DESIGN OF A COMPACT SUPERCONDUCTING RECOIL SEPARATOR FOR HIE-ISOLDE*

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Abstract

The High Intensity and Energy ISOLDE facility (HIE-ISOLDE) at CERN has unprecedentedly expanded the research capabilities to investigate the structure of the atomic nucleus and the nuclear interaction. In this context, to meet the high-resolution mass spectrometry required by the HIE-ISOLDE physics programme, an innovative spectrometer is currently being designed, the ISOLDE Superconducting Recoil Separator (ISRS). The ISRS is based on a compact storage ring formed of iron-free superconducting multifunction Canted-Cosine-Theta (CCT) magnets. In this contribution, we report on the current status of the ISRS design, paying special attention to its optics configuration and beam dynamics aspects.

INTRODUCTION

The HIE-ISOLDE facility at CERN [1] can accelerate more than 1000 isotopes of about 70 elements at collision energies up to ~ 10 MeV/u, thus greatly expanding the research programme in nuclear physics [2]. In this context, the installation of a new high-resolution magnetic spectrometer can largely benefit the HIE-ISOLDE experimental capabilities, e.g., extended particle detection angular range to regions around zero and 90°, improved energy resolution below 100 keV, mass and charge identification above A=200. Recently, within the framework of an international collaboration, we have designed a novel compact superconducting (SC) recoil separator, the ISRS [3], that can meet the demanding requirements imposed by reaction studies with radioactive beams at HIE-ISOLDE.

The ISRS is based on a SC mini-ring, with relatively smaller size than conventional recoil separators [4]. This ring will be able to store a wide range of masses and momentum spread and separe them from the main beam. The ISRS can be used not only as a fragment separator, but also as a storage ring by implementing the possibility to perform in-ring reactions (recirculating target), i.e., thin internal targets could be employed, thus improving energy resolution, beam purity and the effective beam current would be increased by orders of magnitude.

This article summarises the present status of the ISRS design, beam dynamics studies and future plans.

THE ISRS LAYOUT

The ring consists of curved SC CCT magnets and straight sections to include the injection/extraction systems (1.5 m long each), two extra quadrupoles and beam diagnostics. Figure 1 depicts the present ISRS technical layout. It has been updated from previous studies [5].

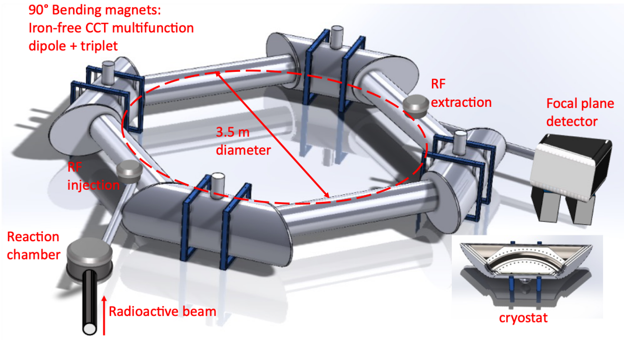

Figure 1: ISRS ring layout showing the main subsystems assembled.

The ISRS working principle is as follows. A radioactive beam accelerated by the HIE-ISOLDE linac hits the reaction target, then reaction recoils and transmitted primary beam are injected into the ring which has an effective diameter of 3.5 m and works as a spectrometer. After recirculating for a few microseconds, neighbouring isotope masses are separated by their cyclotron frequency and selected using a suitable radiofrequency (RF) system synchronised to the duty cycle. When operating in an isochronous mode, the time-of-flight is a direct measurement of the mass-to-charge ratio. Next we briefly describe key elements of the ISRS and its optics.

Magnets

The ISRS ring is based on four SC Nb-Ti CCT magnets with a special coil topology (Fig. 2). They have been designed to act as multifunction magnets with a two-layer coil which includes an alternating-gradient quadrupole triplet nested inside an outer dipole. Each quadrupole component is rotated on axis by 90° to its adjacent quadrupole to form a focusing-defocusing-focusing (FDF) sequence (or DFD, depending on the operation mode). The quadrupoles are at 45° to the dipole. Three quadrupole trim coils, each rotated by 90° and nested into each other ends (Fig. 2(b)), have been placed inside the main coil to allow fine optical

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matching. The magnet has a total aperture of 200 mm which helps to operate with relatively high momentum and angular acceptance.

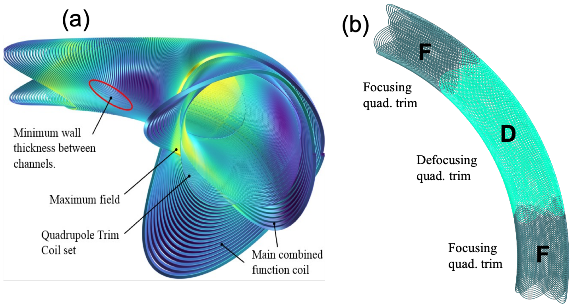

Figure 2: (a) 3D model of the CCT magnet coils. (b) Detail of the sequence of focusing/defocusing quadrupole trim coils which are located inside the main coil.

The dipole bending radius has been established through a balance between available space for the storage ring and limiting magnetic dipolar field. For instance, Fig. 3 shows the dipole field as a function of beam radius of curvature for different isotopes at 10 MeV/u kinetic energy. For this energy, considering that reference rigidity $B\rho \approx 2$ Tm, then a dipole with 1 m bending radius and 90° bending angle must sustain a field of approximately 2 T. The quadrupole component is able to provide maximum gradient fields of approximately 14 T/m to guarantee transverse stability for a wide range of ions with a maximum kinetic energy of 10 MeV/u. The quadrupole trim coils inside the main coil can reach a maximum gradient of ± 2.27 T/m.

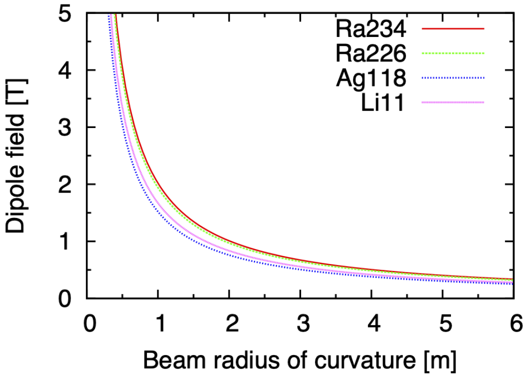

Figure 3: Dipole field as a function of beam radius of curvature for different isotopes at 10 MeV/u kinetic energy.

In addition, to get an iron-free CCT magnet, an innovative stray field shield is being considered to replace the classic iron yoke. A prototype of such CCT multifunction magnets is currently being developed at CERN. More details can be found in Ref. [6].

Isochronous Optics

The ISRS optics can be matched to operate as an isochronous mass spectrometer. The optical matching has been performed using the code BMAD [7], imposing the isochronous condition $\gamma \approx \gamma_t$, where γ is the relativistic Lorentz factor, and $\gamma_t = 1/\sqrt{\alpha_c}$ is the so-called transition point, with α_c the momentum compaction factor of the storage ring. An isochronous optical solution is shown in Fig. 4. For this configuration, relevant parameters and magnet strengths are shown in Table 1. The three quadrupole trim coils have been assumed to be powered independently to fine-tune the quadrupole alternating fields, and two additional quadrupoles (Q) have been included to increase degrees of freedom to match the optics, thus improving the versatility of the lattice to set up different operation modes.

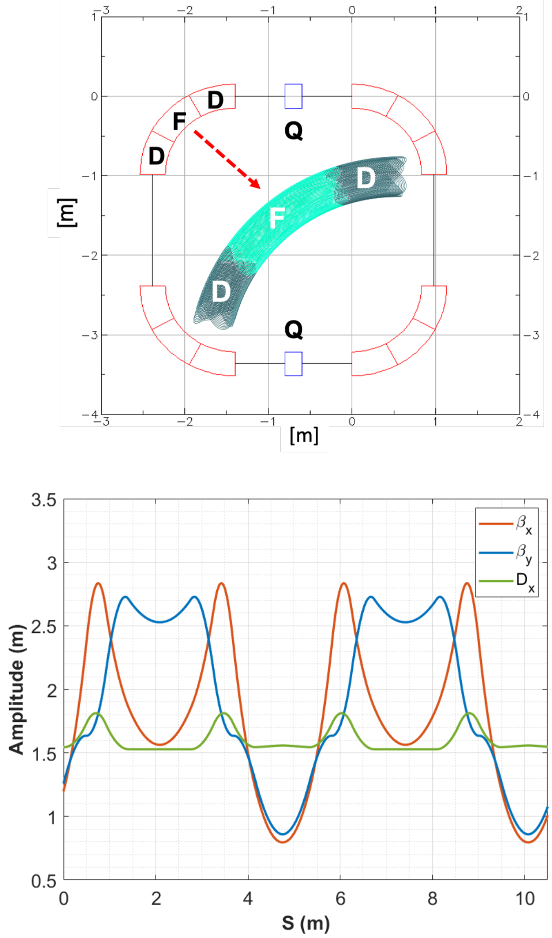

Figure 4: (Top) Floor plan of the ISRS ring. In this case, after matching, the quadrupole triplet adopts a sequence DFD. (Bottom) Beta functions $\beta_{x,y}(s)$ and first order dispersion $D_x(s)$ for the ISRS isochronous optics mode.

For this particular isochronous configuration, the maximum momentum acceptance has been estimated to be $\pm 5.5\%$. To operate with higher momentum acceptance, the dispersion D_x needs to be reduced, and by doing that, the isochronous condition is broken. We are currently investigating further optics solutions with a better balance between high momentum acceptance and isochronicity.

BEAM DYNAMICS STUDIES

The performance of the ISRS, acting as an isochronous mass spectrometer, has been studied by means of tracking simulations using the code BMAD. For example, let us consider an initial Gaussian distribution consisting of a mixture of five Ra isotopes ($^{232-236}$Ra) at kinetic energy of 10 MeV/u. This beam distribution is injected into the ISRS ring with the following characteristics: 5000 macroparticles per isotope, 5 mm-mrad transverse emittance (x and y), 0.01 m rms longitudinal size and 0.01% rms momentum spread. The isotope ^{234}Ra circulates in reference orbit. Figure 5 shows the corresponding longitudinal phase space at different circulation time. In this particular example, after one revolution turn (254.4 ns), the different Ra isotopes separate in bunches with bunch separation of approximately 1.5 ns. The separation between different isotope bunches increases up to 15 ns after 10 turns (2544 ns) and the bunches stay roughly at the same position.

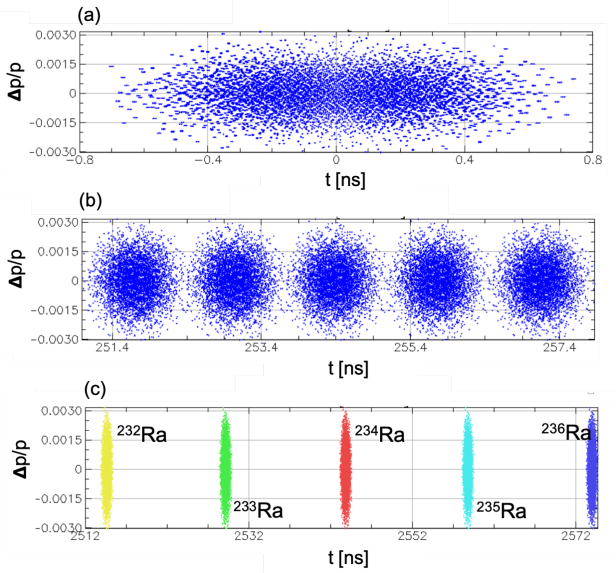

Figure 5: Beam tracking studies: (a) initial longitudinal phase space; (b) longitudinal phase space after 1 turn (254.4 ns); and (c) after 10 turns (2544 ns).

OUTLOOK

The R&D programme for the design and construction of a compact high-resolution recoil separator, the ISRS, is progressing within the framework of an international collaboration. The main aim is to extend the physics capabilities of the HIE-ISOLDE facility at CERN. The ISRS is a mini-ring able to act as a mass spectrometer. It is based on novel SC CCT multifunction magnets which have strong synergies with similar magnets being developed for gantries for hadrontherapy [8, 9]. The ISRS optics is very versatile and, depending on experimental requirements, different operation modes can be set up: isochronous and high momentum acceptance modes, etc. In this paper, an example of isochronous mode for mass spectrometry has been analysed. Beam dynamics simulation studies for the ISRS have been carried out and confirm a good performance of the system. Future plans include further optimisation of the ISRS design and a detailed study of important subsystems, such as the injection/extraction system and beam diagnostics systems.

Table 1: Relevant Parameters for an Isochronous Mode of the ISRS Optics

Beam	^{234}Ra
Kinetic energy [MeV/u]	10
Lorentz factor, γ	1.0107
transition point, γ_t	1.0102
Momentum compaction factor, α_c	0.98
Rigidity, $B\rho$ [T m]	2.0
Maximum beta functions, $\hat{\beta}_{x,y}$ [m]	2.85, 2.72
Maximum dispersion, $\hat{D}_x$ [m]	1.8
F magnet	
Effective length [m]	0.55
Dipole field [T]	2.45
Quadrupole gradient [T/m]	2.531
D magnet	
Effective length [m]	0.497
Dipole field [T]	2.133
Quadrupole gradient [T/m]	-2.967
Additional quadrupoles Q	
Gradient [T/m]	0.423

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