v_{ph}(z) = v_i(z) = \left[2\left(W_{i0} + qzE_{z,eff}\right)/M\right]^{1/2}, \quad (5)$$

where W_{i0} is the initial (injection) energy of the ions, v_i is the ion velocity, $E_{z,eff}$ is the effective accelerating field, q and M are the charge and mass of the ion.

In this case the ADE resonance condition for external non-uniform magnetic field to provide excitation of RF fields and acceleration of ions can be as follow:

$$eH_z(z) = \gamma mc\omega\left[v_e(z)/v_{ph}(z) - 1\right], \quad (6)$$

where γ is the Lorentz factor, c is the velocity of light, e and m are the charge and mass of electron.
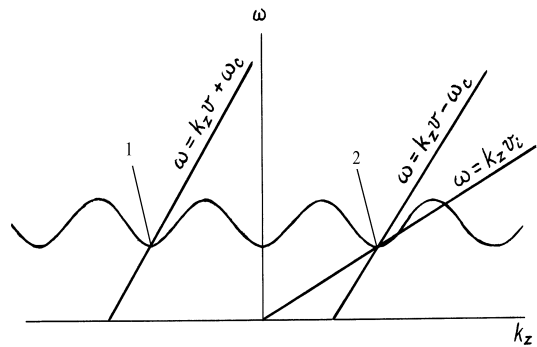
Fig. 15

In Fig. 15 the periodic curve shows the dispersion of the spatially periodic accelerating structure. Here point 1 corresponds to the NDE for electrons, and point 2 corresponds to the ADE for electrons and Cherenkov resonance for ions accelerated. To realize such accelerators, we are working on R & D of the Experimental Accelerating Stand (EAS) that is intended to prove the workability of that new type of accelerators. The EAS (Fig. 16) is described in details in [23,]. It is designed on the basis of the IH-type resonator (the length is 161 cm, the operation frequency is 148.5 MHz, the accelerating field is 56 kV/cm). The linear proton accelerator "URAL-5" of 5 MeV energy and 30 mA current will be used as an injector (ion current in the EAS may exceed 3 A []). The electron gun with the transverse compression will produce the beam of energy 350 keV, current 150 A, time duration 2.5 μs. Proton beam from the "URAL-5" will be injected through a central hole in a cathode of the electron gun, and pass through the H-type resonator to have an additional energy up to 8 MeV. The solenoid will create the ADE resonance space-changed magnetic field (see formulae (5), (6)); it can be at the entrance 609 Oe and at the exit 439 Oe.
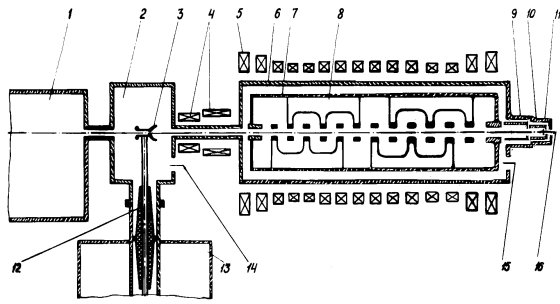
Fig. 16. *The EAS setup. 1-accelerator-injector, 2-vacuum chamber, 3-electron gun, 4, 5-magnetic coils, 6-vacuum chamber, 7-IH-type resonator, 8-support combs with drift tubes, 9-electron collector, 10-ion collector, 11-collector bottom, 12-high-voltage input, 13-high-voltage pulse transformer, 14,15-vacuum pumping, 16-ion outlet*

So, at the moment the physical concept of the two-beam high-current ion accelerator based on Doppler effect is well grounded. This concept may provide the ground for creation of ion accelerators with 10-100 MeV energy, 1-10 A current, and 10-100 MeV/m rate of acceleration. The project of the EAS was developed. The theoretical investigation and computer simulation have been fulfilled. For the experimental setup the planned accelerating gradient of order of 60 kV/cm can be achieved. Initial efficiency of order of 1 % will become higher with keeping resonance by means of specially profiled magnetic field. Coulomb interaction of accelerated ions was taking into account by "large particle" simulation method. It was found that the collective transverse instability defines the upper limit of ion current to be accelerated. For the parameters of the test accelerator EAS the ion limit current about 3 A have been determined. For efficiency increasing, it was investigated the problem of field excitation under alternation of anomalous and normal Doppler effect conditions. At present, the accelerator-injector "URAL-5" of energy 5 MeV is in operation; preliminary experiments on wave excitation at ADE have been carried out; experimental investigations of an accelerating RF resonator model (in 1:1 scaling) have performed. The investigations carried out show this acceleration method to advantage and lead to the R & D continuation.

6. SOME OTHER APPLICATIONS

1. *Application of the anomalous Doppler effect for polarization of electron or positron beams* by resonance microwave pumping was considered in Ref. []. In that work it was proposed the method of longitudinal polarization of free electrons by resonance pumping at a frequency of the electron spin resonance (ESR), using a running wave with phase velocity close to electron beam velocity. Repeatedly alternating of pumping at NDE by the following wave and by the counter wave, it is possible the electrons with various spins to divide in the velocity space. After that, by selection of the ESR pumping frequency, the spin revolution of the resonance electron group can be induced, almost not changing spin orientation of the non-resonance group. Thus the almost full electron polarization can be realized. Similar, and

even more effective, this method can make electron polarization using alternation of NDE on the following wave (thus the wave phase velocity exceeds velocity of the beam) and ADE on the following wave too (when, on the contrary, the velocity of the beam exceeds phase velocity of the wave). In practice, for realization of the described way it is possible to use a racetrack with electron pumping at NDE by the following wave on the one straight site of the racetrack, and at NDE by the counter wave (or at ADE by the following wave) - on the another straight site. The estimation of parameters for polarization of monoenergetic or velocity dispersed electron beams were performed.

2. T*he anomalous Doppler effect at electrons (or positrons) channeling in crystals* was theoretically examined in [-]. As it is noted in this works, an electron (or positron) channeling inside a crystal is an oscillator with superlight velocity, that gives good opportunities for investigation of such fundamental effect as anomalous Doppler one. The radiation is caused by transitions between the energy levels of transverse motion of channeled particle. Anomalous Doppler radiation for channeled electron can be lay in the optical region; quantum levels of channeled particles give a possibility for stimulated radiation. Experimental attempts to observe the anomalous Doppler effect at discussed situation were not yet successful because of luminescent and bremsstrahlung radiation background []. For successful experiments of this sort, a steady-state, precisian relativistic electron beam is needed (e.g., it can be generated by an electrostatic accelerator with good voltage stabilization).

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