DIANA, A NEXT GENERATION DEEP UNDERGROUND ACCELERATOR FACILITY

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Abstract

DIANA (Dakota Ion Accelerators for Nuclear Astrophysics) is a next generation nuclear astrophysics accelerator facility proposed to be built in a deep underground laboratory in the US. The scientific goals of DIANA are focused on experiments related to nucleosynthesis processes. Reaction cross-sections at stellar temperature are extremely low, which makes these experiments challenging. Small signal rates are overwhelmed by large background rates associated with cosmic ray-induced reactions, background from natural radioactivity in the laboratory environment, and the beam-induced background on target impurities. By placing the DIANA facility deep underground (1.4 km) the cosmic ray induced background can be eliminated. In addition, the DIANA accelerator is being designed to achieve large laboratory reaction rates by delivering high ion beam currents (up to 100 mA) to a high density super-sonic jet-gas target (up to 10^{18} atoms/cm^2). Two accelerators are coupled to enable measurements over a wide energy range from 50keV to 3MeV in a consistent manner. The accelerators design and its technical challenges are presented.

INTRODUCTION

Nuclear Astrophysics is concerned with the origin of elements in stars and stellar explosions through charged particle, neutron, and weak interaction induced nuclear processes. Current stellar model simulations have advanced to a level of precision that nuclear-reaction rates represent a major source of uncertainty for theoretical predictions and for the analysis of observational signatures. To address several open questions in cosmology, astrophysics, and non-Standard-Model neutrino physics, new high precision measurements of direct-capture nuclear fusion cross sections will be essential. At these low energies, fusion cross sections decrease exponentially with energy and are expected to approach femtobarn levels or less. Because of large background rates associated with cosmic ray-induced reactions, background from natural radioactivity in the laboratory environment, and the beam-induced background on target impurities, measuring the low-energy cross sections is challenging. An underground location has the advantage that the cosmic ray-induced background is reduced by several orders of magnitude, allowing the measurements to be pushed to far lower energies than presently possible. The DIANA facility (Dakota Ion Accelerators for Nuclear Astrophysics) proposed by a US collaboration between the University of Notre Dame, Colorado School of Mines, Regis University, University of North Carolina, Western Michigan University, Michigan State University, and Lawrence Berkeley National Laboratory, is aimed to address the need for a next generation deep underground nuclear astrophysics facility. The proposal has recently received funds from NSF to produce a preliminary design report and detail cost estimate. The status of the accelerator design and its technical challenges are presented.

TECHNICAL DESIGN CONCEPT

Key novel features of DIANA compared to existing nuclear astrophysics experiments will be:

- The DIANA facility will consist of two accelerators (see Fig. 1) that will cover a wide range of ion beam energies and intensities.
- The 400 keV low energy accelerator will be a major technological advance with regard to ion beam intensity on target in order to address the low count rates close to the Gamow window energies.
- The 3 MeV accelerator will substantially extend the physics reach over what is presently feasible (which is limited to 400 keV at the LUNA facility in Gran Sasso [1].
- The proposed accelerators will have sufficient energy overlap to allow the study of nuclear reaction over a wide range and to consistently connect the results to measurements above ground.
- The facility will feed the low energy target from both the low and the high energy accelerators. This will allow a particular reaction to be measured at both accelerators in complementary energy ranges with identical target and detector set-ups.
- Both accelerators will feed the same gas target station, but an additional, independent target station is planned for the 3 MV accelerator for conducting two experimental campaigns simultaneously or preparing the next experimental campaign. This feature will greatly enhance the ability to timely and efficiently carry out the science program since the experimental set-ups are difficult and time consuming.
- Advanced target and detector technology will be developed in order to take advantage of DIANA's high beam currents.

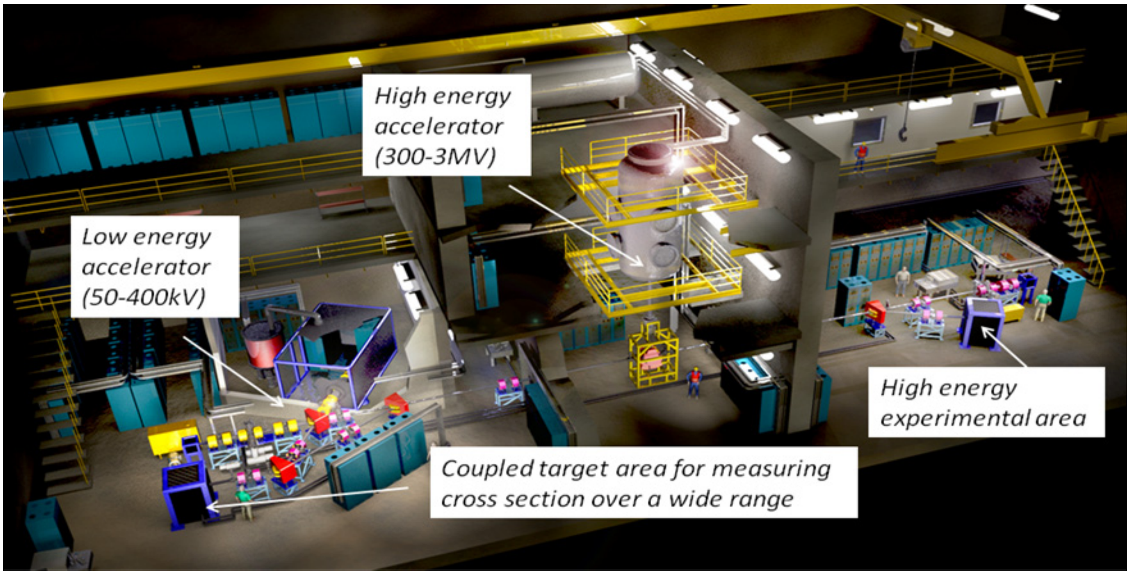

Figure 1: Layout of the DIANA facility at the DUSEL facility at Homestake mine, 4850 ft (1.48km underground).

THE 400 KV ACCELERATOR

The low energy accelerator will have an accelerator voltage capability from 50 kV to 400 kV. To allow for easy access and maximum flexibility, the low energy accelerator has been designed as a 400 kV open air high-voltage platform. The design criteria for the accelerator are high beam currents (up to 100 mA for singly charged ions, which is two orders of magnitude higher than current state of the art accelerators) with tight focus (< 1 cm) and a narrow beam energy distribution (~ 0.1% of the beam energy). Since the low energy cross section depend exponentially on the beam energy, the design criteria for the accelerator is determined by the need of achieving the highest beam currents (100mA) at the lowest beam energy (50keV). The low energy intensity requirement also determines the maximum beam power requirement of the accelerator of up to 5kW of beam power. Figure 2 shows a schematic of the high intensity beam transport line and the beam envelope for a 50 kV beam simulated using the WARP code[2]. The beam is extracted at a fixed extraction voltage of 50kV from an microwave ion source[3] and matched with two solenoids into the high voltage column for the different final energies. In order to avoid beam blow up in the long 400 kV acceleration column for the whole energy range, the HV gap distance needs to be minimized for the lower beam energies. Therefore, a moveable high voltage gap is being designed, which is similar to the moveable high voltage gap designed and tested at GSI [4]. Two more solenoids prepare the beam for the transport through the dipole magnet which separates any beam impurities from the primary beam. Finally two solenoids after the dipole allow for sufficient distance to accommodate differential pumping of the gas jet target and produce the final focus. One final solenoid controls the beam size at the beam dump, where the beam intensity will be monitored using a calorimeter.

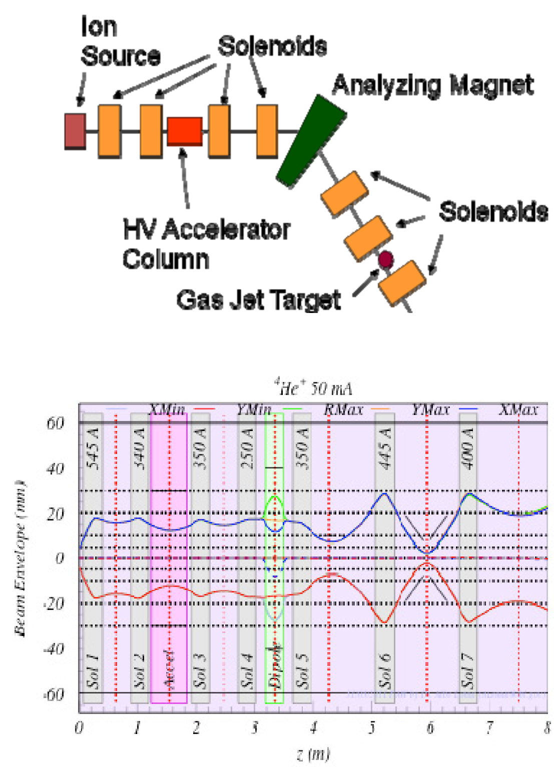

Figure 2: Schematic ion optics layout for the low energy accelerator (above). Beam envelope calculated using the WARP code[2] for a 50keV, 50mA He^{+} beam. 90% beam neutralization is assumed in the beam line outside the acceleration column.

Figure 3 shows the dependence of the optimized HV gap size on the platform voltage for a minimized target spot size on the gas jet target. 90% neutralization has been assumed for the regions outside the HV gap.

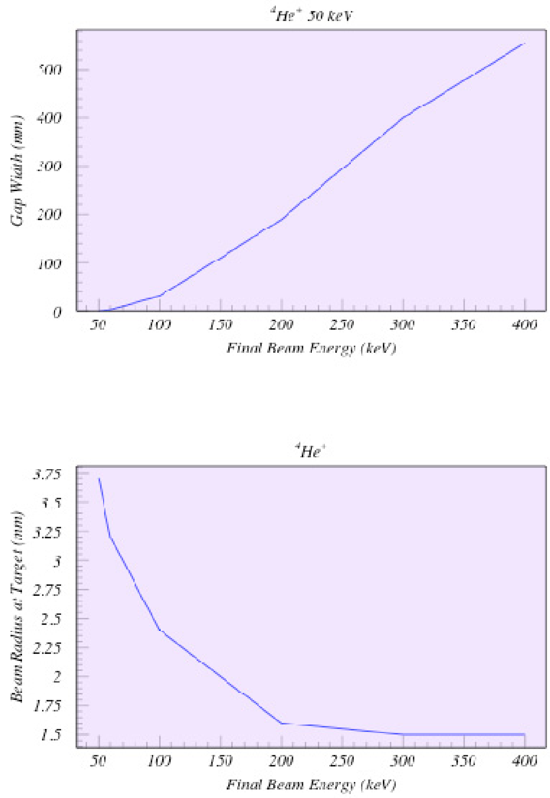

Figure 3: HV gap distance in dependence of the HV platform voltage and optimized beam size on the jet gas target.

THE 3MEV ACCELERATOR DESIGN

The second accelerator has a maximum acceleration voltage capability of 3 MV. The high energy accelerator possibilities under consideration are commercially available pelletron supplied by National Electrostatic Corporation or a dynamitron supplied by IBA Industrial (formerly Radiation Dynamics Inc.).

One technical challenge of this accelerator design is the requirement of the nuclear physics experiments to achieve the highest currents at the lowest energies. This is conflicting with the standard space charge scaling for electrostatic machines, in which the column is tuned for only one particular beam energy and beam intensity. In order to achieve the same beam properties at different accelerating voltages the beam intensities must be scaled according to

$$I = I_{tune} \times \left(\frac{V}{V_{tune}}\right)^{3/2} \quad (1)$$

In order to maintain an ion beam intensity of 1mA over the whole energy range, with a tight radius of few millimeters, the accelerator tube of the high energy machine will be equipped with an embedded Electrostatic Quadrupole Triplet. In addition, the first part of the column will be graded to optimize the beam transport for the lower energy and part of the column will be shorted to ground to maintain the same accelerating gradient throughout the energy range which, reduces the beam blow up in the column at low energy. Figure 4 shows the ion beam optics in the column in a standard equally graded electrostatic pelletron accelerator (top figure 4) and in the proposed DIANA column (bottom figure 4). In both cases a constant ion beam intensity of 1mA of He^{+} beam is modeled for the energy range of 400keV to 3MeV. While the beam blows up to 2 cm in the standard column at the lowest energies, a constant beam envelope of 1 cm can be achieved with the proposed DIANA column. The ion beam optics for the auxiliary beam lines and the four target station has been completed. The preliminary design report is expected to be completed at the end of 2012 after which construction of the facility could start.

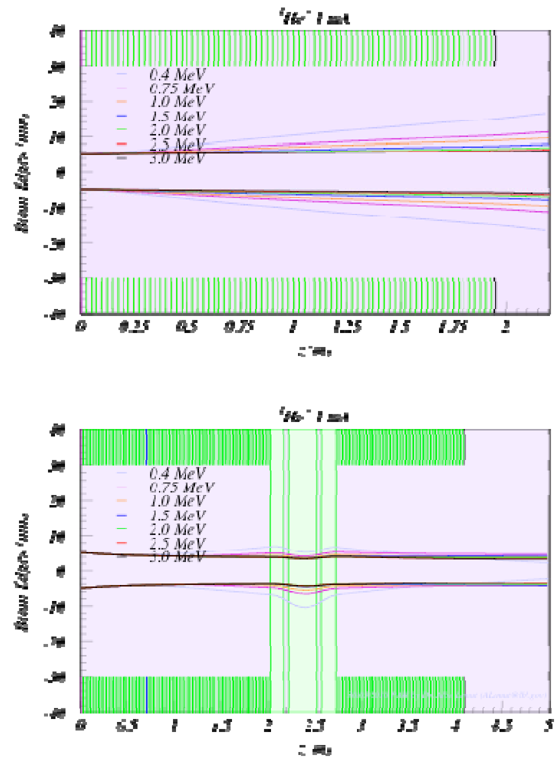

Figure 4: Preliminary ion optics through the high energy accelerator column. The top figure shows the performance of a standard column. The bottom figure shows the performance of the proposed DIANA column, that incorporates a quadrupole triplet, a variable gradient column, and a shortening rod.

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