Heavy Ion Beam Probe for Measurements of Plasma Potential Profile in GDT Device

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Abstract. The project of heavy ion beam probe (HIBP) in Gas-Dynamic Trap (GDT) device is presented in the paper. HIBP will be placed at the midplane of GDT. It will measure electric potential in 8 positions along the plasma diameter simultaneously. Beam of primary ions Xe^{+1} is produced by 4-electrode accelerating system and has the following parameters: current up to 7 mA, ion energy of 60-76 keV, size of 4 mm and angular spread at the level of $1/e$ about 4 mrad. Secondary ions Xe^{+2} are produced by primary beam ionization in plasma and enter the small aperture detector based on 30-degrees electrostatic energy analyzer. Each detector channel provides potential measurement with accuracy of 10-50 V and spatial resolution of 2 cm at sampling rate up to 1 MHz.

INTRODUCTION

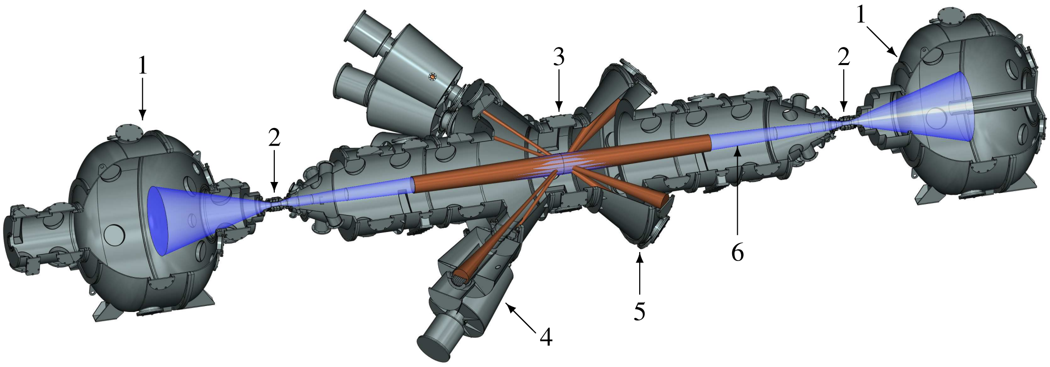

FIGURE 1. GDT device: 1 – expander tanks, 2 – mirrors, 3 – midplane of the central cell (the place for HIBP), 4 – heating beam injector, 5 – heating beam dump, 6 – plasma.

Spatial profile of electric potential is one of the plasma characteristics essential for understanding physics in mirror devices. Potential in Gas-Dynamic Trap (GDT) device (Fig. 1) has been derived from two diagnostics up until now: the set of Langmuir probes and the energy analyzer of ions escaping GDT through the mirrors. However, Langmuir probes can not be used any more in plasma with electron temperature raised up to 1 keV [1, 2]. The second technique is still reliable and gives the average potential at mirror regions. Unfortunately, potential at the midplane of GDT device can not be derived from this data, especially in presence of electron-cyclotron heating [1, 2] and strong peaking of hot ions' density [3]. Therefore, the project of Heavy Ion Beam Probe (HIBP) is proposed to provide accurate measurements of plasma potential at the GDT midplane. The following chapters describe the general design of HIBP and the design of its two main parts – the source (or the injector) of primary beam and the detector of secondary beams.

GENERAL DESIGN

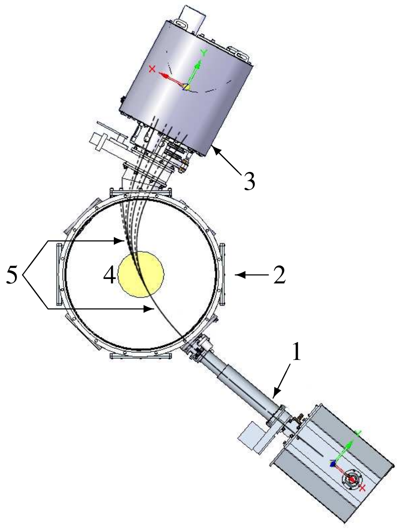

FIGURE 2. GDT midplane crossection: 1 – injector of primary beam, 2 – GDT chamber, 3 – detector of secondary beams, 4 – plasma, 5 – trajectories of Xe ions (the leftest one is the primary beam Xe^{+1}, others are secondary beams Xe^{+2}).

The GDT midplane is the most convenient place for HIBP (see Fig. 2). That is because of two features of magnetic field. Firstly, magnetic field inside the GDT central cell reaches its minimum there. So, the limitation on primary ions' energy become the weakest. Secondly, midplane is the plane of symmetry for magnetic coils of the central cell. Therefore, forcelines at the midplane are perpendicular to it, and the deviations of both primary and secondary ions from the midplane become negligibly small. That simplifies all the HIBP design and makes the problem of beam trajectories calculation planar.

The next challenge is to combine HIBP with other devices placed at the GDT midplane including such crucial ones as the Thomson scattering and the motional Stark effect diagnostics. Only two flanges remain available for use (the upper and the bottom right on Fig. 2). Hence the location of the HIBP proves to be fixed. The following constraints are additionaly assumed:

- The primary beam must be formed from ions of a noble gas. This constraint allows to use existing arc plasma sources as in [4] with a minimal modification.
- Maximum voltage in the primary beam injector must not exceed 100 kV. This reduces safety requirements drastically.
- The primary beam attenuation must be of order of unity, while secondary beams must shine through the plasma without significant attenuation. These conditions allows to get high signals on detectors from all the positions along plasma diameter.

Also let us refer to the parameters of GDT at midplane: magnetic field is 3.1 kGs and linear plasma density is about 10^{14} cm^{-2}. These parameters, the GDT geometry and the limitations assumed identifies two available types of primary beam: Xe^{+1} at energy of 60 keV (attenuates about 10 times) and Kr^{+1} at 90 keV (attenuates approximately 3 times). The accelerating voltage for Kr is close to upper limit and breaks the limit if magnetic field increased up to 3.3 kGs. Therefore, Xe is adopted for the primary beam.

Finally, it should be noted that plasma confinement in GDT is improving together with the magnetic field. To keep all trajectories the same it is necessary to rise the energy of the primary beam as a square of the magnetic field. For example, increasing magnetic field up to 3.5 kGs (that is close to technical limit) leads to the primary beam energy rises up to 76.5 keV.

PRIMARY BEAM INJECTOR

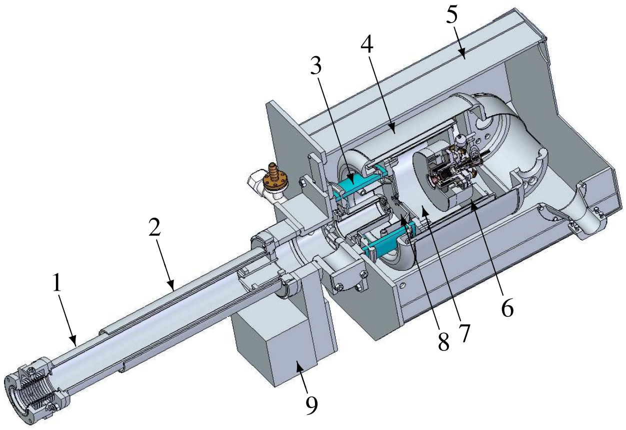

FIGURE 3. Injector of the primary beam: 1 – beam-line, 2 – magnetic shield for beam-line, 3 – insulator, 4 – vacuum chamber at 60 kV, 5 – magnetic and electrostatic shield, 6 – arc plasma source, 7 – volume for plasma expanding, 8 – region of beam formation and acceleration, 9 – gate valve.

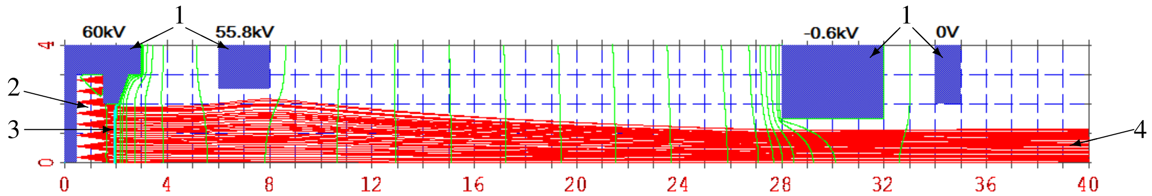

FIGURE 4. Crossection of the beam formation and acceleration region (number 8 on Fig. 3) along the short sides of the slit apertures (or in plane of Fig. 2): 1 – electrodes and their voltages, 2 – plasma coming from the expanding volume (number 7 on Fig. 3), 3 – plasma/beam boundary, 4 – exiting beam. Sizes are given in mm, zero position on the vertical axis denotes center of the beam.

Design of the primary beam is shown on Fig. 3. Calculation of the beam parameters has been done by PBGUNS code (see for example [5]). The beam is formed by 4-electrodes accelerating system with slit apertures. Slits are aligned as follows: long sides are parallel to the axis of GDT (that is perpendicular to the plane of Fig. 2) and short sides are parallel to the midplane (that is the plane of Fig. 2). The key parameters of the beam are the size and the angular spread in plane of Fig. 2. They must be minimized in order to achieve sufficient space resolution of the HIBP diagnostic. The optimal configuration of the apertures is shown on Fig. 4. Resulting beam on exit of the injector has size of 2 mm, angular spread of 4 mrad and current density of about 16 mA/cm^2. Along with this the total current of the beam must be several mA to provide high enough signal on the detectors. To meet this requirement slit apertures have size along the GDT axis of 2 cm. That produce primary beam Xe^{+1} with total current up to 7 mA.

SECONDARY BEAMS DETECTOR

Figure 5 presents the design of the secondary beams detector. Secondary ions Xe^{+2} appears in plasma due to ionization of the primary beam. The detector is based on standard 30° Proca-Green analyzer [6]. Unlike the original concept, high voltage applied to both plates of the analyzing capacitor. Small parallel-plates gaps on entrance and exit of analyzing capacitor forms uniform electric field that decelerates (on entrance) and accelerates (on exit) secondary beam ions. This method modifies the characteristics of secondary beam inside the analyzing 30° capacitor: energy of beam particles decreases, but angular spread rises. The first allows to decrease analyzing field and reach better energy resolution. But the second smears the current profiles on collectors and effectively decreases the energy resolution. As

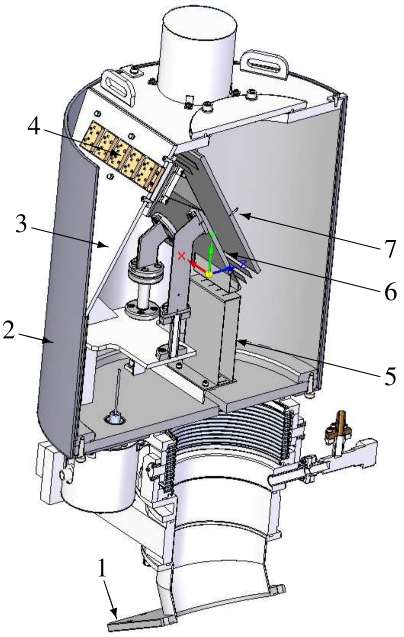

FIGURE 5. Injector of the primary beam: 1 – GDT flange, 2 – magnetic shield, 3 – vacuum chamber, 4 – connectors for amplifiers, 5 – collimators box, 6 and 7 – "lower" and "upper" plates of analyzing capacitor.

a compromise between the size of the detector and its energy resolution, the potential of the lower plate is selected at 18 kV. Under this condition, secondary ions have only 40% of initial energy inside the analyzing capacitor with height of about 4 cm and length of about 30 cm. Resulting coordinate-to-energy resolution at the current collectors becomes of 0.5 cm/keV. All the voltages on the detector are set by resistive dividers from the accelerating voltage of the primary beam.

The detector has 8 channels measuring a potential along the plasma diameter. Each channel receives Xe^{+2} beams of mkA order on 4 separate current collectors. Current is amplified with the gain 0.3 MΩ and detected by 10-bit ADC at rate up to 1 MHz. Like in standard scheme, potential is determined by the center of current profile at the collectors. The width of the single collector is 1 cm, that is about the half of the primary beam size along the GDT axis. All the 4 collectors covers the range from 0 to 3 kV of plasma potential. The error associated with uncertainty of the current profile center calculating does not exceeds 10 V. The overall accuracy estimation including low level of currents on detectors rises up to about 50 V.

Spatial resolution is determined by the collimator together with the primary beam parameters. This value is the maximal size of the "spot" in the midplane, that is formed as intersection between the primary beam and the "line of sight" of the collimator. The key property of the primary beam is the isotopic composition. If the primary beam contains the only isotope, the size of the "spot" will be less than 1 cm. Unfortunately, there are 9 isotopes present in natural Xe. And the spatial resolution is defined not by size of the individual isotope "spot", but by the distance between centers of different "spots". Therefore, we assume two types of operation modes. The first is an adjustment regime with wide input slit of the collimator (width is about 1 mm). It will provide poor spatial resolution, but high currents on the collectors. The second is basic operation mode with thin input slit of the collimator (width is 0.5 mm). In this regime only part of the isotope "spots" are stay "visible" through the collimator. The total spatial resolution is just 2 cm, but signals from current collectors are decreasing several times.

CONCLUSIONS

The project of HIBP is proposed for the midplane of GDT device. The primary beam of Xe^{+1} with energy of 60-76 keV is produced by 4-electrode accelerating system with slit apertures. Characteristics of the primary beam in the plane across the slit are optimized to reach the overall spatial resolution of 2 cm and has the following values: the size is 4 mm, the angular spread is about 4 mrad at the level of $1/e$. The primary beam size along the slit is raised up to 2 cm to reach the total current of 7 mA. The detector of Xe^{+2} secondary beams is based on 30° Proca-Green analyzer. It will provide the measurement of electric potential with accuracy of 10-50 V at sampling rate up to 1 MHz in 8 positions along the plasma diameter.

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REFERENCES

[1] P. A. Bagryansky, A. V. Anikeev, G. G. Denisov, E. D. Gospodchikov, A. A. Ivanov, A. A. Lizunov, Yu. V. Kovalenko, V. I. Malygin, V. V. Maximov, O. A. Korobeinikova, S. V. Murakhtin, E. I. Pinzhenin, V. V. Prikhodko, V. Yu. Savkin, A. G. Shalashov, O. B. Smolyakova, E. I. Soldatkina, A. L. Solomakhin, D. V. Yakovlev, and K. V. Zaytsev, Nucl. Fusion **55**, p. 053009 (2015).

[2] P. A. Bagryansky, A. G. Shalashov, E. D. Gospodchikov, A. A. Lizunov, V. V. Maximov, V. V. Prikhodko, E. I. Soldatkina, A. L. Solomakhin, and D. V. Yakovlev, Phys. Rev. Lett. **114**, p. 205001 (2015).

[3] V. V. Maximov, A. V. Anikeev, P. A. Bagryansky, A. A. Ivanov, A. A. Lizunov, S. V. Murakhtin, K. Noack, and V. V. Prikhodko, Nucl. Fusion **44**, 542–547 (2004).

[4] P.Deichuli, V. Davydenko, A. Ivanov, S. Korepanov, V. Mishagin, A. Smirnov, A. Sorokin, and N. Stupishin, Rev. Sci. Instrum. **86**, p. 113509 (2015).

[5] J. E. Boers, "An interactive version of the pbguns program for the simulation of axisymmetric and 2-d, electron and ion beams and guns," in *Proceedings of the 1995 Particle accelerator conference, Vols 1-5*, 4 (IEEE, 1996), pp. 2312–2313.

[6] L. Solensten and K. A. Connor, Rev. Sci. Instrum. **58**, 516–519 (1987).