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# Initial Operation of the Recoil Mass Spectrometer EMMA at the ISAC-II Facility of TRIUMF

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## Abstract

The Electromagnetic Mass Analyser (EMMA) is a new vacuum-mode recoil mass spectrometer currently undergoing the final stages of commissioning at the ISAC-II facility of TRIUMF. EMMA employs a symmetric configuration of electrostatic and magnetic deflectors to separate the products of nuclear reactions from the beam, focus them in both energy and angle, and disperse them in a focal plane according to their mass/charge ( $m/q$ ) ratios. The spectrometer was designed to accommodate the  $\gamma$ -ray detector array TIGRESS around the target position in order to provide spectroscopic information from electromagnetic transitions. EMMA is intended to be used in the measurement of fusion evaporation, radiative capture, and transfer reactions for the study of nuclear structure and astrophysics. Its complement of focal plane detectors facilitates the identification of recoiling nuclei and subsequent recoil decay spectroscopy. Here we describe the facility and report on commissioning efforts.

*Keywords:* Recoil mass spectrometer, electromagnetic separator, recoil separator

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## 1 **1. Introduction**

2 The Electromagnetic Mass Analyser (EMMA) [1] has been installed at  
3 the ISAC-II facility of TRIUMF [2]. EMMA is a vacuum-mode recoil mass  
4 spectrometer designed to separate the recoils of nuclear reactions from the  
5 primary beam, focus them in energy and angle, and disperse them in a focal  
6 plane according to their mass/charge ( $m/q$ ) ratios. The spectrometer is fixed  
7 at  $0^\circ$  with respect to the beam axis and is mounted on a common support  
8 platform with 1.5 m of longitudinal travel, allowing for the positioning of  
9 various detector arrays at the target position, including the  $\gamma$ -ray spectrom-  
10 eter TIGRESS [3] and the Si charged particle detector array SHARC [4]. As  
11 depicted in Figure 1, EMMA uses a symmetric configuration of two electro-  
12 static deflectors and a dipole magnet to focus reaction products in kinetic  
13 energy/charge ( $E/q$ ). Angular focusing is achieved via quadrupole doublets  
14 at the entrance and exit of the spectrometer, the latter of which enables vari-  
15 able  $m/q$  dispersion. A photograph of the spectrometer taken in December  
16 2016 is shown in Figure 2.

## 17 **2. Ion Optics**

18 The ion optical design of EMMA is similar to those of the Rochester  
19 RMS [5, 6], CAMEL at Legnaro [7, 8, 9], the Oak Ridge RMS [10, 11, 12],  
20 HIRA at IUAC [13, 14], the JAERI RMS [15, 16, 17], and the Argonne Frag-  
21 ment Mass Analyzer (FMA) [18, 19, 20]; it was optimized to provide large

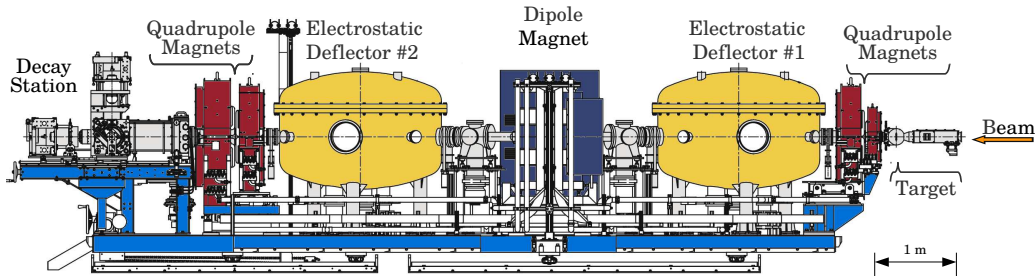


Figure 1: Schematic side view of EMMA, showing the target chamber, quadrupole and dipole magnets, electrostatic deflectors, and focal plane detector chamber surrounded by  $\gamma$ -ray detectors. The spectrometer is mounted on a platform capable of 1.5 m of travel along the beam direction.

22 acceptance without unduly compromising the resolving power necessary to  
 23 study transfer reactions in inverse kinematics as well as fusion evaporation  
 24 reactions. To that end, EMMA features electrodes with larger bending radii  
 25 and a shorter first quadrupole magnet than the FMA. The EMMA electrodes  
 26 have the same bending radii as those of HIRA and are smaller than those of  
 27 the Oak Ridge RMS. For ions of a given electrostatic rigidity, larger electrode  
 28 bending radii allow operation at lower voltages. The ion optics code GIOS  
 29 [21] was used to design the spectrometer, both initially and again after the  
 30 electromagnetic elements were fabricated, to take account of the differences  
 31 between their specified and as-built properties. The standard achromatic ion  
 32 optical tune has a vertical crossover in the centre of the dipole magnet and  
 33  $m/q$  dispersion ( $x|\delta_m$ )  $\equiv \frac{\partial x}{\partial \delta_m}$  of 10 mm/%. Here,  $x$  is the horizontal displacement  
 34 with respect to the optic axis in the focal plane and  $\delta_m \equiv \frac{m/q - m_0/q_0}{m_0/q_0}$  is  
 35 the fractional  $m/q$  deviation with respect to that of the central reference tra-  
 36 jectory,  $m_0/q_0$ . Two quadrupole doublets permit variable angular focussing

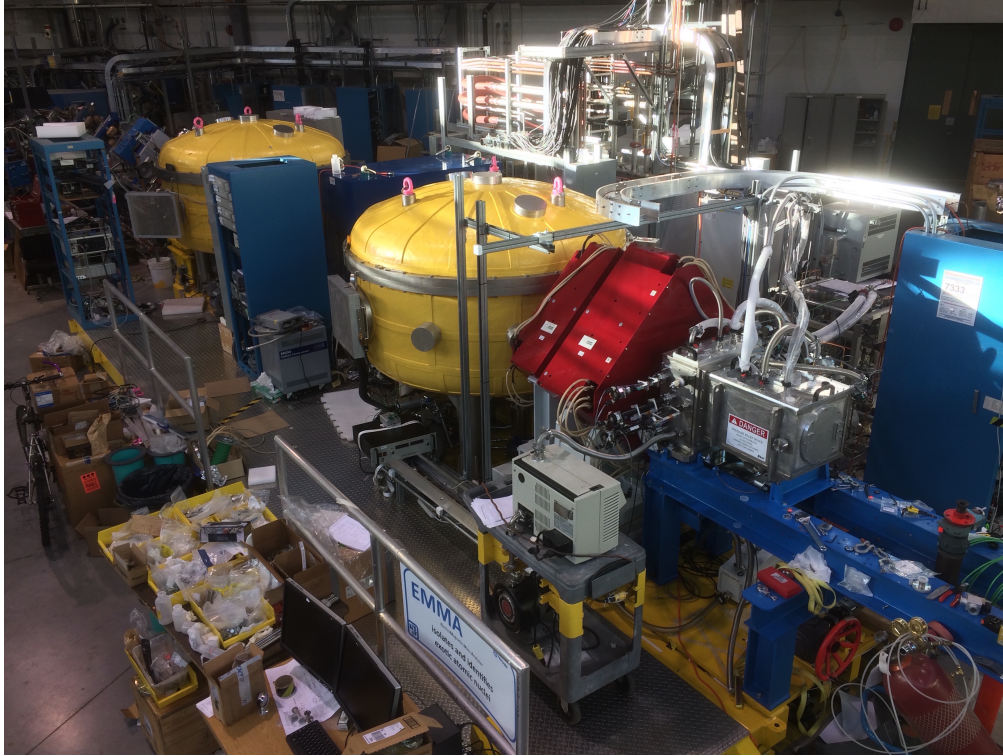


Figure 2: Photograph of EMMA taken in December 2016.

37 modes; by changing the fields in the second doublet, the  $m/q$  dispersion can  
 38 be varied continuously between 0 and 20 mm/%.

39 To first order, given the bending angles and radii of curvature of the  
 40 electrostatic deflectors and the dipole magnet as well as the edge angles  
 41 of the latter, EMMA achieves energy focussing on account of the 1225 mm  
 42 separation between the effective field boundaries of the dipole magnet and the  
 43 electrostatic deflectors on either side of it. Mathematically this is expressed  
 44 as  $(x|\delta_E) \equiv \frac{\partial x}{\partial \delta_E} = 0$  and  $(a|\delta_E) = 0$ . The fractional kinetic energy/charge  
 45 deviation with respect to that of the central reference trajectory,  $E_0/q_0$ , is  
 46 defined as  $\delta_E = \frac{E/q - E_0/q_0}{E_0/q_0}$  and  $a \equiv p_x/p_0 \approx \theta$ , the horizontal angle with

Table 1: As-Built EMMA Dimensions and Maximum Fields

Length from target to focal plane (m)	9.143		
Dipoles	MD	ED1, ED2	
Radius of curvature (m)	1.0	5.0	
Deflection angle ( $^{\circ}$ )	40.11	20.05	
Entrance and exit inclination angles ( $^{\circ}$ )	7.93, 8.67	—	
Effective field boundary radii (m)	3.472	—	
Pole gap (cm)	12	12.5	
Maximum field	1.0 T	40 kV/cm	
Maximum rigidity	1.0 T m	20 MV	
Magnetic lenses	Q1	Q2, Q3	Q4
Bore diameter (cm)	7	15	20
Effective length (cm)	14.0	30.0	40.2
Maximum pole tip field (T)	1.21	0.84	0.80
Maximum field gradient (T/m)	35	12	8.1

47 respect to the optic axis. Here  $p_x$  is the horizontal projection of the ion  
 48 momentum and  $p_0$  is the total momentum of the reference trajectory. In  
 49 the horizontal direction the angular acceptance is defined by the gap of the  
 50 first electrostatic deflector and in the vertical direction it is defined by the  
 51 vacuum chamber of the first quadrupole magnet. The standard distance from  
 52 the target to the effective field boundary of the first quadrupole is 25 cm and  
 53 the focal plane position is variable but in the standard tune lies 32 cm from  
 54 the effective field boundary of the fourth quadrupole.

### 55 **3. Electromagnetic Elements**

56 The quadrupole and dipole magnets, their power supplies, and most of the  
57 components of the electrostatic deflectors were fabricated by Bruker BioSpin,  
58 S. A. S. of Karlsruhe, Germany, whereas the other custom hardware was  
59 constructed at TRIUMF, including the high voltage power supplies for the  
60 deflectors. Each of the magnetic elements was mapped by the manufacturer  
61 with a Hall effect magnetometer prior to shipment. All of the fringing fields  
62 were mapped along with the central fields. The as-built properties of the  
63 electromagnetic elements are given in Table 1.

#### 64 *3.1. Quadrupole Lenses*

65 EMMA's first quadrupole lens (Q1) was designed to have high pole tip  
66 fields and a short effective length to minimize chromatic aberrations. Its  
67 cantilevered support was built so as not to interfere with the placement of  
68 12 of the 16 TIGRESS high purity germanium (HPGe) detectors around the  
69 target position while simultaneously keeping the target to Q1 effective field  
70 boundary separation small, thereby maximizing angular acceptance. The  
71 quadrupoles are arranged in two doublets, Q1-Q2 and Q3-Q4. Both Q2 and  
72 Q3 were fabricated according to the same design, while Q1 is smaller; Q4  
73 is larger in order to transmit  $m/q$ -dispersed ions. Field clamps installed on  
74 the upstream and downstream sides of each doublet limit the extent of the  
75 fringing fields, which is particularly important given the presence of HPGe  
76 detector photomultiplier tubes nearby at the target and focal plane positions.  
77 At the factory, the higher multipole components, effective field boundaries,  
78 and deviations between the mechanical and magnetic axes were measured

79 with the field clamps in place and found to meet our specifications.

80 A transverse Hall probe inserted just below the bore of each quadrupole  
81 is used as a reference to set and monitor its field. The Hall effect mag-  
82 netometers used in all the magnets are model FM-3000-BB-10 Teslameters  
83 produced by Projekt Elektronik Mess- und Regelungstechnik GMBH. The  
84 field gradient was measured as a function of the reference Hall probe voltage.  
85 For each quadrupole, a cylindrical holder with multiple Hall probe positions  
86 was precisely machined and aligned, via a laser tracker, to make these mea-  
87 surements. Corrections due to the  $< 0.1$  mm offset between the mechanical  
88 and magnetic axes obtained from the factory field map were neglected. This  
89 method produced a calibration that allows the field gradient to be inferred  
90 from the reference probe voltage to a precision of 0.1%. Accurate calibration  
91 of the Hall effect magnetometers was confirmed by comparing with an NMR  
92 magnetometer using a uniform dipole reference field.

### 93 *3.2. Dipole Magnet*

94 The dipole magnet is a  $40^\circ$  homogeneous field magnetic sector that was  
95 specified to have effective field boundaries (EFBs) inclined by  $8.3^\circ$  with re-  
96 spect to normal incidence. In order to reduce the horizontal focussing of  
97 the sector and increase its vertical focussing, these inclinations are such that  
98 ions following trajectories with large bending radii pass through less field and  
99 those on small-radius trajectories pass through more field than they would  
100 in the case of normal incidence. The poles of the magnet were designed in  
101 a three-piece arrangement with small pole edge inserts on either side of a  
102 large central piece. These pole edge inserts were machined and re-machined  
103 until the measured inclinations of the entrance and exit EFBs were  $7.93^\circ$



104 and  $8.67^\circ$ , respectively. The average of the two is  $8.3^\circ$ ; the effect of these  
105 distinct entrance and exit angles on the overall ion optical performance of  
106 the spectrometer was studied using GIOS and found to be compatible with  
107 the design requirements after a slight ( $< 1$  mm) adjustment to the separa-  
108 tions between the effective field boundaries of the magnet and the EDs.  
109 Each effective field boundary is curved with a radius of 3.47 m to provide a  
110 second order correction designed to minimize the  $(x|\delta_E^2)$  term. An 8 mm ver-  
111 tical gap between the bottom pole and the vacuum chamber was preserved  
112 to allow the placement of thin correction coils on the pole face should they  
113 be deemed necessary. A decision to fabricate and install such coils would  
114 be made only after a detailed study of ion optical aberrations, which is not  
115 currently planned. The field is measured by a Hall probe fixed to the bottom  
116 pole piece at a location well within the uniform field region.

117 The dipole magnet vacuum chamber has rectangular entrance and exit  
118 apertures that measure 205 mm horizontally and 92 mm vertically. In the  
119 central region the chamber expands to a maximum horizontal extent of 491  
120 mm. Two straight-through ports aligned with the incoming and outgoing  
121 beam axes proved useful when aligning the slit systems located at the en-  
122 trance and exit of the chamber. Sheets of aluminum honeycomb cores made  
123 by Plascore line the vertical walls and bottom surface of the vacuum chamber  
124 to minimize scattering of ions on grazing trajectories. The honeycomb cells  
125 are 6.35 mm in diameter and the sheets are 3.2 mm thick.

### 126 *3.3. Electrostatic Deflectors*

127 Each of the two electrostatic deflectors (EDs) includes a pair of polished  
128 solid titanium electrodes backed by an array of Ti ribs intended to provide

129 structural stability. The ribs and the 25 mm thick electrode of each cathode  
130 were machined from a single piece of Ti, as were the 20 mm thick, rib-backed  
131 anodes, which were bolstered from behind with an additional ribbed piece  
132 of Ti. Each of the four electrodes is supported by four cylindrical ceramic  
133 insulators. The insulators were brazed into Ti feet that attach to adjustable,  
134 polished Al mounting blocks connected to an Al support frame that rests  
135 in a stainless steel vacuum vessel. The vacuum-insulator-conductor triple  
136 points are shielded by Al corona rings and all sharp corners and edges are  
137 concealed behind polished electrostatic shields fashioned from Al. Figure 3  
138 shows the interior of the ED2 vacuum tank. All the components subject to  
139 high electric fields were polished extensively using a combination of fine grit  
140 sandpaper and a succession of five varying grades of diamond pastes from  
141  $9\ \mu\text{m}$  down to  $0.25\ \mu\text{m}$  grit sizes. For the rounded electrode surfaces that  
142 sustain the highest fields, an additional phase of polishing with a colloidal  
143 silica suspension was employed.

144 The electrode support structures were assembled in a clean room to min-  
145 imize dust deposition on the surfaces. Alignment of the electrode pairs was  
146 done to a precision of 0.1 mm inside the clean room using a FARO coordinate  
147 measuring machine with an articulating arm and a Leica laser tracker. Dur-  
148 ing the alignment procedure a significant discrepancy was discovered between  
149 the measured and specified radii of curvature of the anodes; they are listed  
150 for comparison in Table 2. The electrodes were positioned such that the gap  
151 between them is 125 mm in the centre, which results in a reduction of the gap  
152 at the electrode edges compared with the design due to the smaller radii of  
153 curvature of the anodes. This manufacturing defect means that the electric

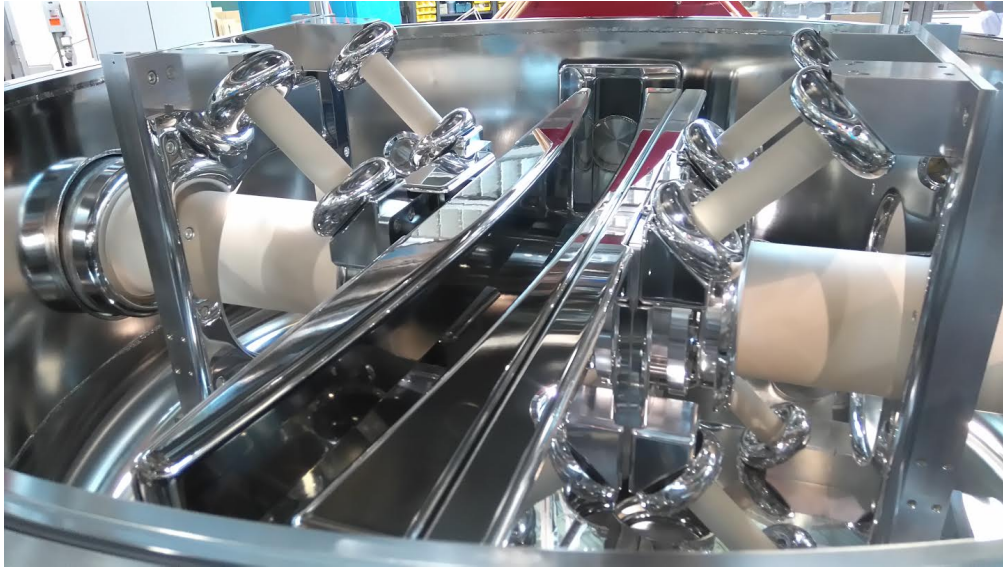


Figure 3: Photograph of the interior of the 2nd electrostatic deflector vacuum vessel.

154 fields in the gap are not as homogeneous as specified and that unanticipated  
155 second- and higher-order ion optical aberrations are present in the system; it  
156 also implies that the first order energy dispersion ( $x|\delta_E$ ) is not quite as small  
157 as planned. These flaws were highly impractical to correct, as the polished,  
158 cleaned, and aligned electrodes would have had to be removed, re-machined,  
159 and re-polished.

160 High voltage is provided to the electrodes via internal, 40 stage full-  
161 wave Cockcroft-Walton DC multipliers built at TRIUMF. The multipliers are  
162 driven by external 1 kW Glassman High Voltage Inc. PG010K100JD2DRV  
163 DC supplies that allow for constant voltage or constant current operation.

Table 2: EMMA Electrode Radii of Curvature in mm

Electrode	ED1	ED2	Specification
Anode	5007.3(55)	4977.1(55)	5062.5
Cathode	4953.3(55)	4952.0(55)	4937.5

164 Each multiplier has been tested without a load to a maximum potential dif-  
165 ference of at least 325 kV. To prevent breakdown the multipliers are housed  
166 within re-entrant ceramic vessels pressurized with 3 bar of electrically in-  
167 sulating SF<sub>6</sub> gas. As bias is applied during conditioning, steady state load  
168 currents can reach as much as 35  $\mu$ A, leading to the emission of X-rays. For  
169 shielding purposes, the entire surface of the stainless steel dipole vacuum ves-  
170 sels are covered with 6.35 mm thick lead sheets cut and pounded into various  
171 shapes that were affixed using epoxy. All the ports and windows are covered  
172 with caps containing the same thickness of Pb. Thus far, the first and second  
173 electrostatic deflectors have been conditioned to maximum stable potential  
174 differences of 340 kV and 440 kV, respectively. We plan to condition them  
175 further to a potential difference of 500 kV.

176 Each electrostatic deflector vacuum tank is pumped by an Agilent TV1001  
177 1000 L/s turbomolecular pump, an Oxford Instruments CryoPlex 8 1500 L/s  
178 cryopump, and a Gamma Vacuum TiTan 600L 500 L/s ion pump. The ion  
179 pumps run on a diesel-generator-backed uninterruptible electric power circuit  
180 in order to ensure high vacuum continuously through electric power bumps  
181 and failures. Pressures in the mid 10<sup>-9</sup> Torr range are typically observed  
182 with only two pumps running in each isolated vessel.

#### 183 4. Experimental Apparatus

184 Two 10" OD ConFlat vacuum crosses mounted symmetrically between  
185 the electrostatic deflectors and the dipole magnet house horizontal slit sys-  
186 tems that can block ions on unwanted trajectories. The two 1.6 mm thick  
187 stainless steel plates that make up each slit system can be driven indepen-  
188 dently to create an opening from 0-180 mm wide. The opening need not be  
189 centred on the optic axis. One cross has a 1500 L/s cryopump and the other  
190 has a 1000 L/s turbomolecular pump. When either of these pumps is used  
191 to evacuate the isolated MD vacuum chamber section a pressure in the low  
192  $10^{-9}$  Torr range is typically observed.

193 Several experimental systems have been designed and installed at EMMA  
194 while others are still under construction. These include target and focal plane  
195 detector systems and their associated chambers and accessories. Notably,  
196 some are being developed with off-site collaborators, such as those at the  
197 University of York in the UK.

198 A 20 cm diameter spherical target chamber couples to the vacuum cham-  
199 ber of the first quadrupole magnet. The chamber is designed to accommodate  
200 12 TIGRESS detectors in a closely packed configuration. It contains a ro-  
201 tary target mechanism that allows for the manual positioning of up to three  
202 target foil positions into the beam path. The target chamber also houses an  
203 integral, suppressed Faraday cup on a separate rotary actuator; a Ta aper-  
204 ture plate at its entrance lies in the same plane as the target foils. The Ta  
205 plate has a 1 mm diameter aperture through which the beam is tuned by  
206 maximizing the current on the Faraday cup while minimizing that on the  
207 aperture plate.

208 The target chamber has provisions for mounting two 150 mm<sup>2</sup> silicon  
209 surface barrier detectors centred at 20° angles with respect to the beam  
210 axis downstream of the target. They are used to monitor the beam flux  
211 and target condition via elastic scattering and are primarily intended for  
212 the normalization of reaction cross section measurements. Additionally, a  
213 highly-segmented, annular silicon detector can be mounted 33 mm upstream  
214 or downstream of the target position to detect light charged particles. A thin  
215 C foil can be positioned 116 mm downstream of the target position in order  
216 to restore the charge state distributions of transmitted ions to equilibrium  
217 through charge-changing collisions following possible internal conversion de-  
218 cays. Similarly, an energy degrader foil can be mounted 68 mm downstream  
219 of the target. To exclude ions on trajectories outside of the angular ac-  
220 ceptance of the spectrometer, a circular aperture at the exit of the target  
221 chamber defines a cone of half-angle 4.2° and a solid angle of 17 msr; an ad-  
222 ditional, optional ±2° aperture can be used to restrict the horizontal angular  
223 acceptance when high  $m/q$  resolving power is required, as described in Ref.  
224 [1].

225 A separate target chamber designed to accommodate highly-segmented  
226 rectangular and annular silicon detectors as well as 12 TIGRESS detectors,  
227 dubbed SHARC-II, has been designed at the University of York and is in the  
228 final stages of fabrication. It can be positioned so that the target is separated  
229 from the Q1 effective field boundary by the standard 25 cm.

230 The focal plane station has a modular design in which detectors may  
231 be inserted and removed easily according to the experimental requirements.  
232 A position-sensitive parallel grid avalanche counter (PGAC) and an energy-

233 sensitive ionization chamber (IC) make up the standard complement of focal  
234 plane detectors. They are mounted in separate vacuum chambers that can be  
235 joined together, allowing for the use of the PGAC without the IC if energy  
236 loss signals are not required. In the current configuration, the use of the  
237 PGAC is mandatory while the IC is optional. A 3000 mm<sup>2</sup> ion-implanted Si  
238 detector can be mounted directly behind the PGAC, as can a double-sided  
239 Si strip detector. The latter can also be mounted behind or inside the IC. All  
240 of the detectors are read out using a version of the MIDAS data acquisition  
241 system.

242 Both the PGAC and the IC are filled with isobutane as an ionization  
243 medium and have an active area of 154 mm by 54 mm, with a larger extent  
244 in the horizontal, dispersive direction than in the vertical direction. The  
245 PGAC, which measures 73 mm between entrance and exit foils, operates at  
246 pressures between 2 and 4 Torr while the 40 cm long, 16 anode segment IC  
247 is designed to operate at pressures of 10 – 100 Torr. Provisions have been  
248 made to mount up to 4 clover-shaped HPGe detectors of the type used in the  
249 GRIFFIN spectrometer [22] at the focal plane to study isomers and delayed  
250 activities.

251 The focal plane station has a set of 4 independently actuated 1.6 mm  
252 thick stainless steel plates just upstream of the PGAC that together consti-  
253 tute a slit system. Two of the plates are mounted on combined rotary and  
254 linear motion feedthroughs that present different profiles to the incident ions  
255 depending on their angle. In this way the focal plane slit system can obscure  
256 the entire focal plane except for 1 – 3 openings of continuously variable po-  
257 sition and width, enabling the simultaneous transmission of up to 3 charge

258 states.

## 259 **5. Initial Measurements**

260 Due to a flurry of last minute activity on the focal plane station vacuum  
261 and control systems just prior to its first scheduled beam time, there was no  
262 opportunity to first test the spectrometer with an alpha source. Hence initial  
263 focussing and dispersion tests were carried out by bombarding a  $4.5\ \mu\text{m}$  thick  
264 Au foil with an 80 MeV  $^{36}\text{Ar}$  beam. The spectrometer was initially set to  
265 transmit multiply scattered, 19 MeV  $^{36}\text{Ar}^{13+}$  ions. The foil was sufficiently  
266 thick that the multiply scattered Ar ions filled the angular and energy accep-  
267 tances of the spectrometer. After observing a single, well-defined  $m/q$  peak  
268 we set the fields for the same energy but charge state  $13.5^+$  and transmit-  
269 ted the  $13^+$  and  $14^+$  charge states simultaneously. As shown in Figure 4,  
270 the peaks of the two charge states were separated by the expected 66 mm  
271 distance corresponding to the design  $m/q$  dispersion of 10 mm/%. The dif-  
272 ferent peak heights reflect the charge state distribution of the transmitted  
273  $^{36}\text{Ar}$  ions.

274 Following this initial in-beam test, we carried out a series of ion optical  
275 studies with a  $^{148}\text{Gd}$   $\alpha$  source to study the angular focussing,  $m/q$  disper-  
276 sion, and energy dispersion cancellation. These tests will be described in a  
277 forthcoming publication. The spectrometer was further tested when we bom-  
278 barded a  $900\ \mu\text{g cm}^{-2}$  natural Cu target foil with both stable and radioactive  
279 Na beams and set the spectrometer to detect fusion products. In these mea-  
280 surements the  $\pm 2^\circ$  horizontal aperture was in place, the PGAC was operated  
281 at a pressure of 2 Torr, and the  $3000\ \text{mm}^2$  Si detector was positioned directly



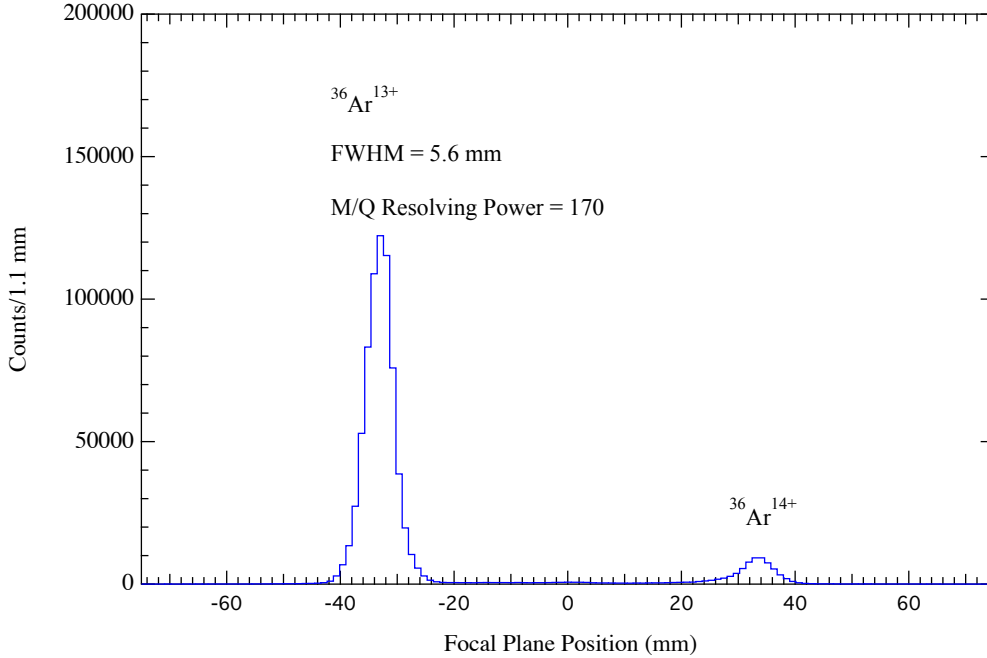


Figure 4: First  $m/q$  spectrum obtained with EMMA; it resulted from bombarding a 4.5  $\mu\text{m}$  Au foil with an 80 MeV  $^{36}\text{Ar}$  beam. Multiply-scattered Ar ions filled both the angular and energy acceptances of the spectrometer. The two detected charge states are separated by the 66 mm expected from the tuned  $m/q$  dispersion of 10 mm/%.

282 behind the PGAC to aid in distinguishing fusion products from scattered  
 283 beam ions. We first bombarded the Cu target with an 84 MeV  $^{23}\text{Na}$  beam  
 284 from the ISAC offline ion source [23] and set the spectrometer for 18.4 MeV,  
 285 81 u,  $10^+$  recoils.

286 After we obtained  $m/q$  spectra of the fusion products with several over-  
 287 lapping spectrometer settings, the operations group delivered an 87 MeV,  
 288 radioactive  $^{24}\text{Na}$  beam produced in a SiC target by TRIUMF's 500 MeV  
 289 proton beam and doubly ionized by a forced electron beam induced arc dis-  
 290 charge ion source [24]. The operators succeeded in tuning more than 90%

291 of the radioactive beam through the 1 mm aperture of EMMA's Faraday  
 292 cup. Beam intensities on target ranged from 1 to  $4 \times 10^7 \text{ s}^{-1}$  and spectra  
 293 were measured at several field settings. Figure 5 shows that obtained when  
 294 the spectrometer was set for 17.1 MeV, 82 u,  $10^+$  recoils. Beam suppression  
 295 at these settings exceeded a factor of  $10^9$  and the  $m/q$  resolving power was  
 296 measured to be as large as 240 (FWHM), which is more than adequate to  
 297 resolve masses around  $A = 90$ .

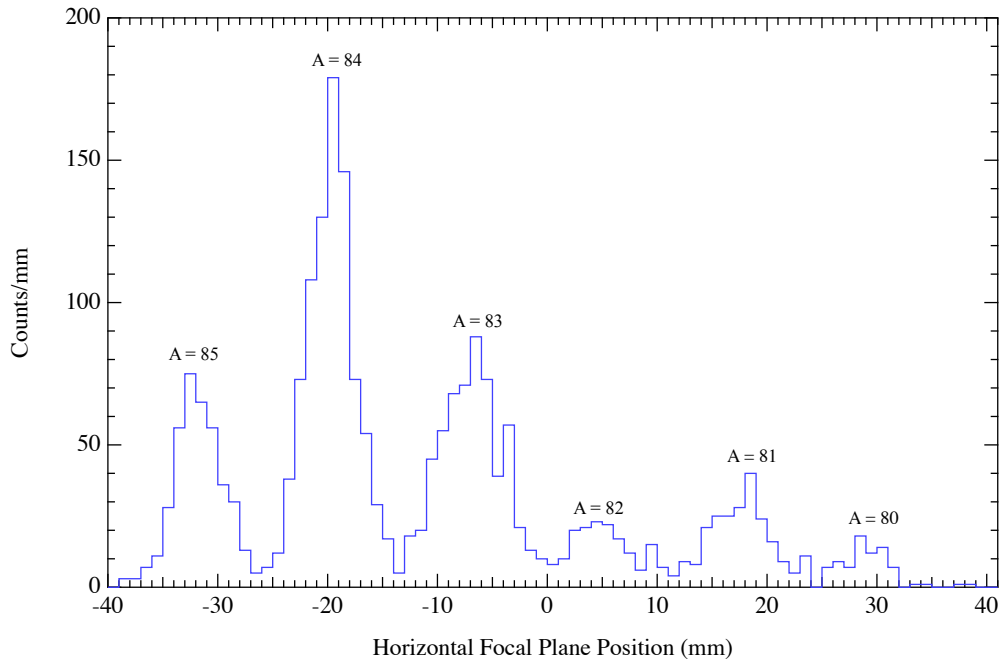


Figure 5: First  $m/q$  spectrum obtained using EMMA to detect products of reactions induced by a radioactive beam. A  $900 \mu\text{g cm}^{-2}$  natural Cu foil was bombarded with an 87 MeV  $^{24}\text{Na}$  beam and the spectrometer was tuned to transmit 17.1 MeV, 82 u,  $10^+$  recoils. This position spectrum from the PGAC was gated to include only events with an energy signal in the Si detector corresponding to fusion residues.

## 298 **6. Status and Future Plans**

299 High voltage conditioning is expected to be completed within the next 2  
300 months, at which point the spectrometer will have been fully commissioned.  
301 Four EMMA experiments and two letters of intent have been approved by  
302 the TRIUMF subatomic physics experiment evaluation committee. All are  
303 motivated by nuclear astrophysics and all but one of them require the in-  
304 stallation of the TIGRESS  $\gamma$ -ray spectrometer around the EMMA target  
305 position to provide spectroscopic information. This installation is planned  
306 to be completed in the spring of 2019, at which point the EMMA scientific  
307 program can begin in earnest.

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