PROGRESS ON BEAM DYNAMICS STUDIES FOR THE ISRS ISOCHRONOUS RING SPECTROMETER *

F. Taft†, Y. Fontenla, J. Giner-Navarro, J. Resta-López
Instituto Universitario de Ciencia de los Materiales (ICMUV), Valencia, Spain
I. Martel , Universidad de Huelva, Huelva, Spain
E. Martínez-López , Instituto de Física Corpuscular (IFIC), Valencia,Spain

Abstract

A new lattice configuration is being developed for a compact, isochronous ring for the ISRS project, as an innovative spectrometer at HIE-ISOLDE. The design incorporates ten combined-function, Canted Cosine-Theta (CCT) superconducting magnets, enabling the ring to fit within a constrained 5x5 meter hall space. This design presents significant challenges, particularly in accommodating the injection and extraction of a high beam rigidity beam, as the CCT magnets mechanical dimensions severely limit the space available for these subsystems. Using Xsuit code simulations, the performance of beam injection and extraction, based on a high-field, superconducting septum and a fast magnetic kicker, is evaluated, along with the time-of-flight separation of various isotope ion products from selected nuclear reactions of interest.

INTRODUCTION

The discovery and study of exotic, short-lived nuclei have expanded our understanding of nuclear matter evolution and element formation in the universe. To access these rare isotopes, nuclear physics laboratories rely on advanced separators and detector systems [1]. The High Intensity and Energy ISOLDE (HIE-ISOLDE) linac accelerator [2] plays a pivotal role in this endeavor, capable of accelerating radioactive isotopes to energies between 0.5 and 10 MeV/u, producing over 1300 isotopes spanning 70 elements, from ^{6}He to ^{234}Ra. In order to enhance the experimental capabilities of the HIE-ISOLDE infrastructure, a compact high-resolution spectrometer, known as the ISOLDE Superconducting Recoil Separator (ISRS), was first proposed to separate reaction fragments from a primary beam of radioisotopes [3]. The design of the proposed ring leverages the compactness and high field quality of Canted Cosine-Theta (CCT) superconducting magnets, which integrated dipole and triplet focusing quadrupoles into a 90-degree sector bend [4, 5]. Recent progress in the manufacturing of these magnets has led to a shorter magnet design, consolidated in the MAGDEM prototype demonstrator [6], featuring a 36-degree bend, with combined dipole and quadrupole functions.

This paper details the new beam dynamics designs for the ISRS ring, based on the actual dimensions and specifications of MAGDEM. We explore the lattice tuning to achieve isochronous conditions, and mass-to-charge ratio separation using time-of-flight (TOF) detectors, alongside injection and extraction strategies tailored for high magnetic rigidity beams.

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† fataft@uv.es

MAGNETS

The main component of the ISRS ring lattice is the already mentioned MAGnet DEMonstrator (MAGDEM), a Nb-Ti superconducting, helium-free, iron-free, CCT system under development at CERN [6]. MAGDEM integrates dipole and quadrupole coils into a compact, tapered structure, achieving a 36° bend with field errors below 1 unit at 4 T. Operating at 100 A and 4.5 K via a single cryocooler, it combines energy efficiency with mechanical stability. A shematic drawing of MAGDEM is depicted in Fig. 1 and a summary of the magnet specifications are detailed in Table 1.

Table 1: MAGDEM Parameters.

Parameters	Values
Total length	720 mm
Effective length	580 mm
Maximum Dipole field	2.2 Tm
Maximum gradient	10 T/m
Aperture size diameter	200 mm

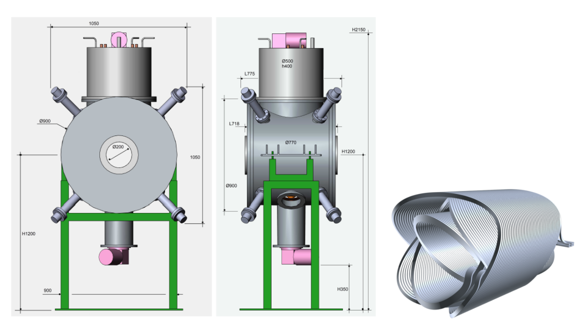

Figure 1: View of MAGDEM fully-integrated system and only magnetic coils.

ISRS RING DESIGN AND PRINCIPLE

Considering the actual dimensions of the magnets, the ISRS ring (Fig. 2) features a symmetric lattice comprising ten CCT magnets arranged in two arcs. Each magnet provides a bending angle of 36°, forming a closed orbit optimized for $^{234}Ra^{+53}$ ions at an energy of 10 MeV/u. The speed of these ions present a Lorentz factor of γ =1.01054 and the magnetic rigidity of the beam is 2.01 T · m. The lattice adopts an alternating FDFDF quadrupole pattern, where "F" (focusing) and "D" (defocusing) quadrupole magnets are utilized to stabilize transverse beam dynamics. Two straight sections are reserved for essential subsystems, such as injection, extraction, and diagnostic instruments.

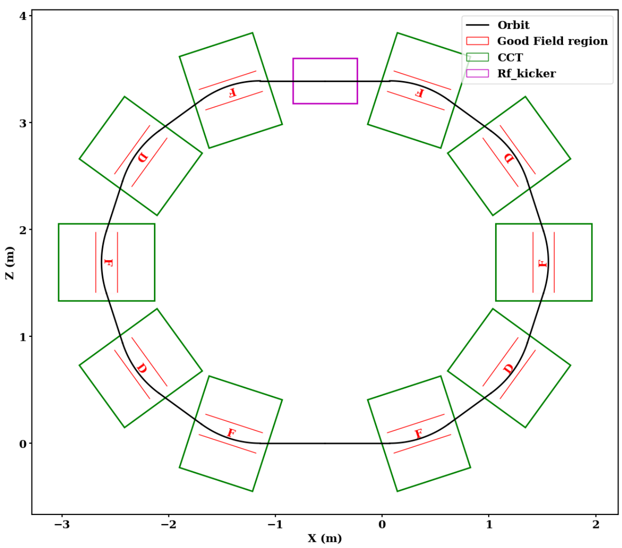

Figure 2: Floor layout of the ISRS ring.

The beam is injected into the main orbit via an Radio Frequency (RF) kicker. Due to differences in magnetic rigidity, ions with varying mass-to-charge ratios travel on different trajectories within the ring, resulting in distinct travel times. The operating principle of the spectrometer relies on time-of-flight techniques for particles stored in the ring. For an ion with a variation in mass-to-charge ratio $\Delta(m/q)$ and a velocity deviation Δv relative to the reference ion circulating in the ring, the deviation in the revolution period is expressed as [7]:

$$\frac{\Delta T}{T} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} - \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}, \tag{1}$$

where γ is the Lorentz factor, and $\gamma_t = 1/\sqrt{\alpha_c}$ is the transition energy factor of the ring. To ensure a constant revolution time in a storage ring that depends only on the mass-to-charge ratio of the particles, it is essential to eliminate the momentum-dependent variations introduced by the second term in Eq. (1).

This is achieved when the transition factor is approximately equal to the Lorentz factor of the reference beam, $\gamma \approx \gamma_t$. Such a condition represents the isochronous mode of operation, which is highly suitable for discriminating exotic isotopes with short lifetimes, as each species in the beam becomes temporally separated after just a few turns, regardless of their velocities.

At this point, it is necessary to remark that although the isochronous condition is generally valid, the resolution of the mass-to-charge ratio measurement also depends on higher-order contributions, from optical nonlinearities and aberrations, magnetic field errors, and fringe field effects [9]. In future studies, we plan to investigate in detail the performance of the ISRS lattice in the presence of magnetic high-order harmonics and imperfections, as well as explore correction methods to counteract their effects.

BEAM DYNAMICS STUDY AND PERFORMANCE

The beam dynamics for the ISRS ring are studied using the Xsuit code [10]. A combined-function magnet (rectangular bend), with an effective length of 580 mm, introduces dipole field and quadrupole gradients. The gradients of the magnets are adjusted to have isochronous modes in the ring. In this mode, the gamma transition aligns with the particle's gamma factor, γ = 1.01054. The particles completely eliminate the momentum dependency, and the time of flight of the ions is determined solely by their mass to charge ratio in linear calculation. Betatron tunes are set to (Q_x = 1.03, Q_y = 1.3), achieving a maximum dispersion of 2.03 m that is shown in the Fig. 3. This corresponds to 5 % momentum acceptance in the ring.

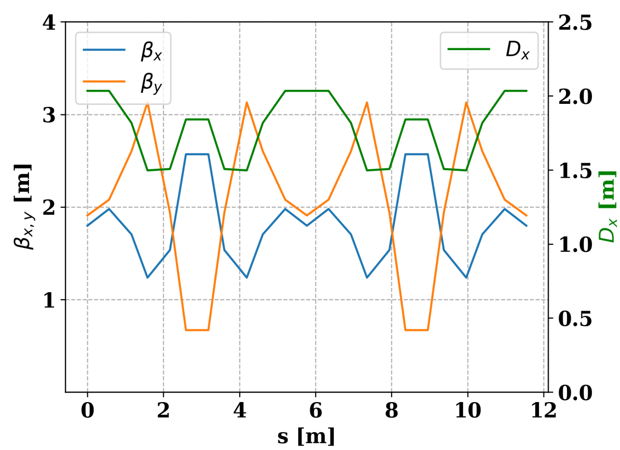

Figure 3: Betatron functions ($\beta_{x,y}$) and first order horizontal dispersion function (D_x) in the ISRS ring operating in isochronous mode.

Time of flight detection is essential for distinguishing particles based on their mass-to-charge ratio in the ISRS system. A particle bunch with an Emittance: $\varepsilon_{x,y}$ = 12.5 mm · mrad and 9 different mass-to-charge ratios is introduced at the center of the RF kicker. The storage ring enables precise mass separation using Xsuit simulations, where ^{234}Ra, as a reference ion with a charge state of +53, completes a revolution in 267.5 nanoseconds. Mass separation is achieved within 10 revolutions, with a time-of-flight difference of 11 nanoseconds between masses, as shown in Fig. 4.

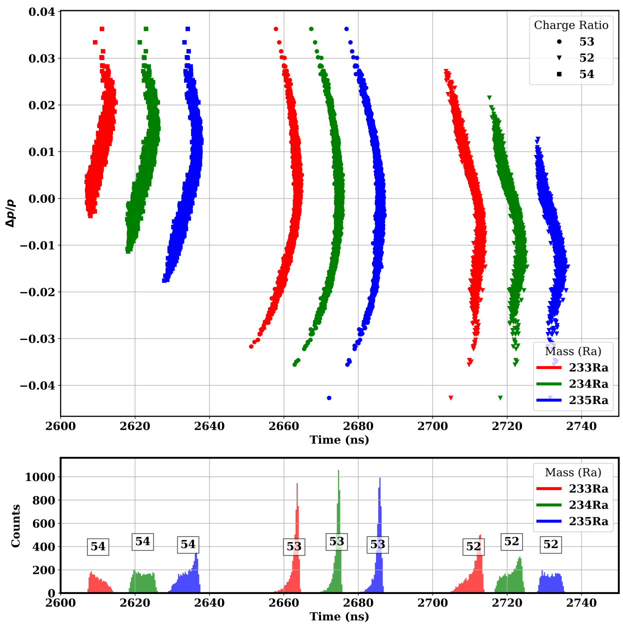

Figure 4: Time of flight separation after 10 turns in isochronous mode.

INJECTION AND EXTRACTION SUBSYSTEMS

The mechanical design of the Canted-Cosine-Theta (CCT) magnets in the ISRS ring occupies a significant amount of space, posing challenges for the incorporation of additional essential devices. A critical component in this setup is the injection system, which demands careful integration to ensure the efficiency of the particle trajectory within the ring. Due to the high magnetic rigidity of the ISRS ring, conventional electric kickers are not viable. Instead, a combination of an RF kicker magnet and a superconducting septum magnet (SuShi) has been identified as an effective solution for the injection process and similar setup for extraction [11]. The specification details of the RF kicker and Sushi magnet are depicted in Table 2. Figure 5 illustrates the beam trajectory, starting from the septum magnet and passing through two CCT magnet to decrease the required momentum deflection in the RF kicker. The key parameter in achieving a stable injection is maintaining a phase advance of $\pi/2$ between the septum and the kicker [12].

CONCLUSION

The development of the ISRS ring marks a significant advancement in the separation of short-lived radionuclides. Its compact design, featuring a specialized CCT magnet, enables compatibility with other separator rings while operating efficiently within a 5-square-meter space. The ring's capability to handle high-magnetic-rigidity particles in such a compact machine, occupying only 5×5 square meters, stands out as a key feature. In isochronous mode, particles with a $\gamma_t = 1.0105$ achieve sub-nanosecond precision. Through precise beam dynamic calculations, the ISRS demonstrates effective isotope separation after ten turns even for heavy ions, and particularly for $^{234}Ra^{+53}$ at 10 MeV per nucleon, the highest energy provided by HIE-ISOLDE linac. Resolving power of up to 11 ns is achieved in isochronous mode. For this reason, the ring is ideally suited for integration into this facility. Future work aims to incorporat sextupole magnets to fix higher-order chromatic issues and test the injection and extraction systems. The ISRS ring's in isochronous modes is a powerful tool for studying nuclear astrophysics and exotic isotopes. It helps uncover important insights into rare nuclear species.

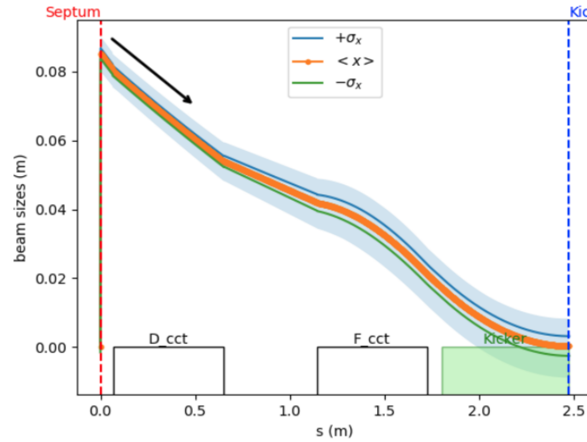

Figure 5: Beam envelope of injection system.

Table 2: Specifications for Septum and RF Kicker.

Septum parameters	
Bending Angle	45°
Effective Length	400 mm
Magnetic Field	3.8 T
RF Kicker parameters	
Kick Angle	50 mrad
Effective Length	600 mm
Magnetic Field	0.16 T
Integrated Field	0.1 T m
Pulse Rise/Fall Time	300 ns

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