1 Studying Heavy-ion Collisions with Coverage Near Zero 2 Degrees using FAUST-QTS

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12 Abstract

Heavy-ion collisions around the Fermi energy provide a rich environment for investigating reaction dynamics and provide an opportunity to explore the transition from quasi-fission to multi-fragmentation. A new detection system, FAUST-QTS has been commissioned at Texas A&M University in order to investigate the reaction dynamics in this transitional energy regime. FAUST-QTS is constructed through the coupling of the FAUST array to a large bore quadrupole triplet spectrometer, and designed to detect heavy fragments near the beam axis coincident with lighter particles.

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14 time-of-flight

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16 1. Introduction

17 Heavy-ion collisions below the Fermi energy (10 - 15 MeV/nucleon) provide
18 a rich environment to study reaction dynamics, as there are a number of com-
19 peting reactions mechanisms at play[1, 2]. This competition between dynamical
20 emission, pre-equilibrium emission and statistical decay of reaction products
21 results in the entanglement of a number of underlying processes. This energy
22 range also provides an opportunity to explore the transition from quasi-fission
23 to multi-fragmentation. Recent theory[3–7] has suggested interesting reaction
24 dynamics via deformations of the reaction system and few body breaking of the
25 deformed, primary reaction partners.

26 In order to reconstruct the reaction plane and the fragmenting quasi-projectile,
27 the ability to detect the lighter reaction products with high granularity and good
28 solid angle coverage, combined with the detection and identification of the heav-
29 iest fragment is required. For systems using inverse kinematics, a forward array

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with good coverage near the beam axis is also an important feature. These criteria also hold true for the study of fusion reactions, in inverse kinematics, where the fusion residue lies near the beam axis with lighter particles emitted transverse to the beam axis.

Recently, we have completed construction and commissioning of a new detection system. This system combines the Forward Array Using Silicon Technology (FAUST)[8] with a Quadrupole Triplet Spectrometer (QTS) to form FAUST-QTS. This detector configuration provides good granularity, solid angle coverage, and isotopic identification of particles emitted off beam axis while allowing for the coincident identification of heavy, projectile-like fragment near the beam axis. This manuscript will detail the design and implementation of the FAUST-QTS detection system, simulations to describe the transport of heavy fragments near the beam axis, and initial performance results. Data collected for this initial commissioning campaign of experiments were from reactions of ^{136}Xe , $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{124}\text{Xe}+^{58}\text{Ni}$ at 15 MeV/nucleon using the K500 superconducting cyclotron at Texas A&M University.

2. Experimental Design

2.1. FAUST Upgrade

The FAUST array[8–11] has been coupled to a large quadrupole triplet spectrometer (QTS). The QTS has been previously used for radioactive-ion beam (RIB)/facility upgrade experiments with BIGSOL[12–16]. FAUST-QTS was designed to make Time-of-Flight (ToF) mass measurements in FAUST and the QTS for heavy projectile-like fragments (PLFs) as well as ΔE -E measurements in FAUST for good isotopic resolution of light charged particles (LCPs) and intermediate mass fragments (IMFs)[8, 17]. FAUST is constructed of 68 Si-CsI(Tl) ΔE -E telescopes arranged into five concentric square rings of detectors, as can be seen in Figure 1. The rings of FAUST are designed as squares projected spheres. The array provides 89.7% solid angle coverage from 2.3° to 33.6° . Partial coverage exists from 1.6° to 2.3° and from 33.6° to 45° . Each Si detector in FAUST is a 2 cm x 2 cm single edge mounted, 300 μm thick silicon wafer backed by a CsI(Tl) inorganic scintillator read out by photodiode.

The ToF mass identification in FAUST is achieved via newly designed integrated charge sensitive, timing pickoff (CS/TPO) pre-amplifiers as part of the upgrade to FAUST. The external Zepto systems preamplifiers[18] were replaced with new charge-sensitive timing pick-off (CS-TPO) preamplifiers and motherboards from RIS-Corp[19] for Rings A-D silicon detectors. The new CS-TPO preamplifiers occupy a slightly larger footprint than the Zepto systems preamplifiers, as seen in Figure 2, due to two extra pin connectors for the timing signal.

The timing on the new CS-TPO preamplifiers is accomplished by detecting charge fluctuations at the detector input to the charge sensitive portion of the CS-TPO. Specifically, the change in JFET current is passed through the emitter of the pnp transistor (connected to the JFET source/emitter) and is amplified

Figure 1: A 3D rendering of the FAUST array from the GEANT4 environment.

Figure 2: Zepto Systems preamplifier (left) and RIS-Corp[19] preamplifier (right) shown side-by-side.

73 to provide a timing signal in the amplifier circuit shown in Figure 3. There is
 74 a sharp change in JFET current for the time it takes to collect the charge de-
 75 posited by the particle of interest in the detector. This change in current (flux)
 76 generates the timing signal. This signal is then integrated to generate a voltage
 77 signal with $\sim 1\text{ns}$ rise time. This allows for fast-timing of the incident particle
 78 simultaneously with charge sensitive pre-amplification in one integrated circuit
 79 chip-set without added bulk or additional cabling. The new motherboards are
 80 backwards compatible with the Zepto systems pre-amplifiers and allow for in-
 81 dividual biasing of each Si detector via WIENER Plein and Baus MPOD High
 82 Voltage power supply modules.

83 In order to generate a common stop timing signal, a thin film, fast plastic
 84 scintillator (BC-408) was installed up-stream of FAUST. The plastic scintillator
 85 was sandwiched and glued between two Lucite light guides and then wrapped
 86 with $2.4\mu\text{m}$ aluminized Mylar. The light guide assembly was then mounted

Figure 3: Brief schematic of the RIS-Corp[19] charge sensitive, timing pick-off preamplifiers.

87 within a custom designed housing. The light generated from the BC408 plastic
 88 was read out via a Hamamatsu R1635 photomultiplier tube. The fast sig-
 89 nal from the photomultiplier tube was used as the common stop in the timing
 90 electronics after being processed by a Tennelec 454 constant fraction discrimi-
 91 nator (CFD) and subsequently delayed by 135ns. The timing signal from each
 92 of the 68 Si detectors in FAUST was processed by CAEN V812B CFDs and
 93 used as the start timing signal. The time difference between the CFD signals
 94 from the FAUST silicon detectors (start) and the fast plastic (stop) was de-
 95 termined via CAEN V775 time-to-digital converter set to maximum resolution
 96 (35 ps/channel, 143 ns full range). The preamplified energy signals from both
 97 the Si and CsI(Tl) detectors in FAUST were shaped by custom bipolar shaping
 98 amplifiers, as described by Ref [8], and read out by Mesytec MADC32 analog-
 99 to-digital converters.

100 In offline testing, we were able to achieve a time resolution of up to ~ 150
 101 ps full-width half-max (FWHM), as seen in Figure 4. This ideal resolution was
 102 possible because of a small angular coverage of the detector due, largely, to
 103 distance from the source, low noise and single isotope analysis using elastically
 104 scattered $^{129}\text{Xe} + ^{197}\text{Au}$ at 15A MeV. However, in the experiment, we were
 105 able to achieve a maximum timing resolution of $\sim 400\text{ps}$. This was highly de-
 106 pendent on the condition/level of radiation damage, background noise, large
 107 angular coverage of each telescope ($\theta_{\text{lab}} \sim 8^\circ$) and a wider range of isotopes de-
 108 tected at varying energies on each individual silicon detector. On average, most
 109 silicon detectors had a timing resolution between 600-1200ps during the actual
 110 experiment.

111 2.2. Quadrupole Triplet Spectrometer

112 The Quadrupole Triplet Spectrometer (QTS) consists of three large bore
 113 (8 inch inner-diameter) quadrupole magnets focusing in the X-, Y-, and then

Figure 4: Preamplifier resolution in a best case scenario in the lab using a plastic scintillator and FAUST silicon detectors. Maximum resolution is on the order of 150 ps at full-width half-maximum.

Figure 5: A 3-dimensional rendering of the FAUST-QTS beam line showing detector and beam-line component positioning.

114 X-direction (respectively) relative to the beam axis. The spectrometer also
 115 consists of two customizable detection chambers, one before and one after the
 116 magnets, to allow ToF mass particle identification (PID) and/or ΔE -E isotopic
 117 identification depending on the energy range of the particles of interest. For
 118 this experiment we employed ToF mass PID.

119 The ToF mass measurements in the QTS were made using Parallel Plate
 120 Avalanche Counters (PPACs)[20] to measure the fragment time-of-flight coupled
 121 with a $1000\mu\text{m}$ silicon detector (MSQ-25, Micron Semiconductor, Lancing, UK)
 122 at $\theta_{\text{lab}}=0^\circ$ for accurate particle energy measurement. The PPACs were mounted
 123 before and after the quadrupole triplet, for accurate time of flight measurement.
 124 The 5 cm x 5 cm, $1000\mu\text{m}$ thick, quadrant segmented silicon detector was

125 mounted after the last PPAC for accurate particle energy measurement and
 126 was chilled to 5°C with thermal and vibrational isolation. A 1/4 inch thick
 127 aluminum collimator was placed just upstream of the 1000 μ m silicon detector
 128 in order to decrease the rate of elastically scattered beam particles not stopped
 129 by a Faraday cup (covering $\theta_{\text{lab}} = 0^\circ - 2.3^\circ$) mounted between FAUST and
 130 PPAC#1. The full detector arrangement is shown in Figure 5 via 3D rendered
 131 CAD drawing of the FAUST-QTS beam line.

132 As has been previously mentioned and shown in Figure 5, the PPACs were
 133 mounted one in front of the triplet and one after the triplet spectrometer but
 134 before the silicon detector. Each PPAC, with 6 torr of isobutane gas flowing
 135 at 30-40 cc/second, was biased to 530V via a Tennelec High Voltage Power
 136 Supply. The signals from the up (U), down (D), left (L) and right (R) signal
 137 were pre-amplified by custom designed hex-amplifiers. The U, D, L and R
 138 signals were then shaped by a CAEN N568B, 16-channel Spectroscopy amplifier.
 139 The resultant amplified signals were then digitized via Mesytec MADC32 peak
 140 sensing ADCs. The timing signal from the PPAC was passively split via Spieler
 141 Timing Pick-off amplifier (LBL-21X7422)[21, 22], with half of the signal being
 142 pre-amplified, shaped, and digitized like the U, D, L and R signals. The other
 143 half of the passively split signal generated a fast timing signal that was cleaned-
 144 up and amplified by an ORTEC timing filter amplifier and discriminated by
 145 a Tennelec 454 CFD. The signals from both PPACs were treated in the same
 146 way. The timing signals resulting from both PPACs were then routed from the
 147 CFDs and measured via an ORTEC 566 time-to-amplitude converter (TAC)
 148 with PPAC#2 utilized as the start signal and PPAC#1 as the stop (effectively in
 149 common stop mode). The TAC output was then digitized via Mesytec MADC32
 150 ADC.

151 Optimal magnetic settings for the QTS were determined through a series of
 152 optical transport calculations. Basic, 1st order optics were calculated analyt-
 153 ically using the TRANSPORT[23] code based on the flight path of the beam
 154 through FAUST-QTS to the detection plane at the 5 cm x 5 cm Si detector
 155 located at the end of the QTS. This allowed for the determination of the base
 156 magnetic field settings (in kiloGauss) for the spectrometer and was the basis for
 157 higher-order calculations via RAYTRACE[24] and COSY-Infinity[25]. Magnet
 158 current settings for experimental data collection were determined by using the
 159 measured minimum current to generate a magnetic field as measured by a Hall
 160 probe. These currents were then compared to previous campaigns of experimen-
 161 tal data[12–16] taken with the QTS. A linear fit for current(A) as a function of
 162 magnetic rigidity ($B\rho$) was obtained.

163 3. Quadrupole Triplet Transport Simulations

164 An important consideration of using a spectrometric device is understanding
 165 the physics that affect particle transport. This is important in order to antic-
 166 ipate what particles are likely to be transported and detected, in addition to
 167 determining which particles can be separated spectroscopically. The particles'
 168 mass, charge state, angle of entrance into the spectrometer, and momentum are

all important considerations that must be carefully taken into account when calculating charged particle transport flight paths.

Figure 6: COSY-Infinity simulations showing the XZ- and YZ-plane flight path of a PLF emitted at $\theta_{\text{lab}} = 1.5^\circ$. The five, discrete magnetic rigidities are centered around a $B\rho = 1.45\text{Tm}$ for the QTS magnets. Red = $\pm 0\%B\rho$, Light Blue = $+5\%B\rho$, Dark Blue = $-5\%B\rho$, Green = $+10\%B\rho$, and Black = $-10\%B\rho$.

Simulations have been examined for a number of probable cases of transport through the QTS using RAYTRACE and COSY-Infinity. This was done in order to examine the theoretical, optical transport considerations required to conduct the proposed experiment. This is especially important since the entrance flight path is significantly shorter than the exit flight path. This, combined with the spectrometer being positioned at zero degrees with respect to the beam, requires careful calculation of the magnetic fields required to transport particles of interest.

179 Simulations via COSY-Infinity illustrate the effects of the $B\rho$ on the ability
 180 to focus particles through the triplet, as shown in Figure 6. Figure 6 illustrates
 181 several values of $B\rho$ for a PLF with a single theta value of $\theta_{\text{lab}} = 1.5^\circ$. As the
 182 value of theta increases (up to a maximum of $\theta_{\text{lab}} = 2.3^\circ$) so do the aberrations
 183 in the focal image. This is particularly true for the YZ-plane where it can be
 184 seen that even at $\theta_{\text{lab}} = 1.5^\circ$ the flight paths of the particles are nearing the
 185 edge of the triplet aperture in the 2nd quadrupole magnet (Q2). The aberration
 186 in the XZ-plane is less than that of the YZ-plane simply because Q1 focuses
 187 initially in the X-direction and, thereby, defocuses in the Y-direction. Some
 188 adjustment can be made to help mitigate some of the higher-order effects by
 189 decoupling the magnetic fields on Quadrupole#1 (Q1) and Quadrupole#3 (Q3),
 190 both X-focusing quadrupoles. By decreasing the Q3 magnetic field by 5% of that
 191 on Q1, there is a significant decrease in the predicted aberrations. Typically, for
 192 a symmetric spectrometer, the coupling of the X-focusing magnets (Q1 and Q3)
 193 would be preferred. However, the decoupling of Q1 and Q3 in the QTS improves
 194 the focusing power by decreasing the focal plane aberration and allows for fine,
 195 empirical adjustment when tuning the fragments of interest.

196 In addition to aberrations in the focal plane image, and exclusion of reaction
 197 products not of interest, it is also important to ensure that scattered, beam-
 198 like particles are not overwhelming the data stream or masking the particles
 199 of interest detected at the focal plane of the QTS. To address this concern,
 200 GEANT4[26] was used to simulate elastically scattered beam particles through
 201 FAUST-QTS. The entire FAUST array and the QTS, up to the entrance of the
 202 first quadrupole magnet, were constructed inside of GEANT4. The simulation
 203 included the Faraday cup (beam block) located between FAUST and the QTS
 at zero degrees, and can be visualized in Figure 7. The physical beam pipe

Figure 7: Cross Sectional view of the FAUST-QTS in GEANT4. The FAUST array is shown
 as the array of five, multicolored rings. The beam pipe is hidden to allow the display of the
 detectors and beam line components. The small blue cylinder behind the FAUST array is the
 Faraday Cup covering a range of $\theta_{\text{lab}} = 0 - 0.9^\circ$.

204 is not shown in Figure 7 for display purposes. However, it was included in
 205 the simulation for geometric constraints. The elastic scattering cross-section
 206

as a function of θ_{lab} was extracted from LISE++ [27, 28] using the reaction of $^{136}\text{Xe} + ^{64}\text{Ni}$ at 15 MeV/nucleon.

One billion primary elastic events were simulated covering an angular range that encompassed particles transmitted through the center of FAUST ($\theta_{\text{lab}} < 2.3^\circ$). Ring A of FAUST was allowed to act as a collimator in order to achieve the correct, square angular distribution in θ_{lab} and ϕ_{lab} . Of particular interest were particles that interacted with the knife edge of the cup [29, 30] thereby losing an appreciable amount of energy, thus possibly resembling particles of interest from projectile-target reactions. Once the elastically scattered particles interacted with the edge of the cup, it was postulated that a small number of particles could lose energy, be inelastically scattered, enter the triplet, and be mistaken for particles of interest at the focal plane.

The knife-edge scattered particles span a range of energy that could overlap with the expected energy range of the PLFs of interest in this type of experiment. This, combined with the fact that the inelastic (knife-edge) scattered beam particles are near the expected mass of a number of the PLFs of interest, drew some concern. However, low beam rate ($\sim 1.5 \times 10^5$ particles per second) and theoretical spectrometer transport efficiencies near 68% for PLFs with a $B\rho^{\text{particle}} \leq 90\% B\rho^{\text{beam}}$ resulted in a negligible probability of detecting a coincident IMF in FAUST with a scattered beam particle in the QTS. This probability rapidly diminishes for particles of interest where $B\rho^{\text{particle}} \ll B\rho^{\text{beam}}$ particularly in the case where the particle to be detected in the QTS is a fusion-like residue and is far away from beam rigidity.

4. Experimental Performance

PLF-like particles were transported through the triplet spectrometer utilizing similar spectrometer settings as described above via the optical transport simulations. The focal PPACs, as expected, have inherently good position resolution. This is exemplified in Figure 8a where it illustrates the position resolution of the PLF-like particles focused through the QTS. In Figure 8b, the physical mask constructed of 0.036" thick brass with the Texas A&M Logo CNC milled into the face of the mask. After the particles were focused by the QTS and passed through PPAC#2, they were then filtered by the logo mask before being detected by the silicon detector at the focal plane. The logo mask was mounted 3 cm upstream of the silicon detector on a retractable arm.

The goal of pairing detection devices in the FAUST-QTS system is to provide a coincident measurement of heavier residues near zero degrees (off beam axis) and lighter charged particles emitted across a wider angular range. The isotopic resolution of FAUST remains unchanged from its original capabilities with isotopic resolution beyond $Z=9$. Unit mass resolution may be possible in the QTS, at higher bombarding energies, with the planned upgrade to a ΔE - E technique at the QTS focal plane. However, the ± 3 mass unit resolution achieved in this commissioning campaign will be sufficient to extract information about the dynamical nature of the reaction in this energy regime. The mass measurement of the PLFs made via ToF in the QTS, combined with the

(a) Texas A&M Logo as seen on PPAC#2 for PLF-like events. The PLF like events were coincident with a silicon trigger after passing through both PPAC#2 and the Texas A&M Logo mask.

(b) Texas A&M Logo Mask. The mask was placed between PPAC#2 (downstream) and QTS silicon semiconductor detector (as shown in [Figure 5](#))

Figure 8: Experimental data showing PLF-like particles focused by the QTS, though PPAC#2, a mask utilizing the Texas A&M University logo and detected in coincidence with a silicon detector at the focal plane of the QTS.

251 information gained via the isotopically resolved IMFs in FAUST, will be suffi-
 252 cient to explore dynamical phenomena associated with size asymmetry, relative
 253 energies, and angular correlations. Additionally, this will allow for the ability
 254 to trace the evolution of isospin and its interplay with dynamical phenomena,
 255 dominant at 15 MeV/nucleon.

5. Summary

A new beam line and detection system has been built for the study of heavy-ion reaction products below the Fermi energy. The FAUST-QTS offers the ability to study heavy reaction products near the beam axis via a zero-degree, quadrupole spectrometer combined with a forward array to measure the off beam axis LCPs and IMFs. The detector arrangement has met the design criteria and has been recently used to study the reaction dynamics of ^{136}Xe , $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{124}\text{Xe}+^{58}\text{Ni}$ at 15 MeV/nucleon. Work is currently underway to improve the energy and time (and thereby the mass) resolution of the QTS. FAUST currently offers good isotopic resolution via $\Delta E - E$ just as it has in the past. Further experiments are underway to utilize FAUST-QTS for temperature and particle correlation experiments.

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