Maximum intensity, transmission limited cold electron beams from GaAs photocathode in the eV and sub-eV kinetic energy range

A. Shornikov,^{1,*} D. A. Orlov,^{1,†} C. Krantz,¹ A. S. Jaroshevich,² and A. Wolf¹

¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

²Institute of Semiconductor Physics, Pirogova 30, 630090 Novosibirsk, Russia

(Received 27 October 2013; published 31 March 2014)

The deceleration of electrons confined by a weak guiding magnetic field has been studied with the goal of achieving an intense ultracold electron beam, suitable for electron cooling and electron collision experiments with ion beams of very low velocity. By application of a beam deceleration technique the electron current extracted from a GaAs photocathode has been increased by an order of magnitude at a few eV and sub-eV kinetic energy, keeping a low energy spread of the electrons. The true kinetic energy of the slow electrons has been determined, taking space charge effects and contact potential differences into account.

DOI: 10.1103/PhysRevSTAB.17.042802

PACS numbers: 41.75.Fr, 41.75.Ht, 29.27.-a, 41.85.-p

I. INTRODUCTION

The present paper addresses the controlled generation of electron beams of maximum intensity in the kinetic energy range $E_k \lesssim 1$ eV suitable for velocity-matched merged-beam devices in electrostatic ion storage rings. Our work is motivated by the construction of a new-generation low energy electrostatic cryogenic storage ring (CSR) at Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg. The CSR is designed [1] to store ions of 20–300 keV per charge unit independently of their mass. Even at the highest ion energy of 300 keV, electron cooling by a velocity-matched electron beam and electron-ion collision experiments aiming at meV collision energies require electrons of mean kinetic energy below 20 eV for most of the ion species of interest such as, e.g., 9.7 eV for CH_5^+ , 1.77 eV for an aniline cation, and less than 1 eV for heavier organic molecules.

In pioneering work by Tanabe *et al.* [2] a merged electron beam device operating at energies ~ 10 eV with a thermionic cathode was integrated into the KEK electrostatic ion storage ring in Tokyo. As an indirect signature of transverse phase space compression, an improvement of the ion beam lifetime could be observed for 20 keV stored protons (10 eV electron energy). Experiments with high-mass molecular ions were devoted [3,4] to the study of electron-ion collisions in the merged beams where,

however, the collision energies were of the order of 10 eV at nonmatched beam velocities.

The electron cooling rates scale as $\propto n_e/m_i T_e^{3/2}$ with electron density n_e , electron temperature T_e and ion mass m_i . The total electron current I at a given extraction voltage U_0 is limited by the constant gun perveance p as $I = pU_0^{3/2}$. The electron beam has to be large enough to cover uncooled ion beams. Thus n_e is limited by the gun perveance p . Orlov *et al.* [5] showed that the low emission temperature of the photocathode can ensure low electron temperatures in all degrees of freedom. The advantage of lower emission temperature gets even more prominent at lower energies, where adiabatic emittance damping of the electron beam is less efficient. This was recently demonstrated by the beam dynamics simulations for low energy storage rings by Papash *et al.* [6].

Another aspect becoming important at $E_k \lesssim 1$ eV and correspondingly low acceleration voltages is a reliable energy calibration of the electron gun. In particular the differences between the contact potentials of the cathode and the surfaces surrounding the electron beam are important as they are of the same order of magnitude as U_0 .

Both the maximization of the perveance in the beam overlap region and the energy calibration at beam energies $\lesssim 1$ eV are addressed experimentally in this paper. A specific feature of this work is that we deal with photo-emitted electrons in the energy and current range where the processes in the cathode material and on the cathode-to-vacuum interface play significant roles in the operation of the device.

II. EXPERIMENT

A schematic of the setup is shown in Fig. 1. The electron beams are produced using the continuous photocathode electron source [7–12] realized at the electron target [13] of the magnetic heavy ion test storage ring (TSR) at the

*Present address: CERN, Geneva, Switzerland.
andrey.shornikov@cern.ch

†Present address: Photonis Netherlands B.V., Roden, The Netherlands.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

FIG. 1. Schematic of the TSR electron target in beam deceleration mode. U_{acc} : acceleration voltage; U_{Pierce} : voltage at the Pierce electrode; U_{ext} : extraction voltage; U_r : retarding voltage in the deceleration region tube; I_f : full transmitted current; I_p : fraction of the current cut by a pinhole in the collector used to measure electron beam profiles.

MPIK. This photocathode electron gun is operated at or below room temperature (down to ~ 100 K) and can deliver emission currents up ~ 1 mA at a perveance of $\sim 0.6 \mu\text{A}/\text{V}^{3/2}$. At extraction potentials of $\lesssim 100$ eV, the photocathode gun thus produces space-charge limited beams [11] of the same current as would be obtained with a thermionic cathode, but with a lower emission temperature. Orlov *et al.* [8] showed that electron emission temperatures close to the cathode temperature can be realized with GaAs photocathodes. Ultracold beams with electron temperatures of order 1 meV were reached with this electron gun [14] by a moderate magnetic expansion [15] of the beam and successfully used in electron-ion collision experiments [14] and for fast electron cooling of a CF^+ ion beam with an electron energy in the velocity-matched beam amounting to 53 eV [11]. In the present experiments the cathode was kept close to room temperature and illuminated by a 532 nm laser in reflection mode. Under these conditions the temperature of the emitted electrons was higher than room temperature (30 meV; see Sec. IV), as reflection mode illumination allows only partial thermalization of the excited conduction band electrons to the cathode temperature.

The electron gun is immersed in a guiding magnetic field of $B_c = 0.8$ T. A constant potential U_{Pierce} at the electrode closest to the cathode surface is set to provide the most uniform current density distribution $j = \text{const}$ through the entire beam cross section, minimizing increases/decreases around the edges due to the fringe field. The extraction voltage U_{ext} is used to vary the current. The final acceleration is set by the voltage U_{acc} . At an energy of ~ 20 eV defined by U_{acc} the electrons then continue to drift in the guiding magnetic field that suppresses the space charge spreading of the beam. Hereafter we denote several processes in the beam transport adiabatic, as the corresponding change of electric potential or magnetic field takes place along a

distance of an order of $100 \text{ mm} \gg 2.7 \text{ mm}$ the Larmor length of 20 eV electrons.

At ~ 30 cm downstream of the cathode, the magnetic field strength is lowered adiabatically down to the value of $B_d = 0.04$ T which is kept along the remainder of the electron beam path. This procedure reduces [15] the transverse electron temperature in the comoving reference frame from emission temperature T_c to $T_\perp = T_c/\alpha$, where $\alpha = B_c/B_d = 20$ is the magnetic expansion factor. In our case it gives $T_\perp = 1.5$ meV. A side effect of the lowered temperature is the electron beam radius increase by a factor of $\sqrt{\alpha}$ from 1.5 mm at the cathode to $\rho \sim 6.7$ mm after the expansion region.

After the expansion region and a further drift over ~ 1 m, the 20-eV beam is bent by a toroidal magnetic field into the straight section of 1.5 m length [13] common with the TSR storage ring orbit. In the second 1-m long segment (“Drift 2”) the electrons are decelerated by the retarding voltage U_r .

Beyond the drift region, the beam is bent into a collector by a second toroid. In the collector, the local electron current I_p at a given point of the electron beam can be measured through a $50\text{-}\mu\text{m}$ diameter pinhole, while the integral electron current transmitted through the device is obtained from the full collector current I_f . Steering coils in the region before the collector allow to move the electron beam over the pinhole, which is used to raster the electron beam current density profile.

A diagram of the potentials acting on the electrons in the device is shown in Fig. 2. The left part illustrates the potentials at the photocathode surface [8] including the surface dipole layer, the vacuum level providing negative electron affinity, the cathode W_c and the drift tube W_a work functions. The electrons are emitted over the space-charge barrier of height ΔE_c in front of the cathode surface controlled by the applied extraction voltage U_{ext} . The kinetic energy of the electrons accelerated from the cathode is determined by the local potential in the beam referred to the peak potential U_s of the space charge barrier.

In region Drift 2 the beam is strongly decelerated. On the beam axis, the electron energy can be written as

$$E_{k,0} = e(U_r - U_{acc}) + (W_c - W_a) + \Delta E_c - eU_{SC}, \quad (1)$$

where $|U_r - U_{acc}|$ can become small. The voltage U_{SC} denotes the potential difference due to the electron space charge between the inner surface of the deceleration drift tube (Drift 2) and the electron beam axis (i.e., $U_{SC} > 0$ for electrons). In contrast to Drift 1, in Drift 2 the beam transport conditions strongly depend on the electron current, which is set by ΔE_c via U_{ext} .

For the following, we introduce the effective acceleration voltage U_0 between the surface of the drift tube and the peak (U_s) of the space charge barrier in front of the cathode (virtual electron source). The axial energy of the electrons after deceleration (i.e., within Drift 2) can then be written as

FIG. 2. Energy diagram along the electron track. The emission process at the GaAs photocathode is schematically indicated, illustrating the energy gap E_g in the semiconductor and energy distributions of the electrons (gray shaded areas). The work function of the drift tube is denoted by W_a and the cathode work function by W_c . The electrons are extracted over a potential barrier of height ΔE_c . In addition to the voltages defined in Fig. 1, U_s denotes the potential at the virtual electron source in front of the cathode, U_0 the effective accelerating voltage (see the text), and U_{SC} the space charge voltage of the electron beam in the deceleration drift tube. The magnetic field strength B along the electron beam axis is also shown.

$$E_{k,0} = e(U_0 - U_{SC}). \quad (2)$$

Here, U_0 follows any variations of U_r , but the comparison of Eqs. (1) and (2) shows that its precise value depends on several unknown offsets, specifically the work function W_c and the height ΔE_c of the space charge barrier at the cathode, as well as the work function W_a of the drift tube material. Hence, the true acceleration potential U_0 of the decelerated beam and quantities derived from it cannot be measured directly. The procedure used to determine the value of U_0 including these offsets will be described in Sec. IV.

III. BEAM DECELERATION

Beam deceleration experiments were performed by increasing the retardation voltage U_r in the Drift 2 region for various fixed values of the electron current. In addition to the integral electron current I_f , the current density distribution across the beam was measured for certain values of U_r as described in Sec. II.

Up to a certain value of the retarding potential (point A in Fig. 3) corresponding to onset of the Bursian instability [16] the integral transmitted current I_f is constant. The distribution of the current density across the beam is close to homogeneous (profile A in Fig. 3). Upon rise of the retarding potential above the threshold, the current I_f

FIG. 3. Deceleration curve of an 8- μ A electron beam for an accelerating voltage of $U_{acc} = -20$ V. The curve breaks at $U_r = -16.12$ V retarding voltage. Profile A, measured 50 mV before the break, is still flat. In profile B, measured at $U_r = -16.8$ V, the current density in the beam center is strongly reduced through the enhancement of the space charge in this area. The two lower curves (starting near $I_f = 4.5$ μ A and $I_f = 1.2$ μ A, respectively) demonstrate how the breaking points (arrows) shift when the decelerated current is reduced. The viewing areas of the beam profiles are 20 mm $\times$ 20 mm.

starts to drop. According to [17] the decrease of the current is an intrinsic property of the nonlinear space charge system. This behavior points to the transition from normal C-type solution to the unstable C-overlap solution branch (see α_{SCL} transition point in [17]). The beam energy spread defines the threshold sensitivity to the retarding voltage detuning. A large energy spread smoothens the transition or can even stabilize the Bursian instability [16]. In our case of a cold electron beam the transition is sharp. There are no changes in the current density profile even at retarding voltage only 10–20 mV above the threshold value, at which the integral current starts to drop. Therefore hereafter such points are referred to as breaking points of deceleration curves. The corresponding retarding voltage is denoted as $U_{r,b}$. In case of low total current the total retarding potential is mainly due to the applied voltage. For high integral current, the stopping potential is a superposition of the retarding potential and the beam space charge potential. Since the space-charge potential is higher in the center of the beam, the limitation of the current first occurs in the central area. This can be clearly seen in the current profile B of Fig. 3, where the integral electron current has been cut by a factor of 2.

The principal parameters of the beam deceleration are the current I and the effective potential difference U_0 that is present between the virtual electron source in front of the cathode (potential U_s , see Fig. 2) and the drift tube in the deceleration region. Both parameters, together with the drift-tube (R) and the electron-beam (ρ) radii, determine the electron velocity profile

$$v(r) = \sqrt{2e/m_e} \sqrt{U_0(1-x) + \phi(r)}. \quad (3)$$

Here, $x = U_{SC}/U_0$ is the relative space-charge potential in the center of the beam and $\phi(r)$ is the radial dependence of the space-charge potential, as shown in Fig. 4(a). Considering the emission conditions in the plane-cathode electron gun and the magnetic expansion, we assume the current density j to be constant over the electron beam; then the electron density $n_e = j/v$ is radially dependent according to Eq. (3). The Poisson equation for this case can be solved numerically, or by power-series expansion as considered by Smith and Hartman [18]. This yields a

FIG. 4. (a) Electric potential distribution $U(r)$ (schematic) across the drift tube in the presence of a high perveance electron beam and definition of the quantities for describing the space charge (potentials relative to the effective source potential U_s). (b) The beam perveance as a function of the space-charge parameter x for the geometrical parameters of the TSR electron target. Thick line: result including the electron density variation; thin line: asymptotic slope $p/(66 \mu\text{A}/\text{V}^{3/2}) = x/[1 + 2 \ln(R/\rho)]$ for $x \ll 1$.

relation between the total current and the relative space-charge potential x defined by a function $f(x)$ such that

$$p = I/U_0^{3/2} = f(x), \quad (4)$$

see Fig. 4(b). Values of $f(x)$ and $\phi(r)$ in the present work were found applying series expansion Smith and Hartman [18] until sixth order members using TSR geometry with the drift tube to beam radii ratio of $R/\rho = 7.46$. The series expansion was then compared to numerically solved nonlinear Poisson equation and within the parameters range of interest ($0 < x < 0.41$) the agreement of numeric solution with sixth order expansion is better than 1% while for the second order expansion it yields better than 5% discrepancy through the entire range. Given the good agreement the series expansion was used hereafter.

By inversion of $f(x)$, within the relevant range of $0 < x < 0.73$ and $0 < p < 5.56 \mu\text{A}/\text{V}^{3/2}$, the relative axial space-charge potential x can be found as a function of the beam current and U_0 . Accordingly, with $x = f^{-1}(p)$ this yields the axial kinetic electron energy as

$$E_{k,0} = eU_0(1 - f^{-1}(p)) \quad (5)$$

and its radial dependence

$$E_k(r) = E_{k,0} + e\phi(r). \quad (6)$$

The controlled realization of small kinetic energies by deceleration thus reduces to the determination of the true accelerating drift tube potential U_0 and the application of the space-charge correction for a given current I , as described by Eqs. (5) and (6).

IV. CALIBRATION

In series of measurements for electron currents in the range from $\ll 1 \mu\text{A}$ to $40 \mu\text{A}$ we recorded the values of breaking retarding voltages $-U_{r,b}$. $U_{r,b}$ corresponds to the minimum effective potential difference, $U_{0,b}$, for which a given current can be transported. For finding $U_{0,b}$ at each breaking point we need to determine the potential at the virtual electron source and include any surface potentials of the metal electrodes. As shown in previous work [8], at the applied laser power of $\sim 600 \text{ mW}$ and a high total quantum yield that corresponds to a surface emission of several mA, the currents of at most $40 \mu\text{A}$ extracted from the electron gun represent only the exponential tail of the Boltzmann electron energy distribution in the GaAs conduction band of the cathode (bulk temperature T_c). Hence, the current emitted over the extraction barrier of height ΔE_c can be written as

$$I = I_0 e^{-e\Delta E_c/k_B T_c}, \quad (7)$$

FIG. 5. Calibration of the applied retarding voltage at the breaking point ($U_{r,b}$) to yield the actual potential difference U_0 between the electron source and the drift tube. The dotted line through the data in the low-current region denotes the fitted reference values $\hat{U}_{r,b}(I)$ using Eq. (9). The drift tube potential $U_{0,b}$ with respect to the virtual electron source is obtained as the difference $U_{r,b} - \hat{U}_{r,b}(I)$.

where I_0 is a constant. Accordingly, the height of the extraction barrier varies with the extracted current as

$$\Delta E_c = -(k_B T_c / e) \ln(I / I_0). \quad (8)$$

In the range of very low current, where space-charge effects can be neglected, the retarding voltage $U_{r,b}$ measured at the breaking point identifies the point where the potential at the drift tube becomes equal to U_s or, equivalently, $E_{k,0} = 0$. Defining this low-current limit of the breaking voltage as $\hat{U}_{r,b}$, Eq. (1) with $E_{k,0} = 0$ and $U_{SC} = 0$ yields

$$-\hat{U}_{r,b}(I) = \hat{U} + \Delta E_c = \hat{U} - (k_B T_c / e) \ln(I / I_0), \quad (9)$$

where $\hat{U}$ accounts for all potential differences between the electrodes, in particular the contact potentials and the constant voltage (20 V in the present case) applied to preaccelerate the electron beam behind the cathode. Note that the constants $\hat{U}$ and $\ln I_0$ are additive and can be combined into a single offset for defining $\hat{U}_{r,b}(I)$.

In Fig. 5 we show the breaking voltages $U_{r,b}$ for currents I starting in the sub-nA range and ranging up to $\sim 40 \mu\text{A}$. In the low-current limit, the measured voltages $U_{r,b}$ can be well fitted by the model of Eq. (9). This fit yields the additive constant $\hat{U}$ (I_0 being set to a fixed arbitrary value) and hence the reference voltage $\hat{U}_{r,b}(I)$. Moreover, the source electron temperature is found from the fit to be $k_B T_c = (30 \pm 4) \text{ meV}$. This value is close to the applied cathode bulk temperature, in agreement with the partial thermalization of the extracted electrons expected in our case.

With the reference voltage $\hat{U}_{r,b}(I)$ as a function of the applied current I , using Eq. (9) and the parameters from the low-current fit, the true potential difference between

FIG. 6. Perveance law between the minimum effective accelerating potential realized, $U_{0,b}$, and the extracted beam current. Dots connected by the full line: result of the breaking voltage measurements. The given maximum experimental perveance p_b is determined from the fitted straight line.

the drift tube and the electron source can be obtained for each setting of the retarding voltage U_r (and for any set current I) as

$$U_0 = U_r - \hat{U}_{r,b}(I). \quad (10)$$

In particular, Fig. 5 shows that this way also the minimal effective potential differences $U_{0,b} = U_{r,b} - \hat{U}_{r,b}(I)$ are obtained from the measured breaking voltages. The minimum potential difference $U_{0,b}$ represents the voltages down to which the current I can be transported through the drift tube with the homogenous current distribution as imprinted at the cathode, and under these conditions the space charge potential assumes its maximum value $U_{SC,b}$ (see Fig. 5). The observed minimum potential differences $U_{0,b}$ are found to follow in good approximation a constant-perveance law, which implies the linear dependence $U_{0,b} = c I^{2/3}$ with a fitted constant c , $p_b = c^{-3/2}$ being the maximum (breaking) perveance. This is shown in Fig. 6, where a linear fit yields $p_b = (4.10 \pm 0.43) \mu\text{A}/\text{V}^{3/2}$. Using the geometry-dependent function $f(x)$ discussed in Sec. III, this gives $x_b = f^{-1}(p_b) = 0.41$ for the space-charge parameter x at the breaking condition.

The derived limiting perveance of the decelerating drift tube is much higher than the electron-gun perveance ($0.58 \mu\text{A}/\text{V}^{3/2}$) and approaches the maximum theoretical perveance of the deceleration scheme, that in our geometry amounts to $5.54 \mu\text{A}/\text{V}^{3/2}$ [see Fig. 4(b)]. The fact that the measured value of $4.1 \mu\text{A}/\text{V}^{3/2}$ is lower can be explained by the inhomogeneous current profile showing higher current density near the middle of the beam (see Fig. 3). According to [16] for the electron energies in the range 2–500 eV the experimental values of limiting current

deviate by some 10% from the theoretical calculations, similar to described here.

V. ELECTRON GUN PERFORMANCE

The deceleration scheme presented here offers one to choose the electron density over a wide range without sacrificing the low transverse electron temperature. Which gives clear advantage compared to moderating the electron density with the magnetic expansion, as the expansion trades the increased density for increased transverse temperature.

The procedure of adjusting the parameters of the deceleration scheme for a desired kinetic electron energy $E_{k,0}$ on the beam axis is illustrated in Fig. 7. In the diagram of x versus U_0 , lines of constant $E_{k,0}$ are given by $U_0 = E_{k,0}/e(1-x)$. On the line for the desired $E_{k,0}$, the working point can be chosen in dependence of the space-charge ratio x . Values of x up to ~ 0.41 can be realized at effective perveance values up to maximum achievable $4.1 \mu\text{A}/\text{V}^{3/2}$, as shown in Fig. 6. At a given $E_{k,0}$, the choice of x defines both the perveance $p = f(x)$ and the required value of U_0 . A curve $I = pU_0^{3/2}$ is drawn in the diagram of I versus U_0 for this perveance p and used to read the current I . This current is adjusted by setting the extraction voltage of the electron gun.

FIG. 7. Working diagram of the beam deceleration scheme. In the lower right diagram a space-charge parameter x is chosen on the curve for a desired axial kinetic energy. Three cases are indicated: 1 (green): extracted current corresponding to the electron-gun perveance, using U_0 as the extraction voltage. The beam current (read from the perveance law in the upper right diagram) is $< 1 \mu\text{A}$. 2 (red): Higher extraction voltage is used at the electron gun; the extraction voltage (higher than U_0) is set to obtain an electron current of $\sim 2.5 \mu\text{A}$ and for deceleration, U_0 is adjusted to $\sim 1.2 \text{ V}$ as shown on the line intersecting the right abscissa. 3 (blue): Experimental maximum, for a beam current set to $\sim 8.5 \mu\text{A}$, a space-charge parameter near the limit x_b is reached for this $E_{k,0}$ and U_0 must be set to $\sim 1.7 \text{ V}$.

The retardation voltage U_r to be applied follows from U_0 and the calibration at very low currents using Eqs. (9) and (10). By this method, electron beam energies $E_{k,0}$ in the range of 1 eV or below can be adjusted in a controlled way.

The space-charge parameter x realized in the deceleration scheme also sets the electron density n_e in the center of the electron beam. With Eq. (3) [see also Fig. 4(a)] this can be expressed in terms of the perveance p as

$$n_e = \frac{\epsilon_0(p/p_0)E_{k,0}}{e^2\rho^2(1-x)^{3/2}} = \frac{\epsilon_0 s_\rho^2 E_{k,0}}{e^2\rho^2}, \quad (11)$$

where the second expression includes the perveance-related parameter s_ρ^2 resulting from the solution of the space-charge Poisson equation as discussed in [18], and $p_0 = 16.50 \mu\text{A}/\text{V}^{3/2}$. This implies

$$n_e = 1.23 \times 10^6 \text{ cm}^{-3} \times s_\rho^2 \left(\frac{E_{k,0}}{\text{eV}} \right) \left(\frac{\rho}{6.7 \text{ mm}} \right)^{-2}, \quad (12)$$

with $n_e = 0.70 \times 10^6 \text{ cm}^{-3} \times (E_{k,0}/\text{eV})$ for the maximum $x = 0.41$ of the TSR beam deceleration experiment ($s_\rho^2 = 0.571$). An approximate result for space-charge parameters $x \lesssim 0.4$ is

$$n_e \sim 1.23 \times 10^6 \text{ cm}^{-3} \times \frac{4x/(1-x)}{5.02 + 2 \ln(R/7.46\rho)} \times \left(\frac{E_{k,0}}{\text{eV}} \right) \left(\frac{\rho}{6.7 \text{ mm}} \right)^{-2} \quad (13)$$

neglecting the higher-order terms beyond the parabolic approximation (correction of $\lesssim 5\%$). Thus, for $E_{k,0} = 1 \text{ eV}$ the electron density lies near $2.0 \times 10^5 \text{ cm}^{-3}$ for case 2 of Fig. 7 ($x = 0.17$, $p \sim 2 \mu\text{A}/\text{V}^{3/2}$).

VI. CONCLUSION

In this paper we have investigated the beam performance of the TSR electron target at kinetic energies in the 1 eV range and below. A beam deceleration technique has been used as a prototype scheme for the future operation of an electron cooler at the cryogenic storage ring CSR and can be as well adopted by other proposed low energy storage rings like USR [19]. By experiments with the photocathode electron beam of the TSR electron target, we have shown that deceleration is possible down to a sharp limit, so that still $\sim 20 \text{ meV}$ above this limit the electron transport properties through the deceleration region are essentially undegraded. A calibration technique was described to set the electron kinetic energy in the range of $\sim 1 \text{ eV}$ and below in a controlled way, even under the influence of contact potential differences. Compared to single-step beam extraction from an electron gun, the current applicable at these kinetic energies was shown to be higher by about an order of magnitude.

High beam quality can be maintained for applications where the interest lies in only a small central part of the electron beam, like recombination experiments or advanced stages of electron cooling. The technique will make it possible to explore the limits of electron cooling and merged-beam electron-ion collision experiments with ultracold beams in the eV and sub-eV energy region.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support by the Max-Planck-Förderstiftung.

-
- [1] R. von Hahn *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. B* **269**, 2871 (2011).
  - [2] T. Tanabe, K. Noda, and E. Syresin, *Nucl. Instrum. Methods Phys. Res., Sect. A* **532**, 105 (2004).
  - [3] T. Tanabe, K. Noda, M. Saito, E. B. Starikov, and M. Tatenno, *Phys. Rev. Lett.* **93**, 043201 (2004).
  - [4] T. Tanabe, E. B. Starikov, and K. Noda, *Chem. Phys. Lett.* **467**, 154 (2008).
  - [5] D. Orlov, H. Fadil, M. Grieser, J. Hoffmann, C. Krantz, O. Novotny, S. Novotny, and A. Wolf, in *Proceedings of the Workshop on Beam Cooling and Related Topics (COOL 07)*, edited by R. W. Hasse and V. R. W. Schaa (Joint Accelerator Conferences, JACOW, 2007), pp. 230–233.
  - [6] A. I. Papash, A. V. Smirnov, and C. P. Welsch, *Phys. Rev. ST Accel. Beams* **16**, 060101 (2013).
  - [7] S. Pastuszka, M. Hoppe, D. Kratzmann, D. Schwalm, A. Wolf, A. S. Jaroshevich, S. N. Kosolobov, D. A. Orlov, and A. S. Terekhov, *J. Appl. Phys.* **88**, 6788 (2000).
  - [8] D. A. Orlov, M. Hoppe, U. Weigel, D. Schwalm, A. S. Terekhov, and A. Wolf, *Appl. Phys. Lett.* **78**, 2721 (2001).
  - [9] D. Orlov, U. Weigel, D. Schwalm, A. Terekhov, and A. Wolf, *Nucl. Instrum. Methods Phys. Res., Sect. A* **532**, 418 (2004).
  - [10] U. Weigel, D. Orlov, S. Kosolobov, D. Schwalm, A. Terekhov, and A. Wolf, *Nucl. Instrum. Methods Phys. Res., Sect. A* **536**, 323 (2005).
  - [11] C. Krantz, D. A. Orlov, J. Hoffmann, M. Lestinsky, O. Novotny, A. S. Jaroshevich, A. S. Terekhov, and A. Wolf, *J. Phys. Conf. Ser.* **192**, 012025 (2009).
  - [12] D. A. Orlov, C. Krantz, A. Wolf, A. S. Jaroshevich, S. N. Kosolobov, H. E. Scheibler, and A. S. Terekhov, *J. Appl. Phys.* **106**, 054907 (2009).
  - [13] F. Sprenger, M. Lestinsky, D. A. Orlov, D. Schwalm, and A. Wolf, *Nucl. Instrum. Methods Phys. Res., Sect. A* **532**, 298 (2004).
  - [14] M. Lestinsky, E. Lindroth, D. A. Orlov, E. W. Schmidt, S. Schippers, S. Böhm, C. Brandau, F. Sprenger, A. S. Terekhov, A. Müller, and A. Wolf, *Phys. Rev. Lett.* **100**, 033001 (2008).
  - [15] S. Pastuszka, U. Schramm, M. Grieser, C. Broude, R. Grimm, D. Habs, J. Kenntner, H.-J. Miesner, T. Schüßler, D. Schwalm, and A. Wolf, *Nucl. Instrum. Methods Phys. Res., Sect. A* **369**, 11 (1996).
  - [16] M. V. Nezlin, *Physics of Intense Beams in Plasmas* (Taylor and Francis, London, 1993), 1st ed.
  - [17] P. V. Akimov, H. Schamel, H. Kolinsky, A. Y. Ender, and V. I. Kuznetsov, *Phys. Plasmas* **8**, 3788 (2001).
  - [18] L. P. Smith and P. L. Hartman, *J. Appl. Phys.* **11**, 220 (1940).
  - [19] C. P. Welsch *et al.*, *Hyperfine Interact.* **213**, 205 (2012).