Chapter 1
Introduction

Considering the possible content of our book we have paid the main attention to the following features. First, this should be new material, which has not been completely and consistently presented in previously published books. Second, this should be a presentation of theoretical results, which have some practical applications at present time and which would be prospective for future utilizations in new branches of physics and related spheres of knowledge. And at third, this book should be interesting and useful for young students who would like to study plasma physics.

This book is devoted to studying the properties of surface flute waves propagating in magneto-active plasma, whose boundary has a finite curvature radius. The applications of surface waves are known during a long time. At first they were described by Lord Rayleigh. In [1] one can find a classification of different types of surface waves. We propose for the present considerations a specific type of surface waves, whose field on the plasma-dielectric interface, has a surface type spatial distribution only in the region occupied by the plasma, but in the dielectric region it has a bulk type distribution. This is the first peculiarity of the material presented in this book. Because of the leakage of wave energy into the dielectric region, we are considering here metal waveguides with plasma filling.

The second peculiarity of our book is connected with the geometry of the magneto-active waveguides, in which these waves can propagate. Most of monographs and reviews, where surface waves are considered, make their theoretical study for the case of planar geometry, or they apply either cylindrical geometry inconsistently, or they consider only the case of non-magnetized plasma [2–5].

The next distinguishing feature of our book is connected with the fact that we study just flute waves. This means that these electromagnetic perturbations have no axial wave number. From one point of view this peculiarity allows one to separate Maxwell equations (in the limiting case of uniformity of the considered plasma system) into two independent sets, and from the other side most papers in the field of plasma physics are devoted to the opposite case, namely to studying azimuthally symmetrical electromagnetic waves. But in any case we restricted the scope of our book just to properties of transverse non-symmetrical eigen waves.

V. Girka et al., *Surface Flute Waves in Plasmas*, Springer Series on Atomic, Optical, and Plasma Physics 79, DOI: 10.1007/978-3-319-02027-3_1,

Nevertheless, in one of the sections we demonstrate that the developed theory can be also successfully applied for consideration of surface waves with a finite value of their axial wave number.

The fourth distinguishing feature of the presented material is connected with the fact that we consider here only the case of magneto-active plasma. Indicating that we should like to mention a physical incident, which happened with the well-known physicist L. Landau and his scholar, A. Akhiezer (everyone who is interested in plasma physics knows the fundamental monograph devoted to electrodynamics of plasmas, which was written by a team of physicists led by A. Akhiezer [6]). L. Landau worked for a long time in Kharkiv, where he has created the kernel of his huge theoretical school. This story was told to two of the co-authors of the book by old scientific collaborators of the Ukrainian Institute for Physics and Technology (present title is National Scientific Center "Kharkiv Institute for Physics and Technology"). Once A. Akhiezer has shown his work to L. Landau. He read it and asked the question to his scholar: "What is the strange choice of the object of your investigation? Alexander, where you have seen the plasma immersed into a magnetic field?" Maybe it was a joke; we were not present at this dialog. But nevertheless, our book just deals with different cases, where the plasma is influenced by an external magnetic field.

The fifth peculiarity of the book is connected with the applied theoretical method. Using the method of successive approximation we have solved a lot of tasks devoted to the investigation of the influence of plasma density non-uniformity, different types of external magnetic field non-uniformity, spatial inhomogeneity of plasma interfaces, etc. on the frequency spectrum of the extraordinary polarized surface flute waves (X-modes). We have considered mainly these modes because the corresponding ordinary polarized waves (O-modes) in the most cases have a bulk feature. Thus the book will be useful for students, who want to study such a popular analytical method like the method of successive approximations, which is widely used not only in plasma physics but also in other branches of physics.

Plasma filled waveguides are actively studied both theoretically and experimentally for the purposes of plasma physics [7], radio-physics [8], and plasma electronics [9]. Experimental investigations of various plasma filled electronic devices show prospective applications of surface wave propagation, and aim in increasing their efficiency. During recent years plasmas are widely used in various designs of antenna systems. It has been proved experimentally that plasma antenna systems have a lot of advantages compared with conventional metal antenna systems [10]. This is not only valid for military applications, but also for civil communication systems. Moreover, the range of their civil applications becomes more and more wider at present time [8]. Waves being excited in restricted plasma waveguide structures should be eigen waves of such structures. Surface waves can propagate not only in the case of gaseous plasmas but also in the case of solid state plasmas, see e.g. [11, 12]. Moreover, they can propagate in multilayered planar waveguide structures where the layers can be produced from meta-materials with different electro-dynamical properties. The possibility of surface wave propagation along a flat plasma-metal boundary was indicated for the first time in [13] and after that their properties have been actively studied by many other authors. A review devoted to properties of surface waves propagating along planar plasma-metal boundary across an external magnetic field is given in [5]. However, in experimental practice one often deals with a plasma boundary, which is characterized by a curvature radius of finite value and this circumstance strongly affects the properties of surface waves propagating in such plasma-waveguide structures. The finite curvature radius leads to changes of the frequency ranges where these waves can propagate, of the spatial distribution of their fields, of their polarization and so on, see e.g. [14].

The propagation of SWs is also widely used in various plasma technologies, which utilize gas discharge for cleaning and polishing solids, for lasers pumping and plasma production, elaboration of fullerenes etc. This can be explained by the fact that these waves possess a lot of advantages over bulk waves, for instance, they can produce plasmas with more spatially uniform density profile, and the efficiency of their interaction with plasma particles is also higher [15]. Surface localized plasmons (special type of surface waves connected with perturbations of conducting electrons in metals) are actively applied for formation of nano-structures using metal plasmas. Progress in elaboration of the bio-sensors based on the surface plasmon resonance technique indicates new prospective areas of surface wave applications.

At present time the world community is actively searching for new sources of energy. The International Thermonuclear Experimental Reactor (ITER) is being built in Cadarache, France. Surface waves can propagate in such fusion devices as well. Their propagation has a double role: on the one hand their excitation in fusion reactor leads to losses of RF power intended for ion cyclotron resonance heating (ICRH) of the fusion plasma core, impurity generation and other undesirable events, but on the other hand they could be utilized for cleaning the inner surface of the reactor vessel.

Construction of more complicated plasma devices unavoidably leads to the appearance of more complicated plasma phenomena, for example, to coupling between different electro-magnetic waves. Experimentalists often deal with plasmas, which are either sustained by a flow of electric current, or when flowing of a current in the confined plasma is necessary for plasma stability, if the plasma is sustained by another method. For instance, in tokamaks the plasma is confined both by toroidal and poloidal magnetic fields, the last one is mainly produced just by the axial electric current. That is why we also studied the case of surface flute waves propagating in current-carrying plasmas. In ordinary practice the value of an axial electric current is sufficiently small to consider the azimuthal magnetic field produced by it as a small parameter of the studied problem. Thus we have restricted our research here to the case of small values of this azimuthal magnetic field.

Chapter 2 of the book is entitled "Surface flute waves propagating in uniform magneto-active plasma filled waveguides". Here the influence of the various waveguide parameters on surface flute wave properties is examined under the condition of uniform plasma filling; the external constant magnetic field is assumed to be uniform and directed strictly along the axis of the cylindrical waveguide. The dependence of the surface flute waves (SFWs) on co-ordinates and time is assumed in the form $\sim \exp(im\varphi - i\omega t)$, where φ is the azimuthal angle, m and ω are the azimuthal mode number and their angular frequency, respectively. Application of such a simple waveguide model allows one to study properties of SFWs in a modal approximation. The main attention is paid to the properties of X-modes, because the flute O- modes are often of bulk type.

It will be shown that flute X-modes can propagate both along plasma-dielectric and plasma-metal boundaries and if the external magnetic field turns to zero. The problems of SFW damping are also studied here. It is proved as well that application of the SFW theory allows one to describe dispersion properties even of the eigen non-symmetrical surface waves, which have a finite value of the axial wave number. The theory of SFWs developed in this Chapter is applied in the following Chapters for solving corresponding problems by the aid of the method of successive approximations.

Chapter 3 considers coupled surface flute waves, which propagate in current-carrying cylindrical plasma waveguides. The need for studying such waveguides is explained by the fact that in order to produce gaseous plasmas in laboratory devices one can utilize an electric current. This is why we consider there the influence of an axial electric current on the dispersion properties of SFWs propagating in waveguides with non-uniform plasma filling. The value of this electric current is assumed to be sufficiently small so that either the azimuthal component of an external magnetic field is much less than its axial component or the cyclotron frequency, which appears due to the azimuthal magnetic field, is much less that the eigen frequency of the flute modes in the case if there is no axial magnetic field. Four different geometries of the utilized waveguide structure are studied there, namely: plasma-filled cylindrical metal waveguide, which has a dielectric coating on its inner surface, cylindrical metal rod immersed into magnetized plasma, cylindrical metal waveguide completely filled with plasma, and cylindrical coaxial waveguide completely filled with plasma.

The results of studying the propagation of SFWs in current-carrying waveguides prove the existence of coupling between O- and X-modes while O-modes can be either of surface or bulk type. In different plasma-filled waveguides, coupling between these flute modes leads to different phenomena: appearance of non-reciprocal frequency ranges in their frequency spectrum, change of the sign of their group velocity, damping of the X-modes and so on. The power transfer between these flute modes is characterized by the nonlinear dependence on the small parameter of the problem, which is proportional to the electric current.

The forth Chapter of this book is devoted to investigation of dispersion properties of SFWs while they propagate across the axis of symmetry in cylindrical metal waveguides with non-uniform magneto-active plasma filling. The non-uniformity can be connected with a radial dependence of the plasma density, which fills the waveguide, or with a spatial non-uniform distribution of the applied magnetic field. This could be a radial non-uniformity of the external magnetic field, a toroidal magnetic field non-uniformity utilized in metal waveguides, which are completely filled with plasma, or a non-uniform toroidal magnetic field created along a metal ring, and a weakly rippled magnetic field.

There the frequencies of SFWs and the spatial distribution of their field are examined and the damping rates, which are connected both with collisions between the plasma particles and resonant conversion of these modes into bulk modes, are calculated. It is interesting that from the mathematical point of view radial density non-uniformity is similar to radial non-uniformity of the external magnetic field. Thus influences of these non-uniformities on the SFW frequency spectrum are also similar. A small toroidicity of the external magnetic field leads to SFWs propagation in the form of wave packets. Corrections to the wave field of their main harmonic and to their eigen frequency are proportional to the squared small parameter of the system in this case. Ripples of the confining magnetic field in modern thermonuclear fusion reactors are characterized by a small parameter $\varepsilon_m << 1$. Nevertheless these ripples can influence the conversion and absorption of SFWs. In this case SFWs propagate as well as wave packets, which have six field components. The dispersion equation obtained in Chap. 4 contains small summands proportional to ε_m^2, thus the frequency correction is also proportional to the same value.

Chapter 5 is entitled “Surface flute waves propagating in waveguides with non-circular cross-section”. The most effective way to excite waveguide structures including those, which are corrugated, can be realized for excitation in the range of their eigen frequencies [16]. It is known that the shape of the cross-section of the plasma-vacuum interface in fusion devices also distinguishes from a circular one [7, 17]. In the case of stellarators this peculiarity of the design is particularly well seen. Using an expansion into Fourier series one can simulate any real shape of the cross-section of any plasma device. Thus we have solved the following tasks: propagation of SFWs in corrugated metal waveguides completely filled with plasma and propagation of SFWs in a metal waveguide with non-circular cross-section, which is partially filled with plasma. The influence of a cross-section non-circularity of the plasma column on the dispersion properties of these waves propagating in magneto-active waveguides in both resonant and non-resonant cases have been investigated as well.

Periodical changes of the curvature of the plasma column surface and/or a metal chamber along the azimuthal angle are shown to be the reason for SFWs propagation in the form of wave packets. The SFW eigen frequency correction, which is caused by the deviation of the waveguide cross-section from circular shape, is found to have a small value of second order over the small parameter of the problem in the non-resonant case. But in the resonant cases connected with degeneration of the frequency spectrum, the value of the frequency correction can be proportional to the small parameter of the problem in the first power. Examination of the spectral content of SFWs propagating along such waveguides has also been carried out here.

The sixth Chapter of our book contains a review of the possible applications of surface waves propagation. We tried to show there both existing plasma devices, which apply surface wave propagation and prospective possible future applications of surface waves studied in the previous Chapters. These applications concern the following areas: plasma electronics, including devices utilized for generation of super high frequency radiation, plasma-antenna systems including designs, which utilize plasmas sustained by surface wave propagation, plasma production, especially plasma sources based on surface waves propagation, surface plasmon polaritons propagating in the super high frequency range, plasmonics devices, including bio-sensors, photovoltaic cells etc. (see, e.g. [18–20]), and plasma nano-science. The cases of surface wave propagation in thermonuclear reactors are also considered here and the possibility to utilize SFWs for cleaning the inner walls of large-scaled fusion reactor vessels supplied with superconducting magnetic coils is discussed.

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http://www.springer.com/978-3-319-02026-6

Surface Flute Waves in Plasmas
Theory and Applications
Girka, V.; Girka, I.; Thumm, M.
2014, VIII, 163 p. 50 illus., 3 illus. in color., Hardcover
ISBN: 978-3-319-02026-6