NEW RADIONUCLIDES PRODUCTION ON THE ISOCHRONOUS CYCLOTRON U-120M

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The production of ^{18}F for positron emission tomography (PET) applications and manufacturing of the ^{81}Rb for the $^{81}Rb/^{81m}Kr$ radionuclidic generator (used in lung ventilation studies) have been introduced as a new program of the twenty year old cyclotron U-120M (K=40. A/Z=1-2.8). The cyclotron conversion from positive to H^-/D^- accelerating regimes and the extraction by means of stripping were necessary for obtaining sufficiently high beam intensities. Two possible solutions of H^- gain - either from the external high intensive (1mA DC) old TRIUMF CUSP ion source or from the internal ion source with a cold cathode developed in our laboratory - are described. Axial injector characteristics for H^- currents up to 1mA together with optimizing the central region, the ion extraction system and upgrade of the vacuum system are presented. The realization of the enriched H_2O^{18} target, its setting into operation and the first results of ^{18}F production (average yields ~ 2GBq/μA.hour at EOB) are briefly discussed.

1. Introduction

After 20 years of operation, the cyclotron U-120M still delivers beams to the community of multidisciplinary users. Beam time allocation is shown in Table 1.

Table 1. Beam time allocation in the period 1995 - 1998.

	1995 [hours]	1996 [hours]	1997 [hours]	1998 I.-V. [hours]
Nuclear reactions	85	89	167	-
Nuclear spectroscopy	-	12	8	-
Nuclear biology	33	25	10	22
Fast neutron generation	17	35	94	-
Solid state physics	7	7	-	8
Stent irradiation	-	10	37	-
Radionuclides production				
^{67}Ga, ^{201}Tl, ^{111}In	861	763	719	314
^{211}At	27	32	32	42
^{18}F	-	-	50	71
$^{81}Rb/^{81m}Kr$	-	4	13	-

Due to the fact that the nuclear physics experiments for the spectrum of ions and energy range (p^+: 10-37MeV, D^+ : 10-20MeV, $^4He^{2+}$: 20-40MeV, $^3He^{2+}$: 17-54MeV) had been in most cases performed in the past (with an average beam time ~ 2500 hours/year), the utilization of the cyclotron has become more oriented to the applications. In particular, the development and consequently the routine production of new radionuclides (^{18}F, $^{81}Rb/^{81m}Kr$) has been introduced as a new program of the twenty year old cyclotron.

The extraction efficiency of the 4-section deflection electrostatic system is in the range of 25-35% and maximum currents reach value of 5μA. For this reason, the conversion of the U-120M into negative accelerator has been accomplished and the extraction of negative H^-/D^- ions by the electric charge exchange has been employed.

2. Cyclotron upgrade

In order to increase the H^- beam currents, the extensive upgrade of the following cyclotron parts had to be undergone.

2.1. Central region optimalization

The central region geometry (i.e. the shape of the puller electrode, mutual positions of the puller and the ion source extraction slits, the vertical position of the extraction slit with respect to the central magnetic plane and the termal vertical dee shift) can degrade the beam quality and cause undesirable vertical and radial beam oscillations. Nowadays, an influence of the particular effects is being intensively studied with the goal to decrease the H^-/D^- beam losses in the central region. Intensive beam currents of positive ions are extracted from the internal H^-/D^- ion source as well. Their impact on the non-cooled mechanical parts can lead to their destruction and result in discharges and consequently in an unstable cyclotron regime. In order to avoid these efects the trajectories of positive ions at different cyclotron regimes were simulated. The parasitic positive ions can be stopped on the newly designed specially shaped puller electrode with a silver brazed water cooling loop and individual cooling circuit. Molybdenum was chosen as the material resistant to bombarding ions with a sufficient thermal conductivity and good machining property. The operation with negative ions was stabilized.

2.2. Vacuum system

The cyclotron vacuum system was not originally designed and optimized from the point of view of the negative ion acceleration where the residual gas pressure is a parameter of a great importance. Especially, the connection of the difussion pump to the vacuum cyclotron chamber and RF system with the 180^0 dee slit of 20mm inner height did not promise the optimal residual gas pressure in the median accelerating plane. This fact was confirmed by the calculated gas pressure (~ 4.3 x 10^{-3} Pa inside the dee at the radius 37.5 cm, with an internal ion source), and consequently by the calculation of the gas stripping losses. An additional difussion pump had to be installed and the old difussion pumps were replaced by the new ones of Balzers production. The total pumping speed has increased approx. by the factor of 1.5 and the H^- beam currents increased twice at the extracting radius of 37.5 cm

The beam losses were evaluated by the relation (1) derived from [1], [2]:

$$\frac{I}{I_1} = \exp(-K \cdot \frac{p \cdot W_{50}^{0.23} \cdot r^{1.46}}{U_d}) \qquad (1)$$

I = beam current at the radius r
I_1 = beam current at the first radius
K = gas stripping constant, experimentally evaluated
p = measured gas pressure
W_{50} = beam energy at the final radius in MeV
r = beam radius in cm
U_d = dee voltage in kV

Calculated (full line) and measured (line with boxes) beam losses with the internal ion source are displayed in Figure 1.

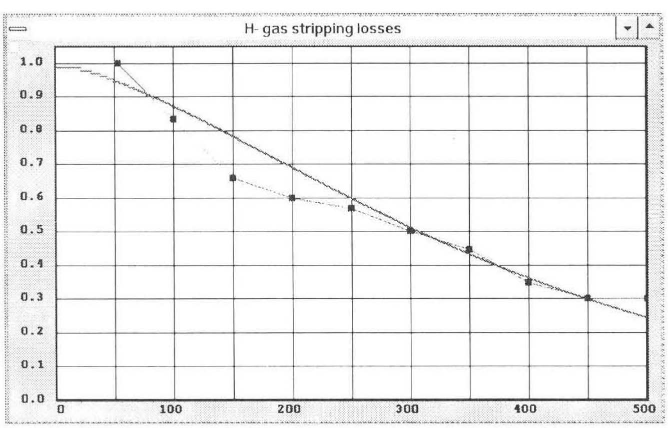

Figure 1. H^- gas stripping beam losses with internal ion source

3. External ion source

In the frame of the cooperation between TRIUMF and NPI, an old TRIUMF CUSP ion source for production of high intensive H^-/D^- currents has been lent to the Accelerator Department. The source was supplemented by the HV platform, the power supply system and extraction optics, which was optimized by means of the AXCEL code. After installation into the axial injecton system, up to 1.3 mA of H^- ions has been easily extracted. The parameters of the axial injection system of the U-120M [4], [5] commissioned in 1992 were tested with high intensive H^- beam currents. The layout of the injector with the average transmission coefficients for the 1mA of H^- ions at the particular points are shown in Figure 2.

Employment of the two-gap first harmonic buncher resulted in the beam current increase by the coefficient of 3.5 for the 50μA H^- beam current whereas the 1mA H^- beam was increased by the factor of 1.1.

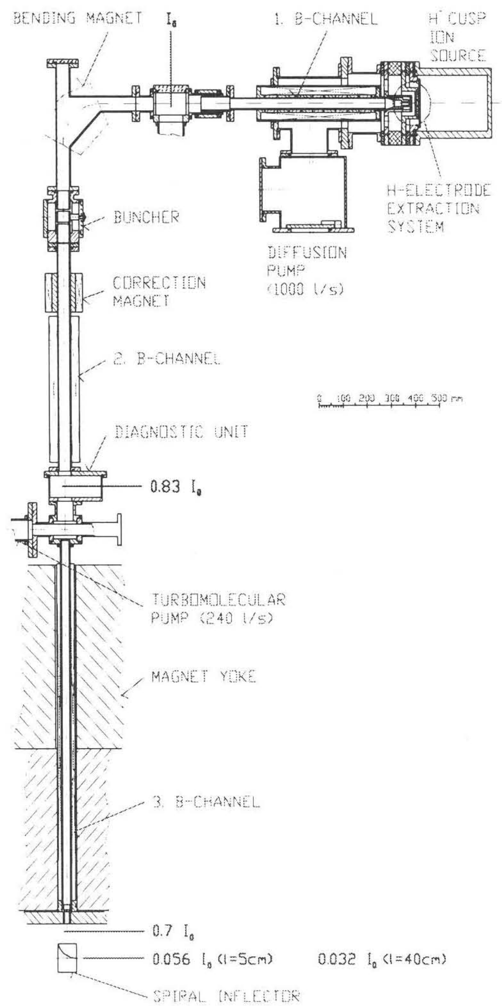

Figure 2. Layout of the axial injector with the transmission coefficients (buncher OFF)

The maximum H^- beam current at the final radius was 37μA (recalculated for the cw regime).

4. Internal ion source

The internal ion source of the PIG type with a hot cathode routinely used on the cyclotron was not suitable for the production of the H^-/D^- ions with high current intensity. The development of a new ion source producing high intensive beam currents of the H^- ions has been accomplished. The experience with the similar ion source optimalization [3] has been taken into account. The source performance has been optimized in terms of the H^- production, the arc volume geometry (the extraction slit dimension, the plazma gap width etc.), the gas flow, and the cathode temperatute. The DC output deduced from the beam current measurement (12μA) at the extracting radius 37.5 cm, RF phase width (~ 50^0), duty cycle (20%), and vacuum characteristics, was in the range of 1.5 - 2 mA. The ion source can also produce higher beam currents of positive ions than the old one. For that reason, it is successfully used for the cyclotron operation. both in the positive and negative regimes without changing the ion source and venting the cyclotron vacuum chamber. The reduction of operator's radiation doses and a better residual vacuum were achieved.

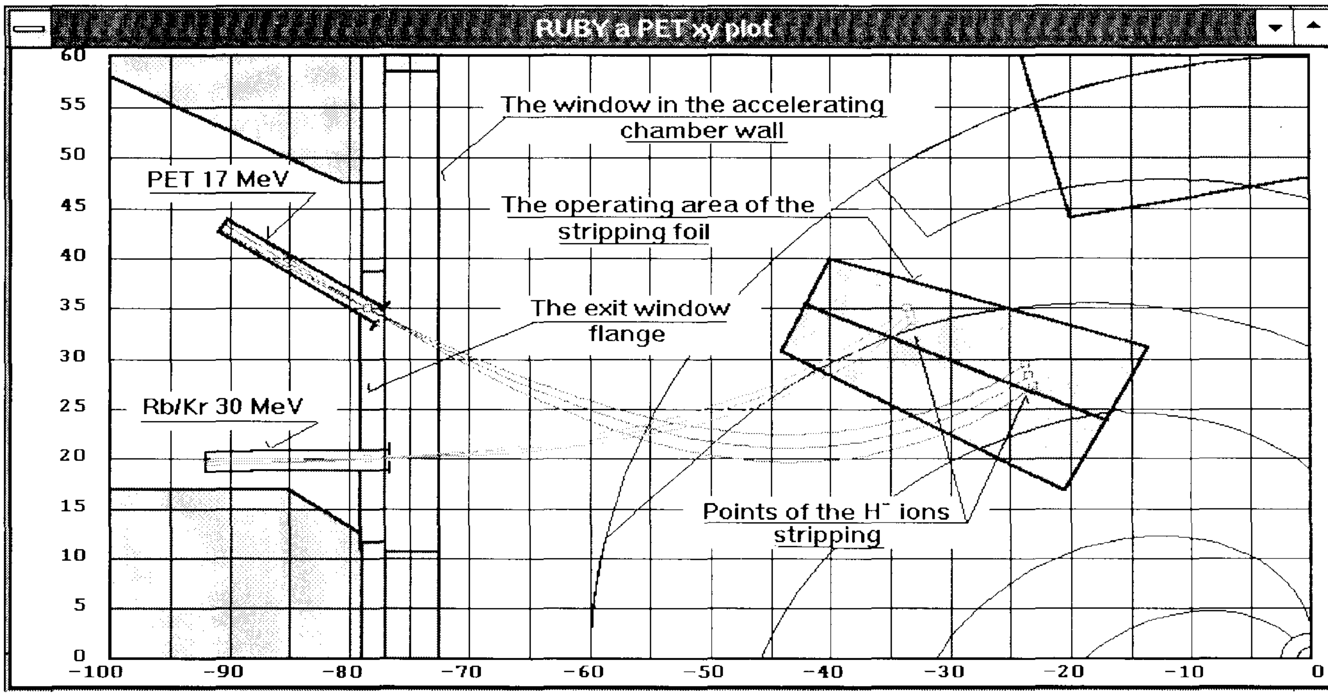

Figure 3. Extraction of the 17MeV and 30MeV protons

5. External target irradiation

5.1. Acceleration regime

The parameters of the acceleration regime were calculated and optimized by using the mathematical model developed at the Accelerator Department of the NPI. The detailed description of the model together with the cyclotron control system is presented in [6]. The requirement of a simultaneous acceleration and extraction of both 17 MeV protons for the PET radionuclides production and 30 MeV protons for the Rb/Kr generator was taken into account. The H^- regime with the energy of 32.9MeV at the final radius has been chosen and tuned. The magnetic coil currents and consequently the energy consumption were minimized in order to reach the minimum of operation costs in this regime.

5.2. Extraction of negative ions

The simulation of the ion beam extraction to the PET and Rb/Kr target positions were carried out. The goal was to define operating area of the stripping foil which would enable to deliver the beam to two independent target positions just by a change of the foil position, without retuning of the cyclotron regime. Restrictions given by the construction of the cyclotron vacuum chamber were taken into account. The extraction of the 17MeV resp. 30MeV protons from the regime with the energy of 32.9MeV at the final radius is shown in Figure 3. Based on the calculated area, the supporting mechanism of the stripping foil has been designed and manufactured. The control and power supply unit has been also developed and implemented into the cyclotron control system [6].

6. External targets

6.1. ^{18}F liquid target

The development and realization of the new target system is usually a long time process requiring a lot of experience in many directions. Particularly, in case of the liquid target where the ^{18}F is produced from the enriched water H_2O^{18} via the reaction $^{18}O(p,n)^{18}F$, the choice of target materials is a crutial point. In order to shorten the time of realization, the commercially produced target system from GEMS company (Uppsala, Sweden) has been purchased. For economical and technical reasons, we have bought only the target body and the target control panel. The system has been supplemented by the compressed air circuit, the He-cooling loop, and the He-filling circuit. An electronic control unit which controls valves and stepping motor, and scans all needed data during the whole process has been developed.

By using time sequences of the particular procedures, necessary control software utilities for routine operation and service have been debugged. The target is controlled via the FEC PC (Front End Computer) in the Ethernet LAN [6]. The view of the target control panel is shown in Figure 4.

The target procedures were tested in details and the target facility has been succesfully set into operation. The average yield of the ^{18}F production in a routine operation is ~ 2GBq/μA.hour at EOB. The maximum current on the target was 25μA.

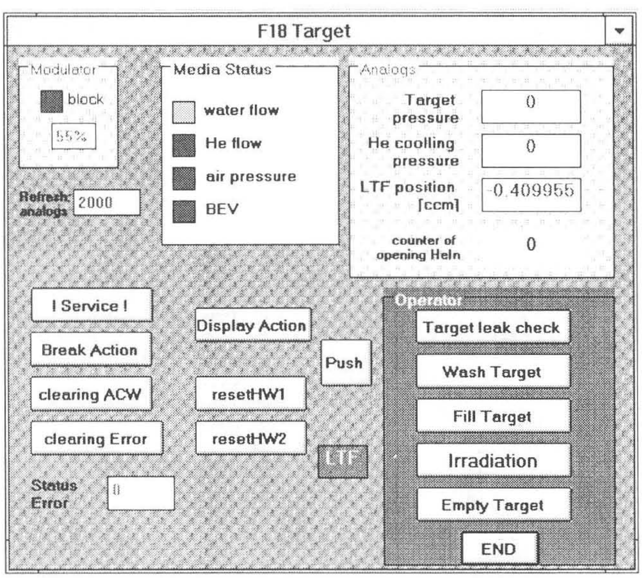

Figure 4. ^{18}F target control panel

6.2. ^{81}Rb/^{81m}Kr gaseous target

The prototype of the pressurised gaseous target for the production of ^{81}Rb via the nuclear reaction Kr(p,xn)Rb has been developed in the Nuclear Spectroscopy Department of the NPI. Using natural Kr as the target material, the yield of approx. 7GBq in 4 hour run has been achieved.

7. Conclusion

The U-120M cyclotron was not originally designed for acceleration of negative ions. Therefore, it was necessary precondition to evaluate if the vacuum capability is suitable for the H^- operation or if it can be upgraded to reach a sufficient residual gas pressure.

The experiments with the H^- accelerated ions both from the external CUSP and developed internal ion source shown that the extracted beam currents of several tens μA can be achieved. Consequently, the old cyclotron can be used for new applications (i.e. production of the ^{18}F radionuclide and the generator Rb/Kr).

In order to increase the beam current intensity, the vertical H^- beam losses at the first orbits has to be reduced.

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