Commissioning and First Operation Experience with the New High-Intensity Ultracold Neutron Source at PSI

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Abstract. A new spallation neutron source at the Paul Scherrer Institut (PSI) dedicated solely to the production of ultracold neutrons (UCN) has successfully started operation in 2011. The UCN source shares the proton beam (2.2 mA @ 590 MeV) in a pulsed mode with SINQ and the meson production targets at a duty cycle of 1%. After successful commissioning of all subsystems the facility is now able to deliver UCN to three experiments on a routine basis. The concept of the new source is based on neutron production by spallation in a Zr-canned lead 'cannelloni' target, followed by moderation in a 3.6 m^3 D_2O tank and conversion to ultracold neutrons in a 30 liter solid ortho-deuterium crystal. Subsequently, the UCN are extracted by a vertical guide into a 2 m^3 storage volume and finally distributed via NiMo coated neutron guides to the experiments. This paper gives an overview of the source layout and the first-year performance of the facility, especially the sophisticated cryogenic system.

1. Introduction

Ultracold neutrons (UCN) are free neutrons with kinetic energies below ~350 neV, corresponding to a few milli-Kelvin. The material optical potential of certain materials (e.g. Ni, Be, diamond-like carbon) is high enough that UCN are totally reflected under all angles of incidence [1]. Hence, UCN can be stored for several hundred seconds in vessels having surfaces coated with these materials.

Ultracold neutrons are ideal candidates to study in detail fundamental properties of the neutron such as the neutron electric dipole moment (nEDM) [2] or the free neutron lifetime [1]. nEDM searches probing physics beyond the Standard Model are presently limited by statistics and are the main driving force behind the proposals of several new high-intensity ultracold neutron sources around the world [7].

Construction of a new user facility providing ultracold neutrons was completed at the Paul Scherrer Institut (PSI), Switzerland, in 2010. The new UCN source is the second spallation target station driven by the PSI ring cyclotron and is designed to take macro-pulses of up to 8 s of the full proton beam intensity. In December 2010 commissioning started with the first production of ultracold neutrons under full beam load. Operation approval from the Swiss Federal Authorities was received in June 2011 and marked the official start-up of PSI's new facility. Soon after start-up, fully-automated UCN fills were being reliably delivered to the experimental areas. While further improvements of the facility are underway, the search for a nEDM at PSI [2] with a dedicated apparatus built up in experimental area South has already begun.

2. UCN source layout

The UCN source at PSI is based on accelerator driven spallation neutron production and using solid deuterium for UCN production. This method was pioneered by PNPI, Russia [3] and Los Alamos National Lab [4]. The source is driven by PSI's high intensity proton beam ring cyclotron ($I_p \geq 2.2$ mA @ 590 MeV). A fast kicker magnet deflects the proton beam — which is normally guided towards the meson production targets and SINQ — for up to 8 seconds onto the UCN spallation target. These pulses are limited by radiation safety requirements to an integrated proton flux of 20 µA·hour. Typically, for example, a 2 mA proton pulse of 6s length is followed by a minimum waiting period of 600 s.

The main components of the UCN source necessary for neutron production and transport are shown in Fig.1: When protons hit the target (indicated by (a) in Fig.1), several neutrons per proton are produced via the spallation process. The target consists of 760 lead filled Zircaloy tubes (“Cannelloni-target”), which yield higher neutron fluxes than solid Zircaloy rods [5]. It is cooled with D_2O streaming in from the target head.

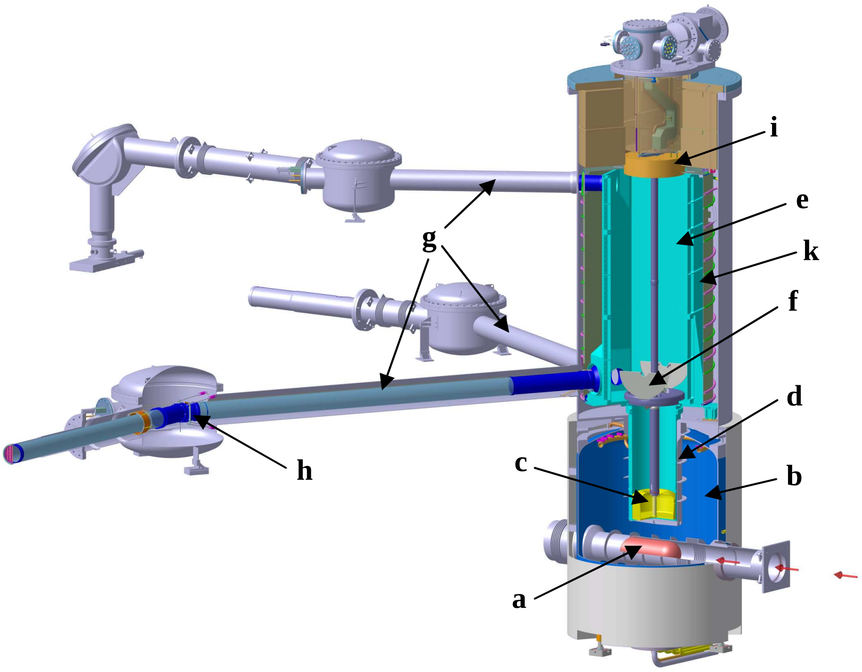

Figure 1: UCN source layout. Cut view of the PSI UCN source inside the 7 m high vacuum tank. The indicated components are described in the text.

Spallation neutrons are thermalized in the surrounding 3.6 m^3 heavy water tank (b). The D_2O has a purity of 99.8 % and is permanently cleaned by means of an ion exchange column. The thermal neutrons are further cooled and downscattered into the ultracold regime in a 5K solid-deuterium (SD_2) moderator (c). The cold moderator is installed 37 cm above the target. It consists of a cylindrical aluminium alloy (AlMg4.5) vessel with a diameter of 50 cm, filled with 30 liter of high purity deuterium (~99.95 %). The deuterium crystal has a height of ~15 cm. Some UCN are able to leave the crystal in upward direction, where they get a 102 neV boost from the SD_2 material potential at the crystal surface. The top cover of the moderator vessel is a 0.5 mm thin toroidal-shaped lid made from AlMg3. This special geometry was chosen to prevent the top lid from buckling or plastic deformation in case of an emergency, such as a vacuum break-down or rapid deuterium boil-off. At the same time the thickness had to be minimized in order to allow maximum UCN transmission. With a lid thickness of 0.5 mm a UCN transmission probability of about 60 % was measured [6].

The UCN leaving the moderator vessel in upward direction enter via a vertical UCN guide (d) the UCN storage volume (e), which is coated with diamond-like carbon (DLC). This material is particularly suitable for storing UCN as it has a high material optical potential of about 235 neV and a very low neutron loss per bounce.

Once the beam pulse is finished, and hence the UCN production, the main UCN shutter (f) is closed and the produced UCN are trapped inside the storage volume. Three UCN guides (g) lead through the radiation shielding to experimental areas. The storage volume exits for the neutron guides can be opened and closed by means of shutters operated by the experiments.

In order to provide optimum UCN transmission through more than 8 m of tubes penetrating the radiation shielding, most of the guides are made of 180 mm inner diameter Duran® glass tubes with approximately 1 nm surface roughness and sputter-coated with 500 nm thick NiMo on the inner surface. A 80 cm long polished steel guide connects the glass guides at room temperature to the UCN storage volume being at 80 K. For radiation protection reasons a 30° bend (h) made from polished stainless steel prevents direct sight into the storage volume. Prior to installation the transmission of all neutron guides was determined to be better than 98 % per meter.

On top of the UCN storage volume a large cryo-pump (i) is placed loaded with activated charcoal. Operating at 5 K it is the coldest spot of the source vacuum. Its main purpose is to pump efficiently residual hydrogen gas which would otherwise condense on the SD_2 moderator vessel or other cold spots inside the storage volume.

3. The cryogenic system

The UCN production rate strongly depends on the deuterium temperature and spin [7] favoring solid ortho-deuterium as production medium. A large, specially adapted cryogenic system had to be built for this purpose. Operation of the PSI UCN source requires the solidification of 30 liters (5 kg) of D_2 in a large crystal and maintaining it at a stable temperature around 5K. For this purpose 30 m^3 of pure D_2 gas is stored at 1 bar at room temperature in large storage tanks.

The cryogenic system carries out the following operations: The D_2 gas is retrieved from the storage tanks by condensing/freezing it into a 'condenser' volume. When all gas is frozen, a valve is closed and the temperature of the condenser is slowly increased to liquefy the D_2 again. By means of gravity the cold liquid is then transferred to the 'para-ortho-converter' which is partially filled with paramagnetic chromium-oxide (Oxisorb®) acting as a catalyst speeding up the para to ortho conversion of the D_2 molecules. The temperature of the para-ortho-converter is kept at 19 K to allow the boiling D_2 to reach its equilibrium ortho/para ratio within a day. Raman spectroscopy of the rotational transitions in D_2 on extracted gas samples showed an ortho-D_2 concentration of 97±2 % as expected for equilibrium conditions at 19 K. Finally, the oD_2 is transferred either as liquid or as vapor via a ~10 m long transfer line to the SD_2 moderator vessel inside the UCN tank. This allows to freeze the D_2 crystal either from the liquid or gas phase. As a last but important step the crystal can be treated by re-melting and subsequent slow re-freezing. The whole process to prepare an oD_2 crystal takes several days.

Supercritical helium at 4.5 K and 4.2 bar is used as coolant. It is provided by a helium refrigerator delivering a cooling power of 370 W at 4.5 K and 2.5 kW at 80 K. The refrigerator is solely dedicated to operate the UCN source. The 80 K He gas is used to cool a thermal radiation shield (k) surrounding the UCN storage volume. Temperatures in the range of 20 K necessary to condense/melt the D_2 are generated by heating 4.5 K helium with electrical heaters. Inside the condenser and the para-ortho-converter the liquid level of D_2 is measured with special high-frequency dielectric sensors. Temperatures are measured with commercial CERNOX™ sensors. Redundantly, two thermocouples and a gas thermometer are used to measure the temperature of the moderator where the level of neutron radiation is high. The helium and the deuterium systems are equipped with standard piezo-resistive pressure gauges. In order to cover a very large pressure range between 10^{-6} mbar (solid D_2) to 1000 mbar (D_2 at RT) in the deuterium circuit, pressure is measured using several sensors with different precision. The helium mass flow is measured with orifice flow meters of special in-house design.

4. Assembly and Commissioning

Mid 2010, a large assembly consisting of the UCN storage volume, the surrounding thermal shield and the vertical UCN guide was inserted en bloc into the UCN vacuum tank. Fig. 2 shows the insertion of the assembly. Visible is the vertical neutron guide at the bottom, the radiation shield made of pure aluminium with the 80 K cooling pipes and the iron shielding at the top.

Figure 2: The storage volume inside the thermal shield before insertion into the vacuum tank.

Figure 3. Insertion of the moderator unit into the UCN vacuum tank. The SD2 moderator vessel can be seen at the lower end.

The mechanically most challenging component was the moderator vessel for the solid D_2. The thin aluminium vessel has a double-wall structure, allowing the He coolant to circulate in a multi-channel labyrinth through the side wall and bottom plate in order to maximize the area for heat transfer from D_2 to He. Development and testing of the moderator vessel took about three years. Two identical vessels were produced, since one had to be destroyed in a burst test. With this test, which was carried out at LN2 temperature, it could be shown that the vessel withstands an inner pressure of up to 7.3 bar, whereas the maximum pressure in all accident scenarios does not exceed 3 bar. In November 2010, the assembly of a 5 m long unit consisting of the SD_2 moderator, its cryogenic piping, the main UCN shutter and the cryopump was completed and successfully installed inside the UCN tank (see Fig. 3).

The complete cryogenic system was commissioned during the first half of December 2010, culminating in cooling 27 m^3 of Deuterium gas in 60 hours down to a temperature of 5 K, yielding about 27 liters of solid D_2.

Testing of the proton accelerator beamline and beam diagnostics was very successful and the desired pulses were reliably delivered. Full pulses of the 1 MW beam were always preceded by a 7 ms pilot pulses running a few seconds ahead to guarantee perfect adjustment of the beam position. The heavy-water cooling system, combining the cooling of the D_2O tank, the spallation target and the target window, operated reliably, as expected. The cryogenic system behaved satisfactorily in its first-ever cool-down, even under full beam load. At all times, the performance of the source was monitored by neutron detectors at the end of all beamlines.

5. First operation and results

After the accelerator shutdown 2010/2011 approval for regular operation was obtained from the Swiss Federal authorities in June 2011. The UCN source started beam operation on August 3 and delivered neutrons until the accelerator shutdown on December 2. Over this period, all subsystems were safely operated and studied in some detail. From the beginning, enough neutrons were produced to allow commissioning of the nEDM apparatus, along with the UCN source optimization studies, such as shutter timing, beam optics tuning or cryogenic operation sequences. Operation with full proton current was soon standard and many measurements were carried out to better understand the source performance. By November, the UCN intensity delivered was by a factor of 67 higher than the best value obtained during commissioning in December 2010. This can be mainly attributed to a high ortho-concentration of the deuterium (~98% instead of ~66% in 2010), better crystal quality (now frozen from the liquid state) and higher proton beam intensity (2.2 mA instead of 1.8 mA). This increase in UCN count rate is displayed in Fig. 4 which shows the UCN counts observed in a detector on beam-line West after a proton beam pulse. To reliably compare the source performance, 2 s long pulses ('normpulses') with all shutters open were used (black and blue curves). A short, 7 ms pilot pulse (PP) was used for proton beam positioning before the normpulse. The third curve (red) shows the counts for the case when, after a 6 s beam pulse, the shutter on the storage vessel bottom is closed and UCN are then guided to the detector.

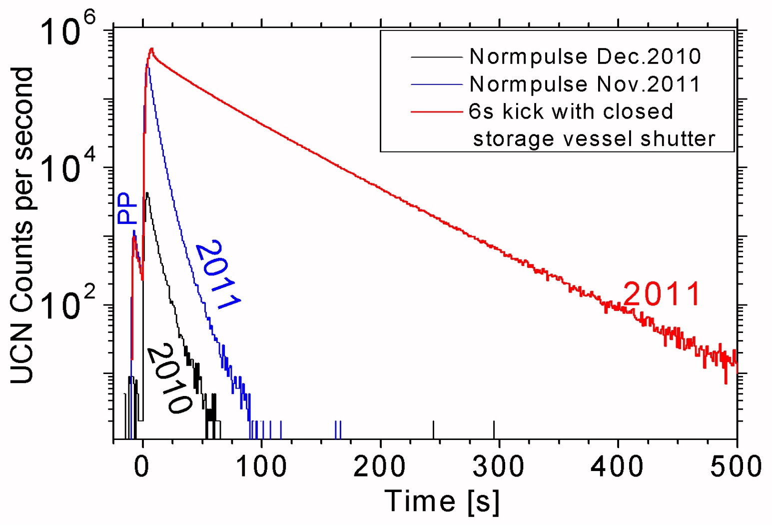

Figure 4. UCN count rate observed in a detector on beam line West for normpulses taken at different times of the commissioning phase. Details of the plot are described in the text.

The large, 30 liter deuterium crystal was liquefied and refrozen several times under different conditions to study the effect of re-crystallization on the UCN yield. Fig. 5 shows the liquefaction of the solid deuterium crystal monitored with UCN counts. The high initial UCN production in the solid deuterium crystal (red dots show the integrated counts for normpulses) decreases during warm-up, because of increasing crystal temperature. While warming up, the D_2 pressure (blue curve) shows an increase up to the triple-point pressure (171 mbar), followed by a constant regime, where the solid-to-liquid phase transition takes place. Further warming vaporizes the liquid and the pressure increases again.

It was found that the cool-down process for the crystal needs some improvements, as the presently used control valves did not allow a sufficiently slow and reproducible crystallization process. Variations in UCN yield of about a factor of three were observed between different freezing cycles. One possible explanation are the large thermal stresses building up across the 50 cm wide ice block during rapid cool-down which could cause cracks in the crystal resulting in a reduction of the UCN yield [8]. We are confident that the replacement of the control valves during the 2011/2012 shutdown will help to precisely regulate the coolant temperature, hence the D_2 temperature and the crystal growth, during slow cool-down (18.7 K to 5 K). This might account for a considerable part of the factor of ~30 which is still necessary to reach full design intensity.

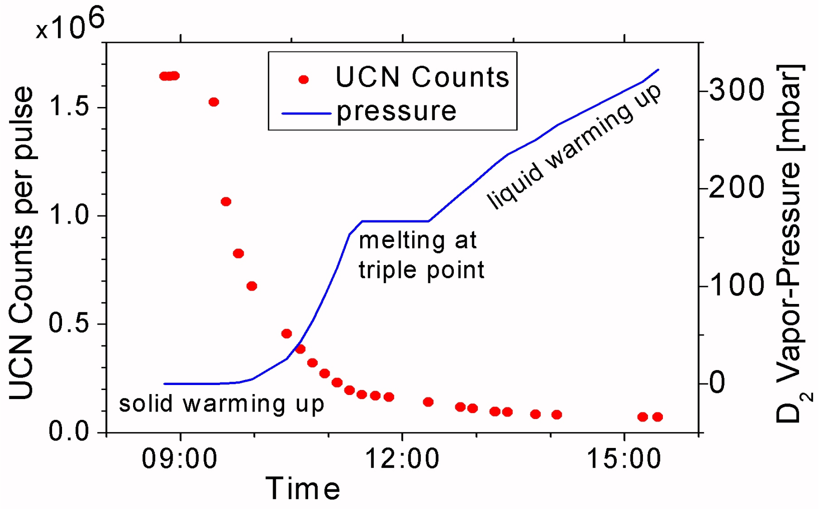

Figure 5. Liquefaction of a SD_2 crystal monitored with UCN counts. The red dots show the integrated counts for different normpulses taken at different vapor pressures (blue line) or different crystal temperatures, respectively.

6. Summary

The new ultracold neutron source at PSI successfully started operation in August 2011. All subsystems are operating reliably. Sufficient ultracold neutron intensities already allowed starting commissioning of the nEDM experiment, which is be the flagship experiment at this new user facility. UCN source optimization procedure is in progress having already gained an increase in UCN intensity of a factor of 67 in 2011. Another factor of ~30 lies ahead to reach the design value. As a next step, the focus is on better temperature control of the D_2 moderator crystal below 18.7 K. In 2012, user operation of the UCN source is planned to start in May, immediately after the end of the accelerator shutdown.

7. References

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