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Use of the focusing multi-slit ion optical system at RUssian Diagnostic Injector (RUDI)[a)]

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The upgrade of the diagnostic neutral beam injector RUDI in 2010 was performed to increase the beam density at the focal plane in accordance with the requirements of charge-exchange recombination spectroscopy diagnostics. A new focusing ion-optical system (IOS) with slit beamlets and an enlarged aperture was optimized for 50% higher nominal beam current and reduced angular divergence with respect to the previous multi-aperture IOS version. The upgraded injector provides the beam current up to 3 A, the measured beam divergence in the direction along the slits is 0.35°. Additionally, the plasma generator was modified to extend the beam pulse to 8 s. © *2012 American Institute of Physics*. [doi:10.1063/1.3669794]

I. INTRODUCTION

The neutral beam injector Russian Diagnostic Injector (RUDI) was developed in 1998 at the Budker Institute of Nuclear Physics (Novosibirsk, Russia) for a charge-exchange recombination spectroscopy (CXRS) diagnostic at the tokamak TEXTOR (Juelich, Germany).[1]

To form an ion beam, RUDI utilizes an ion-optical system which consists of four electrodes with a spherical shape of the curvature radius of 4 m (distance to the TEXTOR plasma core) to provide geometrical focusing of the beam (Fig. 1). In order to improve the diagnostic CXRS signal intensity, several upgrades of the ion source were done during the period 2000–2010. The last upgrade included the design of the new ion optics with parallel slit beamlets.[2]

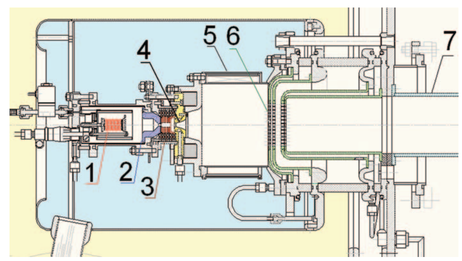

FIG. 1. (Color online) RUDI ion source overview: (1) filament heater, (2) cathode insert, (3) washers of arc discharge channel, (4) anode, (5) plasma box (expander), (6)accelerating grid system, and (7) neutralizer tube.

II. MULTI-SLIT GRID SYSTEM DEVELOPMENT

In 2005–2007, the numerical simulations of beam formation by a single slit and the experimental measurements of the beam divergence in both directions at the Budker Institute test-stand were performed.[3] According to the real beam scan results, the achievable value of the beam divergence across the slit was noted about 0.6°, while in the direction along the slit it was around 0.35°. During the development of new RUDI ion-optical system (IOS), several versions of the grid geometries were considered with different transparencies, slit arrangement, and slit lengths in order to define the electrode geometry with the maximal stability during a beam pulse under intensive heating loads. The final slit geometry is shown in Fig. 2, right; the slits of 4 mm width were arranged with 6 mm step. The transparency of the slit grid forming area reached 67% instead of 53% in the case with the old geometry. This factor together with the grid aperture enlargement allowed an increase of the nominal ion beam current from 2 to 3 A. The first and the second electrodes were produced of the molybdenum alloy TZM, and the electrodes 3 and 4 were fabricated of copper (Fig. 3). The electrodes were manufactured by the German factory PLM.[4]

III. BEAM FORMATION BY MULTI-SLIT OPTICS

The ion source parameters were tuned to find the minimal value of the beam angular divergence experimentally. The beam profiles were scanned by the custom-built optical spectroscopic means.[5]

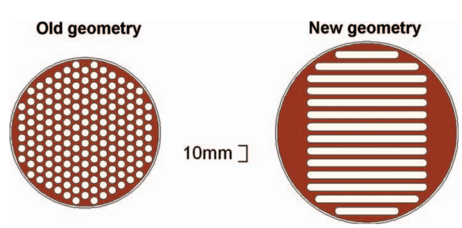

FIG. 2. (Color online) Previous and new grid aperture configurations.

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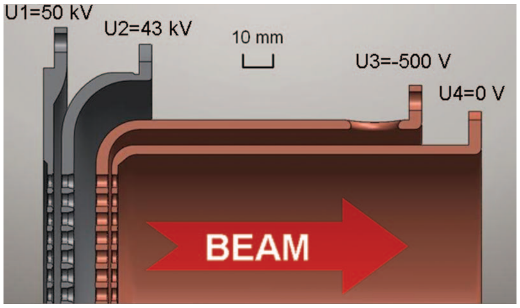

FIG. 3. (Color online) Ion-optical system electrodes. Beam is directed from the left to the right.

The values of the beam angular divergences in both directions were accurately evaluated from the optical chord profiles using the computer modeling taking into account the emitter aperture shape, geometrical focusing, and different beam divergences across and along the slits.[6] The beam divergence scans were recovered in the current range of 1.6–3.0 A at the accelerating voltage of 45 kV (Fig. 4). According to these results, the optimal beam current for the forming system developed was 2.7 A, with the corresponding divergence across the slits of 0.6° for the full energy component (Fig. 5). The beam divergence along the slits was around 0.35-0.4°, which was apparently determined by the ion temperature in the plasma box.

IV. LONG-PULSE PLASMA GENERATOR

In addition to IOS modernization, the new plasma generator with increased heating stress limit was introduced. The arc-discharge plasma source with a directly heated LaB_6 hollow cathode is used at the RUDI injector from 2006. Typically the arc-discharge element has a limited pulse duration, due to local overheating of the channel elements by the arc power. For the new RUDI plasma generator, the metal-ceramic arc channel with actively cooled elements was designed using ANSYS computer simulations of long-pulse heating regimes.

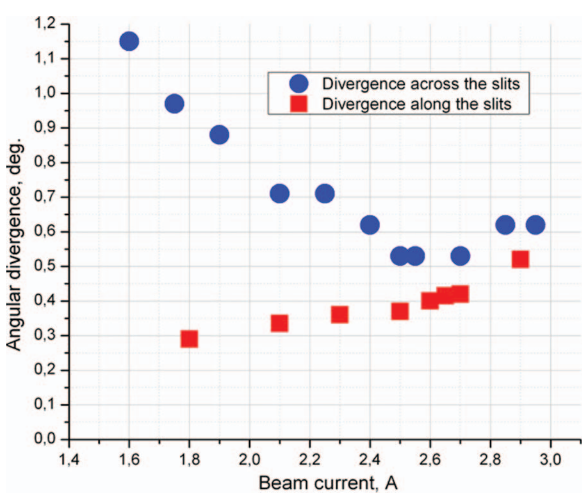

FIG. 4. (Color online) Divergence scans of full energy component across and along the slits for 45 kV beam.

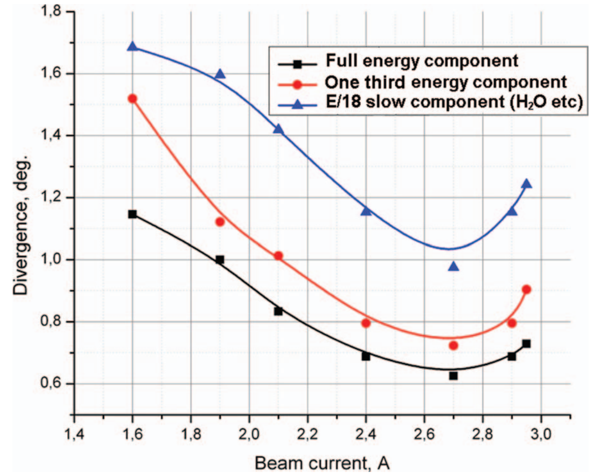

FIG. 5. (Color online) Divergence scans of beam components in the direction across the slits for 45 kV beam.

The channel geometry is presented in Fig. 6. The cathode insert was produced of molybdenum since it had the maximal heating temperature due to the cathode drop region of the discharge. The stack of copper washers is assembled with viton-sealed ceramic spacers providing the galvanic isolation for each channel element. The anode inner shape was accurately elaborated in accordance with the field lines of the magnetic insulation in order to spread the discharge power density over its surface. The use of the new plasma source provided the sufficient extension of the beam duration. The tests have shown that the slit electrodes with peripheral water cooling provide the stable beam formation without any substantial evolution in the pulses up to 6–8 s long with a modulated regime.

V. CHARGE-EXCHANGE RECOMBINATION SPECTROSCOPY MEASUREMENTS AT TEXTOR

The diagnostic injector RUDI was designed to be used at the tokamak TEXTOR for CXRS of the plasma ion temperature and rotation velocity distributions. The plasma temperature is evaluated from Doppler broadening of the spectral line,

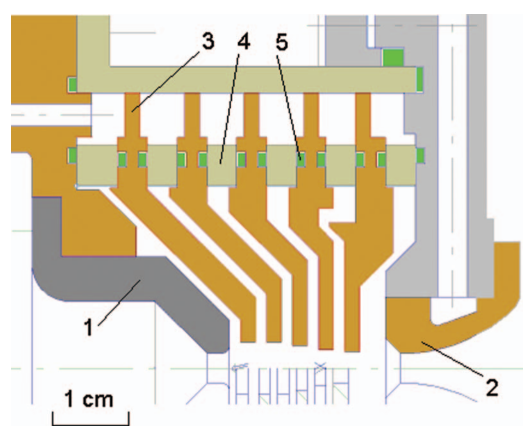

FIG. 6. (Color online) O-ring-sealed arc channel. Filament heater is not shown. Plasma expander is on the right side. (1) cathode insert, (2) anode, (3) washer, (4) ceramic spacer, and (5) o-ring.

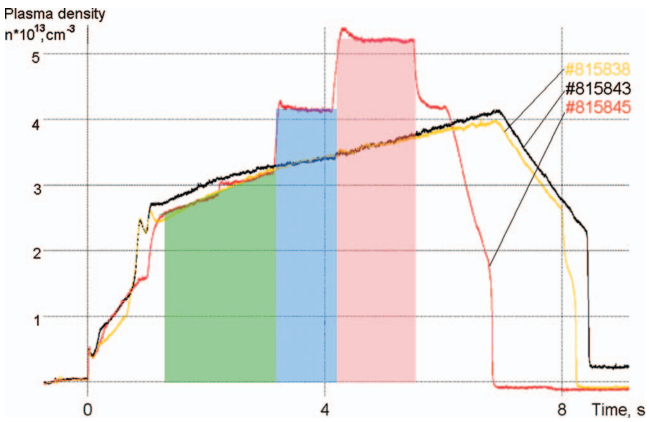

FIG. 7. (Color online) TEXTOR plasma density traces.

emitted (at 529 nm) by excited fully ionized carbon ions due to interacions with fast hydrogen atoms of the beam, while the plasma rotation velocity can be recovered from the Doppler shift of the line observed relative to the unshifted reference.

Figure 7 shows the plasma density traces for three TEXTOR shots, which were analyzed by CXRS measurements. Shots 815838 and 815843 were fully covered by RUDI beam duration allowing the measurements of average T_i and rotation velocities with the best accessible precision. For the ion temperature, the measurement error was only 3–5 eV at the plasma edge, the velocities were recovered with an accuracy around 0.5 km/s.

In shot 815845, the plasma density was intentionally set with rising steps in order to prove the possibility of plasma evolution measurements with short-time averaging ($\sim$1 s). Figures 8 and 9 demonstrate the measurement results of the three plasma phases of shot 815845, corresponding to time intervals 1.3–3.1 s, 3.1–4.1 s, 4.1–5.5 s, respectively. The presented plots are in good agreement with the theoretical predictions, when the plasma density growth influences the ion temperature reduction, since the energy accumulated in the plasma is distributed to a larger number of particles. A similar explanation is for the velocity drop, when the addition of the plasma density causes an inertia increase.

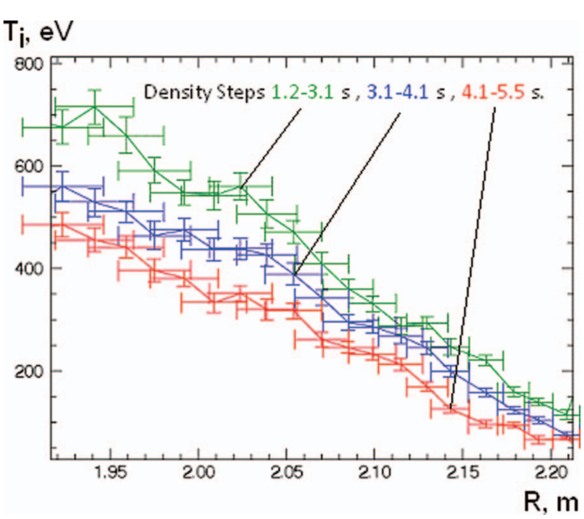

FIG. 8. (Color online) Ion temperature profiles for shot 115845.

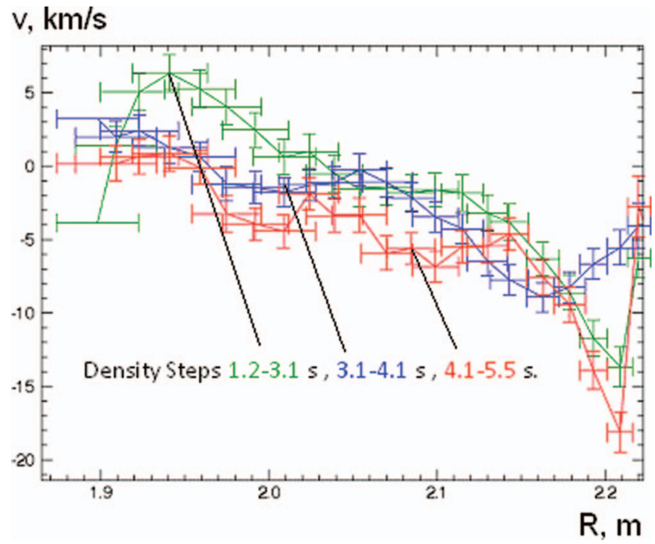

FIG. 9. (Color online) Poloidal rotation profiles for the shot 115845.

VI. SUMMARY

The ion source improvements have lead to the beam density increase at the focal point, which have made a sufficient contribution to the diagnostic signal level and significant enhancement of the CXRS measurements. In May 2011, the experimental session with the new ion source configuration was carried out at TEXTOR, and the CXRS optical signal increased more than twice. The use of the new long-pulse plasma source made it possible to cover the whole TEXTOR discharge duration.

At present several neutral beam injectors are under design at the Budker Institute, which can be made on the basis of the slit ion optics. These include the large diagnostic injector RUDI-X for the Wendelstein-7X device, diagnostic and heating neutral beams for the TCV tokamak, and other projects.

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