# THE PROSPECT ON THE USE OF BE MIRRORS IN A FUSION REACTOR WITH BE FIRST WALL

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Many methods of plasma diagnostics in a fusion reactor (FR) require the use of so called first mirrors (FM) disposed inside the vacuum vessel. One reason of FM degradation is the deposition on the FM surface of material eroded from the inner components subjected to most intensive plasma impact, i.e., deposition of beryllium in the case of experimental FR (ITER) with Be wall protection. Thus, in ITER only Be mirror can sustain its optical properties for long time and in the present paper results are presented of the simulation experiments on some ITER environment effects on FM made of Be. Namely, effects of bombardment by D ions on reflectance, R(λ), in the λ=220-650 nm range was studied as modelling the impact of charge exchange atoms. It was found that with high ion energy (600-1350 eV) the sharp drop of R(λ), 5-20 %, rising with decreasing wavelength of reflected light, was observed after ion fluence ~$10^{18}$ions/cm$^2$. It was supposed that under deuterium ions the BeO surface film was transformed into the $Be(OD)_2$ film accompanying by changing the refraction and extinction indices of the film, as was registered by ellipsometry measurements. Effects of ion energy and ion fluence variation on R(λ) of Be mirrors are discussed in detail.
PACS: 28.52.-s; 52.40.Hf

## INTRODUCTION

Spectroscopic and laser methods of plasma diagnostics in a fusion reactor (FR) and optical methods of controlling the state of FR inner components, require to use the first mirrors (FM) disposed inside the vacuum vessel. The FMs have to maintain the initial optical properties during the time comparable with whole FR operational time. The FM longevity will depend on the resistance to main damaging factors: neutrons and charge exchange atoms (CXA) resulting in volumetric swelling and sputtering, what increases the mirror surface roughness. The optimal choice of FM material is an actual problem of plasma diagnosing in FR, which is being solved by providing simulation experiments. One more reason of FM degradation is the deposition on the FM surface of material eroded from the inner components subjected to most intensive plasma impact. In the case of ITER FEAT the highly probable deposit on the FMs for the core plasma will consist of beryllium because a beryllium is chosen as the first wall material. If deposit grows with time, beryllium as a material for fabrication of FMs would have definite advantages compare to other metals. This is because, according to calculation, only ~20 nm thick Be film coating transfers mirror of any metal into mirror with optical properties close to ones of a bulk beryllium, as seen from Fig.1 where results of calculation are shown for reflectance of Cu mirrors with Be film of different thickness. Thus, due to re-deposition of eroded beryllium, the optical properties of in-vessel Be mirrors would be self-sustained for long time duration.

The absolute reflectance of clean Be mirror is close to reflectance of molybdenum and tungsten and rather weakly depends on the wavelength in the range 200-700 nm [1].

In this paper we give the description of some results obtained in simulation experiments provided with an aim to get data on behavior of samples of Be mirrors subjected to bombardment by ions of deuterium plasma.

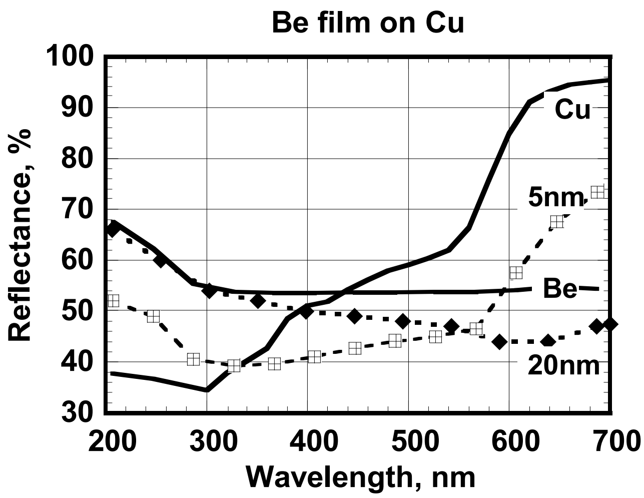


*Fig. 1. Effect of Be film coatings (5 and 20 nm thick) on reflectance of Cu mirror compare to bulk Be mirror*

## EXPERIMENT

As plasma source a cw Electron Cyclotron Resonance (ECR) discharge in deuterium at the frequency 2.37 GHz was sustained inside the stainless steel vacuum chamber placed into a double-mirror type magnetic field. Typical plasma parameters at ~400 W UHF power: $n_e$~$10^{10}$ cm$^{-3}$ and $T_e$ ~5 eV. The water-cooled holder with Be mirror samples was placed into the plasma stream flowing out of the magnetic trap and kept under a fixed negative voltage in the range of 0.02-1.35 keV. The samples were exposed to ion bombardment (with ion current density ~1 mA/cm$^2$) step by step with every step duration from several minutes to one hour.

After every sample exposure the following characteristics were measured *ex situ*: the reflectance at normal incidence (wavelengths λ=220-650 nm), the resolving power in visible, the optical indices of the surface film (by ellipsometry at λ=632.8 nm), the surface structure (by means of scanning electron microscopy), and the mass loss (accuracy ~20 μg) for controlling the erosion rate due to ion sputtering. The Be sample nomenclature included samples of TGP-56, TShP-56, HIP'd spherical powder, cast beryllium, Be film on quartz and Cu substrates.

## RESULTS AND DISCUSSION

The strongly different dependences of spectral reflectance, R(λ), on ion energy were found. For low energy (20-70 eV) ions most frequently the increase of R( λ) was registered, probably due to cleaning the surface. For much higher ion energy (0.2-1.35 keV) the sharp drop of R(λ), 5-20 % absolute, rising with decreasing wavelength of reflected light, was observed for all samples tested after ion fluence ~10$^{18}$ions/cm$^2$ [2]. The further increase of ion fluence did not result in additional, comparable in value, decrease of R(λ). Because there was not registered any mass loss of Be samples after such small fluence at the initial stage of bombardment, the sharp drop of Be mirror reflectance without any sputter erosion has to be rated exclusively as the surface effect due to impact of D ions. The most probable surface process can be a partial transformation of the BeO film, covering the Be sample, into a $Be(OD)_2$ film [3] according to reaction:

$$2BeO + 2D \Rightarrow Be(OD)_2 + Be + 0.7\ eV/D.$$

This process is accompanied by changing the refraction and extinction indices of the film, as ellipsometry measurement showed. Namely, it is known from [4] that the extinction coefficient, k, of BeO is near zero, but after $D^+$ ion bombardment, for the modified film k≈0.1 was measured at λ=632.8nm.

The Be hydroxide film is known to disintegrate slowly at room temperature, and the rate of disintegration can be accelerated with increasing temperature. In our experiments the annealing in vacuum of exposed Be samples at ~300°C during ~2 hours significantly canceled the effect of BeO layer transformation due to D ion bombardment, i.e. after annealing the reflectance of Be mirror was partly restored.

The decrement of sharp drop of Be mirror reflectance rises with increasing $D^+$ ion energy. As an example, Fig. 2 shows the experimental data on variation of decrement of the reflectance, i.e. $\Delta R=(R_E - R_0)$ for three wavelengths ($R_0$ is reflectance before ion exposure and $R_E$ - reflectance after bombardment by ions with energy E) for the same Be sample exposed to ions of different energy. The time of every exposure was 10 min, and after each exposure the reflectance was restored using a procedure described below. It is seen that the decrement rises with increasing ion energy but trends toward saturation. Such behavior of ΔR(E) can be explained by differences in thickness of transformed layer at different ion energy. The small energy ions have the short mean projected range in the BeO film and correspondingly a thin BeO outer layer is transformed into the hydroxide film. With increasing ion energy the thickness of hydroxide layer rises due to increase of the mean range of $D^+$ ions inside the oxide film and thus the portion of transformed oxide layer also grows. Fig. 3 shows the energy dependence of the calculated mean range of deuterium ions in a BeO environment. From data of Fig. 2 the energy of ions when the reflectance drop (after 10-min exposure) trends to saturate can be evaluated in the limit 1.2-1.5 keV. The comparison of Fig. 3 data with results of Fig. 2 gives the approximate thickness of the oxygen containing layer in the range ~20-25 nm what looks quite reasonable.

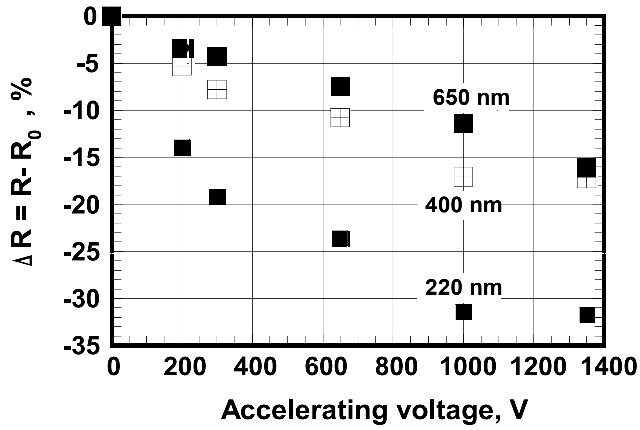


*Fig. 2. Drop of Be mirror reflectance at indicated wavelengths after 10 minute exposure to D ions with energies indicated along horizontal axis*

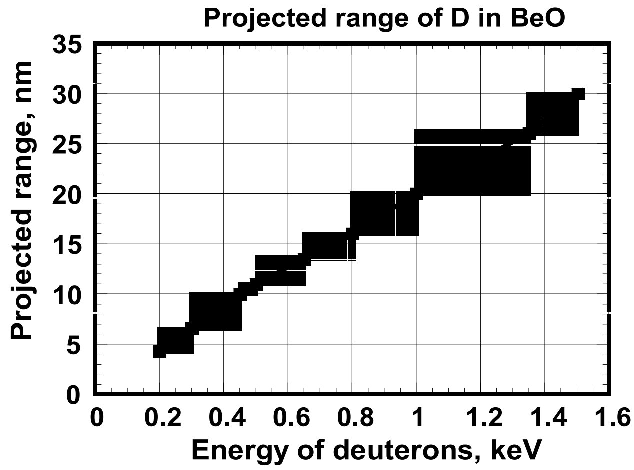


*Fig. 3. The energy dependence of projected range of D ion in the BeO environment*

To support the hypothesis that the initial sharp drop of Be mirror reflectance is only a surface effect and does not relate to surface microrelief modification, we repeated several times the operations leading to sharp degradation of reflectance and following operations resulted in restoration of R(λ). The corresponding data are presented in Fig.4. Here the dynamics of reflectance at 220 and 650 nm of one Be sample at different repeated procedures is presented: (1) – 10min bombardment by $D^+$ ions with energy 1.35keV, (2) – annealing in vacuum during 2 hours at temperature between 100-200 °C, (3) – long-time bombardment by $D^+$ ions of 70eV energy.

It is seen that the Be mirror reflectance, being sharply dropped after a short exposure (10 min) to high energy ions, can be significantly restored by combination of annealing in vacuum (1-2 hours) and by long-term (up to several hours) bombardment with low energy D ions (in different experiments the energy of low energy ions was: 20, 60, or 70 eV). As evident from Fig. 4, the exposure of Be sample to low energy ions, after its reflectance dropped due to high energy (1.35 keV) ion bombardment, is more effective for reflectance restoration than annealing at temperatures 100-200 °C. The mechanism of this low energy ions effect is not clear yet and requires additional investigations. Nevertheless, this fact allows to hope that in a fusion reactor with low energy CXA fluxes considerably exceeding high energy CXA fluxes [5], similar effect will counteract a reflectance degradation of Be mirrors.

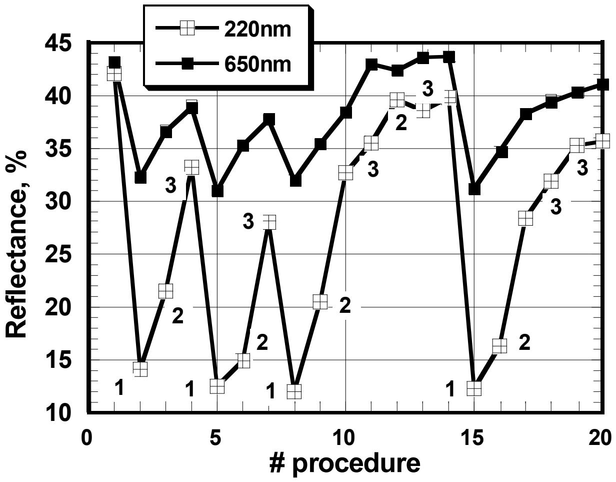


*Fig. 4. Behavior of Be mirror reflectance at two wavelengths after: (1) 10 min. bombardment by 1.35 keV energy D ions, (2) annealing at 100-200°C (2 hours), and (3) bombardment by 70 eV energy D ions (15-90 min)*

With much longer time of Be samples exposing to 1.35 keV $D^+$ ions the effect of surface modification becomes apparent, and it is strongly depended on the initial structure of mirror material. In Fig.5 such data, i.e., reflectance at 650 nm as a function of exposure time, are shown for 4 samples with their types indicated in the insert. For all samples the sharp drop of R takes place after a few minute exposure. Later on the R value decreases much slowly or does not change at all. The fastest degradation showed the Be sample pressed of practically spherical grains and the lowest – the Be samples fabricated as Be film on the Cu substrate, Fig. 5. According to estimation, the latter sample continued to maintain a good resolving power after the layer of ~2μm thick was eroded due to ion sputtering.

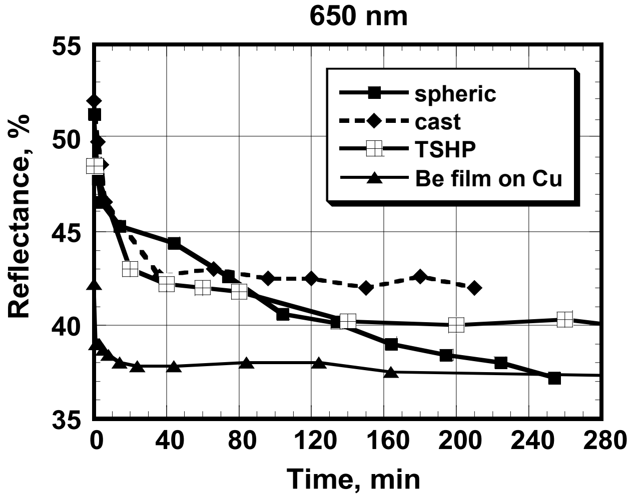


*Fig.5. Dependence of reflection for mirrors fabricated of different kind beryllium on exposure time to ions of deuterium plasma with 1.35 keV energy*

## CONCLUSION

1. The strong effect on reflectance in UV and Visible parts of spectrum was found for Be mirrors subjected to D ion bombardment. The effect depends on the D ion energy, probably due to difference of D ion ranges inside the upper BeO layer.
2. The effects of reflectivity change is hypothesized to be due to partial transformation of the BeO layer into a $Be(OD)_2$ film.
3. The annealing in vacuum of Be mirrors exposed to D ion bombardment reveals in partial restoration of reflectance probably due to backward disintegration of $Be(OD)_2$ film. A significant reflectance restoration was observed after Be mirror with transformed top layer was exposed to low energy $D^+$ ions (20-70eV).
4. The long-term effect of high energy D ion bombardment on Be mirror reflectance does strongly depend on the initial structure of material and is probably connected with surface morphology modification.

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## ПЕРСПЕКТИВА ЗАСТОСУВАННЯ ДЗЕРКАЛ З БЕРИЛІЯ В РЕАКТОРІ СІНТЕЗУ З ПЕРШОЮ СТІНКОЮ З БЕРИЛІЮ

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Багато методів діагностики плазми в реакторі синтезу (РС) вимагають використання так званих перших дзеркал (ПД), розташованих у внутрішній частині вакуумної камери. Одна з причин деградації ПД - осадження на поверхні ПД матеріалу ерозії внутрішніх компонентів, що піддавались найбільш інтенсивній плазмовій дії, тобто, осадження берилію у випадку експериментального РС (ITER) із захистом стінки з Ве. Таким чином, тільки в ITERі дзеркало з Ве може зберігати оптичні властивості протягом довгого часу, і в наведеній роботі представлені результати експериментів моделювання деяких ефектів середовища ITER для ПД, виготовленого з Ве. А саме, вплив бомбардування іонами D на коефіцієнт відображення, R(λ), у діапазоні λ=220–650 нм вивчався у рамках моделі ударного впливу атомів перезарядження. При високих енергіях іонів (600-1350 еВ) було виявлене різке зниження R(λ), 5-20 %, зростаюче при зменшенні довжини хвилі відбитого світла, яке спостерігалось після флюенса іонів ~$10^{18}$ іонів/см$^2$. Передбачалося, що під дією іонів дейтерію поверхнева плівка Ве була перетворена на $Be(OD)_2$ плівку, що супроводжувалось зміною показників рефракції і экстинкції плівки, як було зареєстровано вимірами эліпсометрії. Докладно обговорювалось вплив енергії іонів і варіацій флюенсу іонів на R(λ) Ве дзеркала.

## ПЕРСПЕКТИВА ИСПОЛЬЗОВАНИЯ ЗЕРКАЛ ИЗ БЕРИЛЛИЯ В РЕАКТОРЕ СИНТЕЗА С ПЕРВОЙ СТЕНКОЙ ИЗ БЕРИЛЛИЯ

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Многие методы диагностики плазмы в реакторе синтеза (РС) требуют использования так называемых первых зеркал (ПЗ), расположенных во внутренней части вакуумной камеры. Одна из причин деградации ПЗ – осаждение на поверхности ПЗ материала эрозии внутренних компонент, подвергавшихся наиболее интенсивному воздействию плазмы, то есть, осаждение бериллия в экспериментальном РС (ITER) с защитой стенки из Ве. Таким образом, только в ITERе зеркало из Ве может сохранять оптические свойства в течение долгого времени. В данной работе представлены результаты экспериментов моделирования некоторых эффектов влияния среды ITER на ПЗ, изготовленное из Ве. А именно, влияние бомбардировки ионами D на коэффициент отражения, R(λ), в диапазоне λ=220-650 нм изучалось в рамках модели ударного воздействия атомов перезарядки. При высоких энергиях ионов (600–1350 эВ) было обнаружено резкое снижение R(λ), 5-20%, возрастающее при уменьшении длины волны отраженного света, которое наблюдалось после воздействия флюенса ионов ~$10^{18}$ ионов/см$^2$. Предполагалось, что под действием ионов дейтерия поверхностная пленка BeO преобразовалась в $Be(OD)_2$ пленку, что сопровождалось изменением показателей рефракции и экстинкции пленки, как было зарегистрировано измерениями эллипсометрии. Подробно обсуждалось влияние энергии ионов и вариаций флюенса ионов на R(λ) Ве зеркала.