NUMERICAL SIMULATIONS AND EXPERIMENTAL ASPECTS OF SPACE CHARGE COMPENSATION IN A HIGH ENERGY ELECTRON BEAM

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Abstract

A high energy electron beam tightly focused on a heavy material target is used to generate X-rays from bremsstrahlung interaction in order to make radiographic experiments. During the interaction, the energy deposited heats the target, vaporizes its compounds and ionizes the vapor. The self potential of the electron beam accelerates the ions such created which contribute to a time dependant space charge compensation. As a consequence the size of the beam at the focal point is not kept constant in time and degradation of the the quality of the photon source is observed, except if proper control of the ion emission is done. We present both theoretical and numerical simulation aspects of this phenomenon that has been studied in our laboratory. Among possible solutions to counteract the effect of the ions, we have designed a self-biased target configuration which has been tested successefully on the PIVAIR accelerator facility at CESTA. Experimental results are reported.

1 INTRODUCTION

Radiographic machines such as AIRIX make use of an intense relativistic electron beam (20 MeV, 3 kA) striking a high Z target to generate bremsstrahlung radiation. The high-resolution required by the radiographic chain implies that the electron beam should be focused on a millimeter-sized spot for the duration of the pulse. For this purpose the beam which is accelerated through a linear induction accelerator machine has to be tightly focused on the target during the final focusing scheme. Among effects likely to occur in limiting the spot size, the local change of the focusing force due to ions originated in the target and accelerated backstream in the electron beam, was proposed by several laboratories[1]. In absence of any ion, space charge forces for a relativistic beam balance and spot size is fixed once emittance, momentum spread, lense aberrations and beam instabilities are taken into account. As soon as ions are created, they are accelerated in the axial field produced by the beam at the target surface and move upstream in the electron beam. The net electrical charge is compensated by the presence of the ions and the balance between focusing forces is upseted. Focus is then altered and time dependent behavior is observed. Beam pinches at the target surface until a minimum size which depends upon the emission current drawn from the target. Then the size grows corresponding to the propagation of the ions in the electron beam channel. The time at which the minimum size is reached depends upon the time delay required to emit a substantial part of Child-Langmuir emission current and upon the ion charge to mass ratio.

2 MODEL FOR ION PRODUCTION

The relativistic electrons of the high intensity beam I, with section ΔS, deposit high amount of energy in the target by ionisation and by bremsstrahlung emission[2]. The energy deposit at the target surface induces temperature rise until vaporisation. The metallic and impurity species are thus emitted with atomic and ionic charge states concentration depending upon the surface temperature. We build a model based on multiple scattering theory to estimate the energy and particle balance for electrons and photons, as well as the absorption, transmission and backscattering coefficients. In this transport model of the electrons in matter, we take into account the multiple scattering process, following Moliere’s theory[3] with both angular distribution and mean spatial position and the energy losses by ionisation (Bethe’s formula) and bremsstrahlung radiation. The results are in good agreement with those obtained with monte Carlo simulations. The energy deposited at the target surface by unit length, $(dE/dx)_0$ contains the following contributions : the ionisation process of the direct and backscattered electrons. The target ablation is calculated in the following way. The density and the pressure at each part of the discontinuity frontier (in the solid and in the vapor) are obtained by solving the shock wave equation at the discontinuity. The temperature T of the vapor expanding from the target derived by solving the energy equation [4] is given by

$$T(t) \cong T(0) + \frac{1}{a}\left\{ \frac{I\,t\,(dE/dx)_0}{\rho\, e\, \Delta S} - b - \frac{2}{r}\int_0^t \left\{ \left[(aT+b) + \frac{P_s}{\rho} \right] \sqrt{\frac{\gamma RT}{A}} + \frac{\varepsilon \sigma T^4}{\rho} \right\} dt \right\}$$

where $a = c_v + \frac{R}{2A}\left(\gamma + 3\sum_{z=1} z\frac{n_z}{n} \right)$, and $b = \frac{N_a}{A}\sum_{z=1}\frac{n_z}{n}E_{z-1}$.

The target has atomic mass A and specific gravity ρ ; e is the elementary charge, R the gas constant, $\gamma = c_p / c_v$, n_z is the density of the ion with charge z, n is the total atomic density of the metal, N_a is the Avogadro number, E_{z-1} is the total ionisation potential, ε is the total emissivity and σ is the Stephan-Boltzman constant. The term b corresponds to the energy stocked in the excited and ionized levels. The first term under the integral corresponds to the energy loss by the hydrodynamical expansion and the second term corresponds to the energy carried out by the blackbody radiation (the latter gives a small contribution). The thermal conductivity is neglected here because the characteristic time of conduction of heat is larged compared to the beam pulse duration. The ionization rates at each part of the frontier are determined by assuming the Saha equilibrium. The vapor pressure P_S is considered to follow the Clapeyron-Clausius law in the target region and the perfect gas law is used in the vapor region.

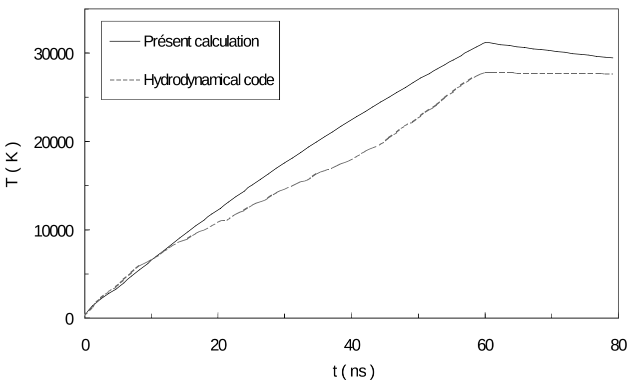

Fig. 1. Surface temperature of a tantalum target on PIVAIR device. Incident beam energy : 7.2 MeV, ion beam current : 3 kA, beam radius : 1 mm, pulse length : 60 ns.

The ionization rate of the singly charged ion in the vapor is thus given by

$$\tau_1 = 1/\sqrt{1+\frac{P_s}{g\ kT\left[1+\gamma(1-u)\right]}}\ ,$$

with the Saha law : $g=\frac{n_1 n_e}{n_0}=2\frac{Z_1}{Z_0}\left(\frac{2\pi\, m_e kT}{h^2}\right)^{3/2}\exp\left(-\frac{E_0}{kT}\right)$,

where $u=\frac{1+1/\gamma}{2}\left[1-\sqrt{1-\frac{4P_s m}{(\gamma+1/\gamma)^2\rho\, kT}}\right]$. The temperature rise represented in Fig. 1 is in satisfactory agreement with the one obtained by an hydrodynamical code, (the ionization rate of an uranium vapor is close to that obtained experimentally). The ionization of the expanding vapor by the electron beam and by the backscattered electrons is also taken into account. The release of impurities absorbed in the metal, as H, C, N or O, is also modeled. The total available ionic emission current of ions Ta^+ and H^+ produced in the vapor are represented versus time in Fig.2. It can be seen that the Child-Langmuir currents of the ions H^+ and Ta^+ are reached respectively at about 6 and 9 ns.

The total ion current thus calculated includes both contributions from the metal species constituting the target and from the contaminant elements. The result is introduced in a PIC Maxwell code in order to calculate the transport of the ions in the electron beam.

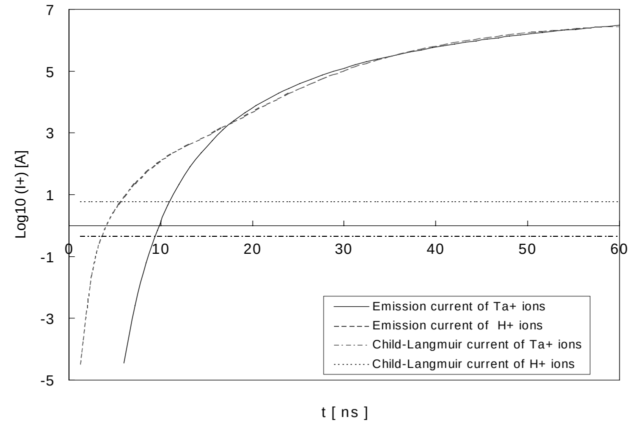

Fig. 2. Total available emission current of ions Ta+ and H+ on PIVAIR device, where H is absorbed in the target

3 TIME DEPENDENT FOCUSING EFFECTS DUE TO BACKSTREAMING IONS

Computer simulations of the interaction of the electron beam with the target were carried out using a two-dimensional, self-consistant, relativistic particle code named M2V[5]. The electron beam, initiated at the outer boundary is set with a finite emittance. An external magnetic lense focuses the electrons on the target to the initial desired spot size. We have first studied the ion emission effects on spot size versus time for light ions, as contaminants and for metallic ion emission from the target in the case of space charge limited current.

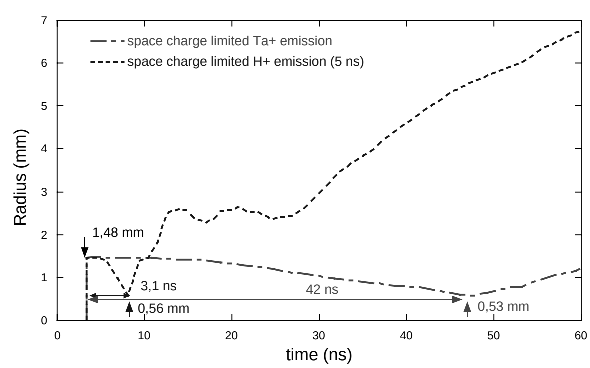

Fig. 3 : Time evolution of the beam radius for Ta^+ and H^+ ions in the case of Child-Langmuir emission law

Fig.3 shows the evolution of the beam radius at the target surface versus time. Total beam duration is 85 ns (rise and decreasing time are about 10 ns). Beam over focusing is always observed and the minimum size is reached after a time delay. This delay corresponds to the time for the production of the ions and the time of flight of the ions in the electron beam. The waist moves upstream the electron beam and leads to the defocusing of the beam at the target. This effect occurs more quickly and with a greater amplitude with the ratio z/m i.e for light ions as H^+. Depending upon the current extracted from the target, over focusing and defocusing are weaker. We see also that Child-Langmuir is reached after a short while and that only a burst of about 10 ns of ion emission is sufficient to produce the same behavior.

4 TRAPPING OF IONS USING A SELF-BIASED TARGET TECHNIQUE

The experimental set up of the self-biased target experiment designed to trap the ions in the target electric field is shown in Fig.4. The magnitude of the self-biased voltage is chosen by selecting a desired value of the equivalent radial resistor made of 4 resistor bars in parallel. The electrical resistance can be easily varied by replacing the entire set. Experiment where carried out with the PIVAIR induction accelerator which is a 7.2 MeV 3 kA facility. The electron charge deposited in the target assembly establishes a biased potential on the tantalum target. To start with, we plotted the electron beam diameter versus the magnetic lense focusing in order to determine experimentally its minimum value using the OTR method. A 2 mm beam diameter has been thus obtained. Radiographic measurements were then carried on 1.2 mm thick tantalum target in the configuration where the target is short circuited to ground. In absence of self-biased voltage, the diameter of the radiographic spot, measured using the roll-bar method was 6 mm. For a resistance value of 150 ohms a bias potential of approximately 350 kV , deduced from the current flowing through a Rogowski coil, was developped at the target surface. This voltage allowed to trap the ions, thus limiting their axial motion. As a result, a reduction of the diameter of the radiographic spot down to about 3 mm has been observed. The stabilisation of the electron beam size versus time from numerical simulations is shown in Fig.5.

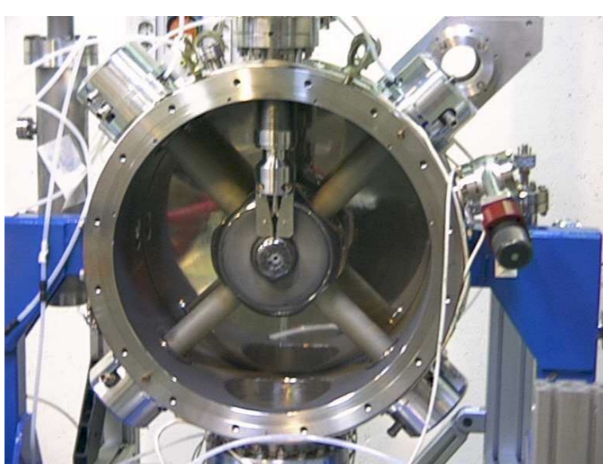

Fig.4 : View of the target assembly in the converter chamber

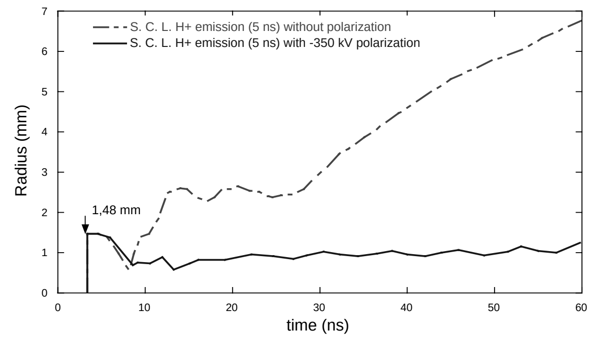

Fig.5 : Time evolution of the beam radius with 350 kV self-biased potential applied (simulation is for H+)

5 CONCLUSION

It is found that the energy deposited at the target surface is sufficient to produce ions in a large amount allowing to satisfy the Child-Langmuir condition. On the other hand, computer simulations revealed that light ion emission such hydrogen can initiate focusing and stronger defocusing than metallic ions from target for the duration of the beam pulse. It has been also shown that control of the ion motion can be obtained if appropriate voltage is applied to the target. An indirect experimental evidence of the ionic emission is obtained by self-biasing the target to retain the ions near its surface. Another way to prevent the effects of the ionic emission is to remove the target from its contaminants, especially the light ones. It has been found that if hydrogen is absorbed in only 20 monolayers, the ionic effects remain small since emission current is well under Child-Langmuir limit. In order to remove the contaminants, electron beam of 10 keV or laser process in the UV range could achieved the cleaning in a minimum depth of 50 µm. We expect to test experimentally these solutions.

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