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DESIGN OF HIGH RESOLUTION MASS SPECTROMETER FOR SPES

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Abstract

Within the framework of the SPES (Selective Production of Exotic Species) project at National Institute of Nuclear Physics (INFN laboratory, Legnaro, Italy) the High-Resolution Mass Spectrometer (HRMS) will be build. HRMS needs to provide full separation of the ions with mass resolution 1/20000 for the following breeding and acceleration stages on ALPI Linac. In this article the main design choice of the HRMS and of the transport channel will be reported.

INTRODUCTION

In the framework of the SPES project [1], the High-Resolution Mass Spectrometer must provide high purification of the 132Sn ion beam and >95% transmission. The HRMS will be installed on a High Voltage platform with a maximum operating voltage of -240 kV. Before mass separation, the beam having an energy of 40 keV go through an RFQ Cooler developed by LPC, LPC, whose design goals are output energy spread +/- 1ev and transverse emittance reduction by a factor 10, for a nominal 1/20000 mass resolution [2][3].

HRMS LAYOUT

The main design choices are made as for the medium mass separator (MRMS) of SPES [4].

The HRMS is consisting of: two magnet dipoles of R=1.5 m with deflector angle 90° (HR.D.01-2), one electrostatic multipole in between them (HR.EM.01), six electrostatic quadrupoles (HR.EQ.01-6), two electrostatic hexapole (HR.EH.01-2) and two electrostatic triplets (HR.3EQ.02-3) before and after the slits on the object and image point (HR.BI.03-6) with integrate a diagnostic box. All these elements will be located on the negative high voltage platform. This choice will reduce the relative beam energy spread, ($\Delta w/w$= 1 eV/260 keV) and the geometric emittance. A drawback to the use of the platform is the dynamic stability of the high voltage that must be in the order of 10^{-5}.

The main limit to the HRMS design is the small space available on site for the platform itself and the overall services around it.

In Fig. 1 the layout of HRMS platform is reported, while Table 1 summarizes the specification of all the elements from object slit to image slit. The selected beam can be transported to the low energy beam experiments or to the charge breeder by dedicated electrostatic transfer lines. These are specifically designed for large dispersion environment [5].

BEAM DYNAMICS

In the HRMS, the magnetic dipoles are symmetrically placed between the entrance (object) and exit (image) aperture slits.

Similarly, to the CARIBU separator [6] all focusing and corrective elements are electrostatic, so that the settings are mass independent.

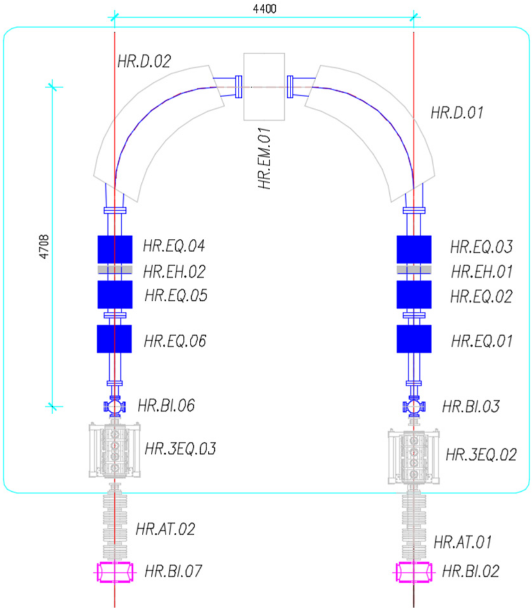

Figure 1: HRMS Layout on high voltage platform.

Table 1: HRMS Specifications

Element	Nominal Value	Units/ Note
HR.3EQ.02/03	-7 / +6 / -7	kV / triplet
HR.BI.03/06	1.1	mm/object-image
HR.EQ.01/06	-9.6	kV
HR.EQ.02/05	+4	kV
HR.EH.01/02	< 1	kV / hexapole
HR.EQ.03/04	-6	kV
HR.D.01/02	0.5623	T
HR.EM.01	< 1	kV /multipole

The entrance and exit edges of the magnetic dipoles are angled with respect to the normal to the beam trajectory to add vertical focusing, while the system is designed to achieve imaging of unit magnification on the horizontal plane. These elements define the linear beam motion with

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a linear dispersion of D= 90 m. Hexapoles are added to provide dynamics correction for manufacturing tolerances in machining the dipole edge angles or any other possible aberration issues.

Furthermore, the dipole entrance and exit edges presents also curvature that provides a second order correction to nonlinearities in the HRMS optics. The electrostatic multipole between the two dipoles, allows for fine-tuning to the second order correction. It also allows for additional corrections of higher order aberrations by providing an octupole, decapole and duodecapole component.

Figure 2 shows the horizontal and vertical beam motion across the HRMS elements, from object to image slit. This beam dynamics study was done with the simulation code TraceWin [7], and the main parameters are reported on Table 2.

The results at nominal resolution are reported in Fig. 3, where the output phase space for 3 beams are shown. The beams are separated of 1/20000 on mass and the final distance is about 6σ i.e. 2.26 mm.

Table 2: Beam Dynamics Parameters

Geometric Emittance	2.7	4σ mm*mrad
Ion Mass (q=1)	132	amu
Beam Energy	260	KeV
RMS Energy Spread	1	eV
RMS Spot size at image	0.3	mm
Maximum X range	440	mm

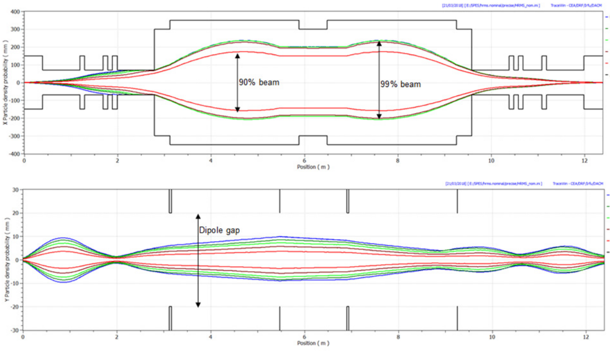

Figure 2: Beam Density on horizontal (x) and vertical (y) planes, from object slit to image slit.

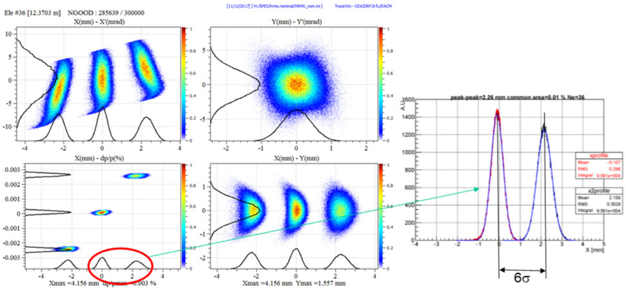

Figure 3: Three Beams phase space separated on mass of 1/20000, at image slit.

ERROR STUDY

From the main relation:

$$\frac{\Delta m}{m}-\frac{\Delta w}{w}=2\frac{\Delta B\rho}{B\rho}$$

where m is the mass, *w* the energy and Bρ the dipole field and radius, it is easy the make the logarithmic derivative to get:

$$\frac{\Delta m}{m}-\left[\frac{\Delta V}{V}+2\frac{\Delta B}{B}+2\frac{\Delta \rho}{\rho}\right]=4\frac{x_{min}}{D}+\frac{\Delta w}{w}$$

Where V is the platform voltage, x_{min} the spot size at image point, D the dispersion. The formula shows that the effective mass resolution $\Delta m/m$ is reduced by the voltage stability $\Delta V/V$, magnetic fields stability $\Delta B/B$, geometrical errors $\Delta\rho/\rho$, energy spread $\Delta w/w$ and spot size. In this way, it is possible to calculate the relative tolerance required to preserve the goal of 1/20000 on mass resolution. Hence, it is necessary to keep all the dynamics relative stabilities of HRMS components, like power supply, vibrations, etc... in the order of 10^{-5}.

A full errors study was performed with TraceWin to consider the real position of the elements, the energy and voltage jitter and the dipole zone flatness.

The errors study was performed over a statistic of 1000 random runs. Each run presents two beams with a mass difference of 1/20000.

The post-analysis was done on the accumulated statistics, by calculating the peak-peak separation of the two beams, the RMS beam size and the overlapping area, i.e. the contamination of the nominal beam, at the image slit position.

In Fig. 4 is reported the displacement tolerance for the quadrupole position on horizontal plane, while in Fig. 5 the energy spread impact on the HRMS performance are reported as example (red and black lines are the two beams data, blue lines are fit results).

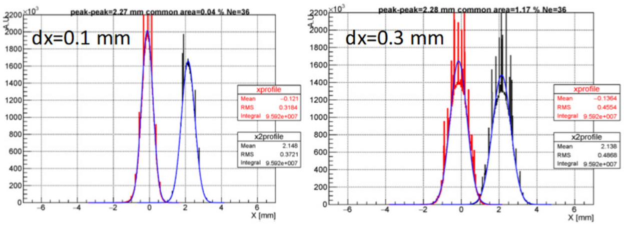

Figure 4: Quadrupoles off-center position effect on two beams separated of 1/20000.

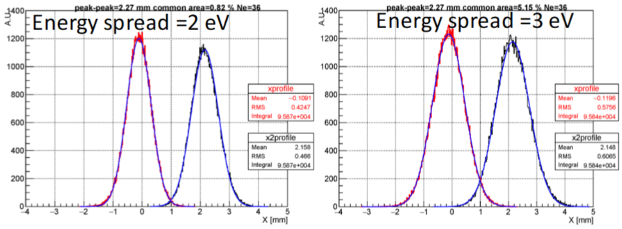

Figure 5: Energy Spread effects on two beams separated on mass of 1/20000.

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The main results of the error study are reported in Table 3.

Table 3: Tolerance Required on Platform

Dipole Magnetic homogeneity	10^{-5}
Dipole homogeneity range [mm]	+/- 200
Element allignement [mm]	+/- 0.05
Energy Spread [eV]	+/- 1.5
Platform Voltage stability	10^{-5}
Platform dynamic displacement [µm]	10
Max Emittance [mm*mrad]	4

DIPOLE DESIGN

The main dipoles parameters are reported on Table 4.

Table 4: Dipole Parameters

Radius	1.5	m
Bending Angle	90	deg
Full Vertical Gap	40	mm
Nominal Magnetic Field	0.5623	T
Edge Angle	27.16	deg
Edge Hexapole radius	2.7 / 0.86	m

From the error study of the previous paragraph, this HRMS is really demanding in terms of tolerances and the constraint to have a magnetic homogeneity along the beam path of 10^{-5} is very challenging.

To achieve this very high field homogeneity within the pole gap an extensive study of the detailed iron yoke geometry was done, and it is still ongoing, by using the simulation tool OPERA/TOSCA [8].

The study is following a step-by-step approach. At first, only the transverse 2D geometry was considered and a common H-dipole design was the starting point. The dimensions of its return yoke and height were chosen by the constraint to keep iron magnetization far from the saturation (<1.7 T), at nominal magnetic field. Instead, the transverse pole dimension was chosen as approximately double the beam horizontal size, given by TraceWin simulation in Table 2. Then, different pole shape solutions were tested to achieve the target homogeneity: shims and Rogowsky shaped pole ends and the effect of a thin cut within the pole iron were the main design solutions. The result of this investigation suggested that a floating pole design (or Purcell design), meaning that the pole is completely detached from the rest of the iron yoke, in combination with a Rogowsky shaped pole edge gives a field homogeneity up to 5 10^{-6} (see Fig. 6), in the area in which the beam is expected. This result is even better than the target needed for the HRMS.

This 2D design was the base for the full 3D model. However, the simple transposition of the 2D design to the third dimension (with the parameters given by Table 4) gives a field homogeneity of 10^{-4} only and just in the centre of the dipole, due to the intrinsically asymmetric dipole shape. Therefore, the study of the 3D design is still ongoing. Again, several solutions are under investigation, concerning the entrance and exit edges and the use of field clamps in their proximity.

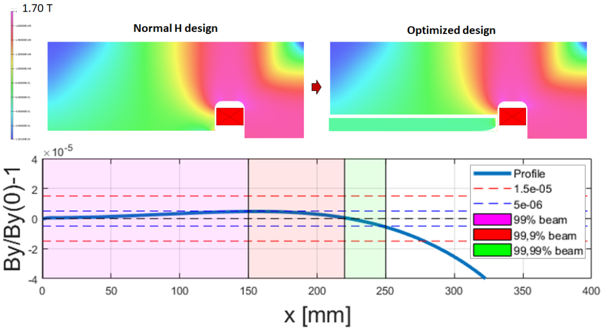

Figure 6: Upper part: 2D (one quarter) dipole design from the standard H-dipole design to the Purcell design, with Rogowsky shaped pole edge. Lower part: The By profile flatness in the center of the pole gap.

Since the very high level of accuracy needed in these investigations, the complex geometry and the considerable size of the dipole, the simulations of the full 3D model are heavy and, therefore, the design process is very slow, compared to the 2D case.

CONCLUSION

For the SPES project, a highly accurate mass separation of 1/20000 is needed. Simulations have shown that, the request for precision and tolerances for the HRMS that must guarantee this target are strict, in all its aspect. The need for a field homogeneity of 10^{-5} for the dipoles is the most demanding one. Dedicated simulations to the dipoles design are giving good results, but, since the very high level of accuracy needed and the complex geometry, investigations are still ongoing.

A review on the HRMS system is expected in fall 2018, followed by the detailed design and construction. Assembly will be done in 2022 and first highly resolved beams will be available in 2023.

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