NEUTRAL BEAM DUMP UTILIZING CATHODIC ARC TITANIUM EVAPORATION

A. Smirnov,[1] A.S. Krivenko,[2] S.V. Murakhtin,[2] V.Ya. Savkin,[2] S.A. Korepanov,[1] and S. Putvinski[1]

[1] *Tri Alpha Energy Inc., P.O. Box 7010, Rancho Santa Margarita, CA 92688, USA, asmirnov@trialphaenergy.com*
[2] *Budker Institute of Nuclear Physics, 11 Acad. Lavrentyev Ave., Novosibirsk 630090, Russia*

Unlike tokamaks, where the neutral beam shine through is rarely an issue, open magnetic systems with neutral beam injection oftentimes suffer from incomplete beam capture, which necessitates the handling of the shine through power load and beam particle recycling. The cathodic arc gettering, which provides high evaporation rate coupled with a fast time response, is a powerful and versatile technique for depositing clean getter films in vacuum. A compact neutral beam dump utilizing the titanium arc gettering was developed for a field-reversed configuration plasma sustained by 1 MW, 20 - 40 keV neutral hydrogen beams. The beam dump is capable of handling large, pulsed gas loads, has a high sorption capacity, and is robust and reliable. The beam recycling coefficient, measured under the beam particle flux density of 5×10^{17} H/(cm^{2}s) sustained for 3 - 10 ms, is ~ 0.7. The use of the beam dump allows to reduce the recycling of the shine through neutral beam by factor of 3 - 5, as well as to improve the vacuum conditions in the machine.

I. INTRODUCTION

In various types of fusion plasma devices with neutral beam injection, an incomplete beam capture can adversely affect the plasma performance. For example, the shine-through beam particle recycling can cause a dramatic reduction of the fast ion life time in the open magnetic systems.[1-4] Neutral beam dumps are employed for handling the shine through beam power and particle loads. To achieve low beam recycling, the interior surfaces of a beam dump must be cleaned of sorbed residual gases, which can be nontrivial to accomplish even in a UHV environment. To provide sufficiently high neutral removal rate in the beam dump, some kind of hydrogen capture mechanisms must be used, such as, for example, implantation and entrapment of fast neutrals in vanadium[4] or carbon,[3] or chemisorption of the recycled gas by means of titanium gettering.[4,5]

The cathodic arc gettering is a powerful and versatile technique for depositing clean metallic films in vacuum.[6,7] Its potential in the fusion research applications has been largely unrealized, despite several critical advantages that this method has in comparison with the conventional sublimative gettering, namely: i) 2 - 3 orders of magnitude higher evaporation rate, ii) short switch on and switch off time, and iii) 2 - 3 orders of magnitude higher energy efficiency. The pulsed cathodic arc evaporation allows to getter large surface areas immediately prior to a plasma shot and to vary the average evaporation rate widely.

In the study reported here, a compact neutral beam dump with a cathodic arc gettering system was developed for the C-2 device, in which six 1 MW, 20 - 40 keV neutral hydrogen beams are used to sustain the high-temperature field-reversed mirror plasma formed dynamically by merging two compact toroids.[8,9] The beam dump is designed to operate at the full neutral beam power and particle flux, ~ 25 kW/cm^2 and 5×10^{17} H/(cm^{2}s), respectively. The beam duration is 3 - 10 ms. The cathodic arc evaporators[10] feature a new, improved design.[11] The beam dump is capable of handling large, pulsed gas loads, has a high hydrogen sorption capacity, and is robust and reliable. The use of the beam dump allows to significantly reduce the neutral recycling arising from the incomplete beam capture, as well as to improve the vacuum conditions in the machine.

II. EXPERIMENTAL SETUP

C-2 is an FRC machine and, thus, is inherently compact due to the plasma's high β. The relatively large neutral beam injectors, which are attached to the plasma confinement vessel, constrain the NB dump geometry. This makes the NB dump design quite challenging. The NB dump chamber (see Fig. 1), which has the volume of ~ 150 liters, houses a beam dump plate, two identical, elongated Ti arc evaporators, and a system of chevrons that expands the surface area accessible for Ti deposition and, thereby, increases the pumping speed. The total geometrical surface area covered by Ti is ~ 3 m^2. The aspect ratio of the chevrons is optimized numerically through Monte Carlo simulations to provide the maximum neutral trapping efficiency. The interior of the dump chamber, including the chevrons, dump plate, and side walls, have been bead-blasted to improve the Ti coating adhesion. The beam dump plate is made of molybdenum and can withstand a full power shot with the beam duration of up to 1 second.

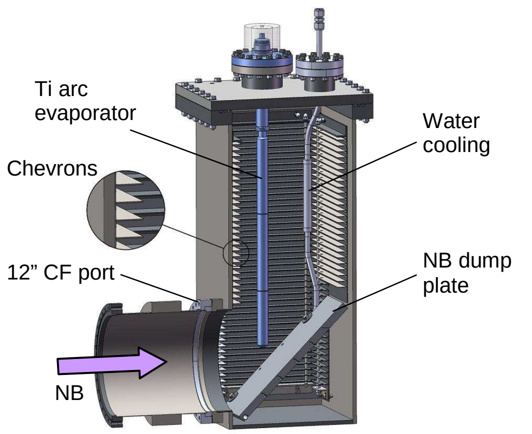

Fig. 1. The sectional view of the NB dump along the vertical midplane. The paired Ti evaporator (not shown) is placed symmetrically with respect to the midplane.

The arc discharge runs between the Ti cathode[11] (see Fig. 2) and the grounded chamber walls, which serve as the anode. The arc current and voltage are about 200 - 250 A and 60 V, respectively, and can be varied. The Ti evaporation rate is ~ 5 - 10 mg/s, which provides the instantaneous deposition rate of ~ $(2 - 4)\times10^{15}$ Ti/(cm^2·s) on the internal surfaces of the dump. Thus, a few seconds long arc discharge can deposit several monolayers of fresh Ti coating immediately prior to the beam shot.

The incident beam is captured in the Ti coating on the dump plate, and then gets partly desorbed as (primarily) molecular hydrogen. The hydrogen concentration in Ti, which depends on many factors such as the incident flux density, beam duration, shot duty cycle, hydrogen diffusivity, coating microstructure, etc., should not be too large, because otherwise the amount of desorbed gas can exceed the incident particle load.[12] The molecular hydrogen desorbed from the dump plate is partly gettered by the Ti-coated surfaces in the dump chamber, and partly backstreams to the confinement vessel. The latter flux determines the apparent beam recycling coefficient. The dump plate was tilted so as to preferentially direct the desorbed gas into the NB dump chamber.

The NB dump was tested on a 2.6-m^3, UHV electropolished stainless steel test vessel equipped with 1000 L/s magnetically levitated turbo pump and a dry roughing pump. No plasma target was generated in these experiments.

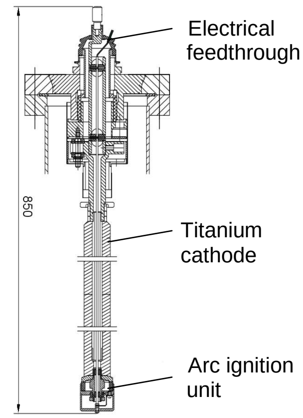

Fig. 2. The schematic of the Ti evaporator.

III. RESULTS AND DISCUSSION

The NB dump works as a high-throughput getter pump. The pumping speed for hydrogen $U \sim (2 – 5)\times10^4$ L/s was measured with a calibrated hydrogen flow. The estimated value of the hydrogen sticking coefficient on a fresh Ti film is ~ 0.03, which compares well with the average values found in the literature.[13]

To estimate the beam recycling, the neutral beam with the energy of 30 keV, equivalent atomic current of 28.4 A (particle flux Γ = 5.1 TorrL/s), and pulse duration of 3 ms was used in the experiments. The average particle load on the NB dump plate was ~ 1.5×10^{15} H/cm^2 per shot. The time behavior of the gas pressure in the test vessel (TV) and beam dump (BD) chamber, which was measured with fast ionization gauges, is shown in Fig. 3. Curve 1 - TV pressure, the beam is fired into the closed gate valve isolating the NB dump chamber. Curve 2 – BD pressure, beam is fired into an old Ti film in the dump chamber ($U \approx 0$). 3 – TV pressure, the beam is fired into a fresh Ti film in the dump chamber ($U \approx 5\times10^4$ L/s). 4 – BD pressure, the beam is fired into a fresh Ti film in the dump chamber

It is evident from Fig. 3 that the NB dump with Ti gettering reduces the beam recycling. However, the effect of interest is obscured due to the fact that the neutral beam used in this study scraped the entrance of the NB dump port. To quantify the beam recycling, we used a model based on the coupled particle balance equations for the test tank and NB dump vessel.[11] The beam recycling coefficient R is defined as twice the ratio of the flux of thermal hydrogen molecules leaving the beam dump to the incident flux of the energetic neutral atoms. We find that in terms of the neutral beam recycling, a fresh Ti film is a particle *sink* ($R \approx 0.7$), while an old Ti film is a particle *source* ($R \approx 1.4$). A fresh Ti film reduces the recycling coefficient by factor of ~ 3 - 5 as compared with a UHV electropolished and plasma cleaned wall, which is a significant improvement. The value $R \approx 0.7$ agrees favorably with the earlier observations of plasma and fast particle recycling on Ti-gettered surfaces in mirror machines.[14,15]

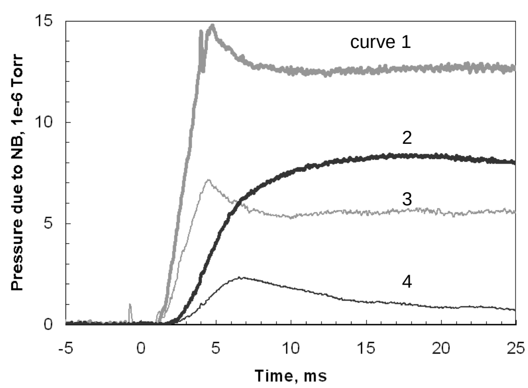

Fig. 3. The gas pressure in the test vessel (1, 3) and NB dump chamber (2, 4) due to the neutral beam. The beam is turned on at t = 1 ms and turned off at t = 4 ms.

It is important to note that the design and operating conditions of the NB dump with Ti arc gettering attained here have not been completely optimized. The flexible design of the NB dump allows us to explore alternative means to suppress the gas backstreaming into the confinement vessel. For example, a honeycomb structure aligned with the incident beam and placed in the entrance port of the dump chamber could decrease the gas conductance to the confinement vessel, and thus further reduce *R*. Furthermore, the geometry of the arc evaporator can be readily adjusted to optimize the directionality of Ti spraying.[16]

IV. CONCLUSIONS

An incomplete neutral beam capture can degrade the plasma performance in neutral beam driven plasma machines. The beam dump mitigating the recycling of a shine through beam must entrap and retain large particle loads while maintaining the beam-exposed surfaces clean of the residual impurities.

The cathodic arc gettering is a powerful and versatile technique for depositing clean metallic films in vacuum. Its potential in the fusion research applications has been largely unrealized, despite several advantages that this method has in comparison with the conventional sublimative gettering. In particular, the pulsed cathodic arc evaporation allows to getter large surface areas immediately prior to a plasma shot and to vary the average evaporation rate widely.

A neutral beam dump with a cathodic arc Ti gettering system was developed for the C-2 device, in which 1 MW, 20 - 40 keV neutral hydrogen beams are used to sustain the high-temperature field-reversed mirror plasma. The beam dump was tested with hydrogen beams having the particle flux density of 5×10^{17} H/(cm^{2}s) and duration of 3 - 10 ms. The fresh Ti film provides the beam recycling coefficient $R \sim 0.7$, which is notably less than $R \sim 1.4$ with the saturated Ti coating and $R \sim 2 - 4$ characteristic of the UHV and plasma cleaned stainless steel surface of the C-2 vacuum vessel.

ACKNOWLEDGMENTS

The authors would like to thank Professor Alexander Ivanov and Dr. Efim Bender for fruitful discussions, Rod Andow, Mark Rouillard, and Jon Schroeder for the excellent engineering support, and Dr. Ryan Clary for his help with the experiments. The technical assistance of George Strashnoy, Ed Jettón, and the TAE technical personnel is appreciated. We are grateful to the TAE shareholders for their continued support.

REFERENCES

1. F.H. COENSGEN et al., *Phys. Rev. Lett.*, **44**, 1132 (1980).
2. A. A. IVANOV et al., *Phys. Rev. Lett.*, **90**, 105002 (2003).
3. Y. ISHIMOTO et al., *J. Nucl. Mat.*, **313-316**, 194 (2003).
4. R.P. DRAKE et al., *J. Vac. Sci. Technol.*, **20**, 1288 (1982).
5. W.C. TURNER et al., *J. Vac. Sci. Technol. A*, **2**, 1576 (1984).
6. J.M. LAFFERTY, *Vacuum Arcs. Theory and Application*, J. Wiley & Sons, Hoboken, NJ (1980).
7. I. G. BROWN, *Ann. Rev. Mater. Sci.*, **28**, 243 (1998).
8. M.W. BINDERBAUER et al., *Phys. Rev. Lett.*, in press.
9. M. TUSZEWSKI et al., these proceedings.
10. E.D. BENDER et al., *Instr. Exper. Techniques*, **30**, 405 (1987).
11. A. SMIRNOV et al., submitted to *Rev. Sci. Instrum.* in June 2010.
12. B.L. DOYLE, *J. Nucl. Mat.*, **111-112**, 628 (1982).
13. K. WELCH, *Capture Pumping Technology*, pp. 195-223, Elsevier, Maryland Heights, MO (2001).
14. P.A. BAGRYANSKY et al., *J. Nucl. Mat.*, **265**, 124 (1999).
15. W.L. HSU et al., *J. Vac. Sci. Technol. A*, **4**, 1764 (1986).
16. E.D. BENDER and G.I. DIMOV, *Instr. Exper. Techniques*, **30**, 1241 (1987).