SPIRAL2/DESIR High Resolution Mass Separator

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Abstract

DESIR is the low-energy part of the SPIRAL2 ISOL facility under construction at GANIL. DESIR includes a high-resolution mass separator (HRS) with a designed resolving power $\frac{\Delta m}{m}$ of 31 000 for a 1π-mm-mrad beam emittance, obtained using a high-intensity beam cooling device. The proposed design consists of two 90-degree magnetic dipoles, complemented by electrostatic quadrupoles, sextupoles, and a multipole, arranged in a symmetric configuration to minimize aberrations. A detailed description of the design and results of extensive simulations are given.

Keywords:
High-resolution isobar separator, Charged-particle spectrometers

1. Introduction

The DESIR (Désintégration, Excitation et Stockage d'Ions Radioactifs) [1] facility is part of the new equipment necessary for exploitation of the radioactive beams produced by SPIRAL2 (Système de production d'Ions Radioactifs en Ligne de 2ème génération) [2] at GANIL (Grand Accélérateur National d'Ions Lourds), France. DESIR includes a laboratory equipped with low-energy experiments that can receive radioactive beams from the SPIRAL1, SPIRAL2 and S3 (Super Separator Spectrometer) installations at GANIL. Because increasing intensities of radioactive beams also leads to increased isobaric contamination, DESIR also includes an important instrument for beam purification: a high-resolution mass separator (HRS) for high-intensity beams, located in the production building housing the uranium ISOL target (see Figure 1).

SPIRAL2 is not the first radioactive beam installation to attempt the construction of an HRS. In fact, there is limited success in obtaining high resolving power with magnetic dipoles, despite extensive efforts. The ISAC facility at TRIUMF recovered the mass separator from Chalk River Laboratories when the TASCC facility there was closed. At Chalk River, the separator achieved a resolving power of 20 000 using collimated (0.1 mm) stable beams and 5700 for exotic species [3]. At the Oak Ridge Holifield ISOL facility, the use of a two-stage mass separator allows resolving power up to 10 000 [4]. Another example is the ISOLDE HRS, originally designed for 30 000, which routinely achieves only 4500, although a different configuration is now used [5]. A more recently designed separator, for the CARIBU project at ANL [6] has not yet achieved its design goal of 20 000, but tests are underway. The design goals for the DESIR-HRS are a high transmission (ideally close to 100%), a compact configuration (must fit in the SPIRAL2 production building) and a high resolving power ($\frac{\Delta m}{m} \approx 20\,000$) to provide isobarically pure beams of exotic nuclides. In the following sections, we describe the corresponding ion-optical design and the technical choices taken to achieve such requirements for the DESIR-HRS.

2. Ion optics design

The proposed design for the DESIR-HRS is shown in Figure 2. Inspired by the CARIBU HRS at Argonne National Laboratory, it consists of two 90-degree magnetic dipoles (D) with 36-degree entrance and exit angles, matching quadrupoles (MQ), focusing sextupoles (FS), focusing quadrupoles (FQ), and one multipole (M) with the configuration: MQ-MQ-FS-FQ-D-M-D-FQ-FS-MQ-MQ. Mirror symmetry is imposed with respect to the mid-plane to minimize aberrations. Focusing and corrective elements are all electrostatic so that the settings are independent of mass. To inject the purified beam into the 1^+ line of the production building, a transport section is placed at the exit of the HRS, consisting of two quadrupole doublets and two 45-degree electrostatic benders.

The ion-optical code COSY INFINITY [7] was used for the baseline design. The phase space dimensionality used was $x-a$ (horizontal) and $y-b$ (vertical) while δm and δE are calcu-

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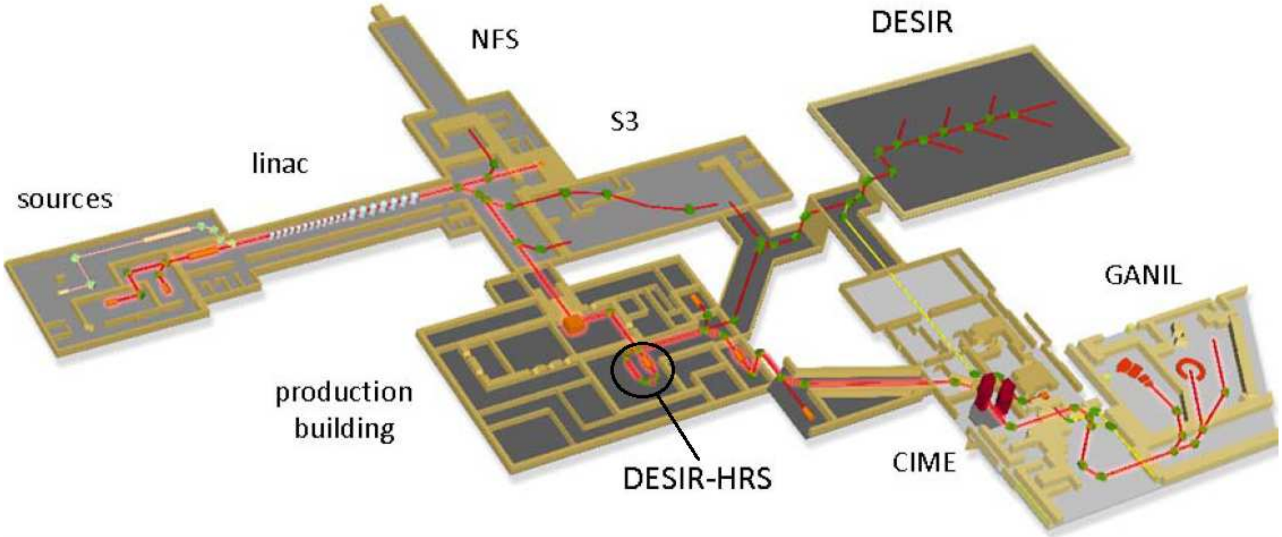

Figure 1: Schematic layout of the GANIL and SPIRAL2 facility including S3 and DESIR

lated as parameters. Thus all calculations are performed in the following scaled coordinates: x; $a = p_x/p_0$; y; $b = p_y/p_0$; $\delta m = (m - m_0)/m_0$; $\delta E = (E - E_0)/E_0$.

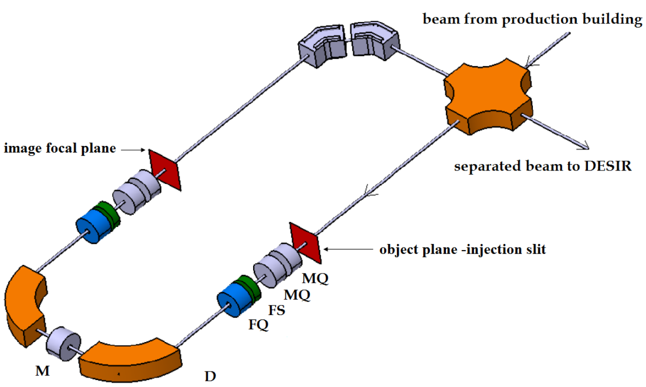

Figure 2: Optical layout of the DESIR-HRS. Separation is performed using two 90-degree magnetic dipoles (D) with 36-degree entrance and exit angles. Mirror symmetry is imposed with respect to the mid-plane to minimize aberrations. The entrance beam optics was designed using matching quadrupoles (MQ), a focusing sextupole (FS), and a focusing quadrupole (FQ). A multipole (M) is placed at the mid-plane, between the two magnetic dipoles. The overall configuration is: MQ-MQ-FS-FQ-D-M-D-FQ-FS-MQ-MQ. After the image focal plane, two quadrupole doublets (not shown) and two 45-degree electrostaticl benders transport the beam to DESIR.

The beam enters the HRS by a 1 mm^2 slit, with a maximal angular dispersion of ±10 mrad (both in horizontal and vertical planes) and passes through the first quadrupole doublet, which consists of a pair of quadrupoles of opposite polarity. Focusing conditions at this point are (x, a) and $(y, b) \sim 0$. This produces a narrow ribbon-shaped beam with reduced y angles, (x, x) and $(b, b) \approx 0.2$, which minimizes vertical b aberrations. The next quadrupole makes the beam diverge horizontally and converge vertically. The divergent beam envelope is designed to occupy the entire dipole magnet acceptance to maximize mass dispersion. The combined effect of the entrance and exit angles of the dipoles produces a parallel beam in the horizontal direction. The focusing condition at the mid-plane is $(a, a) = (y, b) = (b, y) = 0$: point-to-parallel in x, and point-to-point/parallel-to-parallel in y. The second (symmetric) half of the separator allows refocusing the beam to a 1 mm^2 envelope and making the mass selection with the slits placed at the image focal plane.

In Table 1, the main first-order ion-optical parameters of the HRS are listed. The HRS at the final focal plane shows mirror symmetry, $(x, x) = (a, a) = -1$ and $(y, y) = (b, b) = 1$, and is point-to-point in x, and point-to-point/parallel-to-parallel in y, with mass and energy dispersion ≈ 31 cm/%.

The mass resolving power of a separator is given by

$$R = \frac{D_M}{2x_0|M_x| + \delta_{aberrations}} \qquad (1)$$

where D_M is the mass dispersion, x_0 is half the initial object width in horizontal direction, M_x is the horizontal magnification and $\delta_{aberrations}$ the width increase due to the total amount of aberrations. Resolving power depends thus on magnetic dispersion and inversely on beam emittance. As elaborated in the EURISOL Design Study [8], the recent development of ion trap beam coolers opens the possibility of reducing beam emittance upstream of the mass separator to increase the resolving power. Therefore, the DESIR-HRS is preceded by a beam-cooling device SHIRaC [9] that will provide the lower-emittance beams necessary for higher mass resolving power. Assuming x_0=0.5 mm and a cooled emittance of 1 π-mm-mrad from SHIRaC, a mass dispersion of 31 m gives a maximal resolving power of 31 000 for the DESIR-HRS.

Several ion optics codes have been used to verify coherence of the optical solutions and to cross check the predicted performance. In addition to COSY INFINITY used for the baseline, the other optics codes are: TRANSPORT [10], GALOP [11],

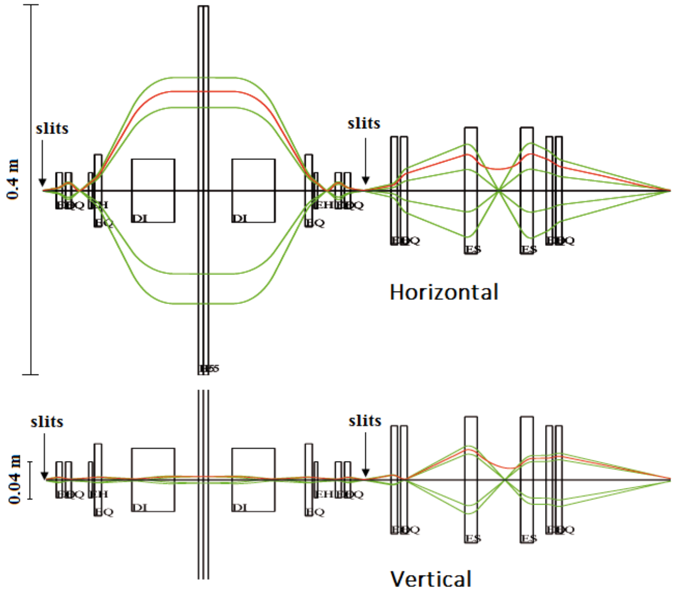

Figure 3: Beam envelopes of the HRS in the x-(dispersive) (top) and y-(non dispersive) (bottom) planes calculated with the program COSY INFINITY. The transport section for matching the 1+ line is included.

Table 1: Calculated first-order transfer matrix elements at the focal planes F1 (after matching quadrupoles), F2 (mid-plane) and F3 (final focal plane) of the HRS.

Matrix elements	F1	F2	F3
(x, x)	-0.23	-33.10	-1.00
(x, a) [m/rad]	-0.76E-2	-18.14	-0.40E-5
$(x, \delta m)$ [cm/%]	0.	1.20	-31.32
$(x, \delta E)$ [cm/%]	0.	1.20	-31.32
(a, x) [rad/m]	-8.04	0.55E-1	-3.65
(a, a)	-4.53	0.79E-4	-1.00
$(a, \delta m)$ [mrad/%]	0.	8.63	-571.6
$(a, \delta E)$ [mrad/%]	0.	8.63	-571.6
(y, y)	-2.61	7.07	1.00
(y, b)[m/rad]	0.63E-1	-0.56E-4	-0.60E-6
(b, y)[rad/m]	-6.53	-0.17E-4	0.50E-4
(b, b)	-0.22	0.14	1.00

GICOSY [12] and ZGOUBI [13], with calculations up to 5th order. Figure 3 shows the beam line envelopes as calculated by COSY INFINITY.

Aberration correction up to 5th order is accomplished by means of a 48-rod electrostatic multipole (placed between the two bending dipoles) with sextupole, octupole, decapole and dodecapole components to correct (x, aa), (x, aaa), $(x, aaaa)$ and $(x, aaaaa)$ aberrations respectively, and by means of two sextupole singlets placed adjacent to the two quadrupole singlets, before and after the dipoles, to correct (x, yy) aberrations. Other aberrations are compensated by symmetry. The dominant correction is of 2nd order, and is mainly due to large horizontal angles. The design for the magnetic dipoles includes the possibility of easily changing magnetic curvature edges to correct (x, aa) aberrations already within the dipoles. The evaluation of the second order aberrations over the whole HRS has been stud-

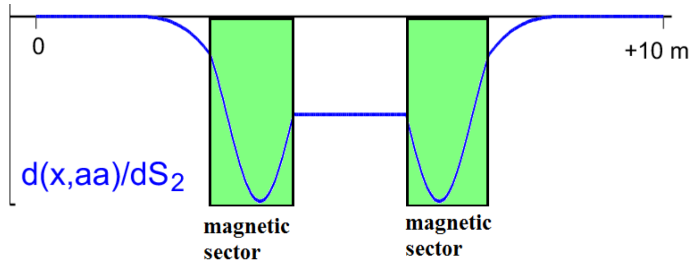

Figure 4: Influence of the short sextupole of strength S_2 on the final aberation (x, aa) as calculated using GICOSY.

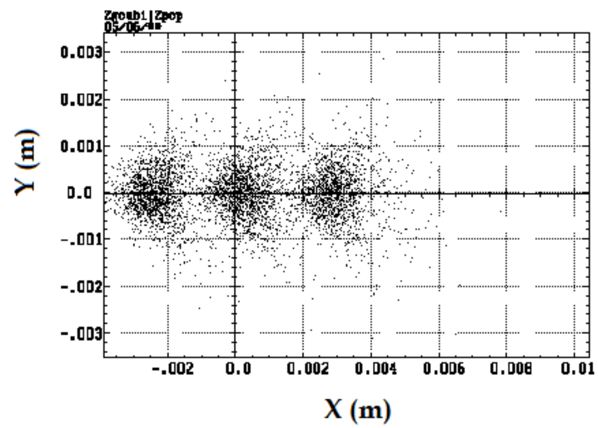

Figure 5: $x-y$ phase space calculated with ZGOUBI using the OPERA 3D magnetic-field maps calculated for dipoles with curved inner faces of 4 m radius.

ied using the method described in Ref. [14]. Assume a short sextupole of strength S_2 at some point in the system. Then the influence on the 2nd order coefficients can be expressed by the size of the 1st order. The influence of the coupling coefficient (x, aa) is given by

$$d(x, aa)/dS_2 = 2(((x, a)_f(x, x) - (x, x)_f(x, a))(x, a)(x, a)) \quad (2)$$

where $(x, a)_f$ and $(x, x)_f$ are taken at the end of the system and the other terms at the position of the sextupole. For the HRS, $(x, a)_f = 0$ and $(x, x)_f = -1$ and the equation becomes much simpler,

$$d(x, aa)/dS_2 = 2(x, a)^3 \quad (3)$$

Figure 4 shows the evolution of $d(x, aa)/dS_2$ over the whole lattice. This study shows that the inner sides of the dipoles will be more sensitive to perform the corrections. Figure 5 shows the X-Y phase space as calculated with ZGOUBI using the OPERA 3D magnetic-field maps calculated for dipoles with curved faces of 4 m, only in the inner faces (before and after the multipole).

After the HRS, an ensemble of two quadrupole doublets and two 45-degree electrical benders allows to transport the beam until the compensation point of the 1^+ line, homothetically (meaning different emittance but with the same relative orientation of the components) at 80 π-mm-mrad. At this point the beam is considered as emitted from a minimum envelope of marginal dimensions of ± 2.25 mm horizontally and ± 7.45 mm vertically.

3. Design of the magnetic dipoles

The magnetic dipoles are the most critical and costly single elements of the DESIR-HRS. Simulations have been performed using the specifications shown in table 2.

Table 2: Dipole specifications.

Characteristic	Value	Units
Field max	0.7	T
$B\rho_{max}$	0.61	Tesla-meters
Vertical gap	0.07	meters
Homogeneous region	0.40	meters
Curvature	0.85	meters
Angle	90	degrees
Pole face angles	36	degrees
Iron mass	6000	kg
Copper mass	390	kg
cooling circuits	6	
Cooling circuit length	74	m
Conductor	8/8/4.5	mm
Turns	96	
Current	210	A
Power supply	17	kW

Simulations were made using the magnetostatic module of the software OPERA [15]. The dipoles have been designed in order to obtain the best homogeneity in the central zone, where most of the particles are transmitted. The obtained homogeneity on the field simulation is shown in Figure 6.

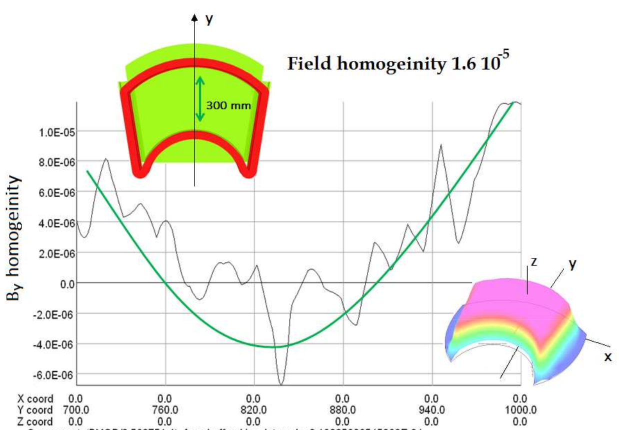

Figure 6: Dipole magnetic field homogeneity along the central axis calculated using OPERA.

A field transverse homogeneity of 1.6×10^{-5} is obtained over a zone of ± 150 mm around the central beam trajectory. Beyond this zone the field homogeneity is 10^{-4}. The central (middle deviation) homogeneity obtained on the simulations represents the best we could achieve with the specifications, but it might be difficult to obtain over the whole range of B_ρ. At $B_{\rho min}$, the homogeneity is around 1.1×10^{-4}. The sensitivity of the homogeneity to different characteristics of the magnet has been evaluated with simulations to allow for deviations due to fabrication. The simulation field maps have been used in several beam optics calculations, in order to validate the design. Note that this design is adapted to the $B_{\rho max}$, and is not suitable for higher magnetic rigidity.

4. Mechanical integration

For safety requirements of the SPIRAL2 project, the DESIR-HRS is divided into seven modules, each of which is separated by gate valves, as shown in Figure 7. Each module can be isolated and removed independently in case of contamination. The mechanical integration has been performed at CENBG. The seven modules essentially follow the DESIR-HRS optics design: (1) injection quadrupole-quadrupole and hexapole-quadrupole lenses; (2) first magnetic dipole; (3) electrostatic multipole; (4) second magnetic dipole; (5) extraction quadrupole-quadrupole and hexapole-quadrupole lenses; (6) first 45-degree bender; (7) second 45-degree bender.

The modular requirement of the DESIR-HRS complicates the mechanical design. The dimensions of the different elements, as well as optical distances have been adapted to obtain the best possible compromise between the performance of the separator and the safety requirements. Geometry, materials and thicknesses of each mechanical piece have been designed to fulfill these constraints. Finite element analysis using the software ANSYS [17] has been done to optimize the thicknesses of the vacuum chambers.

In the mechanical conception, the positioning precision of the different elements is a strong constraint. The many mechanical parts can easily compromise the alignment of the optical elements and degrade significantly the resolution achieved by the HRS.

An optical study has been conducted to investigate the effects of the positioning precision of the different elements of the DESIR-HRS on the final resolution. The aim of this study is to determine the level of precision required for the mechanical design itself and for the repositioning alignment procedures. This study considers translations and rotations of the different modules and sub-module elements of the HRS.

A Monte Carlo code has been developed for these studies. This code takes as input the transfer matrices as calculated from COSY INFINITY up to 5th order and propagates the beam through the different lattice elements. The outputs 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.

Figure 8 shows the phase space diagrams before and after the separator assuming perfect geometrical alignment and the resulting focal plane mass spectrum. To simulate realistic conditions reflecting manufacturing defects and optical element misalignment, the simulations were repeated while varying the positions for each element. The tolerance limit for such deviations

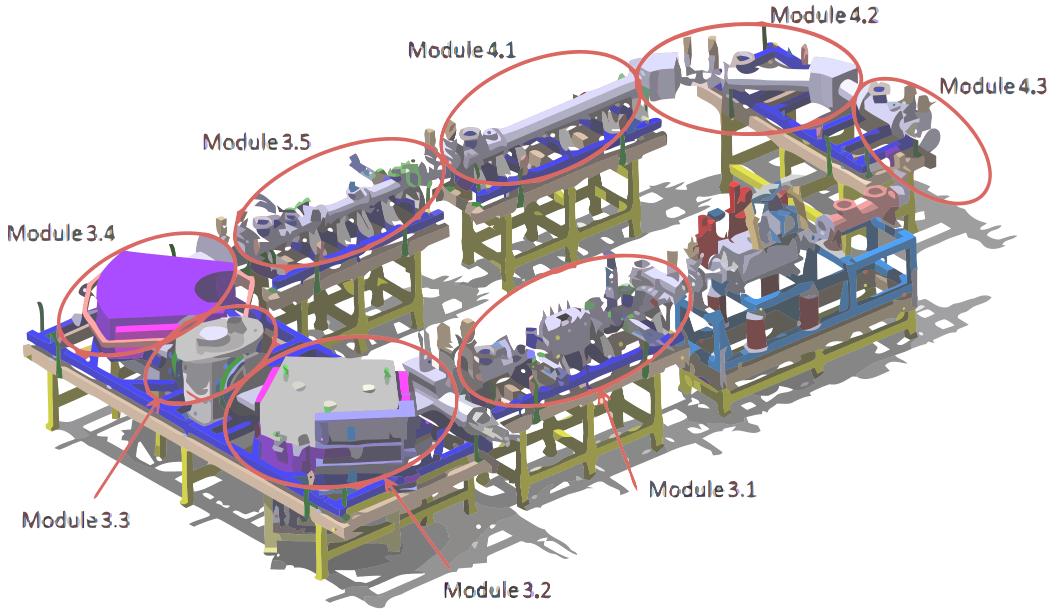

Figure 7: Mechanical design of the DESIR-HRS showing the modular structure with separation by gate values required by the SPIRAL2 safety authorities.

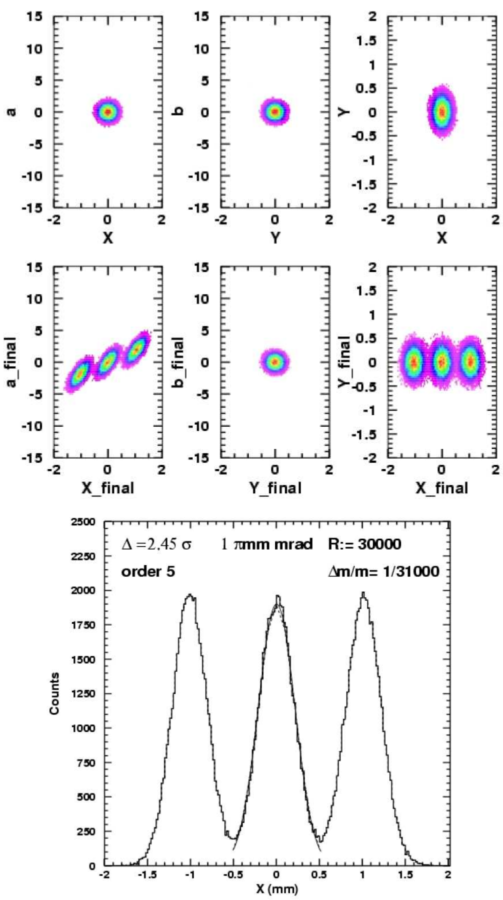

Figure 8: Phase space calculated at 5th order for 50000 particles with mass deviations of -1/31000, 0, +1/31000. Top: Beam phase spaces at the exit of the cooler SHIRaC. Bottom: Phase spaces at the image focal point of the HRS. Mass spectrum calculated to 5th order for 50000 particles with mass deviations of -1/31000, 0, +1/31000.

have been fixed to allowing degradation of the resolving power up to ≈ 20 000, which is our design goal. The positioning precision tolerances of the different elements of the HRS are summarized in table 3. The corresponding phase space plots and mass spectrum for the worse case are shown in Figure 9. The reliability of such tolerances has been validated from the mechanical integration point of view and from the alignment procedures by the surveyor of the SPIRAL2 project.

Table 3: Positioning precision tolerances for the DESIR-HRS.

	X shift (mm)	Y shift (mm)	X tilt (mrad)	Y tilt (mrad)	θ (mrad)
MQ	± 0.1	± 0.1	± 3.5	± 3.5	± 3.5
FS	± 0.1	± 0.1	± 0.35	± 3.5	± 3.5
FQ	± 0.1	± 0.1	± 0.35	± 3.5	± 3.5
D	± 0.1	± 0.1	± 0.35	± 3.5	± 3.5
M	± 0.1	± 0.1	± 3.5	± 3.5	± 3.5

The energy spread used in the aforementioned simulations has been set to $\Delta E/E = \pm 10^{-6}$. Figure 10 shows the effect of a finite energy spread (1 eV/60 keV, or 2×10^{-5}) on the mass resolution. This simulation also takes into account that the neighboring isobaric masses are not of equal intensity. For this case isobaric beam intensities predicted from neutron-induced fission of a 50-kW deuteron beam, on a 280-g (3.5-g/cm3) UCx target [16], for masses $A = 100$ are used.

From Figure 10, it is clear that the energy dispersion destroys the resolution. Second order chromatic aberrations are negligible compared to that effect. From the results obtained with SHIRaC-1, we can expect to have a good energy spread of ∼ 0.15 eV [9] for low-intensity beams, which would be enough to avoid such problems. For high intensity beams of ∼ 1μA a new version of the cooler, SHIRaC-2, has been developed. The cooler has been completed and it is right now under inten-

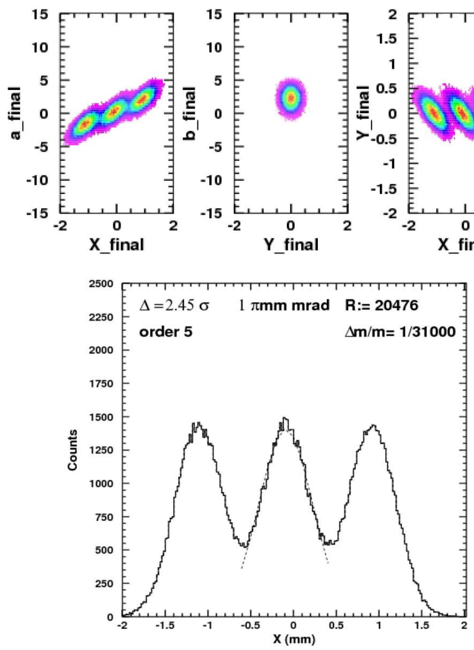

Figure 9: Top: Phase space after the separator calculated using the maximal tolerance on the misalignment of the different optics modules, calculated at 5th order for 50000 particles with mass deviations of -1/31000, 0, +1/31000. Bottom: corresponding mass spectrum, showing the mass resolution decreased to 20000 for the worse case.

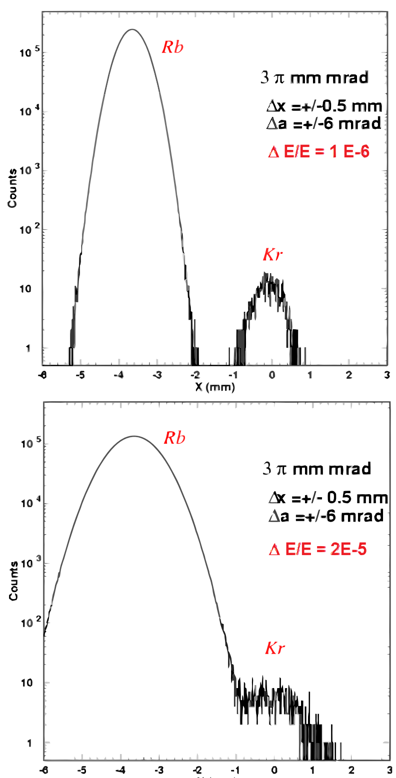

Figure 10: Mass spectrum calculated at 5th order considering $A = 100$ elements produced from neutron-induced fission of a 50-kW deuteron beam, on a 280-g (3.5-g/cm3) UCx target, with the separator tuned to center ^{100}Kr. Intensities are taken from [16]. Top: Energy spread used in the simulation $\Delta E/E = \pm 10^{-6}$. Bottom: a energy spread (1 eV/60 keV) is used.

sive tests and characterization with a surface ionization off-line source.

5. Summary and current status

The optical design for the DESIR-HRS is now complete. The design takes into account past experience from separator experts at radioactive beam installations worldwide. Several ion optics codes have been used to verify the coherence of the optical solutions and to cross check the predicted performance.

The design of the HRS relies on a strong optical focusing for a wide illumination of small dipoles in order to minimize 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. Dipoles have been designed in order to obtain the best homogeneity in the central zone. A field transverse homogeneity of 10^{-5} is obtained over a zone of ± 150 mm around the central beam trajectory. Beyond this zone the field homogeneity is 10^{-4}. The design for the magnetic dipoles also includes the possibility of easily changing magnetic edges to refine the minimization of aberrations.

Considering the maximal tolerance on repositioning alignment procedures, a resolving power of ≈ 20 000 can be achieved for a beam emittance of 1 π-mm-mrad at 60 keV.

Status (February 2013): The mechanical design and integration of the DESIR-HRS to fulfill safety requirements is ready. The dipole magnets have been ordered with delivery expected before the end of 2013. All other elements will be designed and manufactured at the CENBG. The first module of the HRS will be constructed in 2013. Commissioning of the full HRS is foreseen during 2014 and 2015 before installing the complete system in the SPIRAL2 production building.

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