COMPACT CYCLOTRON AS A PROTON SOURCE FOR THE DETECTION OF EXPLOSIVES BASED ON NUCLEAR RESONANCE ABSORPTION IN NITROGEN

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Abstract

In the proposed operational implementation of the Nuclear Resonance Absorption (NRA) method for explosives detection, the inspected object is scanned by a beam of 9.17-MeV gamma rays of a precise energy to determine the fraction of the beam resonantly absorbed in the nitrogen nuclei of the explosive in the reaction, ^{14}N (gamma, p) ^{13}C. The 9.17-MeV gamma rays are most readily generated in the inverse reaction, ^{13}C (p, gamma)^{14}N, in which a 1.747-MeV proton is resonantly captured by C^{13}, followed by the emission of gamma rays from the recoiling N^{14} nucleus. To achieve the stringent requirements of a 1.747-MeV proton beam with an intensity of several milliampere and with as small as possible energy spread and angular divergence, a compact isochronous cyclotron with internal H^{-} ion source and current of ~2mA was considered as a stand-alone source or as an injector (with a current of ~200 microA) into a storage ring. This report describes the main cyclotron design consisting of an internal ion source, magnet, acceleration system, extraction system, and beam delivery system.

BACKGROUND

Earlier investigations [1], [2], [3], [4], [5], [6] of the beam dynamics in a cyclotron with an external H^{-} source resulted in the following characteristics:
maximum current (~1.8 MeV): 2.2-2.5 mA,
transverse emittances: 150-300π mm·mrad,
energy spread, ΔE/E: ±8%.
Since these beam parameters do not meet the proton source requirements for nuclear resonance absorption, a cyclotron with a reduced current of ~200 μA with the transverse emittances and the energy spread reduced by an order of magnitude was proposed. This tailored beam could then be injected into a small storage ring in which the desired final beam parameters could be achieved.

To simplify the design and reduce costs, an internal ion source was examined with 6 mA of H^{-} ion current into the continuous mode of the cyclotron. Due to the 30-fold decrease of the average captured beam current for acceleration (from 6 mA to 200 μA), delimited by a diaphragm on the first turn, it became possible to reduce the transverse emittances and the energy spread. Calculations were performed taking into account the 3-D distributions of the electric fields of beam space charge as well as the field of the accelerating system.

BASIC CYCLOTRON PARAMETERS

The basic cyclotron parameters are listed in Table 1. The general view of the cyclotron is shown in Fig. 1

Table 1. Basic cyclotron parameters

Type of ion	H^{-}
Extraction energy, keV	1747
Average magnetic field, T	0.64
Number of sectors	4
Number of dees	2
Betatron frequencies, Qr , Qz	1.1, 0.85
Angular span of dees, (°)	45
RF voltage, kV	60
Orbital frequency, MHz	9.76
Harmonic number	4

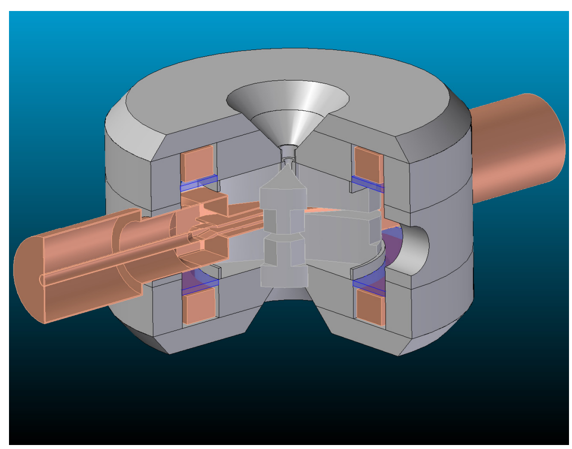

Fig. 1. Magnet and RF structures

MAGNET

The 4-fold type magnet with all-round yoke chosen for the cyclotron (Refs [2] and [7]) is shown in Fig. 1. The magnet poles and yoke shape the vacuum chamber for this design. The parameters of the magnet are given in Table 2.

Table 2. parameters of the magnet

magnet height	89 cm
magnet outer radius	70 cm
pole outer radius	35 cm
final orbit radius	30 cm
hill field at final radius	1.35 T
valley field	0.2 T
hill gap	3 cm
valley gap	40 cm
sector angular width	10º-30º
power consumption	10 kW

The choice of magnetic field strength (0.64 T) is a compromise between several options. The higher the field, the smaller will be the cyclotron size. A higher magnetic field also ensures a larger space-charge limit due to the effects of increased axial focusing. On the other hand, the turn separation is decreased along with the extraction efficiency.

ACCELERATION SYSTEM

The radio frequency (RF) system consists of two resonators with two 45º dees (the axial-dee aperture is 20mm) located in the opposite valleys (Fig. 1) and with two resonance lines supplied by feeders and RF voltage and phase stabilization and control.

The RF frequency ~39 MHz corresponds to the 4^{th} harmonic of the ion orbit frequency. The accelerating voltage amplitude is U=60 kV and the peak energy gain per turn is ΔW=4U. The dissipated power in each resonator is ~5 kW.

Electric field simulation of the selected electrode structure was performed with the help of the well-known computer code "Mermaid" [8], [9]. The purpose of this calculation is to generate the spatial distribution of the acceleration electrical field to be used for the beam dynamics study.

BEAM ACCELERATION

When the cyclotron is used as an injector, the system consists of a compact cyclotron, a beam delivery system (BDS), and a storage ring [10]. Given the requirement for the beam intensity and quality, H^{-} ions were selected for acceleration in the cyclotron with the goal of achieving high-efficiency extraction by the electrostatic deflectors(ESD1: E=28.6 kV/cm Grad=–3.7 kV/cm^2; ESD2: E=28.6 kV/cm, Grad=–14.8 kV/cm^2) and magnet(MC: B=0.45T, Grad=0 T/m).The tracking calculations in the cyclotron were performed by the homemade CBDA code [11] taking into account beam space-charge effects [12]. The main criteria imposed in the selection of the operational parameters were good centering, as high as possible energy gain of the ions in the accelerating gaps, maximum transmission through the machine, and the best possible beam quality at the final energy. Adjusting the corresponding parameters of the cyclotron optimized the overall performance of the system. Simulation of the interface between the cyclotron and the storage ring was performed in order to provide the required intensity and beam quality for injection into the storage ring.

The projections of the emittance of the extracted bunch at the entrance of the BDS are given in Fig. 2.

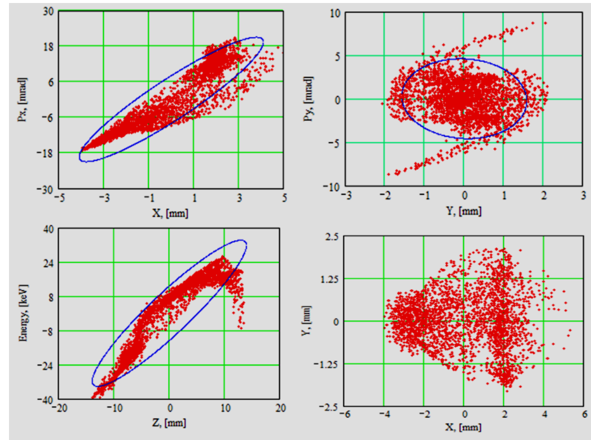

Fig. 2. Effective emittance of the beam at the BDS entrance, 260 µA beam intensity

BEAM DELIVERY SYSTEM

Dedicated structure elements in the injection channel provided dispersion control at the storage-ring injection. The optical elements were chosen to regulate the beam parameters at the target point--beta functions and dispersion. By adjusting the corresponding parameters of the cyclotron and the BDS, the required intensity and beam quality for injection into the storage ring were provided.

Figure 3 depicts the layout of the cyclotron, the BDS with the structure elements mentioned above, and the storage ring. H– ions from the cyclotron strike charge-exchange target 1 H^{-}–→H_0 and, subsequently, charge-exchange target 2 H_0→H_+. The dispersion function at target 2 is controlled to provide the proper correlation between the particle momentum and horizontal position needed for injection into the storage ring. Two triplets and a bending magnet were selected to satisfy the majority of the requirements.

Estimation of the BDS parameters requires knowledge of the energy dispersion function *D* and its derivative *D*_ along the beam central trajectory at the exit of the cyclotron. To define those parameters, the dependence of the particle energy on its transverse horizontal displacement from the central trajectory was calculated at two successive points along the trajectory. The results obtained at the BDS entrance, summarized in Table 3, show the impact of the space charge on the beam quality. The results were used for particle tracing through the BDS to the injection point in the cooling ring.

In order to eliminate a mismatch between the injection parameters and the beam, i.e., beam widening in the ring, the necessary energy dispersion of the beam Fig. 4 was produced in the injection channel. The improved qualities of the injected beam, compared to the previous case, permit a substantial increase _by a factor of 4, up to 40% in the intensity of the particles captured into the ring.

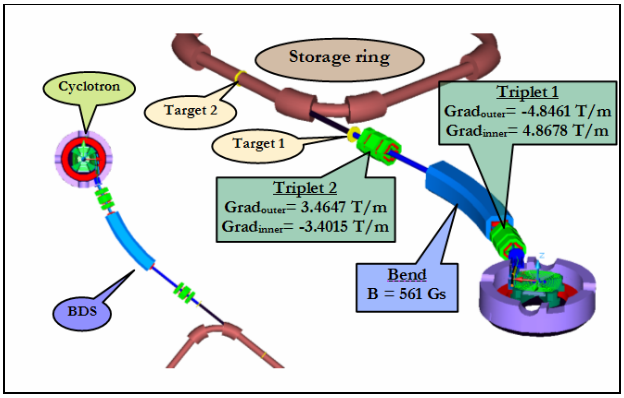

Fig. 3. General view of the facility

Table 3. Beam characteristics at the BDS entrance

Intensity, µA	**100**	**260**
Effective horizontal emittance, π•mm•mrad	24.2	33
Uncorrelated horizontal emittance, π•mm•mrad	3.1	4.9
Energy dispersion function, cm	14.3	15.3
Energy spread, keV	31	34
Axial emittance, π•mm•mrad	3.2	7.2
Longitudinal emittance, π•mm•keV	155	177

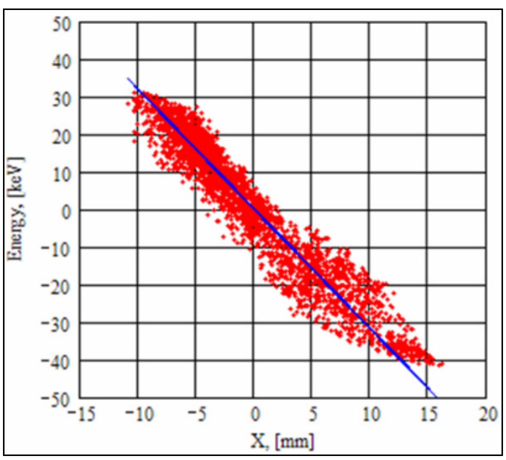

Fig. 4. Estimate of Dispersion at storage-ring injection poit,130µAbeam current

CONCLUSIONS

The beam characteristics at the point of injection into the ring approximate what is required by the storage ring designers. The injection parameters allow ~ 0.1 A of the proton current to be stored according to the numerical simulation. This current is sufficient to conduct the experiments.

The set of optical elements in the injection channel are sufficient to regulate the beam parameters at the target point (beta functions and dispersion) in order to cope with expected experimental uncertainties in the settings of the cyclotron and storage ring.

Development of the cyclotron-storage-ring accelerator system is technologically high-risk but high payoff, and it will require a dedicated experimental effort of significant magnitude to quantify critical issues such as electron cooling and proton beam stability in the storage ring. If such cyclotron-storage-ring system can be realized, this technology will open many new possibilities for applications of high-quality and high averaged current proton beams.

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