MASS ANALYZING RECOIL APPARATUS, MARA*

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An in-flight zero-angle mass separator, MARA, has been recently constructed and commissioned at the University of Jyväskylä, Finland. MARA is a double focusing device, consisting of a quadrupole driplet, electrostatic deflector, and magnetic dipole. This separator is built for nuclear structure studies to be performed around the $N{\sim}Z$ line and at beyond the proton drip line.

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1. Introduction

The gas-filled recoil separator RITU [1, 2] has been in operation since 1994 at Jyväskylä accelerator laboratory JYFLACCLAB. RITU has been in a heavy use and the experimental program performed has been very succesfull. In average, it has yelded more than 10 refereed publications per year and it has been a base for numerous thesis works. Originally, RITU was planned for experiments where the heavy nuclei ($Z \geq 82$) are produced in fusion–evaporation reactions using asymmetric kinematics. In reality, however, RITU separator has been used for studies at the proton drip line starting from lower mass region, as low as ^{66}As [3], up to transactinide region ^{256}Rf [4]. In the region below ^{100}Sn, symmetric kinematics has to be used where the gas-filled separator is not an optimal solution to be employed. Although the program has been successfull, a clear need for a more selective separator system has been demonstrated. In the heavy-mass region, the alpha and the proton decays help with the selectivity, but in the lower-mass region, such a tag is not available. In the region below $Z \leq 74$, the main

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decay mode is beta activity and to gain in the selectivity, a project to obtain an in-flight mass separator was started. In this paper, the layout of the recently constructed MARA [5] separator will be presented. In addition, some results from the commissioning phase of the separator will be given. It will be followed by a short introduction to the performed experimental program so far and the future plans. A more detailed outlook of the MARA separator ion-optics and commissioning phase will be published in the forthcoming paper [6].

2. The layout of the separator

The configuration of the MARA separarator is QQQEM, where Q stands for quadrupole, E for electric dipole, and M for magnetic dipole (Fig. 1). MARA differs from the vast majority of the in-flight vacuum mode separators in that it is not a symmetric device. The combination of electric dipole and magnetic dipole provides a fixed energy focus. Quadrupole triplet is used to obtain angular focus to the point of the energy focus and what is then left is that the ions with different m/q ratios are separated. Into the magnetic dipole correction coils have been added to introduce a small quadrupole component. This will allow the focal plane to be varied ±30 cm along the optical axis from its nominal point. At the entrance of the first dipole, point to parallel focusing is used in order to achieve the best possible mass resolving power. At the focal point, the focal plane is heavily tilted. Movable aperture slits, both in dispersive and non-dispersive planes, are placed at the entrance of the electric dipole. Movable "energy" slits (dispersive plane) are placed between the two dipoles. Due to the heavily tilted focal plane, a double-mass slit system is introduced at the focal plane at the entrance and at the exit of the MWPC-counter (see below). The aperture and the energy slits can be used to improve the final mass resolving power with the cost of acceptance. The mass slits are typically used to allow only two charge states of a given mass to be transported into the implantation detector. The ion-optical elements of the separator are listed in Table I.

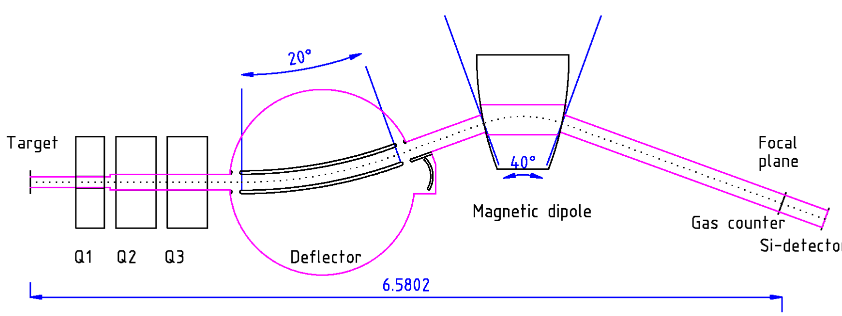

Fig. 1. Ion-optical layout of the MARA separator.

TABLE I

The optical elements in MARA separator.

Length from target to focal plane [m]	6.90	
Dipoles	M	E
Radius of curvature [m]	1.0	4.0
Deflection angle (deg.)	40	20
Effective field boundary inclination angles (deg.)	8.0	0
Effective field boundary radii [m]	2.0	—
Gap [cm]	10	14
Maximum rigidity	1.0 Tm	14 MV
Magnetic lenses	Q1	Q2, Q3
Bore diameter [cm]	10	15
Effective length [cm]	25	35
Maximum field gradient [T/m]	10	10

The main ion-optical properties of the separator using the so-called nominal settings are shown in Table II. The nominal settings are found to give a good mass resolving power with high angular and energy acceptance. The quadrupole triplet gives a freedom to have infinite number of setting values giving double focusing at the focal plane. For example, by varying these setting values, it is posible to increase the angular acceptance with the cost of mass resolving power (or *vice versa*).

TABLE II

The main ion-optical properties of the MARA separators (nominal settings).

Configuration	QQQEM
Horizontal magnifigation	-1.55
Vertical magnification	-4.48
m/q dispersion	8.0 mm/%
First order resolving power (2 mm beam spot diameter)	259
Solid angle acceptance for central m/q and energy	10 msr
Energy acceptance for central m/q and angle	-15%–$+20\%$
m/q acceptance	$\pm 4\%$

3. Detector setup

Separator is not a useful device by itself and needs an efficient detector setup to reach the final selectivity. MARA is a mass separator but it cannot resolve isobars or overlapping evaporation channels involving alpha-particle evaporation, called m/q ambiguity. At the target position, a particle detector array (JYTube) is placed. It consists of 96 separate scintillator detectors whith SiPM (Silicon Photo Multiplier) readouts. Individual detectors have been arranged into two barrels. In addition, both barrels are connected to an end-plate array with a hole in the center for the ion beam and recoil products. The target is placed between these two barrel arrays. The geometrical efficiency of the system is around 80%. It is used to collect evaporated protons and alphas. It can be used as a veto detector to enhance the weak neutron-evaporation channels or if used as a fold one array, it enhances the weak pxn-evaporation channels.

The m/q spectrum is obtained using a position sensitive Multi-Wire-Proportional Counter (MWPC) at the focal plane of MARA. It consists of three wire planes, x-plane, cathode, and y-plane. The wire planes are realized with 20 μm thick gold-plated tungsten wires with 1 mm spacing. Final position is obtained using 2 ns delay lines between the wires and by measuring the delays in the signals between the two ends of the wire planes. The main detector is a double-sided silicon strip detector (DSSD). Models BB17 and BB20 (Micron) have been in use. BB17 has 1 mm strip width and in BB20 the strip width is 0.67 mm. The total amount of strips in BB17 is 48+128 and in BB20 is 72+192 (detector size is then 48 mm (y-plane) $\times$ 128 mm (x-plane)). In addition, behind the DSSD, a second layer of silicon is used for punch through events, and in front of the DSSD, a silicon box array is used for escapes. All this can be surrounded with an array of Ge-clover detectors for gamma-ray collection. All the channels are connected to a digital readout system, in which all channels are triggered independently. On-line and off-line analysis of the data is performed using software package called Grain [7].

4. Commissioning phase

The commissioning of the separator was performed using different target beam combinations covering reaction types from asymmetric, symmetric, and inverse kinematics close to the Coulomb barrier energies. The reactions used are listed in the following, first the used beam then the target. In addition, the detectors used (more and more detectors added when commissioning phase progressed) are listed:

— ^{78}Kr + ^{92}Mo, MWPC, BB17,

— ^{40}Ar + ^{45}Sc,^{nat}Ca, MWPC, BB17,

— ^{78}Kr + ^{58}Ni, MWPC, BB17, punch-through silicon, two Ge-clovers,

— ^{40}Ar + ^{124}Sn, as above and two Ge-clover detectors at the target position, first recoil gating,

— ^{58}Ni + ^{106}Cd, MWPC, BB20, punch-trough and escape silicon detectors, JYTube-detector, four Ge-clover detectors.

As an example of commissioning runs in figure 2, a m/q spectrum *vs.* the position difference between MWPC and DSSD is shown. This position difference corresponds to the incoming angle of the recoil. Spectrum is fusion recoil gated using the energy measured at the DSSD and time-of-flight (ToF) measured between the MWPC and the DSSD. From figure 2, it can be seen that masses are well-separated and that four charge states were collected. Also from this spectrum, the second order abberration from the incoming angle as well as the effect of the tilted focal plane can clearly be seen.

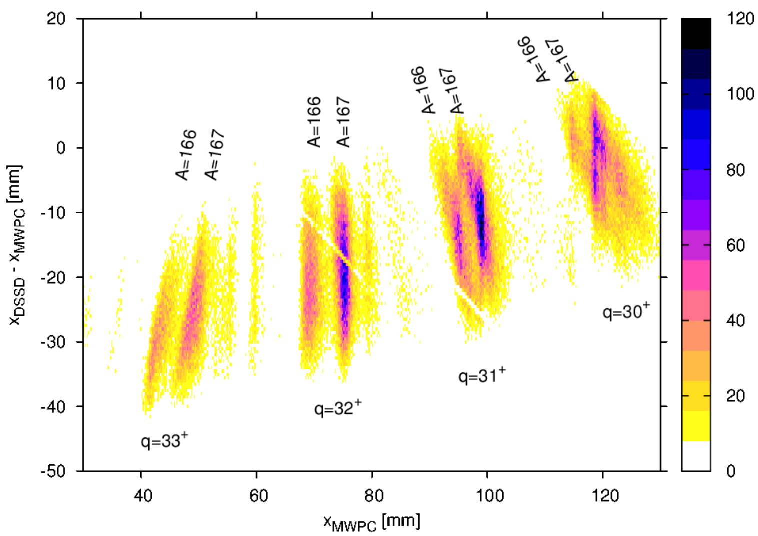

Fig. 2. m/q spectrum measured at the focal plane of MARA. In the x-axis, the position in the MWPC is shown and in the y-axis, the position diffrence between the MWPC and DSSD is shown. The reaction was ^{78}Kr + ^{92}Mo.

In another example in figure 3, a spectrum is shown where in the x-axis is the correlated alpha-particle energy measured at DSSD, and in the y-axis is the m/q measured at the MWPC. Again, it shows the separation between masses and that 4–5 charges states are collected.

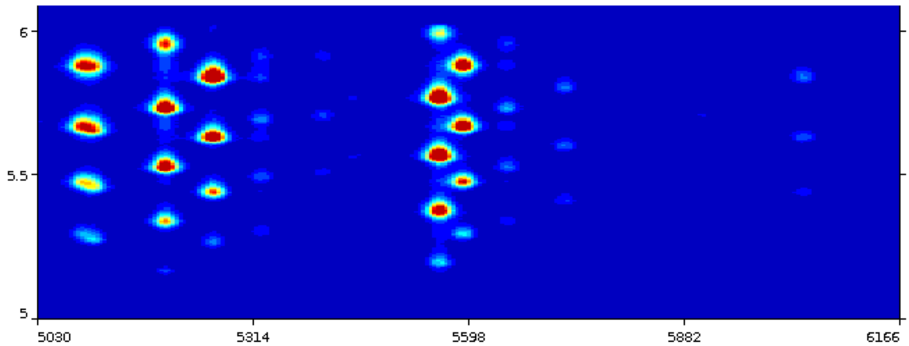

Fig. 3. Alpha-particle energy [keV] spectrum measured at the DSSD *vs.* the m/q spectrum obtained from MWPC is shown. The reaction was ^{58}Ni + ^{106}Cd.

5. Experimental campaign

After the commissioning phase an experimental campaign has been performed using MARA. As a result, for example, five new isotopes have been identified in these studies so far. The data analysis is ongoing and results from those studies will be presented later. As an example, a study on proton emitters is shown in figure 4. Proton energy spectrum (arbitary units, ob-

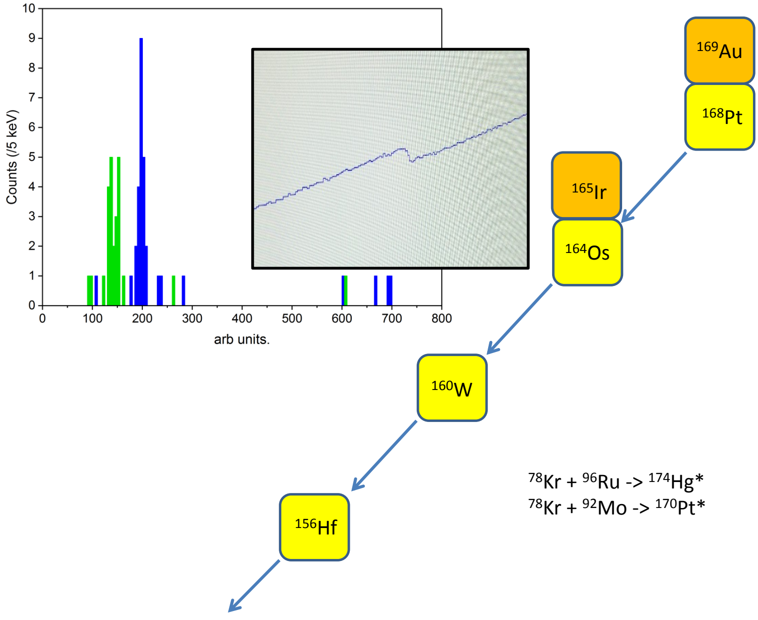

Fig. 4. Particle energy spectrum measured at the DSSD. Events, which are found to be followed by long alpha decay chains, are shown.

tained from traces) as well as one example of a trace from a signal are shown. This trace represents a recoil signal followed by a fast decay signal within 5 μs time window. The proton peaks belong to iridium isotope ^{165}Ir and to a new gold isotope ^{169}Au [8]. Final identification of the decays was based on long correlation chains followed, which is also illustrated in figure 4.

Some properties of the separator can be obtained from those studies and will be presented in the following. The production cross section of proton emitters are rather well-known. In this experimental campaign, some of these known proton emitters were produced. The used reactions, evaporation channels, and cross sections are listed below (cross-section values given as proton yield):

— ^{78}Kr + ^{92}Mo → ^{170}Pt* →^{167,166}Ir + $p2n, p3n, 3$ μb, 0.1 μb [9],

— ^{58}Ni + ^{106}Cd → ^{164}Os* → ^{160}Re + $p3n, 1$ μb [10],

— ^{58}Ni + ^{92}Mo → ^{150}Yb* → ^{147}Tm + $p2n, 30$ μb [11],

— ^{64}Zn + ^{58}Ni → ^{122}Ce* → ^{117}La + $p4n, 240$ nb [12].

From the obtained yields measured at the focal plane of MARA, it can be concluded that MARA transmission for these cases has been 30–50%. These values agree very well with the ion-optical calculations. Also the cleanliness of the separator has been demonstrated. If the tuning of the beam has been acceptable, the portion of the fusion recoils from all the recoils *i.e.* including scattered components has been more than 70% in all cases presented in this paper.

6. Future plans and conclusion

MARA separator has already been in succesful use for delayed focal plane spectroscopic studies. The plan is to start extensive in-beam gamma-ray spectroscopy Recoild-Decay-Tagging (RDT) studies using MARA. A sophisticated rail system has been built to move the LN_2-cooled and HV-biased Ge-detector array (JUROGAMIII) between the target position of the two seprators RITU and MARA (see Fig. 5) without having a full, heavy loading, detector annealing process between. JUROGAMIII is an array of 45 Compton-suppressed HPGe detectors, including Eurogam clovers, Eurogam Phase I, and GASP-type detectors, provided by the GAMMAPOOL Collaboration.

A project to build a stopping gas cell followed by a low-energy branch LEB behind MARA focal plane has also been started (see figure 6 [13]). This setup will be used to measure masses of exotic very proton rich nuclei as well as to perform variety of laser-spectroscopic studies. In this project, MARA

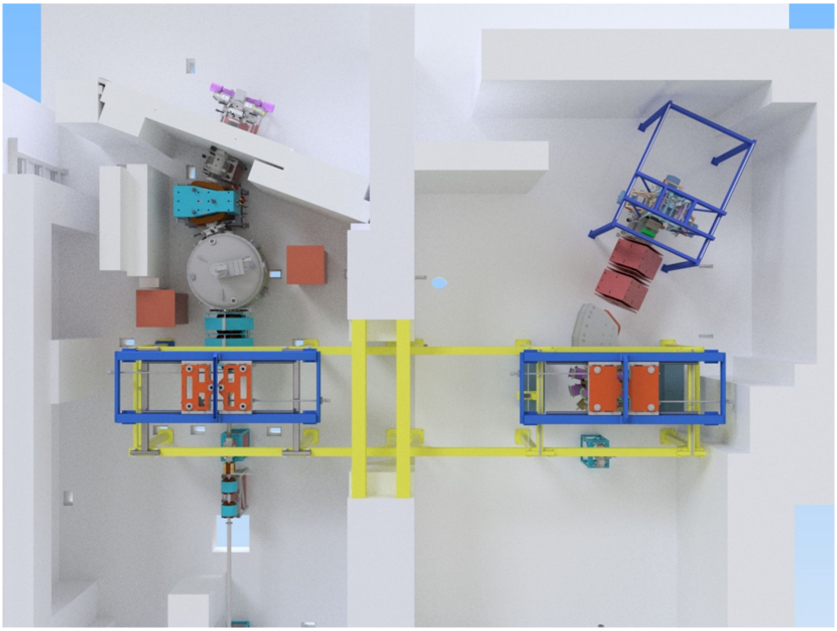

Fig. 5. The rail system to transport the JUROGAMIII array between the two separators.

will be used to separate the fusion products from the unreacted beam and guide the wanted products to the focal plane of MARA where the stopping gas cell will be situated.

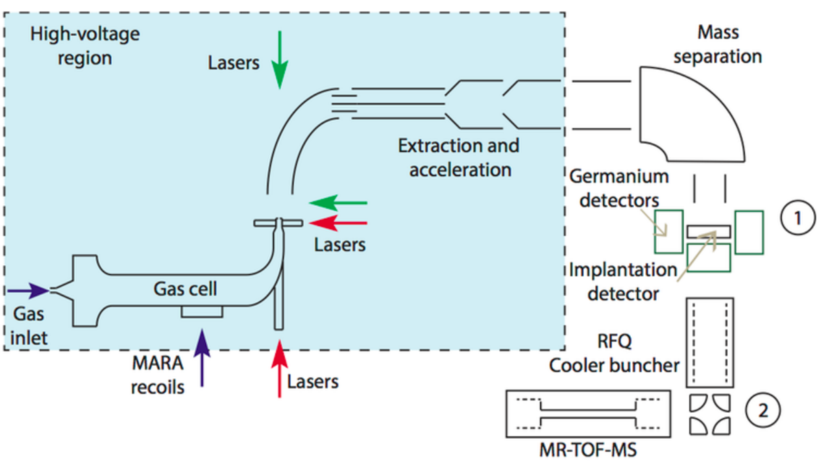

Fig. 6. The plan for the gas-cell and MARA-LEB to be connected to MARA.

A vacuum-mode mass separator MARA has been recently constructed and commissioned. First "real" experiments using MARA have been performed. MARA transmission has been measured and the efficiency of the separator is as high as expected from the ion-optical calculations. MARA has a rather simple configuration, its not a symmetric device, the cyclotron (cyclotron is in use at JYFLACCLAB) beam quality is not as good as with linear accelerators. Nevertheless, MARA performs well and the scattered components entering the focal plane are small. MARA is a complementary device to RITU separator and it opens a new terrain for spectroscopic studies to be performed by the Nuclear Spectroscopy Group at JYFLACCLAB together with a large international collaboration.

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