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RECOMBINATION OF PARTIALLY STRIPPED HEAVY IONS WITH FREE ELECTRONS†

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During acceleration of ions to energies needed for HIF, electron cooling of partially stripped heavy ions may be considered as a tool to increase the phase-space density. The cooling by electrons, however, provides a loss mechanism for the ions stored, if these electrons recombine with the partially stripped heavy ions through radiative electron capture (REC) or dielectronic recombination (DR).

In order to determine cross sections for these loss processes for ions available from the UNILAC, we have set up an electron target as a merged beams experiment. A dense electron beam (up to 10 A/cm^2) is merged with the UNILAC beam over an interaction length of 45 cm by means of suitably bent magnetic flux lines.

In contrast to ion storage rings, we also can measure REC if ions and electrons travel with zero relative energy. First experiments have shown that REC rates are significantly higher than predicted theoretically.

1 INTRODUCTION

The application of electron cooling to improve the phase-space density in ion storage rings has the drawback of introducing losses due to recombination of the partially stripped heavy ions with the free electrons used for cooling. The excess energy available in the capture of the electron by the ion will be used either non-resonantly to excite a core electron by dielectronic recombination (DR) followed by the emission of photons to stabilize the ion in the lowered charge state. Experimental data on these cross sections are still scarce, but from theoretical predictions they may be of such high value that loss rates can become significant for ions stored in cooler rings.

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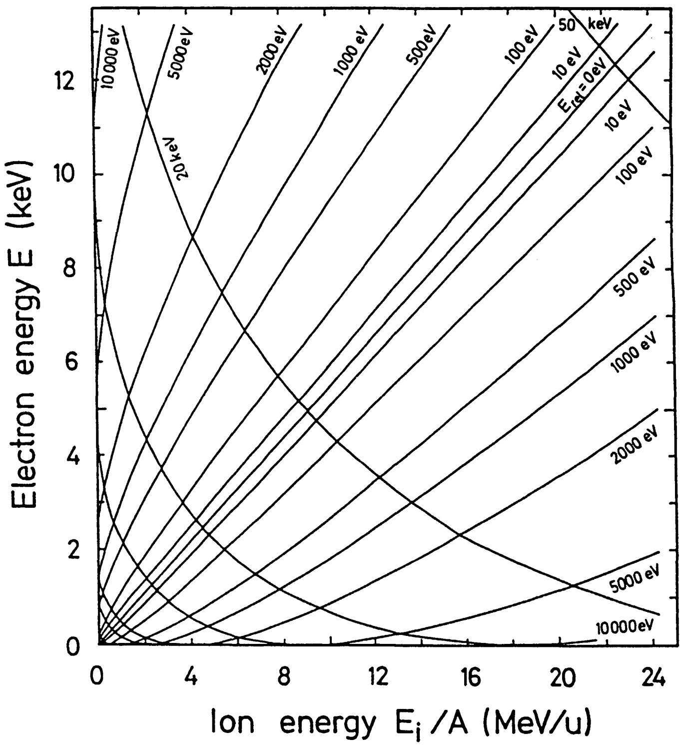

FIGURE 1 Center-of-mass energies accessible by merging electron and ion beams at different laboratory energies.

In the phase of designing the experimental storage ring (ESR) at GSI, the intended application of electron cooling to partially stripped heavy ions motivated the present experiment for the investigation of these processes. The experiment used various ion beams from the existing UNILAC with energies up to 16 MeV/u in a single path experiment.

To obtain zero relative velocity in the rest frame of the colliding particles, the energy range of the electron target has to extend up to 8 keV (Figure 1).Since charge exchange with residual gas ions is a competing process even at UHV conditions of better than 10^{-10} mbar, the event rate should be as high as possible to achieve sufficient signal-to-noise ratios. Therefore the target was designed to deliver electron current densities significantly higher than in comparable devices; the upper limit is 10 A/cm^2 at 8 keV.

2 THE ELECTRON GUN

The demand for high-density electron beams is similar to that of electron beam ion sources (EBIS), where the electron bombardment serves for stepwise ionization up to very high charge states[2]. Current densities of 10^3 A/cm^2 can be achieved using convergent guns at the expense of transverse electron energy increase by the beam compression. In the study of resonant processes such as DR this leads to poor energy resolution, which was observed in a similar experiment even at quite low current densities[3]. To preserve the transverse beam energy spread (limited by the cathode temperature), the electron gun has to be fully immersed in the guiding magnetic field, using the well-known Pierce's resonance focusing. Then available saturation current densities set an upper limit of about 10 A/cm^2.

The gun design was performed using the SLAC electron optics program[4]. The perveance is close to 10^{-6} A/V$^{3/2}$, offering a current of 660 mA at 8 keV[5]. With a beam diameter of 3 mm this corresponds to 10 A/cm^2, which asks for a magnetic field strength of 1 T to keep the transverse beam temperature well below 0.5 eV. Since the electrons stick to their magnetic flux lines, the radial potential drop from the edge to the center of the beam of about 100 V is only observed longitudinally. This energy spread is reduced by kinematics in the merged beams experiments considerably to values of about 0.4 eV near zero relative velocity.

At higher collision energies, of course, the resolution will be limited with such a beam. Reduction of current density at the expense of reaction rate will lower this potential drop. An additional electrode in the gun was included into the design, and by simply changing the gun electrode potentials, the perveance can be lowered by a factor of 10.

A different approach would maintain the advantage of high current density by the use of space charge compensation by protons to reduce the voltage drop. Therefore we have provided a gas feed of hydrogen, which will be dissociated and ionized in the electron beam. The protons will be trapped longitudinally by appropriate electrode potentials, and radially by the space charge of the electron beam. Of course, one has to consider disturbant charge exchange collisions.

3 MAGNETIC FIELD CONFIGURATION

The high magnetic field strength of 1 T with a homogeneity of 10^{-4} necessary to achieve low radial energy spread at a current density of 10 A/cm^2 can easily be provided using a superconducting solenoid wound with thin NbTi wire. Simultaneously, the extreme vacuum requirements are met employing the cold inner bore of the solenoid as a cryopump.

Taking an electron cooler as target, the construction usually consists of separate guiding fields for electron gun, interaction and collector regions, the merging being accomplished by complex toroidal coils[6,7], which is prohibitive in the case of a superconducting solution. Therefore a design was chosen in which all components are installed inside a single straight solenoid (Figure 2). Additional transverse fields superimposed on the axial field serve for the necessary bend of flux lines. Gun and collector are place 22.5 mm off axis, fully immersed in the high-field region. Since it takes 45 cm to deflect the electron beam to the axis, the homogeneous region covering

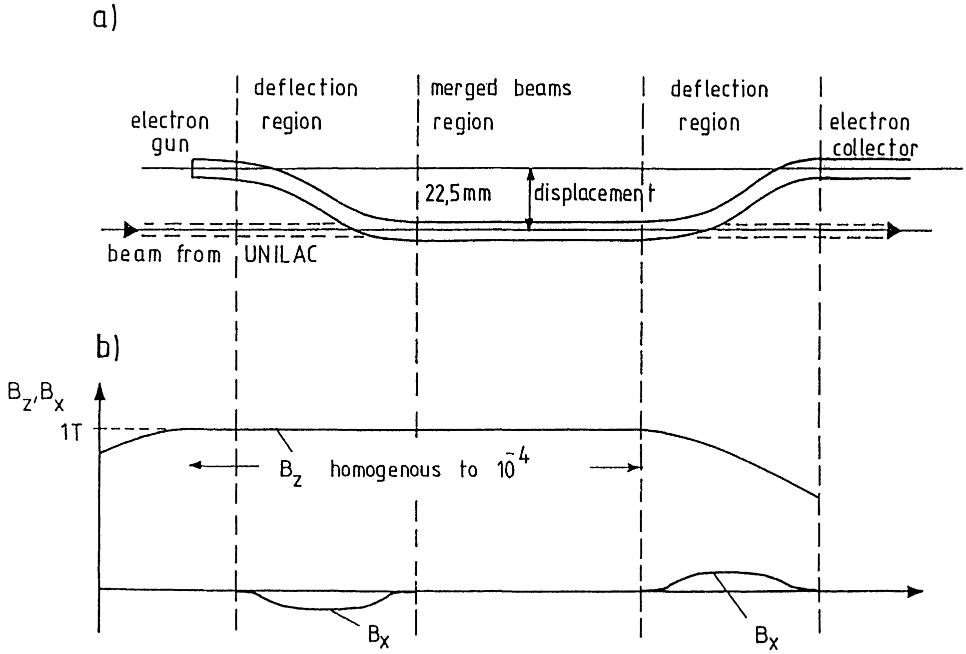

FIGURE 2 Schematic of merging electron and ion beams by bent flux lines.

also the electron gun and merging section has to extend to a length of 1 m, while the collector is situated in the decreasing field.

The limited space (2.3 m available for the whole target length) required special measures to homogenize the 1.9 m long solenoid of 150-mm inner bore diameter over the length of 1 m. This is achieved by the use of additional single current loops excited by the same current (105 A for 1 T) as the main coil, their amount and position being determined by the use of an interactive computer program[8] (Figure 3a).

The transverse magnetic fields are provided by two oppositely energized elliptical coils consisting of 6 × 48 windings of pitch 4/3. This solution was chosen rather than saddle coils because of higher production accuracy. The unwanted return field at the electron gun and interaction region is compensated by further elliptical windings of different pitches (Figure 3b). Additional annular loops compensate for the longitudinal field of all elliptical windings (Figure 3c) except for the regions of deflection, where the small change in field strength has no influence upon the beam temperature.

4 DESIGN CONSIDERATIONS FOR THE ELECTRON TARGET

The superconducting solenoid is shielded by two thermal shields, which are cooled by a closed-cycle refrigerator system to less than 20 or 60 K, respectively. All inserts of the target surrounding the merging section as well as the electron gun are thermally

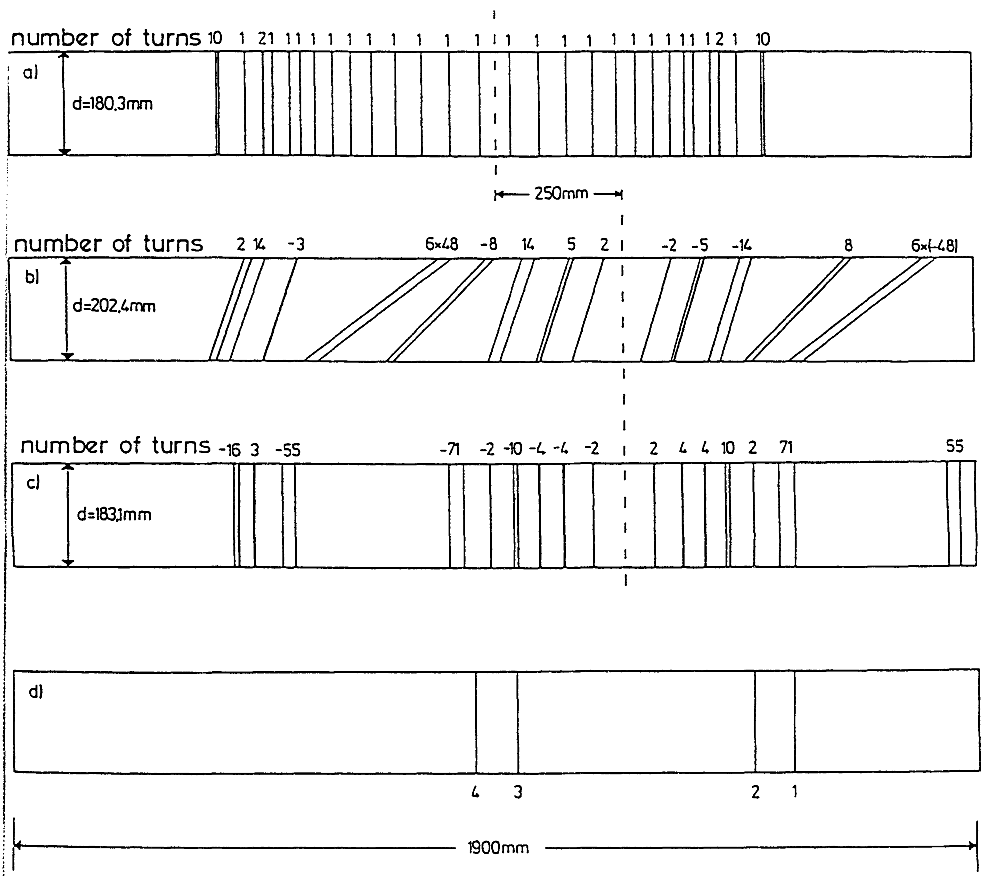

FIGURE 3 Correction windings of the superconducting solenoid (main windings not shown) (a) Single annular loops to improve the central homogeneity (b) Elliptical loops to create and correct the transverse fields (c) Annular loops to compensate the axial field due to the elliptical windings (d) Trim coils for correction

grounded to the 60-K shield. The water-cooled collector is completely thermally isolated. The electron gun and collector are optically shielded from the inner bore of the solenoid former at 4.2 K, using chevron baffles to allow for sufficient pumping.

Perfect radial alignment is achieved by the use of thermally isolating glass stems of accurate length orientating on the precisely machined inner bore of the former of the solenoid. Rigid construction, consisting of tubes connecting all inserts to the 60 K shield, keeps the electron gun, interaction region and collector at the calculated radial positions.

To control the coaxial overlap of both beams, two slit systems adjustable in width from 0 to 10 mm are located on both ends of the merging section. They come also into action for steering of the ion beam onto the target axis, which is quite complicated because of the deflection arising from the transverse fields of the ellipses to merge the electron beam.

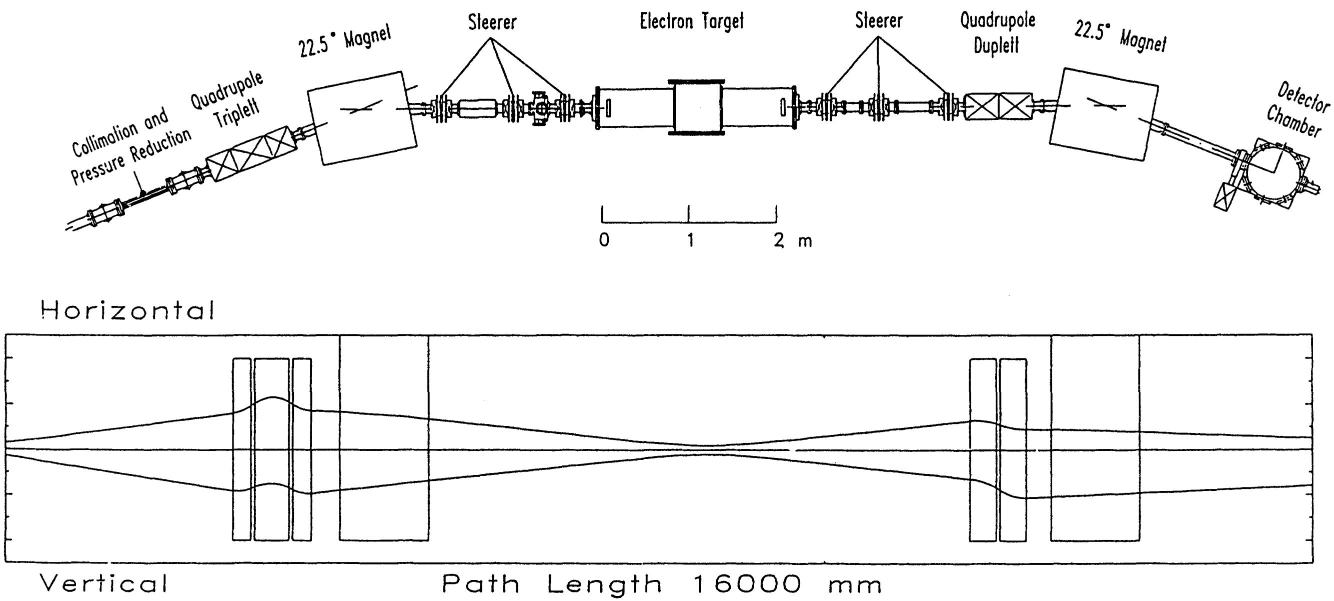

FIGURE 4 Schematic drawing of the experimental set up of the electron target in a beam line of the UNILAC.

5 EXPERIMENTAL RESULTS

The installation of the electron target in one of the UNILAC beam lines with highest magnetic resolution is shown in Figure 4. The heavy ion beam is collimated and charge-purified by the right section, which also serves to reduce the beam line pressure by differential pumping into the 10^{-10} mbar range. Steering dipole magnets, which are fully rotatable about the beam axis, inflect and deflect the heavy ion beam through the transverse magnetic fields of the electron target, in order to merge both beams on axis inside of the homogeneous field region of the target. A magnetic quadrupole doublet is used in conjunction with a dipole magnet in the left part of Figure 4 to separate the recombined ions from primary ones and to form a focus in the detector chamber.

First electron beam tests showed the necessity to improve the thermal isolation and shielding of the cathode heater. Finally the heat load from the electron gun was lowered to emit less than 5 W to the 60-K shield. At beam powers of about 500 W the thermal loading of the refrigerator is sufficiently small for low-perveance operation to reach the rated specifications of 65 mA at 7.5 keV. High-perveance runs with a 6-keV, 500 mA beam showed a steady increase in shield temperature leading to intermissions in the measurements.

In a first experiment, the recombination rates of U^{28+} were measured. The UNILAC was set to an energy of 6.3 MeV/amu, while the energy of the electron beam could be varied in small steps from 3300 to 3550 eV. Within this energy range,

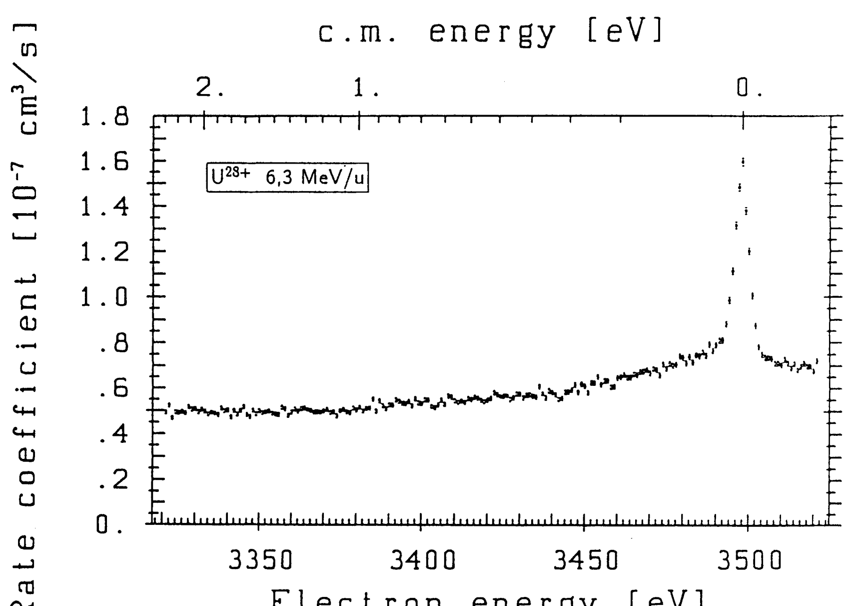

FIGURE 5 Rate for recombination of U^{28+} at zero center-of-mass energy with the free electrons of the electron target.

the parallel velocities of both beams can be made equal in the limit of the remaining velocity spreads. Figure 5 shows the experimentally observed rates of recombination, which are higher by a factor of 5 than expected from a simple estimate[9]. It is, however, not precluded that an additional DR resonance is on top of the REC. While this is an important question for the understanding of the recombination, the result by itself is important for the question of cooling partially stripped heavy ions by electrons. With Au^{25+} ions we observed a recombination rate at zero relative velocity again in the range of 10^{-7} cm^3 sec^{-1} [10]. Since no other strong recombination line could be found up to differences in the center-of-mass energy of 70 eV, it seems to be quite unprobable that there is DR just around zero center-of-mass energy and nowhere else, an argument which applies to both cases, U^{28+} and Au^{25+}.

Measurements on DR of Ar^{15+} show a "regular" peak rate for REC at zero center-of-mass energy[10]. Additionally, we could resolve a number of well separated DR lines, which can be associated with intermediate doubly excited states ($1s^2 2p_{1/2}nl$ and $1s^2 2p_{3/2}nl$) of the Ar^{14+} ion with $n = 11$, 12 and 13. The energy resolution of these peaks corresponds to a maximum transverswe energy spread of the electron beam of about 0.2 eV. This is about the limit by the thermionic cathode and demonstrates that the gun design, using Pierce resonance focusing, was done properly, as well as the alignment of the electron beam to straight flux lines, which reflects the winding accuracy achieved by the manufacturer[11].

6 CONCLUSIONS

First experiments with the UNILAC ion beams show that the electron target can be used successfully to study radiactive electron recombination rates. While the electron beam energy depending on given ion energy was quite moderate to about 3 keV, in the high-perveance mode currents as high as 170 mA were reached, which allowed measurement of dielectronic recombination lines. From the measured line shapes one can deduce electron beam energy spreads of 1 meV longitudinally and approximately 0.2 eV transversely[12].

The recombination rates obtained for U^{28+} and Au^{25+} at zero center-of-mass energy are as high as 10^{-7} cm^3 sec^{-1} and are probably due to radiative electron capture (REC). Recombinations rates of AR^{15+} by dielectronic recombination (DR) are in good agreement with expectations.

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