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Abstract

ISOLDE's HRS (High Resolution isotope Separator) was recomissioned in mid 2000, after a period out of service. Since then the separator has routinely run with a mass resolution of 3000-4500, and during 2001 it delivered 72% of ISOLDE's radioactive output. A concerted effort has been made to understand the ion optics and optimise performance. In this paper we present an overview of the HRS, and investigate the factors which limit the attainable mass resolution: ion-source emittance, optical aberrations, beam instrumentation, and magnet stability.

1 Introduction

ISOLDE's high-resolution isotope separator (HRS), originally known as ISOLDE-3, was built at CERN's 600 MeV synchrocyclotron (SC) alongside ISOLDE-2 [1][2]. Shortly after the new separator was commissioned a decision was taken to shut down the SC, so in 1991 the whole ISOLDE facility decamped to the PS-Booster [3][4][5].

The HRS was rebuilt on the new site, with certain modifications. The bending direction of the second spectrometer magnet was reversed; the straight section between the two magnets was shortened; and one of the focal points was suppressed. The old [6] and new layouts are shown in figure 1. Note in particular that the function of the quadrupole doublet between the two magnets has changed.

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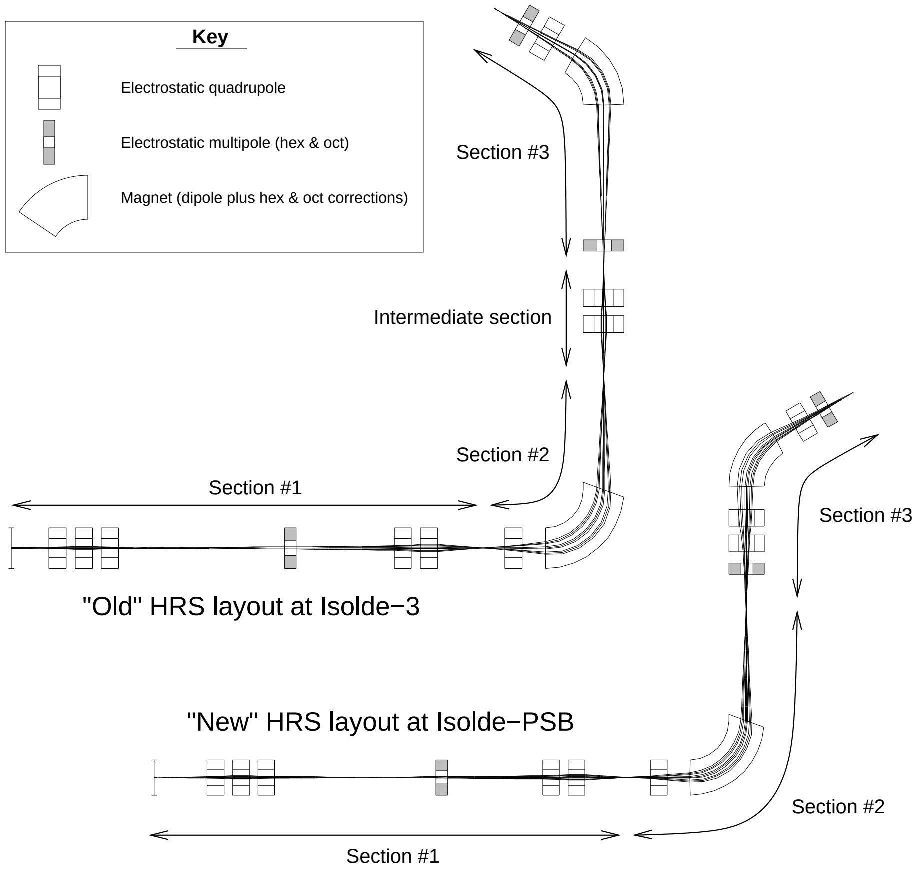

Figure 1: Overview of HRS ion optics — old and new

2 Overview of optics

The optical elements of the HRS are all electrostatic, with the exception of the two large magnets. See reference [7] for an overview of ion optics theory. The spectrometer's optics may be divided into three parts, as shown in the figure.

Section #1 focuses the primary image, just before the 90° magnet. This part of the machine, consisting of five quadrupoles and a single multipole correction element, is designed to have an adjustable magnification. The magnification factor and the ion-source emittance determine the width of the primary image, which in turn determines the maximum attainable resolution of the spectrometer.

Section #2 consists of a defocusing (vertically-focusing) quadrupole and a

90° dipole magnet. The 20° angle on the exit face of the magnet provides additional defocusing. Magnetic hexapole and octupole correction elements [8] are installed on the pole faces of the dipole magnet. The magnification factor is fixed at 1.29.

Section #3 consists of a quadrupole doublet followed by a 60° dipole magnet and a quadrupole singlet. The entrance and exit faces of the magnet are slightly curved to reduce second-order distortions. The magnet also incorporates hexapole and octupole correction elements of the same type as those in the 90° magnet. The magnification factor of this section may be varied, but is usually set to 0.88 (see section 3 below).

3 Resolution

The maximum attainable resolution is determined by the emittance of the ion source, the minimum tolerable transmission efficiency, and the acceptance and dispersion of the spectrometer.

3.1 Dispersion

The dispersion D is a measure of the mass-separating power of a spectrometer: at the final focus the separation Δx between two beams of mass m and $m + \Delta m$ is given by

$$\Delta x = D \frac{\Delta m}{m} \tag{1}$$

The dispersion of the HRS varies depending on the optical setup of the machine, but the optimum resolution is attained when D is 2.7 m. The mass resolution R is therefore given by

$$R = \frac{m}{\Delta m} \cdot \frac{\Delta x}{\delta x} = \frac{D}{\delta x} \tag{2}$$

where δx is the image full-width at the final focus. Thus for an image width of

1 mm, the maximum possible resolution of the HRS is 2700.

3.2 Emittance

The image size at the final focus is determined by the width of the primary image δx_0 and the total magnification of the two subsequent sections, $M = 1.29 \times 0.88 = 1.14$. In turn, the size of the primary image is determined by the emittance of the ion source and settings of section #1. Since emittance is conserved, the minimum size of the primary image is determined by the maximum angular acceptance of the machine. The acceptance is limited by the 140 mm aperture of the quadrupole doublet in section #3, which translates to a maximum angular divergence δa of 90 mrad at the primary focus. The minimum allowable image width may now be calculated from the emittance ε of the ion-source:

$$\varepsilon = \frac{\pi}{4} \cdot \delta x_0 \cdot \delta a \tag{3}$$

Some emittance measurements of standard ISOLDE ion-sources have been made[9] using ISOLDE's "offline" test facility. Under typical operating conditions emittances of 10-20 π.mm.mrad were measured with a beam energy of 30 kV. In the simplest case emittance shrinks during acceleration in proportion to the momentum gained (but see the discussion in [9]), meaning that we would expect to see emittances of 7-14 π.mm.mrad with the nominal ISOLDE beam energy of 60 kV. With our 90 mrad acceptance, the minimum size of the primary image is therefore 0.3-0.6 mm (full-width). From equation 2, this corresponds to a maximum resolution of 7600-3800.

If we are prepared to accept losses — effectively reducing the beam emittance in proportion to the transmission efficiency — the resolution may be pushed higher. Either the magnification of section #1 is reduced, thereby pushing the angular spread of the beam beyond the acceptance of the machine, or the size of the primary image may be artificially reduced by slits. The maximum attainable resolution increases in inverse proportion to the transmission efficiency.

4 Magnet stability and field calibration

Originally the power supplies of the dipole magnets were controlled by feedback from a hall-probe, via a standard hardware field-controller. It was found that this arrangement was not sufficiently precise, for two main reasons: Firstly the resolution of the hall probe is only 5 μT, and for mass resolutions of the order of 10 000 we need a precision of 0.5 μT. Secondly the field controller takes no account of hysteresis in the magnets. It regulates the field at a single point, and since hysteresis effects are not uniform throughout the body of the magnet, the integrated field seen by the ion beam is not necessarily exactly proportional to the field measured at the hall probe. The field-controller was therefore replaced by an intelligent software program, which uses feedback from an NMR probe with a resolution of 0.1 ppm and an absolute accuracy of 5 ppm (the maximum field is 0.52 T). The software cycles the magnet in such a way that the field always follows the same hysteresis loop. This means that for a given field (measured at a point) the hysteresis effects in the rest of the magnet will always be the same. In this way we can ensure that the integrated field of the magnet, and therefore the beam position, is accurately reproducible between field changes.

This field control system was installed and tested during the 2001/2002 shutdown, and is now working routinely.

5 Optical aberrations

In the preceding discussion, we have assumed ideal spectrometer optics. In the real world each optical element introduces aberrations — image distortions which have the effect of increasing the image sizes at the foci — which limit the achievable resolution. Accelerator physicists call the effect "emittance blowup". In the case of the HRS, uncorrected aberrations may increase the image size by a factor of five or so, with a proportional reduction in mass resolution. The HRS contains hexapoles and octupoles (collectively referred to as "high order" elements) which correct for 2nd and 3rd order aberrations introduced by the dipoles and quadrupoles ("low order" elements). Simulations show that the magnetic multipoles may reduce aberrations to the point that the final image is broadened by 20-30%. The electrostatic multipoles however have little effect. This means that we might hope to achieve resolutions of 2900-6300, depending on the ion source, with a transmission efficiency of 100%.

Unfortunately the maximum field strength of the magnetic multipoles is rather small — 34 $\mathrm{T/m^2}$ for the hexapoles and 163 $\mathrm{T/m^3}$ for the octupoles. At higher fields the ohmic heating in the magnet windings becomes unacceptable. In terms of ion masses, this means that the hexapoles can correct 2nd-order distortions up to $A = 33$ and the octupoles can correct 3rd-order distortions up to $A = 15$. Above these limits the correcting effect of the multipoles is reduced. See the upgrades section below for further discussion.

6 Upgrades

6.1 Beam diagnostics

A new diagnostics unit is being designed, which will improve and speed-up the process of tuning the HRS optics. Three units will be built and installed at the three focal points, with each unit incorporating

- a transverse emittance meter to aid tuning multipoles and measure ion-source performance online.
- scanners capable of accurately measuring the profiles of the very narrow HRS beams.
- an improved slit system, better adapted to very small image sizes

- a wiregrid and a faraday cup

6.2 Magnetic Multipoles

As already mentioned above, the maximum field strength of the magnetic multipoles is rather low. Optical aberrations may be corrected for light ion beams, but above $A = 15$ the correction is only partial. Experiments need high mass resolution in the ranges $A = 70 - 80$ and $A = 130 - 140$, for which we need a 2-fold increase in the hexapole field and a 3-fold increase in the octupole field strength. Ohmic heating in the coil windings increases with the square of the field strength, so it seems unlikely that a "quick-fix" can be applied to the existing multipoles. We are therefore working on a design for a set of replacement multipoles.

6.3 RFQ beam cooler

A beam cooler is being designed for ISOLDE, based on a gas-filled RFQ [10], which will be capable of delivering

- reduced transverse emittance
- reduced energy spread
- beam bunching capability

The primary motivation for installing a beam-cooler comes from the REX experiment, which also needs the HRS. Taking account of these two requirements, the places available for the beam-cooler are extremely limited:

- Before the HRS's 90° magnet the RFQ cannot handle the high beam current.
- If the 90° and 60° magnets were moved apart the RFQ could be installed between, although the optics of the HRS would be disrupted. The RFQ would effectively decouple sections #2 and #3, reducing the dispersion at

the final focus to 1.04 m. This could be tolerated if the beam emittance was sufficiently reduced. Eventually this option was rejected because of the difficulty of moving the HRS magnets: the layout of the building confines the magnets to their current positions.

- The only remaining possibility is the area between the final focus of the HRS and the first switchyard of the experimental hall. Even so, it will be an extremely tight fit. Special miniature quadrupoles will need to be designed to match the beam into and out of the RFQ, since standard ISOLDE quadrupoles will not fit. With the beam cooler installed in this position the mass resolution of the HRS will be unchanged, but cooled beams will be available to almost all the experiments at ISOLDE.

7 Conclusions

The HRS has now become part of routine ISOLDE operation, and has shown itself to be a reliable machine. To first order the optics are understood, and we are already reaching mass resolutions 5 times higher than ISOLDE's other mass separator, the GPS (General Purpose Separator). Later this year work will start on upgrading the beam diagnostics, which will give us a much better insight into the higher orders of the optics and help us to design improved correction elements. When these two important upgrades are in place, we can hope to routinely deliver very high mass-resolutions with a predictable beam transmission efficiency.

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