ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-TUPSB39

STUDY OF SPACE CHARGE COMPENSATION PROCESS OF A 400 KeV PULSED HYDROGEN ION BEAM

A. S. Belov, S. A. Gavrilov, O. T. Frolov, L. P. Netchaeva, A. V. Turbabin, V. N. Zubets,
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

Abstract

A three grid energy analyzer of slow secondary ions with a twin analyzing grid is described. The analyzer has cylindrical geometry and π angle for recording of the slow ions. The analyzer has been used for measurements of degree of space charge compensation (SCC) of a pulsed hydrogen ion beam with energy of 400 keV and peak beam current of 60 mA. Results of the measurements are presented and compared with theoretical estimations based on model in which the SCC degree is limited by heating of electrons in collisions with fast ions of the beam.

INTRODUCTION

Transport of high intensity ion beams in low energy beam transport (LEBT) for injection into linear accelerators is usually space charge dominated. The space charge field can be reduced by process of gaseous SCC. The SCC process consists in the fact that the ions of the beam ionize the residual gas, and the electrons that arise during the ionization of gas molecules compensate the space charge of the beam of positive ions. The slow ions arising due to gas molecules ionization are accelerated in radial direction and acquire energy that determined by the space charge electric field of the ion beam. The degree of SCC can be determined by measurement of the energy distribution of slow ions produced in the beam region.

Electrostatic ion energy analyzers are used to measure slow ions energy spectra [1, 2]. A three grid electrostatic energy analyzer (TGA) has been used to measure SCC of hydrogen ion beam produced by a proton injector of Moscow INR linac [3, 4]. The hydrogen ion beam has peak current of up to 70 mA, energy of 400 keV, pulse duration of 200 μs and repetition rate of 50 Hz. The beam consists mainly from protons (~80%) and H_2^+ ions.

In this paper the TGA improvement and calibration is described, and results of study of the SCC process for different ion beam density are presented.

THE TGA DESCRIPTION

The TGA cross section view is shown schematically in Fig. 1. The analyzer has cylindrical geometry and π angle for recording of the slow ions. The TGA consists of three grids, a collector and a heater. First grid of the TGA is grounded to eliminate influence of electric fields on the ion beam. Second grid is analyzing one. The second grid is twin to decrease effect of electric field penetration through the grid cells. It is under positive potential relative the ground. Retarding field between the first and second grids leads to deceleration of slow ions and to partial decrease or to complete stopping of the slow ion current to the collector in accordance with the slow ions energy spectra.

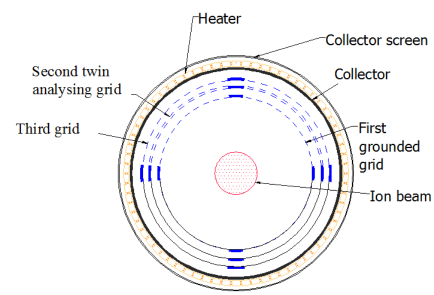

Figure 1: Schematic drawing of the TGA cross-section.

Third grid is under a negative potential (typically -300 V). It is necessary for suppression of secondary electrons from the collector and electrons from the ion beam. The grids have rectangular cells of 0. 5 x 0. 5 mm.

Heating of the TGA is necessary to eliminate systematic error connected with shifting of the TGA characteristics due to charging of the surface layers of the TGA electrodes by the slow ions [2].

Residual gas pressure in vacuum chamber (mainly hydrogen and water vapor) with the TGA was $1.1 \cdot 10^{-5}$ mbar.

Electric field of the TGA as well as ion transport from ion beam to the collector was simulated with COMSOL MP. Figure 2 shows electric field map near the TGA analyzing grid.

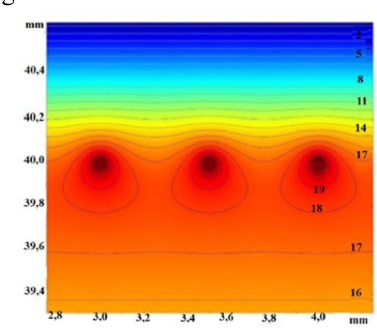

Figure 2: Electric field map of the TGA region near the analyzing grid. Ug2 = 20 V. Ug3 = -300 V.

TheTGA energy resolution is reduced due to the effect of field penetration through the grids and, as the simulation shows, is about 2 eV.

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THE TGA CALIBRATION

The TGA has been calibrated with slow electrons using low current electron gun with tungsten filament thermo cathode. The gun has been placed near axis of the TGA. Electrons were accelerated by voltage applied between the filament and grounded extraction electrode. The electrons energy dispersion of 1.5 eV arises due to potential drop at the thermo cathode filament. Negative potential has been applied to the analyzing grid for the recording of electrons spectrum.

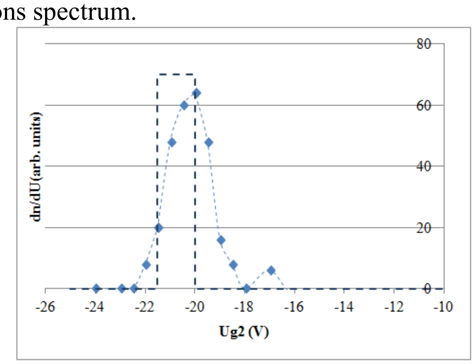

Figure 3: Measured spectrum of electrons with the gun accelerating voltage of 20 eV. U_{g3} = -10 V. The dashed line is the expected electron spectrum; the points are results of the measurements. Temperature of the TGA was 100°C.

It was found that the recorded spectrum changes with change of the TGA temperature. Temperature above 100°C makes no further change of the spectra.

The example of electron energy spectrum measured with the TGA is shown in Fig. 3 for accelerating voltage of 20 eV. The expected spectrum is shown in Fig. 3 by a dashed line. Resolution of the TGA as follows from the data is about 2 eV as expected from a simulation of the TGA electric field distribution.

RESULTS AND DISCUSSION

Complete compensation of positive ion beam space charge by electrons is limited by heating of the electrons in Coulomb collisions with fast ions of the beam [5, 6]. It is follows from the model that potential difference in an ion beam with compensated space charge is proportional to the square root of ion density of the fast ion beam:

$$\Delta\varphi_{comp} \propto n_b^{1/2}$$

We have measured the dependence of the SCC degree of a pulsed hydrogen ion beam with a peak current of 60 mA on the beam density using the TGA described. The ion beam density was changed by changing the focusing voltage of the lens installed downstream the duoplasmatron type ion source. The radial distribution of the ion beam current density was measured by a slit profilometer with a current collector of a cut-out ion stream and suppression of secondary electrons. The recorded ion beam profiles were fitted assuming Gaussian type ion densitydistribution. The characteristic radiuses of ion beam density distribution found this way are shown in Fig. 4.

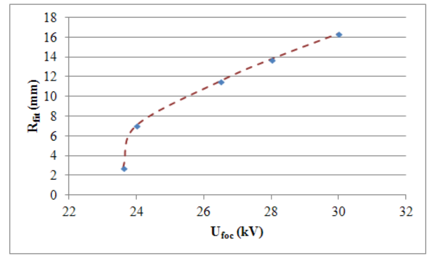

Figure 4: Characteristic radius of the ion beam density distribution vs. focusing voltage of the ion source.

Averaged ion beam density changes from $4.5\cdot10^{7}$ cm^{-3} for focusing voltage of 30 kV to $1.5\cdot10^{9}$ cm^{-3} for focusing voltage of 23.6 kV.

Respective dependences of the TGA collector slow ion current on the potential of the analyzing grid (TGA characteristics) are shown in Fig. 5. We determined degree of SCC of the ion beam using next formula:

$$f_e = 1 - \frac{\varphi_{b\,comp}}{\varphi_{b\,noncomp}},$$

where fe is degree of SCC of an ion beam, $\varphi_{b\,comp}$ is potential difference between axis of the ion beam with compensated space charge and grounded transport tube wall and $\varphi_{b\,noncomp}$ is the potential difference for the ion beam with non compensated space charge.

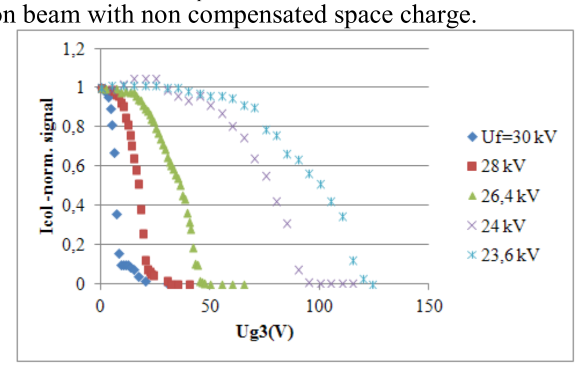

Figure 5: Characteristics of the TGA for different focusing voltage of the ion source.

Value of $\varphi_{b\,comp}$ was determined from the TGA characteristics using fit of the recorded data assuming Gaussian ion beam density distribution.

An example of a TGA characteristic with the fit is shown in Fig. 6. We determined $\varphi_{b\,comp}$ as point where the fitting curve crosses the horizontal axis (20.9 V for Fig. 6). The $\varphi_{b\,noncomp}$ value was determined by solving Poisson equation with known ion current and radial ion density distribution.

The Gaussian fit shown in Fig. 6 is satisfactory except for the "tail" of the current of higher-energy ions. A similar "tail" was observed in [2]. Among possible explanations made in [2] was decay of excited H_2 molecules to charged particles with energy of ~10 eV or collective oscillations in the ion-beam plasma.

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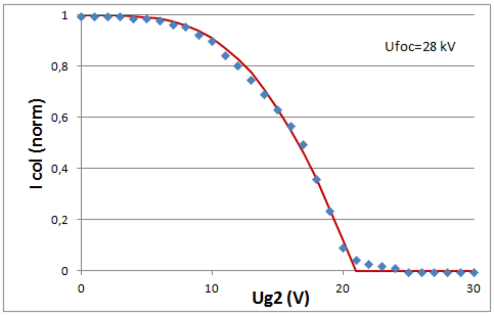

Figure 6: The TGA characteristic for U_{foc} = 28 kV. Points are recorded data; solid line is a fit with Gaussian ion beam density distribution.

We assume that the "tail" origin for our measurements is connected with anomalous ion beam density distribution near the ion beam axis region. The ion beam radial density distribution for case where the "tail" is most pronounced (U_{foc} = 30 kV) is shown in Fig. 7.

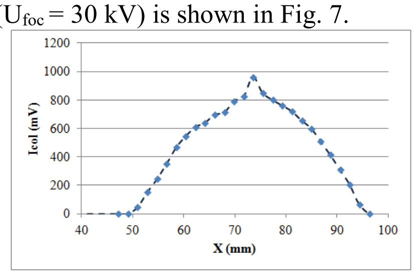

Figure 7: Radial profile of the hydrogen ion beam for Ufoc = 30 kV.

The distribution has characteristic peak at the ion beam axis. The distribution shape can probably be explained by the influence of a weak magnetic field in the ion source plasma expander on the plasma density distribution.

The measured degree of SCC of the hydrogen ion beam was compared with theoretical estimation based on Gabovich – Soloshenko model [5, 6].

Dependences of measured and calculated degree of SCC of hydrogen ion beam on ion beam density are shown in Fig. 8.

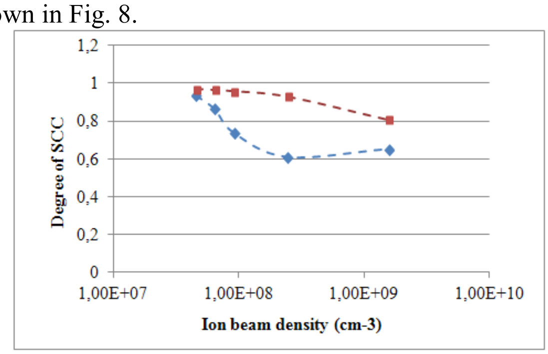

Figure 8: Measured and calculated data for degree of SCC of hydrogen ion beam with peak current of 60 mA and energy of 400 keV vs. the ion beam density. Brown squares are calculation from Gabovich-Soloshenko formula, blue diamonds are results of the measurements.

There is a significant difference between the measured and calculated data. One of the reasons for the discrepancy may be approximation of homogeneous ion beam accepted in the Gabovich-Soloshenko model. For comparison with measurements the model has to be extended to include non homogeneous ion beam density distribution. An ion beam simulation which takes into account complicated processes of SCC [7] is an alternative method for prediction of the SCC degree.

Another factor that reduces degree of SCC may be dynamic decompensation. However, our hydrogen ion beam has a low current noise level. Faraday cup has used to measure the noise value of the ion beam current. It was found that the noise is less than 1% of the ion beam current amplitude. That makes dynamic decompensation an insignificant factor for the ion beam SCC.

CONCLUSION

The three grid energy analyzer of slow secondary ions with the twin analyzing grid is described. The analyzer has been used for measurements of degree of SSC of hydrogen ion beam with peak current of 60 mA and energy of 400 keV. The measurement results qualitatively coincide with the predictions made by the ion beam decompensation model due to the heating of compensating electrons in Coulomb collisions with fast beam ions (model of Gabovich- Soloshenko). But the numerical discrepancies with the model are significant.

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