NEGATIVE ION BEAM SOURCE PHYSICS AS A COMPLEX SYSTEM: IDENTIFICATION OF MAIN PROCESSES AND KEY INTERDEPENDENCE


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Abstract

Complex network theory is applied to the physical processes affecting generation, extraction and acceleration of negative ions using as a case study the negative ion source NIO1 which at present operates without caesium. The subset of driver processes which in principle allow the system to be controlled have been identified and discussed. The caesium coverage and the high voltage holding processes known to be key processes in a NBI system have been also presented discussing the parameters entering in their potential controllability.

1. INTRODUCTION

A key component of ITER is the Neutral Beam Injector (NBI) heating system, which at present relay on two injectors to deliver 33MW of power to the plasma. The achievement of the NBI nominal parameters (40 A negative $\text{H}^{-}/\text{D}^{-}$ ion beam accelerated to 1 MeV and then neutralized) and its reliable operation are challenging tasks, which are the objective of an extensive international research and development activity. Despite significant progress in getting closer to the target parameters, reliable operation of NBI remains an open issue, as it is the result of several processes, mutually interacting often in a non-linear way. Given these characteristics, the NBI system can be regarded as an example of a complex network, whose controllability can be investigated and tackled by novel tools offered by modern physics.

2. CONTROLLABILITY OF A SIMPLE NETWORK: THE CASE OF NIO1

In this contribution the network of relevant processes affecting generation, extraction and acceleration of negative ions is reviewed in a simple case offered by the negative ion source NIO1 which is in operation at Consorzio RFX [Cavenago2009] where the processes behind the generation and extraction of negative ions have been subject of a thorough investigation. At present NIO1 operates without caesium, which is well known to be able to enhance the production of hydrogen and deuterium negative ions $\text{H}^{-}/\text{D}^{-}$ by surface processes. In NIO1, the processes requiring to be controlled are: the divergence of the beam, the beam aiming error, the current density ratio, the non-uniformity of the beam, the temperature of mechanical components and the current output. The system has been studied by applying the controllability theory of complex systems [Liu2011] which allows the sub-set of key processes driving the whole NBI to be identified. These driving processes are therefore discussed with reference to their level of applicability to the control. Being aware of the importance of the extension of the controllability analysis to sources with caesium and high voltage acceleration, the role of surfaces in negative ion generation and the processes behind the high voltage holding has been addressed, identifying those parameters influencing their state and which could be added in coming analysis.

With reference to the NIO1 experiment, in a previous work a graph-theoretical model was generated based on the estimate of the main physical processes involved in negative beam generation without caesium [Antoni2018]. A total of 40 processes (called nodes in complex system theory) were identified. Hopcroft-Karp algorithm was used to find multiple sets of driving processes (driver nodes) for that network and the number of driver nodes was found to be four [Antoni2018], so that as a result the control over the entire system was guaranteed by the control of only four of the forty total processes. The Hopcroft-Karp algorithm also provides the structure through which control signals spread across from driver nodes to output nodes. This structure is referred as maximum matching.
In previous works, several maximum matchings of the NIO1 graph were enumerated with the key idea that if a node recurs in several different maximum matchings this may suggest some intrinsic importance of the associated physical phenomenon. Since the current techniques to enumerate all the maximum matchings of a network are expensive [Uno1997], enumeration was performed by taking advantage of a side effect [Antoni2018] of the preferential matching algorithm [Zhang2014]; the algorithm allows to express a preference on what nodes should be driver in the maximum matching by inputting a “matching queue” along with the network. However, the algorithm can be used iteratively to find different maximum matchings if the matching queue is changed in each iteration. Here the results obtained with the modified preferential matching algorithm are verified in two ways: by studying NIO1 network with a novel implementation of the enumeration algorithm [Uno1997] and by applying the “all possible input nodes” algorithm [Zhang2017]. Both of them cannot handle self-loops, but it can be shown that removing self-loops from the network does not change its controllability [Zhao2015]. The enumeration algorithm [Uno1997] is so far the only one capable of enumerating all the Minimum Driver Node Sets (MDNSs) along with the corresponding maximum matching. Conversely, the “all possible input nodes” algorithm is much faster and can provide alternative nodes for each node in a MSDN, while it does not provide the corresponding maximum matchings [Zhang2017]. Remarkably, all of the three techniques show a good accordance in predicting the distribution of driver nodes among the network. This confirm the correctness of the analysis of the network.

Among the many possible maximum matchings of NIO1 network, the most common by far is the driver node set involving the following processes: plasma drifts in ion source, density of $H_0$ between plasma grid and extraction grid, deflection of $H^{-}$ ions between plasma grid and extraction grid, and density of $H_2$ inside the vessel. Thus, by controlling these processes, control over the whole system should be achieved. However, the first three processes are especially difficult to control from the outside, and focus should be on different nodes. The “all possible input nodes” algorithm provides, along with a list of the synonymous all possible input nodes, possible substitutions for them all whenever this is possible. Remarkably, each substitution is not independent: that is to say, substituting one of the driver nodes with one of possible alternatives also changes the possible alternatives for the rest of the set. For example, when substituting the plasma drifts with the source pressure as suggested by the algorithm, the same process cannot be used as a substitute anymore. For the same reason deflection of $H^{-}$ ions between plasma grid and extraction grid is often required to be part of the control mix.

Using the “all possible input nodes” algorithm and its alternatives, the most desirable driver node set was build. It involves mostly nodes that are easy to control plus the essential deflection of $H^{-}$ ions between plasma grid and extraction grid. As anticipated, plasma drifts were substituted with the pressure inside the ion source and the density of $H_0$ between plasma grid and extraction grid with the gas temperature in extraction region. By using the enumeration algorithm, the maximum matching corresponding to these driver nodes was found. So for example, one instance of the MSDN is composed by: source pressure, density of atomic $H_2$ in the gap between Plasma Grid (PG) and Extraction Grid (EG), deflection of $H^{-}$ in the PG-EG gap, density of $H_2$ in the vessel. Fig. 1 shows this control structure. In the following each of these control parameters will be discussed.

3. DRIVER NODES

Results prompt us to explore more deeply the nodes suggested as important by the various network analyses as discussed below. The complex network analysis showed [Antoni2018] and the present one confirms that deflection of $H^{-}$ in the PG-EG gap is always selected as one of the driver nodes and the asymmetry of the meniscus, the region where negative ions are collected and start accelerating, was inferred to cause such deflection (see Fig.2). Simulations of negative ion extraction [Fubiani2017 and F. Taccognia 2017] have shown the existence of a drift motion of the plasma inside the magnetized plasma source. Using PIC codes, they showed that in a negative ion source, due to the effect of magnetic filter field, a plasma drift is established, with the consequent effect that the negative ion density at meniscus exhibits a top-bottom non-uniformity. In particular the presence of a non-uniform ion flow near the meniscus region was experimentally demonstrated [Tsumori2017]; the ensuing asymmetry due to the beamlet deflection is found consistent with measured heat load patterns [Veltri2017, Chitarin2018] and with numerical simulations of plasma sources [Fubiani2017]. Recent work based on the particle tracing OPERA code was used to describe single beamlet deflection, upon assuming non-uniformity of the meniscus in the presence of magnetic field drifts, and was compared with experimental results; in some cases a perfect compensation of the ion deflection was achieved [Chitarin2018]. The results therefore pave the way to possible control of such non-uniformity by actively controlling the configuration of the magnetic field.

Source pressure is known to affect the efficiency of the magnetic filter: the collisions of electrons with the gas determine the colder bulk and the hotter tail of the electron energy distribution therefore influencing the efficiency of the magnetic filter. In this case, the control of the parameter is relatively simple.

The density of atomic $H_0$ in the gap between Plasma Grid (PG) and Extraction Grid (EG) is related to the molecule dissociation degree which in turn affects the mass flow out of the ion source and inside the accelerator. Indeed as the dissociated atoms are faster than the molecules, the pressure inside the source tends to decrease with increasing dissociation degree with a beneficial effect on the stripping losses. In principle it is possible to measure such a parameter and to control it by gas injection and pumping.

The last driver node of the network is related to the molecular hydrogen pressure in the vessel. In the peculiar case of negative ion beams for fusion, the beam transport cannot be ensured by magnetic devices, so it must rely on background gas to produce space-charge compensation: the high-energy beam particles ionize the background gas, generating electrons and positive ions, which are affected by the potential well of the negative ion beam. The overall potential approaches zero and its precise value depends on the balance between generation and diffusion of the particles [Serianni 2017]. In these conditions of compensation of the beam space charge, the ion beam can propagate in the absence of the electric fields that would otherwise cause repulsion between beam like particles and consequently growth of beam divergence. The properties of the resulting ionized gas (beam plasma) are therefore important for the propagation of the beam over long distances. Space charge compensation evolution was simulated [Sartori 2017a] and the results have shown that in about 3 μs the beam manages to propagate straight. The NIO1 facility at Consorzio RFX is operated in steady state, meaning that the compensation time is negligible with respect to the length of the beam pulse; the ion beam is always transported through a background plasma. To characterize the background plasma, results obtained by a Retarding Field Energy Analyzer in NIO1 [Sartori 2017b] have been shown particularly helpful as they provided non-perturbative measurements of the energy distribution of the compensating species, diffusing away from the beam plasma; hence, beam potential can be inferred and compared with numerical simulations. Fig. 3 shows the relative variation of the plasma density in NIO1 as well as the dependence of the beam plasma parameters as a function of the distance from the beam; it has been found that the density increases with the gas pressure so that the higher the pressure the better the compensation charge effect.

The parameter density of molecular hydrogen in the vessel affects also the stripping losses in the accelerator region so it is a balance between the beneficial effect on the optics of the beam and the stripping losses. Such parameter can be controlled by an effective differential pumping in the different regions of the NBI system.

4. CAESIUM COVERAGE

It is known that negative ion production is enhanced by evaporating caesium so to cover the surfaces exposed to the plasma so that the caesium is redistributed by plasma diffusion and is greatly affected by the plasma-wall interactions. The temperature of the grids has been found to play a key role in determining the performance of the system and a recent investigation for Molybdenum surfaces has confirmed the role of surface temperature in optimal Cs coverage with closely-packed structure [Damone 2015]. Due to the larger atomic radius of Cs with respect to Mo, the highest Cs coverage is characterized by Cs atoms occasionally closer than the perfectly ordered film, while many appropriate Cs sites on Mo are left empty, resulting in lower global coverage. This was demonstrated by molecular dynamics simulations of random deposition of Cs over Mo, with scaled Lennard-Jones potentials, where equilibrium distance of Cs-Cs and Mo-Mo interactions is equal to the respective molecular diameter, and experimental atomization enthalpies of pure Cs and Mo are matched based on their BCC crystal lattice. It was found that an imperfect film obtained by random deposition not only has a suboptimal shape, but also grows irregularly when a second layer is deposited, all these characteristics being noxious to negative ion production. Because of the small barrier separating the Cs equilibrium sites on Mo, a relatively fast surface diffusion of Cs atoms is expected by raising the substrate temperature. Temperature can remediate an initially imperfect film, when Cs atoms move to the lowest energy state corresponding to an ordered film. An exceedingly high temperature, however, will again disorder the film, allowing Cs atoms to migrate occasionally to higher energy sites and ultimately evaporating the film, leading to a negative effect. Those results were obtained in the absence of hydrogen or deuterium co-absorption and impurities.

A more recent investigation has revised the main processes that occur at the wall, based on the first experimental results obtained in the caesium test stand [Sartori 2018a]: thermal desorption (evaporation), physical desorption (sputtering), backscattering and adsorption, with the latter being most significant. These processes occur in
response not only to the wall temperature but also to the influx of particles to the wall, and generate atoms/ions outwards towards the plasma bulk, which must first cross the collisional plasma sheath and pre-sheath. It was found that the behaviour at the walls and of the grids is quite different and determined by different parameters, the difference being even bigger for H and D. At the plasma grid surfaces, the resulting desorption fluxes are shown in figure 4(a) for a deuterium plasma discharge as a function of caesium coverage, which is the parameter regulating the formation of negative ions. Oxygen ions are shown as a possible impurity in the plasma, but for the sputtering yield to be comparable with thermal desorption at 150°C, the oxygen ion density would need to be very high. The contribution from Cs self-sputtering is also minor. The dominant effect is thermal desorption, due to the high surface temperature (in SPIDER ~150°C) and sputtering by deuterium ions. The contribution of the latter could be up to ten times higher, if surface roughness is considered (effect of non-normal incidence). The desorption yield for Cs compounds is shown for comparison, indicating that at 150°C such oxides cannot be formed. The incoming flux corresponding to an experimental scenario in IPP RF sources [Sartori 2018b] is indicated by the arrow for comparison.

Fig. 4(b) shows the effect of thermal desorption and sputtering due to plasma at the lateral walls of the ion source and the back plate, as a function of the wall temperature. The SPIDER cooling system is such that the water temperature can be controlled in the range 35-50°C, and the average wall temperature is indicated in the figure. It is clearly shown that the thermal desorption of Cs compounds is not as effective as plasma sputtering, apart from the case of the driver, where higher wall temperatures are expected. The use of temperature-programmed-desorption technique has therefore been proposed to deduce the adsorption energies of Cs compounds growing on the relatively cold surfaces of the ion sources.

The effect of oxygen contamination has been recently addressed [Sartori 2018b], showing that, beside thermal desorption, also sputtering yield is important to determine the quality of cesiated films and optimal coverage. This turns into a whole set of processes to be included in the complex network. In the case of deuterium the effect of sputtering is even more important. In terms of controllability, present results confirm that grid and surface temperatures can be controlling parameters, provided the impurity content is kept below some critical value. This emphasizes the role played by differential temperature control on grids and walls, aimed at controlling build-up and purity of the coverage and to maintain the optimum coverage during the pulses, being aware that the behaviour for hydrogen and deuterium is different.

5. HIGH VOLTAGE HOLDING

Impurities play an important role also in another key process: the high voltage holding of the system which is of particular importance when operating the accelerator at a voltage close to 1 MV as that required for ITER and a reactor. Indeed it has long been known that, even in vacuum, a small DC current between electrodes is generated above a certain electric field value, due to tunnelling through an ideal metallic surface. However the analytical solution leads to inconsistency with surface roughness and sometimes with emitting surface area. To overcome the inconsistency, a novel model has been proposed [Spada2018], based upon the hypothesis that the electrode surface is not an ideal metal but instead it is covered by an oxide dielectric layer.

The model, while resulting in more realistic surface roughness and emitting areas, has been proved quite effective to explain Fowler-Nordheim (FN) emission [Fowler 1928], with superimposed random bursts during the conditioning processes, eventually ending in a breakdown. According to the Breakdown Initiated by Rupture of Dielectric layer or BIRD model, the process leading to the current burst is found to be associated to the electron depletion of the cathode layer, due to FN-like emission. Under certain conditions, the electric field inside the layer exceeds its dielectric strength, producing a micro-breakdown and a burst of current. The evaluation of the FN-like current has been set and solved imposing quantum indetermination relations to a solution based on classical theory. The burst can therefore end up into a full breakdown, provided the voltage is high enough to start avalanche process at the anode.

The emitted current is then a consequence of the extraction of polarization electrons from a dielectric layer at a sufficiently high electric field value and could lead to the rupture of the dielectric layer itself and to a disruptive breakdown. The process is therefore different from that described by the Fowler and Nordheim theory, which applies only to ideal metal surfaces. However, even in this case the problem could be adequately framed in the context of Quantum Mechanics, the main difference between ideal metal and ideal dielectric surfaces being due to the different mobility of electrons within the surface boundary. Inside metals, electrons can be considered to be freely moving, while in the dielectric case they are strongly bounded in the dielectric polarisation structure. Thus
a functional solution similar to that of an ideal metallic surface (i.e. the classical FN emission) is found, but with different constants. As a conclusion, the status of the surfaces and the related electron emission are found the parameters to be measured in order to contribute to the controllability of the system, during conditioning and operation. In terms of controllability accurate and timely measurements of burst amplitude and frequency can in principle anticipate the occurrence of breakdowns, therefore helping controlling the voltage within safe limits.

6. CONCLUSIONS

The controllability of a network of processes, which enter in the generation, extraction and acceleration of negative ion beams has been analysed. A simple system without caesium as in the ion source NIO1 has been found controllable and four drive nodes have been identified and discussed. As a result, by properly controlling the pressure of the source, the gas introduction and vacuum pumping and by a system of actively controlled magnetic fields, the system looks in principle controllable. With reference to the NBI system foreseen for ITER the caesium coverage of the surfaces and the High Voltage holding have also been addressed as key processes entering in an extended network. For both of them, it has been found crucial to control the contamination of the surfaces by impurities (in particular by oxygen), so that differential control of the temperature of the walls and of the grids appears beneficial. Future work will be devoted to verifying the effective controllability a real case such as that offered by the NIO1 experiment, addressing the modifications of the output parameters as a function of the four driver nodes/processes identified and to carry on the breakdown of the processes behind the caesium coverage and high voltage holding to contribute to extend the network of processes to the full NBI system.

REFERENCES

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FIG. 1. NIO1 and one of its control structure. Driver processes (or nodes) are red. Each path spreading signal through the network is in a different colour. The grid region (where most of the processes concentrate) is highlighted.

FIG. 2. Scheme of the effect of the meniscus non uniformity on the beam deflection
FIG. 3. Example of measured characteristics of the RFA as a function of the distance from the beam.

FIG. 4. (on the left hand side) Calculated Cs desorption fluxes as a function of fractional coverage at the plasma grid surface, including thermal desorption and physical sputtering; (on the right hand side) calculated physical sputtering by deuterium plasma and thermal desorption in the case of the lateral Wall LW, ion source back plate BKP, and driver plate.