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Design of the low energy astrophysics research facility CLAIRE

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Abstract

A novel nuclear astrophysics facility, CLAIRE (Center for Low Energy Astrophysics and Interdisciplinary REsearch), is being designed at Lawrence Berkeley National Laboratory to address the need for precise fusion cross section measurements at near-solar energies (~20 keV). At these low energies, fusion cross sections decrease exponentially with energy and are expected to approach femtobarn levels or less. In order to measure such small cross sections, the CLAIRE facility will incorporate a versatile accelerator capable of transporting high current (>100 mA), low energy (50–300 keV) ion beams with a tight focus (<1 cm) to a cooled, dense gas-jet target. The conceptual design for this accelerator is discussed, and simulations of both beam extraction and transport are presented.
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1. Introduction

To address several pressing problems in cosmology, astrophysics, and non-Standard-Model neutrino physics, new high precision measurements of direct-capture nuclear fusion reaction cross sections will be essential. To address this need, Lawrence Berkeley National Laboratory (LBNL) is in the design phase of a new facility that will allow for the measurement of essential cross sections at low, near-solar, energies.

Next generation solar neutrino oscillation experiments (Borexino, KamLAND solar phase, SuperK, new SNO analysis) will measure the flux of solar neutrinos from ^{7}Be and the CNO cycle solar neutrinos. Interpreting these data requires comparison to flux calculations from the so-called Standard Solar Model (SSM). An analysis by Bahcall and Peña-Garay [1] highlights substantial uncertainties (>8%) in the calculated fluxes of ^{8}B, ^{7}Be, and CNO cycle neutrinos. This is a consequence of uncertainty in the solar fusion reaction cross sections, particularly ^{3}He(^{4}He,γ)^{7}Be (S_{34}) and ^{14}N(p,γ)^{15}O ($S_{1,14}$). Other uncertainties in the SSM fluxes (~20%) arise from solar properties. If there were precise measurements of the ^{7}Be or CNO neutrino fluxes, and precise measurements of S_{34} and $S_{1,14}$, these solar properties (total luminosity, metallicity) would be determined. These properties are otherwise difficult to constrain. This information would aid theories of stellar and galactic lifetimes and formation. Precise comparison of measured and calculated solar neutrino fluxes also tightly constrains sterile neutrino models or other "exotic physics" which would generate "invisible" energy from the sun (e.g. axion emission, extra dimensions). An improved measurement of S_{34} would also illuminate the discrepancy in the calculated primordial ^{7}Li abundance in Big Bang Nucleosynthesis (BBN). The measured ^{7}Li abundance disagrees by more than 3σ from theory, despite the success of BBN at explaining the abundances of lighter nuclei [2].

Many challenges must be addressed in order to accurately measure these cross sections. Measurements must

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be taken at energies close to those found in main-sequence stars ($\sim$20 keV) to minimize the uncertainty from the theoretical extrapolation of cross sections to low energy. At such low energies the cross section falls exponentially with energy and the cross sections produce almost impossibly small event rates. Therefore, experiment must be performed with either very low background or high statistics in counting the resulting end product. Additionally, energy losses in windows, impurities, and uncertainties in beam or target density can be major sources of systematic error and must be minimized.

The new Center for Low Energy Astrophysics and Interdisciplinary REsearch (CLAIRE) is being designed at LBNL to achieve large event rates by delivering high current ion beams to a high density, cooled gas-jet target. The design work is underway on both the accelerator and the gas-jet target. The current accelerator design is presented here, while the target and detectors will be presented in a later paper.

2. CLAIRE

The CLAIRE facility is being designed to deliver constant wave (cw) ion beams with energies between 50 and 300 keV and with currents in excess of 100 mA. The beams must be delivered to the gas-jet target with a diameter less than 1 cm, and must have a narrow beam energy distribution (<3%). Impurity ions must be removed from the beam before the target, therefore the beam must pass through an analyzing magnet between the source and the target. In order to get large measurement statistics, the accelerator must be capable of being run continuously for periods up to weeks.

The accelerator is being designed to extract all beams at 50 keV and post-accelerate beams to higher energy if necessary. This approach allows for the optimization of the ion source independent of beam species or required final energy. In addition to S_{34} and $S_{1,14}$ reactions, CLAIRE is being designed to be flexible enough to investigate other reactions such as d(p,γ)^{3}He, p(n,γ)d, ^{14}N(p,γ)^{15}O, ^{7}Be(p,γ)^{8}B, ^{7}Li(d,p)^{8}Li, and ^{17}O(p,α)^{14}N. Of these, the S_{34} (^{3}He(^{4}He,γ)^{7}Be) reaction is of particular interest for solar models as its femtobarn or smaller cross section at solar energies will require some of the highest currents. The discussion of the design will focus on this reaction.

The transport of high current, low energy ion beams is made difficult by rapid beam expansion due to space charge repulsion. For a uniform density, parallel beam of radius R and current I made up of ions of mass m, charge q, and kinetic energy qV_{ext}, Gauss' Law states that the potential difference between a point inside the beam and the outside of the beam is given by $\Delta V = \frac{I}{4\pi\varepsilon_\circ}\sqrt{\frac{m}{2qV_{\mathrm{ext}}}}\left(1 - \frac{r^2}{R^2}\right)$. For a 100 mA, 50 keV ^{3}He$^+$ beam with an assumed 10 mm radius, the potential difference between the center of the beam and the edge of the beam is 500 V. This large potential difference will lead to considerable beam growth over short transport distances. In order to limit this growth, the effective current can be reduced by the introduction of electron screening of this potential (space charge neutralization).

As the ion beam is transported through the beam line it will ionize background gas. Electrons liberated by this ionization can be confined radially by the strong potential of the beam. These electrons will act to screen the potential and reduce beam growth, while the positive ions created in the process are ejected from the beam. If no electrons are lost in this screening mechanism, the beam potential will be reduced until an equilibrium is reached between beam potential and electron energy. Studies by Holmes showed that neutralization levels of 99% were found for high current beams when the pressure was in the 10^{-4} Torr range [3]. The transport of beams in the CLAIRE facility will require a high level of space charge neutralization. In addition to running the source at a higher pressure, we are investigating methods of injecting low energy electrons into the beam. Experimental measurements of beam neutralization levels using retarding potential analyzers have been initiated using the beam transport system of the superconducting ECR ion source VENUS at LBNL [4]. Further measurements with an improved retarding potential analyzer in conjunction with various neutralization schemes will be performed in the near future in order to more accurately estimate neutralization levels. For simulation purposes, we have assumed a 70% neutralization of beams during transport.

2.1. Ion source

The ion source that is currently envisioned for the CLAIRE facility will be a simple microwave ion source based on the one developed at Chalk River Laboratories [5]. These sources use the resonant absorption of microwaves by electrons in a solenoidal magnetic field to create a cold plasma from which ion beams may be extracted. Since these sources require no filament, they are very low maintenance and can run uninterruptedly for extended periods of time.

The source for the CLAIRE facility, like the Chalk River source, will use two solenoid coils to produce a constant axial magnetic field near 875 G and will use 2.45 GHz microwaves to resonantly heat electrons to form and maintain the source plasma. The Chalk River ion source operated at Los Alamos National Laboratory using this same field and microwave combination has been shown capable of producing a 130 mA proton beams using a 4.3 mm-radius aperture [6]. The Child-Langmuir law states that extracted current density is inversely proportional to the square-root of the mass-to-charge ratio: $j = \frac{4}{9}\varepsilon_\circ\sqrt{\frac{2q}{m}}V_{\mathrm{ext}}^{3/2}/d^2$, where q is the ion charge, m is the ion mass, V_{ext} the extracting voltage difference, and d is the extraction gap width [7]. The CLAIRE ion source is being designed to extract more than 100 mA of ^{3}He$^+$ and other heavier mass ions, therefore the source aperture has been increased to 8 mm-radius—theoretically enough to extract more than 100 mA $^{14}N^{+}$.

In addition to the source aperture, the CLAIRE ion source will incorporate two additional electrodes for beam extraction. An intermediate electrode for surface shaping is located very close to the 50 kV extraction aperture and a negatively biased electrode is used to accelerate the beam and prevent the loss of neutralizing electrons along the transport system through back-streaming into the source. The positions, sizes, and potentials of these electrodes are optimized for 100 mA $^{3}He^{+}$ extraction using the simulation code IGUN [8], as shown in Fig. 1. For this simulation the intermediate electrode has an applied potential of 45.5 kV and is positioned 4.5 mm after the 50 kV extraction aperture. The strong beam potential requires that a relatively large negative potential be applied to the last electrode in order to have negative potential contours pass completely through the axis of the beam and prevent electrons streaming back into the source. The magnetic field of the source solenoid is also included in the simulation, though it introduces very little rotation to the beam.

The source extraction electrodes will have to undergo further shaping including rounding of corners, but this design provides a preliminary source configuration that can be used to design the remainder to the beam transport system. Particle phase space data at the end of the IGUN simulation shown in Fig. 1 is used as the initial conditions for the simulation of the beam transport system.

2.2. Beam transport

The beam transport system must incorporate both an analyzing dipole magnet in order to isolate the beam of interest from impurity ions and an acceleration column to post-accelerate beams up to 300 keV (as needed). Three solenoid lenses are incorporated before the analyzing magnet with one solenoid lens after the magnet, as shown in Fig. 2. The first lens converts the diverging beam to a near-parallel beam, and the second focuses the beam to a waist near the third lens in order to reduce the beam size and therefore the necessary dipole gap. The third lens makes a parallel beam to pass through the double-focusing analyzing dipole, and the lens after the dipole provides final focusing to the gas jet. The entire transport system from the source to the second solenoid lens is located on a high voltage platform, and an accelerator column between the second and third lenses will allow for post-acceleration of the 50 keV beam up to 300 keV.

The entire beam transport system has been simulated using the matrix code Trace 3-D [9], as shown in Fig. 3 with no post-acceleration and 70% beam neutralization. All solenoids coils have 20 cm apertures and 30 cm effective lengths. The 60° analyzing dipole has a 8 cm gap and a 30 cm bend radius. Simulations in Trace-3 D indicate that the configuration shown in Fig. 3 is capable of producing a sub-centimeter beam diameter having at the end of the transport system (gas-jet target).

The analyzing dipole must be capable of completely separating the beam of interest from any impurities present in the beam. Impurities with mass-to-charge ratios close to that of the beam of interest will be most difficult to separate. For the $^{3}He^{+}$ beam these are expected to be deuterons or alpha particles ($A/Q = 2$) and $^{4}He^{+}$ ($A/Q = 4$). Since Trace 3-D is not capable of simulating beam separation, the particle-in-cell code WARP [10] is used to simulate transport of a 70% neutralized 100 mA $^{3}He^{+}$ beam in the presence of 1 mA each of deuterons and $^{4}He^{+}$ through the 60°, 30 cm bend radius dipole. As can be seen in Fig. 4, this dipole satisfies full separation of the beam.

The acceleration column between the second and third solenoids is expected to provide a voltage gradient of 250 kV/m. When energized, there will be no space charge neutralization within the column and the simulations must incorporate the increased radial growth in this region. This was done in Trace 3-D by splitting the simulation of Fig. 3 into three parts by introducing breaks immediately before and after the accelerating column. The sections before and after the column maintain the assumed 70% beam neutralization while the section that represents the column used the full 100 mA beam current, and the final conditions of the first two sections are used to initialize the last two.

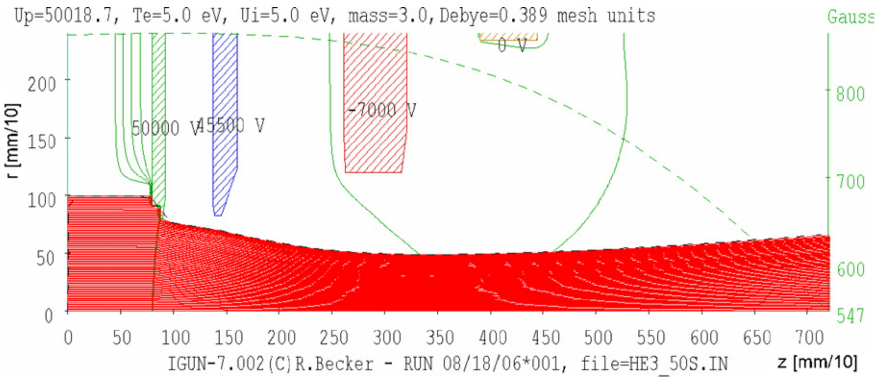

Fig. 1. IGUN simulation of the extraction of 100 mA $^{3}He^{+}$. The −200 V equipotential contour is plotted near the center of the simulation. This contour touches the z-axis and will serve as a barrier to back-streaming electrons.

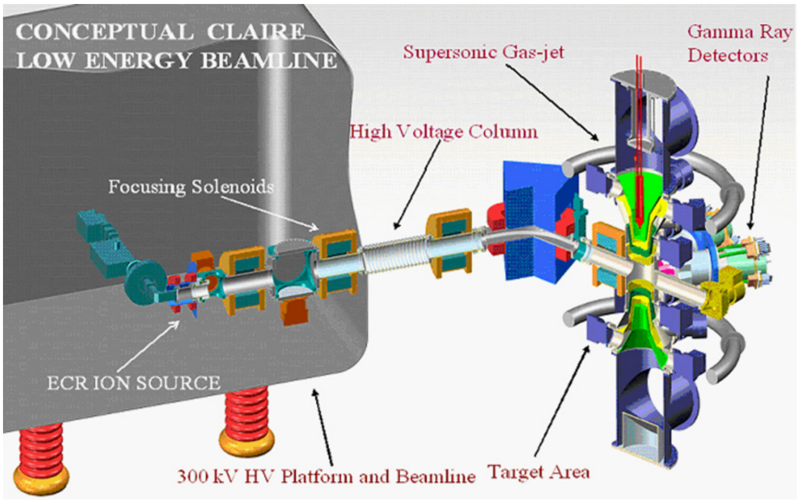

Fig. 2. CLAIRE low energy beam line conceptual layout.

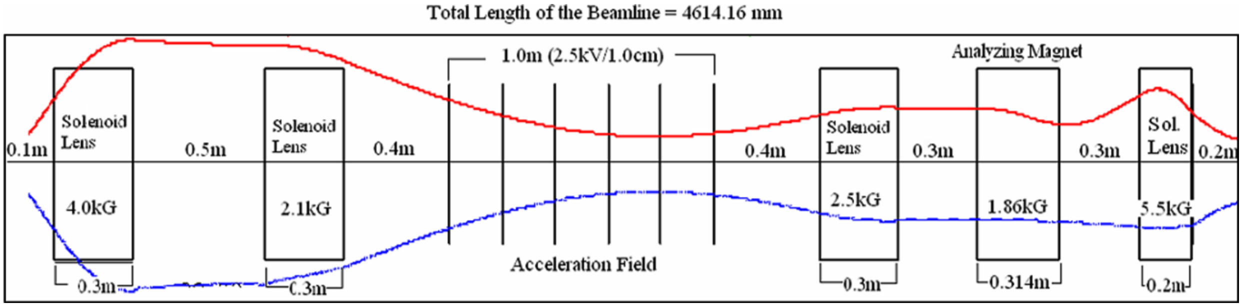

Fig. 3. Horizontal (above) and vertical (below) beam edges are shown for a Trace 3-D simulation of the beam transport system.

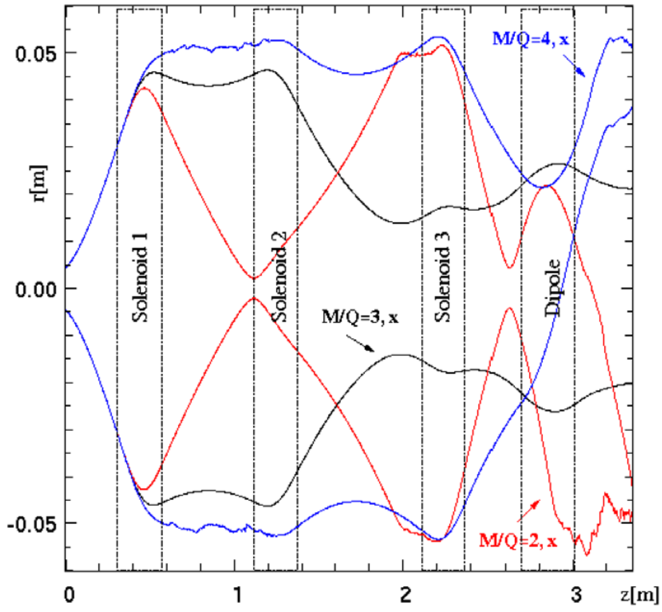

Fig. 4. Horizontal beam edges are plotted as a function of transport distance for a beam composed of 100 mA $^{3}He^{+}$ and 1 mA each of $^{4}He^{+}$ and $^{4}He^{2+}$ assuming 70% neutralization. The 60° dipole completely separates the $^{3}He^{+}$ from the background beams.

By varying lens strengths it was found that a 100 mA $^{3}He^{+}$ beam could be accelerated from 50 keV to 300 keV and could form a 8-mm diameter waist at the location of the gas-jet target.

3. Further studies

The configuration of CLAIRE presented is capable of delivering 100 mA of $^{3}He^{+}$ at energies of 50 and 300 keV when 70% space charge neutralization is assumed. Higher levels of space charge neutralization would make beam transport considerably easier and allow for a reduction in size of the accelerator. Upcoming experimental measurement of the effects of active neutralization techniques on ion beams at LBNL will be used to better determine the final CLAIRE design. In addition, simulation efforts initiated using the particle-in-cell code WARP will be continued to more accurately model aberration effects and to analyze the energy resolution of the beam delivered to the gas-jet target.

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