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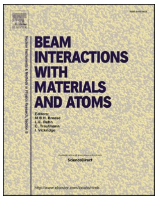

An innovative Superconducting Recoil Separator for HIE-ISOLDE

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ABSTRACT

The ISOLDE Scientific Infrastructure at CERN offers a unique range of post-accelerated radioactive beams. The scientific program can be improved with the “Isolde Superconducting Recoil Separator” (ISRS), an innovative spectrometer able to deliver unprecedented (A, Z) resolution. In this paper we present an overview of the physics and ongoing technical developments.

1. The ISRS recoil separator

The HIE-ISOLDE facility at CERN can accelerate more than 1000 isotopes of about 70 elements at collision energies up to ~ 10 MeV/A, thus making it an ideal testbench to probe nuclear theories by selecting optimum (N, Z) combinations. The ISRS collaboration has recently proposed the construction of a novel high-resolution recoil separator, the “ISOLDE Superconducting Recoil Separator” (ISRS) [1]. The aim is to extend the physics programme [2] to more exotic isotopes produced in the secondary target by combining focal plane spectroscopy with particle and photon detection using different detector devices at HIE-ISOLDE [3–7].

A wide variety of reaction mechanisms can be used to investigate nuclear structure and reactions of exotic nuclei. Transfer reactions in inverse kinematics exhibit very high cross sections at HIE-ISOLDE beam energies. Fragment angular distributions are very sensitive to the details of the nuclear wave-functions, such as energies, angular momenta, and spectroscopic factors. They can be used for example to study the evolution of nuclear structure and reactions relevant for nucleosynthesis around closed shells $N \approx 82$ and $N \approx 126$ [8,9]. Multinucleon transfer processes via deep inelastic, quasi-elastic and quasi-fission reactions [10–12] can produce many levels of interest in exotic nuclei, including the drip line region around ^{78}Ni and the closed-shell region $N = 126$ [13] which are crucial for studying shell-quenching and the astrophysical r-process. Charge-exchange reactions allow to investigate the dynamics of spin and isospin excitations, the structure of particle-hole states and the scalar and isovector components of nuclear matrix elements relevant for nuclear beta decay, thus connecting strong and weak interactions [14,15]. Fusion-evaporation reactions can produce very exotic residues [16] for which the ISRS spectrometer brings the opportunity of performing lifetime measurements with plungers [17]. Direct or inverse kinematics with light or heavy targets will be used, and therefore the spectrometer should be able to rotate to cover zero to the typical heavy-ion grazing angles ($\sim 50^\circ$ – 70° Lab). Some ISRS physics requirements are given in Table 1.

Table 1
ISRS spectrometer properties.

Energy resolution	< 100 keV	Angular acceptance	> 15°, 100 msr
Time resolution	< 100 ns	momentum-acceptance	> 25%
$\Delta Q/Q$	< 1/70 (FWHM)	$\Delta M/M$	< 1/250 (FWHM)

2. ISRS design studies

State-of-the-art spectrometers [18–21] are linear arrays of magnets with performance limited by the length of drifts and dispersive planes. Spectrometer operation suffers also from magnetic-field iron-induced nonlinearities, hysteresis, remnant magnetization and ohmic losses (cooper wiring), which demands efficient cooling systems. Precision rotation of such a structure to accommodate experiment requirements needs complex mechanical systems due to its relatively large weight. The design of the ISRS spectrometer follows a different conceptual approach, see Fig. 1. Instead of using dispersive planes, particle separation is obtained by injecting the reaction fragments into a particle storage system composed of an array of iron- free superconducting multifunction magnets (SCMF) cooled by cryocoolers, integrated into a compact storage mini-ring using Fixed Field Alternating Gradient focussing (FFAG). In a recent paper [22] we have studied a very compact configuration having only 1.5 m diameter and relatively low magnetic field (<5 T), which is able to recirculate with 100% efficiency a cocktail beam of radium isotopes at 10 MeV/u with a 20% momentum spread, and fully separate single unit masses.

The layout of ISRS is shown in Fig. 1. When the radioactive beam hits the reaction target, both reaction recoils and transmitted primary beam are injected into the spectrometer. After recirculating for a few microseconds, neighbouring masses are separated by their cyclotron frequency and selected using a suitable RF system synchronized to the duty cycle. When operating in the isochronous mode, the time-of-flight is a

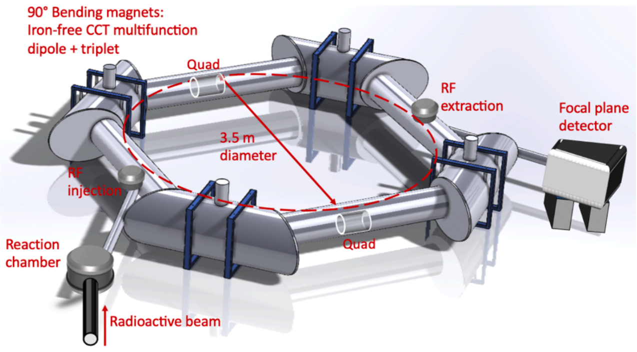

Fig. 1. A conceptual design of the ISRS ring showing the main subsystems.

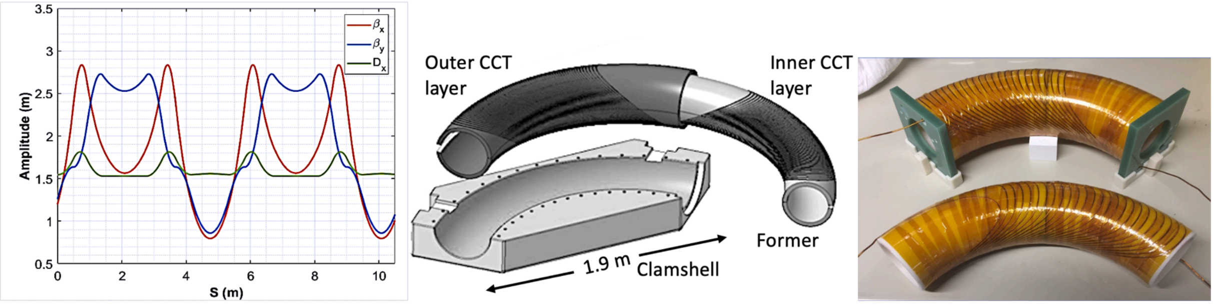

Fig. 2. Left: Betatron functions. Centre: FUSILLO assembly. Right: pulsed-resistive models of the CCT coils.

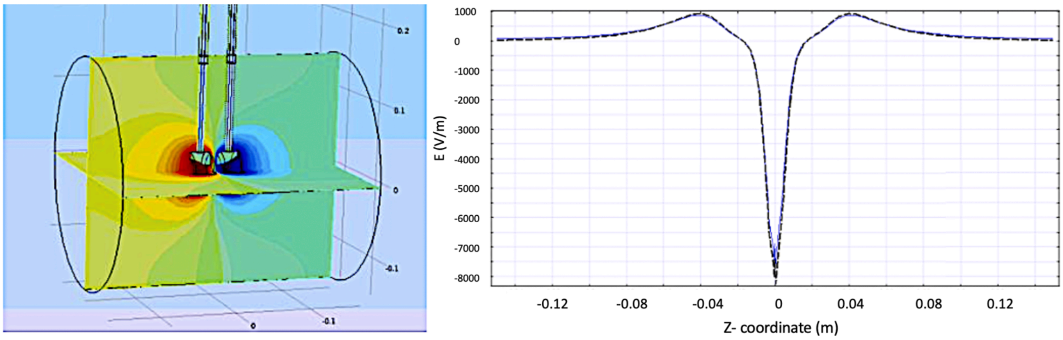

Fig. 3. Left: Electromagnetic 3D model of the MHB. Right: Field profile along the beam axis (right).

direct measurement of the M/Q ratio. The ISRS ring features a ∼ 3.5 m diameter (which is larger than in [22] to reduce the bending magnetic field) four SCMF iron-free 90° Canted Cosine Theta (CCT) [23] bending magnets of 1 m radius, which include dipole and triplet focusing quadrupoles, two additional quadrupoles in the straight sections to complete the FFAG cell, an injection/extraction system inspired by the SuShi magnet system developed for the HiLumi project [24], and a focal plane detector. The complete assembly is currently being studied to maximise transmission efficiency and mass resolution. The FFAG optical lattice allows for efficient recirculation of an ion beam with large energy and momentum spread, whereas the CCT SCMF coils reduce aperture and radius of the ring leading to a very compact configuration. The suppression of the iron joke eliminates iron non-linearities and hysteresis and reduces magnet weight. In comparison to a standard spectrometer with comparable resolving power and efficiency, the ISRS will be an order of magnitude smaller, three orders of magnitude lighter, and will have small energy losses down to a few watts per meter. The reduced thermal mass opens the possibility to use cryocoolers instead of a liquid Helium bath, avoiding the need of a complex LHe system, and simplifies the mechanical structure needed for rotation as well. Beam optics parameters for the ISRS layout are shown in Fig. 2 (Left panel) for an isochronous optics solution.

The collaboration is developing a prototype of a 90° bending magnet (MAGDEM) composed of a CCT solenoid (FUSILLO) with a pure dipole central field of 3.0 T (prototype shown in Fig. 2, centre and right panels), and a dedicated cryostat (PENTOLA). First reduced scale pulsed-resistive models have been developed and tested with current pulses at CERN, and the magnetic measuring system to produce the field maps. The design study of a low frequency multi-harmonic buncher system has started (Fig. 3) based on previous work developed in the context of the HIE-ISOLDE buncher [25].

3. Summary and conclusions

The R&D program for the design of the Isolde Superconducting Recoil Separator is under development. Major advances include the optics layout, beam dynamics and the design study of a curved multi-function coil with nested trim coils. First resistive models of CCT coils have been successfully developed and tested. Studies of the cryostats and the multi-harmonic buncher are ongoing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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