ACCELERATORS IN INDUSTRY

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Abstract

Accelerators and total accelerator system packages are used in industry for a wide range of applications in medicine, industrial processing and research services. The needs of industry are rapidly changing and the behaviour of commercial companies depend on their position in a complex product-supply chain and on external factors affecting the industry in which they operate. The overall industry position is reviewed, the status of the medical isotopes area is described as well as some external factors affecting this segment of industry; possible future accelerator -based projects are discussed.

1. INTRODUCTION

The use and application of accelerators in industry involve a broad range of machines and systems, varying from the small but non-trivial TV monitors to the use of large facilities such as the latest third generation synchrotron light sources. Technical review papers[1,2] and various meetings [3,4] have fully chronicled this rich and diverse range of applications. However, the structure of some of these accelerator-based industries is altering rapidly and the external commercial environment is also changing.

2. INDUSTRY STRUCTURE

During the last decade, markets for accelerator based products and services have become more competitive due to improved designs, the service use of accelerators for new products or research information, and requirements for deliveries of total integrated systems have become common-place. In the different industry sectors of material processing, research services and medicine, the concept of a product chain[5] has now become accepted. Within any 'product-chain' the role of an industrial organisation or company can be considered as

- The 'developer' - generating scientific and technical know-how,
- The 'constructor' - manufacturing saleable machines, systems or facilities,
- The 'operator' of the accelerator facility,
- The 'user' of the service or the information,
- The 'consumer' of a final product.

There is considerable overlap of these discrete functions with companies attempting to 'integrate vertically' inside a chain; and every company will be aware of its obligations and commitments for service or delivery within each of these roles and will seek 'add value' at each particular stage.

3. EXTERNAL FACTORS

The environment for accelerator based industry is now subject to major external changes which are more political or economic than technical:-

- Increasing resistance to the use of radiation,
- Emergence of alternative methods,
- Faster moving technology changes,
- More stringent international regulations,
- Reluctance to high (risk) capital investment,
- Increasing demand for shareholder return.

These factors impinge on the use of most of the different types of accelerators in industry and one particular industry segment is used to illustrate some of these issues - medical isotope production.

4. MEDICAL ISOTOPES

Nuclear medicine can be considered as one of the major successes of modern physics and this technology supports a large global market which is obliged to comply with the standards of the large ethical pharmaceutical industry. The table below illustrates the product supply chain structure for one specific medical isotope product and its applications:-

Industry role	Nuclear Medicine Imaging e.g. Tl^{201}
developer	Univ Louvain-la-Neuve
constructor	IBA S.A.
operator	Amersham Medi+Physics Inc
user	US nuclear pharmacy
consumer	US nuclear medicine clinic
consumer	cardiology patient

Table 1: Product Supply Chain

Isotope based medical products or radio-pharmaceuticals can be divided into four separate categories:-

- diagnostic imaging with PET isotopes,
- nuclear medicine imaging,
- therapy using sealed sources,
- therapeutic radiopharmaceuticals.

5. POSITRON EMISSION TOMOGRAPHY

The short-lived PET imaging isotopes C^{11}, N^{13}, O^{15}, and F^{18} all possess high sensitivity, excellent spatial resolution and low radiation dose for the imaging of functional and metabolic processes within the human body[6]. However, purchase of a small PET cyclotron, its target chemistry system, a PET camera and all the necessary analytical instrumentation, leads to a very expensive imaging technique requiring significant specialist attention. The lack of patent protection on PET isotopes and the absence of pharmaceutical licences have left this technique in the domain of clinical research centres. However, F^{18}-deoxyglucose has become so useful as a tracer, that distribution by industry of the isotope F^{18} has just started in several countries.

6. PRODUCTION CYCLOTRONS

Historically, many medical imaging isotopes had been produced by positive ion cyclotrons with internal targetry or with low intensity external beams. The power limitation presented by electrostatic extraction devices was effectively removed in third generation machines by new technology - negative ion extraction. At present, all the main radiopharmaceutical companies own one or more of these third generation, low power consumption cyclotrons, eg Cyclone 30, EBCO TR30, which operate at energies up to 30MeV and with extracted proton intensities between 300-500µA.

However, some exciting developmental work is being carried out on these compact cyclotron designs which can increase the output tenfold. In the wake of the recent high intensity record[7] of the PSI cyclotron complex where the general space charge barriers have been overcome using separated sector technology, these barriers for compact, industrial isotope producing cyclotrons are also being pushed aside. By using basic techniques such as improving the brightness of ion sources, introducing boosters into injection beam lines, optimising the inflection optics and injecting at higher energies, then much higher intensity, good quality, low emittance proton and deuteron beams can be accelerated. Further, enhancement of the RF systems, vacuum systems and extraction hardware are planned by the cyclotron manufacturers which will not require major re-design of the basic cyclotron configurations.
Already at TRIUMF, the EBCO TR30 has been upgraded to deliver 1000µA intensity at extraction[8] and early trials with a test facility have indicated a possible available proton beam of 2.1 mA[9]. Also, the original Cyclone 30, manufactured by IBA, is under development using a 'super-bright' ion source with a potential extracted beam of 3mA[10].

These advances offer efficiency improvements for radiopharmaceutical production by reducing schedule times and consumption of raw material. Isotope production increases linearly with particle intensity; however it should be noted that with bombardment periods comparable to the isotope's half-life then the efficiency improvement can be greater than linear. The primary challenge to the isotope manufacturer will be to organise higher thermal capacity targets capable of sustaining extremely high power densities up to 10 $KW.cm^{-2}$, without incurring high surface temperatures leading to volatilisation of the expensive isotopic target material. In addition, another major problem will be the design of beam line equipment with sufficient protection at these elevated power levels and also the resulting neutron increase will demand higher efficiency biological shields.

7. BRACHYTHERAPY

Significant advances have been made in the use of isotopes for treatment of disease and particularly for the use of sealed radioactive sources inserted into the human body i.e. brachytherapy. So far, these isotopes have always been produced by neutron irradiation in research reactors. One clinical area that has become important is the treatment of prostate cancer which is the second most prevalent cancer in men in western countries. Its early treatment has proven to be very successful due to new screening procedures and to improved ultrasound guided brachytherapy methods[11]. Traditionally, the 60 day half-life, I^{125} isotope has been favoured but recently Pd^{103} has been shown to be effective for aggressive tumour growths indicated by higher Gleason numbers. The isotope Pd^{103} has only been made available in sufficient quantities because of the recent development of a high intensity cyclotron (by IBA) at 2mA 20MeV, albeit with internal beam.

8. RADIONUCLIDE THERAPY

In contrast to the rapid improvement of cyclotron capacity, development of new isotopes and new pharmaceutical products progresses slowly due to the constraints of the drug regulatory process for licensing. In order for isotope based nuclear medicine to succeed

long-term it is clear that new radiopharmaceuticals for therapy must be developed to produce high rates of disease regression or even cure. At present, cancer treatment by isotopes is a common procedure, usually with β-particle emitting radionuclides. The current choice of isotopes are those with high β-energies with accompanying large volume energy deposition and therefore poorly defined low dose rates, eg P^{32}, Y^{90} or Sr^{89}. The more recently developed isotopes have slightly lower β-energies and slightly more precise dose characteristics but rely on the use of special chelating compounds and other biologically directed molecules, eg, Re^{186} HDMP, Sm^{153} EDTMP. Future generation isotopes will possess even lower β-energies, and will have more precise dose characteristics but will demand even better precision biological delivery mechanisms. Most of these therapeutic isotopes are currently produced using neutron irradiation in research reactors. However, with a potential tenfold intensity increase in the compact cyclotrons, some charged particle reactions will be accessible for producing some of the newer isotopes. Charged particles bombardment changes the Z-number of the nucleus and therefore the chemical properties which will assist in the manufacture of carrier-free and higher specific activity isotopes, that are required for therapy.

9. NEUTRON FIELDS

Some 80% of the present day medical isotopes are produced by neutron irradiation in research reactors and Tc^{99m}, the daughter product of Mo^{99}, is the most commonly used. The legacy of the 'Atoms for Peace' programmes is the abundance of high neutron flux 'research-reactors' and the accompanying low cost of thermal neutron irradiation. However increasing safety demands for ageing reactors and reducing funding for power and weapons programmes has resulted in the closure of many facilities[12]. The recent hiatus in reactor availability has stimulated new innovative ways of isotope production - using accelerators:-

- Tc^{99m} production by an accelerator route[13],
- spallation production of Mo^{99} with an accelerator[14],
- spin-off from accelerator driven energy production[15],
- accelerator based BNCT[16],
- accelerator based spallation sources.

10. ISOTOPE ENRICHMENT

The basic raw material for the production of these radiopharmaceuticals is the enriched species of the isotope which is naturally occurring and non-radioactive; for instance for the production of I^{123}, then Xe^{124} is used which has a natural abundance of 0.1% but is enriched to levels greater than 20%. For the last 50 years, copious supplies of the enriched stable isotopes have been produced in electromagnetic separators which are themselves types of accelerators and which were originally built for the early weapons programme in the 1940's. The two ageing facilities at Oak Ridge[17] and the secret city of Sverdlovsk-45 in Russia employ the same basic beam optical designs but are considered to have a limited lifespan. This threat to the supply of strategic raw materials has prompted innovative technology solutions but still employing the basic science of uranium separation such as laser separation (AVLIS) or centrifuge separation for some volatile materials.

11. CONCLUSION

Even against the background of decreasing public tolerance for radioactivity, diagnostic imaging with radioisotopes continues to grow healthily because of the unique clinical information that can be accessed. The range of available therapeutic radionuclides will also increase for treating different diseases. Reliance on research reactors will diminish but only slowly and only when accelerator based alternatives are developed which provide adequate technical performance but at a cost level which industry can support.

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