Book of Abstracts

NIBS24 – 19th – 22nd November 2024

Institute for Plasma Research, Bhat, Gandhinagar, Gujarat – 382428, India

Improved RF coupling in a powerful H- source for fusion

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The Neutral Beam Heating systems of ITER rely on large sources for negative hydrogen ions. The plasma in these sources is generated in eight cylindrical drivers by inductive coupling of up to 100 kW RF power per driver (about 7 litre volume). Typically, 6 coil windings are used for a driver length of about 18 cm. As the voltage per coil winding is directly linked to the RF frequency, an RF frequency of 1 MHz, together with the availability of high-power RF generators at that time, has been chosen at the beginning of the RF ion source development in the 1980s.

Measurements of the RF power transfer efficiency at the ITER NBI prototype ion source installed at BATMAN Upgrade revealed that only about 60% of the RF generator power is coupled into the plasma [1]. Although extrapolations from the half-size ion source ELISE show that the required negative ion current should be achievable in the full-size ITER sources an improved RF coupling would be desirable to increase the margin.

Results from a well benchmarked, self-consistent fluid model [2] predict that the RF power transfer efficiency is significantly increased by either a higher RF frequency and/or an increased length of the driver [3] at the low pressure of 0.3 Pa. Changing the frequency to 2 MHz would increase the RF coupling to about 80% whereas the increase of the RF voltage per coil winding is marginal (from 2.2 kV to 2.25 kV) and should thus not enhance the risk of RF breakdowns at the RF coils. Increasing the length of the driver to about 30 cm is predicted to increase the coupling by the same amount.
In order to proof these predictions, an experimental validation of the RF power transfer efficiency is presently carried out at BATMAN Upgrade. The installed 75 kW Transradio solid state RF generator can be modified with medium effort from a frequency of 1 MHz up to 1.7 MHz (higher frequencies than 1.7 MHz would require a new RF generator) and is done first. In a second step, a longer RF driver will be tested.

This contribution summarizes the predictions of the simulations and gives the status of the experimental validation regarding the increased RF frequency. The experimental validation is part of the activities of ITER's Neutral Beam Test Facility (NBTF) hosted by Consorzio RFX (Padua, Italy) and is co-funded by an ITER-NBTF, NBTF-IPP Agreement.

[1] D. Zielke et al., J. Phys. D: Appl. Phys. 54 (2021) 155202.
[2] D. Zielke et al., Plasma Sources Sci. Technol. 30 (2021) 065011.
[3] D. Zielke et al. (2023) arXiv:submit/4836974

Evaluation of Beam Properties Using a Checkerboard Masking Configuration at the NNBI Test Stand BATMAN Upgrade

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The ITER Neutral Beam Injection (NBI) system must deliver intense beams of neutral hydrogen and deuterium atoms in order to provide current drive and heat the core of the tokamak plasma to fusion relevant temperatures. The RF ion sources used in each NBI beamline must deliver 66 A of hydrogen and 57 A of deuterium negative ions which are then accelerated to energies of up to 1 MeV, for pulse lengths of up to 3600 s. The ion beam will be composed of 1280 individual beamlets and has strict requirements on the beam optics and uniformity in order to minimise the power loads deposited on beamline components. The divergence of each beamlet must have a maximum divergence of 7 mrad, with a uniformity of the extracted beam ≥ 90 % to ensure that the individual beamlets are close to the divergence optimum whilst minimising the power loads on downstream beamline components.

The BATMAN Upgrade (BUG) test facility contributes to the development of the ITER N-NBI and is a 1/8 size ITER source with 70 extraction apertures to closely approximate an ITER beamlet group, with a maximum ion energy of 45 keV. BUG has a suite of diagnostics for characterising the negative ion beam properties, such as beam emission spectroscopy, CFC tile calorimetry, and beam dump calorimetry. In previous campaigns the divergence of a single beamlet was estimated by isolating a single beamlet in the upper half of the plasma grid and measuring the spatial properties of the resulting image on the CFC. However, the magnetic filter field used to cool electrons in the extraction region of the source leads to a pronounced vertical asymmetry in the plasma and the extracted current density. As a result, the beamlet properties are also not likely to be uniform across the whole extraction area. In order to provide better spatial information of the beam properties, a checkerboard masking configuration of the BUG extraction system was implemented. Whilst there is still much more beamlet overlap than the single beamlet masking, the checkerboard masking allows the beamlets to be better isolated on the CFC tile across the whole extraction area when compared to that of the open configuration. This contribution outlines the analysis process for the estimation of both the individual beamlet divergence and the uniformity of the extracted beam, including some initial results from a recent experimental campaign characterising the BUG beam in both plasma drift up and drift down configurations.

Power Transfer Efficiency of SPIDER drivers against source parameters: investigation through calorimetry, comparison with simulations

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SPIDER, the full negative ion source prototype for ITER Neutral Beam Injectors (NBI) is being developed at the Neutral Beam Test Facility (NBTF) at Padua, Italy. A first experimental campaign on this facility was conducted between 2018 and 2021 and a second campaign is ongoing. In SPIDER, the plasma is produced by Radio Frequency (RF) on eight chambers located at the back of the ion source, referred to as drivers.

Only a fraction of the total RF power is transferred from the RF coil to the plasma, the rest being dissipated on the passive elements of the structure via Joule heating. The fraction of power effectively coupled to the plasma is referred to as Power Transfer Efficiency (PTE) and is around 50% for the design of SPIDER drivers. In previous activities, calorimetry on the driver hydraulic circuits coupled with a set of electromagnetic and thermal simulations was used to assess the PTE of each driver for the pulses of the 2018 campaign. In particular, the electromagnetic simulations with a 3D calculation code provide predictions of the PTE evolution with the ion source gas pressure and the magnetic filter field intensity.

In this study, the simulation suite has been completed to provide a self-consistent estimation of the power deposition on the driver passive parts, and the calorimetry measurements of the 2024 campaign on SPIDER are used to estimate the PTE evolution against the plasma pressure and filter field intensity. Moreover, SPIDER currently features two kinds of ElectroMagnetic Shields (EMS) positioned around the drivers. Since calorimetry allows to estimate the PTE for each single driver, the influence of this new EMS design and the PTE is assessed.

The results provide an experimental test for the 3D electromagnetic code developed at Consorzio RFX and gives insights to optimize the PTE in future experiments.

Development of Beam Monitoring System for the Large Beam of ITER HNB

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The negative ion accelerator of ITER neutral beam injectors for heating and current drive (HNB) utilizes large area grids (0.64 m wide by 1.6 m long) with 1280 apertures to produce high power negative ion beams such as a deuterium negative ion (D-) with 1 MeV, 40 A for 3600 s, and a hydrogen negative ion (H-) beams with 0.87 MeV, 46 A for 1000 s. The required beam divergence angle is less than 7 mrad in order to suppress excess power loads on the beamline and acceleration grids during long pulse beam injection.

Recently, the carbon-fiber composite (CFC) tile is used to study the beam divergence in several laboratories. Because it is useful to examine each beamlet since the beam footprint of each beamlet can be seen on this tile. However, in the ITER HNB and its prototype (so-called MITICA in the NB test facility), such diagnostics cannot be installed, and it is difficult to check the beam divergence during beam operation. However, the visible camera to monitor the whole view of the large beam from afar will be installed. In this study, the direct comparison of the divergence angle observed in the CFC target and the visible camera is examined by using MeV-class beam in the MeV test facility (MTF).

For the ITER HNB and MITICA, considering the superposition of the beamlets, it is difficult to observe every single beamlet. The beamlet at the edge of entire beam (the foothills of entire beam) was thought to be observable. Therefore, the beam divergence of each beamlet and expected beam divergence from edge of beam were compared by using the experimental result of MTF. As results of demonstration, the beam divergences obtained from the edge of beam are estimated as smaller value than that from each beamlet, however, both values have a similar dependence during long pulse operation. It is revealed that this evaluation method can be used for the time-evolution of beam divergence.

In this presentation, the result of the demonstration experiment at MTF and its applicability to the ITER HNB will be reported.

ITER-relevant steady-state hydrogen beams at ELISE

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The ELISE test facility with its half ITER-size ion source is an essential part of the European Roadmap towards the ITER NBI system. The 2024 experimental campaign of ELISE aimed to demonstrating the ITER hydrogen target values for the extracted current density, the ratio of co-extracted electrons to extracted ions and the uniformity of the extracted beam at a filling pressure of 0.3Pa during short and long pulses. Following the upgrade of the HV system in 2022, ELISE is capable of performing steady-state extraction pulses. The flat-top length in the ITER baseline scenario will be 400s; including ramp-up and ramp-down the length of the pulses will be 600s.

The main result is that 90% of the ITER target for the extracted current density was achieved in hydrogen for the ITER-relevant 600s, i.e. the pulse length over which such current densities are possible has been increased by a factor of more than ten. For ten second beam pulses the ITER target current density was achieved. These breakthrough results are quite impressive regarding the fact that ELISE has only RF power of 75kW/driver, which correlates to 75% of the power of the ITER NBI system. The results are made possible by applying physics insight gained during previous campaigns, namely the use of an improved version of the internal potential rods and a modified topology of the magnetic filter field.

The caesium conditioning status allowing for such pulses was achieved after only 4 days and 19 hours of experimental time after the caesiated inner surfaces of ELISE had been exposed to air for maintenance. This result is important in view of the operation of the ITER NBI system where the time needed for reaching an optimum caesium conditioning status is crucial.

The results from the 2024 campaign will be presented and discussed, together with an outlook: one of the next steps will be to develop even faster and reproducible caesium conditioning procedures. There are also plans to further optimize the hydrogen operating scenarios and to demonstrate the ITER target for the current density for operation in deuterium, in particular for long pulses (up to 3600s).

Stripping losses measurements at ELISE during hydrogen and deuterium operation

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The ITER Neutral Beam Injection (NBI) system is based on negative ions, produced in an RF-driven plasma source. The ITER NBI lines must deliver over 1000 s a current density of 230 A/m2 of negative hydrogen ions, accelerated to 870 keV, or over one hour a current density of 200 A/m2 of negative deuterium ions accelerated to 1 MeV. NBI systems, based on negative ions, are compromised by a process known as stripping losses, in which negative ions are neutralized in the grid system before achieving full energy. For a source filling pressure of pfill = 0.3 Pa, 29% of the extracted H^-/D^- ions are predicted to be lost by stripping in the ITER full-scale NBIs system (7 grid acceleration system). To compensate for these stripping losses, a larger amount of negative ions has to be extracted from the source (329 A/m2 in hydrogen and 286 A/m2 in deuterium). The ELISE test facility is based on a 1/2 size ITER source. It extracts H^-/D^- ions using a 3-grid acceleration system, with a maximum extraction voltage of 10 kV and acceleration voltage of 50 kV is achieved. In a 3-grid acceleration system, 10% of stripping losses is predicted. This contribution focuses on experimental measurements of stripping losses at ELISE.

Experimentally, stripping losses are monitored using Beam Emission Spectroscopy (BES), which analyzes the Doppler shifted spectrum of the Balmer Hα/Dα. Information on stripping losses is found in the BES spectra between the Main Peak (background H2 dissociation and excitation) and the Doppler Peak (fully-accelerated beam particles excitation). Stripping losses can be determined by integrating the stripping peak (standard method) or the entire stripping area (full range method). The standard method avoids signal-to-noise issues but underestimates the losses. In contrast, the full range method is susceptible to signalto-noise problems. This contribution presents a systematic comparison of stripping losses between hydrogen and deuterium under various experimental conditions. It presents and discusses both analysis techniques, examining the influence of BES background and signalto-noise ratio on the calculation of stripping losses, as well as the effect of different source filling pressures on beam properties.

High power beam operation with full segment in SPIDER, the prototype negative ion source of the Neutral Beam Injector for ITER

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To reach fusion conditions and control plasma configuration in ITER, a suitable combination of additional heating and current drive systems is required, which includes two Neutral Beam Injectors (NBIs) providing a total of 33MW hydrogen/deuterium particles electrostatically accelerated to 0.87/1MeV; efficient gas-cell neutralisation at such beam energy requires negative ions, obtained by plasma-assisted caesium-catalysed surface conversion. The source plasma is generated by 8 inductively-coupled drivers (typical electron density of the order of 1018m-3 and electron temperature of 10-20eV at 0.3Pa filling pressure), expanding into a single 2m-tall chamber. The plasma diffuses through a magnetic filter, which lowers the electron temperature and density, creating the conditions for the existence of an ion-ion plasma in front of the apertures of the plasma electrode, but introducing plasma non uniformities. The features of the beam (made of 1280 beamlets, divided into 4 segments) depend on the parameters of this plasma.

The ITER NBI specifications are: beam uniformity >90%, negative ion current density 330A/m2 (for one hour), beam divergence <7mrad, beam aiming direction within 2mrad. As such requirements have never been simultaneously attained, the Neutral Beam Test Facility (NBTF) was set up at Consorzio RFX (Italy), hosting two devices, which integrate the experience of several research groups worldwide. MITICA represents the full-scale NBI prototype with 1MeV particle energy. SPIDER, with 100keV particle energy, has started testing and optimising the full-scale ion source aiming at the ITER NBI requirements.

After 3.5 years of operation with reduced parameters, in which all plants were verified and the beam features proved in line with similar experiments, SPIDER entered a major shutdown, devoted to fixing several issues, either known since the beginning of operations or identified during the experimentation.

The present contribution will describe the first outcome of the operations after such major shutdown. Some weeks were dedicated to commissioning all plants at low parameters, to fine tuning the plants, with improvements on the maximum achievable RF power, and to enhancing the immunity of the system to breakdowns. Caesium operation is due to start in September 2024. The main goal will be the characterisation of the beam in full segment, which will be operated for the first time: caesium-assisted generation of negative ions in such a large source will be assessed, the beam optics and aiming will be checked and the beam uniformity will be studied. Further specific modifications and improvements performed during the major shutdown will be verified.

Study of Ion Beam Production and Acceleration in the Negative Ion Based Injector Prototype

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A prototype of negative ion based neutral beam injector is under study at the Budker Institute of Nuclear Physics. It employs an original scheme with the low energy beam transport section (LEBT) installed between the ion source and accelerator, which purifies the beam before entering the accelerator tube. Up to 1.5 A, 120 keV negative hydrogen ion beam was produced with the RF power and accelerating system increase. About 80% of the 0.8 A, 114 keV beam produced were transported to accelerator entrance, and ~0.5 A beam was accelerated to energy 380 keV. The data on 1.5 A beam production in the inductive RF surface-plasma negative ion source, on multi-jet beam transport through the 3 m long LEBT and on beam post acceleration in the wide-aperture accelerating tube will be discussed

Work Function of Caesiated Molybdenum Surfaces under Different Water Partial Pressures and Surface Temperatures

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Negative hydrogen ion sources for neutral beam injection (NBI) rely on low work function (WF) converter surfaces for the generation of negative ions. The low work function is typically created by evaporating caesium into the ion source. Recent research has shown that in the ion source of the BATMAN Upgrade (BUG) test facility a WF of 1.2-1.5 eV is given in a well Cs conditioned source, where the co-extracted electron current is well below the extracted ion current [1]. The WF is below the value of bulk Cs (2.0−2.1 eV) and even below the typical sub monolayer minimum of 1.5-1.6 eV [2]. This is explained by the formation of Cs oxides at the converter surface from reactions between Cs and oxygen or/and residual water, the latter being inevitably present in BUG due to the given non-ultra-high vacuum (UHV) conditions (base pressure $\sim 5\times10^{-7}$ mbar). Since the NBI for ITER aims for UHV conditions with a background pressure of 10^{-8} mbar, the question arises if the background pressure at ITERs NBI provides enough oxygen for the formation of Cs oxides and thereby WFs <1.5 eV.

To investigate the WF behaviour upon Cs and water co-adsorption, a polycrystalline molybdenum surface is caesiated in a UHV experiment (base pressure 10^{-10} mbar), which provides the possibility to add water vapour into the vacuum chamber in a controlled manner. The vacuum conditions envisaged for the ITER ion source and those at BUG are realized by adding water vapour up to a pressure of 10^{-7} mbar. The WF is measured via the photoelectric effect with the same setup that is used at the BUG ion source [1]. Up to a water pressure of 10^{-9} mbar the typical WF minimum curved is measured [2], with a minimum WF of 1.5±0.1 eV in the sub monolayer regime and an increase up to 1.9±0.1 eV for longer caesiation times. For higher water pressures, the WF decreases and saturates at 1.1±0.1 eV, indicating the formation of a Cs oxide layer with a sufficient flux ratio of Cs to water onto the surface. Further, it is investigated how typical temperatures applied at ion sources and above influence the WF of the caesiated molybdenum sample. The results are compared to measurements performed at the ACCesS experiment [3], which is currently upgraded to make it UHV-compatible and where the influence of a hydrogen plasma on the WF can be investigated.

References:

[1] A. Heiler et al 2024 J. Phys.: Conf. Ser. 2743 012025
[2] L. W. Swanson and R. W. Strayer 1968 J. Chem. Phys. 48 2421
[3] A. Heiler 2022 PhD thesis University of Augsburg

RF Driver Operation in the Cesiated Hydrogen Negative Ion Source

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The main reason to use the RF discharges in the N-NBI injectors is the necessity to decrease the maintenance in the fusion devices like ITER or DEMO. The 1.5 A RF negative ion source, developed at the Budker Institute of Nuclear Physics for the negative ion based injector, employs the 70 kW, 4 MHz inductive RF discharge. The study of RF Driver operation was done at the two BINP test stands - at the high voltage test stand with negative ion beam production from the cesiated negative ion source and at the special driver test stand equipped with various diagnostics. The data on driver power efficiency and on operation of driver with various configurations and various cesium feed will be presented.

Analysis of the optical emission spectroscopy results obtained from the SPIDER facility

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Abstract

SPIDER experiment, the full-size ion source of the ITER neutral beam injector, which is located at the Neutral Beam Test Facility in Padova, resumed operation in 2024 and operated with different configurations of the driver geometry, magnetic filter field direction, and with Cs injection. SPIDER aims at extracting 355 A/m2 of negative hydrogen ions (285 A/m2 in deuterium) with a source filling pressure of 0.3 Pa. The beam produced by the ITER-like ion source has to have a uniformity, defined between beamlets, better than 90%.

A tunable magnetic field, present in the ion source to extend the lifetime of negative ions by lowering the electron temperature, plays a key role in negative ion production but introduces not negligible plasma drifts that affect plasma and, consequently, beam uniformity. Among the different diagnostics available in SPIDER, optical emission spectroscopy is applied to study the line-of-sight-integrated plasma emission in the driver region, i.e. where the plasma is generated in the ion source, and in the expansion region, close to the extraction area. The interpretation of the spectral measurements is supported by collisional-radiative modelling and by complementary data provided by other diagnostic systems.

This work aims at characterizing the plasma by optical emission spectroscopy in the ion source under different SPIDER operational conditions. Special focus will be devoted to the magnetic filter field configuration and its effect on the plasma and beam features, with a particular emphasis on the properties of positive ions and neutrals, which are the precursor of negative ions.

Assessment of the optimal plasma parameters in SPIDER for efficient negative ion production

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ITER will be heated by fast neutral beams generated by accelerating and neutralizing negative ions, produced in a RF inductively-coupled plasma. The prototype negative ion source used for this purpose (SPIDER), constructed at the Consorzio RFX (Padua, Italy), consists of 8 RF driver volumes and one expansion chamber containing a magnetic filter. Recent results from SPIDER indicate plasma non-uniformities, which affect the properties of the beam, as well as an unexpected large beam divergence (larger than the required <7 mrad). With the long-term aim of understanding reasons for this beam behaviour and optimizing the source performance, both experimental activities and numerical investigations are being carried out.

The results of numerical studies of the plasma parameters in typical geometries of RF sources are presented. Analyses are done by means of the numerical code FSFS2D which gives self-consistent two-dimensional description of the source, including neutral gas flow, plasma chemistry, RF coupling in the driver and plasma transport through the magnetic filter. Different particle species are described by separate continuity equations and the electron temperature is governed by the electron energy equation whereas the plasma potential is described by the Poisson equation.

Numerical investigations are focused on understanding how different geometrical approaches (Cartesian or cylindrical) can be suitable to best reproduce the experimental situation, which in fact, is three dimensional. In addition, parametric investigations are performed to find the best operational conditions for efficient negative ion production.

Results of simulations are compared with the experimental data obtained in SPIDER, and in a dedicated experimental setup with single RF driver. The first simulation results indicate that the Cartesian geometry seems to be more appropriate for reproducing experimental results from SPIDER. The paper presents critical assessments of the benchmarking results and outlines the necessary code/model enhancements to improve the predictive capability of the FSFS2D code

Improving the performance and understanding of the SNS RF-driven H- ion source

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Recently, significant improvements to the design, diagnostics and modelling the SNS H- ion source and electrostatic LEBT have been undertaken. Design improvements have dramatically boosted the available H- beam current from the source from ~60mA to >100mA at 6% duty-factor providing considerable margin for future SNS upgrade plans. Design improvements include simple modifications to the ion source extraction system and diagnostics upgrades include implementation of thermal IR imaging of the LEBT and time-resolved plasma spectroscopic and Langmuir probe techniques. Modelling improvements include developing COMSOL models of the ion source RF plasma, heat transfer, Cs transport and LEBT beam transport. This talk will summarize these developments specifically for the SNS ion source and discuss their general applicability to other high intensity ion sources employed to major accelerator facilities worldwide.

Achievement of the ITER initial target

with 870 keV, 230 Am-2 hydrogen negative ion beams using five-stage accelerator

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In the heating neutral beam injector (HNB) of ITER, hydrogen negative ion (H–) beams with 0.87 MeV, 46 A (230 Am-2) for 50 s using multi-aperture and five-stage accelerator are required in the initial operation of the HNB, and then, pulse length will be extended up to 1000 s. Finally, deuterium negative ion beams with 1 MeV, 40 A (200 Am-2) for 3600 s are required. The gap length of each acceleration stage is 88 mm, and 1280 apertures are drilled in each acceleration stage to accelerate high current beams. In QST, the demonstration of high power density and long pulse beam has been proceeded with a five-stage accelerator, so-called MeV accelerator. The number of apertures is limited to nine due to the capability of the power supply. In previous experiment, the 1 MeV H– beam with 200 Am-2, which is equivalent beam power density for D– in ITER, was demonstrated for 60 s, but the beam current was reduced gradually because the plasma grid (PG) temperature was not controlled due to inertial cooling. To solve this issue, compressed air was selected as a coolant to control the PG temperature in the range from 200 deg. C to 300 deg. C, whereas conventional refrigerant such as water and oil is available up to 200 deg. C. The fast cut-off system of abnormal discharge in the ion source was developed to protect the filament under powerful and long-pulse operation.

As the result, it was confirmed that the PG temperature was successfully controlled during 300 s at 275 keV. The beam current was stabilized within 10% variation. The beam energy was gradually increased with the negative ion current increases. As the result, the H– beams with 0.5 MeV for 160 s and 0.7 MeV for 113 s were achieved, and finally, 0.87 MeV with 230 Am-2 has been successfully generated for 46 s, which is equivalent level beam of the HNB initial operation.

Experiments towards operational improvements of the ISIS Penning H- Ion Source

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The ISIS Penning ion source is a caesiated pulsed DC discharge surface plasma source routinely delivering 55 mA beam of negative hydrogen ions (H-) in 250 µs pulses for neutron and muon physics at 50 Hz pulse repetition rate. Currently, when operating the ion source, technicians adjust certain parameters to achieve optimal output and stability of the beam pulses. These adjustments are made reactively based on monitored outputs, such as discharge arc noise, and temperatures of the source body and electrodes. The control parameters used for operations are, caesium delivery temperatures, and hydrogen flow rate, and during a source start-up the strength of the Penning magnet field.

To enhance the reliability and predictability of the ISIS Penning ion source and allow for proactive adjustments, we have recently introduced discharge voltage monitoring. This is because the ion source operates at constant, pre-set discharge current, and the voltage then adjusts depending on the discharge impedance. The discharge voltage monitoring also helps identifying failure modes such as secondary discharges.

An experimental campaign has been conducted on our development rig (ISDR) to support this initiative. During this campaign, the continuous discharge voltage monitoring was implemented to measure data over a pre-determined range of operational parameters. The data collected from the results of these measurements will be used to analyze how the discharge caharacteristics including the discharge arc noise are affected by these control parameters. This helps to identify patterns that lead to suboptimal performance or failures of the ion source. These results will also be used to support a physics model attempting to identify the underlying reasons for the change of the discharge voltage during the plasma pulse and the parameters affecting the duration of the discharge noise.

By following this approach, the ISDR campaign will provide valuable insights and technological advancements to improve the operation of the ISIS Penning H- Ion Source, leading to enhanced performance and reliability.

Commissioning of the first H^- beam through the LEBT from the RF Ion Source at ISIS

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A high power RF driven negative hydrogen ion source is currently in development as part of the Pre-Injector Test Stand at the ISIS pulsed spallation neutron and muon facility, UKRI-STFC Rutherford Appleton Laboratory. The source is now operating reliably with an extracted H^- beam current of 17 mA at RF power up to 60 kW and pulse lengths up to 500 μs. This paper will detail both the re-commissioning of the ion source after upgrades were made to the RF and high voltage systems and the commissioning of H^- beam transport through the LEBT to the RFQ mask Faraday cup. Results from the ongoing optimisation campaign will also be presented.

Recent development on RF-driven H- source and LEBT in CSNS

Weidong Chen, Hui Liao, Hui Li

The RF-driven H− ion source has been commissioning in China Spallation Neutron Source (CSNS) for three run cycles. It demonstrates more than 7500 hours life time and almost 100% availability. To further promote the performance of the whole front-end system, researches on beam intensity, transverse emittance, and stripped proton beam elimination have been carried out on a newly constructed test bench. This report presents the up to date experimental results from these researches and the issues encountered during the commissioning. A featured work is on the elimination of the stripped proton beam in LEBT section. It results a ratio of proton over H− less than 0.01%, minimizing the heat load and radioactive rate caused by the stripped protons loss in superconducting linac section, planned for CSNS-II.

Mass spectrometry of an ECR based large volume negative ion beam system

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Extraction of H- ions from plasma and their implementation in applications like high energy linear particle accelerator, neutron generation, tandem accelerator, accelerator based mass spectrometry, plasma thrusters for space application, microelectronics etching and most importantly in fusion science for heating and diagnosis of thermonuclear fusion plasmas [1] has led to significant research and development in the field of Hydrogen (H2) plasmas and negative hydrogen ion sources. Plasma Lab, IIT Delhi has been associated with Hydrogen plasma studies for the past few years and the achieved plasma parameters inside the expansion chamber had encouraged studies related to negative hydrogen ion production for fusion applications [2]. This paper presents studies related to the detection of negative hydrogen ions in a large volume plasma system. Experiments are performed in a cylindrical expansion chamber with height and diameter of 1m. Hydrogen plasma is produced using a compact ECR microwave plasma source [3] mounted onto the top dome of the chamber. The magnetic field configuration of the source section (cylindrical, diameter □ = 91 mm and length, l = 110 mm) has the field strength decaying exponentially into the plasma expansion chamber of 1 m diameter.

In this work, plasma was characterized under different operating conditions of microwave power (400-600W) and gas pressure (1-3 mTorr) using axial and radial Langmuir probes along with a retarding field energy analyzer that have been fabricated in-house. The low-pressure plasma sampling probe of Hiden HPR-60 quadrupole molecular beam mass spectrometer (MBMS) was inserted into the expansion chamber through one of the radial ports located at z = 37.5 cm plane where z is axial distance from the source mouth. Uniform plasma was found to be produced at that plane with density ne ~ 8 × 1010 cm-3 and low electron temperature Te ~ 1 eV favoring volume mode H- production. The MBMS could be tuned accordingly for the detection of both ion (positive & negative) and neutral (RGA mode) particles inside the expansion chamber. Initial results indicated presence of significant concentration of H- ions inside the expansion chamber. Different positive ions (H+, H2+, H3+) produced in the hydrogen plasma were also detected. Detailed experimental results and analysis will be presented in the paper.

References:

- Y. Takeiri, Negative ion source development for fusion application, Rev. Sci. Instrum. 81, 02B114 (2010).
- S. Sharma et. al. “Characterization of Hydrogen Plasma in an ECR based Large Volume Plasma Chamber." Journal. of Phy.: Conference Series, vol. 2244, no. 1, IOP (2022): 012055.
- Ganguli et al. "Development and studies on a compact electron cyclotron resonance plasma source." Plasma Sources Sci. Technol. 25, no. 2 (2016): 025026

Beam current deterioration in a 13.56 MHz RF negative ion source

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D-Pace is developing a 13.56 MHz Cesium-free RF ion source for producing negative ions (H^-, D^-). The RF ion source is a hybrid design between the TRIUMF-licensed filament ion source and the RADIS ion source licensed from the University of Jyv¨askyl¨a. Plasma is generated inside the ion source using RF power coupled to the plasma chamber from an external planar spiral antenna through an AlN ceramic window. The present challenge with the RF ion source is the deterioration in H^- beam current extracted from the ion source during its operation over several days. Sputtering of the plasma chamber and the window was considered as a likely reason for the beam loss and new planar Faraday shields were installed to reduce the capacitive coupling effect. Experiments were also carried out with different plasma chamber materials to understand the problem . The current paper describes the details of the H^- beam loss from the ion source and conclusions drawn so far from the experiments

Time-resolved plasma spectroscopy of the SNS RF-driven H- ion source

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The SNS RF-driven H- ion source is capable of producing beam currents of more than 100 mA in 1 ms pulses at 60 Hz. The H- are surface-produced on a caesiated molybdenum converter adjacent to the extraction aperture. The caesium is dispensed from cartridges, which contain a mixture of Cs chromate (Cs2CrO4) and getter materials (Zr, Al), and are embedded into a temperature-controlled collar. The caesiation is carried out by heating the collar up to ~550 °C with an estimated dose of 10 mg of Cs released per caesiation. During the ion source operation the collar and converter temperatures are kept at 180-320 °C to achieve and maintain the required beam current. The SNS ion source is equipped with a viewport for monitoring the time-averaged hydrogen and caesium line intensities during the caesiation procedure and source operation by optical emission spectroscopy. A time-resolved spectroscopy setup based on bandpass filters and photodiodes has been recently implemented to measure the transient behaviour of the hydrogen and caesium emissions simultaneously with the time-averaged emission spectrum. The sensitivity of the diagnostics system allows detecting the weak Cs emission lines and recording the intensities of several atomic emission lines or molecular bands within each high-power plasma pulse. This information can be used for example to study the Cs dynamics and temporal evolution of the molecular dissociation rate during the plasma pulse. In this paper we describe the optical diagnostics system and report the results of an experimental campaign where the ion source control parameters, i.e. the 2 MHz RF power, H2 flow rate, converter temperature and the RF duty factor were systematically varied and the emission intensities of atomic and molecular hydrogen (Balmer-alpha, Balmer-beta and Fulcher band) as well as neutral Cs (852 nm and 894 nm) were measured. The results can be used to support modelling of the plasma parameters, electron impact process rates and Cs coverage of the converter affected by thermal and kinetic desorption.

Overview of activities at the ITER Neutral Beam Test Facility (NBTF) in view of the ITER NBI

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The ITER Neutral Beam Test Facility (NBTF) was set up at Consorzio RFX premises (Italy) aimed at reaching ITER target parameters for this type of additional heating system. It includes two test beds: the full-scale Heating Neutral Beam (HNB) prototype, named MITICA, expected to enter into operation in the next future, and SPIDER, with 100keV particle energy, aimed at testing and optimizing in advance the ITER-size ion source, already inaugurated in 2018.

After the conclusion of the initial experimental campaign at the end of 2021, at the beginning of 2024 the first SPIDER major shutdown was concluded: all systems have undergone refurbishment in order to restart operation as soon as possible and to aim at the target parameters; in particular the beam source requested major efforts for repairs and modifications.

Two main enhancements are still pending completion and are going to be integrated in a shorter shutdown foreseen to start by the end of 2024: the installation of a new Non-Evaporable Getter (NEG) pump-based additional pumping system, in order to keep the pressure in the vessel low enough to avoid RF electric field induced discharges on the source side, and the replacement of the RF generators based on oscillators with solid state amplifiers, so that intrinsic frequency instabilities on resonant loads and presence of high voltage inside the generator are avoided, hence operating more efficiently and reliably at the required conditions.

While restoration of MITICA power supply is progressing after the damages suffered in particular on the 1MV insulating transformer during the integrated commissioning, an experimental campaign is ongoing to address high voltage holding capability of the vacuum insulation under realistic conditions using full-size mock-up electrodes reproducing in detail the outer geometry of the MITICA Beam Source and Accelerator, which represents one of the most challenging novelty in MITICA with respect to previous injectors.

Once these tests will be completed, the new power supply components will be installed and additional activities will be carried out in parallel, in view of MITICA operation and relevant for ITER HNB as well: installation trial of the cryopump and functional integration with the cryoplant shall provide indications also on the future pumping performances, while preparations for the installation of the remaining in-vessel mechanical components will be finalized.

An overview of the efforts devoted to SPIDER and MITICA will be provided in the present contribution, together with the overall NBTF plan recently revised, to be fully integrated with the ITER plan, emphasizing milestones and links with contributions from the other laboratories involved in the ITER NBI system supporting the NBTF programme.

Stationary Negative Ion Beam Injector for Tandem Accelerator BNCT

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Since 2006 the BINP SB RAS has been operating an accelerating neutron source, based on a 2.5 MeV tandem accelerator. It uses a surface-plasma negative hydrogen ions source, providing the reliable tandem operation with accelerated proton current of up to 8 mA [1]. The negative ion injector of tandem was upgraded in 2022. The modified negative ion source with reinforced electrodes and an internal magnetic system was installed [2]. The source power systems were upgraded, providing the control of source run by computer according to a scenario selected by the operator. The low energy beam transport line was modernized. To focus the ion beam, an additional magnetic lens was installed, and the source pumping was enhanced. The characteristics of the negative ion beam and the data of the injector operation will be presented.

An Update on the ITER Neutral Beam Progress and Development

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ITER will have 2 Heating Neutral Beams (HNBs), with a possible third to be installed at a later date, and a Diagnostic Neutral Beam (DNB). The HNBs are designed to provide 16.7 MW of power for ITER, as either 1 MeV D0 (from 40A D-) or 0.87 MeV H0 (from 46A of H-) for up to 3600s. The DNB will provide a 100kV (from 60A of H-) beam, for use with charge exchange spectroscopy at the edge of the ITER plasma.

Following technical challenges, a large re-baselining effort has been performed for the whole ITER Program. The new strategy maintains the same timescale for achieving first Deuterium operation, although with a shorter operational period before this. An overview of the key changes will be presented.

The current state and focus of ITER NBI research and development is then discussed, including developments on the Magnetic Field Reduction System (MFRS) and the focal points of research for the ITER NBI Experimental Advisory Committee presented.

The latest procurement status of the main components will also be shown, along with the developments on the ITER site related to the Neutral Beams.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

The NBI related test facilities in ASIPP CHINA

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The test facility plays an important role in the R&D of NBI related science and technology. There are two sets of test facilities set up in the past in ASIPP CHINA. In order to facilitate the development of EAST NBI system, a test facility for positive ion based NBI system (PNBI test facility) was set up in the year of 2011. An upgrade of the PNBI test facility is ongoing to extend its capability from 80keV, 70A to 140keV, 100A positive ion beam conditioning. After the upgrade the PNBI test facility can meet the requirements of conditioning up the beam sources of BEST NBI system (BEST, is a under construction TOKAMAK device developed for burning plasma experiments). Aiming at facilitating the development of negative ion based NBI system, a test facility (NNBI test facility) with the capability of 200 keV, 28A negative ion beam conditioning was primarily set up in the end of year 2023. A capability extension effort to the NNBI test facility is ongoing, upgrading the facility capability to meet the requirement of 1 MeV, 10A, 1000s ion beam conditioning. A detailed introduction to the mentioned test facilities are given, including their sub-systems, capabilities, typical experimental results and experience. Some suggestions and proposals are also given in the end. It seems the introduction is meaningful for developing a new NBI test facility and seeking NBI related international research cooperation.

Keywords: Neutral beam injection; Test facility; Negative ion source; High voltage power supply; Control system; Plasma and beam diagn

The Front End Test Stand (FETS) - Journey to full Duty Cycle

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FETS is a platform to develop the high power beams required to feed the next generation of particle accelerators. FETS aims to produce a perfectly chopped 3 MeV 60 mA H-minus beam at a 10% duty factor (2 ms pulse length at 50 Hz).

Here we give an update on the 3 MeV commissioning process and the journey to full duty cycle. We detail the overall performance with our existing, duty cycle limited, negative Penning Surface Plasma Source (SPS), along with optical diagnostic and electron energy distribution measurements of space charge compensation processes in the low energy beam transport.
We also present the beam transport design to install our 2X scaled Penning SPS ion source on the beamline, which will allow us to deliver the full duty factor beam.

Laser-assisted atomic and molecular negative ion production in pulsed operation of a SNICS ion source

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Caesium sputter ion sources are used for the production of negative ion beams for Ion Beam Analysis (IBA) and Accelerator Mass Spectrometry (AMS) applications. The negative ion production in the Source of Negative Ions by Caesium Sputtering (SNICS) occurs on the surface of a cathode, which contains the ionized materials and is exposed to caesium ion bombardment. We have previously demonstrated that laser-assisted beam current enhancement occurs due to the photoelectron emission and optimisation of the cathode surface Cs coverage. As such, the method is not element selective and can be applied for boosting the beam currents of not only single atom but also molecular beams. The Cs coverage can also be controlled by pulsing the cathode voltage, which has been recently demonstrated to enhance the negative ion beam current from the SNICS source in pulsed operation mode. Here we demonstrate the laser enhancement for molecular beams alongside presenting the first results of comparing the effects of the laser exposure and cathode pulsing on halogen ion beam currents.

Decrease of H- ion beam emittance with increased frequency in RF discharge.

Vadim Dudnikov

In recent years significant progress in increase intensity of H- beam in RF surface plasma sources. H- beam intensity in RF SPS of J-Parc was increased up to 145 mA. Intensity of H- in RF SPS of SNS was increased up to 110 mA [ ], which is enough for European spallation source storage ring. Reduction of beamlet divergence in RF negative ion source for NBI is one of high-priority targets to be solved. Minimum beamlet 1/e divergence In RF H- ion sources with low RF frequency (2-4 MHz). mach higher than in ion sources with DC discharge.

- min. q div(FA) ≤ 5 mrad (obtained at NIFS and QST with DC discharge)
- min. q div(RF) ≤ 12 mrad (obtained at IPP and RFX RF ion sources)
- max. q div(ITER NB) < 7 mrad.In RF H- ion sources

In H- ion sources with low RF frequency (2-4 MHz) is observed significant modulation of beam intensity at first and second harmonic. This should lead for vibration of the meniscus shape and increase angle spread. Work with higher RF frequency (13,56 MHz) should decrease intensity modulation and decrease emittance to two times. RF SPS with a frequency 13.56 MHz could be a good solution for a European spallation source with a storage ring.

Assessment of signal reconstruction techniques for critical signals in high power negative ion based plasma sources

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In order to develop reliable heating systems for ITER and other tokamak, multiple neutral beam test facilities are being developed. These facilities are based on ICP based plasma sources and often embedded with a lot of diagnostics and sensors which enable in depth characterization of these systems. Due to presence of high power RF radiations and HV transients, these facilities suffer from high level of noise which lead to degradation of signal quality and often makes their analysis challenging.

In order to solve issues related to noise and fault detection, autoencoder (AE) [1] based machine learning models can be explored. These models are formed using multiple deep neural networks and have strong ability to reduce dimensionality of input data by extracting important features of the input data in form of latent variables.

In present work, we highlight the implementation of an optimized AE which models the various current based signals from a high power negative ion source, ROBIN [2]. The paper describes the application of various types of AE models in order to explore the efficient model which can support in de-noising and fault detection based on the input time series based signals. The paper describes the training process and assessment of various architectures in detail for obtaining an acceptable signal reconstruction which can be utilized by the control system.

Ref:

[1]: Garola, A. Rigoni, et al. "Diagnostic data integration using deep neural networks for real-time plasma analysis." IEEE Transactions on Nuclear Science 68.8 (2021): 2165-2172.
[2]: K Pandya, et al., " First results from negative ion beam extraction in ROBIN in surface mode",. AIP Conf. Proc. 9 August 2017; 1869 (1): 030009

Preliminary Design of the SF6 Gas Insulating HV-Bushing for CRAFT NNBI

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The full-scale beam source of CRAFT NNBI is proposed to adopt the vacuum-insulated ion source scheme to obtain a negative hydrogen ion beam with an energy of 400 keV through a two-stage 200kV acceleration voltage. The two-stage 400kV HV-bushing was preliminarily designed for the insulation and sealing connection between the SF6 transmission line and the vacuum chamber. The vacuum side insulation design was carried out, and the electric field strength of the cathode surface, anode surface, insulator surface and triple point also has been analyzed and improved, which met the standard requirements of the JAEA for the design of HV-bushing for ITER. The cooling water flow channel of the 200kV bushing section is designed, and the pressure drop of the channel is calculated based on the flow rate required under the highest heat load. The mechanical strength of the bushing structure was analyzed, the structural stress and deformation magnitude under the load of 0.6MPa SF6 gas in the transmission line, 1MPa air between the insulating ceramic ring and the fiber plastic ring and the gravity were considered. The influence of the deformation caused by the temperature change of the cooling water of the 200kV bushing on the electric field strength is analyzed.

Keywords: NBI; HV-bushing; vacuum insulation; cooling water pressure drop; Structural strength

THE 1MV MITICA POWER SUPPLY BEYOND THE MODERN TECHNOLOGICAL LIMITS: STATUS AND OVERVIEW OF HIGH VOLTAGE TESTS IN VACUUM

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MITICA, the full-scale prototype of ITER Heating Neutral Beam (HNB) presently under realization at the Neutral Beam Test Facility (Padova, Italy), is characterized by a complex power supply system, beyond the present standard for insulation voltage level (-1MVdc) and dimensions. Five -200kVdc DC generators, series connected to produce -1MVdc acceleration voltage, are linked via a SF6 insulated Transmission Line to the Beam Source (BS), installed inside the vacuum vessel. The Ion Source and Extraction Power Supply system is installed inside a large air insulated Faraday cage and fed by the 1MVdc Insulating Transformer.

After successfully performing in 2019 the site insulation tests (up to 1.265MVdc), during subsequent integrated tests two major faults, originated by breakdowns (BD) occurred in the High Voltage (HV) plant, damaged the system. Additional protection components, identified by means of transient electric models developed ad hoc, are presently under manufacturing and will be installed early 2025 together with all the required interfaces for integration with building and existing components and the new insulating transformer.

Further tests and plant inspection pointed out a couple of possible critical situations in SF6 and vacuum insulations that, even if not proved to be the effective source of the BDs, were fixed before reaching newly in 2023 the -1MVdc performance. The detection system was further enhanced by identifying suitable diagnostics for DC application that, once optimized, will be definitively adopted, also in the HNB's, as early breakdown detection system.

The electrical insulation in vacuum at -1MVdc of MITICA BS is a challenging issue. Therefore, it was decided to use the procurement time for the new transformer and protections to perform HV test campaigns on a full-size mock-up electrodes system reproducing in detail the outer geometry of the MITICA BS and Accelerator. This allows to validate and optimize the BS voltage holding capability and, if necessary, to anticipate the development of effective modifications in advance to the BS installation.

This contribution deals on the the status of the MITICA power supply modifications and refurbishment and gives an overview of the results of the MITICA HV holding tests.

Neutral Beams in ROBIN: Present Status and Future Plans

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1/8th size ITER reference design source ROBIN (RF Operated Beam source in India for Negativeions) is operational at IPR, Gandhinagar. The ion source has achieved optimal performance in terms of negative ion current density (> 30 mA/cm2) with electron-to-ion ratio (<1) for surface-assisted negative ion production (with Cesium (Cs)). The source performance is optimized with minimal Cs consumption (<10 mg/hr.). Operations of the source with wall magnets were not seen to show any substantial improvement in its performance in terms of current densities. However, changing magnetic configuration in the vicinity of the filter fields was seen to lower the electron-to-ion ratio by a factor of 2 and changes in the top-bottom plasma asymmetry for different magnetic configuration studies. Since then the experimental setup has been upgraded to carry out and gain experience with ion beam neutralization experiments in ROBIN. The facility has been upgraded with an additional 1m diameter, 1.5 m long vacuum vessel to enable integration of beamline components viz. gas neutralizer, electrostatic residual ion dump (ERID), and thermal differential calorimeter. Experiments have been performed for various operational parameters of the source, the gas flow of the neutralizer, and the application of ERID voltage. The beamline pressure and ERID voltage shielding observations have been noted. The present experimental setup is limited in terms of its performance due to limitations in the ERID high voltage feedthroughs (10kV) and power supply rating (10kV, 400mA). The ion beam neutralization efficiency has been estimated for various flow settings of the gas flow into the neutralizer. Further experiments with additional upgrades to overcome the present limitations are planned in the coming months to enable neutral beam experiments at higher energies and currents. The facility upgrade and experimental results obtained for various parametric optimisations shall be presented and discussed.

Recent Diagnostic and Beam Performance Tests on the LANSCE H− Ion Source

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The filament arc driven plasma, cesiated surface conversion H− Ion Source used at the Los Alamos Neutron Science Center (LANSCE) has a long legacy of providing reliable beam to the LANSCE user program. Despite the long history of beam delivery, there remains valuable opportunity for fundamental diagnostic studies, and subsequent operational improvements of the LANSCE H− Ion Source based on these diagnostics. The LANSCE H− Ion Source Laser Diagnostic Stand (HLDS) was built to study these fundamental diagnostics. HLDS is currently capable of measuring Cesium density/temperature via Tunable Diode Laser Spectroscopy (TDLAS), the H− density via Cavity Ring Down Spectroscopy (CRDS), and the Balmer Hα,β plasma properties via Optical Emission Spectroscopy (OEM) and TDLAS. An update will be given on measurements taken using these diagnostic tools. In particular, detailed focus will be given on how results from the Cs density/temperature diagnostic was used to improve the speed of the Cs conditioning process for the LANSCE H− Ion Source, and the mitigation of cesium burst induced arc and converter transients. In closing, possible future diagnostic channels to be installed on HLDS, and their implications for the LANSCE H− Ion Source will be discussed.

Negative-ion surface production on electride C12A7 surface: work-function and negative-ion flux measurements

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This work deals with negative-ion surface production studied in a low-pressure deuterium plasma. In the case of using a metal surface, a positive ion coming from the plasma captures two electrons and is backscattered from the sample surface giving a negative ion, but the inverse process of loss of electrons back to the surface is highly probable, resulting in a globally low NI yield. Lowering the work-function reduces the loss back towards the surface (as well as increases the electron capture probability) and produces much higher yield. However, inherent problems caused by cesium introduction to the low work-function metals push towards the use of alternative materials. When using semiconductors or insulators, the energy required to capture an electron is very high, hence extraction of negative ions is a challenge. But the presence of a large band gap diminishes the chance of loss of electrons back to the surface, possibly leading to high negative-ion yields.

The electride material 12CaO-7Al2O3 (C12A7) is a ceramic material, whose electrical properties can be maneuvered using various external factors. C12A7 has a cage-like structure. The interstitial site of the C12A7 is occupied by an O-2 ion which maintains electrical neutrality with the Ca+2 that is a part of the crystallographic cage-like molecular structure. These clathrated O-2 ions can be removed and replaced by electrons resulting in the formation of an electride. The electride has four electrons in the interstitial site in replacement of O-2. The electrons can tunnel from one cage to the adjacent, forming a cage conduction band (CCB). The electronic structure is made of a deep valence band separated by a gap of 5.5eV from a narrow occupied CCB (work-function 2.4 eV), itself separated from the main conduction band by a band gap of 2eV. The low work-function and the presence of a band gap makes the electride an interesting option for exploring the possibility of surface NI production provided the electronic structure can be maintained under plasma exposure.

In this work, we explore the interaction of the electride material with deuterium plasma using Photoemission Yield Spectroscopy, Mass spectroscopy and Langmuir probe measurements. The electride sample is exposed to deuterium plasma at a pressure of 2 Pa and different bias voltages, and then the photoemission spectra of the sample, measured immediately after the termination of plasma. This gives information on the electronic structure and in particular the photoemission threshold (the minimum energy required to extract one electron from the electride). Mass spectrometry is used to measure the relative flux of negative-ions emerging from the surface. The sample bias is made of a DC signal superimposed with a -20V (or -60V) extraction pulse (20µs at 1KHz frequency) applied to the sample. The DC bias sets a certain surface state while the extraction pulse is used to drive the negative-ions from the sample towards the grounded aperture with always the same extraction probability whatever the DC bias applied. This technique allows a decorrelation between the surface state changes due to the positive ion bombardment (DC bias) and the extraction probability (extraction pulse). Langmuir probe and sample current measurements give quantitative knowledge about the positive ion energy and flux bombarding the surface from the plasma.

In this work, we will present the changes of the electride photoemission spectra upon deuterium plasma exposure, and will try to infer from that information on the evolution of the electronic structure. The photoemission threshold (work-function) evolution versus sample bias voltages will be compared to the negative-ion flux evolution in order to better understand the electron capture mechanism on electride.

Negative ion source R&D in IPR: Modeling contributions

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A thorough understanding of plasma and beam physics plays an important role in the successful operation of RF-based negative ion sources envisaged for neutral beam systems, being developed and tested at various test beds including IPR for ensuring the successful operation of the neutral beam injectors at ITER. Plasma modeling using particle-in-cell (PIC) simulation and COMSOL-Multiphysics simulation enriches this understanding of the ion source characteristics and the various asymmetries of the plasma and the negative ion density profiles. A 2D-3V PIC simulation code has been developed to probe the plasma dynamics and asymmetry. The simulation has identified the role of TMF, and plasma grid bias voltage in the presence of the plasma absorbing side wall in plasma asymmetry. The simulation also shows the presence of a double layer at a location where TMF starts to rise. The double layer influences the ion energy distribution function and is also seen to be responsible for observed plasma instabilities. Further, simulations using COMSOL-Multiphysics have been performed to understand the physics of plasma coupling evolution in the RF driver and its dynamics in the downstream expansion chamber. The influence of the Faraday shield and its backplate magnets are significant in power coupling and the spatiotemporal evolution dynamics of the plasma. The modeling efforts and the results obtained for the above simulations shall be presented and discussed.

Probing into Space Charge Interactions of Negative Ion Beams through Imaging Diagnostics

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Space charge(SC) interactions play a major role in the spatial distribution and transport of ion beams from a multiaperture ion source[1]. The ion sources designed for neutral beam injectors (NBIs) in ITER will work with multiple apertures (1280 apertures) distributed into 16 groups. The SC interaction within individual beamlets and the beamlet groups(beam groups) will influence the uniformity and orientation of the merged beam to be transported across the beamline.
The influence of SC interactions between beamlets on the merged beam has been explored in the context of both positive and negative ions[2][3]. A similar study for beam groups is carried out in a ROBIN source having a segmented masked LAG grid set having 146 open apertures(73 top and 73 bottom)[4]. The tilted grid halves(0.873∘) of ROBIN provide a vertical focus to merge the top and bottom beam groups' central mean position(beam-group axis) at ∼ 3.3 m from the Grounded grid(GG). In the absence of any interactions, the axis of the top and bottom beam groups should follow the same tilt with the beam axis i.e. 0.873∘, and the separation of the beam group axis should approximately be ∼45 mm.

The Visible camera-based diagnostic(VCD) placed at ∼ 1.9 m from the grid set reports a beam-group axis separation of ∼ 205 mm for an extraction voltage of 3.5 kV, acceleration voltage of 12 kV, and a total beam current of 450 mA. The variation in separation over the voltage sweeps provides concrete evidence of this interaction. It is observed that the separation rises with extraction voltage but decreases with a rise in acceleration voltage confirming the involvement of space-charge forces acting between the beam-groups.

To probe deeper into the merging phenomena, a numerical beam group simulation based on the work of Kim and Whealton is developed for the ROBIN configuration. The tilt of the grid set is incorporated into the model through simple axis transformations. The model is simulated with input parameters resolved from VCD. It renders the beam groups originating from the grids in a 3D volume(512×512×3072 mm3) of the transport vessel. As the model does not incorporate any space charge interactions, the merging of beam groups occurs earlier along the beamline compared to experimental observations. This results in a lower spread of the merged beam than what is observed by the beam interceptor. A comparative study of the observations from the VCD and the numerical model of the beam is highlighted in the context of space charge interactions.

[1] Song, F., Zou, G., Li, D., Zuo, C., Chen, D., & Lei, G. (2023). Simulation of beamlet deflection and its compensation by aperture displacement for a NBI negative ion source prototype. Fusion Engineering and Design, 190, 113538.
[2] Gilardoni, S., Giovannozzi, M., & Hernalsteens, C. (2013). First observations of intensity-dependent effects for transversely split beams during multiturn extraction studies at the CERN Proton Synchrotron. Physical Review Special Topics—Accelerators and Beams, 16(5), 051001.
[3] Haba, Y., Nagaoka, K., Tsumori, K., Kisaki, M., Nakano, H., Ikeda, K., & Osakabe, M. (2020), Characterisation of negative ion beam focusing based on phase space structure. New Journal of Physics, 22(2), 023017.
[4] Dash, S., Bandyopadhyay, M., Pandya, K., Bhuyan, M., Mistri, H., & Singh, M. (2024, May), Visible camera-based diagnostic to study negative ion beam profiles in ROBIN ion source. In Journal of Physics: Conference Series (Vol. 2743, No. 1, p. 012074). IOP Publishing.

Negative-ion surface production on diamond and electride C12A7 surfaces investigated using photoemission yield measurements

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This work is dealing with D- negative-ion surface production in caesium-free plasmas for applications to negative-ion sources for fusion. Several materials in contact with a low-pressure D2 plasma are explored with the aim of detailing negative-ion surface production mechanisms at play [1]. We are particularly interested in dielectric materials for which it is known that electron capture by an incident particle is made more difficult by the high energy required, but electron loss to the surface from the negative-ion created is greatly reduced due to the presence of a band gap. To that aim a conductive ceramic, the electride material C12A7 [2], and several diamond layers are compared together. The electride material is of particular interest for its peculiar band structure, with a band gap on top of a conduction band close to the vacuum level (work-function of 2.4 eV). Diamond is of interest for its negative-electron affinity (the conduction band minimum lies above the vacuum level) which sets the valence band closer to the vacuum level. In particular, we have investigated for the first time negative-ion surface production from a phosphorous-doped diamond layer (type n doping). The phosphorous dopant level lies only 0.6 eV below the conduction band. These dielectrics are compared to metal-like materials.

Measurements are performed in an ICP reactor at 2 Pa and 150W injected power. A negatively biased sample material is placed in the middle of the plasma chamber 40 mm away from a mass spectrometer used to detect negative-ions. Positive ions from the plasma bombard the sample and form negative-ions, which are then accelerated toward the detector and collected. The interaction of the plasma with the material lead to an evolution of the surface state. In order to collect in-situ information about changes of surface electronic properties due to plasma exposure a photoemission yield spectroscopy (PYS) diagnostic has been developed to measure material work-function.

In this contribution, negative-ion and photoemission measurements will be presented. We will emphasise how the photo-emission yield technic can help determining the electronic structure of the material in contact with the plasma. Photoemission measurements will be compared with negative-ion yields and tentative correlations will be made with the aim of determining the parameters influencing at most on negative-ion surface production, for both metal-like and dielectric-like materials.

[1] Cartry, G. et al (2017). New Journal of Physics, 19(2), 025010
[2] M Sasao et al, Applied Physics Express, 11(6), 2018

Enhanced Plasma Density Prediction for HELEN-I Using Bayesian Optimization Guided Machine Learning

Authors:
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Predicting plasma density is critical for the optimal functioning of devices like HELEN-I, a negative hydrogen ion source. This study leverages Automated Machine Learning (AutoML) integrated with Bayesian Optimization to enhance the accuracy of plasma density predictions. AutoML automates the end-to-end machine learning process, while Bayesian Optimization efficiently explores the hyperparameter space to identify optimal configurations, improving model performance. Our method involves collecting high-quality experimental data from HELEN-I, pre-processing it, and utilizing AutoML frameworks to train various models, guided by Bayesian Optimization to ensure predictive accuracy and computational efficiency. The results demonstrate that this approach significantly outperforms traditional methods, reducing the time and expertise needed to develop high-performing models and providing a scalable solution for future plasma experiments. This study showcases the potential of combining automated machine learning with advanced optimization strategies to advance plasma physics and enhance the capabilities of negative hydrogen ion experiments like HELEN-I.

Plasma Density estimation using Machine Learning for High power Ion Source

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Plasma density is one of the most critical parameters of an Ion sources. In order to achieve a required plasma density, operators scan a wide operating range of input parameters such as RF power, gas pressure and magnetic field. Estimation of plasma density is based on data from a set of diagnostics such as CRDS and Langmuir probe which needs intense analysis and is often time consuming.

Hence in present work, an alternative approach of utilizing data driven principle is explored based on machine learning algorithms to predict plasma parameters including density. Experimental data from a high power RF source, ROBIN [1] is used for developing the models. ROBIN is an experimental negative ion facility powered by a 1MHz, 100kW RF generator being operated at IPR, India and has generated considerable dataset. The paper presents the steps undertaken to arrive at an acceptable model which could predict the plasma density with R2 score of 0.92 after identifying the right set of input parameters and performing model optimization techniques. Various algorithms such as Random Forest and Deep Neural networks are explored and compared in terms of performance against the test dataset. The paper discusses the model training and performance improvement techniques on actual experimental data in order to achieve acceptable accuracy which could be further deployed.

[1]: K Pandya, et al., “First results from negative ion beam extraction in ROBIN in surface mode”,. AIP Conf. Proc. 9 August 2017; 1869 (1): 030009

NEURAL NETWORK APPLICATIONS FOR NBI PERFORMANCE STUDIES USING SYNTHETIC DATA FROM BTR CODE

Eugenia Dlougach, Margarita Kichik

BTR (Beam Transmission with Re-ionization) code [1-4] is routinely used for applications in neutral beam injection systems (NBI) design. The main task of BTR is to simulate NB neutralization and transmission and to deliver thermal power deposition resulting from direct tracing billions of particles from the ion source exit until their capture by plasma or hitting the tokamak first wall. Being the most detailed NBI simulator, BTR can be efficiently used for scanning NBI operation scenarios within wide range of input parameters. Due to BTR high performance, interactivity and user control over the input and results resolution, the investigated NBI model is flexibly adapted to various design applications [5-8].

The work presents neural network (NN) based applications for neutral beamlines analysis and performance control. BTR code is used for NN training and evaluation by generating synthetic experimental data on thermal power loads along the injector beamline. The datasets are next processed for the load type classification and for reconstruction of the operational conditions in the studied beamline, such as pressure profiles. The model testing is made on the dataset prepared by BTR as well. Various NN models performance and predictive quality is investigated. The results obtained can be next applied in physical environment, to support NBI diagnostics and control in experiments. Possible applications of the results include: the source beam parameters reconstruction from measured power distributions along the beamline, neutralization efficiency and the beam content definition, and indirect data retrieval on operational conditions, like gas pressure profiles which are difficult or impossible to measure directly in some parts of the beamline.

Python machine learning (ML) tools [9, 10] are applied to classify the power deposition origin. The implemented ML algorithm includes datasets generation using BTR code, data labeling and preparation for training, setting up loss function and quality criterion, NN training on the main dataset, and model evaluation on a control dataset. A comparative analysis of the performance and training quality for various NN architectures is given. The overfitting problem is addressed.

The work has been partially supported by NRC "Kurchatov Institute".

[1] E.Dlougach, BTR code for neutral beam design. https://sites.google.com/view/btr-code/home
[2] Dlougach E.D. BTR code for NBI Design and Optimization. AIP Conf. Proc., 2021, v. 2373, p.080004
[3] Dlougach E.D., Veltri P. BTR code recent modifications for multi-run operation. AIP Conf. Proc., 2021, v. 2373, p.080010
[4] E. Dlougach, M. Kichik, Beam Transmission (BTR) Software for Efficient Neutral Beam Injector Design and Tokamak Operation. Software 2023, 2, 476-503
[5] Bandyopadhyay M, Singh M.J., et al. Beamline optimization for 100-keV diagnostic neutral beam injector for ITER, IEEE transactions on plasma science, 2010, vol. 38, no. 3
[6] Chang D.H. et al, Performance of 300 s-beam extraction in the KSTAR neutral beam injector, Current Applied Physics 2012, Vol 12, Issue 4, 1217-1222
[7] Veltri P. et al. Evaluation of power loads on MITICA beamline components due to direct beam interception and electron backscattering, Fusion Eng. and Design 2013, 88 1011– 1014
[8] Sartori E. et al, Benchmark of numerical tools simulating beam propagation and secondary particles in ITER NBI, NIBS-2014 AIP Conference Proceedings 1655, 050006, 2015
[9] A C Müller, S Guido, Introduction to Machine Learning with Python, O'Reilly Media, Inc., 2016, ISBN: 9781449369415
[10] I Goodfellow, Y Bengio, A Courville, Deep Learning, MIT Press, 2016

VERIFICATION OF THE BTR CODE FOR NEUTRAL INJECTION SYSTEMS DESIGN

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The BTR (Beam Transmission with Re-ionisation) code [1-2] has been actively used for many years in the design and engineering-physics analysis of neutral injection systems, including the ITER project [3]. In 2008, ITER commissioned the verification of the initial version of BTR [4], which demonstrated the high quality of the code and the consistency of its results with calculations from the ION code for the JET tokamak injection system. Over the years, the BTR code has actively evolved based on user feedback, leading to new versions, including BTR-5 (in 2020). With each new version, the functionality of BTR expanded, and the entire project's source code underwent significant changes. Given the updates and the ongoing need for BTR code, verification is essential. This verification not only ensures the reliability of individual computational procedures but also serves as a guide for the correct application of the code to various optimization tasks and the analysis of processes in neutral beam injection ducts.
This work presents a set of tests divided into two groups: checking the proper functioning of BTR and investigating the sensitivity of models to input data. These tests apply not only to BTR-5 and earlier versions but are also intended for future BTR versions, which are expected to undergo full verification using manually or automatically applied tests. The first group of tests includes the verification of physical models and conditions: particle motion equations in electromagnetic fields; phase distribution of the beam from the ion source-accelerator; neutralization in the gas target, re-ionization losses, ionization in the tokamak plasma; particle conservation and power balance in the system. The second group of tests involves parametric scaling demonstrating the impact of individual input parameters on modeling results: exploring the influence of magnetic fields on injected power; gas target parameters on neutralization efficiency; beamlet focusing errors on overall beam transport efficiency; beamlet shape parameters on final power load profiles; detailing of the injector geometry on the accuracy of calculating heat loads and injector performance.
A comparison of BTR results with analytical solutions is provided, demonstrating that when used correctly, the BTR code serves as a reliable tool for detailed analysis and optimization of injection systems. Additionally, the BTR code can be applied to study the efficiency of various injection and power capture in the tokamak plasma schemes.

This study was supported by the ITER organization.

References

[1]. E. Dlougach, BTR code for neutral beam design. https://sites.google.com/view/btr-code/home
[2]. E. Dlougach, M. Kichik, Beam Transmission (BTR) Software for Efficient Neutral Beam Injector Design and Tokamak Operation. Software 2023, 2, 476-503 https://doi.org/10.3390/software2040022
[3]. ITER Final Design Report; NB H&CD, DDD 5.3; IAEA: Vienna, Austria, 2001.
[4]. Damian B. King, Review of the Beam Tranport and Re-ionisation Code. 2008

A Particle-In-Cell Study of Space Charge Compensation in Negative Hydrogen Ion Beams

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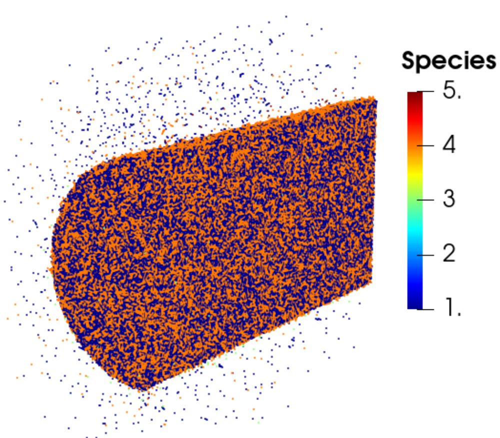
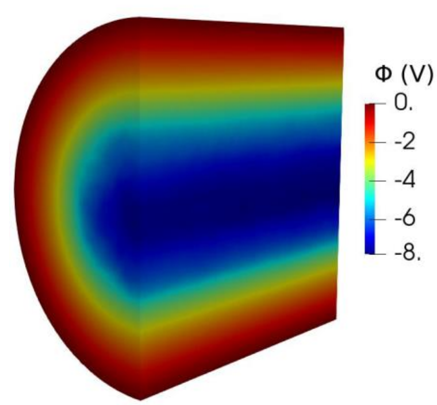
Negative hydrogen ion sources are extensively used in particle accelerators worldwide for a variety of applications (e.g. for high-energy particle physics in CERN and in spallation neutron source facilities like ISIS). An inherent problem in the low energy beam transport (LEBT) region of particle accelerators is beam divergence and transport losses due to space charge effects from beam particles. Space charge compensation (SCC) [1] is therefore crucial for counteracting the repulsive space charge force between the beam particles and minimizing beam transport losses. For ISIS H-ion beamline sources, SCC is typically initiated by the interaction of the beam with a background gas, causing ionisation and the creation of positive ions, leading to a decrease of the local charge density and electric field inside the beam.

The objective of this study is the investigation of SCC processes for a range of operating conditions using the particle-in-cell (PIC) method [2], enabled by the open source, plasma kinetic PIC code, PICLas [3]. PICLas enables high-fidelity, three-dimensional simulations using high performance computing and is well suited for coupling electromagnetic fields with the transport and collision of neutral and charged particles like electrons and ions. Simulations considering the main background gas ionisation reaction ($H^- + H_2 \rightarrow H^- + H_2^+ + e$), electron detachment ($H^- + H_2 \rightarrow H + H_2 + e$) and electron ionisation ($e + H_2 \rightarrow H_2^+ + 2e$) reactions show that SCC is effective in reducing the beam potential (see Figure 1). In the final paper, we will report on additional aspects like the role of electrons in accelerating the SCC process and the impact of different magnetic field intensities on the evolution of beam and plasma species, and how they affect the beam dynamics and transmission. Finally, experiments are underway at ISIS to correlate the beam transport and light emission signals observed with the dynamics of the beam potential. The implementation of light emission as a PIC simulation output will also be reported in the final paper.





THE BENCHMARK OF REVERSE-CALCULATION MODEL

Hui Li

In charged particle beam simulations, inverse modeling is commonly used to calculate beam characteristics that are difficult to measure using instruments. In order to obtain the meniscus of the ion source under different conditions, a reverse model was established using Comsol software. The correctness of the calculations was verified through forward and reverse modeling in the simulation. Furthermore, the accuracy of the reverse model was experimentally validated using a double-slit emittance meter and a pepper-pot emittance meter at the CSNS-II LEBT experimental platform. Under the experimental and simulation conditions, the results of the simulation and experimental validation demonstrate that the initial state of the beam can be inferred from the final state of the beam using the reverse model.

Critical Components: Developing Data Acquisition and Trigger Systems for CRDS for High power RF Operated Beam source in India (ROBIN)

Mainak Bandyopadhyay, Arun Chakraborty1, Manas Bhuyan, Hiren Mistri, Debrup Mukhopadhyay, Kaushal Pandya, Mahendrajit Singh, Himanshu Tyagi , Ratnaka Yadav

Negative ion density measurement in ion sources for neutral beam injector application plays a critical role for the identification of optimum operational parameters for maximum negative ion density yield. One such non-invasive diagnostic employed for such purposes is Cavity Ring Down Spectroscopy. In this study we portrayed instrumentation and signal acquisition of CRDS system which is interfaced with Rf Operated beam source in India (ROBIN) which is single driver RF (100kW, 1 MHz) based Negative Ion source being operated at IPR for its negative ion characterization. A passive stable optical resonator made out of highly reflecting dielectric mirrors is the encompasses the basic structure of the CRDS system. The measurement of negative ion density involves recording of the decay rate of the photons inside the optical cavity which is excited by a pulsed laser both in presence and absence of plasma with the aid of fast photodiode. Thus, for any successful implantation of CRDS system a development of reliable electronic system is necessary with fast response time. The system describes for ROBIN in this work comprises of mainly two components, a precise laser triggering system synchronized with the RF plasma pulse, and high bandwidth data acquisition which is based a combination of FPGA and high-speed digitizer for recording micro sec ring down decay. The main challenges faced while implementing laser triggering for CRDS system in ROBIN was high voltage reference system and fast sampling. ROBIN control and data acquisition system is based on S7400 Siemens plc and PXI with 0.1 ms time resolution thus such system was not suitable for application of CRDS system The developed triggering and acquisition system meets the challenges with sampling rate of more than 40 mega sample per sec along with the necessary electrical isolation for safe operation. Further, the proper triggering of laser pulse within the RF plasma pulse is of utmost importance for obtaining negative ion density measurement in the stable region of the plasma duration which is not affected by gas puff. Additionally, a LabVIEW based program facilitating the scope for real time data visualization and analysis is also incorporated with the acquisition system. Some test results implementing the developed system are also illustrated in our current study. Few results regarding negative ion density measurements are also shown.