Design study of a pre-separator for the LINAG super separator spectrometer

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Abstract

The Super Separator Spectrometer (S^3) is a device being designed for experiments with the very high intensity stable beams of LINAG, the superconducting linear accelerator of GANIL, which will be built in the framework of SPIRAL2. These beams, which will be provided in the first phase of SPIRAL2, ions with A/q = 3 can reach intensities exceeding 100 pμA for lighter ones $A < 40 - 50$ depending on the final choice of the ECR (Electron Cyclotron Resonance) ion source. These unprecedented intensities open new opportunities in several physics domains, e.g.: super-heavy and very-heavy nuclei, spectroscopy at and beyond the dripline, multi-nucleon transfer and deep-inelastic reactions, isomers, ground state properties and molecular resonances. An international collaboration has been formed for proposing physics experiments and developing technical solutions for this new instrument. All of the experiments mentioned have the common feature of requiring the separation of very rare events from intense backgrounds. Hence, the present study is aimed at finding an appropriate technical solution for a pre-separator stage of S^3. In this paper we propose some possible approaches and discuss the challenges in addressing the ion optical issues of this device. Three different layouts have been considered to date. These studies are on-going.

Key words: Spectrometer, GANIL, SPIRAL2
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1. Introduction

SPIRAL2 is a project to expand the capabilities of the GANIL facility in nuclear physics research with exotic beams [1]. One of the new instruments envisioned is the Super Separator Spectrometer (S^3) for high intensity stable heavy ion beams [2,3]. The physics that is proposed to be studied with the instrument includes super heavy elements synthesis and spectroscopy, fusion and evaporation reactions, nucleon transfers, deep inelastic reactions, production of rare isotopes via secondary reactions, astrophysics at very low energy, and plasma studies [1]. A working group was formed to establish the design objectives and find innovative solutions for the S^3 device [2]. This paper summarizes the current status of some preliminary design studies of the separator stage.

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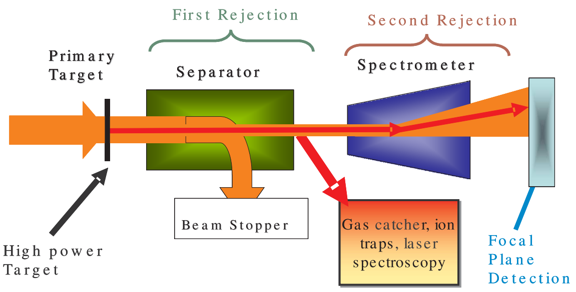

Fig. 1. Schematic idea for S^3 showing two stage separator

2. Design Objectives

It is envisioned that S^3 will be a two stage device with a separator stage and a spectrometer stage. The schematic idea for the layout is shown in Fig. 1. The purpose of the separator stage is to reject the primary beam and perform m/q selection of the recoil particles. The spectrometer stage following the separator stage will be used for secondary reaction studies.

	$B\rho$(Tm)	$E\rho$(V)	Q	β_{rel}	x(mm)	θ(mrad)	y(mm)	ϕ(mrad)	δp/p(%)	δQ
Symmetric reaction ^{40}Ca + ^{40}Ca → ^{78}Zr + 2n										
Beam Parameters ^{40}Ca	0.602	1.394×10^7	+16	0.077	0	7	0	7	0	±1
Recoil Parameters ^{78}Zr	0.507	0.603×10^7	+19	0.39	0.5	50	5	50	5	±1
Inverse kinematics: ^{208}Pb + ^{48}Ca → ^{254}No + 2n										
Beam Parameters ^{208}Pb	1.197	3.702×10^7	+56	0.103	0	5	0	5	0	±1
Recoil Parameters ^{254}No	1.132	2.861×10^7	+59	0.084	0.5	7	10	7	1	±1
Direct kinematics: ^{48}Ca + ^{238}U → 114*										
Beam Parameters ^{48}Ca	0.947	3.046×10^7	+17	0.107	0	5	0	5	0	±1
Recoil Parameters 114*	0.534	0.250×10^7	+26	0.015	0.5	30	10	30	5	±1

Table 1
Table listing the parameters for the examples chosen for the three reaction types.

It is a design goal for S^3 to work for symmetric, inverse kinematics and direct kinematics reactions. It will use high power targets, large beam spots, ± 0.5mm x 10 mm, and gas targets. 1 to 100 pμA stable beams will be used. Very high primary beam suppression is required ($\geq 10^{13}$) for the operation of S^3. The recoil beam will have large angular spread, ± 80 mrad in X and Y, magnetic rigidity Bρ spread of ± 10%, and electric rigidity E$\rho \leq$ 30MV. Due to large angular and rigidity acceptance the aberration corrections to fifth order will be required. Another design goal is high selectivity for weak reaction channels, requiring a high mass resolving power ($\approx$ 1:350). The spectrograph stage is envisioned to have large acceptance for secondary reaction studies. The device will have different operation modes in which the separator/spectrometer are turned on and off independently from each other.

No existing devices can presently achieve all the above objectives. Due to the high intensity and the low energy of the primary beam conventional techniques can not be used for the separation of the primary and recoil beam. The design of S^3 will be unique and challenging in this respect.

3. Proposed layout

Since the energies of the primary beams and the reaction products are low ($\leq$ 10 Mev/nucleon) both the electric and magnetic elements, and devices such as Wien filters, comprising of crossed electric and magnetic field, can be used for separation of the primary beam and recoil beam. The electric and magnetic elements provide separation based on rigidity difference, where as the Wien filter provides separation based on the velocity difference between the primary beam and the recoil particles. To separate particles with specific ratios of m/q requires use of both electric and magnetic elements.

For ion optics design purposes three reaction types, (a) symmetric reaction, (b) inverse kinematics and (c) direct kinematics, were identified to cover the gamut of nuclear reactions under consideration for experiments at S^3. One representative example was considered for each of the reaction types. Beam parameters necessary for the ion optics simulations, like the energy, mass and charge of the reference particle and the spot size, momentum, charge and mass spread for the incident and recoil beam were determined for all three examples. Codes such as HIVAP [4] to determine reaction cross sections were used to identify nuclear physics specific constraints. The parameters are listed in Table 1.

The ion optics design studies for S^3 have so far focused on the separator stage, and three different ion optics layouts have been proposed. Some of the designs use the Wien filter in a non standard mode for rejecting the primary beam, see Appendix A for details. First order design studies have been performed for the proposed design layouts using beam optics codes COSY Infinity [5] and Zgoubi [6]. The findings are summarized below.

3.1. *Velocity filter chicane achromat*

The layout being considered is a sequence of four Wien-filter stages arranged as a chicane. The Wien filter chicane is preceded and followed by quadrupole triplets. The Wien filters are tuned to transport all charge states of the primary beam undeflected to an intermediate image between the second and third Wien filters, the mid-point of the mirror symmetric layout. There is a beam stop at this location and the lower-velocity fusion products are deflected and pass around the beam stop. The overall system is fully achromatic so that the full velocity range and all charge states of the fusion products are imaged at the exit of the pre-separator. The schematic layout of the device and the beam and recoil trajectories for a symmetric reaction case are shown in Fig. 2. The down side of the design is that it suffers from inefficient use of the Wien filters and the need for large Wien filters. Also the device only performs beam rejection and requires a second separator stage for making m/q selection. A second concept was proposed to overcome some of these drawbacks.

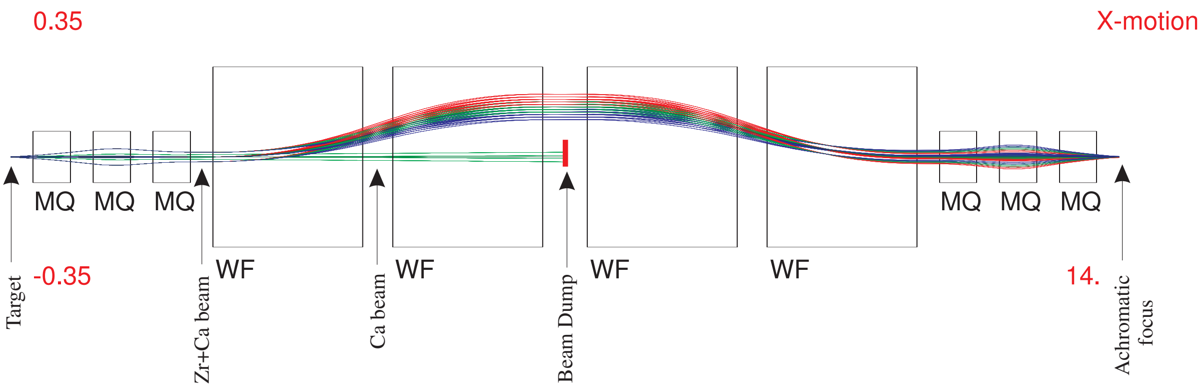

Fig. 2. For the symmetric reaction case the plot shows the separation of the ^{40}Ca primary beam from the ^{78}Zr recoil beam and the position of the beam dump. The trajectories are plotted in the dispersive plane.

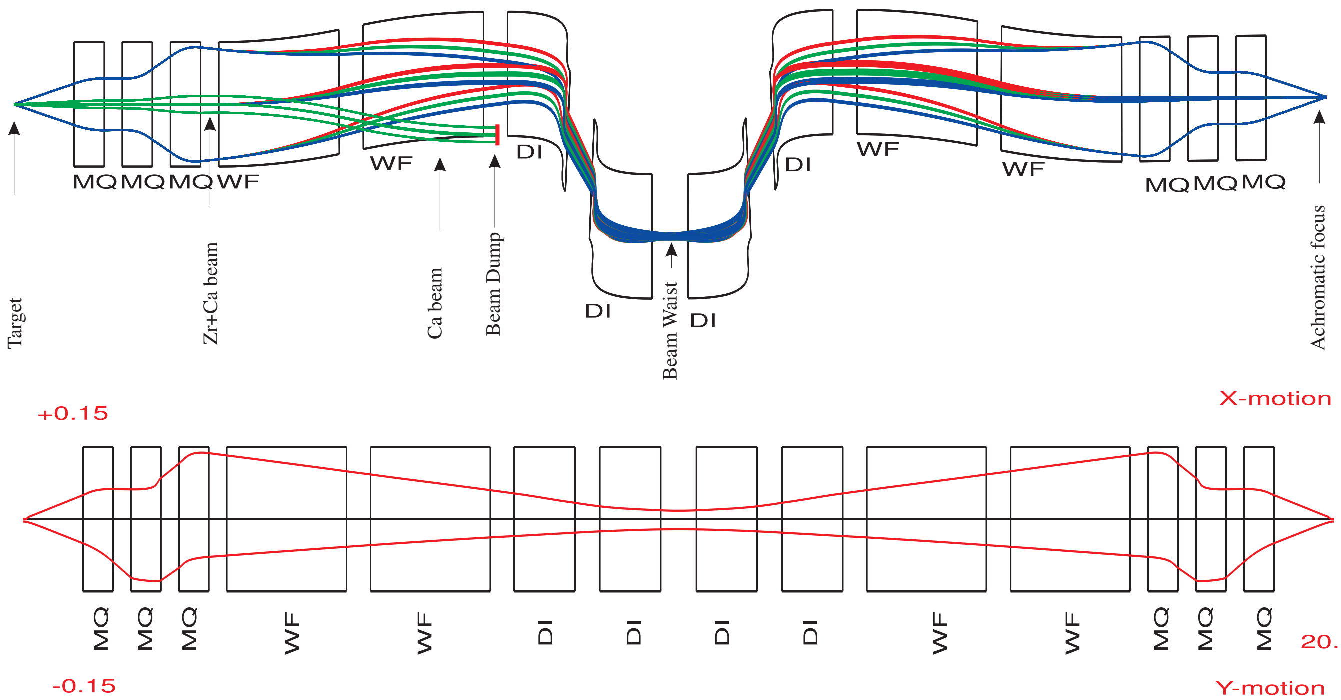

Fig. 3. For the symmetric reaction case the upper plot shows the separation of the ^{40}Ca primary beam from the ^{78}Zr recoil beam and the position of the beam dump. The trajectories are plotted in the dispersive plane. The lower plot shows the X and Y envelopes for the ^{78}Zr reaction products.

3.2. *Velocity filter and mass separator achromat*

The idea of the second concept is to integrate both the beam rejection and the mass selection into one stage. The design consists of four Wien filters and four magnetic dipoles. The magnetic chicane is sandwiched between the Wien filters and the entire setup is preceded and followed by quadrupole triplets. The layout is mirror symmetric about the center. The Wien filters are tuned to a velocity that produces symmetric but opposite deflection of the primary and recoil beams. Thus utilizing the entire volume of the Wien filter and ensuring that the beam does not hit the end plates of the Wien filter. This velocity is approximately given by

$$\beta c \approx \frac{(1/\chi_m^b + 1/\chi_m^r)}{(1/\chi_e^b + 1/\chi_e^r)}, \tag{1}$$

where χ_m^b and χ_e^b refer to the magnetic and electric rigidity of the beam and χ_m^r and χ_e^r refer to the magnetic and electric rigidity of the recoil.

The primary beam is stopped immediately after the second Wien filter. The dipoles provide the m/q dispersion at the center, making it possible to select specific reaction channels. The strengths of the quadrupoles are optimized to obtain a waist at the center. The design allows transmitting many charge states of fusion products. The design is fully achromatic to first order in energy, mass, and charge state. The schematic layout of the device and the beam and recoil trajectories, and beam envelop for the recoil beam, for a symmetric reaction case are shown in Fig. 3. If necessary, the separator stage can even be turned off to transport full primary beam straight through to the spectrograph target. The shortcoming of this layout is that the beam dispersion at the center is limited by the requirement to keep the beam from hitting the plates of the second Wien filter.

3.3. *Integrated layout*

The idea behind this layout is to not only integrate both the beam rejection and the mass selection but to minimize number of components used for the purpose. It is achieved by a two stage design where the first stage performs the beam rejection in the vertical plane, and the second stage performs the mass selection in the horizontal plane. The beam rejection is achieved by using a Wien filter tuned to the reaction products in the vertical plane followed by a magnetic chicane, which further separates the primary beam and the reaction products. A beam rejection factor of 10^5 can be achieved in this stage. At the end of the magnet chicane the reference orbit for the recoil beam is once again planar. The m/q selection is done with a layout similar to that of VAMOS [7]. The layout consists of a Wien filter followed by a dipole magnet, which provides beam rejection factor of 10^7. Hence an effective beam rejection factor of 10^{12} can be achieved using this design. Fig. 4 provides the schematic view of the layout showing the top view, side view, two stages and the positioning of the beam dump. Only a preliminary first order layout of the concept has been developed to date. Further study is required to determine its overall selectivity. To make this separator achromatic in energy spread and m/q requires another stage following the components illustrated in Fig. 4.

4. Conclusion

The present conclusion is that current designs have several advantages but also several disadvantages that will require further study and modifications. In all the design layouts the optimal Wien filter configuration is different for different reactions. Only symmetric reaction cases have satisfactory m/q resolution. For the inverse kinematics case it was found that very high voltage for the Wien filters was necessary. Also it is not clear how aberration correction can be done for such devices which have both the velocity and m/q dispersion. Hence future study to improve the current concepts will be necessary. Alternative designs based on electric sectors and magnetic sectors may lead to better design and easier aberration corrections. These options should be explored.

Appendix A. Transfer map for an off-axis Wien filter

The motion of particle in a beam can be treated in a perturbative fashion by considering motion of a reference particle, representative of the beam, and motion of other particles relative to it (relative particles). In the standard mode of the Wien filter the reference particle orbit goes undeviated through the system. For this case it is sufficient to solve the ODE's for the relative particles of the recoil beam. The formulation and solution of ODE's for the relative particles using differential algebra techniques are described in [8]. In the non standard mode where the reference particle enters the Wien filter off-axis the reference orbit is no longer a straight line. Both the radius of curvature and the electric potential simultaneously change along the reference curve. Enge fringe field model [9,10] is used to describe the field in the entrance and exit region of the Wien filter. Though the net energy change is zero, the energy of the particle inside the Wien filter varies continuously. It is necessary to solve the ODE's for both the reference and relatives particle to describe the beam optics of the Wien filter. Below we derive the ODE's for the reference particle and establish connection between the electric and magnetic fields used in describing the motion of the reference and relative particle.

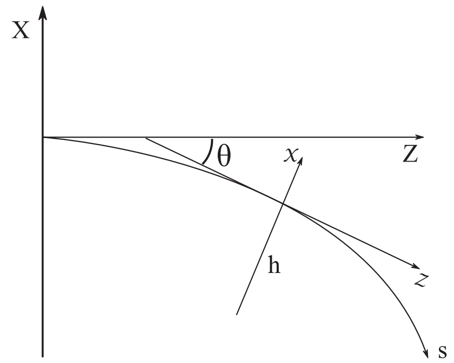

Fig. A.1. Figure showing the reference trajectory and the local coordinate system (x, z).

Assuming that the motion of the reference particle is planar let (X, Z) be the position on the trajectory of the reference particle in fixed lab coordinates. A Wien filter is characterized by horizontal electric field, E_X, and vertical magnetic field, B_Y. Let h be the radius of curvature and θ the angle subtended by the tangent to the curve, as shown in Fig. A.1. The electric potential $V(X)$ inside the Wien filter is given by $V_0(X) = -(V_{0X}/a_w)X$, where a_w is the half aperture in X, and V_{0X} is the plate potential. The electric field in X is $E_X = V_{0X}/a_w$.

For a reference particle with rest mass m_{00}, momentum p_0 and charge q the magnetic rigidity χ_{m0} and the electric rigidity χ_{e0} are given by, $\chi_{m0} = p_0/qe$ and $\chi_{e0} = p_0 v_0/qe$. Using s, the length along the reference orbit, as an independent variable the reference particle coordinates, $(X(s), Z(s))$, can be given as the solution to ODE's

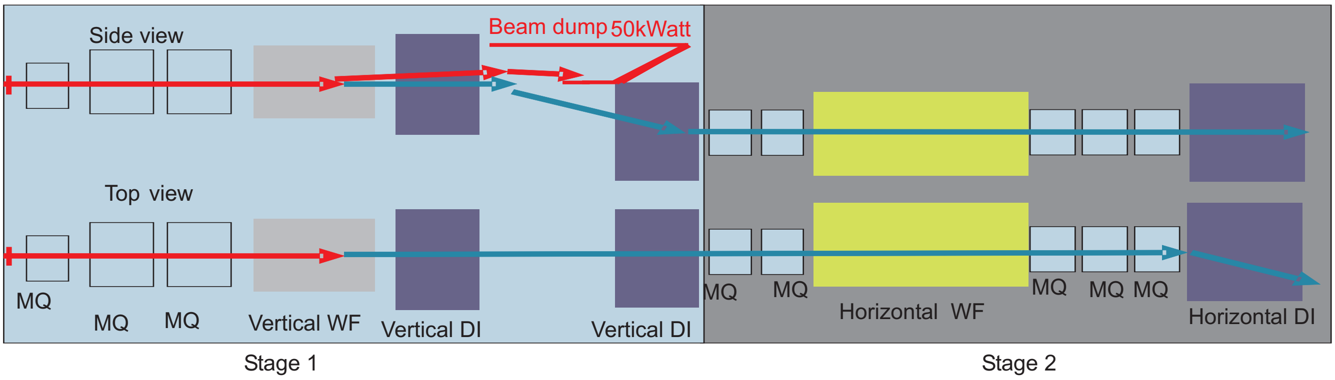

Fig. 4. The schematic view of the layout showing the top view, side view and the positioning of the beam dump.

$$\frac{d\theta}{ds} = h(s) = \frac{B_Y}{\chi_{m0}} - \frac{E_X}{\chi_{e0}}, \tag{A.1}$$
$$\frac{dX}{ds} = -\sin(\theta), \tag{A.2}$$
$$\frac{dZ}{ds} = \cos(\theta). \tag{A.3}$$

The total energy and factor η of the reference particle at point s is given by

$$TE_0(s) = \sqrt{p_0^2 c^2 + m_{00}^2 c^4} - m_{00}c^2 + eV_0(X(s)),$$
$$\eta_0 = \frac{TE_0 - eV_0(X(s))}{m_{00}c^2},$$

We now consider the motion of particles relative to the reference particle. In the rotated frame attached to any point s on the reference curve the electric field and the potential are given by

$$\boldsymbol{E}(x,z) = (E_X \cos(\theta), 0, -E_X \sin(\theta))$$
$$V(x,z) = V_0(X(s) + x\cos(\theta) - z\sin(\theta))$$

The equations A.1,A.2 and A.3 along with the ODE's describing the motion in relative coordinates [8] form a coupled system of ODE's which are solved using the DA techniques and DA version of an 8th order Runge Kutta integrator implemented in the code COSY Infinity [11].

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