Extremely High Intensity Cyclotrons for Radioisotope Production

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Abstract

We describe the construction and operation of a 18 MeV proton cyclotron, operating routinely on an internal target at average currents in excess of 2mA. Currents up to 5mA have been observed at lower energies. Space charge calculations indicate that average beam currents in excess of 10mA can be obtained in cyclotrons where turn separation is not required.

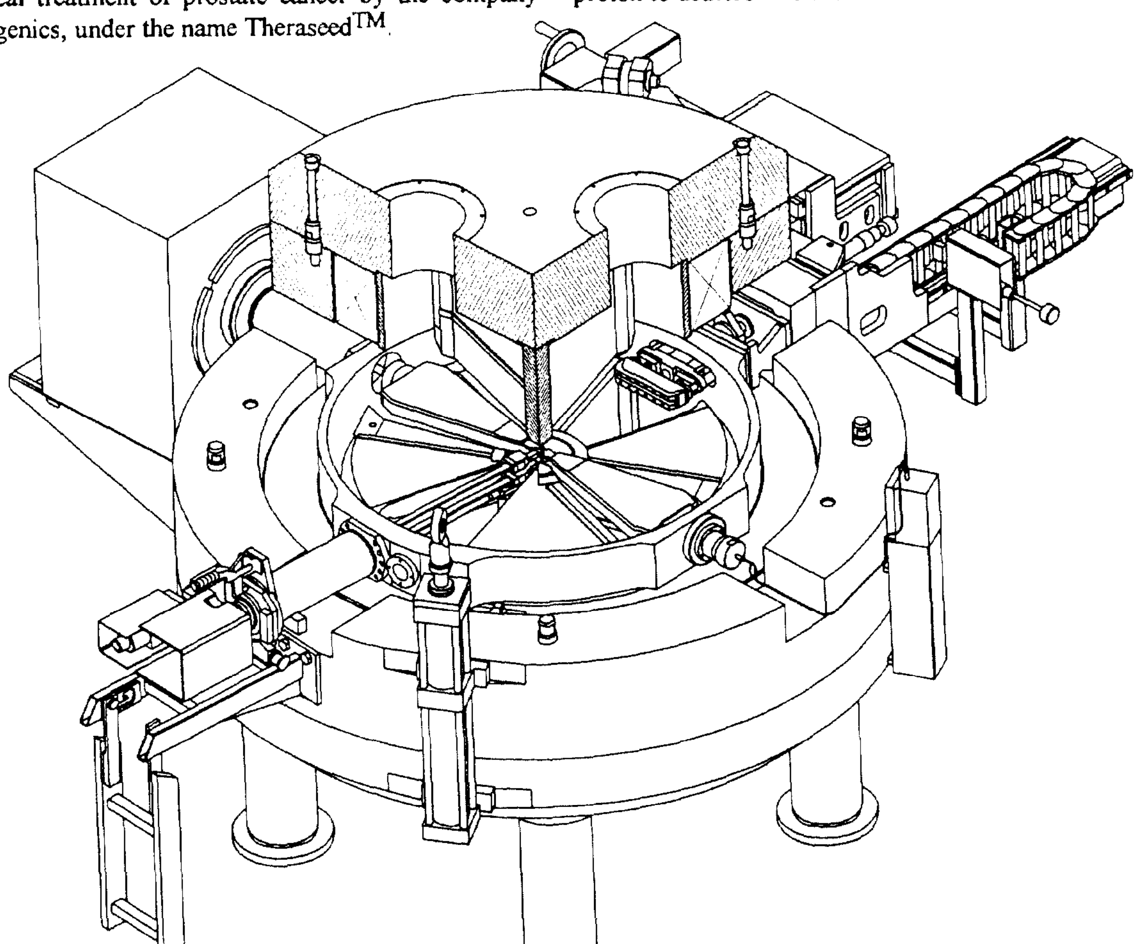
1 INTRODUCTION

In 1992, IBA was asked to develop a very high intensity, 18 MeV cyclotron for the production of the radioisotope ^{103}Pd. ^{103}Pa is marketed, in small sealed sources, for the local treatment of prostate cancer by the company Theragenics, under the name Theraseed™.

^{103}Pd can be produced by a (p,n) reaction on Rhodium 103 (Rhodium is monoisotopic). Rhodium is a good material for internal target : it is refractory and allows high quality electroplating. On the other hand, the reaction yield is low and large beam currents are needed to achieve the desired production levels.

2 BASIC MACHINE DESIGN

The CYCLONE 18+ is directly derived of the well known CYCLONE 18/9, a cyclotron designed for Positron Emission Tomography applications and able to accelerate H- ions to 18 MeV and D- ions to 9 MeV. The magnetic structure is kept essentially unchanged, but the movable iron pieces allowing to switch from the proton to deuteron field are omitted.



The RF structure is similar also, but the dee voltage is increased from 32 kV to 45 kV. The choice of second harmonic operation with dees having an azimuthal angle of 30° is hardly optimum to maximize the energy gain per turn, but was selected for technological reasons. It also makes the central region design easier. In this design the energy gain per turn is 200 * dee voltage, or 90 keV/turn. To provide the large RF power needed for beam acceleration, a 42 Mhz, 45 kW amplifier was directly coupled to the RF cavity. The central region was designed to accomade intense proton beams with a large axial size. The protons are produced by a PIG source with self-heated cathodes. The beam extraction slit can be adjusted by exchange of the chimney, but a slit of 0.5 x 14 mm is normally used. The source to puller gap is set at 5 mm.

3 CYCLOTRON OPERATION

The CYCLONE 18+ was ordered in January 1992. The accelerator construction was completed in September 92 and beam test were conducted in the factory. In October the cyclotron was shipped to the USA, and installation stated in November 92. On January 15, 1993, all acceptance tests were successfully passed. The cyclotron specifications called for a beam on target of 1.0 mA, but the design was made with ample safety margin, so that, during acceptance tests, the current reaching the target exceeded 2 mA. Since this date, the cyclotron has been operated continuously at 16 MeV, 2mA. This represents a beam power of 32 kW, when only 8 kW are dissipated in the RF cavities, so the beam loading represents 80% of the RF power. The cyclotron runs unattended for week long irradiations under automatic control. Most of the time, no one is even present in the building. The Programmable Logic Controller (PLC) controlling the cyclotron is connected by modem to the telephone system and, in case of problem, calls automatically the service engineer at home. Through the modem link, the service engineer is able to emulate completely the cyclotron control screens on a p.c. at home.

The cyclotron beam current is presently limited by the available RF power. When tests were conducted in the factory on a beam probe at low energy (1MeV) currents of 3mA, and even for a short time 5mA were observed.

4 SPACE CHARGE LIMITS IN A CYCLOTRON WITHOUT SEPARATED TURNS

For cyclotrons where a positive ion beam is extracted, a good turn separation is required at the extraction radius. To obtain such a turn separation, the energy spread of the beam at extraction needs to be smaller than the energy gain/turn. For high intensity beams, longitudinal space charge forces set an upper limit to this energy spread as shown by Gordon [1] and Joho [2]. Furthermore, as shown by Adam [3], non linear effects can cause a filamentation of the beam bunch and strongly degrade the turn structure.

In such cyclotrons, those longitudinal space charge effects are the dominant limit on the beam current. The maximum currents scale therefore as the cube of the energy gain/turn.

In contrast, cyclotrons where the beam is used to irradiate an internal target or cyclotrons where the beam is extracted by charge exchange are only limited in intensity by the transversal (mostly axial) space charge effects and, possibly, by the longitudinal space charge limit in the source to puller gap.

A good treatment of the transversal space charge effects is proposed by Joho [2]. He makes the simplifying hypothesis that the emittances and betatron frequencies are identical in both planes : $\varepsilon_x = \varepsilon_y = \varepsilon$ and $\nu_x = \nu_y = \nu$. Using the normalized emittance $\pi\varepsilon_n = \pi\varepsilon\beta\gamma$. He defines a critical current IT and a dimensionless space charge parameter ω

$$I_T = \frac{M}{Q^2}\frac{\varepsilon_n \nu_0}{R}\beta^2\lambda^2\frac{\Delta\Phi}{2\pi}I_0$$

with $$I_0 = 4\pi\varepsilon_0\frac{m}{e}c^3 \approx \pi 10^7 A$$

$$\omega = \frac{<I>}{I_T}$$

Q is the charge state, M the atomic mass in A.M.U. (=1 for protons), $\Delta\Phi$ is the phase width of the beam and R is the radius of the orbit. Knowing I_T and ω, we can calculate the betatron frequency and amplitude as modified by the space charge

$$a^2(I) = a_0^2\left[\omega + \sqrt{1+\omega^2}\right]$$

$$\nu(I) = \nu_0\left[\sqrt{1+\omega^2} - \omega\right]$$

$a_0 = \sqrt{\frac{\varepsilon R}{\nu_0}}$ is the amplitude and ν_0 is the betatron frequency at zero current.

If we introduce the values after the first turn of the above described cyclotron, we find I_T = 5.95 mA and, consequently

<I>(mA)	0	2	5	10
ω	0.00	0.34	0.84	0.03
ν_z	0.13	0.09	0.06	0.03
a_z(mm)	5.22	6.16	7.65	9.95

5 SPACE CHARGE LIMIT IN THE SOURCE TO PULLER GAP

Another limit to be considered is the space charge limited current in the source to puller gap. In this cyclotron, the source to puller gap is well described by a planar geometry. We can therefore use the Child-Langmuir law [4]

$$J = \chi \frac{V^{3/2}}{a^2} \quad \text{with } \chi = \frac{4Eo}{9}\left(\frac{2e}{m}\right)^{1/2}$$

where J is the current density (A/cm2)
V is the accelerating voltage (V)
a is the accelerating gap (cm)
χ, as defined above, is 5.45 10^{-8} A $V^{-3/2}$ for protons

applying V = 40 kV, a = 0.5 cm, S = 7 10^{-2} cm^2 (source slit surface)

I_{peak} = 122 mA
<I> $\approx$ 10 mA

Actually, the beam is probably diverging between the source slit (0.5 mm wide) and the puller slit, (2 mm wide). In this case we are not in a planar geometry, but in a cylindrical geometry and the actual current limit is higher than the above calculated value.

6 CONCLUSIONS

We have demonstrated experimentally that a cyclotron with an internal target can operate routinely at 2mA beam current, and that 5mA currents have been observed. Space charge calculations made for cyclotrons that do not require turn separation indicate that the intensity limit is probably around, or above, 10 mA average beam current. 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.

7 REFERENCES

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