Positron beam optics for the 2D-ACAR spectrometer at the NEPOMUC beamline

H Ceeh\textsuperscript{1}, J A Weber\textsuperscript{1}, C Hugenschmidt\textsuperscript{1,2}, M Leitner\textsuperscript{1} and P Böni\textsuperscript{1}

\textsuperscript{1} Technische Universität München, Physik Department, Lehrstuhl E21, James-Franck-Straße, D-85748 Garching, Germany
\textsuperscript{2} Technische Universität München, Forschungs-Neutronenquelle Heinz Maier-Leibnitz, Lichtenbergstraße 1, D-85748 Garching, Germany

E-mail: hubert.ceeh@frm2.tum.de

Abstract. In the last year a conventional 2D-ACAR spectrometer has been set up and brought to operation at TUM. Once the NEPOMUC beamline is extended to the new experimental hall at the research reactor FRM-II the conventional 2D-ACAR spectrometer will be upgraded with a second sample chamber in order to be integrated to the NEPOMUC beamline facility. This spectrometer will add a complete new quality to 2D-ACAR experiments as it allows to track the evolution of the electronic structure from the surface to the bulk. We present the design features of the positron beam optics and the sample environment.

1. Introduction

Two-dimensional angular correlation of annihilation radiation (2D-ACAR) is a powerful tool to determine the electronic structure of a material. Almost all properties of a material are defined by its electronic structure, in particular its Fermi surface, which is the boundary between occupied and unoccupied states in reciprocal space. 2D-ACAR is used to investigate phenomena which are closely interconnected with the shape and topology of the Fermi surface. Such phenomena are for example the spin density wave anti-ferromagnetism in Chromium or the helical magnetic ordering in GdY. In both of these systems the magnetic ordering is driven by so called nested Fermi surface segments, meaning that different segments of the Fermi surface can be connected by a common spanning vector. These are just two examples among many where nested Fermi surface segments were identified by means of 2D-ACAR investigations\cite{1, 2}.

Typically 2D-ACAR studies are performed using $\beta^+$-sources such as $^{22}$Na \cite{3} with a mean positron energy of 216 keV. This corresponds to material dependent implantation depth of up to 200 $\mu$m. Therefore the information of the electronic structure obtained in conventional 2D-ACAR originates almost exclusively from the bulk of the material. However, in many cases it is of high interest to gain insight to the electronic structure at the surface or at the interfaces in layered systems. Once again a prominent example are Chromium thin films and Chromium superlattices which exhibit different properties than bulk Chromium \cite{4}. Therefore, an energy-tunable high intensity positron beam is needed to perform such investigations \cite{5}.

In order to operate a 2D-ACAR machine at a positron beamline several design criteria have to be met. To minimize the effect of anisotropic angular resolution the positron beam spot size on the sample has to be as small as possible. Using apertures in the positron beam this
could be easily achieved, however at the expense of count rate. Also, the sample needs to be
coolable, which allows study of temperature dependent effects and also further improves the
angular resolution as the thermal smearing of the positron momentum is decreased.

To meet these criteria two possible options lie at hand: magnetostatic or electrostatic
focussing of the positron beam. Though both methods have advantages and disadvantages (see
[6] and references therein). We decided to adopt an electrostatic beam focussing because the
sample mounting on a cryostat gives rise to several problems, for example, a strong constraint to
the magnetic lens system design, or an obstructive magnetic field for the spectrometer. Based on
designs of Stadlbauer [7] and Strasser [8] a positron beam optics has been developed which fulfils
the requirements to operate a 2D-ACAR spectrometer at a slow positron beam. In the following
we present the results of this design study together with an outlook on future measurements.

2. Positron beam optics

In order to focus a positron beam electrostatically the positrons first have to be extracted from
the magnetic field. One has to make sure that this process is strongly non-adiabatic, because
otherwise the positrons would follow the magnetic flux lines into the field termination. Therefore,
two things are required: a long gyration length \( l_g = \frac{2\pi p_l}{qB} \) (with the longitudinal momentum
\( p_l \), the magnetic flux density \( B \) and the electric charge \( q \)) and a steep gradient in the magnetic
flux density with \( \nabla B \gg \frac{1}{l_g} \). This is achieved by accelerating the positrons and by choosing a
small aperture for the field termination. A very elegant way to increase \( \nabla B \) was implemented
by Piochacz [9], he uses magnetic vanes inside the termination aperture to increase the gradient
proportional to the number of vanes.

In the present setup a less elaborate scheme is used, the field termination consists of a soft
magnetic iron disk with a bore of 25 mm which is placed inside a CF100 flange, which is also
soft magnetic (see fig. 1). It is held by three ceramic insulators to create an air gap of 1 mm
so an electric potential can be applied to the inner disk. A FEM simulation of the magnetic
flux density is shown in figure 3. The NEPOMUC guiding field, which has strength of \( \approx 70 \text{ G} \)
is terminated in the soft magnetic flange (\( \mu_r = 5000 \)) and fed back via mu-metal pipes. The
residual flux density after the termination is lower than 0.1 G.

The positron beam is accelerated between two fine meshed grids with a distance of 5 mm
about 50 mm before the field termination. In this way it is ensured that the positrons do not
acquire additional transverse momentum by \( E \times B \) drift, since the electrical and magnetic field
lines are parallel within the acceleration gap and the region in the vicinity of the field termination
(high \( \nabla B \)) is electrical field free (see fig. 2). In this study the accelerating potential was chosen
such that the positrons enter the field termination with about 1 keV kinetic energy.

The next component of the beam optics is an Einzel lens which images the beam at the exit
of the magnetic field termination. The Einzel lens is designed to operate in deccel-accel mode
as this offers higher refractive power compared to accel-deccel mode. The zoom of the Einzel
lens is adjusted by ratio \( \frac{U_2}{U_3} \) of the potentials at the lens elements 3 and 2 while lens element 1 is
kept at the same potential as the magnetic field termination. The lens elements have a tubular
graphy with an inner diameter of the lens \( D = 50 \text{ mm} \) and a length of \( l = 25 \text{ mm} \). The
diameter \( D \) is chosen to be about 10 times the expected beam diameter to minimize spherical
aerations as the beam travels closer to the optical axis. Also, the focal length \( f \) can be tuned
in a wider range. For \( \frac{U_2}{U_3} = 1 \) (when the potential at lens element 2 matches the beam energy)
the lens has its highest refractive power with \( f \approx 2D \) (for \( U_1 = U_3 \)). By changing \( U_3 \) the focus
can be fine tuned.

The drag field which is created by the sample potential and also defines the implantation
energy shifts the focal plane towards the sample. The sample itself is elevated 10 mm above a
metal plate, which is kept at the same potential. This way the field of view of the detectors
remains unobstructed and the electrical field between the lens system and the sample is nearly
homogeneous close to the optical axis. With increasing sample potential the focal plane of the Einzel lens has to be moved further away from the sample by decreasing $U_3$.

3. Performance

Particle tracing calculations using the electric and magnetic fields from the FEM simulation show that a positron beam with realistic parameters ($p_{L}/p_{L} \leq 0.05$ and $200 \text{eV} \leq E \leq 1000 \text{eV}$) can reliably be extracted from the magnetic guiding field (exemplary shown in fig 4 for a 300 eV beam). As a result, a beam spot diameter of $(5.0 \pm 1) \text{mm}$ for a sample potential of $-10 \text{kV}$ is readily achieved, which is sufficient for a 2D-ACAR experiment. The major reason for this limitation is the initial divergence $p_{L}/p_{L}$ of the beam. In particular the additional transverse momentum that is acquired in the field termination limits the achievable beam focus on the sample. This is due to the fact that in cylindrical symmetric configuration the canonical momentum $p_{\Phi} = m\dot{\Phi} + qB\dot{r}$, which is a conservative of motion, couples the longitudinal and the transverse motion. A positron which is created in a magnetic field with $B = 70 \text{G}$ at a distance $R$ from the symmetry axis is extracted to $B = 0$ at a distance $r$ will acquire a transverse energy of $E_{\perp} = \frac{1}{2}m(\omega_{g}R)^{2}(\frac{R}{r})^{2}$ (with the gyration frequency $\omega_{g} = \frac{qB}{m}$) which results in this case for $R = r = 3.5 \text{mm}$ to $E_{\perp} = 13.2 \text{eV}$. Therefore, even a monoenergetic beam will experience a smearing of the longitudinal energy which then leads to an imperfect focussing due to chromatic aberrations of the lens system. A way to reduce the amount of additional transverse momentum would be to break the rotational symmetry in the field termination, for example with the magnetic vane design by Piochacz [9].
**Figure 3.** FEM Simulation of the magnetic flux density at the field termination calculated for the nominal operation conditions of the NEPOMUC beamline ($\approx 70$ G). The absolute value of the magnetic flux density is color coded, the arrows indicate its strength and direction. The strength of the field drops rapidly after the field termination. While the guiding field is homogeneous the field exhibits a significant radial component in the field termination.

**Figure 4.** Particle tracing simulation of a 300 eV positron beam with divergence corresponding to $p_{\perp}/p_L = 0.05$. The diameter of the primary beam is assumed to be 7 mm. The diameter of the beam spot on the sample is in the range of $(5.0 \pm 1)$ mm depending on the initial conditions, i.e. the initial beam divergence.

4. Conclusion and Outlook
The extraction and focussing assembly we devised for this study resembles a fusion of different known and applied concepts in positron beam optics. The strength of our design lies in the electrostatic preacceleration prior the extraction of the beam from the magnetic guiding field in combination with a simple yet versatile electrical lens system.

In our simulation we could show that this assembly works under realistic conditions and fulfils the requirements to operate a 2D-ACAR spectrometer at a slow positron beam.

Acknowledgements
This project is funded by the Deutsche Forschungsgesellschaft (DFG) within the Transregional Collaborative Research Center TRR 80 “From electronic correlations to functionality”.

References
[1] Hughes R J, Dugdale S B, Major Z, Alam M A, Jarlborg T, Bruno E 2004 Phys. Rev. B 69 174406
[2] Fretwell H M, Dugdale S B, Alam M A, Hedley D C R, Rodriguez-Gonzalez A, Palmer S B 1999 Phys. Rev. Lett. 82 3867
[3] Ceeh H, Weber J A, Hugenschmidt C, Leitner M, Böni P 2013 Rev. Sci. Instrum. 84 043905
[4] Zabel H 1999 J. Phys-Condens. Mat. 11 9303
[5] Falub C V, Mijnarends P E, Eijt S W H, van Huis M A, van Veen A, Schut H 2002 Phys. Rev. B 7 075426
[6] Coleman P 2000 Positron Beams (Singapore: World Scientific) pp 22-33
[7] Stadlbauer M, Hugenschmidt C, Schreckenbach K 2008 Appl. Surf. Sci. 255 136
[8] Strasser B 2001 Dissertation Technische Universität München
[9] Piochacz C, Kögel G, Egger W, Hugenschmidt C, Mayer J, Schreckenbach K, Sperr P, Stadlbauer M, Dollinger G 2008 Appl. Surf. Sci. 255 98