Program and status for the planned underground accelerator in the Dresden Felsenkeller

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Abstract. The scientific program and current status of the planned accelerator laboratory in the Felsenkeller shallow-underground facility in Dresden, Germany, are reviewed.

1. Introduction
The increasing precision of nuclear reaction cross section data is one of the main drivers of progress in nuclear astrophysics [1]. For reactions induced by light, stable ions, the preferred experimental technique to obtain such data is to perform ultra-low background experiments at an underground ion accelerator [2]. The only such device worldwide is the 0.4 MV LUNA (Laboratory for Underground Nuclear Astrophysics) accelerator in the Gran Sasso underground facility, Italy.

Based on the great success of LUNA [2, and references therein], the nuclear physics communities in Europe and in North America have recognized the need for one or several new, higher-energy underground accelerators, stating e.g. that

"Providing an underground multi-MV accelerator facility is a high priority. There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible." [3]

As a consequence, a number of related projects are being developed, amongst others, in Europe [4] and North America [5]. The planned underground accelerator in the Dresden Felsenkeller, Germany, is described in the present contribution.

2. Site and background
The Felsenkeller tunnel system in Plauenscher Grund, Dresden/Germany, consists of nine mutually connected tunnels that have been dug in the 1850s to serve a nearby brewery (fig. 1).
Since 1982, an underground low-background activity counting laboratory is hosted in one of the tunnels, currently including about ten well-shielded germanium $\gamma$-ray detectors [6].

Inside the Felsenkeller tunnels, the cosmic ray muon flux is suppressed overall by a factor of 20-40 when compared to the Earth’s surface. A detailed measurement with the REGARD muon tomograph has recently been performed showing the flux and angular distribution of incoming muons [7].

It has been shown previously that an actively vetoed high-purity germanium (HPGe) detector, when used in a shallow underground site like Felsenkeller, has a very low background level in the crucial 6-8 MeV $\gamma$-ray energy range, comparably even to the ultra-low background at LUNA [8]. To give an example, in a 44 keV wide region of interest near 6 MeV, the background level in one and the same actively vetoed HPGe detector was found to be 1.39±0.05 h$^{-1}$ at the Earth’s surface, 0.039±0.007 h$^{-1}$ in Felsenkeller, and 0.021±0.006 h$^{-1}$ at LUNA [8]. It should be noted that the deep-underground (LUNA) background level can in principle be further improved by a passive neutron shield [9]. However, even without such a shield the background at LUNA is already low enough to enable highly sensitive nuclear astrophysics measurements [2].

The Felsenkeller site offers horizontal access, by lorry, to all parts of the tunnel system and is located inside the Dresden city limits at a distance of 4 km to Dresden central railway station and the TU Dresden campus, and at 25 km distance to the HZDR Rossendorf campus. This urban location greatly facilitates scientific and educational use and the maintenance of the planned facility by qualified specialists.

3. Accelerator status and planned upgrades
In order to speed up progress, an immediately available high-energy accelerator system was acquired in June 2012 and transported to Dresden (fig. 2). It consists of a National Electrostatics (NEC) 5 MV pelletron tandem, model 15SDH-2, external 134 MC-SNICS multi-cathode cesium sputter ion source [10], electromagnets for the low and high energy ends of the tandem, and complete beam lines. This system has previously served as an accelerator mass spectrometer for $^{14}$C analyses in an industrial setting [11].
The cesium sputter ion source supplies a $^{12}$C$^-$ current of 50 $\mu$A, as measured behind the injector magnet, enabling high-current carbon beam experiments for astrophysics. The accelerator is equipped with double pelletron charging chains, thus permitting 250 $\mu$A of upcharge current.

However, an external ion source such as the existing one is not optimized for noble-gas beam implantations, as are routinely done at the HZDR ion beam center for industrial applications. Therefore, it is presently under study whether the existing pelletron can be upgraded by placing an internal radio-frequency (RF) ion source on the terminal (fig. 3). Such an ion source has the advantage that easily obtainable positive ions can be directly accelerated, obviating the need for inefficient charge-exchange channels.

One possibility currently under study is to adapt and use the design for an RF ion source that has been used for more than 30 years now on the high voltage terminal of the HZDR 2 MV Van de Graaf accelerator. The source would be placed at an angle of 30-45° with respect to the beam axis, either below or above the beam axis. In the latter case, the foil stripper would need to be sacrificed, maintaining the gas stripper intact. In order to couple in the beam emitted from such a source, one option being studied is to use an electrostatic deflector with a hole in it, as has been suggested previously [12]. In any case, the tandem capability will be maintained also with the additional RF ion source.

4. Windowless gas target

For the low background, low counting rate experiments of underground nuclear astrophysics, special care must be taken to ensure that the targets being irradiated with intensive ion beams are stable and sufficiently pure. In particular, any remaining impurity may serve as target for the light-ion beam and give rise to parasitic $\gamma$-ray emissions.

High purity can be most easily achieved when the target is in a gas phase. Windowless gas targets, either of the static or of the jet gas type, give the additional benefit that they are continuously flushed with either commercially available fresh or chemically purified gas, so that any impurities transported in with the ion beam or diffusing out of the vacuum chamber walls...
are kept on a manageable level. What is more, windowless gas targets are inherently stable and do not suffer from disturbing effects in target entrance foils, as e.g. energy and radial straggling of the incoming beam, foil heating, and accidental breaches of the foil.

The main disadvantage of windowless gas target systems are the high demands placed on the pumping system. In order to limit geometrical footprint, investment, and running cost all at the same time, a windowless gas target system is being developed for Felsenkeller that relies purely on turbomolecular pumps and one powerful backing pump of 60-90 m$^3$/h (fig. 4).

Ion optical calculations using the SIMION code show that this gas target system has satisfactory ion optical properties when its entrance is placed at a distance of 1.7 m downstream of the analyzing magnet, both for carbon beam (1-5 MeV) and even for an extreme test case with low-energy hydrogen beam. Pumping speed calculations indicate that it can be operated purely with turbomolecular pumps (appropriately equipped with backing pumps) for hydrogen, helium, carbon dioxide, and nitrogen gases at target pressures up to 2 mbar. Such a target pressure value should be sufficient for most low-energy nuclear astrophysics experiments.

5. Scientific program

The existing, 0.4 MV LUNA underground accelerator has made landmark contributions to the study of solar fusion reactions [2, 13]. However, in order to fully address key cases such as the $^{14}$N(p,$\gamma$)$^{15}$O and $^{12}$C(p,$\gamma$)$^{13}$N reactions that are necessary to precisely understand the Bethe-Weizsäcker or CNO cycle of hydrogen burning, data over a wide energy range including higher energies than those available at LUNA are needed. Therefore, solar fusion reactions are part of the scientific motivation for the planned Felsenkeller accelerator. They can be studied either in
direct kinematics, using the intense hydrogen beam by the RF ion source, or in inverse kinematics using carbon and nitrogen beams provided by the cesium sputter source (table 1). The planned new data on CNO cycle nuclear reactions are a necessary ingredient in order to address the so-called solar abundance problem [14]. With such new nuclear cross section data, the expected measurement of the flux of CNO neutrinos e.g. by the BOREXINO [15] detector for low-energy solar neutrinos may then be used to constrain the carbon and nitrogen elemental abundances in the solar core [16].

A second science field to be addressed concerns the nuclear reactions producing radionuclides that are observable in space-based observatories [17]. Such radionuclides offer a unique view on nucleosynthesis in action, either integrated over the galaxis [18] or for one particular object [19]. Of particular interest is the $\alpha$-rich freezeout in supernovae, which is believed to dominate the synthesis of $^{44}$Ti (half-life 60 years). This radionuclide has recently been proven to be the energy source in the present-day emissions of supernova remnant 1987A [19]. Experiments addressing this case require an intense $^4$He beam at energies of a few MeV, as in a recent related study at HZDR [20].

A third science field is given by the reactions of carbon burning [21]. Here, some disputed claims of low-energy resonances affecting the stellar reaction rate need to be clarified [22], and overall the uncertainty in the reaction rates can be significantly reduced by new experimental data. As is the case for several hydrogen burning reactions, also the carbon burning reactions may affect the nucleosynthesis in supernovae of type Ia, which are not only cosmological standard candles but also important contributors to the chemical enrichment of the universe.

A fourth topic is the applied physics potential of a high-current, low background accelerator. One relevant example is ion beam based analytics, where in particular the proton-induced $\gamma$-ray emission (PIGE) technique [23] may benefit from the drastically reduced laboratory background when very clean samples must be analyzed. In an underground low-background environment such as Felsenkeller, hydrogen depth profiling by $^{15}$N beam induced reactions can be performed at much lower beam intensity, conserving sample integrity, and for much lower hydrogen concentrations, increasing sensitivity. Finally, the planned RF ion source will enable intensive noble-gas beams that may serve a useful purpose for industrial implantations e.g. in the production of power transistors.

When sorting the possible reactions by the required beams and, by extension, ion source, it is apparent that several topics can already be addressed by the existing MC-SNICS ion source, while other topics will require the use of the RF ion source that is under development (table 1). Detailed counting rate estimates and feasibility studies for selected cases have been presented elsewhere [8].

In addition to work on the research topics outlined here, the planned accelerator will be open to the worldwide scientific community as a facility. Proposals from all fields of science will be

| Ion   | Ion source             | Scientific topic                                      |
|-------|------------------------|------------------------------------------------------|
| $^1$H | MC-SNICS (Tandem) or   | Solar fusion reactions                                |
|       | RF (single-ended)      | Proton-induced $\gamma$-ray emission (PIGE)          |
| $^4$He| RF (single-ended)      | Reactions of the $\alpha$-rich freezeout in supernovae|
|       |                        | High-energy ion implantations                         |
| $^{12/13}$C | MC-SNICS (Tandem) | Solar fusion reactions                              |
|       |                        | Stellar carbon burning and type Ia supernovae       |
| $^{14/15}$N | MC-SNICS (Tandem) | Solar fusion reactions                              |
|       |                        | Hydrogen depth profiling                             |
6. Status, permissions, and operations

The features of the Felsenkeller site from a nuclear physics point of view are by now known: The background in a typical detector for nuclear physics experiments has already been studied experimentally [8]. Recently, also the muon flux and angular distribution have been measured, indicating a muon flux at the site of the proposed accelerator that is even slightly lower than at the nearby site of the existing $\gamma$-counting lab [7].

The work planned here will require a construction permit and an operating permit from the radiation safety point of view. Test measurements carried out during experiments at the HZDR 3 MV Tandetron, which can be extrapolated to the ones planned here, have shown that no special shielding will be required for the typical, low-background experiments. It is envisaged that the high voltage will be removed by an automatic system if the measured radiation dose rate exceeds a predetermined threshold.

The site is privately owned, and a long-term rental contract similar to the existing one for the low-activity counting laboratory is envisaged. The tunnels have been scanned with a three-dimensional laser-based system. Based on these data and the known dimensions of the pelletron, a full feasibility study and detailed cost estimate for the preparation of the site are now complete. As of the writing of this report, a third of the necessary construction cost has been pledged, but construction presupposes full funding.

For the day to day operations, a scientist and an engineer, both HZDR staff, will be available on a full time basis. In addition to this, students (currently four PhD students and three Diploma students) and postdocs (currently one) will take part in the work on site, based on projects. This team will work on the above described scientific program (sec. 5) and also support external users.

A large share of the beam time will be allocated to external users from all fields of science, based on the recommendations by an independent panel of outside scientific advisors judging the scientific merits of proposals brought before them. For the external users selected by this panel, the accelerator and laboratory will function like a user facility providing all necessary support.

7. Summary and outlook

A project for a new, 5 MV underground accelerator is under development for the Dresden Felsenkeller, Germany. This shallow-underground site offers good background conditions and excellent access capabilities. A used, high-current 5 MV pelletron accelerator was already bought for this laboratory and recently transported to Dresden. Areas of ongoing development work include a radio frequency ion source to be placed on the high voltage terminal and a windowless gas target system.

The highly promising scientific program that can be addressed with such a laboratory has been outlined. A full feasibility study has been performed for the site preparation. This civil construction work is at present only partially funded. As key components are already available, the laboratory is expected to be running less than one year after the point in time when all of the construction funding is available.

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