Abstract. A decelerator will be installed at GSI in order to provide and study bare heavy nuclei or heavy nuclei with only few electrons at very low energies or even at rest. Highly-charged ions will be produced by stripping at relativistic energies. After electron cooling and deceleration in the Experimental Storage Ring the ions are ejected out of the storage ring at 4 MeV/u and further decelerated in a combination of an IH and RFQ structure. Finally, they are injected into a Penning trap where the ions are cooled to 4 K. From here, the ions can be transferred in a quasi dc or in a pulsed mode to different experimental setups. This article describes the technical concepts of this project as well as planned key experiments.

Keywords: highly charged ions, QED test

PACS: 07.90.+c,12.20.Fv

1. INTRODUCTION

The theory that is normally regarded as best understood is quantum electrodynamics (QED). This theory is, for instance, able to predict with remarkable accuracy atomic level energies in the hydrogen atom. However, in the very high electromagnetic fields of highly-charged heavy ions the usual perturbative approach is no longer applicable. Experimentally, such high fields become accessible by stripping heavy atoms off all or most of their electrons. There are two approaches: stripping of the projectile at high energy or collisions with high-energy electrons in an ion source. If moderately charged ions are accelerated and sent through a target they will lose all or most electrons in collisions with the target atoms if the ion energy is high enough. Similarly, atoms placed in an electron beam will be stripped sequentially off their electrons, if the energy of the electrons in the beam is high enough. It has been demonstrated that both approaches can produce heavy highly-charged ions (HCI) [1, 2]. The most intense source of bare uranium ions is at GSI where the high-energy stripping approach is used.

For precision experiments the HCI must be prepared at low energy, i.e. at nearly rest in space or with only a few keV total energy with a very small energy spread. For this the produced HCI will be injected into the Experimental Storage Ring (ESR) [3], electron cooled and decelerated to an energy of 4 MeV/u. After ejection out of the ring the ions are further decelerated by a combination of IH and RFQ structures and injected into a Penning trap. Here the ions are accumulated and cooled to 4 K. For this purpose the decelerator-cooler facility, called HITRAP, has been designed and is now under construction at GSI.

In addition to HCI of stable nuclei, those of radioactive ones will become available.
Radionuclides are produced and separated by use of the fragment separator (FRS) [4] and then injected into the ESR. In the more distant future, HITRAP will be a part of the Facility for Low Energy Antiproton and Ion research (FLAIR) at the planned international accelerator Facility for Antiproton and Ion Research (FAIR). There, HITRAP will not only provide low-energy highly-charged stable and radioactive ions but also low energy antiprotons.

2. EXPERIMENTS WITH HIGHLY-CHARGED, HEAVY IONS

2.1. Precision experiments with single ions

Precision measurements of basic quantities have been conducted successfully using HCI. Examples are the electronic g-factor, the binding energy of the electrons, and the atomic mass. The electronic g-factor of hydrogen-like ions can be used to test the theory of quantum electrodynamics in strong fields. In turn, fundamental constants like the electron mass or the fine-structure constant $\alpha$ can be determined by these measurements if the results of reliable quantum electrodynamics calculations are used as input [5]. The mass of HCI is another important quantity. A determination of the mass of the ion in different charge states gives a new access to the binding energy of the inner electrons. Measured for different isotopes, nuclear binding effects can be determined with high precision.

The g-factor measurement is based on the continuous Stern-Gerlach effect [6] where the g-factor of the bound electron

$$g = \frac{2 \omega_L m q}{\omega_C M e}$$

(1)

is determined by the ratio of the Lamor frequency $\omega_L$ of the electron to the cyclotron frequency $\omega_C$ of the ion [7, 8]. Additional quantities needed are the ion mass $M$, its charge state $q$ and the mass $m$ and charge $e$ of the electron. Remarkable accuracy can be reached since the frequency of the oscillations of an ion confined in a Penning trap can be determined with extremely high accuracy.

If the electronic g-factor of the bound electron can be calculated reliably to an accuracy that matches that of the experiment, then the electron mass can be extracted from equation (1). Using the g-factor measurements of O$^{7+}$ and C$^{5+}$ ions [9, 10] the electron mass has been obtained with a four-fold improved accuracy [11]. When these measurements can be extended to heavier ions and the QED calculations can be further improved, then the fine structure constant $\alpha$ can be determined in a way completely independent from present procedures [5].

Some of the most precise mass measurements have been performed using HCI [12]. For this the ion is stored in a Penning trap and its cyclotron frequency $v_C$ is measured. Then the mass $M$ can be determined using the relation

$$v_C = \frac{1}{2\pi M} q B.$$  

(2)
The magnetic field strength $B$ is determined via an ion with a well known mass or even using $^{12}\text{C}$ which is the microscopic mass standard. Since the cyclotron frequency depends linearly on the charge state $q$ of the ion, a higher resolving power and hence accuracy can be reached [13]. The pioneering experiment for mass measurements on HCI [12] reaches a relative mass uncertainty of about $10^{-10}$ by use of a trap at room temperature and a destructive detection technique. Mass measurements with a precision of $2 \cdot 10^{-11}$ have been performed by the use of singly-charged ions in a cryogenic Penning trap [14]. Here, the motion of only a single ion stored in the trap has been detected directly and non-destructive. Combining both methods, as possible at HITRAP, will push the relative mass uncertainty even below $1\cdot 10^{-11}$.

By this, it will be possible to measure the mass differences between bare, H-like, He-like and so on uranium ions to 2 eV or better. Such measurements would provide the most accurate measurement of the $1s$ Lamb shift in hydrogen-like heavy ions and provide a stringent test of atomic theory including electron-electron correlations in strong fields. Furthermore, the possibility to produce radioactive nuclei using the FRS will enable for the first time mass measurements with such high precision on radioactive nuclei. Since these measurements are limited by the half-life of the nucleus of interest and the cooling and preparation will take about 10 seconds, the half-life of the isotope under investigation should be longer than 10 seconds.

### 2.2. Experiments with beams of slow heavy highly-charged ions

Atomic collisions at low energy provide valuable and indispensable data for many areas of physics, e.g. plasma physics, accelerator physics, and astrophysics. Atomic structure and collision dynamics can be studied by kinematically complete collision experiments using the COLTRIMS technique [15, 16]. For HCI charge exchange is the dominating process at energies of less than a few keV/u. Single or multi-electron capture occurs into high-lying states of the highly charged ion which forms strongly inverted systems, so-called hollow atoms. The initial capture process as well as the deexcitation via x-rays or Auger electrons can be monitored in detail by detecting in coincidence the recoil ion, the emitted electrons and photons (in the x-ray as well as in the optical spectral region) and by determining their energies.

Electron capture processes will be studied with the available beam intensity of about $10^4$ HCI per second. For this the beam of HCI is directed onto a target of, for instance, helium atoms in a supersonic jet. The determination of the recoil ion momentum along with the projectile properties gives informations about the energy difference between initial and final state, i.e. the Q-value. If performed for different states this enables high-resolution spectroscopy of the HCI energy levels. The presently achieved resolution of 0.7 eV and accuracy between 3 and 300 meV [17] is already competitive with the methods of conventional spectroscopy. In the future, an improved momentum resolution can be envisaged and hence a reduction of the uncertainty towards the sub-meV level.

Highly charged ions can be used to deposit large amounts of potential energy on surfaces. For instance, the potential energy of several hundred keV of a single bare uranium ion is deposited in a very small area of just a few square nanometers. This
high energy density leads in general to a highly non-linear response of matter. For experiments it is, however, important to distinguish between processes induced by the potential energy of the ion due to the high charge state and those induced by kinetic energy. This requires well defined beams of very low kinetic energy and very small energy spread.

The measured quantity is the number of electrons emitted from the surface during the collision. If this is investigated for different charge states information can be gained on the non-linear response of semi-conductors and insulators to strong Coulomb fields and on defect-induced mobility in the limit of high defect density. The main parameter is the speed at which the insulating material can replenish electrons in the nanometer-sized impact region. A wide range of semiconducting and insulating surfaces produced by thin-film coating shall be studied using this method. In first experiments ions in low charge states were impinging on thin films of LiF [18] and C_{60} [19] evaporated on Au. These experiments indicate that electron spectra depend strongly on the properties of the thin film.

For a certain range of kinetic energy it might happen that the impinging ion is repelled from the surface. This so-called trampoline effect occurs because the positive charges, created on the surface by the first electrons transferred to the incoming ion, are not compensated fast enough. So far experimental evidence for this effect could not be found [20]. Up to now the experimental search was limited by the low charge states available and the large energy spread for beams of only a few eV. Both limitations will be eliminated by use of the low-energy beam available at HITRAP.

### 2.3. Photon spectroscopy of highly charged ions at rest

Generally electronic transitions in HCI are in the far ultraviolet or X-ray spectral range, beyond the access by laser light in the visible spectral region. However, for very highly charged ions, for instance hydrogen-like \(^{207}\)Pb, the ground-state hyperfine transition (21 cm microwave radiation for atomic hydrogen) is moved into the spectral region accessible by conventional lasers. Since also the lifetime of these states (proportional to \(Z^{-9}\)) lies in the microsecond or millisecond range laser spectroscopy can be performed with high precision. In this way, the magnetic sector of high-field QED can be tested and, if successfully done, the distribution of the nuclear magnetization can be extracted.

At the HITRAP facility laser spectroscopy will be performed in a cryogenic Penning trap kept at 4 K. This offers several advantages: The ions are stored as a dense and well localized cloud (up to 100 000 ions stored within a few cubic millimeters) enhancing this way the overlap with the laser beam. Due to the low temperature the resonance is barely Doppler broadened. In combination with an easily achievable high collection efficiency for the fluorescence photons these properties will allow for an excellent signal-to-noise ratio. Furthermore, the long storage time enables one to optically pump the ions even using the rather weak M1 transition and to reach a high degree of electronic and nuclear polarization.
3. THE PLANNED HITRAP FACILITY

An overview of the planned facility is presented in Fig. 1. After production the ions will be decelerated down to 4 MeV/u using the Experimental Storage Ring (ESR) at the present GSI facility. Similarly, at the future FAIR facility the New Experimental Storage Ring (NESR) followed by the Low Energy Storage Ring (LSR) will be used for HCl and antiprotons deceleration. This will be accompanied by electron cooling in the storage ring, such that the emittance of the beam does not grow. Finally, the ions will be collected into a single bunch, extracted from the ESR and injected into a linear decelerator. After re-bunching with a double drift buncher (DDB) the beam will enter an interdigital H-type (IH) structure and will be decelerated to 0.5 MeV/u. Then it will be matched in longitudinal and transverse direction to a four-rod Radio Frequency Quadrupole (RFQ) decelerator. The final energy after the RFQ will be as low as 6 keV/u.

The beam properties of the different structures are listed in Tab. 1. Since there is no cooling applied in the linear decelerator section the absolute emittance increases considerably with decreasing energy. Further emittance growth occurs due to non-

---

**FIGURE 1.** Overview of the planned HITRAP facility.

<table>
<thead>
<tr>
<th>TABLE 1. Beam properties along the decelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part of the decelerator</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>ESR - IH</td>
</tr>
<tr>
<td>IH - RFQ</td>
</tr>
<tr>
<td>RFQ - cooler trap</td>
</tr>
<tr>
<td>cooler trap - experiment</td>
</tr>
</tbody>
</table>

* not normalized  † simulated
linearities in the RF-gap fields and due to ion optical aberrations. The beam after the RFQ will have about $100 \pi \text{ mm mrad}$ transversal emittance and an energy spread calculated to be in the order of $\pm 4\%$. In order to further slow down the antiprotons or highly-charged ions, the beam is captured in a Penning trap. There, electron cooling and, subsequently, resistive cooling will be applied to cool up to $10^5$ HCl.

A cylindrical Penning trap in a magnetic field of 6 T will be kept at the temperature of liquid helium, 4 K. This will ensure the best possible vacuum that is needed to store antiprotons or HCl for an extended period. When injected into the strong magnetic field the ions or antiprotons will be decelerated further to energies below 2 keV/u. The strong magnetic field prohibits the transversal blow up of the beam in this phase. After in-flight capture by closing the trap after the ion bunch entered, the ions or antiprotons will be first cooled by interaction with a dense electron plasma. After about 1 s the ions or antiprotons will be separated from the electrons and stored in a harmonic electric field region. Here, it is planned to apply resistive cooling in order to cool the particles to final temperatures close to 4 K, equivalent to energies below 1 meV. Then the ions or antiprotons will be ejected and sent to experiments in either of two ways, as a quasi dc beam of $10^5$ particles distributed over up to 10 s or as a pulse with a bunch length of a few microseconds.

### 3.1. The IH structure and the double-drift buncher

H-type structures are the most efficient ion accelerator structures in the low-$\beta$ range due to their high shunt impedance. For heavy ions in the low energy range ($< 10 \text{ MeV/u}$) the IH-structure is the best choice within drift tube structures since effective acceleration voltages up to 6 MV/m can be established. The HITRAP IH-structure operates at 108.408 MHz and 0.2% duty cycle. It has 25 gaps, one tripllett inner-tank quadrupol lens and is 2.7 m long. An overall effective acceleration voltage of 10.5 MV is required to decelerate ions with a mass-to-charge ratio of 3 to 500 keV/u, the energy required for the injection into the RFQ [21]. The cavity design is optimized in order to reach an effective shunt impedance of 255 M$\Omega$/m. In that case 165 kW power would be sufficient to reach the required tank voltage and a 180 kW power amplifier can be used which is available at GSI.

The ions extracted from the ESR are continuously distributed over a macro bunch with a length of 1.2 $\mu$s [22]. Thus the ions spread out over 360° RF-phase. The typical phase acceptance of the IH-decelerator is about 10°-15°. Therefore a buncher is required, which matches a larger fraction of the particles into the IH phase acceptance. A single harmonic buncher has a maximum phase acceptance of 130°, which corresponds to 37% of the particles bunched into the 10° phase acceptance of the HITRAP-IH-structure. A much better efficiency is obtained by using a multi-harmonic re-buncher or a double-drift buncher (DDB) [23]. However, a multi-harmonic buncher is difficult to implement due to the complicated adjustment of phases and amplitudes of the different harmonics. A DDB has the same bunching efficiency like a three-harmonic driven single buncher, i.e. about 67%. Therefore, a DDB has been chosen for the HITRAP setup, which is located 6.1 m in front of the IH-structure. It uses a 108.408 MHz cavity and a 216.816 MHz...
cavity separated by a 0.8 m drift. Both cavities are designed as coaxial quarter-wave resonators with four gaps each. The calculated shunt impedance of both cavities is larger than 60 MΩ/m and therefore RF generators with a power of 2 kW are sufficient to drive the cavities.

3.2. The radio frequency quadrupole structure

The design of the HITRAP 4-rod-RFQ is very similar to the 108 MHz structure of the high charge state injector LINAC at GSI [24]. However, the RF-power requirements are much more relaxed due to the lower A/q, which is <3 instead of 9. The low A/q allows a short structure of 143 cells with a length of 1.9 m and a maximum rod voltage of 70 kV. The mean aperture radius is about 4 mm which reduces the peak fields to safe values. The phase spread of ±40° of the ion bunches extracted from the IH-structure must be matched to the RFQ acceptance of ±10°. Thus in the matching section between IH-structure and RFQ, an existing two-gap spiral re-buncher will be used that has to be adapted to the right cell length. The beam at the exit of the RFQ has an emittance of 100 π mm mrad in both transverse directions.

The rod design had to be optimized with respect to the transverse angular spread of the ions at the RFQ exit. A small beam size and large angular spread are the result of strong quadrupole focusing. Ion beams with such properties would require lenses with large apertures close to the end of the rods. For sufficient transport to and injection efficiency into the cooler trap a minimum energy spread of the ions is required. To reduce the energy spread of ±7% from the RFQ a low energy de-buncher will be installed at the RFQ’s exit. Hence a drift length of 200 mm towards the first focusing lens of the low energy beam line is necessary. Simulations have shown that the energy spread of the ions can be reduced to ±4% using a single-harmonic buncher. The transmission is about 90% in that case. With a saw tooth like RF-excitation of the buncher, a final energy spread of ±3% and full transmission could be reached.

3.3. The low energy beam line and the cooler trap

3.3.1. The low energy beam line

The main challenge for the low energy beam line is the transport of a beam with very large angular divergence and an energy spread of ±4 % (see also Tab. 1). Great care has to be taken when designing the ion optical elements in order to reduce geometrical as well as chromatic aberrations to a minimum. Usually electrostatic quadrupole lenses would be very well suited for beams with an energy of a few keV per charge [25], since the voltages at the electrodes can be kept low and the power supplies are cheap. However, due to the large angular spread quadrupoles are not advantageous in comparison to cylindrical einzel lenses. Furthermore, ion beams with a very low mass-to-charge ratio (<3) are very vulnerable to stray magnetic fields and even to the magnetic field of the earth. Therefore, the distance between two focal points should be less than 1 m. For
differential pumping at least two diaphragmas have to be foreseen, i.e. two focal points along the transfer line between RFQ and cooler trap. The presently best solution seems to be electrostatic einzel lenses in accelerating mode, relying on a spherically symmetric beam that is produced by the RFQ by shaping the RFQ rods accordingly. An arrangement of six einzel lenses will generate the necessary two focal points and enable the matching of the beam into the magnetic field of the cooler trap. The electric and magnetic fields along the transfer line are plotted in Fig. 2. By the use of einzel lenses in the accelerating mode aberrations can be kept low since the lenses can be small and still the beam does not fill the lens too much.

### 3.3.2. The cooler trap

The cooler trap serves to capture the highly charged ions in flight and to decrease its phase space volume and hence to cool the ion beam. A cylindrical Penning trap in a magnetic field of 6 Tesla is used. The trap will consist of 23 electrodes that can be used to shape the potential very flexibly and to create three harmonic trap regions for ions.
and two for electrons. The central electrode will be split into eight radial segments to enable different schemes of radial excitation and observation of the ion cloud. The two outermost electrodes have a reduced inner diameter for differential pumping. They are biased to about 18 kV in order to confine the ions as for instance $^{238}$U$^{92+}$ entering the trap with an energy of 6 keV/u. Figure 3 shows the design of the trap electrodes along with a possible potential slope on the symmetry axis of the cylindrical electrode stack.

The first step of the cooling process is the in-flight capture. For this, the ion bunch with a pulse length of about 1 μs will be injected into the trapping region and decelerated further from 6 keV/u to approximately 2 keV/u while the ion beam is kept radially small by the strong magnetic field. The incoming bunch is reflected at the downstream trapping electrode and trapped by switching the upstream trapping electrode from the initial potential of $\approx$11 kV to about 18 kV just after injection of the ion bunch. The switching has to be performed within less than 400 ns.

During the second step the HCI interact with two electron clouds which are stored simultaneously. The electrons have a kinetic energy corresponding to 4 K since they emit synchrotron radiation during their storage in a high magnetic field and hence are in equilibrium with the surrounding. To avoid ion-electron recombination it is necessary to separate the ion and electron clouds as soon as their velocities get similar, i.e. for an ion energy below about 10 eV. Since dielectronic recombination is not possible for bare ions and the electron densities are still too low for three-body recombination processes, only radiative recombination must be taken into account. Calculations show that more than 90% of the bare uranium ions sent initially into the trap remain in the original charge state within the projected cooling time of a few seconds [26].

FIGURE 3. Schematics of the trap electrodes (top) and calculated potential on the axis of the cylindrical electrodes (bottom).
After separation of electron and ion clouds the ions will be cooled further using resistive cooling. The ion cloud oscillating in the Penning trap induces an image charge and hence an image current in the trap electrodes. If this signal is detected and fed into a resonant circuit kept at 4 K, the ion motion is damped [8].

Two modes of extracting the cooled ion cloud are foreseen: slow extraction and bunched extraction. If extracted in a bunch, the scheme is very similar to existing trap facilities where up to 100 million singly charged ions are extracted in a 15 μs pulse [27]. This mode is especially well suited such experiments where the ions need to be recaptured in a trap. The slow extraction mode will allow one to distribute the 100 000 ions over the 10 s that are available until the next decelerated ion bunch arrives. This mode is for example well suited for the ion-surface interaction experiments in order to avoid detector saturation.

### 3.3.3 Vacuum requirements

Due to the high charge states the cross sections for electron capture are rather high. Therefore, the residual gas pressure has to be kept as low as possible.

For heavy, HCI as for instance U$^{92+}$ no experimental data exists for ion energies
around 2 keV/u relevant for the low-energy beam lines of HITRAP. Therefore, two theoretical approaches have to be used instead: the classical over-barrier model [28] and an empirical formula by Schlachter [29] that is fitted to experimental data for slightly lower charge states. Both, model and formula, depend on the ionization potential of the residual gas atom and the charge state of the ion. For simplicity a constant ionization potential of 10 eV has been assumed, which is well below the one for common residual gas components like O\textsubscript{2}, H\textsubscript{2} or H\textsubscript{2}O and hence yields rather pessimistic values. Then, the cross sections for single-electron capture from U\textsuperscript{92+} into U\textsuperscript{91+} are 3 \cdot 10^{-13} cm\textsuperscript{2} for the classical over-barrier model and 5 \cdot 10^{-13} cm\textsuperscript{2} for the Schlachter formula. Neither the over-barrier model nor the Schlachter formula depends on the energy of the ion. They are both regarded as valid for ion energies between 10 eV and 25 keV/u. The uncertainties are very hard to estimate for the Schlachter result, since it is in fact an extrapolation of experimental data. The cross sections calculated with the classical over-barrier model are normally valid within 20%. For ion energies below 10 eV, relevant for the last cooling stage in the trap, the semi-empirical model by Olsen and Salop is valid [30]. In this model the charge exchange cross section depends linearly on the relative velocities of the collision partners and gives for very low energy (equivalent to 4 K) slightly higher cross sections than the other two formulas.

Using this information it is possible to calculate the fraction of the ion beam that will undergo a charge exchange reaction and hence be lost for the experiment. The fractional loss per meter is calculated using the Schlachter formula as a function of the residual gas pressure and plotted in Fig. 4. Evidently, a residual gas pressure below 1 \cdot 10^{-9} mbar is required to keep the beam losses below 1% for a 10 m beam line. Since all estimates were done using the less favourable values for ionization energy and cross section a pressure below 1 \cdot 10^{-9} mbar should be sufficient for the transfer beam lines.

The vacuum requirements for the trap itself are of course much more stringent. Here, it should be possible to store heavy HCl at least for 10 seconds without losses due to vacuum conditions. Therefore, the pressure has to be well below 1 \cdot 10^{-13} mbar assuming above mentioned cross sections for electron capture. This is one of the reasons why the trap region will be kept at a temperature close to 4 K.

The vacuum system sketched in Fig. 5 is based on ultra-high vacuum technology. Turbo-molecular pumps will be used during the bake-out period. After bake-out the

**FIGURE 5.** Sketch of the vacuum system for the low energy beam line between RFQ decelarator and cooler trap and for the cooler trap (all dimensions in mm). The letters name the sections. The arrows indicate positions where pumping takes place. The RFQ will be connected at position (1).
system will be pumped by standard ion getter pumps (3001 s⁻¹), indicated in the figure by the arrows numbered (2), (3), (4) and (6). The system has been analyzed using first-order principles like tube conductances at different temperatures [31]. An out-gassing rate of 10⁻¹² mbar·l·s⁻¹ cm⁻² has been assumed after bake-out for all surfaces outside the trap region. The pressure in the RFQ is assumed to be about 10⁻⁸ mbar (position (1) in Fig. 5). Assuming H₂ as main gas component one calculates a pressure of 5 · 10⁻⁹ mbar in section A and already 2 · 10⁻¹⁰ mbar in section B. In sections C and E the pressure is estimated to 1 · 10⁻¹¹ mbar. The cryopumping effect of the trap has been accounted for by simulating a pump at position (5). The assumption of a pumping speed of 5 l·s⁻¹ cm⁻² [32] yields a total pumping speed of about 12.000 l/s for the available surface at 4 K. A pressure of < 10⁻¹³ mbar is obtained inside the trap with the installed diffusion barrier with an inner diameter of 10 mm. Even lower pressure can be envisaged if this diffusion barrier is opened only for the short period of time when the ion bunch is injected into the trap every 10 seconds.

4. STATUS

HITRAP is a project to produce and slow down highly charged ions up to bare uranium. The construction of the major parts of the decelerator has been started in the beginning of 2005. The superconducting magnet will be ordered mid of 2005. Many of the experimental setups presented in this paper are already prepared and are proceeding with tests using lower charged ions.

HITRAP is also an integral part of the low-energy antiproton and ion facility FLAIR. There the evaluation of the experimental program yielded very positive results for FLAIR and the technical design issues are being worked out.

ACKNOWLEDGMENTS

We would like to thank those who contributed to the HITRAP technical design report. Many of the information presented here has been taken from this report. We thank also M. Kauschke and C. Welsch for valuable discussions. We acknowledge furthermore the support by the European Commission under contract number HPRI-CT-2001-50036 (HITRAP) and by the German Ministry for Education and Research (BMBF).

REFERENCES


