1 Introduction

Ian Brown

This book is an introduction to the physical principles of ion sources and a detailed review of a number of different kinds of sources. It is intended to serve both as an introductory textbook for newcomers to the field, and as a guide and reference for seasoned ion source users and researchers. The various chapters of the book have been written by researchers who are expert in the topic discussed. The chapters are independent and largely self-contained. While the scope covers much of the ion source field, the book is not encyclopedic. However, the principles described and the kinds of sources considered span a large part of the ion source activity that is taking place around the world today.

The ion source research and development community is composed of workers from a rather wide variety of scientific disciplines. These researchers have been drawn from the various application areas of ion sources, and as such they have a variety of different backgrounds and fields of expertise. A major subset of the ion source field has to do with particle accelerator injection, and workers in this area are largely nuclear or accelerator physicists and engineers, with support derived from and ion source goals directed toward the requirements of the various kinds of particle accelerators in operation around the world. A major industrial application of ion sources is for semiconductor ion implantation, a multi-billion dollar world activity, and many workers in this subfield come from backgrounds in solid state or materials science and from electrical engineering backgrounds. There is also a large and active research community worldwide in the field of non-semiconductor ion implantation for material surface modification for purposes as diverse as, for example, wear resistance, biological compatibility, and optoelectronics. An area in which a vast amount of progress has been made is that of the giant neutral beam injectors for heating and fueling experimental fusion reactor devices; the intense, high energy neutral beams are formed by charge-exchange from intense, high energy ion beams, and the ion sources used for this purpose are most impressive indeed. For the most part workers in this ion source subfield come from a plasma physics background. And there are many more application areas, each with its own ion source needs, constraints, and driving forces.

Workers in the various application areas naturally tend to communicate mostly with researchers in their own field, to participate in conferences within their own

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field, and to read journals that address primarily their own field. Thus there arises a problem endemic to the ion source field, that of insularity. This is unfortunate, since there is often much to be learned from the work of researchers in neighboring ion source subfields – cross-field fertilization. The International Conference on Ion Sources, held every two years at changing locations around the world, attempts to bring together workers from a wide range of ion source subfields. This book may also play a helpful role.

The first part of the book is introductory, with a presentation of basic plasma physics and the basic ideas behind ion source design and operation. This is followed by a look at some of the computer simulation work that has been used in the field and that is available to the researcher. The remainder and the bulk of the book consists of chapters that address specific kinds of ion sources, written by leading researchers actively engaged in the specific ion source considered. The kinds of sources treated in-depth are: high current gaseous ion sources, Freeman and Bernas ion sources, RF-driven ion sources, microwave driven ion sources, ECR ion sources, laser ion sources, vacuum arc ion sources, negative ion sources, ion sources for heavy ion fusion, and the giant ion sources for neutral beams.

Chapter 2 is an outline of the basic plasma physics necessary for an understanding of ion source physics. It is only an outline and summary; references are given to other more complete introductory plasma physics texts. Nevertheless, a familiarity with this basic plasma physics should go a long way toward understanding most of the ion source related plasma physics in the subsequent chapters. Topics addressed include basic parameters, the plasma sheath, magnetic field effects, and the various ionization phenomena.

A brief and very basic introduction to the fundamental concepts underlying the physics and operation of plasma-based ion sources follows in Chapter 3. This is the "Ion Sources for Beginners" chapter. The student or scientist who has had no previous experience with ion sources at all should find here the information that he or she needs to understand the principles involved. Following a step-by-step discussion of how the components of an ion source come together to create an ion beam, an example of a simple ion source is presented that demonstrates the fundamentals.

Computer simulation of the ion beam formation process has evolved immensely over the years, and it is now possible to simulate the processes to considerable precision. Chapter 4, by Peter Spädtke of GSI Darmstadt, Germany, discusses the computer simulation of beam extraction. The chapter is divided into the cases of positive ion beams and negative ion beams, with various kinds of ion sources discussed in detail.

The beam formation process from the perspective of the laboratory physicist is discussed in Chapter 5 by Ralph Hollinger, also of GSI Darmstadt, Germany. Here the extractor geometry is considered in detail, with consideration given to how all of the beam parameters are affected by the extractor design. There are a great many highly interactive considerations that all add up to good overall design of the beam formation and acceleration electrode system. Various different kinds of extractors are considered, for the formation of different kinds of beams.

After the beam is formed it must inevitably be transported away from the source and toward the application region. The final application may be an accelerator, an implanter, an ion analysis instrument, a fusion reactor, or any of a great many possibilities. The transport distance can be less than a meter or many tens of meters and the beam might be of very small cross-sectional area or it might be a very broad beam, but in virtually all cases the beam must be passed through a vacuum pipe of some sort with minimal loss. A good working knowledge of factors that influence the beam transport is important. The tendency of high current beams to space-charge blowup and the critical role played by background electrons in space-charge neutralization (or compensation) is one such factor. Beam transport is discussed jointly by Spädtke and Hollinger (GSI) in Chapter 6.

High current gaseous ion sources are discussed by Nikolai Gavrilov, from the Institute for Electrophysics at Ekaterinburg, Russia, in Chapter 7. The kinds of sources discussed include filament driven sources, high frequency sources, and cold cathode sources. The performance that can be obtained from modern versions of these sources is impressive. Here the basic plasma physics involved and the considerations related to beam extraction are discussed. Examples are presented of a number of working cold-cathode ion sources.

One of the major technological applications of ion sources is in the semiconductor ion implantation industry. The Freeman source and the Bernas source are the usual sources of choice in this field. These sources have been improved over the years to a very fine pitch. Freeman and Bernas sources are considered in depth in Chapter 8 by Marvin Farley, Peter Rose and Geoffrey Ryding of the Applied Orion Group, Beverly, Massachusetts. Following a detailed discussion of the physics of the plasma in these sources, means of ion source control are described, and the key issues of source maintenance and lifetime are discussed. This chapter should provide a valuable reference for workers in the semiconductor implantation community.

Radio frequency (RF) driven ion sources have been a staple of the ion source platter available to the experimenter for many years. Recent development has extended the ion beam parameter range and improved the overall performance greatly. RF ion sources are discussed in Chapter 9 by Ka-Ngo Leung of the Lawrence Berkeley National Laboratory. Both capacitively coupled and inductively coupled source types are addressed, as well as the key role played by the multicusp magnetic confinement geometry.

Plasma formation by means of RF power and microwave power are related approaches. Thus in a sense the microwave driven ion source is a sibling to the RF driven source. The current status of microwave ion sources is described in excellent detail in Chapter 10 by Noriyuki Sakudo of the Kanazawa Institute of Technology, Ishikawa, Japan. The basic plasma physics involved in the absorption of microwave radiation in a plasma is discussed, including the phenomenon of overdense plasma production, when the plasma density can be greater than the microwave cutoff density by an order of magnitude or more. Microwave power coupling to the source plasma and ion beam extraction techniques are then considered. Finally, the application of microwave ion sources to commercial ion implanters is discussed.

Microwave power can be coupled resonantly to a plasma by matching the microwave frequency to the electron cyclotron frequency in the magnetic field by which the plasma is confined – the electron cyclotron resonance (ECR) frequency. If the gas pressure is also sufficiently low and the plasma confinement sufficiently high, then the electrons can be heated to substantial energy by the resonant microwave field and the ions can be stripped to high charge state. An ion source incorporating these principles is called an ECR ion source. Though also of course a kind of microwave ion source, the terminology used has now solidified to distinguish the microwave ion source and the ECR ion source quite clearly. ECR ion sources are described in Chapter 11 by Claude Lyneis and Daniela Leitner of the Lawrence Berkeley National Laboratory. The primary application of ECR ion sources is for generation of high charge state ions for injection into particle accelerators, mostly cyclotrons. The chapter summarizes the history of ECR sources, outlines the plasma physics involved, design considerations, microwave and magnetic field technologies involved, and the production of metal ion beams. The chapter should provide an excellent reference for the laboratory worker.

Sources in which the plasma is formed by an intense pulsed laser beam focused onto a solid target are called laser ion sources. These kinds of sources are addressed in Chapter 12 by Boris Sharkov of the Institute for Theoretical and Experimental Physics, Moscow, Russia. Laser ion sources are used primarily for particle accelerator injection into heavy ion synchrotrons. This chapter covers the basics of laser plasma physics, the details involved in putting together a laser ion source, and the beam parameters that can be obtained. Examples of laser ion source facilities at some major accelerator laboratories are described.

The vacuum arc ion source is a high current metal ion source. Whereas it is often the case that metal plasma (plasma formed from a metal) is more problematic to form than a gaseous plasma (plasma formed from a gas), the vacuum arc discharge is a relatively simple means of generating large amounts of metal plasma, and the vacuum arc ion source, in turn, is a relatively simple means of generating high current beams of metal ions. These sources are described in Chapter 13 by Efim Oks of the High Current Electronics Institute, Tomsk, Russia, and Ian Brown of the Lawrence Berkeley National Laboratory. Following a brief summary of vacuum arc plasma physics, ion source operating principles are described, then the beam parameters that can be obtained, and some recent new developments in these kinds of sources. The chapter concludes with a summary description of some of the source embodiments that have been made and are in use at various laboratories around the world.

Negative ion sources play an important and unique role in the ion source universe. Because the ions carry a negative charge, the plasma physics involved, the means of ion beam extraction, and the kinds of applications for which the sources are used are all significantly different from all the positive ion sources. Negative ion sources are treated in Chapter 14 by Junzo Ishikawa, Kyoto University, Japan. The two different approaches to negative ion formation in plasmas, surface production and volume production, are considered in detail, and the ways in which negative ions sources have been constructed to take advantage of these two approaches are described by reference to many different examples.

The ion beam requirements for heavy ion fusion are quite different from beam parameters offered by the mainstream kinds of ion sources. The beam must be very high current, short pulse, fast pulse rise and decay times, single charge state, highly reproducible and low noise. At the same time the source lifetime (number of pulses between maintenance downtimes) must be very high. These are difficult requirements. This subfield is discussed in Chapter 15 by Joe Kwan of Lawrence Berkeley National Laboratory. Surface ionization sources, the research approach taken at present, are firstly described, followed by consideration of gas discharge sources, laser and vacuum arc sources, and negative ion sources.

By far the largest ion sources are those that have been developed for the neutral beam injection devices for fusion plasma heating. The requirements of these sources and the associated beam requirements are daunting. Nevertheless, impressive progress has been made. Unique features of the sources include the large volume plasma production that must first be done and the extremely precise but very large area beam extraction and acceleration electrodes that must be manufactured. Sources based on positive ions are used in the lower energy regime and negative ion based systems are used for sources with ion energy in the multi-hundreds of keV range. The giant ion sources that have been developed for the neutral beam development program are described in Chapter 16 by Yasuhiko Takeiri of the National Institute for Fusion Science, Toki, Japan.

The ion source coverage spanned by the contents of this book is not total. Indeed it would be a nigh impossible task to treat in detail all of the different existing kinds of ion sources in a manageable book. Nevertheless the range of sources considered here does span a diverse spectrum of beam parameters and source techniques. Perhaps, with a little serendipitous fortune, some of the ideas presented here might prove to be fertile material for the generation of new kinds of ion sources and ion beam devices.

There are other resources available to the ion source investigator, both novice and expert. These include books, journals, and conference proceedings. Some previous ion source texts are referenced below [1–6]. Many of the topical conferences have considerable ion source content, and the International Conference on Ion Sources (ICIS) is an established conference that is held every two years (odd-numbered years) at various locations around the world. A web search will quickly lead to information about the next planned ICIS. The Proceedings of the ICIS meetings are published in *Rev. Sci. Instrum.*, usually in the first quarter of the (even-numbered) year following the ICIS meeting. The ICIS Proceedings [7] are a very rich source of up-to-date information on a wide range of ion source physics and technology.

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