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GISMO GASDYNAMIC ECR ION SOURCE STATUS: TOWARDS HIGH-INTENSITY ION BEAMS OF SUPERIOR QUALITY*

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Abstract

GISMO, a CW high-current quasi-gasdynamic ECR ion source, is under development at the IAP RAS. The quasi-gasdynamic confinement regime, featuring high plasma density (up to 10^{14} cm^{-3}) and moderate electron temperature (~100 eV), allowed to extract pulsed beams of H^+ and D^+ ions with current of 450 mA and RMS emittance <0.07 π·mm·mrad [1]. It has been already demonstrated that major benefits of quasi-gasdynamic confinement, previously tested in pulsed mode at SMIS37 facility [1], are scalable to the CW operational mode. In first experiments at GISMO facility, the ion beams were extracted in pulsed mode from the CW plasma of ECR discharge due to technical limitations of cooling circuits. Proton beams with current up to 65 mA were achieved at extraction voltage of 40 kV. A new unique extraction system especially effective for the formation of high current density ion beams was developed.

INTRODUCTION

A distinctive feature of gasdynamic ECR ion sources being under development at IAP RAS is a confinement regime of a high density plasma. It was demonstrated [1–3] that the use of high-frequency gyrotrons is very beneficial for a dense plasma production and high-current ion beams formation. Previously, ion beams of both light (hydrogen) and heavy (nitrogen, argon) elements were extracted from the plasma of ECR discharge sustained by 37.5 [1] and 75 GHz [3] radiation, demonstrating ion beam currents on the level of 100–500 mA with normalized RMS emittance below 0.2 π·mm·mrad in a pulsed operation mode. This success stimulated the construction of the facility named GISMO (Gasdynamic Ion Source for Multipurpose Operation) [4] at IAP RAS, which main application is a powerful neutron generator [5]. The scheme of the facility is shown in Fig. 1. A 28 GHz/10 kW CW gyrotron is used for the plasma heating, manufactured by Gycom. The microwave generator is equipped with power supplies suitable for CW or pulsed operation. The plasma trap has an all-permanent magnet design. To ensure sufficient plasma confinement, the magnetic field configuration is designed to be similar to a simple mirror trap close to the system axis, and the magnetic field strength is 1.5 T at plugs and 0.25 T at the trap center, yielding the mirror ratio of 6. The distance between magnetic mirrors is 12 cm. The magnet bore is 50 mm, thus allowing the use of a water-cooled plasma chamber with a vacuum bore of 32 mm. An ion beam extraction system has been designed to use the acceleration voltage of up to 100 kV. A high source potential requires a development of an appropriate high-voltage insulation of the plasma chamber from unbiased components of the facility. A quasi-optical system, shown in Fig. 1, is implemented instead of a convenient waveguide DC-break. The electro-magnetic radiation of the gyrotron (TE02 mode of a circular waveguide) is converted to the Gaussian beam, which then propagates in open air through the gap of 15 cm, acting as a DC-break. The radiation is received by the horn antenna, converted into a TE11 mode of a circular waveguide, and then focused to the plasma with a microwave-to-plasma coupling system embedded into the vacuum chamber.

GISMO plasma chamber is schematically shown in Fig. 2 together with the simulated temperature on the surface of the chamber touching the magnets (temperature simulations were conducted taking into the account plasma flow and power distributions) and the electromagnetic field distribution inside the chamber (calculated in vacuum, i.e. in absence of the plasma). Simulations show that the unique design of the plasma chamber allows us to safely inject the nominal power of 10 kW with the microwave transmission efficiency close to 95%, (estimated when no reflection from the plasma is present) and without having any cooling issues. Having the plasma volume of 40 cm^3, injected power density reaches 250 W/c^3, whereas conventional ECRISes usually operate at ~1–10 W/cm^3 power density. Such level of deposited power allows to run the ion source in quasi-gasdynamic mode (which is naturally featured with very high energy losses due to low plasma lifetime) while keeping the electrons hot enough to maintain 100% ionization degree.

The main motivation of studies at GISMO facility is the development of a powerful D-D neutron generator [5] capable of producing the neutron flux sufficient for boron neutron capture therapy (BNCT). The D-D neutron generator scheme based on a high-current gasdynamic ECR source should provide the necessary neutron flux once the ion beam current reaches ~1 A at 100 keV energy.

Besides BNCT, neutronography is the application which demands high density neutron fluxes. The use of a high-current ECR ion source with quasi-gasdynamic plasma confinement and heating with gyrotron microwave radiation allows us to produce light ion beams with uniquely low emittance (for a given current level) [6]. Such a low emittance enables the focusing of the ion beam into the spot of several tens of micrometers in diameter. The suggested approach may be exploited for the development of the point-like neutron source with the size of emitting area comparable to

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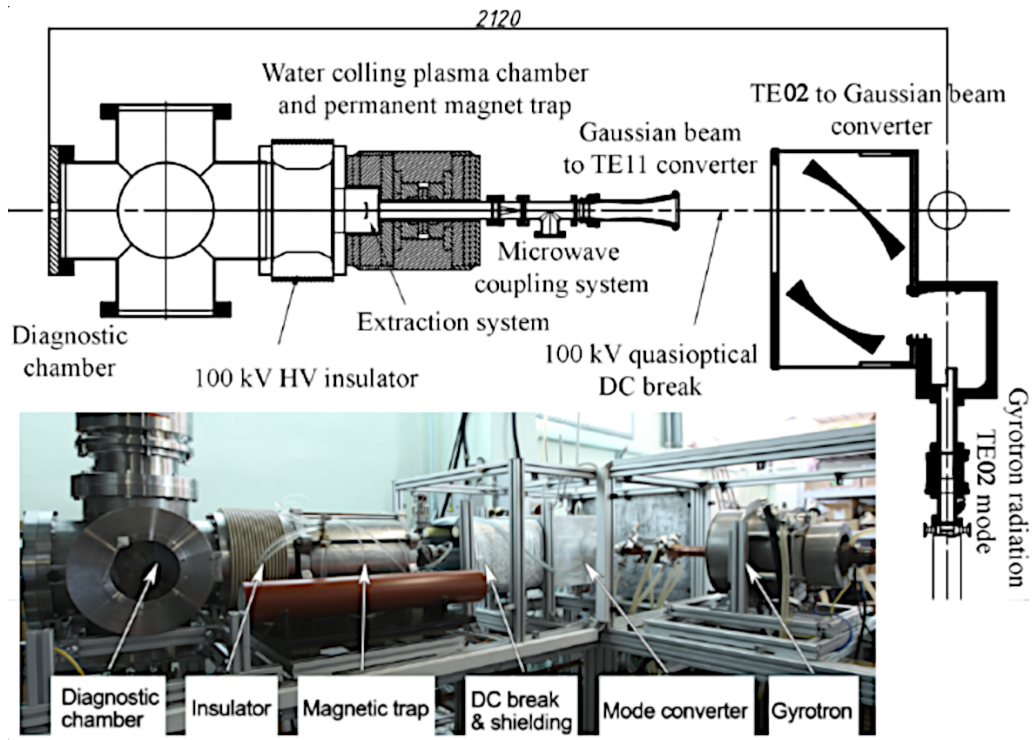

Figure 1: GISMO experimental facility layout.

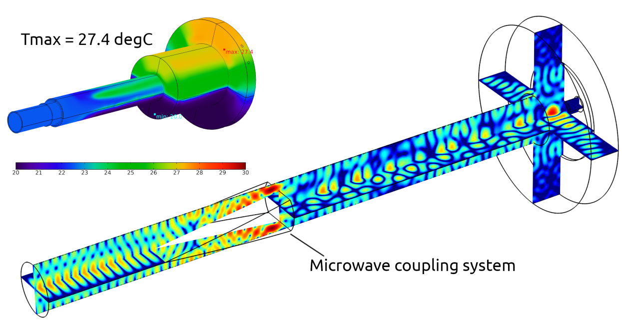

Figure 2: Simulated plasma chamber temperature and RMS electric field distributions at 10 kW of injected power.

femtosecond laser systems, but with significantly higher neutron yield.

FIRST EXPERIMENTS

It has been shown earlier that the plasma density can reach a level of 10^{13} cm^{-3} [7]. As a first step, we have used a simple 2-electrode extraction system for a beam formation. This system is obviously non-optimal for plasma parameters achieved at GISMO, as it has a very long (250 mm) and narrow (30 mm) puller tube, which leads to a more than 90% of beam losses, as was confirmed with IBSimu code [8].

Thus, instead of the extracted ion beam current measured with the conventional Faraday cup, the power supply drain current has been used for a beam current evaluation in the first experiments. The dependence of the drain current on the hydrogen pressure in the plasma chamber is shown in Fig. 3, right axis shows the corresponding current density, assuming 3 mm extraction aperture, the microwave power was equal to 2 kW.

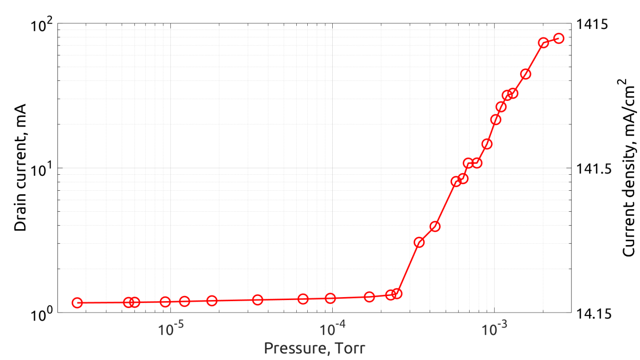

Figure 3: Drain current and corresponding current density as a function of hydrogen pressure in the plasma chamber.

Despite the fact we are not able to extract the whole beam with such extraction system, we estimated the emittance of the beam with pepper-pot method. The beammask was located at the exit of the puller tube (i.e. 260 mm from the plasma electrode), CsI scintillator was placed 50 mm downstream from the mask and its luminescence was captured with synchronized CCD camera. The example of emittance diagram obtained at 1 mTorr pressure and 2 kW of microwave power and 30 kV of extraction voltage is shown in Fig. 4.

RMS normalized emittance calculated from the data in Fig. 5 is equal to 0.019 π·mm·mrad, which seems to be as low as the method precision for the used geometry. We

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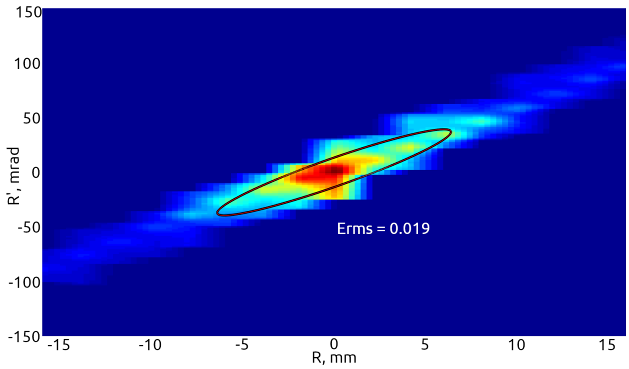

Figure 4: Emittance diagram example, obtained at a hydrogen pressure of 1 mTorr, 2 kW of microwave power and 30 kV of extraction voltage.

would like to underline that once the whole beam would be extracted, the emittance will be likely greater, though these preliminary experiments and IBSimu simulations together indicate that it is reasonable to expect the emittance on the level of 0.1–0.2 π·mm·mrad.

SPHERICAL EXTRACTOR

In order to address the problem of high current density beam formation, the new type of extraction geometry is proposed [9]. The main idea is to change the shape of the electrodes, which exploits an inhomogeneous distribution of the electric field in the accelerating gap of the ion beam formation system. This method may be especially effective in systems with a high current density, mitigating the negative effect of the space charge of the beam on its quality. It allows for significant enhancement of the current and/or reducing the emittance at a certain accelerating voltage and characteristic size of the system, especially when the extraction system operates in the space charge limited regime, which is the case for GISMO facility. The problem of the dense ion beam formation is due to the harmful influence of the self space charge, which distorts the shape of the meniscus, making it convex. Accordingly, the accelerating field near the meniscus forms a diverging beam, which cannot be transported efficiently. The increase in the electric field near the meniscus provides higher beam acceleration gradient and reduces the region with high space charge level. It is proposed to consider the combination of electrodes shown in Fig. 1. Hereinafter we denote such a system as a "spherical" because the puller and the tip of the plasma electrode form plates of a hollow hemispherical capacitor (this region is highlighted with a rectangle in Fig. 5a), whereas the conventional flat structure shown in Fig. 5b forms plates of a flat capacitor.

The use of inhomogeneous accelerating field allows an increase of the electric field magnitude near the plasma meniscus without raising the extraction voltage or reduction of interelectrode distance (see Fig. 5). In this work we consider a new electrode geometry which produces an inhomogeneous electric field providing higher gradients of ion beam

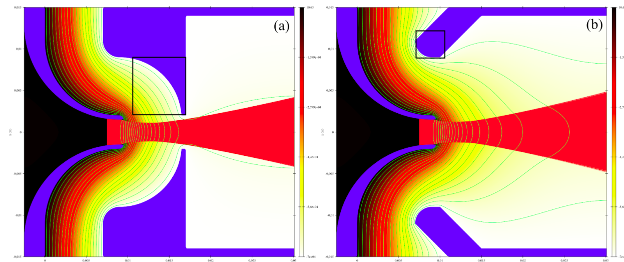

Figure 5: Distribution of the electric field modulus in the interelectrode space (a - spherical, b - flat). Distribution of the electric field along the axis of symmetry (c). The voltage between electrodes is the same and equal to 70 kV.

acceleration and reducing the space charge influence on its quality.

It is of note that the new geometry can be used for a wide range of the ion beam sources and its applications. This approach in extraction system design allows for increase of the current of the beam at proton injectors [10, 11] and multi-charged ion sources for accelerators [12]. The current density can exceed the level of 1 A/cm^2. Such high current densities are available at ion sources for focused ion beams (FIBs) [13] but the total current is lower by several orders of magnitude. On the other hand, the use of a new geometry allows for significant decrease of the extraction voltage and hence it is useful for low energy ion beam production. Such beams are required for ion implantation [14]. The decrease of the optimal extraction voltage can also significantly reduce the co-extracted electron flow in negative ion sources [15]. In many nuclear physics facilities injecting heavy ion beams into cyclotron accelerators the experimental program often requires high currents of medium charge state ions. The currents of such beams often cannot be maximized because the injection energy (source potential), defined by the design of the central region of the cyclotron, is too low to reach the plasma density-limited operation mode of the ion source. The novel approach for the beam extraction system could overcome such limitations and is therefore of interest for various accelerator facilities. In particular, this is relevant for the 3rd and 4th generation ECR ion sources where the plasma density is as high as 10^{12}–10^{13} cm^{-3}, and very high extraction voltages are required to reach the plasma density-limited operation. In this case the new extraction system allows exploiting the full capacity of the ion source in a wider range of extraction voltages. Another technical advantage of the proposed system is the possibility to use puller with much greater aperture than in conventional extraction systems, as the puller aperture barely affects the the shape of the meniscus and the mode of extraction of the beam. The example is shown in Fig. 6, where two significantly different puller apertures are simulated. The reason for that being the puller part highlighted in the Fig. 6a has a weak effect on the electric field distribution, while the highlighted part in the Fig. 6b makes the main contribution.

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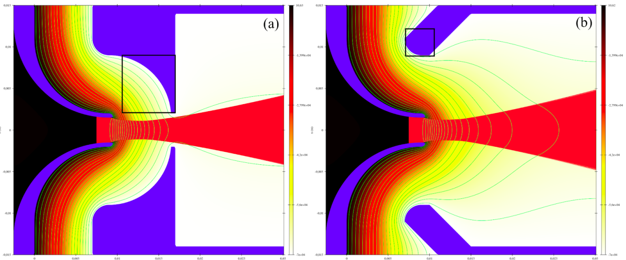

Figure 6: Formation of an ion beam with various puller designs. A significant increase in the aperture of the puller slightly affects the beam.

A set of tungsten electrodes of a new type was designed and fabricated at IAP RAS for initial test on GISMO facility. A photograph of electrodes is shown in Fig. 7. The first experiments with new electrodes are in progress at the moment and will be published soon.

CONCLUSION

New gasdynamic CW ECRIS named GISMO is now operational at IAP RAS. Hydrogen plasma emissivity of >1 A/cm^2 has been demonstrated. A new type of extraction system geometry able to handle beam current densities of >1 A/cm^2 is developed and manufactured. Proton beams with current of 65 mA were successfully obtained at extraction voltage of 40 kV. Judging from conducted experiments and IBSimu numerical investigations, the extraction system consisting of 4 electrodes and new spherical geometry would be able to extract the beam current on the level of 250 mA, Preliminary estimations of normalised RMS emittance suggested that the emittance of such a beam should be lower than 0.2 π·mm·mrad. Thus, GISMO facility may be able to fulfill the requirements of future proton accelerator projects, such as ISIS upgrade (ISIS-II) and DARIA [11].

Figure 7: A photograph of spherical plasma electrode and a set of puller electrodes.

REFERENCES

[1] S. Golubev *et al.*, "High current ECR source of multicharged ion beams", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 256, pp. 537-542, March 2007, doi:10.1016/j.nimb.2006.12.053

[2] V. Skalyga *et al.*, "New progress of high current gasdynamic ion source (invited)", *Rev. Sci. Instrum.*, vol. 87, p. 02A716, 2016, doi:10.1063/1.4934213

[3] V. A. Skalyga *et al.*, "Study of hydrogen ECR plasma in a simple mirror magnetic trap heated by 75 GHz pulsed gyrotron radiation", *Rev. Sci. Instrum.*, vol. 88, p. 033503, 2017, doi:10.1063/1.4978278

[4] V. A. Skalyga *et al.*, "Status of a new 28 GHz continuous wave gasdynamic electron cyclotron resonance ion source development at IAP RAS", *AIP Conf. Proc.*, vol. 2011, p. 030013, 2018, doi:10.1063/1.5053274

[5] V. Skalyga *et al.*, "High yield neutron generator based on a high-current gasdynamic electron cyclotron resonance ion source", *J. Appl. Phys.*, vol. 118, p. 093301, 2015, doi:10.1063/1.4929955

[6] V. Skalyga *et al.*, "High current proton beams production at Simple Mirror Ion Source 37", *Rev. Sci. Instrum.*, vol. 85, p. 02A702, 2014, doi:10.1063/1.4825074

[7] V. Skalyga *et al.*, "First experiments with gasdynamic ion source in CW mode", *Rev. Sci. Instrum.*, vol. 87, p. 02A715, 2016, doi:10.1063/1.4934208

[8] T. Kalvas *et al.*, "IBSIMU: A three-dimensional simulation software for charged particle optics", *Rev. Sci. Instrum.*, vol. 81, p. 02B703, 2010, doi:10.1063/1.3258608

[9] S. S. Vybin *et al.*, "High current ion beam formation with strongly inhomogeneous electrostatic field", arXiv:2009.02757

[10] J. Knaster *et al.*, "Overview of the IFMIF/EVEDA project", *Nucl. Fusion*, vol. 57, no. 5, 2017, doi:110.1088/1741-4326/aa6a6a

[11] S. Grigoriev *et al.*, "Spin-echo Small Angle Neutron Scattering for a Compact Neutron Source Daria", *J. Surf. Invest.*, vol. 13, pp. 1132–1134, 2019, doi:10.1134/S1027451019060314

[12] J. C. Yang *et al.*, "High Intensity heavy ion Accelerator Facility (HIAF) in China", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 317, pp.263-265, 2013, doi:10.1016/j.nimb.2013.08.046

[13] N. S. Smith *et al.*, "High brightness inductively coupled plasma source for high current focused ion beam applications", *J. Vac. Sci. Technol., B*, vol. 24, p.2902, 2006, doi:10.1116/1.2366617

[14] Michiro Sugitani, "Ion implantation technology and ion sources", *Rev. Sci. Instrum.*, vol. 85, p. 02C315, 2014, doi:10.1063/1.4854155

[15] D. Faircloth *et al.*, "ISIS Penning source extraction studies reveal the 3-dimensional Child–Langmuir effect", *Rev. Sci. Instrum.*, vol. 91, p. 043307, 2020, doi:10.1063/1.5129675