HIGH BEAM INTENSITIES FOR CYCLOTRON-BASED RADIOISOTOPE PRODUCTION

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1 INTRODUCTION

Cyclotron technology is largely disseminated into the medical and radio-pharmaceutical community. In particular, cyclotron-based systems devoted to radioisotope production, both for therapy and diagnostics, are commercially available and used since many years. Today, almost 10 years after the construction of IBA's first CYCLONE 30, a cyclotron that revolutionized cyclotron technology for medicine and industry, the requirement for high beam intensities is becoming more and more important. As a consequence, and favored by continuous developments in target technology and on ion sources, the maximum beam intensity available from these cyclotrons has increased, with years, from a few hundred µA to a few mA. The present paper will focus on some of the applications for which high beam intensities are required, as well as on the achievements and developments at IBA in relation with these applications.

2 NEGATIVE-ION CYCLOTRONS FOR THE PRODUCTION OF RADIOISOTOPES FOR IMAGING AND DIAGNOSIS IN NUCLEAR MEDICINE

Commercial companies operate several cyclotrons in the same facility and produce different radioisotopes [1] that they market themselves. Many important hospitals and clinics are now also equipped with cyclotrons producing radioisotopes for their own use or for distribution on regional scale. This evolution was possible because of the high degree of automation, reliability and simplicity characterizing the negative-ion cyclotrons used nowadays for radioisotopes production.

2.1 Negative ion technology

IBA was at the root of an important development step in radioisotope production, ten years ago, with the introduction of the innovative CYCLONE 30 cyclotron and its negative ion technology. Today, CYCLONE 30 is the world standard for radioisotope production [2]. It is a 30 MeV, fixed-field, fixed-frequency, dual extracted beam, H^- cyclotron. Cyclone 30 is a reliable, fully automated push-button system, with minimal activation of the machine and minimum radiation exposure for the personnel thanks to the H^- technology. It was designed to give high extracted beam intensities (up to 500 µA) while keeping the power consumption very low (less than 100 kW with a 15 kW extracted beam).

The acceleration of negative H ions in a fixed-field, fixed-frequency cyclotron offers several advantages. Among others, the extraction is straightforward by means of stripping of the H^- ions in a thin carbon foil, leading to an extraction efficiency close to 100%. The negative hydrogen ions are produced by an external multicusp arc discharge ion sources producing an H^- beam. This external source is combined with axial injection. The use of an external source avoids the vacuum problems leading to beam losses and activation of cyclotrons with internal sources. The adopted solution of an external H^- source with its own pumping system allows the neutral gas to be pumped in the external source system, and moderate size pumps are sufficient to obtain a very low operating pressure in the cyclotron. This reduces beam losses and implies a very low activation of the cyclotron. Maintenance is easier and safer.

2.2 The requirement for higher beam intensities for cyclotron-based production of nuclear medicine radioisotopes

The first CYCLONE 30's used a 2 mA external multicusp ion source made by IBA, and a 25 kW output R.F. final amplifier. The extracted beam intensity was 500 µA (design value), 350 µA guaranteed, with actual maximum currents varying from machine to machine between 450 µA and 600 µA. These characteristics, in particular the extracted beam intensities, were up to now well adapted to the production constraints, in particular from the point of view of the maximum current the targets may support.

However, recent developments in target technology are at the root of an increasing interest, from the radioisotopes producers, for higher beam intensities. In parallel, there have been important progress in negative ion source technology. In this field, IBA is working in collaboration with A.E.A. Technology, Culham, in the UK.

As a consequence, IBA proposes today high intensity versions of CYCLONE 30, with maximum extracted beam intensities up to more than 2 mA. These systems include, among others, a new ion source series, able to produce 7 to 25 mA of H^- into a small emittance, developed for IBA by A.E.A. Technology.

IBA is also proposing an intensity upgrading system allowing a significant increase of the beam intensity (up to 2 mA typically) of any existing Cyclone 30. For the radioisotopes producers, the main advantage of this option is that the isotope production rate of their existing CYCLONE 30 can be increased while keeping unchanged the production facility (no need for an important investment in a new building) and most of the cyclotron operation costs (no need for additional personnel for example). Alternatively, this may be a way of reducing operation costs.

2.3 Radioisotopes for imaging and diagnosis in nuclear medicine: the particular case of ^{99m}Tc

Gallium 67 and thallium 201 are among the most common medical radioisotopes produced with cyclotrons, but the most frequently used radioisotope for nuclear medicine is produced with nuclear reactors: technetium 99m, distributed as ^{99}Mo => ^{99m}Tc generators. The preferred reaction for the production of ^{99}Mo in nuclear reactors is the neutron induced fission on highly enriched uranium 235 targets. Most of the nuclear reactors used for this production are due, in the next years, for a major refurbishment or for decommissioning [3]. This problem of the future availability of nuclear reactors suitable for ^{99}Mo production has prompted a renewed interest on alternative production methods.

Two alternative production methods are presently under development: one of them is based on the direct accelerator production of ^{99m}Tc or ^{99}Mo, the other one is the proton-driven fission neutron source for the production of fission ^{99}Mo as proposed by IBA [3] and presented in another paper to this conference. Both methods require the use of high intensity cyclotrons.

As far as the direct accelerator production of ^{99m}Tc or ^{99}Mo is concerned, three possible cyclotron production techniques (one for ^{99}Mo and two for ^{99m}Tc) are currently being investigated [4]. The technical feasibility of these alternative production methods is still being evaluated. Among others, there are questions regarding the specific activity of “instant Tc” and the separation chemistry of ^{99}Mo, as well as licensing and distribution issues. Nevertheless, directly produced Tc could become, in the future, a product complementary to generator produced Tc. In this case, the most promising methods will require high intensity proton beams, in the 2 to 5 mA range.

As far as the production of fission ^{99}Mo is concerned, the IBA proposal is based on a 150 MeV, up to 2 mA cyclotron driving a sub-critical intense neutron source, generating thermal neutron fluxes similar in intensity to those of nuclear reactors used for the production of ^{99}Mo.

Both alternative methods will therefore require several mA of beam. The proposed accelerators will include most of the advanced fundamental characteristics of existing IBA cyclotrons, in particular the negative ion technology. Experience on high efficiency RF power amplifiers developed for the Rhodotron [5], on Cyclone 18+ high beam power conversion efficiency (see § 3 and ref. [6]), and on the high intensity versions of Cyclone 30 (see § 2.2) will be valorized.

3 PRODUCTION OF RADIOISOTOPES FOR THERAPY

Medical radioisotopes are generally used for imaging and diagnosis in nuclear medicine. But some of them are used for cancer therapy. Radioisotope production for therapy applications may require extremely high intensity cyclotrons. In 1992 IBA was asked to develop a very high intensity, 18 MeV cyclotron for the production of the radioisotope ^{103}Pd. This radioisotope is marketed, in small sealed sources, for the local treatment of prostate cancer by the company Theragenics. It can be produced by a (p,n) reaction on Rhodium, a good material for internal target. However, the reaction yield is low and large beam currents are needed to achieve the desired production levels.

The development of this cyclotron by IBA, the CYCLONE 18+, was a new step in the evolution of cyclotrons for radioisotope production, in particular from the maximum intensity point of view. Indeed, CYCLONE 18+ operates continuously at 2 mA beam on target. It is therefore demonstrated today, experimentally, that a cyclotron with an internal target can operate routinely at 2 mA beam current. Also currents in excess of 5 mA have been observed during factory tests, and space charge calculations made for cyclotrons that do not require turn separation indicate that the intensity limit is probably around 10 mA average beam current [6]. This applies not only to positive ion cyclotrons using an internal target but also to negative ion cyclotrons where the extraction is made by charge exchange.

4 THE INNOVATIVE CONCEPT OF AUTO-EXTRACTION OR THE REBIRTH OF THE POSITIVE ION TECHNOLOGY

The use of negative ion technology allows an extraction by means of stripping of the H^- ions in a thin carbon foil, leading to an extraction efficiency close to 100%. This technology is therefore, up to now, the technology of choice for applications where high intensity beams must be extracted. However, the requirements on the vacuum quality are high and, to avoid electromagnetic dissociation, low magnetic fields must be used. The consequence is that high energy cyclotrons quickly become very large machines if negative ions are accelerated, which is nevertheless necessary if high intensity extracted beams are required. From this point of view, any technological innovation leading to the use of positive ion technology together with an extraction system allowing a nearly 100% extraction efficiency would represent an unquestionable improvement.

IBA is presently working on a totally new concept for the extraction of high currents of positive ions [7]. This new concept, called the auto-extraction will provide close to 100% extraction efficiency without the need of extraction elements that could easily be damaged by high currents, like septa for electrostatic or magnetic extractors.

The basic principles are the following. In an isochronous cyclotron, the average field increases with radius to compensate the relativistic mass increase of the accelerated particles. Close to the pole edge, it become impossible to maintain an isochronous radial field profile. The actual field falls below the ideal field, reaches a maximum, and starts to decrease. When the actual field starts departing from the ideal isochronous field, the accelerated particles start to lag with respect to the accelerating voltage on the dee. When the phase lag reaches 90°, the acceleration stops: this point represents the limit of acceleration. At an other (generally larger) radius, the field index, defined as $N = R/B\ dB/dR$, reaches the value -1. This point is the limit of radial focusing. Past this point, the magnet is unable to hold the ions, and the ions escape the influence of the magnetic field. We call the radius where N reaches -1 the limit of self-extraction. If the gap is large, like in most existing cyclotrons, the radial fall of the field is quite gradual, and the limit of acceleration is found at a radius significantly smaller than the limit of self-extraction. Transporting the beam from the first limit to the second is the task of the extraction system, including generally an electrostatic deflector.

In a magnet with a smaller gap, the fall of the magnetic field close to the pole boundary is much sharper. As a result, the limit of acceleration falls much closer to the limit of self-extraction, and the extraction is much easier. When the magnet gap at extraction becomes very small (like smaller than 20 times the radius gain per turn at extraction), the limit of self extraction is reached before the limit of acceleration, and the beam escapes spontaneously the magnetic field when the pole edge is reached. This corresponds to the auto-extraction.

Provided that experiences confirm our numerical simulations in progress, this new extraction method for positive ions is likely to replace the use of negative ions in cyclotrons designed for high currents.

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