# DESIGN AND BEAM DYNAMICS STUDIES OF A NOVEL COMPACT RECOIL SEPARATOR RING FOR NUCLEAR RESEARCH WITH RADIOACTIVE BEAMS

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### *Abstract*

The recent development of radioactive beam facilities has significantly expanded the capabilities for investigating the structure of the atomic nucleus and the nuclear interaction. For instance, the HIE-ISOLDE facility at CERN delivers presently the largest range of low-energy radioactive beam available worldwide. This energy range is ideal for the study of nuclear structure, low-energy dynamics and astrophysics by using nucleon transfer, Coulomb excitation and deep inelastic reactions. All these studies require an efficient and high-resolution recoil separator for the clear identification of medium and large mass reaction fragments. To meet these needs, we propose a versatile recoil separator for radioisotopes based on a compact storage ring, the Isolde Superconducting Recoil Separator (ISRS) formed of superconducting combined-function nested magnets with both, bending and focusing/defocusing functions. The ISRS is designed to operate in high momentum acceptance and isochronous modes. In this paper, we present the optics design and preliminary beam dynamics studies for the performance characterisation.

## INTRODUCTION

The radioactive beam facility Isotope mass Separator On-Line facility (ISOLDE) at CERN started operation 50 years ago [1], and since then several transformations and upgrades have resulted in a world leading facility, most remarkably the recent commissioning of the High Intensity and Energy - ISOLDE (HIE-ISOLDE) linac accelerator [2], able to drive the radioactive species produced at ISOLDE from 0.5 up to about 10 MeV/u. The facility can produce the largest range of isotopes worldwide –over 1300 isotopes of more than 70 elements–, from $^{6}$He up to $^{234}$Ra.

To increase the experimental capabilities of HIE-ISOLDE, we propose a new superconducting (SC) recoil separator based on a compact non-scaling Fixed-Field Alternating-Gradient (FFAG) ring, the Isolde Superconducting Recoil Separator (ISRS). This machine will be able to store a wide range of masses and momentum spread and separate them from the main beam using RF devices, reducing the size with respect to standard non-SC recoil separator configurations.

This article presents the current status of the design study of the ISRS. After presenting the conceptual design, different optics layout configurations are discussed. The particles are bent and guided by innovative curved Canted-Cosine-Theta (CCT) magnets [3] with nested dipole and quadrupole components. Eventually, preliminary tracking studies are presented for the performance characterisation of the machine.

## CONCEPTUAL DESIGN

Figure 1 shows a simplified sketch of the ISRS ring with a total flight path of 11.28 m. It consists of four curved CCT magnets of 1.6 m length, 1 m bending radius and 90 degree bending angle. For a maximum magnetic rigidity of 2.2 Tm, the dipole must sustain a maximum field of 2.2 T. There are four straight sections to allocate injection/extraction systems and beam diagnostics.

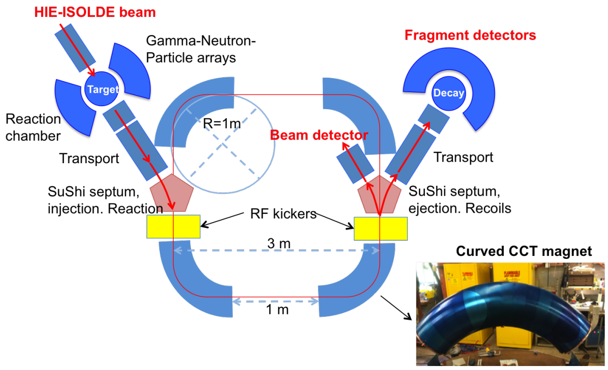

Figure 1: Conceptual layout of the ISRS. The ring consists of curved CCT magnets and straight sections to include the injection/extraction systems (1.5 m long each) and beam diagnostics (1 m long each). A prototype of an assembled curved CCT magnet is shown on the bottom right (courtesy of Lucas Brouwer [4]).

The main beam and its reaction products after target scattering are injected into the recoil separator ring. Tuning the optics to the isochronous mode of a given mass-to-charge ratio $A/Q$ (reference rigidity $B\rho$) the revolution frequency depends only on $A/Q$. This will determine the time-of-flight (ToF) between neighbouring masses.

The operation of ISRS is determined by the beam time structure of HIE-ISOLDE [5,6] and bunch separation should be of the order of 100 ns. This can be achieved by using a multi-harmonic buncher (MHB) [7], which could also extend the gap ~ 200 ns, thus improving the ToF capabilities.

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The injection and extraction systems of the ISRS present several technical challenges and requires further investigation. As a first step, the possible operation modes (DC with continuous input, or pulsed mode with an injection-storage-extraction cycle) will be studied. In the pulsed mode the beam capturing efficiency depends on the ratio of revolution time and storage time, which in turn will limit the achievable signal-to-noise ratio. If a pulsed mode (offering longer storage times) is affordable, in the straightforward concept, a combination of a septum magnet and an RF kicker could be inserted in two opposite straight sections for injection and extraction, as shown in Fig. 1. A potential solution based on a Superconducting Shield (SuShi) septum [8] or an opposite-field septum [9], and a RF helical stripline chopper [10] is now being investigated. The proposed septum concepts promise a magnetic field difference of 3 or 1.4 T with a wall thickness of around 20 or 4 mm, respectively. Given the very tight space available for these systems in the present conceptual design of Fig. 1, the feasibility of this concept –especially for the kicker– is very challenging. The study of the technical details and specifications of the injection/extraction system is currently ongoing and will be reported in future publications.

The basic spectrometer requirements guiding the ISRS design are summarized in Table 1.

Table 1: Minimum Spectrometer Requirements

| **Parameters** | **Values** |
|---|---|
| Momentum acceptance | $\pm 10\%$ |
| Resolving power $p/\Delta p$ | 2000 |
| Angular acceptance | $\pm 10^\circ$ |
| Angular resolution | $0.1^\circ$ |
| Solid angle | 100 msr |
| Charge resolution $\Delta Q/Q$ | 1/70 (FWHM) |
| Mass resolution $\Delta M/M$ | 1/250 (FWHM) |
| Rotation | $0 - 70^\circ$ |

## *Optics Layout*

The ring is based on a FFAG lattice, where the CCT magnets has both a dipole component and an alternating quadrupole triplet FDF (or DFD, depending on the operation mode). The optical lattice has been matched using the codes BMAD [11] and MADX [12]. The ring floor plan is shown in Fig. 2.

We have found several optics configurations that guarantee the orbit stability for a wide range of isotope beams from $^{11}$Li to $^{234}$Ra. Next, two examples are described.

**Isochronous mode** Considering a $^{234}$Ra beam with 10 MeV/u kinetic energy, an isochronous optical solution has been obtained (Fig. 3), fulfilling the isochronous condition $\gamma \approx \gamma_t$, where $\gamma$ is the Lorentz factor, and $\gamma_t = 1/\sqrt{\alpha_c}$ is the transition point with $\alpha_c$ the momentum compaction factor of the ring. For this lattice the maximum betatron functions $(\beta_x, \beta_y) \approx (4.8, 1.8)$ m and the maximum first order horizontal dispersion $D_x \approx 2.1$ m.

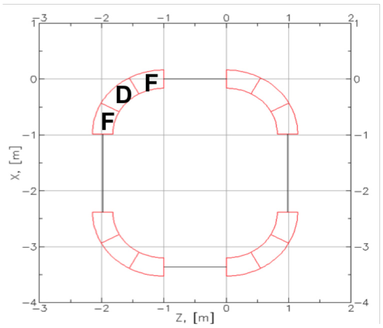

Figure 2: Updated floor plan of the ISRS facility.

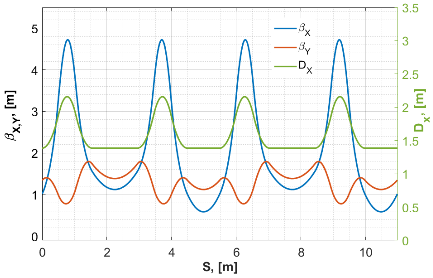

Figure 3: Beta functions $\beta_{x,y}(s)$ and horizontal dispersion $D_x(s)$ for an isochronous optics.

Although this operation mode guarantees isochronicity, the expected maximum momentum acceptance is reduced to $\pm 5\%$.

**High momentum acceptance mode** For the sake of comparison, here we show another optics operation mode, where $D_x$ is reduced to 0.32 m, and the maximum $\beta_x$ and $\beta_y$ are equal to 7.8 m and 13.5 m, respectively. See Fig. 4.

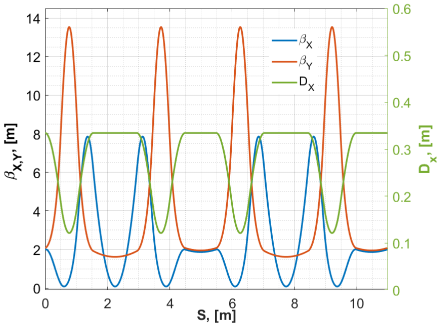

Figure 4: Beta functions $\beta_{x,y}(s)$ and horizontal dispersion $D_x(s)$ for a high momentum acceptance optics.

In this case, although the expected momentum acceptance is > 20%, the isochronicity condition is not fulfilled.

## *Magnet Design*

As mentioned before, the main magnets of the ISRS ring are based on SC Nb-Ti CCT technology with nested dipole and quadrupole functions. The prototype is being designed with a curved shape with 1 m curvature, 90 degree bend and total transverse aperture of 200 mm (Fig. 5). It consists of a two layer coil containing both dipole and quadrupole in a single conductor pack. This design has strong synergies with similar type of CCT magnets for medical gantries [4, 13].

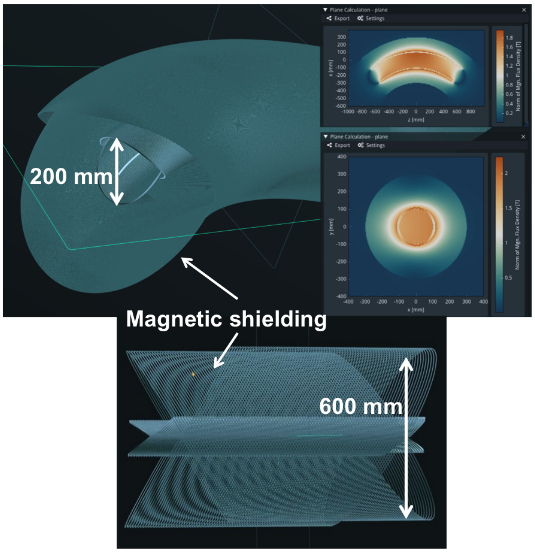

Figure 5: 3D model of the CCT magnet coils. (Top) Perspective view, showing an example of field density on the right. (Bottom) Lateral view of the coils. This figure has been produced using the Rat program [14].

The required maximum dipole field is 2.2 T with field reduction at the ends and error cancellation from the curved coils. The quadrupole has three sections rotated by ±45 degree to make a FDF (DFD) triplet focusing/defocusing configuration. According to previous optics and beam dynamics studies, a maximum quadrupole gradient of approximately 13 T/m will guarantee orbit stability for heavy ions with a maximum kinetic energy of 10 MeV/u.

The magnet also includes an innovative stray field shield (see Fig. 5) that replaces the classic iron yoke. In addition, a set of trim quadrupoles could be added to the aperture to be able to fine-tune the dipole to quadrupole ratio.

## BEAM DYNAMICS

Tracking studies using the code BMAD have been carried out to characterize the performance of the ring in terms of dynamic aperture (DA), momentum acceptance and beam stability for many circulation turns.

Figure 6 compares the DA for both the isochronous and the high momentum acceptance modes. This particular example corresponds to the case of a single $^{234}$Ra particle for 500 turns.

These simulation results confirm a maximum momentum acceptance of approximately ±5% in the case of the isochronous optics. In the case of the high momentum optics, we have obtained a clear asymmetric distribution between positive and negative momentum deviations, and there seems to be a minimum acceptance for negative momentum deviations.

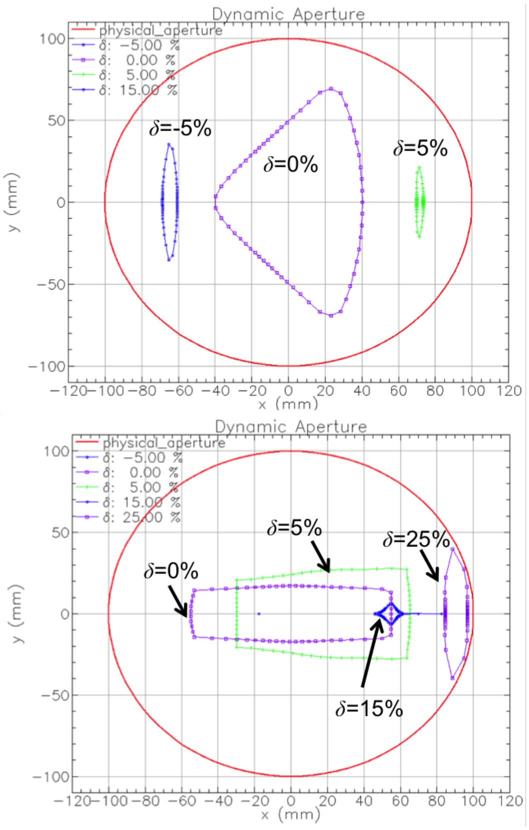

Figure 6: Transverse ellipse profile of a $^{234}$Ra isotope after 500 turns for different momentum deviations $\delta \equiv \Delta p/p$ in the case of the isochronous operation mode (top), and in the case of the high momentum acceptance mode (bottom). The solid red line represents the physical aperture of the magnets.

## OUTLOOK

To increase the physics capabilities of the HIE-ISOLDE facility at CERN, a compact SC recoil separator ring is proposed, the ISRS. It is a based on innovative CCT magnet technology to configure a versatile non-scaling FFAG optics. Optics and beam dynamics studies are ongoing to optimise the ISRS design and find an optimal trade-off between isochronous operation, high momentum acceptance and lattice compactness.

## ACKNOWLEDGEMENTS

We thank our colleagues from the ISRS collaboration for fruitful discussions and continuous support. Javier Resta acknowledges support from the Generalitat Valenciana's Gen-T Programme under grant agreement CIDEGENT/2019/058.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB180

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