The experimental determination of the phase space distribution of a positron beam

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Abstract. The NEPOMUC positron beam facility hosts four successfully operated positron instruments which cover the fields of solid state, surface and fundamental physics. Two further setups are under construction and a variety of positron experiments were accomplished at the open beam port. The success of almost all experiments till now has been dependent on the quality of the positron beam provided by NEPOMUC. Therefore, the source, the beamline, and some key components as e.g. the remoderator and the beam switch are the subject of continuous optimizations and improvements. A crucial part of our efforts is a meaningful characterization of the positron beam. The most important measure of the quality of a positron beam is the phase space volume occupied by the beam particles and hence, a novel device was developed whose measurement concept is presented here.

1. Introduction
The NEutron induced POsitron source Munich (NEPOMUC) provides the world’s most intense positron beam, and by installing the NEPOMUC remoderator a high-brightness beam became available. This unique beam is used routinely for several experiments and in many of them, the positron beam has to be focused onto the sample in order to allow laterally resolved measurements [1].

2. The phase space concept
The minimal focus which can be achieved depends first of all on the size of the phase space volume (PSV) which is occupied by the beam particles. Only if the spot gets very small, the aberrations of the used lenses get dominant. In general, the phase space is spanned by 3 space and 3 momentum coordinates and has hence 6 dimensions. Due to this construction, the state of one positron of a beam at a certain time is entirely described by a point in the phase space. Consequently, a positron beam—which is an ensemble of positrons—can be described as a set of points in the phase space or as a volume which enclosures these points. The important theorem of Liouville states, that this 6-dimensional PSV keeps constant under the influence of conservative forces. By regarding symmetries and approximations the 6-dimensional phase space can be divided in subspaces in such a way, that the Liouville theorem applies also for each PSV in these subspaces. E.g. in rotational symmetric systems, where only paraxial rays are regarded, the four lateral components \((x, p_x, y, p_y)\) of the 6 dimensional space can be substituted by a two dimensional subspace spanned by the distance from the optical axis \(r\) and by the conjugated
canonical momentum $P_r$, which equals the physical momentum $p_r$ in the electrostatic case. In this representation of the phase space, the volume which includes a certain amount of the beam intensity has a simple 2 dimensional geometric shape as e.g. an ellipse.

If aberrations are neglected lenses shear the transversal phase space volume along the $P_r$ axis, and drift sections lead to a shearing along the $r$ axis. The aberrations of lenses lead to a nonlinear transformation of the phase space volume and hence to a perturbation of it as shown for spherical aberrations in Fig. 1. In addition, this figure helps to understand, why (second order) aberrations lead to a blur of the geometric focus and why not the real PSV but the effective PSV is the determining parameter of the minimal spot size. Since the effective PSV is the envelope of the real PSV, the effective one is always larger. Not only the classical aberrations of lenses but also imperfections in longitudinal magnetic fields, which are used for adiabatic beam guidance, lead to nonlinear perturbations of the PSV. Especially in the case of long beam lines as at the NEPOMUC facility, were the solenoidal magnetic field has to be interrupted several times for e.g. pumping and beam diagnostic, the effective PSV can increase considerably.

Figure 1. Due to the aberrations of lenses and due to imperfect magnetic, adiabatic beam transport the initial PSV (dashed ellipse) gets perturbed. Because of the Liouville theorem, the perturbed PSV (gray shaded area) must have the equal size as the initial volume, however, the volume of the envelope, i.e. the effective PSV is remarkable larger.

3. Measurement of the PSV

Until now, at NEPOMUC and its instruments the lateral PSV has been only estimated by two different methods. The first is based on measuring the beam diameter and the longitudinal energy spread within the magnetic guiding field. Due to energy conservation the transversal energy spread should be in the same order of the longitudinal energy spread and hence the transversal PSV can be estimated. By the other approach the smallest attainable spot which can be achieved with a rotational symmetric focusing lens is measured. By knowing the details of the imaging and the aberrations of the lens, the PSV can be calculated in principle. However, some of the imaging or lens probabilities have to be gained e.g. by simulations or have to be estimated. Hence, both approaches may lead only to rough values and moreover, they provide only an absolute value of the PSV and no information of the intensity distribution within the phase space.

In order to overcome this a novel method for the determination of the intensity distribution of a positron beam within the lateral phase space was developed. The experimental setup consists of a magnetic field termination to extract the positrons from the magnetic guiding field, a mask, which divides the beam in several sub-beams, and a lateral resolving intensity sensitive detection system made of a MCP, a scintillation screen and a CCD camera (see Fig. 2). After the magnetic field termination and after the mask the beam diverges free, where the diverging angle is determined by the ratio of the transversal and longitudinal momentum. As the longitudinal momentum can be tuned separately in front and behind the mask a homogeneous illumination and a proper imaging of the mask pattern onto the MCP can be ensured. The mask selects certain radii $r_i$ of the lateral phase space $(r, p_r)$. Due to the transversal momentum $p_{r_i}^t$ the image of these radii $r_i'$ are enlarged. Hence, (the averaged) transversal momentum $p_{r_i}^t$ of one sub-beam
can be determined by measuring the growth \((r_i' - r_i)\). With the obtained set of \((r_i, p_i)\) and the relative intensity \(I\) of the subbeams, the orientation and the intensity distribution along the main axis of the PSV can be plotted (see Fig. 3).

In order to determine the extension of the phase space volume, the radial intensity distribution of the subbeams has to be regarded. By considering a hypothetical phase space distribution which is constant up to a maximum radius and up to a maximal radial momentum, the radial intensity distribution at the MCP can be deduced from simple geometric considerations (see left column of Fig. 4). Due to the drift the initial PSV gets sheered along the r-axis. Hence, the rectangular PSV is mapped to a parallelogram. The mask selects from this enlarged beam well defined areas with certain radii and hence from the PSV slices with a width equivalent to the hole diameters of the mask. Since after the mask a second drift follows, these slices are also sheered. Because the measured radial intensity distribution of the beams is the projection of the PSV onto the radial axis, the radial intensity distributions of the subbeams have to be isosceles trapezia. This means, the subbeams appear with blurs at the MCP and the width of these blurs depends on the ratio of the transversal to the longitudinal momentum of the subbeams and the length of the second drift.

A more realistic radial PSV distribution and the according radial intensity distribution are given on the right side of Fig. 4. In this case numerical simulations are necessary to reveal the exact shape of the radial intensity distributions but as shown in the last sub-figure, the characteristic slopes at the borders are still observable.

1 This does not hold for subbeams which stem from the border of the primary beam. In this case the shape might be an irregular pentagon.
4. Conclusion

In this work the setup of a novel device is presented and by numerical calculations it is demonstrated that not only simple but also non-uniform PSV distributions can be measured. An implementation of the setup was constructed and very first experiments were successfully performed. However, for the measurement of the PSV of the NEPOMUC beam further experiments are necessary.

![PSV and radial intensity distribution](image)

Figure 4. The subfigures show from the top to the bottom the PSV and the radial intensity distribution at the positions A, B, C, D marked in Fig. 2. On the left side a rectangular and homogenous filled PSV is supposed and on the right side the simulation of a more realistic 2-dimensional Gaussian distribution is shown.

References

[1] C. Hugenschmidt et al., In this proceedings