Introduction to the Physics of Gyrotrons

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To my teachers:
A. V. Gaponov-Grekhov, M. I. Petelin, and V. K. Yulpatov

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Foreword

It is a great pleasure to write a foreword for this book, *Introduction to the Physics of Gyrotrons,* by Gregory Nusinovich. Dr. Nusinovich has been a pioneer in the field of gyrotron research for over three decades. His journey in this world of science and engineering took him from the Institute of Applied Physics in Nízhny Novgorod to his present home at the Institute for Research in Electronics and Applied Physics at the University of Maryland, College Park. Along the way, he has been a leading scientist in the gyrotron research program, first in Russia and today in the United States. This journey has given him a unique perspective on the exciting, developing field of gyrotron research. We believe that it is accurate to say that Dr. Nusinovich is today the single leading authority in the field of gyrotron research.

The gyrotron was developed to help bridge the gap between the realm of conventional microwave tubes at low frequency and the realm of lasers at high frequency. In the past few years, gyrotrons have been demonstrated at average power levels near one megawatt and at wavelengths of a few millimeters, resulting in unprecedented levels of power density over an extensive portion of the electromagnetic spectrum. This recent progress more than justifies the writing of a new, specialized book explaining the physics and engineering of gyrotron devices. This new progress has built on a long history of intensive research in the field. One may count over two thousand papers published in the field of gyrotrons in the past thirty years. It is remarkable that Dr. Nusinovich is an author or co-author of about two hundred of them, surely indicating his impact on the field. Dr. Nusinovich and colleagues were the first to calculate the generalized, nonlinear efficiency of the gyrotron and the first to explain and estimate the effects of mode competition, to name just two early contributions. More recently, he has pioneered research on gyrotron amplifiers at both the fundamental cyclotron resonance and at cyclotron harmonics.

The present book is a remarkable achievement. It begins with material introducing the gyrotron, a device that can be built in many forms: oscillator, amplifier, multicavity, traveling wave, etc. The great strength of this book lies in the subsequent analysis that provides rigorous derivations of the key equations of the gyrotron interaction. This rigorous derivation is very useful for scientists working in the field of gyrotron research. It also forms a model for developing the theory of any vacuum electron device. The book provides detailed results for all of the various forms of the gyrotron that are being studied today. Numerous excellent examples make the material much easier to understand.

Scientists and engineers working in the field of gyrotrons and related devices owe Dr. Nusinovich a debt of gratitude for producing this excellent volume. It will help young people entering the field and will serve as a valuable reference work for more experienced scientists. We believe that the field of gyrotron research will progress more rapidly and vigorously as a result of the publication of this excellent volume.

Victor Granatstein, *College Park, Maryland*
Richard Temkin, *Cambridge, Massachusetts*

Preface

Gyrotrons are well recognized as high-power sources of coherent electromagnetic radiation. In the millimeter- and submillimeter-wavelength regions, the power that gyrotrons can radiate in continuous-wave and long-pulse regimes exceeds the power of classical microwave tubes (klystrons, magnetrons, traveling-wave tubes, backward-wave oscillators, etc.) by many orders of magnitude.

This gyrotron superiority stems from the physics of gyrotron operation. Classical microwave tubes are based on such kinds of electron coherent radiation (Cherenkov radiation or transition radiation) that require microwave structures with elements smaller than a wavelength. For instance, traveling-wave tubes and backward-wave oscillators are based on the Cherenkov synchronism between electrons and slow waves whose phase velocity should be close to the electron velocity. Such waves can be excited in periodic slow-wave structures whose period should be smaller than a wavelength. The distance between electrons and walls of these structures should also be much smaller than a wavelength, because slow waves are localized near the structure walls. All these factors cause rapid miniaturization of the interaction space with the wavelength shortening even at millimeter wavelengths. Correspondingly, the power that can be handled by such structures decreases drastically.

Gyrotrons, however, are based on the mechanism of coherent cyclotron radiation from electrons gyrating in a constant magnetic field. In these devices, the electrons can resonantly interact with fast waves, which, in principle, can propagate even in free space. Therefore, the interaction space in gyrotrons can be much larger than in classical microwave tubes operating at the same wavelength.

The arrangement of a simplest gyrotron is shown schematically in Fig. P.1. Here, a magnetron-type electron gun is shown on the left. The voltage applied to the anode creates the electric field at the cathode. This field has both the perpendicular and parallel components with respect to the lines of the magnetic field produced by a solenoid. Thus, electrons emitted from the cathode acquire there both the orbital and axial velocity components. Then,