Computer simulation of thin stripper target behavior under bombardment of intense pulsed ions

S. G. Lebedev

Abstract— **(The problems of stripper target behavior in the nonstationary intense particle beams are considered. The historical sketch on studies of radiation damage failure of carbon targets under ion bombardment is presented. The computer simulation model of target evaporation under intensive pulsing beam is supposed. Lifetimes of stripper targets under intensive nonstationary beams can be described by two failure mechanisms: radiation damage accumulation and evaporation of a target. At the maximal temperatures less than 2500 oK the radiation damage dominates; at temperatures above 2500 0K the mechanism of evaporation of a foil prevails. The proposed approach has been applied to the description of stripper foils behavior in BNL linac and SNS conditions.**

Index Terms—**Stripper, bombardment, BNL, SNS.**

I. INTRODUCTION

Thin solid-state targets are widely used in the world to strip ions in charged particle accelerators. The thickness of a stripper target is defined by the type, energy, and charge state of the ions before and after stripping. The processes occurring in a target bombarded by ion beams have been the subject of numerous studies over the past few decades. Extensive research in the mechanisms of destruction of targets by ion beams has been carried out in the 1970's and 1980's—during a period of rapid development in particle accelerators and ion implantation techniques. With the recent development of high-intensity and high-energy ion accelerators at Fermi Lab and Spallation Neutron Source (SNS) in the U.S.A. and Japan Proton Accelerator Research Complex, the interest in studying the processes of failure of solid-state targets under ion beam bombardment has been renewed. From the point of view of obtaining the highest charge states of a beam, loading of the vacuum system, and small overall dimensions, solid-state strippers are preferred compared to gaseous strippers. The main disadvantage of all solid-state strippers is their limited service life, which limits the overall performance of accelerators and raises the radiation load of service personnel. From the first use of thin strippers until now, there has been a struggle to improve their manufacturing techniques with the purpose of increasing their lifetime. The wide use of carbon as a material for thin stripper targets is explained by its high melting point and mechanical strength. Because of its small nuclear mass carbon introduces minimal distortions to the parameters of a particle beam. In the late 1970's a prospective method of manufacturing carbon foils was developed—the cracking of hydrocarbon in glow discharge [1]. This method has been used for a long time for the manufacturing of long lifetime carbon foils. Later on, the method of manufacturing carbon foils by means of laser ablation was developed [2]. Longer lifetime foils were produced by this latter method. Recently, a significant improvement in the technology of making thin solid-state targets and increasing their lifetime took place at KEK [3], where a whole series of methods of manufacturing of carbon targets has been developed. These methods are the controlled DC-arc discharge, the controlled AC-arc discharge, the mixed ionic beam sputtering, the high ion beam sputtering, and other methods.

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II. INFLUENCE OF RADIATION DAMAGE ON THE FOIL LIFETIME

The author of this paper has devoted some years to the research of behavior of thin film targets under ion bombardment [4-8]. In Ref. [4] the relation described the lifetime of a carbon foil has been deduced from the first principles of physics of radiation defects and the stress-deformed condition of solid state. It is known that under irradiation in the solid state two kinds of point radiation defects are created - the displaced atoms (or interstitials) and vacancies. The displaced atoms possess a high mobility. Most of them annihilate with vacancies in a lattice, and the rest form the molecular complexes. The sizes and number of the complexes depend on the temperature of irradiation, the defect generation rate, etc. The vacancies formed during irradiation usually remain isolated and inactive at low temperatures, but at high temperatures they also become mobile. As a result of irradiation, there is an accumulation of radiation defects, which deforms the crystal lattice. Around the vacancies there is a compression of the lattice. Due to the mobility of the displaced atoms a number of them recombine with the vacancies, and the rest create the complexes. As a result, a considerable amount of vacancies remain isolated and cause all-around compression of the crystal lattice. The deformation of the lattice causes internal pressure in the foil. If this pressure reaches the ultimate strength of a foil, it fails. This is a destruction picture of carbon foils under irradiation, which creates a physical basis for evaluation of their lifetime. Omitting the detailed calculations, presented in [4-6], we shall write out the resulting relation for the lifetime:

$$t = 0.23\left(\frac{3\rho_i\sigma_P}{\xi\Delta\rho\, M}\right)^{\frac{3}{2}} \frac{\nu^{\frac{1}{4}}}{K_d^{\frac{5}{4}}} \exp\left(-\frac{E_m^i}{4k_BT}\right). \qquad (1)$$

Here, σ_P is the ultimate strength, M - the elasticity module, ν - the oscillation frequency of atoms in the lattice ($5{\cdot}10^{13}$ *Hz*), E^i_m – the migration energy of the displaced atoms in the foil, k_B – Boltzmann's constant, $\Delta\rho = \rho_i - \rho_f$ – the change of density of a foil material due to irradiation, ρ_i – the density of the initial phase, ρ_f – the density of the final phase. The factor ξ

defines the conditions of fastening a film on the frame (in case of rigid fastenings of a flat foil on the frame $\xi = 1$).

For estimation of the rate of atom displacement it is possible to use the well-known expression:

$$K_d = \frac{S_n \bar{\varphi}}{2E_D}, \qquad (2)$$

where S_n characterizes the energy losses of a moving particle on the defects production. The expression for S_n, describing the experimental data on elastic scattering of ions on atoms, looks like this used in [9]. The migration energy E^i_m of the displaced atoms is related to the crystallite melting point T_m by means of the expression:

$$E^i_m = kT_m. \qquad (3)$$

Then for *GD* – foils the resulting formula for calculation of the lifetime can be written as follows [4]:

$$t = 50K_d^{-\frac{5}{4}} \exp\left(-\frac{870}{T}\right). \quad (4)$$

The last expression has been used for the carbon stripper lifetimes and their comparison with the experimental data. The calculated results have been found to be in good agreement with the measured lifetimes for foil types *GD* and *CA* [4-5].

III. EVAPORATION OF A TARGET BY AN INTENSE PULSING BEAM

In the designing of intense accelerators of the charge particles, such as *SNS*, the estimation of the lifetime of stripper targets is important for definition of efficiency and radiation load on the personnel. Modeling the stripper targets behavior under irradiation at *SNS* was carried out at the *BNL* linac [10]. Parameters of a H^- beam at *SNS* and modeling beam at *BNL* are presented in Table 1.

Table 1.The parameters of H^- beams at *SNS* and *BNL* linac according to Ref. [10].

	Energy	Duration of an impulse	Frequency	The maximal current	The beam size
SNS	1 GeV	1 ms	60 Hz	32 mA	3x2 mm^2
BNL linac	750 keV	0.5 ms	6.7 Hz	2.02/2.2 mA	3 mm dia

For the analysis of the behavior of the *SNS* stripper target except for radiation damage it is necessary to also consider the evaporation due to intensive heating by the circulating H^+ beam.

The energy losses of a bombarding beam in a target due to multiturn injection leads to heating up to 2500 – 4800 ^oK. This leads to sublimation of atoms from the surface of a target and its thickness decreases. On the other hand, with reduction of thickness, beam energy losses decrease. Therefore the temperature of the target decreases, the process of sublimation slows down, and the thickness of a target gets a new stationary value $h_1 < h_0$. Thus, the processes of heating, sublimation and change of thickness of a target are interdependent, and they must be taken into account in the description of evaporation of a target under irradiation. Unlike the case of stationary heating, the feature of loading of stripper targets at *SNS*, *BNL* and many other new facilities is a pulsing character of a bombarding beam. The average temperature of a target at $h_0 = 200\ \mu g/cm^2$ makes only 997^oK therefore the evaporation is improbable. However, calculations [10] show that at the same thickness the peak temperature in an impulse reaches 2350^oK. Therefore, in the analysis of experimental data on the behavior of a target at *BNL* linac conditions it is important to consider the pulsing character of the H^- beam. The feature is that the evaporation occurs in that time interval of an impulse when the target is bombarded by ions, and the temperature of heating exceeds the threshold of sublimation.

For the adequate description of heating, cooling and evaporation processes in a pulsing mode we use a non-stationary heat conduction equation. Detailed deriving procedure of thermal equations has been described in [11]. As a result, for the description of the interconnected processes of heating and evaporation of a foil in a pulsing beam of ions, we can obtain the following set of equations:

$$\frac{dT}{dt} = \frac{1}{C(T)h(t)}\left(P(t) + 2\varepsilon\sigma_0 T_0^4 - 2\varepsilon\sigma_0 T^4(t)\right), \qquad (5)$$

$$\frac{dh(t)}{dt} = -8{,}12 \cdot 10^{10} \frac{\exp\left[\frac{-83500}{T}\right]}{\sqrt{T}}, \qquad (6)$$

where $P(t)$ is the pulse power, which is defined in [13], T_0 - an ambient temperature, ε – the radiating ability of a foil, $\sigma = 5.67 \cdot 10^{-12}\ W/cm^2K^4$ – Stephan-Boltzmann constant. In equation (5) the dependence of a thermal capacity C vs. temperature is used in the form of [12].

The solution of the set of equations (5) - (6) was made by numerical methods by means of the program *MATLAB7.0* (The Math Works, Inc.). In Fig.1 the calculation results of temperature of a *BNL* linac target are presented for the first second of irradiation at a pulse current of protons of *2 mA*. The contribution of stripped electrons to foil heating can be estimated as follows. Each *1 GeV* proton comes in with *2* electrons, and each electron has *545 keV* of kinetic energy. The total electron energy is about *1.6 kW* which is substantially less compared to *2 MW* from protons. Note: only a small fraction of the electron energy is deposited into the foil.

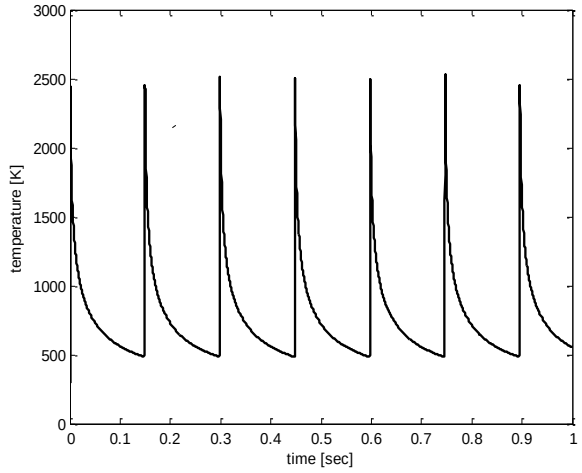

Fig.1. A temperature field of a *BNL* linac target in the first second of work at a pulse current of *2 mA*.

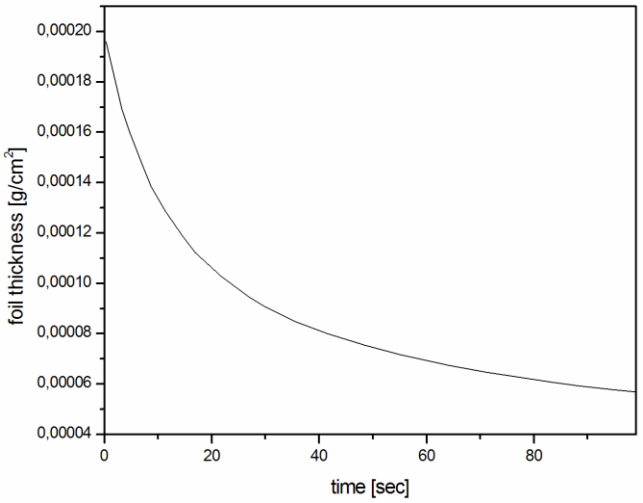

Fig. 2. Nonlinear foil thickness decreasing caused by the reduction of temperature at the *BNL* linac pulse current of *3 mA*

The resulting maximal temperature is 2532 ^{o}K, which exceeds the value of 2350 ^{o}K, obtained for the similar case in [10]. The distinction can be caused by using a temperature-dependent thermal capacity. The offered algorithm of calculation is powerful to account for the effect of influence of heating and evaporation. In Fig.2 and Fig.3 the dependences of temperature and thickness of a foil vs. irradiation time of a pulsing beam of *BNL* linac with a pulse current of *3 mA* are shown. As it is possible to see, the evaporation rate and a temperature of a foil vary during the time. Such behavior can be explained in terms of interference of heating and evaporation. The results of calculation of a lifetime of a target are presented in Fig.4 (please compare with Fig.4 of [10]). For this calculation it was supposed that the lifetime corresponds to a reduction of the foil thickness by a half, though the given approximation demands further refinement. In the experiments [10] the target lifetime was defined as the time of reduction of the current through the foil by *10 %*. There is a question: to what change in thickness does the given change in current correspond? For the answer it is necessary to measure the dependence of change in current behind the target vs. change in its thickness. In Fig.4 the results of calculation of the lifetime of a target at the *BNL* linac conditions, according to the mechanism of radiation damage are also presented. It is seen that for maximal temperatures less than *2500* ^{o}K the radiation damage dominates; at temperatures above *2500* ^{0}K the mechanism of foil evaporation prevails. As can be seen these two complementary pieces of dependence of foil lifetime vs. maximum temperature well describes the experimental data of work [10]. In the case of foil evaporation we use the universal critical parameters for saturated vapor of carbon. This means that in terms of evaporation there is no difference between various kinds of carbon materials such as graphite and diamond. So it is supposed that the lifetime of various kinds of carbons under evaporation is the same. As for the *SNS* stripper foil conditions presented in Table 1, our calculation shows that the maximum foil temperature of *2650* ^{o}K and the corresponding foil lifetime of *0.5-1 hours* can be obtained, which is limited by the evaporation process. As can be seen there is more than *30%* decrease of the *SNS* stripper foil lifetime as compared with the modeling *BNL* linac case of Fig.4, which can be attributed to the difference in the beam time structure. More exact evaluation of *SNS* stripper foil lifetime can be obtained by refining of the differential equations (5-6) to account for the thermal conductivity and beam intensity distribution across the hot spot. A detailed computer simulation of the *SNS* foil temperature distribution accounting for the pointing beam properties is presented in Ref. [14].

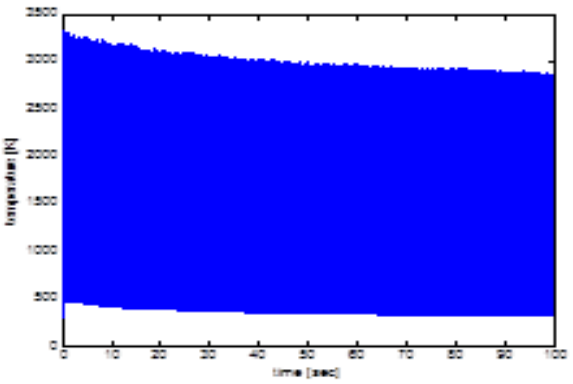

Fig.3. Deformation of a temperature field in a target of *BNL* linac, caused by the decreasing of the foil thickness due to its evaporation.

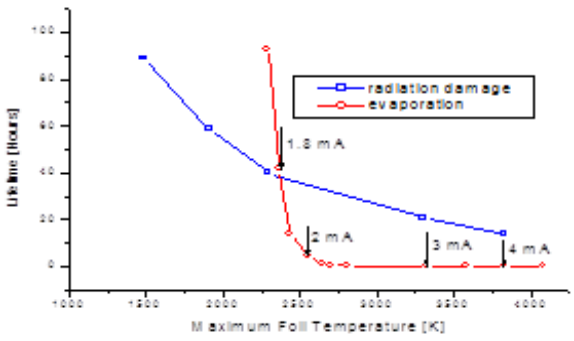

Fig.4. Calculated dependences of the lifetime of *BNL* linac foil due to processes of radiation damage and evaporation.

IV. CONCLUSIONS

1. Lifetimes of stripper targets under intensive nonstationary beams can be described by two failure mechanisms: radiation damage accumulation and evaporation of a target. At the maximal temperatures less than $2500\ ^{o}K$ the radiation damage dominates; at temperatures above $2500\ ^{0}K$ the mechanism of evaporation of a foil prevails.
2. The time structure of a pulsed beam can influence the lifetime.

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