The Upgrade of the Neutron Induced Positron Source NEPOMUC

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Abstract. In summer 2012, the new NEutron induced POsitron Source MUniCh (NEPOMUC) was installed and put into operation at the research reactor FRM II. At NEPOMUC *upgrade* 80% ^{113}Cd enriched Cd is used as neutron-gamma converter in order to ensure an operation time of 25 years. A structure of Pt foils inside the beam tube generates positrons by pair production. Moderated positrons leaving the Pt front foil are electrically extracted and magnetically guided to the outside of the reactor pool. The whole design, including Pt-foils, the electric lenses and the magnetic fields, has been improved in order to enhance both the intensity and the brightness of the positron beam. After adjusting the potentials and the magnetic guide and compensation fields an intensity of about $3 \cdot 10^9$ moderated positrons per second is expected. During the first start-up, the measured temperatures of about 90^oC ensure a reliable operation of the positron source. Within this contribution the features and the status of NEPOMUC *upgrade* are elucidated. In addition, an overview of recent positron beam experiments and current developments at the spectrometers is given.

1. Introduction

High intensity positron sources are in high demand for a large variety of positron beam experiments in solid state and surface physics as well as for fundamental studies. At electron accelerators (linacs) positrons can be created from absorption of high-energy bremsstrahlung, which is released by decelerating electrons in a target. The absorption of high energy γ-radiation from nuclear fission can be used to generate positrons by pair production at a research reactor, e.g. at the POSH beam in Delft [1]. At NEPOMUC the nuclear reaction ^{113}Cd(n,γ)^{114}Cd is applied in order to provide high-energy γ-rays for pair production in Pt foils [2]. Pt is applied as positron moderator as well, since it leads to the emission of mono-energetic positrons. Similar sources have been designed at the PULSTAR reactor in the USA [3] and at the research reactor in Hamilton, Canada [4].

Up to now, NEPOMUC has been operated successfully with an intensity of about 10^9 moderated positrons per second [5]. The design and features of the positron source as well as the positron beam facility are reported elsewhere (see e.g. [2] and references therein). After five years of reactor operation, the beam tube SR 11 had to be replaced due to the burn-up of ^{113}Cd inside the tip of the beam tube. The main change of NEPOMUC *upgrade* is the application of highly enriched ^{113}Cd in order to ensure a lifetime of 25 years. In order to enhance the intensity

and the beam brightness, additional improvements have been made to the design of the source components [6]. In this work, the improvements of the final layout of NEPOMUC *upgrade* and the expected beam parameters are presented. Results of the calculated temperature field inside the beam tube are shown and compared with the thermal behavior during the first start-up of the reactor with the new positron source. Finally, a short overview of positron beam experiments at NEPOMUC is given.

2. The new positron source NEPOMUC

2.1. In-Pile Positron Source

As in the previous setup, the principle of NEPOMUC *upgrade* at the research reactor FRM II is based on the emission of high-energy prompt γ-rays after thermal neutron capture in ^{113}Cd. A structure of Pt foils converts the released high-energy γ-radiation into positron-electron pairs and leads to the emission of mono-energetic positrons (see e.g. [2]).

The lifetime of the first source, which used an converter of natural Cd with a thickness of 3 mm, was limited by the burn-up of the ^{113}Cd after 1250 days of reactor operation at the nominal power of 20 MW. For this reason, the inclined beam tube SR11 with the in-pile positron source had to be replaced. The main task was a considerable extension of the operation time of the positron source to 25 years. Therefore, Cd enriched with 80% ^{113}Cd, i.e. 6.5 times higher amount of ^{113}Cd than in natural Cd, is applied at NEPOMUC *upgrade*.

As shown in figure 1, NEPOMUC *upgrade* consists of three main components: (i) the outer 'beam tube' surrounded by the D_2O of the moderator tank and with Cd as converter inside the tip, (ii) the evacuated 'experimental tube' carrying the magnetic coils for positron beam transport, and (iii) the innermost 'potential tube' with the Pt foil structure and electric lenses.
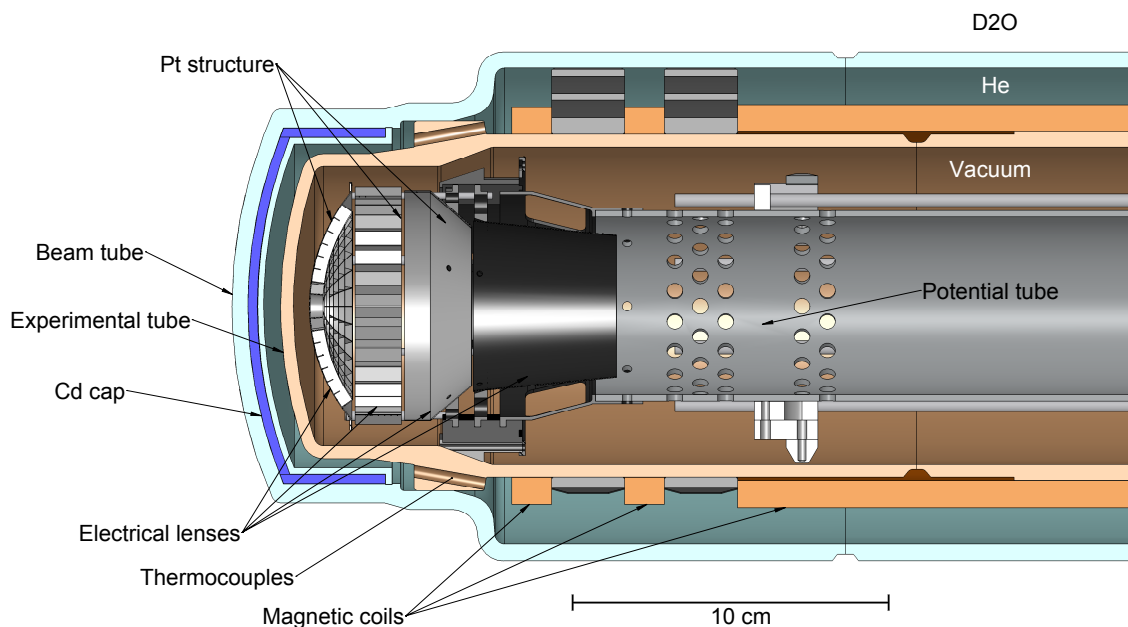

Figure 1. Cross sectional view of the new in-pile positron source NEPOMUC *upgrade*.

Compared with the previous position, the Cd cup is 50 mm closer to the fuel element which leads to a higher thermal neutron capture rate. In addition, the smaller Cd cup at NEPOMUC *upgrade* leads to a lower neutron flux depression. The according increase of the positron production rate in Pt is about 20%.

The design of the inner parts has been improved in order to enhance both the beam intensity and its brightness. For this reason, the electric and magnetic fields in the beam formation stage were simulated for various configurations by finite element (FE) calculations [6].

Absorption of high energy γ-quanta in the Pt front section with additional small vanes and in the electrical lenses contribute to the positron production. For the formation of a high brightness beam, only the moderated positrons from the Pt front plate with low transverse momentum are collected. A higher total moderation efficiency is expected due to the improved geometry and (inelastic) scattering of positrons from the Pt lenses onto the front moderation foil.

A combination of electric and magnetic fields is used to accelerate and to form the beam. In order to minimize transport losses the positrons should be guided adiabatically, i.e. with low kinetic energy. For this reason, the potential of the 'potential tube' and the insulated tube inside the chicane through the biological shield can be biased at any desired value to ensure a fully adiabatic beam transport. Outside the biological shield, the positron beam can be guided to a remoderator using a W(100) crystal in back reflexion geometry for brightness enhancement [7]. A new beam switching and remoderation unit allows quick toggling between the primary high-intensity and the high-brightness remoderated positron beam [6].

The γ-heating generates a thermal power in the Al/Cd/Al structure of about 1.35 kW. Dependent on the material the heat density of the inner parts in the front section is typically between 0.4 and 1 W/g leading to an additional heat power of approximately 0.6 kW and hence to a total of about 2 kW. The heat conductance between experimental tube and beam tube has to be sufficient since the heat load has to be dissipated in the surrounding heavy water. In order to ensure a high durability in the long term and for safety reasons, the temperature in the experimental tube must not exceed 150 ^{o}C.

FE calculations have been performed in order to display the temperature field in the outer tubes at a reactor power of 20 MW (see figure 2). The heat load in the components mainly due to γ-absorption was taken from Monte Carlo calculations. The heat transmission coefficient from the beam tube to the surrounding water (45 ^{o}C) was set to 2200 W/m^{2}K. Heat transport by He (1.2 bar) between the tubes barely contributes to the cooling. Most important is the contact area between the tubes for heat conductance. As expected, the maximum temperature is reached at the tip of the experimental tube and amounts to 110 ^{o}C.

2.2. Positron beam parameters

The positron beam is transported in a magnetic guide field of typically 7 mT with a kinetic (longitudinal) energy of E_L=1 keV (20 eV) of the primary (remoderated) positron beam. The relevant beam parameters such as Y^+_{mod} yield of (re)moderated positrons, i.e. beam intensity, transverse energy $E_\perp$, and diameter d^+ of the positron beam are described and compared with the former NEPOMUC beam in [6]. The according values expected for the primary moderated and the remoderated positron beam at NEPOMUC *upgrade* are summarized in Table 2.2.

For NEPOMUC *upgrade*, a maximum intensity of about $3 \cdot 10^9$ moderated positrons per second is expected. The correct number of the positron intensity strongly depends on various effects such as amount of (in-)elastically scattered positrons, which contribute to the primary positron beam, moderation efficiency of the Pt moderator at high temperature and in the radiation field, and beam extraction and formation at the tip of the beam tube. However, the more conservative estimation of the beam parameters are given in parentheses. The total efficiency of the beam guiding and focusing at the remoderator –and hence Y^+_{mod} of remoderated positrons– is expected to be higher due to the higher brightness of the primary beam at NEPOMUC *upgrade*.

2.3. Commissioning of the new positron source

During the first start-up of the reactor the temperature of the experimental tube at the contact area to the outer tube was measured with four independent thermocouples in order to ensure a
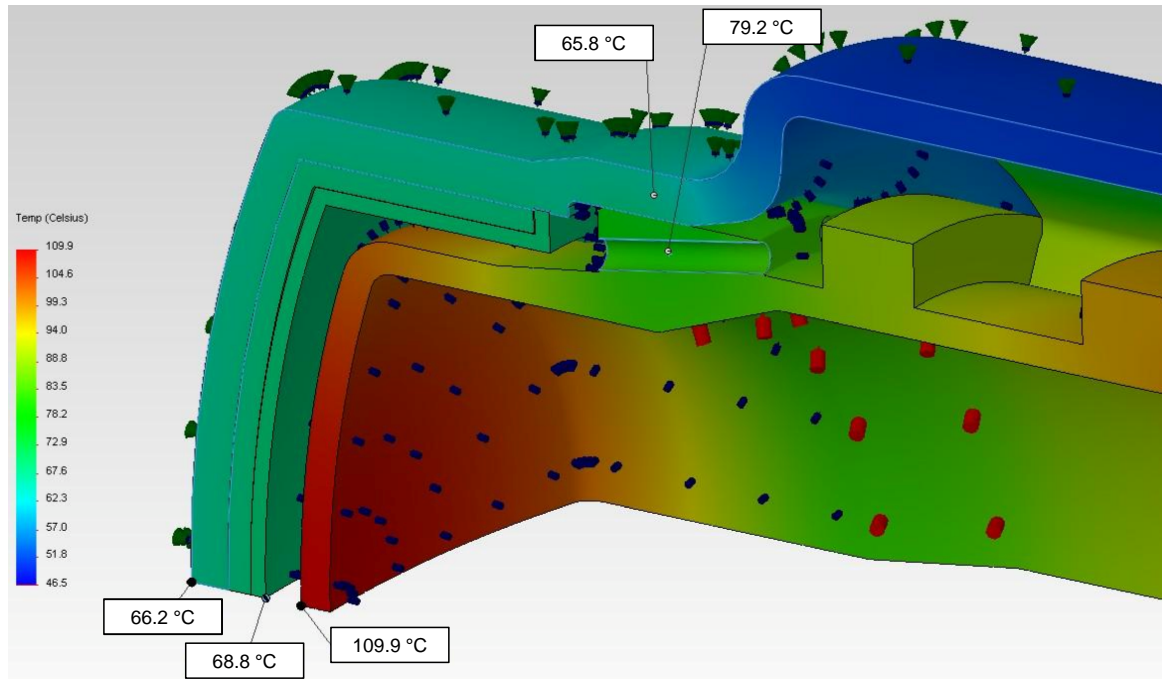
Figure 2. FE-calculation of the temperature field in the beam tube and experimental tube during reactor operation at 20 MW. For details see text.

	NEPOMUC *upgrade*	
	primary	**remoderated**
Y^+_{mod} $[s^{-1}]$	$3{\cdot}10^9$ $(2{\cdot}10^9)$	$\approx 2 \cdot 10^8$
$E_{\perp,\mathrm{FWHM}}$ $[eV]$	0.6 (1.2)	≈ 1
d^+_{FWHM} $[mm]$	< 7 $(d_{full} < 22)$	< 1 $(d_{full} < 2)$

Table 1. Expected beam parameters at NEPOMUC *upgrade* for the primary moderated (values from [6]) and the remoderated positron beam: Y^+_{mod} yield of (re)moderated positrons, $E_\perp$ transverse energy, and d^+ diameter of the positron beam. Standard settings are a magnetic guide field of 7 mT, a kinetic (longitudinal) energy of $E_L{=}1$ keV and 20 eV for the primary and the remoderated beam respectively. (Conservative limits in parentheses.)

safe operation of SR11. The mean temperature T_m and the reactor power P are shown in figure 3 (left). A maximum temperature of about $90(2)\,^o$C is reached at 20 MW. During the increase to the power steps of 5, 10, 15, and 20 MW the temperature almost immediately follows the increase of the reactor power and shows a nearly linear behavior (figure 3 (right)), that indicates

a sufficient good heat conduction between the two tubes. The further temperature increase during the power steps is attributed to the warming of the SR11 and the surrounding D_2O. Compared to the FE-simulation the measured temperature is slightly higher, which is explained by a lower heat transmission coefficient from the beam tube to the D_2O.
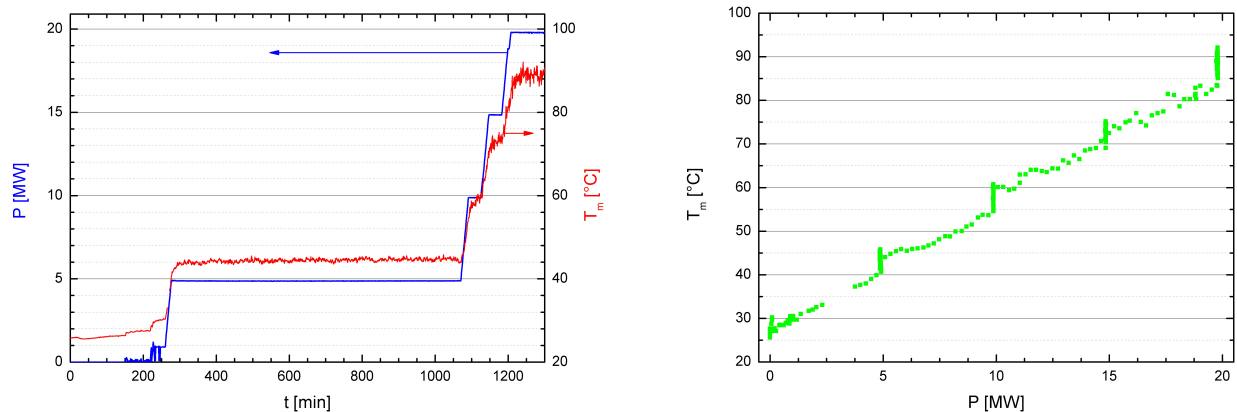

Figure 3. Reactor power P and temperature of the experimental tube T_m during start-up of the reactor (left), almost linear increase of T_m as function of reactor power (right).

In August 2012, first tests confirmed the operational reliability of SR11, and first positrons were successfully guided from the source to the outside of the reactor pool. Presently, various parameters are adjusted such as potentials of the moderator, electric lenses and potential tube as well as magnetic guide and compensation fields for proper beam extraction. The shape and the intensity of the positron beam are measured at the first accessible place outside the reactor shielding.

3. Positron Beam Experiments

NEPOMUC *upgrade* will enable the continuation of a large variety of studies using the high-intensity positron beam as well as the development of new experiments. These experiments range from high-sensitive and elemental selective investigations in surface physics over defect spectroscopy in thin films and solids to fundamental studies in atomic and plasma physics.

3.1. Surfaces

Positron annihilation induced Auger electron Spectroscopy (PAES) for element selective surface studies has several advantages over conventional AES such as suppressed secondary electron background in the range of Auger-transition energies and exceptional surface sensitivity. Only a few PAES studies have been performed so far due to the very long measurement time of up to 20 days per spectrum with conventional positron sources. After upgrading the spectrometer at NEPOMUC, we succeeded in recording PAES spectra with high energy resolution within several minutes. For example, the surface coverage and island growth were studied in the systems Cu/Pd and Cu/Fe [8]. Moreover, with first *time-dependent* PAES the theoretically predicted segregation process of Cu in Pd could be observed experimentally [9].

Currently a x-ray source is installed in order to gain element information of the surface with complementary techniques such as XAES and XPS. An additional STM is also mounted for the examination of the surface topology.

3.2. Defects and thin films

Coincident Doppler-Broadening Spectroscopy (CDBS) enables defect studies and element specific measurements in the near surface region and in the bulk of the specimen up to a few μm according to a positron energy of up to 30 keV. The sample defects can be mapped by scanning the beam in two dimensions with a lateral resolution of $<300\,\mu$m. Since depth dependent CDBS is particularly suited to study the elemental surrounding of the positron annihilation site metallic layers and (nano-)clusters embedded in Al were investigated by CDBS [10, 11]. Defect annealing in thin films [12] or in Cu and Ni after severe plastic deformation [13] can be observed by in-situ DBS as a function of time and temperature. Presently, a new sample stage is installed in order to extend the temperature range to 100...1300 K [14].

The Pulsed Low-Energy Positron System (PLEPS) was developed at the Universität der Bundeswehr (UniBW) München for depth dependent positron lifetime measurements. At NEPOMUC, lifetime spectra can be recorded within a few minutes, and the high peak-to-background ratio of 10^4 allows the extraction of at least three lifetime components reliably [15]. Several PLEPS experiments were performed e.g. on the free volume in polymer films [16] or in bioadhesive [17], on irradiation induced defects after He implantation in InN and GaN [18] or on vacancies in a thin film perovskite oxide [19]. An interface including pulsing units and an additional remoderator for brightness enhancement was developed in order to enable the operation of the Scanning Positron Microscope (SPM) [20] at the NEPOMUC beam line [21].

3.3. Fundamental experiments

Additional experimental setups can easily be connected to the positron beam line at the open beam port. Examples are, a nitrogen-filled drift chamber for the investigation of positron moderation by inelastic scattering [22], a coincidence setup for the detection of the correlated electron-electron and electron-positron emission from surfaces after slow positron impact [23] or a high precision measurements of the decay rate of the negative positronium ion Ps$^-$ [24]. Due to the limited place at the present position, it is planned to extend the positron beam facility to a new experimental hall at the east side of the reactor building. A new spectrometer for the measurement of the Angular Correlation of Annihilation Radiation (ACAR) using a ^{22}Na source has been set up recently [25]. It is planned to move this apparatus to the new hall in order to enable depth dependent ACAR experiments for non-destructive studies of the electronic structure –in particular anisotropies of the Fermi surface– in thin films, at interfaces and surfaces. Another longterm experiment at an additional beam port will be the implementation of a stellarator setup for the creation and studies of electron–positron plasmas [26].

4. Summary and outlook

The main change of the new beam tube at NEPOMUC *upgrade* is the utilization of 80% enriched ^{113}Cd in order to provide a long-life high intensity positron beam. A new design of the positron beam extraction was developed, which is expected to lead to an increase of both beam intensity and brightness. The anticipated intensity of the mono-energetic positron beam is about $3.0\cdot10^9$ moderated positrons per second. In addition, a new beam switching and remoderation unit was constructed in order to allow quick toggling between the primary high-intensity and the high-brightness remoderated positron beam. Presently the beam parameters are adjusted for providing a high positron intensity. In 2012, the spectrometers PLEPS, CDBS and PAES will be connected to the beam line in order to continue the positron beam experiments.

Acknowledgements

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