The NEPOMUC *upgrade* and advanced positron beam experiments

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**Abstract.** The neutron-induced positron source NEPOMUC at the FRM II provides a mono-energetic positron beam of high intensity of the order of \(10^9\) moderated positrons per second. The new layout of NEPOMUC *upgrade* is presented and the constraints for operating an in-pile positron source at a research reactor are discussed. Inside the tip of the new beam tube, 80\% \(^{113}\)Cd-enriched Cd is used as a neutron-\(\gamma\)-converter that has a projected lifetime of 25 years of reactor operation and thus ensures positron beam experiments in the long term. The source consists of Pt foils that both generate positrons, by pair production, and moderate them. The layout of these foils, the electric lenses and the magnetic fields for positron extraction and beam formation have been improved. In addition to a higher beam intensity, it is expected that the beam brightness will improve by at least one order of magnitude. The present and planned experiments range from fundamental studies in nuclear, atomic and plasma physics to high-sensitivity and element-selective investigations in surface and solid state physics to applications in materials science. The upgrade of several positron spectrometers as well as new positron beam experiments are presented. In addition, a new switching and remoderation unit will allow us to toggle from the high-intensity primary beam to a brightness enhanced remoderated positron beam.

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1. Introduction

Low-energy, high-intensity positron beams are in great demand for (pulsed) remoderated micro-beams, for positron-scattering experiments and for a variety of coincidence techniques used in solid state physics: angular correlation of annihilation radiation (ACAR) for the investigation of the electronic structure, coincidence Doppler broadening spectroscopy (CDBS) for elementsensitive defect spectroscopy and age momentum correlation (AMOC) for the study of positron and positronium (Ps) states in matter. In positron lifetime spectroscopy for defect studies, the high beam intensity leads to a drastically reduced measurement time and hence to a considerably enhanced signal-to-background ratio. Moreover, the maximum available intensity of slow positrons is crucial for positron annihilation-induced Auger electron spectroscopy (PAES), which is applied at element-selective surface studies, and for a number of fundamental experiments such as spectroscopy on Ps and Ps−, as well as the creation of a positron–electron plasma or the production of anti-hydrogen.
In the future, possible positron sources, which might benefit from bright $\gamma$-sources, could be developed at synchrotron radiation facilities or by using powerful lasers. If photons of high enough energy become available at synchrotrons, positrons could be created by pair production after photon absorption [1, 2]. For instance, it was proposed to install a superconducting wiggler at Spring-8 in Japan to obtain synchrotron radiation with an energy well above 1 MeV [3]. Another approach would be to utilize the inverse Compton effect by scattering photons from an intense laser with a relativistic electron beam. The generated high-energy $\gamma$-radiation is ideally suited to the production of a positron beam with high brightness [4]. Moreover, the produced positrons show a high degree of polarization by using a circularly polarized laser beam interacting with a GeV electron beam [5].

However, at present, positrons are either provided by $\beta^+$-emitters in all kinds of positron (beam) experiments in the laboratory scale or generated by pair production at large-scale facilities such as electron linear accelerators (linacs) or nuclear reactors. At linacs, positrons can be created from the absorption of high-energy bremsstrahlung, which is released by decelerating electrons in a beam dump. There are several slow positron beams in operation at linacs in Japan [6–8], China [9], USA [10] and Germany [11]. At nuclear reactors, the absorption of high-energy $\gamma$-radiation can be used to generate positrons by pair production. At the research reactor in Delft, the $\gamma$-radiation from nuclear fission is absorbed in an assembly of thin tungsten foils in order to generate positrons by pair production [12, 13].

Another approach for creating positrons at reactors is to utilize the emission of high-energy prompt $\gamma$-rays after thermal neutron capture. This method, based on the nuclear reaction $^{113}$Cd($n, \gamma$)$^{114}$Cd, is applied at the NEPOMUC (NEutron-induced POsitron source MUniCh) [14]. Cd absorbs thermal neutrons very efficiently due to the huge capture cross-section for thermal neutrons in $^{113}$Cd, which amounts to $\sigma_{\text{cap}} = 20600$ barn. A structure of Pt foils is used for the conversion of the released high-energy $\gamma$-radiation into positron–electron pairs. Platinum is applied as a positron moderator as well, since it leads to the emission of mono-energetic positrons [15]. For the sake of clarity, in the following, the Cd inside the tip of the beam tube SR11 is named the Cd converter, and we distinguish between the Pt production foils and the Pt moderator, i.e. the front plate from which moderated positrons are extracted.

To mount an in-pile positron source close to the fuel element of a reactor, several aspects have to be taken into account, e.g. fast and thermal neutron flux, burn-up of the absorbing isotope $^{113}$Cd, neutron flux depression and $\gamma$ heating. Details of the positron production and the design of NEPOMUC as well as the positron beam facility are reported elsewhere (see, e.g., [14] and references therein). Based on the principle of the NEPOMUC source, two further positron sources have been designed: one at the PULSTAR reactor in the USA [16] and another at a research reactor in Hamilton, Canada [17].

From the beginning, NEPOMUC was planned and built as a user-dedicated facility at the Forschungs-Neutronenquelle Heinz Maier-Leibnitz FRM II of the Technische Universität München (TUM). For the first time, a positron beam facility, which included several spectrometers, became available for all external scientists proposing experiments that require a high-intensity low-energy positron beam. Until now, out of more than 130 submitted external proposals, 95 experiments have been accepted and carried out at NEPOMUC. Hence, NEPOMUC has operated successfully, providing about $10^9$ moderated positrons per second [18]. However, after five years of reactor operation, the beam tube SR11 had to be replaced due to the burn-up of $^{113}$Cd in the Cd-cup inside the tip of the beam tube. In the course of the reconstruction of the beam tube, several changes have been made to various components,
and the design of the electric and magnetic positron beam extraction has been improved. For this reason, an enhanced beam brightness is expected, not only due to the gain in positron intensity of more than a factor of two, but also due to a reduction of the transverse positron momentum by at least one order of magnitude compared to the previous design.

In this paper, we present the upgrade of the NEPOMUC source as well as the new beam switching and remoderation unit. It is also explained how to achieve the aim of producing an intense positron beam of high brightness. The paper is organized as follows. Firstly, the constraints that have to be taken into account for designing an in-pile positron source at a nuclear reactor are summarized. Secondly, the results of the calculated values for the neutron field, positron production rate and heat production are presented. In section 3, we present the simulation of positron trajectories of the final layout, which is compared with two other electric lens designs and different magnetic guide fields. In section 4, the new setup for beam analysis, brightness enhancement and toggling between the primary and remoderated beams is presented. The expected beam parameters for the NEPOMUC upgrade in comparison with the previous source are also listed in section 4. Finally, a short overview of applications and the upgraded positron beam experiments is given.

2. Positron production at the NEPOMUC upgrade

2.1. Constraints and the design of the in-pile positron source

The in-pile positron source NEPOMUC is mounted inside the beam tube SR11 of the research reactor FRM II, which is operated for typically 240–260 days per year. At least four fuel elements, with the commissioned lifetime of 60 days each, are normally used per year. In the reactor, several constraints—such as heat load, neutron activation, accessibility, low change of reactivity and flux reduction of the surrounding beam tubes—have to be considered. In addition, the challenges of the new source design are to extend the operation time and to increase the beam intensity and its brightness.

The construction of the whole positron source is separated into three main components: the outer beam tube containing the Cd converter inside the tip, the inner ‘experimental tube’ that carries the magnetic coils for positron beam transport and the innermost ‘potential tube’ with the Pt foil structure and electric lenses for beam extraction. A cross-sectional view of the positron source inside the beam tube tip is shown in figure 1. The beam tube is surrounded by the D$_2$O of the moderator tank. During operation, the gap between the experimental tube and the outer tube is filled with He. The potential tube is placed in the evacuated experimental tube.

In order to avoid using an active cooling device, the heat load due to the $\gamma$-heating has to be dissipated in the surrounding heavy water. For this reason, the mass of the used materials has to be as low as possible. In addition, ceramics insulators with high thermal conductivity and high electrical resistivity even at elevated temperature and in the high radiation field have to be used. For reconstruction or dismantling purposes, both the accessibility of the components and the total radioactivity after operation due to neutron activation have to be taken into account. In addition to Cd as n-$\gamma$-converter and Pt for the production and moderation of positrons, the materials used are AlMg$_3$ (with low Co content), Al, Ti, Al$_2$O$_3$ and AlN are also used.

In the new design, the neutron capture rate is improved and the solid angle of the Pt production foils with respect to the Cd cup is optimized. In addition, one can benefit from the emission and reflection of fast, or not fully thermalized, positrons from the electrical lenses onto...
the moderating front plate. The effective area from which moderated positrons are extracted is the (spherically shaped) front plate (see section 3). The extraction and acceleration by electric lenses as well as the magnetic guide field are optimized with respect to this positron-emitting surface.

The potential of the ‘potential tube’ and the tube inside the chicane through the biological shield is electrically decoupled from the outer tube and can hence be biased at any desired value. Therefore, the positrons can be guided with low kinetic energy and hence fully adiabatically. This leads to a more brilliant beam at the first accessible position outside the reactor, in particular at the remoderation device.

2.2. Optimization of the Cd converter

Besides the high intensity and high brightness of the positron beam an additional important task is a considerable extension of the operation time of the positron source. For this reason, the main difference compared with the Cd converter used in the first design is the application of highly enriched $^{113}\text{Cd}$. The amount of enriched $^{113}\text{Cd}$ is 80% and hence about a factor of 6.5 higher than in natural Cd. This value was confirmed experimentally to be 81(2)% by using an isotope separator at TUM [19].

For the optimization of the geometry of the Cd converter, several aspects have to be considered: $\gamma$-heating of not only Cd itself but also the inner components, the (total) neutron capture rate and the flux depression, the total Cd mass and also the cost of the $^{113}\text{Cd}$-enriched material. The new position of the Cd cup is 50 mm closer to the fuel element. Compared with the previous position, the unperturbed thermal neutron flux of $2.4 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ is about 9% higher and thus leads to an accordingly higher thermal neutron capture rate. The fast neutron flux is still rather low, i.e. the flux ratio of thermal to fast neutrons is in the range of $10^4$. 

Figure 1. Cross-sectional view of the new in-pile positron source inside the beam tube SR11.
A reduction in the size of the Cd converter leads to a lower neutron flux depression and hence to a higher neutron capture rate per unit area as well [19].

As shown in figure 1, the Cd cup is sandwiched between the outer beam tube and an inner Al cup. The thickness of 3 mm was found to be a good compromise between self-absorption of the released $\gamma$-radiation and the lifetime of the Cd, which is limited by the burn-up of $^{113}$Cd. The outer diameter of the slightly convex-shaped front plate of the Cd cup is 112 mm and the length of the collar, i.e. the cylindrical part, is reduced to 30 mm. Hence, in comparison with the previous Cd converter, the total Cd mass is lower and leads to a lower total heat production due to $\gamma$-heating.

The expected neutron flux, neutron capture rate, heat production and positron production rate were calculated based on Monte Carlo simulations with the MCNP software package [19]. The smaller collar of the Cd converter and the smaller distance to the fuel element lead to an increase in the neutron capture rate of about 20–22%. This leads to an accordingly higher positron production rate per unit area in Pt of about 20%. The capture rate averaged over the Cd volume would lead to an operation time of 6170 days at the nominal reactor power of 20 MW, i.e. to about 25 years of reactor operation with four cycles of 60 days each according to $1.23 \times 10^5$ MWd.

Inside the tip of the outer beam tube, i.e. the Al–Cd–Al structure, a thermal power of about 1.35 kW is generated, which is easily dissipated in the surrounding water. The material-dependent heat density of the inner parts in the front section typically ranges between 0.4 and 1 W g$^{-1}$, leading to an additional heat power of approximately 0.6 kW and hence to a total of about 2 kW.

The thermal neutron flux of the nearest beam tube SR3 is affected by the Cd in the SR11. The new position of the Cd cup leads to an additional flux decrease of only 1% compared with the previous geometry. The reactivity change of the reactor core is about $-2 \times 10^{-5}$ and hence is within the range of accuracy of the calculation [19].

2.3. Positron production and moderation in Pt

A structure of Pt foils is used for positron production since the pair production cross-section is about 11% higher than that at other sources using W [20]. Compared with W, Pt has the additional advantage of a lower annealing temperature, which leads to the in situ annealing of irradiation-induced vacancies. Moreover, due to its negative positron work function of $\Phi_{pt} = -1.95(5)$ eV [21], Pt leads to the emission of mono-energetic positrons. In general, the yield of moderated positrons $Y_{mod}^+$ is increased as the mass of the Pt foils and the moderating surface is maximized.

The font plate with additional small vanes and the electrical lenses are made from Pt and contribute to the positron production by absorption of high-energy $\gamma$-quanta. In the previous setup, the source design was optimized with respect to the maximum number of extracted moderated positrons. This required designs for the extraction lens and magnetic fields that enabled the collection of positrons from a large emission area and for a beam energy in a wide range between 10 and 3000 eV (see, e.g., [21]). At the NEPOMUC upgrade, only the moderated positrons from the Pt front plate with low transverse momentum are to be collected for the formation of a high-brilliance beam.

Based on the calculated numbers for the positron production and assuming a similar moderation efficiency as in the previous source, the positron yield $Y_{mod}^+$ is estimated to be...
2 × 10^9 moderated positrons per second. However, a higher moderation efficiency due to the improved geometry as well as the reflection and (inelastic) scattering from the Pt lenses onto the front moderation foil would lead to a further increase of roughly 30–50%. In addition, the fully adiabatic guidance of the low-energy positron beam would lead to lower transport losses. Consequently, the NEPOMUC upgrade is expected to increase both the beam intensity by a factor of 2–3 and the brightness by at least one order of magnitude, compared with the previous source.

3. The Positron beam formation

3.1. Principal considerations

Moderated positrons leave the Pt moderator perpendicular to its surface—blurred by their thermal motion—with a discrete energy of about 2 eV. The aim is to conserve the high phase space density of the emitted positrons, i.e. ideally no additional transverse momentum should be transferred to the positrons during acceleration and beam formation. For this reason, it was specifically investigated how the positrons can be guided by an inhomogeneous magnetic field at the emission site into the homogeneous magnetic field in the potential tube. The acceleration and beam formation is realized by a combination of electric and magnetic fields provided by electrical lenses and by magnetic field coils with optional magnetic shielding. During the positron transport to the experiments the kinetic energy should not be too high in order to ensure fully adiabatic beam guidance. Therefore, for all simulations the potential tube was set to a voltage of +980 V.

The electric and magnetic fields in the beam formation stage of the NEPOMUC upgrade were calculated by the finite-element method (FEM) implemented in the COMSOL multiphysics package. The so-called particle tracer of COMSOL was used for the calculation, analysis and visualization of the positron trajectories in the electromagnetic fields calculated by the FEM. The calculations were performed in a simplified two-dimensional (2D) model given by the axial symmetry of the relevant parts of the experimental setup. In the following, we examine the magnetic field defined by the geometry and current density of (short) solenoids as well as an optional magnetic shielding with two different geometries of the positron moderator. In section 3.3 the final layout of the NEPOMUC upgrade is presented.

3.2. Optimization of the beam generation stage

The applied magnetic field guides the positrons from the Pt front plate into the potential tube. In order to avoid too high γ-heating the magnetic coils should not be too close to the Cd converter. The magnetic flux density near the front side of the experimental tube is limited by the maximum current density of 2 A mm\(^{-2}\) in the coils. Additional magnetic shielding allows positron transport without perturbation by external stray fields. These constraints limit the options for the design of the magnetic transport system. Thus, the position and shape of the magnetic shielding (outer Fe mantle of the experimental tube) and the magnetic coils were treated as fixed input parameters for the simulation. Two coils (two layers of a 4 mm thick Al wire) and the solenoidal coil of the beam tube were implemented in the basic simulation model (see figure 2(a)). With a current density of 0.8 A mm\(^{-2}\) in coil 1 and 1.6 A mm\(^{-2}\) in coil 2, a magnetic field up to about 10 mT at the symmetry axis of the experimental tube can be achieved.
**Figure 2.** Positron beam formation: (a) cross-section of the cylindrical symmetric geometry. (b) Magnetic flux density and field lines near the center of the experimental tube: the strength and direction of the magnetic flux are determined by the magnetic shielding (0.3 mm μ-metal), coil 1 (0.8 A mm$^{-2}$) and coil 2 (1.6 A mm$^{-2}$). The long solenoidal coil (see figure 3(a)) of the beam tube adjacent to coil 2 is not shown. (c) Concentric alignment of the hemispherical moderation foil with the Cd converter (not shown): the emitted positrons are formed into a beam of high intensity. Positrons not emitted close to the center of the foil show a transverse motion with an energy of more than 7 eV at a kinetic energy of 22 eV (see the outer trajectory). (d) Optimized Fresnel-like geometry: the bending radii of each of the four segments are adjusted to the magnetic field lines. In this layout, the positron trajectories exhibit nearly no significant transverse momentum. For clarity, the magnetic flux lines and the magnetic field coils are omitted in figures 2(c) and (d).

In the given magnetic field, basically two different geometries for the Pt production and moderation foil were examined.

In a first example (see figure 2(c)), the hemispherically shaped production foil was chosen to be concentric with the Cd converter in the beam tube and the magnetic shielding on the outer mantle of the experimental tube. Due to the minimal distance to the Cd converter, this setup leads to the maximum beam intensity compared to other setups. The applied voltages of 999.5 and 999 V to lenses 1 and 2, respectively, lead to an electric field that allows the positrons to travel into the homogeneous magnetic field of coil 2 without significant deterioration of the beam quality as a result of acceleration in the non-homogeneous electric field.
Figure 3. Final design of the beam formation stage (a). The foremost production and moderation foil has a spherical shape (bending radius 55 mm). Compared to the design in figure 2(a), the magnetic shielding is omitted, coils 1 and 2 are replaced by Helmholtz-like coils and the lens system is slightly adjusted. In the applied magnetic field (b), positrons can still be guided into the beam line (c).

The two exemplary positron trajectories plotted in figure 2(c) show that positrons emitted from the center have no significant transverse momentum, whereas positron emission near the edge leads to a transverse motion with an energy of more than 7 eV in the longitudinal magnetic field of coil 2 ($B_{\parallel} \approx 10$ mT). The trajectory of the outer positron exhibits a large gyration radius $r_g$ directly after the emission whereas no increase of $r_g$ is visible during acceleration between lens 2 and the potential tube in the field of coil 2. Consequently, the transverse momentum of the positrons is caused by the magnetic field, which is not exactly perpendicular to the moderation foil.

A promising approach for the minimization of the transverse momentum is the reduction of the bend radius of the Pt moderation foil since positrons at the edge would be emitted with a smaller angle with respect to the field lines. However, this would lead to a smaller beam intensity, since the distance between production foils and the Cd converter increases. In order to
overcome this disadvantage, a Fresnel-like geometry for the front moderation foil is proposed (see figure 2(d)). In this geometry, the production foil is subdivided into various segments with optimally adapted bending radii. The segments are enveloped by the concentric shape of the previously shown production and moderation foil in order to ensure a maximum positron intensity.

The simulations showed that it is sufficient to use a Pt moderator which consists of four segments where the outer segments have a larger bending radius than the inner ones. For the Fresnel-like geometry, the calculated trajectories (see figure 2(d)) demonstrate clearly the reduction of transverse momentum compared to the previous design. From nearly all starting points the positrons are emitted parallel to the magnetic field lines.

3.3. Beam formation at the NEPOMUC upgrade

Since the $\gamma$-heating leads to an elevated temperature, a more conservative layout with reduced mass at the experimental tube was studied. For this purpose, the additional magnetic shielding and coil 1 are omitted, and coil 2 (see figure 2(a)) is replaced by Helmholtz-like coils due to their less mass (see figure 3(a)). In addition, a compromise between the hemispherical and the Fresnel-like design was chosen, which consists of a spherical moderation foil with a smaller bending radius than in the concentric alignment first presented.

In order to find out to what extent the modifications affect the beam quality the model shown in figure 3(a) was investigated in COMSOL. In the Helmholtz-like coils, a current density of 1.6 A mm$^{-2}$ was assumed, and the solenoid of the beam line has a current density of 0.96 A mm$^{-2}$ with a resulting strength of about 7 mT (figure 3(b)). Slight modifications in the electric lens systems account for the different progression of the magnetic field lines. Two exemplary positron trajectories are shown in figure 3(c).

In the simulation, several curvature radii of the Pt moderator were tested in order to find the optimal bending radius of 55 mm where the lowest transverse positron momenta can be observed. The trajectories of the moderated positrons emitted perpendicular to the surface taking into account the thermal motion were simulated for several initial points on the Pt moderation foil. In figure 4, the characteristic parameters, i.e. the resulting beam radius in the solenoid $r_{\text{beam}}$ and the energy of the transverse motion $E_\perp$ for various starting points at $r_{\text{start}}$, are given.

The observed behavior of $r_{\text{beam}}$ (distance from the $z$-axis in the guiding field with a strength of 7 mT), which increases linearly with $r_{\text{start}}$, is a direct consequence of the progression of the magnetic field lines (see the fit in figure 4). The gyration radius of the trajectories lies within the symbols and leads to only a small increase of the beam radius. In comparison with the first positron source, the mean diameter $d_{\text{FWHM}}$ at the NEPOMUC upgrade is expected to be smaller than 7 mm in a guiding field of 7 mT.

The transverse momentum increases with the distance $r_{\text{start}}$ from the central axis $r_{\text{start}} = 0$. A maximum energy ($E_\perp = 0.94$ eV) of the transverse motion is found for the outermost positrons with $r_{\text{start}} = 34$ mm. Assuming a homogeneous positron emission rate at the moderator foil the mean transverse spread of $E_\perp$ would be about 0.6 eV. Besides the emission perpendicular to the Pt surface the thermally induced transverse momentum was considered. For this reason, a transverse component with an energy of $E_\perp = \pm 50$ meV was added at the positron starting point. The resulting spread of $E_\perp$ in the homogeneous guiding field, which amounts to $\pm 0.3$ eV for the outermost trajectories, is plotted as error bars in figure 4.

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Figure 4. Characteristic parameters of the positron beam in the magnetic guide field of the solenoid: the resulting beam radius $r_{\text{beam}}$ with a linear fit (left) and the energy of the transverse motion $E_{\perp}$ (right) as a function of the distance of the emission position to the central axis $r_{\text{start}}$ of the Pt moderator. The error bars result from trajectories with added thermal energy ($E_{\perp} = 50$ meV) at the emission point on the Pt surface.

A well-suited figure of merit for a positron beam is its brightness $B$ defined as

$$B = \frac{Y_{\text{mod}}}{\theta^2 d^2 E_{L}} = \frac{Y_{\text{mod}}}{d^2 E_{\perp}}$$  \hspace{1cm} (1)

with a divergence $\theta = \sqrt{E_{\perp}/E_{L}}$ and transverse (longitudinal) component of the positron energy $E_{\perp}$ ($E_{L}$). Based on the calculated data, the upper limit for the beam parameters would be a total diameter of approximately $d^+ = 22$ mm and $E_{\perp} \approx 1.2$ eV in the guiding field of 7 mT. Hence, the corresponding brightness would be at least $B = 3.4 \times 10^6$ mm$^{-2}$ eV$^{-1}$ s$^{-1}$. This estimation is consistent with the expected brightness directly at the Pt moderation foil at a magnetic field of 0.7 mT, a foil diameter of 70 mm and $E_{\perp} \approx 0.1$ eV accounting for the thermal spread and possible field inhomogeneities. The beam parameters of the new and the previous source are compared in section 4.5.

4. The high-intensity beam and the high-brightness positron beam

4.1. Brightness enhancement

The beam brightness is a key feature because a small divergence and a high intensity within a small beam spot leads to a higher performance for positron beam experiments. The brightness of the positron beam can be further enhanced by the application of a positron remoderator. For this reason, the primary 1 keV positron beam of NEPOMUC has been remoderated using a W(100) single crystal ($\Phi^+ = -3.0$ eV [22]) in back reflection geometry. This remoderation device, which is based on the remoderator design as already applied at the SPM [23], has been installed and set into operation at the first accessible position of NEPOMUC. The energy of the remoderated beam can be adjusted between 20 and 200 eV and was usually set at 20 eV for most experiments. The total efficiency of the setup is about 5% and the beam diameter of the
Figure 5. Overview of the new setup for the analysis (3) and brightness enhancement (7) of the NEPOMUC positron beam. The most obvious improvements to the former setup are the two beam switches (4, 8) allowing the toggling between the high-intensity and the brightness-enhanced beam.

A remoderated beam is less than 2 mm (full-width at half-maximum (FWHM)) in a 6 mT guiding field [24].

4.2. The new switching and remoderation unit

A new beam switching device for optional brightness enhancement was developed and built (see figure 5) in order to provide the primary high-intensity beam or the remoderated one.

In the first section (1), a turbo molecular pump provides a high vacuum of about $10^{-8}$ mbar in the experimental tube. After a gate valve (2), a beam monitor (3) follows, which consists of a carriage with four slots. The first slot contains a combination of a micro channel plate, a phosphor screen and a mirror to enable the measurement of the beam profile. An annihilation target in the second slot allows the determination of the total intensity of the primary positron beam. The last two positions are used for different-sized apertures. In this section, a Helmholtz-like coil configuration is used, because the geometry of the first parts (1)–(3) would necessitate several large gaps in a solenoidal coil design.

4.3. The adiabatic beam switch

Two so-called beam switches were built (see (4) and (8) in figure 5) in order to enable a computer-controlled toggling between the primary and the remoderated positron beam. The chosen design does not necessitate the extraction from the longitudinal magnetic guiding field. The simplest approach is the superposition of the longitudinal main field generated by
Figure 6. Sketch to scale of the beam switch (parts (4) and (8) in figure 5) together with the simulated vertical magnetic field and selected magnetic field lines resulting from the superposition of the longitudinal and vertical magnetic fields. The beam is deflected in the $x$-direction by $d = 25$ mm; the $y$-direction points out of the drawing plane. For better visibility, the thicknesses of the coils and the $\mu$-metal parts are not to scale.

A solenoidal coil with a transverse switching field. The field is provided by a $\mu$-metal core which extends over the middle third of the switch and on which toroidal coils are wound. The whole switch as well as the entrance and exit ports are shielded by $\mu$-metal. The magnetic fields and the according particle trajectories of the setup were simulated with the help of the software packages COMSOL and MATLAB (see figures 6 and 8).

A major aim in the design of the beam switch was the conservation of the properties of the positron beam. Simulations of the positron trajectories showed that a sufficiently large number of gyrations during the deflection $d$ are necessary for conserving the phase space volume (PSV) of the beam. Therefore, the length $L$ over which the transverse deflection is performed has to be large and the positron velocity has to be low. The kinetic energy can be simply tuned to accordingly low energies by setting the desired voltage to the inner potential tube.

A bunch of trajectories with representative start conditions was computed in order to evaluate the effect of the deflection on the beam. Due to the lack of rotational symmetry of the setup, no cylindrical coordinates could be used either for the calculation of the magnetic field or for the calculation of the trajectories. However, in the entrance and the exit ports of the setup, the beam is guided by a homogeneous, rotationally symmetric magnetic field. This allows us to plot the transversal part of the PSV in the common style by using the radial momentum $p_r = \sqrt{p_x^2 + p_y^2}$ and the radius $r$ as the distance from the beam center to the particular trajectory. Reasonable cross-sections of the PSV are made at the image planes which occur with the period of the gyration length. Although the rotational symmetry is given at the beginning and at the end of the simulations, not only particles starting at different radii $r$ but also those
Figure 7. The drift motion in the y-direction during the deflection in the x-direction. The coloring is according to the z-coordinate. A single trajectory is plotted starting with a radial momentum of $p_r = 1.98 \times 10^{-3} m_0 c$ according to an energy of 1 eV in the y-direction.

starting at different azimuthal angles $\varphi$ pass through slightly different field strengths, leading to deformations of the PSV. Due to the symmetry of the setup it is obvious that the field differences are larger for particles starting at a line along the x-axis compared with those starting on a line parallel to the y-axis. Hence, the starting points of the trajectories were set to $(x_0, y_0, z_0) = (x_n, 2 \text{ mm}, -120 \text{ mm})$, where $x_n$ ranged from $-10$ to $10 \text{ mm}$ in steps of $2 \text{ mm}$. To reduce the memory requirement during the FEM calculations, the symmetry of the setup with respect to the $y = 0$ plane was used and only one half space was calculated. The slight displacement in the y-direction ensures that the whole trajectory fits within the calculated half-space.

The $p_r$ component of the initial momentum was set in 20 equidistant steps from $p = -\sqrt{2m_0E}$ to $p = \sqrt{2m_0E}$ with $E = 1 \text{ eV}$. By setting them along the y-direction the center of the gyrations is at the entrance and the exit of the setup within the y-plane in which the particles started. The x-deflection in the first half of the setup leads to a drift motion out of this plane due the curvature drift. However, due to the sigmoidal shape of the deflection in the x-direction the displacement after the first half is canceled by a drift in the opposite direction in the second half of the setup (see figure 7). The longitudinal momentum was set according to an energy of 20 eV. Therefore, the variable starting points and momenta can be summarized in a 2D grid spanned...
Figure 8. The density distribution of the simulated beam in the radial part of the PSV before and after deflection.

by 11 values of $r$ and 20 values of $p_r$. In each transversal cross-section of the PSV, each of the simulated trajectories is represented by one of 220 points.

In reality, the occupation density in the transversal PSV follows a certain distribution. For the simulation, a 2D Gaussian distribution of an ensemble of positrons was considered with a width of $p_r = 1.98 \times 10^{-3} m_0 c$ FWHM (according to an energy of 1 eV) and $r = 10$ mm FWHM, respectively. Each trajectory was weighted according to this Gaussian distribution in order to generate smooth distributions in the phase space cuts from the 220 simulated trajectories. In figure 8, only a slight deformation of the density distribution after the beam deflection is visible. It is caused mainly by the fluctuations of the longitudinal magnetic field strength, especially at the entrance and the exit of the beam switch.

4.4. The Positron remoderator

Using the first beam switch (4), the primary beam can be either deflected toward a second switch (8) and hence guided directly to the experiments or it can be deflected to the remoderation stage where the beam brightness is enhanced. In the so-called decompression line (5), the longitudinal guiding field is decreased sufficiently slowly so that the beam diameter increases and the transverse momentum of the positrons decreases. Hence, the ratio of these quantities can be matched to the requests of the remoderator optics. The adjacent electrostatic accelerator (6) in front of the remoderator stage will be used to adjust the ratio of the transverse and the longitudinal components of the positron momentum.

The setup of the remoderator (see figure 9) is described in detail in [24], but for the sake of completeness a short summary is given here. At the entrance of the remoderator, the positron beam is extracted from the magnetic guiding field by a field termination (1). It consists of a $\mu$-metal flange holding 25 $\mu$m thin metallic glass stripes in a venetian blind configuration and with a gap size of 2 mm to each other. The transverse momentum transferred to the positrons is kept low since most of the magnetic flux is led within the metallic glass stripes outside of the beam area. After extraction, the positron beam is transported by a long focal electrostatic lens (2) into the operational area of the short focal magnetic main lens (3), which focuses the beam onto a W(100) single crystal. The remoderated positrons are accelerated and formed to a beam by electrostatic lenses (4) before they are separated from the primary beam and deflected toward the exit of the remoderator by a dipole field (5). The action of the dipole field is much stronger.
Figure 9. Cross-sectional view of the NEPOMUC remoderator. The primary NEPOMUC beam (red lines) is extracted from the magnetic transport field by a special field termination before it enters the remoderator. The electrical entrance lens images the positron beam toward the operational field of the magnetic main lens, which generates a small spot on the W(100) crystal where the positrons are remoderated. In front of and behind the magnetic dipole, which deflects the remoderated positrons (blue lines) toward the exit of the setup, are several electrical lenses used for acceleration and imaging purposes.

onto the remoderated beam due to its much lower energy compared to the primary beam. Two further electrostatic lenses (6) are used to form the beam before it is reinjected into a magnetic guiding field. After the remoderator the second beam switch (see (8) in figure 5) injects the enhanced positron beam into the beam line which leads to the experiments.

4.5. Positron beam parameters

The beam parameters, which are estimated for the NEPOMUC upgrade (see section 3.3), are compared with the previous positron source and the remodered beam. The relevant values of the intensity $Y^+_{\text{mod}}$, the transverse energy $E_L$, and the diameter $d^+$ of the positron beam at a kinetic energy of $E_L = 1 \text{ keV}$ are summarized in table 1. The values given for the primary and the remoderated beam of the previous source were measured. It is worth mentioning, that for the remoderated beam (diameter $\approx 2 \text{ mm}$) the theoretically achievable brightness, i.e. only accounting for the thermal spread at the remoderation crystal, would be about $5 \times 10^8 \text{ (mm}^2 \text{ eV s)}^{-1}$. The lower value, which was determined experimentally, is attributed to field inhomogeneities which lead to additional transverse momentum.

For the NEPOMUC upgrade, a maximum intensity of about $3 \times 10^9$ moderated positrons per second is expected. The values based on the more conservative estimation, which refer to
Table 1. Expected beam parameters for the NEPOMUC upgrade in comparison with the measured values of the primary and the remoderated positron beam of the first NEPOMUC source. $Y_{\text{mod}}$ yield of (re)moderated positrons, i.e. positron beam intensity, $E_\perp$ transverse energy, $d^+$ diameter and $B$ brightness of the positron beam at $E_L = 1$ keV in a magnetic guide field of 7 mT. The conservative limits of the beam parameters estimated in section 3 are given in parentheses.

| Parameter                          | NEPOMUC | NEPOMUC upgrade |
|------------------------------------|---------|-----------------|
| $Y_{\text{mod}} (s^{-1})$          | 9.0 × 10^8 [18] | 4.5 × 10^7 [24] | 3 × 10^6 (2 × 10^6) |
| $E_\perp \text{FWHM (eV)}$        | 50      | 1               | 0.6 (1.2) |
| $d^+ \text{FWHM (mm)}$            | 7 [14]  | < 2 [24]        | < 7 (d_{total} < 22) |
| $B \left[(\text{mm}^2 \text{eV s}^{-1})\right]$ | 3.7 × 10^5 | > 1.1 × 10^7 | < 10^8 (3.4 × 10^6) |

the upper limits for the beam parameters presented in section 3, are given in parentheses. In addition, at the NEPOMUC upgrade, the total efficiency of the beam guiding and focusing at the remoderator is expected to be higher due to the higher brightness of the primary beam. Consequently, the parameters of the new remoderated beam would exceed those of the former positron source by more than the intensity gain of the positron source.

5. Current and future positron instrumentation at the NEPOMUC upgrade

The high-intensity positron beam at the NEPOMUC upgrade will enable the continuation of a large variety of positron beam experiments in the long term and the development of new experimental setups. According to the present and planned instrumentation, the experiments range from fundamental studies in atomic and plasma physics to high-sensitivity and element-selective investigations in surface and solid state physics to applications in materials science.

At present, three experiments are in routine operation at NEPOMUC for PAES, coincidence Doppler broadening (CDB) studies and positron lifetime measurements at the Pulsed Low-Energy Positron System (PLEPS) [25, 26]. An interface has been installed in order to enable the operation of a scanning positron microscope (SPM) at the NEPOMUC beam line [27]. In addition, an open multi-purpose beam port (OP) is available, where various experimental setups can be connected to the positron beam line for short-term experiments.

5.1. Positron annihilation-induced Auger electron spectroscopy

PAES is particularly suited for element-selective experiments with extremely high surface sensitivity. Besides high-resolution measurements on pure metals [28], the Cu coverage of Fe and Pd was studied and compared with conventional AES [29]. Due to the high positron intensity and an improved electron detector, time-dependent PAES was applied for the first time in order to reveal the surface segregation process in Cu/Pd [30]. At present, the PAES spectrometer has been upgraded with an x-ray source and an STM that will enable complementary examination of both the elemental composition and the topology of surfaces.
5.2. Positron lifetime spectroscopy: the Pulsed Low-Energy Positron System and a scanning positron microscope

Depth-dependent positron lifetime measurements are carried out at PLEPS using a positron beam energy between 0.5 and 20 keV [26]. An acquisition time of only 3 min leads to $2.5 \times 10^6$ counts in the lifetime spectrum, the overall timing resolution is 240 ps and the peak-to-background ratio is better than $3 \times 10^4$ [26]. Examples are the determination of the free volume in polymer films [31] or the correlation of the positron lifetime with the open volume in bioadhesive [32]. In particular, positron lifetime experiments and additional DBS yield to a deeper insight into the nature of defects, e.g. irradiation-induced defects after He implantation in InN and GaN [33], H-induced defects in Pd films after different H loadings [34] or the vacancy defects in thin film perovskite oxides [35, 36]. Recently, first AMOC spectra were recorded at PLEPS by using a fast BaF$_2$ detector and a Ge detector in coincidence. For the positron lifetime measurement with a micro-beam, the Munich SPM [23] will be connected to the NEPOMUC beam line. For this purpose, an interface including pulsing units and an additional remoderator for brightness enhancement were developed and installed [27].

5.3. Coincidence Doppler broadening spectroscopy

The CDB spectrometer enables defect studies by conventional DBS and element-specific measurements with CDBS in the near-surface region and in the bulk of the specimen up to a positron implantation energy of 30 keV with a lateral resolution of 300 µm [37, 38]. DBS can be performed in the single mode with a typical photo peak single count rate of $3-5 \times 10^4$ s$^{-1}$ and an energy resolution of $< 1.4$ keV at 511 keV. In the coincidence mode for CDBS, the coincident photo peak count rate amounts to typically $10^3$ s$^{-1}$. Typical applications are the investigation of irradiation-induced defects, e.g. in Mg and Mg alloys [37], and defect annealing in thin films [39] or in Cu and Ni after severe plastic deformation by high-pressure torsion [40]. High-element-selective studies on Sn layers embedded in Al were performed by CDBS [41], followed by other Al samples with embedded layers of Au, Cu and Cr of different positron affinities for systematic studies in order to observe positron trapping in Au (nano-)clusters [42]. Examples of technical alloys are defect mapping in Al and Al alloys after mechanical load [43] or the investigation of friction stir welded Al–Fe samples [44]. Moreover, several experiments were done on PLEPS for positron lifetime measurements and with energy-dependent DBS at the same systems, e.g. on silica glass after Au implantation [45].

5.4. Experiments at the open beam port—OP

At the OP, experimental setups can easily be connected to the UHV system of the positron beam line. For example, a time-of-flight system for the detection of (Auger-)electrons has been set up [46, 47]. The positron moderation by inelastic scattering in nitrogen [48], positron–He scattering [49] as well as the correlated electron–electron and electron–positron emission at surfaces after slow positron impact were investigated [50]. An apparatus for the production of the negatively charged positronium ion Ps$^-$ [51, 52] was transferred from the Max-Planck Institute for Nuclear Physics in Heidelberg to NEPOMUC. After an improvement of the hole setup [53], the Ps$^-$ decay rate $\Gamma$ was determined with unprecedented accuracy as $\Gamma = 2.0875(50)$ ns$^{-1}$ [53]. At present, a new apparatus has been set up for the spectroscopy of Ps and Ps$^-$ in collaboration with the LMU München and the MPI Heidelberg.
5.5. Positron electron plasma

A completely new project will be the installation of a stellarator [54] for neutral and non-neutral positron–electron plasma experiments. After exploration of the feasibility together with T Pedersen from the MPI for Plasma Physics Greifswald, it is planned to connect a magnetic positron storage device (see, e.g., [55]) at NEPOMUC which will allow us to inject intense positron pulses into the stellarator.

5.6. Angular correlation of annihilation radiation

The electronic structure and anisotropies in the Fermi surface will be measured in strongly correlated materials and in particular in thin film samples. For this purpose, at present, a 2D-ACAR system has been installed that will enable both bulk measurements with a $^{22}$Na source and (near) surface studies using the NEPOMUC beam. Compared to complementary methods, e.g. de-Haas–van-Alphen measurements, low temperatures and strong magnetic fields have not to be applied for ACAR experiments.

6. Summary and outlook

After the successful operation of the first high-intensity positron source NEPOMUC, the construction of a new in-pile source became necessary due to the burn-up of the $^{113}$Cd of the Cd converter, which provides the high-energy $\gamma$-rays for pair production. The main change in the new beam tube is the utilization of 80% enriched $^{113}$Cd in order to provide a high-intensity positron beam in the long term. A new design of the positron beam extraction was developed for the NEPOMUC upgrade, which would lead to an increase of both beam intensity and brightness. For this purpose, detailed simulations of the magnetic guiding and electric acceleration fields as well as the resulting positron trajectories were performed for various geometries of the Pt production and moderator foils. 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.

The NEPOMUC upgrade is expected to provide a mono-energetic positron beam with an intensity of up to $3.0 \times 10^9$ moderated positrons per second. The diameter of the primary beam will be comparable to the beam of the previous positron source but the brightness is expected to be one order of magnitude higher.

At the FRM II, the SR11 was the first activated beam tube which was dismantled including all inner parts of the in-pile positron source. At the beginning of 2011, the outer beam tube including the $^{113}$Cd-enriched Cd converter was installed. Due to major construction work in the experimental hall it is planned to start the operation of the new positron source and the positron beam experiments in 2012. In parallel with this work, all the spectrometers—PLEPS, CDBS, PAES and SPM—have been extended and upgraded. In addition, new experiments such as 2D-ACAR, positron–electron plasma and Ps spectroscopy are developed. In 2013/2014, it is planned to move the positron instrumentation into the new experimental hall located east of the FRM II. This new experimental area has several advantages, such as negligible vibrations in comparison with the present experimental platform, lower $\gamma$-background from the surrounding experiments and more available space for the experiments. Fewer bends and $\mu$-metal shields of
the new beam line to the east hall will lead to lesser deterioration of the beam quality during the magnetic transport.

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