DESIGN OF A DUAL EXTRACTION SYSTEM FOR THE ULTRA-COMPACT MULTIFUNCTIONAL CYCLOTRON CYCIAE-36A

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Abstract

The growing demand for medical isotopes and mobile neutron sources has motivated the development of compact and multifunctional accelerators. China Institute of Atomic Energy (CIAE) has developed an ultra-compact superconducting cyclotron, CYCIAE-36A, capable of accelerating H_2^+ and α particles and delivering proton and α beams for applications including ^{211}At production, PET isotope supply, α-irradiation studies, and neutron imaging. The highly compact layout leads significant challenges for beam extraction. A dual extraction system combining electrostatic deflection and carbon-foil stripping is proposed under the constraints of superconducting magnets, RF cavities, and limited space. In this scheme, α particles are extracted using an electrostatic deflector, while H_2^+ ions are extracted by stripping, enabling variable-energy proton beams in the opposite direction. Phase width control is critical for extraction efficiency. Particle tracking simulations starting from the central region assume phase widths of 20° for α particles and 40° for H_2^+ ions, yielding extraction efficiencies of 85% and 99%, respectively. In addition, the effects of 1st and 2nd harmonic magnetic field components introduced by the magnetic channels during precession extraction were analysed, and corresponding compensation methods were developed to mitigate their impact on beam dynamics.

INTRODUCTION

The strong demands for α particles and high-intensity proton beams in novel α -emitting radionuclide R&D, mobile neutron imaging, solid-target radionuclide production, industrial irradiation have made multi-purpose accelerators an increasingly active area of research. It directly supports national imperatives for comprehensive research platforms and medical-engineering applications. Globally, cyclotrons delivering high-energy α particles are costly and massive, and primarily devoted to basic research (e.g., Russia's Dubna U-200/U-400 [1], Italy's INFN-LNS K800 [2], and South Africa's iThemba K200 [3]).

In the 1960s and 1970s, a few commercial cyclotron manufacturers developed a limited number of normal-conducting heavy-ion cyclotron models to meet the needs of that era, capable of accelerating H^+, H^-, and α particles. With the subsequent rise of the medical radioisotope market, these accelerators have been used mainly for accelerating H^- ions to produce common medical isotopes.

CIAE proposed an ultra-compact superconducting cyclotron. Characterized by its highly compact structure, low cost, and low power consumption, it provides a flexible scientific solution for the aforementioned applications. By utilizing low-temperature superconducting (LTS) technology, external dual beam injection, and bidirectional extraction, it simultaneously accelerates and extracts both α particles and H_2^+ ions, achieving a "five-in-one" multi-purpose functionality.

The overall schematic of CYCIAE-36A and principal parameters are presented in Figure 1 and Table 1, respectively.

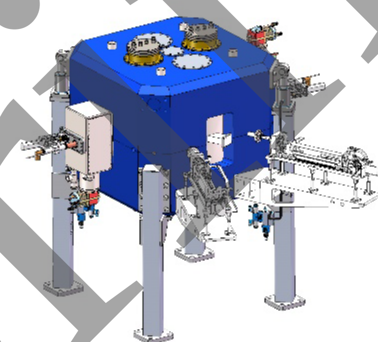

Figure 1: Schematic diagram of CYCIAE-36A.

Table 1: Main Parameters of CYCIAE-36A

Parameters	Value
Sector number	4
Pole radius [cm]	45
Angle of Pole [deg]	42.3
Central field [T]	2.138
RF frequency [MHz]	65.5/65.27
Dee voltage [kV]	50
Weight of Magnet [t]	12.6

EXTRACTION METHOD

The ultra-compact architecture of the CYCIAE-36A imposes strict constraints on the space available for the extraction system. Accommodating the extraction elements for two distinct particle types in a conventional, unidirectional layout is physically infeasible. To address this fundamental spatial constraint, a bidirectional extraction system is proposed.

Because α and H_2^+ possess fundamentally different physical characteristics, their extraction mechanisms must be tailored accordingly. By separating the two extraction paths to opposite sides of the machine, the extraction system optimally utilizes the limited valley space.

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This work was supported by the National Natural Science Foundation of China under Grant of 12427810.

Extraction of α Particles

As α particles are fully stripped from helium nuclei, charge-exchange extraction is not feasible. Therefore, utilizing an electrostatic deflector (ESD) is considered. The ESD is positioned on the pole of the magnet to provide a strong DC electric field, providing the necessary radial kick to separate the beam from the last orbit. Due to the limited internal space, an extraction scheme based solely on acceleration-driven turn separation was initially considered. The turn separation is determined as follows [4]:

$$\Delta r(\theta_n) = \Delta r_0(\theta_n) + \Delta x \sin(2\pi n(\nu_r - 1) + \theta_0) + 2\pi(\nu_r - 1)x \cos(2\pi n(\nu_r - 1) + \theta_0) \quad . \tag{1}$$

The calculated turn separation contributed by acceleration is approximately 3.3 mm. However, with an emittance of 2 pi·mm·mrad, the radial beam envelope exceeds 2 mm. In addition, to achieve complete single-turn extraction via acceleration, the required RF peak voltage can be derived from the following expression [5]:

$$\frac{qV_{rf}}{E} \geq \pi N_h \gamma(\gamma + 1)\frac{g^2}{R^2} \quad . \tag{2}$$

According to the formula, the loop energy gain needs to be greater than 2.27 MeV to achieve accelerated extraction, which is an order of magnitude higher than the current performance. Therefore, it is necessary to increase the turn separation by crossing resonance ν_r=1 and the precession.

After crossing the ESD, the deflected α beam is subsequently guided through a series of passive magnetic channels to safely traverse the steep gradient of the cyclotron's fringe field.

Extraction of H_2^+ Particles

Unlike α particles, H_2^+ ions retain a bound electron and can undergo charge exchange. A carbon-foil stripping mechanism is employed on the opposite side of the cyclotron. When the H_2^+ ions cross the stripping foil, the electron is stripped away, instantly converting the molecular ion into two protons H^+. This sudden alteration in the charge-to-mass ratio (from 1/2 to 1) drastically reduces the magnetic rigidity of the particles, causing the protons to sharply move inward and exit the main magnet. A primary advantage of this method is the capability to deliver variable-energy proton beams simply by adjusting the radial and azimuthal placement of the stripping foil.

The bidirectional arrangement of the electrostatic deflector and stripping foil resolves the space constraint of the ultra-compact design, separates the proton and alpha beamlines, and simplifies layout for five-in-one operation.

DUAL EXTRACTION SYSTEM

Electrostatic Deflection System

The electrostatic extraction system comprises the electrostatic deflector (ESD) and extraction magnetic channels. The primary objective of the extraction design is to establish a viable extraction trajectory while optimizing component layout and parameters to maximize extraction efficiency. For the CYCIAE-36 cyclotron, extraction is implemented using a single electrostatic deflector followed by passive focusing elements for beam transport. In this specific machine, the critical factors governing extraction efficiency include the radial oscillation amplitude, the thickness of the septum, and the beam centering conditions. Given a relatively large phase width, any off centering will induce beam precession during acceleration, thereby increasing the oscillation amplitude. Consequently, stringent requirements are imposed on beam centering within the acceleration region. The centering results, tracked from the central region to the acceleration zone, are illustrated in Figure 2.

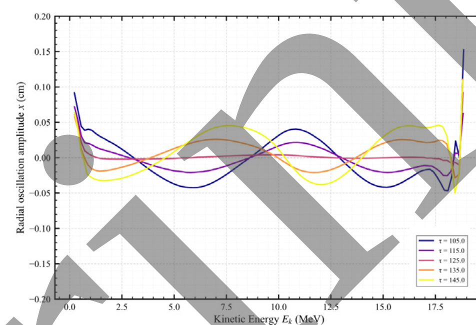

Figure 2: Radial motion during acceleration.

The extraction workflow comprised initial multi-particle tracking from the matched central-region phase ellipse, septum positioning from the radial density at the deflector entrance, single-particle determination of deflector voltage, arc length, and curvature, iterative efficiency optimization, envelope control with magnetic channels, and harmonic-field compensation.

The resulting multi-particle trajectories are shown in Figure 3, and the ESD parameters are listed in Table 2. After the ESD, the beam stays within one RF dee, is guided by the magnetic channels, and exits through the extraction port. The optimized design yields an extraction efficiency of about 85%.

Table 2: Main Parameters of ESD

No.	E[kV/cm]	Voltage[kV]	Width [deg]
1	95	57	37

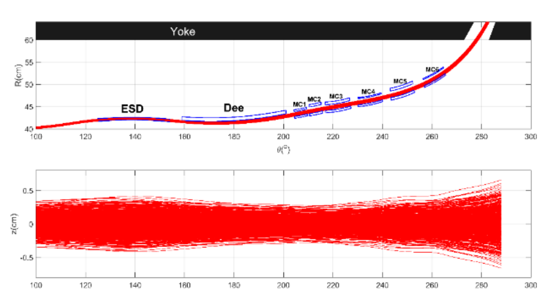

Figure 3: Trajectory and envelope of extracted beam.

To generate the first harmonic required for precessional extraction, we assessed using the magnetic channels instead of tuning coils or trim rods. Superposing the first harmonics from MC1-MC6 and C1-C2 yields a resultant first harmonic of 4 Gs at 360°, shown in Figure 4. This simplifies hardware, but its limited tuning range must be coordinated with field shimming results.

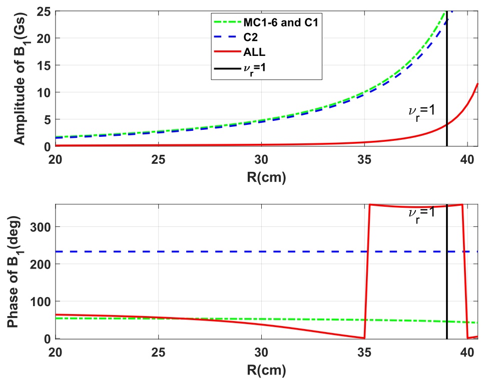

Figure 4: Amplitude and phase of the 1st field.

Stripping Extraction System

The simulation of the H_2^+ stripping trajectory was performed using Goblin, a single-particle tracking program rewritten by CIAE. Two-dimensional parameter scans (energy E and angle θ) were conducted at different angles to extract two energy beams without crossing the central region and the RF gap.

Based on the parameter scans, the stripping foil was placed at two working positions to cover two energy ranges. The reference operating points were (25.3°, 6.5 MeV) and (65°, 9 MeV); the lower-energy beam is extracted after two turns, whereas the higher-energy beam is extracted after one turn.

The two extraction trajectories almost intersect at a single point at the yoke (see Figure 5). A switching magnet is installed outside the magnet to adjust the directions of two beams so that the beams of two energies enter the same beamline.

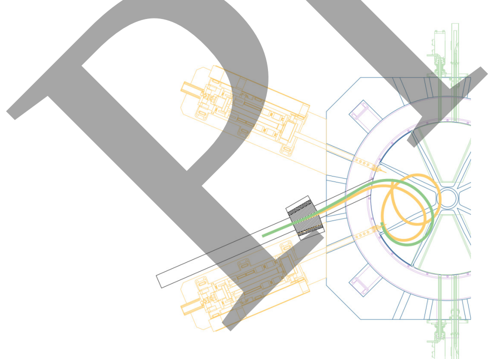

Figure 5: H_2^+ beam trajectories for different extraction energies.

The simulations described above were performed using single-particle tracking and not including space charge effects. Since the high-intensity proton beam extracted from CYCIAE-36A is expected to reach mA level, multi-particle simulations including space charge effects are essential. To this end, the OPAL code was employed to simulate the extraction region. The initial beam parameters were as follows: E0=1.82 MeV, a phase width of ±20°, and a normalized transverse emittance of 4 pi·mm·mrad. A beam current of 1 mA was simulated, and the initial beam was assumed to have zero energy spread. The stripping point was located at an azimuthal angle of 68° and a radius of 41.5 cm, with a stripping foil tilt angle of 12°. The simulation results indicate that the beam spot size at the stripping foil is approximately 4 mm × 6 mm, and the extracted beam exhibits an energy spread of 0.073 MeV. The corresponding parameters are summarized in Table 3.

Table 3: Extracted Beam Parameters

Parameters	**Value**
ϵ_x [pi·mm·mrad]	11.84
x [mm]	5.24
x' [mrad]	5.67
ϵ_z [pi·mm·mrad]	12.86
z [mm]	2.37
z' [mrad]	5.76
$\Delta E/E$ [%]	3.28

For H_2^+ extraction in CYCIAE-36, the stripping foil receives energy from both the ions and the stripped electrons. For a 1 mA, 18 MeV beam, the H_2^+ ions deposit 6.9 W on the foil, while the electrons deposit 24.8 W in the foil and frame, with about 4 W lost elsewhere in the accelerator.

The final layout of the dual extraction system is shown in Figure 6. One branch contains the ESD, six magnetic channels, and compensation irons C1 and C2, whereas the stripping branch uses two targets for different proton energies. The opposite-valley layout keeps the system nearly symmetric, reduces first-harmonic perturbations, and still requires validation in the strong superconducting field.

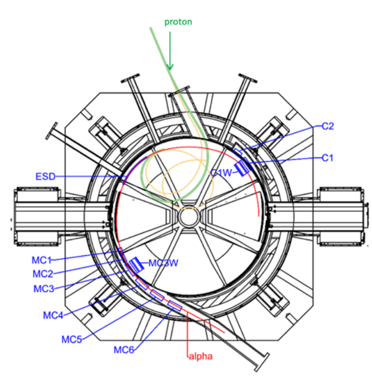

Figure 6: Overall layout of the dual extraction system.

CONCLUSION

A dual extraction scheme was designed for the ultra-compact CYCIAE-36A cyclotron. Electrostatic extraction is used for alpha particles and charge-exchange stripping for H_2^+ ions, providing variable-energy proton beams with acceptable simulated beam quality in a symmetric layout.

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