DESIR HIGH RESOLUTION SEPARATOR AT GANIL, FRANCE

by

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A high-resolution separator for the SPIRAL2/DESIR project at GANIL has been designed. The extracted isotopes from SPIRAL2 will be transported to and cooled in a RFQ cooler yielding beams with very low transverse emittance and energy spread. These beams will then be accelerated to 60 keV and sent to a high-resolution mass separator where a specific isotope will be selected. The good beam properties extracted from the RFQ cooler will allow one to obtain a mass resolution of 26000 with the high-resolution mass separator.

Key words: separator, resolution, COSY INFINITY, aberration, ion optics

INTRODUCTION

The advent of radioactive beam facilities has given a new impetus to nuclear structure physics during the last two decades [1, 2]. It has led to several major unexpected discoveries such as the existence of dilute neutron matter in halo nuclei, the modification of shell structure and magic numbers far from stability, proton and two-proton radioactivity, new regions of shape coexistence. There are two main methods to produce radioactive ion beams: projectile fragmentation and isotope separation on-line (ISOL). The fragmentation facility will be FAIR [3] in Darmstadt, Germany, while the ISOL facility is named EURISOL [4]. The technical challenges for EURISOL were found to be too great to envisage rapid construction and a European roadmap towards the ultimate facility EURISOL was proposed. This plan encompasses the construction of three intermediate generation ISOL facilities: HIE ISOLDE at CERN [5], SPES at Legnaro [6] and the most ambitious of the three, SPIRAL2 at GANIL.

The SPIRAL2 facility at GANIL will produce radioactive isotopes ranging from the lightest to very heavy elements beyond uranium [7]. Different production mechanisms will be utilized [8]: fission of ^{238}U to produce medium-mass, neutron-rich isotopes, fusion evaporation for medium-mass, neutron-deficient nuclei, and transfer and deep-inelastic reactions for light to heavy nuclei closer to the line of β stability. Therefore, the SPIRAL2 driver accelerator will accelerate deuterons to 40 MeV and medium-mass, heavy ions to 14.5 MeV/nucleon with a mass-over-charge ratio of 3. The deuteron beam will be used to induce fission of ^{238}U in a thick target, whereas the heavy ion beams can be used to produce radioactive isotopes either in a thick target – ion-source ensemble or in a thin target coupled to a separator-spectrometer. The interest of the presented work here is the thick-target approach.

After their production in the thick-target, the nuclei of interest must quickly and efficiently diffuse to the surface of the target/catcher material, be released from there and be transferred into a region where they can be ionized with a suitable method (surface, plasma or laser ionization). This target – ion-source ensemble will be installed on a high-voltage platform, which will produce ion beams of a few tens of keV. These ion beams can then be used either at an ISOL facility, where *e. g.* decay studies, laser spectroscopy, mass measurements can be performed, or they can be accelerated by the CIME cyclotron and be used to induce nuclear reactions [7].

The DESIR installation consists of an RFQ [9] plus high-resolution mass separator (HRS) ensemble located in the production building close to the other GANIL/SPIRAL1 and SPIRAL2 facilities.

ION-OPTICAL DESIGN CONCEPT

A high-resolution separator concept has been elaborated in the framework of the EURISOL study [ref. 8, p. D-53] (by T. J. Giles at CERN-ISOLDE). This concept, based on the CARIBU project [10] at

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Argonne National Laboratory, uses a variable pole gap magnet designed to correct distortions and requires no electrostatic corrections.

The design of the HRS should fulfill the following requirements:

– high transmission (ideally close to 100%) and high resolving power ($m/\Delta m$ ~20000) to provide monoisotopic beams of exotic nuclides,
  match beam emittance from RFQ cooler (ε mm mrad, ΔE < 1 eV at 60 keV),
– compact configuration. Must fit in the SPIRAL2 production building (see ref. [11]),
– should be robust in order to tolerate errors in alignment and component manufacturing, and
– cheep, concerning both installation and operation costs.

The ion optical design of the separator is presented in fig. 1. Proposed design will consist of four 67.5 degree magnetic dipoles (D) with 27.5º entrance and exit angles, eight matching quadrupoles (Q_m), four focusing quadrupoles (Q_f), four focusing sextupoles (S), two multipoles (M), and four correcting quadrupoles (Q_c) with the configuration $Q_mQ_mSQ_fDMDQ_fSQ_mQ_mQ_cQ_c$-$Q_cQ_cQ_mQ_mSQ_fDMD$ $Q_fSQ_mQ_m$. The optical axis has a length of 17.82 m, measured from the first to the last quadrupole. The HRS is mirror symmetric with respect to the mid-plane to minimize aberrations.

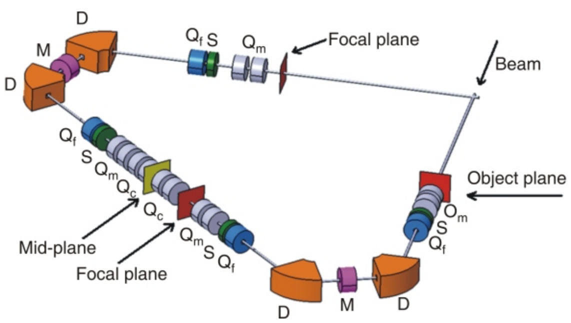

Figure 1. 3-D layout of the DESIR HRS consisting of eight matching quadrupole doublets (Q_m) and four correcting quadrupoles (Q_c), four focusing sextupoles (S), four focusing quadrupoles (Q_f), four 67.5 degree dipoles (D) and two multipoles (M)

The DESIR installation consists of an RFQ + + HRS ensemble located in production building and a building located close to the other GANIL/SPIRAL1 and SPIRAL2 facilities (see fig. 1 in the ref. [11]).

Quadrupoles are used as the focusing mode in the y-direction and defocusing in x-direction. This offers two advantages simultaneously: *high transmission* as well as *small image magnification* to attain high resolution. The first quadrupole doublet produces a ribbon-shaped beam, so y angles are small minimizing y angle aberrations. The quadrupole placed before the dipole diverges in x-direction and converges in y-direction. The small y size minimizes y aberrations and the large x area in the dipoles gives mass dispersion. The reverse matching section transforms the ribbon-shaped beam back to a circular cross-section at the focal plane. The two sextupoles and the central multipole (sextupole, octupole, decapole, and duodecapole) allow correcting aberrations to 5th order.

The detailed information about the exact location of the different elements and the corresponding sizes are summarized in tabs. 1, 2, and 3.

Table 1. Lattice configuration of the first cell

Element	Length [mm]	Element	Length [mm]
Drift length	300	Drift length	1271
Matching quadrupole Q_{m1}	200	Focus quadrupole Q_{f2}	240
Drift length	100	Drift length	60
Matching quadrupole Q_{m2}	200	Focus sextupole S_2	120
Drift length	295	Drift length	295
Focus sextupole S_1	120	Matching quadrupole Q_{m3}	200
Drift length	60	Drift length	100
Focus quadrupole Q_{f1}	240	Matching quadrupole Q_{m4}	200
Drift length	1271	Drift length	250
Dipole D1 ρ = 50 cm, θ = 67.5°	589	Drift length	250
Drift length	360	Correcting quadrupole Q_{c1}	200
Multipole M	240	Drift length	300
Drift length	360	Correcting quadrupole Q_{c2}	200
Dipole D2 r = 50 cm, θ = 67.5°	589	Drift length	300

Table 2. Technical specification of bending dipoles

Angle [°]	Radius [mm]	Pole gap [mm]	Pole width [mm]	Entrance angle [°]	Exit angle [°]	Flux density at pole tip (T)	Field index n
67.5	500	80	620	27.5	27.5	0.81	0

Table 3. Specifications of electrostatic elements

Electrostatic element	Length [mm]	Diameter [mm]	Voltage at pole tip [kV]
Matching quadrupole Q_{m1}	200	40	–0.7874
Matching quadrupole Q_{m2}	200	40	+0.9164
Focus quadrupole Q_{f1}	240	80	–1.0291
Focus quadrupole Q_{f2}	240	80	–1.0291
Matching quadrupole Q_{m3}	200	40	+0.8891
Matching quadrupole Q_{m4}	200	40	–0.7644
Focus sextupole S_1	120	40	0.1133
Focus sextupole S_2	120	40	0.1133
Multipole M: Quadrupole component Sextupole component Octupole component Decapole component	240	400	 0.0000 –0.6106 –0.0202 –0.0025

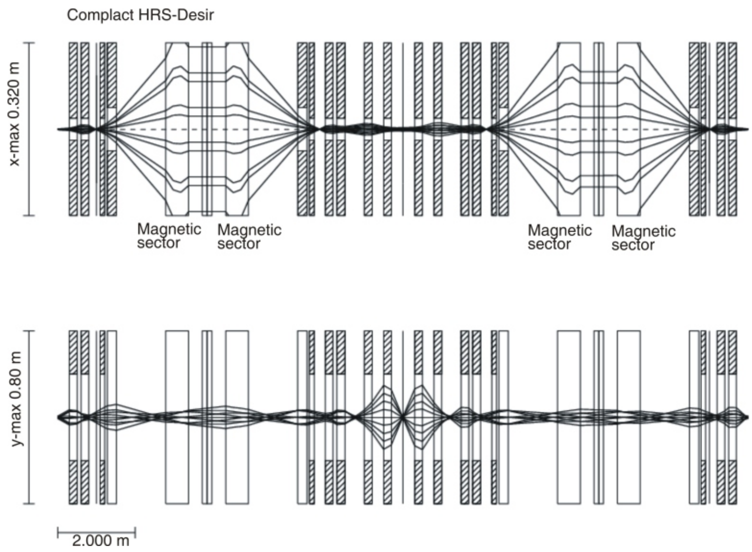

Figure 2. Ion optics of the DESIR HRS in the horizontal (dispersive) plane (up) and vertical (non-dispersive) plane (down)

ION-OPTICS DISCUSSION

The calculated ion optics is shown in fig. 2. The ion-optical code COSY INFINITY [12] was used for these calculations. The phase space dimensionality used was 2, being the $x – a$ (horizontal plane) as well as $y – b$ (vertical plane) motion computed.

For the reference particle, the particle with mass (m_0) 122 amu, charge (Z_0) 1 ($^{122}Sn^+$), electric rigidity of 0.121 MV, and kinetic energy (K_0) of 60 keV, is chosen. It is considered as the particle with relative mass deviation of $dm/m_0 = 4\ 10^{-7}$, relative kinetic energy deviation of $dK/K_0 = 0$ and relative charge deviation of $dZ/Z_0 = 0$. The starting points of this particle in the initial horizontal and vertical phase spaces are

$$x_0 = y_0 = 0.5 \text{ mm}$$

$$a_0 = b_0 = 2 \text{ mrad}$$

which corresponds to the beam emittance [13, 14] in horizontal and vertical plane $\varepsilon_x \quad \varepsilon_y$ mm mrad. x_0 and y_0 are the horizontal and vertical displacements from the optic axis, a_0 and b_0 are the angles between paraxial ray and optic axis in horizontal and vertical planes, respectively.

Kinetic energy (K_0), mass (m_0) and charge (Z_0) of the reference ion are used as parameters in the code COSY INFINITY and thus all the calculations are performed in the following scaled co-ordinates [12, 13]

$$x$$

$$a \quad \frac{p_x}{p_0}$$

$$y$$

$$b \quad \frac{p_y}{p_0}$$

$$\delta_K \quad \frac{K \quad K_0}{K_0}$$

$$\delta_m \quad \frac{m \quad m_0}{m_0}$$

$$\delta_Z \quad \frac{Z \quad Z_0}{Z_0}$$

where p_0 is the total momentum of the reference ion and p_x and p_y are its horizontal and vertical components, respectively.

Resolving power

Focusing and corrective elements are all electrostatic and so settings are independent of mass.

The final first order transfer matrix is

	x	a	y	b
x	–1.0048	–4.5179	0.0000	0.0000
a	–0.0021	–1.0047	0.0000	0.0000
y	0.0000	0.0000	0.9991	–0.0459
b	0.0000	0.0000	–0.0369	0.9919
δ_K	–26.5060	–59.7333	0.0000	0.0000
δ_m	–26.5060	–59.7333	0.0000	0.0000
δ_Z	53.0120	119.4666	0.0000	0.0000

As a pure magnetic separator, the dipole disperses ions according to their rigidity, and then, the mass and energy dispersions are equivalent and equal to half of the momentum dispersion D_p [13]. The calculated D_p is 53 cm and the value for corresponding energy and mass dispersion is 26.5 cm. The charge dispersion D_Z is equal to $–D_p$.

The resolving power R is defined as

$$R \quad \frac{(x|\delta_m)}{2x_0\,(x|x) \quad \Delta}$$

where Δ is the total amount of aberrations [13].

In the first order of calculations; $\Delta = 0$, the resolving power R of the DESIR HRS is

$$R \quad \frac{(x|\delta_m)}{2x_0\,(x|x)} \quad 26500$$

In order to get a high resolving power, a large value of $(x\,\delta_m$ and a small value of $(x\,x$ and Δ are desirable.

The final mass dispersion is $D_m = \delta_m$ = 26 cm which will allow one to obtain a maximum mass resolution of 26500 for a beam of 1 mm mrad emittance. The full system is point-to-point in both horizontal ($x – a$) and vertical ($y – b$) planes, so that ($x\,\alpha$ $y\,\beta$ and parallel-to-parallel in the vertical ($y – b$) plane, so that ($b\,y$) = 0. The system is symmetric in the vertical plane, so that magnifications ($y\,y$) = ($b\,b$ = 1, and mirror symmetric in the horizontal plane, so ($x\,x$) = = ($a\,a$ = –1.

Higher order aberrations

All non-zero non-linear terms blur the final image and reduce the resolving power. Sextupoles allow correcting the second order aberrations. Its first order transfer matrix is that of a drift space and so does not affect the first-order optics of the beam line. However, the presence of more than one sextupole in the beam line may induce significant third or higher order aberrations and as a consequence multipole elements should be included (sextupole, octupole, decapole and duodecapole) to correct the induced higher order effects. In this design of DESIR HRS two multipoles with octupole, decapole, and duodecapole components are used to correct the aberrations up to 5^{th} order. The mass separation spectrum as calculated by the Monte Carlo code at the final focal plane of the DESIR HRS is shown in fig. 3. The transfer matrices (calculated by COSY INFINITY code up to 5^{th} order) are taken as input for the Monte Carlo code. The output of the code are the initial and final phase spaces of the beam and the mass spectrum as calculated for the different masses introduced in the simulation. In this way a large number of particles can be transformed through the transfer matrix. The initial beam phase space was assumed to be elliptic with Gaussian width FWHM values Δx = 1 mm and Δa = 12 mrad. The final position of each particle is calculated as the sum of all aberrations.

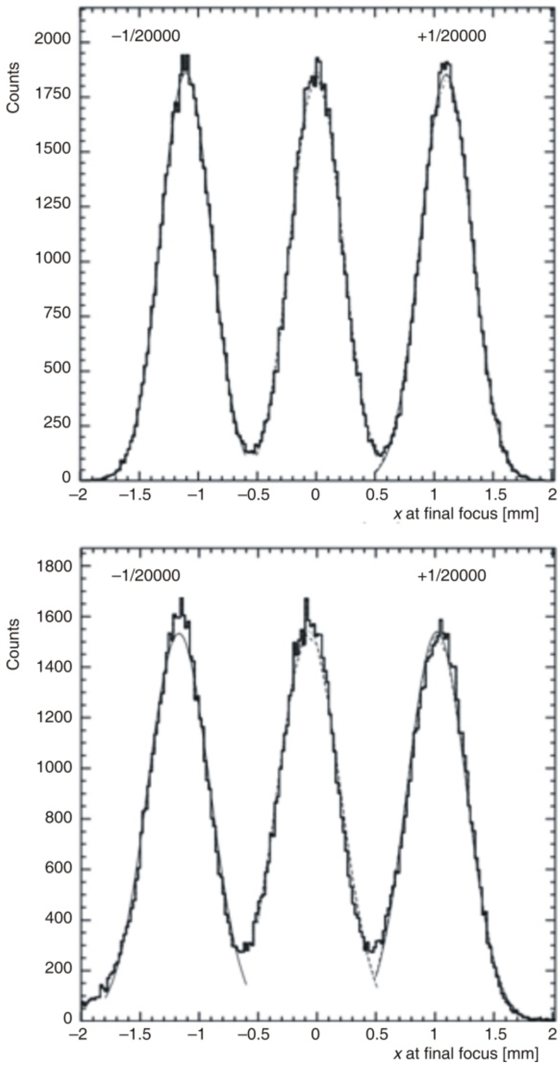

Figure 3. Mass separation spectrum as calculated by the Monte Carlo code at the final focal plane of the DESIR HRS. 50000 particles with mass deviations –1/20000, 0 and +1/20000 were transformed through the first order (up) and 5^{th} order (down) transfer matrix as calculated by COSY INFINITY. The initial beam phase space was assumed to be elliptic with Gaussian width FWHM values Δx = 1 mm and Δa = 12 mrad

CONCLUSIONS

The ion-optical study of the DESIR HRS has been performed up to 5^{th} order of calculations using the COSY INFINITY code. A fringe field effects are not included in the calculations. A design resolving power is around 26000.

The design studied relies on a strong optical focusing for a small dipoles in order to keep as low as possible the size of the separator. This optical condition makes the system more sensitive to the fringe field effects and to the homogeneity of the dipole field. A correct simulation of such effects is important in order to perform a correct design of the separator.

In the near future, we will use 3-D TOSCA maps of magnetic fields to include fringe field effects and later on perform a detailed study of possible misalignment effects on the final resolving power.

AUTHOR CONTRIBUTIONS

Theoretical analysis and numerical simulations were carried out by D. Toprek and T. Kurtukian-Nieto. Both authors analyzed and discussed the results. The manuscript was written by D. Toprek and the figs. 1 and 3 were prepared by T. Kurtukian-Nieto.

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DESIR СЕПАРАТОР ВИСОКЕ РЕЗОЛУЦИЈЕ У GANIL-У, ФРАНЦУСКА

У овом раду разматран је дизајн сепаратора високе резолуције на SPIRAL2/DESIR постројењу које се гради у институту GANIL у Француској. Екстраховани изотопи из SPIRAL2 постројења транспортују се и хладе у RFQ хладиоцу дајући на тај начин снопове веома ниске трансверзалне емитансе и енергијског распона. Ови јонски снопови убрзавају се до енергије 60 keV и усмеравају у сепаратор високе резолуције у коме се специфични изотоп селектује. Снопови добрих карактеристика екстраховани из RFQ хладиоца, уз помоћ овог сепаратора високе резолуције, омогућиће постизање масене резолуције око 26000.

Кључне речи: сепаратор, резолуција, COSY INFINITY, аберација, јонска оптика