EXPERIMENTAL RESULTS OF ELECTRON BEAM NEUTRALIZATION INDUCED BY A LIMITED SPACE-CHARGE EMISSION

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Abstract

At the exit of the flash X-ray photography accelerator AIRIX, an intense relativistic electron beam (4 kA, 16-20 MeV, 80 ns) impinges on a high-Z target. The quality of the radiograph obtained is directly tied to the properties of the electron beam (RMS size and position, energy and current).

In a study on the LELIA linac (1 to 2 MeV, 1 kA) to study optical diagnostics, a very strong time-dependent focusing effect near the target was observed. The size of the spot emitting Cerenkov light was found to vary with time during the beam pulse. This observation was confirmed on the last Optical Transition Radiation (OTR) studies with the PIVAIR linac (7.2 MeV, 4 kA, 80 ns).

After analysis of this experimental results, an explanation of the effect in terms of the emission of positive ions by the target, and their subsequent tendency to move upstream has been simulated using a PIC code. The results support the concept of backstreaming ions adding an additional time-dependent focusing force that acts on the electron beam.

1 THE EXPERIMENTS

After a short description of the experimental set-up, we present the observed phenomena. An hypothesis is proposed to explain this observation.

1.1 Description of the accelerators and the optical diagnostics

Two different induction linear accelerators have been used. The first, LELIA, delivers a 1 kA electron beam with an energy up to 2.2 MeV. Initially developed to perform microwave FEL experiments [1-2] it has also been used as a test bed for the AIRIX induction accelerator [3], in particular for beam transport studies and diagnostics development.

The second, PIVAIR, is the prototype of AIRIX. It operates at 3.5 kA with an energy from 3.5 MeV up to 7.3 MeV.

At low energy, as in the case of LELIA, the optical observation is based on the emission of Cerenkov light which occurs when the beam hits a transparent target. The analysis of a part of this light, collected by optical cameras, allows us to measure the e-beam transverse dimensions [4]. Above 3 MeV, as in the case of PIVAIR, our optical diagnostic is based on the OTR [5] process.

Figure 1 presents the two different configurations we have adopted.

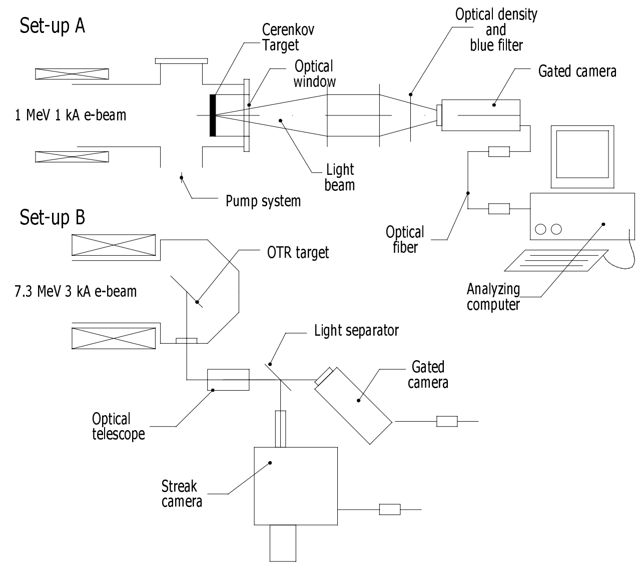

Figure 1: Schematic drawings of the two different set-up.

1.2 Results of the observation

During a "Cerenkov" measurement which used a 1 mm-thick fused silica foil (set-up A), we have observed a dependence of the beam radius as a function of time. Neither the beam current nor the beam energy exhibit a time variation fast enough to explain this behavior. An empirical solution has been found to reduce this effect by coating the target with aluminum to increase its conductivity. An example of the results obtained is given in Figure 2.

2 THE IONIC EMISSION HYPOTHESIS

2.1 General description

It is well-known that [6-7] the energy deposited in a target by an electron beam can produce free positive ions. In our case, their dynamic behavior is very interesting. The strong axial electric field generated near the target can accelerate and propagate upstream this ionic current to the primary beam. This mechanism is different from the one described in the references mentioned above. A neutralization of the strong electron beam current can appear and explain its focusing to small radii.

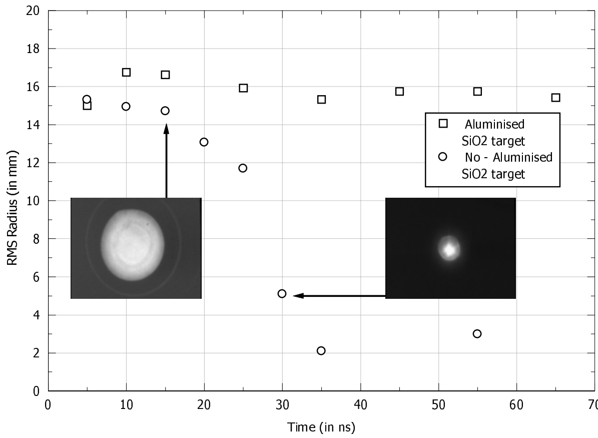

Figure 2: Behavior of the beam radius as a function of time. Two Cerenkov images of the beam at different times show its convergence.

2.2 *Analytical approach*

A simple model can be used to take into account the effects of the ions in the calculation of e-beam transport. We have computed the stationary longitudinal electric field generated by the e-beam itself [8]. By neglecting its transverse variations we have shown that close to the target, the electric field variations with z can be linearized. Then, the motion of the ions in this field can be calculated and the corresponding space charge-limited current is given by the following equation:

$$I_{ion} = \left(\frac{e}{M\varepsilon_0}\right)^{\frac{1}{2}} \left(\frac{I_e}{\pi\, c}\right)^{\frac{3}{2}} \qquad (1)$$

where M is the ion mass, e the elementary charge, I_e the e-beam current and c the light velocity. The ion energy becomes constant after a distance at which the electric field vanishes and is given by:

$$E_{ci} = \left(\frac{3\,e}{\pi^3 \varepsilon_0\, c}\right) I_e \qquad (2)$$

If the e-beam current is 1 kA we find a proton current of 4 A and a maximum energy of 40 keV. These 2 values can be used to introduce a neutralization factor in the space charge term of the envelope equation in order to determine the influence of the ionic emission on the radius of the electron beam. The results of this calculation have shown a substantial focusing effect over in the pulse duration.

2.3 *"PIC" simulations*

We have developed a "Particle In Cell" code to simulate the experiment. It uses a 2D "Maxwell-Vlasov" algorithm in a cylindrical space. The electron beam initial conditions are determined thanks to the transport code ELECTRA [9]. Different species of ions are generated at the target position, the electromagnetic field and the particle dynamics are computed in order to obtain the effects of the ions on the electron beam radius.

3 COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

3.1 The parameters of the simulation

The main parameters are the mass and the charge of each kind of ion, their production rates and their initial energies. We have compared the experimental results by considering only protons. Their production rate is chosen to obtain the limited space charge ion current and they are emitted with a kinetic energy close to zero (10 eV).

3.2 Variations with the beam density

In the case of the experiment performed with the LELIA linac, we have varied the magnetic fields of the guiding coils in order to obtain, at a fixed total current, different values of the initial e-beam size, i.e. different beam densities. The current density has a strong influence on the evolution of the beam radius as a function of time. As shown in Figure 3, the higher the beam density the earlier the focalisation appears.

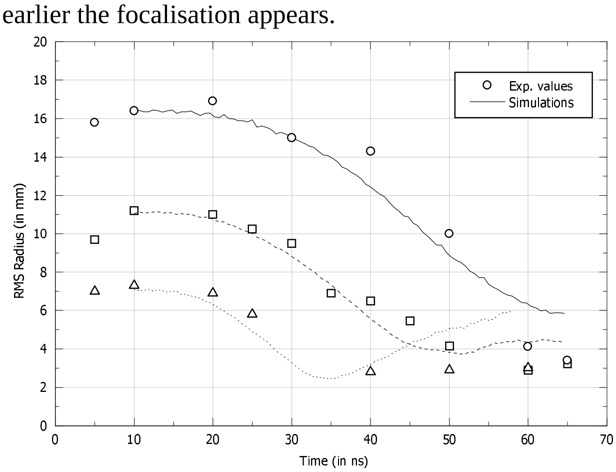

Figure 3: Numerical and experimental behavior of the beam radius versus time for three different initial beam densities.

4 OBSERVATIONS ON PIVAIR

The existence of this phenomenon, which has been observed with LELIA at CESTA as well as at LANL with ITS [10], has to be understood in order to evaluate its effects on the final focus of the AIRIX accelerator. Consequently, we have installed the experiment at the PIVAIR facility (Set-up B, figure 1).

4.1 OTR Time resolved measurement

The behavior of the e-beam size has been measured with an OTR diagnostic. The optical system was developed to obtain both the transverse dimensions of the beam with a 5 ns gated camera and a time resolved 1D image with a streak camera. In this way, we are able to know the position of the slit of the streak camera in the transverse beam spot. Two images from the streak camera are displayed in Figure 4. They have been obtained for two distinct initial electron beam radii. As in the case of LELIA, we observe a variation of the radius during the beam pulse. It appears earlier for the small radius which corresponds to a higher beam density. The images from the gated camera exhibit the same behavior. Furthermore, these images reveal an unexpected bump in the beam transverse profile.

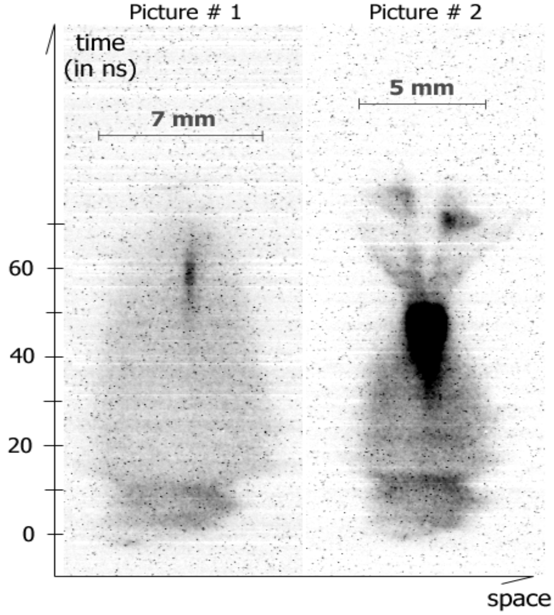

Figure 4: Examples of time resolved OTR images for 2 different beam radius at the target position.

4.1 Time behavior of the radial beam profile

The radial profile of the beam as a function of time has been studied and compared with the results of the PIC code. In Figure 5, we present the charge density of the electron beam at different times, both for LELIA and PIVAIR, the experiment shows a bump on the axis which blows up as the time increases. The numerical results reproduce this effect as indicated in the figure 5 for the LELIA case. We think this behavior, associated with the decrease in beam radius versus time, is the signature of the ionic focusing effect. It is present in the PIVAIR experiment though the beam parameters are very different. Consequently, the ionic focusing could be of prime importance in a higher energy accelerator like AIRIX.

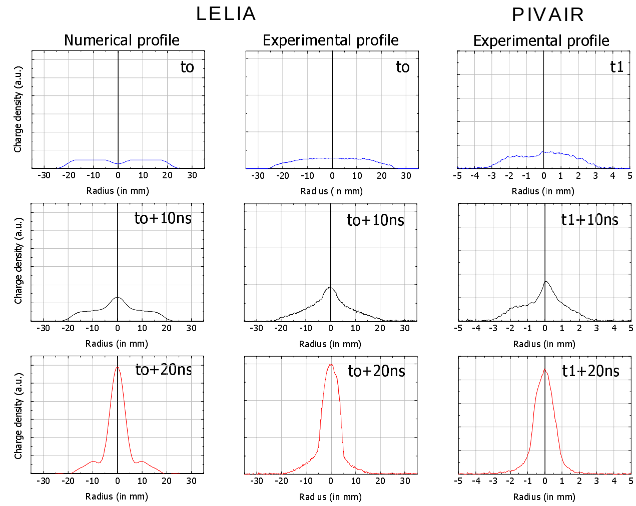

Figure 5: The structure of the e-beam radial profile versus time. The signature of the "ionic effect" appears with the two different accelerators.

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