Enhancement and Transformation of the Phase Space Density of the NEPOMUC Positron Beam

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Abstract. At NEPOMUC, four different experiments are installed permanently and one beam port is open for positron experiments provided by external users. To match the different demands of these experiments on the phase space density of the positron beam, the established NEPOMUC remoderator was relocated and two novel beam switches were installed to provide the primary high-intensity beam or the remoderated high-brightness beam within short switching times. At the present state, the remoderated beam has a mean diameter of 1.85(35) mm and an intensity of $3.0(3) \cdot 10^7\,e^+/s$. For the transformation of the longitudinal phase space density a new buncher setup was developed which converts the continuous positron beam into a pulsed beam.

1. Introduction

The demands on a positron beam depend strongly on the experiment which should be performed. The highest intensity is in most cases desired to gain high statistic within a reasonable time or to investigate time dependent processes. However, some experiments have special requirements on the phase space volume (PSV). If laterally resolved measurements with high resolution are in the scope of interest at least the diameter and the radial momentum have to be sufficiently small, hence the radial part of the PSV has to be regarded. If the positron beam should be bunched to short pulses the energy spread has to be accordingly low and therefore the longitudinal part of the PSV is of special interest. Due to the theorem of Liouville the minimal attainable spatial focus is determined mainly by the radial PSV and the refractive poser of the lens; and the smallest temporal focus is determined by the dimension of the longitudinal PSV and the effective energy modulation performed by the buncher. The easiest way to reduce the PSV is given by apertures and energy filters which can be used to crop small parts of the PSV. In some cases the comparably high intensity losses caused by these tools might be justifiable. However, more preferable is the technique of remoderation by which not only the PSV is reduced but also the phase space density is enhanced and therefore the intensity loss is much lower. Nevertheless, there are situations, e.g. if highest resolution should be attained, where a trimming of the PSV is unavoidable and appropriate tools have to be provided for both, the longitudinal and the radial PSV.

At NEPOMUC, most experiments need the brightness enhanced positron beam generated by the remoderator [1]. However, there are experiments planed and have be already performed which barely depend on a small phase space volume but benefit from the higher intensity of the primary beam [2,3]. Therefore, an easy switching between these two beam options is mandatory to enable a broad range of experiments. This is now realized in a new setup which is presented in the first part of this paper. Another basic demand on a positron beam is the impact energy which enables depth resolved measurements. Usually the variation of the implantation energy is achieved by altering the potential of the source or of the sample; hence the variation is attained by a variation of the potential difference. At NEPOMUC the source potential is limited to 1 kV due to the restrictions of insulators in the high radiation field of the nuclear reactor. There are also experimental constraints, where the sample has to be potential free e.g. if re-emitted charged particles after positron impact are in the scope of interest. In these experiments the total energy of the beam has to be raised. This is only possible by time dependent fields acting on a pulsed beam.

For this purpose a novel system was developed, which converts the continuous positron beam into a pulsed beam and enhances afterwards the total energy of the beam [4]. Recently, the bunching system has been assembled and first measurements have been performed. The bunching units consist of a high efficiency pre-buncher which uses a sawtooth-like function with a repetition rate of 5 MHz and a double-gap main-buncher using a high amplitude sine wave function. While in a previous study [4] the concept of the whole setup is explained in-depth, in this paper the focus is on the results of time dependent particle tracing simulations and technical details.

2. Central setup for beam selection, enhancement and characterization

Due to larger reorganizations in the experimental hall of the FRM II also most of the positron experiments and the beam lines had to be relocated or rebuild from scratch. Especially the inevitable relocation of the remoderator opened the possibility for an entirely new setup for the characterization and enhancement of the positron beam. With this new setup two beam switches were introduced (4, 8 in figure 1) which enable a computer-controlled toggling between the primary and the remoderated positron beam. These switches use the superposition of a transversal and a longitudinal magnetic field to guide the positrons adiabatically from one end to the other. Special attention was drawn to an aberration free guidance through the new setup. Electrodes within the whole setup, which continues the potential tube of the source beam tube, enables the variation of the kinetic energy and provides therefore the basis for an adiabatic beam transport from the source through the setup. Computer simulations of the PSV development through the beam switches showed that besides appropriate low kinetic energy special attention has to be paid to a constant longitudinal guiding field [5]. This requires well dimensioned coils and proper positioning of the μ-metal shielding.

The remodertator setup itself underwent only minor changes for the improvement of the vacuum and a residual gas analyzer was installed. In addition, the magnetic field termination was electrically insulated from ground potential, advancing the imaging of the primary positron beam toward the remoderation crystal. With the two beam monitors (3, 10 in figure 1) the primary and the remoderated beam can be observed. The beam monitors consists of a carriage which can be moved by a stepper motor to one of four slots. The first slot contains a combination of a micro channel plate and a phosphor screen. By a mirror in the same slot, the intensity distribution of the beam can be observed by a camera. The measurement of the total beam intensity is done with a calibrated NaI-detector which has a collimated view onto an annihilation target mounted at the second slot of the carriage. The last two positions are used for different-sized apertures which can be used to crop the diameter of the beam.

The fully computer controlled adjustment of all beam guiding parameters and the permanently installed beam monitors simplified the recommissioning of the relocated remoderator considerably. The remoderated beam is slightly elliptic shaped were the major and minor axis have a length of about 2.2 mm (FWHM) and 1.5 mm (FWHM) respectively

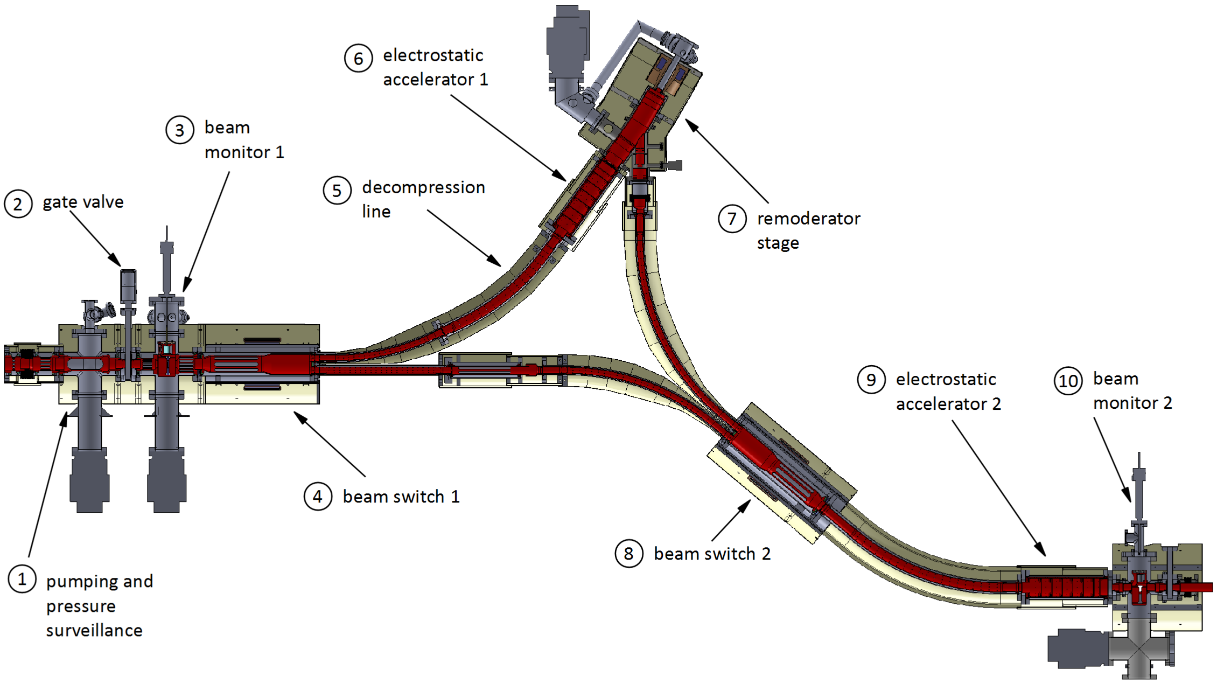


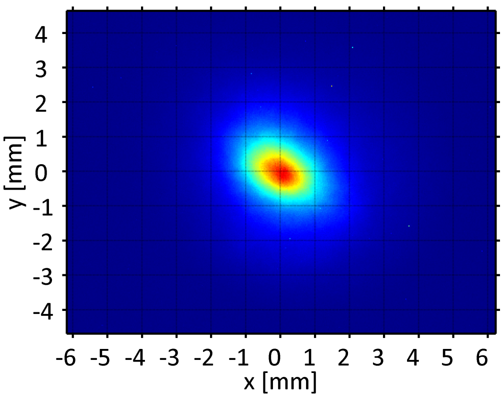
Figure 1: Overview of the new setup for the analysis (3, 10) and brightness enhancement (7) of the NEPOMUC positron beam. The two beam switches (4, 8) allow the computer controlled toggling between the high-intensity and the brightness-enhanced beam.

(see figures 2a, b). 90 % of the total intensity of the remoderated beam is within a diameter of roughly 6 mm (see figure 2c). The total intensity of the remoderated beam was determined to $3.0(3) \cdot 10^7\,e^+/s$. The total efficiency of the remoderator setup is about 3 % and is about half of the value attained with the former setup. It is expected to increase efficiency by using computer-controlled optimization routines.

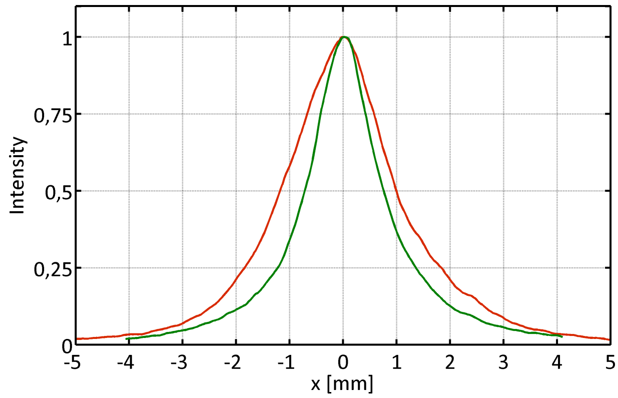
3. The positron beam energy elevation project

3.1. Motivation

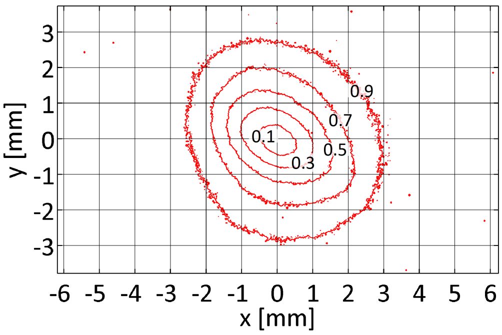
At the NEPOMUC positron beam facility, a comprehensively equipped SUrface SPECTrometer (SusSpect) exists which was used mainly for Auger electron spectroscopy (AES) by using positrons, electrons or x-rays for the initial excitation. It offers the possibility to clean the samples with an argon sputter gun and anneal them at a heater stage [6, 7]. Layer systems can be produced by molecular beam epitaxy (MBE) and the surface topology can be investigated with a scanning tunneling microscope. For AES and X-ray photoelectron spectroscopy (XPS) the hemispherical analyzer is used in the electron mode. This analyzer has also a positron mode allowing angle resolved reemitted positron spectroscopy (RPS). First measurements have been already performed with a sodium source in transmission geometry and with the primary positron beam in reflexion geometry [8]. During the beam measurements the positron impact energy was kept at 1 keV. However, for comprehensive studies a variable impact energy up to several keV is crucial. As the sample has to be grounded and the maximum bias voltage of NEPOMUC is limited to 1 kV the possible implantation energy is restricted up to now. For this reason the bunching and elevator setup was developed.



(a) Two dimensional intesity distribution.



(b) Intensity profiles along the major and minor axis.



(c) The plotted lines enclose the given percentage of the total beam intensity.

Figure 2: Different representations of the intensity distribution of the remoderated beam measured at the second beam monitor of the NEPOMUC beam line facility. The total positron beam intensity was determined with a calibrated NaI-detector to about $3.0(3) \cdot 10^7\,e^+/s$.

3.2. Design and first experimental results of the bunching units

In the presented setup work two different bunchers consecutively. The pre-buncher has a repetition rate of $f_{pb} = 5\,\text{MHz}$ and utilizes an arbitrary, sawtooth-like function. To attain the highest energy transfer to the positrons, the energy modulation should occur instantaneously. Therefore, the gap on which the energy modulation occurs has a small diameter of 7 mm to keep the fringe fields and hence the transit time effects low (see figure 3). To avoid a wrong energy modulation at the opposite gap of the modulation electrode the potential difference is spread over eight additional electrodes on which the sawtooth function is applied with a linearly reduced amplitude. If the velocity of the positrons through this equalization drift is matched to its length, the transit time equals one period of the sawtooth function and the energy modulation averages to zero.

The used arbitrary function generator (Agilent 81150A) can provide a maximal peak to peak voltage of $U_{pb} = 20\,\text{V}$ in the high voltage mode. With Liouville's theorem and by supposing an initial energy spread of the continuous beam ΔE_i of about 1 eV the minimal time focus τ_{pb} can be estimated to:

$$\tau_{pb} \approx \frac{\Delta E_i}{eU_{pb}} \frac{1}{f_{pb}} \approx 10\,\text{ns} \tag{1}$$

This value is confirmed perfectly by time dependent particle tracing simulations (see figure 5a).

A buncher driven by a sine wave function can provide much higher modulation voltages by resonant amplification and hence produce much sharper time foci. The main buncher is built up equivalently to the approved sine wave function bunchers in the Munich Scanning Positron Microscope (SPM) [9] and the Pulsed Low-Energy Positron-beam System (PLEPS) [10]. In this design the center electrode acts as the main capacity in a resonant circuit and a coil outside the

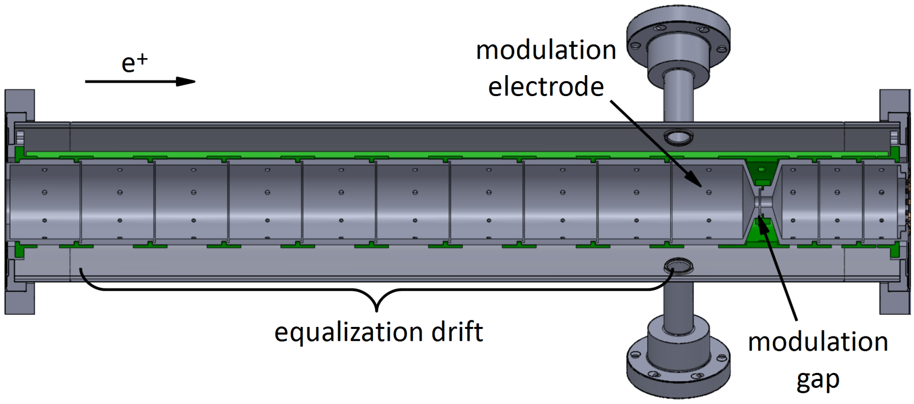


Figure 3: Sectional view of the pre-buncher. The so-called equalization drift consists of eight additionally introduced electrodes which elongate the time dependent potential difference to the modulation electrode over a longer distance. By this the energy modulation averages to zero. Hence, an effective energy modulation occurs only at the gap after the modulation electrode.

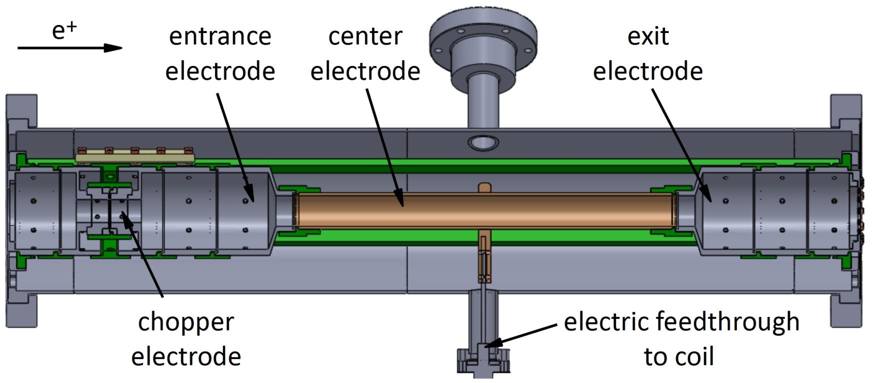
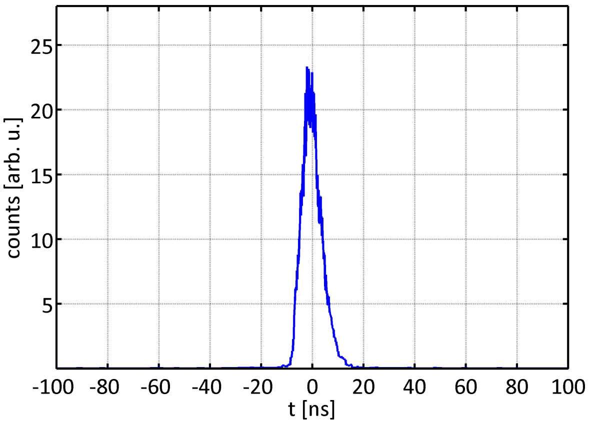


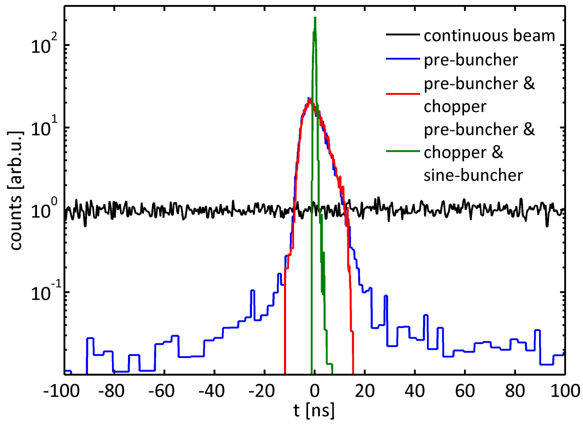
Figure 4: Sectional view of the main-buncher and chopper. The coil, which forms together with the center electrode a resonant circuit, is placed outside the vacuum.

vacuum provides the main inductance (see figure 4). The linear part of a sine wave function, which leads to a correct energy modulation with low aberrations, is about one third of the repetition time. The temporal extension of the pre-bunched beam fits therefore perfectly into the acceptance window of about 17 ns provided by a 20 MHz sine wave buncher. With the high bandwidth mode of the arbitrary function generator a rise time of about 2 ns can be attained, resulting in a very high efficiency of the bunching system. However, in this mode the output voltage is limited to 10 V leading to a time focus of the pre-buncher not lower than about 20 ns that could also be confirmed by simulations (see figure 5b). This time focus is slightly more than the optimum acceptance window of the main-buncher but well below the half sine wave. Consequently, the total time focus will increase slightly due to spherical aberrations but no additional background will be generated.

Although the background of the pre-buncher is low and smooth it is also modulated by the main-buncher which works at a four times higher repetition rate. This would lead to much lower but observable side peaks in the total time spectrum. Although this would not harm the suitability for the energy elevator but might be inappropriate for timing measurements in the future. Therefore, a simple retarding field chopper has been foreseen to clean the time spectrum (see figure 4).



(a) Time focus of the prebuncher. Used values: Initial energy spread $\Delta E_\mathrm{i} = 1\,\mathrm{eV}$, modulation voltage of $U_\mathrm{pb} = 20\,\mathrm{V}$, ideal sawtooth-like function.



(b) Used simulation values: Initial energy spread $\Delta E_\mathrm{i} = 1\,\mathrm{eV}$, modulation voltage of $U_\mathrm{pb} = 10\,\mathrm{V}$, ideal functions for pre-buncher and chopper.

Figure 5: The simulated time focus attained with the proposed setup. The used ideal functions for pre-buncher and chopper result in a sharp time peak and very low background. For the visualization of the background, a variable bin size was used in sub-figure (b).

3.3. Progress of the elevator project

The time-dependent particle tracing simulations demonstrated that the attainable time focus of the pre-buncher is short enough for the acceptance window of the main-buncher and that the simple approach for the chopper is well suited to clean the timing spectrum (see figure 5b). The pre-buncher, main-buncher and the drift lines are manufactured, assembled and electrically connected. First adjustment measurements showed, that the main-buncher components act as a resonating circuit with a Q-value of about 80 and reaches therefore sufficient high modulation voltages. Preliminary timing spectra attained solely with the main-buncher showed a time focus of about 2.2 ns. The performance of the pre-buncher was below the expectations mainly due to an imperfect electrical matching of the electrodes of the equalization drift. Due to the promising bunching results, the manufacturing of the elevator itself will be started soon. A completion of the whole setup and full work capability is planed till August 2014.

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