Emission Properties of Inductively Driven Negative Ion Source for NBI

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Abstract. H^- beam with current ~1A and energy up to 90 kV was routinely produced by the negative ion source, developed at Budker Institute of Nuclear Physics for N-NBI use. The essential source features are: the surface-plasma negative ion production on the plasma grid surface, the active temperature control of the ion-optical system electrodes, the convex magnetic field in the ion optics for the high-voltage holding enhancement, and the directed cesium deposition to the plasma grid electrode. The emission properties of the source have been studied for two RF driver configurations: with and without Faraday screen. Negative ion beam with current of 1.1 A, energy 93 keV and duration 1.6 s was produced in the cases of driver without Faraday screen. Beams with current of 0.6 A, energy 74 keV were obtained in pulses with duration of 25 s for driver with Faraday screen. Long-term stability of the beam current during 25 s pulse confirms the dynamic stability of cesium coverage on emission area of plasma grid electrode.

INTRODUCTION

The powerful neutral beam injector for thermonuclear fusion applications has been developed at Budker Institute of Nuclear Physics [1]. The injector scheme consists of the negative ion (NI) source, separated from 1 MeV accelerator with a low energy beam transport line. Multiaperture RF driven surface-plasma negative ion source is used to produce H^- beam with current above 1 A and energy of 90 kV. The experimental results of emission properties study for the ion source, operated in the hydrogen-cesium mode, will follow.

SOURCE DESIGN AND MEASUREMENTS SCHEME

A principal scheme of the ion source is shown in Fig.1. The large-area inductively driven radio frequency (RF) surface-plasma NI source was previously described in detail in [2]. The RF diver (4 MHz, 40 kW) is equipped with removable Faraday screen (FS), which protects ceramic insulator of the driver form produced plasma and heat fluxes. The screen was made of 0.5 mm thick molybdenum and consists of 10 mm bands with 3 mm slots for eddy currents prevention. A three electrode ion optical system (IOS) consists of plasma and extraction grids (PG and EG) with 21 circular apertures, and acceleration grid (AG) with slit apertures 16x108 mm. Grids have internal channels for heating and cooling by circulating of thermal fluid. The thermo-stabilization system sustains PG and EG hot during the source operation to optimize cesium coverage on PG emission surface and prevent accumulation of cesium. The source uses system of direct cesium deposition to the plasma grid periphery. Transverse magnetic field in the extraction gap deflects co-extracted electrons for interception by EG. The convex shape of magnetic field lines in the extraction and acceleration gaps prevents formation of electron traps.

The source grids were fed by three power supplies. A positive bias, applied to PG relative to plasma driver and expansion chamber U_{PG} = 8÷40 V, decreases the electron flux extracted together with H^- ions. Extraction voltage, supplied to EG, varies in the range U_{ex} = 7÷12 kV, and acceleration voltage U_{ac} was up to 80 keV. The currents of plasma, extraction and acceleration grids (I_{PG}, I_{ex}, and I_{ac} respectively) were directly measured in the power supply circuits. Emission properties of ion source were characterized by the IOS electrode currents and by beam current to the distant Faraday cup (FC). The total current to EG was determined by the difference $I_{EG} = I_{ex} - I_{ac}$. In the case of optimal IOS voltages, providing the highest NI transmission, the current I_{EG} is mainly composed of the co-extracted electrons, intercepted by EG plus current of back streaming positive ions and of the secondary electrons appeared at the acceleration gap side of EG.

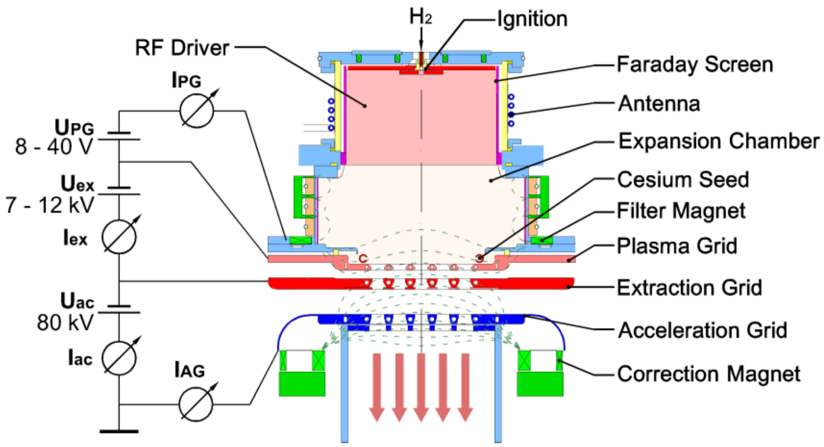

FIGURE 1. The ion source scheme.

The NI current, outgoing from the source $I_b = I_{ac} - I_{AG}$ was determined as a difference of the directly measured currents I_{ac} and I_{AG}. This current consists mainly of the NI, while all electrons, entered and produced in the acceleration gap, are deflected by the transverse magnetic field to AG and its support. The differential current $I_e = I_{ex} - I_b = I_{EG} + I_{AG}$ is equal to the total current, intercepted on EG and AG. At optimal IOS voltages, when the NI interception is small, this I_e current is composed of the electrons, co-extracted with NI form the emission apertures, and electrons, produced in the IOS gaps due to gas ionization and NI stripping. Within the accuracy of small stripping current, the value of I_e can be used as an upper estimation of the co-extracted electron current. A current of transported negative ion beam I_{FC} was measured by ∅170 mm Faraday cup at the distance of 1.6 m from the source exit.

EMISSION CHARACTERISTICS

The traces of emission currents and FC current versus acceleration voltage U_{ac} are presented in Fig. 2. Data was obtained without FS in RF driver at high introduced to the plasma RF power $P_{RF} \approx 36$ kW. The traces were recorded during the single pulse, when U_{ac} rises after voltages on EG $U_{ex} = 12$ kV and on PG $U_{PG} = 9.5$ V has been set. The current density profile of transported negative ion beam at the distance of 1.6 m from the source exit was recorded by moving FC. The total H^- beam current was calculated by integration over beam profile [3]. The plotted trace is I_{FC} multiplied by factor of 2.4, which corresponds to the ratio of integrated beam current to the current registered by ∅170 mm FC at the beam center.

At zero acceleration voltage electrons, passed from extraction into acceleration gap, are deflected by magnetic field and returned to EG. Applied extraction voltage of 12 kV is optimal for NI beam formation in extraction gap and interception of NI by EG is small. The current on EG is produced by co-extracted electrons, and equals to $I_{EG} = 1.05$ A. Negative ions passed into the acceleration gap are partly intercepted by AG and partly pass though slit apertures and produce NI beam with current $I_b = 0.7$ A. In these conditions the current $I_{AG} = 0.4$ A mostly consists of intercepted NI and includes small fraction of electrons, produced as result of stripping and ionization in the vicinity of AG and its support. The total current of extracted negative ions can be estimated as $I_{AG} + I_b = 1.1$ A, and the ratio of extracted NI to co-extracted electron currents is almost 1:1. Due to big divergence of produced NI beam, current registered by FC is negligibly small.

With increase of U_{ac} accelerated electrode current I_{AG} rises due to increased transport of secondary electrons and due to backstreaming positive ions, produced in the acceleration gap and in the beam transport area, and reaches the maximum of ~0.65 A at $U_{ac} \sim 20$ kV. Further increase of acceleration voltage improves focusing and decreases NI interception by AG. I_{AG} decreases and becomes constant at $U_{ac} > 50$ kV. The saturated value of 0.45 A is produced in a balance between stripping electron current, which decreases at higher U_{ac}, and by the current of secondary and co-extracted electrons, which increases with U_{ac} rise.

At high acceleration voltage due to focusing and smaller stripping of NI the current at the source exit rises to $I_b = 1.2$ A. The 0.1 A excess compared to the case of zero acceleration voltage could be explained by decrease of NI stripping it the acceleration gap. Average stripping cross-section is by 40% smaller at full acceleration voltage, and total stripping losses at full voltage can be estimated as 0.15 A. Formed beam of NI was registered by FC, and current, calculated from beam profile, is about 1.1 A. The calculated value is in the reasonable agreement with estimated 10% NI stripping losses during 1.6 m transport to the FC.

Recorded dependencies of I_b and intercepted currents are in qualitative agreement with numerical calculations, made by PBGUNS code for the single aperture cell. Calculation results are plotted in Fig.2 with filled symbols and connected with dashed lines. In calculations NI current density at emission aperture was set equal to current density of 1.2 A beam. The resulted curves were scaled, that measured and calculated transmitted currents (green triangles) coincide at 80 kV. The NI stripping inside the IOS was not taken into account. For quantitative agreement with experiment, NI stripping and other factors should be considered. The calculations give the estimation of intercepted by AG fraction of NI current (blue dots), which decreases from initial 0.4 A to zero at $U_{ac} > 50$ kV. Similar, but more gradual drop of $I_{EG} + I_{AG}$ and corresponding rise of I_b were recorded in the experiment.

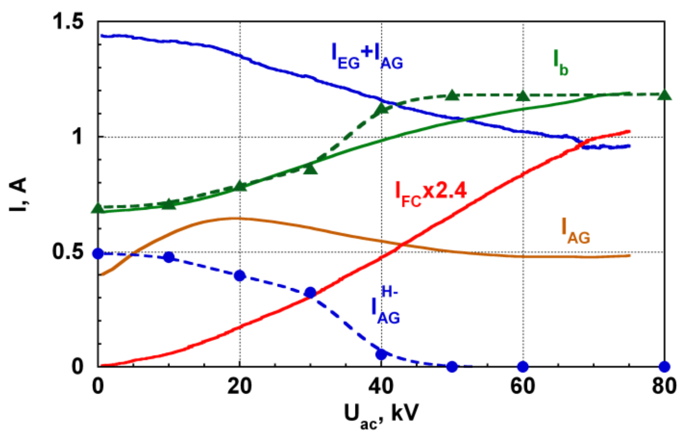

FIGURE 2. Dependencies of ion source currents vs acceleration voltage U_{ac}. Dashed lines – dependencies, calculated by PBGUNS code. Parameters of operation: driver without FS; $P_{RF} = 36$ kW; $P_{H2} = 0.4$ Pa, $U_{ex} = 12$ kV; $U_{PG} = 9.7$ V.

Faraday screen reduces RF field and decreases the contributed in the plasma power P_{RF}. The contributed power rises with hydrogen filling pressure P_{H2}, but resulted NI current I_b is reduced by enhanced stripping. The comparison of drivers with and without FS is shown in Table 1. In both cases operational filling pressure P_{H2}, extraction voltage U_{ex}, and PG voltage U_{PG} were optimized for maximal NI beam production. Driver without FS produces 36 kW power at 20% smaller hydrogen feed. Generated NI current was $I_b = 1.2$ A. Higher emission current density in the case without FS requires bigger extraction voltage $U_{ex} = 12.3$ kV against 9.5 kV. As it was found earlier [4], the PG voltage U_{PG}, required for co-extracted electron flux suppression, is ~10 V higher for driver with FS due to change of plasma potential. For the case with FS obtained at optimal condition value of the beam current 0.8 A is reduced directly proportional to contributed power decrease to 23 kW.

TABLE 1. The source parameters, obtained for operation with and without FS.

Case	P_{RF}	P_{H2}	I_b	I_{ex}	U_{ex}	U_{total}	U_{PG}
No Faraday Screen	36 kW	0.4 Pa	1.2 A	2.2 A	12.3 kV	85.2 kV	9.6 V
With Faraday Screen	23 kW	0.5 Pa	0.8 A	1.8 A	9.5 kV	85.4 kV	21 V

Oscillograms of emission currents for the pulse with 25 s duration are shown in Fig. 3. To prevent overheating of driver's ceramic insulator in long pulse, the 0.5 mm FS was used and power of RF discharge was limited to 17 kW. As one can see, the H^- beam current has a value of $I_b = 0.55 \div 0.6$ A during the pulse. Extracted current I_{ex} is $10 \div 20$% higher than accelerated current I_{ac} and two times higher than the beam current. Total current intercepted by EG and AG $I_{AG} + I_{EG}$, which gives the top estimation of co-extracted electron current, varies in the range of

0.5 ÷ 0.65 A, and most of the time does not exceed NI current. $I_{AG} + I_{EG}$ and I_{ex} increase by ~20% at the end of the 25 s pulse, while NI current remains constant. The stability of NI current indicates that ion temperature and density of the plasma remains constant, while cesium coverage on emission surface is dynamically sustained during pulse. The boost of I_{ex} is produced by additional co-extracted electron current, which could be caused by plasma potential rise due to by the cesium coverage depletion in areas around the emission zone of PG.

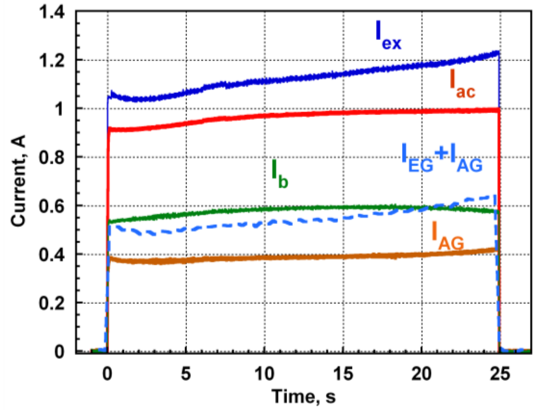

FIGURE 3. Oscillograms of ions source currents during 25s pulse. Parameters of operation: Driver with FS; P_{RF} = 17 kW; P_{H2} ≈ 0.35 Pa, U_{ex} = 7kV, U_{ac} = 75кВ.

Efficient NI beam production depends on conditions of cesium coverage on emission surface of PG. In the previous experiments [5] the formation of cesium coverage and its recovery by RF discharge were described. It was found, that the PG heating from 90°C to 250°C gradually increases the NI yield by 15% and decreases the co-extracted electron current. Heating of plasma grid stimulates cesium diffusion toward the emission zone, optimizes coverage homogeneity, and eventually enhances the H- surface production. During the cooling phase H- current decreases to its initial values. The recorded increase of H- production was reproduced during subsequent heating-cooling cycles.

CONCLUSION

The emission properties of RF driven negative ion source has been studied. Negative ion beam with current of 1.1 A, energy 93 keV and duration 1.6 s was produced in the cases of driver without Faraday screen at RF power of 36 kW. NI beams with current of 0.6 A, and energy 74 keV were obtained in pulses with duration of 25 s for driver with FS at RF power 17 kW. Long-term stability of the beam current confirms the dynamic stability of cesium coverage on emission area of PG electrode. The NI current, measured directly by distant Faraday Cup, corresponds considering stripping to the differential current I_b, determined by the electrical currents, measured in the power supplies circuits. The reproducible 15% increase of H- current was recorded in subsequent heating cycles of plasma grid in the 90°C ÷ 250°C range.

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