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FECR Ion Source Development and Challenges

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FECR or the First 4th generation ECR ion source is under development at Institute of Modern Physics (IMP) since 2015. This ion source is aiming to extract intense highly charged heavy ion beams in the order of emA from the dense plasma heated with 45 GHz microwave power. To provide effective magnetic confinement to the 45 GHz ECR plasma, a state of the art Nb3Sn magnet with min-B configuration is a straightforward technical path. As there is no much precedent references, it has to be designed, prototyped at IMP through in-house development. Meanwhile, other physics and technical challenges to a 4th generation ECR ion source are also tackled at IMP to find feasible solutions. This paper will give a brief review of the critical issues in the development of FECR ion source. A detailed report on the status of FECR prototype magnet development will be presented.

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LECR5 Development and Status Report

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LECR5 (Lanzhou Electron Cyclotron Resonance ion source No. 5) is an 18 GHz room temperature ECR ion source featuring Ø80 mm ID (Internal Diameter) plasma chamber and high magnetic fields. It has been successfully constructed at IMP recently and has been fully commissioned to meet the requirements of SESRI (Space Environment Simulation and Research Infrastructure) project. According to the test results, LECR5 can meet the requirements of SESRI with sufficient beam intensities within the required the transverse emittances. As LECR5 is designed to be optimal for the operation at 18 GHz, we have managed to explore the source performance at 18 GHz with a maximum microwave power around 2 kW. Recent source test indicates, LECR5 can produce not only high intensity ion beams such as 2.12 emA O6+, 121 e¿A of Ar14+, 73 e¿A of Kr23+, 145 e¿A of

Xe27+, but also very high charge state ion beams such as 22 e¿A of Bi41+. This paper will present the recent progress with LECR5, especially the intense ion beam production and the beam quality investigation.

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Status of the AISHa Ion Source at INFN-LNS

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The AISHa ion source is an Electron Cyclotron Resonance Ion Source designed to generate high brightness multiply charged ion beams with high reliability, easy operations and maintenance for hadrontheraphy applications. The R&D performed by the INFN-LNS team during the 2019/2020 has allowed the improvement of the AISHa performances up to 20% for some of the extracted beams: both injection and extraction flanges has been improved and a movable electrode has been installed. The low energy beam transport has been equipped of an Emittance Measurement Unit (EMU), working through the beam wire scanners principle, for the measurement of the vertical and horizontal emittance of the beams of interest for hadrontherapy applications. Beam emittance has been characterized as a function of q/m and of the beam intensity to highlight space charge effects. If necessary, the beam wire scanners can be used for the characterization of the beam shape. The perspectives for further developments and plasma diagnostics will be also highlighted.

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Gismo Gasdynamic ECR Ion Source Status: Towards High-Intensity Ion Beams of Superior Quality

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GISMO, a CW high-current quasi-gasdynamic ECR ion source, is under development at the IAP RAS. The quasi-gasdynamic confinement regime, featuring high plasma density (up to 10^14 cm^-3) and moderate electron temperature (~100 eV), allowed to extract pulsed beams of H+ and D+ ions with current of 450 mA and RMS emittance <0.07 pi mm mrad*. It has been already demonstrated that major benefits of quasi-gasdynamic confinement, previously tested in pulsed mode, are scalable to the CW operational mode. In first experiments at GISMO facility, the ion beams were extracted in pulsed mode from the CW plasma of ECR discharge due to technical limitations of cooling circuits. Proton beams with current up to 70 mA were achieved at extraction voltage of 40 kV. A new unique extraction system especially effective for the formation of high current density ion beams was developed and tested. Latest results of beam current, emittance and charge state distribution measurements are presented. Another possible application of a quasi-gasdynamic plasma might be the intense source of vacuum ultraviolet radiation (VUV). Results of VUV measurements performed at GISMO facility are also presented.

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Status of the 45 GHz MARS-D Ion Source

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Development of the MARS-D ECR ion source, a 45 GHz next generation ECRIS using a NbTi MARSmagnet, has been continuously moving forward at LBNL. Recent stress analyses and other key components of the MARS-D ion source have been essentially finalized. This article presents and discusses the status of this new 45 GHz ECR ion source, such as the latest design features and the fabrication plan with funding available in the very near future.

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Conceptual Design of Heavy Ion ToF-ERDA Facility Based on Permanent Magnet ECRIS and Variable Frequency RFQ Accelerator

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Ion beam analysis is typically based on tandem accelerators and negative ions. The required 5-20 MeV energies for heavy ion time-of-flight elastic recoil detection analysis*(ToF-ERDA) can be achieved with a high charge state ion source and RFQ accelerator. We present a conceptual design of a ToFERDA facility based on a permanent magnet ECRIS* *and variable frequency RFQ accelerating 1-10 pnA of 40Ar8+, 84Kr17+ and 129Xe24+ ions to 4-7, 10-15 and 13-20 MeV. We present the PM ECRIS requirements focusing on the CUBE-ECRIS** with a quadrupole min-B field topology. Beam dynamics studies demonstrating good transmission of the heavy ion beams from the ion source to the RFQ entrance through the electrostatic low energy beam transport (LEBT) and a permanent magnet dipole are presented. The predicted LEBT transmissions of the CUBE-ECRIS (rectangular extraction slit) and a conventional ECRIS (circular extraction aperture) are compared. The conceptual design of the RFQ is described and the implications of the energy spread on the high energy beam transport are discussed. It is demonstrated that an energy spread below 0.2 % is necessary for appropriate resolution of the heavy ion ToF-ERDA.

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FRIB 28 GHz ECR Ion Source Development and Status

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To satisfy ultimate performance requirements for heavy ions, a 28 GHz superconducting ECR ion source is under development at the Facility for Rare Isotope Beams (FRIB) in collaboration with Berkeley National Laboratory. The construction and testing of the superconducting magnet was completed at Berkeley and delivered to FRIB in January 2018. The magnet and cryostat have been assembled on the high voltage platform. Magnet cooldown and field mapping are planned by the end of 2020. The source commissioning shall start in early 2021. Details of the ion source design, current status of assembly, and commissioning plan will be presented in this paper.

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Imaging in X-ray Ranges to Locally Investigate the Effect of the Two- Close-Frequency Heating in ECRIS Plasmas

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Plasma instabilities limit the ECR Ion Sources performances in terms of flux of the extracted highly charged ions by causing beam ripple and unstable operation conditions. In a 14 GHz ECRIS (Atomki, Debrecen), the effect on the plasma instabilities in an Argon plasma at Two Close Frequencies heating scheme (the frequency gap is smaller than 1 GHz) has been explored. A special multi-diagnostic setup [1, 2] has been designed and implemented consisting of detectors for the simultaneous collection of plasma radio-self-emission and of high spatial resolution X-ray images in the 500 eV - 20 keV energy domain (using an X-ray pin-hole camera setup). We present the comparison of plasma structural changes as observed from X-ray images in single and doublefrequency operations. The latter has been particularly correlated to the confinement and velocity anisotropy, also by considering results coming from numerical simulations.

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High Resolution X-ray Imaging as a Powerful Diagnostics Tool to Investigate ECRIS Plasma Structure and Confinement Dynamics

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High resolution spatially-resolved X-ray spectroscopy, by means of a X-ray pin-hole camera setup* operating in the 0.5-20 keV energy domain, is a very powerful method for ECRIS plasma structure evaluation. We present the setup installed at a 14 GHz ECRIS (ATOMKI, Debrecen), including a multi-layered collimator enabling measurements up to several hundreds of watts of RF pumping power and the achieved spatial and energy resolution (0.5 mm and 300 eV). Results coming by a new algorithm for analyzing Integrated (multi-events detection) and Photon-Counted images (single-event detection) to perform energy-resolved investigation will be described. The analysis permits to investigate High-Dynamic-Range (HDR) and spectrally resolved images, to study the effect of the axial and radial confinement (even separately), the plasma radius, the fluxes of deconfined electrons distinguishing fluorescence lines of the materials of the plasma chamber (Ti, Ta) from plasma (Ar) fluorescence lines. This method allows a detailed characterization of warm electrons, important for ionization, and to quantitatively estimate local plasma density and spectral temperature pixel-by-pixel.

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The Relationship Between the Diffusion of Hot Electrons, Plasma Stability, and ECR Ion Source Performance

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Plasma instabilities complicate the operation of electron cyclotron resonance ion sources. In particular, quasi-periodic losses of electrons from confinement due to kinetic cyclotron instabilities hinder ion source performance. Empirical scaling laws help guide the development of sources away from the most unstable operating points but are poorly understood. Further advancement of ECR ion source technologies requires a deeper understanding of instabilities, scaling laws, and internal processes of the ion source plasma itself. We present here results of an experimental study into these instabilities and scaling laws, and measurements of hot electron diffusion (E > 10 keV) from the 18 GHz SUSI ECRIS at the NSCL. Measurements of the average argon current and the standard deviation of their variations across multiple unstable operating points are shown. These measurements are compared to measurements of electrons that diffuse axially from the plasma chamber. In doing so it will be shown how controlling the diffusion of electrons control the stability of the plasma and optimize the ion source's performance.

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Production of 48Ca and 48Ti Ion Beams at the DC-280 Cyclotron

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The heaviest known elements (up to 118Og) were synthesized at the U-400 cyclotron (FLNR JINR, Dubna) by using a beam of 48Ca ions. During the tests of the DC-280 cyclotron, intense beams of 48Ca ions were produced. For the synthesis of the elements 119 and heavier, intense and stable beams of medium-mass elements are required, such as 50Ti and 54Cr. Before starting the main experiments, we test the production of 48Ti ion beam, which is less expensive than 50Ti. The article describes the method, technique, and experimental results on the production of 48Ca and 48Ti ion beam at the DC-280 cyclotron from the DECRIS-PM ion source.

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ECR Discharge in Solenoidal Magnetic Field as a Source of Dense Wide- Aperture Plasma Fluxes

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Sources of dense plasma fluxes with wide aperture are extensively used in applied science, i.e. surface treatment, and as a part of neutral beam injectors. ECR discharge in a solenoidal magnetic field (i.e. with no magnetic mirrors for plasma confinement), sustained by a powerful radiation of modern gyrotrons is under consideration at IAP RAS as a

possible alternative to widely used vacuum arc, RF and helicon discharges. The use of a high frequency radiation (37.5 GHz) allows to obtain a discharge at lower pressure, sustain almost fully ionized plasma with density more than 10^13 cm^-3, whereas the power on the level of several hundreds of kW allows one to create such a plasma in considerably large volume. In the present work fluxes of hydrogen plasma with the equivalent current density of 750 mA/cm2 and the total current of 5 A were obtained. A multi-aperture multi-electrode extraction system design capable of forming the non-divergent ion beam was developed with the use of IBSimu code.

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Stable and Intense 48Ca Ion Beam Production With a Microwave Shielded Oven and an Optical Spectrometer as Diagnostic Tool

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The CAPRICE ECRIS installed at the High Charge Injector (HLI) of GSI produces highly charged ion beams from gaseous and metallic elements. A high demand of metal ions comes from the nuclear physics, material re-search, and Super Heavy Element group (SHE), and the most requested element, besides 50Ti, is 48Ca. When this chemical reactive material is deposited inside the plasma chamber at internal components the stability can be com-promised. Furthermore, it is difficult to find a working point to guarantee a long-term stability as the oven re-sponse time and the reaction of the ECRIS are relatively slow. The monitoring by using an Optical Emission Spectrometer (OES) facilitates immediate reactions when-ever plasma instabilities occur. For this reason, a real-time diagnostic system based on an OES has been in-stalled at the ECRIS at HLI for routine operation during the beam-time 2020. The measured spectra revealed a parasitic oven heating by coupled microwaves often com-promising the ion source performance. Therefore, a tung-sten grid has been installed to shield the oven orifice from the coupled microwaves. The results in terms of 48Ca beam intensity and stability are reported here.

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New Metallic Stable Ion Beams for GANIL

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GANIL has been producing many stable beams for nearly 40 years. Constant progress has been made in terms of intensity, stability and reliability. The intensity for some stable metallic beams now exceeds or approaches the pμA level at an energy up to 95 MeV/u: 1.14 pμA for 36S (65% enriched) at 77 MeV/u, 0.35 pμA for 58Ni (63%) at 74 MeV/u. The presentation highlights recent results obtained for 28Si, 184W and 130Te using the GANIL s LCO (Large Capacity Oven) on the ECR4 ion source. To produce the tungsten beam, two injection methods were compared. For the first one, we evaporated some tungsten trioxide (WO3) with GANILs LCO. For the second one, the injection in the plasma chamber was made by using MIVOC (Metallic Ions from VOlatile compounds) with a tungsten hexacarbonyl (W(CO)6) compound. It was the first time that we used metal carbonyl compounds and the result is promising. All the tests have been qualified to obtain the level of intensity and beam stability. Theses good results led us to propose them for Physics experiments.

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A New Resistive High Temperature Oven for Metallic Beams Production

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For the Super Separator Spectrometer (S3) [1] currently under construction on Spiral 2 facility, metallic beams of high intensities must be delivered to impinge a target aiming to produce rare radioactive isotopes for fundamental nuclear studies. First requested beams are 58Ni, 48Ca, 50Cr, 50Ti or 50V with an intensity about 1,2.1013 pps. The metallic ion beams will be produced by the Phoenix V3 ECR ion source combined with a resistive oven newly designed to cope with the beam specifications. The evaporation of low vapor pressure metallic elements (Ti, V…) requires temperature within a range of 1900℃ to 2000℃. A new design of a resistive oven has been developed for this purpose. The oven reached 2000℃ in a test vacuum chamber during 8 days. It has worked out in the Electron Cyclotron Resonance Ion Source ECR4 at GANIL for Titanium beam production. Further tests using this ion source are under preparation for Ti and V beam production. Flux and angular distribution of atoms released by the oven are going to be measured offline for optimizing crucibles geometries. Finally, the oven will be integrated into the Phoenix V3 ECRIS for Ti and V production.

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Microcontrollers as Gate and Delay Generators for Time Resolved Measurements

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The diffusion of electrons from ECRIS plasmas results in the emission of bremsstrahlung distributions from the plasma chamber. ECRIS bremsstrahlung measurements that are both time- and energyresolved are often challenging to perform due to the 10's; 100's ms timescale that the plasma evolves over. However, the advancement of low-cost microcontrollers over the last decade makes timing and gating photon spectrometers easier. We present a proof of principle measurement which uses an Arduino microcontroller as a gate-and-delay generator for a High Purity Germanium (HPGe) detector. An example plot of the time-resolved bremsstrahlung spectrum, triggered by beam current variation induced by kinetic instabilities, is shown.

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Plasma Parameters at Upper/down Stream Region Near Ecr Zone and Optimizing Microwave-Launching on ECRIS

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We have investigated how to produce multicharged ions efficiently. Recently, we have focused on waves propagations in plasma and conducted the Upperhybrid Resonance (UHR) experiments. [1] We have also conducted experiments heating by the coaxial semi-dipole antenna to enhance the right-hand polarization wave, which contributes to ECR. [2] Multicharged ion beams have been improved using various means, e.g., the increase of the magnetic field and the microwave frequency, the DC biased plate-tuner, mixing low z gases, and the multiplex frequencies heating. However, the microwave launching position has been empirically determined on conventional ECRIS's. There is still some room for improvement with the respect to more efficient excitation of the wave propagation. In this research, we estimate the wave propagation near the ECR zone, and in the opposite peripheral region beyond it. We measure plasma parameters in those regions by two Langmuir probes inserted into each location at the same time. In near future, we optimize the

microwave-launching in the case of the fundamental frequency for ECR and the second frequency for UHR in order to enhance their incidence to the vacuum chamber.

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Tentative Solution to Plasma Chamber Cooling for High Power ECR Ion Source Operation

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High charge state electron cyclotron resonance ion source (ECRIS) is characterized by a so-called min-B magnetic field configuration, which provokes the localized plasma over-heating to plasma chamber especially for the 3rd generation ECRISs at high power operation condition. With the increase of rf power, more plasma energy will be dumped to tiny areas and result in a very high localized power density, which is estimated to be up to 1 kW/cm2. Few existing ECR plasma chamber cooling designs can withstand such high heat fluxes. In this paper, we report a new plasma chamber cooling design with so-called Micro-channel cooling technology, which can not only realize efficient heat transfer, but also retains a small radial thickness that is beneficial for the radial magnetic field. In order to evaluate the performance of the cooling structure with microchannel design, experimental cooling loop for high heat flux has been designed and built at IMP. Initial experiments demonstrate that optimized configuration can achieve high heat flux cooling in the range of 1 kW/cm2 and beyond. Based on these results, a plasma chamber with micro-channel design for SECRAL has been designed and tested.

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Development of HTO with Inductive Technology for Uranium Beam Production

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A High-Temperature Oven (HTO) with inductive heating technology has been developed successfully in 2019 at Institute of Modern Physics. This oven features durable operation temperature of >2000℃ inside the tantalum susceptor. By careful design the oven structure, material compatibility and thermal stress issues at high temperature has been successfully handled, which enables the production of

400 eμA U33+ with SECRAL-II*. With necessary refinement, this type of oven could also be available with room temperature ECR ion sources, like LECR4 and LECR5. Some improvements in structure have been proposed in this year. The design and testing results will be presented in this contribution.

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Influences of Magnetic Field Parameters to ECRIS Plasma Characteristics

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To investigate the hot electron population and the appearance of kinetic instabilities in ECRIS plasma, the axially emitted bremsstrahlung spectra and microwave bursts emitted from ECRIS plasma were synchronously measured on SECRAL-II ion source with various magnetic field configurations. The experimental results show that when Bmin/Becr is less than ~0.8, the spectral temperature Ts increases linearly with the Bmin/Becr-ratio when the injection, extraction and radial mirror fields are kept constant. Above this threshold Ts saturates and the electron cyclotron instability appears simultaneously. This study has also demonstrated that Ts decreases linearly with the increase of the average gradient over the ECR surface when the on-axis gradient and hexapole field strengths are constant. In addition, it is found that Ts decreases with the increase of the gradient at the resonance zone at relatively low mirror ratio and is insensitive to the gradient at high mirror ratio when Bmin is constant. Compared to a recent study taken on a fully superconducting ECRIS, this study shows different results discussing the mechanisms behind the correlation of magnetic field parameters to Ts.

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A Theoretical Model of High-Bmin Instabilities and Experimental Tests of Its Predictions

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It is well known that ECR ion sources exhibit instabilities when the source's minimum magnetic

field is approximately 80% of the resonant field or greater, but the reasons for this instability have yet to be satisfactorily explained. In this paper we present a simple theoretical model that has the highminimum-B instability as a consequence. We show that this model predicts modes of operation with high-minimum B that avoid that instability (including multiple-frequency heating), and present results from experimental tests of some of these predicted stable modes.

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Experimental Evidence of Trapped Waves in a Simple Mirror Magnetic-Trap

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This work presents the first experimental characterization of cavity modes trapped within a plasma column in an axis-symmetric magnetic trap. Trapped wave has been characterized by means of a movable antenna as a function of the B_{min}/B_{ECR} ratio and plasma parameters. The study demonstrates that E.M waves can be trapped between two R-cutoff layers, in proximity of the B minimum position. Results suggest that the trapped waves consist of Whistler waves, propagating perpendicularly to the magnetic field and storing large part of the E.M power introduced in the plasma chamber. If R-cut-off is removed by increasing the density, trapped waves are not detected anymore. A typical Electron Energy Distribution Function composed by two different electron populations is measured in the layer where trapped waves are revealed, suggesting that additional heating is occurring. The existence of trapped waves in a plasma column was already foreseen by several studies concerning the development of kinetic instability in plasmas and this experimental characterization allows to shed more light on nonlinear plasma coupling and to the generation of supra-thermal electrons in ECRIS plasmas.

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Simulation and Experimental Investigation of an Ion Source Metallic Oven

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Oven are widely used to produce metallic ion beams in ECRIS. A calcium oven dedicated to metal evaporation up to 650°C has been investigated by simulation and experience. The differential atom emittance has been measured and is well reproduced by the results of a Monte-Carlo simulation code. The absolute atom flux was measured as a function of the oven temperature and compared with theoretical predictions. A quite good agreement is obtained with theory and new values of Antoine's coefficient for calcium are proposed. The simulation is used to investigate the probability of on flight atom ionization by the plasma as a function of the oven distance to the ECR zone. With the PHOENIX V3 geometry, when the oven is placed in the injection biased disk plane, the ionization efficiency is 14%. This value in quite good agreement with experiment. Theoretical efficiency up to 57% is reachable when the oven distance is reduced to 1 cm to the ECR zone.

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Progress in Self-Consistent Modeling of Time- and Space-Dependent Phenomena in Ecris Plasma

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Resonant interaction with the microwave radiation in ECRIS plasma leads to a strongly anisotropic electron energy distribution function (EEDF), given as a combination of two to three electron populations, with the possibility to trigger kinetic instabilities. At the INFN, further efforts have been paid to improve and update self-consistent 3D numerical codes for plasma electrons kinetics. Progresses have opened several perspectives. It is now possible to derive space-resolved EEDF, and compute space-dependent energy and density maps. Also, the code has been updated to provide reaction rates of electromagnetic emissions, including X-ray fluorescence. An estimate of the local ion charge state distribution is potentially possible, and first evaluations are ongoing. Dealing with fast-transient mechanisms, such as electromagnetic emission via the electron-cyclotron MASER instability, the code is now updated for locally evaluating the EEDF anisotropy. We will present the collected results, which we believe to have a relevant impact both on the ECRIS plasma physics and on the INFN's PANDORA project that plans to use ECR plasmas for fundamental studies in Nuclear and AstroNuclear Physics.

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A Guiding Centre Approximation Approach for the Simulation of Electron Trajectories in ECR and Microwave Ion Sources

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The Boris algorithm has become the standard for particle trajectory integration in a magnetic field. The high frequency electron cyclotron motion (GHz) constrains the time-step below 10 ps. A guiding centre approach neglects the detailed particle cyclotron motion, describing its trajectory through free motion of the orbit's centre along the field lines and corresponding drifts. It works on the assumption that the magnetic field strength varies in a much larger length scale than the cyclotron orbit. This approach is more computationally expensive per step than direct orbit integration, but a shorter overall computation time may be expected by using a larger time-step (~100 ps). This work presents a study on implementing the guiding centre approach in ECR ion sources. It is shown to reproduce accurately the trajectory drifts and confinement of electrons in a minimum-B field, but the use of long time-steps exacerbates a non-physical kinetic energy loss. Following, non-confined electron trajectories in a flatter field are analysed, as in a microwave discharge ion source, where this method's drawbacks are avoided due to a smaller magnetic field gradient and a shorter electron lifetime.

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Electromagnetic Simulation of 'plasma-shaped' Plasma Chamber for Innovative ECRIS

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The plasma chamber and injection system design play a fundamental role in ECRISs with the aim to obtain an optimized electromagnetic field configuration able to generate and sustain a plasma with a high energy content. In this work we present the numerical study and the design of an unconventionally-shaped cavity resonator* that possesses some key advantages with respect to the standard cylindrical cavities, usually adopted in ion sources setups. The cavity geometry, whose design has been completed on January 2020, has been inspired by the typical star-shaped ECR plasma, determined by the magnetic field structure. The chamber has been designed by using the commercial softwares CST and COMSOL, with the aim to maximize the on-axis electric field. Moreover, a radically innovative microwaves injection system, consisting in side-coupled slotted waveguides, has been implemented, allowing a better power coupling and a more symmetric power distribution inside the cavity with respect to the standard rectangular waveguides. This new 'plasma-shaped oriented' design could relevantly improve the performances of the ECRISs while making more compact the overall setup.

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Characterization of 2.45 GHz ECR Ion Source Bench for Accelerator-Based 14-MeV Neutron Generator

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The 2.45 GHz Electron Cyclotron Resonance Ion Source (ECRIS) has been indigenously developed. This development of ECRIS aims to provide high brightness, stable, and reliable D+ ion beam of 20 mA in continuous (CW) mode operation for accelerator-based D-T neutron generator. The ECR ion source setup consists of a microwave system, a magnet system, a double wall water-cooled plasma chamber, a high voltage platform, a three-electrode ion extraction system, and a vacuum system. The ECR ion source test setup is installed and deuterium plasma generated. Three-electrode extraction system is designed and fabricated for the ion beam extraction. A ~10 mA deuterium ion beam is extracted from the ECR ion source. The paper covers the detailed experimental setup of ion beam characterization and diagnostics used for measurement of beam profile, beam current, and beam emittance measurements. It also covers the latest results of beam profile, and beam current measurement as a function of extraction voltage, gas flow, and acceleration voltage.

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Electron Cyclotron Resonance Ion Source Related Research and

Development Work at the Department of Physics, University of Jyväskylä (JYFL)

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Recent research work of the JYFL ion source team covers multi-diagnostic studies of plasma instabilities, high-resolution plasma optical emission spectroscopy, ion current transient measurements to define the total life-time of a particle in the highly charged plasma. The JYFL team also elaborates the magnetic and technical design of the unconventional ion source named CUBE. The R&D work includes, in addition, the commissioning and operation of the highperformance 18 GHz ECRIS, HIISI. The instability measurements have revealed new information about the parameters affecting the onset of the plasma instabilities and shown that different instability modes exist. The ion-beam transient studies have given information about the cumulative life-time of highlycharged ions convergent with the ion temperatures deduced from the Doppler broadening of emission lines. The CUBE prototype has a minimum-B quadrupole magnetic field topology, similar to ARCECRIS, and its all-permanent magnet structure has been optimized for 10 GHz frequency. The CUBE design will be presented along with its commissioning status. The status and operational experience with HIISI will be reported as well.

9

Study on the Correlation between Energy Distribution of Electrons Lost from the Confinement and Plasma Bremsstrahlung on a min-B ECR Plasmas

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The study of plasma bremsstrahlung has been used as a diagnostic tool for understanding the behavior of confined plasma in Electron Cyclotron Resonance Ion Sources (ECRIS). In order to understand the relation connecting the confined plasma and the electrons escaping the confinement, a series of measurements have been made to measure the bremsstrahlung produced in the axial and radial direction along with the Lost Electron Energy Distribution (LEED) axially on JYFL 14 GHz ECR. We present here the effect of various source parameters on the axial and radial bremsstrahlung along with the LEED on a min-B confined ECR plasma. The measured LEED has been found to show a correlation with bremsstrahlung measurement and also have observed as a potential diagnostic method for instability. The explanation for observed LEED and bremsstrahlung trends is provided.

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Ultra-High Current Density Produced by a 60 Ghz Ecr Ion Source

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SEISM is a compact ECR ion source operating at 60 GHz developed up to 2014. The prototype uses a magnetic cusp to confine the plasma. This simple magnetic geometry was chosen to allow the use of polyhelix coils (developed at the LNCMI, Grenoble) to generate a strong magnetic confinement featuring a closed ECR surface at 2.1 T. The plasma is sustained by a 300 kW microwave pulse of 1 ms duration and with a 2 Hz repetition rate. Previous experiments at LNCMI have successfully demonstrated the establishment of the nominal magnetic field and the extraction of ion beams with a current density up to ~ 1A/cm2. The presence of "afterglow" peaks was also observed, proving the existence of ion confinement in a cusp ECR ion source. The last run was prematurely stopped but the project restarted in 2018 and new experiments are planned in 2021. A new transport beam line has been designed to improve ion beam transport towards the beam detectors. Short- and long-term research plans are presented, including numerical simulations of the beam transport line and future upgrades of the ion source with the main goal to transform the high current density measured into a real high intensity ion beam.

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Multi-Species Child-Langmuir Law with Application to ECR Ion Sources

Chun Yan Jonathan Wong[None]

We generalize the classical single-species Child-Langmuir Law to analyze multi-species beams from ECR ion sources. The formulation assumes the relative weight of each species in the extracted beam is known. We applied the results to charge state distribution data from Artemis- and Venus-type sources at the NSCL and LBNL respectively. The total measured beam current is close to the maximum current predicted by the multi-species Child Langmuir Law in each case, which indicates that beam extraction occurs around the regime of space charge limited flow. Prospects for application of the results and further studies on the topic are outlined.

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Beams with Three-Fold Rotational Symmetry: A Theoretical Study

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Beams from ECR ion sources have 3-fold transverse rotational symmetry induced by the ECR sextupole. The symmetry imposes equality constraints among transverse beam moments, which can be derived using a theoretical framework we developed. Since the constraints are solely a consequence of the rotational symmetry of external fields, they hold for arbitrary charge state distribution and space charge intensity. These constraints provide a new tool to analyze phase space properties of ECR beams and their impact on low-energy transport. We prove that, regardless of their triangulation, beams with 3-fold rotational symmetry have the same rms emittance and Twiss parameters along any transverse direction. These counter-intuitive results are applied to the FRIB Front End to demonstrate how symmetry arguments challenge long-standing assumptions and bring clarity to the beam dynamics.

39

Improvement of the Cryostat System Performance of 28-Ghz Electron Cyclotron Resonance Ion Source of the Biba by a Radiation Shielding

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The BIBA (Busan Ion Beam Accelerator) is a compact linear accelerator facility using the 28 GHz ECRIS at the KBSI (Korea Basic Science Institute). Our goal is to generate high current fast neutrons using the heavy ion interaction with a proton target. For a stable operation of the superconducting magnets, the performance of cryostat system is very essential at the 28 GHz ECRIS. However, the emitted x-ray from inner plasma chamber contributes to increase an extra heat load to the cryostat system by absorbing the cold mass of the superconducting magnet. Therefore, we have measured X-ray spectra from the

28 GHz ECR ion source and tried to improve the performance of the Cryostat System by a radiation shielding. In this paper, we will present the test results of X-ray emission on 28GHz KBSI ECRIS and improved cooling system performance.

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Precise Identification of Extracted Ion Beam Spectrum Initially Obtained in Synthesizing Iron-Endohedral Fullerenes on ECRIS

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Electron cyclotron resonance ion source (ECRIS) plasma has been constructed for producing synthesized ion beams in Osaka Univ.[1,2] We hope that it can become a universal source capable of producing ions with wide range mass/charge ration (m/q). We have been trying to produce endohedral fullerenes in the ECRIS. We have conducted initial experiments on production of them only in the second stage of ECRIS. We have been using iron vapor source by induction heating (IH) from the mirror end along to the geometrical axis, and C60 crucible from the side wall, respectively. We succeeded in realizing ECR plasma that fullerene and iron ions coexist on the single stage ECRIS, even by 1kV extraction voltage.[3] By these experimental series, the typical CSD suggests that there is possibility of slight formation of iron fullerenes compounds and iron endohedral fullerenes. We are continuing to investigate the experimental conditions that maximize spectrum corresponding to iron endohedral fullerenes. In this paper we describe preliminary experimental results of synthesizing ironendohedral fullerene on the ECRIS.

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High Intensity Vanadium-Ion Beam Production to Search for New Super- Heavy Element with Z = 119

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We have begun searching for the new super-heavy element (SHE) with Z=119 at RIKEN Heavy Ion LINAC (RILAC). To overcome the small production

cross section of vanadium (V) beam on the curium target, the project requires a very powerful V beam. In order to optimize the beam intensity of V with the charge state of 13+, we have investigated the effects of the amount of V vapor, the power of 18- and 28-GHz microwaves, and the strength of the mirror field. While no significant effect was seen by changing the mirror field Bext from 1.4 T to 1.6 T, the amount of V vapor and the microwave power strongly affected. Based on the correlation between the V-vapor and the microwave power, we obtained a 600-euA V(13+) beam with the V consumption rate of 24 mg/h and the microwave power of 2.9 kW in order to execute about 1-month SHE experiment. Furthermore, because such strong mirror field enhances the transverse beam emittance, it is important to control the emittance with small reduction of the intensity. We have successfully controlled the beam emittance by using three pairs of slits (triplet slits) in LEBT by eliminating the peripheral beam components in both of the x-x' and y-y' phase spaces.

8

Enhancing Production of Multicharged Ions by Pulse Modulated Microwaves under Low Z Gas Mixing Operation on ECRIS

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We are aiming at producing various ion beams in ECRIS. In the case of producing multicharged ion beams, we try to enhance loss channel of low Z ions by means of adding pulse modulated microwaves to conventional gas mixing method.*Through these experiments, we explore the feasibility of selectively heating specific ions with pulse modulated microwaves and launching another low frequency RF waves. In gas mixing experiment, we use Helium as low Z gas for production of multicharged Ar and Xenon ion beams. These experiments are conducted by keeping the total pressure constant and changing the mixing ratio of Helium. The time scale of pulsed microwave is typically several to several hundreds of microseconds. We optimize the pulse period and duty ratio for producing multicharged ion beams. These effects are investigated to measure Charge State Distributions (CSDs). Also, we can measure the emittance using wire probe and multi slit attached to Ion Beam Irradiation System (IBIS).** We estimate the normalized emittance from this measurement to determine index of ion temperature in the ECRIS. In this paper, we mainly describe the results of these active and additive methods at the ECRIS.

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Beam Profile Measurements of Decelerated Multicharged Xe Ions from ECRIS for Estimating Low Energy Damage on Satellites Components

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Electron cyclotron resonance ion source (ECRIS) has been constructed for producing synthesized ion beams in Osaka Univ.,* Xe is used as fuel for ion propulsion engines on artificial satellites. There are problems of accumulated damages at irradiation and sputtering by low energy Xe ion from the engine. It is required to construct experimentally sputtering yield databases of ion beams in the low energy region from several hundred eV to 1keV, since there are not enough data of satellite component materials. Therefore, we are trying to investigate experimentally sputtering yield on materials by irradiating the low energy single species Xeq+ ion beams. However, there is a problem that if the low extraction voltage, the amount of beam currents is not enough to obtain ion beam flux for precise evaluation of sputtering yield data. Thus, we conduct to decelerate Xeq+ ion beams required low energy region after extracting at high voltage, e.g., 10kV. We measured the decelerated beam profile with x and y direction wire probes. As a result, we were able to estimate the dose of ion fluxes. We are going to conduct irradiation experiments on various materials.

5

Observation of Cyclotron Instabilities in SECRAL-II Ion Source

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Cyclotron instabilities in Electron Cyclotron Resonance Ion Source (ECRIS) plasmas are related to non-linear interaction between plasma waves and energetic electrons, resulting in strong microwave emission, a burst of energetic electrons escaping the plasma, and the periodic oscillations of the extracted beam currents. Precedent investigation of cyclotron instabilities has proved that Bmin/BECR can be treated as a magnetic field threshold. Recently, experiments with SECRAL-II ion source demonstrate that Bmin/BECR is not the only knob, and other field parameters have also been found to be related to cyclotron instabilities, such as mirror ratio and radial field. Namely, the trigger of cyclotron instability is a combination of many magnetic field parameters. This paper will give the experimental setup at IMP for cyclotron instability investigations and experimental observations will be presented.

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High Intensity Ion Beam Extraction System for FECR

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To meet the beam requirements of High Intensity heavy ion Accelerator Facility (HIAF), the Institute of Modern Physics is developing a Fourth generation ECR ion source (FECR). Targeting at the operation frequency of 45 GHz, FECR is expected to produce very high intensity highly charged heavy ion beams, such as 1.0 emA 238U35+, 2 emA 78Kr19+, 10 emA 16O6+, etc. Based on the records with the 3rd generation ECR ion source operating at 24~28 GHz, the corresponding total drain current of FECR could reach 20 ~ 60 emA. To extract such high intensity multi-charged ion beams from the source with high beam quality and transmission efficiency, conventional diode or triode extraction system might not be suitable, and therefore a 4-electrode extraction system with a total extraction voltage of 50 kV is designed to mitigate the space charge influences and minimize the beam emittance growth in the extraction region. In this paper, a 3D model of the FECR extraction system is built using the IBSimu code. The electrode angles, voltages and electrode spacings are optimized for different ion beam conditions respectively. Beam properties comparison of various simulation conditions are presented.

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39Ar Enrichment System Based on a 2.45 GHz ECR Ion Source

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Aimed at improving the ATTA's (Atom Trap Trace Analysis) dating efficiency with 39Ar radioactive isotope, an isotope enrichment system has been developed at IMP (Institute of Modern Physics) to increase the abundance of 39Ar in the incident sample gas. In this enrichment system, a 2.45 GHz ECR ion source was designed to ionize sample gas and produce isotopes beams with several mA, and the isotopes beam is transported and separated in the separation beam line, which is consisted of two quadrupoles and an analysis magnet. The separated isotopes are collected by a rotated aluminum foil target. According to the recent cross-checked results with ATTA, high enrichment factor of 39Ar isotope has been successfully reached. This paper will give a general introduction to the platform setup. The isotope enrichment efficiency is the critical issue for such a platform and will be specially discussed.

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Conceptual Design of an Electrostatic Trap for High Intensity Pulsed Beam

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Highly charged ion sources play an important role in the advancement of heavy ion accelerators worldwide. The beam requirements of highly charged heavy ions from new accelerators have driven the performance of ion sources to their limits and beyond. In parallel to developing new technologies to enhance the performance of ECR ion source, this paper presents a conceptual design of an ion trap aiming to convert a cw ion beam into a short beam pulse with high compression ratios. With an electron gun, a solenoid and a set of drift tubes, the injected ions will be trapped radially and axially. By manipulating the potential of drift tubes, ions can be accumulated with multiple injections and extracted at a fast or slow scheme. This paper presents the simulation and design results of this ion trap prototype.

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Numerical Simulations of Plasma Dynamics in ECRIS Afterglow

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Plasma dynamics in the afterglow of ECRIS has been studied through the Particle-in-cell (PIC) simulations. A full 3D implicit electrostatic PIC code was developed to meet the needs of ECRIS simulations and to study the characteristics of the ECR plasma during the afterglow. The initial plasma parameters at the simulation start-up were assumed by referring to the experimental diagnostics of the ECRISs from IMP, Lanzhou. The dynamics of electrons and ions in the presence of the external magnetic field and at the absence of the microwave energy were simulated to study the mechanism of afterglow. Through the abundant diagnostics of the 3D PIC simulation, some ECR plasma features during afterglow including the plasma potential and electron energy distributions could be obtained and analyzed. The goal was to determine the important evolutions that contribute to the afterglow and thus to have a clearer understanding of ECRIS afterglow mode.

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Production of Metal Ion Beams From ECR Ion Sources

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The work describes the preparation of metal ion beams from ECR ion sources by the MIVOC (Metal Ions from Volatile Compounds) method. The method is based on the use of volatile metal compounds having high vapor pressure at room temperature: for example, Ni(C5H5)2, (CH3)5C5Ti(CH3)3 and several others. Using this method, intense beams of chromium, titanium, iron, and other ions were obtained at the U-400 FLNR JINR and DC-60 cyclotrons (Astana branch of the INP, Alma-Ata, Kazakhstan Republic).

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Present Status of HIMAC ECR Ion Sources

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High-energy carbon-ion radiotherapy is being carried out at Heavy Ion Medical Accelerator in Chiba (HIMAC). Over 12000 cancer patients have been treated with carbon beams having energies of between 56-430 MeV/u since 1994. There are two injectors in the HIMAC for medical and experimental use. First injector consists of two ECR ion sources and one PIG ion source, the RFQ linac and the DTL. Usually, this injector suppling the carbon ion for cancer therapy and various ion such as H, He, Fe, Xe are accelerated for biological and physical experiment. The 10 GHz NIRS-ECR ion source produce the carbon ion for cancer therapy. The 18 GHz NIRS-HEC ion source produce He to Xe ions for experimental use. Second injector consists of the compact ECR ion source with all permanent magnet, the RFQ linac and the APF IH-DTL. This injector supplies the carbon ion for experimental use. Additionally, we tried production of the Indium and the Tin ions by using the In(C5H5) and the Sn (i-C3H7)4 at the NIRS-HEC. Beam current of the 115In20+ and 120Sn18+ were 90 and 15 micro A, respectively. Present status of ECR ion sources and some development will be described.

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Attempt to Develop a 2.45 GHz Microwave Driven Source for Plasma Flood Gun

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Plasma flood guns (PFGs) are widely used to neutralize wafer charge during the doping process in modern ion implanters. Compared with traditional dc arc discharge with filament and RF discharge, the microwave driven source that has long lifetime and has no metallic contamination is regarded as a potential choice of PFG [1]. Attempt to develop a large scale PFG based on 2.45 GHz microwave driven sources was launched at Peking University (PKU). A prototype one is a miniaturized 2.45 GHz permanent magnet electron cyclotron resonance (ECR) source to produce point-like electron beam. In previous experiments, more than 8 mA electron beam has been extracted with a Φ6 mm extraction hole at an input microwave power of 22 W with argon gas [2]. Recently, studies are focusing on the possibility of producing of ribbon electron beams as PFG with 2.45GHz microwave driven surface wave plasma (SWP) source. A cylindrical chamber surface wave plasma generator with a using cylindrical dielectric waveguide and a 70 mm×3 mm extraction slit was fabricated. The primary test results were obtained. More details of this PFGs will be discussed in this work.

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Role of the 1+ Beam Optics Upstream the SPIRAL1 Charge Breeder

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The SPIRAL1 charge breeder (SP1CB) is under operation. Radioactive ion beam (RIB) has already been delivered [1] to Physicist for experiments. Although charge breeding efficiencies demonstrated high performances for stable ion beams, those efficiencies regarding RIB are lower. The beam optics, prior to the injection of the 1+ ions into the SP1CB, is of prime importance [2] for getting such high efficiencies. Moreover, the intensities of the radioactive ion beams are so low, it is really difficult to tune the SP1CB. A stable beam having a close B is required to find out the set of optic parameters preceding the tuning of the RIB. Hence, it has been decided to focus our effort on that issue as to get control of the 1+ beam optics leading to high charge breeding efficiencies whatever the 1+ mass, energy and Target Ion Source System used (TISS). Being aware that TISS's provide ion beams with a specific energy spread and knowing that the acceptance energy of the SP1CB is rather narrow; that parameter must play also a role in the charge breeding efficiency. This contribution will show the strategy undertaken to overcome that problem and the results already obtained.

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LNL GANIL LPSC Collaboration On The Contaminants Reduction In ECR Charge Breeders

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Contaminants reduction in Electron Cyclotron Resonance Charge Breeders (ECRCB) is a key point for the future experiments foreseen at LNL and GANIL Isotope Separation On Line (ISOL) facilities. According to the mass separator resolution set downstream the ECRCB, the radioactive ion beam study can be challenged in case of low production rate. An ongoing collaboration between LNL, LSPC and GANIL laboratories aims to improve the beam purity, acting on all the pollutant causes. Comparative experiments will be done at LPSC using different techniques, like covering the plasma chamber wall with liners in several material. Different configurations of the ECRCB will also be tested, with the enhancement of the efficiency and charge breeding time parameters as additional objectives. A presentation of this program is proposed together with the effective upgrade of the LPSC 1+N+ test bench which goal was to improve the vacuum quality and clean all the beam line devices.

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ECR3 Commissioning and Planning for C-14 Ion Beams at the Argonne Tandem Linac Accelerator System

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The Electron Cyclotron Resonance Ion Source ECR3* has recently been commissioned at the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory. While ECR3 can provide many of the stable ATLAS beams, its other intended purpose is the production of C-14 ion beams which were previously produced by a now-retired negative ion source. This paper will discuss the final installation and commissioning of the ion source as well as the preparations for running C-14. A stable C-13 ethylene gas was used as a surrogate to determine the expected level of N-14 contamination when running C-14 since they are inseparable at ATLAS. We were also able to confirm consumption rates and charge state efficiencies under different C-13 running conditions in order to optimize the upcoming C-14 beam production.

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Improvement of the Efficiency of the Triumf Charge State Booster

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The Electron Cyclotron Resonance Ion Source is a versatile and reliable source to charge-breed rare isotopes in TRIUMF's Isotopes Separation and Acceleration (ISAC) facility. Significant research work has been done by different groups worldwide to improve the efficiency and performance of the ECRIS as a charge state booster. The most recent of these research works is the implementation of the twofrequency heating on an ECRIS. At the ISAC facility of TRIUMF, a 14.5 GHz PHOENIX booster which has been in operation since 2010 was recently upgraded to accommodate the two-frequency heating system using a single waveguide. The efficiency for charge breeding into a single charge state, which depends on the rare isotope that is being charge-bred, has been determined to be between 1 - 6 %. The CSB is being upgraded to improve its charge breeding efficiency. A detailed investigation of the effect of the twofrequency heating technique on the intensity, emittance and the efficiency of the extracted beam is presently being conducted.

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Studies of ECR Plasma Chamber Contamination With Accelerated Beams and Diamond Detectors

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While developing stable and re-accelerated rare isotope beams (RIB) for acceleration with the TAMU K500 cyclotron, a background of various stable beams has been observed. It has been determined that this background is arising from alloys and contamination in the components of our ECR ion sources, in particular, the aluminum alloy plasma chamber. We have developed a detector system based on diamond detector telescopes that allows us to measure the composition of the beam after acceleration with the K500 cyclotron at TAMU. Using this technique, we have been able to develop ion source and cyclotron tuning methods to minimize the stable beam background and maximize the stable beams of interest and/or the RIBs. We also endeavor to reduce the stable beam background from the ECR ion sources using techniques such as pure aluminum liners. In my presentation, I plan to show our accelerated beam detection setup with diamond detectors. I also plan to present about the background we have measured with this setup from the ECRIS components, in particular, the plasma chamber. Finally, I will comment on our efforts to reduce this background.

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Electron Cyclotron Emission Imaging of Electron Cyclotron Resonance Ion Source Plasmas

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A new imaging system for Electron Cyclotron Resonance Ion Sources (ECRIS) has been designed and is being built. This K- and Ka-band camera will extract localized measurements of absolute energy and relative number density for ECRIS plasma electrons by imaging their Electron Cyclotron Emission (ECE) spectra, as the frequency, shape, and strength of the ECE harmonics correlate directly with the local magnetic field, electron energy, and plasma density. The design of the overall quasi-optical system will be presented, including novel ceramic optics for the radial viewports of the Cyclotron Institute's ECRIS and metamaterial mirrors with electronically controllable reflectivity. Spatial resolution sufficient to distinguish important plasma regions and temporal resolution sufficient to study dynamic plasma processes is expected.