The Future of Industrial Accelerators and Applications

*B.L. Doyle, Sandia National Laboratories**
F.D. McDaniel, University of North Texas (retired)
R.W. Hamm, R&M Technical Enterprises, Inc.

Abstract

This section updates Volume 4 of the *Reviews of Accelerator Science and Technology* titled "Accelerator Applications in Industry and the Environment," published in 2011 [1]. We also include the new material available about this field following the publication of "The Beam Business: Accelerators in Industry" in 2011 [2] and "Industrial Accelerators and Their Applications" in 2012 [3], both written and co-edited by one of us (RWH). We start with some general trends in industrial accelerator developments and applications, and then move to bringing up-to-date the developments in each article of Volume 4. In this regard, we owe a debt of gratitude to many of the authors of sections of *RAST-4*, and they are gratefully acknowledged in each of their individual update submissions.

1.0 Introduction

In the final report of the symposium and workshop of *"Accelerators for America's Future"* [4], the authors Walter Henning and Charles Shank wrote one of the most profound statements ever made about particle accelerators, *"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or discover the secrets of the*

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

universe." The disparate nature of the last two items is typical of applications of accelerated ions and electrons.

From the standpoint of industrial applications, one can ask what do accelerated beams of particles offer that provides competitive advantages. Such advantages are probably not always about cost savings, because for the most part, these accelerators are expensive, difficult to maintain and require highly trained (and paid) scientists and engineers to support their operation. Therefore, the evolving and growing uses of particle accelerators in industry must depend on the fact that they <u>enable</u> the manufacturing of products and provide treatments that would otherwise be impossible. In this regard, one can think of using accelerated particles in manufacturing as a way to bypass thermodynamic processes to speed the realization of products, and in some, maybe most, cases result in structures not possible to form by relying on natural processing, such as heating, cooling, machining, etc. Remember the margarine commercial several years back? There was lighting and thunder and a stern voice stating, "It's not nice to fool Mother Nature." It may not be nice to fool her, but it sure is fun, and that is precisely what accelerators can do!

The utilization of accelerators in industry has benefitted greatly from the advances in modern physics over the past century. Industrial applications of energetic beams of particles, such as electrons or ions obtained directly from accelerators, or neutrons and photons, which can be produced by accelerators, rely on a deep understanding of their interactions with matter. Electrons can modify chemical (e.g. de-polymerization) and even physical properties (e.g. melting) of materials by breaking bonds through ionization or the deposition of heat, in many cases very deeply in the material. The most common use of both very high and very low energy ions in industry remains implantation doping of semiconductors. This application utilizes the detailed understanding of the physics of ion-atom and ion-electron collisions that has resulted from over a century of research at universities, in industry, and at national laboratories. Borrowing from the Henning-Shank quote, this research has proven necessary to determine the right energies and right fluences in order to place the right dopants at the right concentration at the right depth that is required for the right performance of modern integrated circuits. The same is true for virtually all applications of accelerated ions, e.g. placing the right dose within the right volume in the human body when performing hadron radiotherapy.

2. General Trends

Since the publication of *RAST-1* article on "Industrial Accelerators" [5] a decade ago, more than half of the particle accelerators produced worldwide are now used for industrial applications. These commercial systems utilize a wide range of accelerator technologies and cover numerous applications over a broad range of business segments. While this is not a high-profile business, these "industrial accelerators" have a significant impact on people's lives and the world's economy, as many products contain parts that have been processed by charged particle beams. The wide scale adoption of many of these processing tools has resulted in the rapid growth of the utilization of accelerators by industry that has occurred since the *RAST-1* [3][5] article. As this present article reveals, there have been considerable changes; therefore, readers are strongly recommended to combine the information in *RAST-1* [3][5] with the new and updated material presented here.

As in the original article, "Industrial Accelerators" are defined here to be charged particle accelerators that generate external beams. These beams are used in ion implantation, ion beam analysis, neutron generation, radioisotope production, e-beam material processing, e-beam irradiation and e-beam based inspections. Electron and hadron accelerators used for medical treatment and systems used for basic physics research are mentioned, but are generally outside of the scope of this article; since these topics are covered in other articles of this last issue.

Present day industrial accelerators have evolved from the early physics research machines into systems for use in a wide range of specialized applications. These systems and applications can be grouped into broad categories as listed below:

•Materials processing — This remains the largest use of industrial accelerators and encompasses both ion and electron beam systems. Applications include ion implantation of semiconductors and metals; irradiation of plastics, food and other products by ions, electrons and x-rays to promote chemical changes and sterilization; and electron beam welding, melting and cutting of ceramics and metals.

•Materials analysis — This category is unique to ion accelerators and includes all the ion beam analysis techniques used for trace element detection and quantification, element profiling, and precision determination of elemental ratios, including accelerator-based mass spectrometry.

•Nondestructive analysis — This category includes the use of x-rays or neutron beams to examine materials for flaws and hidden features and to detect contraband, including security inspections at borders and transportation hubs. It also includes the use of neutrons for mineral detection.

•Radioisotope production — This group includes all electron and ion accelerators employed to produce radioactive materials for use in medical procedures and industrial applications.

The market for industrial accelerators has grown to be a significant international business over the past decade. Figure 1 plots the number of accelerator systems sold to date for each application, as estimated by the authors from available literature and consultations with vendors. These quantities include many accelerators originally purchased for physics research, but now used primarily for industrial applications. This figure also shows the sales totals for all medical treatment accelerators and the total number of accelerators installed.

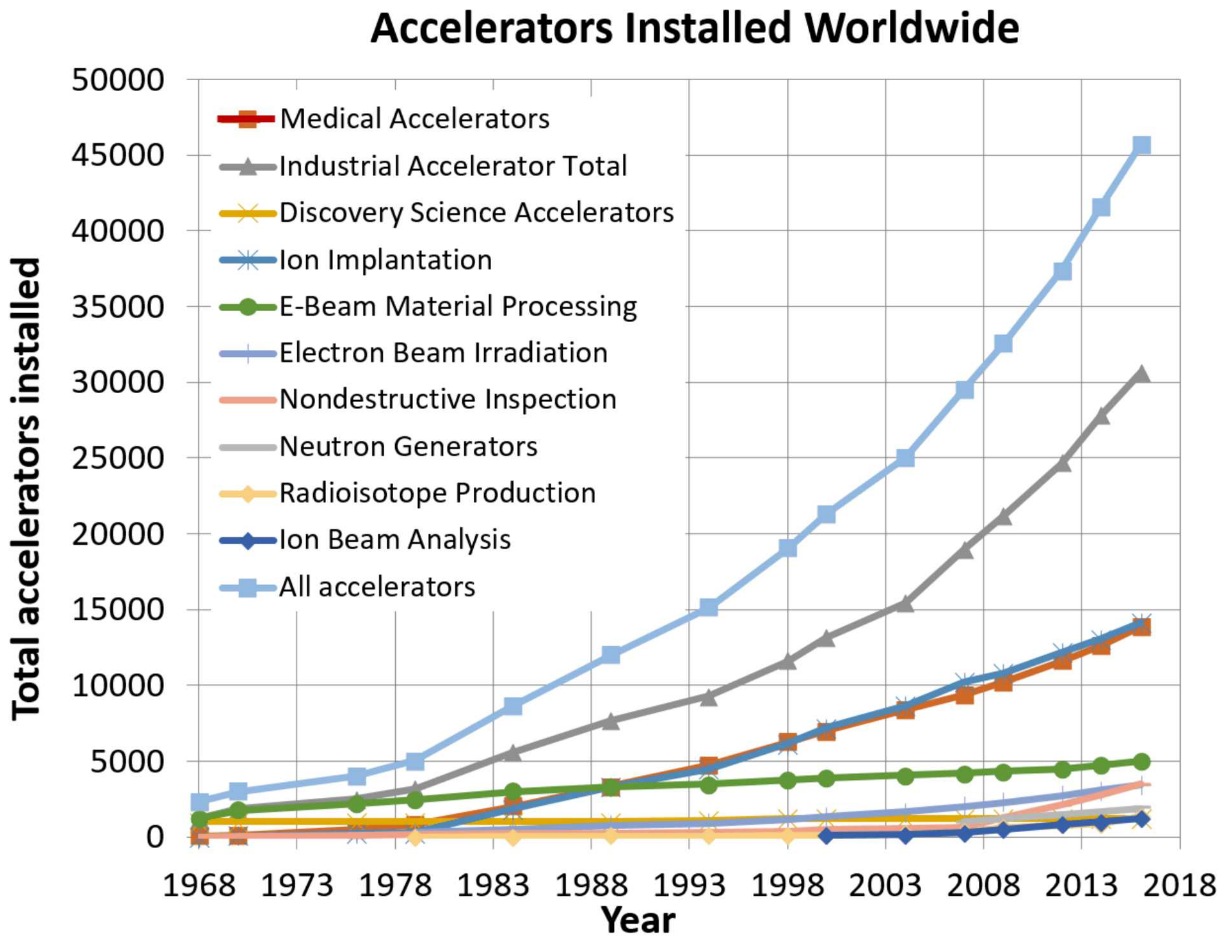

Figure 1: The number of all accelerators built and installed for various applications worldwide over the past five decades. These totals are greater than the current installed base in each application, as some of the older systems have been decommissioned. Note the sales increases over the past decade since the publication of the RAST series began in 2008. Some of the data here was taken from **[6]** and estimates were made for others using fits to reported data by one of the authors (RWH) **[7]** .

Ion implantation remains the largest market for industrial accelerators. With ~14,000 units sold from 1968 to 2018, this market is about the same size as the market for medical accelerators, which was reported recently to have a worldwide installed base of also ~14,000 systems. There have been ~5,000 accelerators added to the industries utilizing ion implantation, since the publication of the first article in *RAST-1* [4].

The distribution of all accelerator applications, except for basic research, is plotted below in Figure 2 as of 2016.

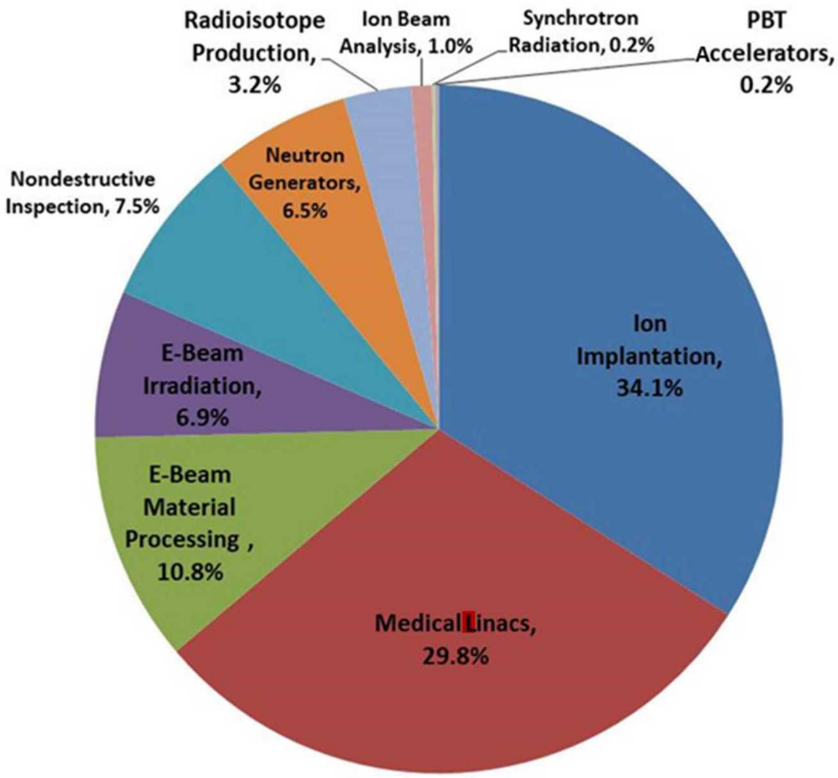

Figure 2: Pie chart of the disparate applications of the ~46,000 commercial accelerators installed around the world. PBT stands for proton beam therapy. It is clear, that since most of the medical linacs and nondestructive inspection systems are electron accelerators, ~half of the applications shown here employ electron accelerators with the other half employing ion accelerators. Interestingly, the field of two authors of this article (BLD and FDM) is Ion Beam Analysis (IBA), which only represents 1% of the accelerator applications.

Another way of examining current trends in commercial accelerator growth is to look at the percentage annual growth in each of these application areas, as shown in Figure 3.

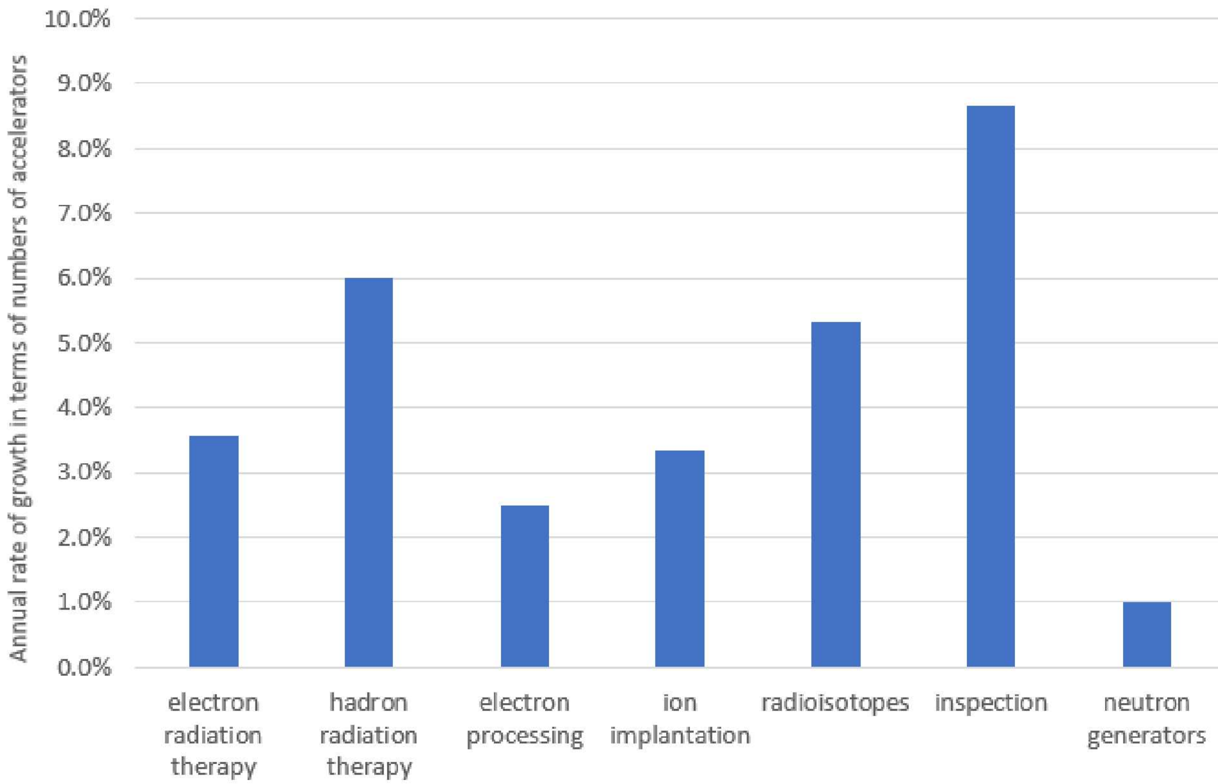

Figure 3: Percentage annual increase in the number of accelerators used in each of the labeled areas between 2008 and 2018.

The two largest growth areas are: (1) electron and neutron inspection with over 7,500 of these units having been sold to date and (2) hadron therapy, with ~75 facilities in operation for treatment of cancer patients with protons or carbon ion beams and 43 more facilities under construction. It is also important to note that the increases, while not overly large, were realized during one of the deepest world-wide recessions in history.

The growth of accelerators used for inspection is obviously due to increased security at airports and other transportation hubs, as well as heightened concerns over terrorists smuggling radioactive material across borders. A related terrorist issue that has led to an increase in electron processing systems is the trend to replace radioactive isotopes such as ^{60}Co and ^{137}Cs, which could potentially be used as a radiological dispersal device or dirty bomb.

While hadron radiation therapy represents only a small number of accelerators in use today, this area is highly visible because hadron therapy is saving lives. This situation is not that different from that of Wilhelm Roentgen's discovery in 1895 of x-rays [8] generated by accelerated electrons in a Crookes tube [9] and his creation of the field of diagnostic radiology. Both are examples of "fooling mother nature" discussed earlier in the Introduction. In Roentgen's case, he took advantage of the penetrating power x-rays have in matter that ordinary light doesn't have. In the case of hadron therapy, one exploits the Bragg peak [10], which is the maximum in the energy loss rate and hence ionizing dose rate of ions in matter, in this case the human body. By positioning the Bragg peak right at the site of a tumor by adjusting the ion energy, minimal dose is given along the trajectory to the tumor, thereby reducing the unintended collateral dose to healthy tissue. With gamma-rays and electrons, that is not the case, as they both lose more energy and cause more damage to healthy tissue along their trajectory to the tumor. Hence, mother nature is fooled again with hadron therapy. Sadly, Roentgen died in 1923 from carcinoma of the intestine, which today could be treated with hadron therapy.

So, it is quite apparent looking at Figures 1 and 3, that the field of industrial accelerators is quite healthy and still growing.

3.0 Introduction to following individual sections updating articles in *RAST*-4

The major industrial areas where accelerators are used has not really changed significantly since the *RAST-4* issue was published in 2011[1]. Convenient sources that update the progress in these areas are the most recent abstract books [11] starting in 2008 and continuing until the present of the International Conference on Applications of Accelerators in Research and Industry (the biennial CAARI meeting), which two of the authors of this section have co-chaired since 2004 (BLD and FDM). In this review, we are not covering the areas of Healthcare (except for isotope production), Energy (except for radiation effects), and Security and Defense, as they are being updated in other parts of this last issue of *RAST*. The industrial application areas we are covering are listed under the following four headings:

1. **Research** – this includes applied science performed at universities, national laboratories, and in some cases industry itself. While much of the ion-atom collision physics has been developed over the past century, there are still cross sections being measured, new atomic and nuclear interactions studied to better understand radiation effects, and new applications of accelerated ions and electrons being found that better the field of ion beam analysis (IBA) of materials. The IAEA "Accelerator Knowledge Portal" [12] is a good starting point to find these materials. This research has led to many computer codes that enable such analyses, and a convenient place to find such codes are in the "Code List" [13] of the Portal.

   Below in this issue are individual articles by Chris Jeynes from the University of Surrey that update the status of IBA and from Mark Roberts from NOSAMS - Woods Hole Oceanographic Institute, which updates the rapidly expanding field of Accelerator Mass Spectrometry (AMS).

2. **Energy/Environment/Radiation Effects** – There are large-scale accelerator applications under development in this area including future energy generation using subcritical fission plants, transmutation of nuclear waste, accelerators for both magnetic and inertial confined fusion energy. In all of

these evolving areas, including advances in future generation fission reactors, radiation effects to the materials used is of critical concern. These effects include atomic displacement damage and nuclear transmutation that results in swelling, creep, and the possibility of material failure. Khalid Hattar of Sandia National Laboratories summarizes advances in accelerator-based radiation effects research in a section below, and Andrzej Chmielewski of the Institute of Nuclear Chemistry and Technology, Warsaw updates electron beam technologies for pollution control.

3. **Medical/Isotope Production** - Radioactive isotopes continue to be used in a wide range of medical, biological, environmental and industrial applications. Cyclotrons are the primary tool for producing the shorter-lived, proton-rich radioisotopes. In this area are approximately the same number of medical particle accelerators as those used for ion implantation. Most of those reading this article will likely benefit from radioactive isotopes either used for diagnostics or treatment of various ailments, mainly cancer. One of the authors of this section (BLD) certainly has. Paul Schmor, TRIUMF emeritus and owner of Schmor Particle Accelerators Consulting, Inc. reviews the current uses of cyclotrons for producing medical isotopes for both treatment and diagnostics in a section below. While we tangentially touch on hadron therapy, it is being covered in another section of this final RAST issue.
4. **Industrial Applications** – These applications naturally factorize under two categories: electrons and ions.
    a. Electrons have found broad usage for cross-linking polymers, curing inks and adhesives, medical applications, and shrink wrapping your holiday turkey (see the Henning and Shank reference above). Valeriia Starovoitova of Idaho State University and the Niowave Corporation reviews advances in using electrons for irradiating food, sterilization for medical applications, and blood irradiations. Marshall Cleland of IBA Industrial, Inc. updates progress that has occurred regarding RF electron accelerators used by industry.
    b. While ion accelerators have found applications for producing harder and more wear resistant artificial joints (another example where accelerated ions could affect many of us personally), most are used for

ion implantation into semiconductors which has become a key process in the commercial production of integrated circuit devices, advanced engineering materials and photonic devices. Michael Current of Current Scientific Inc. has indicated that almost all of the tools described in his chapter in the Hamms' book [3] and *RAST-4* article have been completely replaced by new equipment in the near-decade since they were written. Michael Current updates his *RAST-4* article and adds a review of the history and future of ion implantation in semiconductors below.

4.0 RAST-Volume 4 Updates

This next section on the future of industrial accelerators now updates each of the articles in the *RAST-Volume 4* issue on "*Accelerator Applications in Industry and the Environment*" [1]. These articles appear in the same order as they did in Volume 4.

4.1 Update to Industrial Applications of Electron Accelerators

Valeriia Starovoitova, Idaho State University and Niowave Inc.

The history and trends of industrial applications of electron accelerators have been described in detail elsewhere, for example see S. Machi's nice review [14] in *RAST-4* and the author's (RWH) book [2]. Here we add a few paragraphs concerning three particular applications of electron linacs.

Food irradiation

Food irradiation was described in the *RAST-4* paper [14]. Since 2011, food irradiation has come into greater focus because many other pathogen intervention technologies have been unable to provide sustainable solutions to address pathogen contamination in foods. In *RAST-4* [14], a facility in Odessa, Ukraine was described. Another example is the National Center for Electron Beam Research at Texas A&M University [15]. The center, directed by Prof. Suresh Pillai, is focused on enhancing food safety and protecting against the invasive imported insects and pests. They use both e-beam and x-ray technologies (but mostly e-beam), customized for different foods and agricultural products. Decreasing the post-harvest loss remains one of the biggest issues, especially given the growing demand for food worldwide.

Sterilization of medical products

The United States has the largest medical device market in the world, estimated at $110 billion a year with more than 6,500 medical device companies. Moreover, medical device demand continues to grow at a 5 to 7% rate per year due to an aging population and greater access to high quality healthcare globally. Historically, steam autoclaves or dry ovens were used to sterilize reusable medical items. However, they can easily damage many types of plastics used in "single-use" medical items, such as syringes, surgical gloves, artificial joints, etc. As a result, 40-50% of all disposable medical products manufactured in North America are currently radiation sterilized, primarily at ^{60}Co irradiation facilities.

Recently there has been an initiative to replace ^{60}Co sources (which can potentially be turned into a dirty bomb) with high power electron accelerators. Electron beams can be used directly or as x-ray sources, depending on the size/mass/density of the product. Electron linacs for medical sterilization were first implemented in 1990's. Niowave Inc. has done some feasibility studies and showed that high power (7-8 MeV, and tens of kW) machines have similar (or even greater) penetration than ^{60}Co, and comparable processing cost. Niowave Inc. also irradiated many products and they were confirmed to be sterile. They are currently working on scaling up their irradiation facility.

Blood irradiation

A special case of "sterilization" is blood irradiation. Irradiating donated blood components before transfusion is the only accepted method to prevent transfusion-associated graft-versus-host-disease (TA-GVHD), an extremely dangerous blood complication with fatality rates reaching 90%. The difference in susceptibility to radiation between red cells and lymphocytes is the key for using x-ray and gamma-ray treatments for blood products. A typical radiation dose required to deactivate harmful donor T-lymphocytes while leaving the other blood components viable is 15 Gy to 50 Gy. High activity ^{137}Cs sources are the primary method for blood irradiation in approximately 80% of American hospitals that irradiate blood. Cesium sources are typically used in the form of cesium chloride, which is extremely dangerous if used as a radiological weapon. It is easily dispersible, water soluble, highly reactive, and remains detrimental to humans and the environment for over 100 years. It is not surprising that ^{137}Cs sources are being phased out. Alternative methods of blood irradiation are urgently needed. Blood irradiation using x-ray tubes and up to 3 MeV electron linacs are currently being developed.

4.2 Update and Historical Perspectives on Ion Implantation for CMOS Channel Scaling

Michael Current, Michael Current Scientific, San Jose, CA 95124 USA

4.2.1. Early years: 1965 to 1990

The past informs the future, especially when viewed over considerable time scales. In 1965, Gordon Moore, then at Fairchild, reviewed his 5 years of experience at making increasingly complex integrated circuits (ICs) and proposed that: (1) the number of transistors per IC would increase steadily (at a rate of doubling every 1 to 2 years) and that (2) the cost per function (or “component”) would decrease with improvements in production yields as capability for producing increasing complex circuits improves [16]. Moore did not indicate how this would be accomplished, only that he expected that it would, in the face of certain obstacles such as the need for higher resolution patterning and concern for chip heating with more complex circuits.

Almost a decade later, the mainstream transistor design based on bipolar junctions was beginning to be challenged by metal-oxide-semiconductor (MOS) transistors. In 1974, Robert Dennard at IBM published a model for how one could systematically shrink the dimensions of MOS transistors while also increasing the switching speed while reducing the switching power levels [17]. The key features of “Dennard scaling” were the proportional shrinking of both lateral and vertical transistor dimensions along with decreases in the drive voltages, maintaining approximately constant local electric fields in the MOS transistor leading eventually to what was referred to as "well-tempered" Complementary Metal Oxide Semiconductor (CMOS). While the proportional scaling of drive voltages was nearly universally ignored [18] [19] in favor of higher switching speeds, the core dimensional scaling eventually matured into the framework for a "Roadmap" which drove 4 decades of transistor size shrinkage, improvements in IC performance, and reduced component cost (see Fig 4 below) [20].

The key MOS structural elements scaled with the lateral dimensions (gate length) included the channel and gate oxide thickness, with threshold voltage also set by design choices for gate length and work function (by choice of doping type and level in the case of poly-Si gates). The central element was reduction of the channel depletion layer thickness through a combination of precise control of the steadily increasing channel doping and shrinkage of the source/drain (S/D) junction depths, leading to the use eventually of "ultra-shallow" junctions for S/D extensions.

Since the controls on the MOS channel doping called for the use of precise dopant concentrations, which were several orders of magnitude lower than what could be achieved with chemical processing (i.e. diffusion doping), Dennard scaling made channel doping by ion implantation an absolute requirement for MOS device fabrication. As prevalence of MOS and then CMOS ICs increased in the 1970's and 1980's, ion implanters were developed for applications beyond the relatively low-dose "threshold adjust" steps to become the dominant means for doping and materials modification of IC structures [21]. The reduction of S/D junction depths with each new device generation led to the continual improvements in the low-energy beam currents for commercial ion implanters designed for high-dose doping. Requirements for CMOS well doping and image sensor formation extended the practical ion energies upward into the multiple MeV range [22].

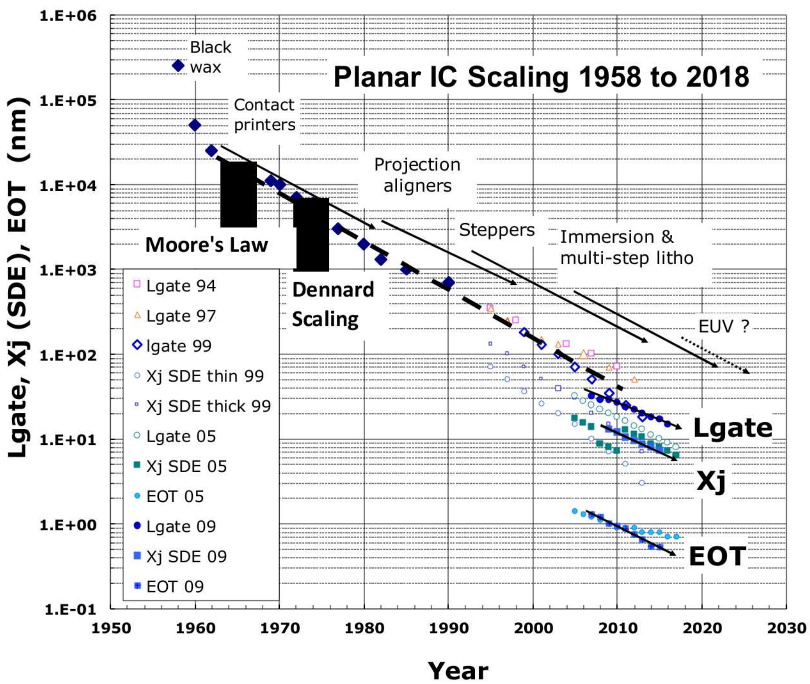

Figure 4: Systematic decrease in MOS gate length (Lgate), S/D extension junction depth (Xj (SDE)) and equivalent oxide thickness (EOT) for gate dielectrics with "ITRS Roadmap" projections from 1994 to 2009 reports. Also shown are the dates of papers by G.E. Moore and R.H. Dennard and the principal lithography tools in use at various times.

4.2.2. The "End of the Roadmap" (for planar CMOS on bulk Si wafers): 2000-2012.

By 2000, the limitations of dimensional scaling of CMOS transistors were widely recognized. The introduction of strain-enhanced carrier mobility techniques enabled continual improvements in transistor performance along with dimensional shrinkage. However, delays in implementing a partial replacement of Si-based gate dielectrics and heavily-doped poly-Si gate electrodes led to various suggestions for increased shrinkage of S/D junction depths. This was to partially compensate for the delays in EOT scaling (note the "noisy" trends for various editions of the International Technology Roadmap for Semiconductors (ITRS) for the later 2000's and beyond in Fig. 4).

In 1998, Y. Tauer, then at IBM, predicted that planar CMOS transistors with gate lengths approaching 25 nm would face significant challenges. These challenges were from such issues as depletion of doped poly-Si gate electrodes and band-to-band tunneling leakage currents from the highly-doped channel "halos" required for punch-through protections for these short channel transistors [23].

With the ion implantations process, the early 2000's saw the full development of "ultra-shallow junction technologies." There was the wide use of sub-keV dopant implants with low energy beamlines, plasma immersion tools, and use of large-dopant number molecular implants coupled with short-time thermal anneal tools designed to strongly limit dopant diffusion while still providing high-dopant activation levels [20] [22].

Increased concerns for minimizing junction leakage currents (and transistor power levels) led to many process innovations. One was the use of "cryo" implants, where S/D junction implants were done with wafer temperatures well below 0 C to enhance the damage accumulation during implant, resulting in thicker surface amorphous layers. During post-implant thermal annealing, the cryo-implanted amorphous layers recrystallized with high levels of structural perfection and dopant activation along with reduced concentrations of residual "end-of-range" damage, reducing junction leakage current [20].

By 2008, Intel microprocessor gate lengths for its 32 nm node devices were averaging 30 nm with the use of Hf-based gate dielectrics and metal gate electrodes in conjunction with continued use of strain enhanced mobility methods. This was the end of the line generation for Intel's use of bulk planar CMOS transistors for high-performance microprocessors.

4.2.3. Fully-depleted CMOS: 2012-2020

In 2011, Intel announced that transistors used in their "22 nm" node devices would contain fully-depleted vertical channels with multi-sided gate electrodes formed as bulk finFETs [24]. In fully-depleted channels, such as finFETs or as planar CMOS with very thin channel layers (FDSOI), the channel thickness is determined by the physical dimension of the channel structure and no longer by the "Dennard scaling" methods of channel doping levels and S/D extension junction depths. One of the many positive features of fully-depleted channels is that the channel region can be un-doped, where the transistor threshold voltage is set by the channel thickness and gate electrode work function. This removes issues related to random statistical threshold variations and removes carrier scattering limits on carrier mobility.

Even in this new regime of fully-depleted channels, some core concepts of Dennard scaling still remain. For both finFETs and FDSOI transistors, the channel thickness continues to be reduced with each new device generation, with the actual dimensions closely following the late-1990's ITRS Roadmap projections for planar S/D extension junction depths (See Fig. 5 below). The average gate lengths for recent finFET are approaching 10 nm, well shorter than the practical limits, ≈30 nm, for advanced bulk planar CMOS devices [23] [25].

The vertical orientation of dense arrays of finFET channels limits the angle of incidence of ion beams to near-vertical directions for doping of S/D regions, leading to innovations in the beam focusing and the exploration of alternative techniques such as plasma immersion and recoil implant doping from thin dopant-rich surface films [24].

In contrast to amorphous regions created by high-dose implants in planar CMOS S/D junctions, re-crystallization of amorphous fin structures is limited by the small area of crystalline Si "seed" at the bottom of the implanted fins and by pinning of the crystal regrowth front at the fin side surfaces. The result is a highly defective crystal structure in annealed fins, which leads to increases carrier scattering and recombination in the S/D junction, limiting channel drive currents [24].

In planar CMOS S/D implants, junction leakage could be reduced by increasing damage accumulation rates by implantation with "cryo" wafer temperatures where improved finFET electrical performance can be achieved by reducing damage accumulation to a level below the formation of fully-amorphous fin volumes. This can be done by raising the wafer temperature during implant to 300 to 500 C [26].

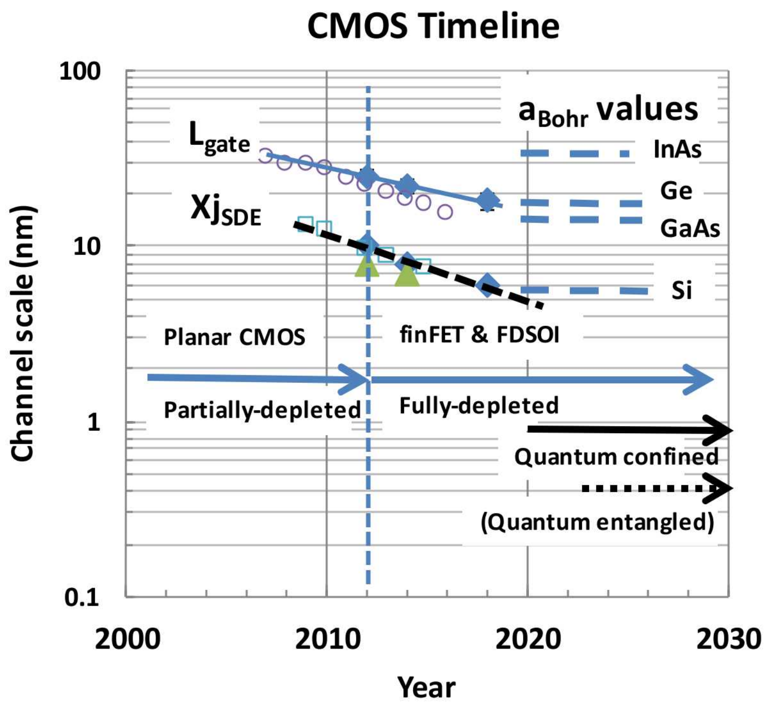

Figure 5: Dimensions for gate length and channel thickness for fully-depleted CMOS transistors for Intel finFETs and planar FDSOI for 22, 14 and 10 nm "nodes". Also shown are the projections for gate length (Lgate) and S/D extension junction depths (XjSDE) for planar bulk CMOS from the ITRS-2009 edition, the exciton radii (aBohr) for Si, GaAs, Ge, InAs and the channel character for various time periods.

A fundamental limit to the scaling of fin thickness, independent of the doping method, is the effects of quantum confinement on the semiconductor density of states. When the physical size of a 2D (fin), 1D (wire) or 0D (dot) semiconductor material becomes small enough so that the fundamental nature of the band structure is altered by interaction with the confined dimension walls, i.e. quantum confined, the density of states for electrons and holes is sharply reduced, reducing the carrier conduction in the material. A figure of merit for the onset of quantum confinement effects is a material dimension less than the radius of the orbital size of an electron orbiting around a hole location (an exciton), which is referred to as the "Bohr radius" because of the analogy to Hydrogenic states (see the Bohr radii of excitons in Si, GaAs, Ge and InAs in Fig. 5).

The onset of the quantum confinement regime for Si is ≈5 nm. Fully-depleted thicknesses for finFETs and FDSOI channels are already close to this value. If finFET and FDSOI channels are scaled to ≈3 nm, deep into the quantum confined regime for 2D Si structures, the sharp reduction in the density of states for both holes and electrons will result in significantly reduced carrier conduction than what would be expected from 3D (bulk) conditions.

Much discussion and study has been devoted to replacing Si as a fin channel material with semiconductors with higher carrier mobility, such as Ge and InGaAs, etc. However, many of these candidates for Si replacement have much larger exciton radii (see Fig. 5 for examples). So for example, replacing Si with InGaAs in nMOS finFETs at the same dimensions as present-day Si (≈7 nm) would result in carrier mobility at far lower levels than would be expected based on bulk characteristics. Similar concerns for quantum confinement effects exist for the higher degree of confinement for 1D structures, such as nano-wires, where quantum confinement effects occur at similar and larger dimensions [27]. This is yet another “red brick” wall confronting the ongoing efforts to continue the CMOS transistor scaling progression begun over a half century ago.

4.2.4. Ion implantation for quantum confined and quantum entangled devices.

Looking ahead to the near (5 years) future, one major challenge for the use of ion beam processing of nm-scale structures will center on delivery of energetic species, dopants and other atoms, at energies of ≈100 eV. Commercial ion implantation systems have been capable of delivering dopant ions at 200 eV since the mid-1990’s. However, the shift to 100 eV, approximately at the boundary between implantation and deposition (and overlapping on many etching processes), is a new regime for machine design and operation. The implementation of the precise control of dose and penetration depth, hallmarks of ion implantation for many years, to penetration depths of a few nm will encourage the development of new machine technologies and processes.

Energetic neutral beams.

Delivering 100 eV ions to surfaces with tightly controlled incidence angle, energy and dose is challenged by the difficulties in maintaining space charge balance and controlling beam divergence for these slowly moving ions [28]. One approach is to replace low-energy ions with energetic neutrals, an approach already used in commercial etch tools [29]. Controlled flux of energetic neutral atoms can be provided by combining a pulsed plasma volume and a separately pulsed extraction plate, which is perforated for many high-aspect ratio channels above a grounded wafer (Fig. 6). The energetic ions, which are extracted by the grid potential from the plasma boundary, are neutralized by pick up of electrons during grazing angle collisions with walls of the grid channels. Similar to plasma-immersion ion implanters (PIII) used for low-energy, high-dose doping, by controlling the pulsed grid voltage, one can deliver energetic neutrals to a wafer surface for implantation (at energies somewhat above ≈100 eV), deposition (at energies at and below ≈100 eV) and etching/oxidation (with the use of reactive species). Additional reactivity could be supplied by optical excitation of the neutral atom flow with scanned laser beams at selected photon energies.

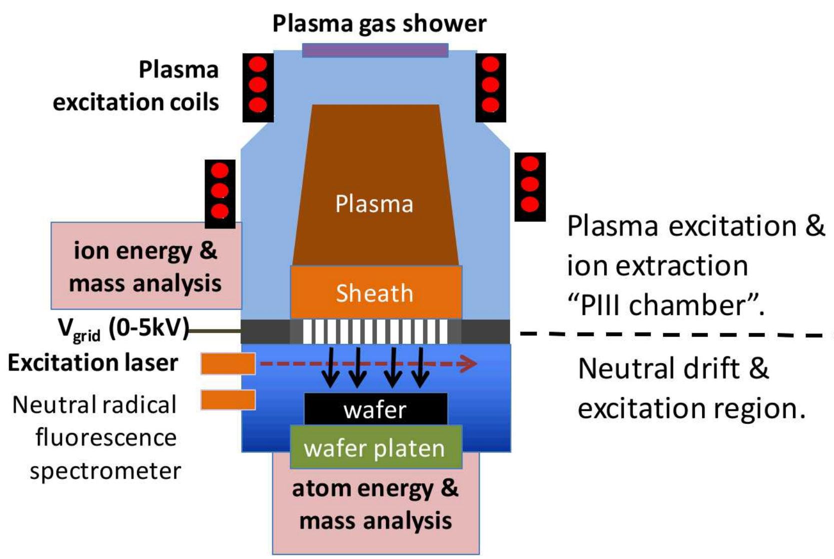

Figure 6: Schematic diagram of a pulsed plasma source and biased grid containing many high-aspect ratio channels providing a controlled flux of energetic neutrals on a wafer surface. Also shown are a variety of process analysis and neutral atom excitation tools that could be useful in such a process tool for neutral beam implantation, deposition, oxidation and etching.

Single atom channels and quantum entangled devices.

Early experiments with "single-shot" ion implanters demonstrated the improvements in control of device properties, such as threshold voltage, with the use of carefully placed arrays of dopant atoms over a random distribution of dopant locations from a typical ion beam [30]. Recently, 3D arrays of single dopant atoms, constructed by manually opening of bonding sites on H-passivated Si surfaces with an STM tip and controlled epitaxial Si growth, have demonstrated MOS transistors with single-atom channel doping, low-resistivity monolayer lines and many properties required for construction and operation of quantum-entangled computers [31].

Bringing these advances to bear on larger-scale quantum computers and other entangled devices requires a high throughput single-atom delivery system with atomic resolution on the atom placement and dose. Multiple approaches are under development for sustained targeting of single and controlled small numbers of atoms into near-atomic resolution targets, referred to as "deterministic doping" [32]. One approach is to count the passage of single ions "on the fly" and use fast ion deflection and precision target stage motion to direct single and countably small numbers of ions to specific target locations (e.g., See Fig. 7) [33]. High throughput, commercial single-ion delivery systems will certainly follow in the coming decade as quantum entangled devices enter wide use for computation, encryption, data storage and other applications.

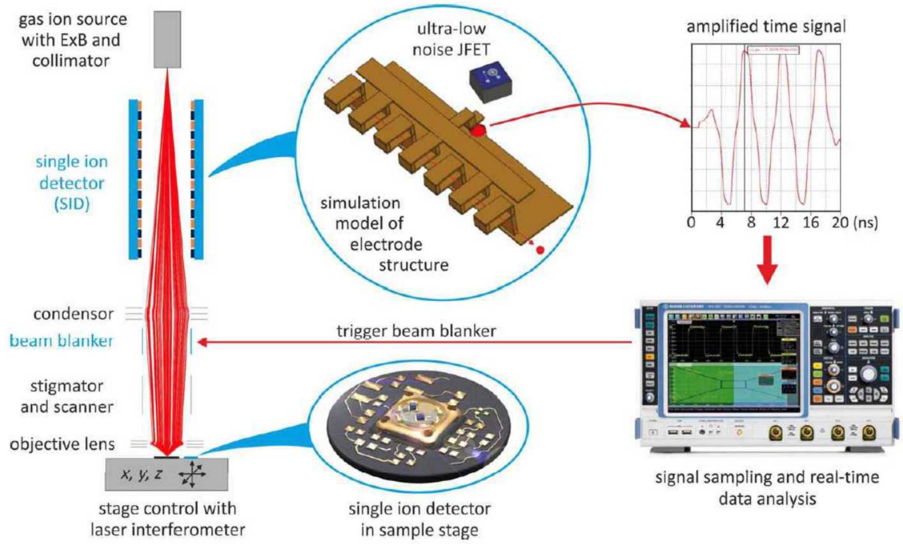

Figure 7: Components of a multi-shot, single ion implanter with atomic resolution placement using an in-flight ion sensor and controlled target location stage [33].

4.2.5. Summary

Ion implantation, first used for commercial IC fabrication in the early 1970's has evolved into the dominant means of doping semiconductor devices for digital electronics, power switches, optical sensors, large-area displays and is just now entering the world of high-throughput doping of high-efficiency PV cells. In the IC device area, doping applications for CMOS transistors have now been joined by an even larger number of non-dopant, "materials modification" implant steps, accounting for a total of 50 to 80 passes through some form of implant tool for each completed advanced IC device. Requirements for ion and neutral beam processing of nm-scale materials and devices are driving development of new accelerator technologies for new applications using quantum-determined properties.

4.3 Update to Ion Beam Analysis

Chris Jeynes, University of Surrey, Guildford, UK

The *RAST-4* article's abstract's last two words were "analytical power": such power must be based on quantifiability, and there have been some notable advances since our *RAST* article was published related to what we could call the metrological properties of IBA, that is, the strength of IBA in quantification. Recognition of these advances caused the last IBA Conference to introduce a new session "Quantitation and Total-IBA".

Specifically, an unprecedentedly high accuracy (standard combined uncertainty of 1%) was demonstrated in an interlaboratory comparison (Surrey, Lisbon, Budapest) for determining "Quantity of Material" (atoms/cm^2) in a particular case, published in Analytical Chemistry [34]. This paper also contains a rigorous treatment of RBS, including careful discussion of second- and third-order effects. Of course, this was not new, but the presentation was designed to show the full traceability of the technique to the metrologists.

In fact, the Anal. Chem. 2012 paper [34] was not fully-traceable, since it was based on knowledge of the stopping power. There was good reason to suspect that the stopping power used was accurate (based on the IAEA IBA software Inter-comparison summary of 2008 [35]), but this was not established unequivocally until 2014 [36]. A full treatment of this method, together with an application to the Surrey Quality Assurance program for the qualification of our ion implanters, was published in the Analyst in 2015 [37]. This paper was based on two accompanying technical papers, one in Nuclear Instruments and Methods B (NIMB) [38] showing that non-Rutherford elastic scattering resonances can be used to determine the beam energy (at much higher accuracy than is usual for RBS). The other paper in Analytical Methods [39] establishing that the spectrometer gain can also be established with an order of magnitude better accuracy than is common in RBS.

These metrological details have allowed us to obtain an accreditation as a Calibration Laboratory under ISO 17025: this is the world-first such accreditation for RBS. Charles Evans is accredited as a Test Laboratory. Moreover, the accredited reference-free absolute accuracy is significantly better than is possible with the standard commensurate techniques: XRF and XPS can be used very precisely, but rely on reference materials for accuracy. The accuracy of XRF (including EPMA) is limited to ~5% by the relatively poor knowledge of the X-ray spectrometry "Fundamental Parameters" (FP); that of XPS is limited to ~10% by inability to calculate the EMFP (electron mean free path) more accurately from first principles.

A full technical summary was published in NIMB [40] pointing out that from a metrological point of view RBS can now be counted as a new and powerful Primary Reference Method; a wide-ranging (invited) "Tutorial Review" for the chemists was published in Analyst [41]. PTB (the German National Metrology Institute) is about to submit a paper to Journal of Atomic Analytical Spectroscopy. reporting XRF ionization probabilities for Ga at unprecedented accuracy using a reference certified by accurate RBS.

There is growing excitement in this new capability for the metrologists. There is a BIPM/CCQM-sponsored Pilot Study, P-190 for the certification of hafnia thin films, where it turns out that the absolute independent traceability for Quantity of Material is provided only by RBS. A similar absolute traceability of the linear film thickness at high accuracy is provided only by MEIS, albeit used in a novel way pioneered by the Brazilians [42]. Industrial metrologists are using WD-XRF to provide comparable certified materials. Clearly, there are a substantial number of applications of this advance in quantitation, which we have not even started to tap.

This new capability includes the ability of Total-IBA methods to inherit the accuracy of RBS. Geoff Grime and Elspeth Garman have used this inheritability since 1995 (and before) to quantify PIXE in the reliable determination of the metal content of proteins [43] [44]. The new routine PIXE/RBS methods may be very useful to improve the accuracy of the (very large) protein database in current use. These methods are described in one of the Case Studies published by the IAEA [45]; also see 2016 Tutorial Review [40].

Just as XRF can use standards certified by RBS to increase accuracy, so can PIXE, EBS, NRA etc. We have not really seen the IBA community make great use of this heritability as yet, perhaps partly due to the difficulty of using the only software currently available that allows exploitation of the synergy between PIXE and RBS/EBS (DataFurnace) [46] [47]. But, the Brazilians [42] look as though they are about to change this with their extension of SIMNRA into "MultiSIMNRA". Tiago Silva gave the invited talk in the Quantification and Total-IBA session in Shanghai [42], describing this new code to exploit synergy. But as yet, MultiSIMNRA does not handle PIXE.

If the IBA community can continue to concentrate on metrology, we can start making larger contributions in the analytical chemistry community, leading to new IBA laboratories. The current position is that the number of IBA laboratories is decreasing as the older IBA methods are increasingly viewed as having had their heyday in the 1980s, but now look very outdated. XRF had a huge boost with the very substantial international investment in light sources, but XRF needs IBA to back it up, as the new developments have made very clear!

There are not many Primary Reference Methods, but RBS is a new one together with Total-IBA, through the heritability of accuracy in synergistic methods.

4.4 Update to Review of Cyclotrons for the Production of Radioactive Isotopes for Medical and Industrial Applications

Paul Schmor, TRIUMF emeritus and owner of Schmor Particle Accelerators Consulting, Inc.

Radioactive Isotopes are used in a wide range of medical, biological, environmental and industrial applications. Cyclotrons are the primary tool for producing the shorter-lived, proton-rich, radioisotopes. Commercial suppliers of cyclotrons are responding by providing a wider range of cyclotrons in the energy range of 3 to 70 MeV for the differing needs of the various applications. Various low energy superconducting compact cyclotrons are in design, fabrication, and operation. It has been demonstrated that low energy cyclotrons can replace nuclear reactors in the production of ^{99m}Tc. This update of the 2018 review paper outlines some recent advances. [48]

4.4.1. Medical & Industrial Cyclotrons

The rapid worldwide increase in isotope producing cyclotrons continues. In 2006, the IAEA estimated that there were worldwide about 350 cyclotrons that were primarily used in the production of radionuclides. The 2008 IAEA cyclotron directory indicates that over 600 compact medical cyclotrons have been installed. [49] [50] Recent estimates claim that over 950 compact medical cyclotrons and as many as 1093 cyclotrons are in operation worldwide [51]. Many of the larger fabricators now supply complete medical isotope production and diagnostic equipment with their installations. The majority of these 950 compact medical cyclotrons are producing isotopes for PET and SPECT applications. Fabricators and designers are responding to an anticipated new market by introducing a variety of low energy compact superconducting cyclotrons.

4.4.1.1. Superconducting Cyclotrons

Advanced Biomarker Technologies, has installed its cyclotron system with isotope on demand in over 20 locations worldwide. Their BG-75 self-shielded mini-cyclotron provides a total of 5 µA of 7.5 MeV protons to three internal targets for the production of ^{18}F. [52]

AMIT (Advanced Molecular Imaging Technologies) is a collaboration of 10 companies and 14 research labs, led by CIEMAT in Madrid, Spain. They are developing an 8.5 MeV superconducting cyclotron with currents >10µA. It is designed for onsite production of single dose quantities of ^{11}C and ^{18}F. The cyclotron has a central magnetic field of 4T and uses a warm iron pole. [53] [54]

VECC in India has explored the design of an ultra-light superconducting cyclotron. Their cyclotron design does not use steel poles and yokes. The result is a proton cyclotron capable of accelerating H- ions to 25 MeV in an average magnetic field less than 1.7 T and weighing less than 2,000 kg. [55]

IONETEX has installed and commissioned a prototype 12.5 MeV 25 µA superconducting cyclotron at the University of Michigan aimed at producing ^{13}N for PET cardiology applications. The cyclotron uses cold steel with a central field of 4.5 T. The cyclotron has an internal cold-cathode proton ion source as well as a movable internal target. [56]

Smirnov and his team at JINR have designed a 14 MeV compact superconducting cyclotron for producing ^{18}F and ^{13}N isotopes. Their calculations suggest that the current will exceed 500 μA. This design uses an external H- ion source, room temperature steel poles and yoke, an average magnetic field around 3.5 T, and extraction by stripping the H- to H+. [57]

ISOTRACE is a 12 MeV superconducting cyclotron designed for currents up to 50 μA and manufactured by PMB-ALCEN. The cyclotron uses an external H- ion source, a Helium free persistent magnet, a magnetic field of 2.35 T and has four ports for targets. [58]

4.4.1.2. Conventional Low Energy Cyclotrons

IBA has introduced a new cyclotron named the Cyclone Kiube for radioisotope production. Three options are available for accelerating H- from either one of two internal ion sources to 18 MeV, namely, 100 μA, 150 μA or 180 μA. A self-shielding option is available for the two higher current machines. A maximum of eight targets may be placed around the vacuum chamber for isotope production. The design is similar to their 18/9 dual particle Cyclone without the deuteron option [59] [60] [61].

GENTrace is a recent self-shielded 7.8 MeV cyclotron fabricated by GE Healthcare for the production of ^{11}C and ^{18}F [62].

Siemens, the fabricator of the Eclipse product line, has stopped production of their 11 MeV cyclotrons.

4.4.2. Radioisotopes for Medical Diagnostics

Technetium-99m (^{99m}Tc) is widely used around the world. Technetium-99m is used in more than 20 million diagnostic nuclear medical procedures every year. Approximately 85% of diagnostic imaging procedures in nuclear medicine use ^{99m}Tc as a radioactive tracer for imaging and functional studies of the brain, myocardium, thyroid, lungs, liver, gallbladder, kidneys, skeleton, blood, and tumors. Approximately two thirds of the world's supply of ^{99m}Tc is produced by two aging nuclear reactors. The AECL-NRU reactor in Canada is scheduled to be shut down in 2018. It produces nearly one third of the world's supply. Shortages are anticipated and alternative production techniques are being explored. A number of experiments have demonstrated that PET cyclotrons can be used to produce ^{99m}Tc directly using ^{100}Mo targets. The optimum energy is less than 30 MeV. [51]

The use of ^{11}C for clinical medical imaging is currently limited because of the 20 minute half-life, which implies that the production must be done on-site. It is believed that the medical use of ^{11}C would dramatically increase if low cost compact cyclotrons providing low-energy protons were available. Industry and cyclotron designers are responding with a variety of small low cost superconducting cyclotrons in the 8 to 10 MeV range. When coupled with a target system capable of providing on-demand ^{11}C, it is anticipated the system would be widely used.

4.5 Update to Development of Accelerator Mass Spectrometry and Its Applications

Mark Roberts, NOSAMS - Woods Hole Oceanographic Institute

Since the comprehensive review of Accelerator Mass Spectrometry (AMS) and its applications in *RAST* [63], the trend in AMS towards smaller systems has continued. Commercially, Ionplus (Zurich, Switzerland), National Electrostatics Corporation (NEC, Middleton, Wisconsin, USA), and High Voltage Engineering Europa (HVEE, Amersfoort, Netherlands) all now offer compact AMS systems. These systems work well for ^{14}C while providing acceptable performance for a subset of other radionuclides commonly measured by AMS. To varying degrees, the manufacturers also now offer automated ^{14}C graphitization and gas interface systems. Such systems allow for a high degree of automation.

A growing trend in ^{14}C AMS is the use of CO_2 accepting ion sources. Gas ion sources are of interest because they eliminate the graphitization step, saving time and labor in the sample preparation process. Gas sources typically do not provide the comparable accuracy and precision of graphite sources, but recent efforts at optimizing operating conditions have narrowed the gap [64] .The prospect of time-savings, improved precision, and analytical flexibility makes the further development and increased use of gas ion sources likely.

Lasers seem to be finding their way into the AMS method. For sputter sources, there is some evidence that tuned laser radiation can be used to enhance ionization efficiency [65]. An efficient ion source is important for sample-limited small mass samples. For carbonates, laser ablation has shown promise for rapid and high-spatial-resolution ^{14}C [66] [67]. Finally, Cavity Ring Down spectroscopy shows promise for non-AMS detection of ^{14}C [68] [69] [70]. However, Cavity Ring Down spectroscopy has not yet been applied to natural samples and is not likely to be commercially available in the near future.

Recently, proof-of-principle measurements were made for radiocarbon positive-ion mass spectrometry (PIMS) [71]. In PIMS, interfering nitrogen and hydrocarbon molecules are eliminated in a charge-exchange cell operating on non-metallic gas. The positive-to-negative ion conversion is the reverse of that conventionally used in AMS and is compatible with positive ion sources (e.g., a plasma or electron cyclotron resonance (ECR) ion source). The low cost and simplicity of a plasma source, as compared to a negative ion cesium sputter source, and the lack of an accelerator, is a distinct advantage for the PIMS method.

A recent development in AMS sample preparation methodology is Ramped Pyrolysis Oxidation (RPO) for ^{14}C analysis. See Figure 8 below. RPO involves the controlled step heating of samples containing organic carbon, with or without oxygen. As heating proceeds, the most reactive organic components become volatile and are swept into an oxidizing reactor by a helium stream, allowing separation of CO_2 from other pyrolysis/combustion components and collection of CO_2 over discrete temperature intervals for analysis of both stable and radiocarbon isotopes. A major advantage is the capability to analyze all the organic matter in a sample, not just an isolated fraction. This capability was initially used to improve the chronologies of Antarctic sediments [72], but has since been applied to a wide variety of biogeochemical questions, including riverine particulate organic carbon transport and deposition [73], soil organic carbon turnover [74], and lacustrine carbon cycling [75]. RPO has also been used to study the fate of petroleum hydrocarbons, both natural and pollutant, in marine and coastal ecosystems [76] [77]. Figure 9 below shows the thermogram of the variation of the ppm of CO_2 versus temperature.

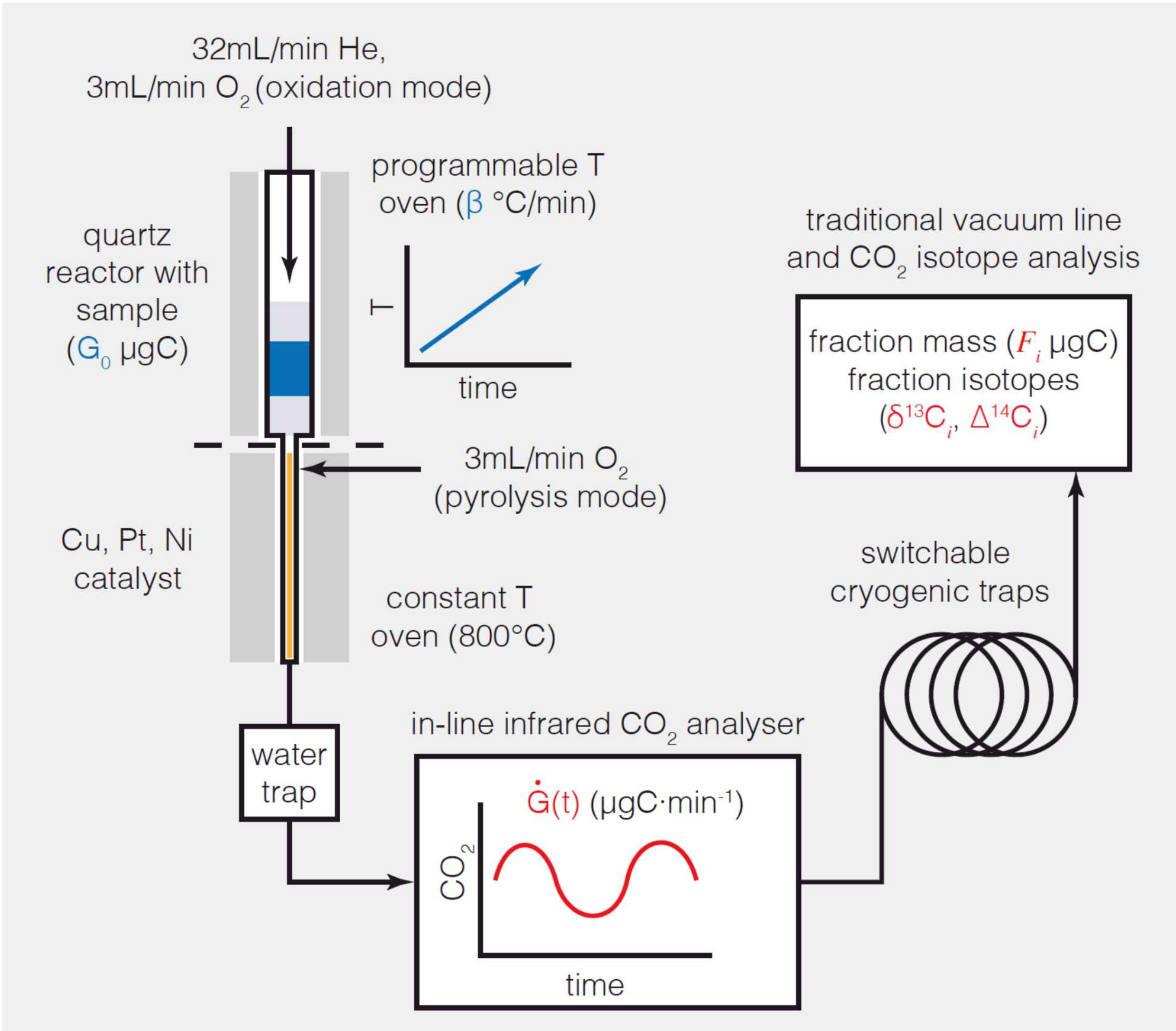

Figure 8: Schematic of the RPO reactor (above) and the results (below) from a particulate organic carbon sample collected from the Narayani River, Nepal [78]. The top half of the quartz reactor heats the sample, while the gases are swept into a CO_2 analyzer before passing through a cryogenic trap.

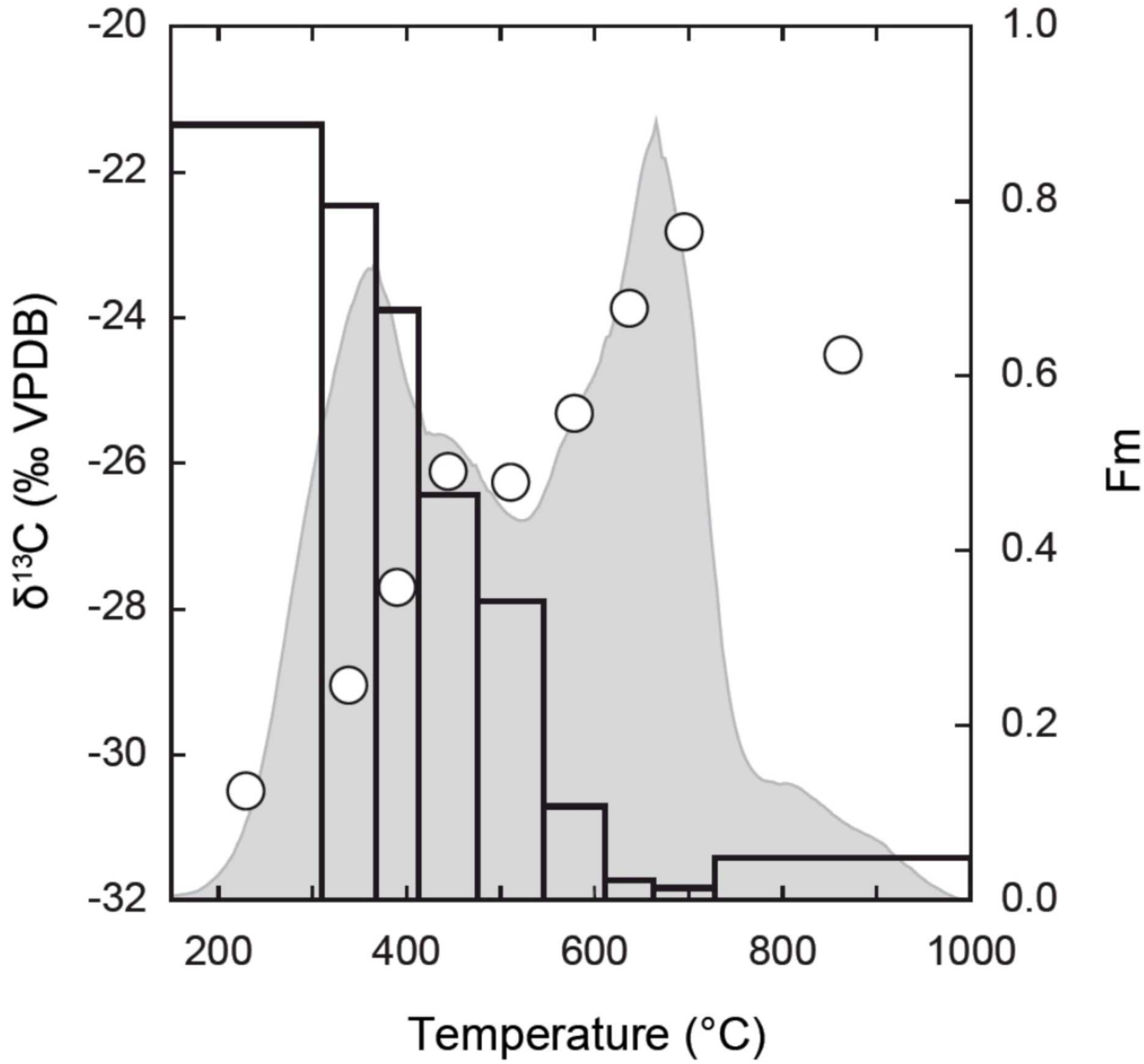

Figure 9: The gray shaded region is the thermogram, the variation in ppm CO_2 versus temperature (units not shown), white circles show the ^{13}C values, and bars show the fraction modern values for each temperature interval. The data show that the higher temperature, more refractory, fractions have dramatically less ^{14}C (i.e. are older) than the lower temperature fractions.

4.6 Update to Electron Accelerators for Environmental Protection

Andrzej G. Chmielewski, Bumsoo Han - Institute of Nuclear Chemistry and Technology, Warsaw, Poland

Parts taken from “Electron Beam Technology for Environmental Pollution Control”, Andrzej G. Chmielewski, Bumsoo Han, Top. Curr. Chem. (Z) (2016) 374:68.

Worldwide, there are over 1700 electron beam (EB) units in commercial use, providing an estimated added value to numerous products, amounting to 100 billion USD or more [79]. High-current electron accelerators are used in diverse industries to enhance the physical and chemical properties of materials and to reduce undesirable contaminants such as pathogens, toxic byproducts, or emissions. Over the past few decades, EB technologies have been developed aimed at ensuring the safety of gaseous and liquid effluents discharged to the environment. It has been demonstrated that EB technologies for flue gas treatment (SO_x and NO_x removal), wastewater purification, and sludge hygienization can be effectively deployed to mitigate environmental degradation. Recently, extensive work has been carried out on the use of EB for environmental remediation, which also includes the removal of emerging contaminants such as volatile organic hydrocarbons VOCs, endocrine disrupting chemicals (EDCs), and potential EDCs [14].

Rapid population growth combined with industrialization, urbanization, and energy-intensive lifestyles has resulted in severe problems in the environment, especially in large cities. In many countries where industry is concentrated in urban areas, severe air- and water-pollution problems have arisen in most of the large cities. Therefore, pollution control has become an important subject in the field of environmental engineering [80]. EB processing of off-gas, wastewater, and sludge is a non-chemical and additive free process that uses the short-lived reactive species formed during the radiolysis of the EB process for efficient decomposition of the pollutants. Such reactive radicals are strongly oxidizing or reducing agents that can transform the pollutants in the wastes from the industries and different origins. Thousands of electron accelerators based on different principles have been constructed and used in the field of radiation chemistry and radiation processing.

The progress in accelerator technology means not only a growing number of units, but also lower cost, higher dose rate, more compact size suitable to the production line, beam shaped adequately to the process, reliability, and other parameters that are important in radiation processing applications. At present, EB technology for environmental pollution control has not found wide application and is used much less often than conventional methods. However, in recent years pilot plants and industrial scale studies have shown that EB treatment could occupy an important place in the future. Currently, EB treatment in combination with conventional methods has been shown to provide noticeable reductions in the amount of time, area, and power needed for environmental pollution control. Continuous emphasis on ecological standards will be an additional motivation for the elaboration and industrial application of EB treatments. Propagation of EB treatments can improve environmental protection and provide essential support in industrial development.

4.7 Radiation Damage in Structural Materials by Using Ion Accelerators

Khalid Hattar – Sandia National Laboratories, Albuquerque, NM

Over the last two decades, we have seen a trend of ion accelerators transitioning from being a tool of the particle physicist to a tool of the materials scientist. This trend started at the lowest of energies and has continuously worked its way up in energy during this time-period. This can best be seen starting with the Focused Ion Beams (FIB). [81]

However, it has expanded to helium ion microscopes, plasma FIBs, ion implanters, and now into medium energy linear accelerators. This transition has many advantages, as many accelerators are finding new life simulating various radiation environments (nuclear reactors, outer space, medical treatment and applications, etc.). These advantages include the incorporation of low energy accelerators in dual and triple beam FIB systems with a number of other characterization tools. Similarly, in the middle energy regime, there has been a consolidation of the accelerator facilities around the US and to a lesser extent in the world. These facilities that are willing and able to push the limits of producing new and novel far-from-equilibrium materials with unique applications in fields ranging from nano-photonics to the ubiquitous sliding electrical contacts. [82] [83].

The above applications are advanced by the combination of multiple accelerators into a single end station and the addition of various end station environments and in-situ testing capabilities, which is highlighted in the references that follow. As such, ion beam facilities have a bright future as a materials science tool set to advance the functionality of far-from-equilibrium materials and assist in lifetime predictions of materials exposed to radiation environments. Convenient sites to read about progress made over the past few years in this area are the proceedings and abstract books for the Workshop On TEM With In Situ Irradiation [84] [85]. The website for the next workshop in this series can be found at in Reference [86].

4.8 Update to Recent Developments on DC Accelerators for Industry

Harry J. Whitlow[a] and Ragnar Hellborg[b]

[a] *Louisiana Accelerator Center and Department of Physics, University of Louisiana at Lafayette, Lafayette LA 70504, USA*
[b] *Department of Physics, Lund University, Box 118, SE 221 00 Lund, Sweden*

Over the past 5 years or so many nanotechnological products are reaching the industrial production phase. This has led to a fundamental change in the nature of industry to become more flexible and knowledge based. Today even development of new nanotechnological methods for specific small-scale production is evolving into a knowledge-based industry. Objects interact with the environment through the surface. It follows that modifying the surface modifies the property of the material. This has been used to enhance the corrosion resistance of aluminium alloys, titanium and stainless steels as well as modifying the hydrophobicity of glass and sapphire, which is important for anti-fogging windows and other optical applications. Low energy ion bombardment accelerators based on Electron Cyclotron Resonance (ECR) ion sources at GANIL were developed for this purpose by Quertec (recently acquired by the Belgian company Ionics [87]). The accelerating voltage is a few 10s of keV. The technology is being improved by Ionics who are piloting an industrial scale plant [88]. Even where a traditional thin film coating must be used, ion beam irradiation is beneficial to form a graded junction by ion beam mixing. A good example of this is the CrN super-slip coating [89] produced by sputtering followed by ion irradiation to form a graded interface by ion implantation. Injection moulding screws coated with this process show superior release and wear properties. Ion implantation doping has long been a major driving force in development of industrial ion implantation accelerators. Moore's law has proved to hold true for over 50 years. At the time of writing the 5-10 nm node is emerging, using e.g. FinFET technology. Ultra-low energy (30 keV) high fluence (10^{19} ions cm^{-2}) ion implantation is used to reduce contact resistance [90]. This can be achieved using plasma immersion ion implantation where ions are implanted from a plasma by biasing the work piece. The PULSEION® tool [91] is a commercial tool to 3D conformably implant whole wafers.

There is much current debate and activity around smart factories, where intercommunication via the internet of materials and use of cloud computing to facilitate flexible manufacturing, e.g. Platform Industry 4.0 [92]. It is remarkable that the major accelerator manufacturers already offer computer control systems that perform functions such as sample/work-piece change, process end-point detection as well as monitoring and control of subsystems (e.g. ion source, high voltage, vacuum) which makes them inherently compatible as flexible processing tools for highly customized products.

Although in their early life, ion accelerators in the form of Calutrons were handling many kg of toxic ^{nat}U feedstock material. Today compared to chemical- and physical vapour deposition (CVD and PVD) or chemical bath processes (cyanide bath case-hardening), only tiny (g) amounts of toxic materials like Cr and As are needed. Often the feedstock materials can be H_2, He, C, N_2, O_2, Ar etc. which are not toxic at all. This low toxic load on the environment makes accelerator-based technology attractive. Moreover, compared to the accelerators of the 1960s and 70s, which produced considerable X-ray radiation, the development of modern accelerator tubes has advanced so that today's accelerators can be operated in a normal factory or laboratory environment with little, or no need for radiation shielding. Taken as a whole, accelerators mainly consume electrical energy (that can be produced by renewable sources). Making accelerator-based technology extremely green compared to other production processes. This is advantageous compared to other production technologies (chemical treatment, PVD, CVD) not only from the customer viewpoint but also economically, because of low feedstock cost, lower compliance costs from e.g. the EU REACH [93], and US EPA Toxic

Substances Control regulations [94] as well as lower clean-up costs when production ceases.

MeV ion microprobes have considerable promise for flexible manufacture as well as industrial production development of pharmaceutical and biomedical devices. This development has been hampered by the lack of ion source brilliance (That is the current of ions emitted per unit area per steradian and volt.) from currently available ion sources. This restricts the attainable current that can be focused into a small spot. An intriguing possibility is to use a micro-machined cold cathode ion source [95] where an electron gun is used as an injector. This achieved brightness of up to 800 A/(m^2srV) which is some 40 times that of a rf positive ion source. Multicusp ion sources are capable of producing extremely high currents but the large aperture usually used limits ion source pressure and hence plasma density. By using a small aperture, the high current can be traded-off for high brightness (1000 A/m^2srV) source can be realized [96].

4.9 Update to Rhodotron Multiple-Pass Radial Electric Field Accelerators

Marshall R. Cleland, IBA Industrial, Inc.

A Rhodotron^{TM} is an electron accelerator, which recirculates an electron beam in successive passes through a single coaxial resonant cavity in the VHF frequency range. The electrons gain from 0.8 to 1.2 MeV of energy per pass through the cavity. Higher energies up to 10 MeV are produced by multiple passes through the same cavity. Different versions of these accelerators are designed with 6, 10 or 12 passes.

IBA is now offering RF Rhodotron accelerators with on-time RF and beam pulse modulation to reduce the average beam power. This technique maintains the high RF power efficiency of a continuous wave Rhodotron accelerator by allowing the instantaneous RF and beam power ratings to be the same as with a continuous wave system, but it reduces the average RF and beam power ratings. This is analogous to the pulse modulating technique, that is used with most microwave linear accelerators (linacs). The main differences between a pulse modulated Rhodotron accelerator and a microwave linac is the much lower resonant frequency (about 10^2 MHz) in a large Rhodotron accelerator resonant cavity and the much longer beam pulse of a Rhodotron accelerator system in comparison to a linac.

There are now two modes with which the Rhodotron accelerator can be operated: the continuous or pulsed wave modes.

4.9.1 Continuous Wave Mode

The large 2 m in diameter size of a Rhodotron accelerator cavity, its high Q factor of 50,000, and the low energy gain of 1 MeV per pass allow the cavity to be energized in a continuous wave (cw) mode. This produces an average beam current that is bunched at the resonant frequency. The absence of macrobunching reduces the peak beam current, in comparison with an ILU RF accelerator or a microwave linear accelerator. The very short time interval of about 9 ns between beam bunches allows the beam to be scanned with variable frequencies up to 200 Hz without producing gaps on a moving product conveyor.

Several models of these accelerators with different electron energy and beam power ratings are made by selecting the appropriate number of passes and the power of the RF amplifier. The basic ten-pass electron beam model provides electron energies up to 10 MeV with beam powers from 40 to 200 kW [97] . The six-pass models are intended for high-power X-ray processing of materials. They are available with maximum electron beam power ratings of 200, 450 and 700kW at 7.0MeV [98] .

Electron energies above 7.5MeV are not used in the X-ray mode, to avoid causing nuclear reactions in the X-ray target, which is made of tantalum. The main isotope of tantalum, ^{181}Ta, has a photon-neutron threshold energy of 7.6MeV. Tungsten should not be used for an X-ray target above 6.0MeV, because one of its isotopes, ^{183}W, has a threshold energy of 6.2 MeV. A gold target could be used up to 8.0 MeV, because the only isotope, ^{197}Au, has a threshold energy of 8.1 MeV. High-power X-ray generators are now economically competitive with industrial gamma-ray facilities containing several megacuries of ^{60}Co [99].

Rhodotron accelerators can provide lower beam energies by turning off one of the dipole magnets so that the beam is not deflected back into the cavity. Many

Rhodotron accelerator facilities are equipped with two beam lines, one at 5 MeV and another at 10 MeV. One facility has three beam lines: two for X-rays at 5.0 and 7.0 MeV, and one for electrons at 10 MeV.

4.9.2 Pulsed Wave Mode

For applications that do not require the high beam power of a continuous wave system, the average beam current and beam power can be reduced by operating a Rhodotron accelerator in the pulsed wave mode. This would be analogous to the operation of a microwave linear accelerator (linac). Pulsing the radio-frequency power as well as the beam power maintains the relatively high electrical efficiency of a Rhodotron accelerator as the average beam power is reduced. A variety of pulsed wave as well as continuous wave Rhodotron accelerators for a wide range of beam power systems are listed in Table 1 along with many of their specifications.

In addition to these products, the pulsed wave mode allows for higher energies per pass, which has enabled operation of 12 pass Rhodotron accelerators with electron energies up to 40 MeV. These systems are of interest in the production of ^{99}Mo as a relatively long-lived radioactive source to produce ^{99m}Tc for medical diagnostic applications.

	TT 50	**TT 100**	**TT 200**	**TT 300**	**TT 1000**
Energy	2 to 10 MeV	2.5 to 10MeV	2 to 10 MeV	2 to 10 MeV	2 to 7 MeV
Maximum Power at Maximum Energy	20 kW	40 kW	100 kW	245 kW	560 kW
Maximum Current	2mA	4 mA	10 mA	35 mA	80 mA
Diameter	1.3 m	1.6 m	3 m	3 m	3 m*
Height	1.6 m to 2.4m	1.7 m	2.4 m	2.4 m	2.4 m
MeV/Pass	0.8 to 1	0.833	1	1	1.166
Number of Passes	10	12	10	10	6
Modular Design	No	Yes	Yes	Yes	Yes
Beam Profile	Pulsed	CW	Pulsed or CW	Pulsed or CW	Pulsed or CW

Table 1. Specifications of Pulsed Wave and Continuous Mode Rhodotron Accelerators

4.9.3 Conclusions

Both ILU and Rhodotron accelerators are employed extensively for industrial radiation processing applications. (The ILU type electron accelerator is a related accelerator, which is a single-resonator linear accelerator operating in the pulsed regime.) The industrial applications include plastic cross-linking for irradiation of cables, thermo-shrinkable tubes, plastic pipes and fittings for hot water systems, sterilization of medical devices like syringes and tools, producing and sterilizing pharmacological products, sterilizing food containers, food pasteurization, etc. The ILUs have mainly been used for applications that can be done with electron energies below 5.0MeV, while the Rhodotrons are mainly used for energies above 5.0MeV. Because of such differences, these have not been competitive accelerator technologies.

5. Conclusions and Future Prospects

A famous quote from Yogi Berra is*, "It's tough to make predictions, especially about the future"*, and that certainly fits here in trying to forecast how new types of accelerators, just recently or yet to be invented, will find utility in industries.

Before launching into this, we would be remiss not to mention some of the numerous international programs that have summarized the progress in accelerator science and technology, and made their own predictions of future impact. These include, but are not limited to, the DoE Accelerator Stewardship Program [100] , the Illinois Accelerator Research Center IARC [101], and the European EuCARD Applications of Accelerators program [102].

Of the new types of accelerators, two really stand out and are starting to be utilized by industry:

1. Superconducting Linacs & Cyclotrons
   The use of superconductivity will lead to increases in efficiency and size reduction of systems for cancer therapy, and radioisotope and neutron production. [103]
2. Fixed Field Alternating Gradient (FFAG) Cyclotron
   FFAG Cyclotrons are being developed as a neutron source for BNCT, a hadron source for radiotherapy, and for inspecting the contents of cargo containers. FFAGs could even be used as a new type of nuclear reactor called an energy amplifier. The Electron Machine with Many Applications (EMMA) was completed at Daresbury Laboratory, UK [104]. This was the first non-scaling FFAG accelerator, which has many advantages because large and heavy magnets are avoided.

Several more have the potential to be developed for industrial applications.

3. Free Electron Lasers (FELs) [105] [106]

FELs offer several excellent performance features that surpass conventional lasers, e.g. high efficiency, power, ultra-short pulses, and wavelength tunability. Future lithographic applications to fabricate integrated circuits would seem to become practical in the future.

4. Terahertz Accelerators [107]
   These are still at a prototype stage. The idea is to use terahertz radiation instead of radio frequencies with the resulting accelerator resonant structures becoming quite small, i.e. centimeters.
5. Laser and Plasma Wakefield Driven Accelerators [108]
   With the laser-driven accelerators, extremely high electric field values up to Teravolts per meter can be realized which are much higher than for conventional accelerators. Again, these systems could provide high energy electrons or ions and still be quite small reducing future costs. The LBNL BELLA-i system with ion acceleration using the BELLA PW laser is now in operation. One of the authors of this article (BLD) recommended to the LBNL staff that the high energy ions from BELLA-i could potentially be used for simulating radiation effects of very high energy cosmic rays, inducing single event effects in microelectronics. This work started last year with the first Sandia device exposed to an ion pulse from BELLA-i [109]

So, it should be quite apparent from this article, that the field of industrial accelerators is growing and quite healthy. There are well-established commercial applications such as:

Electron and Photon Cancer Therapy,
Ion Implantation - Semiconductors and Materials,
Radioisotope Production,
Electron Beam Material Processing,
Electron Beam Materials Irradiators,

in addition to developing commercial applications such as:

Proton and Ion Cancer Therapy,
Neutron Generators,
Non-destructive Testing and Inspection Linacs,

Ion Beam Analysis, and
Synchrotron Radiation.

The annual market for all medical and industrial accelerators described is estimated to now be ~ US$5.0 Billion/year and growing at ~4% per year over the past decade, even during the recession. We have covered just a few examples of advanced accelerators that may play important roles in the area of industrial applications in the future. It will be interesting to watch what happens: miniaturized accelerators to treat cancer? Super radiation hard nano-electronics enabled by laser-accelerator tests that can be used during space travel, or even an ion accelerator that propels the spacecraft itself!

6. References

[1] Reviews of Accelerator Science and Technology,Vol. 4, Accelerator Applications in Industry and the Environment, (2011), Eds. Alexander W. Chao and Weiren Chou. .

[2] R.W. Hamm and M.E. Hamm, Physics Today, June 2011, 46-51.

[3] R.W. Hamm and M.E. Hamm, "Industrial Accelerators and their Applications", World Scientific (2012).

[4] Henning W and Schank C 2010 Acclerators for America's Future (www.acceleratorsamerica.org/files/Report.pdf).

[5] Robert W. Hamm, Industrial Accelerators, Reviews of Accelerator Science and Technology,Vol. 1 (2008) 163–184.

[6] Chernyaev, A. P. and Varzar, S. M. (2014). Particle accelerators in modern world. Physics of Atomic Nuclei,77(10):1203–1215..

[7] R.W. Hamm and M. Current, Private Communication.

[8] Wilhelm Röntgen, "Ueber eine neue Art von Strahlen. Vorläufige Mitteilung", in: Aus den Sitzungsberichten der Würzburger Physik.-medic. Gesellschaft Würzburg, pp. 137–147, 1895.

[9] Crookes, William, "On the illumination of lines of molecular pressure, and the trajectory of molecules". Phil. Trans. 170: 135–164.

[10] J. F. Ziegler, J. P. Biersack, and U. Littmark. In The Stopping and Range of Ions in Matter, volume 1, New York, 1985. Pergamon.

[11] https://www.caari.com/node/16.

[12] https://nucleus.iaea.org/sites/accelerators/Pages/default.aspx.

[13] https://nucleus.iaea.org/sites/accelerators/knowledgerepository/Lists/Codelist/AllItems.aspx.

[14] S. Machi, "Trends for Electron Beam Accelerator Applications in Industry", RAST Vol. 4 (2011) 1-10.

[15] http://ebeam-tamu.org/.

[16] G.E. Moore, "Cramming more components onto integrated circuits", Electronics, 38(8), 1965..

[17] R.H. Dennard, F.H. Gaensslen, H-N. Yu, L. Rideour, E. Bassous, A.R. LeBlanc, “Design of ion-implanted MOSFETs with very small physical dimensions”, IEEE J. Solid-State Circuits, SC-9, (1974), 256-268..

[18] B. Davari, R.H. Dennard, G.G. Shahidi, “CMOS scaling for high performance and low power-the next ten years”, Proc. IEEE, 83(3), (1995) 596-268..

[19] M.I. Current, “Ion implantation of advanced Silicon devices: past, present and future”. Materials Science in Semiconductor Processing, 62 (2016), 13-22.

[20] www.itrs2.net..

[21] L. A. Larson, J.M. Williams, M.I. Current, “Ion implantation for semiconductor doping and materials modification”, Reviews of Accelerator Science and Technology, 4 (2011) 11-40..

[22] M.I. Current, “Ion implantation for fabrication of semiconductor devices and materials”, in “Industrial Accelerators and their Applications”, eds. R. & M. Hamm, World Scientific (2012) pp 9-56..

[23] Y. Tauer, C.H. Wann, D.J. Frank, “”25 nm CMOS design considerations”. IEEE IEDM-1998, (1998) 789-792..

[24] M.I. Current, “New applications for ion implantation: Life in a vertical CMOS world, materials modification, PV cell doping, deep proton implants”, in “Ion Implantation Applications, Science and Technology-2014”, ed. J.F. Ziegler, Ion Implantation Tech.

[25] D. James, Siliconics, private communication..

[26] L.C. Pipes, J. McGill, A. Jahagirdar, “NMOS source-drain extension ion implantation into heated substrates”, Ion Implantation Technology-2014, (2014)..

[27] S. Kyogoku, J-I. Iwata, A. Oshiyama, “Relation between nanomorphology and energy bands of Si nanowires”, Phys. Rev. B87 (2013) 165418..

[28] M.I. Current, “Perspectives in low-energy ion (and neutral) implantation”, Proc. Internl. Workshop on Junction Technology-2017, Uji, Japan, (2107)..

[29] T-C. Kuo, T-L. Shih, Y-H. Su, W-H. Lee, M.I. Current, S. Samukawa, “Neutral beam and ICP etching of HKMG MOS capacitors: Observations and plasma-induced damage model”, J. Appl. Phys. 123 (2018) 161517..

[30] T. Shinada, S. Okamoto, T. Kobayashi, I. Ohdomari, “Enhancing semiconductor device performance using ordered dopant arrays”, Nature 437 (Oct. 20, 2005) 1128-1131..

[31] M. Fuechsle, J.A. Miwa, S. Mahapatra, H. Ray, S. Lee, O. Warschkow, L.C.L. Hollenberg, G. Klimeck, M.Y. Simmons, “A single atom transistor”, Nature Nanotechnology (Feb. 19, 2012) 1-5..

[32] D.N. Jamison, W.L.L. Lawrie, S.G. Robinson, A.M. Jakob, B.C. Johnson, J.C. McCallum, “Deterministic doping”, Materials Science in Semiconductor Processing, 62 (2017) 23-30..

[33] Daniel Spemann, private communication (IOM, Leibniz, 2017)..

[34] C. Jeynes, N. P. Barradas, and E. Szilágyi, Anal. Chem. 2012, 84, 6061−6069.

[35] P. Barradas, K. Arstila, G. Battistig, M. Bianconi,N. Dytlewski, C. Jeynes, E. K´otai, G. Lulli, M. Mayer, E. Rauhala, E. Szil´agyi and M. Thompson,Nucl. Instrum. Methods B 266, 1338 (2008)..

[36] J.L. Colaux, C. Jeynes, High accuracy traceable Rutherford backscattering spectrometry of ion implanted samples, Anal. Methods 6 (2014) 120–129.

[37] Julien L. Colaux, Chris. Jeynes, Keith C. Heasman, Russell M. Gwilliam, Certified ion implantation fluence by high accuracy RBS, Analyst 140 (2015) 3251–3261.

[38] J.L. Colaux, G. Terwagne, C. Jeynes, Nuclear Instruments and Methods in Physics Research B 349 (2015) 173–183.

[39] Julien L. Colaux and Chris Jeynes, Anal. Methods, 2015, 7, 3096.

[40] C. Jeynes, Nuclear Instruments and Methods in Physics Research B 406 (2017) 30–31.

[41] Chris Jeynes and Julien L. Colaux, Analyst, 2016, 141, 5944.

[42] T. F. Silva, C. L. Rodrigues, M. Mayer, M. V. Moro, G. F. Trindade, F. R. Aguirre, N. Added, M. A. Rizzutto and M. H. Tabacniks, MultiSIMNRA: A computational tool for self-consistent ion beam analysis using SIMNRA, Nucl. Instrum. Methods Phys. Res., Sect..

[43] E. Garman, Leaving no element of doubt: analysis of proteins using microPIXE, Struct. Fold. Des., 1999, 7, R291–R299.

[44] E. F. Garman and G. W. Grime, Elemental analysis of proteins by microPIXE, Prog. Biophys. Mol. Biol., 2005, 89, 173–205.

[45] “Protein Structure Determination”: https://nucleus.iaea.org/sites/accelerators/CaseStudies/SitePages/Home.aspx.

[46] N. P. Barradas, C. Jeynes and R. P. Webb, Simulated annealing analysis of Rutherford backscattering data, Appl. Phys. Lett., 1997, 71, 291–293.

[47] N. P. Barradas and C. Jeynes, Advanced physics and algorithms in the IBA DataFurnace, Nucl. Instrum. Methods Phys. Res., Sect. B, 2008, 266, 1875–1879.

[48] Paul Schmor, Review of Cyclotrons for the Production of Radioactive Isotopes for Medical and Industrial Applications, Reviews of Accelerator Science and Technology, Vol 4, (2011), 103-116.

[49] Cyclotron Produced Radionuclides; Principles and Practice, Technical Reports Series No. 465, International Atomic Energy Agency, 2008..

[50] Paul Schaeffer et al, Direct Production of 99mTc via 100Mo(p,2n) on Small Medical Cyclotrons, Physics Procedia 66 (2015), 383-395..

[51] Uno Zetterberg, A Change in usage of Cyclotrons for medical isotope production? (2015) .

[52] Advanced Biomarker Technologies (ABT), http://abtmi.com/en/our-solutions/overview ..

[53] Javier Munilla; Compact Accelerators for Radio Isotope Production: The AMIT Project (2016). (https://indico.cern.ch/event/659942/contributions/2691992/attachments/1525348/2384898/AMIT_ARIES.pdf)..

[54] Pedro Calvo Portela, Compact Accelerators for Radio Isotope Production: The AMIT Project (2017) . (https://indico.cern.ch/event/659942/contributions/2691992/attachments/1525348/2384898/AMIT_ARIES.pdf)..

[55] M. K. Dey et al, Design of Ultra-Light Superconducting Proton Cyclotron for Production Isotopes for Medial Applications, Proceedings of Cyclotrons 2013, pages 447-450, Vancouver, BC, Canada..

[56] J. Vincent et al, The Ionetix ion-12SC Compact Superconducting Cyclotron for Production of Medical Isotopes, Proceedings of Cyclotrons 2016, pages 290-293, Zurich, Switzerland..

[57] Smirnov, Victor et al, Physics of Particles and Nuclei Letters, 2014, Vol. 11, No. 6, pp. 774–787. © Pleiades Publishing, Ltd., (2014). .

[58] ISOTRACE, https://www.pmbalcen.com/sites/pmbalcen.com/files/pdf/datasheet_isotrace__imigine.pdf .

[59] J. B. Nacteral et al, Development of the Cyclone KUUBE: A Compact, High Performance and Self-Shielded Cyclotron for Radioisotope Production, Proceedings of Cyclotrons 2016, pages 238-240, Zurich, Switzerland..

[60] S. Zaremba et al et al, Magnet Design of the new IBA Cyclotron for PET Radioisotope Production, Proceedings of Cyclotrons 2016, pages 170-172, Zurich, Switzerland..

[61] W. Kleeven et al, Extraction System Design for the new IBA Cyclotron for PET Radioisotope Production, Proceedings of Cyclotrons 2016, pages 167-169, Zurich, Switzerland..

[62] General Electric Health Care, GENTrace Cyclotron (http://www3.gehealthcare.com/~/media/downloads/us/product/product-categories/moleculer%20imaging/pet%20radiopharmacy/cyclotrons/gt_cyclotron_system_data_sheet_rev2.pdf?Parent=%7B442067E1-C933-4B8E-8D5B-1.

[63] Jiaer Chen, Zhiyu Guo and Kexin Liu, Reviews of Accelerator Science and Technology Vol. 4 World Scientific Publishing Company (2011) 117–145 ..

[64] Fahrni, S. M., Wacker, L., Synal, H. A., and Szidat S., (2013), Improving a gas ion source for C-14 AMS, Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, 294, 320-327..

[65] Vogel, J. S., (2016), Anion formation in sputter ion sources by neutral resonant ionization, Review of Scientific Instruments, 87(2), 504..

[66] Wacker, L., Münsterer, C., Hattendorf, B., Christl, M., Günther, D., Synal H.-A., (2013b) Direct coupling of a laser ablation cell to an AMS, Nuclear Instruments and Methods in Physics Research B, 294, 287–290..

[67] Welte, C., Wacker, L., Hattendorf, B., Christl, M., Koch, J., Synal, H.-A., and Günther, D., (2016), Novel Laser Ablation Sampling Device for the Rapid Radiocarbon Analysis of Carbonate Samples by Accelerator Mass Spectrometry, Radiocarbon, 58, 419–435..

[68] Galli, I., Bartalini, S., Ballerini, R., Barucci, M., Cancio, P., De Pas, M., Giusfredi, G., Mazzotti, D., Akikusa N., and De Natale P., (2016), Spectroscopic detection of radiocarbon dioxide at parts-perquadrillion sensitivity, Optica, 3(4), 385-388..

[69] McCartt, A. D., Ognibene, T. J., Bench, G., and Turteltaub, K. W., (2016), Quantifying Carbon-14 for Biology Using Cavity Ring-Down Spectroscopy, Analytical Chemistry, 88(17), 8714-8719..

[70] Long, D., Fleisher, A.J., Liu, Q., and Hodges, J.T., (2016), Optical radiocarbon detection of 14C using a quantum cascade laser, in Conference on Lasers and Electro-Optics, OSA Technical Digest..

[71] Freeman, S.P.H.T., Shanks, R.P., Donzel, X., and Gaubert, G., (2015), Radiocarbon positive-ion mass spectrometry, Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, 361, 229-232..

[72] Rosenheim, B. E., M. B. Day, E. Domack, H. Schrum, A. Benthien, and J. M. Hayes (2008), Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment, Geochemistry Geophysics Geosystems, 9, Q04005..

[73] Bianchi, T. S.,et. al (2015), Paleoreconstruction of organic carbon inputs to an oxbow lake in the Mississippi River watershed: Effects of dam construction and land use change on regional inputs, Geophysical Research Letters, 42(19), 7983-7991.

[74] Williams, E. K., and Rosenheim, B. E. (2015), What happens to soil organic carbon as coastal marsh.

[75] Gaglioti, B. V., et. al (2014), Radiocarbon age-offsets in an arctic lake reveal the long-term response of permafrost carbon to climate change, Journal of Geophysical Research-Biogeosciences,119(8), 1630-1651.

[76] Pendergraft, M. A., Z. Dincer, J. L. Sericano, T. L. Wade, J. Kolasinski, and B. E. Rosenheim (2013), Linking ramped pyrolysis isotope data to oil content through PAH analysis, Environmental Research Letters, 8(4)..

[77] Adikhari, P.L., K. Maiti, E.B. Overton, B.E. Rosenheim, and B.D. Marx (2016) Distributions and accumulation rates of polycyclic aromatic hydrocarbons in the northern Gulf of Mexico sediments. Environmental Pollution, 212, 413-423..

[78] Hemingway, J.D., D. H. Rothman, K. E. Grant, S. Z. Rosengard, T. I. Eglinton, N. Haghipoure, L. Wacker, and V. V. Galy (2017) Reactivity-isotope relationships of natural organic matter. Proc. NAS (submitted)..

[79] Chmielewski AG et al (2014) Recent developments in the application of electron accelerators for polymer processing. Rad Phys Chem 94:147–150.

[80] Chmielewski AG (2005) Application of ionizing radiation to environment protection. Nukleonika 50(S3):17–24.

[81] Orloff, Jon, Mark Utlaut, and Lynwood Swanson. "Applications of focused ion beams." In High Resolution Focused Ion Beams: FIB and its Applications, pp. 205-290. Springer, Boston, MA, 2003..

[82] Sipahigil, Alp, R. E. Evans, D. D. Sukachev, M. J. Burek, J. Borregaard, M. K. Bhaskar, C. T. Nguyen et al. "An integrated diamond nanophotonics platform for quantum optical networks." Science (2016): 6875..

[83] Mogonye, J-E., K. Hattar, Paul Gabriel Kotula, Thomas W. Scharf, and Somuri V. Prasad. "He implantation for improved tribological performance in Au electrical contacts." Journal of materials science 50, no. 1 (2015): 382-392..

[84] http://wotwisi4.in2p3.fr/IMG/pdf/book_abstracts_wotwisi-4_updatedmarch.pdf.

[85] https://www.jstage.jst.go.jp/article/matertrans/55/3/55_MPR2013908/_pdf.

[86] https://research.hud.ac.uk/institutes-centres/emma/wotwisi-5/ .

[87] Acquisition de la société Quertech par la société Ionics; http://pole-moveo.org/actualites/acquisition-de-societe-quertech-societe-ionics/.

[88] Walibeam Industrial Platform for Ion Implantation; http://www.ionics-group.com/en/research-development/walibeam-industrial-platform .

[89]] CrN-SS coating; Jysk Teknologisk Institut; https://www.dti.dk/specialists/crn-ss-coating/34123?page_order=0.

[90] C.P. Chou, H.H. Chang, Y.-H. Wu; Enabling Low Contact Resistivity on n-Ge by Implantation After Ti Germanide; IEEE Electron Dev. Lett. 39(2018)91-94; DOI: 10.1109/LED.2017.2774502..

[91] Plasma Immersion Ion Implantation; http://www.ion-beam-services.com/.

[92] H. Banthien; Implementation of an Industry 4.0 Strategy - The German Plattform Industrie 4.0; https://ec.europa.eu/digital-single-market/en/blog/implementation-industry-40-strategy-german-plattform-industrie-40.

[93] REACH 2018; European Chemical Industries Website, https://echa.europa.eu/reach-2018.

[94] TSCA chemical substance inventory Website; https://www.epa.gov/tsca-inventory.

[95] X. Xu, P.S. Raman, R. Pang, N. Liu, A. Kursheed, J. A. van Kan; Performance test of a high brighteness nano aperture ion source. Nucl. Instrum. Methid. B 404(2017)52-57..

[96] T. Kalvas, O. Tarvainen, J. Komppula, M. Laitinen, T. Sajavaara, H. Koivisto, and A. Jokinen; Recent negative ion source activity at JYFL; AIP Conference Proceedings 1515, 349 (2013); https://doi.org/10.1063/1.4792803.

[97] Y. Jongen, M. Abs, F. Genin, A. Nguyen, J. M. Capdevilla and D. Defrise, Nucl. Instrum. Methods B 79, 865 (1993)..

[98] M. Abs, Y. Jongen, E. Poncelet and J.-L. Bol, Radiat. Phys. Chem. 71(1–2), 287 (2004)..

[99]] J.-L. Bol, X-ray sterilization: review of available configurations for small to large capacity sterilization facilities, in Proc. 2011 International Meeting on Radiation Processing (IMRP) (Montreal, Canada), to be published: by Radiat. Phys. Chem.

[100] https://science.energy.gov/hep/research/accelerator-stewardship/.

[101] http://iarc.fnal.gov/.

[102] http://apae.ific.uv.es/apae/wp-content/uploads/2015/04/EuCARD_Applications-of-Accelerators-2017.pdf.

[103] Smirnov, V., and S. Vorozhtsov. "Feasibility study of a cyclotron complex for hadron therapy." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 887 (2018): 114-121..

[104] http://www-pub.iaea.org/MTCD/Publications/PDF/P1251-cd/papers/65.pdf.

[105] Carlsten, B. E., et al. "New source technologies and their impact on future light sources." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 622.3 (2010): 657-668..

[106] Yamanaka, C. "Future industrial application of free electron lasers." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 318.1-3 (1992): 1-8..

[107] https://phys.org/news/2015-10-team-particle-prototype-feasibility-terahertz.html#nRlv.

[108] J. Schreiber, P. R. Bolton, and K. Parodi, Review of Scientific Instruments 87, 071101 (2016);.

[109] B.A. Ludewigt, P.A. Seidl, A. Persaud, Q. Ji, S. Steinke, S.S. Bulanov, Short Intense Ion Pulses for Radiation Effects, JOURNAL OF RADIATION EFFECTS, Research and Engineering Vol. 36, No. 1, April 2018.

Barney L. Doyle is a Distinguished Member of the Technical Staff at Sandia National Laboratories in Albuquerque, New Mexico, USA. He received a B.S. in Physics at Kansas State University in 1971, and a PhD in Physics from University of North Carolina at Chapel Hill, NC in 1976 where he performed his research at the Triangle Universities Nuclear Laboratory (TUNL). He joined the Solid-State Physics Center at Sandia National Laboratories in Albuquerque, NM in 1977. After 9 years in the technical staff, Doyle was promoted to manage the Ion Beam Laboratory (IBL), and was in that position for 25 years until he returned to the staff in 2011. His research has been recognized with several national awards including three R&D-100 Awards and a United States Congressional Commendation, all for various developments with accelerators. Five techniques he invented are patented, and he is a Fellow of the American Physical Society.

Floyd "Del" McDaniel is Emeritus Professor of Physics and Materials Science and Engineering and Emeritus Associate Dean for Research in the College of Arts and Sciences at the University of North Texas. He became an assistant professor in 1975, associate professor in 1979, full professor in 1984, and Regents Professor in 2002. He was chair of the Department of Physics from 2003-2007, became Senior Research Facilitator for the College in 2008, and was Associate Dean for Research for the College from 2009-2015, when he retired. He received a B.S. in Physics and Mathematics from the University of Memphis (1966) and an M.S. (1968) and PhD (1971) in Nuclear Physics from the University of Georgia. He has been Director of the Accelerator Laboratory at UNT (Ion Beam Modification and Analysis Laboratory (IBMAL)) from 1992 to 2010, and co-Director of IBMAL from 2010 to 2015. He was Director of the Industry/University Cooperative Research Center since from 1991 to 2001. His research has been recognized by his selection as a Regents Professor and a Toulouse Scholar at the University of North Texas; and an R&D 100 award.

Robert W. Hamm is an industrial accelerator physicist who has designed and built many types of particle accelerators throughout his 40-year career. He received a B.S. degree in Physics from University of Louisiana-Lafayette (1967) and an M.S. degree in Physics from Florida State University (1969), where he stayed as a staff member doing accelerator R&D until 1970. He left there to pursue his PhD degree in Accelerator Physics at Texas A&M University (1977) and then worked at Los Alamos National Lab for 5 years before going to work for an accelerator company as VP of R&D. He retired in 2007 as CEO and President of AccSys Technology, Inc., a successful linear accelerator manufacturing company he co-founded with three other physicists in 1985. He has been CEO of R&M Technical Enterprises, Inc. since 2008, a consulting business he and his wife formed after retiring from AccSys. He has developed several accelerator structures for medical therapy and industrial applications as well as co-editing a book and several other publications on industrial accelerators. He has 12 patents in accelerator technology and was on the team at LANL that received an R&D 100 award.

All three authors of this section have been very involved the biennial International Conference on the Application of Accelerators in Research and Industry, (http://www.CAARI.com) Drs. McDaniel and Doyle have co-chaired the meeting since 2004, and all of us have been part of the organizing committee since 1970's.