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Focus on sources of negatively charged ions

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Abstract

This focus issue presents theoretical investigations, modelling and technical achievements across the large variety of sources of negatively charged ions (NCI). The twenty contributions cover a fraction of the very broad range of applications requiring very different time structure, intensities and beam energies. The world's largest NCI source area is $1 \times 2 \text{ m}^2$ and shall provide 1280 beamlets of $\sim 30 \text{ mA}$ intensity each, while the smallest unit of our selection is only a few mm^2 and requires the highest ionization efficiencies to deliver negative radioisotope-ions far from stability produced via nuclear reactions at rates down to or below few atoms per seconds.

The contribution of negative ion sources to society steadily grows: their impact now ranges over vast and very diverse domains that started last century where negative ion beams allowed doubling the beam energy in tandem accelerators via stripping charge exchange. Today's cyclotrons' H^- beams, stripped during extraction, deliver multi-MeV protons beams (MeV Mega-electron Volt correspond to a kinetic energy of an electron charge quantum ($1.602 \times 10^{-19} \text{ As}$) accelerated by a potential of a million volts) and play a leading role in the production of radioisotopes for pharmaceutical application, spallation neutrons and muons for material sciences.

Surface treatments benefit from negative ion beams, and the injection of negative hydrogen sources into linear accelerators feed the world's most powerful neutron spallation sources and high-energy accelerator neutrino physics experiments. Eventually, looking to the future, the protons required for the detailed analysis of the Higgs sector of the standard model will be originating from an H^- source.

Clean, abundant and sustainable energy for the future is the hope motivating the world's research on fusion [1], ITER, 'path' in Latin, is the flagship of this endeavour and the world's largest tokamak, it is being constructed in France [2]. ITER's neutral beam injector (NBI) needs an ion source capable of providing $> 10^{20}$ negative deuterium ions per seconds (40 A) that once accelerated to 1 MeV energy will sustain and drive its fusion plasma. A fully superconducting tokamak, Japan's Advanced Superconducting Tokamak (JT-60SA) [3], encompasses a 10 MW, 500 kV negative ion beam based neutral injector and shall provide a deep insight to the fusion plasma R&D mandatory for ITER.

This issue focuses on recent developments of sources of negatively charged ion in all aspects of the complex physics, engineering and diagnostics involved namely: plasma heating techniques, simulations and characterization of low temperature plasmas properties. Modelling and benchmarking of the fluxes of plasma species at the plasma sheath. Extraction of negative ions from a low temperature plasma. Generation of negative ions via charge transfer process on alkali coated low work function surfaces.

The plasma 'meniscus' is the plasma-beam boundary, resulting from the equilibrium between the plasma and the extraction electrical field repelling positively charged and extracting negatively charged particles. Obviously, negative ions and electrons share the same charge-sign and are extracted together. The transition from a neutral plasma to space charge-dominated electron and negative ion beams is of utmost importance in the simulation and design of negative ion sources. The distribution of velocities is a key property of an ion beam; understanding and modelling the so-called beam phase space (positions and velocities of each ion and electron in the beam) gives proper input to beam transport engineering, minimization of emittance growth and beam losses. It is highly relevant for engineering to track ion's creation and annihilation coordinates. It must be noted that in H^-/D^- cesiated sources, the low work function surface emits negative ions directly into the extraction

field and therefore volume- and surface-produced ions populate different phase space regions. While negative hydrogen ions are of interest for a wide community, negative deuterium ions are the ultimate goal for fusion applications.

This issue presents theoretical investigations, modelling, measurement techniques and technical achievements across the broad application range of negative ion sources.

Negative ion source beam intensities across 20 orders of magnitude

Over the last 5 decades, mass separator based radioactive ion beam facilities developed chemically selective ion sources [4, 5]. To achieve the mandatory isobaric purity expected in rare and exotic radioisotopes physics experiments; negative ionization of radioactive ions proved a very successful approach. Liu *et al* [6] review the latest achievements of these techniques based on differences in electronegativity and chemical reactivity and applied to provide high purity beams.

Charge exchange injection of negative hydrogen ions from a linear injector is today's most efficient method to fill the synchrotron injection phase space (ensemble of positions and velocities of particles that are likely to be successfully accelerated and not lost during acceleration). At injection energy, the circulating proton beam is slightly deflected and, quasi-undisturbed, passes through a thin stripper foil, H^- ions injected through the same stripper foil, lose two electrons and thus become protons now located precisely within the recirculating beam. It was first reported by Budker *et al* in 1967 [7] and is now widely applied to optimize filling of circular proton accelerators dedicated to spallation neutron sources at Oak Ridge National Laboratory (ORNL-SNS, Oak Ridge Tennessee, USA), the Rutherford Appleton Laboratory (Oxfordshire, UK) or Japan's Proton accelerator Complex (J-PARC, Tokai, Japan) [8–10] or high-energy accelerators at Brookhaven (Upton, New-York, USA) and Fermilab (Chicago Illinois, USA). Charge exchange injection will be implemented to upgrade the accelerator complex of the European Organization for Nuclear Research (CERN, Geneva Switzerland) in order to meet the luminosity required by frontier high-energy physics experiments at CERN's Large Hadron Collider [11–13]. Faircloth reviews the large variety of H^- sources types [14] and presents state-of-the-art research and development on mid-size ion sources (plasma chamber volume of ~ 1 l) specifically designed for accelerators. The production of a negative hydrogen ion via dissociative attachment of a low energy electron to an excited hydrogen molecule is the essence of the so-called 'volume production' [15]. Tarvainen and Peng review volume sources based on radio frequency (RF) and 2.45 GHz electron cyclotron resonance plasma heating; these H^- sources demonstrated maintenance-free and high reliability operation [16]. The kinetics of electrons and neutrals are key aspects of negative hydrogen volume sources—Chung presents detailed analysis and experimental investigation of a 13 MHz RF transformer-coupled plasma driven by a spiral antenna with focus on the local electron energy distribution function and transport of excited hydrogen molecules from their production (driver) to the dissociative attachment and extraction regions [17].

Neutrino [18, 19] and neutron facilities require impressive quantities of high-energy proton pulses—at the ISIS, SNS or J-PARC facilities [9–11], a linear H^- accelerator injects via charge exchange into high duty factor synchrotrons to deliver the required beam intensity and time structure. The emittance of the beam has to match the beam optical properties of the radio frequency quadrupole accelerator. The J-PARC facility encompasses neutrino (Tokai to Kamioka, T2K) and neutron physics experiments; Ueno describes the systematic optimization of the beam emittance of J-PARC's internal RF-antenna (developed by SNS) plasma cesiated surface H^- source [20].

The combination of physics modelling and simulation with experimental methods is the key to improved understanding of NBI's hydrogen and deuterium plasma; Hatayama presents a thorough review of the low temperature plasma modelling [21] and Tsumori presents the most sophisticated measurement techniques to investigate plasma population's properties including those specific to large sources for fusion reactors' NBI heating [22]. As an example, Briefi applied a collisional radiative modelling to analyse high-density low temperature hydrogen plasma; he presents the simulation of inductively coupled plasma (ICP) heating of CERN's Linac4 ion source and its experimental validation via state-of-the-art optical emission spectroscopy measurements of the Balmer lines and Fulcher band [23]. Mochalsky developed the Orsay Negative Ion eXtraction code [24] which simulates the beam formation across the plasma meniscus taking into account the complex 3D geometry of the fields [25].

ITER's program was born in 1985, its agreement signed in 2006 and construction started in 2010. Here, the most powerful heating and current drive system for sustaining fusion plasma is provided by neutral beam injection. The interaction of the NBI influencing the fusion plasma is described by Singh *et al* [26], while Hemsworth describes the scientific and technological challenges of ITER-NBI's large modular RF-ICP H^-/D^- sources [27]. The size of the source and the asymmetry of its magnetic components, set tremendous constraints on the design and simulation. Heinemann *et al* present the extraction from a large ion source experiment

(ELISE); this half-size prototype of ITER's NBI's source is constructed and is being tested [28]. The ELISE test facility first results closely match ITER's requirements and provide the mandatory test facility to optimize the design and benchmark plasma, beam formation and extraction simulations.

Taccogna presents an attempt to model ITER's full-scale ion source via 2.5D particle in cell Monte-Carlo technique [29]. This reveals asymmetries resulting from electron drifts and provides insight into the complexity of the plasma expansion chamber. Fubiani presents a similar approach focusing on meniscus interaction involving high plasma density physics, transport of neutrals and chemistry on low work functions surfaces [30].

Coating the molybdenum plasma electrode with caesium lowers the surface work function and favours production of negative hydrogen and deuterium ions. Cartry investigates alternatives to avoid usage of this very reactive alkali; he reports on innovative approaches aiming at replacing caesium by diamond coating [31].

The ITER H^-/D^- source half-size test unit ELISE is approaching nominal H^-/D^- currents; beam transport and neutralization are the next technical issues to address. An optimum energetic efficiency is mandatory and the very large scale of the device and handling of 1280 beamlets sets a serious challenge. Serianni *et al* present the status of the space charge compensation, charge exchange and beam dynamics simulation and describe the outlook of its experimental validation [32].

The European neutral beam test facility Padova Research on ITER Megavolt Accelerator (PRIMA), aims at demonstrating ITER's full-scale ion source. PRIMA encompasses two test facilities: ITER's full-scale ion source for 100 keV ITER H^- and D^- beams named SPIDER (source for the production of ions of deuterium extracted from a RF plasma) and ITER's nominal 1 MeV NBI beam line MITICA (megavolt ITER injector and concept advancement). It is being designed, engineered and constructed; it will soon enter its commissioning phase. Toigo *et al* present the physics of neutralization and beam transport [33].

The future of fusion power requires a major step to establish the relevant economical and energetic efficiencies and feasibility. The conceptual design of the NBI of the DEMONstration fusion power plant (DEMO) developed within the heating and current drive work package of EUROfusion [34] is introduced [35]. An example on the activities on smaller test facilities is given by McAdams *et al* (Culham Centre for Fusion Energy), in which an RF-driven volume source is used to systematically investigate the limits of neutralization and energy recovery. This is mandatory for very energy-efficient NBI that will be required for fusion reactors beyond ITER [36]. Today's state-of-the-art based on neutralization in a low pressure hydrogen gas may not be sufficient for the post ITER era; Simonin describes the photo-neutralization technique, which has the potential to be more effective at the scale of DEMO [37]. The first private R&D effort on fusion is Tri Alpha Energy [38], instead of the conventional scheme, proton-boron fusion is investigated and dedicated negative ion sources are currently being developed at Novosibirsk [39].

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