THEORETICAL AND EXPERIMENTAL RESEARCH OF ION CHARGE STATE EVOLUTION IN ELECTRON BEAM ION TRAP

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An Electron Beam Ion Trap (EBIT) is a device, which can be used both as a highly charged ion (HCI) source and as a HCI light source for various kind of research. As an ion source, it can basically provide ions of any possible charge state and of any element, for ion surface studies, for ion atom, ion electron, and ion photon collision studies. As a light source, EBITs can basically provide light from visible to X-ray region again from all charge states of all elements. A detailed understanding of the factors determining charge state distribution, ion temperatures etc. in an EBIT device are very important in planning experiments. Adjusting operating parameters such as electron beam energy, electron beam current, magnetic field strength, axial trapping potential, injection density and so on can be facilitated by such an understanding. This requires considerable knowledge of the numerous physical processes taking place in the trap region of an EBIT, such as ionization, recombination, charge exchange, heating, evaporative cooling and ion escape.

In this paper, we will discuss a theoretical simulation on charge state distribution and temperature evolution of the ions in an EBIT. The simulation took into account the main processes in EBIT: electron impact ionization of ions, radiative recombination, muticharge exchange between ions and neutral atoms, electron beam collision heating, ion-ion energy transfer, ion confining and ion escaping from the trap (including radial escape and axial escape), energy escaping from the trap due to the ion escaping, and electron beam space charge neutralization by traped positive ions. The simulations results showed sawtooth oscillation [1], sine oscillation [2] and more normal behaviour of the ion density evolution.

To test the theoretical simulation, experiments were designed and performed at Shanghai EBIT. The time dependent spectra of Xe and Kr ions with Xe-Kr gas mixture injection, and the time dependent spectra of Au ions with Au MEVVA injection were taken. Comparisons between the experimental and theoretical results will be presented and discussed in the paper.

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Simulation of electron beam in Shanghai EBIT

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Electron Beam Ion Traps (EBIT) are sophisticated devices capable of acting both as highly charged ion (HCI) light sources and ion sources. Because the HCIs produced in an EBIT are moving at much lower speed comparing with those produced in heavy ion accelerators, so much less bothered with Doppler shifts and spectral line broadening which is a very good character for spectroscopic research. Because of the flexibility in producing various ions with an EBIT, it is a very powerful tool for studies along iso-electronic and iso-nuclear-charge sequences to reveal the underlying physics behind many physical properties.

For the purposes of guiding operation of EBIT at optimum condition, we made simulations of the electron beam trajectories in Shanghai EBIT, with TRICOMP, a patch of codes from Field Precision Company. The electric and magnetic fields along the electron paths are calculated using finite-element method. Space charge effect and relativistic correction are considered during the simulation. A systematic study was made based on the simulation, for various operation conditions. Fig. 1 shows an example of the resulting intensity distribution of the electron beam in the central drift tube, with an electron beam of 6KeV, and 33mA confined by a magnetic field of 3T, the cathode temperature kT=0.1eV, and the cathode magnetic field Bc=0. The half width at half maximum of the relative current density distribution indicates a radius of about 30 micro meter for the electron beam. This result agrees with the result from a beam imaging experiment at the same condition. More results and discussions will be presented in the paper.

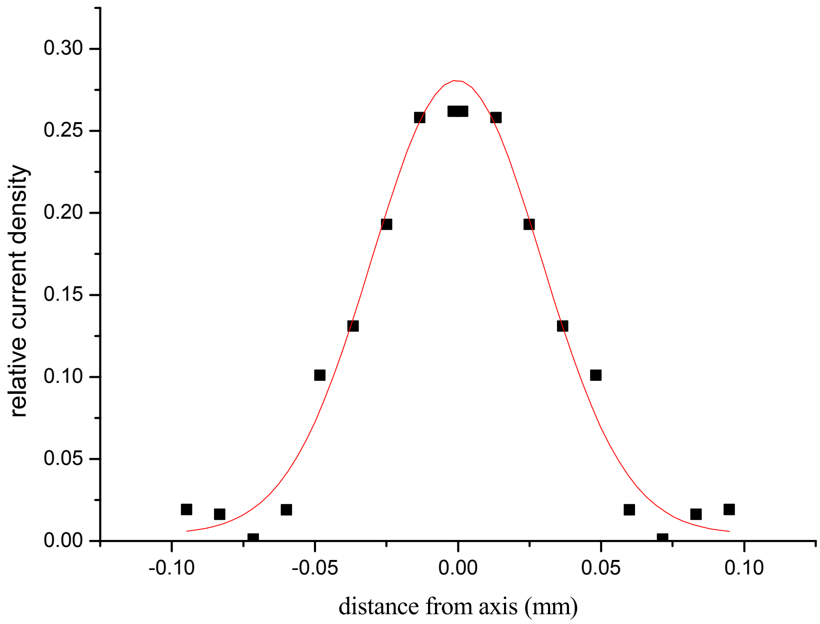

Figure 1 the electron beam current density versus beam radius

A tandem linear Paul trap as an ion source

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A linear Paul trap has been widely used for research. For examples, it is put into practical use as a mass spectrometer. By using laser cooled ions loaded in the trap, frequency standards[1] and quantum computers[2] are studied. Furthermore, the apparatus is used to study the motion of an ion plasma in a linear Paul trap which corresponds to beam dynamics of charged particles propagating through a periodic magnetic lattice[3,4]

Here, we investigated a possible application of a tandem linear Paul trap as an ion source. Compared with highly charged ion sources like electron cyclotron resonance ion source(ECRIS) and electron beam ion source(EBIS, EBIT), a tandem linear Paul trap is quite compact and inexpensive. It can generate ions without intense magnetic field and microwave.

The ion source is composed of three linear Paul traps. Each trap plays a role of generating ions, gate and mass filter. Argon ions were created in the trap by collisions with electrons emitted from an electron gun. The electron energy was $\sim$ 130 eV These ions pass through the gate as a pulsed beam. The filtered ion number is detected by Faraday cup. It was observed that Ar^+ ions were produced about 6×10^6/pulse and Ar^{2+} ions 6×10^4/pulse. Confinement times were also measured to evaluate the ion production process

Also a tandem linear Paul trap has a possibility to be a nano-ion beam source. It is known that laser cooled ions form string crystals in a linear Paul trap containing several Ca^+ ions. The ion crystals extracted from the trap can be a nano-ion beam with ultimately low emittance[5]. Furthermore, it is possible to produce and confine highly charged ions simultaneously with laser cooled Ca^+ ions in a tandem linear Paul trap. The precise measurement of cold highly charged ions will be made easier with the use of a tandem linear Paul trap.

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THE SPARC EBIT AT GSI; COMISSIONING AND FUTURE PLANS AT THE HITRAP BEAMLINE

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A small permanent magnet EBIT (Dresden EBIT [1]) has been installed at GSI to serve as an offline test ion source for the HITRAP project [2] and for use as a test setup for charge breeding explorations. The EBIT is named 'SPARC EBIT' as it will also be used as a test facility for instrumentation under development for the SPARC collaboration [3]. We describe some results of the initial conditioning of this source. X-ray spectra and TOF measurements confirmed the production of highly charged ions up to Ar^{18+} in the trap.

Charge breeding in the EBIT is also being investigated. Singly charged ions will be externally injected from a surface ion source and subsequently trapped in the EBIT and ionized. Simulations of the ion injection and extraction have been performed using SIMION. In the course of 2008 the EBIT will be transferred to the HITRAP beamline and will serve as an offline source for the various HITRAP experiments currently being prepared at GSI [4].

We also describe initial results from a program of atomic physics experiments designed to measure cross sections of charge changing reactions, i.e. ionization, dielectronic recombination, in the trap region via observations of the emitted x-ray spectra and charge balance of extracted ions.

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DEVELOPMENT OF HIGH CURRENT ELECTRON BEAM ION TRAPS FOR CHARGE BREEDING OF RADIOACTIVE ION BEAMS

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Experiments with reaccelerated ion beams are planned in several rare isotope beam facilities. Radioactive rare isotope beams at energies ranging from a few hundreds of keV/amu to more than several MeV/amu are needed e. g. for studying key reactions related to nucleosynthesis in astrophysics, and the structure of nuclei far from stability. Rare isotopes produced by the interaction of powerful proton beams with heavy targets are normally extracted from the bulk by fast thermal and diffusion processes, yielding a cocktail of atoms which are subsequently ionized, mass selected and accelerated. Stripping those ions by means of foils allows raising their charge state before further acceleration steps. However, this method does not achieve optimum yields, and emittance can be rather poor, leading to severe ion losses. An additional step of charge breeding (e.g. in an electron beam ion trap) eliminates the need for conventional electron stripping with the corresponding detrimental effects on the efficiency and the collateral radioactive contamination problems. It also enables simpler accelerator design by aiming at well defined values of the q/m ratio, thus reducing its size and cost. A successful EBIS charge breeder for reacceleration has been demonstrated (REX-ISOLDE at CERN). The new generation of electron beam ion traps developed at the Max Planck Institute for Nuclear Physics in Heidelberg [1-3], one of which is undergoing testing in combination with a precision Penning trap for mass measurements at the ISAC facility (TRIUMF), and the future high current EBIT currently being developed in collaboration with the NSCL (MSU) will permit to further develop this method aiming at improving the yield and emittance of rare isotope beams and reducing the charge breeding time as far as needed for the study of short lived radioactive isotopes.

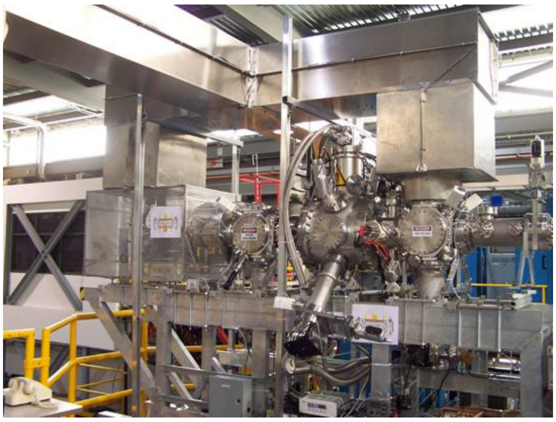

Fig. 1. The TRIUMF-EBIT installed at its stand in the TITAN facility.

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ELECTRON BEAM DENSITY DISTRIBUTION STUDIES USING AN PORTABLE SLIT IMAGING SLIT IMAGING SYSTEM AT THE SHANGHAI ELECTRON BEAM ION TRAP

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In an Electron Beam Ion Trap (EBIT), the density of the electron beam together with electron energy determines the rates of the main physical processes occurring in the trap region. The density of the electron beam is in turn determined by its size, profile and current. In this work, a portable slit imaging system was developed, and used to study the electron beam size and profile of the newly developed Shanghai EBIT. The fluorescence of the ion cloud in the EBIT were detected by a charge coupled device (CCD) sensitive to both visible light and X-rays rather than position sensitive proportional counter for higher resolution [1]. A large scale ray tracing was done for corrections of finite slit width of the slit imaging system and the finite pixel size of the CCD detector. A numerical de-convolution method was developed to analyze and reconstruct the electron beam density distribution in an EBIT.

FIG. 1 shows an image of the electron beam in the trap area recorded using the slit imaging system, at electron beam energy of 81 KeV and current of 80 mA under 3 T magnetic field. We attached a Be window to cover 2/3 of the surface of the CCD chip, and could get the image with only X-ray exposure and the image with both X rays and visible light exposure in a single run. In FIG. 1 the area above the arrow is from all wavelengths exposure, below the arrow is from pure X-ray exposure (from the part where the CCD was covered with the Be window). We can see clear difference both in width and intensity. The causes of the differences, as well as the inference of the fluorescence wavelength region on determination of the electron beam diameter, will be discussed in the paper.

The experiments were done at the electron energies of 100 keV, 81 keV, 50 keV, and 20 keV, with several different electron beam currents at each beam energy. The purpose was to study the energy and current dependence of the electron beam diameter, and hence the current density. The results will be displayed and discussed in the paper.

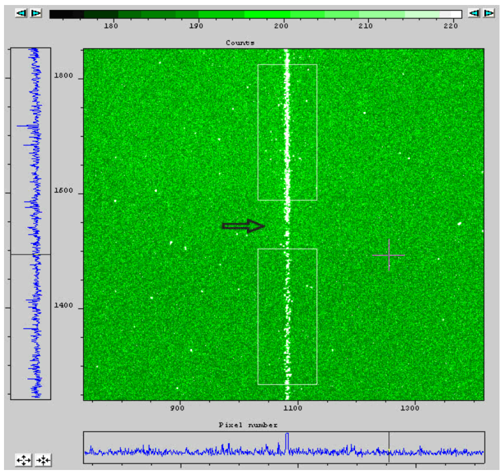

FIG. 1: An image of the ion cloud in the Shanghai EBIT taken using the slit imaging system, with an electron beam of energy of 81 keV and current of 80 mA.

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The multi-parameter data acquisition system at shanghai EBIT

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A multi-parameter data acquisition system (DAQ) for the collision platform has been established at shanghai EBIT. The system is based on VME modules; and fast electronics were used here. The software for the DAQ is written in C language. In the experiment, the multi-coincidence measurements are performed in event by event mode and all data is recorded in list mode. For the first application, a delay-line position sensitive detector [1] has been test with the electronic and DAQ. The signals from the MCP and delay-line are firstly amplified and discriminated by the fast amplifier and the constant fraction timing discriminator. And then the signals are sent to the TDC [2]. The results show that the total time resolution for the system is better than 1 ns and the dead time is shorter than 10 ns. All the tests show that the DAQ system is qualified for the future experiments.

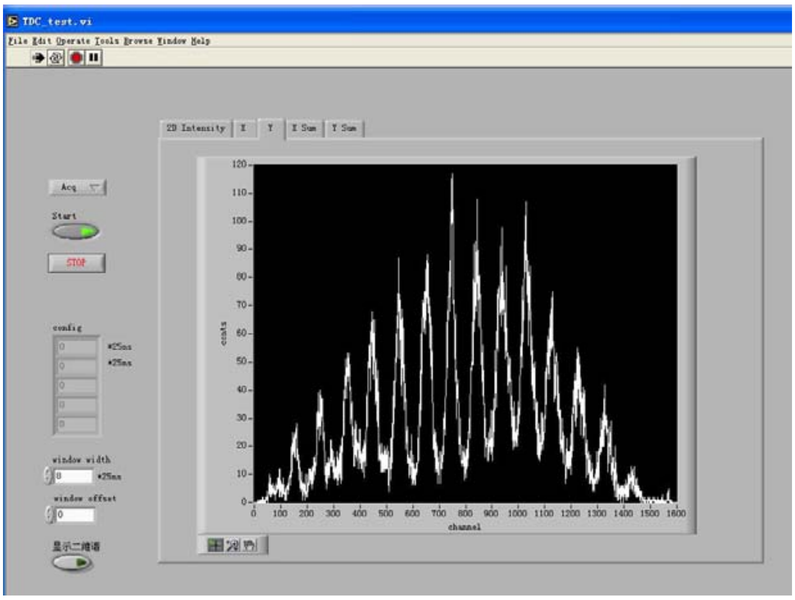

Fig. 1 The work space of the software, which shows the time of flight of each channel, and also the 2 dimensional information according to your command.

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A Progress Report of 320 Kv Multi-Discipline Research Platform For Highly Charged Ions

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The interactions between highly charged ions and materials (atoms, molecules, clusters, surfaces, and bio-molecules, etc) have attracted more and more interests not only in fundamental researches but also in many application fields [1]. The low energy highly charged projectiles are usually provided by ECRIS, where their extraction voltage is below 50 kV. EBIS can provide even higher charge state ions but relatively low beam intensities. A dedicated beam-line for highly charged ions interaction with materials has been constructed at the Institute of Modern Physics (IMP) in Lanzhou, where the projectile energy is extended to 320q keV (where q is the projectile charge). The dynamical range of the projectile velocity will be from 0.1 a.u. to 2 a.u. covering electron capture dominant channel to ionisation dominant channel.

A permanent magnet ECR ion source which sits on the high voltage platform was constructed as shown in figure 1. The ion source can produce various charge states of atoms in the periodic table. The maximum high voltage applied to the platform is designed to 320kV. The beam lines are equipped with five experimental terminals [2]: for (1) surface studies, (2) atomic physics research (collision dynamics as well as spectroscopy with atomic or molecular target beams), (3) multi-purpose experimental terminal, the design is flexible and allows the external users to bring their own set-ups for experiments, (4) material science, and (5) biophysics searches, respectively.

The commissioning of the beam-line has been carried out successfully. Highly charged ions such as Ar^{13+} and Xe^{30+} has been provided for radiation damage studies and surface experiments. Presently the voltage applied to the platform has reached 200 kV.

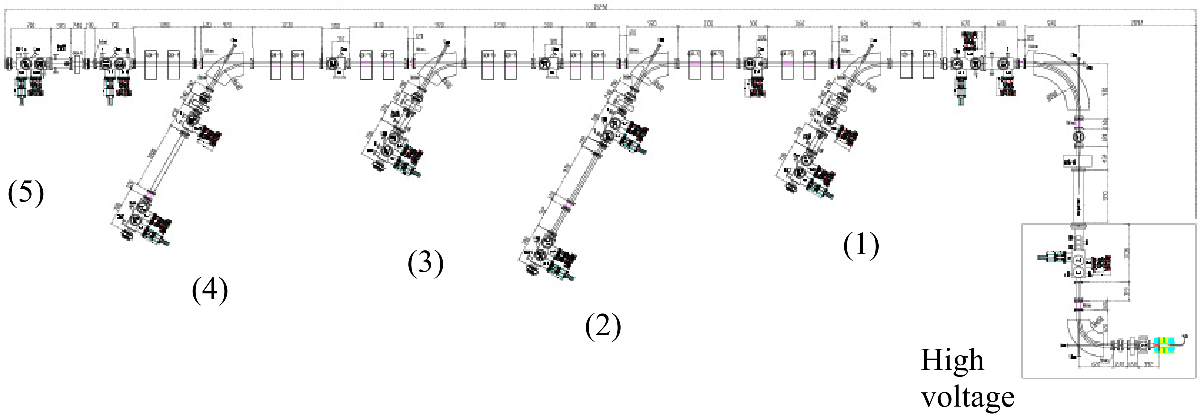

Fig. 1 layout of the high voltage platform and equipped experimental terminals

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Evolution of X-ray Calorimeter Spectrometers at the Lawrence Livermore Electron Beam Ion Trap

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High-resolution broadband, non-dispersive x-ray spectrometers have been under development for spaceflight since 1984. As an offshoot of the significant NASA investment in this technology, we have developed a series of calorimeter instruments for laboratory use and installed them at the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory. Coupled with dispersive instruments at the facility, the calorimeter instruments have made significant contributions to our laboratory astrophysics program. Our laboratory astrophysics program involves benchmarking the spectral synthesis codes and the underlying atomic physics calculations that are used to model high-resolution x-ray spectra obtained with current and future x-ray observatories. The calorimeter instruments at EBIT have significantly enhanced our capabilities to study the physics of highly charge ions including broad band measurements of emission from charge exchange recombination and absolute cross sections for collisional excitation.

The first GSFC calorimeter instrument was installed at the EBIT facility in July of 2000 and has seen two major and a number of minor revisions since then. The performance of the instrument has significantly improved with time from the initial instrument that had a resolving power of ~500 at 6 keV, and essentially no quantum efficiency at energies above 20 keV, to the current instrument that has a resolving power of 1350 and 95% quantum efficiency at 6 keV, and a resolving power of 1800 and 32% quantum efficiency at 60 keV. The advances in resolution are especially apparent at lower energy, where, for example, O VII Kβ at 665 eV evolved from a distinguishable “shoulder” on the high-energy side of O VIII Lyα, to a well resolved line. These improvements have significantly increased the scientific yield of the calorimeter instrument at both high and low energies. We discuss the improvements in the instrument performance and the significant impact on the science yield at EBIT.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and is also supported by NASA grants to NASA/GSFC and LLNL.

THE MEVVA SOURCE ION INJECTION AT THE SHANGHAI EBIT

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A MEVVA ion source was installed to the Shanghai EBIT for metallic ion injection in July 2005. To achieve successful injection of lowly charged ions to the trap region of the Shanghai EBIT, two improvements have been done on the MEVVA source.

First is to improve the work efficiency of the MEVVA source. The performance of the original MEVVA source was unstable because of the loose installation of the cathode, trigger and the insulator between them. It was vacuum discharge between the cathode and trigger while the MEVVA source was running. We modified the construction of the trigger, guaranteed tight assembly of the MEVVA cathode, trigger and the insulator, and coated graphite on the insulator surface to reduce its insulation. Therefore the surface discharge, which is much more stable, would occur along the insulator's surface. In this way, the efficiency was improved to provide enough lowly charged ions for experiments.

Second is to improve the ion injection efficiency. The electron collector of the Shanghai EBIT is located between the MEVVA source and the trap region. The injected ions from the MEVVA source must find a way passing through the collector. The collector could be regarded as an einzel lens, and its potential, which is mainly determined by the electron beam energy, would affect remarkably the trajectories of the injected ions. To get better ion injection efficiencies, some parameters, including the potentials of the extractor and the einzel lens of the MEVVA source, should match appropriately with the electron beam energy. We simulated the ion injection processes under different electron beam energies by SIMION program, and got the appropriate parameters of the extractor and the einzel lens of the MEVVA source under different electron beam energies. These numerical results guided us to get better ion injection efficiency in the experiments.

With these two improvements, now we can achieve better ion injection efficiency with the MEVVA source. Some experimental results of Au ion injection under different electron beam energies will be shown and discussed in the report.

A POWER SAVING AND COMPACT ELECTRON BEAM ION SOURCE USING A PERIODIC PERMANENT MAGNET SYSTEM

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Collision physics of multiply charged ion has aroused an increasing interest in relation to the fields such as astrophysics, space science, radiation physics, and plasma physics. About ten years ago, we had made a power-saving and compact "Electron Beam Ion Source (EBIS)" named "micro-EBIS" using a ring permanent magnet [1]. The charge transfer cross sections of multiply charged neon and argon ions extracted from this micro-EBIS had been measured at keV energy region [2]. This ion source had been developed to more powerful tool by Motohashi *et al*. [3]. There is another method for electron beam focusing, that is "the use of alternating magnetic field. In the 1950s, this technique had already been applied to a travelling wave tube as a microwave amplifier. Becker *et al*. proposed a "mirrored EBIS" using this periodically arranged permanent magnet system (PPM) [4], but performance of their ion source was not clear. In this work, therefore, we have constructed more compact EBIS using the PPM.

The present PPM-EBIS was consisted of an electron gun, the PPM and ion-extracting assembly. The electron beam, emitted from a barium oxide (BaO) cathode of 2.0 mm in diameter, was accelerated with the electric potential deference V_a between an anode and cathode and can be extracted up to a few mA. The PPM was constructed five ring permanent magnets (Fe-Nd-B) of 15 mm inner diameter, 25 mm outer diameter and 3 mm thick with 2 mm thick pole pieces made of SUS430. Thus the magnetic period was 10 mm and the length of axitial ion drifting region was 27 mm. Average value of maximum magnetic flux densities along the central axis of the present PPM-EBIS was observed to be 0.24 T. First pass band for stable transmission of the electron bem will be achieved at $V_a > 3$ kV.

The vacuum system was evacuated with two turbo molecular pumps and residual gas pressure was about 6×10^{-7} Pa. Extracted ions were separated with a Wien filter and detected with a channel electron multiplier or a micro channel plate. The more detailed performance of this PPM-EBIS will be reported in this conference.

The present work was partially supported by the National Institute for Fusion Science, in Japan. We should like to thank Dr. M. Goto for his help.

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DIAGNOSTICS OF THE HIGHLY CHARGED ION BEAM EXTRACTED FROM THE TOKYO-EBIT

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At the Tokyo-EBIT [1], highly charged ions (HCIs) such as bare I^{53+} and He-like Bi^{81+} can be produced and extracted. Fig.1 shows a typical charge state spectrum of extracted Bi ions obtained with a 60 keV electron beam. By using such a slow very highly charged ion beam, we have been studying not only interactions of HCIs with surfaces [2,3] but also the resonant process in the collisions between HCIs and electrons [4,5]. However, the intensity of the beam is not always enough for some experiments. For example, guiding of HCIs with a glass capillary needs an ion current of ~1pA or more to form a charged patch inside the capillary. However, since the charge-selected beam from the Tokyo-EBIT is not enough, an unselected beam is used for the capillary guiding experiments [6]. Thus it is important to increase the ion beam current for extending the experimental subjects can be done with the Tokyo-EBIT.

In this poster, we present the diagnostics of the highly charged ion beam extracted from the Tokyo-EBIT to clarify the problem which limits the ion current and to improve it. In particular, the emittance measurements for the very highly charged ion beams produced with electron energies of up to 100 keV are presented.

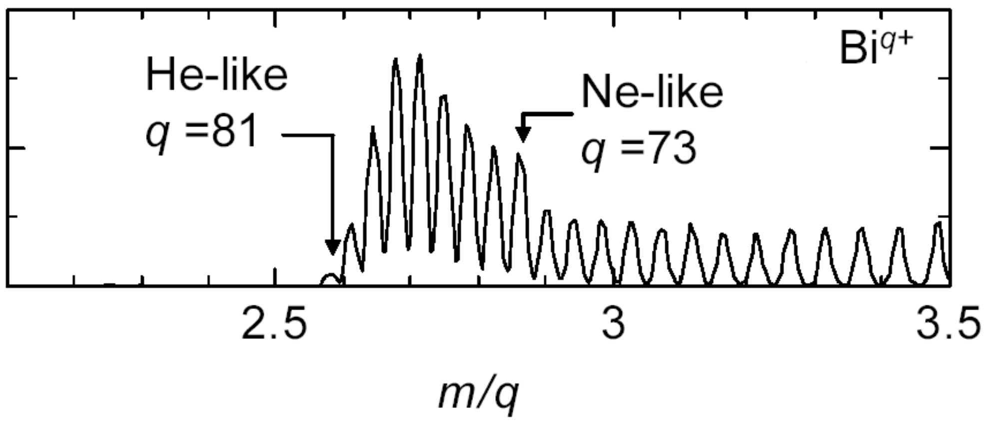

Fig.1. Typical charge state spectrum of highly charged Bi ion beam extracted from the Tokyo-EBIT at an electron energy of 60 keV.

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ENHANCEMENT OF SOFT X-RAY EMISSION FROM FS LASER PLASMA BY USING MIXTURE OF MOLECULE AND ATOMIC GASES AS CLUSTER JET TARGETS AND ITS APPLICATION FOR NANOSTRUCTURE IMAGING

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Using cluster targets allows reaching a very efficient fs laser pulses coupling with plasma. Such approach enables efficiently to produce very bright point plasma X-ray sources, to decrease the quantity of generated hot electrons and owing to the presence of debris. Unfortunately, only 10-30 % of expanded in supersonic nozzle gas could be aggregated in clusters. It means that between clusters, which good absorb laser energy and where plasma produced; also residual gas with enough high pressure presents and absorbs very efficiently soft X-ray radiation of plasma. Additional Soft X-ray radiation absorption also takes place in surrounding the laser interaction zone cold gas-cluster area. At the same time light atomic He gas has a very small absorption of soft X-ray radiation even when the density of this gas is enough high. Unfortunately pure He gas practically do not produce clusters during expansion in supersonic nozzle and it is impossible to produce intensive soft X-ray radiation using such gas. On the other hand, the presence of He gas helps clusterization of molecule gases. Obviously, it is very attractive to use the mixture of atomic He gas with some molecule gases for production of large size clusters target. Indeed, such gases combination will have the advantage of effective production of clusters due to the expansion of molecule gas in mixture with He gas and the advantage of the small absorption of soft X-ray generated in such cluster target, when it irradiates by fs laser pulses.

In this work we present the possibility of efficient production of CO_2 cluster targets by expanding mixture of 90% atomic He and 10% molecular CO_2 gases in the especially designed super-sonic nozzle. Irradiation of these clusters by a fs Ti:Sa laser pulses allows to enhance the soft X-ray radiation of He_β (665.7 eV) and Ly_α (653.7 eV) of Oxygen in 2-8 times compare with the case of using as targets pure CO_2 or N_2O clusters and reach values 2.8×10^{10} (~ 3 μ J) and 2.7×10^{10} (~ 2.9 μ J) ph/(sr · pulse), respectively. Nanostructure conventional soft X-ray images of 100 nm thick Mo foils in a wide field of view (cm^2 scale) with high spatial resolution (700 nm) are obtained using the LiF crystals as soft X-ray imaging detectors. The local inhomogeneities of soft X-ray absorption by the nanometer-thick films are measured with an accuracy of better than ± 3%. It was demonstrated that at the distance about 50 cm from such soft X-ray source the spatial coherence in the spectral range 1 – 5 nm is about 1 μm. Such spatial coherence was enough to obtain high quality phase-contrast soft X-ray imaging of different biological and nano films objects.

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NARROWBAND X-RAY SOURCE FOR APPLICATIONS IN MEDICINE

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Enhancing the efficiency of cancer radiotherapy and reducing the radiation side effects are two of the possible benefits of replacing conventional broadband radiation with narrowband radiation. In binary therapy ("dual targeting"), drugs containing high-Z atoms/nano-particles (e.g., platinum or gold) are made to preferentially concentrate in cancer cells, and then the radiation wavelengths are tuned to match the x-ray photoabsorption peaks (e.g., K-edge) of the heavy elements [1, 2]. Synchrotron facilities can provide the necessary x-ray beams, but are costly and impractical for routine therapy.

A new generation of EBIS/T devices may be a suitable alternative [3]. EBIS/T devices can produce beams of slow highly charged ions (HCI) that contain enormous potential energy. The ions can be easily transported to the vicinity of the body, where they radiate relatively mono-energetic X-rays [4].

In order to achieve the highest charge states with sufficient fluences for use in medicine, a better understanding of the EBIS/T ion trap dynamics may be required. We have analyzed some recorded EUV spectra [5] to estimate number of emitting ions in the trap for charge states up to 68+.

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The atomic model of the Sn plasmas for the EUV sources

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We study the atomic processes in the EUV light sources for the next generation microlithography. We investigate the laser produced plasma (LPP) as well as discharge pumped plasma (DPP) EUV sources for the optimization of the target and pumping conditions, in order to obtain more than 180W of power in the 13.5nm wavelengh region (2%BW), with a high efficiency (≥3%) and small source size. We develop an atomic model of multiple charged ions based on the calculated atomic data using the Hullac code. We find from the dependence of the emission wavelength of multiply charge ions, that Sn is the most efficient source material, because the wavelength of the 4d-4f transition array is in the 13.5nm band and is almost constant over a wide range of charge states (8-12). We also find that the strong 4d-4f transition array is accompanied by satellite lines from multiply excited configurations, which produce the broad emission spectrum observed from high density plasmas. We improved the wavelength of major emission lines, after detailed comparison with measurement, which is carried out based on the charge exchange spectroscopy (CXS), in which the wavelength of resonance lines of each charge state is measured independently. We calculate the emissivity and opacity of the plasma using the collisional radiative model. The atomic states and transitions, which have significant effect on the charge state distribution and spectral structure, are determined using iterative calculations. Calculated opacity of a Sn plasma is found to agree with experiment [1], and the radiation hydrodynamics simulation using the present coefficients of radiative transfer is shown to reproduce experimental conversion efficiency and spectrum. The code calculation suggests the use of low density plasmas to obtain higher conversion efficiency, because the emission spectrum becomes narrower with the reduced satellite contribution, which is verified experimentally in a CO_2 laser pumped plasmas.

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