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Progress at the Heidelberg EBIT

Jose R. Crespo Lopez-Urrutia

Jean Pierre Braun

Gunter Brenner

Hardo Bruhns

et. al. For a complete list of authors, see http://scholarsmine.mst.edu/phys_facwork/785

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Progress at the Heidelberg EBIT

J. R. Crespo López-Urrutia, J. Braun, G. Brenner, H. Bruhns,
C. Dimopoulou, I. N. Draganić, D. Fischer, A. J. González Martínez,
A. Lapiere, V. Mironov, R. Moshhammer, R. Soria Orts,
H. Tawara, M. Trinczek, and J. Ullrich

Max-Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany

Abstract. Two years after the relocation of the Heidelberg EBIT, several experiments are already in operation. Spectroscopic measurements in the optical region have delivered the most precise reported wavelengths for highly charged ions, in the case of the forbidden transitions of Ar XIV and Ar XV. The lifetimes of the metastable levels involved in those transitions has been determined with an error of less than 0.2%. A new, fully automatized x-ray crystal spectrometer allows systematic measurements with very high precision and reproducibility. Absolute measurements of the Lyman series of H-like ions are currently underway. Dielectronic recombination studies have yielded information on rare processes, as two-electron-one photon transitions in Ar¹⁶⁺, or the interference effects between dielectronic and radiative recombination in Hg⁷⁷⁺. The apparatus can now operate at electron beam currents of more than 500 mA, and energies up to 100 keV. A further beam energy increase is planned in the near future. Ions can be extracted from the trap and transported to external experiments. Up to $4 \cdot 10^7$ Ar¹⁶⁺ ions per second can be delivered to a 1 cm diameter target at 10 m distance. Charge-exchange experiments with U⁶⁴⁺ colliding with a cold He atomic beam have been carried out, as well as experiments aiming at the optimization of the charge state distribution of the extracted via dielectronic recombination. Two new EBITs, currently in advanced state of construction in Heidelberg, will be used for experiments at the VUV free electron laser at TESLA (Hamburg) and for the charge breeding of short-lived radioactive isotopes at the TRIUMF ISAC facility.

INTRODUCTION

The availability of ions in the highest charge states is still limited to a few laboratories: Only two sites worldwide can currently carry out atomic physics research with the highest charge states, the H-like ions of the heaviest elements. Even for ionic species at somewhat lower charge states, the selection of suitable facilities is very limited. Thus, as a direct consequence, we are still facing a substantial lack of experimental data. Highly ionized atoms are not exotic artificial objects, but very common constituents of the cosmic visible matter. During nuclear synthesis e.g. in supernovae, extreme temperatures clearly keep electrons unbound around the new nuclei. Also active galactic nuclei, shocks, accretion disks, stellar winds and coronae are characterized by the presence of highly charged ions. In fusion energy research, HCI-related reactions represent an essential part of the energy budget and their spectroscopic observation is a powerful diagnostic tool. Therefore, precise experimental data on their structure, as well as on reactions like recombination, photon and electron impact ionization, or the changes in nuclear reactions (cross sections, rates) sensitive to the electronic structure (e.g.

bound β -decay) are of paramount importance and thus urgently required. The electron beam ion trap has proven to be one of the most useful tools in this field. Apart from the relevance of HCI research for many applications, an intrinsic interest arises from the structural simplicity of few-electron or one-electron ions. The magnification of fundamental effects - scaling with high powers of the nuclear charge Z - makes HCIs ideal objects for the study of quantum electrodynamics (QED) in strong fields. While the average electric field $\langle E \rangle$ experienced by the $1s$ electron in H is 2.8×10^{10} V/cm, it rises in U^{91+} by six orders of magnitude to $\langle E \rangle = 1.8 \times 10^{16}$ V/cm. The local values of E and B on the nuclear surface reach 2×10^{19} V/cm and 10^8 T, respectively. The spatial overlap and field strength seen here make the $1s$ wave function highly sensitive to nuclear size effects, relativistic contributions, parity non-conserving amplitudes and others. Moreover, transition probabilities for higher terms in the perturbation expansion usually scale with high power of Z ; an example among many others in which otherwise weak QED terms and amplitudes become essential and thus easier to analyze.

THE HEIDELBERG EBIT FACILITY

The new Electron Beam Ion Trap in Heidelberg at the Max-Planck-Institute for Nuclear Physics is dedicated to the study of highly charged ions. It has greatly expanded the range of ionization stages and ion velocities available on site, providing an ideal complement to the on-site ion storage ring TSR. Designed to produce up to bare uranium ions (U^{92+}) and keep them trapped at velocities as low as $10^{-4} c$ (c : speed of light), it thus allows precision spectroscopic measurements at negligibly small Doppler broadening. The new laboratory occupies roughly 200 m^2 in the Accelerator Building. It is comprised of a large Faraday room where the EBIT is installed, a control room, a laser laboratory, and an experimental hall with beamlines for research with extracted ions. The site was completely renovated and redesigned in 2001. Two more laboratories, a data acquisition and computing room, a clean room, as well as a high energy beamline in a radiation protection cave add more than 300 m^2 of space to the facility.

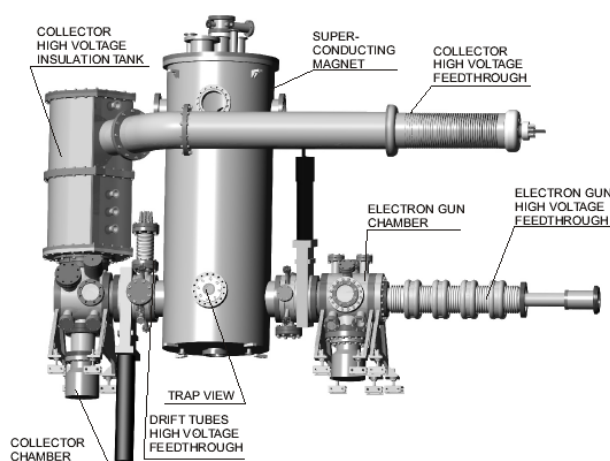


FIGURE 1. The Heidelberg EBIT.

Presently, all other cryogenic EBITs are more or less identical to the Livermore EBIT-II device (those at LBNL, NIST, Oxford, and Berlin) or follow closely the Livermore SuperEBIT design (Tokyo). They can reach electron beam energies of up to 30 keV and typically produce ions like Ne-like Xe⁴⁴⁺ up to He-like Xe⁵²⁺. SuperEBIT can reach energies of 200 keV and has yielded minute amounts of bare U⁹²⁺ (a few ions). Yet the relatively low maximum beam energy (compared with 130 keV U⁹¹⁺ 1s binding energy) and 250 mA beam current impose long measurement times for spectroscopic studies. The Tokyo EBIT has reported operation at 150 keV and 150 mA. Unfortunately, the LLNL original EBIT design suffers from its large liquid helium consumption (5 l/hour) causing high running costs which have probably curbed a wider application of this technique in other laboratories. Furthermore, its vertical arrangement has some disadvantages for the extraction of ions and their transfer to external experiments. Thus, a new design was developed during 1998-99 at Freiburg University and culminated in the successful operation of a horizontal EBIT (cf. Fig. 1) whose helium boil-off is reduced by a factor of 25, being well adapted for spectroscopy and extraction applications. The intended specifications (350 keV, 750 mA) should help reduce measurement times and allow us to work with the most extreme ions. The Freiburg EBIT moved in July 2001 to the MPI-K, resumed operation by the end of that year, and has produced electron beams of 100 keV or currents of 535 mA. The ion yield (U⁸²⁺, Hg⁷⁸⁺, Ba⁵⁶⁺, Kr³⁶⁺) has been satisfactory, although optimization of the high energy electron beam is still in progress. The design values are within reach with the recently set up new high voltage configuration (December 2002); after short conditioning 125 keV has been sustained. A magnetic field of up to 9 T is used for electron beam compression. Two thermal shields (50K, 20K) isolate the 4K magnet surfaces and provide additional pumping. Nine drift tubes give a large flexibility in trap length and ion extraction schemes. Two large radial bores (40 mm diameter) allow good access for diagnostic purposes with optical, UV and x-ray spectrometers already in place. Ions are extracted in pulsed and continuous modes at energies of typically 10 keV/q. After mass selection, they can be further accelerated by floating the entire platform to potentials up to 300 kV. The beamline vacuum in the 10⁻¹⁰ mbar range minimizes charge-exchange losses. The ion beam is switched by a magnet to any of five beamlines in the experimental hall. A reaction microscope for COLTRIMS is also in operation. Some of the beamlines are available for external users from fields such as surface physics, molecular fragmentation, precision mass spectroscopy with Penning traps, and others.

EXPERIMENTAL DEVELOPMENTS

High precision measurements of QED-sensitive transitions in Be-like and B-like Ar ions

An experimental study of the visible magnetic dipole (M1) transitions in the B- and Be-like argon ions (Ar XIV, Ar XV) using an electron beam ion trap (EBIT) has been recently carried out. Their wavelengths were determined with for highly charged ions unprecedented accuracy up to the sub-ppm level and compared with predictions [1]. The

QED contributions calculated in this work are four orders of magnitude larger than the experimental error (cf. Table 1).

TABLE 1. Comparison of the experimental and theoretical results from this work.

Ion	CIDF (cm^{-1})	QED (cm^{-1})	Total (cm^{-1})	QED (nm)	Theory (nm, air)	Experiment (nm, air)
Ar XIV	22612.8(12.0)	49.5(7.0)	22662(14)	-0.96	441.16(27)	441.2559(1)
Ar XV	16770.9(3.0)	53.4(8.0)	16824.3(8.5)	-1.89	594.24(30)	594.3880(3)

The Zeeman splitting of these transitions has also been resolved (cf. Fig. 2). The transition probability was measured with an error smaller than 0.2% in the case of the $\text{Ar}^{13+} 2s^2 2p^1 \ ^2P_{1/2} - ^2P_{3/2}$ transition, where the QED contribution modifies the lifetime by roughly 1%. Thus these results allow to benchmark theoretical models used to predict both the energy levels (in the present work configuration interaction Dirac-Fock, CIDF) and the transition matrix elements under inclusion of QED. Ultimately, the techniques developed in these experiments will be applied to the study of the hyperfine ground state transitions in hydrogenic heavy ions and isotopic shifts [2].

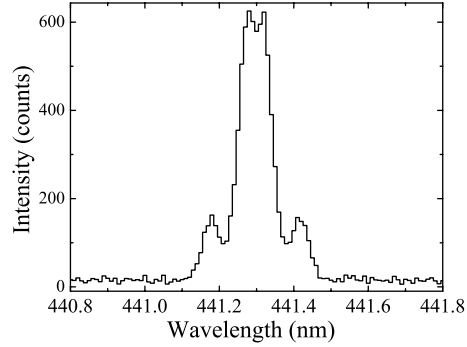


FIGURE 2. Zeeman components of the $\text{Ar}^{13+} 2s^2 2p^1 \ ^2P_{1/2} - ^2P_{3/2}$ transition.

Precision lifetime measurement of the $\text{Ar}^{13+} 2s^2 2p^1 \ ^2P_{3/2}$ metastable level

Another interesting aspect of the EBITs is that they offer the possibility of studying radiative transitions with lifetimes as long as several milliseconds. The first implementation of this method at the Heidelberg EBIT consisted in the lifetime measurement of the first-excited energy level of boronlike Ar XIV. The forbidden transition at 441.26 nm arising from this level was used to monitor its depopulation (cf. Fig. 3). The high light collection efficiency of our setup allowed us to observe evidence of a small population of low-energy electrons trapped in the drift tube region of the trap, which are responsible for reexcitation and quenching of the low-lying metastable levels.

The sensitivity of the decay curves to trap parameters makes it possible to use such electrons to probe ion losses from the trap and to correct this systematic contribution from the apparent lifetimes. In this way, an accuracy level of 0.22% is achieved at the determination of the lifetime of the $\text{Ar}^{13+} 2s^2 2p^1 \ ^2P_{3/2}$ level. The result is $(9.597 \pm$

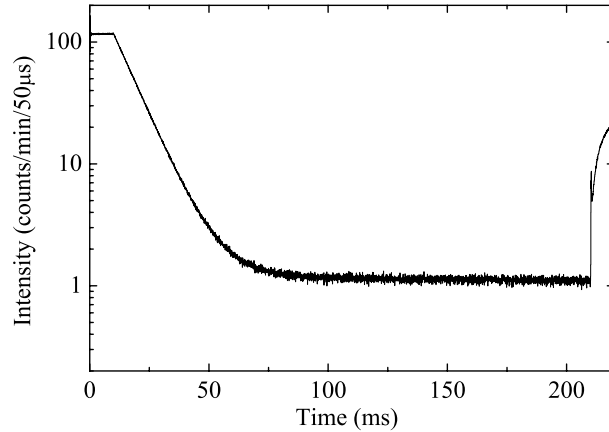


FIGURE 3. Intensity of the 441.26 nm line after turning off the electron beam.

0.021) ms, in agreement with a recent measurement at the LLNL EBIT [3], but almost an order of magnitude more precise, allowing to distinguish between different theoretical models. This measurement sets a new standard regarding lifetime measurements in highly charged ions and offers the possibility of observing the influence of quantum electrodynamic (QED) contributions to the lifetimes of excited-states.

Laser spectroscopy of hydrogenic ions at the Heidelberg EBIT

In order to improve the resolution achievable in the study of transitions in the visible range, an experimental setup for high resolution laser spectroscopy of highly charged ions has also been installed. Heavy ions with few (or even only one electron) are ideal systems to investigate relativistic and nuclear size effects as well as QED in strong fields and to test the corresponding models. In particular, the hyperfine transitions in the ground state of heavy hydrogenic ions have been already investigated in storage rings by means of laser spectroscopy [4],[5] and EBITs with spontaneous emission spectroscopy [6],[7],[8]. These studies have fuelled intense discussions on the contributions of the nuclear magnetization distribution and QED effects to the observed transition wavelengths.

The combination of an EBIT and a tunable laser should provide very appropriate conditions for high-precision studies on trapped highly charged ions. A pulsed Nd:YAG laser (100 Hz, 9ns, 325 mJ at 1064 nm, 100 mJ at 532 nm) is used to pump a tunable dye laser. The spectral range 210-800 nm can be accessed with a resolution of 0.04 cm^{-1} . The beam is superimposed axially upon the trapped ion cloud by means of off-axis parabolic mirrors inside a complex UHV vacuum chamber. The fluorescence detection system uses both a Czerny-Turner spectrometer with a cryogenically cooled CCD and photomultiplier tubes (cf. Fig. 4). A data acquisition system has also been developed and tested. The setup is now undergoing initial tests and adjustments under ion trapping conditions.

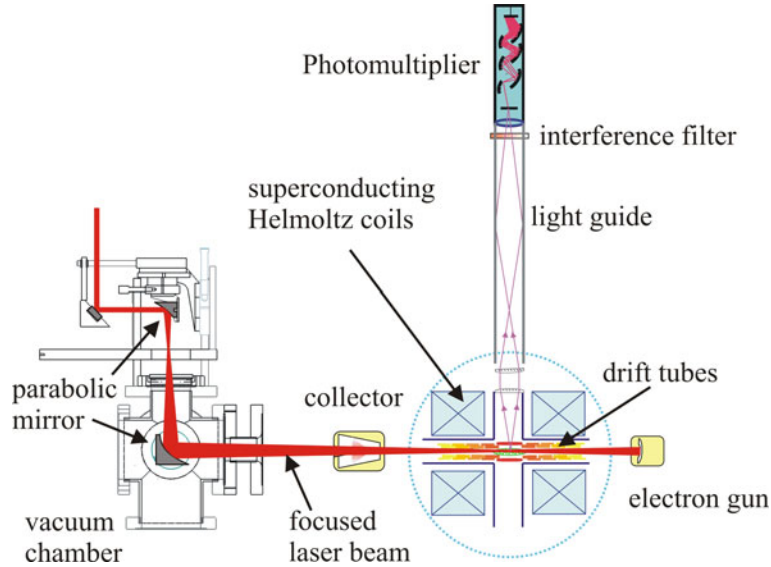


FIGURE 4. Experimental setup for laser spectroscopy at the Heidelberg EBIT.

Absolute wavelength measurements of the Lyman- α transitions in highly charged ions

X-ray spectroscopy of hydrogen-like ions in the mid-Z range has delivered until now the energies of the Lyman- α lines with uncertainties not lower than 5 ppm. These transitions are interesting since they offer the possibility to study QED in strong electrostatic fields. As an example, the contribution of the Lamb shift of the 1s state to the $\text{Ly}_{\alpha 1}$ transition of H-like Ar at 3322.98 eV is larger than 1 eV. Hydrogenic transitions should in future provide new x-ray wavelength standards. A new crystal spectrometer has been built at the Heidelberg EBIT with the purpose of reducing experimental uncertainties to less than 1 ppm and eliminate the need for relative calibrations with secondary wavelength standards. The measurements will deliver absolute energies derived only from the lattice spacing of the crystals used and from angular measurements, and in general independent from other geometry parameters of the setup.

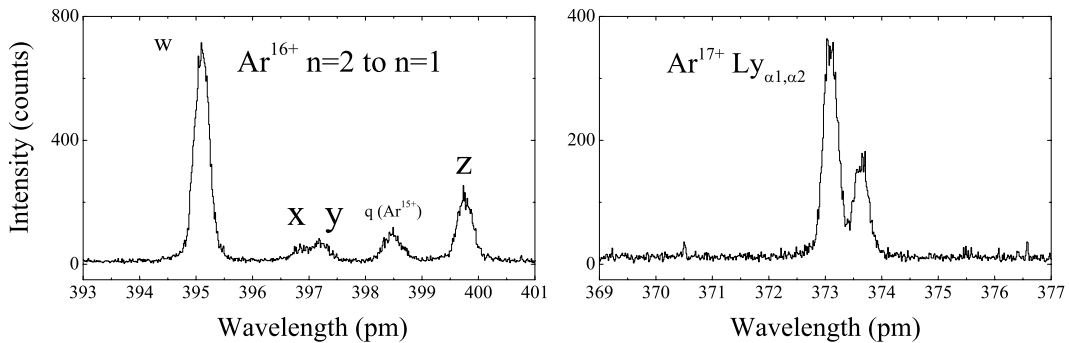


FIGURE 5. Spectra of the $n=2$ to $n=1$ transitions in H-like Ar^{17+} and He-like Ar^{18+} ions obtained with the Heidelberg EBIT flat crystal spectrometer.

The fully automatized spectrometer allows to collect hundreds of spectra at the EBIT (Fig. 5) at variable angles in several days of continuous data acquisition without any operator intervention, thus keeping the experimental conditions very stable and delivering excellent statistics for the intended accuracy. The angular measurements are reproducible at the level of (5×10^{-5}) degrees. Systematic effects due to crystal imperfections, lattice spacing determination and misalignments devices are currently being evaluated. Tests were carried out with Ar ions, for which high precision data are available. Using the position of $\text{Ly}_{\alpha 1}$ to calibrate the Bragg angle, we obtain for the He-like w-transition $1s2p\ ^1P_1 \longrightarrow 1s^2\ ^1S_0$ a preliminary value of 3139.625(20) eV, to be compared an earlier result of 3139.552(36) eV [9]. The largest contribution to our error bars arises from the uncertainty of the $\text{Ly}_{\alpha 1}$ experimental wavelength (5 ppm).

Quantum interference in the photorecombination of the highly charged mercury ions Hg^{78+} to Hg^{75+}

The study of deep-lying dielectronic resonances with EBITs has yielded many interesting results in recent years. A particularly interesting subject is the quantum interference between different channels of the photorecombination process. In the photoionization of atoms the effect of interference between the transitions leading directly into the continuum and those having a discrete autoionizing intermediate state results in asymmetric line shapes. Photorecombination shows similar features through the interference of direct (radiative) recombination and indirect (dielectronic) recombination. As both paths are indistinguishable, interference effects appear. Asymmetric line shapes in the KLL resonance region were observed at the (EBIT) in Heidelberg with He- to B-like mercury ions ($\text{Hg}^{78+ \dots 75+}$), as displayed in Fig. 6. The results confirmed an earlier observation of this effect in equivalent, isoelectronic $\text{U}^{90+ \dots 87+}$ ions. The so-called Fano factor, which characterizes this asymmetry, was obtained for the most intense resonances of the dominant charge states in the trap [11]. In addition, the fine structure splitting be-

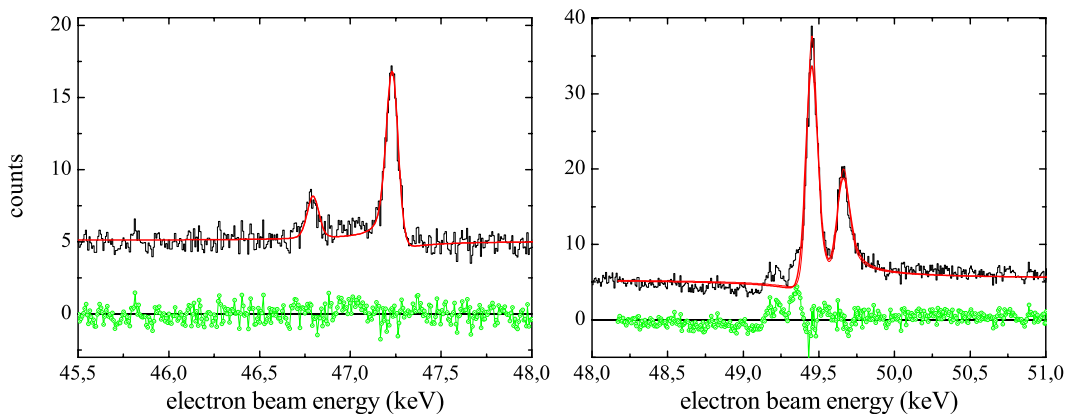


FIGURE 6. Two different dielectronic resonances showing opposite Fano factors.

tween levels with a total angular momentum $J=1/2$ and $J=3/2$, which amounts to roughly 2 keV, was measured for the Li, Be and B-like Hg ions with uncertainties as low as 1

eV. The experimentally determined resonance strengths and Fano parameters are compared with relativistic many-body perturbation theory predictions as well as with *ab initio* QED calculations. Earlier experiments in this area studied the weak two-electron-one-photon transition in He-like Ar [11].

Electron capture in collisions of highly charged ions with neutral atoms studied by cold target recoil ion momentum spectroscopy (COLTRIMS)

The ions extracted from the EBIT are used to investigate the charge-exchange process with state selectivity in kinematically complete experiments. Initial studies in Freiburg dealt with Ne^{7+} colliding upon He [12]. Currently, collisions of U ions in very high charge states are being investigated. The preliminary data analysis shows the population of states with $n \approx 22$, as well as simultaneous multiple electron capture and reemission of the electrons through Auger processes. Figure 7 shows the scattering angle and the Q-value of 640 keV U^{64+} ions colliding with He atoms in a reaction microscope.

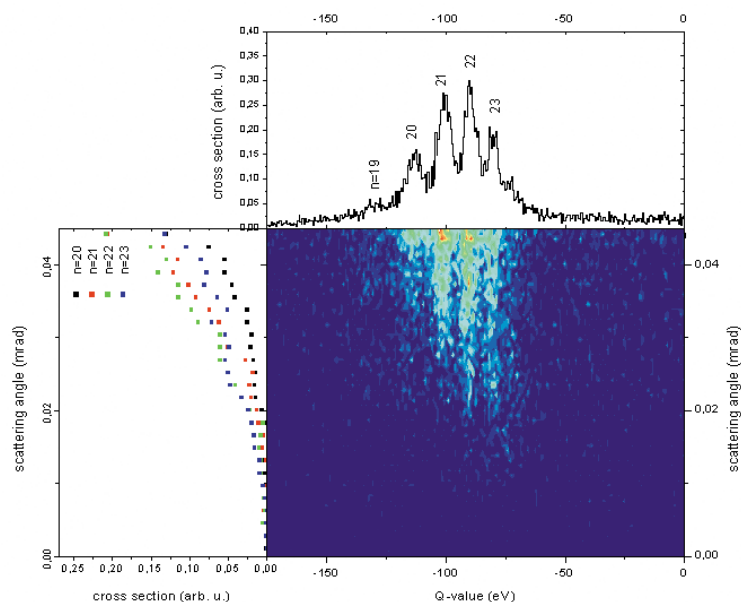


FIGURE 7. Scattering angle for the different states populated in the electron transfer in collisions of U^{64+} and He atoms at 640 keV.

Charge breeding for radioactive ion beams

The Heidelberg-EBIT group is responsible for the setup and commissioning of a new high-current (5 A electron beam) EBIT (Fig. 8), which will be used for charge-breeding purposes. Short-lived radionuclides produced at the ISAC facility at TRIUMF (Vancouver, Canada) will be studied with a Penning trap mass spectrometer in the framework of

the TITAN project. The TITAN high-precision Penning trap is used to determine the nuclear mass by measuring the cyclotron frequency of trapped ions. The cyclotron frequency, ν depends not only on the mass of the ion but also grows linearly with the magnetic field of the trap and the charge-state of the ions; $\nu = B \cdot q/m$. The accuracy in the frequency determination, $\Delta\nu$, mainly depends on the duration of the measurement. Therefore, the relative accuracy of the mass measurement can be increased by preparing the ions of interest in a higher charge state. Another consequence is the fact that the desired accuracy can be attained within a shorter measurement time. This is an important issue for high-accuracy mass measurements on rare isotopes with nuclear half-lives significantly shorter than 1 second. During the charge breeding time, high-resolution spectroscopic measurements in the visible and x-ray region will be carried out with isotopes which become available for these types of studies for the very first time. They should provide a better understanding of isotopic shifts and nuclear size effects and deliver valuable input for nuclear theory. After the favorable review of this proposal by Canada's NERSC Advisory Committee, funding and construction started in 2003. Preliminary measurements (EBIT emittance and admittance, ion yield) are underway. The Heidelberg group also participates in the European network "ADVANCED CHARGE BREEDING project", with the task of optimizing the charge state yield with an EBIT in order to ensure minimum losses of the rare isotopes in future experiments.

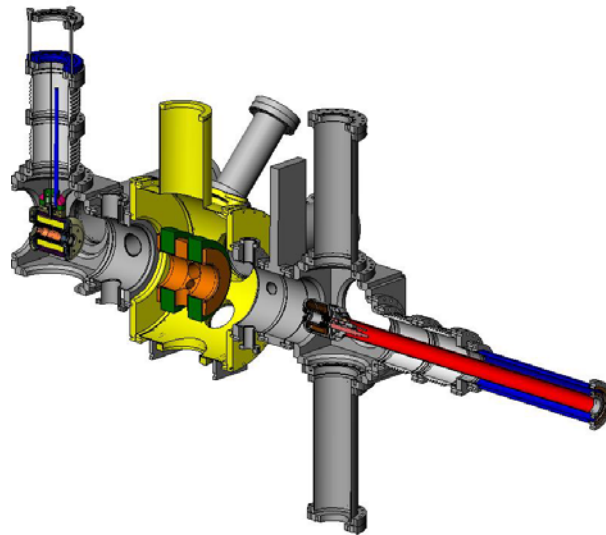


FIGURE 8. Heidelberg design study for the new TESLA/TRIUMF EBITs.

OUTLOOK

The realization of two major projects - an EBIT for the VUV free electron laser at the TESLA laboratory in Hamburg and the development of a new EBIT for the charge-breeding of radioactive isotopes at TRIUMF have been central issues in the period 2003-2004. The VUV-FEL beams (up to 250 eV) at the TESLA Test Facility will allow from 2005 on the detailed study of photoexcitation and multiphoton processes with HCIs

trapped in the EBIT. Fluorescence detection schemes will be applied. The photon flux there is expected to surpass that of any current synchrotrons by orders of magnitude, improving statistics, resolution and, thus, opening new avenues to the study of HCIs. The construction of the two new EBITs, which use cryogen-free 6T superconducting magnets, is already well advanced, and subassemblies such as electron guns, collectors have already been built. Test operation of the new devices is expected to start by the end of 2004. A collaboration with the Vienna University of Technology has started with the purpose of studying ion-surface interactions.

In summary, several new experiments have started to yield scientific results at the new Heidelberg EBIT facility, offering a wide range of possibilities for the study of highly charged ions and their interactions with photons, electrons, atoms and surfaces.

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