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Status and Development of the MARA Low-Energy Branch

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Abstract. The MARA Low-Energy Branch is under development at the Accelerator Laboratory of the University of Jyväskylä. The facility will be employed for laser ionisation and spectroscopy studies and for mass measurements of nuclei close to the proton drip line. This article presents an updated status of the ongoing development of the different parts of this facility, including the buffer gas cell, the ion transport system, the laser system and the detector stations.

INTRODUCTION

The main challenge in the study of rare nuclear phenomena is to successfully produce and disentangle the weakly produced exotic nuclei from the hostile environment of unwanted and often dominant contaminant reaction products. Dedicated novel experimental setups and techniques are required to achieve this. The MARA Low-Energy Branch (MARA-LEB) [1] will provide the efficiency and selectivity required to study exotic nuclei close to the proton drip line, opening the path to laser spectroscopy and mass measurements in this region.

The MARA-LEB facility will combine: (i) the unique MARA (Mass Analysing Recoil Apparatus) vacuum-mode recoil separator [2], (ii) a connecting buffer gas cell and ion transport system, (iii) a state-of-the-art solid-state Ti:sapphire laser system with high-resolution capability, (iv) a radiofrequency quadrupole cooler-buncher and, (v) a Multi-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS) [3]. This combination of experimental tools will offer capabilities for laser ionisation and spectroscopy of rare isotopes both in the buffer gas cell volume and in the low-temperature, low-pressure gas jet, as well as for mass measurements.

One of the key regions of interest for MARA-LEB will be to perform mass measurements of nuclei with a similar number of protons (Z) and neutrons (N) and mass (A) close to 100, which are of key interest in the astrophysical rapid proton capture (rp) process [4]. Very neutron-deficient nuclei are synthesised in astrophysical environments, where extreme temperatures and densities as well as an abundance of hydrogen can lead to the rp-process. To accurately model the process, precise data on atomic masses, which determine the proton capture and beta decay Q values, as well as half-lives and excited states of the key nuclei involved, are required. Additionally, these precise mass measurements will lead to a better determination of isotonic abundance ratios and a more accurate interpretation of X-ray burst light curves in terms of neutron star properties and prediction of the composition of X-ray burst ashes. A better understanding of these phenomena is required for the modelling of neutron star crusts [5]. Several nuclei which are of key interest to the rp-process lie in the regions of ^{80}Zr (e.g. ^{80}Zr and ^{79}Y), ^{94}Ag (e.g. ^{94}Ag and ^{91}Rh) and ^{100}Sn (e.g. $^{99-101}$In) [6]. Other cases of interest, particularly for laser ionisation and spectroscopy, were reported in [1].

CURRENT STATUS OF THE MARA-LEB FACILITY

A small-volume buffer gas cell has been built to stop, thermalise and, depending on experimental requirements, neutralise the recoils exiting from the MARA separator. The gas cell design is based on a gas cell built for the HELIOS facility at KU Leuven [7] and is shown in Figure 1 (a). The gas cell inherits concepts from the dual-chamber design [8] and has separate regions for stopping of recoils and laser ionisation. A gas flow straightening structure after the gas inlet is used to achieve laminar flow and reduce turbulences inside the stopping volume. Two optical windows provide

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access for in-gas-cell laser ionisation and a set of ion collectors is used to collect non-neutralised atoms before entering the laser ionisation volume. Two resistively-heated filaments inside the gas cell can be used to produce stable atoms for offline testing. The high vacuum of MARA (~10^{-8} mbar) is separated from the gas cell by a thin entrance window. The entrance window thickness and material may be adjusted accordingly depending on the reaction of interest, see for example the discussion in [1]. Interchangeable exit nozzles allow the use of exit holes with different diameters or "de Laval" nozzles [9] designed for specific gas jet Mach number. A de Laval nozzle produces a collimated supersonic gas jet with low temperature and density, making it ideal for in-gas-jet laser ionisation and spectroscopy [10].

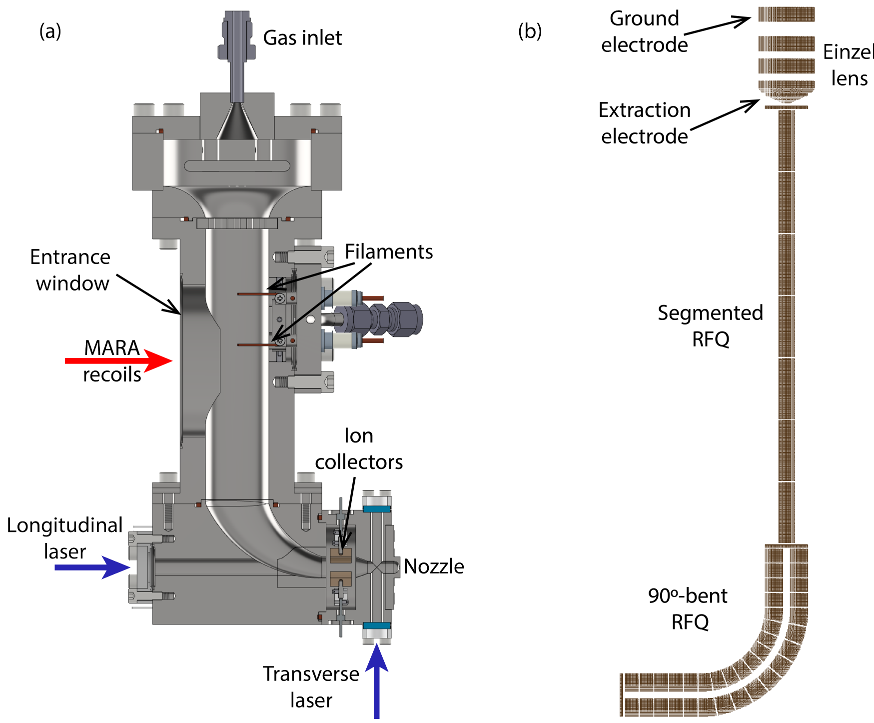

FIGURE 1. (a) The MARA-LEB buffer gas cell. The laser beams and MARA recoils are shown with blue and red arrows respectively. (b) The current design of the RFQ ion guide system including the ion extraction and acceleration electrodes.

After exiting from the gas cell the ions will be transported by a system of ion guides to the extraction electrode which will accelerate them towards a dipole mass spectrometer. The ions will be accelerated up to 30 keV in two stages, first by the extraction electrode and then by a ground electrode. To ensure the required vacuum conditions for the safe operation of the extraction and ground electrodes, a two-stage differential pumping system will be used. The gas cell and a 90°-bent radio-frequency quadrupole (RFQ) ion guide will be housed in the first vacuum region. The gas load from this volume will be removed using a dry pumping system with typical peak pumping speed of ~950 L/s for Ar and He. In the second vacuum region a long RFQ will guide the ions towards the extraction electrode chamber. The pressure in the extraction chamber is anticipated to be in the region of 10^{-6}-10^{-7} mbar. The second volume and the extraction volume will be connected to turbo pumps with typical peak pumping speeds of 1200 and 2000 L/s, respectively. To optimise the ion transmission towards the mass spectrometer the extraction electrode will form part of an Einzel lens. The ion guide system is currently under design using the SIMION software package [11] and is presented in Figure 1 (b).

A state-of-the-art Ti:Sapphire laser system will be used for resonant laser ionisation of neutral atoms. Three pulsed Ti:sapphire lasers with high repetition rate (10 kHz), pumped by a Nd:YAG laser, will provide an almost universal coverage of ionisation schemes. Three new laser resonators have been constructed at the University of Mainz and are currently being installed in Jyväskylä for the MARA-LEB project. Typical pulsed laser systems which are in regular use for laser resonance ionisation have bandwidths of several GHz and are not well matched to the attractive environment of the supersonic gas jet. In order to exploit the full advantage of the cold, low pressure environment for high-resolution spectroscopy, a narrow linewidth pulsed laser is required. A novel, state-of-the-art injection-locked

Ti:sapphire laser system has been developed in collaboration with the University of Mainz, demonstrating a bandwidth of ~20 MHz [12]. A new resonator cavity is currently being built and will be available for this project. It is the unique combination of the gas jet environment and a state-of-the-art laser system which will enable the high-resolution laser spectroscopy studies of exotic nuclei.

Following extraction and acceleration, the ions will be mass separated using a 90° magnetic dipole mass spectrometer with a mass resolving power of ~300. This is necessary since not only the ions of interest will exit the gas cell but also contaminant nuclei which could inhibit measurements unless they are suppressed. A mechanical mass slit system at the secondary focal plane of the dipole mass spectrometer will be used to stop unwanted mass products from reaching the detector stations. The ion beam will be transported and focused towards the experimental stations using RFQ doublets. One doublet will be placed between the extraction electrode and the dipole mass spectrometer, one either side of the secondary focal plane of the spectrometer and one after a 90° electrostatic deflector which will be used for directing the ions towards the experimental stations. These ion-optical elements are currently under design in Jyväskylä.

An MR-TOF-MS will be used for fast and precise mass measurements and is under development in Jyväskylä. To perform mass measurements using an MR-TOF-MS device, an RFQ cooler and buncher is required to transform the continuous ion beam into narrow ion bunches with widths of ~100 ns. This is necessary since time-focused ion bunches are required to accurately determine the flight path of ions within the MR-TOF-MS. The concept of the cooler and buncher lies in the use of a combination of electric fields and helium cooling gas to thermalise and collect the ions in bunches with well-defined time and energy profiles. The design of the RFQ cooler and buncher will be based on a device currently in operation at the IGISOL-4 facility [13].

The MR-TOF-MS consists of two electrostatic ion lenses between which the ions are reflected. The initial kinetic energy of ions in the same charge state is identical, however, due to different mass-over-charge ratio their velocities differ. As a result, over their flight path within the MR-TOF-MS, ion bunches with different mass-over-charge ratios can be separated using a fast Bradbury-Nielsen gate [14]. The fast operating cycle of the MR-TOF-MS combined with suppression ratios of up to 10^4, resolving power up to 10^5 and mass precision of the order of 10^{-7} [15] make it ideal for performing mass measurements of exotic nuclei at MARA-LEB. After passing the Bradbury-Nielsen gate the ions will be detected by a time-of-flight detector such as a multichannel-plate detector or a secondary electron multiplier.

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