CHAPTER 1

COMMISSIONING ST. GEORGE

The St. George recoil mass separator was designed to have an energy acceptance of $\Delta E/E = \pm 8\%$ and an angular acceptance of $\Delta\theta = \pm 40$ mrad, based on the kinematics of a set of astrophysically important (α, γ) reactions [**?**]. In order to use the separator for an experimental campaign, these two properties must be first experimentally determined for a set of magnetic and electric rigidities within the allowable phase space of the separator and near the rigidities of the desired reaction products. To this end, a number of commissioning experiments were performed to determine if the physical energy and angular acceptance of St. George were within desirable limits and to determine field settings for the individual magnets and the Wien filter.

1.1 Theoretical and Experimental Considerations

St. George was modeled within COSY Infinity (henceforth *COSY*), a beam optics and transport language developed at Michigan State University [**?**]. The initial code for the separator was written by Drs. Couder and Berg at the University of Notre Dame during the design and verification portions of the initial grant proposal to maximize the angular and energy acceptance for a point-like target located prior to the separator. Optimization of the individual magnet element properties allowed the separator to achieve the previously-stated energy and angular acceptance, create an achromatic focus at the mass slits, and transport all recoils to the final detector plane (see Section **??**).

Within the code, each magnetic element is represented by a single command, defining the type of element, entrance aperture, length, strength, and a number of other parameters representing the physical shape of the magnetic poles. The three types of magnetic elements (dipoles, quadrupoles, and the Wien filter), accept different sets of values to determine the beam properties. These settings are defined in a set of auxiliary files that are read in by the code, allowing them to be easily viewed and adjusted if necessary. Initial setpoints for the magnets were determined to accomplish the above considerations, and the projected recoil envelope, consisting of a number of sample recoil properties used as representative rays, is shown in Figure **??**. The predicted rays and envelope clearly show some of the design requirements: an achromatic focus at the mass slit location, the rejection of the incident beam by the Wien filter, and the transportation of the recoil particles through the detector system. Note that the transverse scale is highly exaggerated to show detail.

The COSY calculations made some assumptions in order to speed up calculations during the design phase, most notably the reduction of most elements to only consider lower order corrections. This choice sped up transport calculations and allowed for a quick iterative approach to the separator design. Since most magnets are not the ideal magnets assumed by base COSY assumptions, there is the possibility that the higher order corrections to the fields could have a drastic affect on the focusing and deflection properties of St. George and must be explored to fully understand the entirety of the machine. In addition, the fringe fields for the magnetic elements was the default used by COSY, while real magnets are likely to have fringe fields that deviate from that description.

Finally, since setting the correct fields within the magnets is sensitive to the energy of the produced recoil, a strong understanding on the relation between the field setpoints and the energy is required. Since the disjoint between the magnets used within COSY and the physical magnets is known, the required setpoints will be

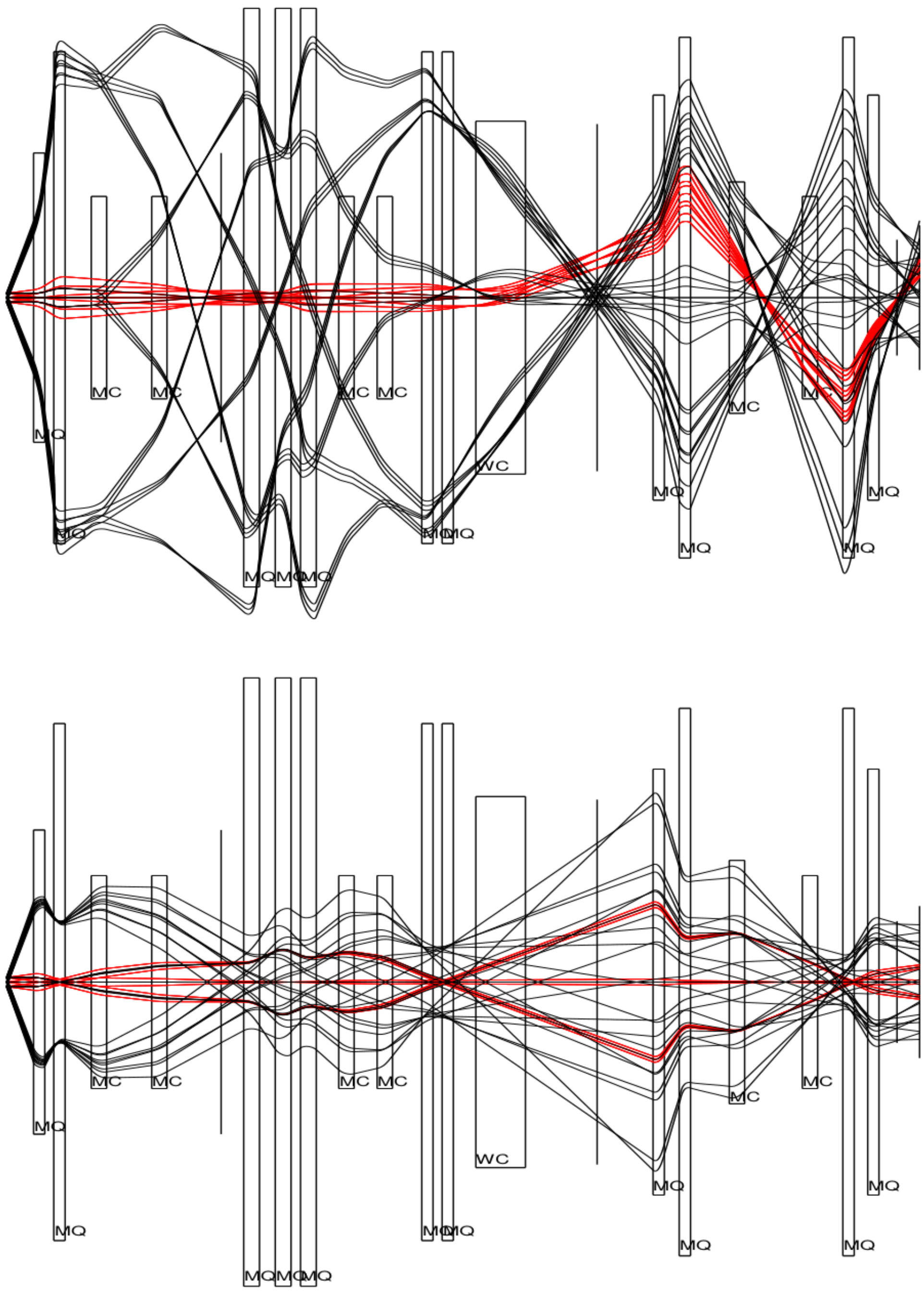

Figure 1.1. Horizontal (upper plot) and vertical (lower plot) rays through St. George. Recoil rays are shown in black and beam rays are shown in red. Test reaction is ^{40}Ca(p, γ)^{41}Sc at $E_{\mathrm{beam}} = 15.6 \pm 1.16$ MeV ($\approx 7.5\%$) and $\Delta\theta = 40$ mrad, highlighting the possibility of St. George probing reactions at the highest range of its design limitations.

different in the theoretical and experimental case and the COSY values may only be useful as a starting point within the search for the proper magnet values.

Experimentally, the Wien filter electrode provides a single free parameter. As the electric field strength only depends on the energy and charge of the particle in question (see Eq. **??**), the electric field by way of the voltages on the electrodes can be tuned separately to achieve the required beam or recoil properties through the remainder of the separator.

1.2 Separator Properties

The magnetic elements for St. George were produced and delivered by [NAME], and the power supplies for these magnets were produced by [NAME]. The magnetic elements are connected to a water cooling system separate from the main NSL water cooling system, and is able to maintain the separator magnets' temperatures at 80 ± 2 °F for extended periods of time. While recycling the magnets (see [SECTION REFERENCE]), the water cooling system is robust enough to keep a steady magnet temperature while all magnets are at their maximum field strength for up to five minutes. Times longer than five minutes were not checked.

The power supply allows for setting the current within each magnetic element down to the mA range, a precision of $< 0.1\%$, depending on the magnet in question. Each magnet must be set individually, and the current must reach its desired value before the next magnet is selected. The power supply itself has hard limits on the current allowed for each magnet, and the separate LabVIEW control program also contains input limits for the magnets. The limits within the control program are generally set lower than the manufacturer's hard limits to help protect the magnets from overcurrent problems.

The high voltage power supplies for the Wien filter electrodes are controlled through a separate program. Power to the control units is provided by the main

St. George power supply, but they may be operated independently. The electrodes have a high voltage limit of ±120 kV, independent of each other. The Wien filter must be conditioned up to high voltages before stable operation, especially following opening the Wien filter inner chamber to atmosphere, requiring the electrodes to be brought above the desired voltage by 10 kV and monitored for voltage stability before bringing the voltage down to the desired value.

1.2.1 Magnetic Fringe Fields

Each of the magnets within St. George were provided with detailed field maps of the magnetic field for various excitations of the magnet. The magnetic field readings were taken at various radii in the plane of the magnet (the exact number dependent on the size of the magnet) and at distances along the axis corresponding to the beam direction and the magnetic optical axis. Readings were taken in mT for three or four excitations per magnet.

The fringe fields for the quadrupoles were explored, initially since the fringe field for Q_{10} was desired by an outside collaborator, but extended to the remainder of the magnets when it was realized that the fringe fields could have a large effect on the beam properties within the separator. The St. George quadrupoles can be characterized as "short" quadrupoles, since the interior field does not equal a single value over an extended length along the beam axis. As such, the fringe field plays a major role both within the magnet and outside of it. A single edge fringe field may be described by the Enge function given by

$$E(z) \equiv \frac{1}{1 + \exp\left[\sum_{k=0}^{N-1} a_k (\frac{-z}{D})^k\right]}, \tag{1.1}$$

where a_k are the desired expansion coefficients and D is the aperture diameter [?]. The expansion coefficients determined above are the same as those desired by COSY to define a fringe field for a single magnet.

Since the St. George quadrupoles are short, we must describe the entire field profile at the same time and cannot separate out the entrance and exit fringe fields from each other. The experimental shape of the entire field can be described in terms of the Enge function as

$$k(z) = k_0 \left[E(L/2 + z) + E(L/2 - z) - 1 \right], \tag{1.2}$$

where k_0 is a parameter describing the central value of the field and L is the effective field length [**?**]. Using the field maps, the magnetic field sufficiently far away from the central axis (usually 2 cm) and at each available radial distance available was scaled to unit height, and the quadrupole was analyzed as a whole. The effective field length, defined as

$$EFL = \frac{1}{B_0} \int_{-\infty}^{\infty} B(z)\, \mathbf{d}z$$

is the field length if the field were described with a pure Heavyside function at the entrance and exit, i.e. no fringe fields. The effective field length was calculated for each radius and excitation separately, and were shown to be the same within a $1-2\%$ percent.

The quadrupole was then fit with Eq. **??** to determine the Enge coefficients, shown in Fig. **??**. Since the form of the data prevented a simple fitting algorithm to progress, the coefficients were determined by performing a Nelder-Mead or downhill simplex minimization routine, provided by the `scipy` package [CITE SCIPY]. The routine minimized the χ^2 difference between the data and the short quad parameterization, updating the six Enge coefficients and the scaling factor k_0 at each iteration. To improve fitting in some cases where the field map did not show the magnetic field falling to near background levels, additional points of zero field were included far (> 5 m) from the center of the magnet.

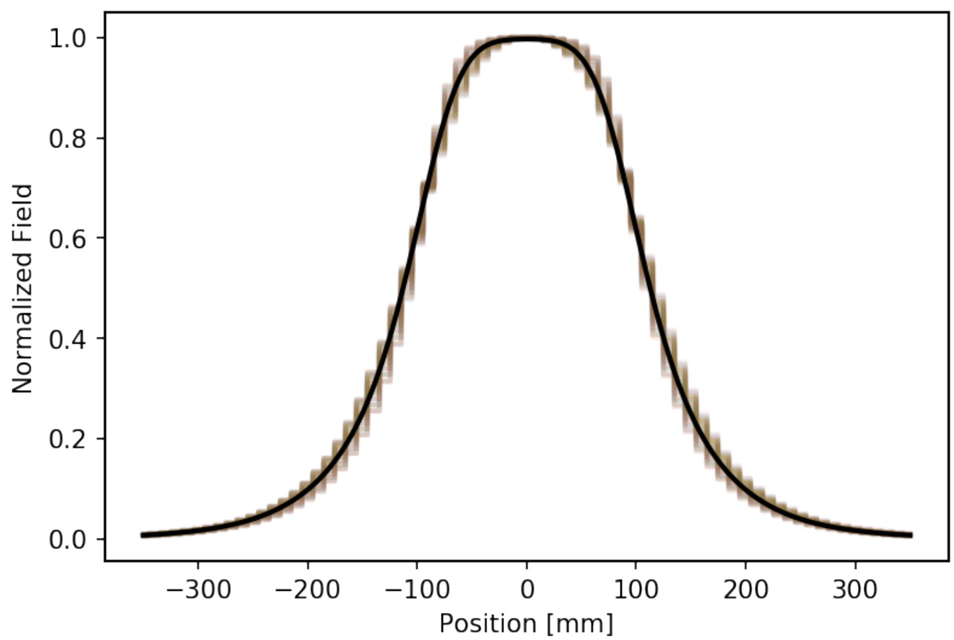

Figure 1.2. Normalized field and the resultant fit to the fringe field for the example quadrupole Q_{10}. The parameters of the fit are given in Table **??**.

The resultant Enge functions were also compared against what the default fringe field characterization for the short quads would give, displaying a distinct difference between the two cases. The comparison for Q_{10} is given in Fig. **??**, with the coefficients for both the fitted fringe field and the default parameters in COSY given in Table **??**.

1.3 Energy and Angular Acceptance

1.3.1 Beam Tuning

1.3.2 Target Properties

1.3.3 Beam Properties

1.4 Reaction Transport Requirements

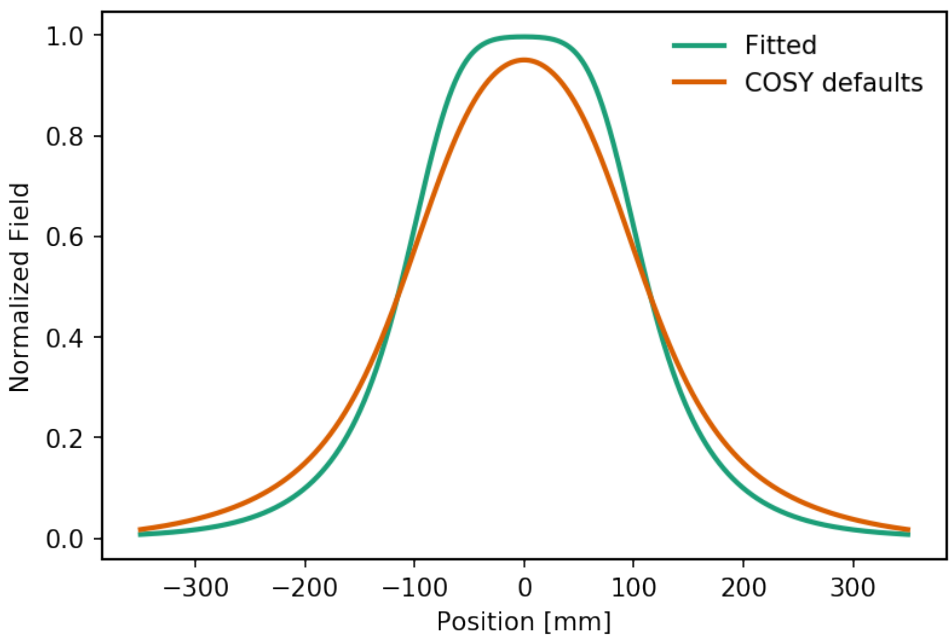

Figure 1.3. Comparison between fringe fields for the example quadrupole Q_{10}. The COSY default parameterization for the fringe field is shown in orange, and the fitted fringe field is shown in green. The distinct difference between the two field characterization requires the higher order effects arising from the fringe field to be taken into account.

Coefficient	Fitted Value	Cosy Defaults
k_0	0.99731489	
a_0	0.37255261	0.296471
a_1	6.18699778	4.533219
a_2	-5.55514115	-2.270982
a_3	6.96210851	1.068627
a_4	-4.82581328	-0.036391
a_5	1.31357875	0.022261

TABLE 1.1

Enge coefficients from fitting Q_{10} with Eq. **??** and the default parameters in COSY for the fringe field. Note that the scaling factor k_0 is not included in the COSY defaults, since those only describe the Enge function and not the short quad parameterization, but can be understood to be 1. Each individual quad would have a unique set of a_k values.

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