3rd International Symposium on
Negative Ions, Beams and Sources

Book of abstracts

Jyväskylä, Finland

3 - 7 September 2012

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Introduction

The Third International Symposium on Negative Ions, Beams and Sources – NIBS2012 – is held in Jyväskylä, Finland, on September 3rd - 7th, 2012 and is organized by University of Jyväskylä.

NIBS2012 covers all areas of science and technology related to negative ions. The symposium was formerly named "Symposium on Production and Neutralization of Negative Ions and Beams (PNNIB)". It was started in 1977 for hydrogen negative ions and beams for fusion and accelerator applications. The symposium has evolved to include other ion species and applications, and for further development the name of the symposium has been changed in 2008. Presently, the symposium is the only international forum dedicated to all aspects of negative ions in physics and technology from formation to application.

Scope and topics

The aim of the symposium is to exchange information on science, technology, engineering and general experience in all areas related to negative ions by providing a discussion forum. Contribution from a wide variety of scientific fields, such as fusion, accelerator and material science, are presented. The main topics are:

Fundamental processes and modeling
Ion sources for fusion
Ion sources for accelerators
Beam formation and low energy transport
Beam acceleration and neutralization
Beamlines and facilities

Social program and technical tour

A half-day excursion to Varjola farm is planned for Wednesday afternoon on September 5. The farm is located about 30 km from the city at 30 minutes' distance by bus. Participants can explore traditional finnish landscape and are offered a possibility to experience white-water rafting and a wire gliding across the rapids. The tour includes a dinner and a possibility for enjoying the traditional finnish smoke sauna. The sauna fits a group of about 20 people, so a pre-reservation is necessary. The reservation can be made at the conference registration desk. Information and pictures on Varjola farm can be found from *www.varjola.com*.

The conference banquet in a local restaurant, Savutuvan Apaja, is scheduled for Thursday, September 6. The symposium participants will board a ship directly from the conference venue for a short cruise (approx. 1.5 hours) on Lake Päijänne to Savutuvan Apaja. Bus transportation back to the hotels will be arranged after the banquet. More information on the cruise and the banquet venue can be found from *www.paijanne-risteilythilden.fi/main* and *www.savutuvanapaja.fi*.

The conference participants are invited to join a tour of the JYFL accelerator laboratory on Friday September 7. The laboratory performs research on accelerator based nuclear, material and applied physics at the highest international level.

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Scientific Programme

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3. Ion sources for accelerators — Oral presentations

3. Ion sources for accelerators — Poster presentations

4. Beam formation and low energy transport — Oral presentations

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5. Beam acceleration and neutralization — Oral presentations

5. Beam acceleration and neutralization — Poster presentations

6. Beamlines and facilities — Oral presentations

6. Beamlines and facilities — Poster presentations

1

Fundamental processes and modeling

Three-Dimensional Particle-in-Cell Model of the Extraction Region in the Surface Negative Ion Source

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2. Istituto di Metodologie Inorganiche e di Plasmi - CNR and Dipartimento di Chimica, Università di Bari, Italy
3. Institute of Physics, Ernst-Moritz-Arndt University, Greifswald, Germany

The radio-frequency driven inductively coupled plasma (RF-ICP) negative ion source developed at IPP-Garching [1] has been chosen [2] by the ITER board as the new reference source for the ITER NBI system, due to the fact that it is potentially able to fulfil all ITER requirements. Experiments [3] have shown that the extracted ion current density increases by one order of magnitude when Cs is introduced into the source. This enhancement is attributed to the surface production of negative ions on the low work function cesiated surfaces close to the extraction aperture. However, only about 30 % of surface-produced negative ions are extracted due to a double layer formed close to plasma grid [4]. In this work, the extraction region, characterized by a complex interplay of magnetic fields, extraction apertures and surface-produced negative ions has been investigated by mean of a three-dimensional fully kinetic particle-based approach [5]. In particular, the use of a radio-frequency capacitive coupled plasma grid will be proposed as an expedient to maximize the extraction of surface produced negative ions.

[1] E. Speth et al., Nucl. Fus. 46, S220 (2006).
[2] R. S. Hemsworth, A. Tanga, V. Antoni, Rev. Sci. Instrum. 79, 02C109 (2008).
[3] U. Fantz, et al., Plasma Phys. Control Fus. 49, B563 (2007).
[4] F. Taccogna, P. Minelli, S. Longo, M. Capitelli, R. Schneider, Phys. Plasmas 17, 063502 (2010).
[5] C. K. Birdsall, A.B. Langdon, Plasma Physics via Computer Simulations (New York: McGraw-Hill, 1985).

Modeling of the Particle Transport and ion Production in a RF Driven Negative Hydrogen Ion Source for ITER NBI

D. Wünderlich, R. Gutser, U. Fantz, P. Franzen, NNBI-team

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NBI systems based on the generation, acceleration and neutralization of negative hydrogen or deuterium ions are foreseen for heating and current drive in ITER. Since 2007 the small (1/8 area of the ITER source) RF driven ion source prototype developed at the Max Planck Institut für Plasmaphysik (IPP) is the ITER reference source.

Negative hydrogen ions are produced by conversion of hydrogen atoms or positive ions at the cesiated surface of the plasma grid (PG), the first grid of a three-grid extraction system. In interaction of the charged plasma particles with a magnetic filter field an extended boundary layer evolves – a several centimeters thick plasma volume close to the PG relevant for the transport and extraction of the negative hydrogen ions.

Several years ago at IPP a dedicated program was started for developing models for the RF ion source prototype. The focus is to improve – in close cooperation with the experiment – the understanding of the complex physics of the boundary layer. Three of these models and the most recent results are introduced and discussed.

The kinetic energy of positive hydrogen ions impinging the PG is calculated using the 3d test particle Monte Carlo code ProtonFlow3d: after the positive ions are generated in the so-called driver they are strongly accelerated in a double layer close to the driver exit. However, after this initial acceleration the positive ions are rapidly thermalized to a low temperature in the ion source volume. Due to this low positive ion temperature surface conversion of hydrogen atoms to negative ions plays an important role, explaining the observation of a homogeneous negative ion beam even in the case of a non-uniform plasma close to the PG.

The 1d Particle in Cell code Bacon revealed the existence of a virtual cathode close to the PG surface, caused by the space charge of the surface produced negative ions. Despite the high relevance of the conversion of atomic hydrogen enough positive ions have to be present in order to compensate for the negative space charge and thus enable the evacuation of a sufficient amount of negative ions.

The trajectories of the negative ions from the PG to the extraction apertures are followed using the 3d test particle Monte Carlo code TrajAn. It is shown that the survival probability of the negative ions strongly depends on their velocity and the strength of the magnetic filter field. This result again is in good agreement with the experiment.

Numerical Modeling of the Linac4 Negative Ion Source Extraction Region by 3D PIC-MCC Code ONIX

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At CERN, a high performance negative ion (NI) source is required for the 160 MeV H^- linear accelerator Linac4. The source requirement is to produce 80 mA H^- ion beam within an emittance of 0.25 mm $\text{mrad}_{\text{N-RMS}}$ that is technically and scientifically very challenging. The optimization of the NI source requires a deep understanding of the underling physics concerning the production and extraction of the negative ions. The extraction mechanism from the negative ion source is complex, the magnetic filter and the electron dump structure significantly decreases the NI beam emittance.

The ONIX (Orsay Negative Ion eXtraction) code is used to address this problem. ONIX was initially developed to model the radio-frequency negative ion source of the ITER Negative Beam Injector, it has been modified and adapted to investigate the transport of NI and electrons in the extraction region of the Lina4 ion source. ONIX is a full 3D Particles-in-Cell Monte Carlo Collisions electrostatic code. It was written to handle the complex boundary conditions between plasma, surface and beam formation at the extraction hole. The code handles the positive electrical field between the extraction electrodes (10-60 kV) that drains out negative ion from the plasma as well as the magnetic field map designed to deflect co-extracted electrons.

This contribution focuses on the modeling of the Linac4 ion sources performance. The most efficient extraction system is analyzed via numerical parametric studies. The influence of several aperture's geometries and extraction electric field strength will be discussed. The emittance form extracted NI and electron currents are presented. The effect of magnetic filter field configurations on the suppression of the co-extracted electron current is discussed. The NI production of sources based on volume extraction and cesiated surface are compared.

Negative Ion Production by Plasma-Surface Interaction in Caesiated Negative Ion Sources

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In a recent report we suggested that the RF negative source operated at low pressure (<0.3 Pa) may contain fast positive ions and atoms [1]. This suggestion was based on the measurement by McNeely et al [2] of the high plasma potential in the driver. The negative ion (NI) yield was calculated using the equations proposed by Seidl et al [3], based on experiments performed with a plasma grid with work function of 1.5 eV. However the plasma grid work function in ion sources may be higher than 1.5 eV, therefore one should be able to evaluate the NI yield for any value of the work function. The purpose of the present work is to calculate the yield due to thermal and fast ions and atoms at any value of the work function. It is also to estimate how large the fraction of the formed negative ions is produced by backscattered or desorbed ions.

A direct way to obtain the work function dependence of the NI yield, Y, is to use Rasser et al equation [4]:

$$Y = R_N \beta^- = R_N (2/\pi) exp\left[-\pi(\phi - E_A)/2aV_{perp}\right] \tag{1}$$

V_{perp} is the perpendicular to the surface component of the outgoing atoms, and a is designated as the decay factor. Using Rasser's equation also allows one to calculate the yield as a function of the energy of the incident particles (through V_{perp}) onto the substrate on which caesium is deposited.

In order to determine the value of the decay factor a we calculated it from data of two experiments ([3] and [5]). We found the values $a = 2.13 \cdot 10^{-5}$ eV s/m using data from [5], and $a = 9.33 \cdot 10^{-5}$ eV s/m using data from [3]. We suggest that the reason for this difference is the different temperature of the plasma grid in these experiments. As a result the NI yield measured by Seidl et al [3] is the *total yield*, while that reported by Hiskes and Schneider [5] is the *backscattered H^- ion yield*. We will present the dependence on work function of the total yield for thermal ions and atoms, and for several energies of ions or atoms, as well as the variation with particle energy of the total, desorbed and backscattered yields.

[1] M. Bacal, Rev. Sci. Instrum., 83 02B101 (2012).
[2] P. McNeely, S.V. Dudin, S. Christ-Koch, U. Fantz and the NNBI Team, Plasma Sources Science & Technology, 18 014011 (2009)
[3] M. Seidl, H.I. Cui, J.D. Isenberg, B.S. Lee, S.T. Melnychuk, J. Appl. Phys. 79 2896 (1996).
[4] B. Rasser, J.N.M. van Wunnik, J. Los, Surface Science, 118 697 (1982).
[5] J.R. Hiskes, P.J. Schneider, Phys. Rev. B, 23 949 (1981).

The Response of Surface Negative Ion Yield and Virtual Cathode Formation to the Effective Work Function of Caesium

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The one dimensional model of the sheath between the plasma and the wall in a negative ion source developed by McAdams et al. [1] has been expanded to include the effects of a variable wall surface work function and fast positive ion species. The plasma consists of positive ions, electrons and negative ions. The model also includes the emission of negative ions from the wall into the sheath and thus represents the conditions in a caesiated ion source with surface production of negative ions. At high current densities of the emitted negative ions, the sheath is unable to support the transport of all the negative ions to the plasma and a virtual cathode is formed. This model takes this into account and allows the calculation of the transported negative ions across the sheath with the virtual cathode.

It has been suggested that the work function of Caesium can be higher than 1.5 eV in certain plasma conditions relevant to H^- production [2]. As the negative ion yield has a dependence on the work function there will be an effect on the negative ion current density from the surface and hence the virtual cathode behaviour. Including this effect has shown that for the parameters in [1] changing the work function from 1.5 eV to 2.2 eV reduces the maximum transported H^- current density by a third.

[1] R. McAdams, D. B. King, A. J. T. Holmes and E. Surrey, Plasma Sources Sci. Technol. 20 035023 (2011).
[2] R. Gutser, et. al., Rev. Sci. Instrum. 82, 023506 (2011).

Effects Due to Adsorbed Atoms upon Angular and Energy Distributions of Surface Produced Negative Hydrogen Ions

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Energy and angular distributions of surface-produced negative ions determine brightness of the beam extracted from a surface-conversion-type negative hydrogen ion (H^-) source. Energy distributions of extracted H^- beam show that two components exist in the beam. The first component exhibits an energy spread as small as several volts, while the second one has a wide energy spread comparable to the potential difference between the plasma potential and the bias voltage applied to the negative ion production surface. It has been experimentally confirmed that the first component, which are most probably produced from the ion stimulated desorption process, has a small angular spread. The second component produced from reflection of plasma ions at the surface possesses a large angular spread, and does not contribute much to enhance the beam brightness.

The amount and the mass of the atoms adsorbed on the negative ion production surface should largely affect the energy and angular distributions of reflected particles. A Monte Carlo binary-collision-simulation-code, ACAT (Atomic Collisions in Amorphous Target), has been utilized to investigate the effects due to adsorbates on the target surface upon the energy and angular distributions of atoms leaving the surface. The code has been modified to compute the particle emission from Mo surface covered with Cs and hydrogen. Calculation results for hydrogen desorption from surface covered by Cs show enhanced scattering of incident hydrogen positive ions at the surface. This will lead to a large angular spread of the atoms leaving the surface. In the meantime, adsorption of hydrogen atoms on the negative ion production surface reduces particle reflection coefficient against incoming hydrogen ions.

Comparison of the calculation results with the experimental data clearly indicates that the surface roughness of the negative ion production surface should be taken into account to simulate the energy and angular distributions of the H^- extracted from an ion source. A model that estimates negative ionization probability for atoms at a given energy can be coupled to ACAT to compute energy dependent angular distribution of surface produced H^- ions. Limitations and applicability of the present model for predicting energy and angular distributions of H^- produced at the plasma grid surface are discussed.

O - 1 07

Neutral Resonant Ionization in the High-Intensity Sputter Anion Source

J. S. Vogel

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We showed that an AMS gave absolute isotope ratios for $^{14}C/^{13}C$ to an accuracy of 0.30±0.06% over one year using 577 individual samples. Absolute measurements, without normalization, must depend on fundamental physical processes that dominate instrumental and sample variations. Isotope ratios depend incidentally on ion optical transmission, but fundamentally on anion source yield and cation conversion yield. Normalization of measurements with equivalent samples of SRM usually corrects for all three effects. We showed that velocity-dependent passage of anions in a gas collision cell within the spectrometer provided cation yields inversely proportional to ion mass at specific energies. Ockham's razor denies that isotopic fractionation in anion production is accurately balanced by spectrometer transmission. Thus, the cesium sputter ion source also involves physical processes that are independent of ion masses.

As Middleton described in 1999 [1] ”[Cs^+] rapidly forms a cavity in the sputter target that is small in diameter but deep. As the cavity deepens, an intense and exceedingly small ball of plasma frequently forms, the appearance of which usually coincides with the maximum output of negative ions”. We modeled volume ionization of a neutral atom flux through a plasma with coupled differential equations for excitation, ionization, transport, and radiation of Cs atoms from hot AMS samples. Many know the cross-sections (XS) of charge exchange in keV alkali collisions, but Vora et al. [2] hinted at large XS of excited states that maximize at lower energies. We fit log-normal threshold functions to the calculations for XS of Cs^0 (6s and 6p) with H and O, stepping up the maximum XS by the ratio of squared energy deficit (ED) and decreasing the energy of that maximum logarithmically. *Cs^0(7p) potentially has a 300 $Å^2$ cross-section for electron exchange with H^0 at 0.5 eV. The relevance of such fitting for sputtering XS with ED^2 amplitudes was tested on heavy-ion sputter data of Heinemeier [3]. Derived *Cs XS for plasma anionization of carbon atoms were integrated against a Sigmund-Thompson energy distribution for sputtered C^0 atoms to yield ionization rates of 3.4 (6s), 74 (6p), 400 (5d), and 860 cm^3/sec (7s) at 2 eV. C^- best followed the *Cs0(5d) population as parameters of dimension, electron yield, fluence, and temperature were varied.

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Plasma Potential Measurements and Their Influences on H^- Beam Currents in a RF Negative Ion Source

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Driving frequency in rf ion source can affect plasma parameters such as electron density and electron temperature and consequently production of H^- ions [1]. Previous experiments revealed that plasma potential structure might enhance H^- beam current via efficient extraction with higher driving frequency [2]. However, measured plasma potentials by a Langmuir probe have ambiguity near the extraction region because of limited access and the existence of filter magnetic field. In order to investigate more rigorously, ion energy analyzer is installed to confirm the plasma potential effect near extraction hole by measuring beam energy distribution of extracted ions. In this paper, plasma potential structures with operating parameters such as driving frequency, gas pressure, and driving rf power are compared. Based on the results, the plasma potential structures as a function of operating parameters are presented, and their influences on H^- extraction are discussed.

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Estimation of Sputtering Damages on a Magnetron H^- Ion Source Induced by Cs^+ and H^+ Ions

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An H^- ion source is being developed for CERN's Linac4 accelerator. A beam current requirement of 80 mA and a reliability above 99 % for 3 month uninterrupted operation periods are mandatory. To design a low-maintenance long life-time source, it is paramount to investigate and understand the wear mechanisms. A cesiated plasma discharge ion source, such as the BNL magnetron source, is a good candidate for the Linac4. However, in the magnetron source operated at BNL, the removal of material from the molybdenum cathode and the stainless steel anode surfaces are visible after extended operation periods. The observed sputtering traces are shown to result from cesium vapours and hydrogen gas ionized in the extraction region and subsequently accelerated by the extraction field. This paper presents a quantitative estimate of the ionization of cesium and hydrogen by the electron and H^- beams in the extraction region of BNL's magnetron ion source. The respective contributions of Cs^+ and H^+ ions to the sputtering process are estimated.

Study of Plasma Meniscus Formation and Beam Halo in Negative Hydrogen Ion Sources

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In large negative ion sources of neutral beam injection system (NBI-System) for large fusion devices, high energy and high current negative ion beams are required. However, heat load on acceleration grid caused by the beam halo has been one of the most critical problems. Recently it is shown that the beam halo is mainly caused by the meniscus, i.e. ion emissive surface, close to the plasma grid (PG) where its curvature is large [1]. To suppress heat load by beam halo, it is important to understand the meniscus formation and H^- extraction process in negative ion sources under the H^- surface production.

The purpose of this study is to understand effects of the plasma meniscus on the beam optics, especially on the beam halo formation with the PIC (Particle-in-cell) modeling in Ref. [2]. The extraction region of the source has been modeled with a simple 2D geometry (see below). The main assumption and parameters are basically the same as those in Ref. [1]. The surface produced H^- ions are modeled to be launched at the surface of the PG. The following parameters have been changed parametrically: 1) Hsurface production rate, 2) initial energy of surface produced H^- ions, 3) electron loss along magnetic field line, and 4) PG bias potential.

As a result, for example, the plasma meniscus is strongly dependent on H^- surface production rate, and also affects the beam optics. The effect of other parameters listed above will be discussed in the presentation.

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Analysis of Double Ion Plasmas in the Extraction Region of Hydrogen Negative Ion Sources

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In negative ion sources of neutral beam injectors (NBI) for large fusion devices such as LHD (Large Helical Device), one of the key issues is to optimize the H^- production and extraction condition. For the optimization, it is indispensable to understand the formation mechanism of the ion emissive surface (so-called plasma meniscus) and its location/shape around the extraction hole.

Recently, in a NIFS-R&D ion source scaled a half size of the LHD ones, the following interesting experimental observations have been reported under the "surface" H^- production case with the Cs-seeding [1] : (1) Plasma layer consisting of positive and negative hydrogen ions (i.e., electrons are excluded from the layer.) is formed in the vicinity of the plasma grid (PG), and (2) the thickness of the plasma layer is relatively large (at least the layer has a thickness of 15 mm from the PG by Langmuir probe measurements). The "double ion plasma layer" with positive and negative hydrogen ions in the vicinity of PG could have strong influences on the formation mechanism of plasma meniscus.

The purpose of this study is to clarify under what condition the double ion plasma is formed. For this purpose, a series of numerical simulations has been done with a 2D PIC (Particle-in-Cell) model [2]. The potential structure in the extraction region has been analyzed self-consistently with the charged particle dynamics. The model geometry and calculation conditions are the same as those in Ref. [2], while the following parameters have been systematically changed in the present simulations: 1) the strength of transverse magnetic field parallel to the PG, 2) electron loss along the field line, and 3) amount of the H^- surface production. From the simulation results, it is shown that these parameters are important for controlling the double-ion plasma formation and the resultant plasma meniscus.

Distribution of the Background Gas in the MITICA Accelerator

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MITICA is the ITER neutral beam test facility to be built in Padova for the generation of a 40 A D^- ion beam with a 64x20 array of 1280 beamlets accelerated to 1 MV. The background gas pressure distribution and the particle flows inside MITICA accelerator are critical aspects for stripping losses, generation of secondary particles and beam non-uniformities. To keep the stripping losses in the extraction and acceleration stages reasonably low, the source pressure should be 0.3 Pa or less. This pressure however is defined as filling pressure in the absence of plasma; during operation the gas mass flow will be maintained constant, but the source pressure will vary according to the gas temperature and the accelerator conductance. The gas flow in MITICA accelerator is being studied using a 3D Finite Element code, named Avocado. The gas-wall interaction model is based on the cosine law, and the whole vacuum system geometry is represented by a view factor matrix based on surface discretization and gas property definitions. Pressure distribution and mutual fluxes are then solved linearly. In this paper the result of a numerical simulation is presented, showing the steady-state pressure distribution inside the accelerator when gas enters the system at room temperature. The accelerator model is limited to a horizontal slice 400 mm high (¼ of the accelerator height). The pressure profile at solid walls and through the beamlet axis is obtained, allowing the evaluation and the discussion of the background gas distribution and non-uniformity. The particle flux at the inlet and outlet boundaries (namely the grounded grid apertures and the lateral conductances respectively) will be discussed.

Small-Radius Planar-Coil Driven Inductive Discharge as a Source of Negative Hydrogen Ions

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The study is in the trends of the development of the concept [1] for a design of a source of negative hydrogen ions as a matrix of small-radius discharges. Former results for strong accumulation of the ions in the region around the maximum of the dc potential, when the discharge radius is small, both in discharges with cylindrical [2-5] and planar [6] coils, are confirmed by the self-consistent 2D model of a planar-coil discharge developed in this study. Fluid-plasma model description of the discharge is coupled with electrodynamics, in which the planar-coil driving is specified in two manners: by including the coil in the modelling domain and by simulating it with a surface current applied as a boundary condition. The analysis stresses on the results from the electrodynamical description. The latter is treated also analytically regarding outlining differences in the behaviour of the small-radius planar-coil discharges compared to that of the large-radius discharges used in the plasma-processing technology. Comparison of the obtained results for the plasma behaviour with results from a previous model [6] where the rf power deposition is simulated with a half of a super-Gausssian profile shows that the latter is an approximation good enough.

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Investigation of H$^-$ Generation in a Directly Launched Multicusp Microwave Plasma Device in Continuous and Pulse Modulated Wave Modes

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Generation of H$^-$ ions is investigated in the newly developed multicusp microwave plasma device in both continuous (CW) and pulse modulated wave modes. In CW operation the vacuum chamber is divided into two sections separated by magnetic filter. The first chamber where microwaves of 2.45 GHz are directly launched to generate plasma is named as the production chamber; the second one is called the attachment chamber because H$^-$ are generated here by dissociative attachment (DA) of electrons to vibrationally excited hydrogen molecules. The magnetic filter allows only the cold electrons ($\sim$ 1 eV) into the attachment chamber for efficient DA process and prevents H$^-$ destruction by electron detachment [1]. The measured H$^-$ current density is $\sim$ 0.26 mA/cm^2 at 2 mTorr pressure and 360 W microwave powers [2]. H$^-$ density is obtained by measuring second derivative of Langmuir probe characteristics [3] by superposing a small modulated ac signal to dc probe bias and detecting the beat component corresponding to the derivative. In presence of negative ions a small kink appears in the second derivative curve, giving information about the negative ion density. H$^-$ density measured this way is compared with the value obtained from a steady state model and also the extracted current density. Reasonable agreement is found.

In pulse mode operation magnetic filter is removed and the concept of temporal filtering technique [4] is employed to generate negative ions. The pulse ON time is varied in the range of 40-400 μs and the period is fixed between 1000-2500 μs. During the pulse OFF period high energy electrons are depleted rapidly, producing a favorable environment for H$^-$ generation by DA process. Time resolved measurement of electron temperature and electron energy distribution function confirms this viewpoint. Plasma potential drops to very low value ($\sim$ 6V) during pulse OFF, which makes H$^-$ extraction easier. The plasma parameters are measured in both H_2 and Ar gas. It is noticed that the electron density, electron temperature and sheath potential falls more rapidly in H_2 than that in Ar. This is possibly due to the rapid depletion of electrons due the attachment of electron to produce negative ions in H_2, as compared to argon which has no stable electronegative component. Experiment on time resolved H$^-$ current extraction and a time-dependent model to estimate H$^-$ density is being carried out. Results will be presented and compared with those from CW mode.

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VUV-Diagnostics of a Filament-Driven Arc Discharge H^- Ion Source

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A VUV-emission study of a filament-driven arc discharge H^- ion source (LIISA) has been conducted at JYFL accelerator laboratory. The volume-type multicusp source is capable of producing DC H^- currents up to a few milliamps and is used as an injector for the JYFL K130-cyclotron. VUV-diagnostics provide information on the interaction between hot electrons and neutrals as well as ion recombination reactions. The obtained data offer insight on power dissipation mechanisms and, thus, can be used to explain differences observed in power efficiencies of various source types. Furthermore, studying VUV-emission of the hydrogen plasma is essential for understanding surface processes induced by radiation exceeding the surface work function of common materials. The VUV-irradiance was measured axially, through the extraction aperture, with a spectrometer . The VUV-irradiance was determined as a function of discharge current and voltage as well as neutral hydrogen pressure. Total VUV-power emitted by the plasma at certain ranges of wavelengths was estimated from the irradiance after calibrating the spectrometer data with a diode and band pass filters. Almost linear correlation between discharge power and VUV-irradiance was observed. Varying hydrogen pressure had only minor effect on the VUV-radiation characteristics. VUV-irradiance was also compared with extracted H^- currents in corresponding range of ion source parameters.

Operation and thermal modelling of the ISIS H^- source from 50 to 2 Hz repetition rates

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CERN's Linac4 accelerator H^- ion source, currently under construction, will operate at a 2 Hz repetition rate, with pulse length of 0.5 ms and a beam current of 80 mA. Its reliability must exceed 99 % with a mandatory 3 month uninterrupted operation period. A Penning ion source is successfully operated at ISIS; at 50 Hz repetition rate it reliably provides 55 mA H^- pulses of 0.25 ms duration over 1 month. Source lifetime is dictated by the rate of electrode sputtering which scales with duty factor. A 25 fold reduction in duty factor should significantly increase source lifetime to within the CERN requirements. The arc discharge plasma ignition is very sensitive to the temperatures of the discharge region especially of its cathode. The investigation by modelling and measurement of the operating conditions suitable for arc ignition and H^- production at 2 Hz is of paramount importance and must be understood prior to the implementation of arc discharge ion sources in the Linac4 accelerator. In its original configuration, the ISIS H^- source is only capable of running at repetition rates above 12.5 Hz. This paper describes the implementation of a heated element to provide temperature control of the electrodes, allowing lower repetition rate operation. The experimental results of the modified source successfully operated down to 1.6 Hz and providing 30 mA H^- pulses of 0.75 ms duration are presented. Thermal modelling of the ISIS ion source using ANSYS gives insight to the relevant parameters. The analysis demonstrates the adaptability of arc discharge sources for the operating conditions of the Linac4.

Study of the Negative Ion Acceleration for ITER Neutral Beam Injector by Coupling Two 3D PIC-MCC Codes ONAC and ONIX

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Despite of its higher cross section, the nuclear fusion reaction between deuterium and tritium requires very high temperature of plasma species, beyond 10 keV. For ITER self-sustained plasma operation, such high plasma temperatures should be maintained for long periods. Plasma ions are much more difficult to heat than electrons. Hence two Neutral Beam Injectors will be installed on ITER that should deliver 35 MW to the core plasma created by the neutralization of a dense beam of negative ions (NI) of 40 A prior accelerate at 1 MeV.

The NIs are extracted from a negative ion plasma source by a high electric field through a complex crossed magnetic field structure in order to reduce the amount of co-extracted electron. ONIX (Orsay Negative Ion eXtraction) 3D Particles-in-Cell Monte Carlo Collisions (PIC-MCC) code was initially developed to model the extraction radio-frequency negative ion source for ITER [1]. The NI neutralization by electron stripping on a gaseous target has been simulated as well by OBI (Orsay Beam Injector) code [2].

ITER accelerator is designed of five accelerating grids (200 kV acceleration stages) and the NI are extracted by a double grid system (called Plasma Grid – PG and Extraction Grid – EG) dc biased at 10 kV each-other, placed between the NI source and the acceleration grids. To prevent electron acceleration very strong magnet bars are embedded in the EG, dumping thus most of the co-extracted electrons from the NI source. This configuration is known as MAMuG (Multi Aperture Multi Grid) [3].

ONAC (Orsay Negative ion ACceleration) 3D PIC-MCC code was developed to self-consistently simulate the NI acceleration and the elementary processes that occur inside the accelerator during the co-extracted electron dump and the beam interaction with the neutral residual gas.

The numerical study shows the 3D modeling of the NI through the accelerator giving the emittance of the energetic (1 MeV) NI beam at the end of the accelerator as well as a detailed estimation of the loss processes inside.

Coupling ONIX output results on the extracted NI and co-extracted electrons with ONAC, which uses them as input data; it is possible to get a realistic picture of the whole configuration. Hence we provide a better comprehension of the physical phenomena governing the system. These results are compared and discussed with respect to ideal beam case and the results from the literature. Further work concerns ONAC code validation and it can be used for future accelerator optimization studies.

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2

Ion sources for fusion

Study of Negative Hydrogen Ion Beam Optics Using the 2D PIC Method

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Negative ion based neutral beam injection system (N-NBI system) is one of the promising candidates for plasma heating and current drive of magnetic fusion reactors. The negative ion source which can produce negative ion beams with high power and long pulse is the key component for the N-NBI system. One of the key issues for the design and development of such a negative ion source is to clarify negative ion trajectories in the cesiated volume ion source.

We have developed the particle-in-cell (PIC) code that is a useful tool for understanding of the physical processes leading to the extraction of H^- ions from the negative ion source and the beam optics [1]. In this PIC code, the electric field for negative ion extraction is calculated from the sheath potential given by the surface production of the negative ions on a plasma grid (PG) and a voltage difference applied between the plasma grid and an extraction grid. By using this code, the physics of the beam optics, especially the beam halo is investigated.

An overall region of the negative ion source from the source plasma to the accelerator is modeled with two dimensions. The x-axis is taken to be the direction of the H^- ion acceleration, while the y-axis is parallel to the direction of a transverse magnetic filter. The model is symmetry with respect to the x-axis. From the source region, electrons, H^+ ions, and volume produced H^- ions are assumed to be launched initially as Maxwellian distributions with the temperatures of 1 eV, 0.25 eV, and 0.25 eV, respectively. The initial ratio of the superparticle numbers for H+ ions, electrons, and volume produced H^- ions is assumed to be NH+ : Ne : NH^- = 10 : 9 : 1. The surface produced H^- ions are modeled to be launched at the surface of the PG with the initial temperature of 1.4 eV. The surface produced H^- ion density is 4 times higher than the volume H^- ion density.

The trajectory of negative ion beam shows that some of the ions are intercepted on the grids in the accelerator although most of the ions pass through the GRG aperture without interception. The potential profile around the PG indicates a large aberration of electrostatic lens for negative ion extraction. By this large aberration, the negative ions extracted from the edge of the meniscus are over-focused in the extractor, and consequently result in the beam halo.

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Commissioning of the Negative Ion Testbed ELISE and First Operation of the Half Size ITER RF Source

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The ITER neutral beam system will be equipped with large RF driven negative ion sources, the design based on small prototypes developed and tested at IPP Garching. The ITER source will have a cross section of 0.9 m x 1.6 m and has to deliver a D^- current of 40 A which will be accelerated to 1 MeV. The tests of this giant source will be carried out on the neutral beam test facility PRIMA in Padua, which is currently under construction; start of operation is planned for 2015.

As an important intermediate step a half size ITER source has been designed at IPP and is in operation since June 2012 on the new test facility ELISE (Extraction from a large Ion Source Experiment). The source plasma is generated in four ”drivers”, which are supplied by two 180 kW/1MHz RF generators. The target is to generate a negative ion beam of 20 A, accelerated to 60 keV. Goal of this experiment is to validate the source concept and to gain experience with beam extraction from an RF source with ITER relevant dimensions. The results of these early experiments will be of great importance for the final design of the full size source.

In this paper the commissioning of the components of the new testbed including first beam extraction is reported. Focus is laid on issues concerning the source operation like RF system, matching and mutual influence of the multi driver system.

Development of Intense Hydrogen-Negative-Ion Source for Neutral Beam Injectors at NIFS

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A high-current hydrogen-negative-ion source is required to a neutral beam injector for fusion plasma development. At National Institute for Fusion Science (NIFS), large-scaled intense hydrogen-negative-ion sources have been developed, and six ion sources are presently operational in three negative-ion-based neutral beam injectors, which are installed to the Large Helical Device, the world-largest superconducting fusion machine. One ion source produces 190 keV – 37 A of negative ions for 1.6 sec at maximum, corresponding to 340 A/m^2 of the current density. With three injectors, the injected neutral beam power is 16 MW.

The negative ion source is a filament-driven dc-arc source with Cs seeding. High-density plasma is produced in the driver region of a large arc chamber of 35 cm in width, 140 cm in length and 24 cm in depth by optimizing the magnetic cusp and filter field configuration. The negative ion accelerator is a four-grids and single-stage accelerator with a grid area of 25 cm x 120 cm with multi-slotted grounded grid for reduction of the grid heat load, leading to a high energy acceleration of a high current negative ion beam.

Plasma characteristics are investigated in the negative ion production region. The cavity ring-down method is applied to measurement of the negative-ion density with a half-sized R&D source. High-density H^- production of $3\text{x}10^{17}$ m^{-3} is measured at the H^- extraction current density of 110 A/m^2, and the linear relationship between the measured H^- density and the extracted H^- current density is confirmed. Recently, an ionic plasma, which consists of almost positive and negative ions, has been observed in the negative ion production region near the plasma grid with Langmuir probe measurement. An increase in electrons there is observed by the negative ion extraction in such an ionic plasma, which would correlate with the mechanisms of the charged particle transport and the negative ion extraction.

Recent activities on the development of hydrogen negative ion sources will be presented, together with the present achievements of the injector performance. The plasma characteristics containing high-density negative ions are also discussed from a perspective of further optimization of the negative ion production and extraction in a large-scaled intense negative-ion source.

Modeling a High Power ITER-Type Ion Source: Effect of the Suppression Magnets and Surface Produced Negative Ions on Volume Plasma Characteristics

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The influence of permanent magnets which are embedded into the extraction grid (EG) of a tandem-type inductively coupled plasma discharged is analyzed. The conditions are similar to those of negative ion sources for fusion applications, i.e., a high absorbed power (on the order of 100 kW) and a high density plasma (typically 10^{18} m^{-3}) in a large volume vessel with a magnetic field barrier. The effect on volume plasma characteristics of a high negative ion current emitted on the plasma grid (PG) is also studied. The numerical model is a two-dimensional (2D) Cartesian, three-velocity (3V), particle-in-cell code with Monte Carlo collisions (PIC MCC) [1].

Firstly, we show that suppression magnets induce a strong reduction of the electron current which is extracted toward the electrostatic accelerator. Electrons are trapped by the magnetic field in the vicinity of extraction holes and efficiently screen the extraction potential (applied on the EG grid). The ambipolar potential in the extraction region is slightly above the bias potential (while it is controlled by the EG potential without the use of suppression magnets). Large differences in plasma parameters (density, temperature, currents and potential profiles) are found between the two cases; suppression magnets modify plasma kinetics in the source volume well beyond the magnetic field direct influence.

In the second part of this work, we analyze the dynamics of surface produced negative ions. The generation of ions on the PG grid induces a decrease of plasma potential and electron density in the extraction region. Negative ion density near PG can be larger than the electron density. Large negative ion current is correlated with the appearance of a virtual cathode. The latter implies than above a given current, negative ions produced in excess are mostly reflected back toward the PG grid; this results also in a saturation of negative ion density in volume. For plasma densities in the driver region of the order of $7 \cdot 10^{17}$ m^{-3}, saturation is observed for a negative ion current on the PG surface of $\sim$60 mA/cm^2.

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Polar Distribution of Ions and Elections in Extraction Region of a Large-Scaled Caesium Seeded Ion Source

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Electro-negative plasma including quite low electron density has been bserved in the beam extraction region of a caesium (Cs) seeded negative hydrogen ion (H^-) source for R&D [1]. The voltage-current curve measured with Langmuir cylindrical probe installed ∼10 mm apart from the plasma grid (PG) is quite symmetric with respect to the inflection point of the curve. It has been reported that the electro-negative plasmas have the inflection points at the origins of the current [2, 3]. On the other hand, the point shifts on negative side of 0.5-0.8 A in our R&D source. This suggests that positive and negative ions have different flow velocities; i.e. the positive ions flow in a direction from driver region to extraction one and the flow velocity of the negative ions is smaller than positive ones. The production mechanisms are different in the positive and H^- ions, and transport directions of them are opposite in electrostatic field caused with plasma potential. The difference of their averaged velocities and directions can affect to sheath formation in the extraction region.

In order to investigate the flow difference, which is important to understand the sheath formation and the particle dynamics in the electron poor plasmas, a directional electrostatic probe has been installed at the extraction region of the R&D ion source. In pure hydrogen discharge at the pressure of 0.2 Pa, one order difference of the electron density on the driver and PG sides is observed at a probe position at 5 mm apart from the PG. In the hydrogen plasma with the pressure at 1.1 Pa, on the other hand, no difference in the electron density is observed on the driver and PG. The probe tip is available to move in the directions parallel and perpendicular to the PG surface, and is rotatable with respect to probe axis. The ratios of negative to positive saturation currents are 1.8 and 2.2 on the driver and PG sides, respectively. This suggests the H^- density is slightly higher in the driver direction.

The H^- production is dominated from volume to surface processes with seeding Cs and the saturation-current ratio is considered changing the distribution, because the direction of the born region is opposite. We will discuss the distribution of negative and positive ions and their flow in the electro-negative plasmas obtained with Cs seeding.

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Construction of a Versatile Negative Ion Source and Related Developments

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The NIO1 project consisting in a 60 kV ion source (9 beamlets of 15 mA each of H^-) is jointly developed by Consorzio RFX and INFN-LNL, with the purpose of providing a test ion source, capable of working in continuous mode and in condition similar to larger ion sources for Neutral Beam Injectors. The modular design allow for quick replacement and upgrading of parts [1]. While the main body of the ion source construction is well progressing at industry and suitable ceramic isolator were procured, some parts were separately developed at participating institution, as described in the following. Particular attention was devoted to the source alignment system, since parts are machined to 20 micron parallelism and the axis of the source is horizontal. The original support was based on a rigid isolating structure in PEEK; to reduce PEEK mass, an improved support envisioning some elastic deformation is being prepared. Two options are being considered for beam calorimetry: 1) water cooled tubes; 2) especially for first operation below nominal beam power (8 kW), water free elements Carbon Fiber Composite (CFC) as in STRIKE concept [2] and prototypes; preliminary calculation of sustainable power were performed. A small rf plasma generator was installed at INFN-LNL and several matching boxes were tested at low power. Two year results suggest to maintain the classical step-up configuration for the high power NIO1 matching box, which is now under construction (with wide tuning range and full I-V passive readout). A Cesium heater controller prototype was also briefly tested. Plasma generator (at lab ground) is followed by a positively biased Faraday cup, so that beam current can be measured; an electrode to suppress secondary emission was recently added. Plasma density estimated with a 4 wire Langmuir probe is consistent with plasma rf simulation, even if electron distribution deviation from Maxwellian seems large (and tail can not be measured with the $[-5, +28]$ V range of the current power supply; better electronics for a second Langmuir probe was procured. Finally site preparation of the NIO1 has begun at RFX and installation of source is expected for the end of 2012.

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Multiaperture Negative Ion Source

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The long-pulse, multiaperture, surface-plasma source with negative ion production on a cesiated plasma grid is under construction at Budker Institute. The surface-plasma source configuration includes a cylindrical RF plasma driver, a cylindrical expansion chamber with the multicusp bucket for plasma confinement, a magnetic filter and a four-electrode ion-optical system for beam extraction and acceleration. The multicusp bucket and the magnetic filter made of external permanent NIB magnets.

The concepts and innovations in the source design and the status of the ion source development will be reported.

The projected parameters of the source are following:

RF power in plasma	40 kW
Hydrogen filling pressure	< 0.5 Pa
Emission current density	30 mA/cm^2
Beam current	1.5 A
Beam energy	120 kV
Extraction voltage	10 kV
Electron : H^- ratio	1:1
Pulse duration	100 s

Analysis of Electron Temperature Distribution by Kinetic Modeling of Electron Energy Distribution Function in JAEA 10 Ampere Negative Ion Source

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In JT-60SA, negative ion sources with large beam extraction area ($\sim$ 0.9 m × 0.45 m) is designed to produce 500 keV and 22 A, D^- beam. However, it has been a serious issue that extracted negative ions was not uniform over the wide grid area.

Previous experiments showed that the uniformity of negative ion production strongly relates to non-uniformity of electron temperature T_e [1]. In Ref. [1], the following reason has been proposed for non-uniformity of Te spatial profile; Fast electrons move toward in one direction in the ion source due to $B \times \nabla B$ drift in asymmetric magnetic configuration by introduction of magnetic filter.

In order to understand T_e non-uniformity, we have developed the kinetic simulation code (K-EEDF code) for the analysis of the EEDF (Electron Energy Distribution Function) in arc-discharge negative ion sources [2]. The code models three-dimensional magnetic configuration with electron energy relaxation and spatial diffusion by collision processes (e.g., electron-electron Coulomb collisions). In the current study, the K-EEDF code is applied to the analysis of the JAEA 10 ampere source and spatial resolution has been improved for the calculation of Coulomb collision by Binary Collision Model [3].

The simulation results of T_e profile are compared with that of measurement by Langmuir probe in the present study. The T_e profile calculated from the K-EEDF code has shown a good agreement with the experimental result. Present analysis of EEDF has led to the following results;

1. Population of high energy (E > 25 eV) electrons is up to 2.6 % out of the total electrons in the region, which electrons are drifted, while the population is only 0.1 - 0.2 % in other region.
2. Thermal electron ($E \lesssim$ 25 eV) is also higher in the region than in other region by an order of magnitude due to sequences of Coulomb/inelastic collisions of the high energy electrons.
3. As a result of 2., electron temperature becomes non-uniform in one direction.

These results show that the K-EEDF code is a useful tool for the analysis of the T_e spatial uniformity in arc discharge negative sources. The T_e spatial distribution obtained in the present study is to be utilized for understandings of the uniformity in negative ions.

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A Comparison of Hydrogen and Deuterium Plasmas in Negative Hydrogen Ion Sources for Fusion

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Negative hydrogen ion sources for fusion have to operate both in hydrogen and deuterium. The required parameters for ITER are even more demanding for deuterium operation. Although the extracted negative ion current density is lower, 285 A/m^2 D$^-$ compared to 345 A/m^2 H$^-$, the source performance has to be stable for 1 hour in D (400 s in H) at a current density ratio of co-extracted electrons to negative ions of below or equal unity. At present, the latter, namely the co-extracted electron current is limiting the source performance especially in deuterium, since the co-extracted electron current is typically four to five times larger than for hydrogen. In order to understand the reason for this difference the plasma parameters of hydrogen and deuterium discharges have been measured in a recent campaign at the prototype RF source test facility BATMAN at IPP. Electron temperature and density are measured with a Langmuir probe system for different magnetic filter fields. The latter plays an important role for the electron suppression of the co-extracted electrons and for the destruction and transport of the negative ions near the extraction system. The negative ions are produced by the surface process, i.e. cesium is evaporated into the source providing a converter surface for hydrogen atoms and positive ions at the first grid of the extraction system. It has been shown, that in the RF source hydrogen atoms dominate the negative ion generation whereas sufficient positive ions are needed to avoid the formation of a potential well in the plasma sheath for the negative ions released from the surface [1]. The amount of negative ions released from the surface has also consequences on the electrons since the negative charge has to be balanced against the positive charge. As a consequence fewer electrons are available in the plasma sheath for extraction. The ratio of atoms to molecules is accessible by optical emission spectroscopy from which also the gas temperature, the vibrational population of the molecules, the negative ion density as well as the Cs amount is obtained. A comprehensive comparison of the plasma parameters will be presented with the aim to identify the reason for the increased amount of co-extracted electrons in deuterium and thus finding the proper method for their reduction.

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Plasma Production and H^- Beam Extraction from a FET-Based RF Ion Source

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High power radio-frequency (RF) ion sources are requisite as H^-/D^- sources for ITER NBI with their maintenance free and long time operation. Recent development of metal-oxide-semiconductor field-effect transistors (MOSFET) enables us to use an inverter circuit for RF power supply with high conversion efficiency. We have utilized a FET-based RF power supply with a RF frequency lower than 1 MHz. Characteristics of plasma parameters were measured in a small ion source, which consisted of a cylindrical RF-driver with an externally winding antenna and a plasma expansion chamber.

In the RF driver axial magnetic field up to 150 G was applied by external Helmholtz magnetic coils. The electron density drastically increased with an axial magnetic field and attained to 1.5×10^{19} m^{-3} in the driver and 5×10^{18} m^{-3} in the expansion chamber with RF power of 10 kW. [1,2] Characteristics of plasma production in the source were measured with helium and argon gases as well as hydrogen gas in order to clarify the high density plasma production with the magnetic field. Long pulse operation of the source using the RF source, which can deliver RF power up to 30kW with CW operation, was also examined.

H^- beam extraction from the source was measured with and without seeding Cs vapor to the chamber. The acceleration electrodes consist of a molybdenum plasma grid, cupper extraction and acceleration grids. Each grid has 9 x ϕ 9 apertures and H^- beam was extracted from a single aperture. The extraction and acceleration voltage can be applied to 10 kV and 20 kV, respectively. The RF power is applied via an isolated transformer (1:1) in order to keep the RF source to be grounded. The transmission efficiency was measured with several kinds of core materials.

An acceleration current (I_{acc}) and an extraction current (I_{ext}) were measured with Cs seeding in a long pulse operation. Optical emission of cesium and hydrogen atoms were measured during the operation.

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Development of a Negative Ion-Based Neutral Beam Injector in Novosibirsk

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The negative-ion based injector of a hydrogen neutral beam with the energy up to 1 MeV and power up to 5 MW is under construction at the Budker Institute. Several innovations are suggested and implemented to the injector design. To achieve high efficiency of negative ion beam neutralization a plasma target will be used. The prototypes and components of 5 MW N-NBI system are under production. The description of injector concepts and basic elements will be presented.

Proposal of Actively Heated, Long Stem Based Cs Delivery System for Diagnostic Neutral Beam Source in ITER

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Positioning of Cesium (Cs) oven modules in the complex interface dominated space envelope of a negative ion source such as Diagnostic Neutral Beam (DNB) source for ITER is a challenge not only for the designer of the ion source, but also that of remote handling. A more user friendly design of the Cs delivery could emerge from the consideration of a possibility of injecting the Cs from an oven located outside the vacuum envelope of the ion source, thereby ensuring an ease of Cs refilling and oven maintenance. The design of such a delivery system involves long transmission path of lengths ≥ 4 m, from ambient to vacuum. System design involves incorporation of a low loss transmission tube enveloped by highly reflective inner surface pipe to reduce the heat losses and therefore heating of the nearby systems. A combination of manual and remotely operated high temperature valves has been incorporated in such a way that the Cs refilling or oven maintenance can be done without breaking the ion source vacuum. Removable joints in the oven heating elements are provided at specific locations to cut remove the Cs oven for ion source maintenance.

Experimental data on Cs transmission over such a long length, required for an effective design of a co-axial transmission, is not presently available. However, an experiment is now under way in ITER-India to make measurements of Cs distribution in coaxial transmission and inputs would aid the design of a long stem based Cs delivery system. Presently going experiment incorporates an additional feature of multiple nozzle distributor based Cs delivery into the ion source which might help in reducing the need of multiple Cs ovens in large ion sources like ITER.

The Cs flux from the oven is measured by surface ionization detector (SID) and is calibrated with a known quantity (typically 10 mg) Cs dispenser. A vacuum compatible quartz microbalance is also used to measure the Cs flux rate. The angular distribution of the Cs flux is measured by a movable SID in linear direction. For Cs flux contour measurements on a plane, a tungsten wire mesh along with a tungsten ionizer is also planned to be used. The measurement of Cs inventory in the oven reservoir is also planned by floating magnet and electrical resistivity measurements methods.

The paper proposes to present the measurement results and also proposes a possible configuration of the Cs oven for ITER DNB ion source.

Flexible Magnetic Design of the MITICA Plasma Source and Accelerator

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MITICA (Megavolt ITER Injector Concept Advancement) is a neutral injector prototype to be installed at the PRIMA test facility for the development of the full-size Heating and Current Drive Neutral Beam Injectors for the ITER Tokamak reactor [1]. The core of MITICA [2] is constituted by a RF-driven plasma Source and by a multi-grid electrostatic accelerator, which shall produce a 46 A H^- ion Beam (or a 40 A D^- ion Beam) with a specific energy up to 1 MeV. The beam consists of 1280 individual ion beamlets issued from a grid system having an overall cross-section of 600 x 1600 mm^2. The beamlets are to be extracted, accelerated and neutralized under well-controlled conditions in order to obtain a focused 1 MeV, 17 MW Neutral Beam on a target at $\sim$25 m.

The transverse magnetic field inside the plasma source and the accelerator [3] is of crucial importance to:

- prevent the electrons in the plasma source from entering the extraction and accelerator zone (Filter field)
- avoid the co-extracted electrons and the electrons generated by stripping reactions from being accelerated at high energy by dumping them as early as possible (Suppression Field)
- guarantee the required optics quality (aiming, divergence and uniformity) of the negative Ion beam.

A flexible solution will be necessary in MITICA in order to allow an independent variation of the Filter field and of Suppression field during the experimental campaign. A specific magnetic design has been developed and optimized to this purpose, which is essentially based on current-carrying busbars with the addition of permanent magnets and/or of coils. According to the MITICA scientific objective, this choice will provide the tools for the experimental validation of the magnetic field profile, the resulting configuration will be subsequently transferred to the ITER HNB.

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Compensations of Beamlet Deflections for 1 MeV Accelerator of ITER NBI

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For 1 MeV accelerator of the ITER neutral beam injector (NBI), beamlet deflections and compensation methods have been studied in a three dimensional (3D) multi beamlet and electric field analysis using OPERA-3d code. This accelerator is a five stage multi-aperture and multi-grid (MAMuG) accelerator to produce deuterium negative ion (D^-) beam of 1 MeV, 40 A with current density of 200 A/m^2 for 3600 s from 1280 apertures drilled in each grid. One of key issues is to suppress grid power load due to direct interception of deflected beamlets. The beamlet deflection is caused by i) magnetic field generated by permanent magnets embedded in the extraction grid (EXG) for electron suppression. Moreover, the beamlets from peripheral apertures in the aperture area are deflected outward by ii) space charge repulsion between the beamlets. To compensate the beamlet deflections due to i) and ii), an aperture offset was applied to the electron suppression grid (ESG) and a metal plate, so-called kerb, was attached around the aperture area at the back side of the ESG, respectively. Detailed geometrical configuration of the compensation methods were also considered so as to suppress degradation of beam optics and voltage holding due to the compensation methods. The beamlet deflection angle due to the magnetic field was 2.8 mrad. To compensate the beamlet deflection without the beam spread due to a distortion of the electric field at the edge of the ESG aperture, the aperture offset of 0.6 mm was proposed in the enlarged ESG aperture from 14 mm in the original diameter to 17 mm.

The beamlet deflection angle due to the space charge repulsion was 4 mrad. Height of the kerb was changed from 1 mm to 3 mm and position of the kerb was tuned. As the result, the beamlet deflection was compensated without degradation of the beam optics when the thicker kerb with 3 mm thickness is distanced from the peripheral aperture, namely at 30 mm from the peripheral aperture axis. This is because the distanced kerb generates weaker electric field for the beamlets and influences them gently. Local electric field concentrations at the kerb which originate breakdowns was reduced to 3 kV/mm by rounding the edge of the kerb to 9 mm in radius. This satisfies the criterion of the electric field design. Thus, this paper clarified the kerb to compensate the beamlet deflection without degradation of the beam optics and the voltage holding.

H^- Density Response to Applied Bias and Extraction Voltage in Negative Hydrogen Ion Source

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In cesium seeded negative hydrogen ion (H^-) source for fusion, most H^- ions extracted as beam are believed to be produced a plasma grid (PG) surface. However, particle dynamics from the H^- production to extraction is not perfectly clear.

To understand the dynamics in experimental study, we performed to measure several physical values in the vicinity of the PG with Langmuir probe, surface wave probe, optical emission spectroscopy, and cavity ring-down method (CRD) with which a line integrated H^- density is evaluated. The H^- density is one of the most important parameters for understanding the dynamics. Our CRD system has a capability of the profile measurement of the H^- density.

The H^- density drop is observed at the moment of applying extraction voltage even of a few kV. This could reflect that accessible H^- ions to measure line of $\sim$10 mm from PG are reduced by extraction field attracting H^- ions to the PG apertures. A bias voltage is applied between the PG and arc discharge chamber as potential of the PG is positive (in normal operations: $\sim$3 V). The H^- density decreases with increase of the bias voltage. This phenomenon could reflect that release speed of H^- form the PG surface decreases.

We have not yet clearly distinguish between both physical descriptions. To clarify the descriptions, we have prepared a power supply with a capability of applying lower extraction voltage than the ordinary use one. The H^- density drop was also observed in the case of applying extraction voltage less than 1 kV. The measurement region has been extended such as 1 mm to 24 mm from PG (in previous system: 5 mm to 17 mm) by changing PG structure and thickening bias insulator. The distance of 25 mm form the PG is an edge of filter magnets. In the previous measure region, we were not able to observe that obvious differences of the H^- density responses to applications of bias and extraction voltages above between PG apertures and PG plate. By measuring H^- density in more neighbor regions of the PG, we scheduled to explore whether there are the differences or not. This knowledge may help to promote for understanding the particle dynamics.

We show the H^- density response to the applications of bias voltage and dozen V to kV order extraction voltage, and discuss H^- particle dynamics.

Cesium Dynamics and H^--Density in the Extended Boundary Layer of Negative Hydrogen Ion Sources for Fusion

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Essential for the performance and reliability of large-scale negative hydrogen ion sources suitable for neutral beam injection of the upcoming ITER fusion experiment is a stable and low work function of the cesiated converter surface, where the conversion of dissociated hydrogen atoms or of positive hydrogen ions takes place. Stable cesium layers are necessary in order to achieve reliable performance. Since the reactive Cs layers can be polluted by background gas atoms or hydrogen gas in the vacuum phase, continuous fluxes of pure Cs onto the converter surface are required. Cs fluxes are created by the evaporation of Cs and desorption of Cs from the walls. The latter is mainly determined by the Cs chemistry, the wall temperature and, during plasma phases, also by interaction of plasma with the wall. Therefore a better understanding of the Cs dynamics is highly desirable for further improvements of source operation.

In previous investigations at the IPP RF-driven negative hydrogen ion source, the prototype source for the neutral beam injection system of ITER, measurements of the Cs dynamics in vacuum and plasma phases by laser absorption (LAS) have been carried out. So far only one line of sight in front of the plasma grid has been used in short pulse operation (6 s plasma including 4 s beam, 200 s between pulses) [1] as well as in long pulse operation (typical several 100 s plasma and beam time, 200 s pause) [2]. However, due to the complex Cs distribution mechanism a spatial resolved detection is desirable. Thus, the LAS at the short pulse testbed BATMAN has been equipped with two lines of sight close to the grid system (top and bottom), which is of particular interest since the Cs oven is located in the upper half of the source. In addition to the performance measurements using the extracted currents also the previous used cavity ringdown spectroscopy [3] has been re-installed for measurements of the line integrated H^- density in front of the plasma grid, providing a more direct access to the production rate of H^-.

The Cs dynamics at two lines of sight for typical source operation and for varying wall temperatures will be shown as well as its influence on the H^- density and the source performance.

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Diagnostics of a Negative Hydrogen Ion Source Based on a Planar Coil-Inductively Driven Discharge

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The study, presenting experimental results, is in the scope of the recent activity on a volume-production based rf source of negative hydrogen ions constructed as a matrix of small-radius discharges inductively driven by a planar coil [1]. A single discharge of the matrix has been studied. Plasma diagnostics has been carried out in the first - small size - chamber of a two-chamber discharge vessel where the rf power deposition is located. The results presented are for the axial distribution of the plasma parameters: electron density and temperature, plasma potential, electronegativity of the discharge (given by the ratio of the densities of the negative ions and of the electrons) and concentration of the negative hydrogen ions. The laser-photodetachment technique is the method applied for determination of the electronegativity of the discharge. The probe diagnostics is the method employed for determination of the electron temperature and density as well as of the plasma potential. The gas-discharge conditions are: gas pressure varied from 4 mTorr up to 10 mTorr and applied rf power varied between 50 W and 200 W. The spatial distribution of both the electronegativity and the negative hydrogen ion density show the presence of two maxima in the first chamber of the source located, respectively, close to the region of the rf power deposition and close to the transition between the two chambers. The positions of these maxima strongly correlate with the measured spatial profile of the plasma potential and the positions of its maxima.

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Investigation of Helicon Discharges as RF-Coupling Concept for Negative Hydrogen Ion Sources

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Currently, the negative hydrogen ion sources for fusion applications are based on inductively coupled RF-discharges. The ITER reference source is operated at 0.3 Pa and driven with a power up to 90 kW per driver (RF-frequency 1 MHz, driver diameter 24 cm, length 15 cm). A more efficient RF-coupling method than inductive coupling is highly desirable as the demands on the RF-generator could be reduced. A promising method particularly at low pressure is Helicon coupling, where the RF-heating is based on wave heating mechanisms that require an external magnetic field. Moreover, Helicon coupling heats the whole plasma volume which reduces the thermal stress of the driver material.

Helicon experiments are typically performed at a RF-frequency of 13.56 MHz in argon using thin long discharge tubes. As the frequency, the geometry and the working gas differs from those used at negative hydrogen ion sources for fusion applications, the investigation of Helicon discharges as RF-coupling mechanism is carried out by stepwise changes from the typical Helicon setup towards the typical ion source setup. The aim is to realize a Helicon discharge in the driver geometry using hydrogen/deuterium that reaches similar degrees of dissociation and ionization as obtained with the inductive coupling but reducing the necessary RF-power considerably.

Investigations concerning the comparison of Helicon discharges in argon and hydrogen have been performed at a small laboratory experiment (discharge tube diameter 5 or 10 cm, length 40 cm). The applied RF-generator operates at a frequency of 13.56 MHz and provides a maximum power of 600 W. Helmholtz coils were used to generate a magnetic field up to 14 mT. First, the investigation focuses on the substitution of argon with hydrogen or deuterium. Using pure argon or argon with small hydrogen admixtures, the transition from inductive coupling to the Helicon mode could be observed. In pure hydrogen or deuterium, this transition could not be achieved due to the limited power of the RF-generator. However, in deuterium the typical low field peak could be observed at a field strength of 3 mT. As the dissociation and ionization degrees are already increased considerably, it could be sufficient to take advantage of the low field peak instead of reaching the full Helicon mode in hydrogen or deuterium.

The next steps towards the ion source setup are utilizing a lower RF frequency (2 MHz) and a discharge vessel with the driver dimensions.

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Influence of Cesium on the Plasma Parameters in Front of the Plasma Grid in Sources for Negative Hydrogen Ions

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A limiting factor for the performance of ion sources based on negative hydrogen ions for the neutral beam heating systems for fusion devices (NNBI) is the co-extracted electron current. The negative hydrogen ions are produced via surface conversion of hydrogen atoms and ions from a hydrogen plasma at the cesiated surface of the first grid, the so called plasma grid. In order to continuously replenish the cesium layer, a permanent flow of cesium onto the plasma grid resulting from evaporation and redistribution inside the vessel is mandatory. Thus the plasma in front of the plasma grid is a cesium seeded hydrogen discharge. As expected, the negative ion current strongly depends on the cesium dynamics. However, it is commonly observed, that the current density of co-extracted electrons is much more sensitive on the cesium conditions [1]. The reason for this behaviour could either be the result of the repression of electrons in front of the plasma grid due to the production of negative hydrogen ions, or the result of the effect of cesium on the plasma parameters in the volume. In order to distinguish between these two explanatory approaches, the investigations of Bacal et al. [2] aiming at the volume effect have been repeated on the basis of the experienced knowledge from the campaigns at the IPP NNBI test facilities [1] at relevant ion source parameters and with extended diagnostic methods. The effect of the heavy mass of cesium and the low ionization energy compared to hydrogen is studied separately by using xenon as a substitute where in contrast to cesium chemical or reactive processes in the plasma volume and/or at the vessel surfaces can be excluded.

Investigations on the dependencies of the plasma parameters on the admixtures of either cesium or xenon to a hydrogen discharge are carried out at a flexible laboratory experiment. The planar ICP (27.12 MHz, 5 - 20 Pa H_2/D_2) has similar plasma parameters as well as comparable cesium densities to those in the extended plasma boundary of the IPP NNBI ion sources. In order to measure the full set of plasma parameters, several diagnostics are applied simultaneously: optical emission and white light absorption spectroscopy, Langmuir probe measurements and residual gas analysis.

[1] U. Fantz, P. Franzen, D. Wünderlich, Chem. Phys. 398 (2012) 7-16
[2] M. Bacal et al., Rev. Sci. Instrum. 71 (2000) 1082-1085

Conceptual Design of Data Acquisition and Control System for Two RF Driver Based Negative Ion Source for Fusion R&D

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Twin Source - An Inductively coupled two RF driver based 180 kW, 1 MHz negative ion source experimental setup is initiated at IPR, Gandhinagar, under Indian program, with the objective of understanding the physics and technology of multi-driver coupling. Twin Source [1] (TS) also provides an intermediate platform between operational ROBIN [2] and eight RF drivers based Indian test facility — INTF [3].

A twin source experiment requires a central system to provide control, data acquisition and communication interface, referred as TS-CODAC, for which a software architecture similar to ITER CODAC core system has been decided for implementation. The Core System is a software suite for ITER plant system manufacturers to use as a template for the development of their interface with CODAC. The ITER approach, in terms of technology, has been adopted for the TS-CODAC so as to develop necessary expertise for developing and operating a control system based on the ITER guidelines as similar configuration needs to be implemented for the INTF. This cost effective approach will provide an opportunity to evaluate and learn ITER CODAC technology, documentation, information technology and control system processes, on an operational machine.

Conceptual design of the TS-CODAC system has been completed. For complete control of the system, approximately 200 Nos. control signals and 152 acquisition signals are needed. In TS-CODAC, control loop time required is within the range of 5–10 ms, therefore for the control system, PLC (Siemens S-7 400) has been chosen as suggested in the ITER slow controller catalog. For the data acquisition, the maximum sampling time required is 100 micro second, and therefore National Instruments (NI) PXIe system and NI 6259 digitizer cards have been selected as suggested in the ITER fast controller catalog.

This paper will present conceptual design of TS-CODAC system based on ITER CODAC Core software and applicable plant system integration processes.

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[2] M.J. Singh, et al. AIP Conf. Proc. 1390 604–613 (2011)
[3] M.J. Singh et al, SOFT 2011, Volume 86, Issues 6-8, 732–735

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CRD Measurements in a FET-Based H^- Ion Source

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We have been developing a H^- ion source operated with a MOSFET based RF power supply. The use of MOSFET enables us to use RF power with high efficiency in the frequency range of lower than 1 MHz. High density H^- ion production is expected in the source, and H^- diagnostics is required. The CRD technique is a powerful diagnostic tool for H^- measurements, because it measures the absolute density and dynamics of H^- ions during beam extraction. This study aims 1) to implement the CRD technique as a H^- diagnostics system in the FET based ion source, and 2) to clarify the characteristics of H^- ions near the plasma grid.

The CRD technique utilizes multi pass laser absorption by photodetach process of H^- ions, and absolute line average H^- density can be obtained. The diagnostic system was set at horizontally aligned diagnostic ports near the plasma grid by attaching two highly reflective mirrors (>99.999%) on each side. A Nd:YAG laser with 1064 nm in wavelength was used. The ring-down time τ was 300 μs in an empty cavity. The lower detection limit was $\sim 10^{15}\ \mathrm{m}^{-3}$, which was small enough to measure the H^- density in our source. The electron density n_e was also measured simultaneously at the center of the optical cavity by a Langmuir probe.

The volume produced H^- was measured. 1) An increase of the H^- density was observed as the electron density as a function of input power. The density attained $1 \times 10^{16}\ \mathrm{m}^{-3}$ and the line averaged H^- density to the local n_e ratio was 3% at each RF power up to 10 kW. 2) The H^- density drastically increased as a function of the external magnetic field in the driver. The RF power and ne also increased as the magnetic field increased, and the density ratio stayed constant. These characteristics showed a strong effect of the external magnetic field on the driver plasma production and confinement. 3) At low source pressures ~0.4 Pa, the H^- density showed a drastic increase while electron density stayed constant, and the density ratio reached 6%. An increase of the electron temperature was observed in the driver. This implies increase of production of vibrationally excited hydrogen molecules that forms the H^- ions, and decrease of dissociation of the H^- ions by collisions with hydrogen molecules. The characteristics of H^- ions when cesium is seeded and during a long pulse discharge will be also discussed.

Neutral Resonant Ionization in Plasma Ion Sources: Cesium as a Catalyst of Electron Transfer

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Electron transfer between colliding atoms occurs at keV energies if both atoms are in their ground states. Vora, et al (1974, Phys Rev A 9:2532), used LZS formalism to suggest that the cross section (XS) for exchange rises as the collision energy deficit (ED) squared, while the energy range of exchange ionization greatly expands for such collisions among atoms including one or both in excited states. We modeled the observed blue plasma that forms in front of recessed samples in high intensity cesium sputter sources as a potential manifestation of atomic anionization in collisions with °Cs^0 in states as high as 7d in order to explain the lack of isotopic fractionation observed in our measurements of absolute isotope ratios by accelerator mass spectrometry. This mechanism is in further evidence in Morgan's review of H collisions with alkali and alkali earth elements where a peak in anion production at hundreds of eV associated with the 2p state of H corresponds to a quantitative loss of metal atoms at this energy well below the peak for ground state interactions (1985 J Phys Chem Ref Data 14:971) Kimura gathered the keV data for H^0 on Cs^0(6s) anionization XS and calculated the *Cs^0(6p) XS, along with the reverse ion neutralization (2007 App Surf Sci 253:6641). We fit log-normal functions including reaction thresholds to his calculations for the *Cs^0(6s, 6p) XS and bravely extended the concept, stepping up the maximum cross-section by the ratio of squared ED while decreasing the energy of that maximum logarithmically. In such a scheme, *Cs^0(7p) potentially has a 300$Å^2$ cross-section for electron exchange with H^0 at 0.5 eV, since the energy deficit is reduced from 3.11 to 0.43 eV. Plasma electron energies after the expansion are still sufficient to "walk" Cs up its collisional excitation ladder, particularly since the rate from the resonant 2p states to the metastable 5d state (1.25 μsec) is 100 Å2-GHz. This mode of volume electron transfer has not apparently been used in resolving the "volume" versus "surface" ionization argument in plasma ion source design. We show our tentative calculations and re-interpret multiple published diagnostics about plasma ion source behaviours using this concept. The author is far from cognizant in the field of plasma ion sources, having worked with high intensity Cs sputter sources for 30 years, but offers the poster for its conversational value, ready for amusement, scorn, or education.

3

Ion sources for accelerators

Recent Performance of the SNS H^- Source for 1-MW Neutron Production

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After a three-year power ramp-up, the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory started in 2009 to operate near 1 MW for the production of neutrons [1]. In 2011 the power was reduced to 800 kW to address budget reductions. However, since December of 2011 SNS is back to 1 MW with an availability of ∼95%.

The 1 MW beam starts from the ion source at -65 kV with ∼0.9 ms long, ∼50 mA H^- beam pulses at 60 Hz. An electrostatic low energy beam transport system (LEBT) refocuses the beam into the radio frequency quadrupole accelerator (RFQ), which accelerates the beam to 2.5 MeV. This paper presents the operational experience with the SNS ion sources and LEBT gained over the last two years running with 33–38 mA LINAC beam current and a 4.4 to 5.4 % source duty factor. Discovered issues and weaknesses, their impact, and implemented, planned, or considered mitigations will be discussed.

Very challenging was a case where two sources got poisoned, with one source loosing ∼1 % beam per hour and the second source loosing ∼20 % per hour. At least initially recesiations restored most of the beam current, but normally increased the loss rate. This was in great contrast to a third source that produced persistent beams when being used before and after the use of a poisoned source.

In addition we encountered large and small air-leaks developing after the source installation, which were initially misinterpreted because the O2 partial pressure barely changed. At least initially, recesiation could restore most of the beam but did not change the loss rate.

On the positive side, we implemented frequency hopping, by increasing the frequency by ∼1.5 % after the first 5 μs, which has significantly reduced plasma outages that required a reduction of beam current. In addition, we started to detune the source before ramping up the 65 kV source voltage, which has significantly reduced the arcing during the startup of the source. We continue to explore the problem of off-nominal voltage conditions that are introduced by protection systems.

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H^- Ion Sources for CERN's Linac4

J. A. Lettry, D. Aguglia, Y. Coutron, A. Dallocchio, H. Pereira, E. Chaudet, J. Hansen,
E. Mahner, S. Mathot, S. Mattei, P. Moyret, D. Nisbet, M. O'Neil, M. Paoluzzi, C. Pasquino,
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The specifications set to the linac4 ion source are: H^- ion pulses of 0.5 ms duration, 80 mA intensity and 45 keV energy within a normalized emittance of 0.25 mm mrad RMS at a repetition rate of 2 Hz. In 2010, during the commissioning of a prototype based on H^- production from the plasma volume, it was observed that the powerful co-extracted electron beam inherent to this type of ion source could destroy its electron beam dump well before reaching nominal parameters. However, the same source was able to provide 80 mA of protons mixed with a small fraction of H_2^+ and H_3^+ molecular ions. The commissioning of the radio frequency quadrupole accelerator (RFQ), beam chopper and H^- beam diagnostics of the linac4 are scheduled for 2012 and its final installation in the underground building is to start in 2013. Therefore, a crash program was launched in 2010 and reviewed in 2011 aiming at keeping the original Linac4 schedule with the following deliverables: Design and production of a volume ion source prototype suitable for 20–30 mA H^- and 80 mA proton pulses at 45 keV by mid 2012. This first prototype will be dedicated to the commissioning of the low energy components of the linac4. Design and production of a second prototype suitable for 40–50 mA H^- based on an external RF solenoid plasma heating and cesiated-surface production mechanism in 2013 and a third prototype based on BNL's Magnetron aiming at reliable 2 Hz and 80 mA H^- operations in 2014. In order to ease the future maintenance and allow operation with Ion sources based on three different production principles, an ion source "front end" providing alignment features, pulsed gas injection, pumping units, beam tuning capabilities and pulsed bipolar high voltage acceleration was designed and is being produced. This paper describes the progresses of the Linac4 ion source program, the design of the Front end and first ion source prototype. Preliminary results of the summer 2012 commissioning are presented. The outlook on the future prototype ion sources is sketched.

H^- Ion Source Development for the FNAL 750keV Injector Upgrade

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The new FNAL 750 keV injector upgrade for the replacement of the 40 year old Fermi National Laboratory (FNAL) Cockcroft-Walton accelerators with a new ion source and 200 MHz Radio Frequency Quadruple (RFQ), Low Energy Beam Transport (LEBT) and Medium Energy Beam Transport (MEBT) [1], has been built and is now being tested prior to installation during the 2012 shutdown. The new H^- ion source is a round aperture magnetron which was developed at Brookhaven National Lab (BNL) by Jim Alessi [2]. Operational experience from BNL has shown that this type of source is more reliable with a longer lifetime due to better power efficiency [3].

The new source design reliably produces 90 mA of H^- beam current at 15 Hz rep-rate, 100 μs pulse width, and a duty factor of 0.2%. The measured emittances at the end of the LEBT are horizontally H = 0.21 mm mrad and vertically V = 0.17 mm mrad. With 35kV extraction the power efficiency is 60 mA/kW. The source design, along with data from a test stand and the LEBT, will be presented in this paper.

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Negative Ion Source Development at the Cooler Synchrotron COSY/Jülich

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The Nuclear Physics Institute (IKP)[1] at the Forschungszentrum Jülich, a member of the Helmholtz Association (HGF), conducts experimental and theoretical basic research in the field of hadron, particle, and nuclear physics. It operates the COSY[2] cooler synchrotron, an accelerator and storage ring, which provides unpolarized and polarized proton and deuteron beams with beam momenta of up to 3.7 GeV/c. Main activities of the accelerator division are the design and construction of the high energy storage ring (HESR)[3], a synchrotron and part of the GSI FAIR[4] project, and the operation and development of COSY with injector cyclotron and ion sources. The Facility for Antiproton and Ion Research (FAIR) in Darmstadt will provide high-energy heavy ions and antiprotons for basic research. Within the FAIR project, Forschungszentrum Jülich is responsible for the construction of the anti proton synchrotron and storage ring HESR. The operation and development of the accelerator facility COSY is based upon the availability and performance of the isochronous cyclotron JULIC as the pre-accelerator and its ion sources. Since 1996 the cyclotron delivers negative light ions for charge exchange injection into the synchrotron, exceeding on average 7000 hours per year . Two filament driven volume sources and a charge exchange colliding beams source, based on a nuclear polarized atomic beam source, provide unpolarized and polarized H^- or D^- routinely. Within the Helmholtz Association's initiative Accelerator Research and Development (ARD) [5] the existing sources at COSY, as well as new sources for future programs, are investigated and developed. The following achievements and activities at Jülich will be presented:

- Improved pulsed beams from the COSY volume sources.
- New components for the COSY polarized ion source.
- 100 keV pulsed H^- source for ELENA commissioning at CERN.
- Polarized ion source for future use at FAIR.

[1] http://www.fz-juelich.de/ikp/EN
[2] http://www.fz-juelich.de/ikp/EN/Forschung/Beschleuniger/_doc/COSY.html
[3] http://www.gsi.de/portrait/fair_e.html
[4] http://www.fz-juelich.de/ikp/EN/Forschung/Beschleuniger/_doc/HESR.html
[5] http://www.helmholtz-ard.de/

Over 60mA RF-Driven H^- Ion Source for the J-PARC

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A cesium (Cs) free H^- ion source driven with a lanthanum hexaboride (LaB_6) filament is being operated at the J-PARC (Japan Proton Accelerator Research Complex) [1]. Although it satisfies the J-PARC first stage requirements of an H^- ion beam of 30 mA and a life-time of 500 hours, it was proven that the current was not increased by seeding Cs [2]. Although a J-PARC Cs seeded H^- ion source driven with a tungsten (W) filament successfully produced an H^- ion beam of 76 mA, its Cs consumption rate was too high for stable operation and its life-time was about 500 hours [3]. In order to satisfy the J-PARC second stage requirements of an H^- ion beam of 60 mA within normalized emittances of 1.5 π mm mrad both horizontally and vertically and a flat top beam duty factor of 1.25 % (500 μs×25 Hz), the development of a J-PARC Cs seeded RF-driven H^- ion source was started by using an internal-antenna developed at the SNS (Spallation Neutron Source) [4]. The J-PARC RF-driven source designed based upon the J-PARC W-filament source with modifications of (1) an internal-antenna instead of a W-filament and (2) a rod filter magnetic field instead of a external magnetic field is presented in this paper. It successfully produced an H^- ion beam with a flat top duty factor of 2.5 % (1 ms×25 Hz) of 77 mA, whose about 90 % (70 mA) of each emittance is within 1.5 π mm mrad [5, 6, 7].

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[5] A. Ueno, Y. Namekawa, S. Yamazaki, K. Ohkoshi, K. Ikegami, A. Takagi, and H. Oguri, in this symposium ”Perfectly matched pulsed 2MHz RF network and detuned CW 30MHz RF network for the J-PARC RF-driven H^- Ion Source”.
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[7] S. Yamazaki, A. Ueno, Y. Namekawa, K. Ohkoshi, K. Ikegami, A. Takagi, and H. Oguri, in this symposium ”Beam enhancement by axial magnetic field optimization in the J-PARC RF-driven H^- ion source”.

Towards Reliable Internal Antennas, Standardizing Baseline Source Performance and Future Plans of the SNS H^- RF Ion Source

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The Spallation Neutron Source (SNS) now routinely operates near 1 MW of beam power on target with 30–40 mA peak current in the linac and an availability of ∼95%. H^- beam pulses (∼1 ms, 60 Hz) are produced by a Cs-enhanced, multi-cusp ion source closely coupled to an electrostatic Low Energy Beam Transport (LEBT), which focuses the 65 kV beam into an RFQ accelerator. The source plasma is generated by RF excitation (2 MHz, ∼60 kW) of a copper antenna, which has been encased with a thickness of ∼0.7 mm of porcelain enamel and immersed into the plasma chamber. Failure of this coating material during operations has been a long-standing problem and recently a significant cause of downtime for the ion source / LEBT system. This report describes a new antenna installation criteria, sorting methodology and startup procedure that have significantly reduced the antenna failure rate since their introduction last fall.

Currently we have an inventory of 5 baseline ion sources, two of which are typically alternated between service periods. Since recently baseline source #3 outperforms all other sources by ∼5 mA, and therefore it is used in consecutive 6–7 week service periods. Source #4, delivering ∼5 mA less, is used in intermittent 1–2 week service periods, where the target power is typically between 900 and 950 kW. To increase the output of all other sources, small mechanical variations have been identified and used to guide modifications to boost the output of source #5 on the test stand.

This report describes the results of the experimental investigation conducted on the test stand where the relative importance of each difference to beam production was determined and significant performance improvements have been realized in source #5. Finally, a brief status of the external antenna source developed for future use on the SNS is given.

Recent Negative Ion Source Activity at JYFL

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A filament-powered multicusp ion source for production of H^- has been developed for the JYFL Pelletron accelerator for use in ion beam lithography and PIXE applications. The source can be considered conventional with the exception of the filter field being created with an electric magnet for continuous adjustability. A permanent magnet dipole-antidipole electron dump is integrated in the puller electrode. The two magnetic fields are separated by a magnetic SS430 plasma electrode insert. The source has been characterized with emittance and current measurements. It provides 50 μA H^- beam at 10 keV energy with 0.019 mm mrad 95 % normalized rms emittance through 2 mm aperture. Lower emittance is achievable by changing the plasma electrode insert to a smaller aperture one if application requires. Comparisons to simulations are presented.

A new commercial MCC30/15 cyclotron has been installed at the JYFL accelerator laboratory providing 30 MeV H^+ and 15 Mev D^+ for use in nuclear physics experiments and applications. The ion source delivered with the cyclotron is a a filament-powered multicusp source capable of about 130 h continuous operation at 1 mA H^- output between filament changes. The ion source is located in the cyclotron vault and therefore a significant waiting time for the vault cooldown is required before filament change is possible. This kind of operation is not acceptable as 350 h and longer experiments are expected. Therefore a project for developing a CW 13.56 MHz RF ion source providing 1 mA of H^- for the new cyclotron has been initiated. A planar RF antenna replacing the filament back-plate of the existing TRIUMF-type multicusp chamber is used for the first tests. The project will continue with design and construction of a new multicusp chamber and extraction. Status of the project is presented.

The extraction code IBSimu has recently gone through a major update on how smooth electrode surfaces are implemented in the Poisson solvers. This has made it possible to implement a fast multigrid solver. Also a method has been made to import 3D CAD geometries into simulations. A brief summary to the recent updates in IBSimu is presented.

Developing the RAL FETS Source to Deliver a 60 mA, 50 Hz, 2 ms H^- Beam

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All the FETS beam requirements have been achieved, but not simultaneously [1]. At 50 Hz repetition rates beam current droop becomes unacceptable for pulse lengths longer than 1 ms. This is fundamental limitation of the present source design. Previous researchers [2] have demonstrated that using a physically larger Penning source should overcome these limitations. The scaled source development strategy is outlined in this paper. A study of time varying plasma behaviour has been performed using a V-UV spectrometer. Initial experiments to test scaled plasma volumes are outlined. A dedicated plasma and extraction test stand (VESPA-Vessel for Extraction and Source Plasma Analysis) is being developed to allow new source and extraction designs to be appraised. The experimental work is backed up by modelling and simulations. A detailed ANSYS thermal model has been developed. IBSimu is being used to design extraction and beam transport. A novel 3D plasma modelling code using beamlets is being developed by Cobham Vector Fields using SCALA OPERA, early source modelling results are very promising. Hardware on FETS is also being developed in preparation to run the scaled source. A new 2 ms, 50 Hz, 25 kV pulsed extraction voltage power supply has been commissioned and a new discharge power supply is being designed. The design of the post acceleration electrode assembly has been improved.

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Potential for Improving of the Compact Surface Plasma Sources

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Compact Surface Plasma Sources (CSPS) such as magnetron, semiplanotron, Penning Discharge SPS can have high plasma density (up to 10^{14} cm^{-3}), high emission current density of negative ions (up to 8 A/cm^2), have small (1–5 mm) gaps between cathode emitter and a small extraction aperture in the anode. They are very simple, have high energy efficiency up to 100 mA/kW of discharge ($\sim$100 times higher than a modern large Volume RF SPS) and have a high gas efficiency (up to 30%) using pulsed valves. CSPSs are very good for pulsed operation but electrode power density is often too high for dc operation. However, CSPS were successfully adopted for DC operation with emission current density $\sim$300 mA/cm^2 in Hollow cathode Penning Discharge SPS and in Spherical focusing semiplanotron SPS.

Factors limiting the operating lifetime of Compact Surface Plasma Sources (CSPS) are analyzed and possible treatments for lifetime enhancement are considered. Noiseless discharges with lower gas and cesium densities are produced in experiments with a modified discharge cell. With these discharge cells it is possible to increase the emission aperture and extract the same beam from a lower current discharge with a corresponding increase in source lifetime. A design of an advanced CSPS is presented.

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Design Study of a Test Vessel to Investigate the ISIS Penning H^- Ion Source Plasma

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A vacuum-vessel for extraction and source plasma analyses (VESPA) has been designed with the aim of understanding the dominant plasma processes used during the creation of negative hydrogen (H^-) ions in the ISIS Penning ion source. The VESPA has been designed to be simple and inexpensive, with all features of the ISIS ion source not directly responsible for plasma formation removed such that there is ample space for diagnostics close to the plasma. Diagnostics will include but is not limited to a beam current density monitor, a high resolution visible-light monochromator, a caesium mass deposition monitor, an electrostatic energy analyser, a magnetic mass spectrometer and an emittance scanner. Several existing parts and ancillary equipment will be re-used to keep costs down and to speed up installation. The ultimate aim of the VESPA is to perform detailed analyses of the H^- production, caesium usage and beam formation such that an upgrade to the ion source is both well informed and possible using this setup. This report will detail the electromagnetic and mechanical studies performed and outline timescales for manufacture and installation.

Vacuum Simulation and Characterisation for the LINAC4 H$^-$ Source

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At CERN, the 160 MeV H$^-$ Linac4 will soon replace the 50 MeV proton Linac2. In the H$^-$ source two major sources of gas are identified. The first is the pulsed injection at about 0.1 mbar in the plasma chamber. The second is the constant H_2 injection up to 10^{-5} mbar in the LEBT for beam space charge compensation. In addition, the outgassing of materials exposed to vacuum can also play an important role in contamination control and global gas balance. To evaluate the time dependent partial pressure profiles in the H$^-$ ion source and the RFQ, electrical network – vacuum analogy and test particle Monte Carlo simulation have been used. The simulation outcome indicates that the pressure requirements are in the reach of the proposed vacuum pumping system. Preliminary results show good agreement between the experimental and the simulated pressure profiles; a calibration campaign is in progress to fully benchmark the implemented calculations. Systematic outgassing rate measurements are on-going for critical components in the ion source and RFQ. Amongst them those for the in-vacuum Cu-coated CoSm magnets, located in the biased electron dump electrode, show results similar to stainless steel at room temperature.

Gas Injection and Fast-Pressure-Rise Measurements for the Linac4 H^- Source

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In the era of the Large Hadron Collider the CERN injector complex comprising the 34 years old Linac2 with its primary proton source is presently upgraded with a new linear accelerator for H^- (Linac4). The design, construction, and test of volume production and cesiated RF-driven H^- ion sources is presently ongoing with the final goal of producing an H^- beam with 80 mA beam current, 45 keV beam energy, 0.5 ms pulse length, and a repetition rate of 2 Hz. In order to have quantitative information of the hydrogen gas density at the moment of plasma ignition the dynamic vacuum properties of the plasma generator were studied experimentally. We describe the experimental setup and present fast-pressure-rise measurements for different parameters of the gas injection system, such as gas species (H_2, He, N_2, Ar), gas pulse length (0.2–0.5 ms), and injection pressure (400–2800 mbar). The obtained data are compared with a conductance model of the plasma generator.

Improving Efficiency of Plasma Generation in H^- Ion Source with Saddle Antenna

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Progress in development of RF H^- surface plasma source (SPS) with saddle radio frequency (SA) (RF) antenna which will provide better power efficiency for high pulsed and average current, higher brightness with longer lifetime and higher reliability is considered. Several versions of new plasma generators with different antennas and magnetic field configurations were tested in the SNS small Test Stand. The efficiency of positive ion plasma generation has been improved $\sim$4x times up to 0.18 A/cm^2 per 1 kW of RF power 13.56 MHz. A first prototype SA SPS with AlN chamber was installed in the SNS Test Stand that achieved current of H^- ions up to 67 mA with an apparent efficiency of up to 1.6 mA/kW at RF frequency 2 MHz. A new version of the RF assisted triggering plasma source (TPS) has been designed, fabricated and tested. A Saddle antenna SPS with water cooling is being fabricated for high duty factor have been tested.

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Upgrade of CW Negative Hydrogen Ion Source

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The developed previously CW surface-plasma source with H^- ion beam current of 15 mA and energy 32 keV [1] was upgraded for higher current production. Basic improvements include the increase of the emission and ion-optical system apertures diameters, the enhancement of power supplies to provide higher plasma density in Penning discharge and the enforcing of IOS electrodes to sustain the higher currents. Parameters for reliable dc source operation, such as hydrogen and cesium flow rate, voltage and current of Penning discharge, optimal geometry of anode cover, of extraction and grounded electrodes were determined by series of experiments. The high voltage holding of IOS was improved after the optimization of extractor electrode temperature. Several long term runs with duration more than 0.5 hour each and with negative ion beam current > 25 mA were studied. Direct measurements of H^- current density profile and of beam emittance were carried out by an electric sweep scanner. No saturation of the CW H^- beam current with the discharge current increase was recorded, and a further increase of H^- beam current could be produced with the power supply and the electrode cooling enhancement.

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P - 3 15

Perfectly Matched Pulsed 2MHz RF Network and Detuned CW 30MHz RF Network for the J-PARC RF-Driven H^- Ion Source

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A cesium (Cs) seeded RF-driven H^- ion source using an internal-antenna developed at the SNS (Spallation Neutron Source) [1] is under development for the J-PARC (Japan Proton Accelerator Research Complex) [2], whose requirements for the J-PARC second stage are an H^- ion beam of 60 mA within normalized emittances of 1.5 π mm mrad both horizontally and vertically and a flat top beam duty factor of 1.25 % (500 μs×25 Hz). An H^- ion beam with a flat top duty factor of 2.5% (1 ms×25 Hz) of 77 mA, whose about 90 % (corresponding to about 70 mA) of each emittance is within 1.5 π mm mrad, is successfully extracted from it [3, 4, 5]. Pulsed high temperature 2MHz RF plasma necessary for the high H^- ion beam is produced without misfire by producing CW low temperature 30 MHz RF plasma as similar as the SNS ion source. The designs by using the circuit simulation code LTSpice IV [6] and the experimental results of the 2 MHz and 30 MHz RF networks are presented in this paper. In addition to the 2 MHz RF network with two variable vacuum capacitors (VVCs), which is a necessary and sufficient condition for the matching with a constant load impedance, the perfect matching of the 2MHz pulsed high power up to 60 kW is successfully accomplished by shifting the RF frequency during the pulse (typically, 2 MHz for initial 40μs then shifting to 2.03 MHz and linearly changing to 2.02MHz) according to the plasma temperature. On the other hand, the detuned network with one coupling VVC successfully produces the CW 30 MHz RF plasma, since the CW plasma easily disappears due to the impedance shift caused by the pulsed high temperature 2 MHz RF plasma, if a 30 MHz RF network with two VVCs was used and tuned to the matching parameters.

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[2] H. Oguri, et.al., Phys. Rev. ST Accel. Beams 12, 010401 (2009).
[3] A. Ueno, et.al., in this symposium ”Over 60mA RF-driven H^- ion source for the J-PARC”.
[4] A. Ueno, et.al., in this symposium ”Emittance measurements of the J-PARC RF-driven H^- Ion Source”.
[5] S. Yamazaki, et.al., in this symposium ”Beam enhancement by axial magnetic field optimization in the J-PARC RF-driven H^- ion source”. [6] LTSpice IV, http://www.linear.com/designtools/software/ltspice.jsp.

Emittance Measurements of the J-PARC RF-Driven H^- Ion Source

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[4] A. Ueno, Y. Namekawa, S. Yamazaki, K. Ohkoshi, K. Ikegami, A. Takagi, and H. Oguri, in this symposium ”Perfectly matched pulsed 2MHz RF network and detuned CW 30MHz RF network for the J-PARC RF-driven H^- Ion Source”.
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Beam Enhancement by Axial Magnetic Field Optimization in the J-PARC RF-Driven H$^-$ Ion Source

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A cesium (Cs) seeded RF-driven H$^-$ ion source using an internal-antenna developed at the SNS (Spallation Neutron Source) [1] is under development for the J-PARC (Japan Proton Accelerator Research Complex) [2], whose requirements for the J-PARC second stage are an H$^-$ ion beam of 60 mA within normalized emittances of 1.5 πmm mrad both horizontally and vertically, and a flat top beam duty factor of 1.25 % (500 μs×25 Hz). An H$^-$ ion beam with a flat top duty factor of 2.5 % (1 ms×25 Hz) of 77 mA, whose about 90 % (corresponding to about 70 mA) of each emittance is within 1.5 πmm mrad, is successfully extracted from it [3, 4, 5]. The experimental results of the axial magnetic field optimization by using an air core solenoid, which significantly enhances the H$^-$ ion beam by typically 10 %, are presented in this paper. Although it is reported that the plasma density and the beam current are enhanced by an axial magnetic of 187 Gauss or higher [6] in an RF-driven H$^-$ ion source of Tohoku University, the physical phenomenon seems to be different form the J-PARC source beam enhancement, since there is the optimal field strength of much lower value (less than 40 Gauss) in the J-PARC source.

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Operation Status of the J-PARC Negative Hydrogen Ion Source

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A cesium-free negative hydrogen ion source driven with a LaB_6 filament is being operated without any serious trouble for approximately six years in J-PARC. Although the ion source is capable of producing an H^- ion current of more than 30 mA [1], the current is routinely restricted to approximately 17 mA at present for the stable operation of the RFQ linac which has serious discharge problem from September 2008 [2]. The availability of the ion source is directly related to the operation time of the J-PARC accelerator. To evaluate the lifetime of the present ion source, we tried to perform two months beam operation in November 2010. As the result of the trial operation, 1,270 hours continuous operation was achieved at the beam current of 17 mA. In January 2011, the ion source was operated at 25 mA for 217 hours at first, then the beam current was decreased to 17 mA. After 1,029 hours operation, the filament of the ion source was cut off and the beam run was interrupted. By considering the consumption rate of the filament is depended on the beam current, these operation results show the lifetime of the ion source is evaluated to be approximately 1,200 hours. For another attempt to improve the ion source availability, we tried to decrease the required time for maintenance. By unitizing the replacement parts and keeping them under the vacuum condition until just before the installing, the maintenance time can be decreased from four to two days or less.

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Optimization of Magnetic Field Structure of a Compact 14 GHz ECR Ion Source

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Plasma excitation by electron cyclotron resonance (ECR) condition requires a complicated ion source structure to realize strong magnetic field, but it can be an effective way to generate a high density plasma inside of the ion source. It can also accelerate electrons in a hydrogen plasma, and may efficiently produce vibrationally excited hydrogen molecules that are converted to negative hydrogen ions (H^-) through electron attachment process. Thus, we have been developing a compact H^- source driven by a 14 GHz microwave. In the previous design we have employed a magnetic field structure produced by a pair of Nd-Fe magnets to achieve the field strength as large as 5 kG, which is the field strength corresponding to the ECR condition for 14 GHz. A strong magnetic field in the direction perpendicular to the beam extraction axis works as the magnetic filter, and H^- are successfully extracted from the ion source. However, the 9 cm distance from the ECR plasma to the extraction electrode has been considered too large for the magnetic field strength of 5 kG, and an ion source with the extraction hole located at the region where the magnetic field is parallel to the beam extraction axis has been designed and tested. The new ion source generates an ECR plasma in a 55.5 mm diameter 42.5 mm long alumina cup. Surfaces of the iron made components to form a magnetic field circuit is coated with 50 micrometer thick copper plating to reduce loss of microwave. Two microwave launching schemes have been examined. The microwave is injected with the electric field parallel to the ECR magnetic field in one configuration, and it is injected with the electric field perpendicular to the static magnetic field in another configuration. The ion source performance is found always better when the electric field of the microwave is aligned parallel to the ECR magnetic field, and the reflected power has become nearly zero for this configuration when the plunger position to form a microwave cavity around the plasma is properly tuned. More positive ions are extracted from the present source, but the magnitude of H^- current has been decreased by orders of magnitude from the previous source design. The reason is attributed to insufficient plasma cooling near the extraction hole, and the improvements of the ion source design are being made to solve this problem.

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RF Plasma modelling of the Linac4 H^- ion source

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The Linac4 is a new H^- linear accelerator currently being constructed at CERN in view of the injector complex upgrade of the Large Hadron Collider. A DESY inspired volume production, pulsed RF-source has been developed to provide H^- beam pulses of 20–30 mA and 0.5 ms duration with a repetition rate of 2 Hz [1]. To generate the plasma, an external solenoid operated at 2 MHz is mounted on the plasma chamber, surrounded by a permanent magnet octopole in an offset Halbach configuration. Source operation and optimization strongly depend on the plasma characteristics and therefore a thorough understanding of its underlying physics is an essential requirement.

This study focuses on the simulation of the RF plasma heating mechanism during the discharge initiation, with particular interest on the effect of the external magnetic field on the plasma properties such as wall loss, electron density and Electron Energy Distribution Function (EEDF). We employ an electromagnetic particle-in-cell method with Monte Carlo collisions (PIC-MCC) [2]. The 2D electromagnetic field is solved by the Finite-Difference Time-Domain (FDTD) method in cylindrical coordinates, while the charged particle energy distribution is analyzed by solving the 3D equations of motion. The most important collision processes are taken into account by the Monte Carlo method. In this study we improve the model by including the external magnetic field in order to investigate its effects.

The employment of a multi-cusp magnetic field can effectively limit the wall losses, particularly in the radial direction. Preliminary results however indicate that a reduced heating efficiency results in such a configuration. Specifically, we notice a depletion of the high energy part of the EEDF, which in turn limits the ionization rate. The effect is possibly due to trapping of fast electrons in the magnetic cusp field, preventing a continuous acceleration in the azimuthal direction, but further studies are currently ongoing to clarify the origin of the behavior. A detailed discussion of the method and the results will be presented.

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4

Beam formation and low energy transport

Injection Optics for Fast Mass Switching for Accelerator Mass Spectrometry

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Accelerator Mass Spectrometry (AMS) measures the ratio of extremely small amounts of a radioactive isotope in the presence of $\sim 10^{12}$ times more stable ones. The isotopes are observed sequentially at the exit of the accelerator so any fluctuations on a comparable time scale in ion source output or transmission through the accelerator will reduce the accuracy of such measurements. This compromise in accuracy can be reduced by reducing the switching time between isotopes from several seconds to a few milli-seconds. New AMS systems accomplish fast switching by modifying the beam energy though the 90 injection magnet by pulsing the voltage by several kV on the flight tube in the magnet. That requires that the flight tube be electrically insulated which competes with having the flight tube as large as possible. At the ANU, insulating the magnet flight tube would not only have reduced the acceptance of the injection system, but conflicted with a beam chopper attached to the flight tube, that would also have had to be insulted from ground. This was not practical so the novel alternative of pulsing the voltage on the high voltage ion source deck is being implemented. Beam optics calculations have been performed and beam tests conducted that demonstrated that, in addition to pulsing the voltage on the 150 kV ion source deck, a pulsed Einzel lens in front of the following electrostatic quadrupole triplet lens is required to maintain isotope-independent transmission through the 14UD Pelletron accelerator. Proof of principle tests will be described.

Emittance Characterization of the SNS H^{-} Injector

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The SNS H^{-} injector consists of an RF H^{-} ion source and a compact electrostatic low energy beam transport section (LEBT). For the 20-week long neutron production runs, several ion sources are rotated for service cycles of 2- and 6-weeks, whereas several LEBT assemblies are rotated for the 20-week long runs. As a part of an effort to understand and minimize the source-to-source beam production variation as well as the LEBT-to-LEBT beam transport variation, including the ion source tilt preference, the beam emittance at the LEBT exit is characterized using an Allison scanner on the Ion Source Test-Stand. Due to the asymmetry caused by the electron-dumping field and the consequent complexity of beam alignment, the horizontal emittance can differ significantly from the vertical emittance both in quantity and phase-space distribution pattern. So far no surprisingly large differences in emittance among different sources or LEBT assemblies have been found.

O - 4 03

A Magnetized Einzel-Lens Electron Dump for the Linac4 H$^-$ Ion Source

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Linac4 is a 160 MeV linear accelerator which will inject negative hydrogen ions (H$^-$) into CERN's Proton Synchrotron Booster, a required upgrade to improve the beam brightness in the LHC injector chain. A volume production RF ion source, using the same design as the DESY RF source was implemented, but showed considerable electron dump ablation during operation at 45 keV beam energy. To reduce the electron beam power density in the dump, a magnetized Einzel lens has been designed, where the electron energy is reduced before permanent magnets steer this beam to a tungsten surface, where the electrons are dumped with an energy up to 10 keV. Simulations of the design using IBSimu will be presented, the tunable range of parameters depending on the H$^-$ and electron current extracted, as well as details of the implementation, the choice of pulsed power convertors and the electrode alignment system. In addition, the simulation of extraction of protons from this source will be shown.

Tube Entrance Lens Focus Control

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The entrance of the accelerator tube in a large electrostatic accelerator imposes a strong lens that dominates the beam optics. The magnification of the lens is large because of the low injection energy, the high voltage gradient of the acceleration tube and the long distance to the terminal. The magnification imposes a large beam spot at the terminal limiting the size of the stripper assembly. The beam size is kept within bounds by the irreducible emittance being the product of beam size and beam velocity. The tyranny of the lens is especially irksome when the accelerator is required to operate at a lower terminal voltage than the one corresponding to the nominal gradient at high voltage. One way around the difficulty, used in NEC Pelletron accelerators, is to insert a series of nylon and steel rods that short together units of the acceleration structure at the terminal leaving the ones near the entrance close to the nominal gradient for optimum transmission. This operation takes time and risks the loss of insulating gas. Another alterative used in the 25URC at Oak Ridge National Laboratory is to focus the beam at the tube entrance, substantially diluting the effect of the entrance lens. The beam then diverges and so requires an additional lens part way to the terminal. This solution is only partially effective and still necessitates use of shorting rods. The fact that these elaborate strategies are used is evidence that the alternative of lowering the injection energy as the terminal voltage is lowered imposes enough problems that it is not used in practice. We have modeled a solution that controls the voltage gradient at the tube entrance using an external power supply. This not only maintains the focusing effect of the lens but provides the opportunity to tune the beam by adjusting the entrance lens. A 150 kV power supply outside the pressure vessel feeds a controllable voltage through a high voltage feed through to the fifth electrode of the accelerator tube. Thus 150 kV on this electrode creates the nominal gradient of 30 kV per gap. The beam optics simulations demonstrating the effectiveness of this will be presented along with first use of the lens.

P - 4 05

Isotope Effect on Hydrogen Negative Ion Production within Electron Cyclotron Resonance Driven Plasma

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The compared data on the hydrogen and the deuterium negative ion generation in an electron cyclotron resonance discharge with driving rings are presented. It is demonstrated that the current of negative ions both of hydrogen and deuterium extracted from the ring driven plasma is significantly higher than the current of the positive ions. For hydrogen and deuterium , the negative ion currents were 4.7 mA and 3.1 mA respectively. Such an isotope effect suppresion is the evidence for the negative ions generation through the state of high vibrational excitation of the molecular hydrogen isotopes.

Metal Negative Ion Production by an RF Sputter Self-Extraction Ion Source

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An 80 mm diameter 70 mm long RF sputter type self-extraction negative ion source equipped with a metal sputter target has been designed and being tested to investigate the performance of producing negative ion beams of Al. An RF power at 13.56 MHz is directly supplied to a 38 mm diameter target containing a cylindrical and a ring permanent magnet to form planar magnetron magnetic field geometry. The target is self-biased to a dc potential at about -200 V with respect to the plasma, and negative ions are self-extracted from the target across the sheath to reach the ion beam extraction hole. An acceleration-deceleration electrode system forms a beam of negative ions passing through a 6 mm diameter single extraction aperture opened at the center of the plasma electrode. The ion source has been mounted on the beam diagnostic system composed of a travelling Faraday cup to measure the spatial profile of the extracted beam, and a 30 degree bending crossed electric-magnetic field deflection type mass analyzer to monitor relative current intensities of the negative ion species in the beam. Through a preliminary test of positive ion extraction, sputtering of Al ions out of the Al target has been confirmed with the intensity comparable to that of positive ions of Ar used for maintaining a discharge. When the polarity of ion extraction has been reversed, negative ions of hydrogen, oxygen, hydro oxide and Al are found. As the affinity level of Al is as small as 0.44 eV, the negative ion current of Al has been found very small compared to impurity ions when Cs is not injected into the source. A compact Cs oven attached to the ion source can produce a directional flow of Cs to the target. Currently, the RF power supply configuration shows a power reflection as large as 15%, and the target size together with the magnetic field intensity is being optimized to reduce the power reflection. The performance of the ion source for producing negative Al ions will be examined with Cs injection after optimizing the RF power supply configuration.

Heat Load Estimation in the Duct and Blanket Module Region of the HNB During Various Operating Scenarios of the ITER Machine

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The neutral beam heating and current drive system in ITER consists of 3 beam lines (2 present plus one future upgrade) with each beam line designed to deliver 40 A of accelerated deuterium beams at 1 MeV with a 25% duty cycle. The beam line is coupled to the vacuum vessel port of the tokamak through a series of front end components and a connecting duct. The edge of the beam line and the walls of the vacuum vessel up to the blanket aperture are lined with duct liners to protect them from heat loads from the direct and re-ionised beam interception during the transport of the neutral beam. The direct interception of the beam is due to the inherent divergence of the beam or its halo component. The re-ionised beam consists of ions born due to the interaction of the accelerated neutral beam with the back ground gas all along the beam line, after the neutraliser exit. The motion of these ions is also affected by the electric field of the residual ion dump (RID) and the magnetic field from the tokamak during its various phases of operation.

A systematic study to assess the heat loads during the neutral beam transport on the different front end components, the various regions of the duct and the blanket modules is necessary to ascertain the proper thermo-mechanical design of these components. The beam transmission code ”BTR” has been used for that purpose. Simulations have been carried out of the gas profile along the neutral beam line considering gas flux from the ion source, the neutraliser, the RID (due to the dumped ion beams) and the flow of the gas from the tokamak to the duct. The re ionisation losses have been estimated to be 13.5% for the region between the exit of the neutraliser and the blanket module edge. The magnetic fields for the various operating scenarios of the tokamak like the start of the burn (SOB), end of burn (EOB), X point formation (XPF), XPF + 20 s, EOB + disruption have been simulated for the 15 MA DT scenario. The beamlet divergence has been considered to range between 3 - 7 mrad for the main beam component and 30 mrad for the halo fraction which has been taken as 15% of the main beam. The simulations have been performed for the neutral beam axis vertical inclination of 49 mrad with an additional 10 mrad vertical tilt, which is required for off-axis current drive and avoidance of beam excited toroidal Alvèn eigenmodes in the ITER plasma. The results of these simulations will be presented and discussed.

5

Beam acceleration and neutralization

Physics Design of the HNB Accelerator for ITER

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Initially two neutral beam injectors, each delivering 16.5 MW D^0 or H^0, are foreseen to be installed on the ITER tokamak. A third injector may be added later. In this paper the physics design of the 5-stage 1 MeV, 40 A D^- electrostatic accelerator for the ITER Heating Neutral Beams (HNB) is discussed.

In the original design from 2001 the gaps between all the accelerator grids were different, the smallest being 50 mm. Concerns about the voltage holding forced larger, equal, gaps. To allow sufficient operating space (at least 1 mm clearance between beam and aperture wall on all grids) and still good beamlet optics ($\sim$3 mrad calculated), the gap spacing was chosen as 85 mm.

The beam is extracted and accelerated from 1280 apertures covering a wide area (0.64 x 1.53 m^2). The extractor contains 5.4x6.0 mm^2 SmCo magnets that cause a ±2.8 mrad zigzag pattern on the beams. This is to be compensated for by either ±0.6 mm aperture offset on the downstream side of the extraction grid or by incorporating correction magnets in the grounded grid. Leakage of co-extracted electrons is calculated to be less than 2%.

The produced beamlets have to be aimed through narrow parts in the beamline, meaning that some beamlets must be steered by 5.6 mrad. Also the beamlet-beamlet interaction (up to also 5.6 mrad) must be compensated for. Although conventional aperture offset steering does not work because the electric fields upstream and downstream of the acceleration grids are equal, it is possible to exploit the consequence of the finite thickness of the grids, i.e. the production of opposing polarity lenses at the entrance and exit of each aperture. By machining oblique or bi-axial apertures in all the four acceleration grids, a steering constant of 6.2 mrad/mm can be achieved. This steering is ”solid” in that it does not depend on the beamlet position in the aperture.

The current design of the (horizontal) magnetic filter field in the ion source produces a very uniform field inside the source, but a very small long-range field outside. However, some field is required to deflect stripped electrons out of the beam and prevent their acceleration to high energy. That is most efficiently achieved with a combination of this horizontal long-range field and local permanent magnets incorporated in the acceleration grids that produce a vertical field.

The paper will summarise the current status of the design, the outstanding issues and the avenues considered for dealing with them.

Successive Acceleration of Positive and Negative Ions for Space Propulsion

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In the context of the PEGASES thruster development, the aim of this work is to accelerate ions to high velocities to generate thrust without the need for electron neutralisation. The targeted end product is a high-performance gridded thruster with a plume composed mainly of fast neutral particles. The source is a purely Inductively Coupled Plasma (ICP) source symmetrically driven at 4 MHz. An ion-ion plasma is formed within and downstream of a magnetic barrier when operating the source in SF_6. A set of two electrostatic grids are placed in the ion-ion region. The plasma grid is biased with square voltage waveforms in the kHz range with amplitude V_{accel} while the second downstream grid is grounded. Hence, a dual ion beam is formed by successive acceleration of positive and negative ions and the respective beam energies can be controlled independently.

A Retarding Field Energy Analyzer (RFEA) is placed 5 mm downstream of the grid and used to measure the time resolved energy distribution function of both positively and negatively charged ions. It is clearly seen that positive and negative charges are measured during the positive and negative bias semi-period, respectively. The positive ion energy distribution function is single-peaked with energy slightly higher than eV_{accel} and with a small tail due to charge exchange collisions. The energy distribution of negative charges is double-peaked: one peak corresponds to a negative ion beam with energy lower than eV_{accel} and with amplitude and width equivalent to the positive ion beam peak. A higher and narrower peak at -5 V is most likely due to secondary electrons and/or electron detachment of the negative ions occurring within the analyzer. A new configuration of the RFEA with magnetic filtering is investigated to address the issue of the low energy electron peak.

The effective acceleration potential for negative ions is lower than the one for positive ions. It has been seen that the difference in beam energy between the positive and negative ions increases with increasing bias voltage. The lower negative beam energies are not yet fully understood. However, we believe this can be due to negative ion space charge neutralization or deposition of a thin dielectric layer on the grids.

Benchmark of the SLACCAD Code Against Data from the MANITU Radio Frequency Ion Source at IPP

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In 2007, the IPP Radio Frequeny (RF) driven negative hydrogen ion source has been chosen by the ITER board as the new reference source for the ITER NBI system due to the intrinsic advantages of its maintenance free operation and the progress in the RF source development. The long-pulse stability of this source has been demonstrated at the test facility MANITU which is now operating routinely with parameters close to the ITER requirements.

The PRIMA test facility for the ITER NBI (Neutral Beam Injector), presently under construction at Consorzio RFX in Padua (Italy), will therefore include RF-driven ion sources in the SPIDER experiment, that will operate with ITER-like beam current and a 100 keV beam energy, and in the MITICA experiment, that will be the prototype of the ITER NBI featuring ITER-like beam current and energy (1 MeV).

An experimental validation of the beam codes has been undertaken in order to prove the accuracy of the simulations and the soundness of the SPIDER and MITICA design. To this purpose, as a first step the SLACCAD code have been applied to simulate the beam optics at the MANITU experiment in a joint activity between Consorzio RFX and IPP, with the goal of comparing and benchmarking the code against the experimental data and to choose reasonable operating parameters as inputs for the design of SPIDER and MITICA. A description of these modeling activities and a discussion of the main results obtained so far are here reported. In particular, the effect of beam halo is studied in detail, which represents an important factor for the beam optics.

Neutralization Enhancement by the Beam Driven Plasma in a Gas Neutralizer

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Improving the overall efficiency of neutral beam systems is a key issue for fusion power plants and a main contributor is the neutralization efficiency. Improving this without incurring additional power requirements could represent a major milestone. This paper describes preliminary work aimed at delivering this objective. The formation of plasma generated by a beam of negative ions passing through a conventional gas neutralizer was modelled in [1], where the plasma density generated was of the order $2 \cdot 10^{14}$ m^{-3}, representing an ionization rate of $5 \cdot 10^{-6}$. In this model the plasma was unconfined and the thermal electrons were simply lost at the neutralizer wall and through its open ends. It was later noted [2] that a significant fraction ($\sim$25 %) of the plasma electrons possessed sufficient energy to create further ionisation of the gas themselves but, in an unconfined system, this amounted to a small effect.

By adding a confining multipole magnetic field, as commonly used for ion sources, to the walls of the neutralizer the plasma density is significantly increased as the effective loss area is then determined by the losses through the magnetic cusps. The field must extend over the mouth of the neutralizer to confine the electrons but need not be particularly strong ($\sim 5 \cdot 10^{-3}$ Tm), so beam displacement will be small. The reduction in loss area can be over 99 % and the plasma and stripped electrons then contribute the major part of the plasma creation and lose most of their energy in inelastic collisions. A 0-D iterative model, based on [1] and [3], has been used to self-consistently solve for the neutral gas density, plasma density, electron temperature and loss area (a function of Te) in the confined neutralizer. For confinement fields of 0.5 T with 80 mm separation, plasma density $\sim 6 \cdot 10^{18}$ m^{-3}, representing $\sim$30 % ionization rate are indicated. This results in a neutralization efficiency of $\sim$80 %, close to the theoretical maximum for a plasma neutralizer but delivered with no additional power.

The details of the model will be presented together with considerations for practical deployment.

The authors are indebted to E. Thomson for illuminating discussions.

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Characterization of the Space Charge Compensation of Negative Ion Beams

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The high energy neutral beams to be used in advanced fusion devices are based on negative ions. After the acceleration stage these particles cross a region of weak electric field, where the space charge compensation processes influence the beam optics, and allow a beam transport at reduced divergence. An investigation of this phenomenon is presented, aiming to characterize, in particular, the spatial extension of the neutralized beam region. To this scope a 2D particle-in-cell code was used [1] and modified to include part of the accelerator at beam entrance, and a grounded plate with a hole at the beam exit plane. With these modifications the simulation of the whole drift region is possible, whereas the original code only simulate a part of it, imposing the axis equilibrium at exit plane under the hypothesis of parallel beam. More realistic 2D beam density profiles were also implemented, whose structure was directly extrapolated from ray tracing codes used in accelerator modeling. This enhancement allows to include in the calculation the beam divergence and the reduction in the beam current due to electron stripping, in order to test their effect on the structure of the shielded beam. The influence of a repeller electrode, located at the entrance of the drift area is also described, influencing the field topology of the region as well as the motion of slow particles. All results are discussed for the reference case of a H^- beam.

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6

Beamlines and facilities

O - 6 01

Diagnostics in Indian Test Facility for ITER Diagnostic Neutral Beam (DNB)

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ITER DNB is a negative Hydrogen ion based 100 kV, 60 A , 5 Hz modulated NBI system having 3 s ON/20 s OFF duty cycle. It will inject hydrogen atom beam into the ITER torus to measure Helium ash density using CXRS diagnostics during ITER's D-T phase. DNB is a technological challenge in terms of producing high current beams with minimal divergence to ensure maximum current transport through a narrow beam transmission duct over a path length of 20.7 m. Modeling calculations have been carried out to optimize the design and dispersion of the beam line components. Besides validating these calculations, new concepts related to establishing the functionality of an eight – driver based inductively coupled RF negative ion source, the beam line components specially electrostatic residual ion dump (RID) and beam transport need to be tested to meet the DNB needs. All these are envisaged in a test facility to be set up in ITER-India lab of Institute for Plasma Research (IPR). For safe operation and characterization of such experimental facility requires a judicious choice of various diagnostics comprises of optical, electrical, calorimetric and thermal based diagnostics including spectroscopic, electrical probe, thermocouple and current measurements. The dispersion of these diagnostic techniques and the measurements envisaged in the test facility shall be presented.

Status of PRIMA, the Test Facility for ITER Neutral Beam Injectors

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To experimentally demonstrate the sustainability of the fusion reactions with a Q factor ranging from 5 to 10 in stationary conditions, the ITER project requires additional heating by two neutral beam injectors (HNB).

Each HNB will accelerate to 1 MV a 40 A beam of negative deuterons delivering to the plasma a total power of 33 MW up to one hour. These requirements have never been experimentally met; hence a strong demonstration activity has been endorsed by ITER to optimise the crucial components and systems.

A test facility, PRIMA (Padova Research on ITER Megavolt Accelerator), is presently in the starting phase of construction and procurement at Consorzio RFX (Padova, Italy) in the CNR research area. The facility requires the construction of new buildings (2 ha) and the adaptation of the existing 400 kV power substation.

A full-size negative ion source, SPIDER (Source for the Production of Ions of Deuterium Extracted from Rf plasma), will be operated in the facility to demonstrate the creation and extraction of a D^-/H^- current up to 50/60 A on a wide surface (more than 1 m^2) with uniformity within 10 %. The ITER diagnostic beam injector, to be built by the Indian Domestic Agency, shares some requirements and components with SPIDER and close collaboration exists. All SPIDER plant systems and components are ready for the procurement phase.

The second experimental device is the prototype of the whole ITER injector, MITICA (Megavolt ITer Injector and Concept Advancement), aiming to develop the knowledge and the technologies to guarantee the successful operation of the two injectors to be installed in ITER, including the capability of 1 MV voltage holding at low pressure. The Japan Domestic Agency will contribute to the construction of MITICA. Many MITICA plant systems and components are well developed and close to be ready for procurement.

The experimental effort is supplemented by numerical simulations devoted to the optimisation of the accelerator optics and to the estimation of heat loads and currents on the various surfaces. Laboratories, such as KIT-Karlsruhe, IPP-Garching, CCFE-Culham, CEA-Cadarache and other European research institutions are also cooperating to the success of the PRIMA enterprise.

In the paper the main requirements will be discussed and the design of the main components and systems will be described. Finally the status and planning of PRIMA will be presented.

This work was set up in collaboration and financial support of F4E.

O - 6 03

Advanced Energy Recovery Concepts for Negative Ion Beamlines In Fusion Power Plants

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A key factor in the realization of economically viable steady state fusion power plants employing heating and current drive (H&CD) systems is the wall plug efficiency of these systems. For negative ion based H&CD systems such as those presently envisaged for DEMO the wallplug efficiency is of the order 30 %. The actual requirement for the wallplug efficiency is determined by the current drive efficiency which is itself dependent on the plasma scenario for the tokamak. Various methods have been proposed to increase this wallplug efficiency such as the use of a photo-neutraliser to increase the neutralised fraction of the negative ion beam and increasing the transmission of the beamline by reduction of the beam halo and divergence. An alternative method to improve the efficiency of neutral beam systems is to use energy recovery of the un-neutralised negative ions to reduce the drain current in the main HV power supply.

In this paper the basic concepts of energy recovery for negative ion based systems are reviewed. In previous proposals for such systems the residual negative and positive ions are separated using electrostatic deflection. As a possible alternative, the potential of using a magnetic separation system is investigated. Simulations of the recovery system show how, in the absence of a beam halo, high collection fractions ($\sim$97 %) of the residual negative ion beam can be achieved through the design of the electrode system. Recovery of the residual positive ion beam, in the same way as the negative ion energy is recovered, is normally not considered as there is no gain in efficiency. However, a novel energy recovery concept is proposed for the positive ions which allows their energy to be converted directly into electrical energy. An example is given, for a DEMO like beamline, where for a system with a wallplug efficiency of $\sim$ 30%. This efficiency can be increased to $\sim$ 35% for negative ion recovery and including recovery of the positive ion energy through power conversion increases this efficiency to $\sim$ 39%. This allows a significant increase in the overall efficiency which makes energy recovery a more attractive option for further development.

Preliminary Results from the Small Negative Ion Facility (SNIF) at CCFE

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At Culham Centre for Fusion Energy, a new beam extraction test facility has been built with the purpose of studying and enhancing negative ion beam production. The multipole hydrogen ion source is based on a RF generated plasma using a 5 kW power supply operating at the industrial standard frequency of 13.56 MHz. The cylindrical source has a diameter of 30 cm and a depth of 20 cm, with a flat spiral antenna driving the source through a quartz window. The magnet configuration is arranged to produce a dipole filter field across the ion source close to the plasma grid. The plasma load is matched to the RF generator using a Pi matching network. The accelerator uses a single extraction aperture of 14 mm diameter, with a bias voltage for electron suppression. The accelerator is a triode design with a beam energy of up to 30 kV. The beamline consists of a turbomolecular pumped vacuum tank with an instrumented beam dump and ports for additional diagnostics.

The ITER Neutral Beam source operates with the enhancement of caesium, which, when scaled up to a reactor, will be heavily consumed, and due to its reactivity in air, may create maintenance issues. The small size of SNIF allows for fast turn around of modifications, and alternative materials to caesium can be tested. A full description of the facility and diagnostics is given. Initial results are presented, including measurements and calculations of the plasma load on the RF generator.

Development of Ion Beam Related Research Around 1.7 MV Pelletron in Jyväskylä During Five Years of Operation

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In September 2006 a fully functional 1.7 MV Pelletron tandem accelerator was donated to the University of Jyväskylä by the Technical Research Center of Finland. At that time the accelerator had only one RF ion source and one beamline for Rutherford Backscattering Spectrometry (RBS), for which it had been used for two decades in Espoo, Finland. In JYFL a new laboratory room was built from three storage rooms for it and after the move and comissioning, first RBS measurement were performed in Jyväskylä in Feb 2007. After an extensive development period over past five years, the facility now contains three ion sources and four beamlines. In addition, the Pelletron has also undergone major upgrades during this period.

The two biggest changes inside the accelerator tank has been the change of corona discharge based potential division to resistor based. This change increased the terminal voltage stability and enabled the use of lower beam energies down to 150 keV. In 2012 the original terminal stripper was changed to one which has turbo pump based gas circulation. This stripper change has improved beam transmission due to the larger diameter holes in both ends of the stripper, decreased the pressure in acceleration tubes which reduces the level of beam contamination for heavy elements, and increased the maximum obtainable beam energy.

In the injector side a new injector magnet was installed to replace original Wien filter, and two new ion sources, sputtering and high current H^-, have been installed. In the high energy area different beamlines for RBS, particle induced X-ray emission (PIXE), time-of-flight elastic recoil detection analysis (TOF-ERDA) and high energy ion beam lithography now exist.

In this paper this development will be discussed as well as the experimental results on how an accelerator can survive from 100 litres of cooling water within the SF6 insulating gas.

Thermal Simulations of STRIKE Tiles for the Assessment of the CFC Prototypes and of the Configuration for SPIDER

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The ITER project requires additional heating via injection of neutral beams, provided by two injectors accelerating negative ions. To study and optimise negative ion production, the SPIDER protype is under construction in Padova, whose beam has an energy of 100 keV and a current of 50 A. The instrumented calorimeter STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment) has been developed with the main purpose of characterising the SPIDER negative ion beam in terms of beam uniformity and beam divergence during short operations (several seconds). STRIKE is made of 16 1D Carbon Fibre Composite (CFC) tiles, intercepting the whole beam and observed on the rear side by infrared (IR) cameras. Prototypes of the CFC material were procured and this contribution presents experimental tests and numerical simulations devoted to the characterisation of the CFC properties and to the assessment of the performance of the diagnostic. Tests are described, performed using a CO2 laser to investigate the spatial resolution of the diagnostic on the scale lengths and with the experimental layout expected in SPIDER. Data recorded by an IR camera during the experiments are compared with simulations aiming to reproducing the experimental data with the purpose of validating the thermal parameters of CFC. The design of the supporting structure for the tests is also described.

This work was set up in collaboration and financial support of F4E.

Upgrade of the ITUR Extraction System at ESS-Bilbao

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The first beam measurements on our modified version of the ISIS Penning source show a beam of relatively low current. As a result of this, the actual extraction system was simulated using IBSimu, and it was found that the configuration is far from the optimal case.

We present a simpler post-acceleration extraction system that avoids the use of a long ($\sim 100\,\mathrm{mm}$) Cs trap. Due to space and budget constraints, the new extraction is composed of only one electrostatic einzel lens. The same configuration, as the ISIS source, is maintained up to the puller electrode; the changes come afterwards, where two circular electrodes with rectangular apertures make up the einzel lens. This configuration lacks the bending magnet found at ISIS because the permanent magnets used in this version of the source provide the Penning field. This difference results in a low angle beam extraction that is compensated by tilting the source to angles near 15°.

In addition to the beam dynamics simulations, the mechanical and electrostatic simulations for the extraction system are presented.