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Nuclear astrophysics studies at LENA: The accelerators

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ABSTRACT

The accelerators of the Laboratory for Experimental Nuclear Astrophysics (LENA) are described. These include a modified 1 MV Van de Graaff accelerator, a new electron cyclotron resonance (ECR) ion source with its 200 kV acceleration system, and the associated beam transport system. The new ECR ion source utilizes an array of permanent magnets to provide the 87.5 mT solenoidal magnetic field needed for ECR at 2.45 GHz. With 300 W of input radio frequency (RF) power and an extraction voltage of 15 kV, a beam current of 7 mA has been extracted from the source within a measured normalized emittance of $0.19\pi-\text{mm}-\text{mrad}$. Proton currents in excess of 1 mA can be accelerated to target from the ECR source over the energy range of 90–200 keV. Beam properties have been measured using low-energy resonances in $^{18}O(p,\gamma)^{19}F$ and $^{27}Al(p,\gamma)^{28}Si$. The Van de Graaff accelerator can produce 250 μA over the energy range 0.3–1 MeV (and somewhat lower currents at lower energies). This new capability will be crucial in the direct search for low-energy resonances in nuclear reactions of astrophysical significance.

1. Introduction

Stars are powered by thermonuclear reactions, which can be studied in the laboratory using low-energy beams from particle accelerators. For example, typical energies associated with stellar hydrogen burning are on the order of tens to a few hundred keV. Measuring nuclear reactions at these low energies is very difficult because Coulomb repulsion makes stellar cross-sections exceedingly small. Count rates can be so low that the desired signals are indistinguishable from environmental backgrounds. Extracting such rare signals requires either reducing background rates or increasing the rate of the desired nuclear reaction. A useful figure of merit is

$$F.O.M. = \frac{\text{Signal rate}}{\sqrt{\text{Background rate}}}. \quad (1)$$

It seems obvious that the experimental sensitivity should be proportional to the signal rate. However, this definition also reflects the fact that the precision in the residual counts is limited by the statistics of the background. Thus, while background suppression is critically important, improving the signal rate will have a greater impact on our ability to measure a weak signal in the presence of a large background. We have demonstrated background suppression through $\gamma\gamma-$coincidence techniques in conjunction with active and passive shielding methods [1]. For further signal-to-background enhancement, we have recently turned our attention to increase the signal rate by increasing the beam current incident on targets. For energies less than 200 keV, we desire proton beam currents on the order of 1 mA, and 0.2–0.5 mA at higher energies. The beam should also be well defined, reproducible, and stable. Finally, since experiments can last a month or longer, the accelerator system should be able to operate reliably for long periods.

In the following, we describe the accelerators at the Laboratory for Experimental Nuclear Astrophysics (LENA). These include recently developed ECR ion source systems and a modified 1 MV model JN Van de Graaff accelerator. These and the associated beam transport system and target station are described in Section 2. Measurements taken to characterize their overall performance are described in Section 3. In Section 4, we propose future developments and improvements. A summary and conclusions are given in Section 5. Throughout this work, E_p and E_R denote the proton bombarding energy and the resonance energy, respectively, given in the laboratory system.

2. Laboratory for Experimental Nuclear Astrophysics

We employ two accelerating systems for beams needed to make direct measurements of astrophysically important nuclear reactions. An ECR ion source sits on a 200 kV air-insulated platform, and produces high-intensity beams used to measure cross-sections at energies below 200 keV. A 1 MV Model JN Van de Graaff accelerator is used for measurements above 200 keV.

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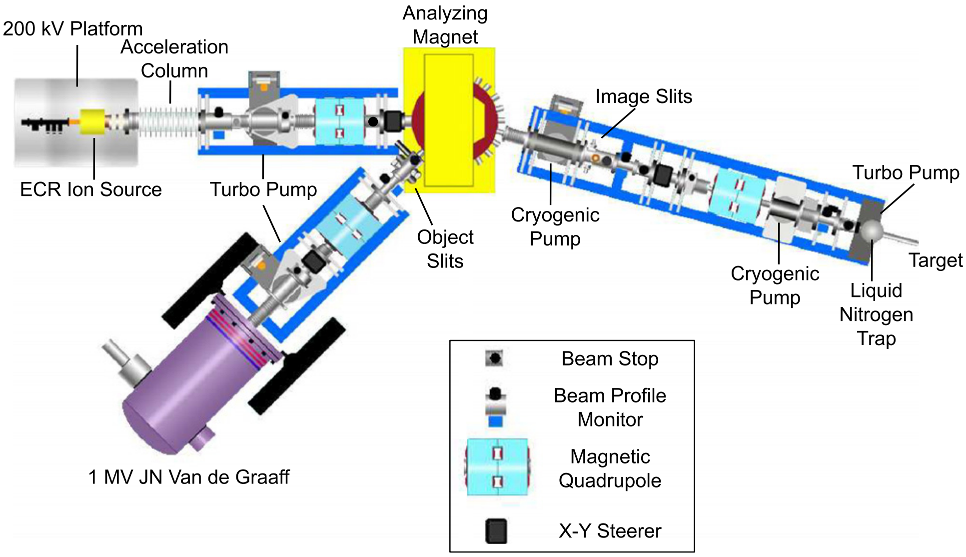

Fig. 1. Laboratory for Experimental Nuclear Astrophysics.

Beams from both accelerators are directed to a bending magnet used to transport them to a single target station. A schematic view of LENA is shown in Fig. 1.

2.1. ECR ion source

Increasing beam current on target required development of a reliable, compact ion source capable of producing milliampere hydrogen beams. Electron cyclotron resonance (ECR) ion sources are known to produce high beam currents and to need very little maintenance. For example, ECR sources designed by Wills et al. at Chalk River Laboratory [2] have been shown to produce intense H^+ beams. These sources employ permanent magnets to produce a roughly constant, solenoidal magnetic field of 87.5 mT over the plasma chamber, which is required for resonance with an input microwave frequency of 2.45 GHz. The use of permanent magnets reduces the need for bulky electromagnet coils, with their associated power supplies and water cooling. This allows the source to be small enough to be conveniently operated on a high-voltage platform, facilitating beam acceleration to a target system placed at ground potential. By pulsing the beam, background from external environmental sources (such as cosmic-ray-induced muons) can also be reduced.

Fig. 2 shows our new ECR ion source and its essential components, which are based on the Chalk River design. It consists of a plasma chamber into which 2.45 GHz microwave power is injected through a tapered waveguide (not shown in Fig. 2), a surrounding solenoidal magnet array, and ion extraction and focusing electrodes, which shape the beam and transport it to the acceleration system.

The microwave system consists of a 500 W magnetron, three-stub tuner, circulator, and dummy load where reflected power is absorbed and monitored. A waveguide break electrically isolates the microwave system from the plasma chamber.

2.1.1. Permanent magnet

The plasma discharge chamber is placed on the axis of a surrounding solenoidal permanent magnet array, which produces the 87.5 mT magnetic field necessary for electron cyclotron resonance within the chamber. The magnet consists of two independent sub-assemblies: an outer solenoidal array that produces the axial magnetic mirror field for plasma confinement and an inner multipole array for additional radial confinement. Before fabrication, the arrays were thoroughly modeled using RADIA, a package developed at the European Synchrotron Radiation Facility (ESRF) [3], which runs in MATHEMATICA. As mentioned above, the overall magnetic field resembles that used by Wills et al. [2], but was modified to produce an axial mirror field, which peaks twice above 90.0 mT within the plasma chamber. This modification was introduced to try to improve both electron confinement and the ionization efficiency of the entering gas, with the goal of producing high-intensity beams of H^+ and He^{2+}.

Fig. 3 shows the complete magnetic geometry that was modeled in RADIA. The main, outer solenoidal array has 12 magnetic bars aligned axially and spaced evenly in a cylinder of inner diameter 120 mm. Each bar consists of two 25 mm × 25 mm × 50 mm neodymium iron boron (NdFeB) magnets (remanent field of 1.42–1.47 T) and one 25 mm × 25 mm × 50 mm piece of low-carbon steel sandwiched between them. The NdFeB magnets are magnetized through the 25 mm × 25 mm face. Low-carbon steel rings (ID: 120 mm, OD: 190 mm, thickness: 5 mm) are placed at each end of the cylindrical array of magnetic bars to shape the rise and fall of the axial field. The permanent magnets fit snugly into slots in a cylindrical sleeve, which was fabricated using a three-dimensional acrylonitrile butadiene styrene (ABS) plastic printer. Additional plastic parts fully enclose the magnet array to isolate it from the interior plasma chamber, which sits at high voltage.

The inner, multipole array was designed with the expectation that it would also help in producing beams with high H^+ or He^{2+} fraction, but its use is optional. It consists of two rings of permanent magnets. Each ring contains twelve 20 mm × 30 mm × 5 mm NdFeB magnets, magnetized through the 20 mm × 30 mm face. Alternate poles around 360° create a multipole (cusp) field. The two rings are further oriented with respect to each other such that the top magnet on the first ring points ‘North’ while the top magnet on the second ring points ‘South’. A low-carbon steel ring is placed between these two rings of magnets, and the entire assembly is contained tightly in a water-cooled copper jacket which fits concentrically around the plasma chamber and within the outer solenoidal magnet assembly.

2.1.2. Plasma chamber

The plasma chamber is made of two copper parts for ease of construction and maintenance. The first surrounds a 60 mm diameter × 60 mm long cylindrical volume, which contains the plasma. Its interior is completely lined with 2 mm of insulating boron nitride to reduce electron loss and increase the ionization