

“DIANA” – A NEW, DEEP-UNDERGROUND ACCELERATOR FACILITY FOR ASTROPHYSICS EXPERIMENTS*

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Abstract

The DIANA project (Dakota Ion Accelerators for Nuclear Astrophysics) is a collaboration between the University of Notre Dame, University of North Carolina, Western Michigan University, and Lawrence Berkeley National Laboratory to build a nuclear astrophysics accelerator facility 1.4 km below ground. DIANA is part of the US proposal DUSEL (Deep Underground Science and Engineering Laboratory) to establish a cross-disciplinary underground laboratory in the former gold mine of Homestake in South Dakota, USA.

DIANA would consist of two high-current accelerators, a 30 to 400 kV variable, high-voltage platform, and a second, dynamitron accelerator with a voltage range of 350 kV to 3 MV. As a unique feature, both accelerators are planned to be equipped with either high-current microwave ion sources or multi-charged ECR ion sources producing ions from protons to oxygen. Electrostatic quadrupole transport elements will be incorporated in the dynamitron high voltage column. Compared to current astrophysics facilities, DIANA could increase the available beam densities on target by magnitudes: up to 100 mA on the low energy accelerator and several mA on the high energy accelerator. An integral part of the DIANA project is the development of a high-density super-sonic gas-jet target which can handle these anticipated beam powers. The paper will explain the main components of the DIANA accelerators and their beam transport lines and will discuss related technical challenges.

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. The field, at the intersection of nuclear physics, astrophysics, and observational astronomy, explores the origin of the elements in our universe. Experimental Nuclear Astrophysics is characterized by four major directions, *nucleosynthesis processes in stars*, which is studied with very low energy accelerator experiments similar to the proposed DIANA facility, *explosive nucleosynthesis processes*, which requires measurements far of stability with radioactive beams, *neutron-induced nucleosynthesis in late stellar evolution*, which is pursued at reactor and neutron spallation facilities, and finally *neutrino-induced nucleosynthesis processes*, which is still largely confined to theoretical prediction and observation.

Measuring nuclear synthesis cross sections at energies (temperatures) relevant to processes in stars is extremely difficult, because of the vanishing small signal rates in comparison to the 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 experiment into an underground location, the cosmic-ray induced background is reduced by several orders of magnitude and the measurements can be pushed to far lower energies than would be possible over ground. The natural shielding provided by the rock has allowed pushing solar cross section measurements to far lower energies than previously possible. This has been clearly demonstrated at the 50 keV LUNA-I and 400 keV LUNA facility located in the Gran Sasso National Laboratory [1].

The “DIANA” project addresses the need for a next generation low energy underground accelerator facility. It is proposed to be part of the integrated suite of experiments of the proposed Deep Underground Science and Engineering Laboratory (DUSEL) in South Dakota, USA.

DIANA will provide much enhanced capabilities in terms of ion beam intensity (which will be more than one order of magnitude higher than in LUNA), ion species, and energy range. This will enable measurements of solar burning cross-sections at lower energies with higher precision. The higher energy capability of DIANA (up to 3 MeV using singly charged ions, or beyond 3 MeV using multiple charged ions) will widen the physics reach of the facility to more complex reaction mechanisms during late stellar burning. In particular, the experimental objectives include the study of low energy capture and fusion reactions with ^{12}C , which are key for the chemical evolution in the universe and production rates of neutrons needed to synthesize elements heavier than iron.

To accomplish these ambitious science goals, we propose to design two complementary, high-current accelerators for installation and operation 1.4 km underground. Substantial R&D is necessary to design such high-intensity beams. A dense gas-jet target will offer well-controlled systematic uncertainties. However, engineering ingenuity will be required to integrate the highest achievable jet target densities with the high ion beam current beamline and the nuclear detection instrumentation. The accelerators should be capable of providing very intense ion-beams (10 to 100 mA) continuously, for periods up to several weeks, on high-density targets (up to 10^{18} atoms/cm²). The design work is underway for both, the accelerator and gas-jet target.

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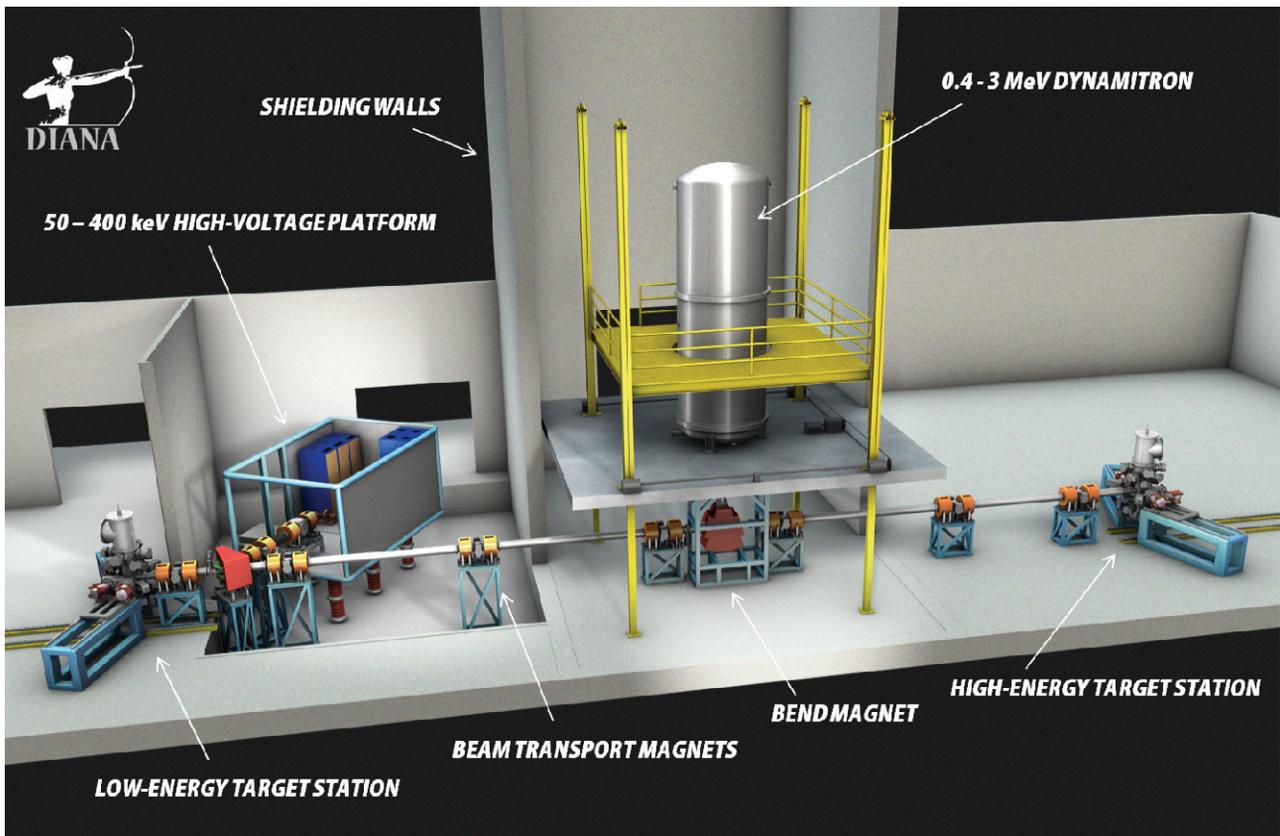


Figure 1: The DIANA facility will consist of two accelerators that will cover a wide range of ion beam energies and intensities.

TECHNICAL DESIGN CONCEPT

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

- (1) The DIANA facility will consist of two accelerators (see Fig. 1) that will cover a wide range of ion beam energies and intensities.
- (2) 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.
- (3) 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]).
- (4) 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.
- (5) 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.
- (6) Both accelerators will feed the same gas target station, but an additional, independent target station is planned for the 3 MeV 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 planned science program, and addresses one of current limitations at the LUNA facility (which has only one target station available) since the experimental set-ups are difficult and time consuming.
- (7) Both accelerators are designed to be able to incorporate highly-charged Electron Cyclotron Resonance (ECR) ion sources to increase the beam energy or to vary the accelerated ions (from hydrogen to heavier elements). This unique feature will allow expansion of the scientific goals in the future.
- (8) Advanced target and detector technology will be developed in order to take advantage of DIANA's high beam currents.

THE 400 keV ACCELERATOR

The low energy accelerator (see Fig. 2) 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, 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). Development of a stable power supply for the whole energy and beam current

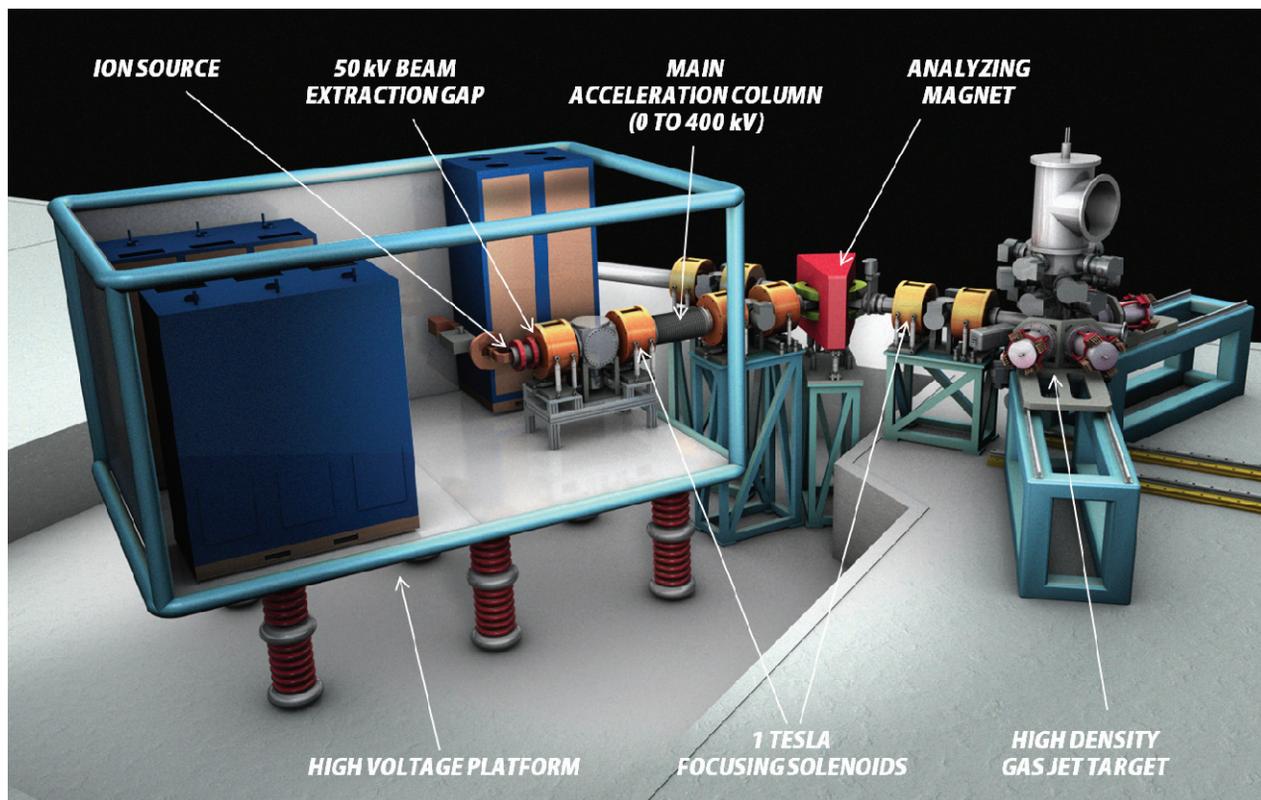


Figure 2: The DIANA low energy accelerator will have an accelerator voltage capability from 50 kV to 400 kV. The design criteria for the accelerator are high beam currents (up to 100 mA for singly charged ions) with tight focus (< 1 cm) and a narrow beam energy distribution ($\sim 0.1\%$ of the beam energy).

range will be important. A company (Kaiser Systems, Inc., Beverly, MA) capable of developing such a supply has been contacted.

Ion Sources for the 400 keV Accelerator

Two types of ion sources are planned for the high voltage platform. High intensity singly charged ions will be produced by a microwave ion source [2]. More than 100 mA of proton beam intensity and 20 mA of helium beam have been demonstrated under continuous operation [3, 4]. In addition, a permanent magnet ECR ion source [5] can be used to extend the energy range of the accelerator for helium to 800 keV up to several hundred μA , for nitrogen to 2 MeV, and for carbon up to 1.6 MeV at beam intensities of up to a hundred μA . The maximum energy specification will depend on a cost/benefit analysis between maximum energy necessary and beam line magnet costs.

Ion Beam Optics for the 400 keV Accelerator

The ion beam will be extracted with up to 50 kV extraction voltage and passed through two solenoid lenses. These lenses will convert the diverging ion beam to a near-parallel beam that is passed through the main acceleration gap that defines the final energy of the ion beam. The transport of high current of low energy ion-beams is made difficult by rapid beam expansion due to space charge forces. As the ion beam is transported along the beam line it will ionize the residual background gas,

and the electrons liberated will be radially confined by the ions therefore compensating the space charge forces. The actual acceleration gap length will be adjustable (see Fig. 3) to allow for minimizing the non-neutralized transport section for the lower energies and thus enabling transporting high intensity beams at the lowest beam energy. A similar concept of a movable high voltage gap has been demonstrated at the GSI facility (Gesellschaft für Schwerionenforschung, Darmstadt Germany) and has been the basis of the present design [6]. Two more solenoid lenses will prepare the beam for the transport

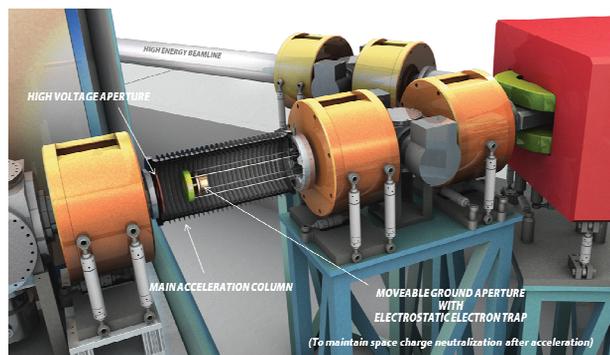


Figure 3: The acceleration gap length will be adjustable to allow for minimizing the non-neutralized transport section for the lower energies and thus enabling transporting high intensity beams at the lowest beam energy.

through the dipole magnet, which isolates the beam of interest from impurity ions. A fourth solenoid will provide the final focus onto the gas jet target [7]. An additional focusing element after the target will be required to focus the beam into the beam dump to reduce beam-induced background.

Preliminary Simulation Results

Fig. 4 shows simulations of the entire DIANA low energy beam transport line using the particle-in-cell code WARP [8]. The bottom plot of Fig. 4 displays the simulated beam edge in both, horizontal (X) and vertical direction (Y) versus beam direction, for a $^3\text{He}^+$ ion beam with 50 keV extraction energy without post acceleration. The top plot displays the same information for a $^3\text{He}^+$ ion beam with 50 keV extraction energy with 250 keV post acceleration (final beam energy 300 keV). In both cases, neutralization factors of 90% and a beam current of 100 mA have been assumed. Both figures show that a beam diameter less than 1 cm can be achieved at the target station to fit within the gas-jet-target entrance and exit collimators.

THE 3 MeV ACCELERATOR

The second accelerator (Fig. 5) has a maximum acceleration voltage capability of 3 MV. One of the options under consideration is a commercially available dynamitron accelerator supplied by IBA Industrial (formerly Radiation Dynamics Inc.). It has the advantage of supporting relatively high ion currents (several mA) over the whole voltage range with good energy resolution and tuneability.

Ion Sources for the 3 MeV Accelerator

Again, the use of two different types of ion sources is currently planned for the dynamitron. A permanent-magnet, microwave ion source will be used for producing several mA of singly charged ions in a reliable manner. In addition, a small permanent magnet ECR ion source will be incorporated to produce up to 30 μA of low charged ions with a total extracted ion beam intensity of 1-2 mA. A key R&D and engineering item of the project will be the design of the high voltage terminal to accommodate the microwave and the ECR ion sources. The use of ECR sources in connection with electrostatic accelerators has been demonstrated, but remains a technical challenge, in particular, the pumping at the extraction region. Successful examples are the BECRIS, a 5 GHz ECR source mounted at the terminal of the CN Van de Graaff of the Hahn-Meitner Institute in Berlin, and a 10 GHz Nanogun (PANTECHNIK, IBA Group) mounted on a 3 MeV single-ended electrostatic UH-2 Pelletron accelerator (National Electrostatics Corp.).

Ion Beam Optics for the 3 MeV Accelerator

Two options for the high voltage column design are currently being considered. The first option would use standard, commercially available accelerator rings. Alternatively, a unique combination of accelerator rings and electrostatic quadrupoles that would provide additional focusing for high intensity beams will be considered similar to ion beam transport systems developed in the heavy ion fusion program at LBNL. After the electrostatic accelerator, the beam will pass through an analyzing magnet that will permit alternatively feeding both target stations. The maximum bending power of the beam elements is proposed to be 1.4 Tm, which will allow bending up to 6 MeV ^{20}Ne .

TARGET AREA

In order to minimize the background radiation for each experiment, the accelerator halls will be separated by low level activity concrete shielding walls, and the two target halls will be pointed in opposite directions.

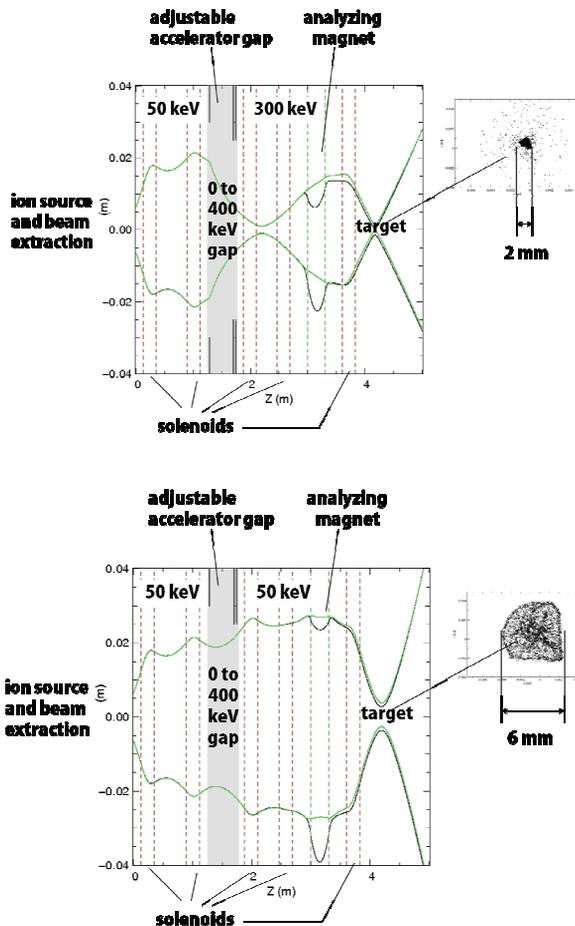


Figure 4: Simulations of the entire DIANA low energy beam transport line using the particle-in-cell code WARP. See text for description.

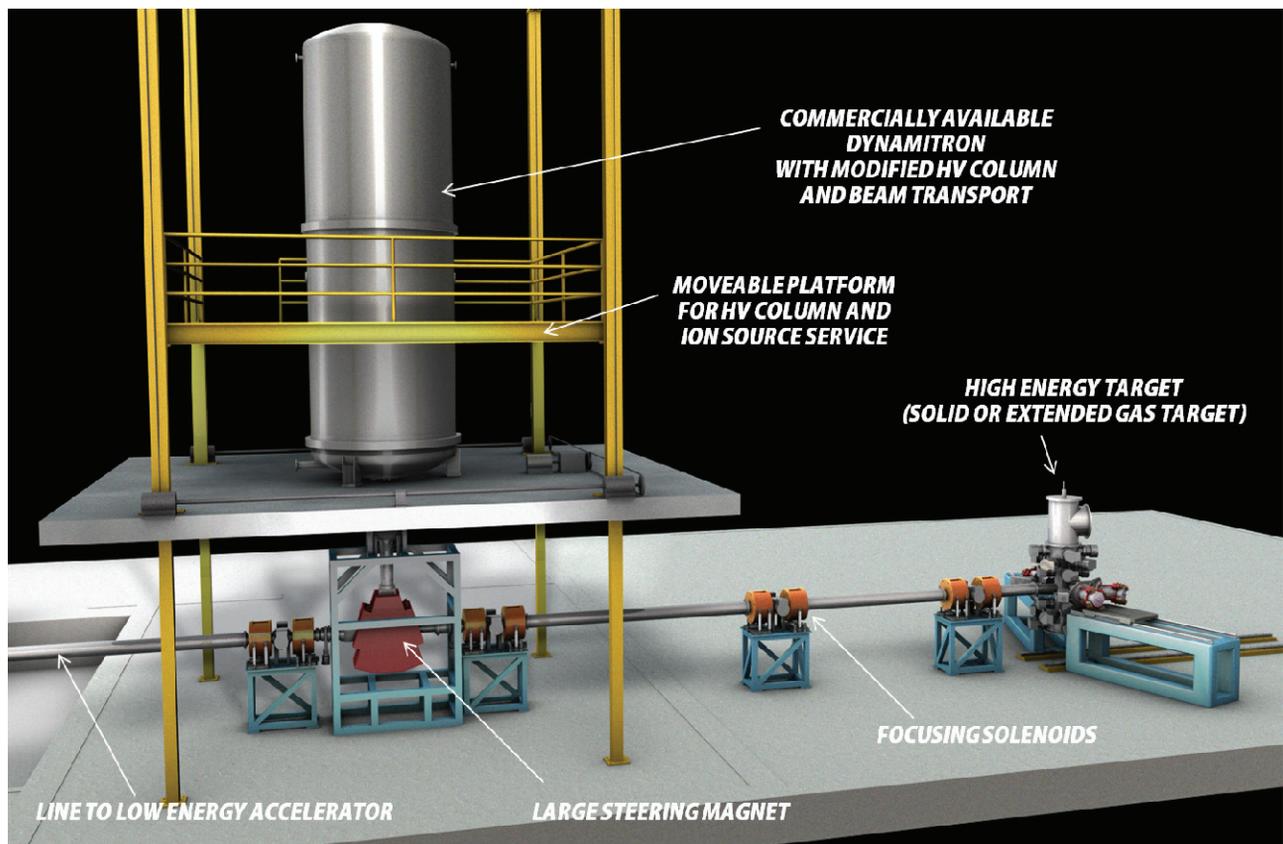


Figure 5: The second DIANA accelerator has a maximum acceleration voltage capability of 3 MV. One of the options under consideration is a commercially available dynamitron accelerator supplied by IBA Industrial.

Initial shielding calculations have already been performed, and results indicate that – even for high intensity ion beam experiments – less than 1 m thick concrete walls will be sufficient. Other DUSEL experimental halls will be separated by distances of approximately 100 meters in rock, so that significant reduction of any gamma or neutron field is expected by local shielding and distance. Further reduction in thermal neutron flux can be made with local placement of boron-loaded water elements immediately around target detectors and beam stops. More complex simulations involving secondary scattering from surrounding materials will be performed in the future to characterize beam-induced background in more detail.

A critical necessity for the low energy experiments using high intensity beams will be R&D on target systems that can withstand high beam currents without significant deterioration. Because of the nearly point-like gas zone, a supersonic gas-jet-target is an ideal target configuration for many investigations of nuclear reactions. Moreover, the power dissipated by an intense ion beam in a solid target could heat the material up to its melting temperature, making it difficult or impossible to operate for several weeks. Furthermore, the purity of the backing material of a solid target should be kept as high as possible to avoid parasitic nuclear reactions contaminating the spectra. Most of these problems could be solved using a gas target, where the target purity can

be better controlled. The gas jet target being considered for DIANA should be able to provide target areal densities up to 10^{18} atoms/cm². Because of the low energy of the reactions to be studied, corresponding to very small stopping ranges of ions in matter, a windowless gas target should be used to prevent beam energy resolution degradation. Thus a differentially pumped windowless gas jet target type, with four pumping stages is under design for DIANA.

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