Negative Ion Source Development for Fusion Application (invited)

journal or publication title	Review of Scientific Instruments
volume	Vol. 81
number	No. 2
page range	02B114-1 - 02B114-7
year	2010-02-01
URL	http://hdl.handle.net/10655/3901

doi: 10.1063/1.3274806

Negative ion source development for fusion application (invited)^{a)}

Yasuhiko Takeiri^{b)}

National Institute for Fusion Science, Toki 509-5292, Japan

(Presented 24 September 2009; received 19 September 2009; accepted 20 November 2009; published online 26 February 2010)

Giant negative ion sources, producing high-current of several tens amps with high energy of several hundreds keV to 1 MeV, are required for a neutral beam injector (NBI) in a fusion device. The giant negative ion sources are cesium-seeded plasma sources, in which the negative ions are produced on the cesium-covered surface. Their characteristic features are discussed with the views of large-volume plasma production, large-area beam acceleration, and high-voltage dc holding. The international thermonuclear experimental reactor NBI employs a 1 MeV-40 A of deuterium negative ion source, and intensive development programs for the rf-driven source plasma production and the multistage electrostatic acceleration are in progress, including the long pulse operation for 3600 s. Present status of the development, as well as the achievements of the giant negative ion sources in the working injectors, is also summarized. © 2010 American Institute of Physics. [doi:10.1063/1.3274806]

I. INTRODUCTION

Plasma heating by neutral beam injection (NBI) is the most reliable method to obtain fusion-relevant high-temperature plasmas. The injection beam energy is determined by the expected penetration depth in the target plasma, and it is getting higher as the plasma size becomes larger. The NB is produced through the charge-exchange conversion of the accelerated ion beam. As the required beam energy increases, the negative ion beam becomes inevitable because the neutralization efficiency is maintained at around 60% for negative ions while it decreases drastically for the positive ions at higher beam energy above 100 keV/nucleon.¹ For a negative-ion-based NBI system, high power and large-scaled negative ion sources, i.e., giant negative ion sources, have been intensively developed.²⁻⁹ Presently, two negative-NBI systems are in operation in JT-60U tokamak¹⁰ and Large Helical Device (LHD).¹¹

International Thermonuclear Experimental Reactor (ITER), which is under construction for starting its operation in 2018, aims at fusion-burning plasma experiments as the next-step fusion research, and requires two high-energy deuterium NB injectors of 1 MeV-17 MW.¹² To realize the ITER-NBI, high energy and high-power negative ion sources producing 1 MeV-40 A for 3600 s have to be developed. This challenge further promotes the giant negative ion source development. From the viewpoint of how to realize a 1 MeV-40 A-3600 s ITER source, giant negative ion source development is reviewed in this article, and key issues for the development, such as plasma production related to the negative ion production and beam acceleration, are discussed.

Giant negative ion sources used in the NBI system are

characterized as large-volume plasma production, large-area beam extraction and acceleration, and high-voltage dc holding. After a brief summary of the negative ion sources used in the working NBI systems, these characteristics of the giant negative ion sources are discussed in the following three sections. Then, present achievement of the long-pulse operation is described. Finally, present status of the ITER source development is summarized.

II. GIANT NEGATIVE ION SOURCE

A negative-NBI system was first operated in JT-60U in 1996, which was designed to inject 500 keV-10 MW of deuterium beams with two negative ion sources. Although the ion source is specified to produce 500 keV-22 A of deuterium negative ions, 400 keV-17 A has been achieved due to insufficient high-voltage holding capability.¹⁰ In LHD, two negative-NB injectors started their operation in 1998 and the third injector was operational in 2001, each of which has two hydrogen negative ion sources. While the designed injection energy and power are 180 keV and 5 MW, respectively, for each injector, the total power of 16 MW has been achieved with the energy of 180-190 keV.¹¹ The employed giant negative ion sources are reliably operated, and 190 keV-37 A of negative hydrogen ions have been produced, which exceed the specified values of 180 keV-30 A.¹³

The negative ion source used in the above two NBI systems is a cesium-seeded plasma source. Figure 1 shows a schematic diagram of the negative ion source in the LHD-NBI system as an example. The source plasma is produced through filament-arc discharge in a large chamber surrounded by multicusp magnetic field for plasma confinement. For negative ion production, a small amount of cesium vapor is supplied into the source plasma. A part of the supplied cesium is adsorbed on a surface of the plasma grid (PG), which is the boundary for the negative ion extraction. Hydrogen atoms and ions are converted to negative ions on

^{a)}Invited paper, published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September 2009.

^{b)}Electronic mail: takeiri@nifs.ac.jp.

FIG. 1. (Color online) Schematic diagram of the negative ion source in the LHD-NBI system.

the cesium-covered surface with a low work function, as illustrated in Fig. 2. The negative ions produced on the PG surface are extracted across multiple apertures of the PG. The magnetic filter is applied as a transverse magnetic field in front of the PG, to divide the plasma into two regions, i.e., the plasma production region and the negative ion extraction region. By the magnetic filter, the electron temperature is lowered in the extraction region, so that the negative ion destruction by the high-energy electrons is prevented and the coextracted electrons are suppressed. The negative ions are extracted and accelerated electrostatically as multiple beamlets with a large-area grid system. The work function of the Cs-covered surface shows the minimum at a half to monolayer of Cs, and it is realized at a PG temperature of 200–300 °C. Thus, the negative ion yield is dependent on the PG temperature, and the PG temperature should be controlled at an appropriate range. Permanent magnets are embedded in the second (extraction) grid (EG) to separate the co-extracted electrons, as shown in Fig. 3, which illustrates a grid system in the LHD source as an example. The extracted negative ions are accelerated with single-stage acceleration in the LHD source and with three-stage acceleration in the JT-60U source, depending on the final energy.

In the ITER-NBI system, the specified injection energy and power are 1 MeV and 17 MW, respectively, using one ion source, which should produce 1 MeV-40 A-3600 s of negative ions.¹² Figure 4 shows a schematic diagram of the designed negative ion source for the ITER-NB injector. The source plasma is produced in a huge chamber by rf-driven discharge, and the negative ions are accelerated as multiple beamlets of 1280 (from four segments consisting of four blocks with 16×5 apertures) with five-stage acceleration. A deuterium negative ion current density is specified at 200 A/m² at the PG. A ratio of the coextracted electrons to

FIG. 2. (Color online) Illustration of the negative ion production on the Cs-covered PG surface.

FIG. 3. (Color online) Illustration of the grid systems with (a) multi-round aperture GG and (b) multislotting GG in the LHD source.

the negative ions should be lower than 1 for avoiding the EG damage. The operational gas pressure should be less than 0.3 Pa for reducing the stripping loss of negative ions during the acceleration, which is caused by collision with the background neutrals. The rf-driven plasma generation is adopted due to less maintenance, i.e., longer lifetime, than the filament-arc plasma generation for limited accessibility to the source due to the radioactive environment in ITER. These requirements for the ITER-NBI negative ion source are very challenging.

Characteristic features of the giant negative ion source for the NBI system is summarized as large-volume plasma production, large-area beam acceleration, and high-voltage dc holding. With the view of development of the ITER-NBI source, these characteristic features are discussed in the following sections.

III. LARGE-VOLUME PLASMA PRODUCTION

The negative ions are produced on the cesium-adsorbed PG surface in the giant negative ion sources. Since the incident atom and ion flux onto the PG surface should have an influence on efficient negative ion production, a uniform and dense plasma production with a high proton ratio is required in a large volume. The multicusp bucket source is suitable to this requirement, and stronger multicusp field at the plasma chamber wall is better to produce high-density plasmas with a high proton ratio.¹ The KAMABOKO source³ shown in Fig. 5(a), which has a semicylindrical chamber shape with strong multiline cusp field, is optimized so that high-density

FIG. 4. (Color online) Schematic diagram of the designed negative ion source for the ITER NBI system. (a) MAMuG and (b) rf-driven plasma generator.

FIG. 5. (Color online) (a) Schematic diagram of the KAMABOKO source. (b) Operating gas pressure as a function of the volume to surface ratio of the plasma.

plasmas with a high proton ratio would be produced at a low gas pressure. The main concept is to maximize the plasma volume and to minimize the plasma loss area, and the KAMABOKO source achieves high negative ion production efficiency at low gas pressure. Figure 5(b) shows the operational gas pressure as a function of the volume to surface ratio of the plasma.¹⁴ Here, the volume means the plasma volume and the surface means the plasma loss area, i.e., the total line cusp area. It is found that lower gas pressure operation is realized in a source with a higher volume to surface ratio.

However, the negative ion sources are equipped with the magnetic filter field, which is transverse inside the plasma and connected to the strong cusp magnetic field. Local connection of the filter field with the cusp field would result in plasma loss and plasma localization. Since the magnetic filter field penetrates in the plasma, the primary electron trajectories are influenced by the grad-B drift motion, and the primary electron distribution becomes nonuniform. As a result, the produced plasma is nonuniform. To optimize the configuration of the confinement magnetic field considering the connection between the cusp field and the filter field, calculation of the primary electron trajectories is effective. Figures 6(a) and 6(b) show calculation results of the magnetic field lines

and the distribution of the primary electrons emitted from filaments, respectively, for nonoptimized and optimized field configurations.² It is found that the primary electrons are more distributed in the plasma volume region in the optimized configuration, where the local connection of the filter field with the cusp field is reduced in an arc chamber with a hexagonal cross section. In the optimized configuration, the plasma production efficiency is improved and, thus, the arc efficiency of negative ion production is greatly enhanced, as shown in Fig. 6(c).

The drift direction of the primary electrons due to the grad-B drift is perpendicular to the filter field direction. Thus, the plasma uniformity is violated in the long-distance direction of the plasma chamber because the filter field is applied in the shot-distance direction. In the filament-arc source, individual control of the arc discharge is effective to achieve uniform plasma production, in which both arc and filament voltages are adjusted with the divided power supply circuits according to the intensity of local arc discharges.² The beam uniformity is much improved along the long-distance direction due to the uniform plasma production by this control technique of the local arc discharge. Instead of the unidirectional filter field, tent filter configuration, in which the filter field is configured from a center area of the backplate to a sidewall area near the PG like a tent shape, has been tested. Since the grad-B drift direction is closed azimuthally in this case, uniform plasma production is expected.¹⁵

Although the large volume plasma production has been effectively accomplished in the filament-arc discharge source, filament lifetime, which is several tens of hours of the arc discharge, would be a problem for the ITER source. Since the ITER-NB injector is remotely handled, the maintenance frequency should be low and, especially, the source opening for the filament exchange should be avoided. Therefore, the rf-driven plasma source has been intensively developed for the ITER source.¹⁶ Figure 7 shows a schematic diagram of the rf-driven source developed in IPP-Garching.¹⁷ Dense plasma is generated by inductively coupled rf in a

FIG. 6. (Color online) Calculation results of (a) magnetic field lines and (b) primary electron distribution, in nonoptimized (bottom) and optimized (top) field configuration for connection between the cusp field and the filter field. (c) H^- currents as a function of the arc power for the corresponding optimized and nonoptimized configurations.

FIG. 7. (Color online) Schematic diagram of the rf-driven negative ion source developed in IPP-Garching.

ceramic cylinder wound by a rf coil. The produced plasma flows into the expansion chamber. Cs is introduced into the expansion chamber, and the negative ions are generated on the PG surface in the extraction region separated by the magnetic filter, which is the same as in the filament-arc source. The rf frequency is 1 MHz and the rf power is about 100 kW.

The electron density and temperature of the plasma produced in the rf-driver region are as high as 10^{18} m^{-3} order and above 10 eV, respectively. Thus, a high plasma flux flows toward the PG. For a large-volume plasma chamber, a number of rf drivers are attached to the backplate of the expansion chamber, as shown in Fig. 8, and homogeneous illumination of the plasma flux on the PG is investigated to achieve uniform negative ion production. In the expansion chamber, the plasma is drifted in the perpendicular direction to the filter field direction by the $E \times B$ force. Including control of the rf coupling in the parallel operation of the rf drivers, the plasma uniformity is investigated with a large-volume rf-driven source with four drivers shown in Fig. 8.

Compared with the filament-arc source, the negative ion production efficiency is lower at a low gas pressure, presumably due to a lower proton ratio. Suppressing the loss of rf-accelerated high-energy electrons is a key subject by optimizing the confinement magnetic field. Investigation of the rf-accelerated electron trajectories would be effective.

IV. LARGE-AREA BEAM ACCELERATION

To extract a large current of ion beams, multibeamlet extraction is utilized in NBI sources. A bundle of beamlets

FIG. 8. (Color online) Extrapolation of the rf-driven negative ion source to the ITER source with multiple rf-drivers.

FIG. 9. Illustration of the principle of electrostatic beamlet deflection by the aperture displacement technique.

have a large cross section and multiple beamlets should be focused so as to pass through the injection port of the fusion device. Thus, the individual beamlet steering is an important technique for the large-area beam extraction and acceleration. Beamlet steering by the aperture displacement (offset) technique, where the aperture axis deviates from the beam axis, is useful for the multibeamlet focusing because an individual beamlet is steered programmably.¹ Figure 9 shows schematically the principle of electrostatic beamlet deflection by the aperture displacement technique. In the giant negative ion source, permanent magnets are embedded in the EG for removing the coextracted electrons, as shown in Fig. 3. The magnetized direction of the magnets is parallel to the beam axis, and the polarity is reversed line by line. The negative ion beamlets are also deflected by this magnetic field, and the deflection direction is reversed line by line, leading to beam expansion as a whole. The aperture displacement technique is applied in the downstream grid or the grounded grid (GG) for the compensation of this beamlet deflection, and the deflected beamlets are successfully corrected.⁶

The beamlet-beamlet interaction is observed in the negative ion source with a large-area accelerator.¹⁸ The space-charge repulsion force makes outer beamlets be deflected outward, and the deviation of the beamlet trajectory causes additional deflection at the downstream grid aperture. The simulation study reveals that outer three to four beamlets are deflected by the beamlet-beamlet interaction while trajectories of the inner beamlets are not influenced, as shown in Fig. 10.¹⁹ The beamlet deflection by the beamlet-beamlet interac-

FIG. 10. (Color online) Calculation result of beamlet-beamlet interaction. Dots indicate the beamlet center and deviate outward.

FIG. 11. (Color online) Illustration of various processes accompanied with the acceleration of negative ions.

tion can be also corrected with the aperture displacement technique, which is considered in the JT-60U source. The multibeamlet steering is a key subject to converge a bundle of beamlets, and the aperture displacement technique is successfully utilized for adjustment of the beamlet deflection by the EG magnetic field and the beamlet-beamlet interaction.

There are various phenomena related to the secondary particle generation during the beam acceleration. Figure 11 schematically illustrates various processes accompanied with the acceleration of negative ions. The negative ions are destroyed by collision with the background neutrals during the acceleration, called the stripping loss, and the stripped electrons are accelerated downward. Direct interception of grids by negative ions causes the secondary emission of electrons, and a part of these electrons are accelerated downward. These accelerated electrons are incident on the downstream grid. The neutralizer plasma is produced downstream from the accelerator, and the positive ions are extracted from the plasma through the GG aperture. Positive ions are also generated in the accelerator due to the ionization of the background gas by collision with the accelerated electrons and negative ions. These positive ions are accelerated backward, and some of them are incident on the upstream grids, which cause the secondary electron emission. Then, these secondary electrons are accelerated downward and incident on the downstream grids. These processes lead to deterioration of the beam-acceleration efficiency and enhancement in the heat load on the grids. The grid heat load is investigated by a simulation code considering the various phenomena related to the secondary particles, and, as a primitive result, it has been indicated that the secondary electron acceleration is a dominant process to the grid heat load.²⁰ Since the stripped electrons are main secondary particles and cause the subsequent secondary particle generation, the operational gas pressure should be lowered to achieve a high acceleration efficiency.

High heat load on the grids would cause outgassing, which enhances the heat load by the increased stripped electrons, leading to the further outgassing. The direct intercep-

FIG. 12. (Color online) GG heat load ratio to the output energy of the acceleration power supply as a function of the GG transparency.

tion of the GG by the negative ions contributes to the heat load and, moreover, leads to secondary ion emission, which is accelerated backward. These processes frequently cause a breakdown at the acceleration gap. A higher transparency of the grids would be effective in reducing the gas pressure in the acceleration gap and, therefore, reducing the grid heat load. Based on this concept, in the LHD source, the GG aperture shape is changed from multi-round apertures, shown in Fig. 3(a), to multislot apertures, shown in Fig. 3(b), to increase the GG transparency.²¹ The GG heat load is reduced to about a half in the multislot GG due to both the reduction in the beam intersection area and the reduction in the stripping loss. As a result, the beam energy is raised with less frequent breakdown. The grid heat load is dependent on the grid transparency, as shown in Fig. 12. The GG heat load is reduced also by enlarging the diameter of round apertures, and the beam energy is also raised in this case.²² In the negative ion source discussed here, the grid area is large and the grid gap length is long, so that the negative ions frequently interact with the background neutrals during the acceleration. Reduction in the background gas pressure is important to reduce the heat load of the grids.

V. HIGH-VOLTAGE DC HOLDING

Negative ions are accelerated electrostatically due to the large current acceleration, and the high-voltage dc holding is a critical subject because the final energy is as high as several hundreds keV to 1 MeV. Since the ITER source is designed as vacuum insulation between the grids in each acceleration stage, high-voltage dc holding in vacuum is a primary subject. In a semiempirical theory, the breakdown voltage is increased proportionally to the square root of the gap length. That means that the total length of the accelerator would be shorter in a multistage acceleration system. On the other hand, as the breakdown phenomenon is a probability event, the breakdown would occur more frequently in a multiple grid system with a larger surface area. The high-voltage holding capability has been tested with a variation in the gap length in the MeV accelerator test facility and in the JT-60U NB injector. The result is summarized in Fig. 13, showing the highest holding voltage as a function of the gap length. It is found that the holding voltage is proportional to the square root of the gap length. The applied dc voltages of 1 MV and

FIG. 13. (Color online) Highest holding voltage as a function of the gap length for the JT-60U accelerator and the MeV accelerator.

500 kV are successfully held in the MeV accelerator test facility and in the JT-60U NB injector, respectively, when appropriate gap lengths are secured.^{23,24}

In the case of the beam acceleration, the secondary particle behaviors have a large influence on the voltage holding capability. As described in the previous section, the secondary particles, such as the secondary electrons, the backstreaming positive ions, and neutrals, are a main cause of the grid heat load, and the secondary particle emission is accelerated by outgassing due to the heat load. When such subsequent particle emission is successively caused like an avalanche, the breakdown would occur.

For the beam acceleration to 1 MeV in the ITER source, two types of accelerators, multiaperture and multigrid accelerator (MAMuG) and single gap and single aperture accelerator (SINGAP), were proposed. In the MAMuG accelerator, the extracted negative ion beamlets are accelerated in multiple stages using grids with multiround apertures, and for the ITER source five-stage acceleration is designed to 1 MeV. In the SINGAP accelerator, the extracted negative ion beamlets are accelerated to 1 MeV in a single stage as a bundle of beamlets using the GG with a single wide-opening aperture. The MAMuG and the SINGAP were compared in the MeV-accelerator test facility in JAEA, as shown in Fig. 14. The results indicate that MAMuG showed superior voltage holding capability in that the secondary electrons includ-

FIG. 14. (Color online) Grid arrangement for the comparison test between the MAMuG and the SINGAP accelerators in the MeV test facility in JAEA.

FIG. 15. (Color online) Example of the long pulse operation with a rf-driven source. The observed line emission of Cs neutrals is also indicated.

ing the stripped electrons are not accelerated to full energy. In the SINGAP, moreover, the amount of backstreaming positive ions is larger due to the wide-opening GG. A large part of them are incident on the upstream grid and generate the secondary electrons, which are accelerated toward the GG. As a result, the accelerated electron ratio is higher about three times in the SINGAP, which would lead to inferior voltage holding capability compared with the MAMuG. Based on this test, the MAMuG accelerator has been adopted for the ITER source.²⁵

VI. LONG PULSE OPERATION

The rf-driven negative ion source has a capability for long-term operation with no maintenance due to no fatigue elements such as filaments. Although the filament-arc source needs a periodic exchange of filaments, it can cope with long pulse operation as well as the rf-driven source. A key subject for the long pulse operation is Cs control for stable negative ion production. As described in Sec. III, the negative ions are produced on the Cs-covered PG surface, and the PG temperature should be maintained at 200–300 °C for efficient negative ion production. For the long pulse operation, control of the PG temperature is essential, and the PG is warmed in the rf-driven source and cooled in the filament-arc source. Cs is continuously supplied into the discharge chamber. The Cs is ionized in the plasma and, then, adsorbed on the chamber surface and the PG surface. Since the Cs adsorbed on cold surfaces is not evaporated, the chamber surface should also be maintained at an appropriate temperature so that the Cs is recycled inside the discharge chamber to minimize the Cs consumption.²⁶

In the rf-driven source, long pulse operation for 3600 s has been demonstrated in IPP-Garching.²⁷ During the operation, the PG temperature and the chamber temperature are maintained at 150 and 50 °C, respectively. Figure 15 shows an example of the long pulse operation of the rf-driven source.²⁸ Since Cs adsorbed on cold chamber walls is regarded as the Cs loss, maintaining the wall at an appropriate temperature for the Cs to be recycled is required to reduce the Cs consumption. Impurities would degrade the Cs effect, and the tungsten vapor is thought to be a possible impurity in the filament-arc source. However, in the rf-driven source, rf-accelerated high-energy electrons sputter the Faraday screen made of copper, and sputtered copper is also a possible impurity. In the long pulse operation with the rf-driven

TABLE I. Present achievements for the ITER source development. The specified values for the ITER source are also indicated in the table.

	Current (A)	Current density (A/m ²)	Coextracted electron current	Ion species	Pressure (Pa)	Pulse length (s)	Energy (keV)
LHD (one source)	37	340	<1	H	0.33	1.6	190
JT-60U (one source)	17.4	130	<1	D	0.27	0.73	400
	10	100	<1	D	0.27	25	360
ITER (one source)	40	200	<1	D	0.3	3600	1000
	46	280	<1	H	0.3	3600	870
Rf source (BATMAN)	1.6	230	<1	D	0.3	4	20
	2.3	330	<1	H	0.3	4	20
Rf source (MANITU)	2.5	120	>1	H	0.4	3600	20
MeV facility	0.323	140		H		0.2	796

source, the negative ion current and the coextracted electron current tend to be gradually decreased and increased, respectively, in time, which is thought to be caused by Cs shortage due to the impurities. By coating the Faraday screen and the backplate with molybdenum, the copper impurity is reduced during the long pulse operation, and the pulse length was extended to 3600 s with nearly constant currents.²⁸

VII. PRESENT ACHIEVEMENTS AND SUMMARY

The negative ion source development for fusion application is reviewed. Presently, Cs-seeded plasma sources, in which the negative ions are produced on the Cs-adsorbed surfaces with a low work function, are utilized as giant negative ion sources for NB injectors. They are reliably operated in the LHD-NBI system, in which 190 keV-37 A of hydrogen negative ion beams are produced. The characteristic features of the giant negative ion sources are discussed from points of view of large-volume plasma production, large-area beam acceleration, and high-voltage dc holding.

The present target for the development is an ITER-NBI source, which should produce 1 MeV-40 A deuterium negative ions for 3600 s. For long-term operation without maintenance, a rf-driven source was selected, and the required deuterium current density of 200 A/m² has been achieved at the specified gas pressure of 0.3 Pa. Long pulse operation for 3600 s has been also demonstrated. Extrapolation of the source size to the ITER source is planned, and the homogeneous plasma illumination on the wide-area PG is a key subject to achieve uniform negative ion production. As a 1 MeV accelerator, a MAMuG accelerator was selected for superior voltage holding capability than a SINGAP accelerator. The present achievements for the ITER source development are listed in Table I, including the achievements in the working NB injectors. Although the individual target values have been almost achieved, the integrated performance should be tested. The ITER NB test facility is proposed to be constructed in RFX Padua, Italy, for the test of a prototype ITER source.²⁹

The ITER source development is a challenge, and re-

quires a high level of the physics and technology of ion sources. Then, it should be completed by worldwide collaboration.

ACKNOWLEDGMENTS

The authors are grateful to researchers in many laboratories developing the negative ion sources for fusion application for providing the present achievements. Especially, Dr. R. Hemsworth in ITER organization, Dr. T. Inoue and Dr. M. Hanada in JAEA, Dr. U. Fantz in IPP-Garching, Dr. V. Antoni in RFX Padua, and Dr. K. Tsumori in NIFS are greatly acknowledged for useful discussions on this review.

¹Y. Takeiri, in *The Physics and Technology of Ion Sources*, edited by I. G. Brown (WILEY-VCH Verlag GmbH & Co. kGaA, Weinheim, 2004), Chap. 16, p. 341.

²Y. Takeiri *et al.*, *Rev. Sci. Instrum.* **71**, 1225 (2000).

³Y. Okumura *et al.*, *Rev. Sci. Instrum.* **71**, 1219 (2000).

⁴Y. Okumura *et al.*, Proceedings of the 16th Symposium on Fusion Technology, London, 1990 (unpublished), Vol. 2, p. 1026.

⁵A. Ando *et al.*, *AIP Conf. Proc.* **287**, 339 (1994).

⁶Y. Takeiri *et al.*, *Rev. Sci. Instrum.* **66**, 5236 (1995).

⁷A. Simonin *et al.*, *Rev. Sci. Instrum.* **67**, 1102 (1996).

⁸O. Kaneko *et al.*, Proceedings of the 16th International Conference on Fusion Energy, Montreal, 1996 (unpublished), Vol. 3, p. 539.

⁹D. Boilson *et al.*, *Rev. Sci. Instrum.* **73**, 1093 (2002).

¹⁰Y. Ikeda *et al.*, *Nucl. Fusion* **46**, S211 (2006).

¹¹Y. Takeiri *et al.*, *Nucl. Fusion* **46**, S199 (2006).

¹²R. S. Hemsworth *et al.*, *Rev. Sci. Instrum.* **79**, 02C109 (2008).

¹³K. Tsumori *et al.*, *Rev. Sci. Instrum.* **81**, 02B117 (2010).

¹⁴T. Inoue *et al.*, *Fusion Eng. Des.* **55**, 291 (2001).

¹⁵H. Tobari *et al.*, *Rev. Sci. Instrum.* **79**, 02C111 (2008).

¹⁶E. Speth *et al.*, *Nucl. Fusion* **46**, S220 (2006).

¹⁷U. Fantz *et al.*, *Rev. Sci. Instrum.* **79**, 02A511 (2008).

¹⁸M. Kamada *et al.*, *Rev. Sci. Instrum.* **79**, 02C114 (2008).

¹⁹M. Kashiwagi *et al.*, *Rev. Sci. Instrum.* **81**, 02B113 (2010).

²⁰T. Mizuno *et al.*, *Rev. Sci. Instrum.* **81**, 02B103 (2010).

²¹K. Tsumori *et al.*, *Rev. Sci. Instrum.* **75**, 1847 (2004).

²²Y. Takeiri *et al.*, *AIP Conf. Proc.* **925**, 211 (2007).

²³M. Taniguchi *et al.*, *Rev. Sci. Instrum.* **81**, 02B101 (2010).

²⁴A. Kojima *et al.*, *Rev. Sci. Instrum.* **81**, 02B112 (2010).

²⁵T. Inoue, private communication (2008).

²⁶Y. Takeiri *et al.*, *AIP Conf. Proc.* **1097**, 470 (2009).

²⁷W. Kraus *et al.*, *Rev. Sci. Instrum.* **79**, 02C108 (2008).

²⁸U. Fantz *et al.*, Proceedings of the 22nd IAEA Fusion Energy Conference, Geneva, October 2008 (unpublished), IT/P7-9.

²⁹P. Sonato *et al.*, *Fusion Eng. Des.* **84**, 269 (2009).