STATUS OF THE G-FACTOR EXPERIMENT ON HIGHLY CHARGED CALCIUM

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Measurements of the anomalous magnetic moment of the electron bound in hydrogen-like ions have proven to be highly sensitive tests of corresponding calculations based on bound-state quantum electrodynamics. The calculations of the g-factors of the electron bound to hydrogen-like carbon and oxygen and their corresponding measurements performed by the collaboration of GSI and the University of Mainz [1,2] agreed within nine significant digits.

Presently, a triple Penning trap experiment on highly charged calcium is prepared (Fig. 1) [3,4], which is expected to yield a precision on the level of 10^{-9} for the electronic g-factor of $^{40,48}Ca^{17,19+}$. This experiment makes use of a cryogenic in-trap electron-beam ion source (EBIS) at T = 4 K, where the charge breeding of the ions is performed by electron-impact ionization [5].

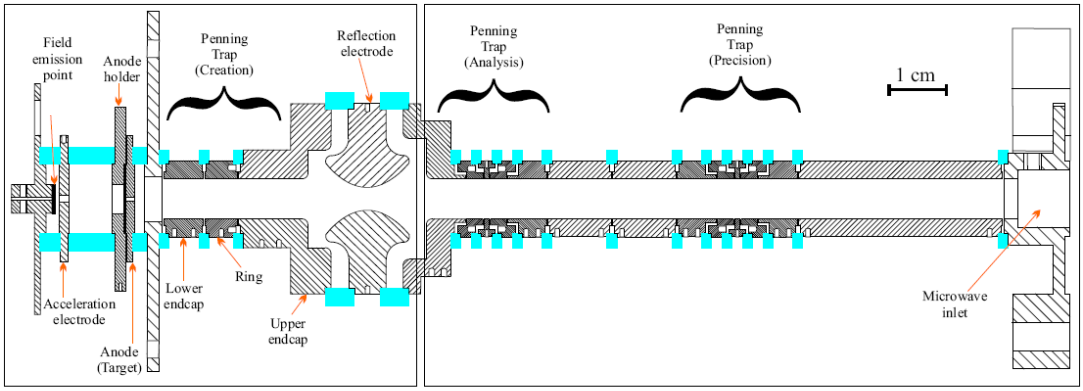

Fig. 1 Experimental setup including the EBIS for charge breeding, the analysis trap for spinflip detection, and the precision trap for the measurement of the eigenfrequencies of a single ion.

The electron source is based on a single field emission point (FEP) made from tungsten. The emission of an electron current of some nA up to 100 nA is achieved by applying a voltage between the FEP and an extraction electrode. The electron beam is reflected several times between a reflector and the FEP until it widens up and hits the target, which consists of graphite with a layer of calcium. Atoms from the target get ionized by electron impact and are trapped in the centre of the EBIS. For recording a mass spectrum, the electric trapping potential is ramped to bring the ions into resonance with an electronic detection circuit. After charge breeding the ions are transported either to the analysis trap or the precision trap. The precision trap has a homogeneous magnetic field for precise measurement of the eigenfrequencies of the stored ion. In the analysis trap the magnetic field is inhomogeneous for the detection of the spin direction. We report on new results regarding successful charge breeding tests in the EBIS and commissioning of the analysis and precision traps.

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HITRAP – A FACILITY FOR PRECISION EXPERIMENTS ON HEAVY HIGHLY CHARGED IONS IN EXTREME ELECTROMAGNETIC FIELDS

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HITRAP is an ion trap facility for heavy highly charged ions at GSI [1-3]. Commissioning is expected for autumn 2008. HITRAP (Fig.1) uses the GSI relativistic ion beams, the Fragment Separator FRS, if required, for production of radionuclides, the Experimental Storage Ring ESR for electron cooling and deceleration to 4 MeV/u, a combination of an interdigital H-mode (IH) structure with a radiofrequency quadrupole structure for further deceleration to 6 keV/u and a Penning trap for accumulation and cooling. Finally, ion beams with low emittance are delivered to a large variety of atomic physics experiments. Transferred to and stored in an ion trap kept at 4 K, a trapped and point-like sample is realized. Such a situation allows for highest accuracy from the experimental as well as from the theoretical point of view. For the most ambitious case, U^{92+}, we expect to load the cooler trap every 10 seconds with 10^5 ions.

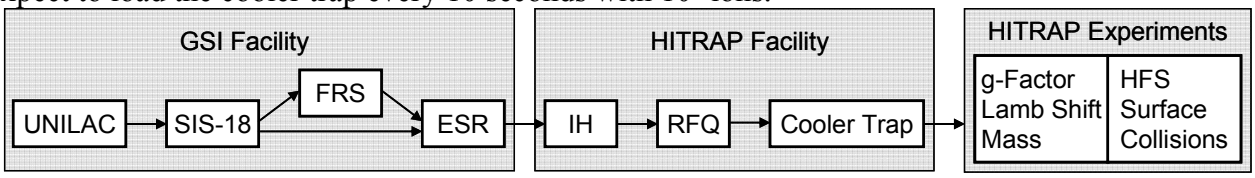

Fig. 1. The HITRAP facility under construction at GSI.

With this novel technique of deceleration, trapping and cooling of highly charged ions, atomic physics studies on slow highly charged ions up to uranium U^{92+} interacting with photons, atoms, molecules, clusters, and surfaces will become possible. In addition to collision studies, high-accuracy atomic physics experiments on trapped or slow HCI will be a significant part of the atomic physics program of the HITRAP facility.

Sensitive tests of quantum electrodynamics (QED) for bound electrons in the strongest electromagnetic fields available in the laboratory for extended periods of time will be performed by measuring the g-factor of the bound electron, the binding energies of a single or of few electrons including the Lamb shift, or the hyperfine structure (HFS) of a stable isotope of an element in different high charge states with utmost accuracy. The results for stable isotopes are then compared with state-of-the-art QED calculations. If the QED effects are under control so that they are calculable with sufficient accuracy or if they can be almost eliminated by measuring the same nuclear quantity in different charge states, the results can be used also to address questions in metrology, in nuclear physics and particle physics.

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Re-trapping and Cooling Highly-Charged Ions

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Presently, a trapping system for cooling highly-charged ions that were extracted from the new Stockholm electron-beam ion trap (S-EBIT) is being set up at AlbaNova (Fig.1). The experiment aims at production of low temperature (emittance) highly-charged ions at very low energy for injection into the precision trap of SMILETRAP II. As a first step the Penning-type cooling trap with deceleration and acceleration system, which facilitates the injection and extraction, was brought into position and successfully tested. Ions can be created either externally, i.e., in the ion sources S-EBIT or SMILIS, or internally by transmitting a 4 kV electron beam through the trap to ionize rest gas. The segmented centre electrode allows for rf-excitation for cleaning the cooling trap from unwanted ions. Currently, a pepper-pot emittance meter is being installed to monitor the emittance of trapped ions in real-time.

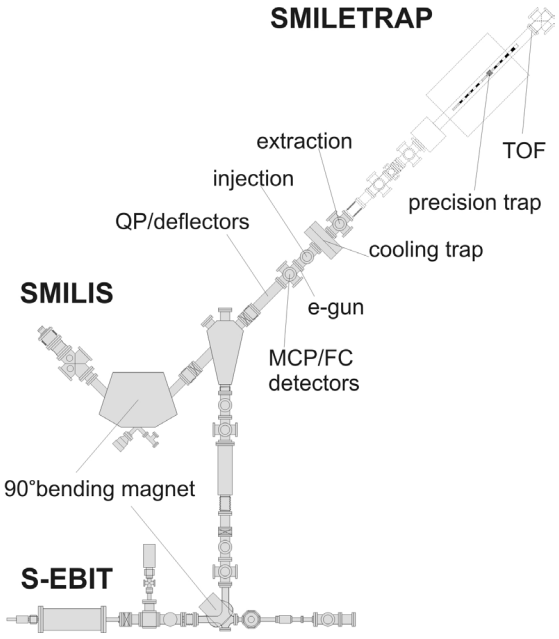

Fig.1 Layout of the HCI facility at AlbaNova.

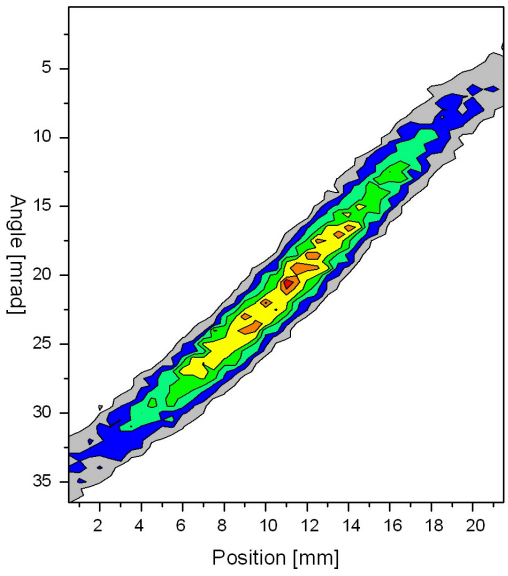

Fig.2 Emittance of Ar^{16+} ions trapped for 100 us.

From S-EBIT and SMILIS two ion species, highly-charged and low charged ions (e.g. S^{14+} or Ar^{16+} and He^{+}) could be injected sequentially and stored simultaneously in the cooling trap. The emittance of the trapped ions was measured (Fig.2), which will be used for optimizing the evaporation of the light ions to cool the highly-charged ions in the cooler trap. For the primary ions, emittances in the order of a few mm·mrad and energy spreads of few qeV were measured. It is expected that these values will be reduced and highly charged ions of 0.1 qeV energy spread can be extracted as pure ion beam.

TRAPPING OF HIGHLY CHARGED IONS WITH AN ELECTROSTATIC ION TRAP

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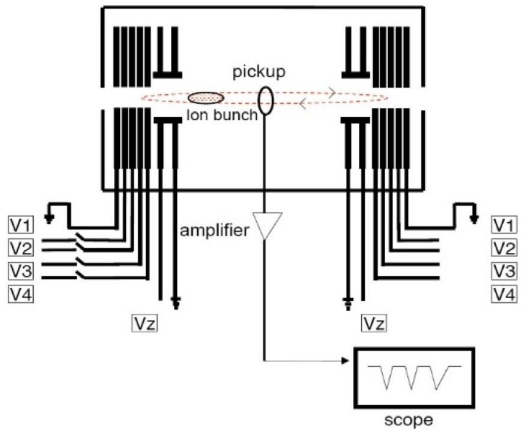
Following a design from the Weizmann Institute [1], an electrostatic trap has been constructed and attached to the beam line of "SIMPA" (Source d'ions Multichargés de Paris) an Electron Cyclotron Resonance (ECR) ion source at LKB (Laboratoire Kastler Brossel) and INSP (Institut des Nano Sciences de Paris). This attempt is the first one to use this type of ion trap for trapping highly charged ions that can give a unique opportunity to measure the life times of metastable states in highly charged ions in the millisecond time range, in a mostly field free design. The electrostatic ion trap is composed of two coaxial electrostatic mirrors, working for charged particles in the same way as a Fabry-Perot interferometer works for light in the optical regime. The figure bellow shows a schematic of the ion trap.



Schematics of the electrostatic ion trap; V1 to V4 are the trap high-voltage electrodes, Vz with the grounded electrodes build an Einzel lens for beam focusing on both ends of the trap.

The central region of the trap between the two mirrors is essentially field-free. With the help of a pick up electrode in the linear center of the trap we have proved trapping for tens of milliseconds in the case of a variety of high charge states of O, Ar, Kr and Xe ions (up to O^{5+}, Ar^{13+}, Kr^{21+} and Xe^{20+}). Using a low (<20 V) radio frequency voltage with frequencies close to the oscillation frequency of the ions in the trap we were able to observe trapping times up to 50 ms. Running the ion trap in the so called "bunching" or synchronization mode [2] in the time domain of the pickup signal we observed a strange oscillation on the millisecond scale superposing the ion oscillation in the trap on the microsecond scale. With computer simulations using and modifying the one-dimensional model presented in [2] we try to explain the observed oscillations by looking at the behavior of a test ion close to a bunch of ions in the trap.
With the use of a digital vector signal analyzer to observe the oscillation frequency of the ion packet we have obtained preliminary results, that confirm of the possibility of using this ion trap as a mass spectrometer [3] with a resolution of 10^{-4} or better, that could be used to study highly charged radioactive ion beams.

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X – ray spectroscopy characterization of Ar^{17+} produced by an ECRIS in the afterglow mode

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The afterglow operation mode in the Electron Cyclotron Resonance Ion Source (ECRIS) has been mostly developed in view of applications as beam-injector of high energy (> MeV/A) accelerators. Indeed it can provide a pulsed beam of highly charged ions (HCI) of much higher instantaneous current than in a continuous mode. It is also of big interest for atomic physics experiments making direct use of H-like and even bare ions in the low energy regime (i.e. a few keV/q). However, control of pulse widths, optimization of the operation conditions and measurements of bare or H-like ions currents are not a trivial matter. Especially for those HCI of medium Z (like argon), a complete characterization of the ion beams delivered in the afterglow mode is needed, since currents range around a few nAe or lower and possible contamination by ions having close m/q ratio may occur. Therefore, classic measurement techniques are almost useless, and to overcome this problem, we make use of more sophisticated X-ray spectroscopy techniques. Having Ar^{q+} ions of a few hundred of keV impinging on a thin carbon foil, we have been able to characterize, for the first time, the production of Ar^{17+} delivered in the afterglow mode by the SUPERSHYPIE ion source of GANIL[1]. Indeed, the K X-ray emission comes from the deexcitation of projectile atomic states populated by charge transfer from the target (single or multiple capture processes occur) and provide, through its energy, a clear signature of both the atomic number **and** the charge state of the emitting projectile. A characteristic K X-ray line at 3.1 keV has been observed, allowing for a precise identification and quantification of the Ar^{17+} ion beam extracted from the plasma explosion when the HF is off, and transported along the beam line of ARIBE[2] to finally impinge on a thin carbon target. Recording x ray emission in coincidence with the HF signal, we are able to measure the temporal structure of the beam in the range of several ms with a time resolution less than one μs.

1 : Grand Accélérateur National d'Ions Lourds.
2 : French acronym for "accelerator dedicated to low energy ions"

HIGHLY CHARGED ION INJECTOR IN TERMINAL OF TANDEM ACCELERATOR

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Electron cyclotron resonance ion source(ECRIS)s are able to produce intense beams of highly charged positive ions, of which charge states are higher than those obtained from charge stripping by carbon foil at the high voltage terminal of tandem accelerators. It is possible to increase beam intensity, beam energy and beam species by utilizing an ECRIS in a tandem accelerator [1]. A 14.5GHz all permanent magnet ECRIS has been installed in the high voltage terminal of the vertical and folded type 20UR Pelletron tandem accelerator at Japan Atomic Energy Agency at Tokai.

The high voltage terminal is in a severe environment, i.e. it is filled with the pressurized insulation gas of 5.5 atm and itself is held at a voltage of 20MV at maximum. The characteristics of withstanding high pressure and electrical discharges are indispensable to the in-terminal ion injector. The components of the injector; ion source, beam line devices, power supplies and vacuum components, have been confirmed to be pressure-resistant. A control system with optical fibers and circuits were designed to prevent damages from electrical discharges, and these electrical devices were heavily shielded. For the reason that ion pumps do not work for inert rare gases, a turbo molecular pump and a rotary pump were newly developed for the use in the high pressure gas. The exhaust gas from the pumps was designed to accumulate in a closed vessel. Even when failure occurs, the pumping system can keep high vacuum.

Highly charged ions of Ne, Ar, Kr and Xe are accelerated from new injector. The rare gas ions have been available, and the intensities were increased from 10 times as much as those before. Xe ion energy reached 400MeV, and the accelerator has become the only accelerator that provides beams in a wide energy range of 20~500MeV. In addition, the beam quality has greatly improved because neither the energy spread nor beam divergence are caused by the carbon foil.

These highly charged ions with wide energy have been applied for atomic collision research [2] and so on.

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Continuous beams of Highly Charged Ions from the Dresden EBIS-A

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We report on investigations of continuous ion beam extraction from the Dresden EBIS-A and compare these results with extraction experiments from the Dresden EBIT. Both ion sources are room-temperature EBIS/T with comparatively low magnetic compression fields (600 mT and 250 mT, respectively) /1/. In the case of the Dresden EBIS-A the presented experiments are done at a beam line as described in /2/. We show that integral currents of some µA can be extracted at electron beam currents of about 100 mA and at a working gas pressure of some 10^{-9} mbar. The charge state distribution of the extracted ions in dependence on the working gas pressure, the electron energy and the electron beam current was investigated to optimize the ion output current.

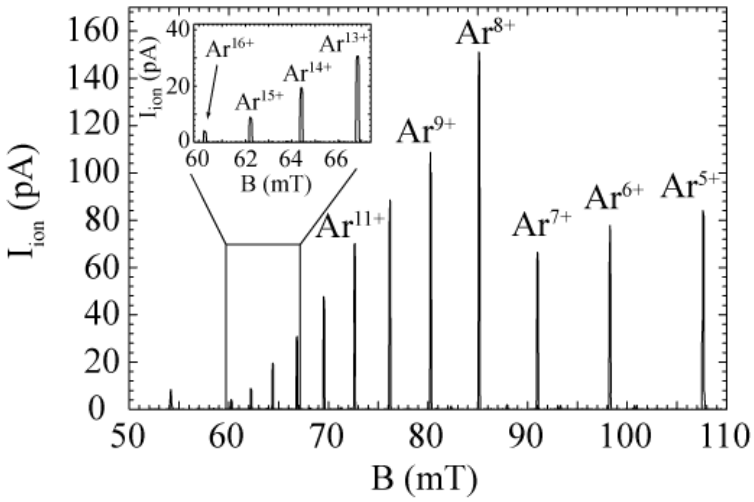

Figure 1
Spectrum of extracted Argon ions measured with the Dresden EBIS-A at an electron energy of 18 keV, an electron beam current of 64 mA and an Argon gas pressure of $3x10^{-9}$ mbar

As an example we extracted maximum DC ion beam currents of 3 nA H_2^+, 6 pA Ar^{16+} and 150 pA Ar^{12+} as well as 300 pA Xe^{14+}, 10 pA Xe^{30+} and 0.6 pA Xe^{44+}, respectively. The spectrum of an argon ion extraction experiment is shown in Fig. 1. We would like to point out that the ion output is very dependent on the selected source operation parameters.

Furthermore, the ion output currents in dependence on the axial trap depth were studied and the radial trap depth of the electron beam was measured to be 25 V for a 30 mA electron beam in the Dresden EBIT and to be 150 V for a 100 mA electron beam in the Dresden EBIS-A. Both values are in good agreement with the calculated radial beam potentials.

The work was supported by the EFRE fund of the EU and by the Freistaat Sachsen (projects No. 12321/2000 and 12184/2000).

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/1/ for details see http://www.dreebit.com
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A Si(Li) MULTISTRIP DETECTOR – AN EFFICIENT COMPTON POLARIMETER

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Polarisation of x-rays coming from recombination processes induced by collisions of heavy and highly charged ions at relativistic energies with electrons or low-density gaseous targets provides a unique insight into the dynamics of charge particles in extreme strong and temporally short electromagnetic fields.
Detailed knowledge of this field has, besides atomic physics itself, a great relevance for plasma- and astrophysics. Due to the observed physical processes one may summarize that one finds significant effects on the linear polarisation of the emitted x-rays in the energy regime between 50 keV and 500 keV [1,2]. Making use of the Compton process which is sensible to the electric field vector of the incoming photon we can address this problem. For photon energies above ~150 keV we have already proven the high sensitivity on linear polarisation of a planar 2D-Ge(i) micro strip detector [3] used as a Compton polarimeter [4]. To have access to the energy regime between 50 keV and 150 keV which is very important for studies of electron ion recombination processes at the ESR of the GSI facility at Darmstadt we developed as a Si(Li) polarimeter. As a rule of thumb one can say that a Compton polarimeter is well suited for an energy if the photo and the Compton cross section is approximately of the same size for a particular detector material. Using silicon for the detector crystal makes the polarimeter due to the lower Z of the material more efficient as Compton scatterer than germanium at lower energies. In addition, the relatively low-Z of silicon leads to a significant reduction of the width of the Compton profile, which is important for imaging applications based on the Compton effect.
Based on advances in the development of large-volume Si(Li) orthogonal strip detectors [5] a two dimensional planar Si(Li) strip detector was built. The key part of the polarimeter is a large-volume 7 mm thick double-sided Si(Li)- strip detector mounted in a cryostat attached to a commercial dewar. The detector crystal itself consists of the Li-drifted silicon bulk which holds a boron-implanted p^+-contact on one side and a thin Li-diffused n-contact. Plasma etched strip structures (2 x 32 strips each 2 mm wide and 64 mm long) provide the position resolution. The strip structures on both sides of the crystal are orientated orthogonally. To reduce distortions of the electric field applied to the crystal due to the limited size of the detector it is surrounded by an 8 mm wide guard ring. The 64 preamplifiers are placed inside the detector housing close to the detector crystal. We will report on first laboratory results which document the good energy resolution below 2 keV and the uniform efficiency of the system.

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THE COMMISSIONING OF THE COOLER STORAGE RING HIRFL-CSR IN LANZHOU

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HIRFL-CSR is a multi-purpose cooler-storage-ring system in the National Laboratory of Heavy Ion Research (HIRFL) In Lanzhou, China [1] including a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) connecting the two rings. The two existing cyclotrons SFC (K=69) and SSC (K=450) of the HIRFL are be used as its injectors. Heavy ion beams in an energy range of 8–30 MeV/u from the HIRFL will be accumulated, cooled and accelerated to the energy of 1100 MeV/u ($^{12}C^{6+}$) and 500 MeV/u ($^{238}U^{72+}$) in the main ring, and then extracted to produce secondary beams (radioactive ion beam or highly charged heavy ions). The secondary beams will be accepted by and stored in the experimental ring for internal-target experiments or for high-precision spectroscopy with beam cooling. The experimental ring CSRe can accept highly charged ions with energies up to 750 MeV/u ($^{12}C^{6+}$) and 500 MeV/u ($^{238}U^{92+}$). The double-ring-system provides flexibility in the production of highly charged ions and of radioactive ion beams, thus offering opportunities for nuclear physics and atomic physics research.

In January 2007 electron cooling in CSRm was successfully finished and the carbon ions up to 1.6mA (corresponding to the ion number of 8×10^9) have been accumulated by using cooling stacking. The multiple multi-turn injection (MMI) was successfully done for $^{12}C^{6+}$, $^{36}Ar^{18+}$ and $^{129}Xe^{27+}$(Fig.1). In October 2007 the 7MeV/u $^{12}C^{4+}$ provided by SFC have been accumulated and accelerated to 660MeV/u in CSRm and then extracted fast to RIBLL II. The 660MeV/u $^{12}C^{6+}$ transferred through RIBLL II was injected into CSRe and reached an intensity of 15mA (1.56×10^{16}pps) in CSRe.

The first two physics experiments were successfully carried out in December 2007. In one of the experiments a Be target of 5 mm was installed at the primary target position of RIBLL II, secondary beams such as ^{34}Cl, ^{32}S and ^{30}P and so on were produced and injected into CSRe which was set in the isochronous mode. The masses of the stored secondary ions could be determined from the revolution time spectrum of the ions. The mass resolution of 10^{-5} was obtained (Fig.2).

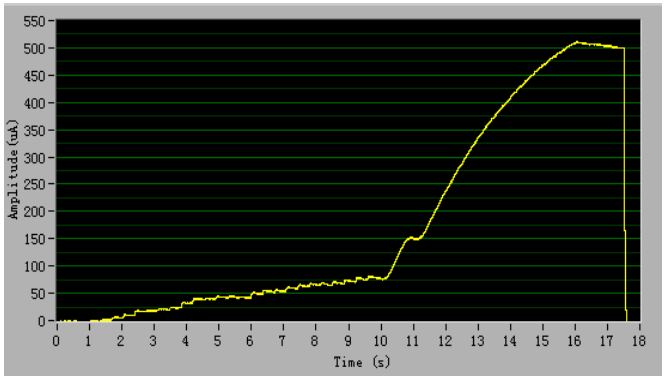

Fig. 1 Multiple multi-turn injection for 2.9 MeV/u $^{129}Xe^{27+}$

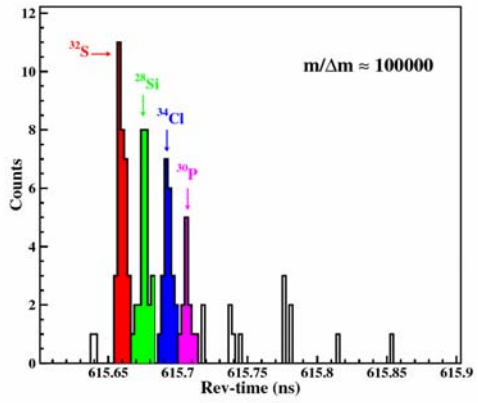

Fig. 2 Mass measurement in CSRe in ischronous mode

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Development of Multichannel Doppler Tuned Beam-Foil X-Ray Absorption Spectrometer at IUAC

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Since decades beam foil time of flight technique serves as a versatile tool to measure the lifetime of different energy levels, which can be applied in principle to any charge state. Due to limitation in resolution of available energy dispersive solid state detectors (resolution ~150 eV at 5.9 keV), this technique does suffer from inherent cascading and blending problems. In order to minimize these problem and spectroscopically resolve the satellite line from the parent line, a high resolution, multichannel Doppler Tuned Spectrometer (DTS) [1, 2] setup coupled with lifetime measurement setup has been developed in general purpose scattering chamber (GPSC) at IUAC.

In most beam-foil experiments, the Doppler effect produces unwanted distortion of emission spectra. But DTS utilizes the Doppler shift as a function of angle of emission from the beam as a dispersive element. When the foil-excited beam emits a photon of energy E_0, will be Doppler shifted and appears at energy $E(\theta)$ to a stationary detector. The relation between Doppler shifted energy $E(\theta)$ and rest energy E_0 can be given by

$E(\theta) = E_0 / \gamma(1 - \beta \cos\theta)$ Where γ and β has their usual meaning and v is the velocity of the post foil beam and θ is the angle of detection of photon with the beam axis. An absorber foil is placed between target foil and the detector (proportional counter), which has an absorption edge energy, E_{AB}, near the rest mass energy E_0. The angle is tuned in such a way that absorption edge energy just coincide with the Doppler shifted energy $E(\theta)$, a dip appears in the spectrum due to the absorption of x-ray by absorber foil. Differentiation of this spectra contains the high resolution feature.

For this setup, a Position Sensitive Proportional Counter (PSPC), having position resolution of 350 μm in the linearity range of 140 mm and the energy resolution of ~22% at 5.9 keV of Fe x-ray, has been developed to use as a detector for multi channel DTS. Further an attempt has been made to energetically resolve M1 transition ($1s2s\ ^3S_1 - 1s^2\ ^1S_0$), M2 transition ($1s2p\ ^3P_2 - 1s^2\ ^1S_0$) in He-like Fe and its satellite M2 transition ($1s2s2p\ ^4P_{5/2} - 1s^22s\ ^2S_{1/2}$) in Li-like Fe and measure the lifetime of corresponding levels. The details of such setup along with preliminary results will be presented.

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ABSOLUTE DETECTION EFFICIENCIES OF AN ION COUNTING SYSTEM WITH A CHANNEL-ELECTRON MULTIPLIER

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Absolute detection efficiencies of an ion counting system have been examined for Li^+, Rb^+, Cs^+, Ar^+, and Ar^{2+} ions as a function of incident ion impact energy. The incident ion energy ranges from 0.5 to 6.0 keV. Figure 1 shows schematic diagram of an ion counting system and a detection efficiency measurement set-up. The ion counting system consists of a converter plate (SUS), an electro-static lens system, and a channel type secondary-electron-multiplier (SEM:Channeltron 4139S). A surface-ionization type ion source employed for singly charged alkali ions, and an ECR ion source for Ar^+ and Ar^{2+}. The incident ions hit the converter plate, and then the secondary electrons emitted from the converter accelerate to the SEM. The output signals from the SEM are counted with a conventional ion counting electronics. The absolute detection efficiency D is defined as

$$D = \frac{eN_{\mathrm{SEM}}}{I_f} \qquad , \qquad (1)$$

where N_{SEM} is the total counting signal from the SEM (count/sec), I_f the ion current measured at the Faraday cup, and the e elementary charge.

Figure 2 shows the absolute detection efficiencies for Ar^+ and Ar^{2+} as a function of the ion impact energy. The detection efficiency increases with the ion energy, and reaches 1.0 above 5keV. For all ions examined in this study, the detection efficiency is about 1.0 as far as the ion energy is larger than 5 keV. Charge state dependence is not so large for Ar^+ and Ar^{2+}. This means that the kinetic emission mechanism dominates the secondary electron emission in this energy region.

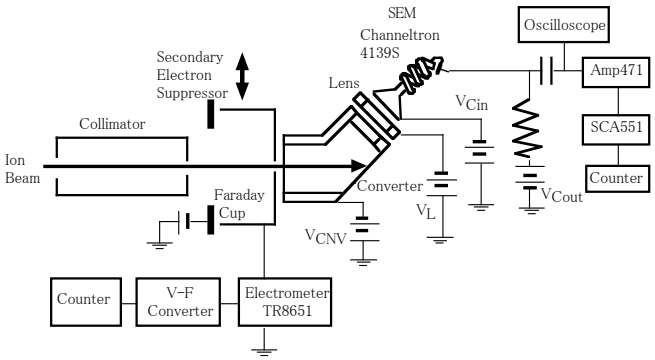

Fig.1. Schematic diagram of an ion counting system and a detection efficiency measurement set-up.

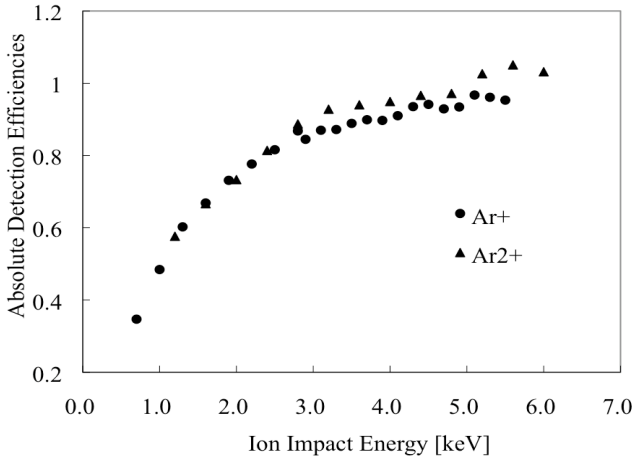

Fig. 2. The absolute detection efficiencies for Ar^+ and Ar^{2+} as a function of the ion impact energy.

Time resolved extreme ultraviolet tin spectra from laser produced plasmas

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Radiation at 13.5 nm is currently of great interest to the semiconductor manufacturing industry – driven to meet Moore's law [1] (*i.e.* a doubling of feature density every two years). Traditionally optical lithography has been at the forefront of the required feature size reduction, due to the decreasing wavelength of the light sources used. However, to make further progress new lithography techniques are needed, with extreme ultraviolet lithography (EUVL) the most promising candidate [2]. The 13.5 nm wavelength is determined by the availability of highly reflective ($\sim$70%) molybdenum/silicon multilayer mirrors with a 2% bandwidth centred at 13.5 nm [3]. Although beta tools are currently in use, a suitable light source for high volume manufacturing has not yet been developed.

The current preferred sources for EUVL are tin [4], lithium [5] and xenon [6]. Atomic and plasma physics show that laser produced plasmas, with electron temperatures of 30 to 70 eV, containing tin can emit brightly in the desired bandwidth. This emission can be ascribed to overlapping 4d subshell atomic transitions ($4p^6 4d^n \rightarrow 4p^5 4d^{n+1} + 4d^{n-1}4f + 4d^{n-1}5p$) from adjacent Sn ions (Sn^{7+} to Sn^{12+}), which merge to form an unresolved transition array (UTA) [7].

Here we present time resolved spectra of this UTA, in the 9–18 nm region. The plasmas under investigation are formed from a pure tin bulk target, by focussing a 500 mJ, 16 ns FWHM, laser pulse from a Q-switched Nd:YAG laser to a power density of $\sim 10^{11}$ $\mathrm{Wcm^{-2}}$ on to the target. The radiation emitted is collected by a toroidal mirror and imaged onto the 20 μm entrance slit of a McPherson 2.2 m grazing incidence spectrograph, equipped with a 1200 groove/mm grating, giving a spectral resolving power of $\sim$1000. The detector consists of a 40 mm microchannel plate, which is coupled via a coherent fibre optic bundle to a 1024 pixel photodiode array. The microchannel plate can be gated to a shutter speed of $\sim$5 ns.

The resulting time and spectrally resolved spectra are compared with atomic structure calculations, performed with the Cowan suite of codes [8], to determine the dominant ion stage as function of time.

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Development and applications of Electron Beam Ion Source for Nanoprocesses

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The interaction of slow HCI with solid surfaces is useful for 'nanoprocess'; the modification, activation, machining and analysis in nanometer scale. An electron beam ion source, 'Kobe EBIS' has been developed for the application of HCIs to nanoprocesses. The EBIS uses a commercial superconducting magnet (3T) cooled by a closed-cycle refrigerator. The schematic diagram of the EBIS is shown below. The design and tentative performance is described on the literature [1,2]. The EBIS is installed in the beamline for the experiments of the irradiation of sample with HCIs and scanning tunneling microscopy (STM) observations of irradiated sample surfaces.

The STM observation of the surface of highly oriented pyrolytic graphite irradiated with Ar^{11+} ions illustrated that the fluence of HCI in the order of $10^{13}/cm^2$ is accessible with the present EBIS. We have also developed an apparatus to process a sample with periodically arranged traces of HCI irradiation using a mask with small holes (the diameter < 100nm) made of a thin film of Si_3N_4.

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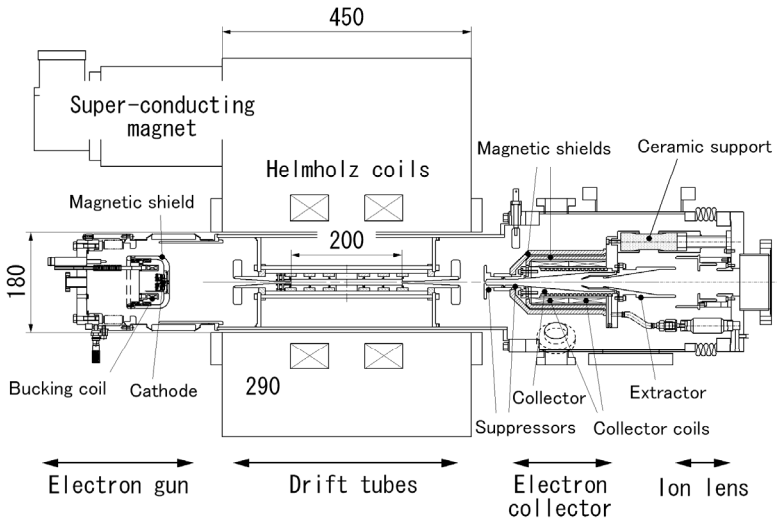

Schematic diagram of Kobe EBIS

TIN LPP SOURCE MODELLING FOR EUVL AT 13.5 nm

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Because of the large number of transitions and complexity of the $4p^6 4d^n - 4p^5 4d^{n+1} + 4p^6\ 4d^{n-1}4f$ unresolved transition array (UTA) responsible for 13.5 nm emission in Sn plasmas, as well as the computationally intensive nature of radiation transport calculations, statistical methods can be used to estimate the spectral profile [1]. Increasing laser power density initially shows increased in-band UTA brightness though emission eventually decreases as the dominant ion stages move beyond the open 4d subshell species responsible for the UTA emission. [2].

The impact of wavelength λ and power density ϕ on ion distribution and electron temperature is calculated for a Nd:YAG (λ = 1064 and 355 nm) and CO_2 (λ = 10600 nm) laser plasmas. The laser power densities, ϕ, are chosen to keep $\lambda^2\phi$ constant, thus keeping the electron temperature constant in the Collisionally Radiative Equilibrium CRE rate equations [3]. (The 355-nm laser is included to highlight the emission dependence on electron density, primarily three-body recombination, and gives greatly reduced Sn^{10+} and Sn^{11+} ion populations, the main emitters at 13.5 nm.) The theoretical intensity shows an increase for the CO_2 laser produced plasma, where the in-band summed oscillator strength is 13.4% greater at 32 eV and 2.7% greater at 36 eV [4].

The influence of reduced electron density in the CO_2 LPP (~ 1/100, where $n_e \propto 1/\lambda^2$) is considered in a 1-D radiation transport model. Plasma opacity is less in the lower electron density CO_2 plasma, resulting in less absorption and a brighter source. A more than 2-fold increase in conversion efficiency is predicted for the CO_2 laser over that attainable with the Nd:YAG, close to the experimentally observed values [5]. The 2-D RMHD code Z* [6] models emission in an optically thick tin LPP. The implicit Eulerian-Lagrangian code solves MHD, ionization kinetics with radiation transport and uses an average atom model to account for all possible states and transitions. Optimum 4-4 in-band emission occurs primarily from the plasma core at an electron temperature of 30-40 eV [7]. However the core emission is reduced by absorption in the colder wings because of the high absorption cross section of lower stage ions.

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ANGLE-RESOLVED STUDIES OF TIN-BASED LASER PRODUCED PLASMA EUV SOURCES

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The proposed use of laser-produced plasmas (LPPs) for EUV. lithography is dependent on a range of factors, including collectable source power and the debris levels emitted by the source. Ions that are emitted from these plasmas will cause significant damage to the optical components in a projection lithography system. One further issue is the level of out-of-band (OOB) radiation, residing outside the narrow extreme ultraviolet band, emitted by the plasma, as this has the potential to cause flare in the wafer plane, leading to a loss of feature resolution.

In this study *three* of the key laser plasma source parameters have been investigated, ion emission from laser plasmas, in-band radiation at 13.5 nm and out-of-band radiation.

We have performed time of flight (TOF) analysis to determine the intensity of ion distribution from tin based LPP for a range of charged tin ions (Sn^{1+}–Sn^{9+}). The source reported here is a plasma formed on a planar bulk tin target by pulses from a Neodymium Yttrium Aluminium Garnet (Nd:YAG) laser delivering 500 mJ per pulse in a time of 7 ns (full-width half-maximum intensity) at the fundamental wavelength of 1064 nm. The laser pulse was focused to a power density of 4 x 10^{11} W/cm^2, close to the value at which the conversion efficiency to in-band radiation at 13.5 nm is a maximum. The plasma formation occurred on a custom made optical system, which could be rotated with respect to the detector so TOF analysis could be preformed at various angles of emission, while maintaining a normal angle of incidence for the laser pulse with respect to the target. The detector used was an energy sector analyser (ESA), which is a well-characterised diagnostic capable of measuring ion energy and discriminating by charge state. Analysis was performed on ions of various charge states, with energy/charge state ratios ranging from 3 keV to 50 eV, for angles of emission from the plasma ranging from 90 to 15 degrees.

Out-of-band (OOB) radiation was also measured over a range of angles between 25 and 85 degrees with respect to the target normal, for six energy bands typically 100 nm wide centred between 200 and 1000 nm. The intensity of the radiation was measured using an absolutely calibrated filter/photodiode combination. The emission was found to be dominated by radiation in the band centred on 214 nm. An $I(\theta) \propto \cos^{\alpha}(\theta)$ approximation was fitted to the angular distribution of the radiation summed over all energy bands, yielding a value for α of 0.23 ± 0.02.

Extreme ultraviolet (EUV) spectra were recorded from a similar plasma were also recorded over a range of angles between 20 and 90 degrees from the target normal. Absolute intensity measurements are presented of both the 2% band centred on 13.5 nm and the total radiation emitted by the plasma between 10 and 18 nm. The in-band intensity is seen to be relatively constant out to an angle of 60 degrees from the target normal, beyond which it drops off quite steeply. The spectra at wavelengths greater than 13.5 nm are strongly influenced by self-absorption by ions ranging from 6^+ to 10^+.

CALCULATION OF STABIL ITY DIAGRAMS AND ION TRAJECTORIES IN QUADRUPOLE ION TRAP WITH IMPULSIONAL POTENTIAL BY MATRIX METHOD

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Despite of the long history of the calculation of the stability of ion motion in radio-frequency quadrupole fields, since about 80 years ago it has remained of interest for several new areas of mass spectrometry. These include the use of higher stability regions[1], application of resonant excitation, and the use of non-sinusoidal trapping voltages[2]. The most general differential equation describing ion motion is the Hill equation. We first discuss the solution of this equation by matrix methods [3] and then calculate the ion trajectories and the first stability region and higher stability regions by employing an impulsional potential of the form $V_0 \cos(\Omega t)/(1-k\ \cos(2\Omega t))$ with (0.0<k<1).We also discuss the fractional resolution $m/\Delta m$ of the confined ions.

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