Commercially Available Compact Cyclotrons for Isotope Production

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Abstract

A variety of different compact cyclotrons are nowadays commercially available The energy ranges from a few MeV to 40 MeV, with beam currents up to 500 microamperes. This overview will cover positive ion machines as well as negative ion machines. It will describe the main specifications, special features and the dominant applications of these modern cyclotrons in research, hospitals and industry.

1. Introduction

Since the last decade the number of compact cyclotrons dedicated to applications has steadily increased from 22 in 1982 to 43 in 1992 (fig. 1).

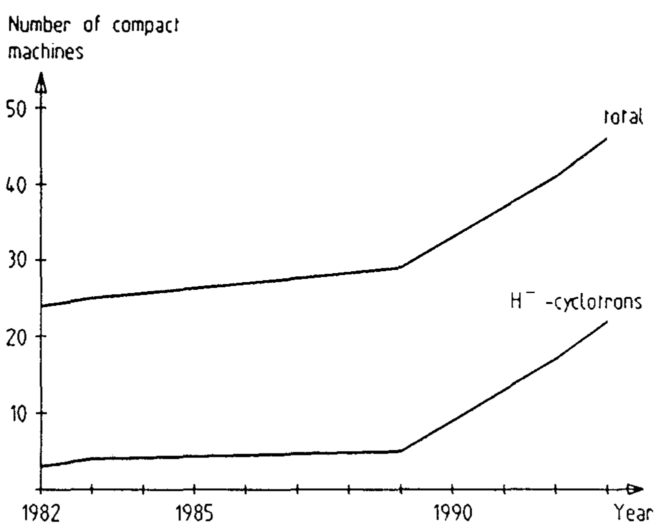

Fig. 1 : Compact cyclotrons for applications in medicine and engineering

These cyclotrons are mostly used for the commercial production of radioisotopes for medical diagnosis like Thallium-201, Iodine-123, Indium-111, Gallium-68, Gallium-67, Rubidium-81 and Fluorine-18. Some institutions are using these cyclotrons for the activation of machine parts for wear studies and for applied research, but they are rarely used for basic nuclear research.

2. Requirements for compact cyclotrons

Modern compact cyclotrons for isotope production should meet the following requirements:

2.1 High beam current > 300 μA

To ensure a high productivity in isotope production the available beam current should be at least 300 μA Higher currents would be desirable but so far appropriate targets are difficult to construct. There are some developments under way e.g. improving the high-power-target design and enhancing the cooling efficiency but these new developments have not proven to be reliable for routine use.

In compact positive ion machines the extraction process limits the availbility of high external currents. As a consequence most isotope productions were done with internal targets (restricted for metallic targets only). This internal irradiations on the other hand are causing also a number of disadvantages:

- complex target transport via air-lock from and to cyclotron vacuum chamber,
- beam handling on target not adjustable,
- beam diagnostic difficult,
- activation of cyclotron components around the target is very high.

The latter restricts the access to the machine for regular maintenance, due to exposure of high level of radiation to personnel.

In contrary a negative ion cyclotron delivers very high external beam currents due to the injection of negative hydrogen ions from an external ion source and the 100 % extraction efficiency via double charge exchange in a thin carbon foil. This type of cyclotron however, is limited to proton and deuteron beams only. But almost all major radioisotopes for medical applications can be produced via (p,xn) reactions (table 1). The advantages of using a negative ion machine are:

- external target located remotely from the cyclotron
- beam handling on target is very flexible
- on-line beam diagnostic during irradiation
- simultaneous extraction of two beams provides more flexibility in the production, splits high current beams on two targets hence reduces beam power on target surface.
- production of two (even different) isotopes at the same time
- activation of cyclotron components very low; access to the machine without high radiation levels within one hour after switching off the cyclotron.

Radioisotope	Half-life	Nuclear Reaction	Bombarding Energy
Gallium-67	78.3 h	Zn-68(p,2n)Ga-67	25 MeV
Gallium-68	1.1 h	Ga-69 (p,2n)Ge-68 Ge-68 → Ga-68	35 MeV
Bromine-77	57 h	Kr-78(p,2n)Rb-77 Rb-77→Kr-77→Br-77	30 MeV
Rubidium-81	4.6 h	Kr-82(p,2n)Rb-81	30 MeV
Indium-111	67.2 h	Cd-112(p,2n)In-111	22 MeV
Iodine-123	13.2 h	Xe-124(p,2n)Cs-123 Cs-123→Xe-123→ I-123	30 MeV
Thallium-201	73.5 h	Tl-203(p,3n)Pb-201 Pb-201→ Tl-201	29 MeV
Fluorine-18	1.8 h	O-18(p,n)F-18	18 MeV

Table 1: Most common cyclotron produced radioisotopes for medical diagnostic

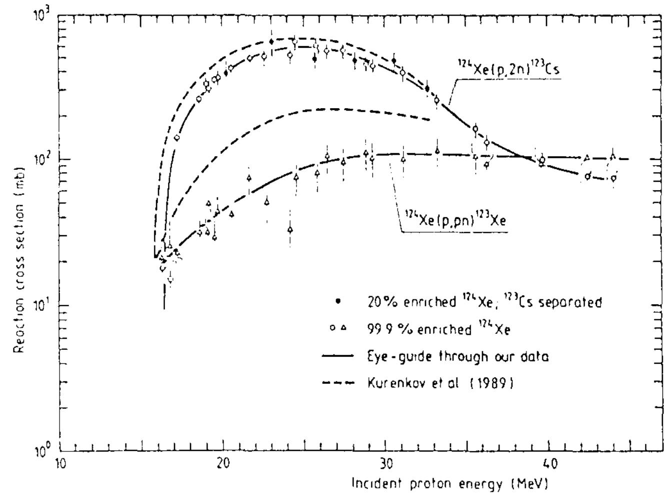

Fig. 2 : Cross section for I-123 via Xe-124(p,2n) taken from ref. 1

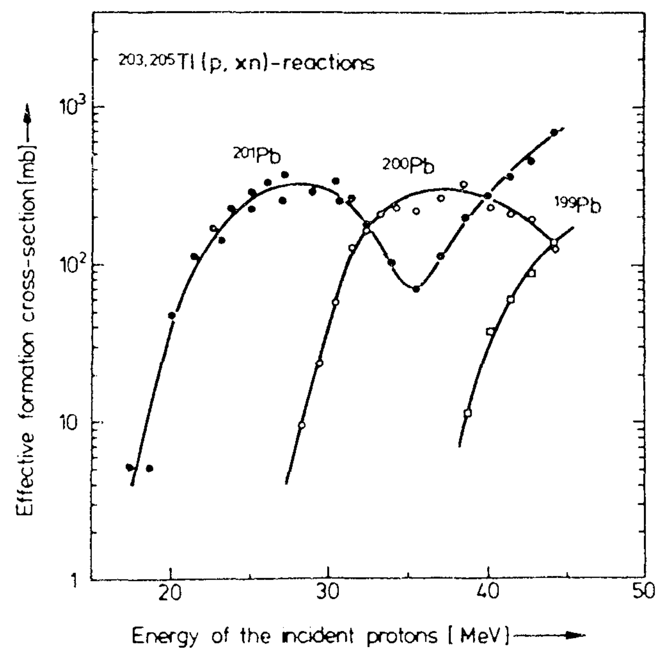

Fig. 3 : Cross section for the nuclear reaction Tl-203(p,3n) taken from ref. 2

2.2 Energy 30 MeV

Most of the machines used so far for routine production have energies between 24 MeV and 26 MeV (e.g. CU-28, CS-30) which are too low. Fig. 2 and Fig. 3 show typical cross section for nuclear reactions in radioisotope production. It can be seen that 30 MeV proton energy is sufficently high for these reactions. For technical reasons some production processes (like in gas- or liquid targets) are using thin metal foils as entrance windows for the beam. While passing the metal foil the beam looses about 1 MeV, but 30 MeV initial beam energy is still sufficient to get maximum production yields. Much higher proton energy than 40 MeV is also not advisable since it will not increase the productivity but only contributes to higher investement- and operational costs.

2.3 Low power consumption

Cyclotrons in the past used typically a few hundred's of kilowatt electrical power while producing less than 10 kW of beam. This energy conversion efficiency (ratio of beam power to electrical power) was only a few (1-3) percent. Due to special magnet design (e.g. four sector compact design with small hill gap) modern compact machines could demonstrate an energy conversion efficiency as high as 15 percent. The total electrical power required should not exceed 150 kW. This keeps operational costs down and makes the radioisotope production more economical.

2.4 Safe and easy operation

For a routinely operated cyclotron in commercial isotope production the use of a fully integrated computer control system is absolutely necessary. It has to be user friendly and should allow the operator to control and monitor every aspect of operation. However, during normal production runs it should not require any operator at all. The software should enable an automatic start-up routine, a safety control for unattended runs and a complete cyclotron trouble shooting to provide an easy, safe and reliable operation.

2.5 Maintenance

The design of the machine has to be very simple and robust to make the operation reliable and to keep the down-time small. Taking into consideration the following subjects the maintenance should require as little time as possible.

- The upper half of the cyclotron magnet can be lifted with jacks sufficiently high for good access to the center of the machine. When opening the cyclotron all components are installed in such a way that there is no need to break any connections. This makes reassembling more save, fast and reliable.

- Activation of cyclotron components and vacuum chamber should be very low. This was feasible since beam losses are kept small due to the axial injection of negative ions from an external ion source, the differential pumping and the highly efficient extraction process via stripping.

- Generally, components are constructed for long life time and the material choosen is radiation resistent or/and gets less activated.

- Components which require a regular service can be isolated by vacuum valves (e.g. ion source, filament, stripper foils)

3. Manufacturers and their compact cyclotrons

The following is a brief description in alphabetic order of the cyclotron manufacturers and their modern compact machines.

- EBCO[3] was established in 1956 as a high tech company. Since 1989 in the cyclotron business based on an TRIUMF-EBCO technology transfer agreement.

- IBA[4] since 1986 established as a Societe Anonyme (SA) with key-experts from the cyclotron department of the University Louvain-la-Neuve.

- NIIEFA[5] is the leading accelerator (cyclotrons and linacs) manufacturer in former USSR since 1952.

- SCX[6] more than 20 years world wide reputation as a cyclotron producer.

- SHI[7] since 1974 producing cyclotrons for research and application in medicine and industry.

Table 2 lists the main specifications of the available cylotrons. Two machines (MC 40 from SCX and 480 from SHI (Fig. 4)) are positive ion cyclotrons with the potential to provide α-particles in addition to hydrogen beams. The available external beam current for protons is limited to 100 μA.

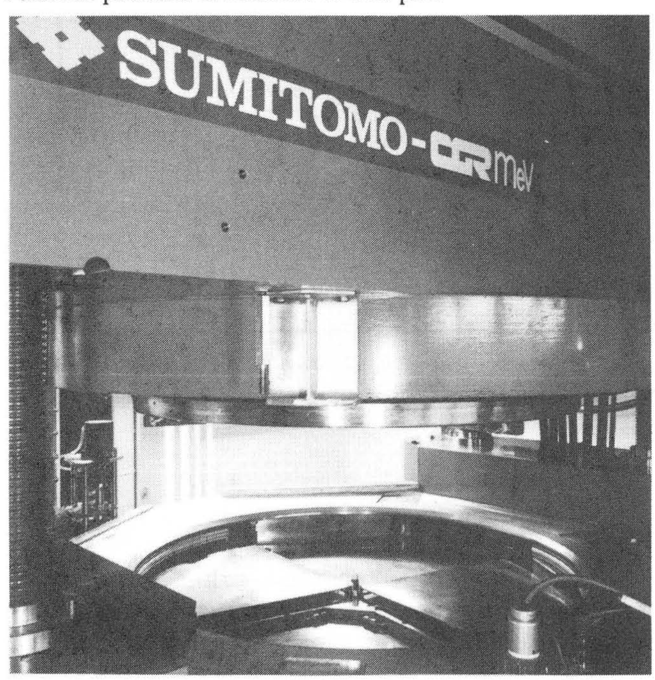

Fig. 4 : 480 from Sumitomo

In commercial isotope production these latter machines are therefore mostly used for internal irradiations.

3.1 Common features

Some common features for these negative ion machines are:

- compact magnet design
- fixed magnet field
- fixed frequency
- variable energy between 15 MeV and 30 MeV
- extraction via stripping
- simultaneous extraction of two beams at different currents and different energies
- external ion source (CUSP-type)
- high extracted beam intensities > 350 µA
- low power consumption < 130 kW
- Vacuum provided by a combination of diffusion pumps and cryopumps
- Controlsystem with commercial PLC's
- D^--option

3.2 The differences

In all machines the rf-amplifier is installed very close to the cyclotron and the power is directly coupled to the cavity. Only the TR 30 (Fig. 5) from EBCO uses a coaxial transmission line between the cavity and the power amplifier.

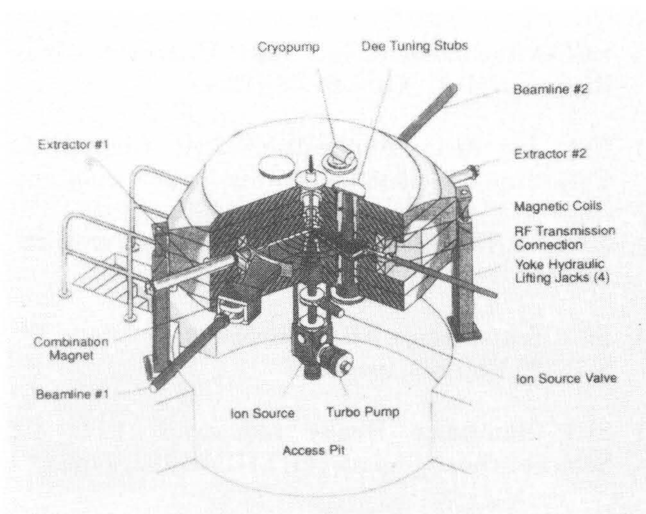

Fig. 5 : TR 30 from EBCO

The external ion source is either installed on top of the cyclotron (Cyclone 30, (Fig. 6) MC 32 NE, Fig. 7)) or in a pit below the machine (TR 30, RIC 35, (Fig. 8)). The TR 30 uses a negative ion source of the CUSP-type with a very high brightness (10 mA dc H beam at 0.44 π mm-mrad).

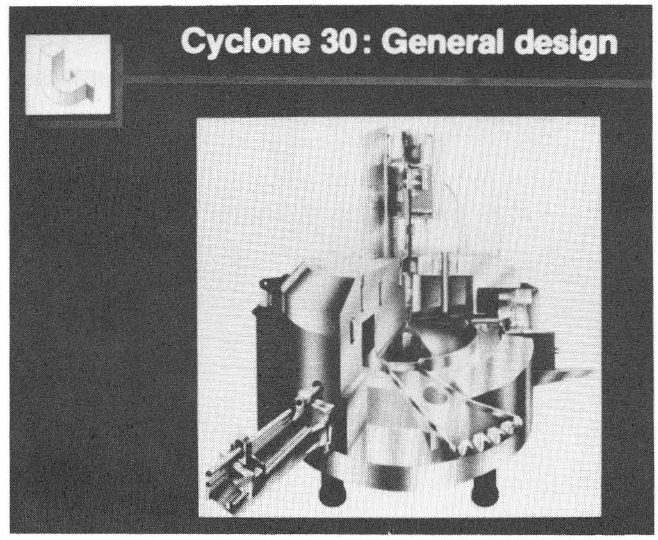

Fig. 6 : Cyclone 30 from IBA

The injection is done with a buncher in the Cyclone 30 and without bunching system in the TR 30, RIC 35 and MC 32 NE.

For the vacuum system of the main vacuum chamber the MC 32 NE uses only diffusion pumps, the RIC 35 and Cyclone 30 have installed diffusions

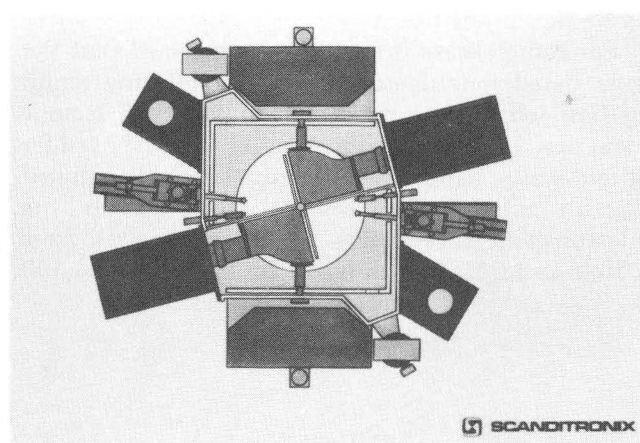

Fig. 7 : MC 32 NE from Scanditronix

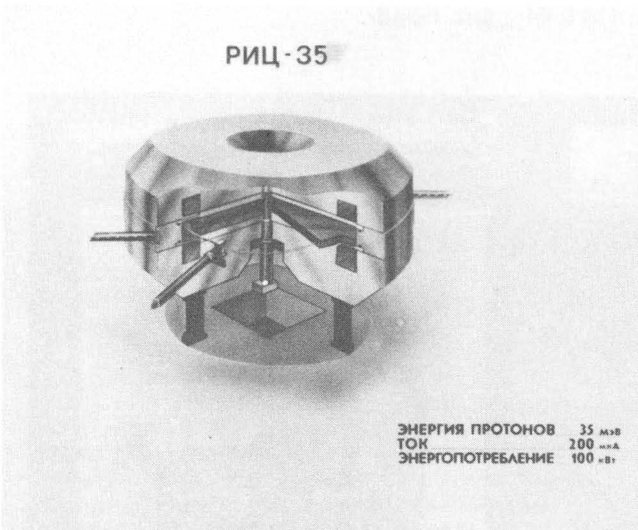

Fig. 8 : RIC-35 from NIIEFA

pump and cryopumps whereas the TR 30 uses cryopumps only.

The beam is generally extracted into two beamlines at 180° except for RIC 35. In this machine there are two beams at 60° available. The Cyclone 30 in addition provides in each opposite exit port a "selection magnet" integrated in the yoke which directs the beam into one of the two possible beam lines.

The maximum beam energy for protons is 30 MeV in the TR 30, 32 MeV in Cyclone 30 and MC 32 NE and 35 MeV in the RIC 35.

For completness it should be mentioned that the above listed manufactures are also offering small negative ion cyclotrons dedicated for PET isotope production. For these applications there is no need for high intensity, hence these machines are all equipped with an internal ion source which makes the cyclotron even more simple. The energy ranges from 10 MeV to 18 MeV with beam intensities up to 100 μA.

4. Conclusion

A variety of compact cyclotrons for isotope production in medicine and industry is commercially available. The presented machines slightly differ in the use and arrangement of external components. The feasibility of providing a high-current, highly power-efficient and fully automated cyclotron for radioisotope production could be shown by the manufactures.

5. Acknowledgment

It is a pleasure to express my appreciation to the cyclotron manufactures who have provided a lot of useful information for this paper. I am also indepted to H. Schweickert for his valuable suggestions and helpful discussions.

6. References

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2) S.M. Raim, R. Weinreich and H. Ollig, Production of Tl-201 and Pb-203 via proton-induced nuclear reactions on natural thallium, Int. J. Appl. Radiat. Isot. 30, 85-95 (1979)

3) EBCO Technologies Inc. 7851 Alderbridge Way Richmond, B.C., Canada V6X2A4

4) IBA, Ion Beam Applications S.A., Chemin du Cyclotron, 2, B-1348 Louvain-la-Neuve, Belgium

5) NIIEFA, D.V. Efremov Scientific Research Institute of Electrophysical Apparatus, Russia

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7) SHI, Sumitomo Heavy Industries, LTD 5-2 Sobiraki-cho, Niihama-shi, EHIME 792, Japan